The future of flavour physics at LHCb Upgrade II

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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.

"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

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:

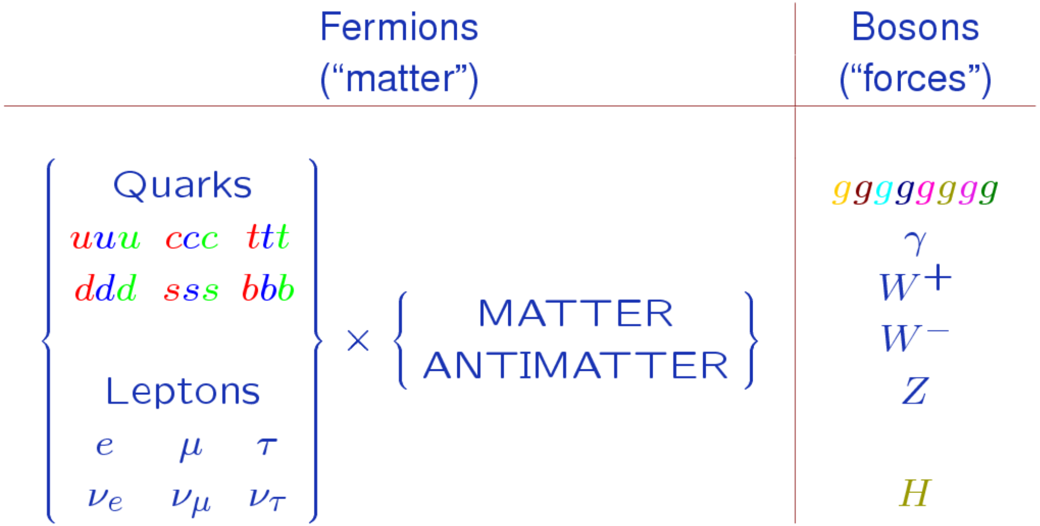
- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity

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?



Can be studied with leptons and light quarks,
but the b quark is especially interesting
[which means studies of b hadrons – important role of QCD)]

The CKM matrix

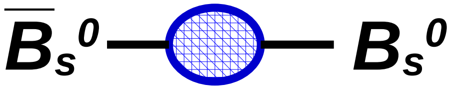
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

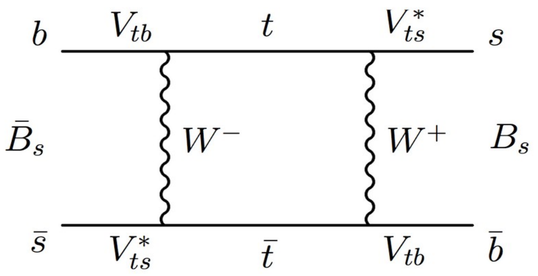
- A 3x3 unitary matrix
  - Encodes relative misalignment of mass and flavour bases that arises in the Standard Model following electroweak symmetry breaking (Higgs mechanism)
- Described by 4 real parameters – allows CP violation (KM: Prog.Theor.Phys. 49 (1973) 652)
- Highly predictive
  - Describes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

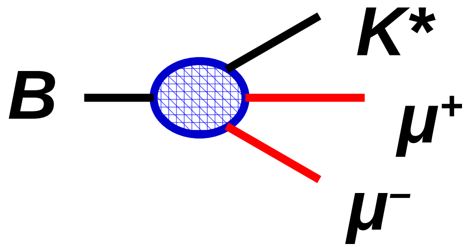
… the b quark is especially interesting
[which means studies of b hadrons – important role of QCD)]

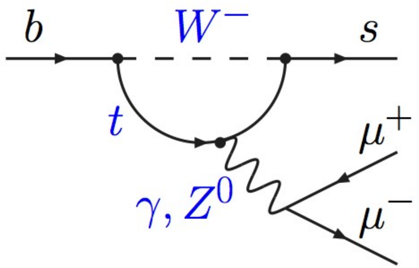
Seeing and inferring

- 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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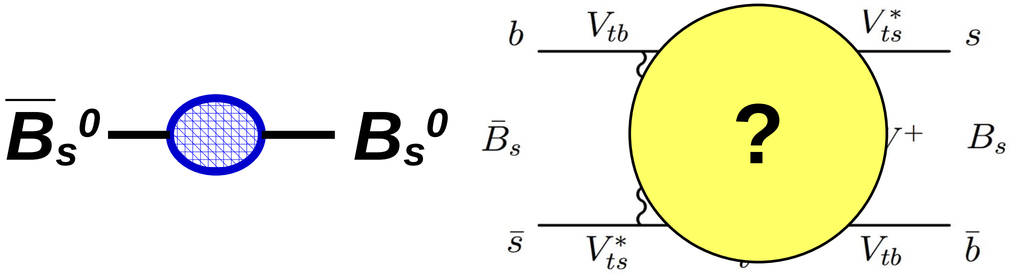
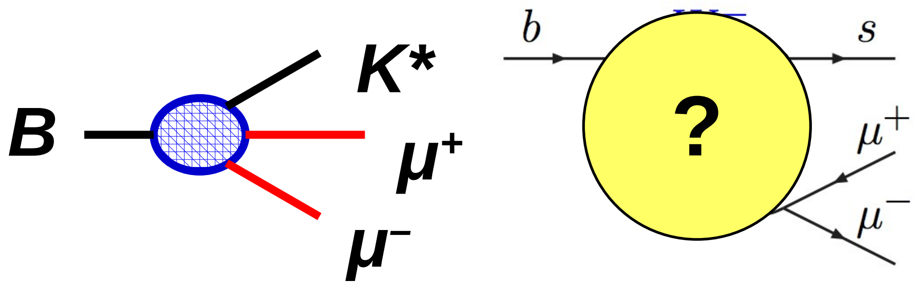
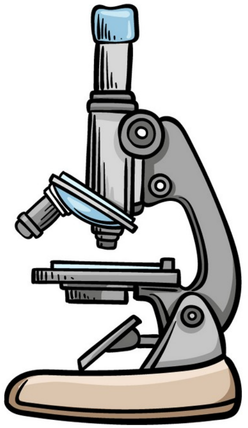
? could be at O(10 TeV)





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

Heavy flavour production at hadron colliders

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\mathrm{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\mathrm{TeV}$) LHC
Production cross-section	1 nb	$\sim 100\,\mu\mathrm{b}$	$\sim 500\,\mu\mathrm{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\mathrm{kHz}$	$\sim 500\,\mathrm{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B^0_s (10%), Λ^0_b (10%), others (< 1%)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

Enormous!

Potentially overwhelming background; can be overcome with **precision vertexing** ...

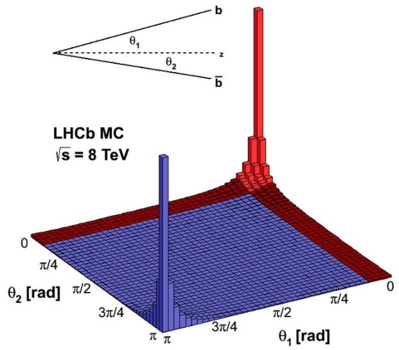
... for which the high boost helps

Many channels can be studied; need **excellent PID and mass resolution**

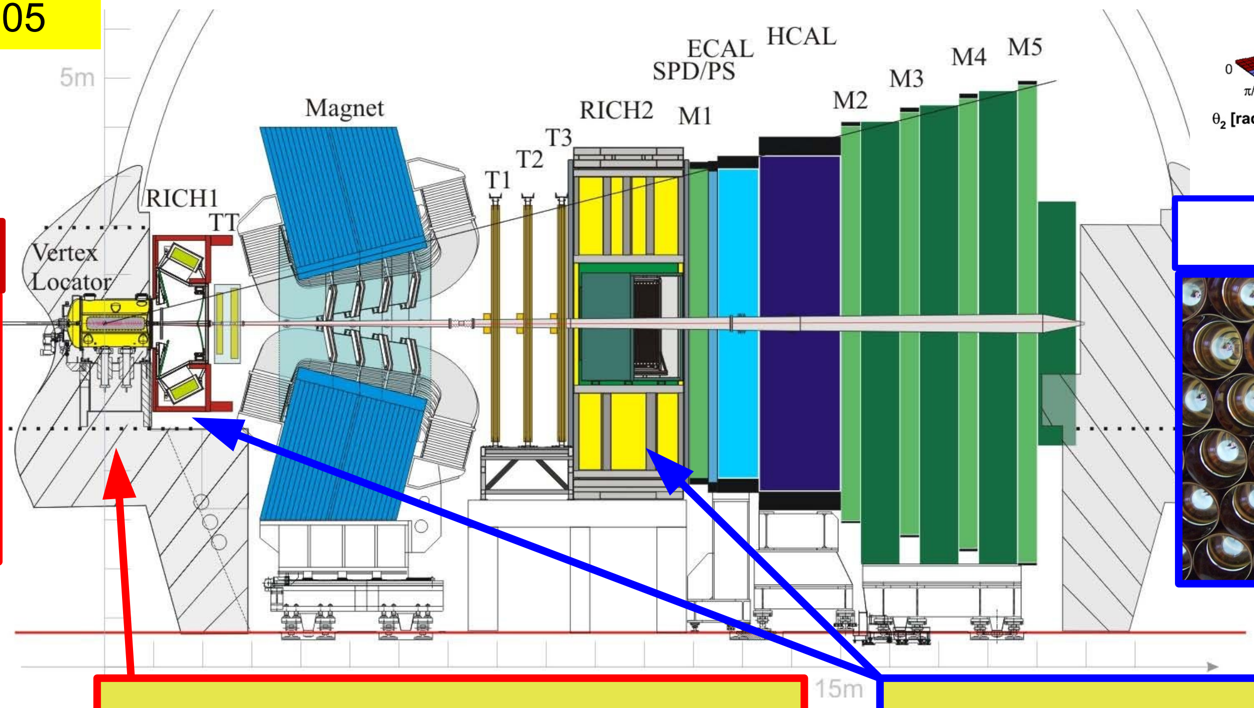
The LHCb detector

(2011-18 edition)

The LHCb Detector
JINST 3 (2008) S08005



VELO silicon strips



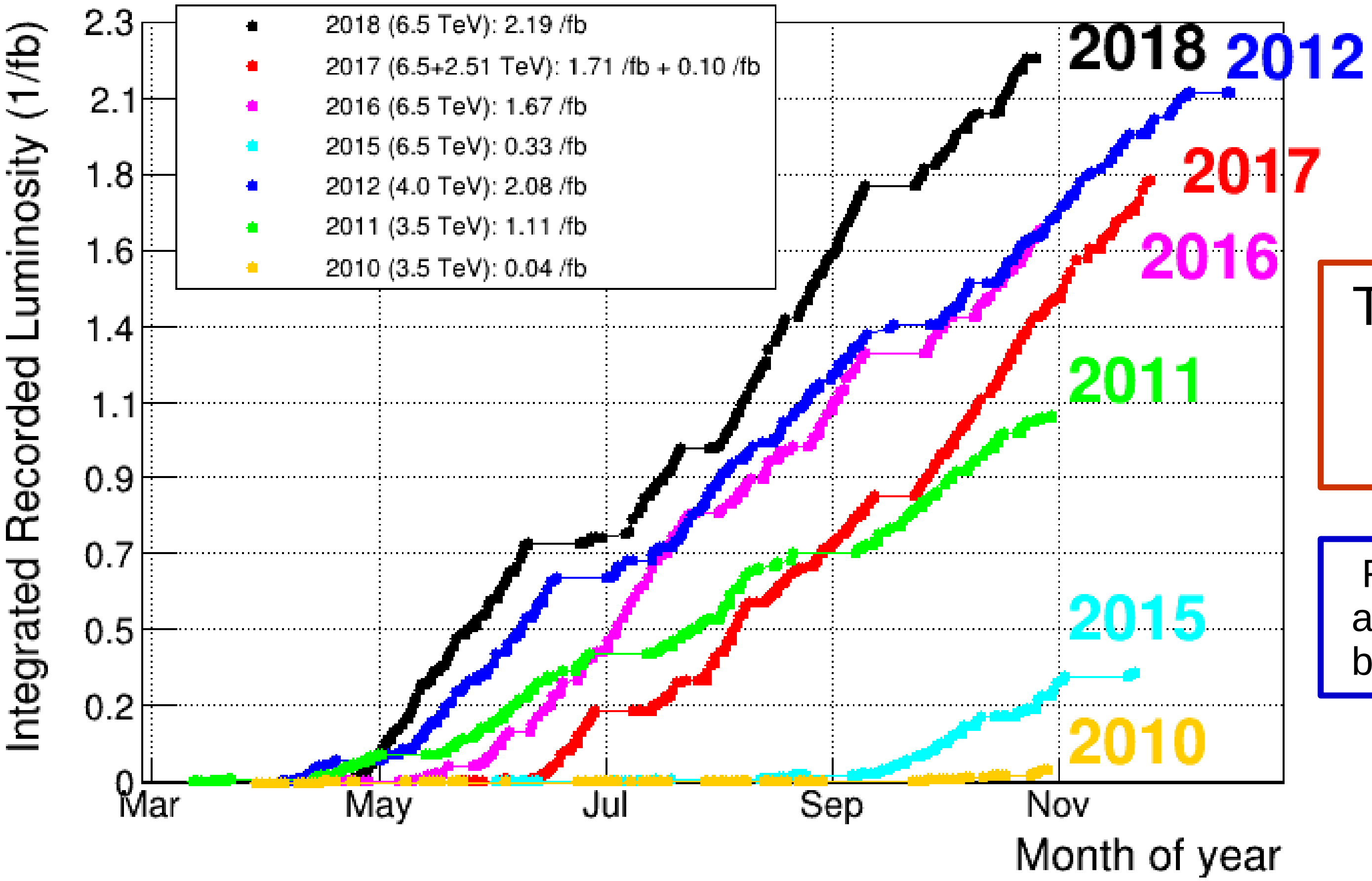
RICH PMTs

Precision primary and secondary vertex measurements

Excellent K/π separation capability

LHCb integrated luminosity

~2010 – 2020

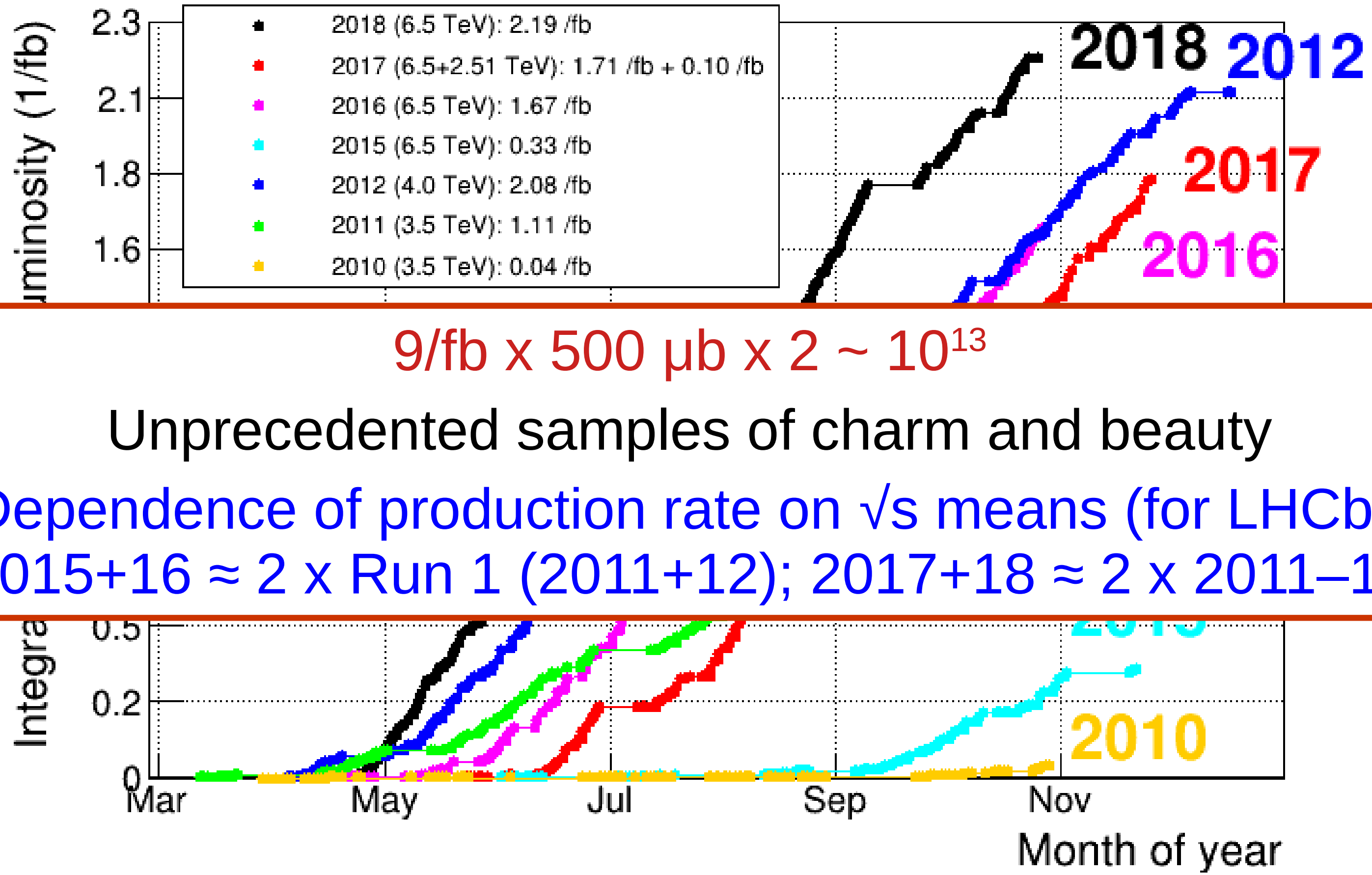


Total sample
2011–18
9/fb

For ∫*L*dt to mean anything, it has to be multiplied by σ

LHCb integrated luminosity

~2010 – 2020



9/fb x 500 μb x 2 ~ 10^{13}

Unprecedented samples of charm and beauty

Dependence of production rate on √s means (for LHCb)
2015+16 ≈ 2 x Run 1 (2011+12); 2017+18 ≈ 2 x 2011–16

