Experimental Overview

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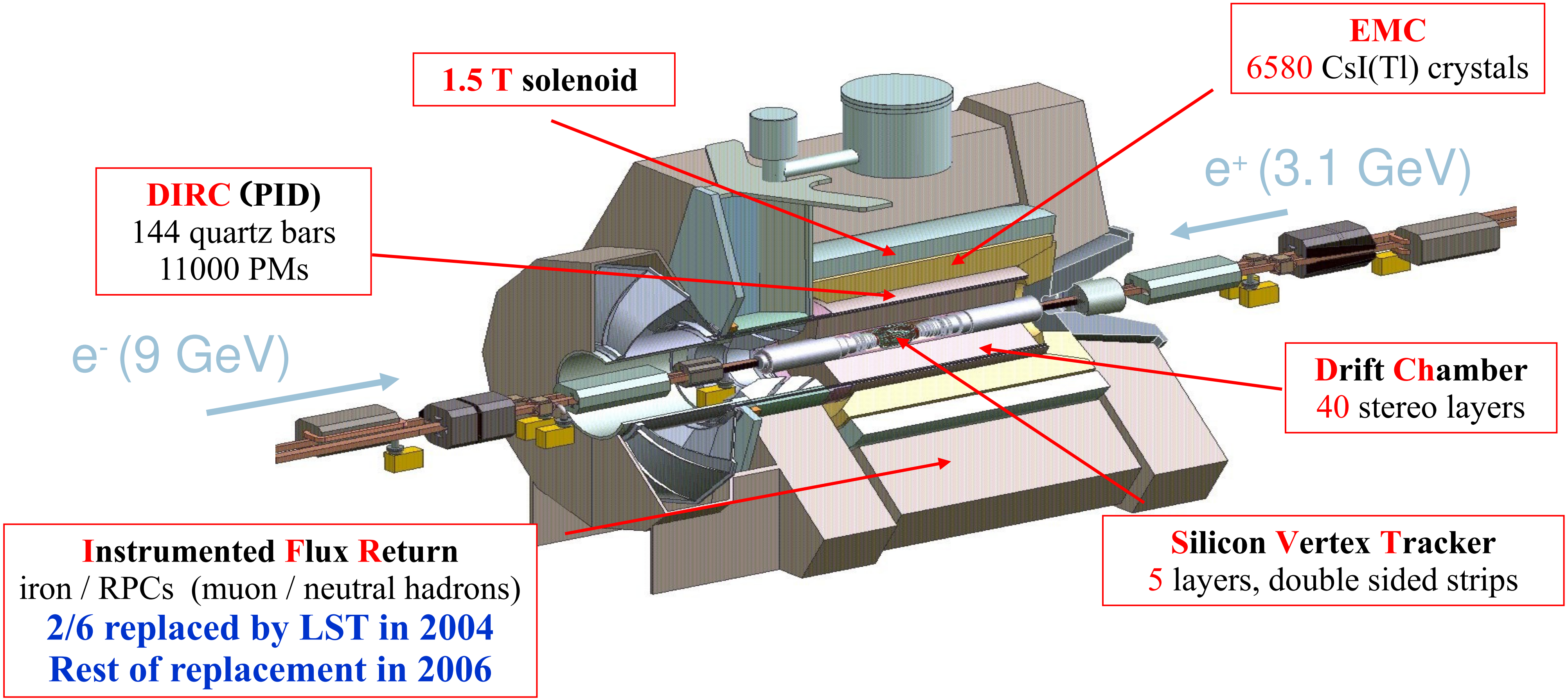
Heavy Flavour 2023 – Quo Vadis?
Ardbeg Distillery, Islay, 20 June 2023

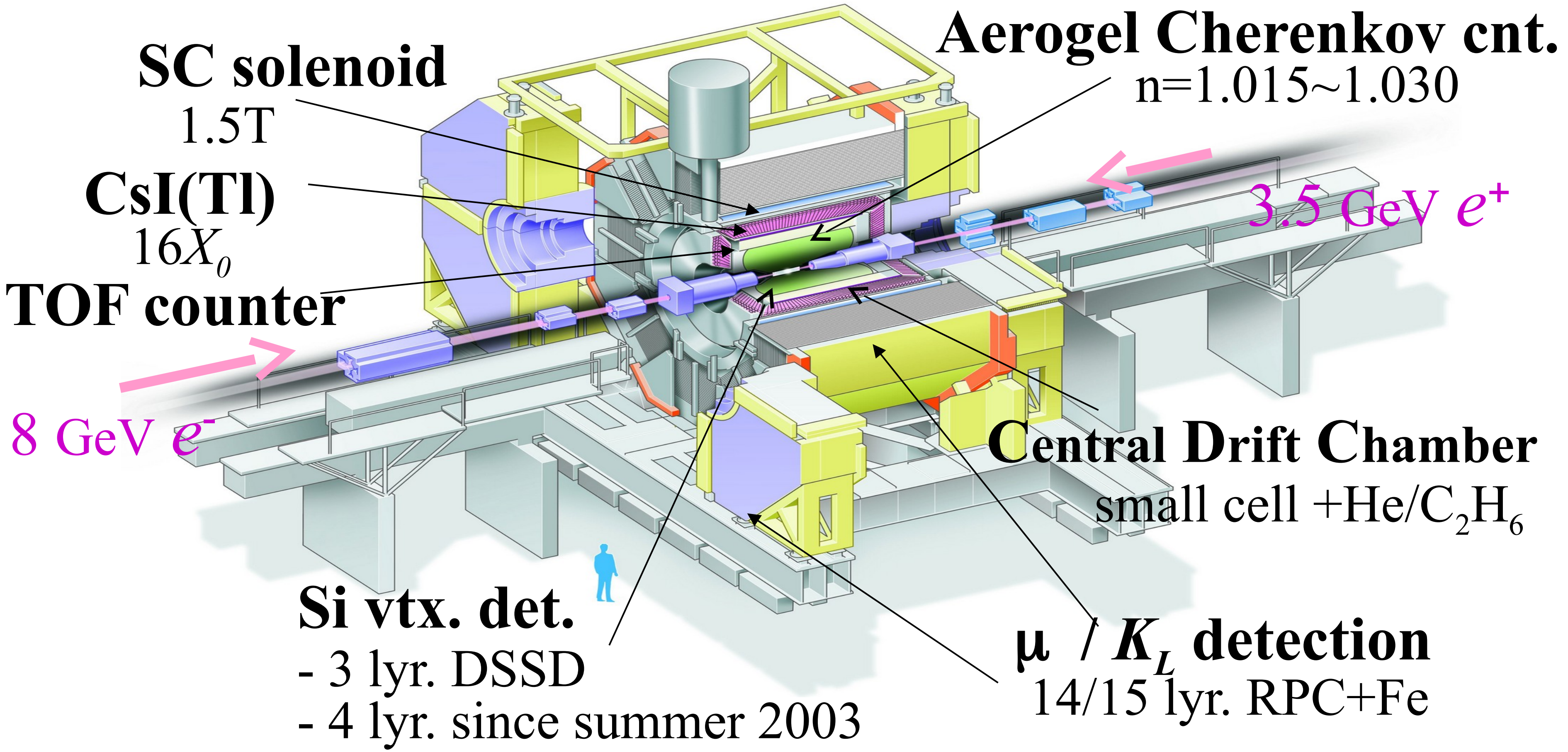
Contents

- Where have we come from and where have we got to?
  - CP violation
  - Rare decays
- Where next?

BaBar Detector

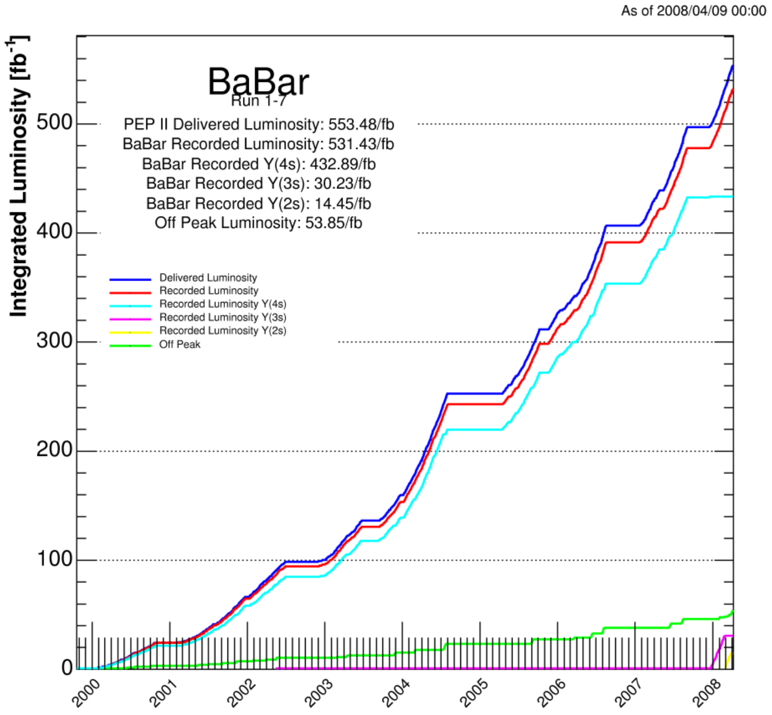


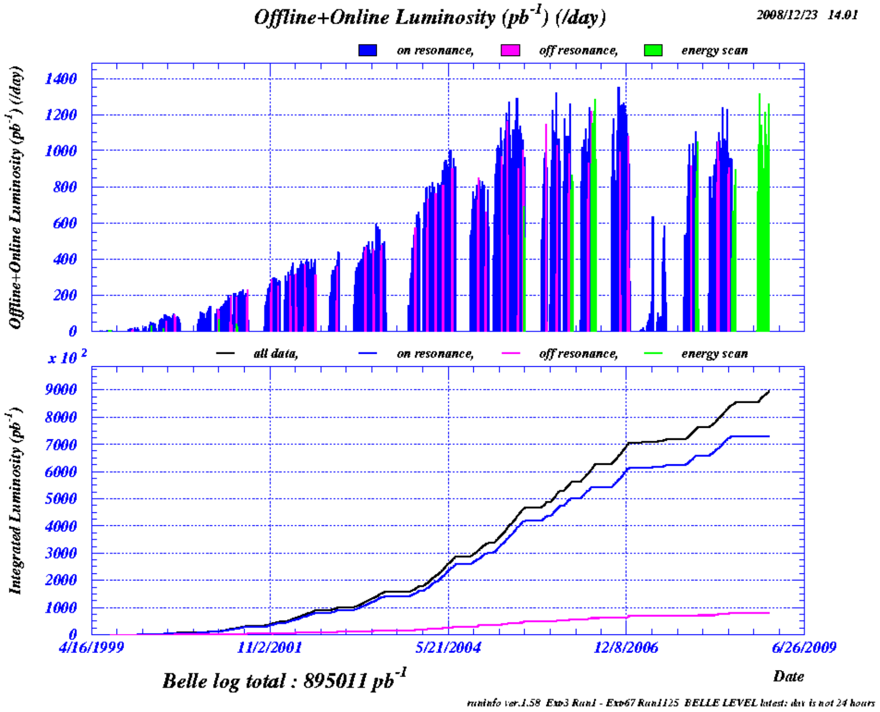
Belle Detector



B factories – world record luminosities

~ 2000 – 2010



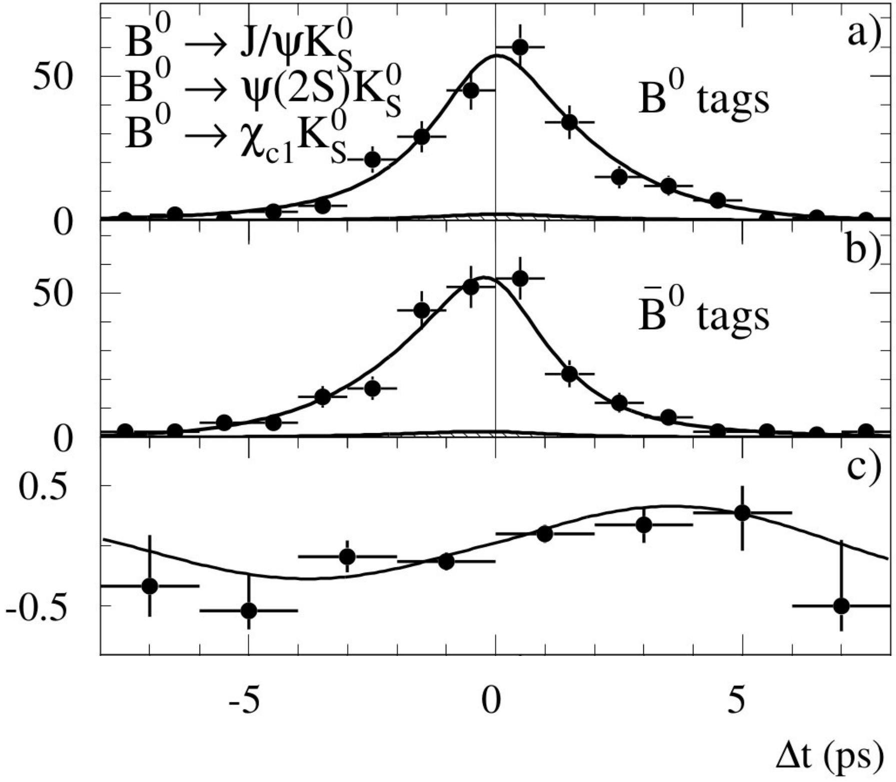


~ 433/fb on Y(4S) **~ 711/fb on Y(4S)**

Total over 10^9 $B\bar{B}$ pairs recorded

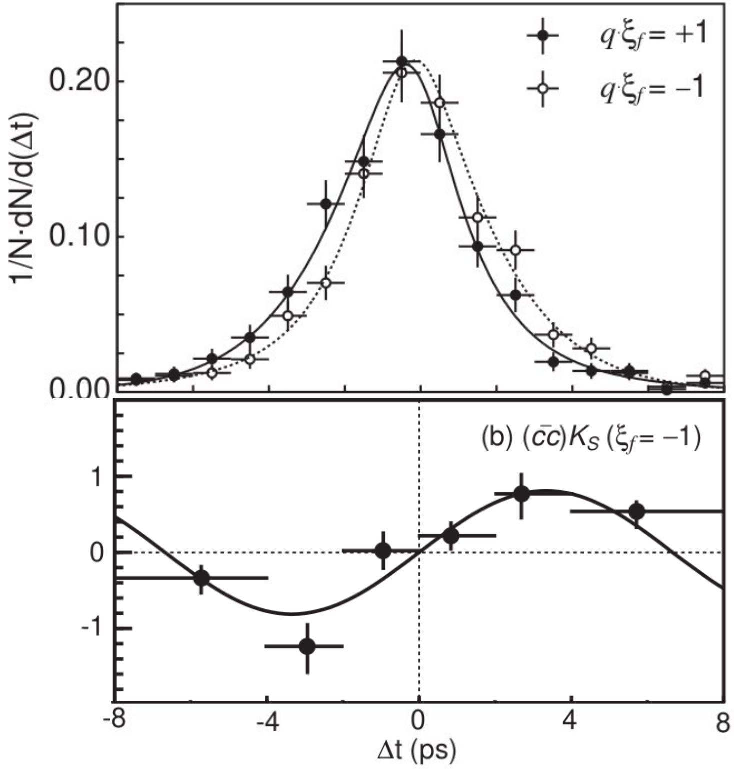
sin(2β), 2001

BaBar, PRL 87 (2001) 091801



$$\sin 2\beta = 0.59 \pm 0.14 \text{ (stat)} \pm 0.05 \text{ (syst)}.$$

Belle, PRL 87 (2001) 091802

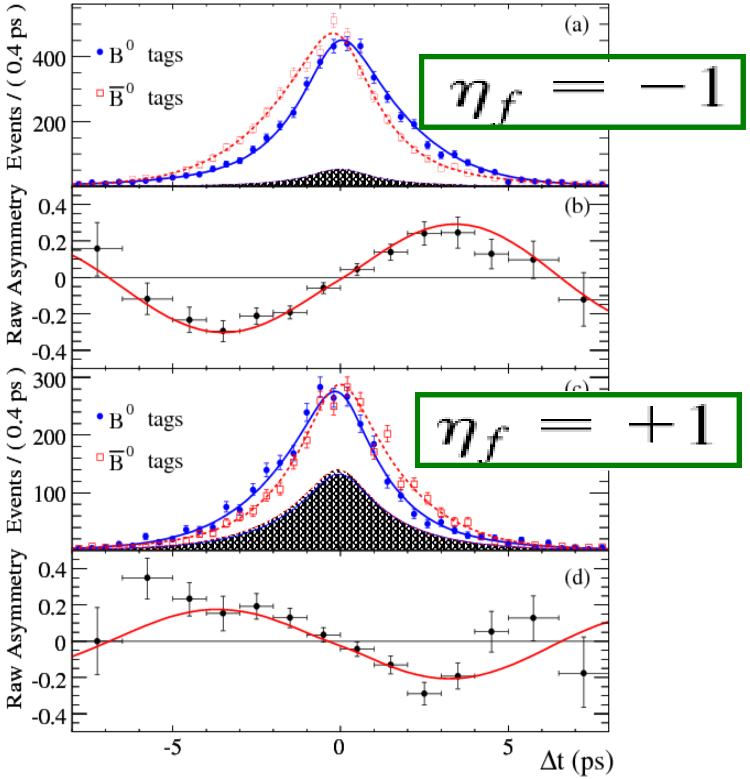


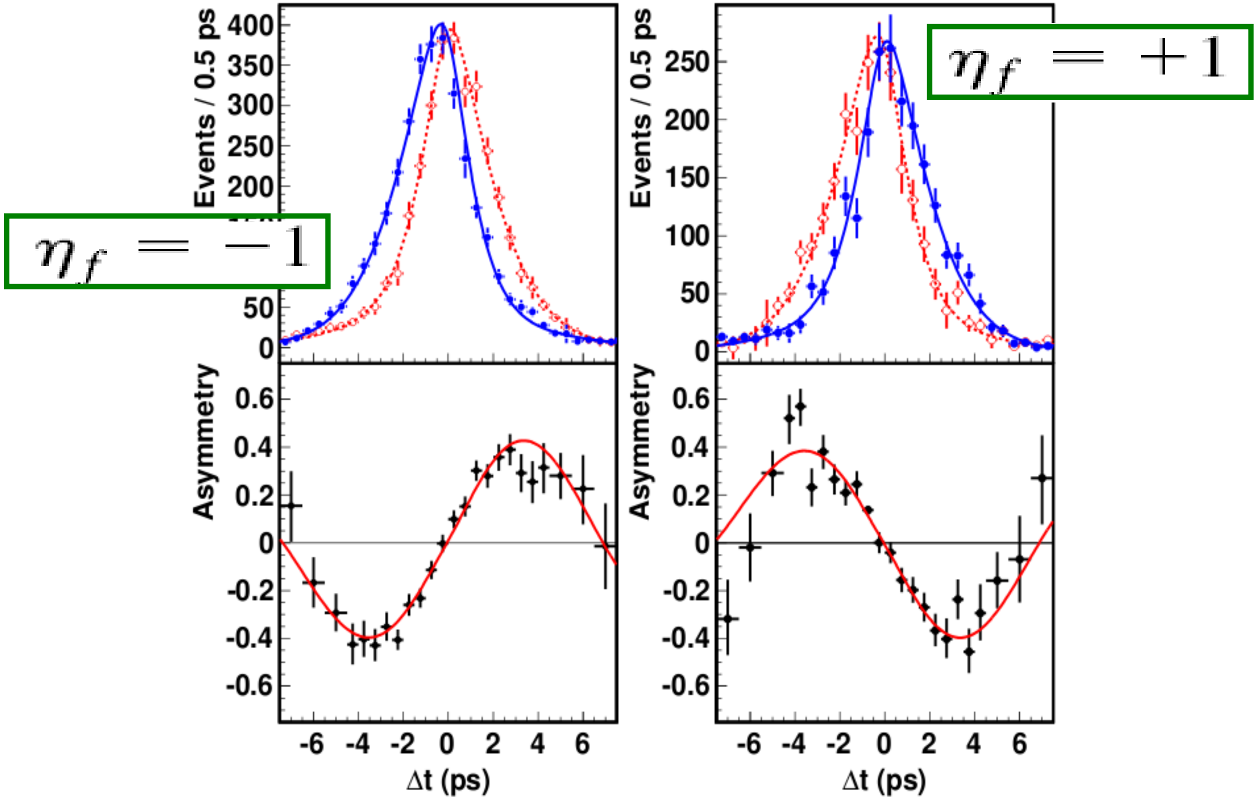
$$\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}).$$

sin(2β), 2012

BaBar, PRD 79 (2009) 072009

Belle, PRL 108 (2012) 171802





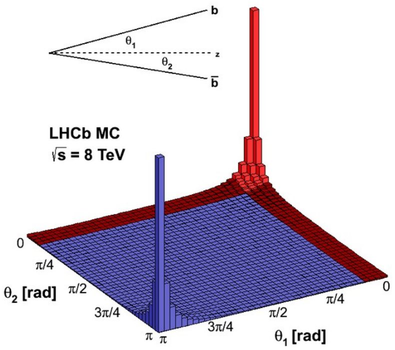
sin(2β) = 0.687 ± 0.028 (stat) ± 0.012 (syst)

sin(2φ_1) = 0.667 ± 0.023 (stat) ± 0.012 (syst)

