Recent experimental results in flavour physics

Tim Gershon
University of Warwick

Portorož 2019: Precision Era in High Energy Physics
April 16, 2019

Contents

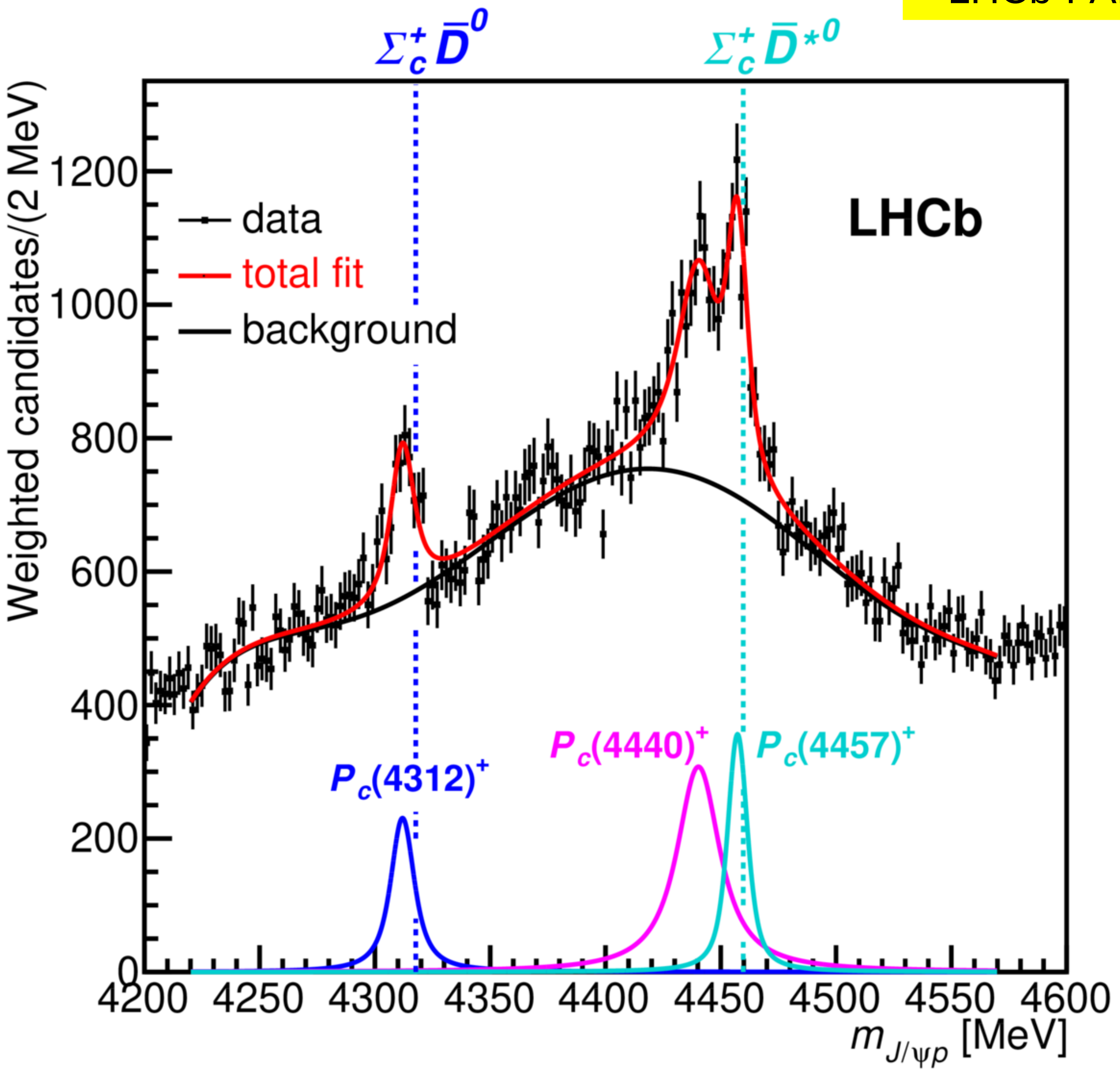
- Latest highlights in CP violation
- Latest highlights in rare decays & lepton universality tests
- Future prospects

- Most results from LHCb, but notable measurements also from BaBar, Belle, ATLAS & CMS

- Not enough time to cover the wealth of exciting recent results, including ...

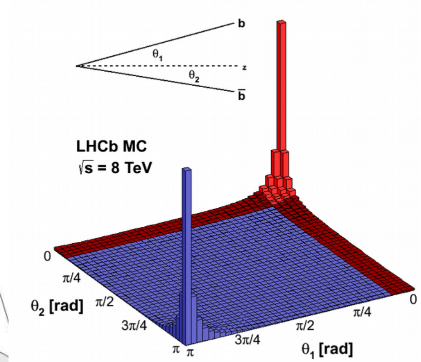
Pentaquarks

LHCb-PAPER-2019-014



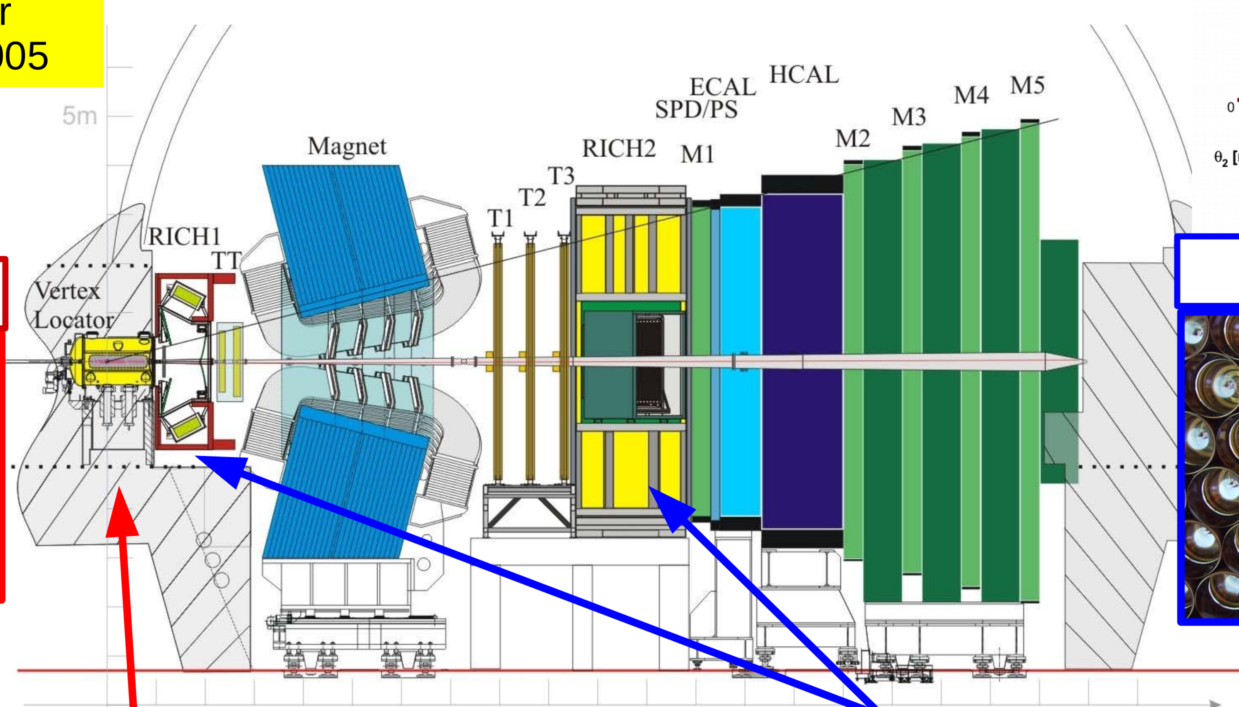
The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb designed as a forward spectrometer



The LHCb Detector
JINST 3 (2008) S08005

VELO silicon strips



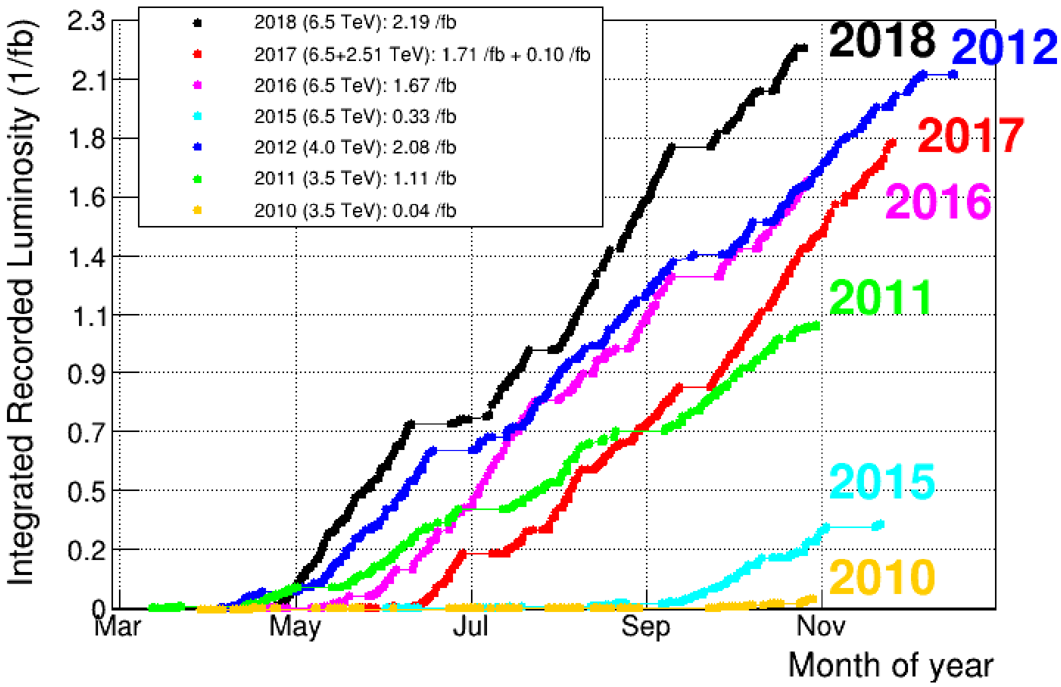
RICH PMTs

Precision primary and secondary vertex measurements

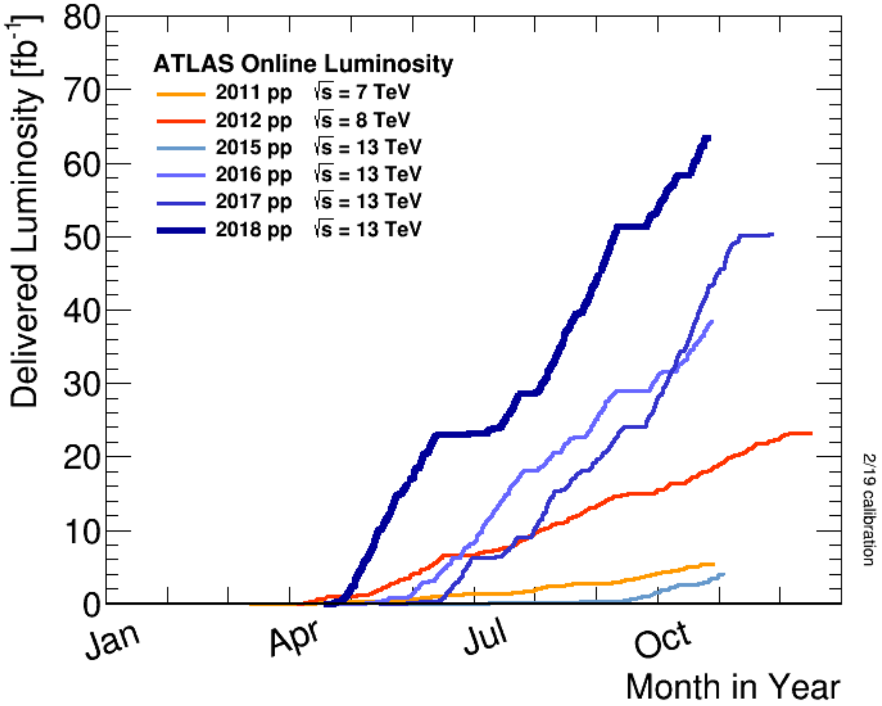
Excellent K/π separation capability

LHC integrated luminosity

LHCb



ATLAS (similar for CMS)

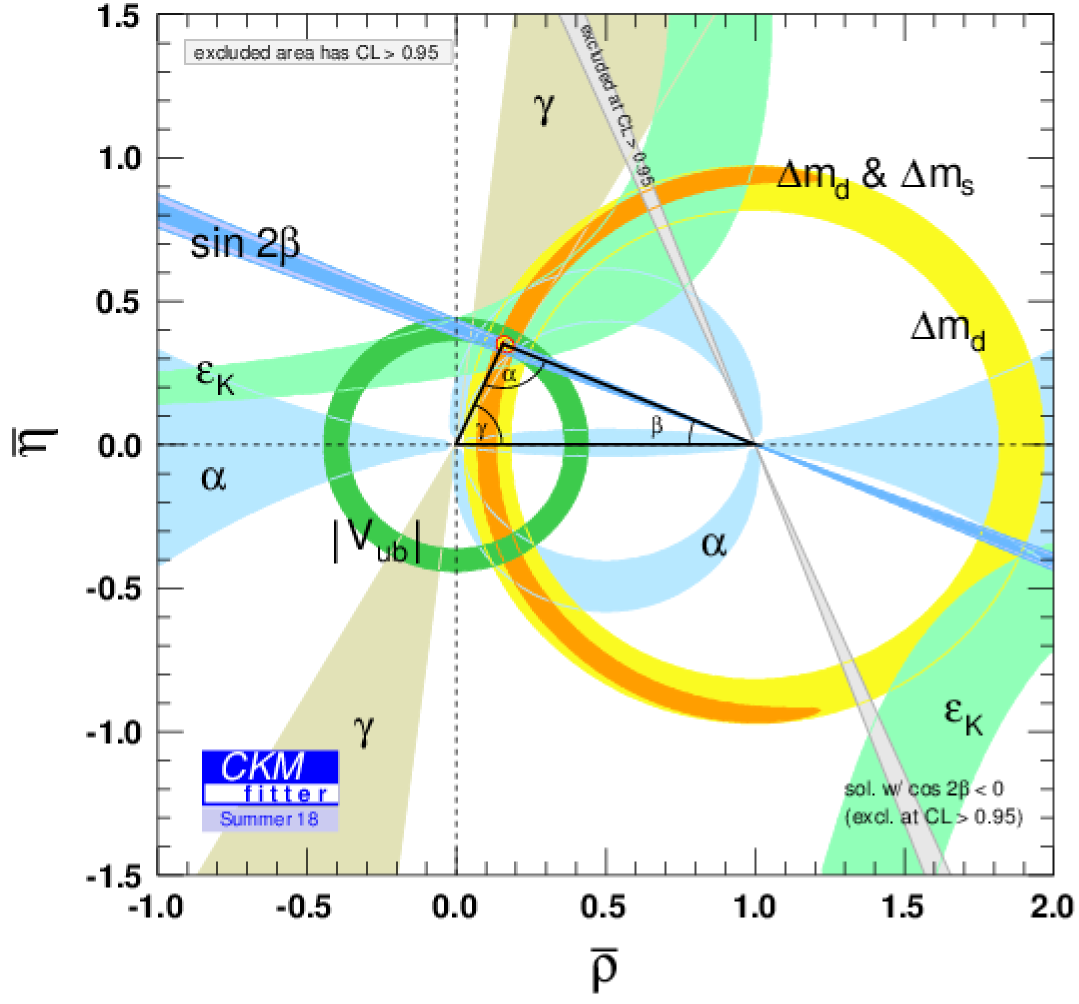


Unprecedented samples of charm and beauty

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

Most results today on Run 1 + 2015+16 – still much more to exploit

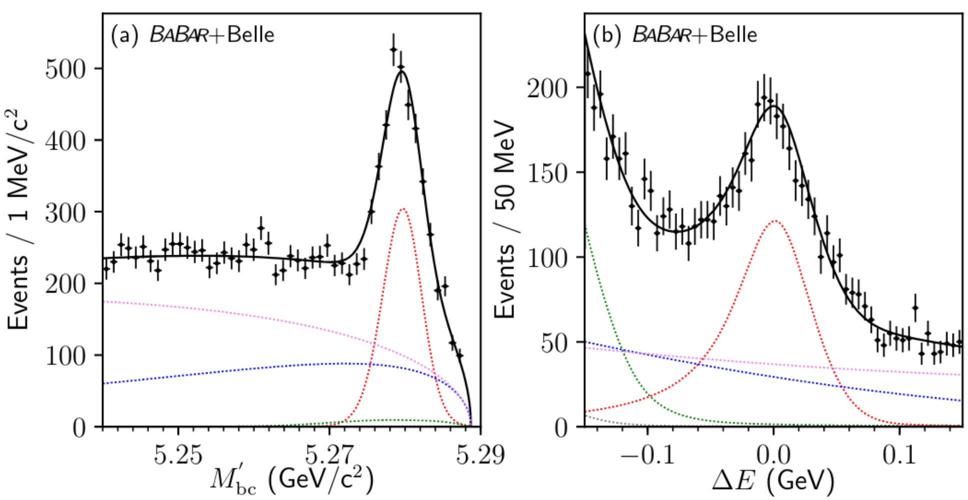
CP violation

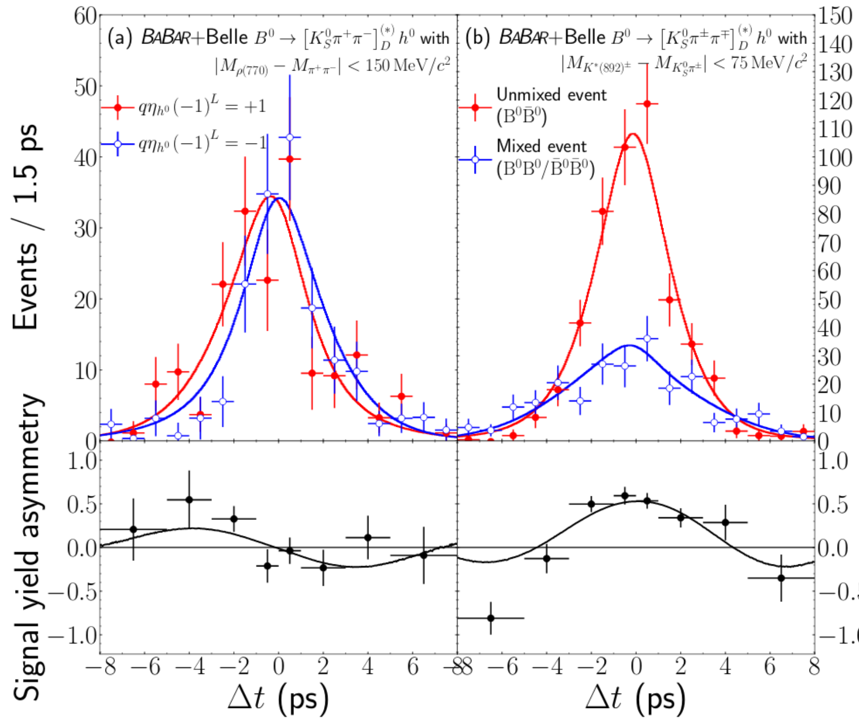

excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
|V_ub|
α
γ
ε_K
CKM fitter
Summer 18
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