Examples of results obtained with original LHCb detector (Run 1 & 2 data; 9/fb)

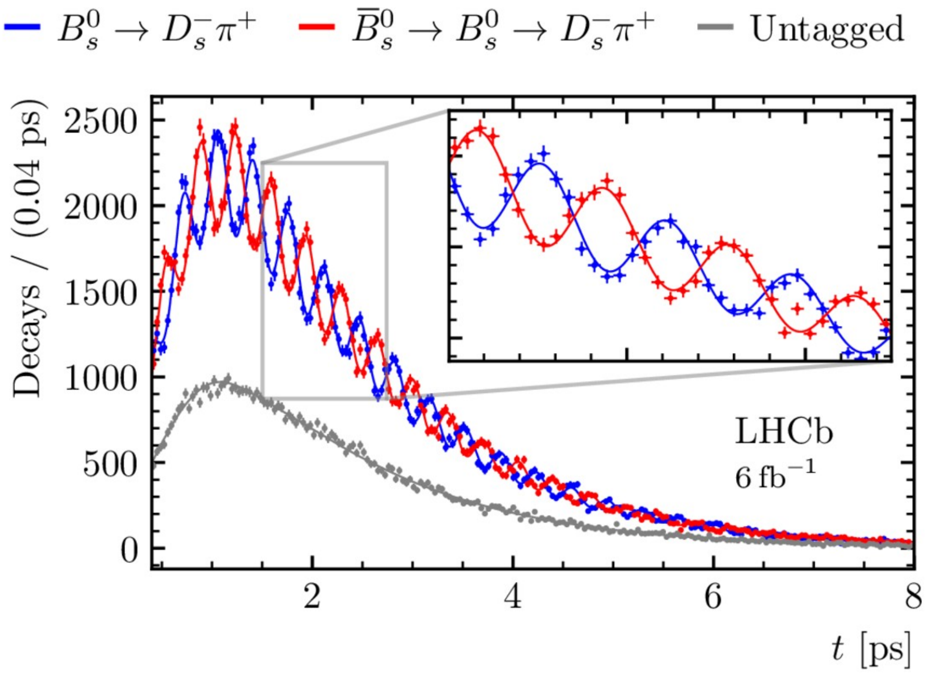
B^0 and B_s^0 mixing rates

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
  - $\Delta z = \beta\gamma c \Delta t$

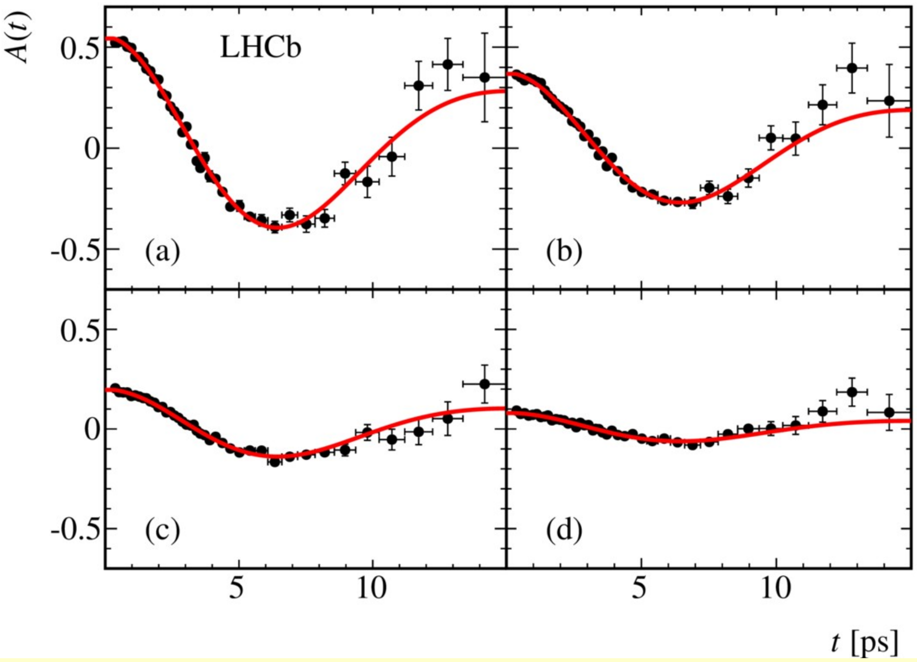
Lorentz boost factors, not CKM angles



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

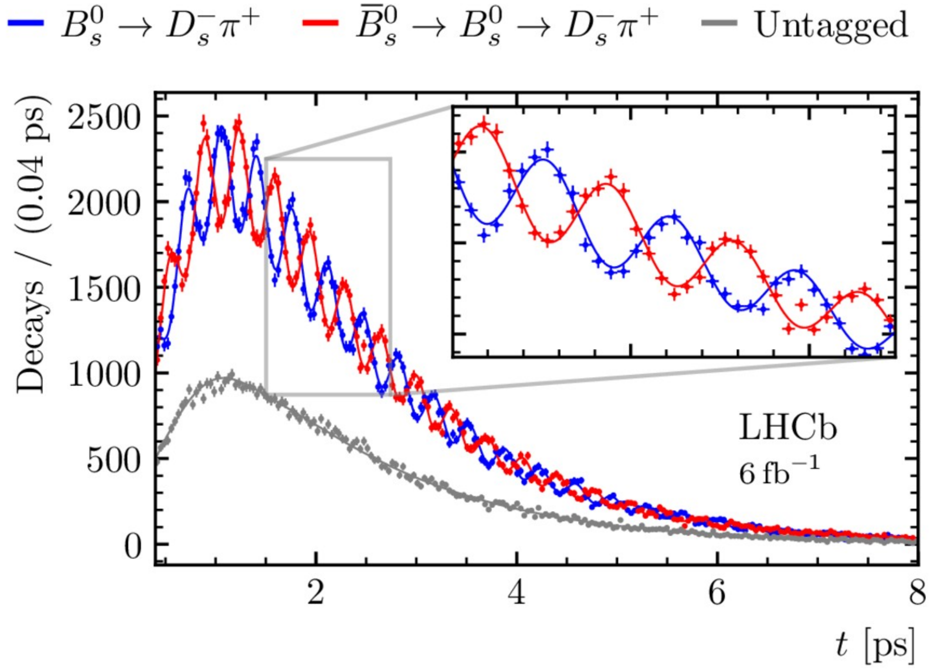
Digression: B^0 and B_s^0 mixing rates

Eur. Phys. J. C76 (2016) 412



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

Nature Phys. 18 (2022) 1



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

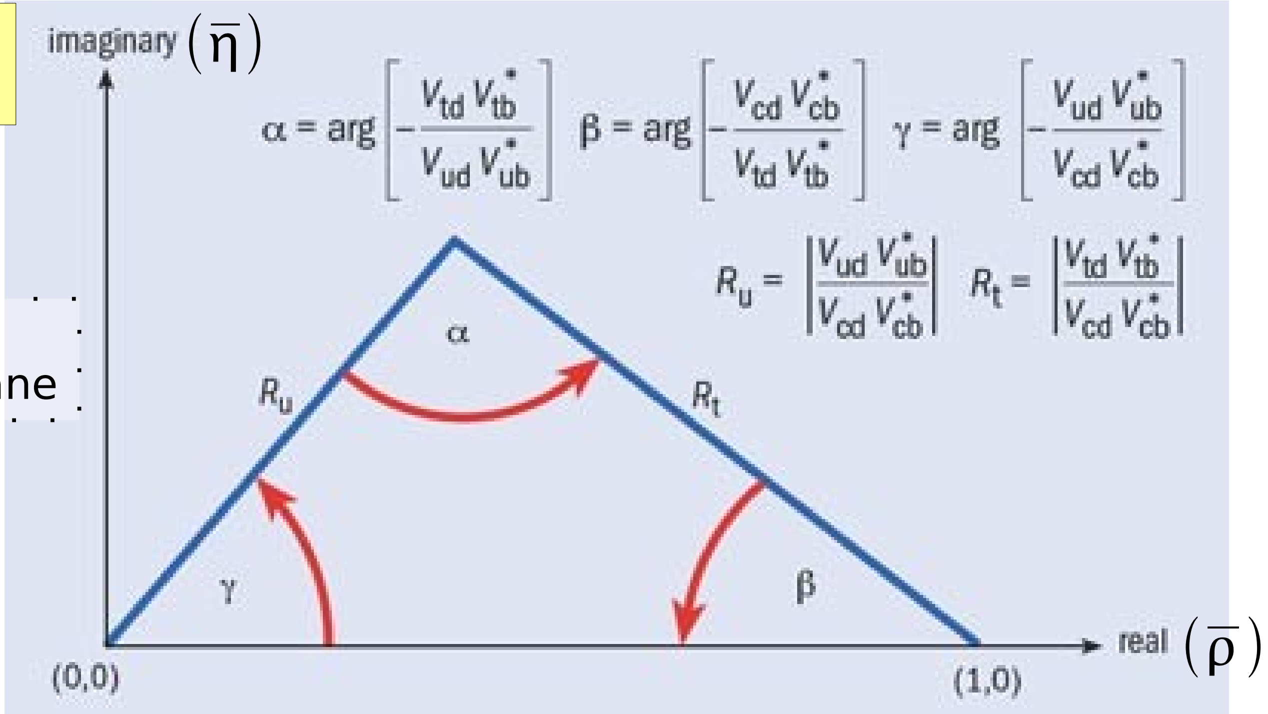
The Unitarity Triangle

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

Three complex numbers add to zero
⇒ triangle in Argand plane

Axes are $\bar{\rho}$ and $\bar{\eta}$:

$$\bar{\rho}+i\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}$$



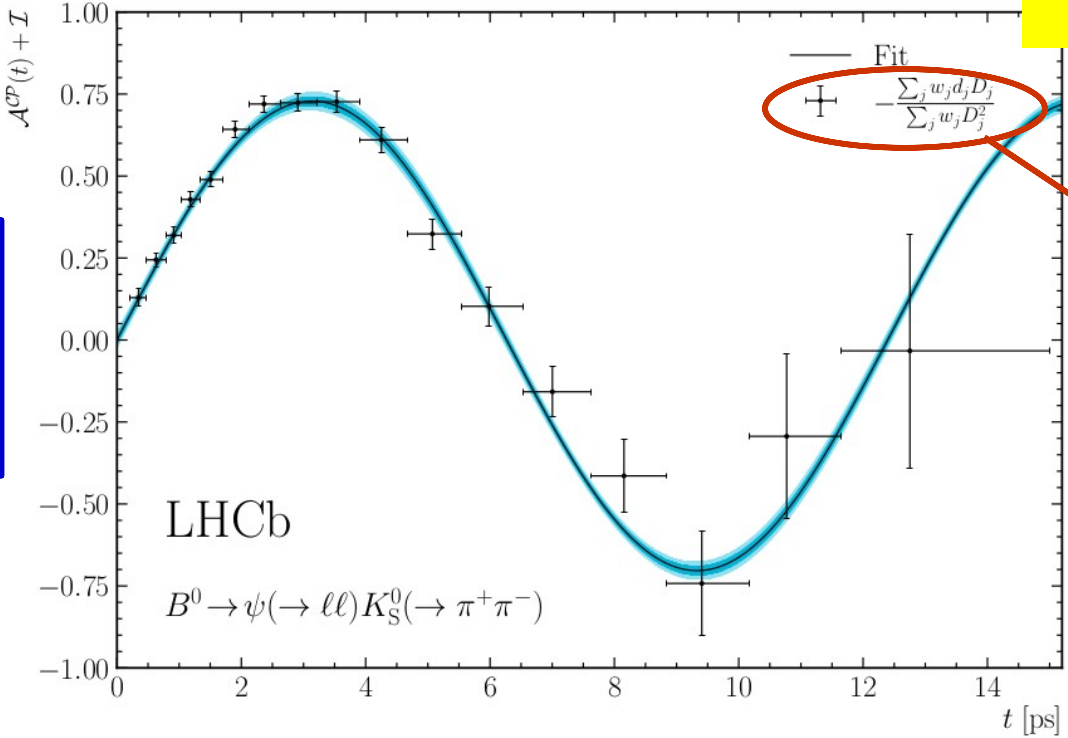
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

sin(2β) from $B^0 \to J/\psi K_S$

LHCb-PAPER-2023-013
arXiv:2309.09728

τ(B^0) = 1.52 ps

Range of plot covers ten B^0 lifetimes!



Asymmetry corrected for tagging dilution

$S(\psi K_S) = 0.717 \pm 0.013$ (stat) ± 0.008 (syst)
[S(ψKS) ≈ sin(2β)]

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

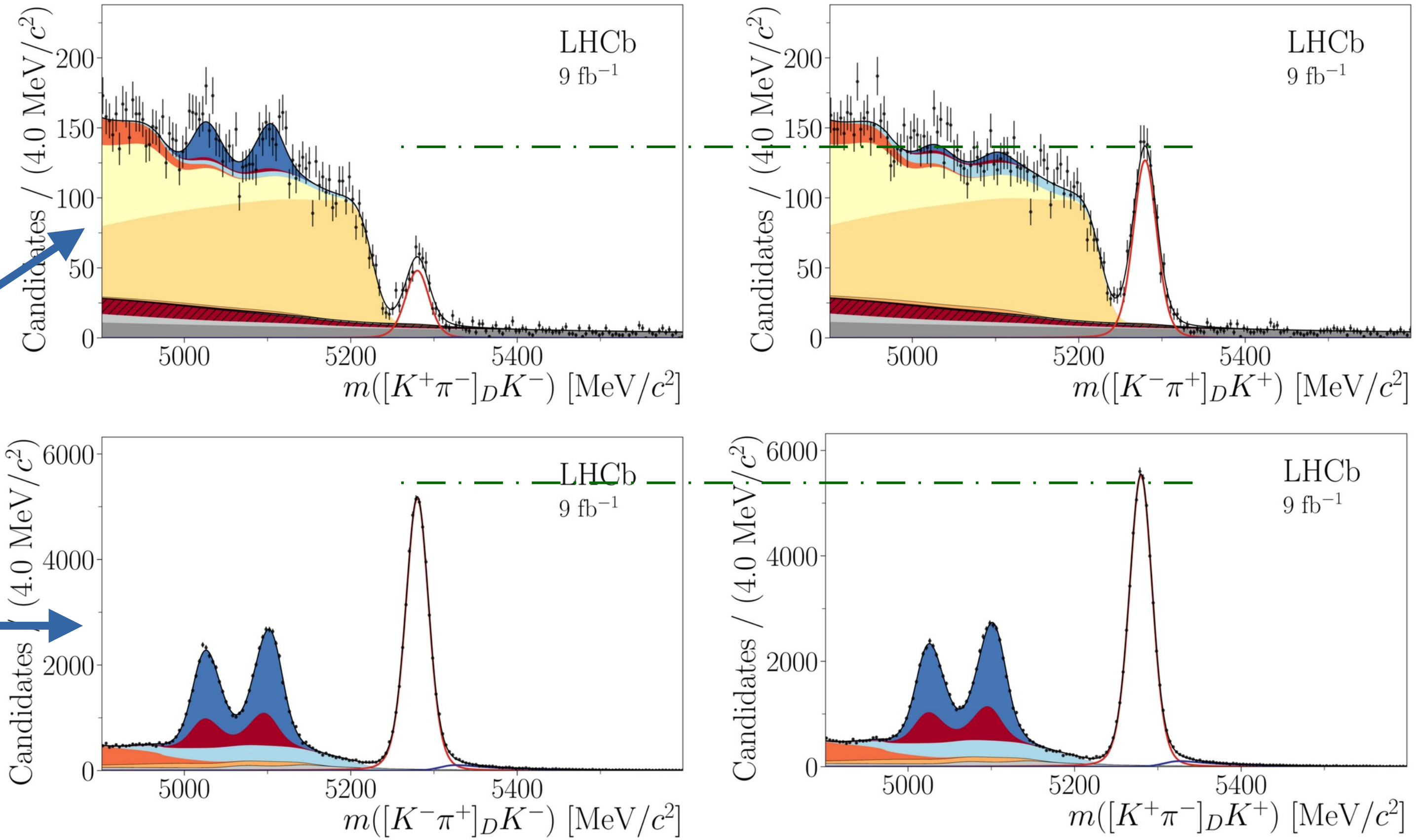
γ from $B^{+/-} \to DK^{+/-}$

JHEP 04 (2021) 081

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

Suppressed $D \to K\pi$ mode: enhanced CP violation
(two amplitudes of comparable magnitude)