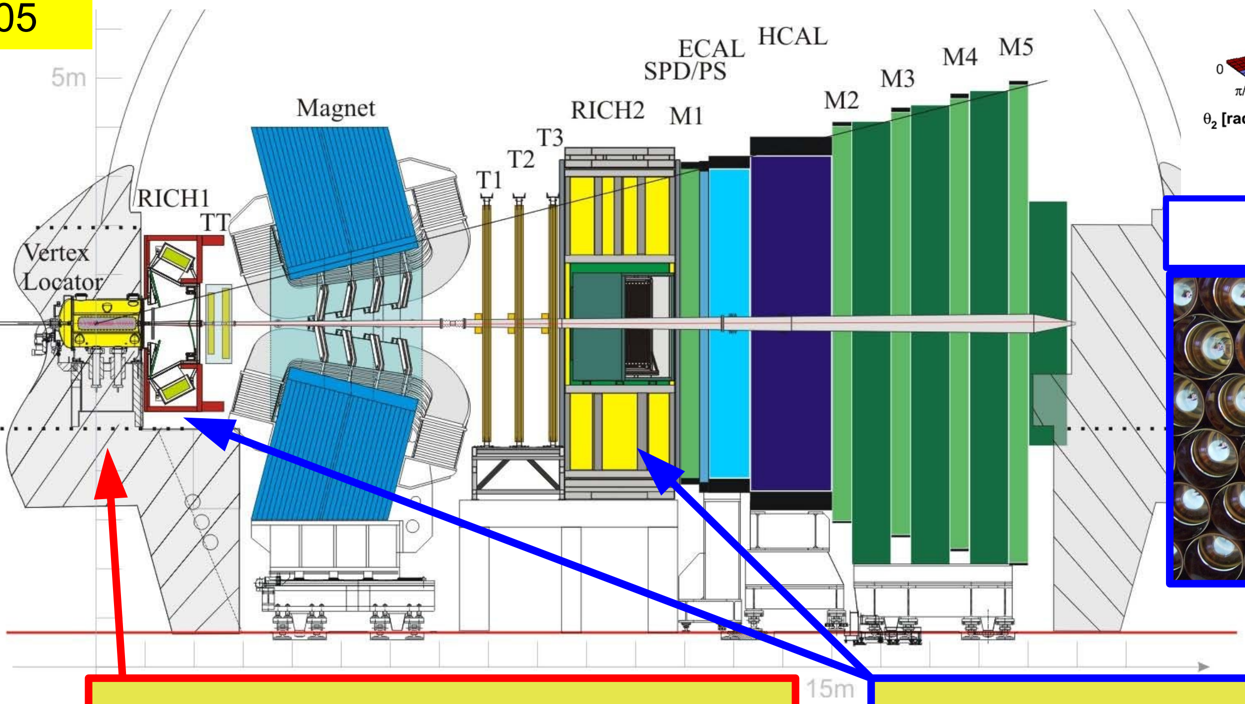
The LHCb detector

(2011-18 edition)

The LHCb Detector
JINST 3 (2008) S08005



VELO silicon strips



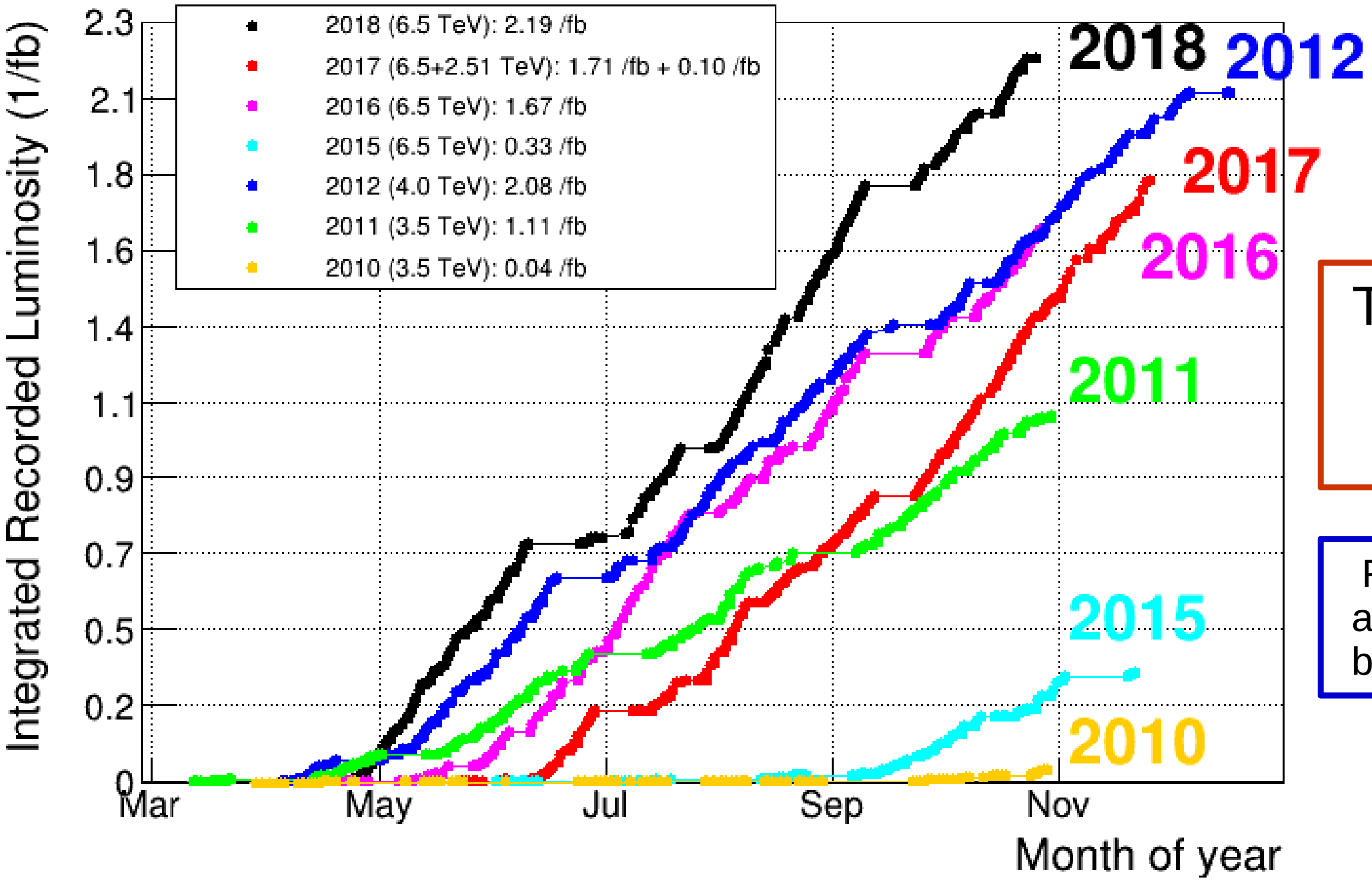
RICH PMTs

Precision primary and secondary vertex measurements

Excellent K/π separation capability

LHCb integrated luminosity

~2010 – 2020

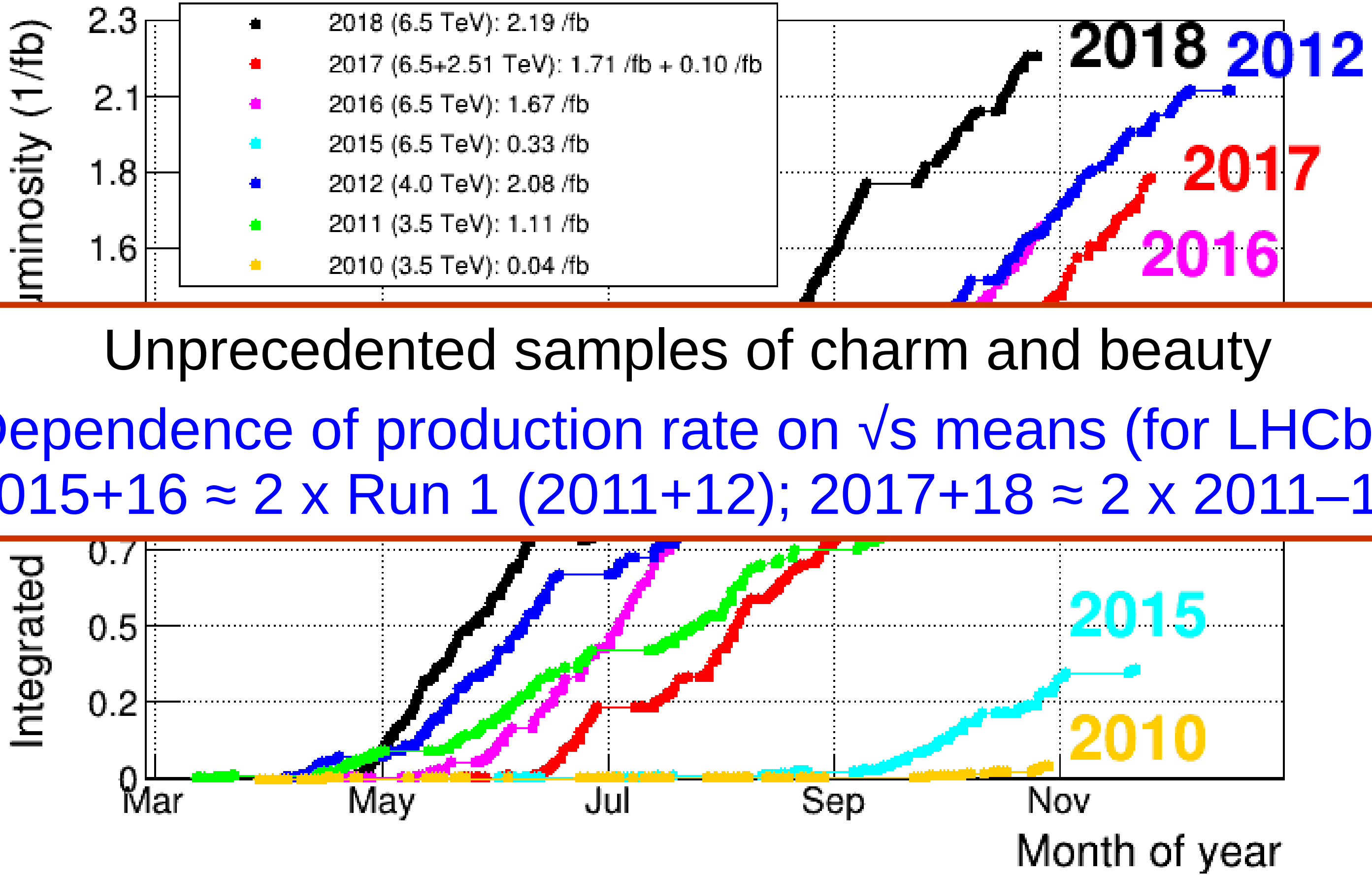


Total sample
2011-18
9/fb

For ∫Ldt to mean anything, it has to be multiplied by σ

LHCb integrated luminosity

~2010 – 2020



Unprecedented samples of charm and beauty

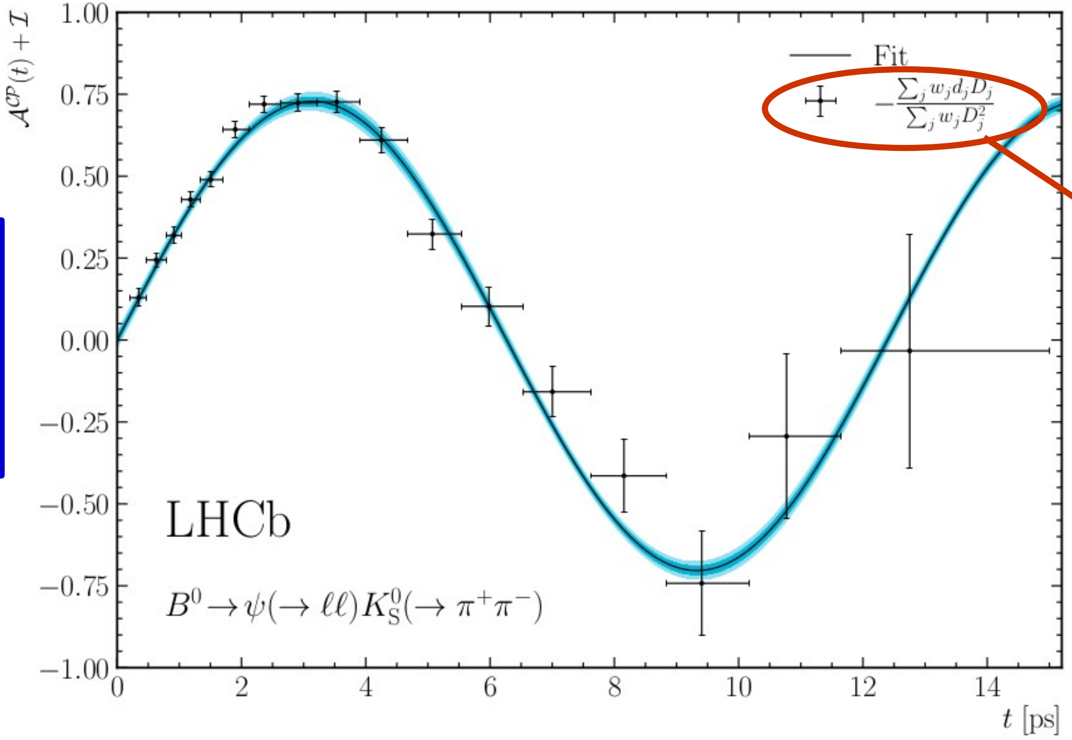
Dependence of production rate on √s means (for LHCb)
2015+16 ≈ 2 x Run 1 (2011+12); 2017+18 ≈ 2 x 2011–16

sin(2β), today

LHCb-PAPER-2023-013
in preparation

τ(B^0) = 1.52 ps

Range of plot covers ten B^0 lifetimes!



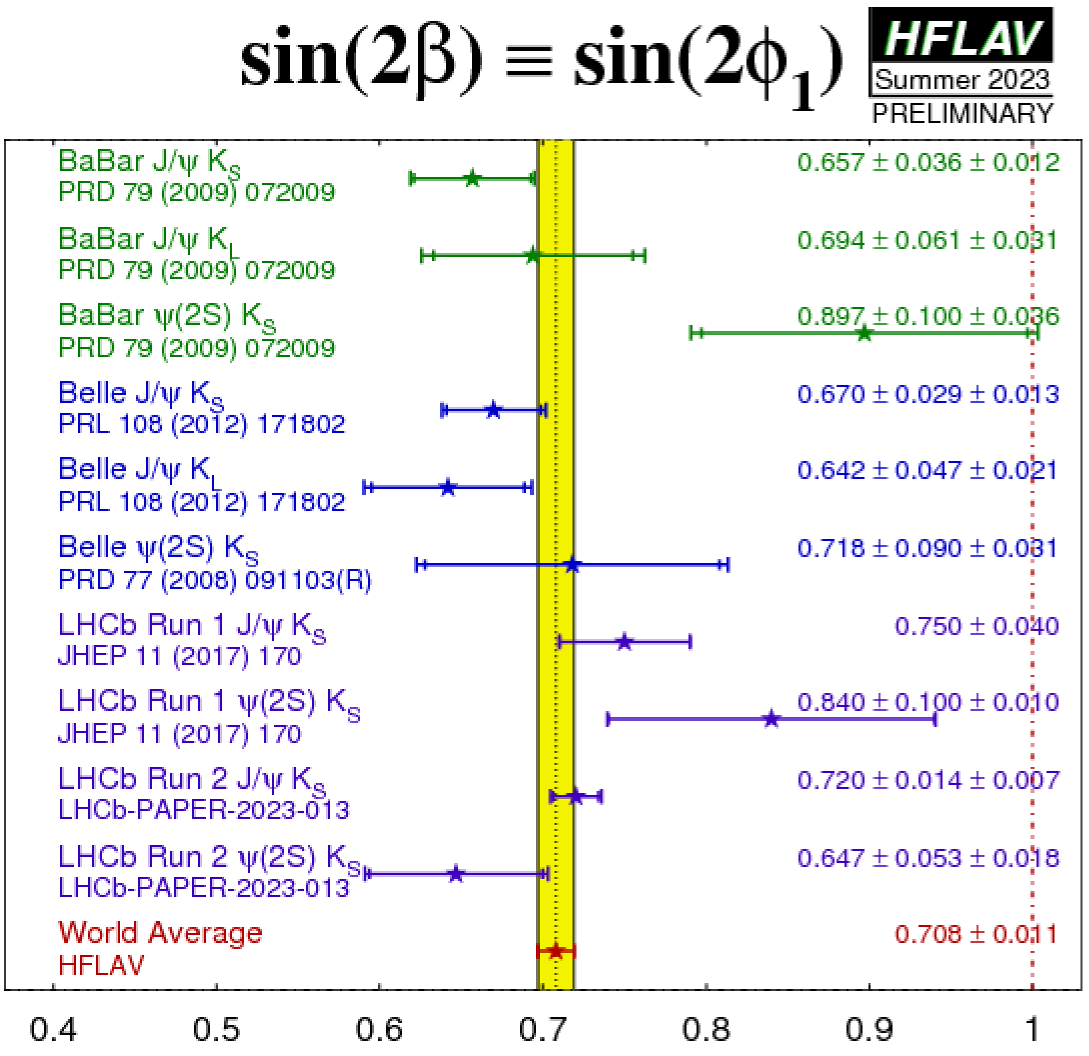
Asymmetry corrected for tagging dilution

sin(2β) = 0.7158 ± 0.0133 (stat) ± 0.0078 (syst)

HFLAV world average 2023 (preliminary)

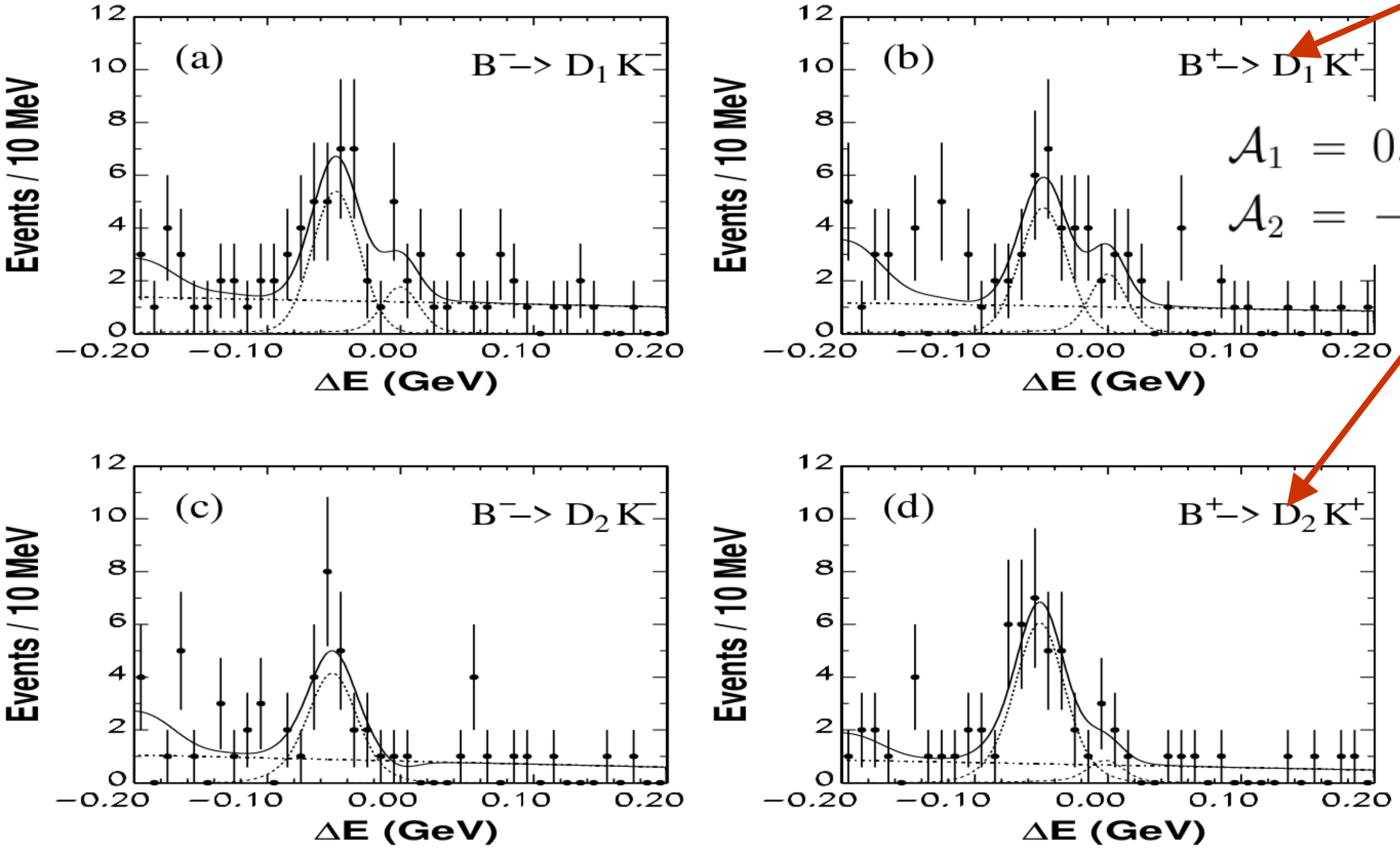
$\sin(2\beta) = 0.708 \pm 0.011$

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



γ from B → DK (GLW), 2003

Belle, PRD 68 (2003) 051101



D_1 = CP even final states

$$\mathcal{A}_1 = 0.06 \pm 0.19(stat) \pm 0.04(sys),$$
$$\mathcal{A}_2 = -0.19 \pm 0.17(stat) \pm 0.05(sys)$$