β from penguin-free transitions

PRL 121 (2018) 261801, PR D98 (2018) 112012

- Standard method using $B^0 \to J/\psi K_S$ reaching precision where penguin effects may be a concern
- Analysis of $B^0 \to D h^0$, with $D \to K_S \pi^+ \pi^-$ provides penguin-free alternative, and cos(2β) in addition to sin(2β)



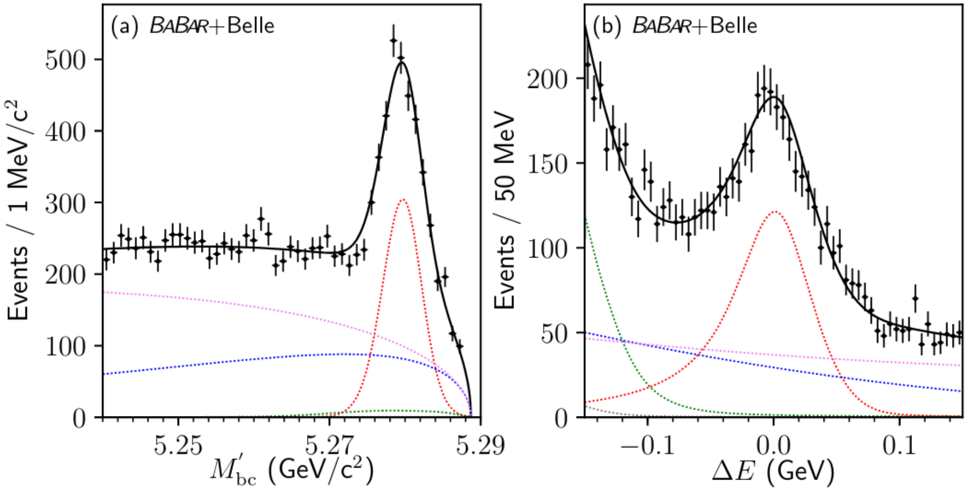


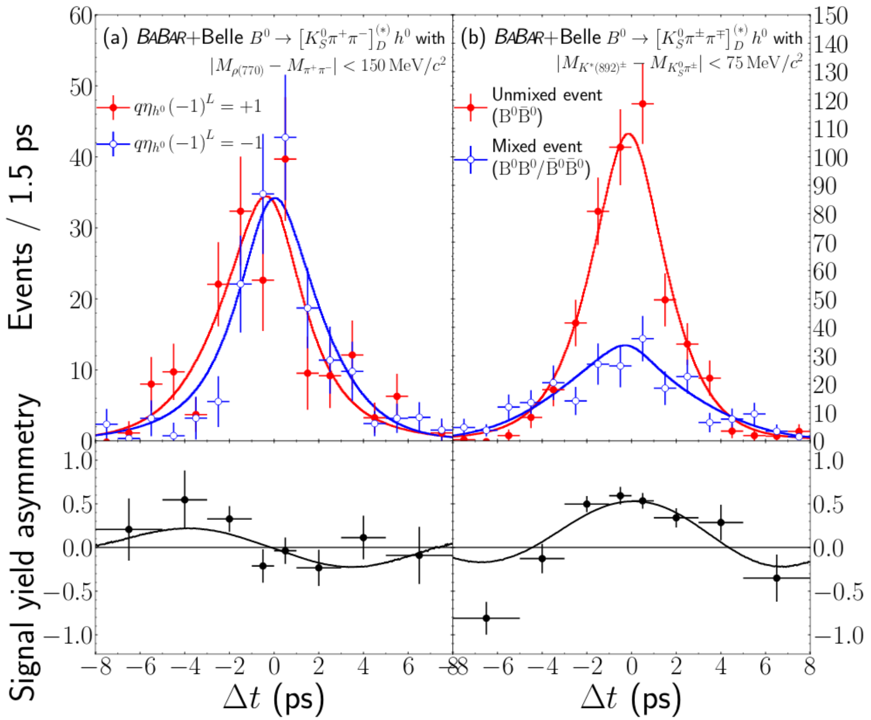
Joint analysis of BaBar & Belle data
Sample of 1.24B $B\bar{B}$ pairs

β from penguin-free transitions

PRL 121 (2018) 261801,
PR D98 (2018) 112012

$$\sin 2\beta = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model}),$$
$$\cos 2\beta = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model}).$$



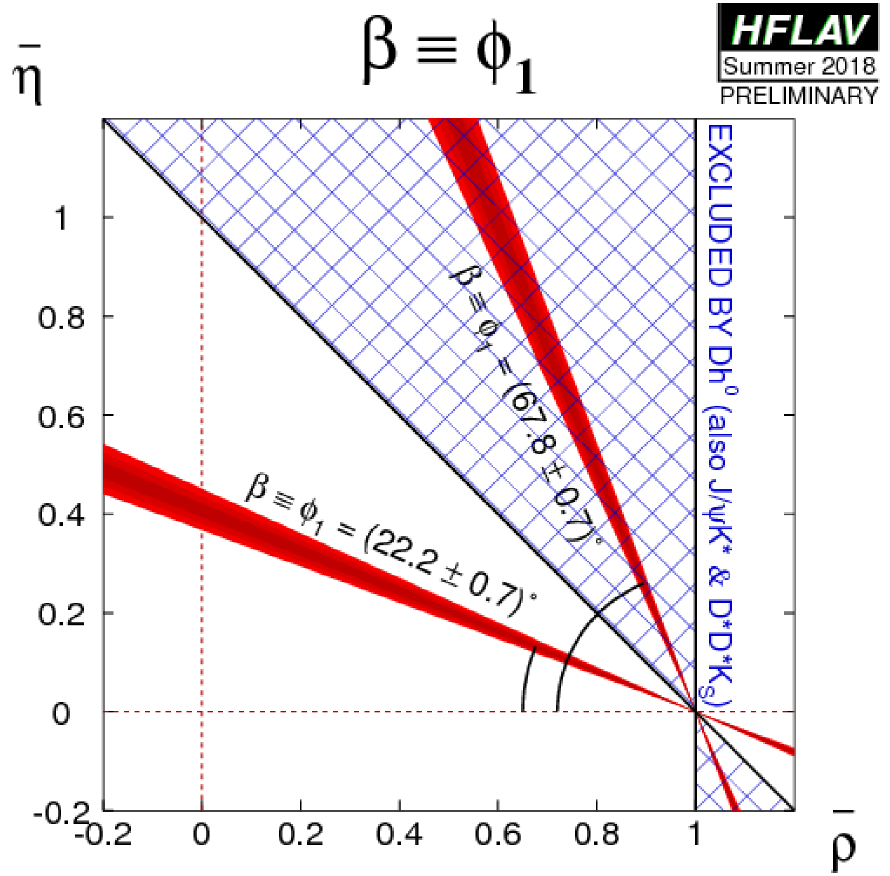


Joint analysis of BaBar & Belle data
Sample of 1.24B $B\bar{B}$ pairs

β from penguin-free transitions

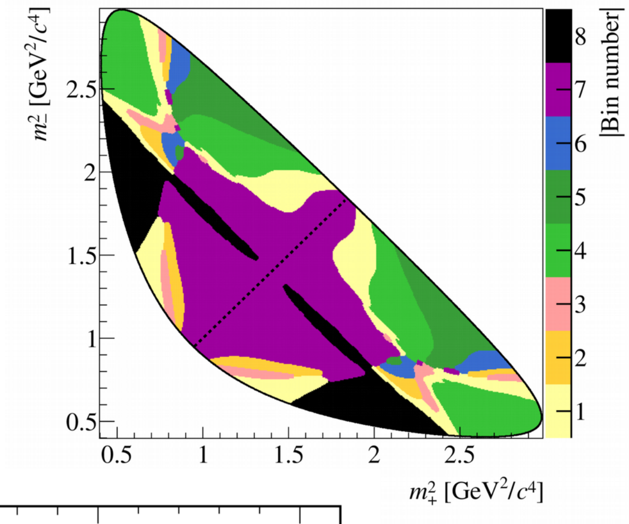
PRL 121 (2018) 261801,
PR D98 (2018) 112012

$$\sin 2\beta = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model}),$$
$$\cos 2\beta = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model}).$$

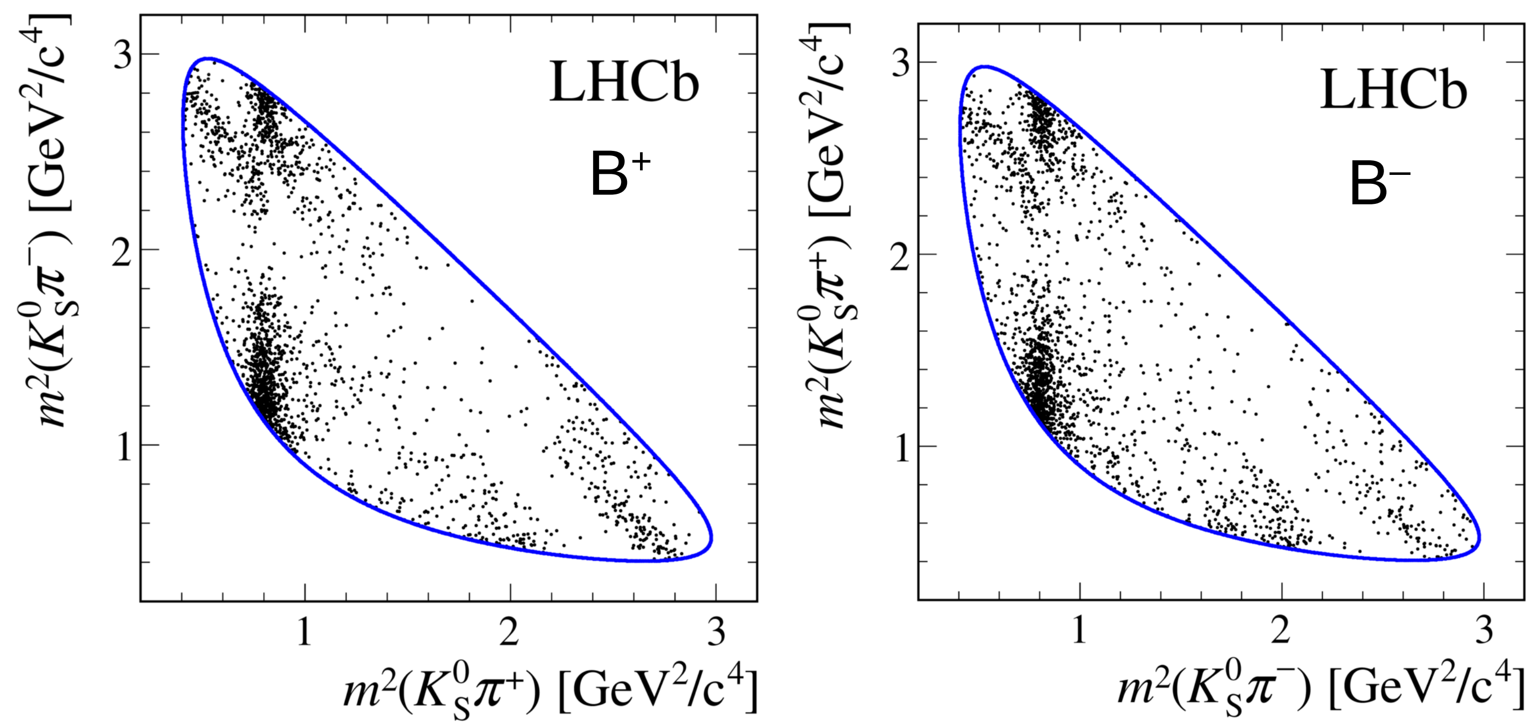


γ from B→DK, with D→$K_S\pi^+\pi^-$

JHEP 08 (2018) 176



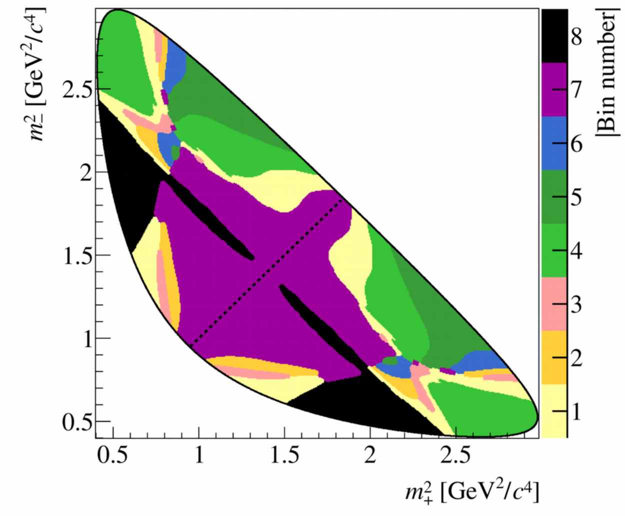
- Model-independent GGSZ method
- Data from 2015-16
- Uses hadronic D decay parameters (c_i,s_i) from CLEO-c

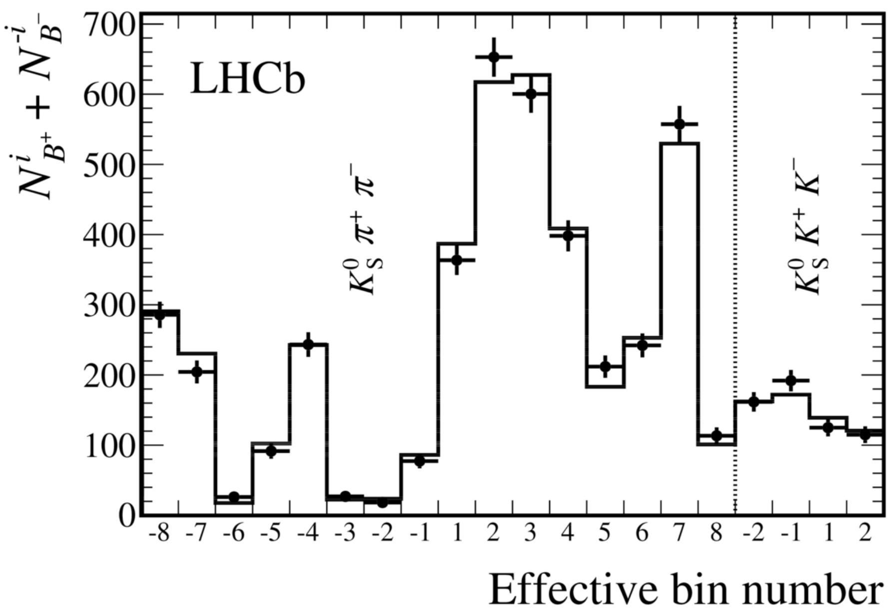


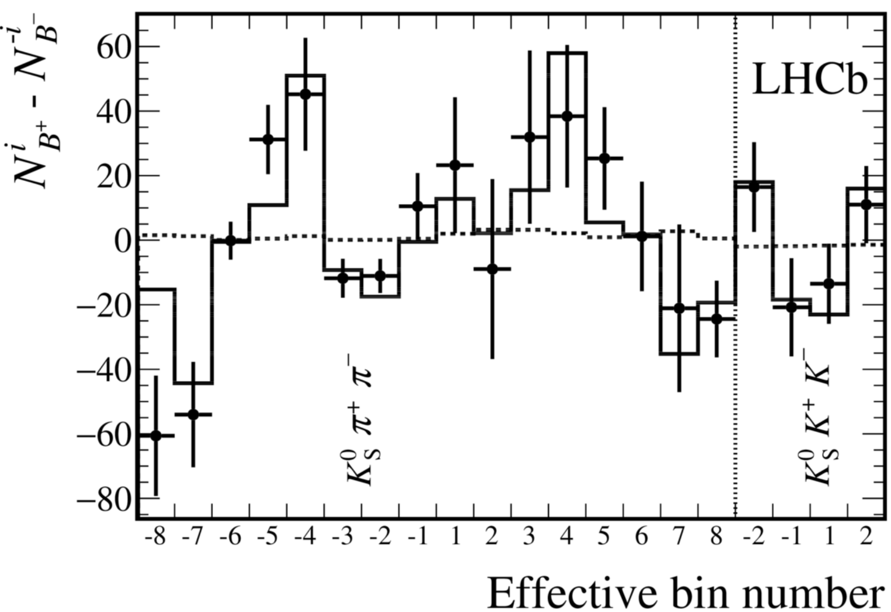
γ from B→DK, with D→$K_S\pi^+\pi^-$

JHEP 08 (2018) 176

- Model-independent GGSZ method
- Data from 2015-16
- Uses hadronic D decay parameters (c_i,s_i) from CLEO-c

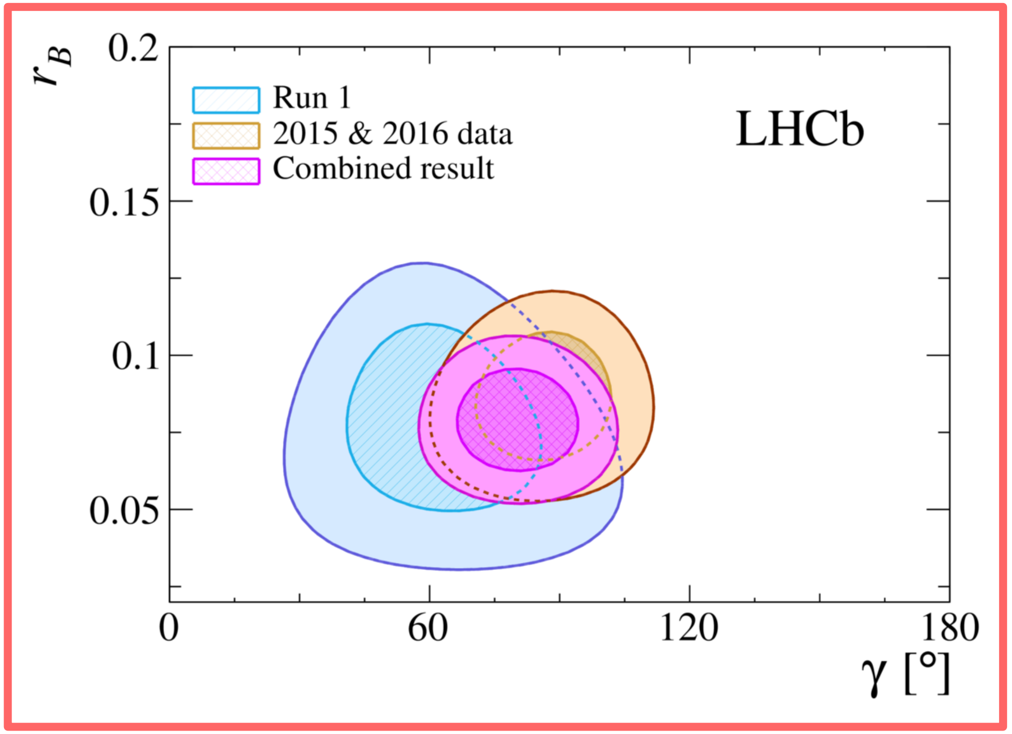


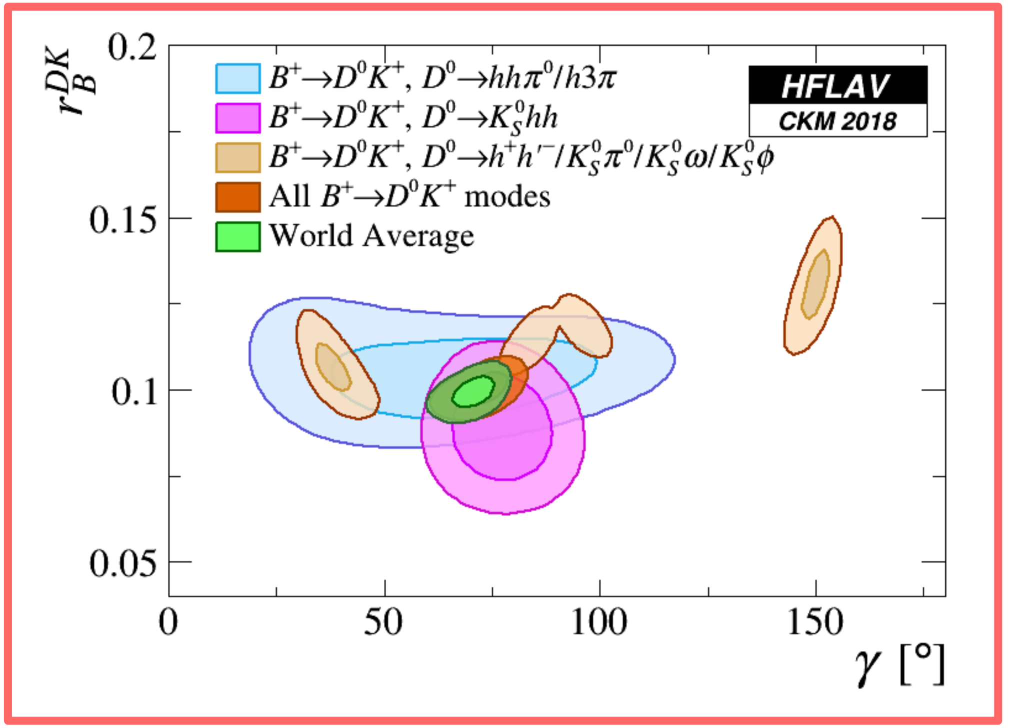




γ from B→DK (and others)