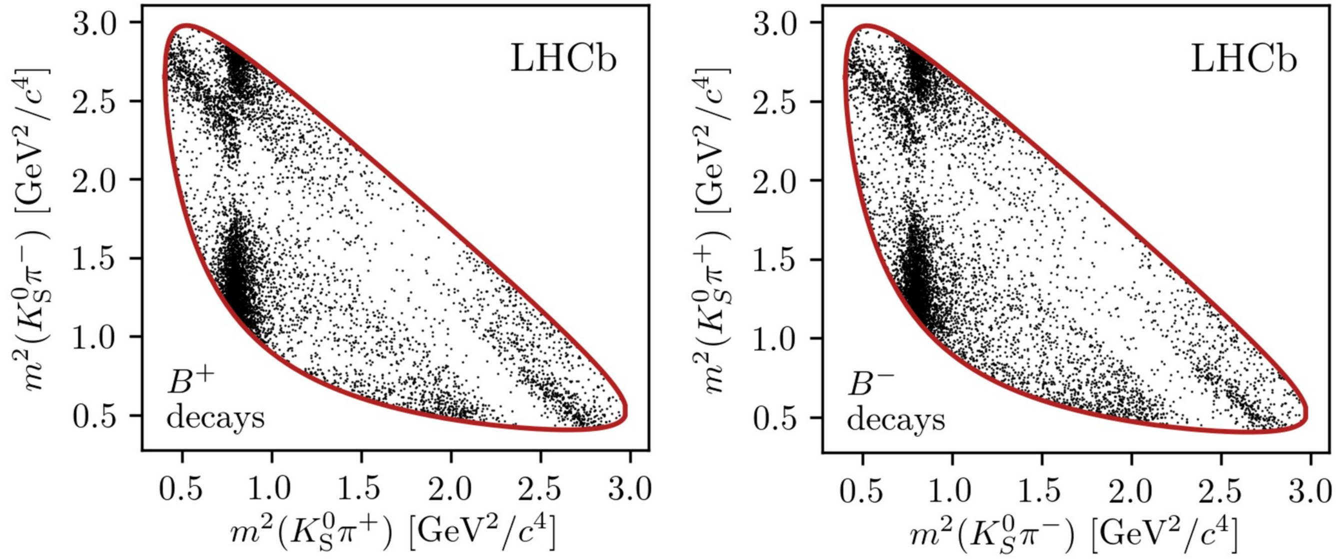
Favoured mode: little CP violation
(but important to control systematics)



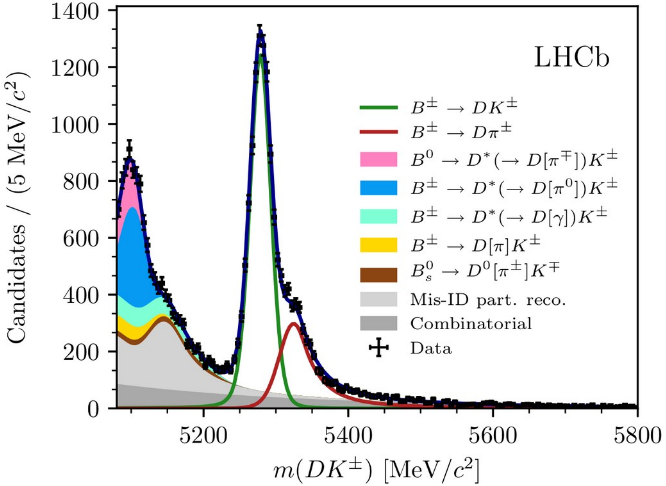
γ from B → DK (BPGGSZ)

LHCb, JHEP 02 (2021) 169

D → $K_S\pi^+\pi^-$ Dalitz plot from
(left) $B^+ \to DK^+$, (right) $B^- \to DK^-$



this plot DD sample only

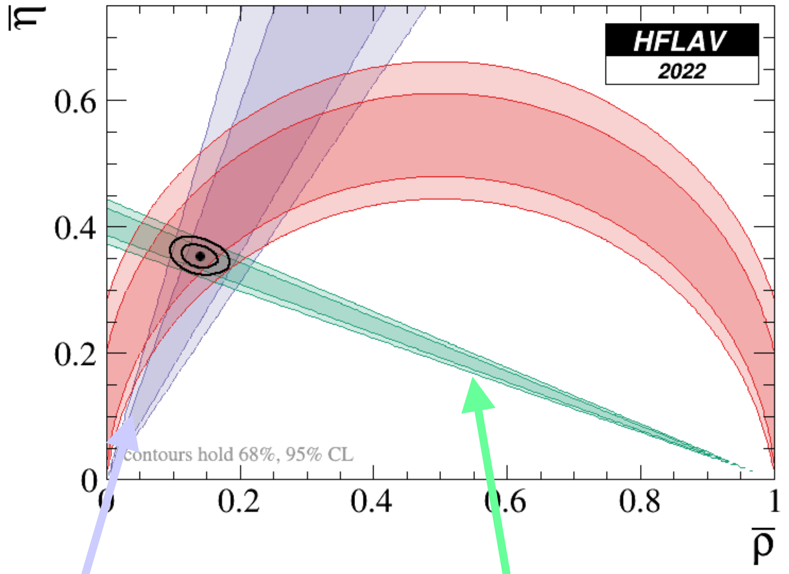


$\gamma = (68.7\ ^{+5.2}_{-5.1})^\circ$

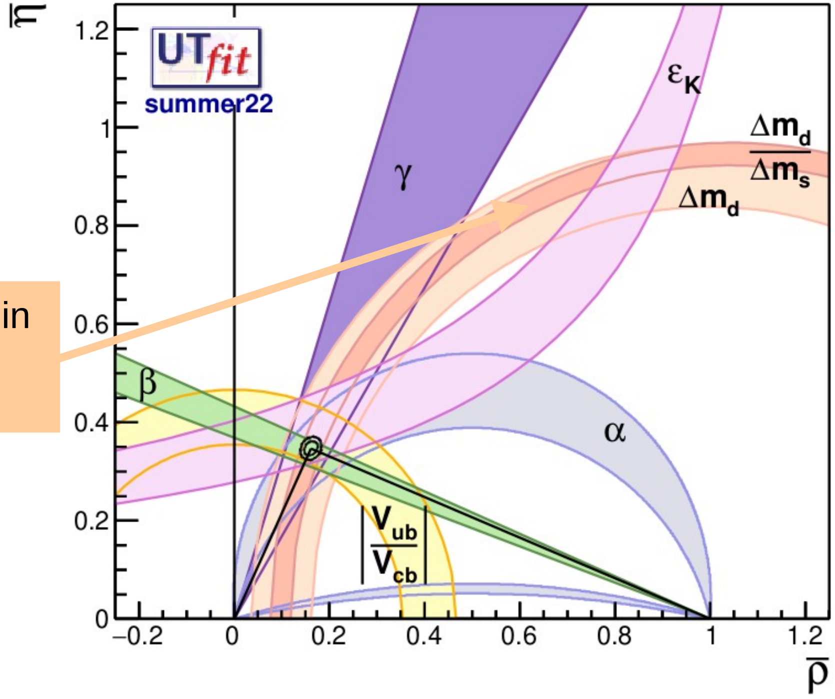
Important input from BESIII measurements with ψ(3770) data

The CKM description of CP violation

arXiv:2206.07501



arXiv:2212.03894



Mixing rates in $B_{(s)}^0$–$\bar{B}_{(s)}^0$ systems

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

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

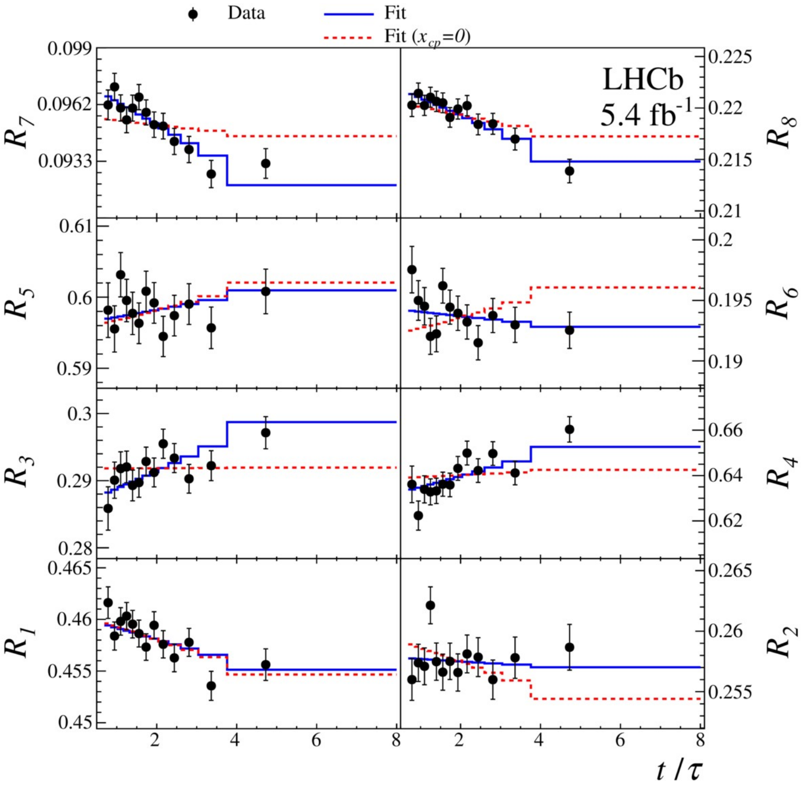
All constraints from different measurements overlap!

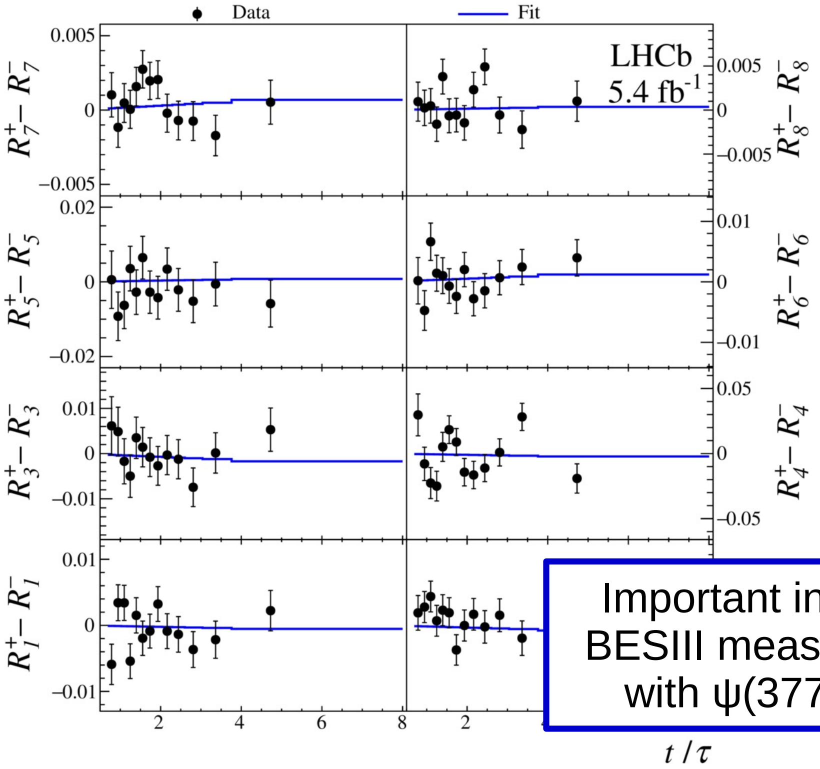
CP violation in charm oscillations

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





Important input from BESIII measurements with ψ(3770) data

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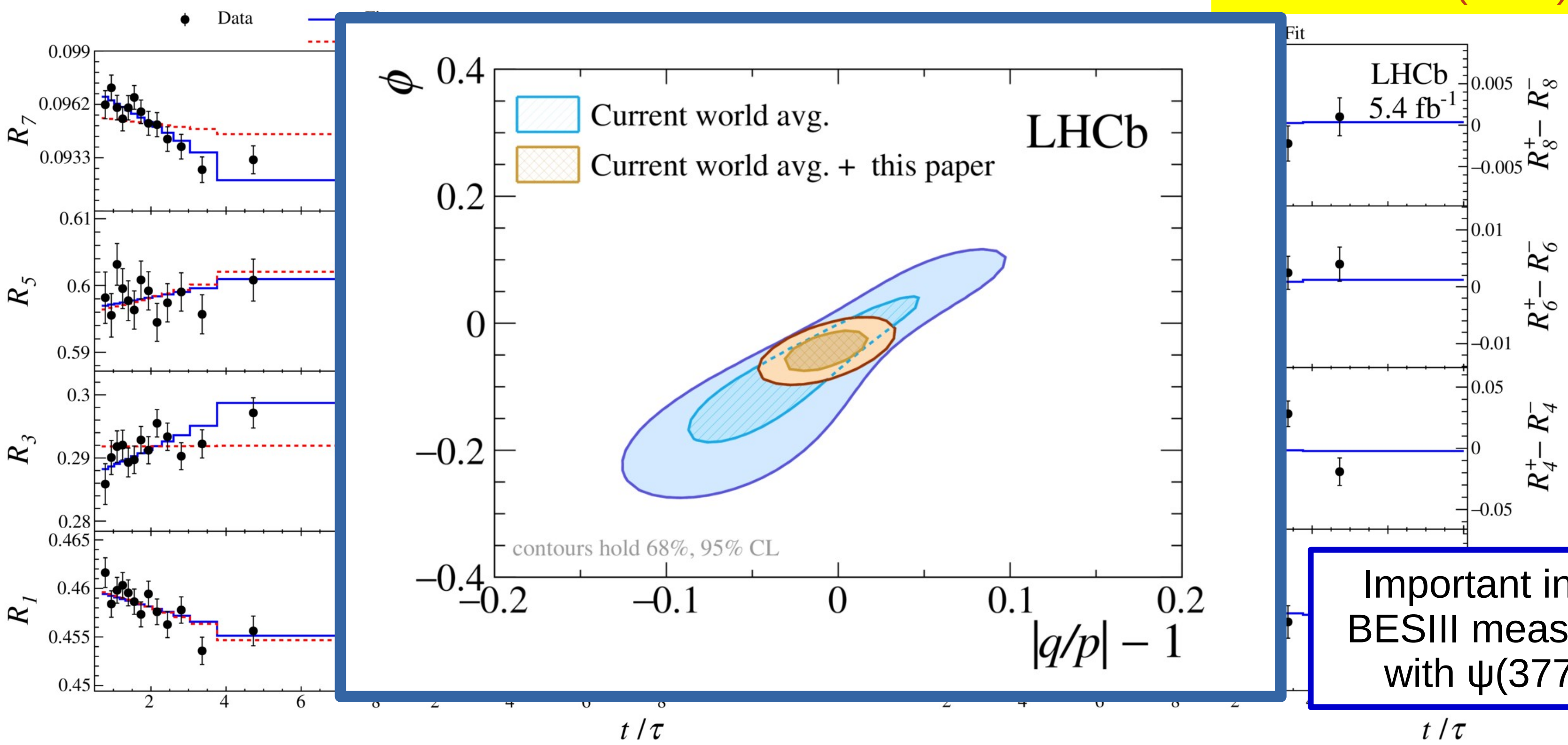
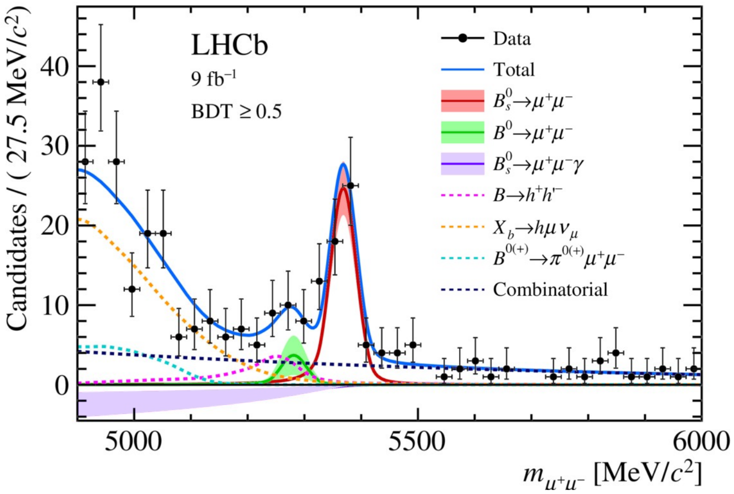
PRL 127 (2021) 111801

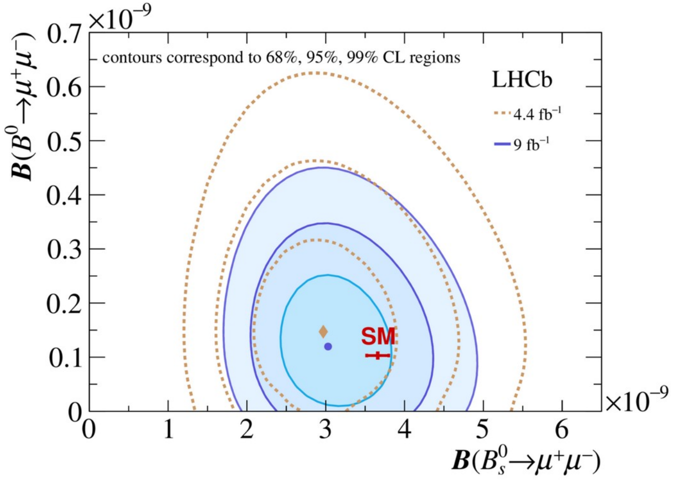


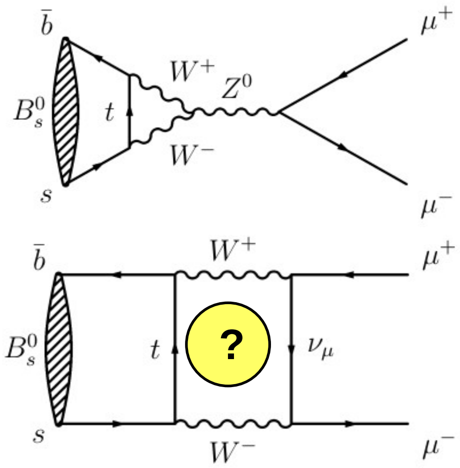
Important input from BESIII measurements with ψ(3770) data