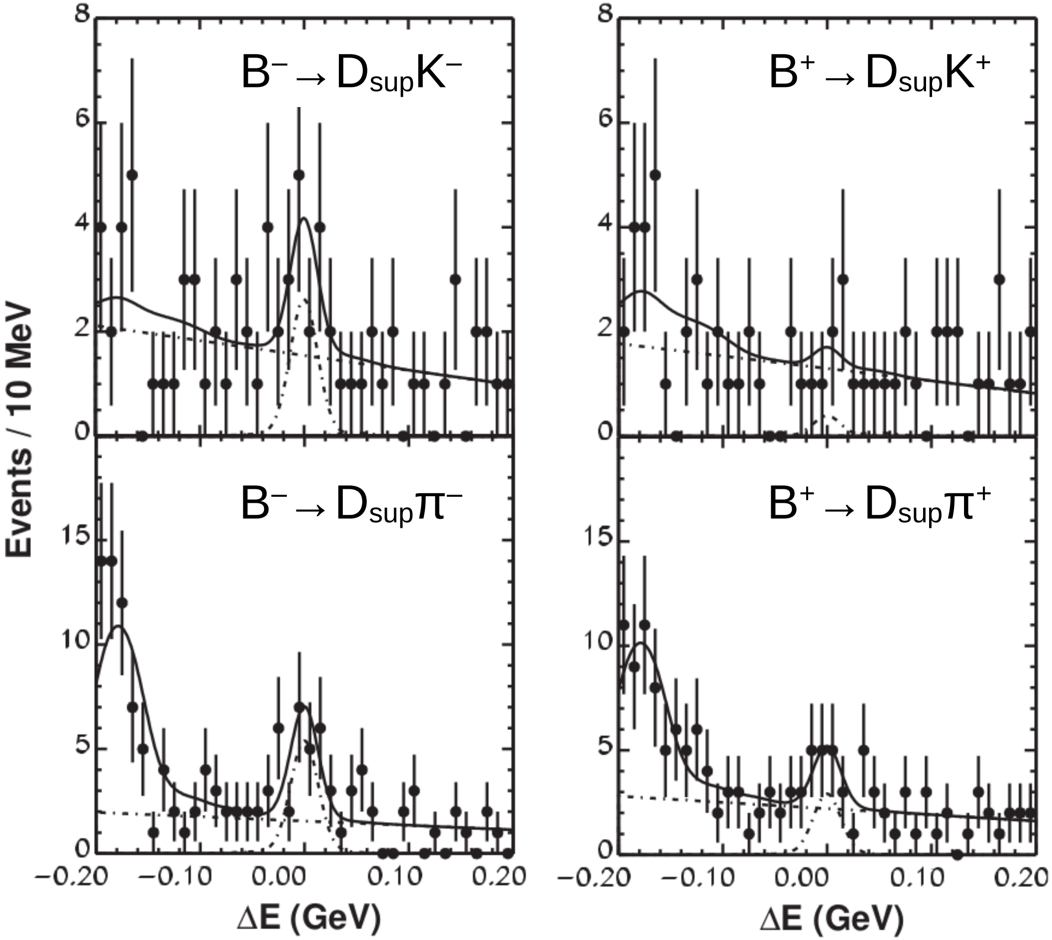
D_2 = CP odd final states

Here, misidentified B → Dπ peaks at 0;

B → DK signal peaks at –49 MeV

γ from B→DK (ADS), 2005

Belle, PRL 94 (2005) 091601



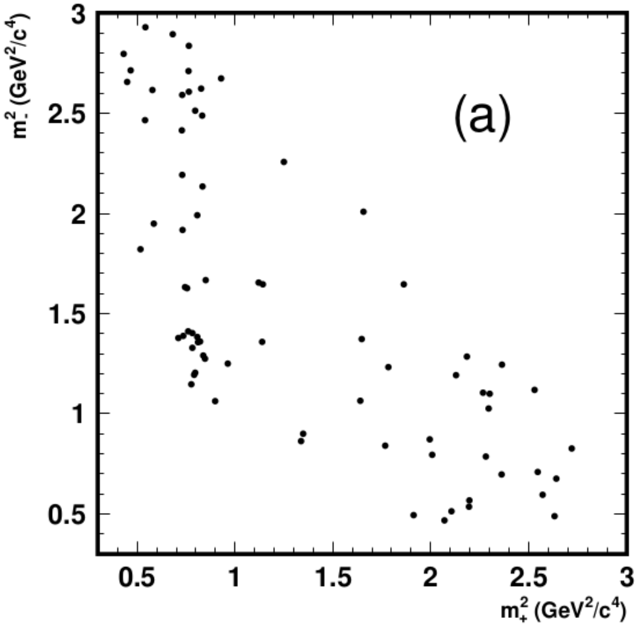
$$\mathcal{A}_{DK} = 0.88\,^{+0.77}_{-0.62}(\text{stat}) \pm 0.06(\text{syst}),$$
$$\mathcal{A}_{D\pi} = 0.30\,^{+0.29}_{-0.25}(\text{stat}) \pm 0.06(\text{syst}),$$

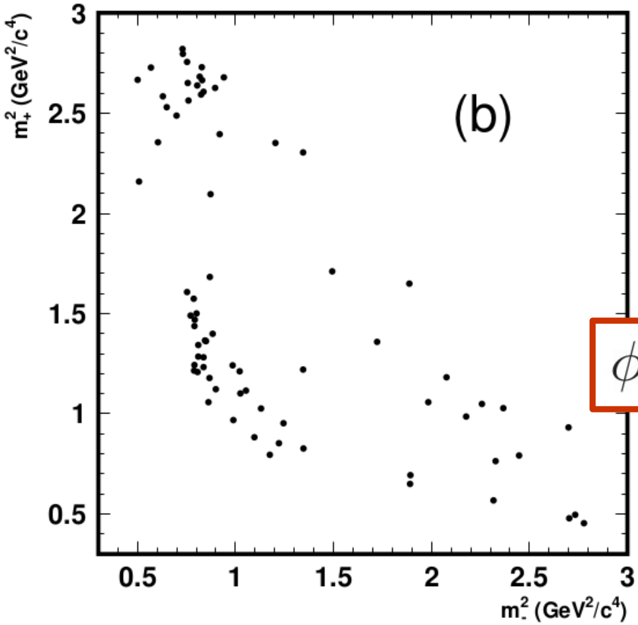
Here, both B→Dh peak at 0 when correctly identified

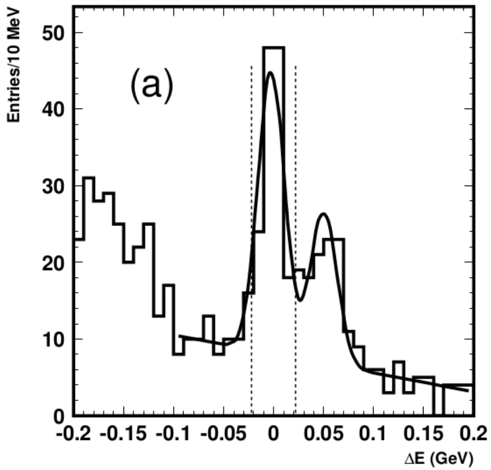
γ from B → DK (BPGGSZ), 2004

Belle, PRD 70 (2004) 072003

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





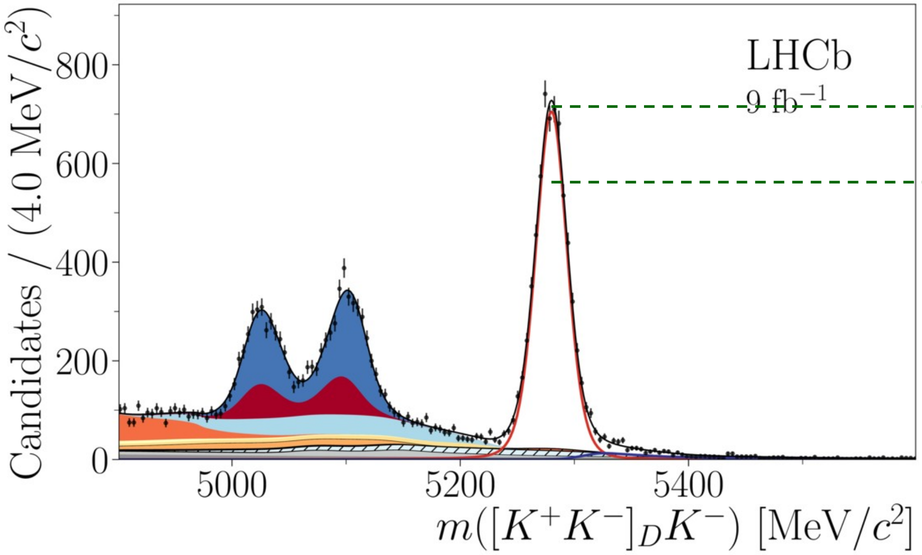


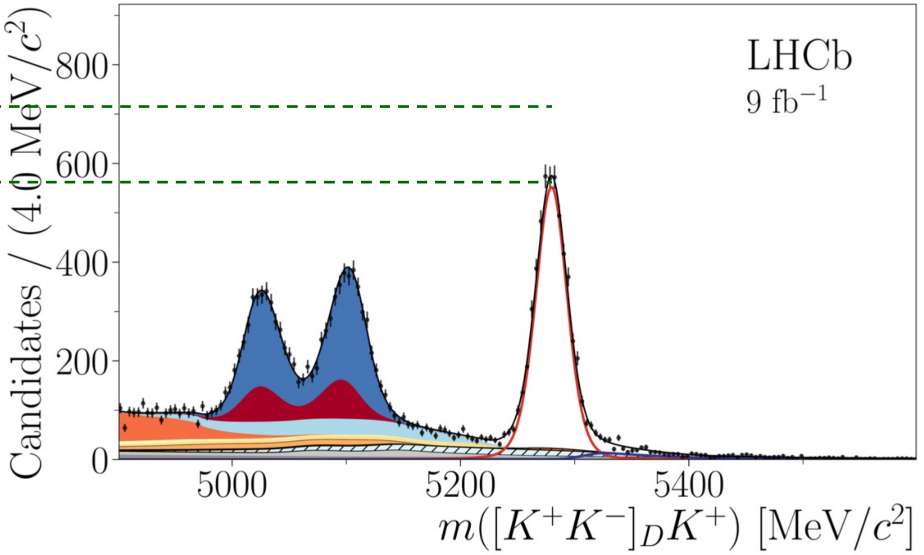
$$\phi_3 = 77^\circ \ {}^{+17^\circ}_{-19^\circ} \pm 13^\circ \pm 11^\circ$$

precision benefitting from upwards fluctuation in r_B

γ from B → DK (GLW), today

LHCb, JHEP 04 (2021) 081



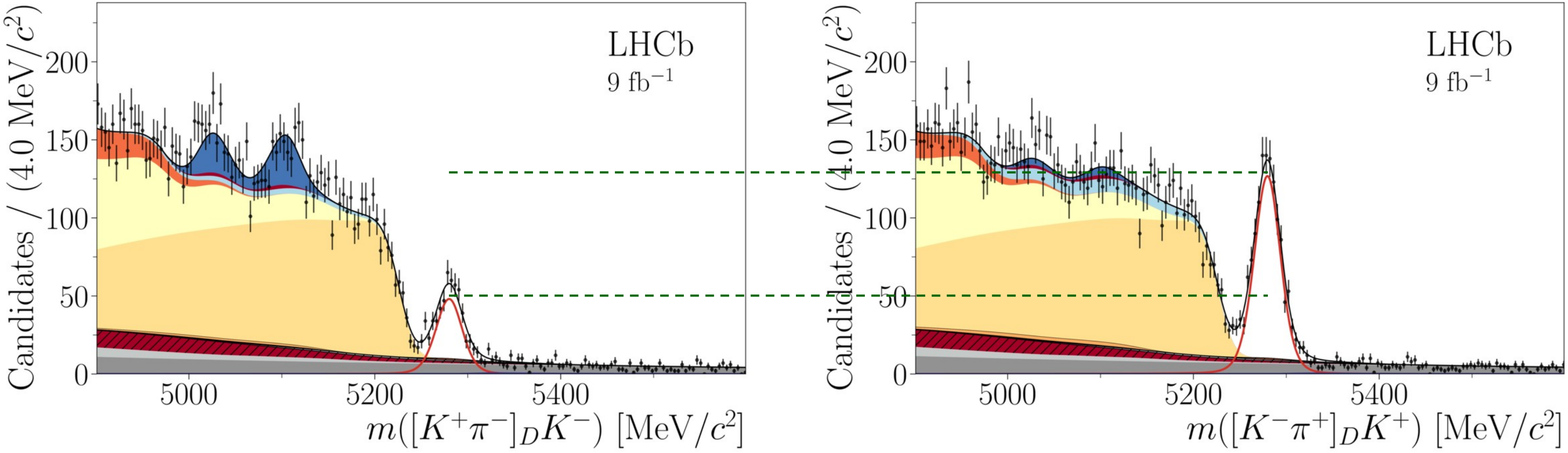


$A_{CP}(B^- \to D_{CP+}K^-) = 0.136 \pm 0.009$ (stat) ± 0.001 (syst)

(result also includes $D \to \pi^+\pi^-$)

γ from B → DK (ADS), today

LHCb, JHEP 04 (2021) 081

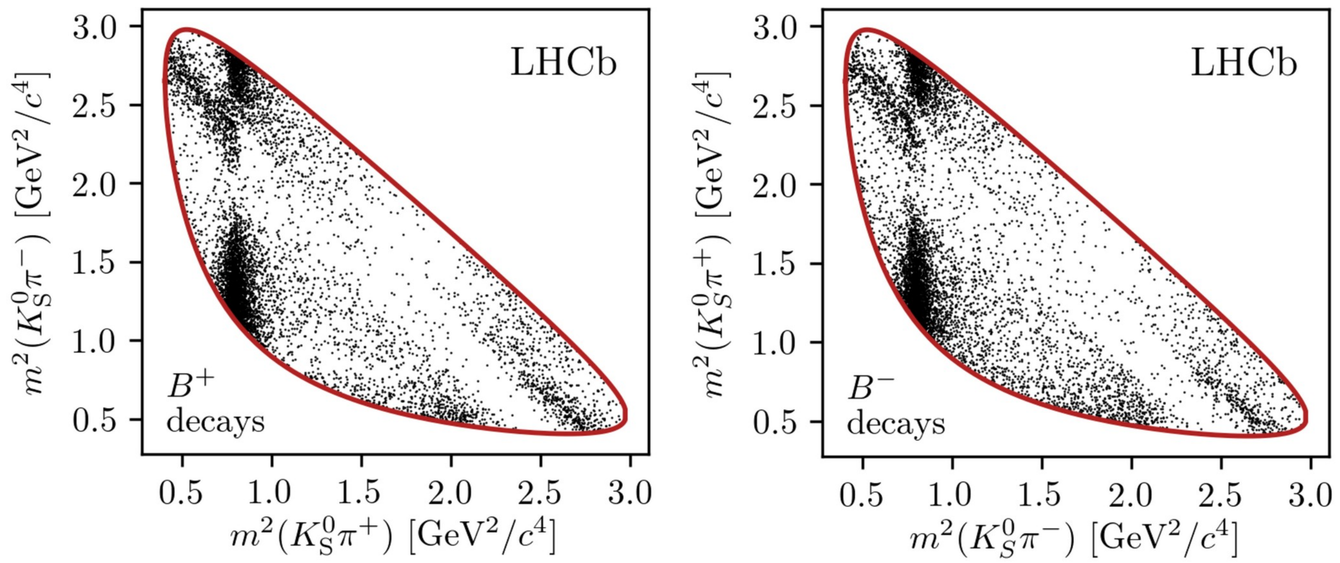


$A_{CP}(B^- \to D_{ADS} K^-) = -0.451 \pm 0.026$

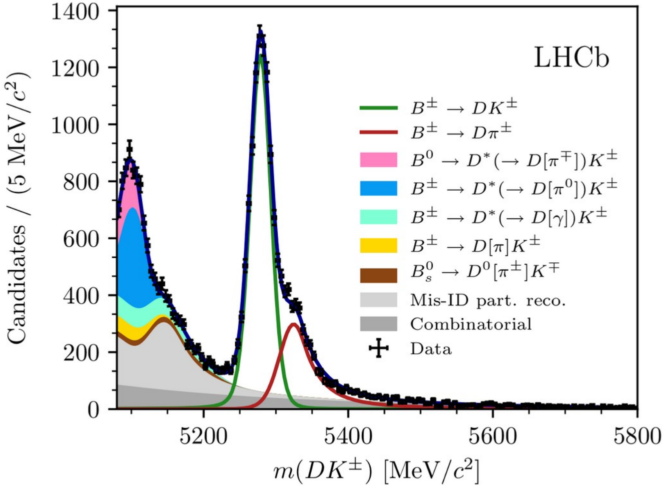
γ from B→DK (BPGGSZ), today

LHCb, JHEP 02 (2021) 169

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



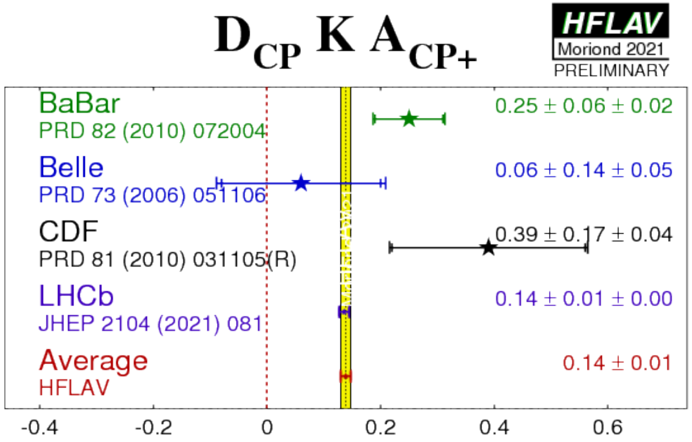
this plot DD sample only

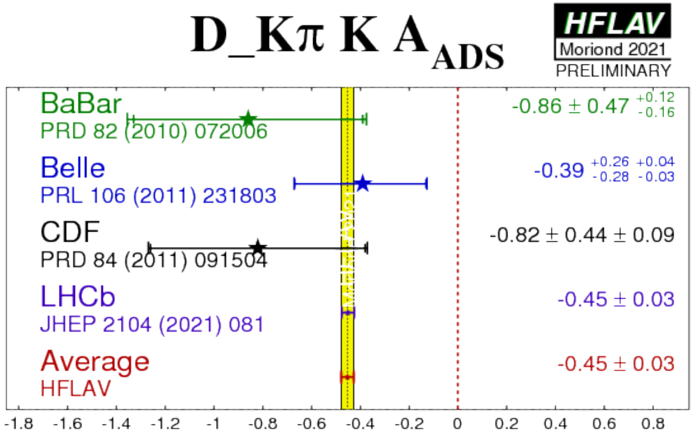


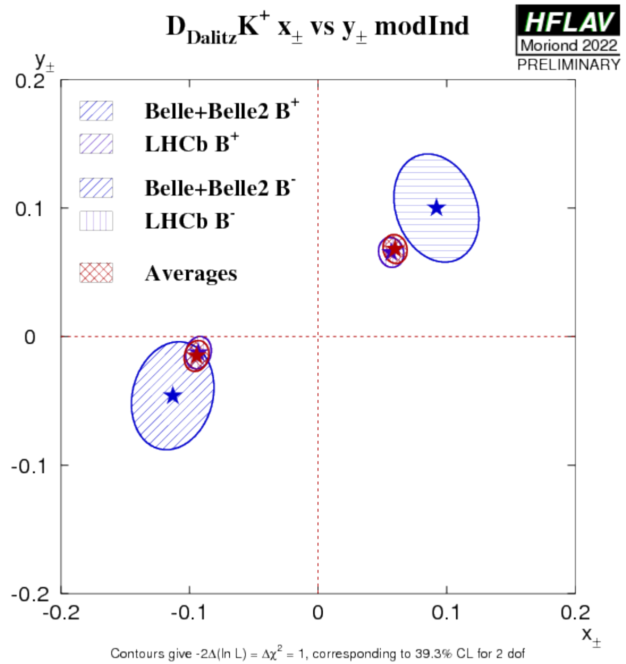
$\gamma = (68.7\ ^{+5.2}_{-5.1})^\circ$

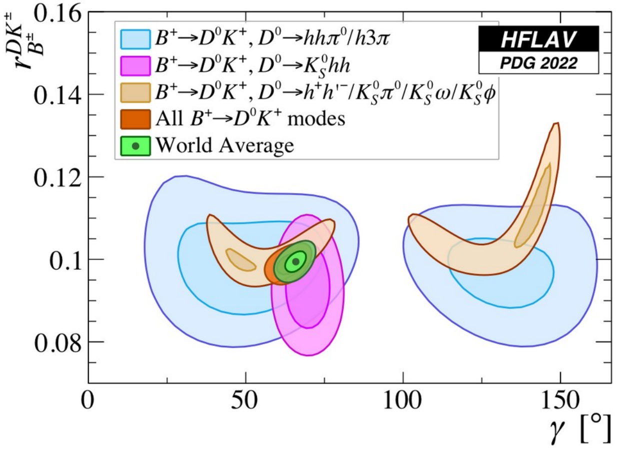
no longer benefitting from r_B fluctuations