JHEP 08 (2018) 176



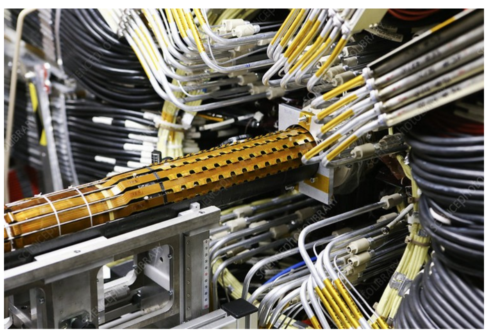


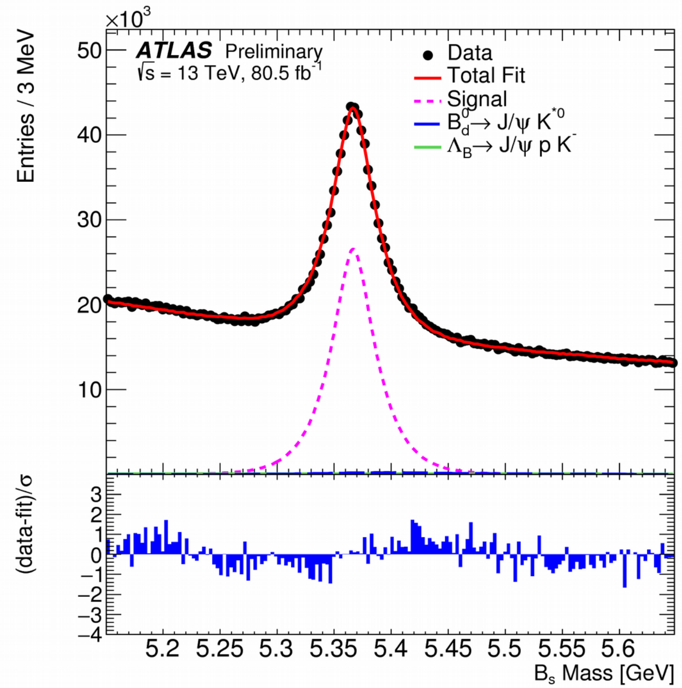
HFLAV world average: $\gamma = (71.1^{+4.6}_{-5.3})°$

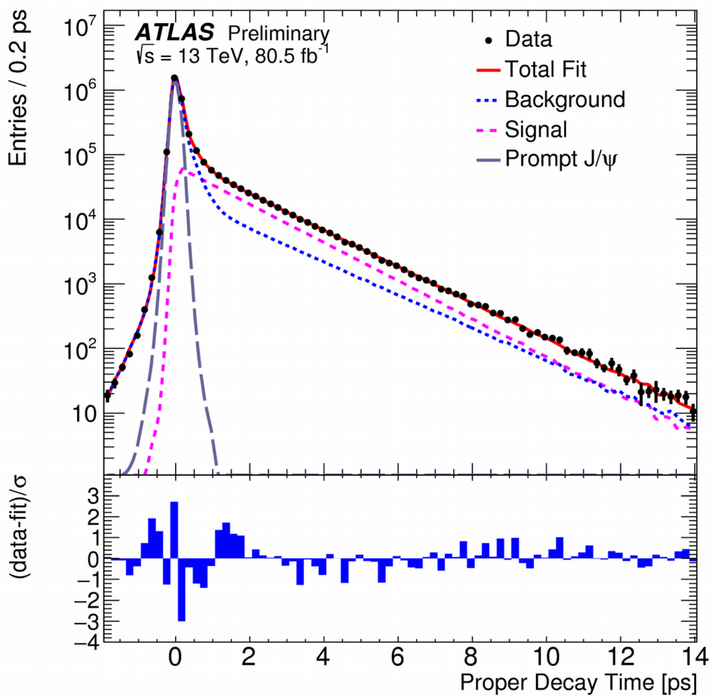
φ_s from $B_s^0 \rightarrow J/\psi\varphi$ (ATLAS)

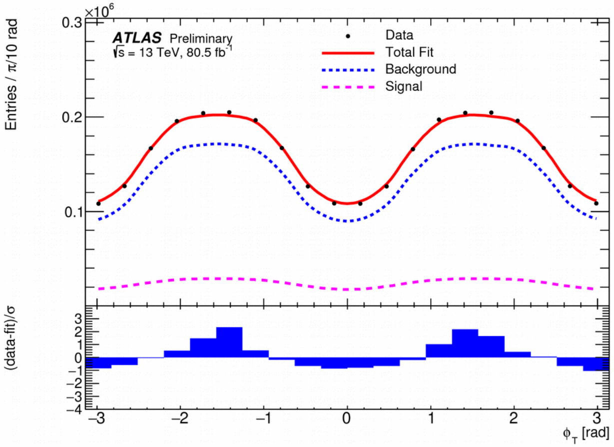
ATLAS-CONF-2019-009

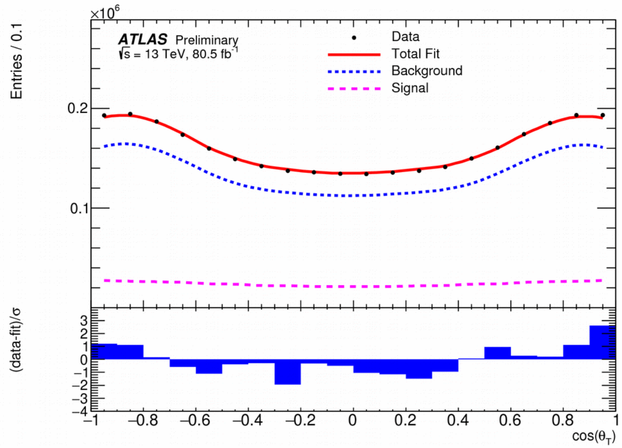
- Data from 2015-17
- Signal yield ~ 450k
- New Insertable B Layer (IBL) detector improves σ_t: 100→70 fs
- Tagging power ~ 1.6%

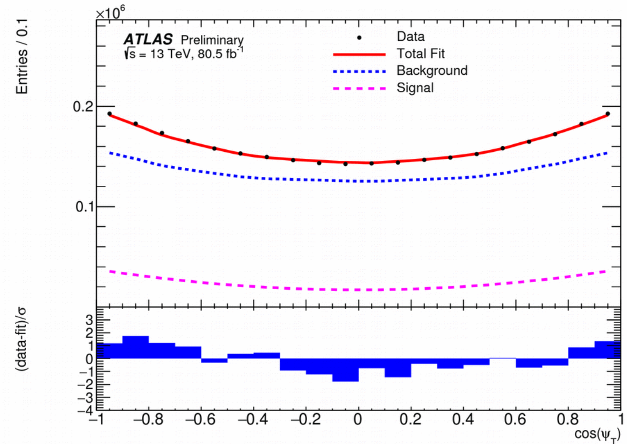








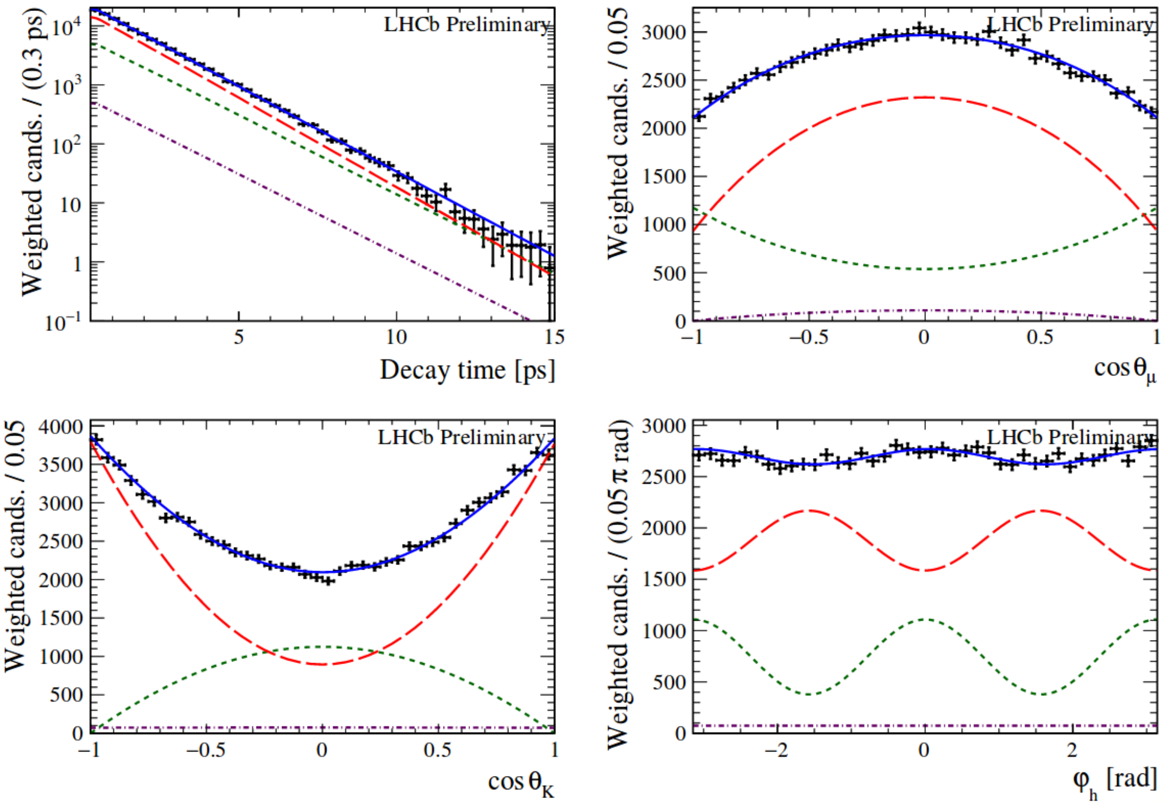


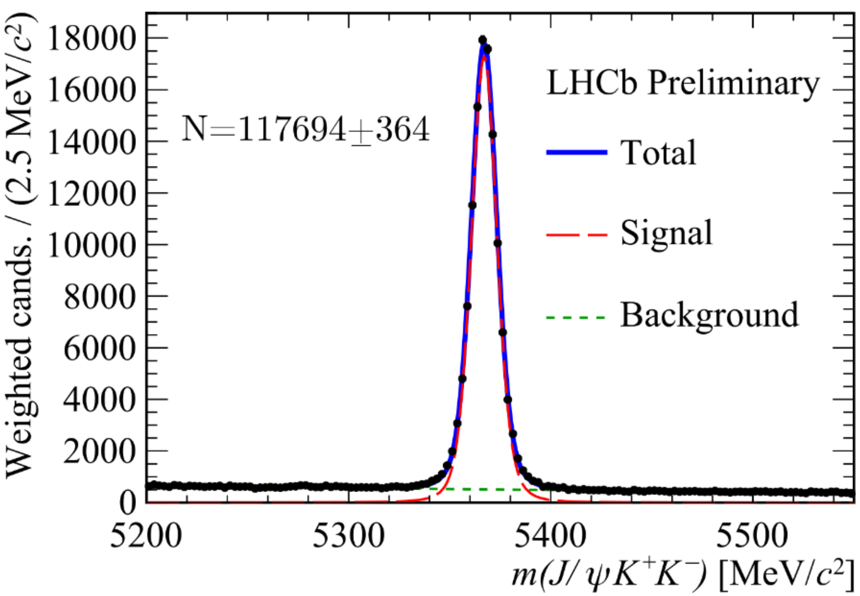


φ_s from $B_s^0 \to J/\psi\varphi$ (LHCb)

LHCb-PAPER-2019-013
in preparation

- Data from 2015-16
- Signal yield ~ 120k
- Time resolution σ_t ~ 45 fs
- Tagging power ~ 4.7%

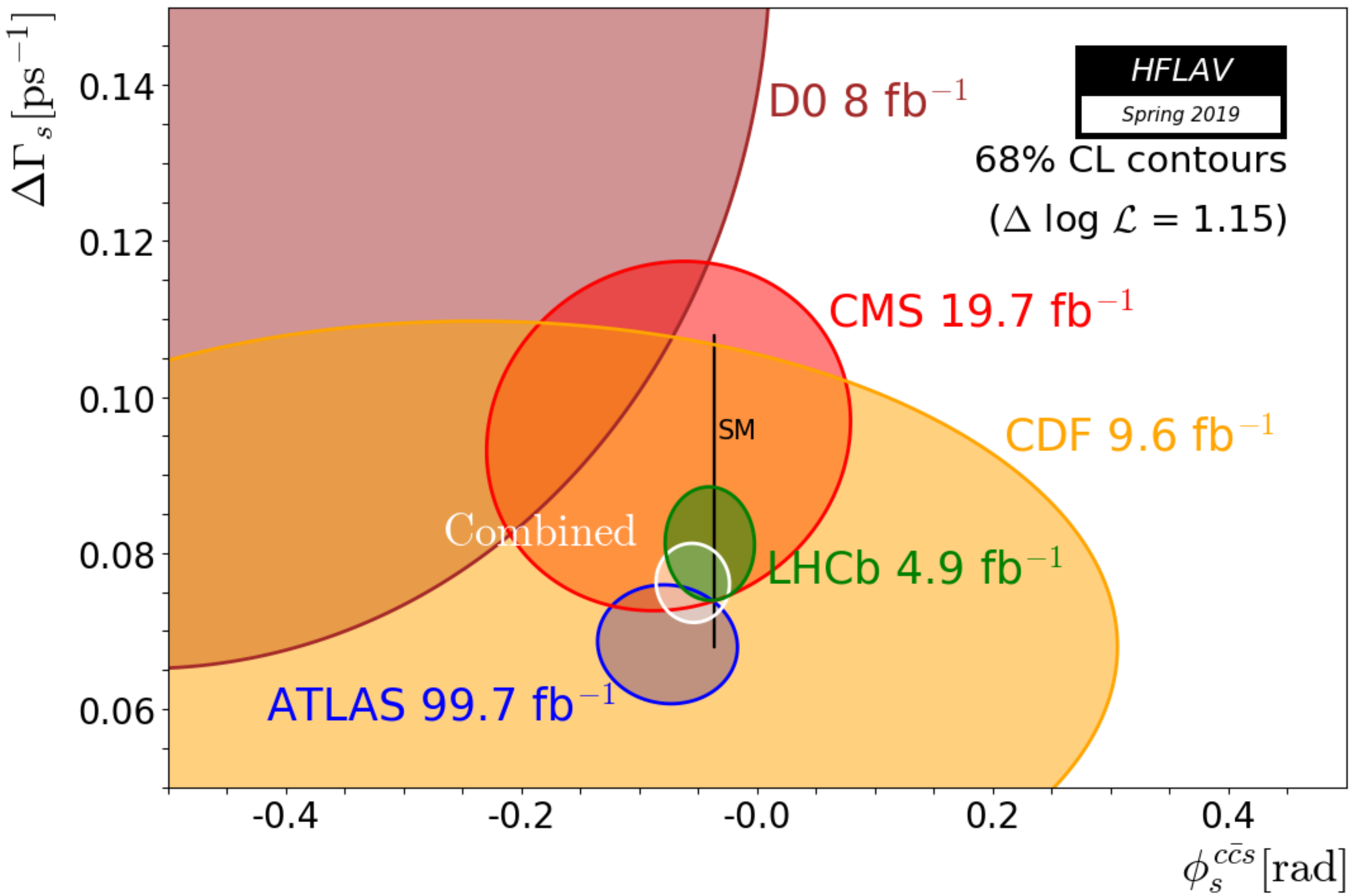




φ_s combination

Also new LHCb results using $B_s^0 \to J/\psi\pi^+\pi^-$

ATLAS-CONF-2019-009,
LHCb-PAPER-2019-013,
LHCb-PAPER-2019-003

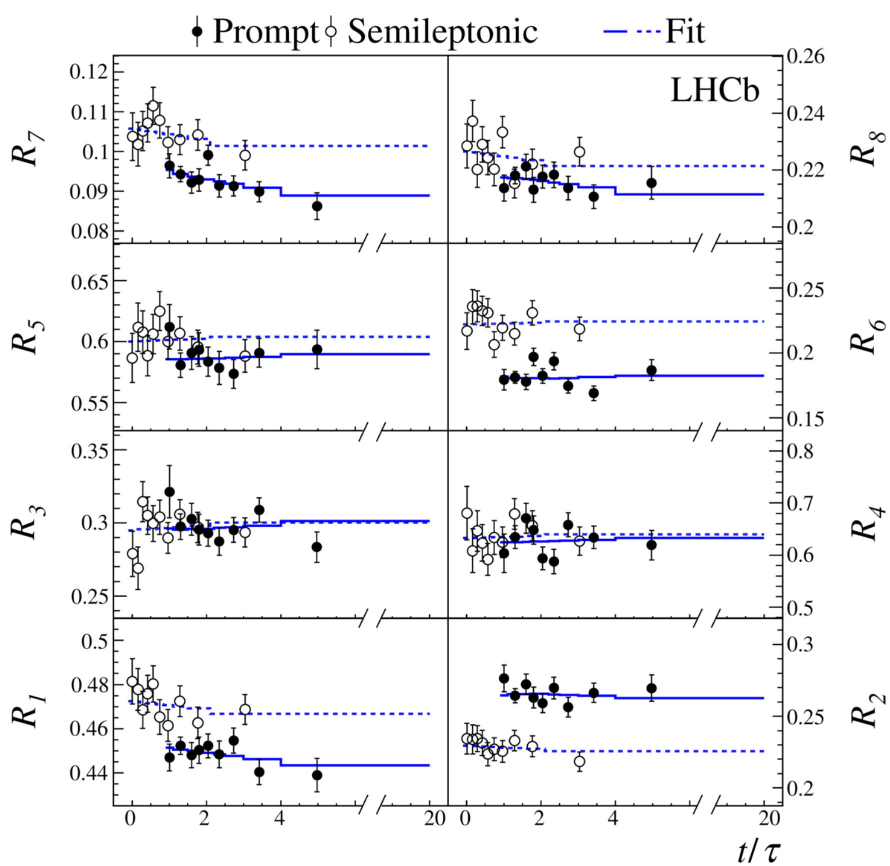


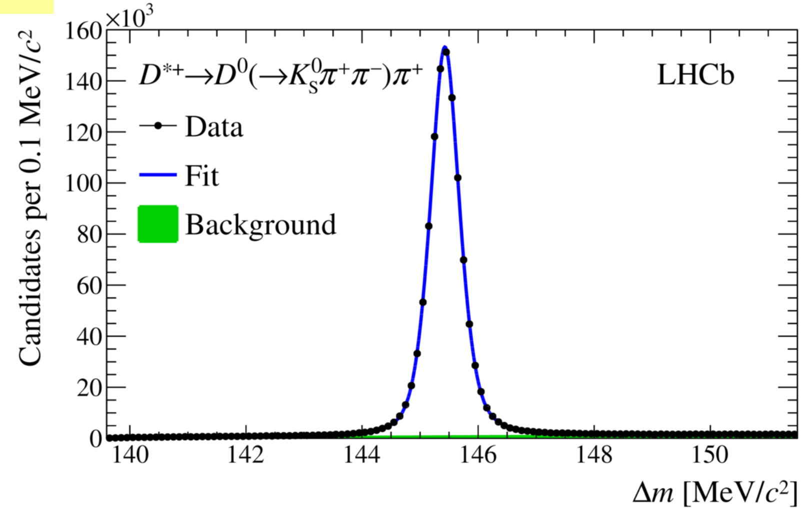
HFLAV world average: φ_s = –0.054 ± 0.020 rad