Testing the SM with highly suppressed $B_{(s)}^0 \to \mu^+\mu^-$

PRL 128 (2022) 041801







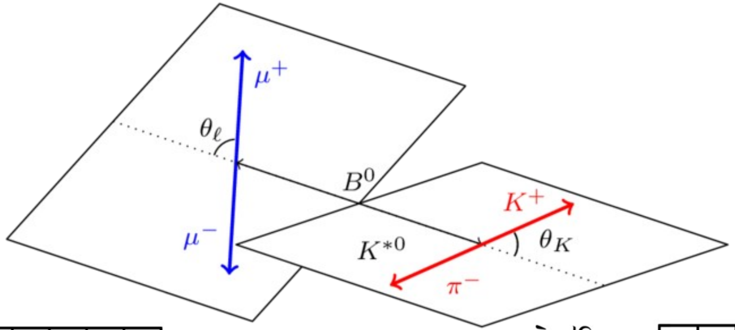
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \;=\; \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

c.f. SM: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$

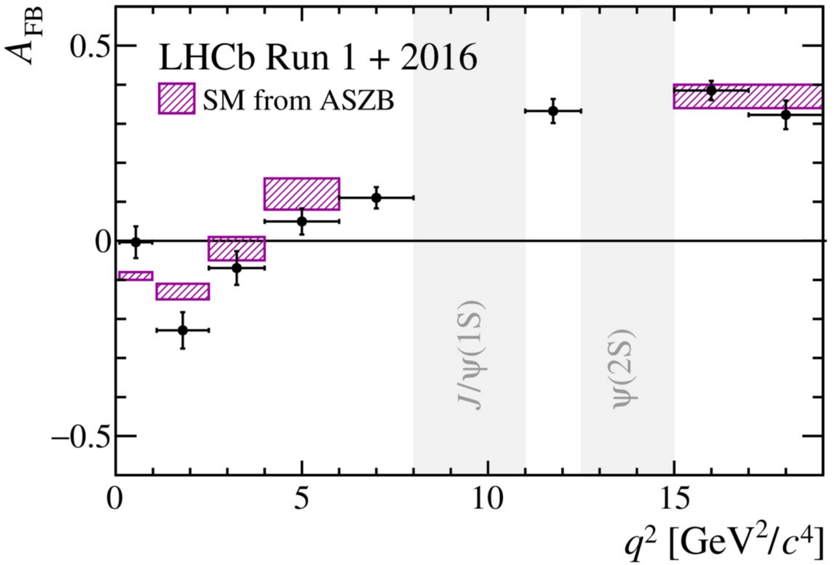
See also CMS PL B842 (2023) 137955
and ATLAS JHEP 04 (2019) 098

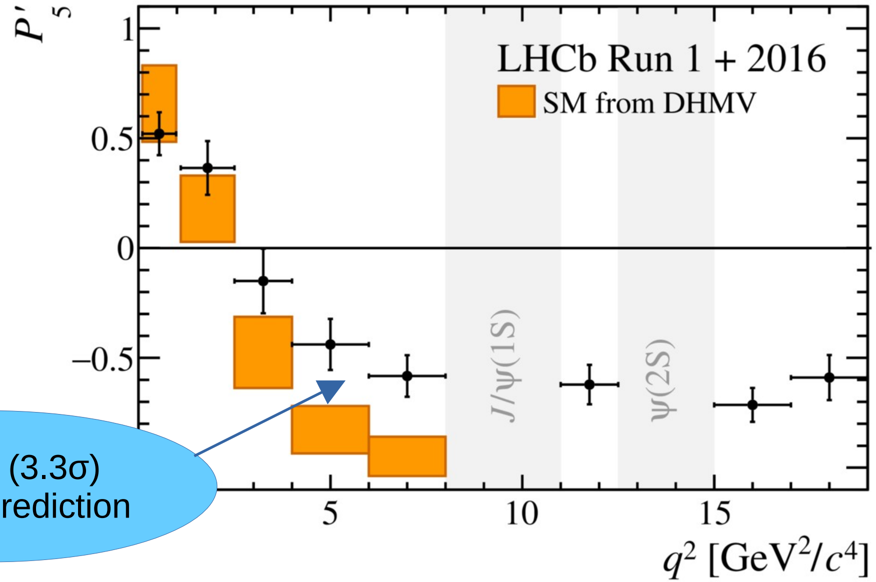
Testing the SM with rare B decays

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



PRL 125 (2020) 011802



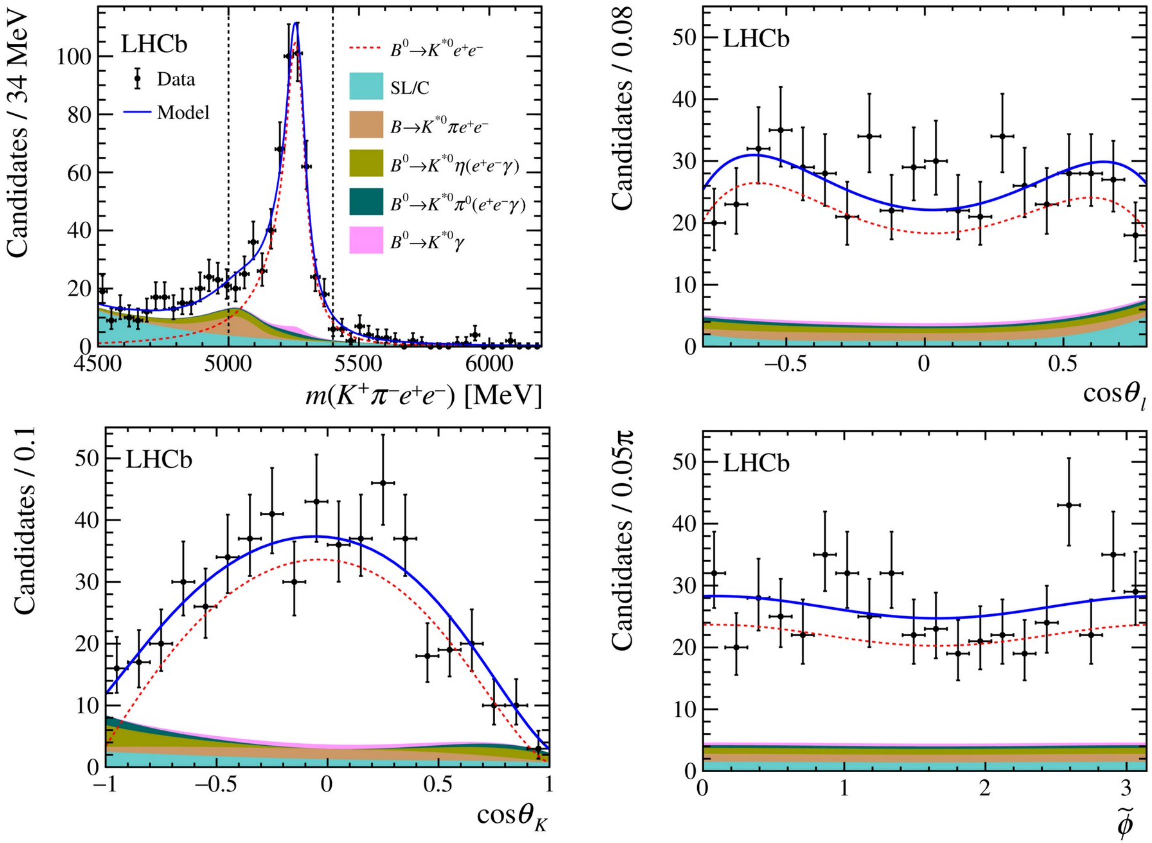


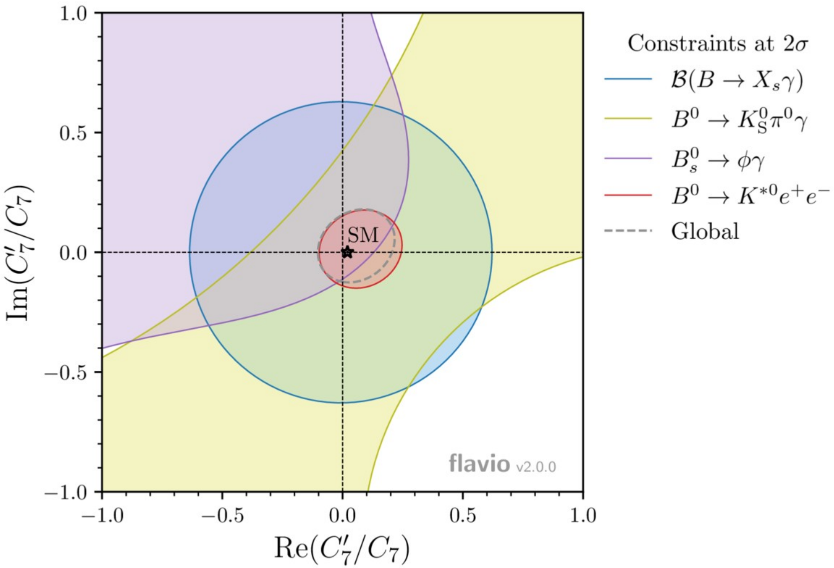
Tension (3.3σ)
with SM prediction

Testing the SM with rare B decays

Angular distributions of $B^0 \rightarrow K^{*0}e^+e^-$ at very low q^2

JHEP 12 (2020) 081

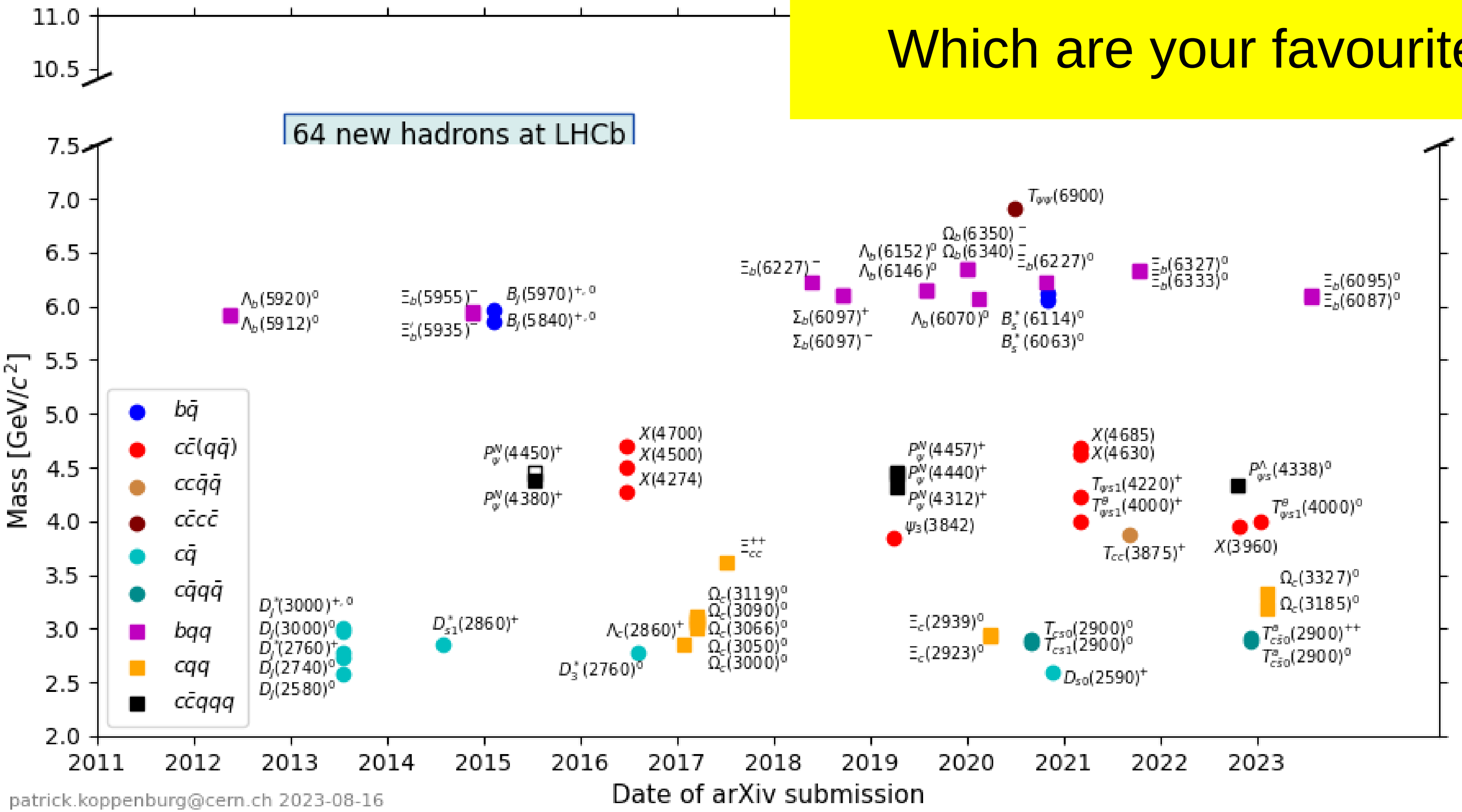




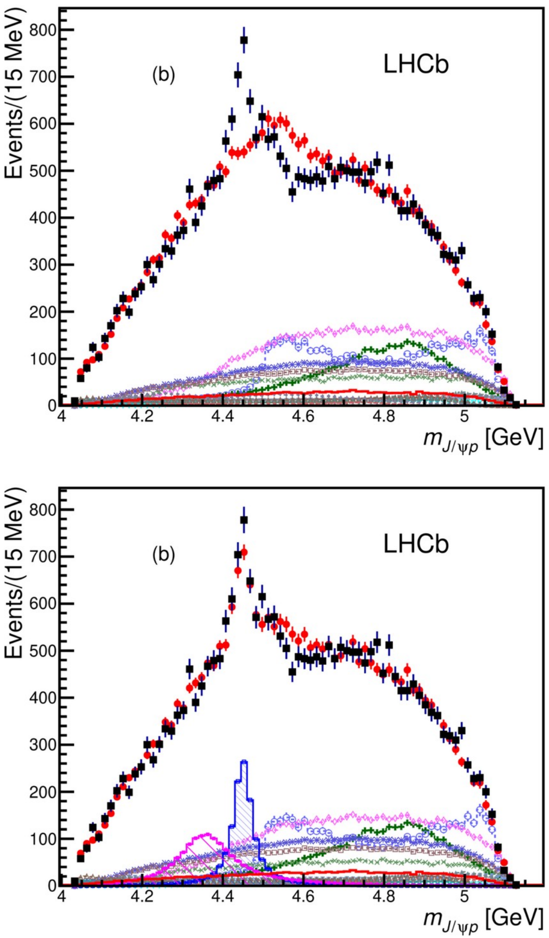
Strong constraints on the polarisation of the virtual photon

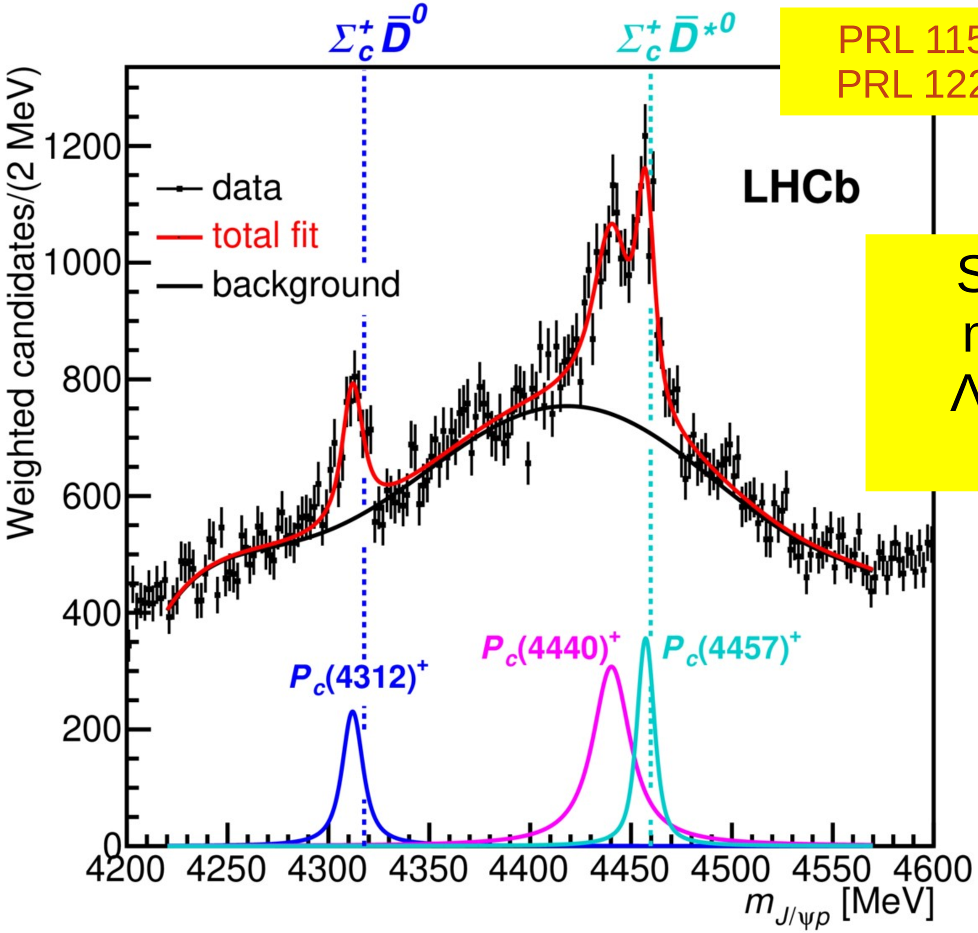
New hadrons!