γ now and then









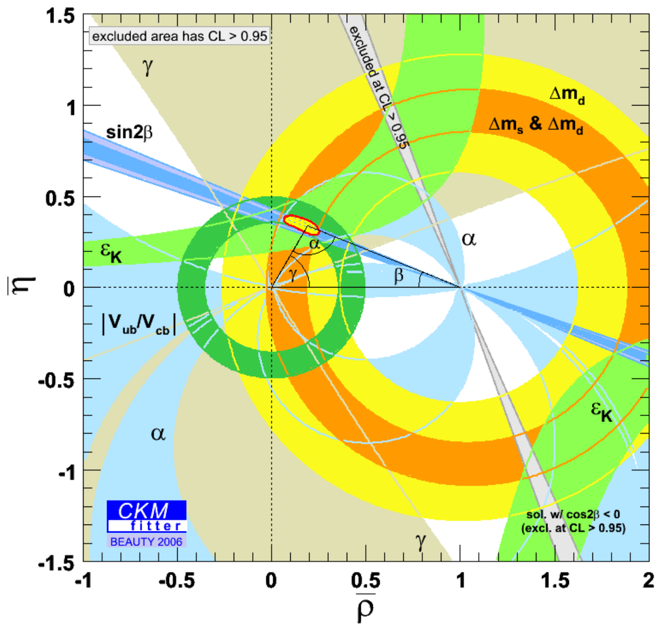
Current HFLAV world average
$\gamma = (65.9\ ^{+3.3}_{-3.5})°$

Precision again about an order of magnitude better compared to 2004

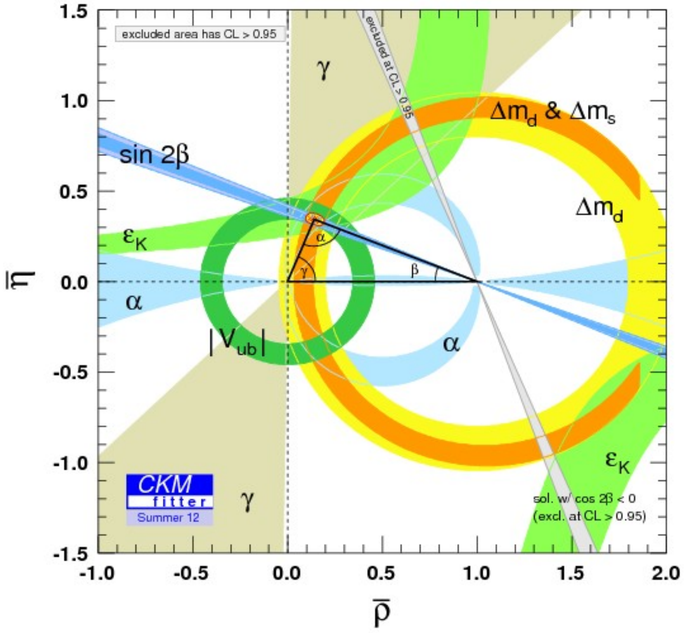
The Unitarity Triangle

http://ckmfitter.in2p3.fr/

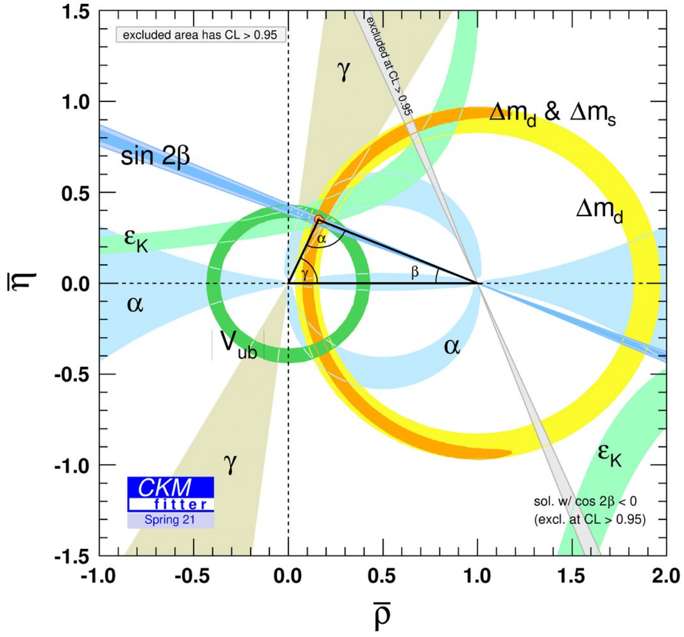
2006



2012

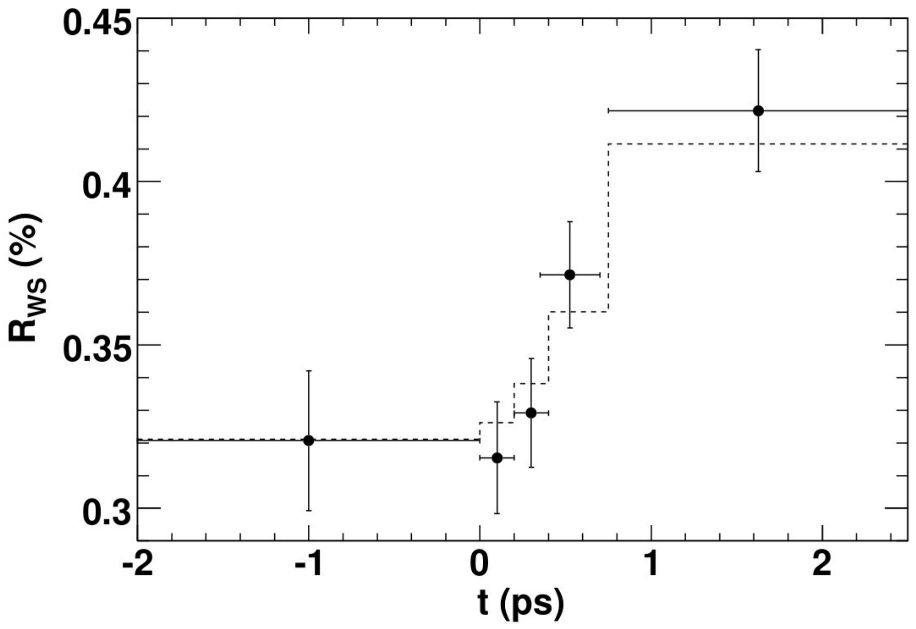


2021



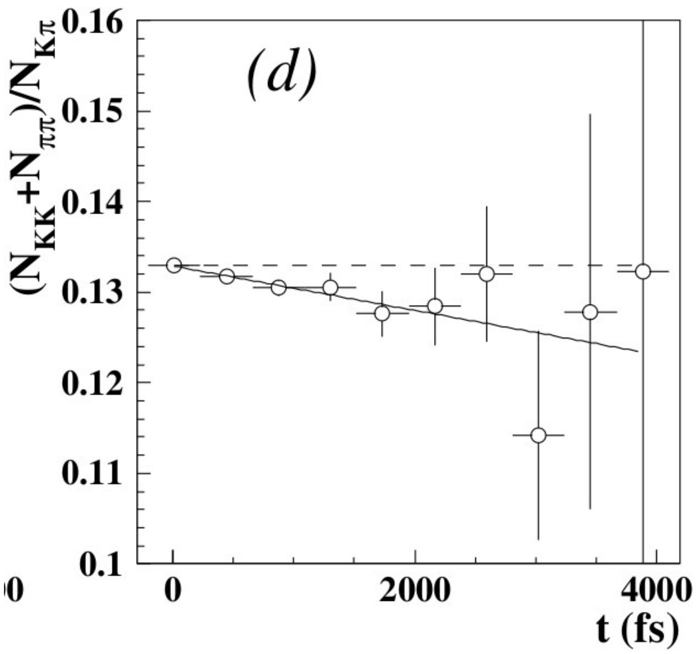
Charm mixing, 2007

BaBar, PRL 98 (2007) 211802



$D^0 \to K^+\pi^-$

Belle, PRL 98 (2007) 211803



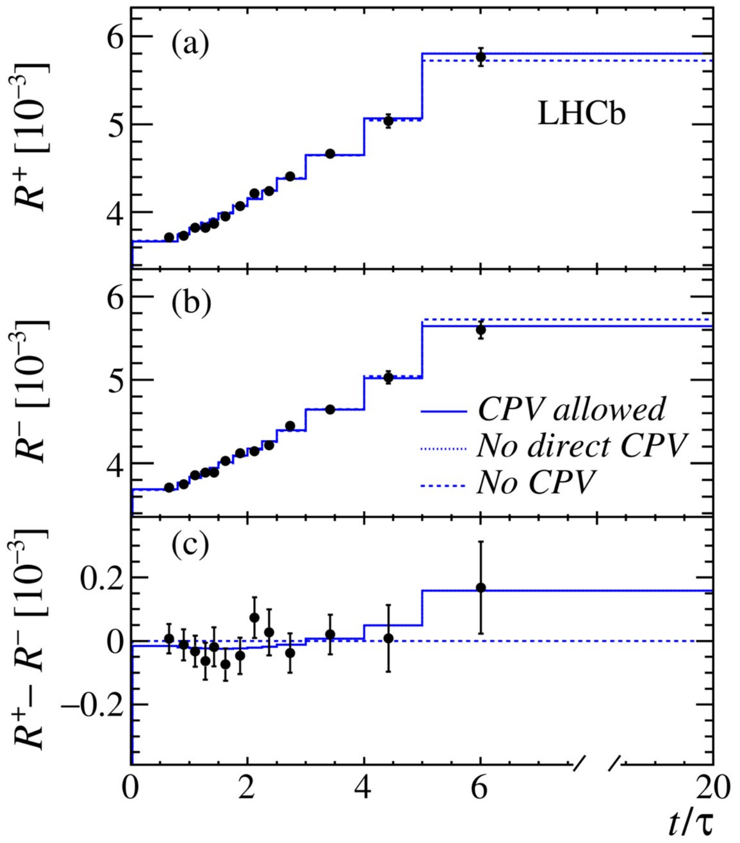
$D^0 \to K^+K^-$, $\pi^+\pi^-$

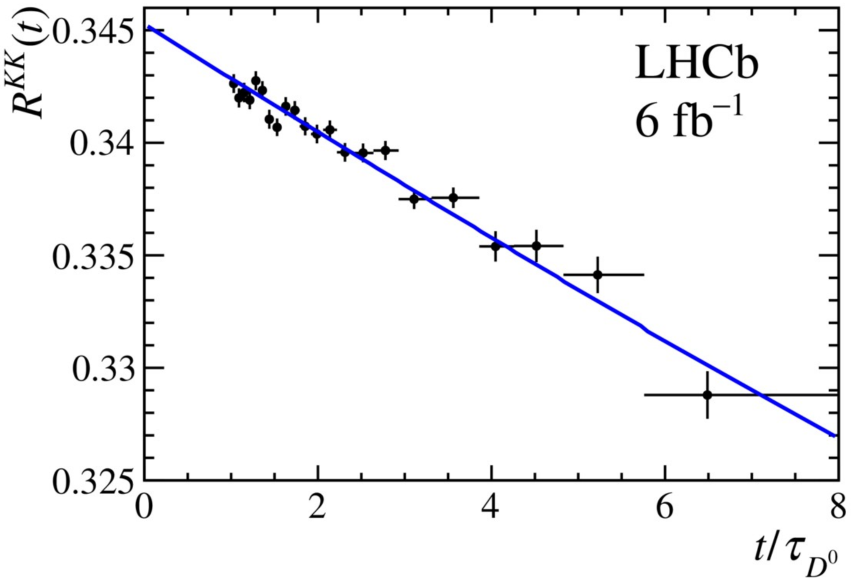
Charm mixing, today

LHCb, PR D97 (2018) 031101

LHCb, PR D105 (2022) 092013

$D^0 \to K^+\pi^-$



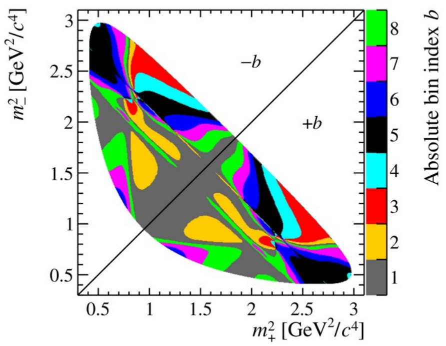


$D^0 \to K^+K^-$

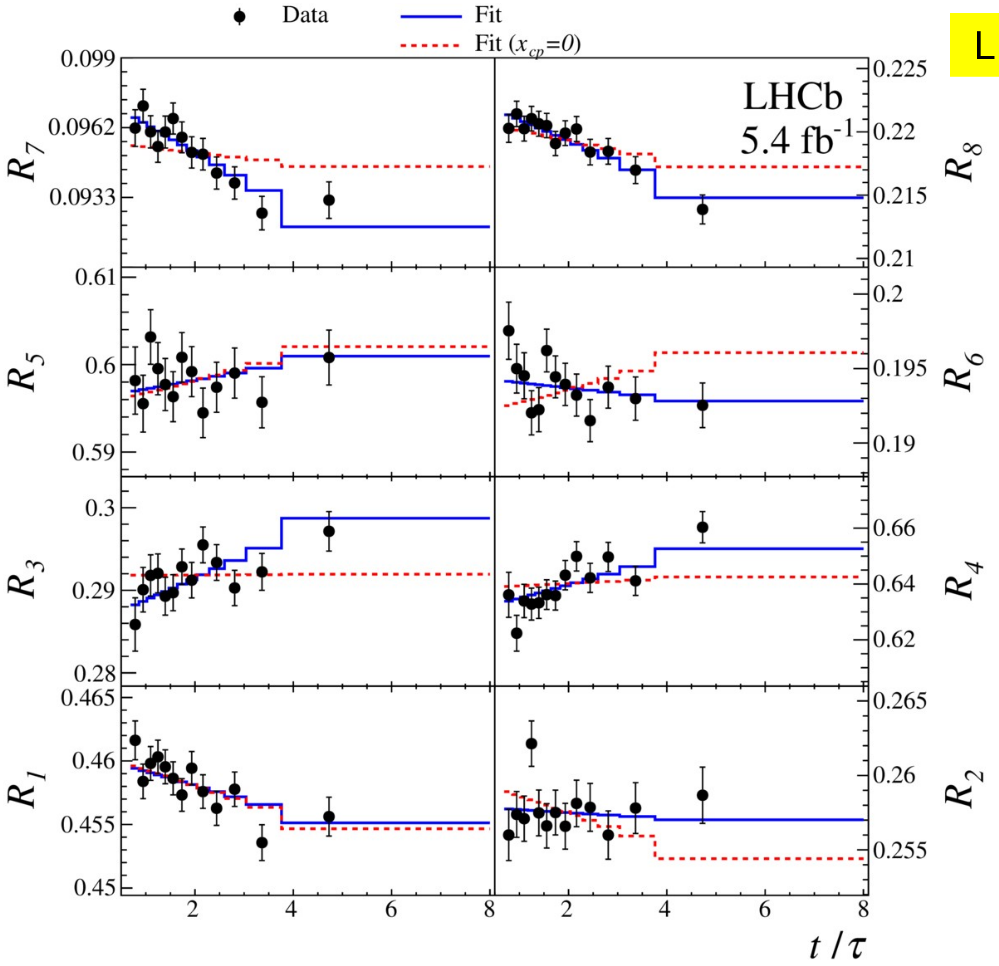
($D^0 \to \pi^+\pi^-$ also studied)

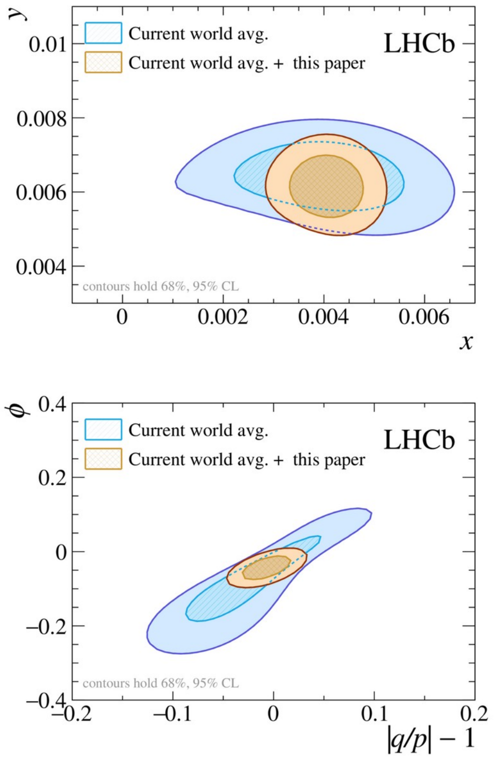
Charm mixing, 2021

LHCb, PRL 127 (2021) 111801



$D^0 \to K_S \pi^+ \pi^-$





Charm CP violation

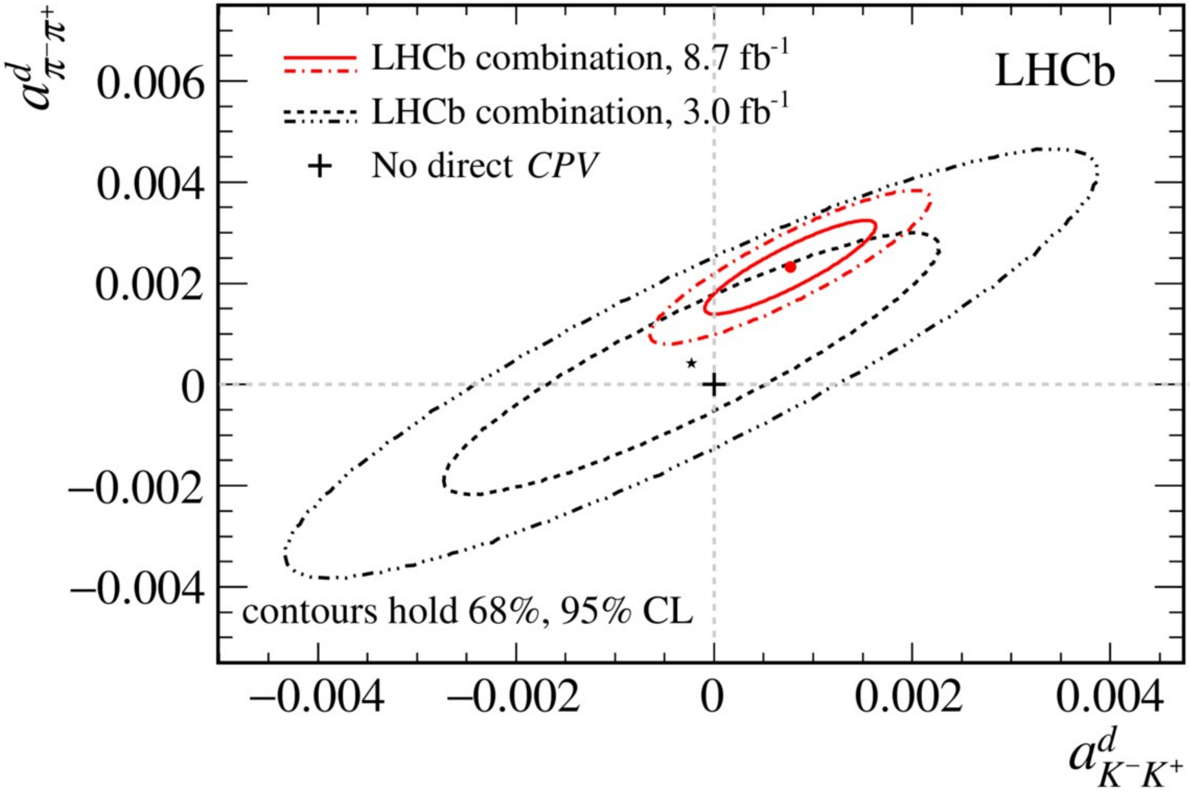
LHCb-PAPER-2022-024
PRL 122 (2019) 211803

Precise diagonal constraint from ΔA_{CP}

Observation of charm CP violation at >5σ

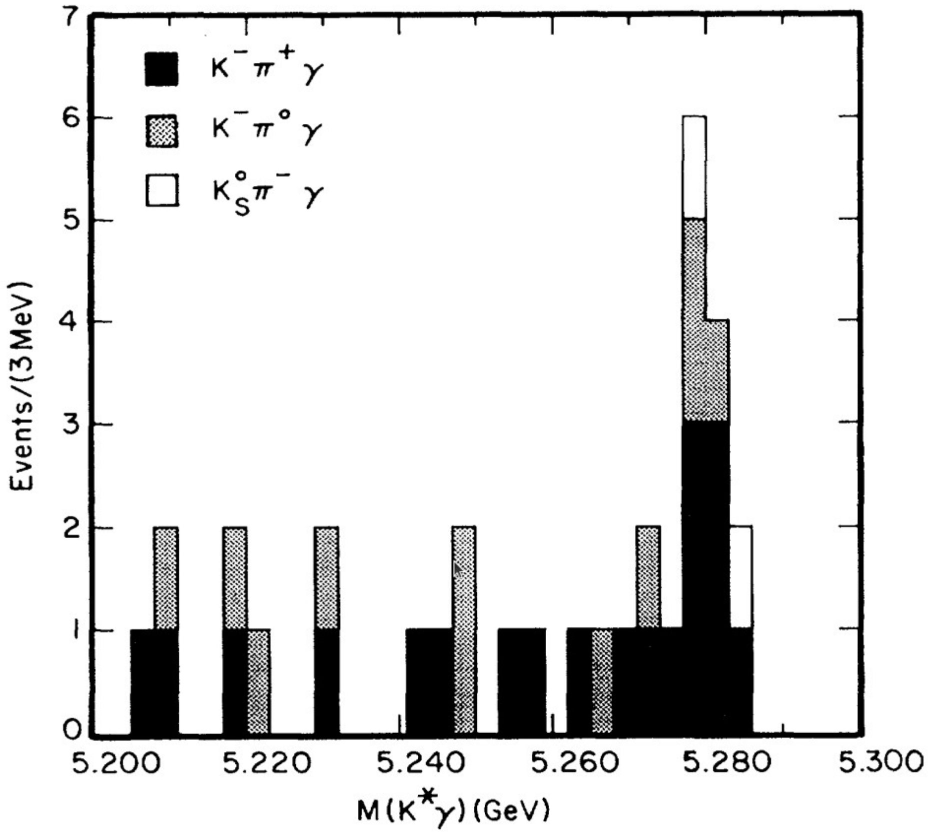
Less precise constraints on individual contributions