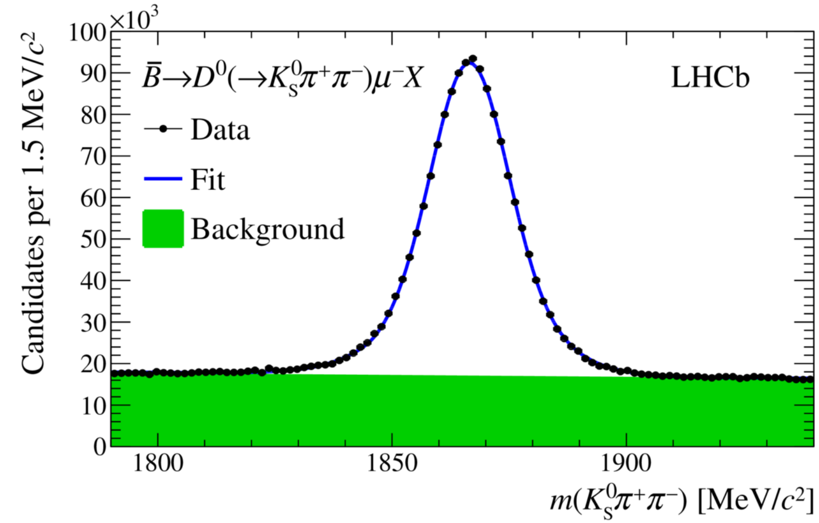
Charm mixing with $D \to K_S \pi^+ \pi^-$

LHCb-PAPER-2019-001

- New "bin-flip" method PR D99 (2019) 012007
  - Inspired by model-independent GGSZ method to measure γ
  - Similar to $D \to K\pi$ WS/RS analysis
- Data from 2011-12



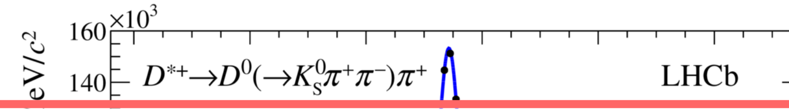


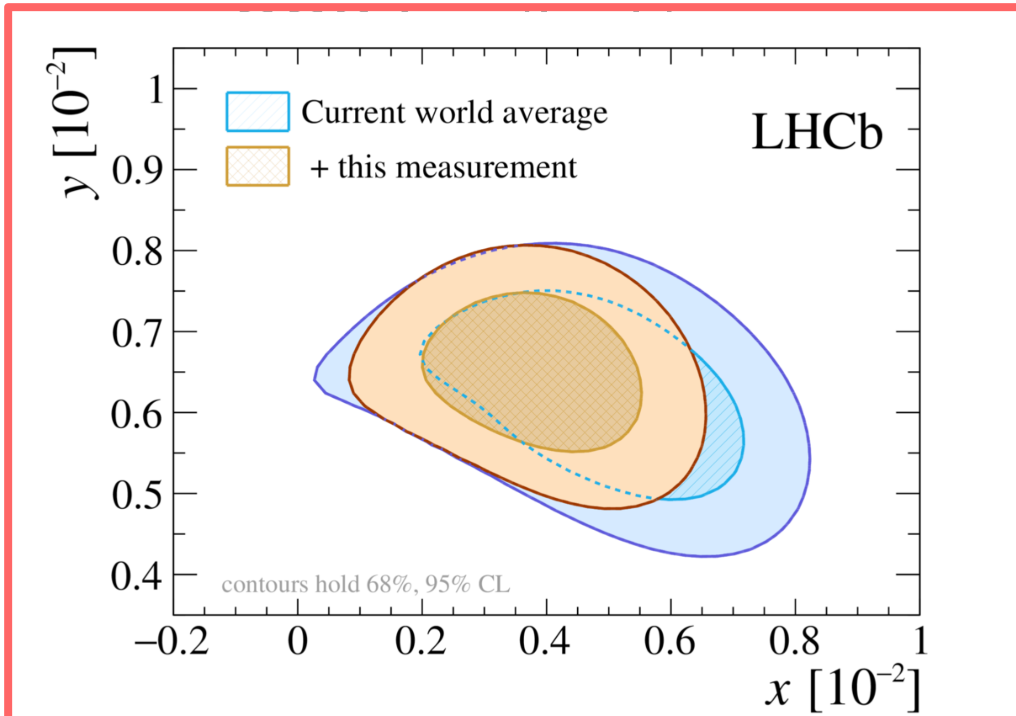


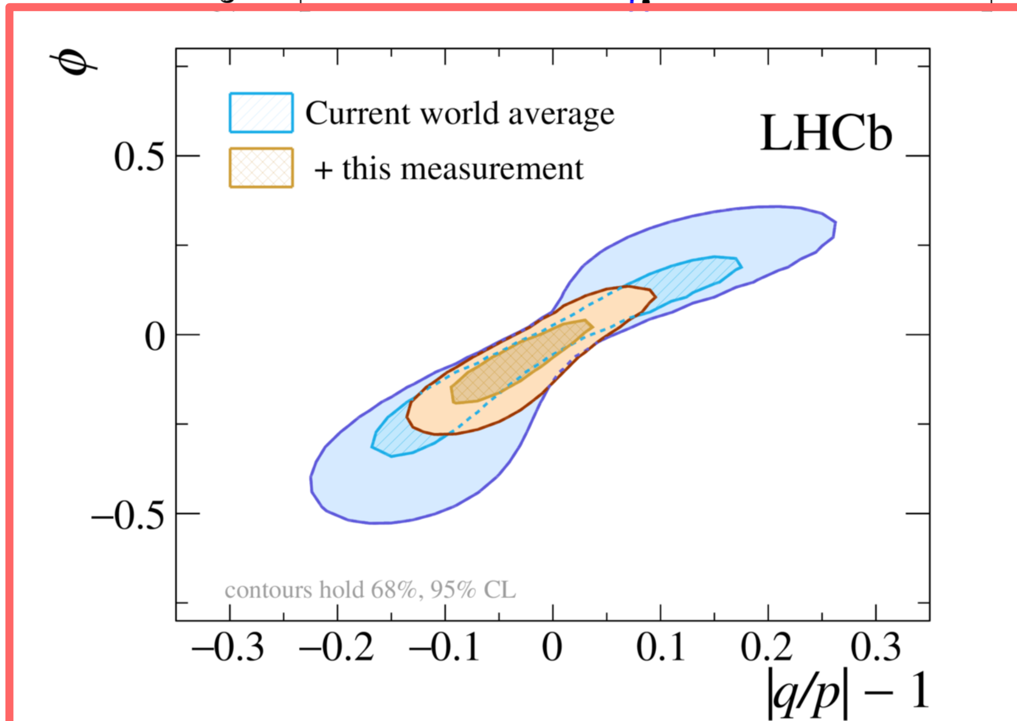
Charm mixing with $D \to K_S \pi^+ \pi^-$

LHCb-PAPER-2019-001

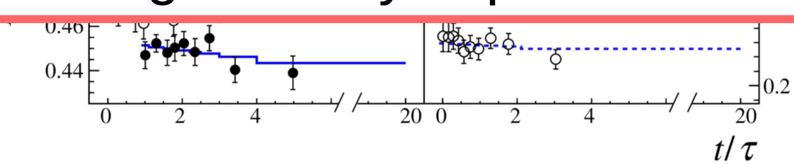
- New “bin-flip” method
  - Inspired by model-independent







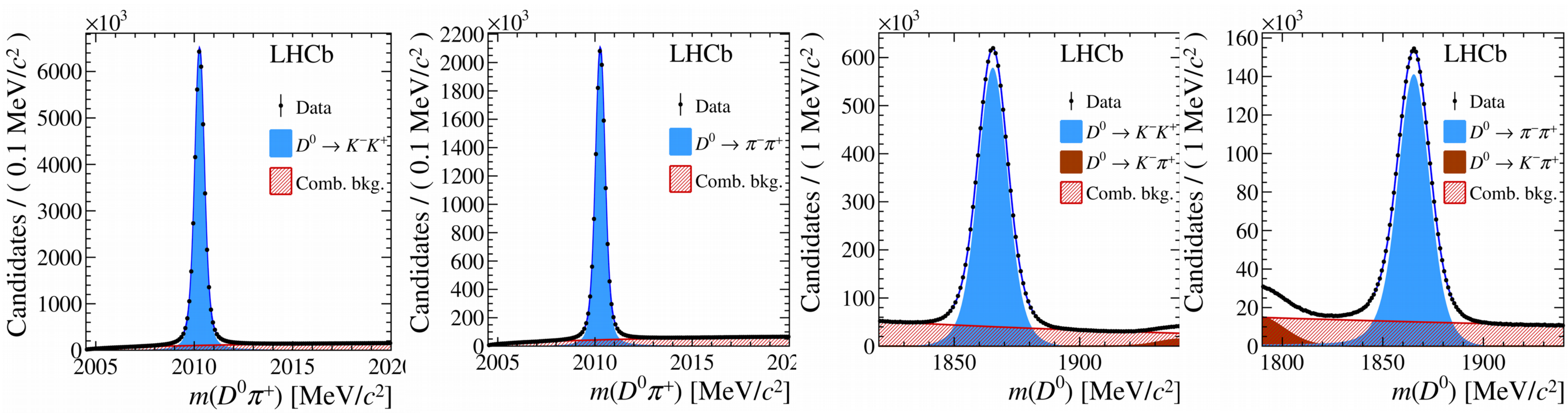
World average now excludes x=0 at 3σ
(i.e. non-zero mass difference between physical neutral charm eigenstates)
and hence significantly improves constraints on CP violation in charm mixing



Observation of CP violation in charm decays

LHCb-PAPER-2019-006

- ΔA_{CP} method: $A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
  - minimises systematic uncertainties due to production or detection asymmetries
- Data from 2015-18, combined with previous Run 1 results
  - tags from both $D^{*+} \to D^0\pi^+$ and $B \to D^0\mu^-X$ decays
  - full LHCb data sample!

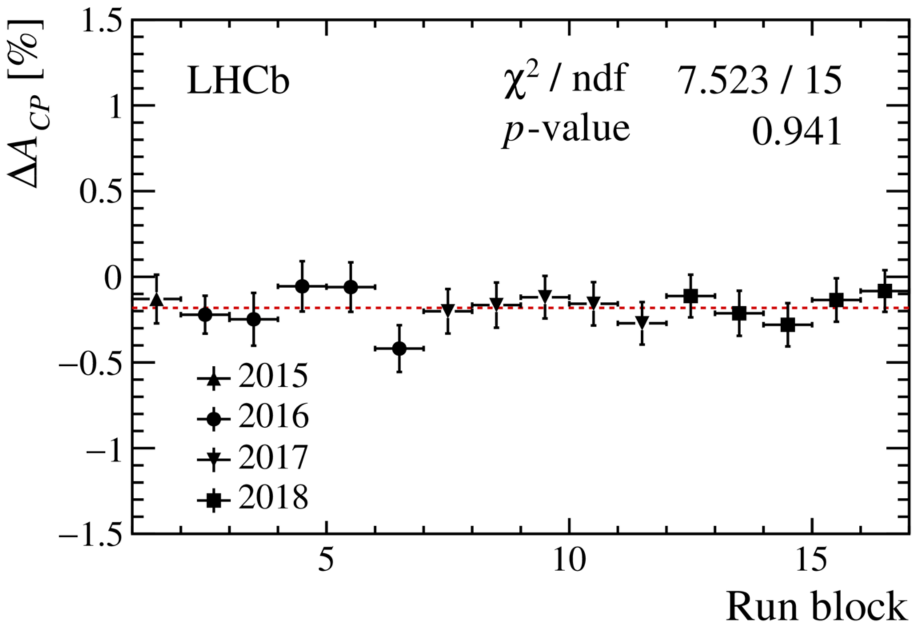


Observation of CP violation in charm decays

LHCb-PAPER-2019-006

Results with Run 2 data:

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$



Observation of CP violation in charm decays

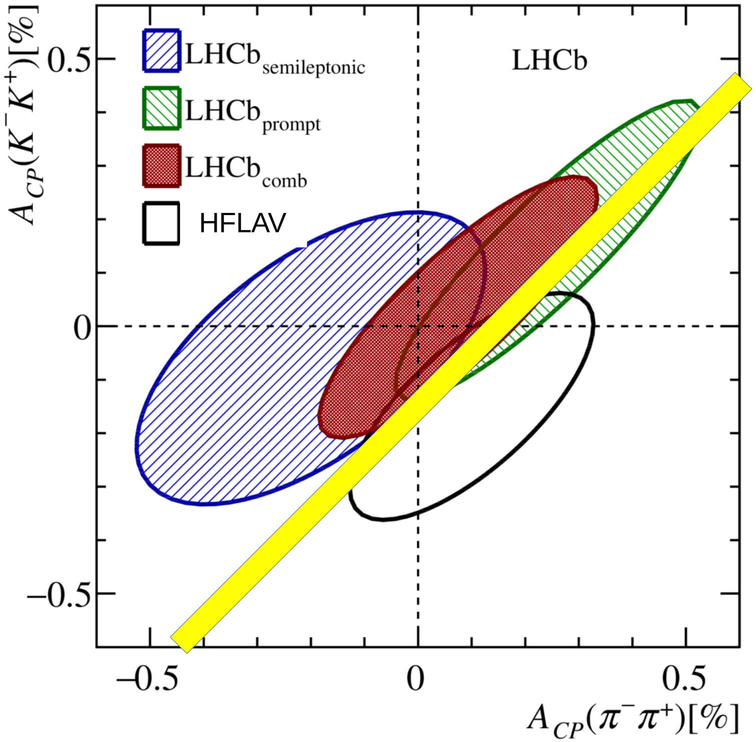
LHCb-PAPER-2019-006

Combined with Run 1 results:

5.3σ

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4},$$

Adapted from
PL B767 (2017) 177

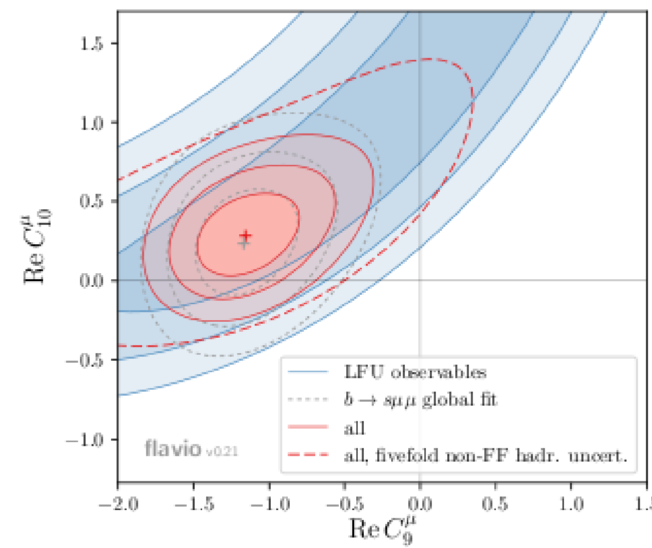


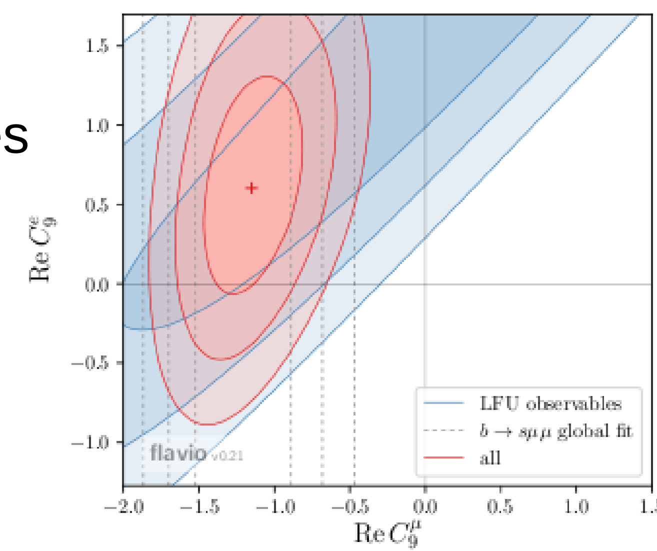
Rare decays & lepton universality tests

Status of $b \to s l^+ l^-$ processes pre-Moriond 2019

Plots from arXiv:1704.05435

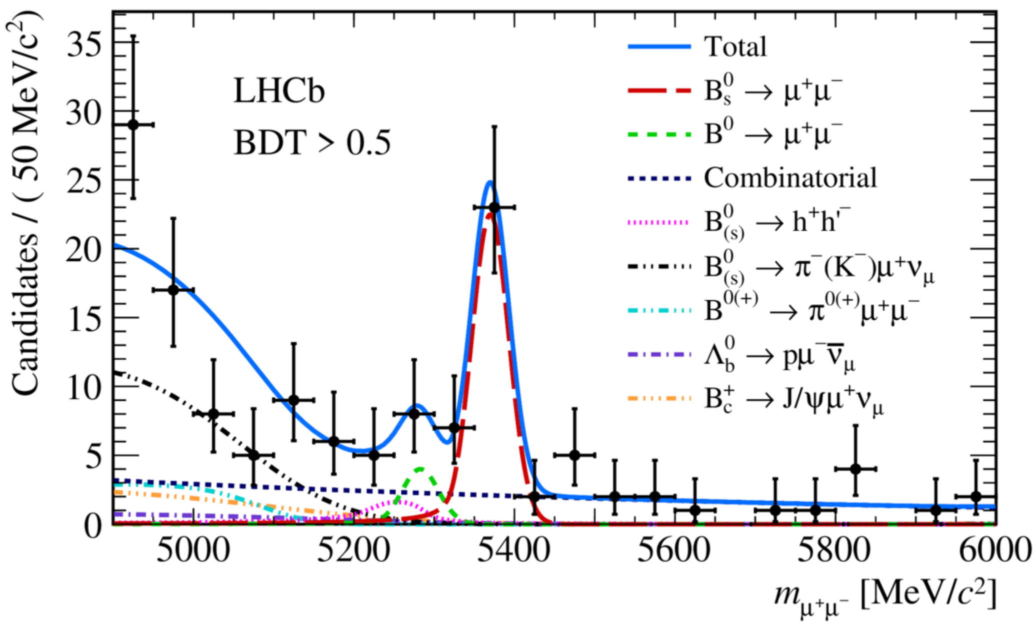
- Several "tensions" with the Standard Model
  - Branching fractions of exclusive $b \to s \mu^+ \mu^-$ decays
  - Angular analysis of $B^0 \to K^{*0} \mu^+ \mu^-$
  - Lepton universality tests: $R_{K(*)}$
- No single measurement above 5σ significance
  - Consistent picture of deviations in model-independent global fits
- Keen interest in updates
  - Especially for the theoretically clean $R_{K(*)}$ observables