Which are your favourites?



Charmonium pentaquarks



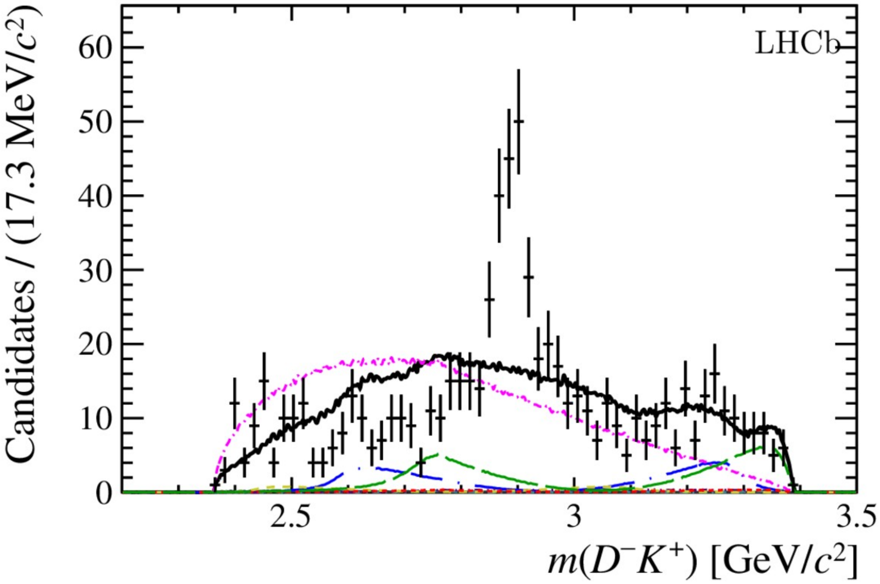


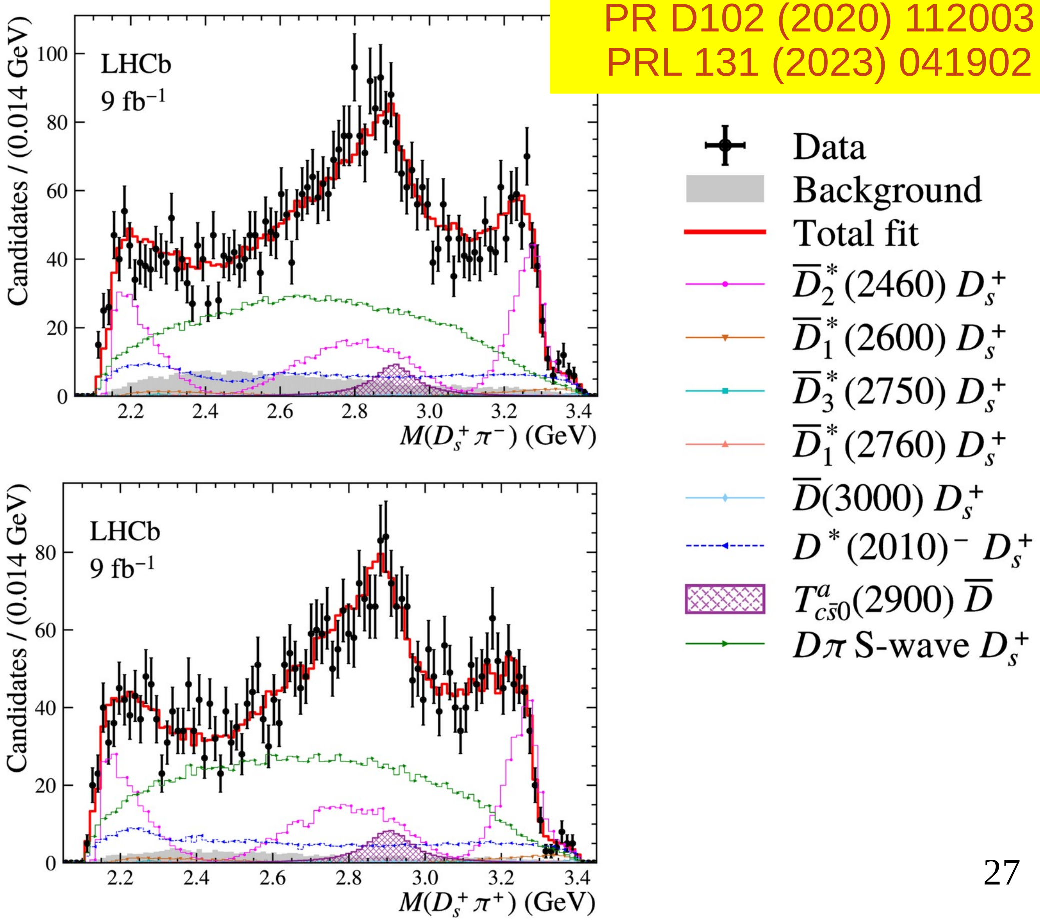
PRL 115 (2015) 072001
PRL 122 (2019) 222001

Structure in $m(J/\psi p)$ in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays

Tetraquarks with 4 flavours

PR D102 (2020) 112003
PRL 131 (2023) 041902

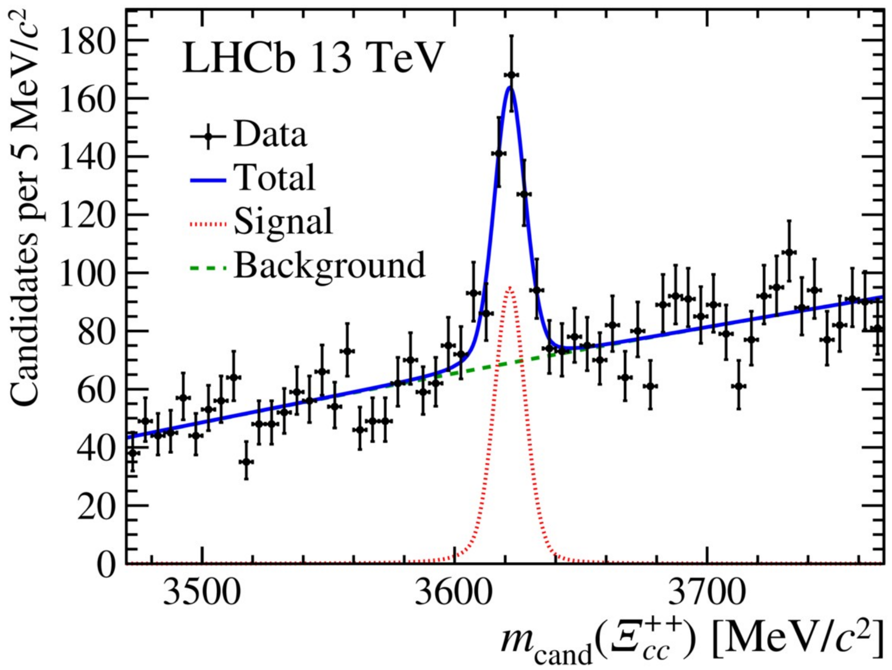


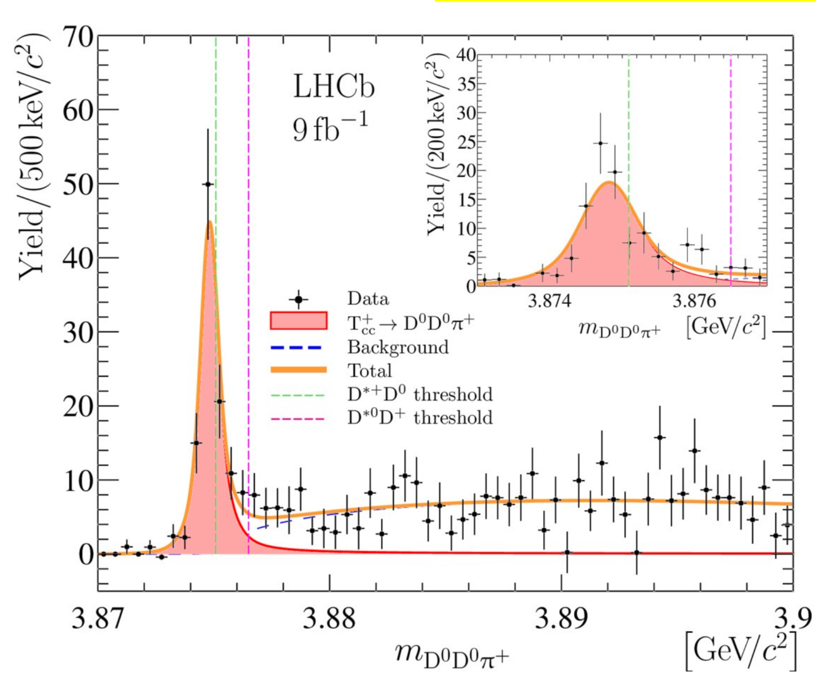


T_{cs} and $T_{c\bar{s}}$ structures in
$m(D^-K^+)$ in $B^+ \to D^+D^-K^+$ decays
$m(D_s^+\pi)$ in $B \to D_s^+\pi\overline{D}$ decays

Double charm hadrons

PRL 119 (2017) 112001
Nature Phys. 18 (2022) 751

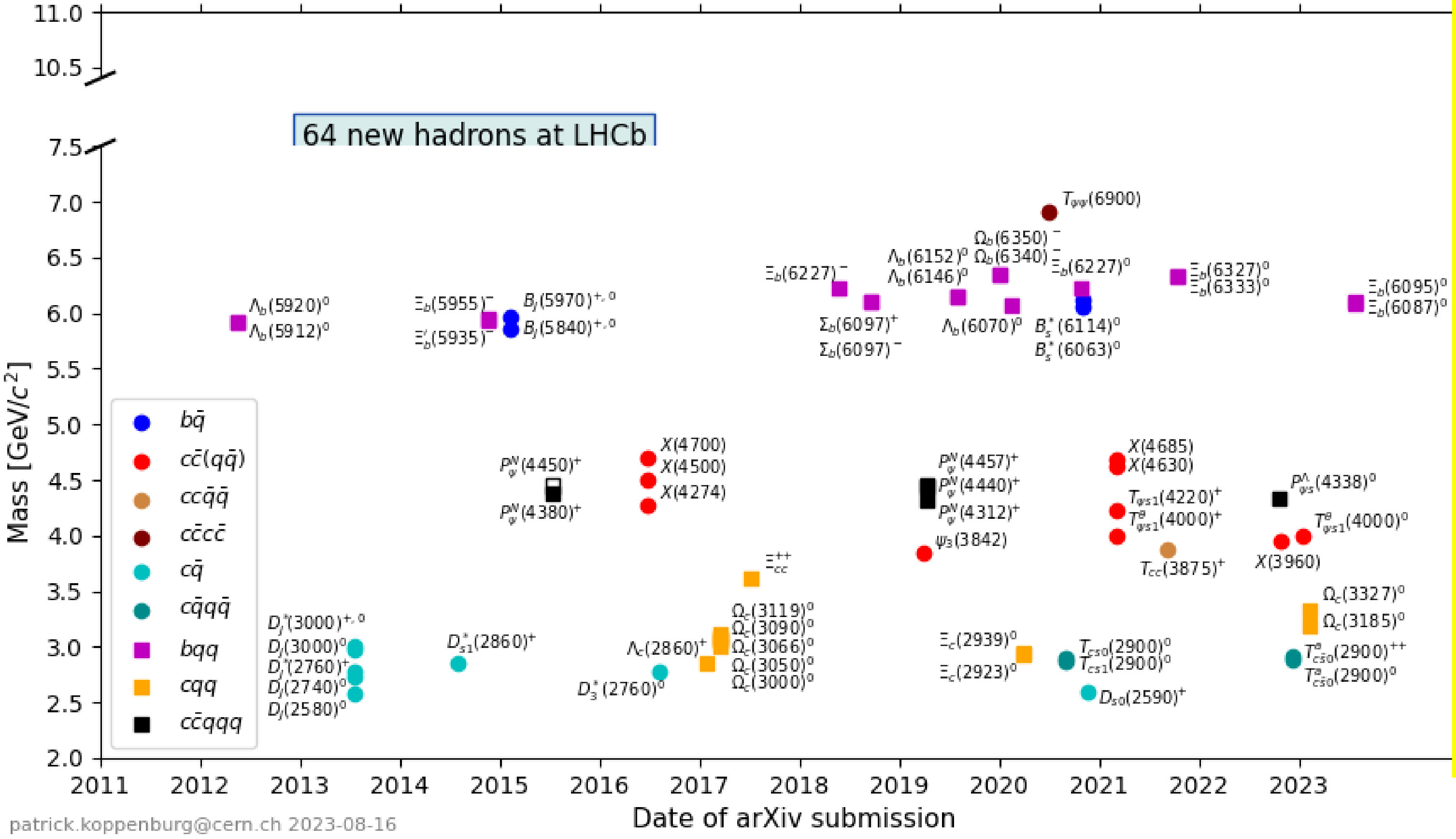




$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

$T_{cc}^+ \to D^0 D^0 \pi^+$

New hadrons!



What new discoveries will come here?

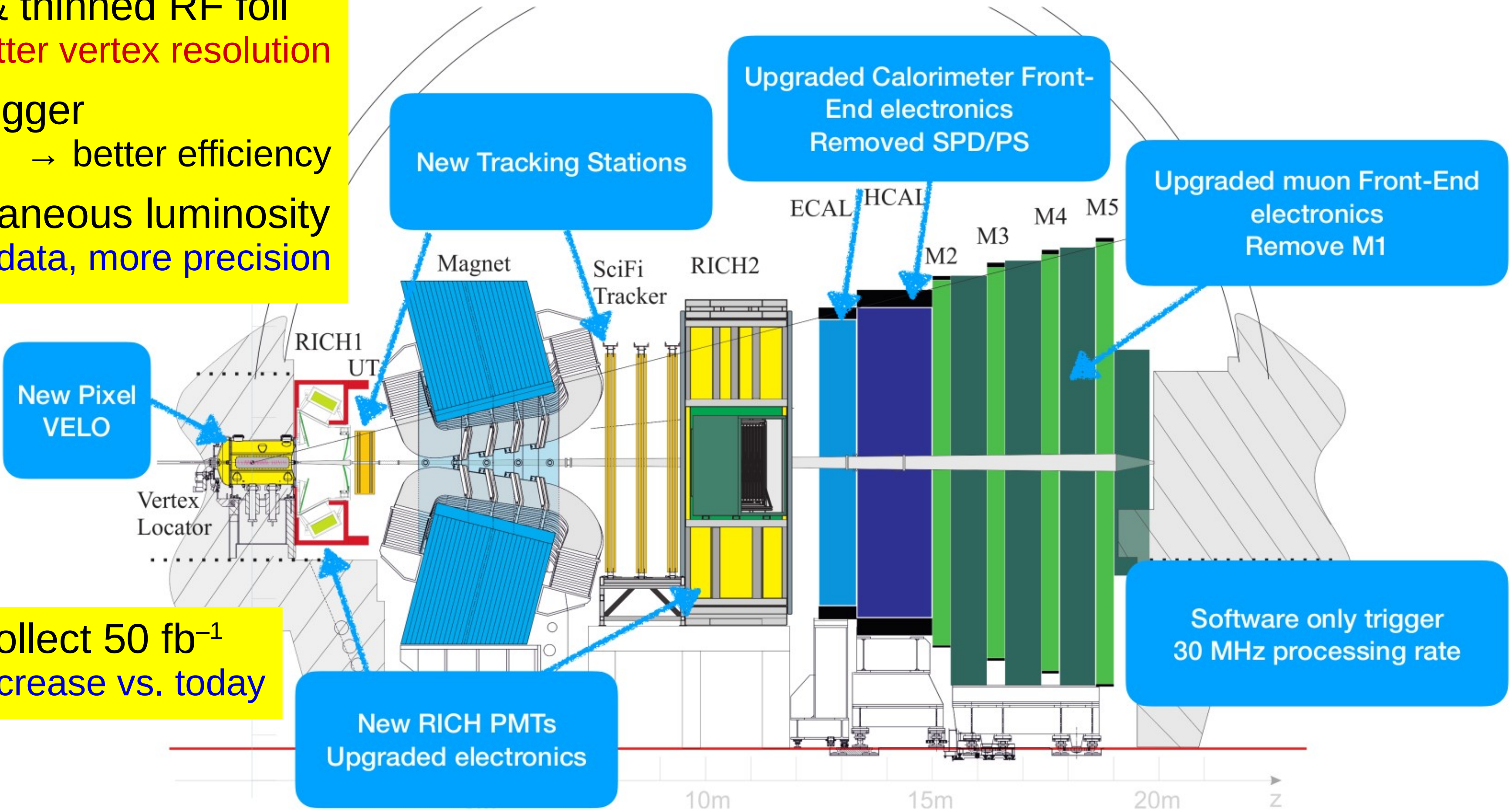
LHCb as of today

LHCb Upgrade I

VELO pixels & thinned RF foil
→ better vertex resolution

All software trigger
→ better efficiency

Higher instantaneous luminosity
→ more data, more precision

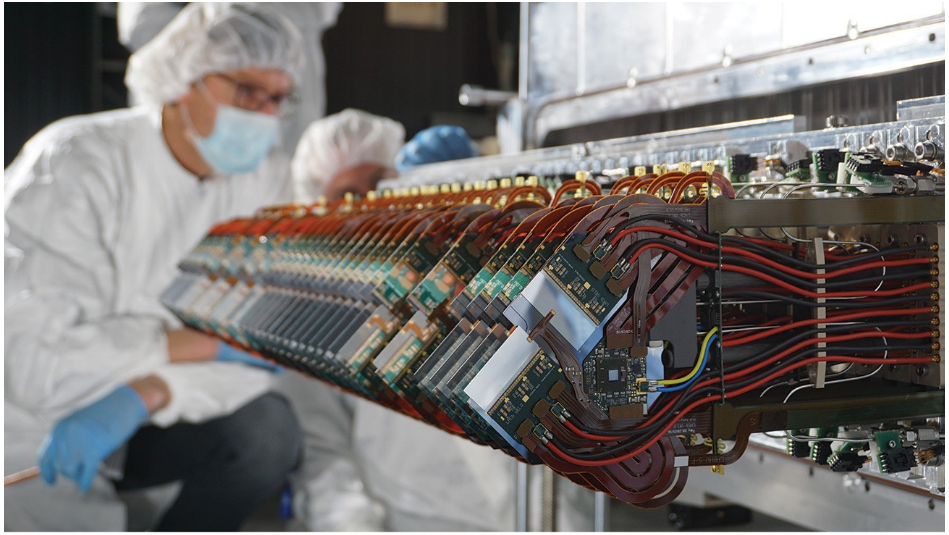


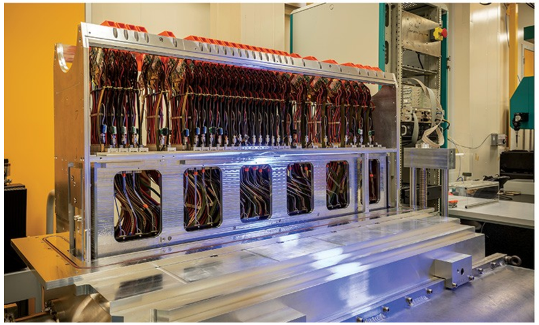
Designed to collect 50 fb^{-1}
→ ×10 data increase vs. today