Evidence for CP violation in $D^0 \to \pi^+\pi^-$



$b \to s\gamma$ decays, 1993

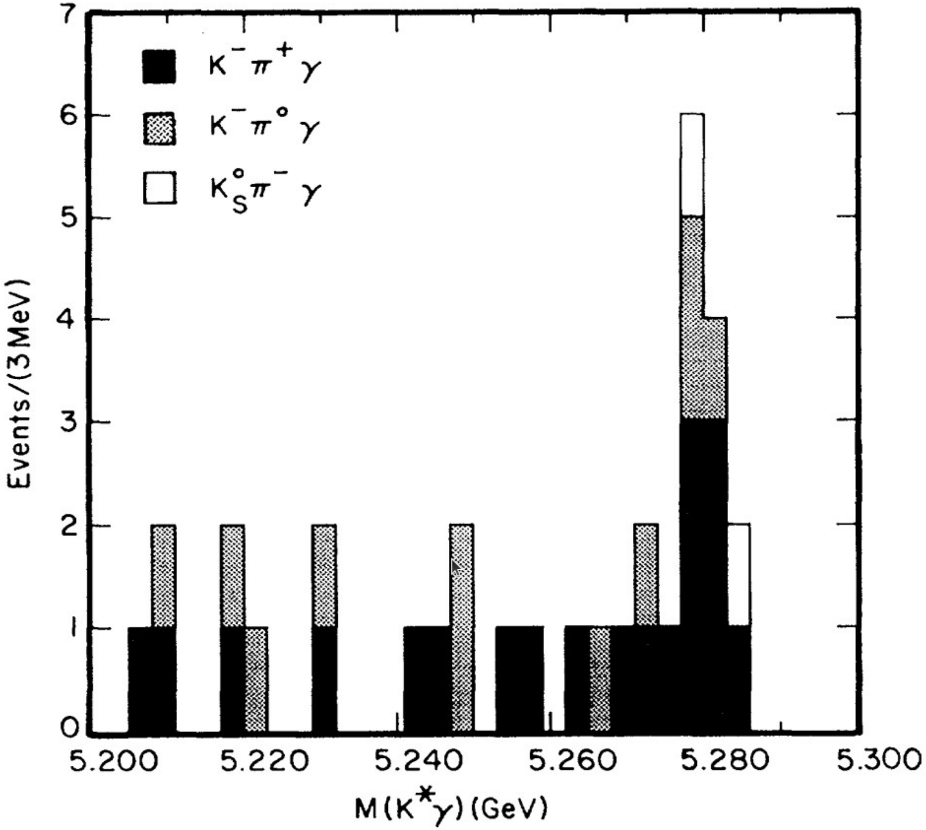
CLEO, PRL 71 (1993) 674

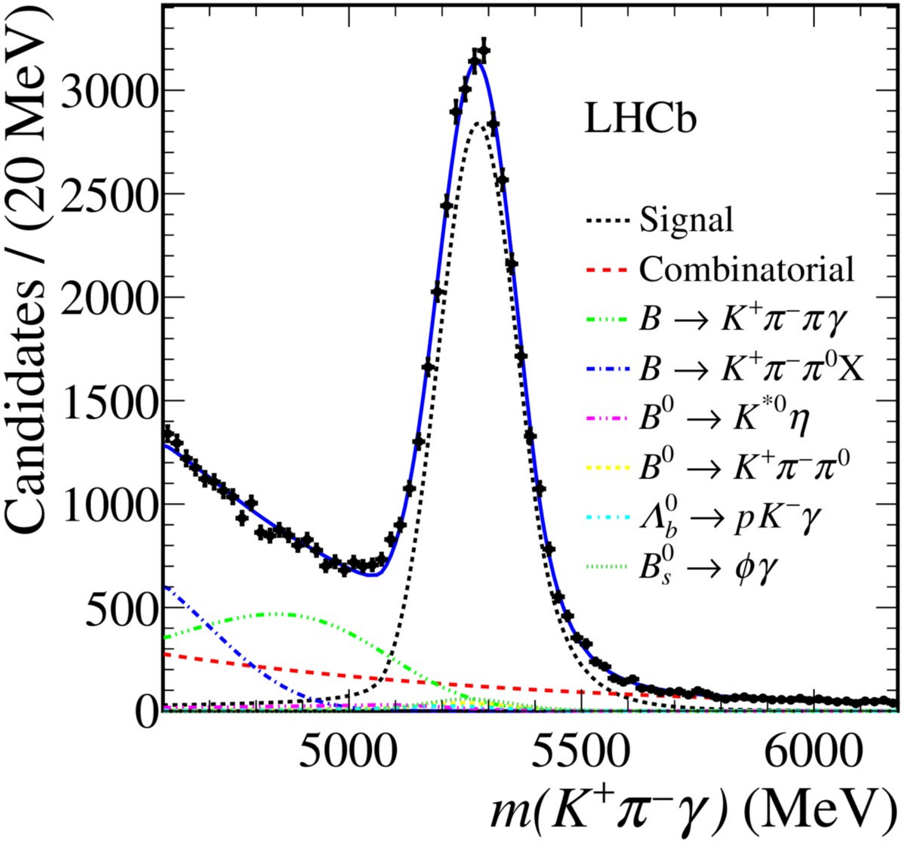


b → sγ decays, today

CLEO, PRL 71 (1993) 674

LHCb, PRL 123 (2019) 031801



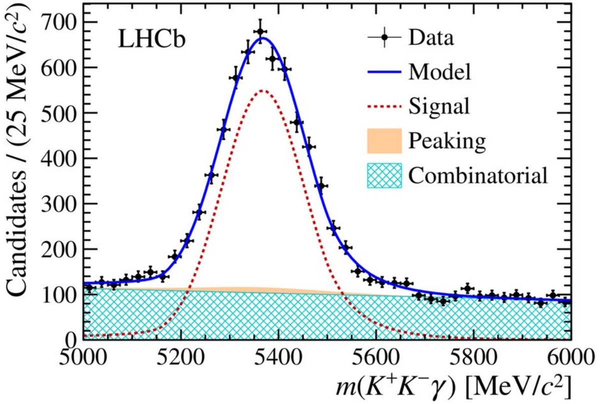


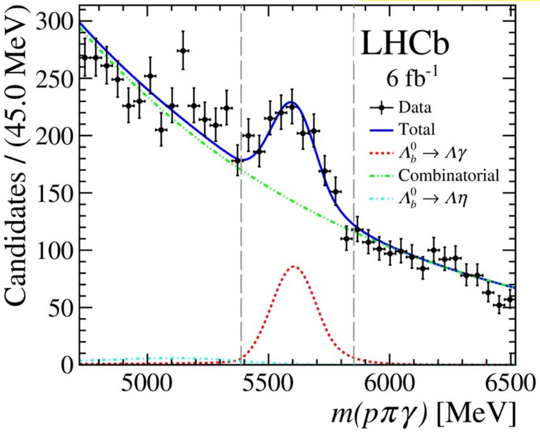
b → sγ decays, today

LHCb, PRL 123 (2019) 081802

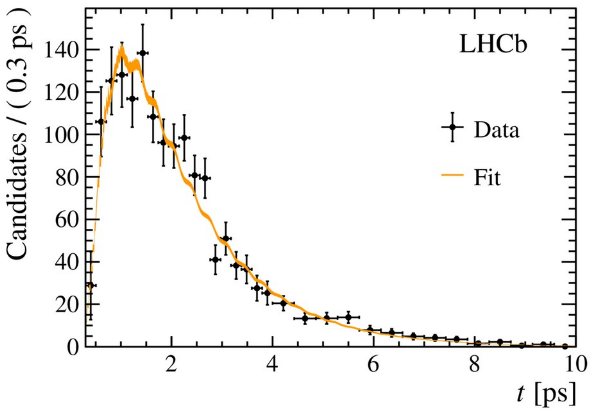
LHCb, PR D105 (2022) L051104

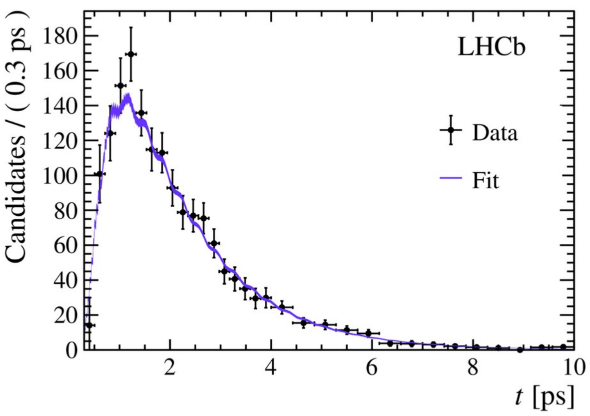
$B_s \to \varphi\gamma$

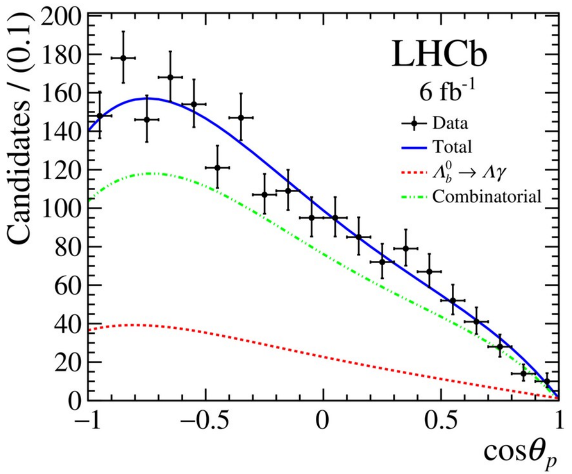




$\Lambda_b \to \Lambda\gamma$



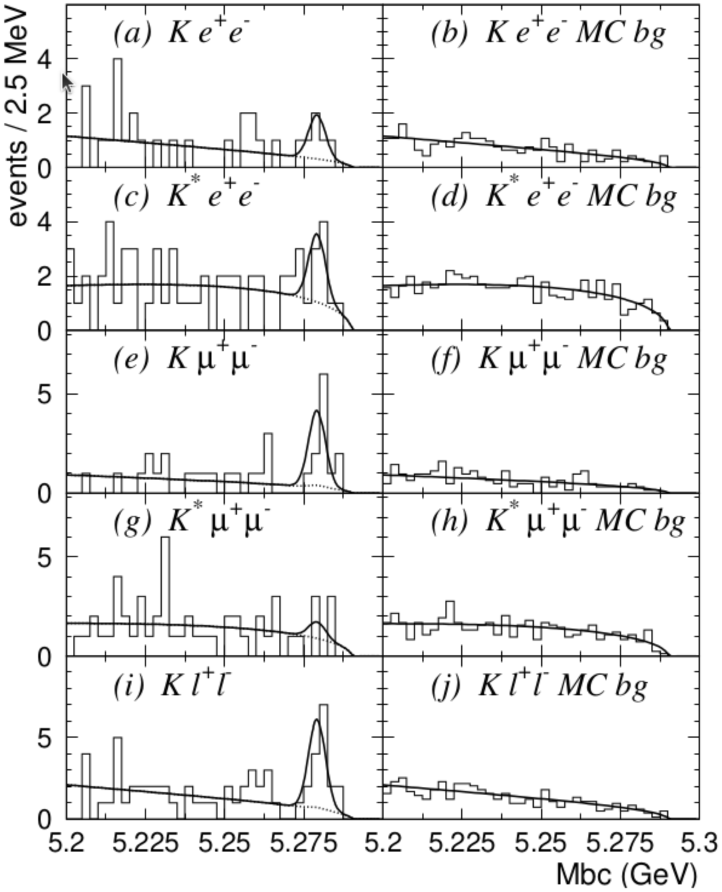


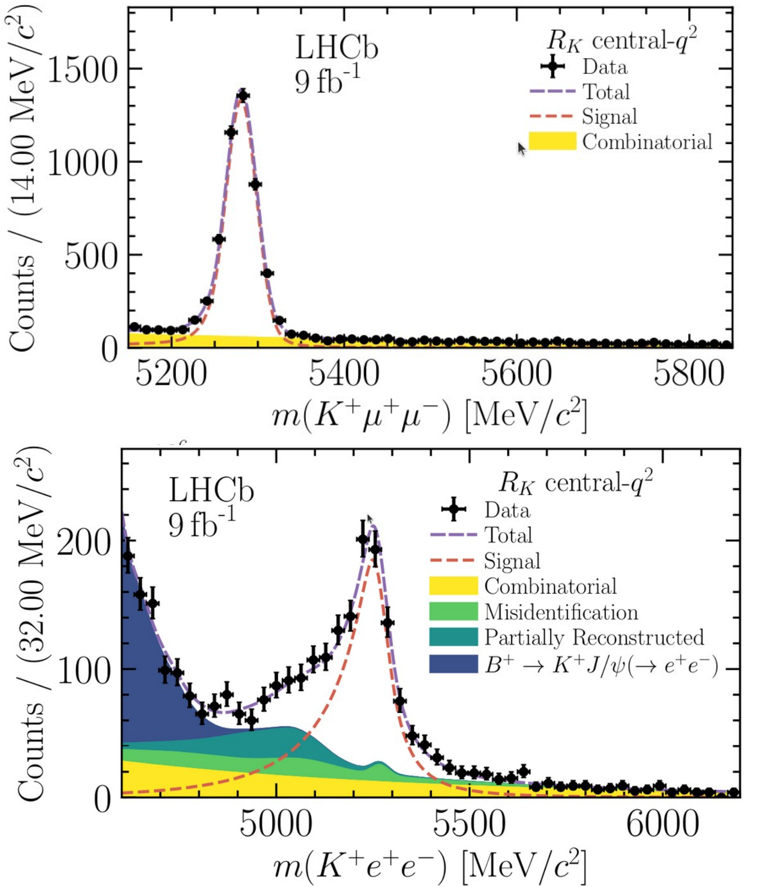


b → sl⁺l⁻ decays, 2002 and today

Belle, PRL 88 (2002) 021801

LHCb-PAPER-2022-04{5,6}

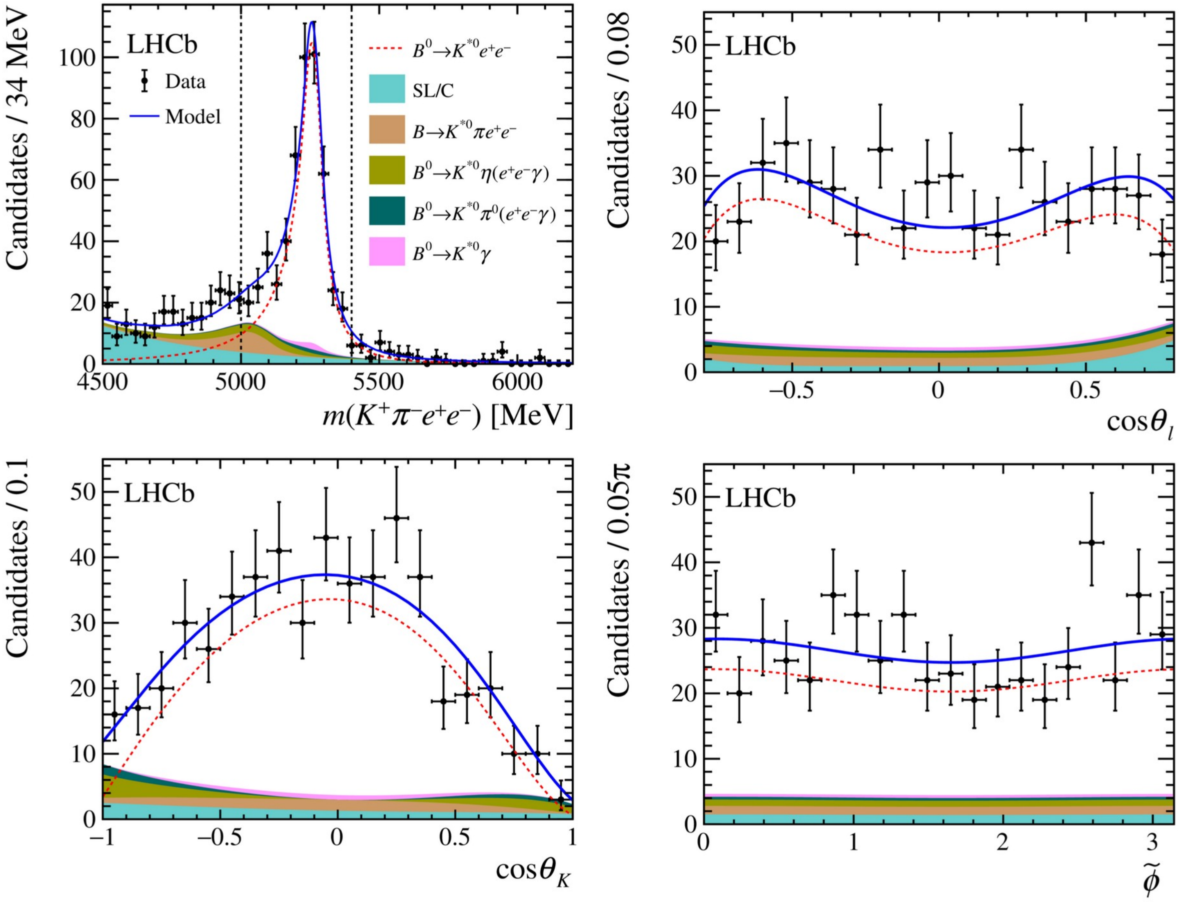




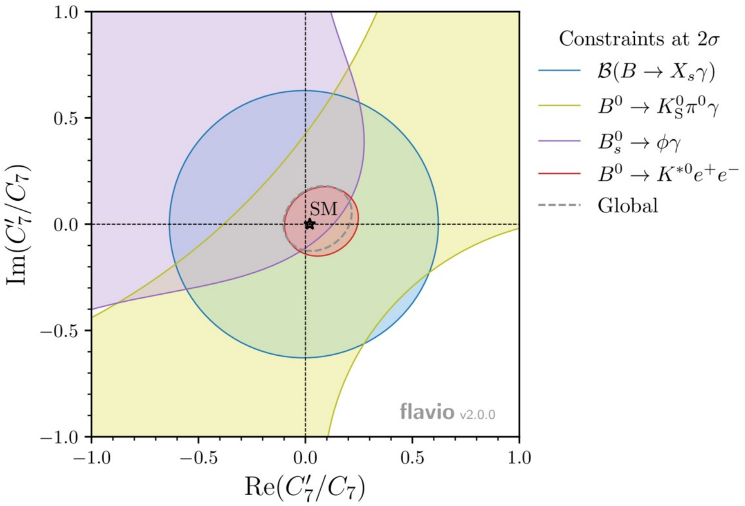
R_K

b → sl⁺l⁻ decays, today

JHEP 12 (2020) 081



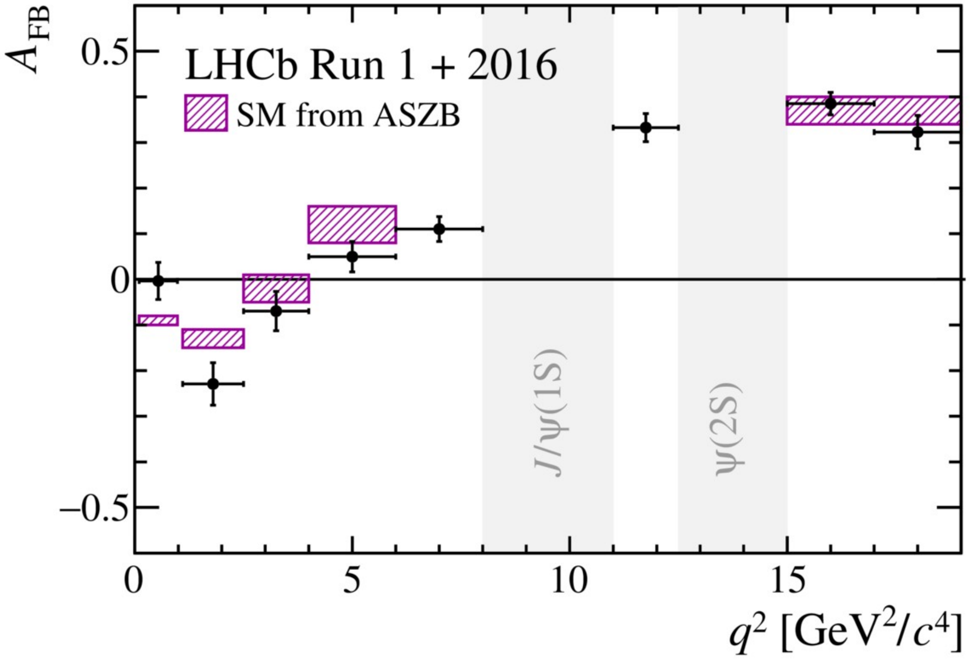
$B^0 \to K^{*0} e^+ e^-$
Very low q^2

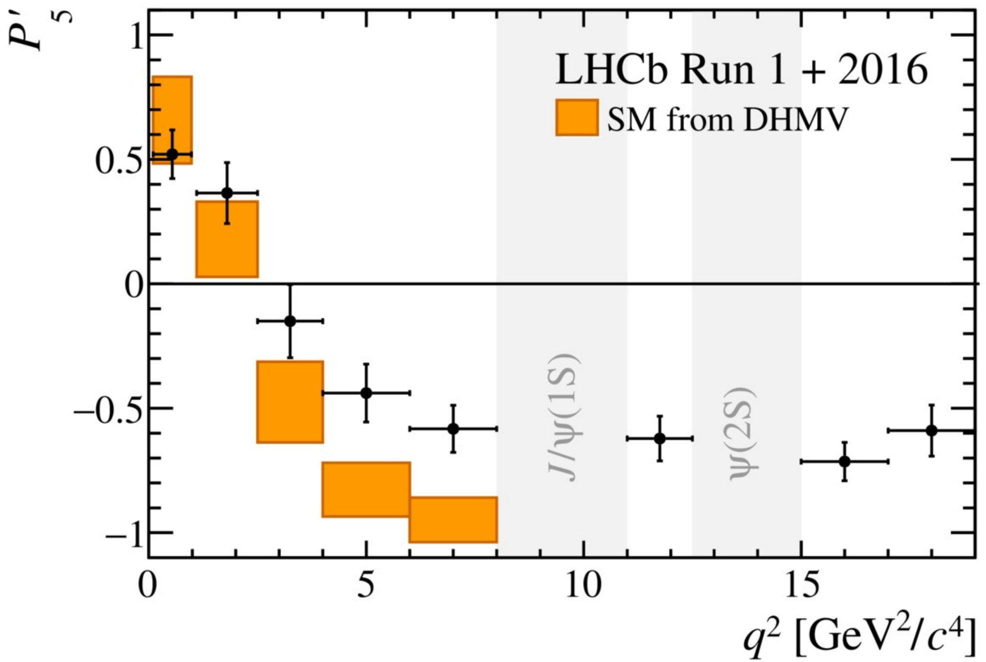


$b \to s l^+ l^-$ decays, today

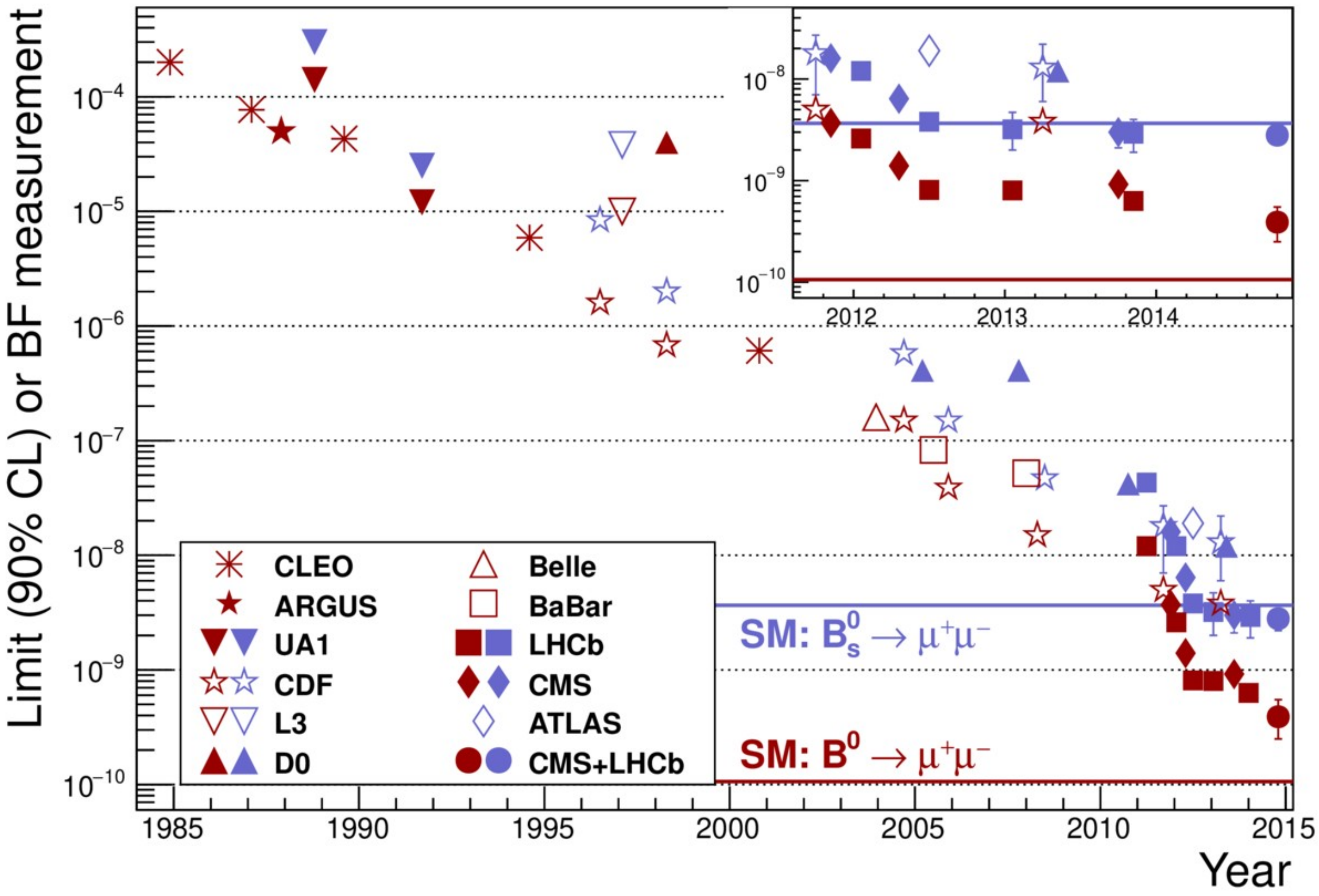
LHCb, PRL 125 (2020) 011802

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





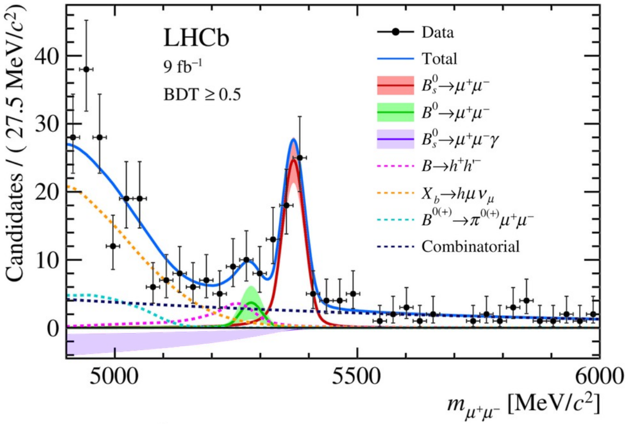
$b \to sl^+l^-$ decays, over time

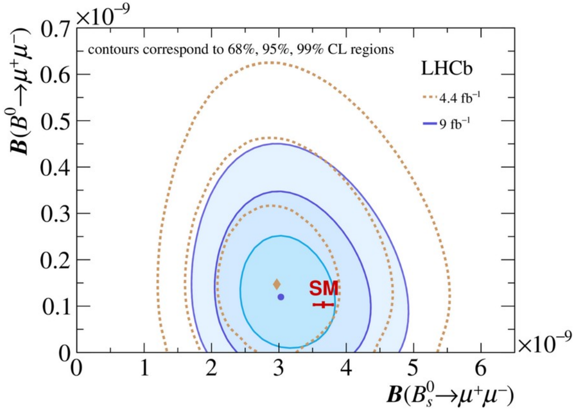


$B_{(s)}^0 \to \mu^+\mu^-$

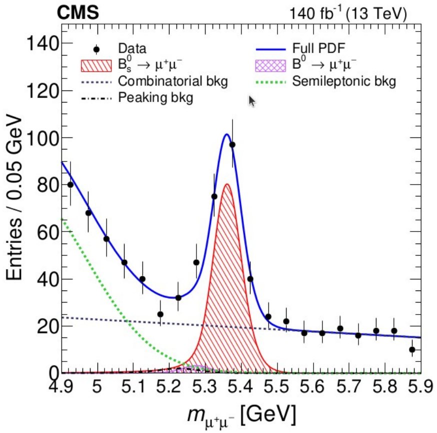
$b \to s l^+ l^-$ decays, today

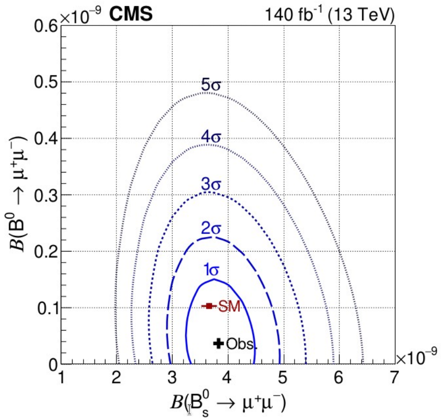
LHCb, PRL 128 (2022) 041801



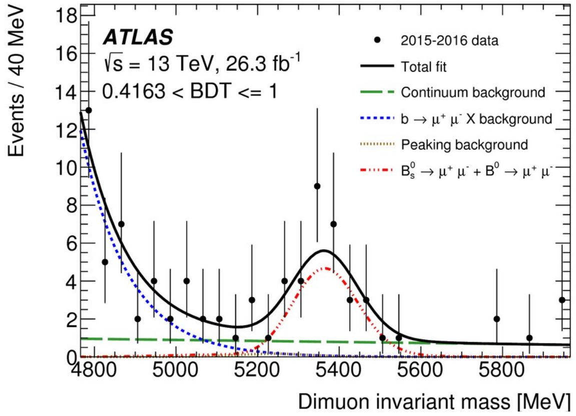


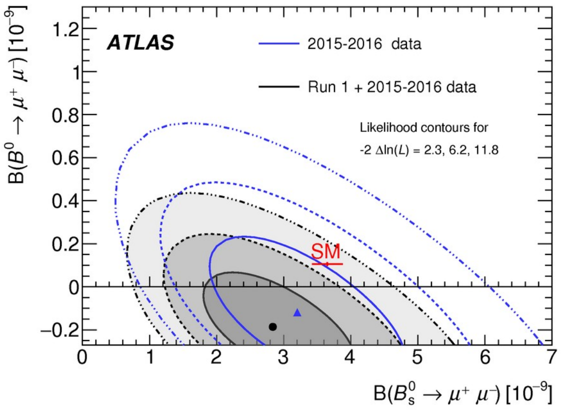
CMS, PL B842 (2023) 137955





ATLAS, JHEP 04 (2019) 098





Quo Vadis?