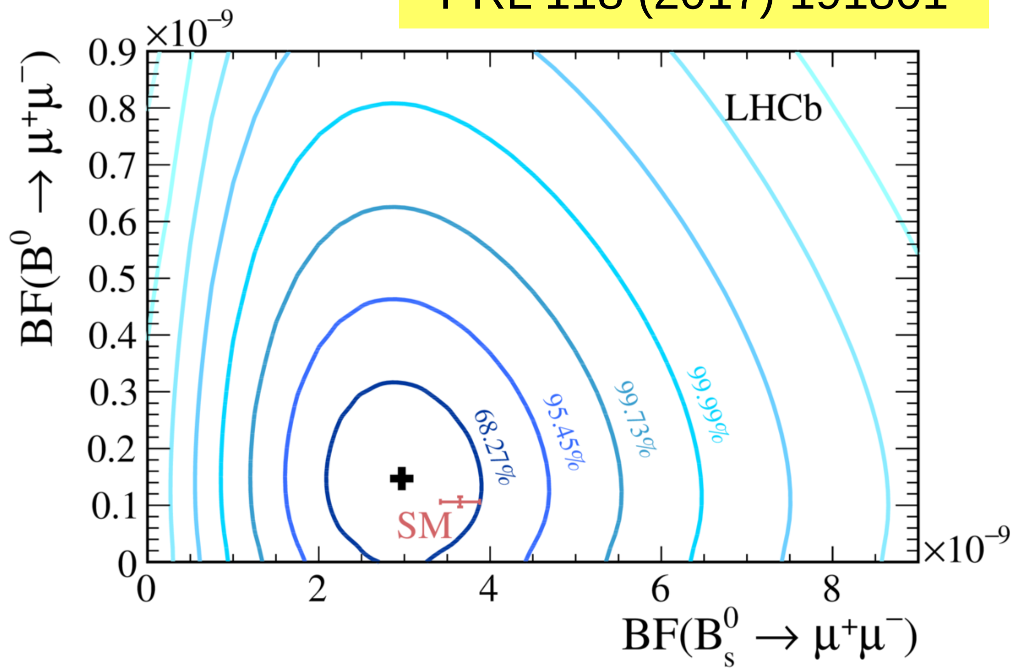




$B_s \to \mu^+\mu^-$ (LHCb)

PRL 118 (2017) 191801





Data sample includes 1.4 fb^{-1} collected in Run 2

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9}$$ 7.8σ

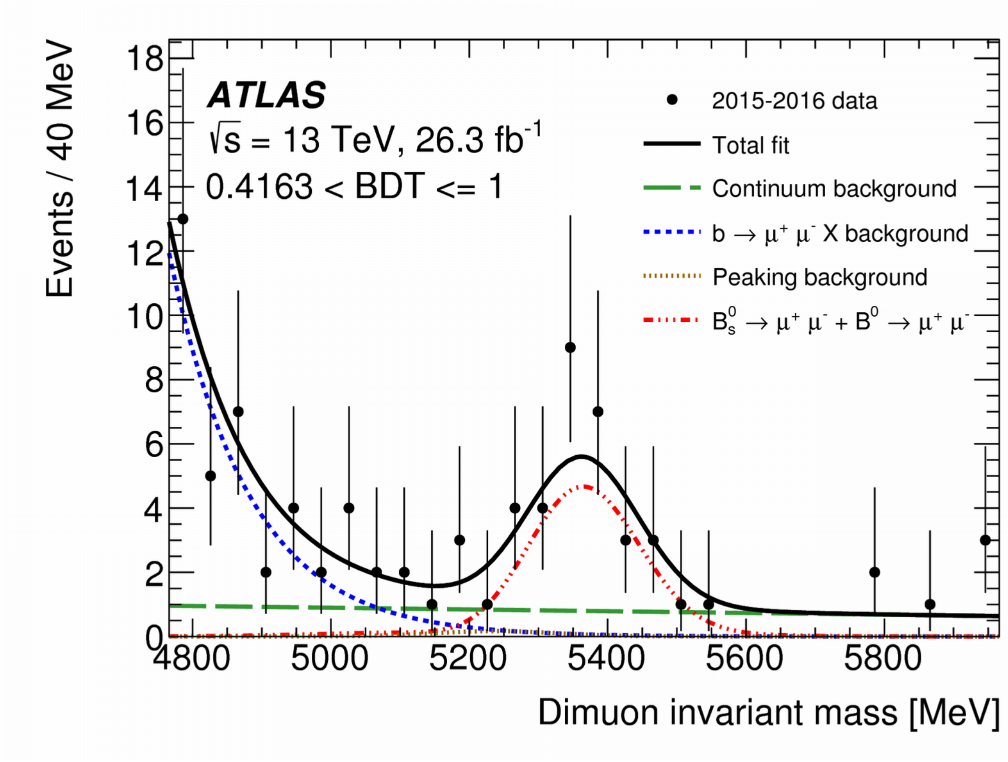
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}\right) \times 10^{-10}$$ 1.6σ

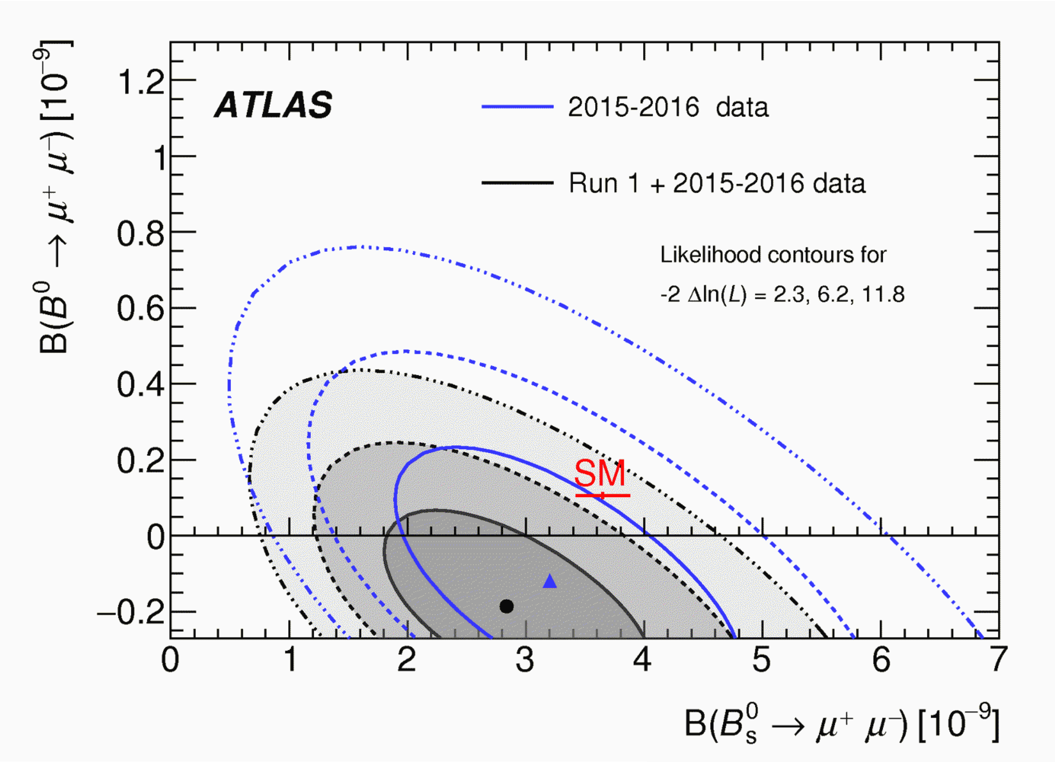
First 5σ observation by a single experiment

Improving on the CMS+LHCb Run 1 combination of Nature 522 (2015) 68

$B_s \to \mu^+\mu^-$ (ATLAS)

arXiv:1812.03017





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9}$$ 4.6σ

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (-1.9 \pm 1.6) \times 10^{-10}$$

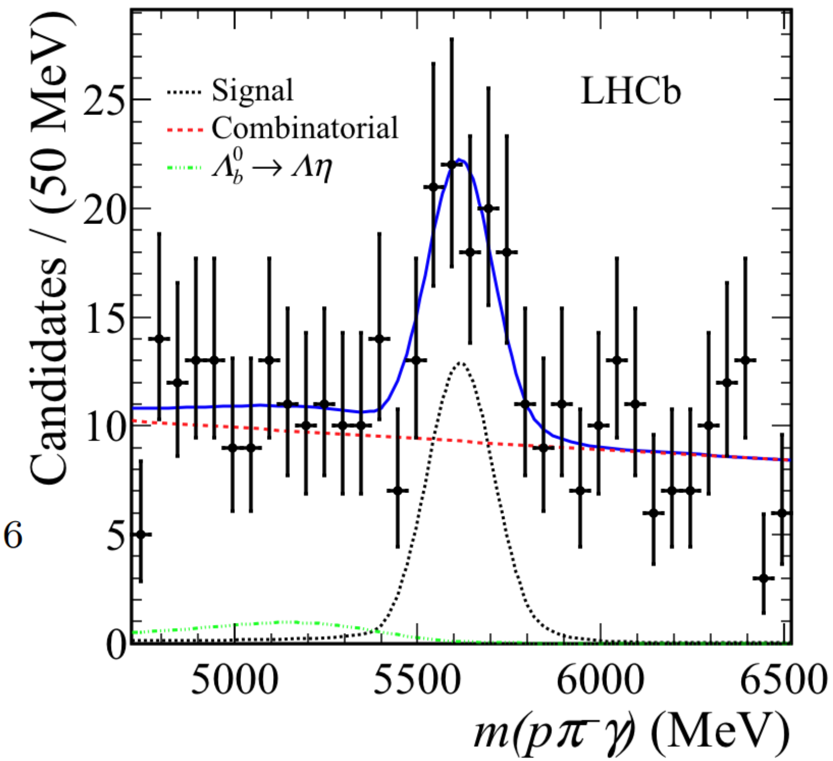
Photon polarisation in $\Lambda_b \rightarrow \Lambda\gamma$ decays

LHCb-PAPER-2019-010

- Can exploit baryon spin to determine photon polarisation
- Very challenging decay topology for LHCb
  - Dedicated trigger since 2016
- Measure branching fraction relative to $B^0 \rightarrow K^{*0}\gamma$

5.6σ

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$



- Photon polarisation measurement will be possible with larger samples

Photon polarisation in $B_s^0 \to \phi\gamma$ decays

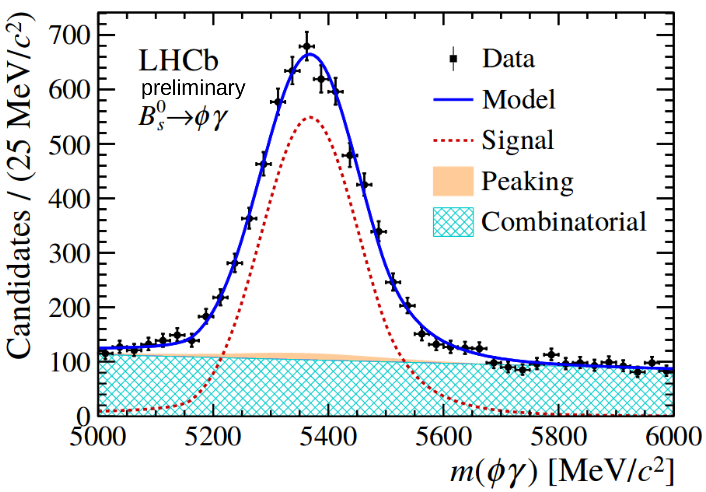
LHCb-PAPER-2019-015
in preparation

$$\mathcal{P}(t) \propto e^{-\Gamma_s t} \left\{ \cosh\left(\Delta\Gamma_s t/2\right) - \mathcal{A}^{\Delta} \sinh\left(\Delta\Gamma_s t/2\right) + q\, C \cos\left(\Delta m_s t\right) - q\, S \sin\left(\Delta m_s t\right) \right\}$$

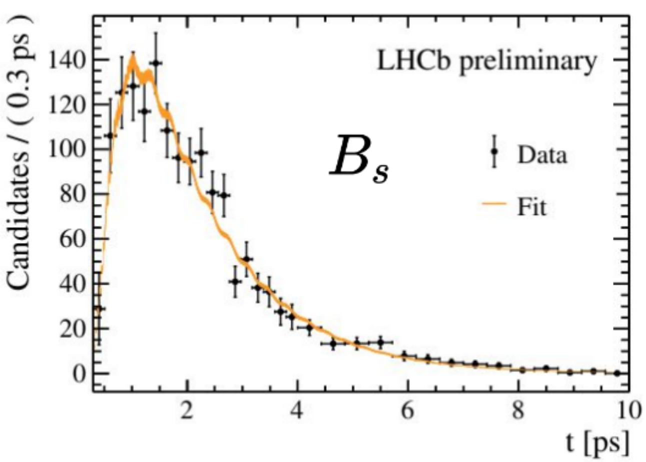
sensitive to photon polarisation

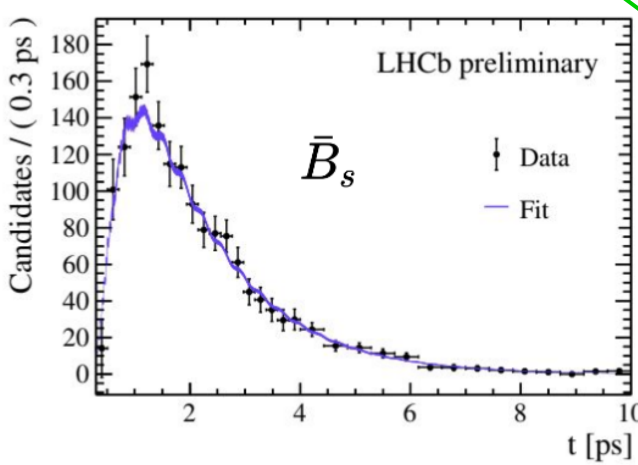
probes CP violation in decay
(expected to be zero)

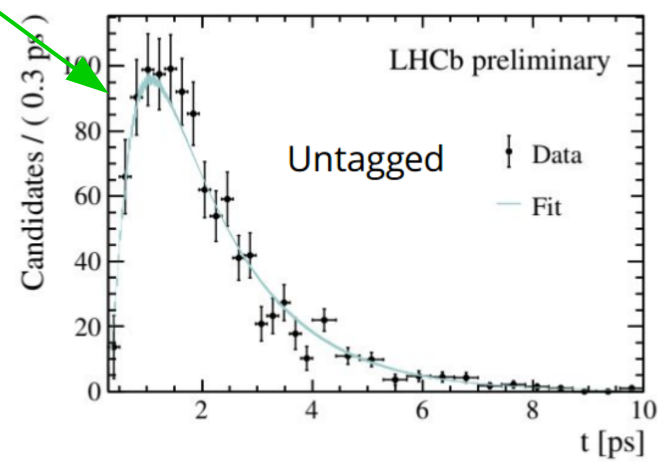
can be measured
with untagged decays



$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17,$$







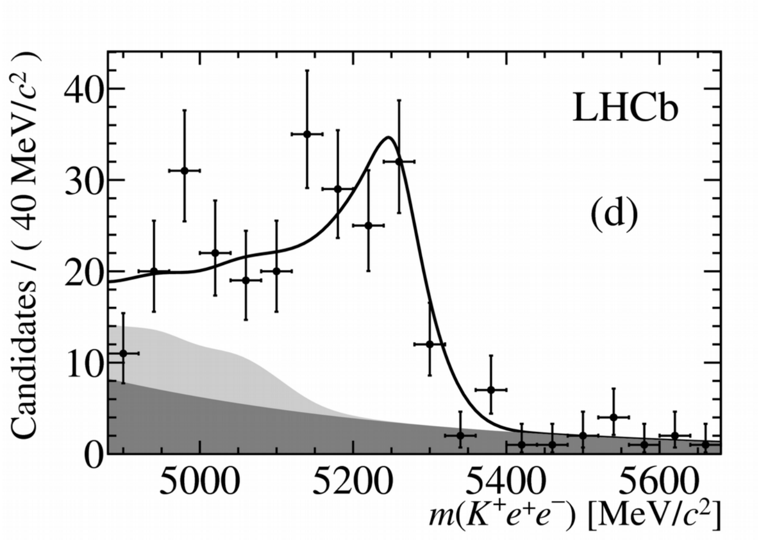
Also recent results from Belle on $B^0 \to K_S^0 \eta\gamma$ [PR D97 (2018) 092003]

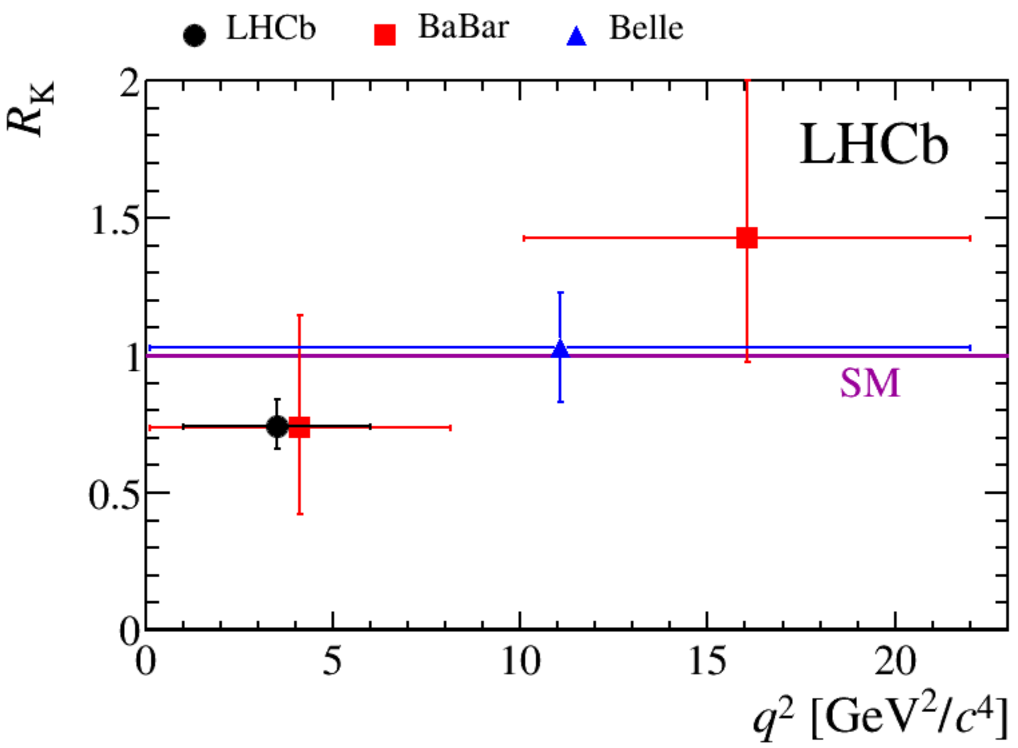
Lepton universality
$R_K \equiv B(B \to K\mu\mu)/B(B \to Kee)$