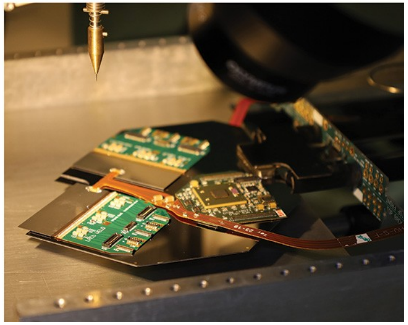
Pixel VELO

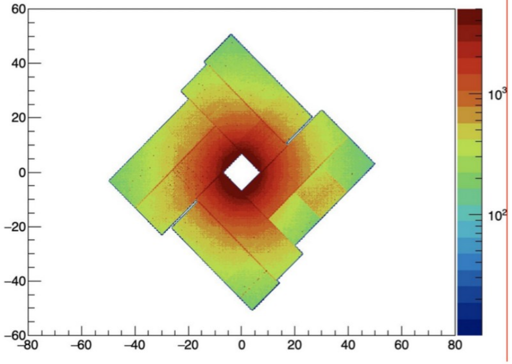
Identification of displaced vertices crucial to identify B decays at hadron colliders

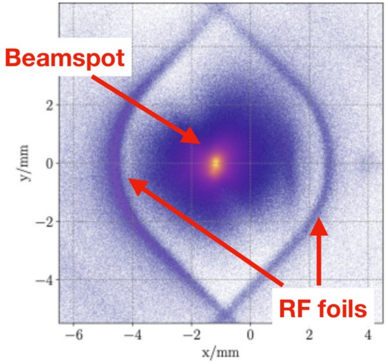
Commissioning ongoing!

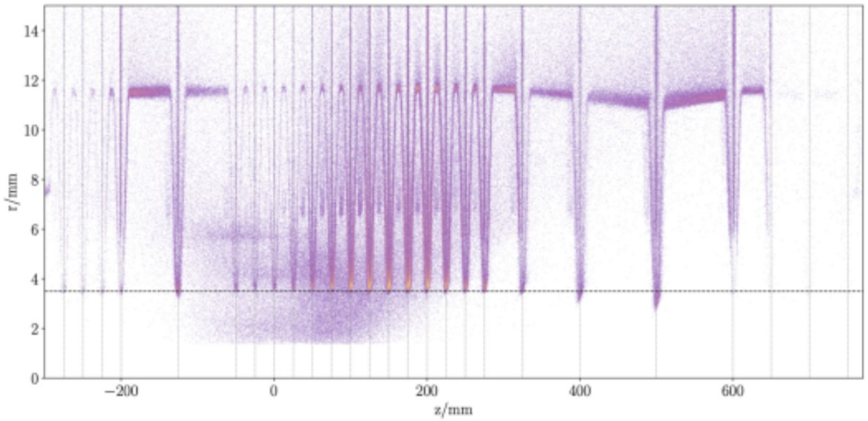












Data processing at 30 MHz

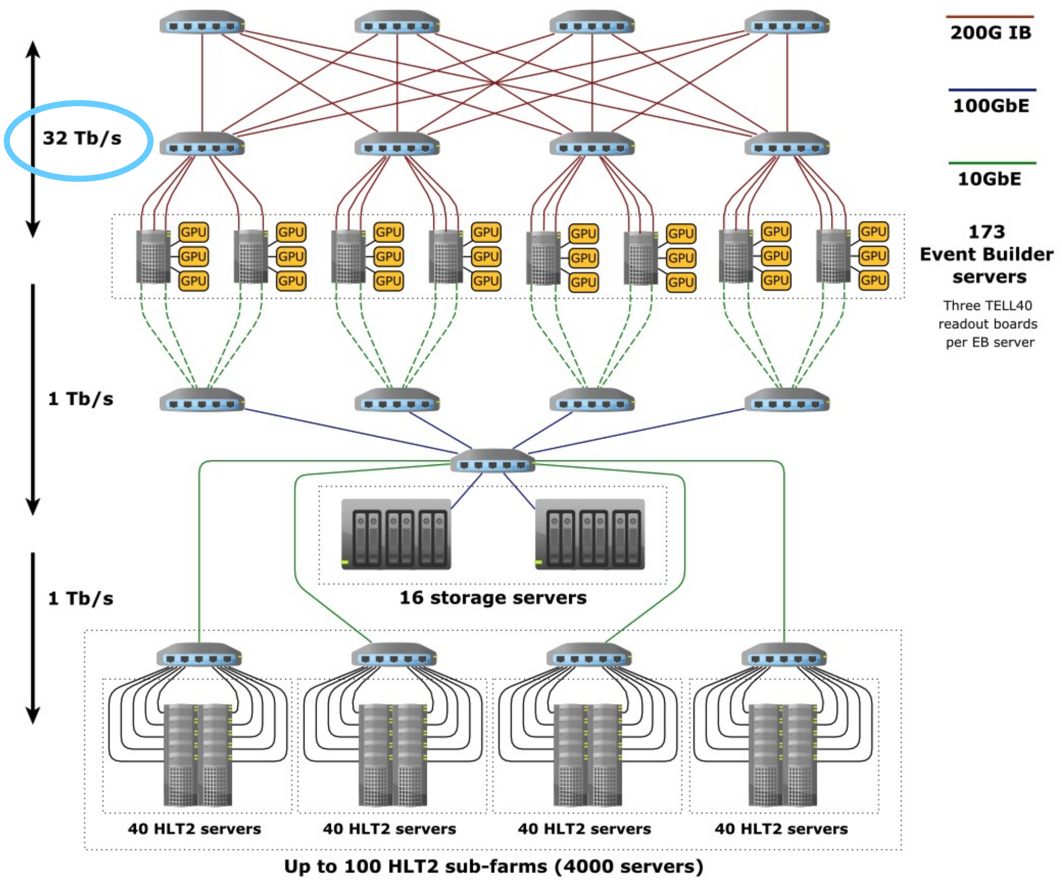
Comput.Softw.Big Sci. 6 (2022) 1

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

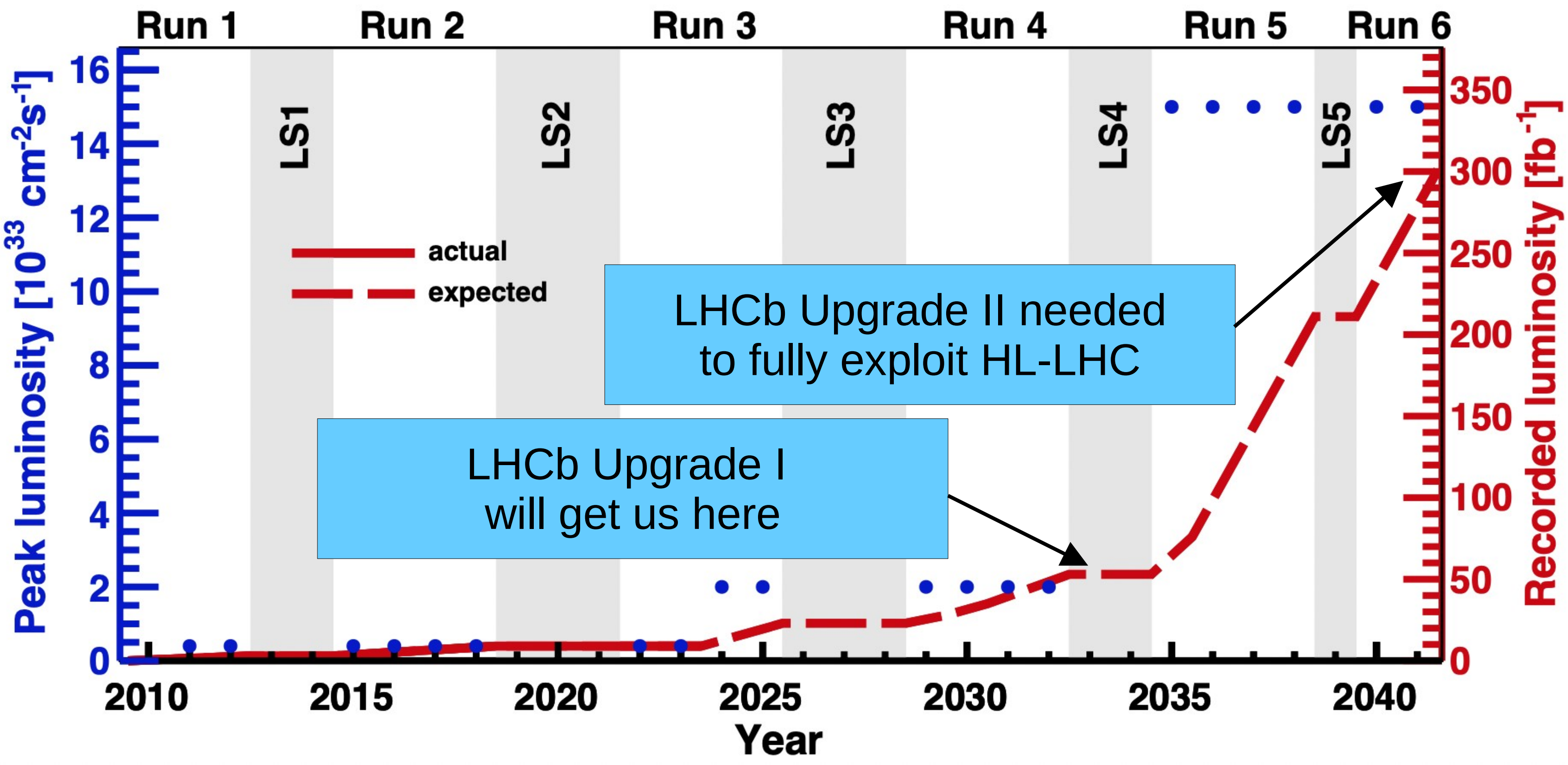
At high luminosity, every pp bunch-crossing contains a potentially interesting event

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)



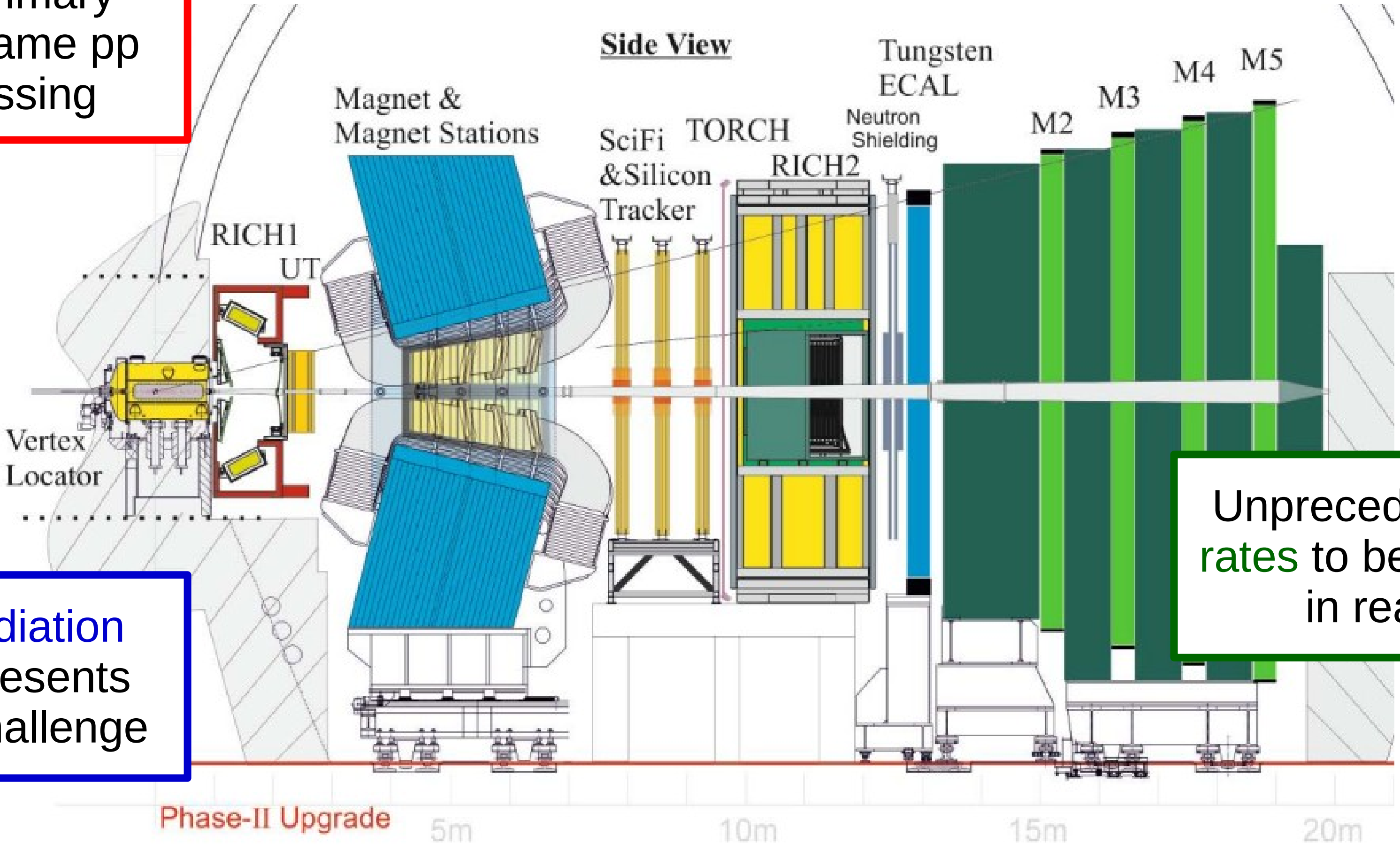
Why stop there?