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- Huge progress over past 20 years
  - BaBar and Belle, followed by LHCb
  - At least an order of magnitude gain in sample size every decade
  - An order of magnitude gain in precision in two decades
- Can we continue this for the next two decades?
- Are there areas where progress has not been so rapid, where we might catch up?

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  - YES
- Are there areas where progress has not been so rapid, where we might catch up?
  - YES

SuperKEKB and Belle II

SuperKEKB Accelerator

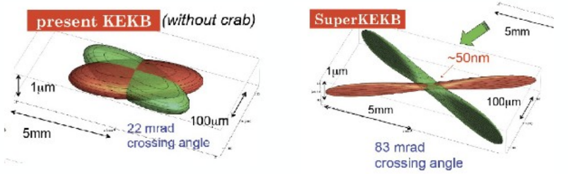
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

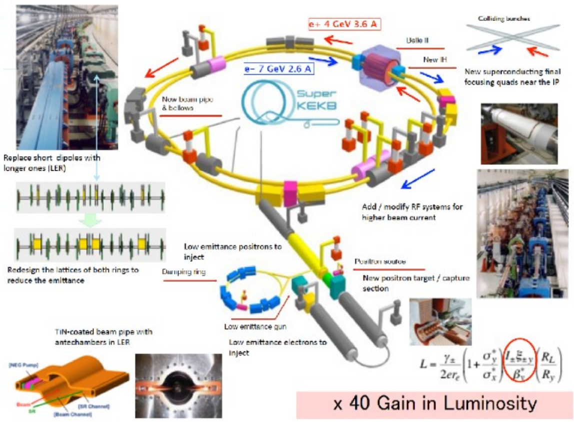
Machine parameters

	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

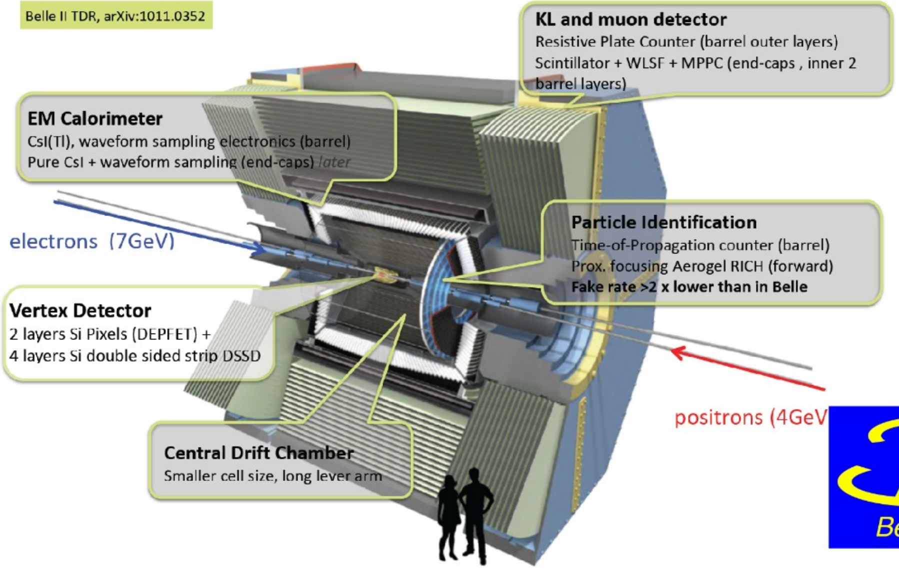
x2





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

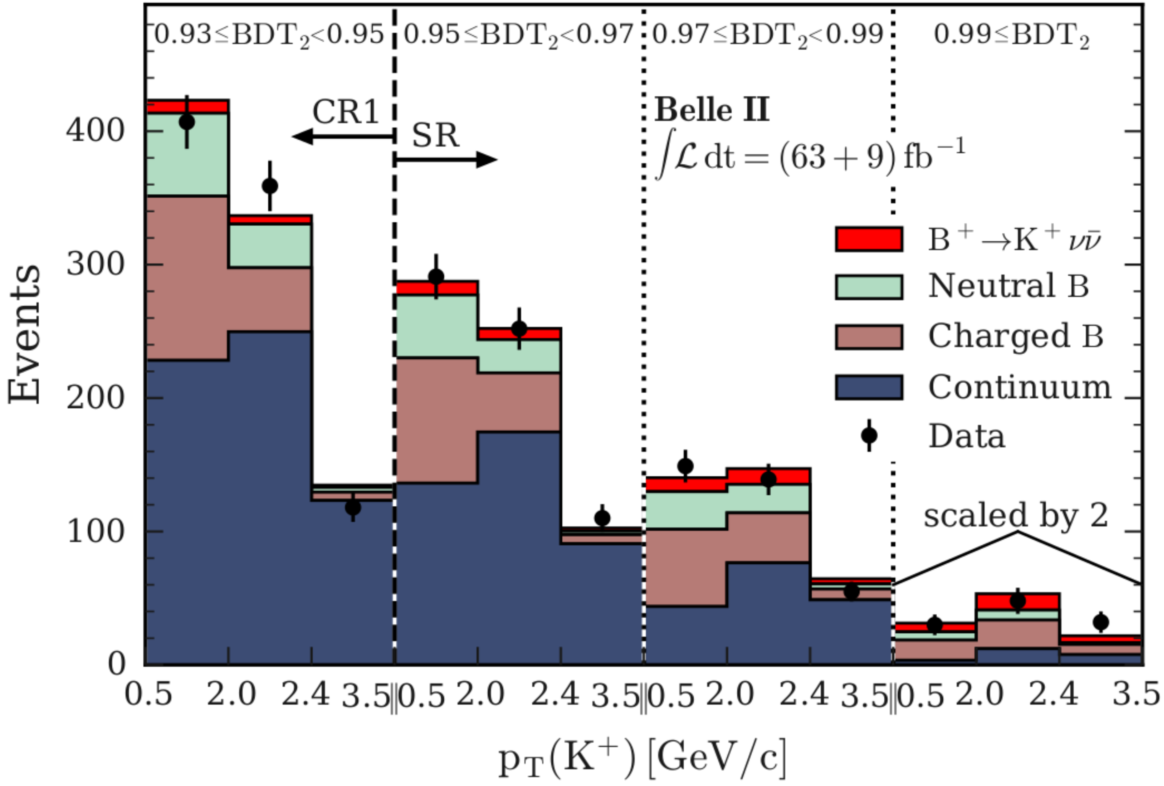
Over 400 fb^{-1} recorded since 2020, will increase ×10 in ~5 years

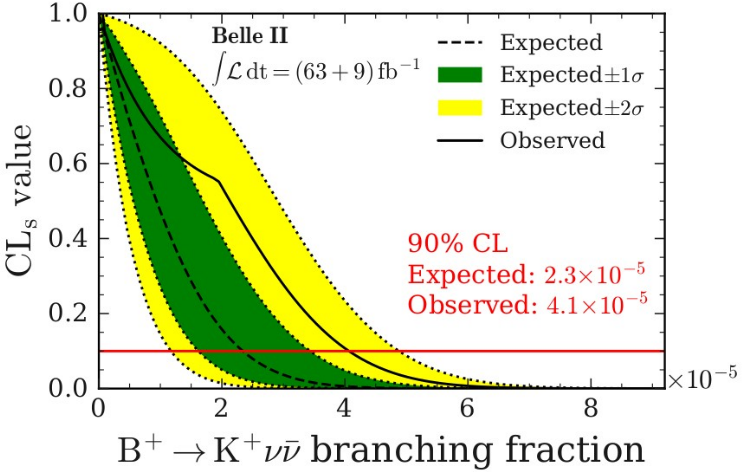
Things to look forward to with Belle II

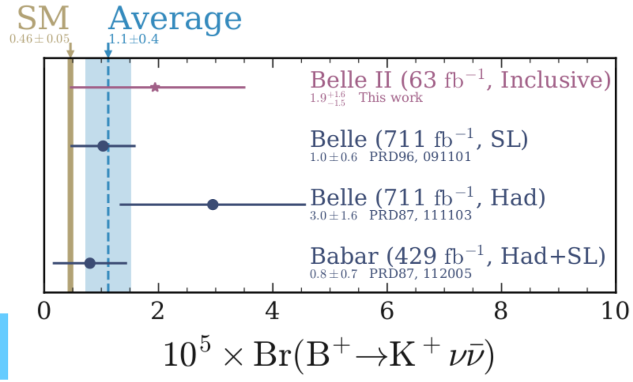
- Lepton flavour violating τ decays
  - and other precision τ physics
  - (complementing precision μ programme elsewhere)
- Searches for $b \to s\nu\bar{\nu}$ decays
  - (complementing $s \to d\nu\bar{\nu}$ programme elsewhere)
- Time-dependent CP violation in $b \to sg$
  - $B^0 \to \phi K_S$, $\eta' K_S$, $K_S \pi^0$, $K_S K_S K_S$, etc. (LHCb not yet competitive)
- Modes with neutrals, allowing flavour symmetries to be exploited
  - $B^0 \to K_S \pi^0$ (isospin sum rule), $J/\psi \pi^0$ (control penguin pollution in $\sin(2\beta)$), etc.
- … much more