PRL 113 (2014) 151601

Deficit of B → $K\mu^+\mu^-$ compared to expectation also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K)

Example mass fit for Ke^+e^-
Note huge tail due to energy loss





$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

Only 2.6σ from SM but suggestive

Update of R_K (LHCb)

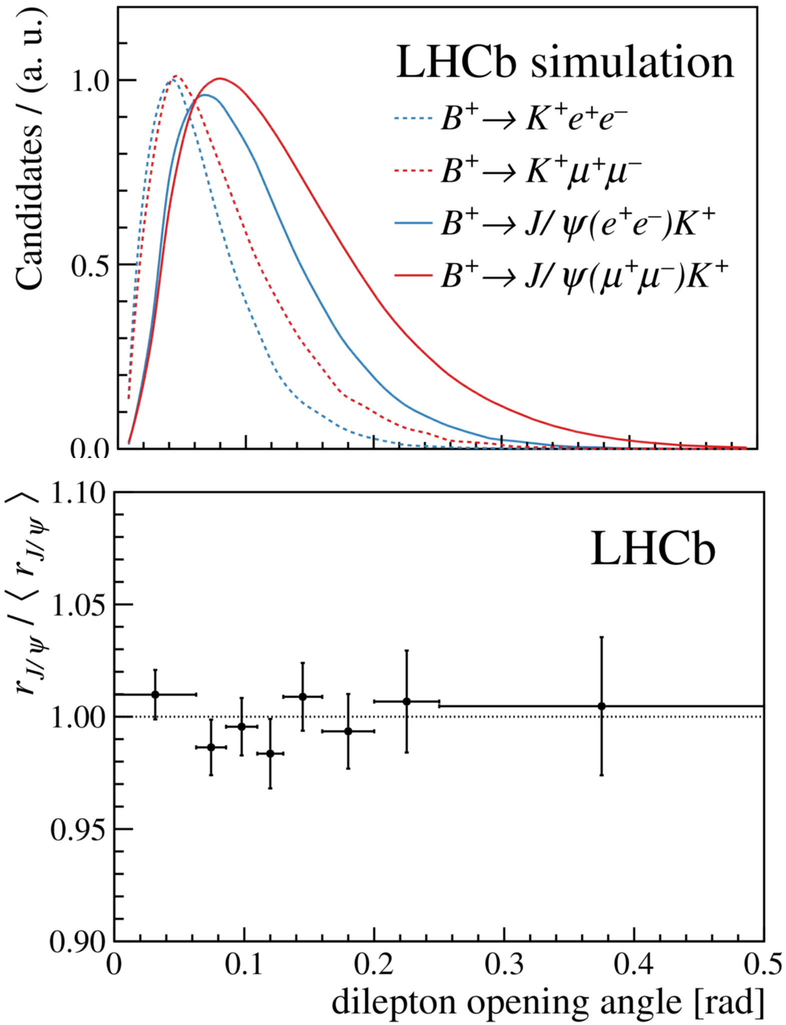
LHCb-PAPER-2019-009

- Add 2015+16 data
- Improved reconstruction and selection
- Better understanding of electron efficiency

- Exploit double ratio method – extremely robust

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+e^-)K^+)}$$

- Validate with studies of $r_{J/\psi}$ and $R_K^{\psi(2S)}$



Update of R_K (LHCb)

LHCb-PAPER-2019-009

- Add 2015+16 data
- Improved reconstruction and selection
- Better understanding of electron efficiency

- Exploit double ratio method – extremely robust

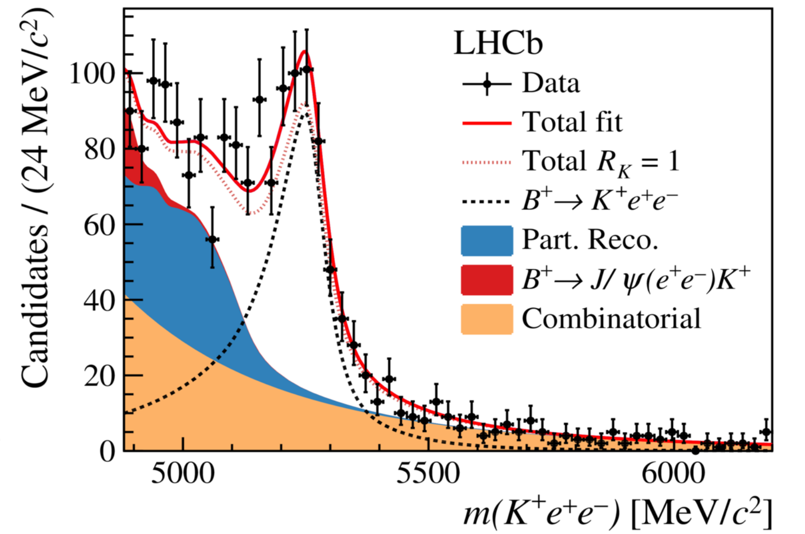
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

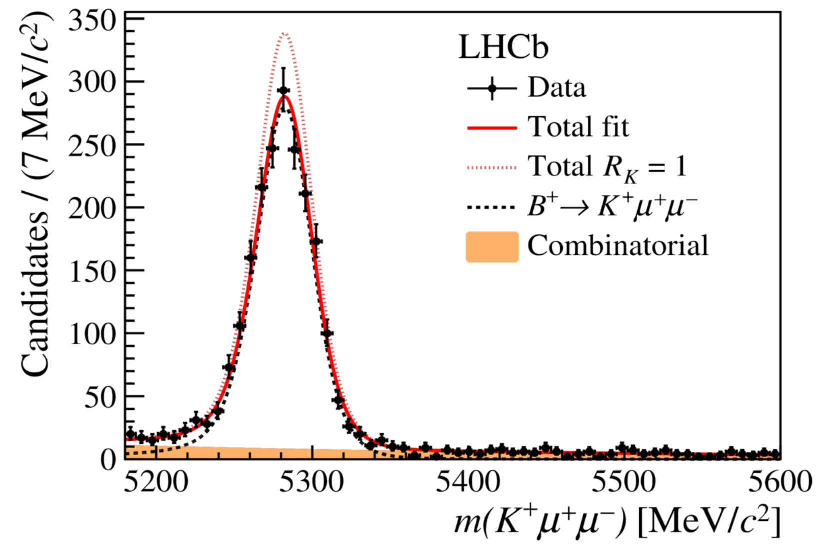
- Validate with studies of $r_{J/\psi}$ and $R_K^{\psi(2S)}$

2.5σ

$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$$

- New Run 1 sample consistent with old result
- Run 1 & 2 consistent at <2σ
- Trigger subsamples all consistent





Update of R_K (LHCb)

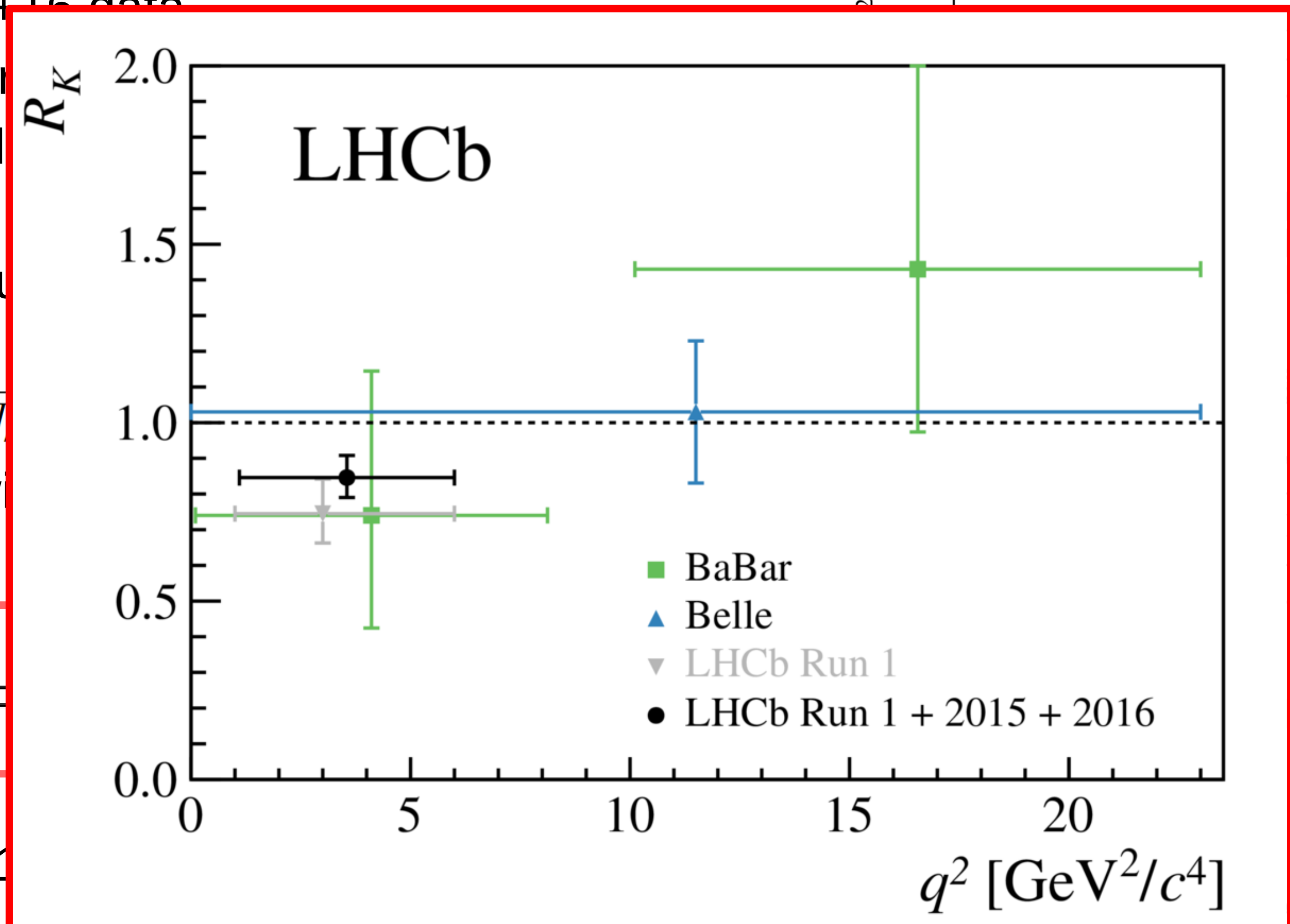
LHCb-PAPER-2019-009

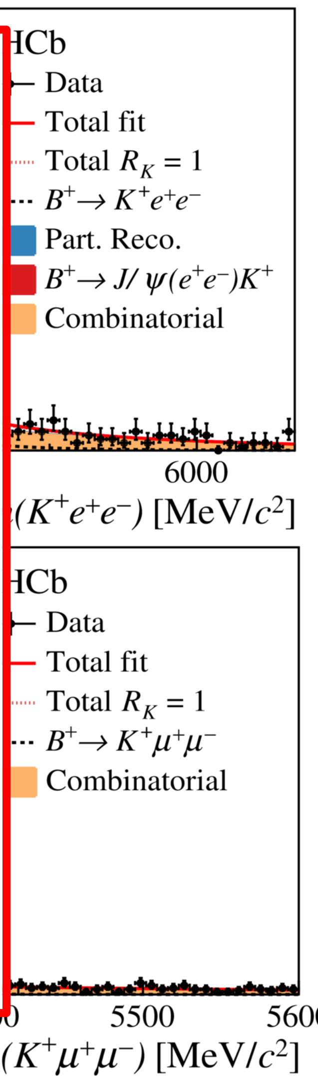
- Add 2015+16 data
- Improved r
- Better und
- Exploit dou

$R_K = \frac{\mathcal{B}(B^+ ...}{\mathcal{B}(B^+ \to J ...}$

- Validate wi

$R_K =$

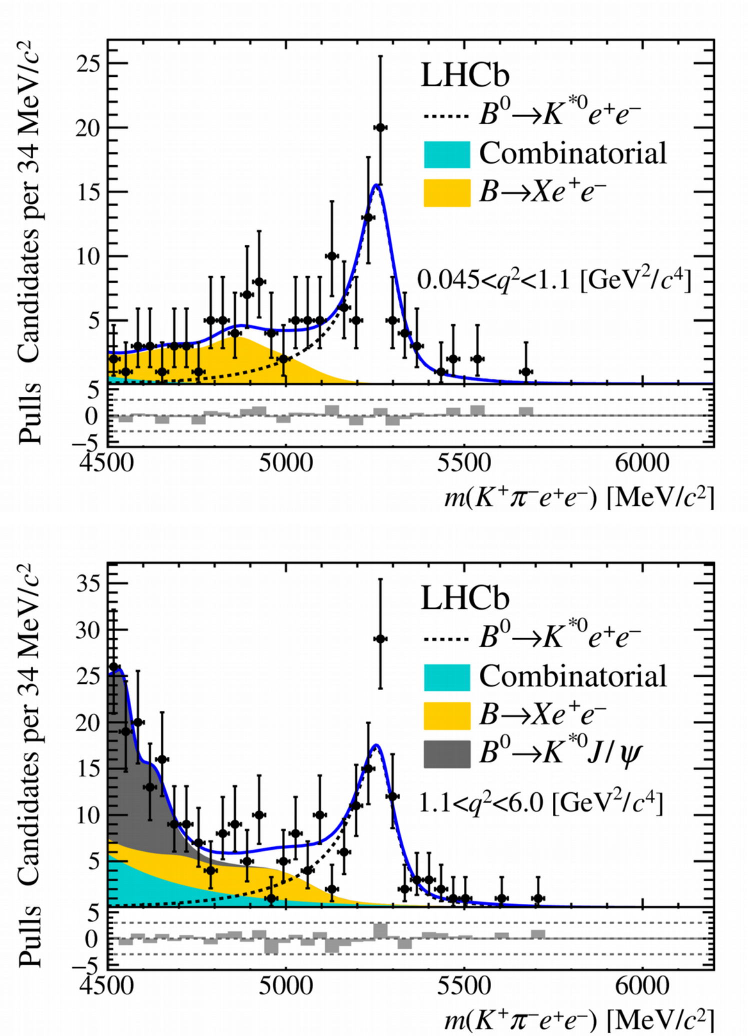




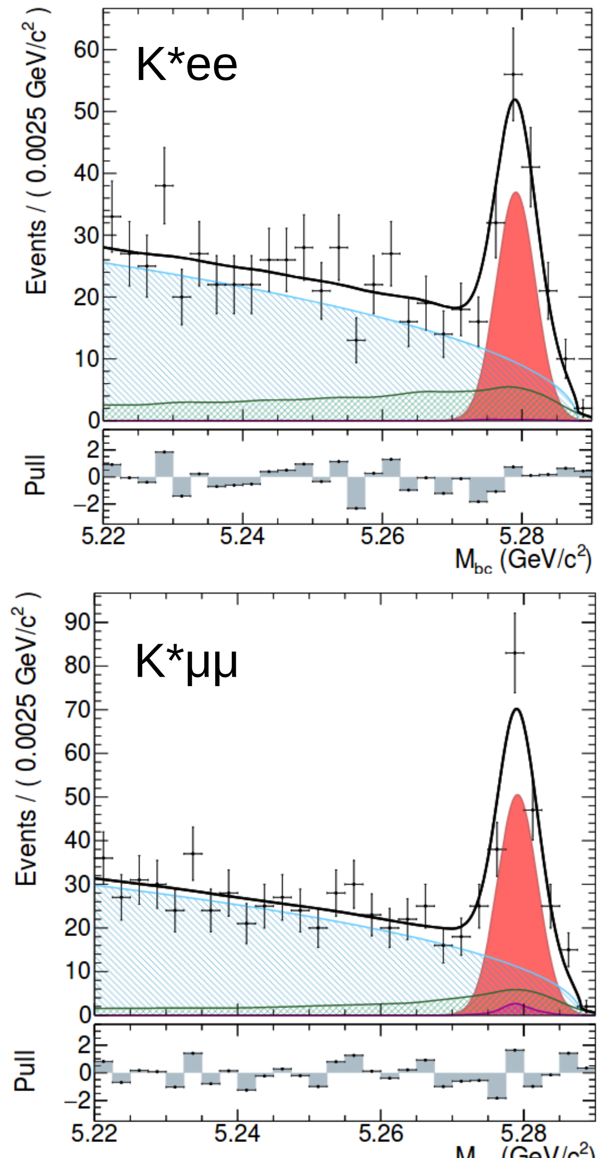
- New Run 1
- Run 1 & 2 consistent at <2σ
- Trigger subsamples all consistent