The future … LHCb Upgrade II

LHCb Upgrade II

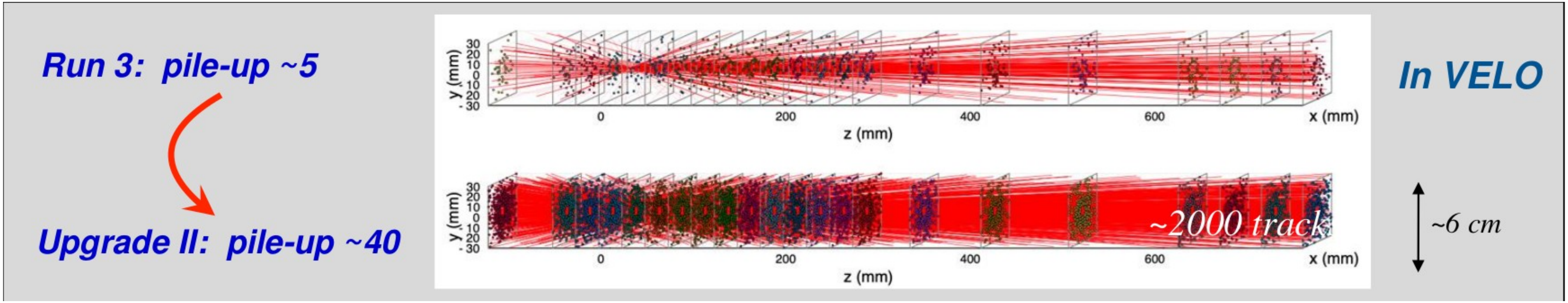
Crucial to use precision timing information to separate primary vertices in same pp bunch crossing



Unprecedented data rates to be processed in real time

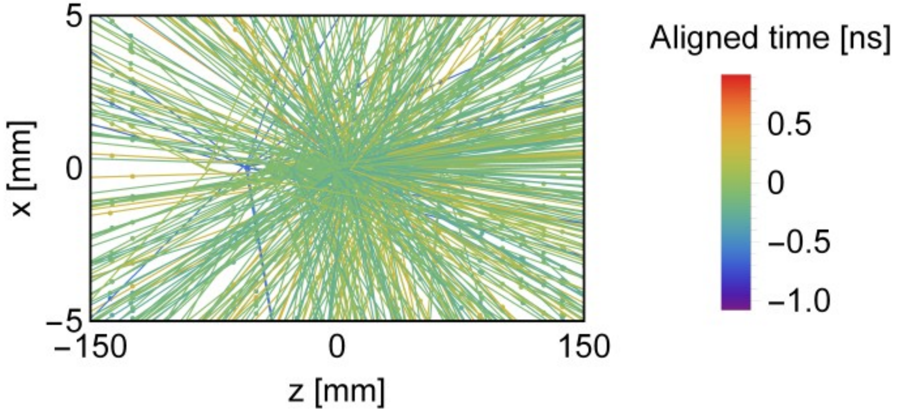
Need for radiation hardness presents significant challenge

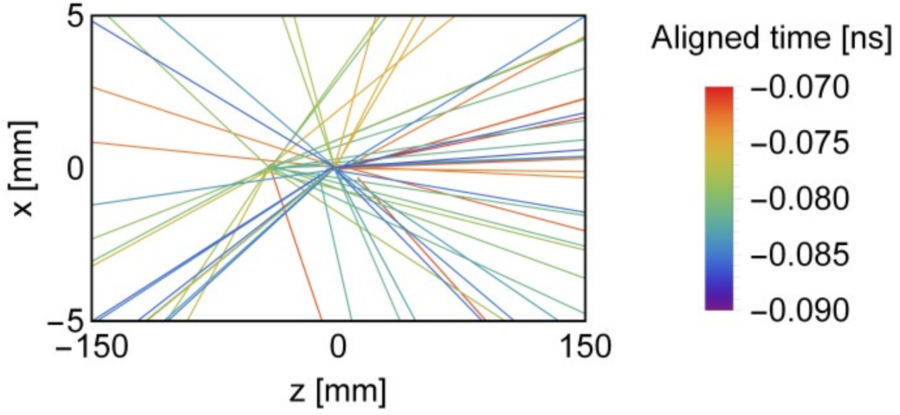
The need for timing



- 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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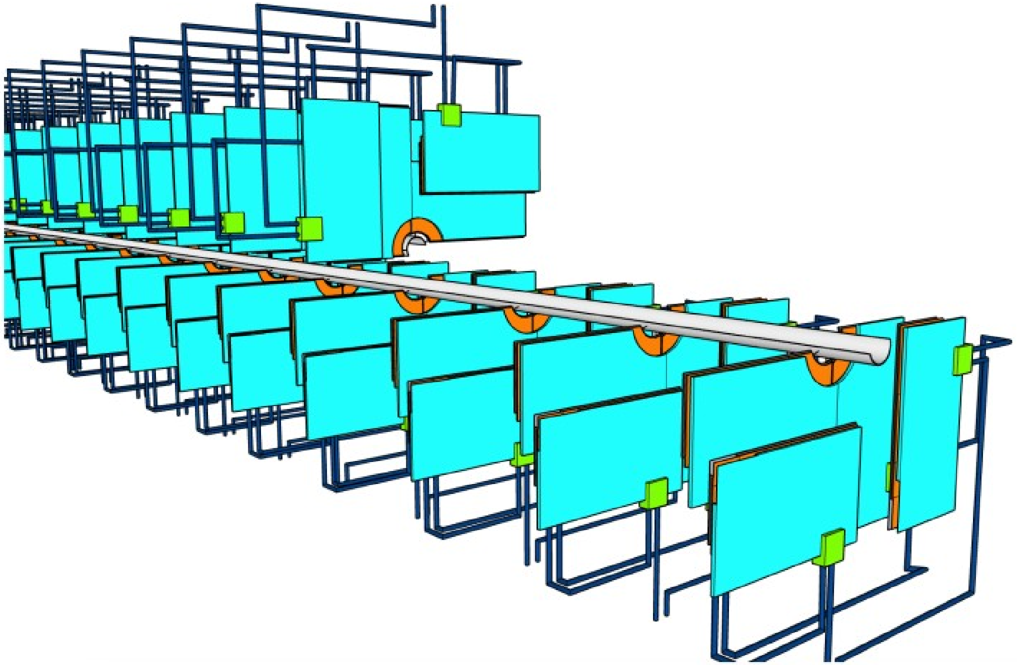
Vertex detector (VELO)

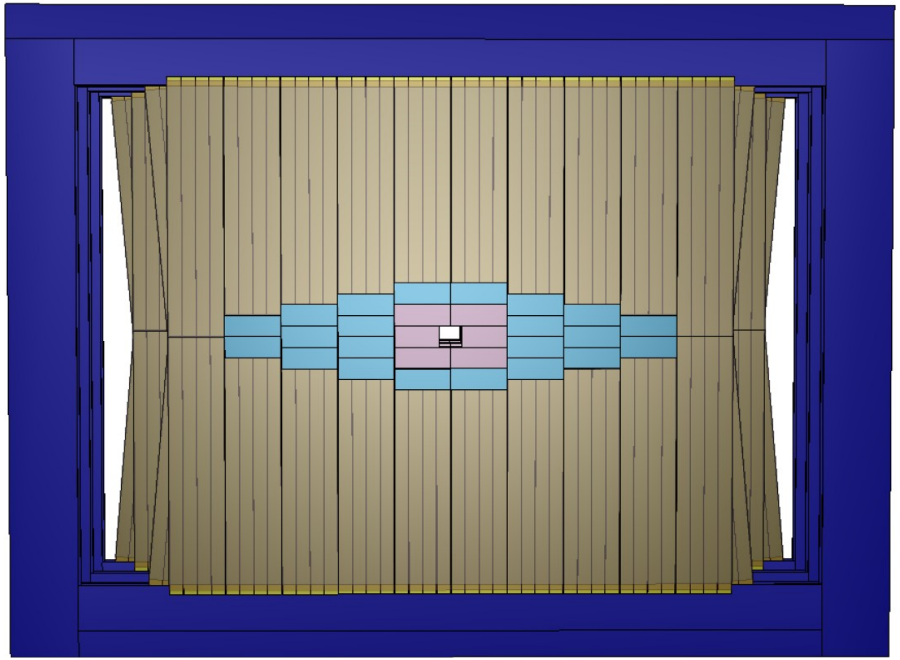
- Candidate sensors
  - thin planar, LGAD, 3D
- Candidate ASICs (28 nm technology)
  - VeloPix2, Timespot
- Mechanical design challenges
  - cooling, module replacement, minimisation of material (RF foil), vacuum compatibility
- Fast tracking, tagging also important for kaon experiments (NA62/HIKE)
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

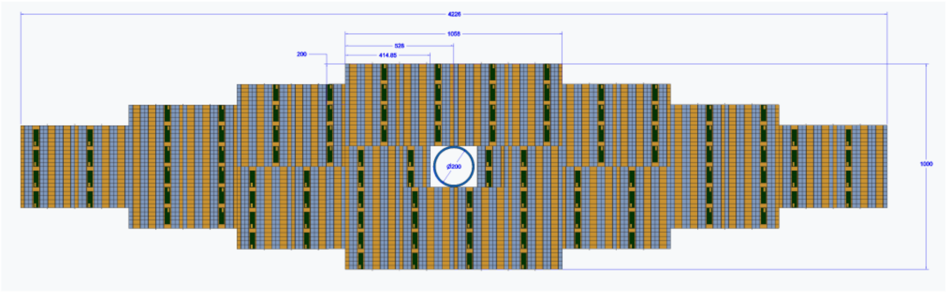
    (see EPJ C82 (2022) 465)



MAPS tracker

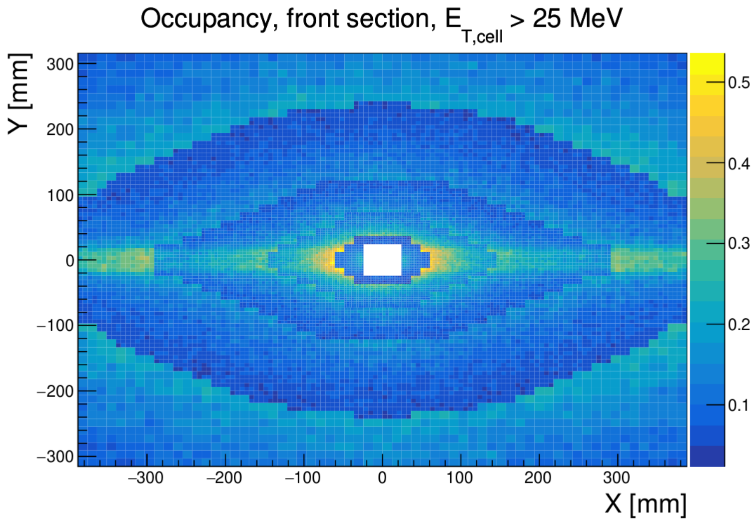
- Central region of SciFi tracking stations to be replaced with silicon detectors
- Use MAPS technology, also for Upstream Tracker (UT)
  - Can meet radiation requirement ($3\times10^{15}\ n_{eq}/cm^2$ at UT)
  - First large scale tracking detector with this technology
  - Building on experience from STAR, ALICE, ATLAS and mu3e

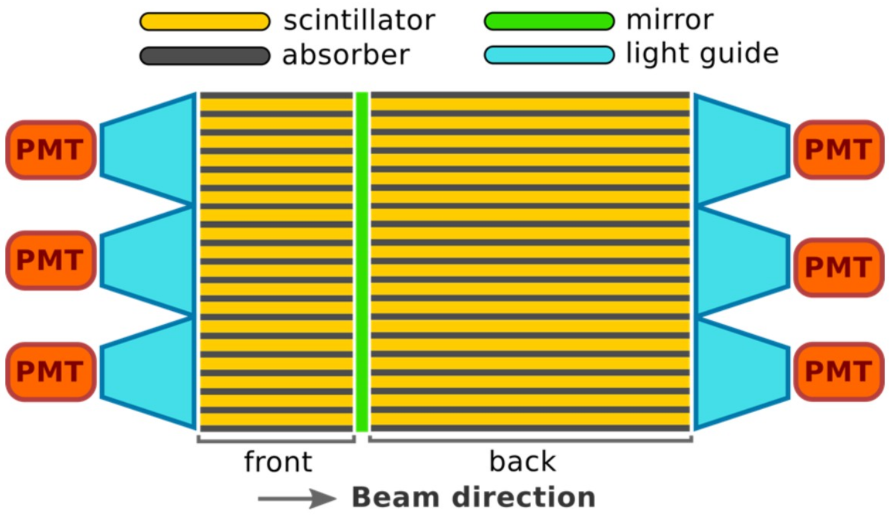




Electromagnetic calorimeter

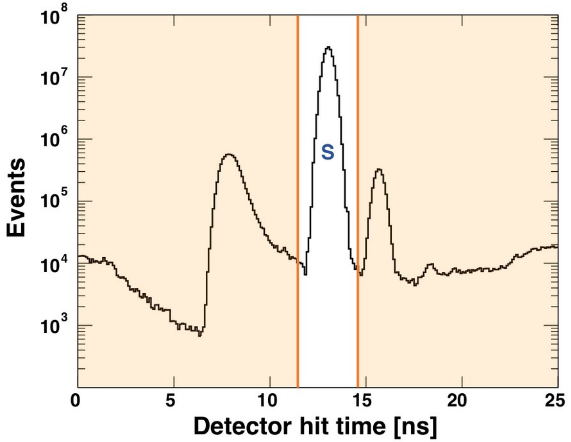
- LHCb ECAL not replaced (except electronics) in Upgrade I
  - in Run 3 will operate at 25× its design luminosity!
- Proposal for crystal fibres (SpaCal) in central region + Shashlik (outer region)
  - timing information (σ_t ~ 20 ps) used to help suppress background

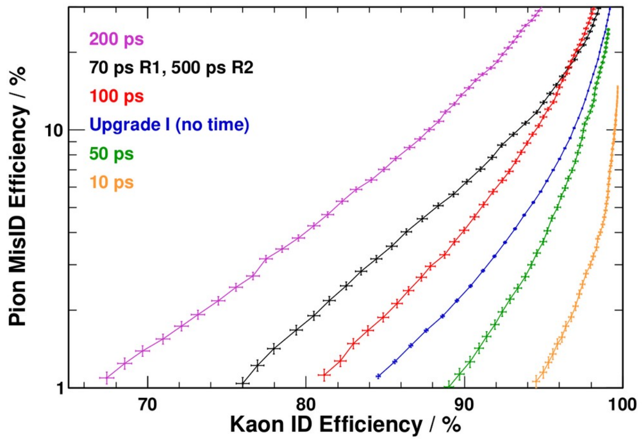


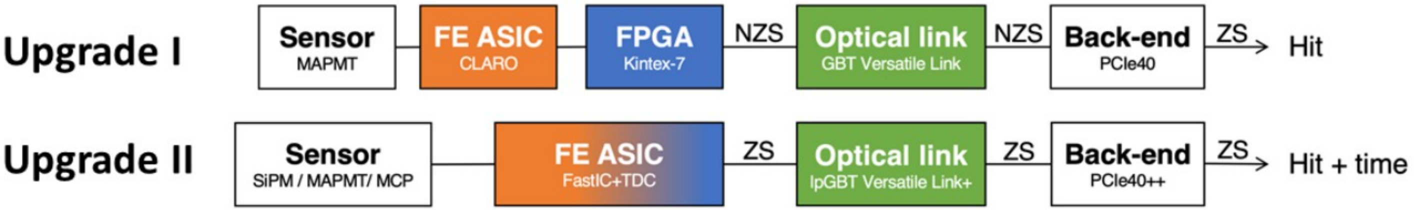


RICH

- Add timing window to reject out of time hits
- Requires new photon detector (SiPM and MCP devices under test), electronics (FastRICH development of FastIC ASIC under development) and optics/mechanics

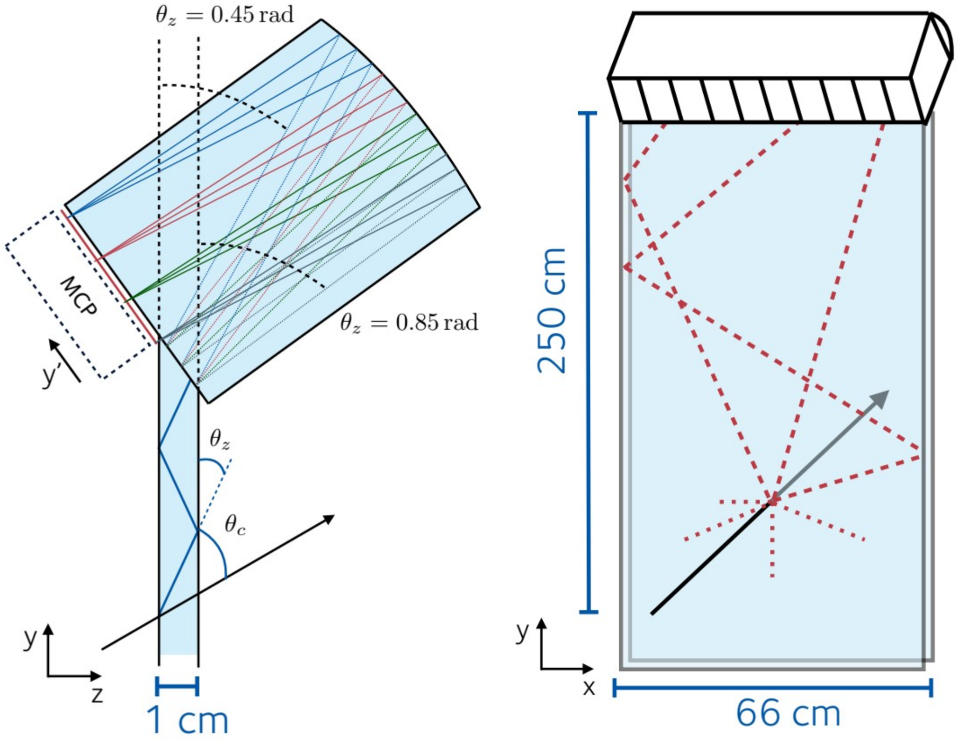






TORCH detector

- 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

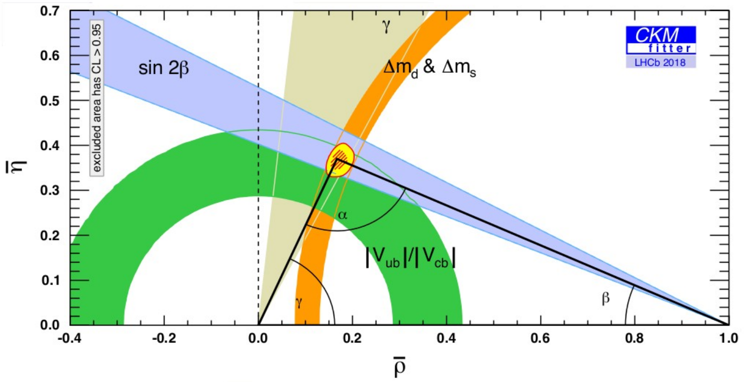


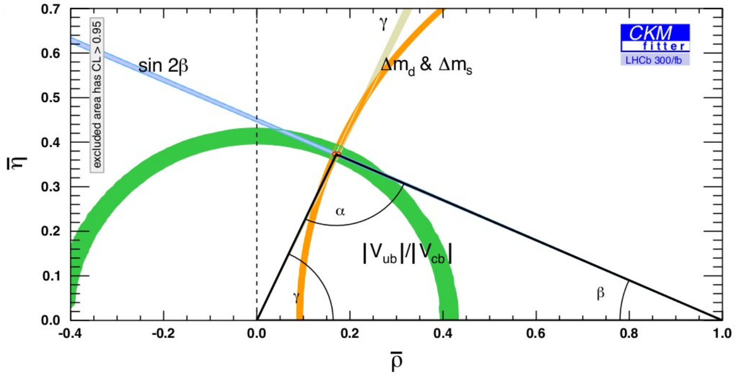
Performance demonstrated in test beam with half-size module: NIM A961 (2020) 163671