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

Belle II, PRL 127 (2021) 181802







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

The LHCb detector

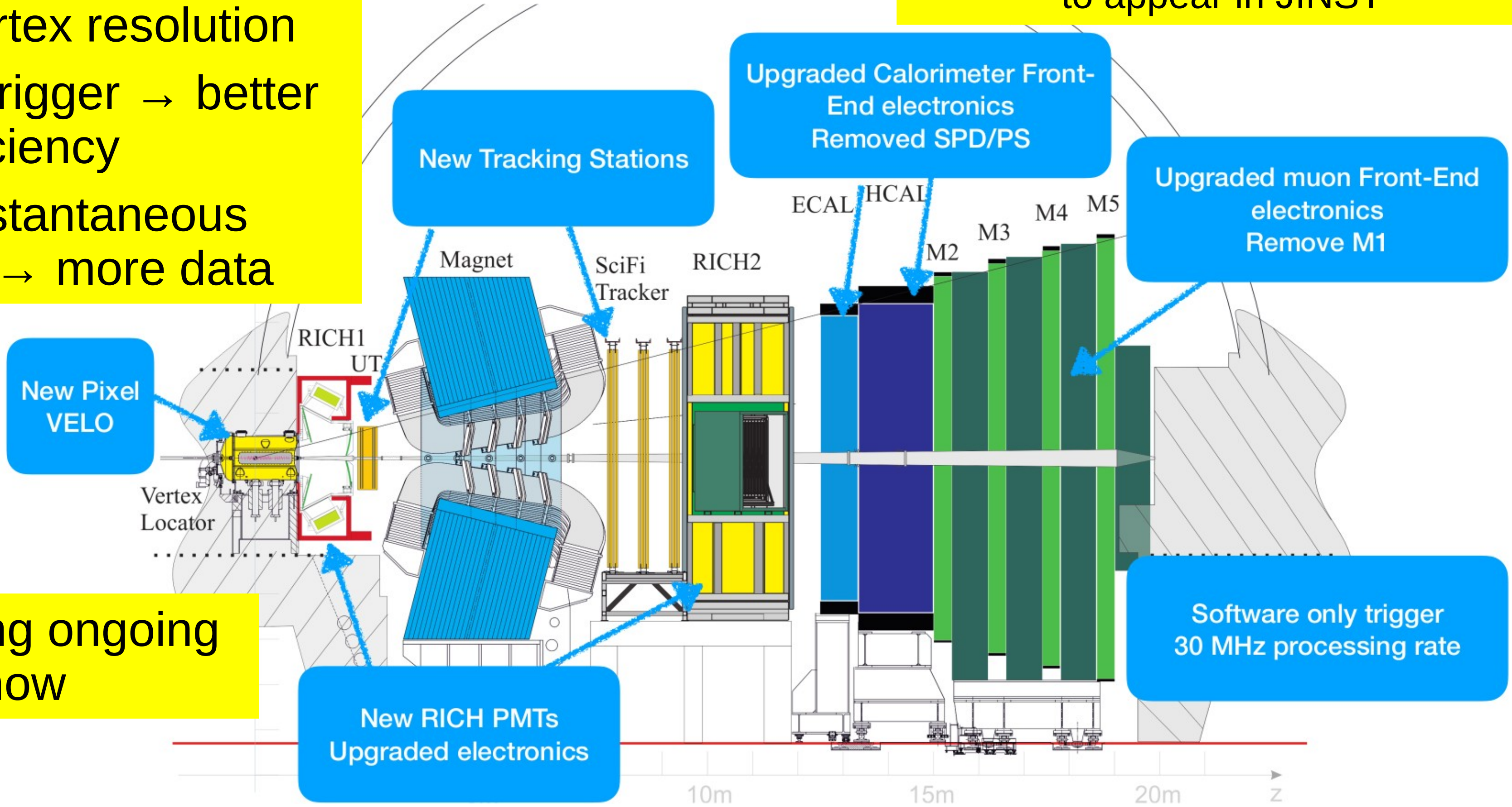
(2022-32 edition)

arXiv:2305.10515
to appear in JINST

VELO pixels & thinned RF foil → better vertex resolution

All software trigger → better efficiency

Higher instantaneous luminosity → more data



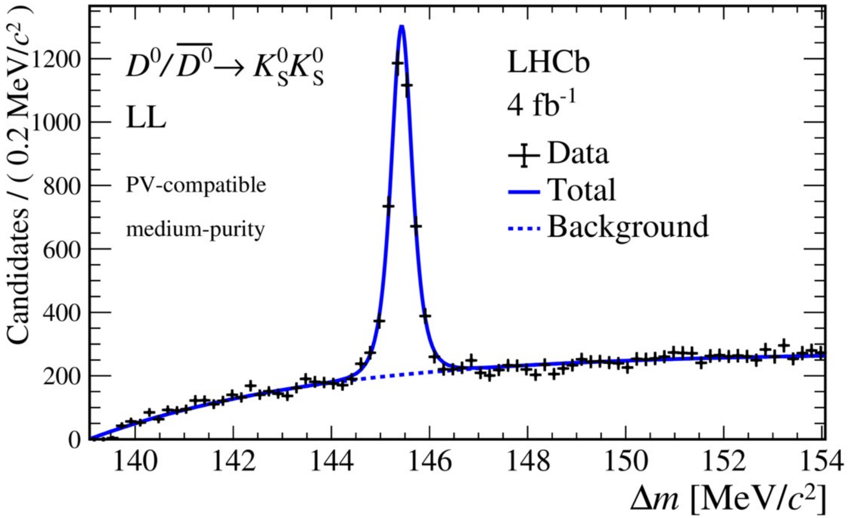
Commissioning ongoing right now

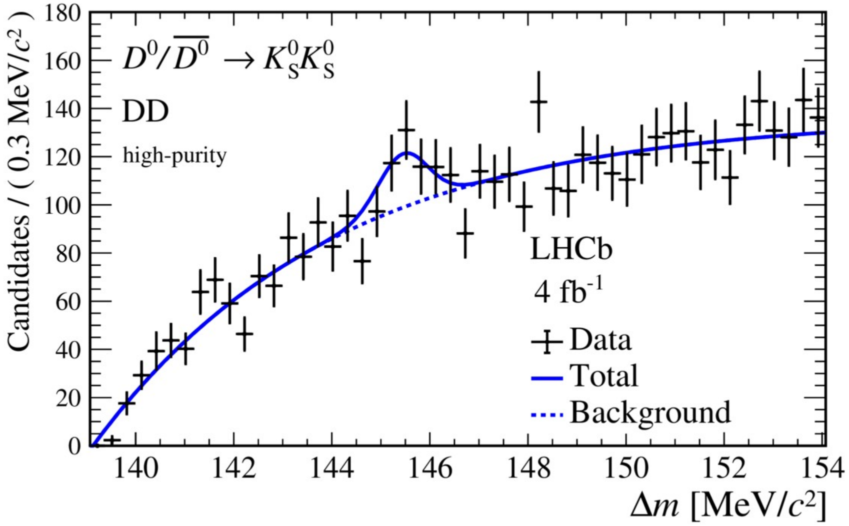
Things to look forward to with LHCb Run 3+4

- 2023: complete commissioning & collect first physics data
- 2024+5: collect >10/fb, >double LHCb sample sizes
  - largest gains where trigger efficiency improves most
- 2026-8: LS3
- 2029-32: complete collection of 50/fb sample

Example: $D^0 \to K_S K_S$

LHCb, PR D104 (2021) L031102



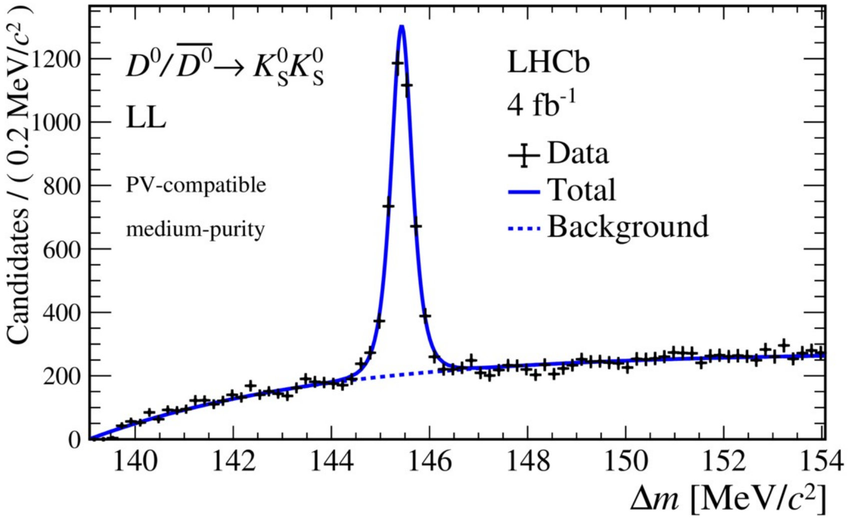


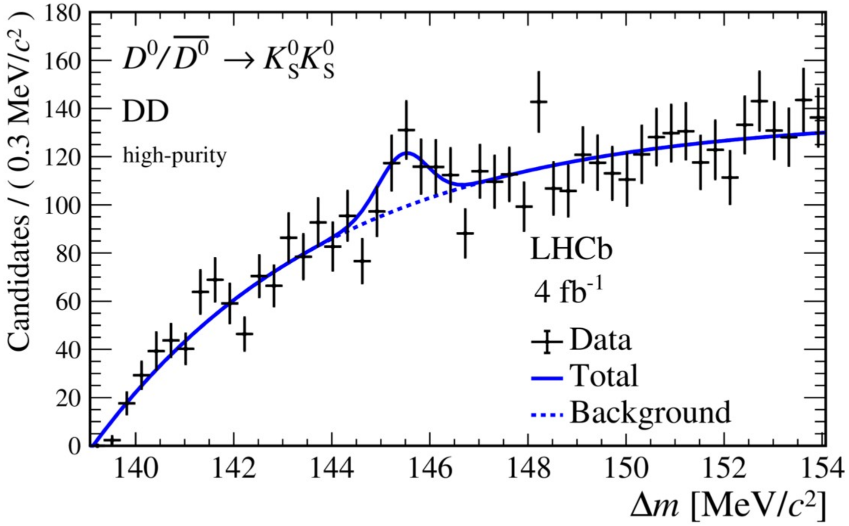
LL = tracks from K_S decays have hits in VELO
Hardware trigger efficiency low

DD = tracks from K_S decays do not have hits in VELO
Hardware and software trigger efficiencies low

Example: $D^0 \rightarrow K_S K_S$

LHCb, PR D104 (2021) L031102





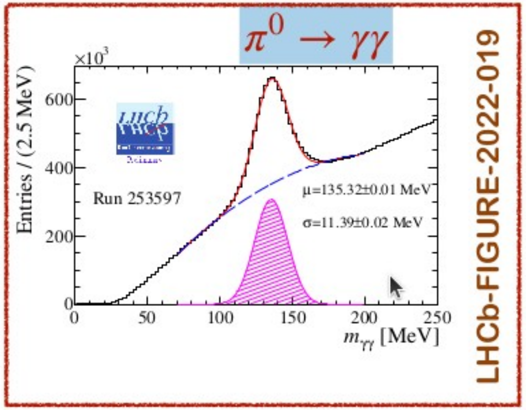
LL = tracks from K_S decays have hits in VELO
Hardware trigger efficiency low

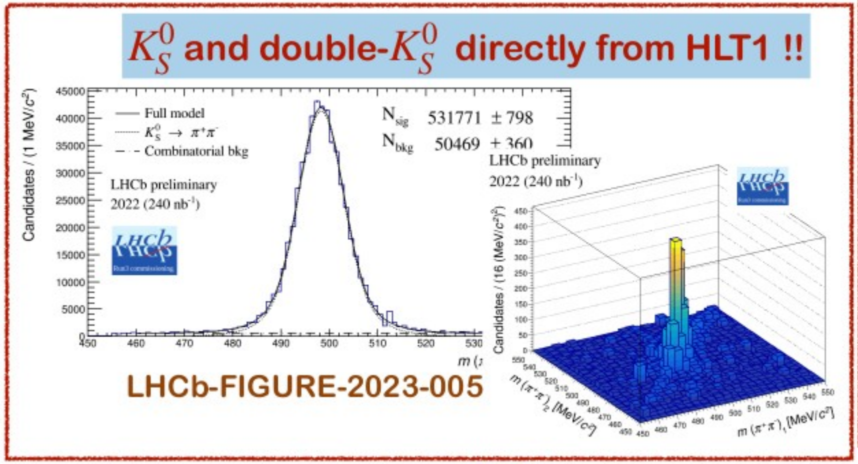
DD = tracks from K_S decays do not have hits in VELO
Hardware and software trigger efficiencies low

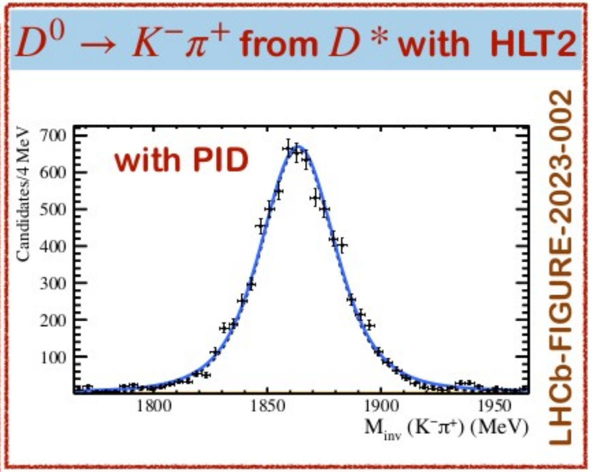
Hardware trigger removed

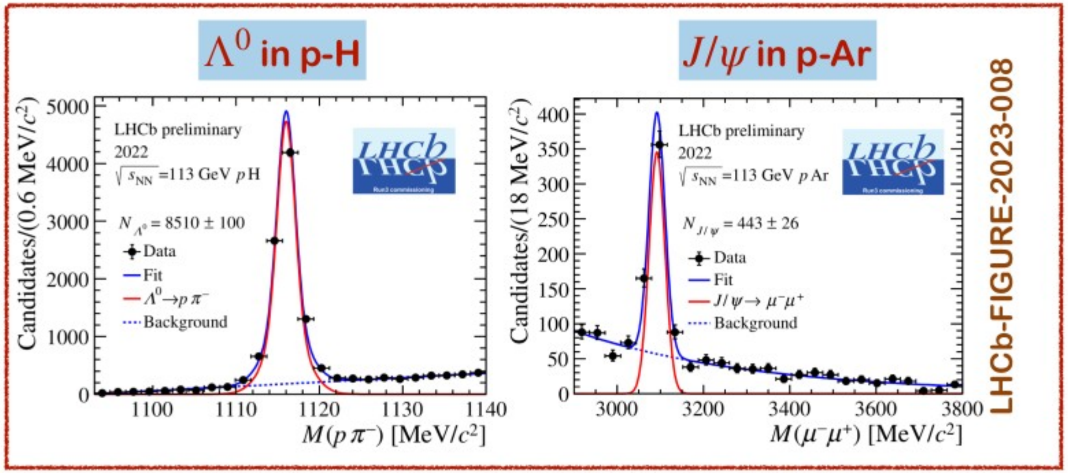
Potential to improve

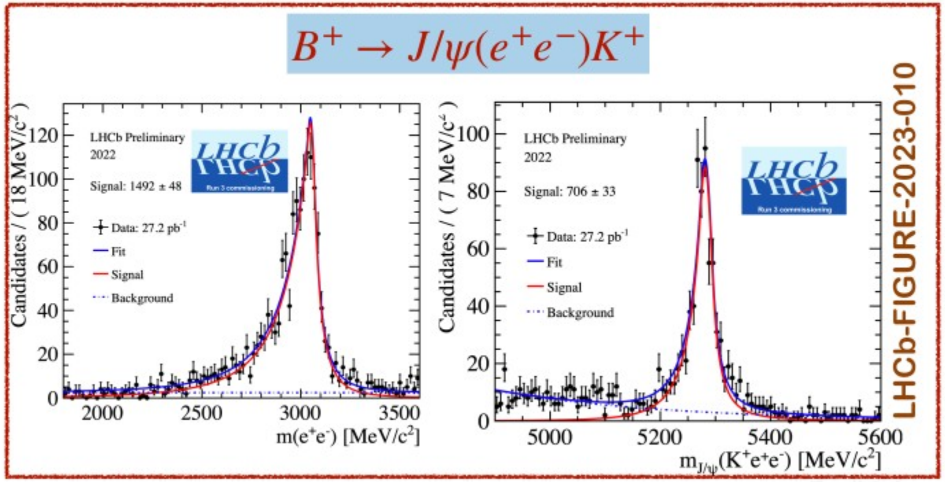
First Run 3 data











The LHCb detector

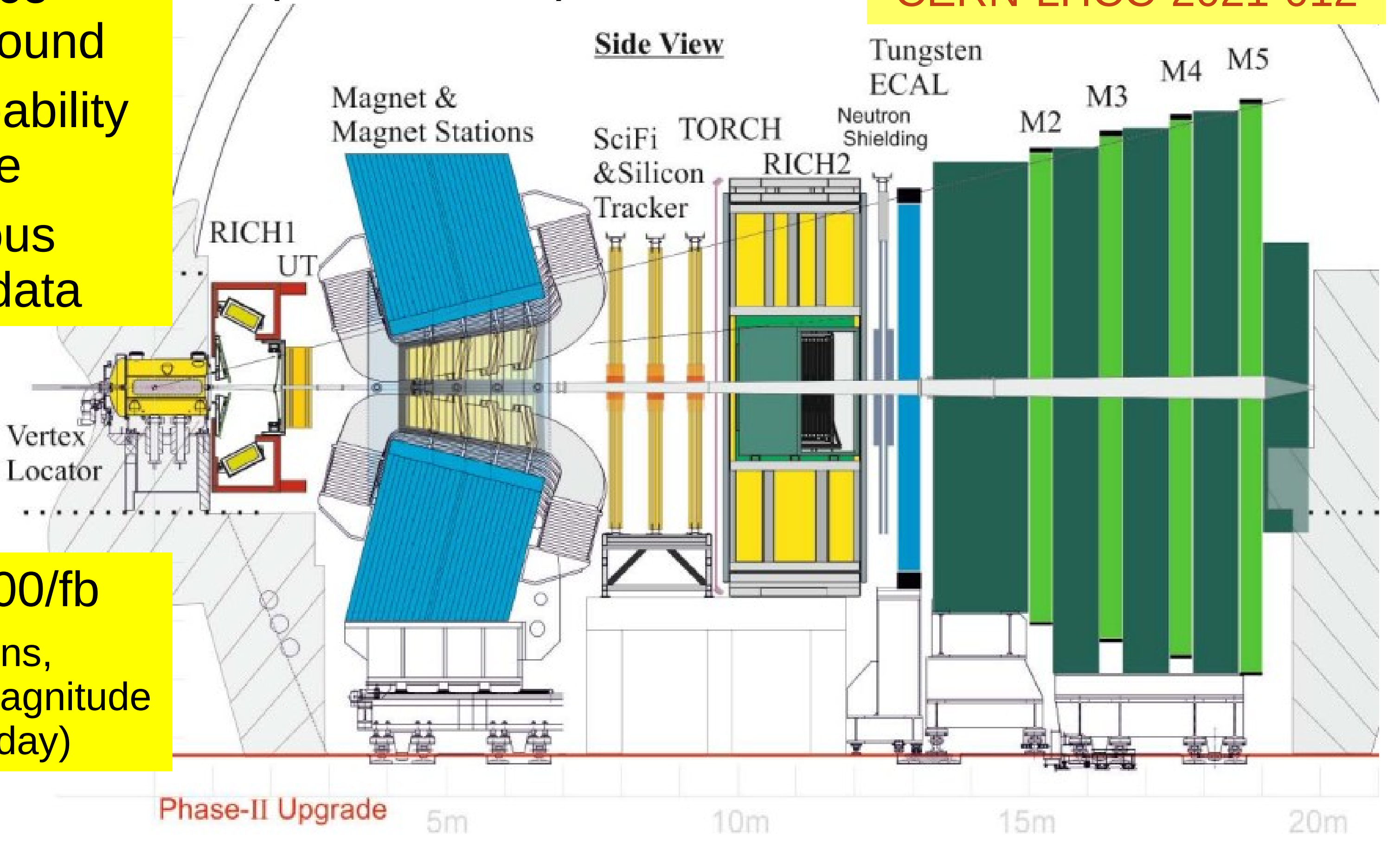
(final edition)

CERN-LHCC-2017-003
CERN-LHCC-2021-012

Use timing to reduce combinatorial background

Improve detection capability wherever possible

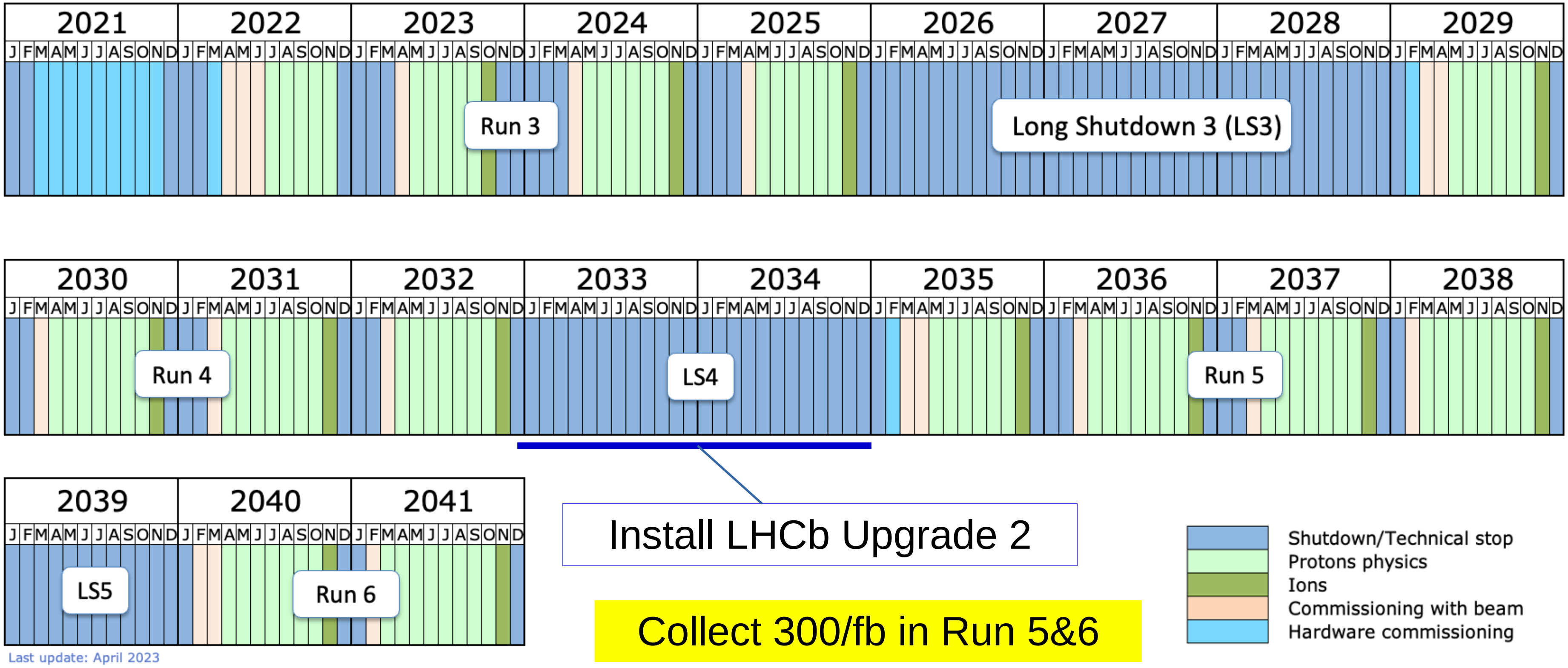
Higher instantaneous luminosity → more data