$R_{K^*} \equiv B(B \to K^*\mu\mu)/B(B \to K^*ee)$

JHEP 08 (2017) 055



BELLE-CONF-1901



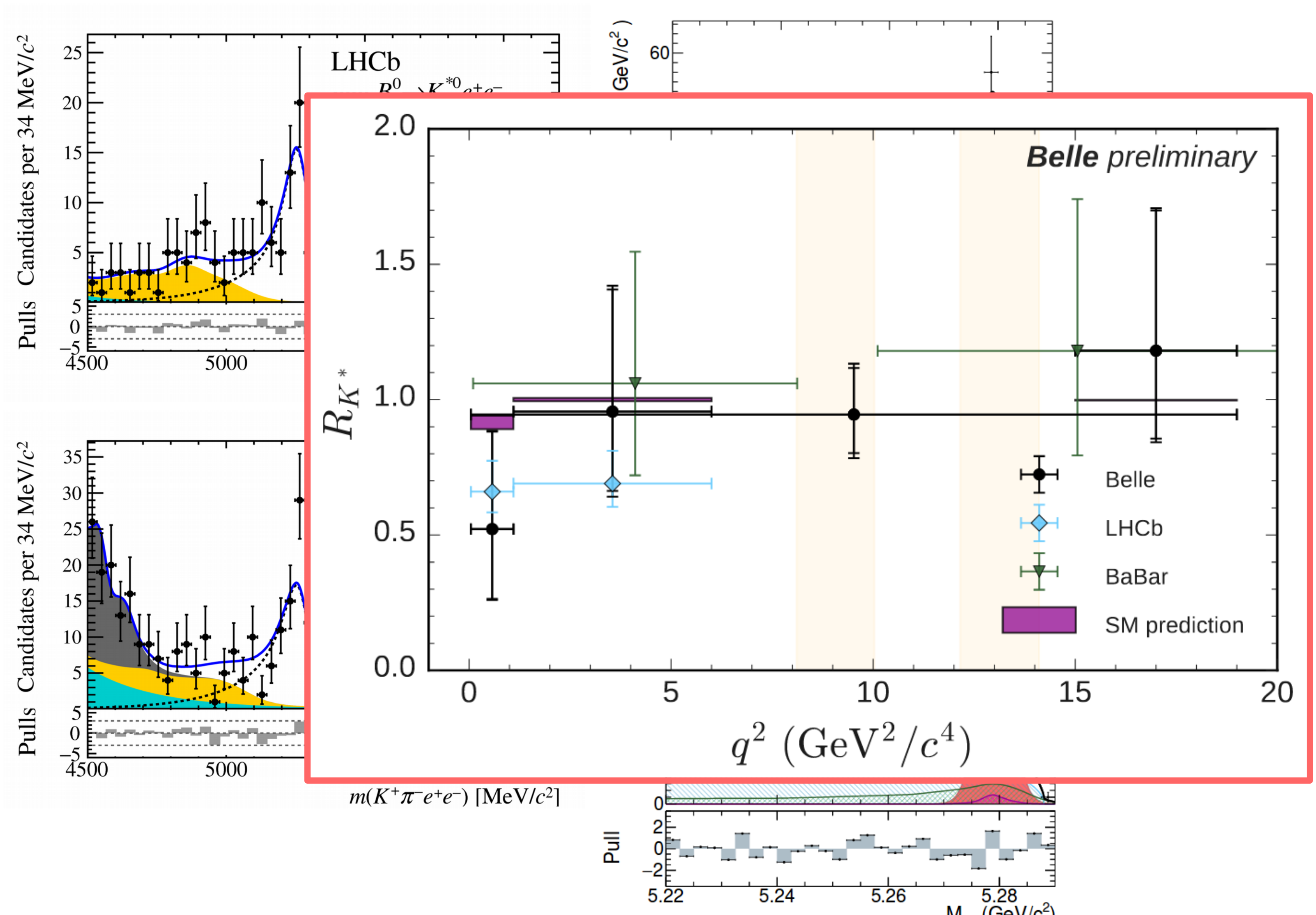
New results from Belle

- Results in 3 q^2 bins
- Both B^0 and B^+ decays

$R_{K^*} \equiv B(B \rightarrow K^*\mu\mu)/B(B \rightarrow K^*ee)$

JHEP 08 (2017) 055

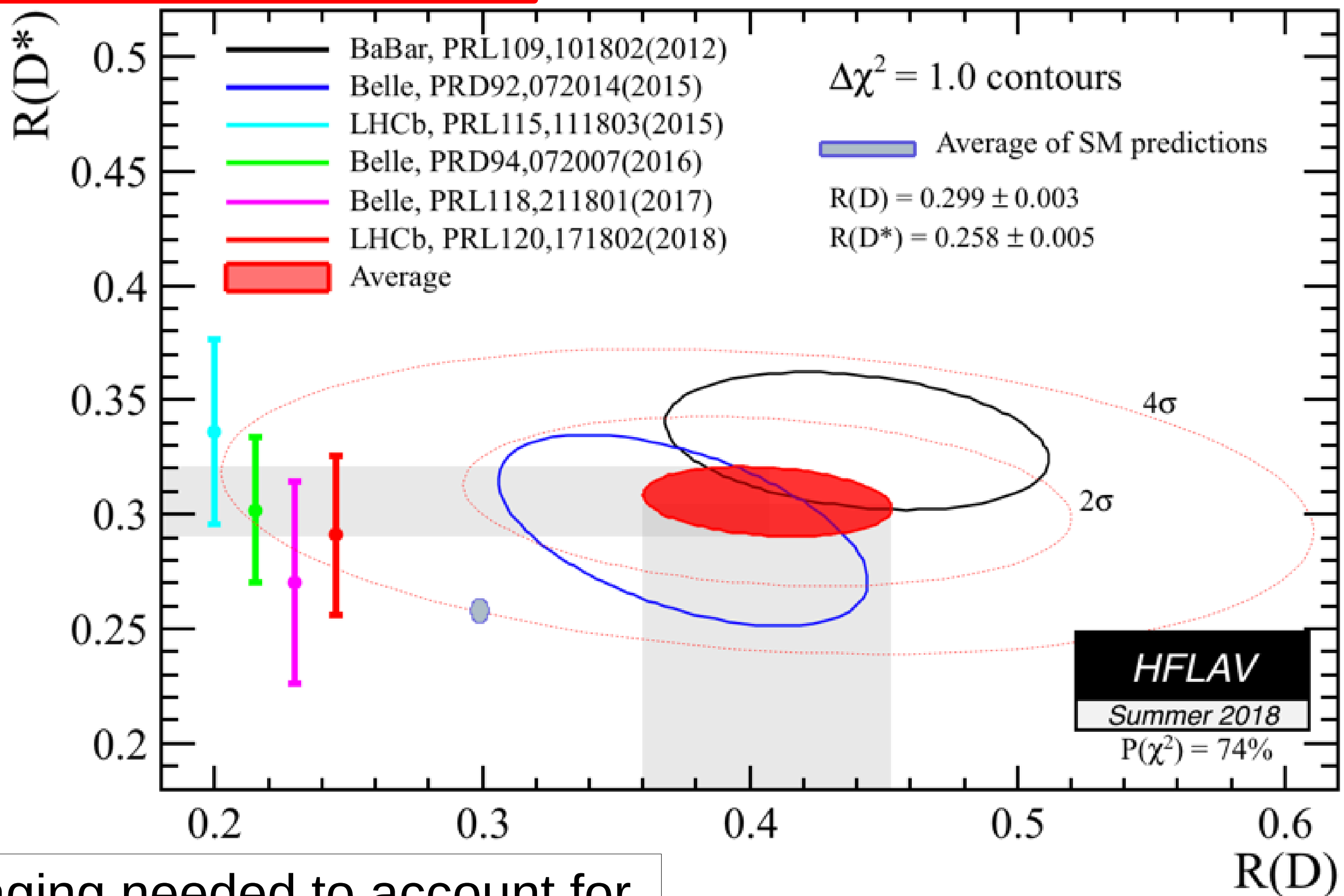
BELLE-CONF-1901



$R(D^{(*)})$ world average pre-Moriond 2019

$R(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}l\nu)$; l=e,μ

Tension with SM at 3.8σ



Careful averaging needed to account for statistical and systematic correlations

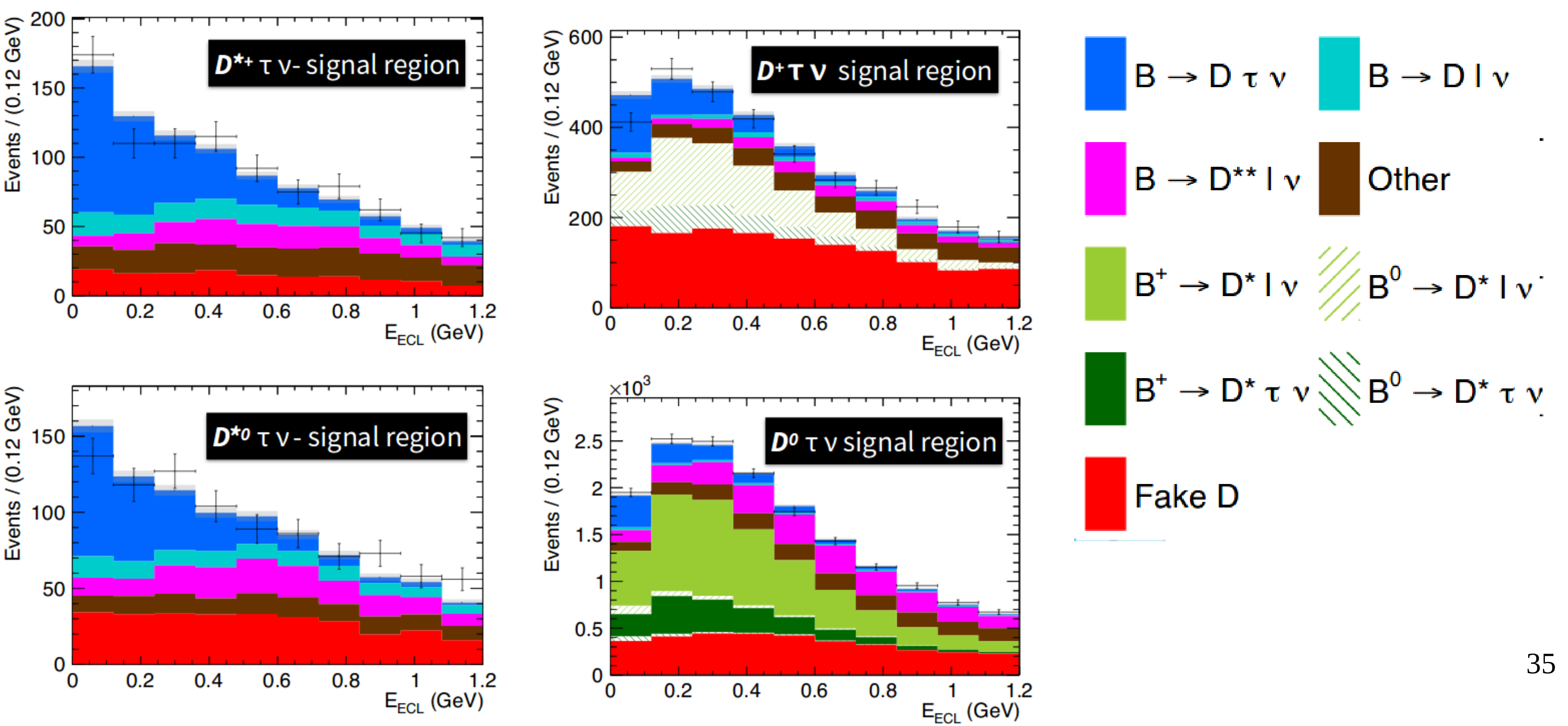
$R(D^*) = 0.306 \pm 0.013 \pm 0.007$

$R(D) = 0.407 \pm 0.039 \pm 0.024$

New Belle results on R(D$^{(*)}$) with semileptonic tag

Belle
Moriond preliminary

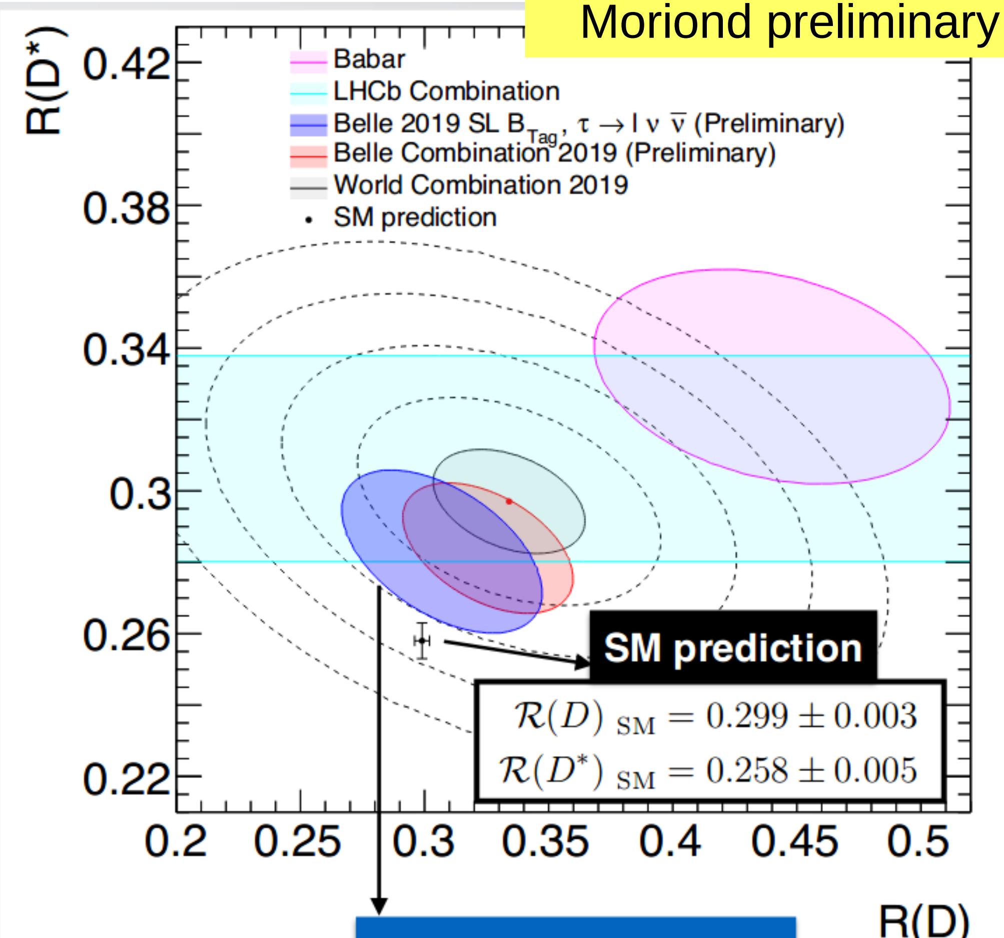
- Semileptonic tag exploiting full event information
  - statistically independent from previous analysis based on hadronic tags
- Determine yields from 2D fit to extra calorimeter energy & BDT classifier



New Belle results on $R(D^{(*)})$ with semileptonic tag

Belle
Moriond preliminary

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Future prospects

SuperKEKB/Belle II

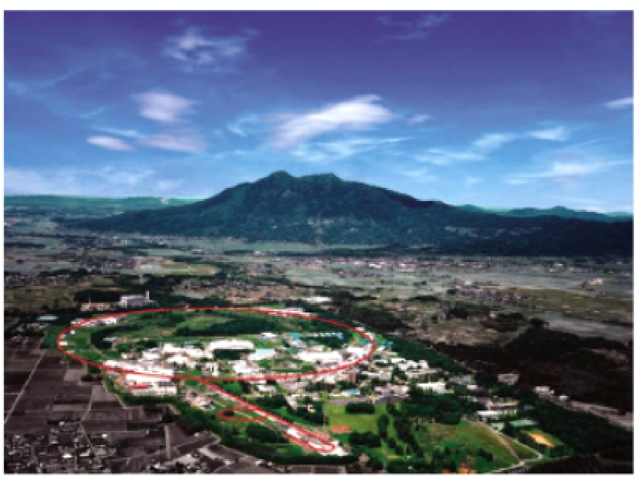
New intensity frontier facility at KEK

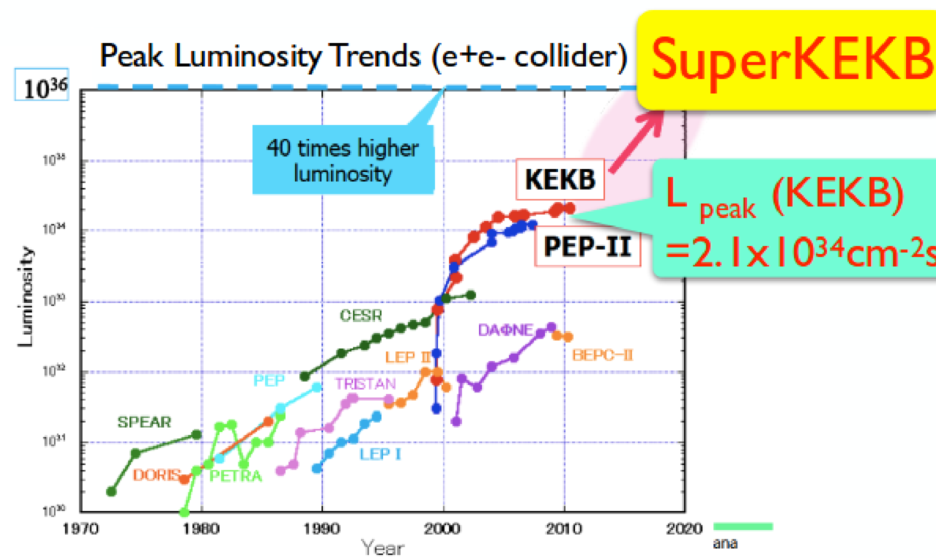
- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}$ $B\bar{B}$, $\tau^+\tau^-$ and charms per year !

  $L_{int} > 50\ ab^{-1}$

- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors)   + more





The first particle collider after the LHC !

SuperKEKB Accelerator

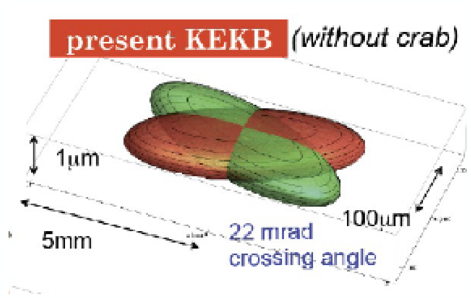
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

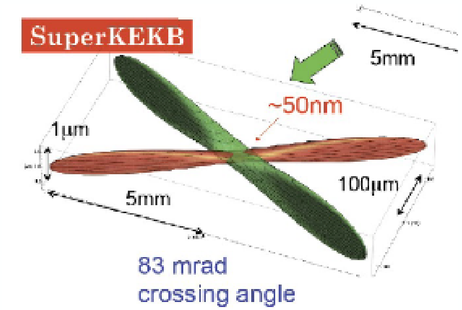
Machine parameters

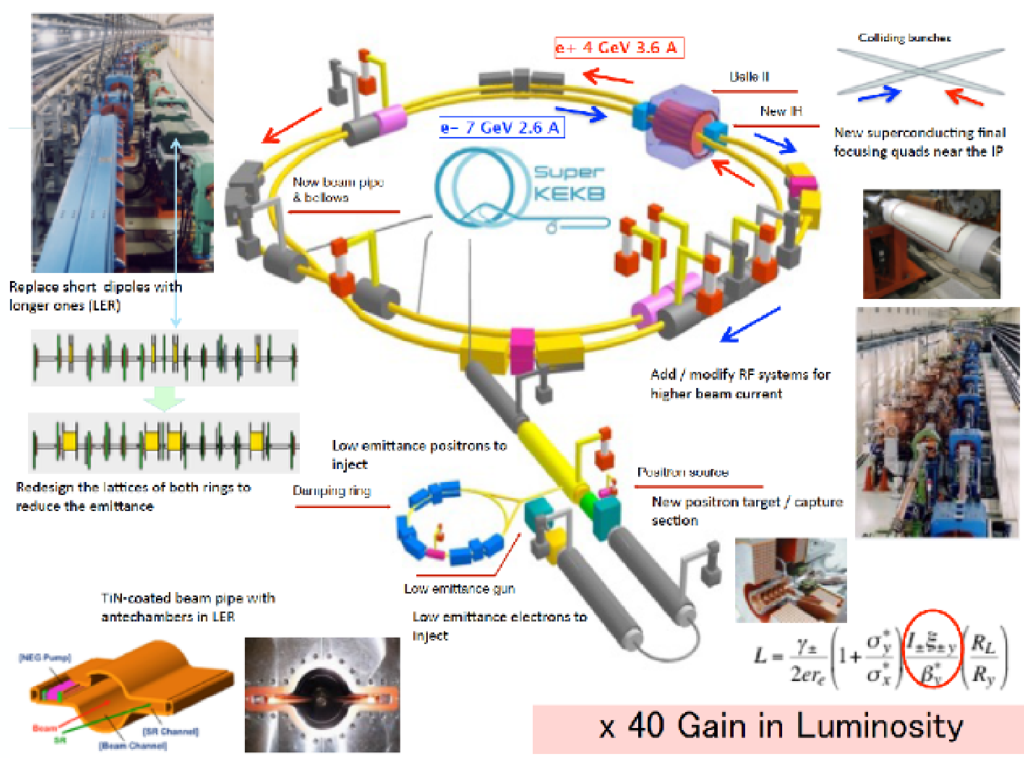
	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L(cm^{-2}s^{-1})	80×10^{34}	2.1×10^{34}