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%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	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

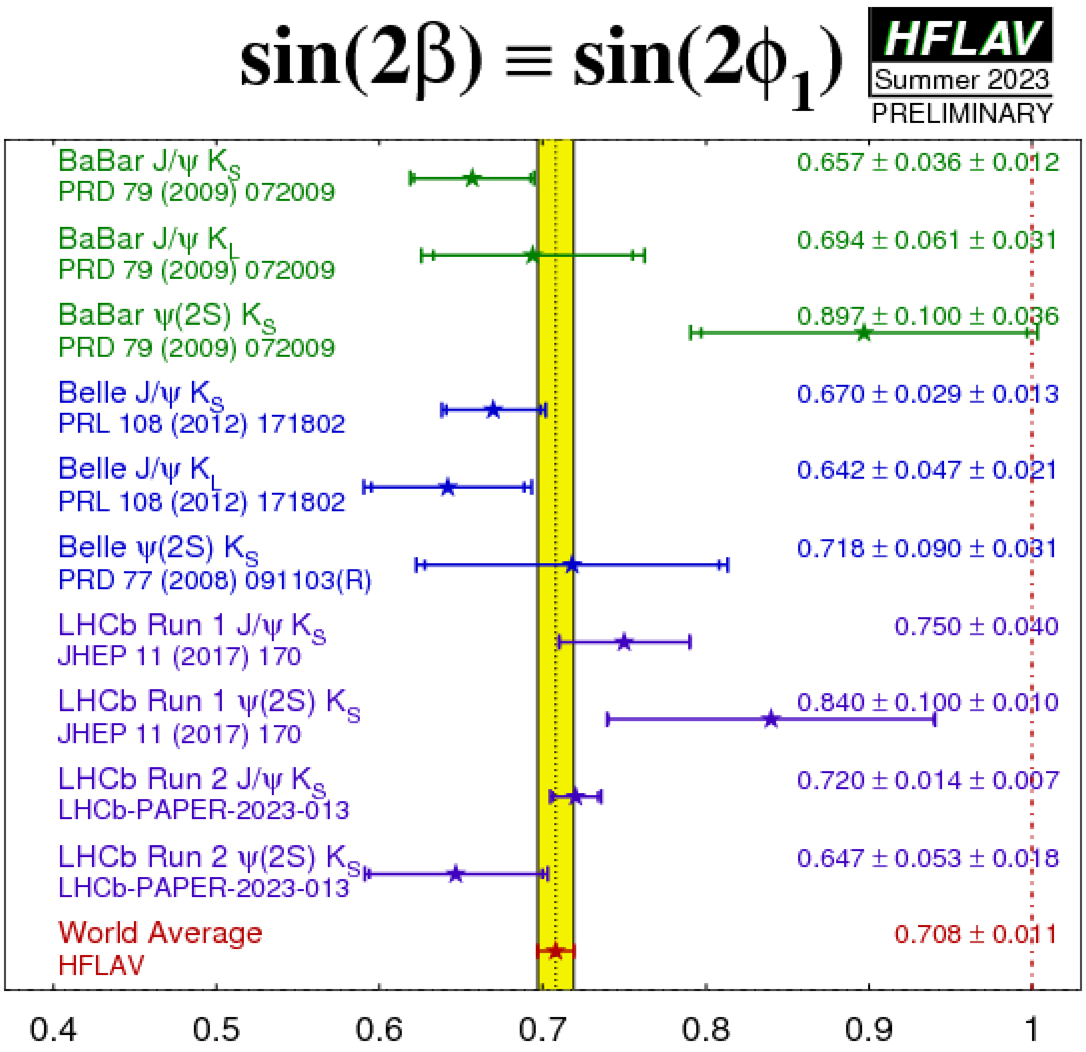
- Flavour physics provides a powerful zeptoscope to probe the smallest scales
  - complementary to Higgs physics and high energy probes
- Enormous progress with breath-taking results from first phase of LHCb
  - some tensions with SM predictions to be understood
- Exciting prospects for 2020s with Belle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

Back up

HFLAV world average 2023 (preliminary)

$\sin(2\beta) = 0.708 \pm 0.011$

Precision now an order of magnitude better compared to first observations of 2001

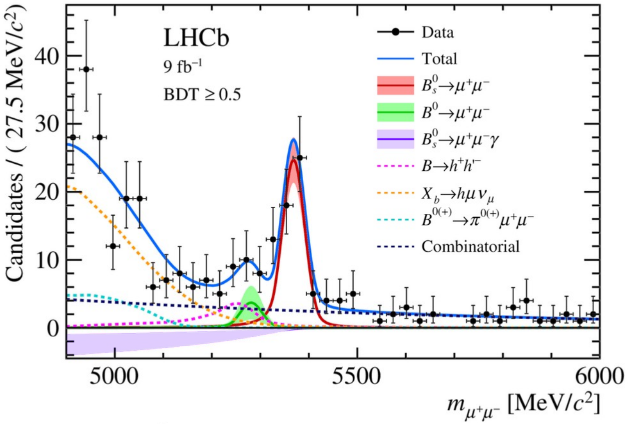


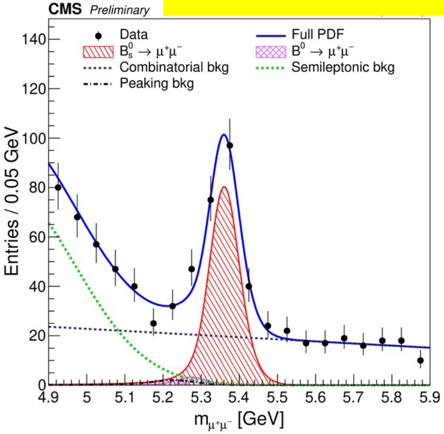
Testing the SM with highly suppressed $B_{(s)}^0 \to \mu^+\mu^-$

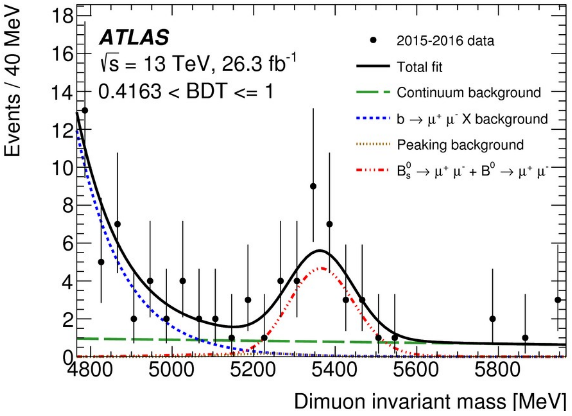
PRL 128 (2022) 041801

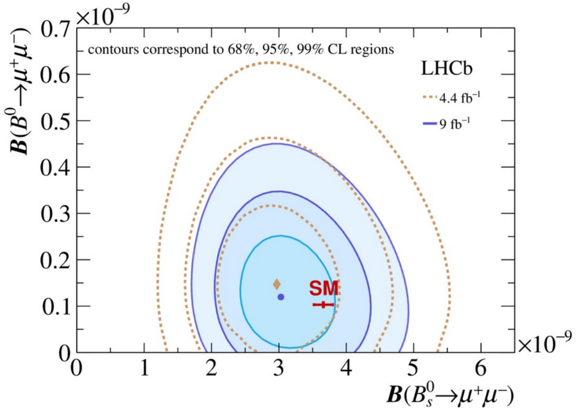
CMS-PAS-BPH-21-006

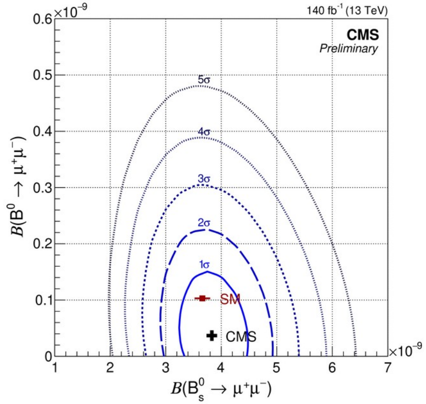
JHEP 04 (2019) 098

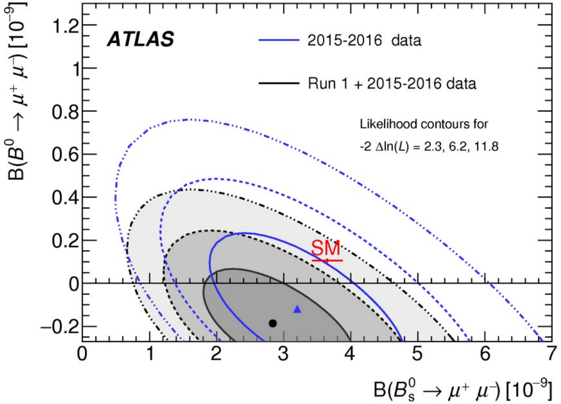








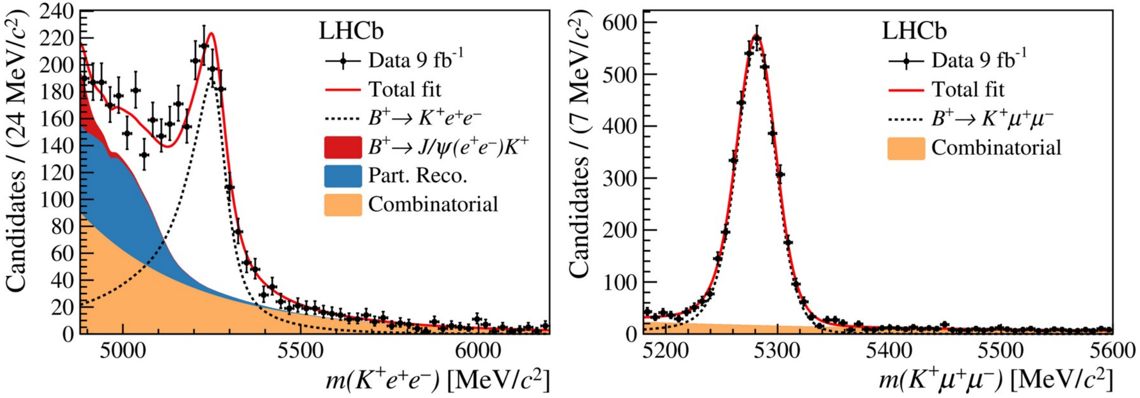




Testing the SM with rare B decays

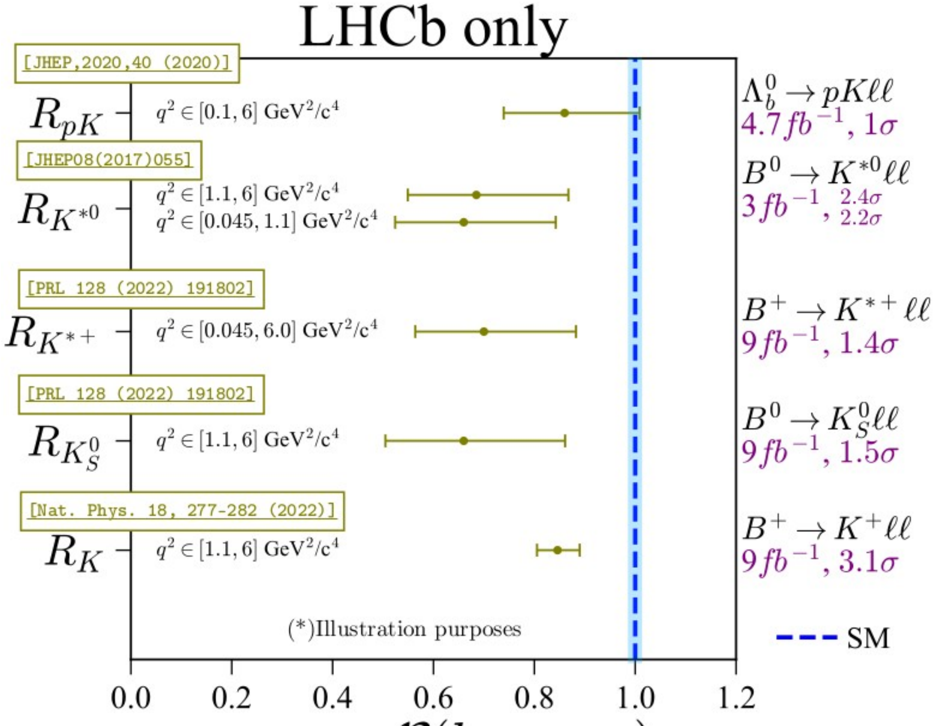
Lepton universality in $B \to K^{(*)} l^+ l^-$ decays

Nature Phys. 18 (2022) 277



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

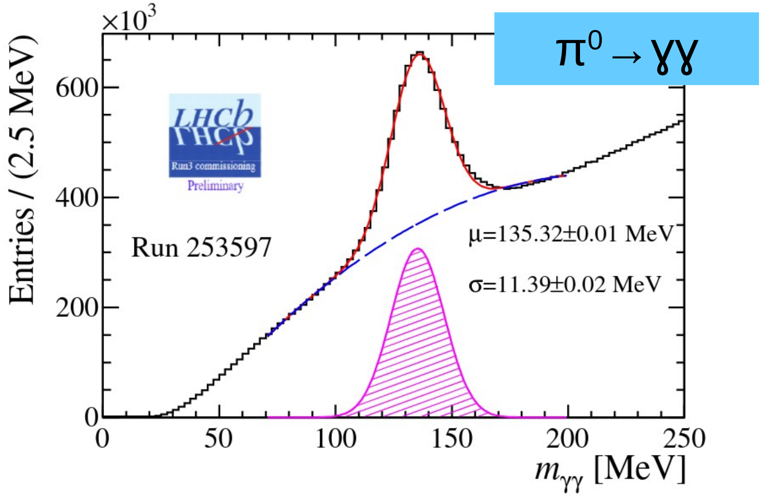
Tension (3.1σ) with SM prediction

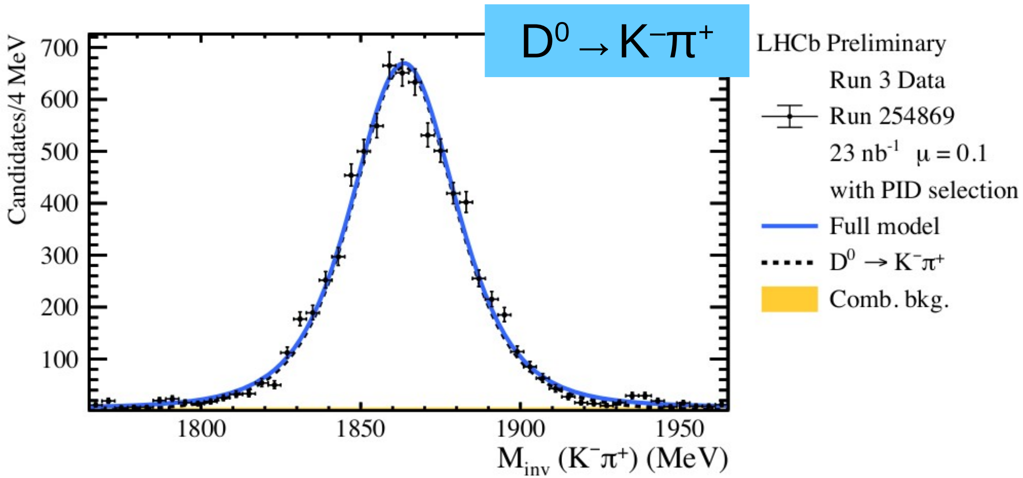


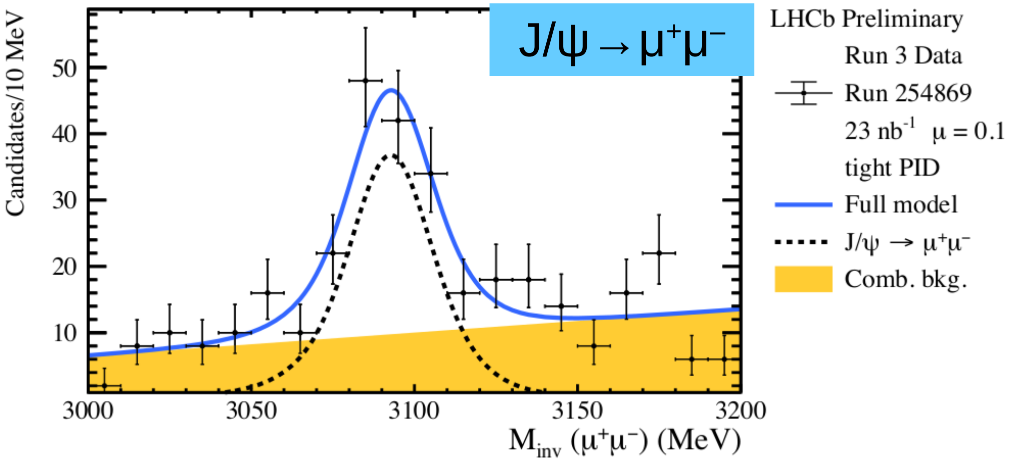
$$R_X = \frac{\mathcal{B}(b \to s\mu\mu)}{\mathcal{B}(b \to see)}$$

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

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