Aim to record over 300/fb

(Including efficiency gains, approximately two order of magnitude increase compared to today)

Long-term LHC schedule



LHCb Upgrade 2 Integrated Luminosity

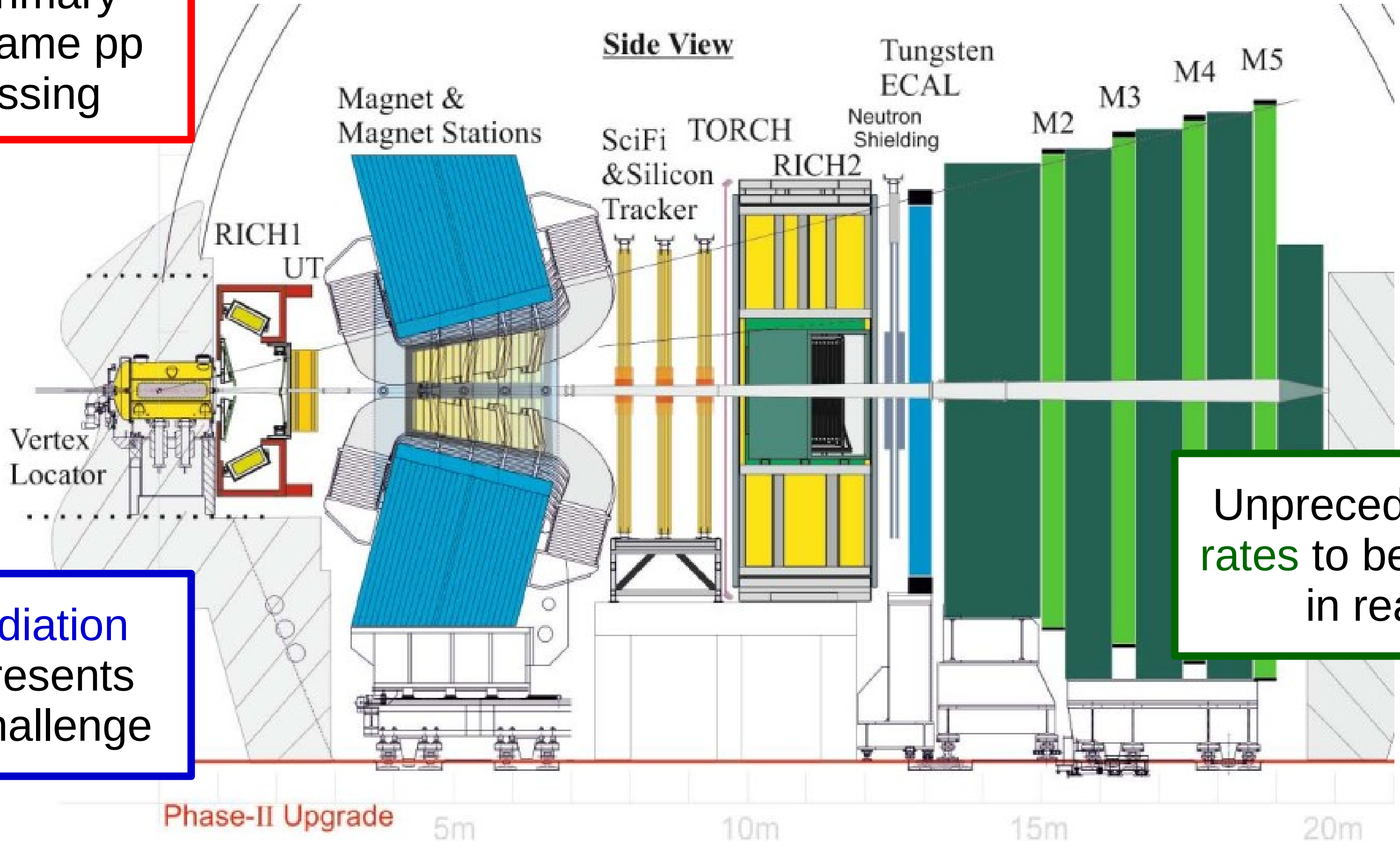
LHCb Upgrade II needed
to fully exploit HL-LHC

LHCb Upgrade I
will get us here

LHCB-TDR-023

LHCb Upgrade II

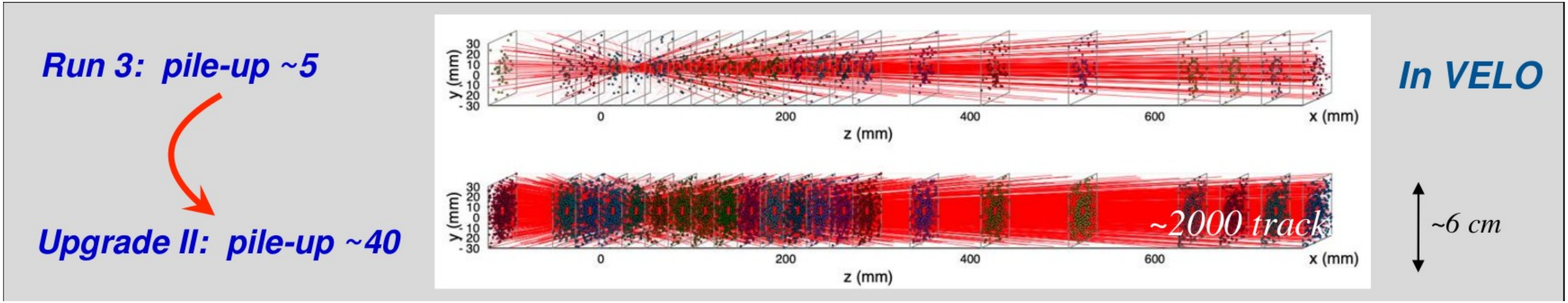
Crucial to use precision timing information to separate primary vertices in same pp bunch crossing



Need for radiation hardness presents significant challenge

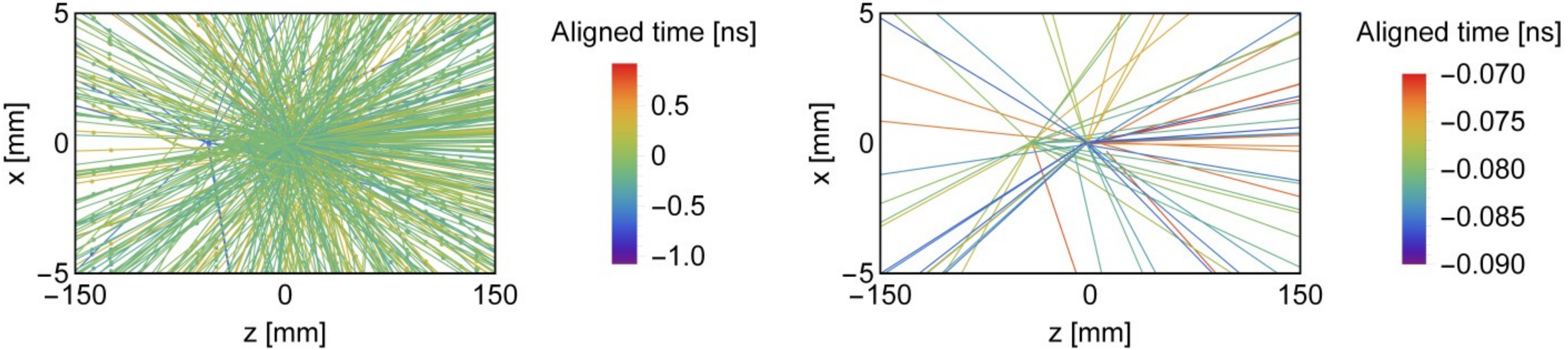
Unprecedented data rates to be processed in real time

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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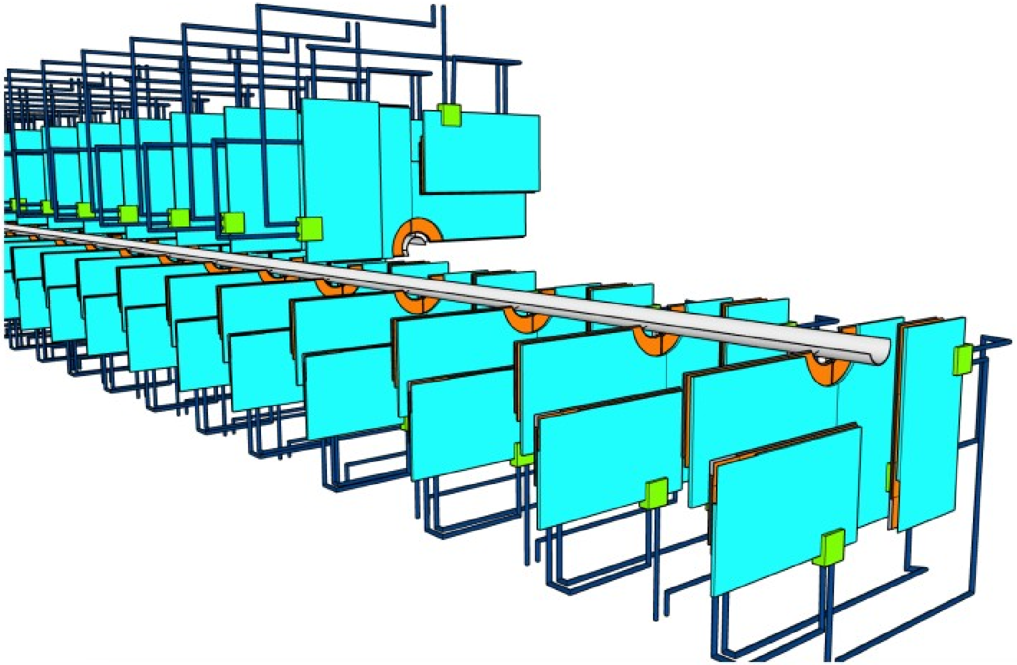
Vertex detector (VELO)

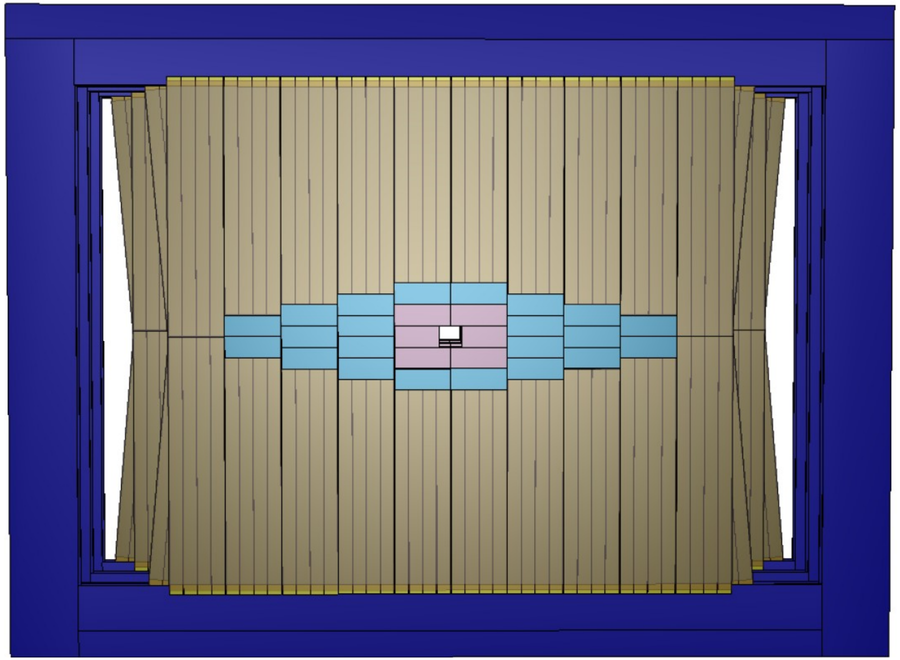
- Candidate sensors
  - thin planar, LGAD, 3D
- Candidate ASICs (28 nm technology)
  - VeloPix2, Timespot
- Mechanical design challenges
  - cooling, module replacement, minimisation of material (RF foil), vacuum compatibility
- Fast tracking, tagging also important for kaon experiments (NA62/HIKE)
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

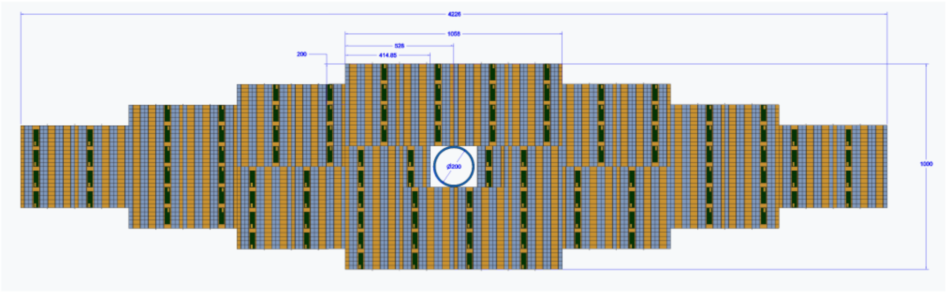
    (see EPJ C82 (2022) 465)



MAPS tracker

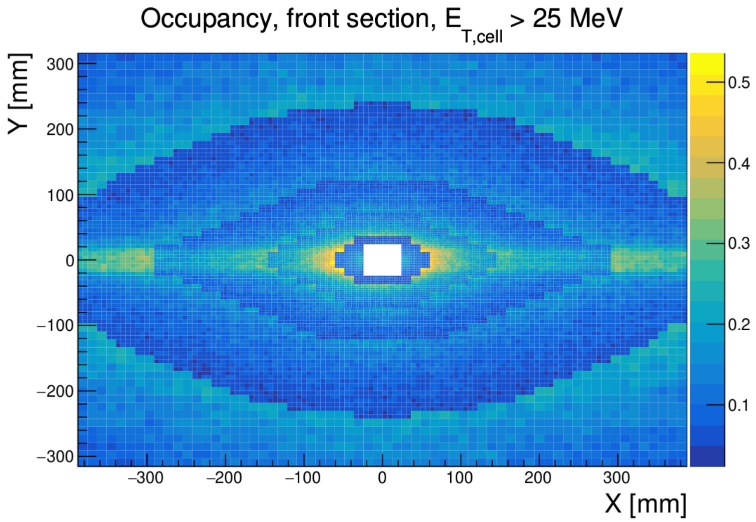
- Central region of SciFi tracking stations to be replaced with silicon detectors
- Use MAPS technology, also for Upstream Tracker (UT)
  - Can meet radiation requirement (3×10^{15} n_{eq}/cm^2 at UT)
  - First large scale tracking detector with this technology
  - Building on experience from STAR, ALICE,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

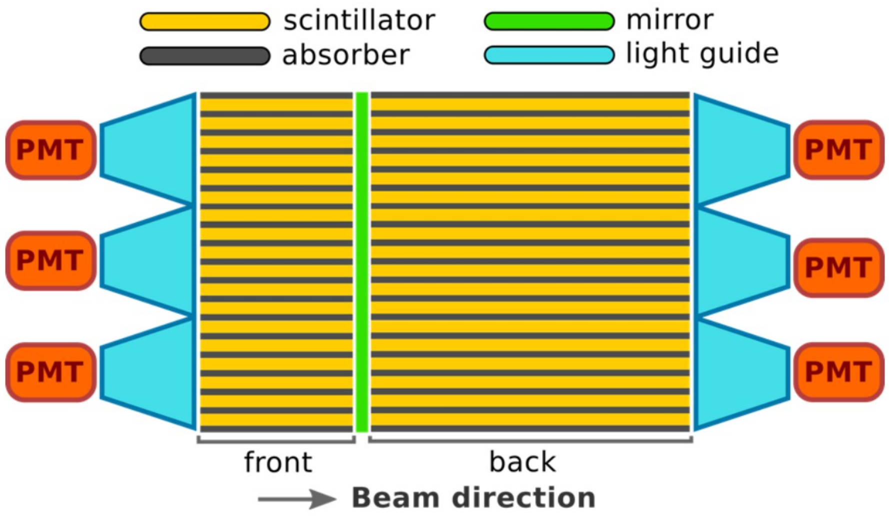




Electromagnetic calorimeter

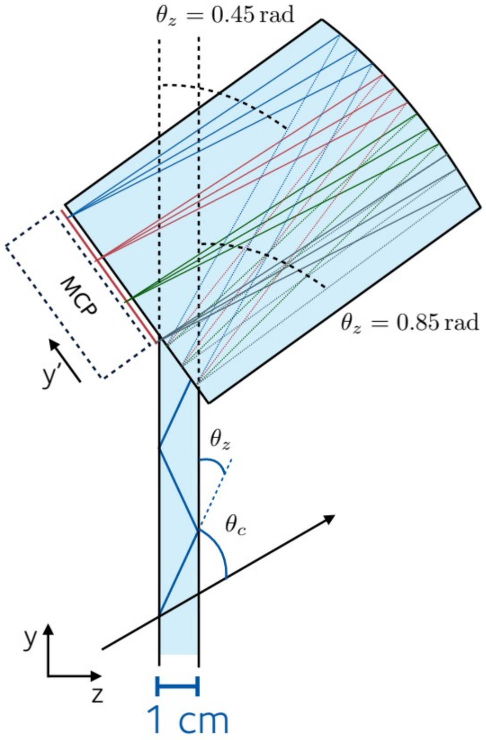
- LHCb ECAL not replaced (except electronics) in Upgrade I
  - in Run 3 will operate at 25× its design luminosity!
- Proposal for crystal fibres (SpaCal) in central region + Shashlik (outer region)
  - timing information (σ_t ~ 20 ps) used to help suppress background

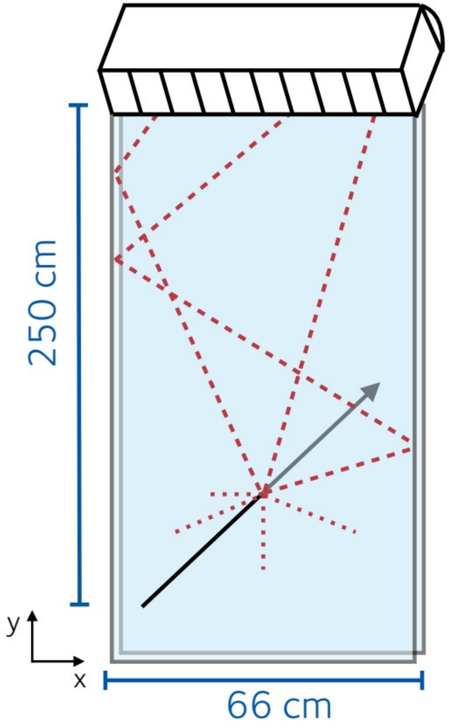




TORCH detector

- 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



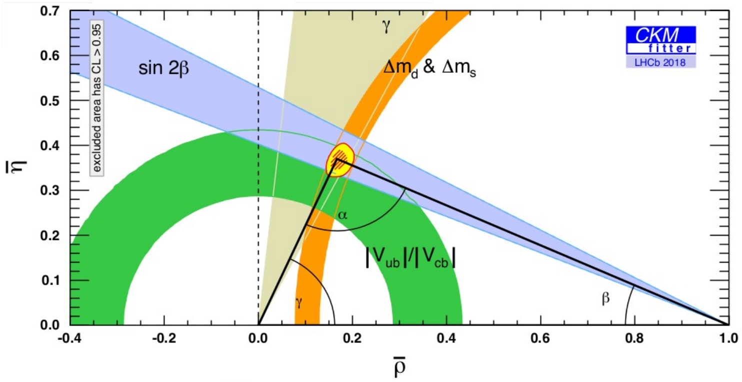


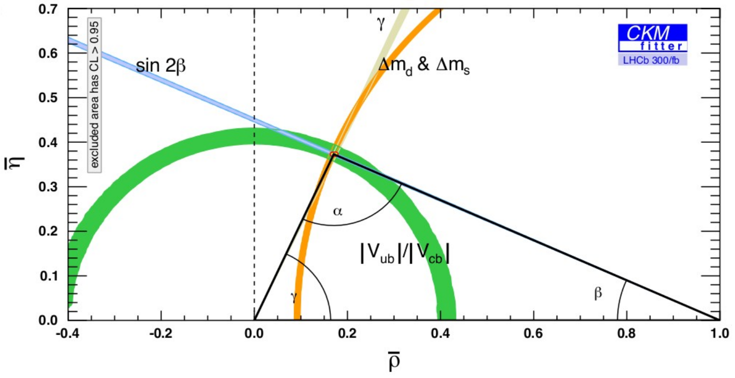
Performance demonstrated in test beam with half-size module: NIM A961 (2020) 163671

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





Last words

- Heavy flavour physics remains an extremely exciting field
  - We have been spoiled by the richness of the data available to us, and can hope for this to continue
  - (Even if we can be impatient during the occasional lulls)
- Despite a few exciting anomalies, no clear indication for BSM at present
  - Several theoretically clean observables remain to be pursued
  - Many possibilities to constrain theory from experiment

Much to do!

Let’s get on with business