x20

x2

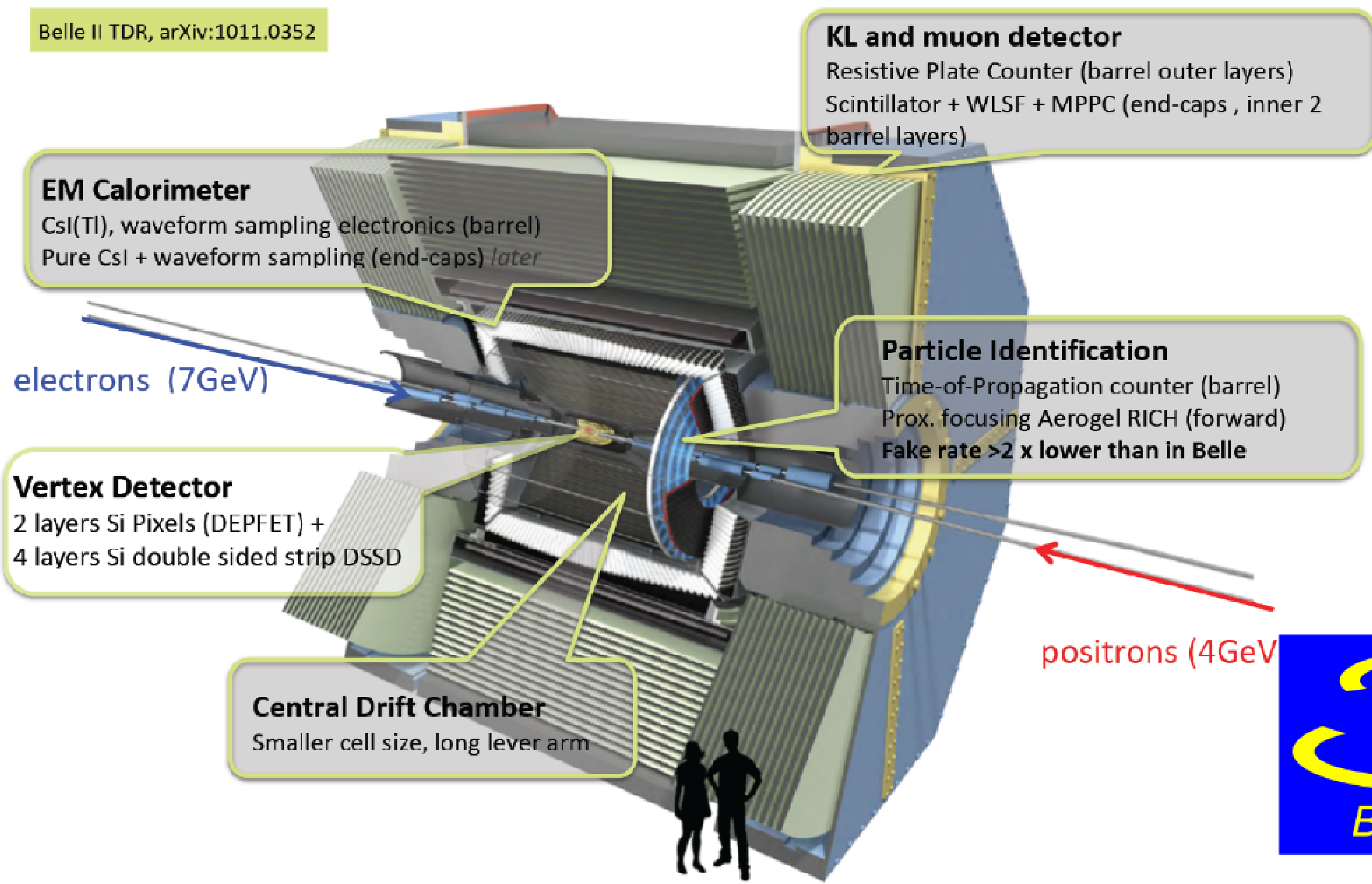






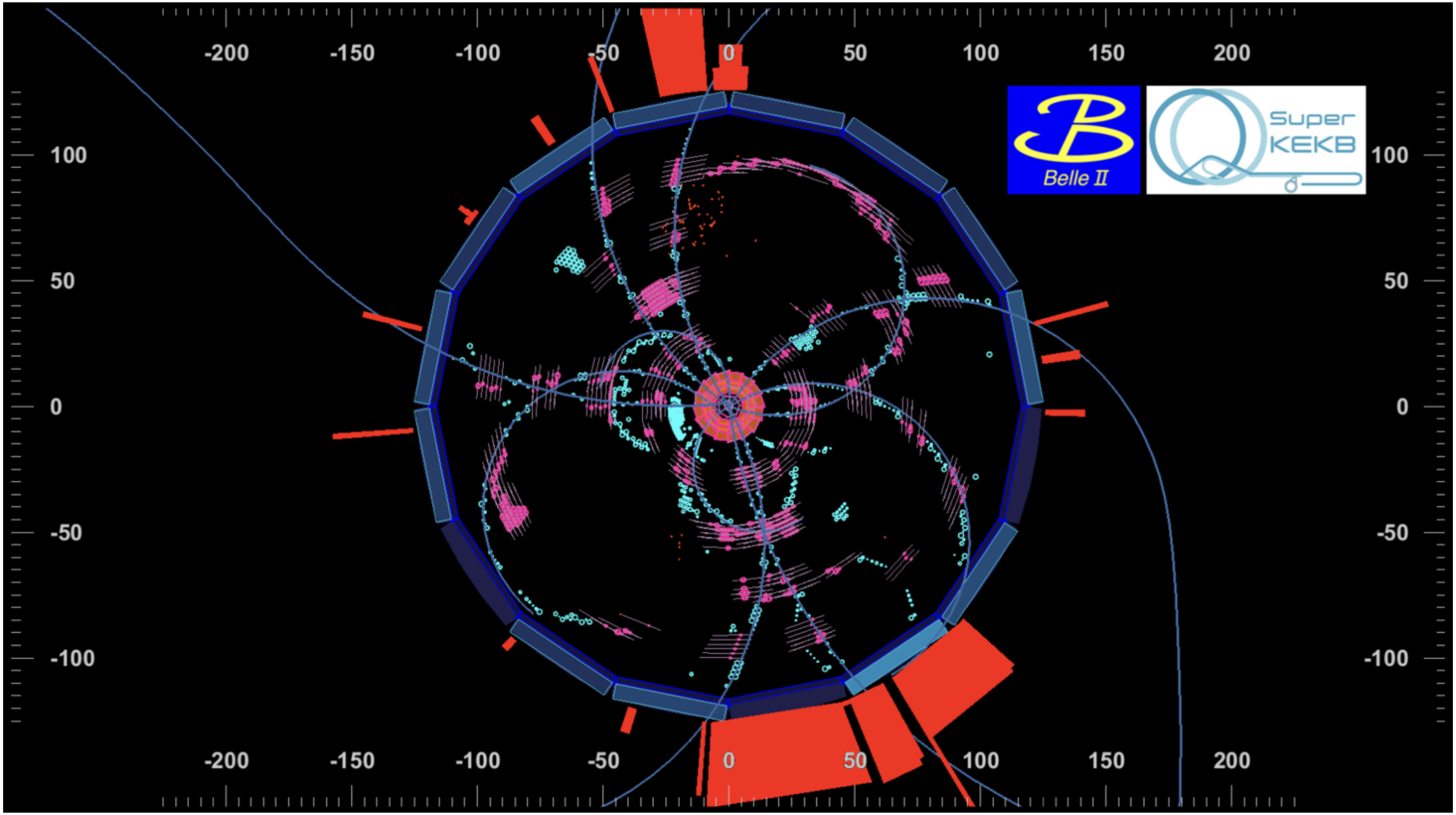
Belle II Detector

- 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

First $B\bar{B}$ event seen in Belle II detector

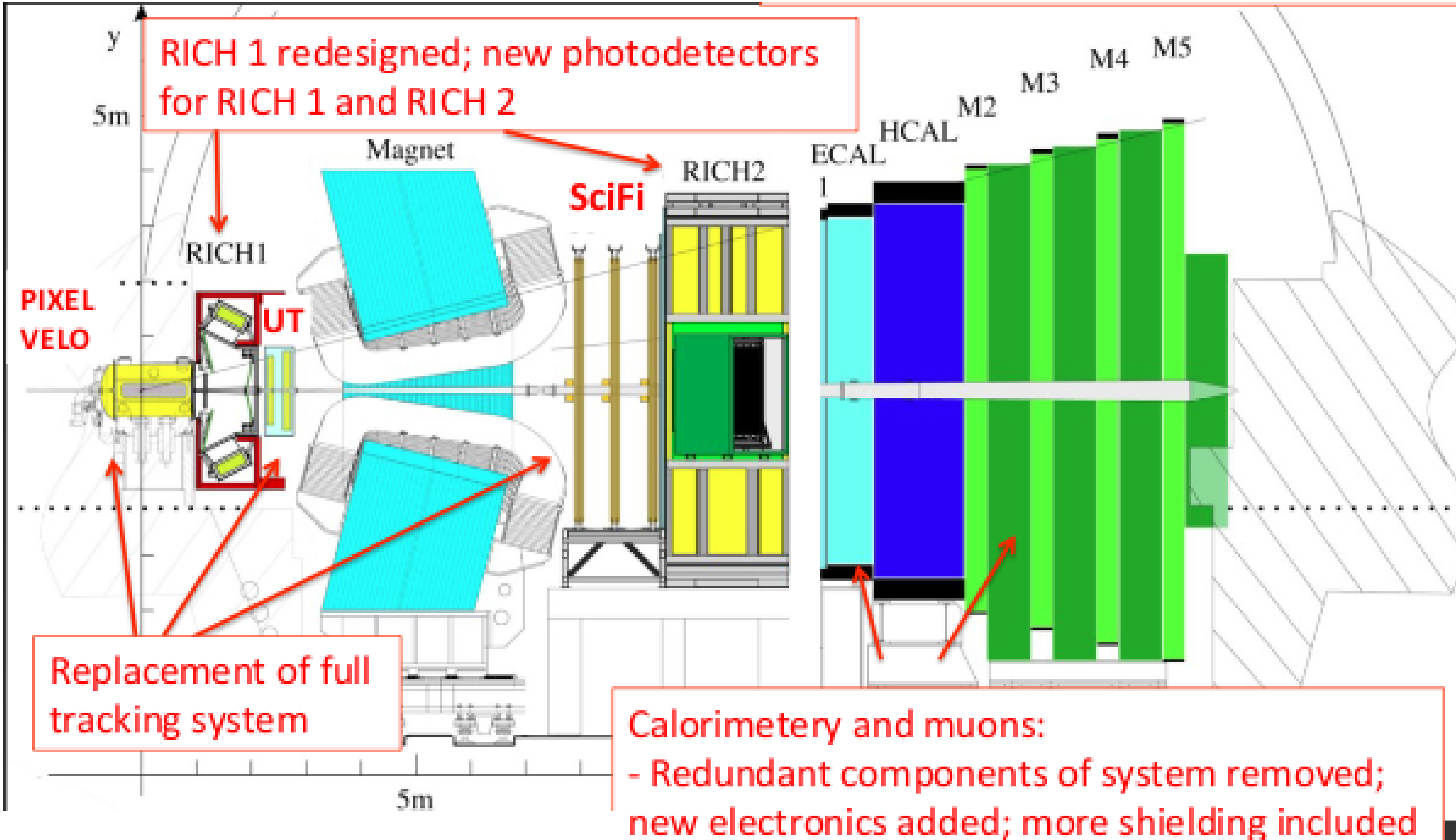


The LHCb Upgrade

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Upgrade the LHCb detector during LHC LS2 (2019-20)
  - Change subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Restart data taking in 2021 at instantaneous luminosity increasing up to $2 \times 10^{33}/cm^2/s$, and with improved efficiency
  - Upgrade detector qualified to accumulate 50/fb

LHCb-TDR-{13,14,15,16}

LHCb detector upgrade



+ novel trigger and offline data management strategies

LHCb upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\text{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\text{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B^0_s mixing	$\phi_s(B^0_s \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B^0_s \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B^0_s)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B^0_s \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B^0_s \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K^0_S)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B^0_s \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q^2_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B^0_s \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K^0_S)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Will not reach limiting theory uncertainty!

Personal view – not an official schedule!

LHC long term future

Bearing in mind that "Europe's top priority should be the exploitation of the full potential of the LHC" it seems natural to aim for a further major LHCb upgrade during LS4

	Run 1	2013/14	Run 2	2019/20	Run 3	2024-26	Run 4	2030/31	Run 5
	Run 1	**LS1**	Run 2	**LS2**	Run 3	**LS3**	Run 4	**LS4**	Run 5
LHC machine		**Energy upgrade**				**Luminosity upgrade**			
ATLAS & CMS		**Detector completion**		Consolidation		**Major upgrades to handle high lumi**		Consolidation	
LHCb		Consolidation		**40 MHz upgrade**		Consolidation		**Major upgrade to handle high lumi**	

Upgrade during LS4 will allow to increase data sample
50/fb → 300/fb

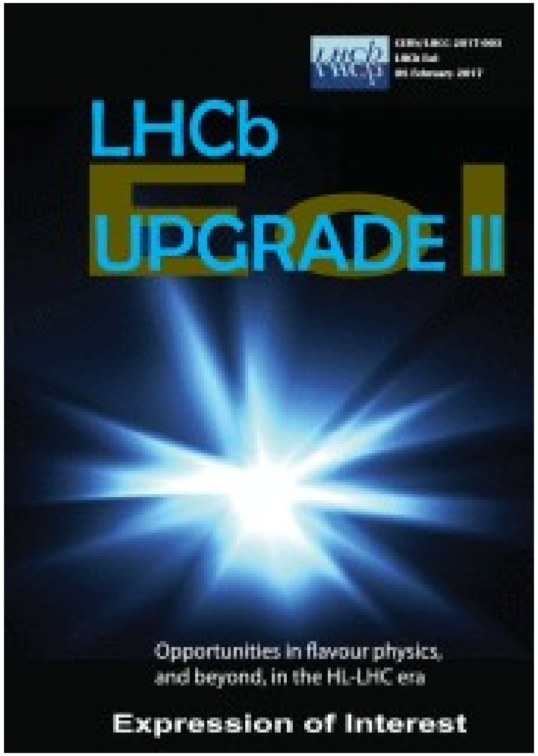
CERN-LHCC-2017-003,
CERN-LHCC-2018-027

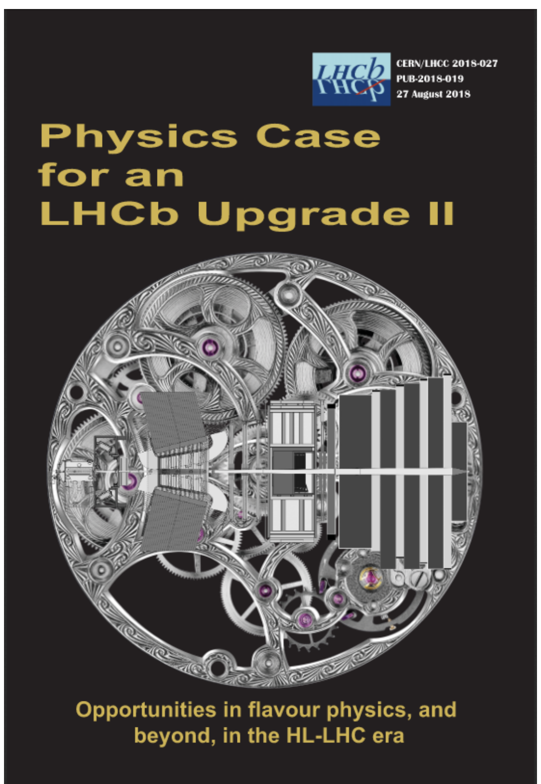
“Phase II” upgrade

- Increase total integrated luminosity 50/fb → 300/fb
- Improve detector capabilities

  (options currently under discussion)

  - improve EM calorimetry
  - increase tracking acceptance
  - reduce material
  - add timing to control pile-up
- Enhance HL-LHC discovery potential!





LHCb upgrade II sensitivities

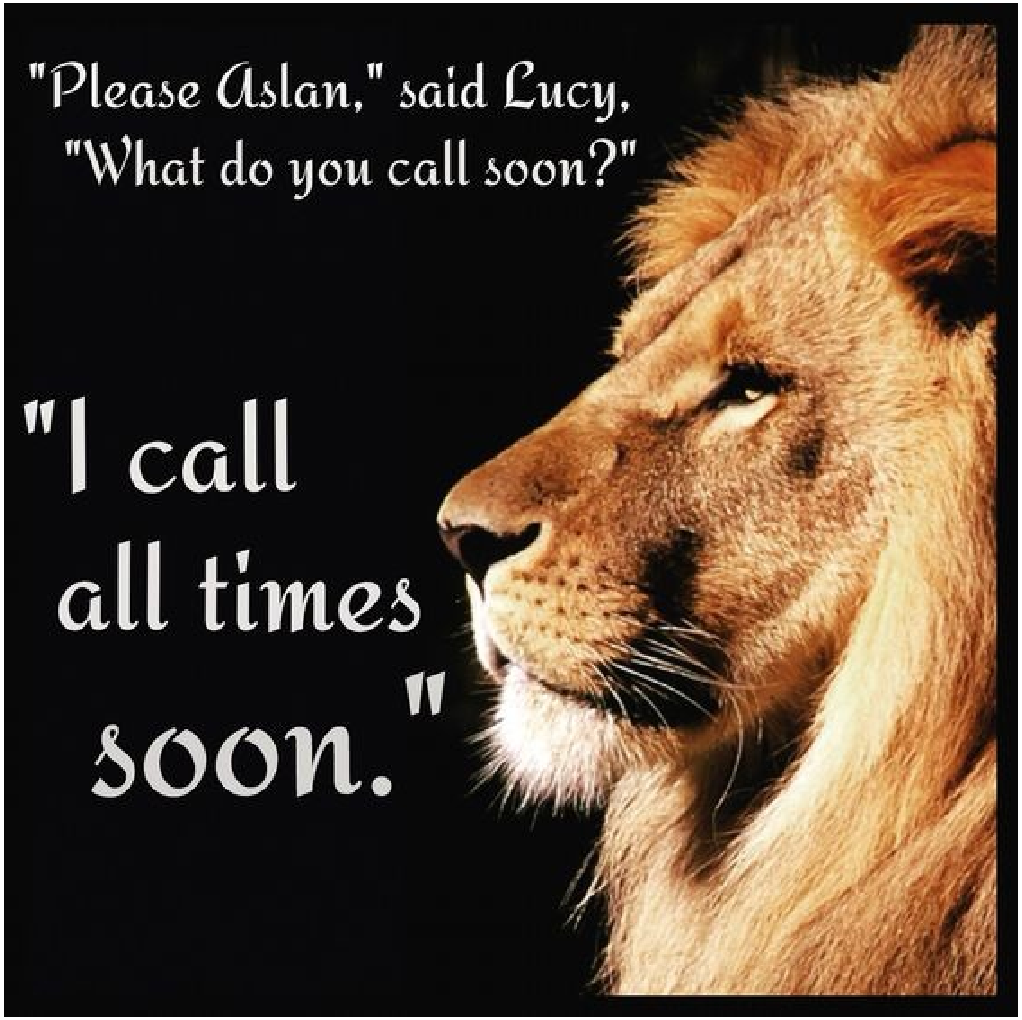
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- Many exciting new results in flavour physics
  - Improved φ_s determinations
  - New method to probe charm mixing and CP violation
  - First observation of CP violation in charm decays
  - New tests of lepton universality
  - … and many more! (Apologies for omissions.)
- Excellent prospects for progress
  - Most LHC Run 2 data still to be analysed
  - Belle II starting to take data
  - LHCb upgrade around the corner
  - … and Upgrade II to exploit fully HL-LHC potential

When are the updates coming?

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



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