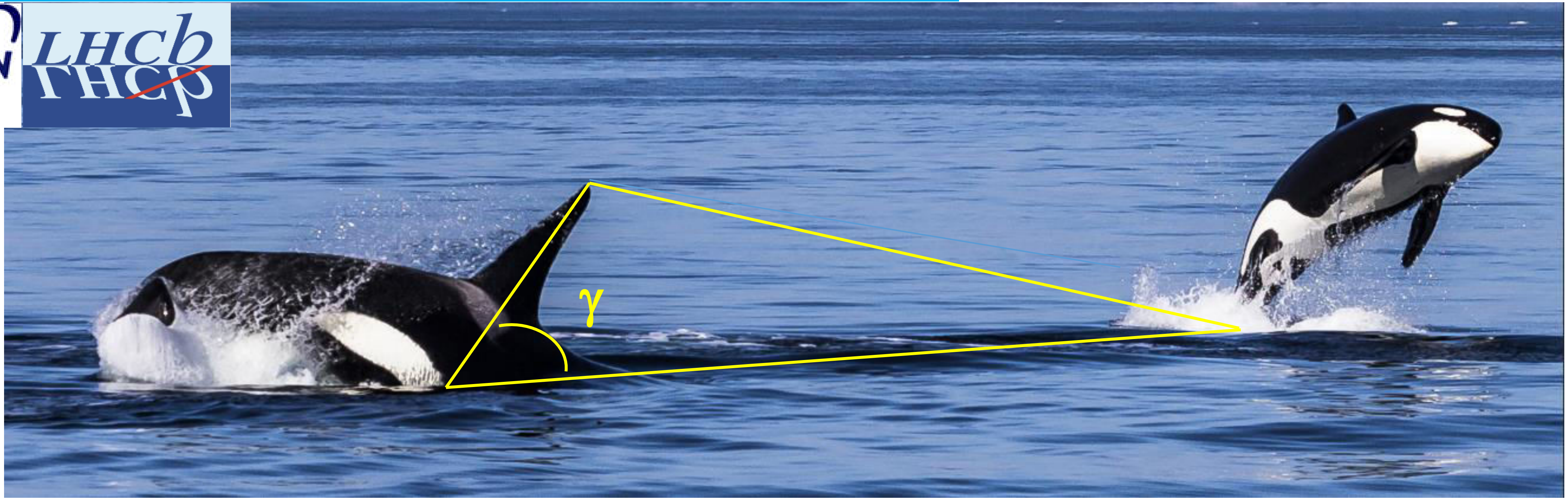
Flavor Physics and CP Violation
Victoria, British Columbia, 2019-05-06

Measurements of γ from tree-level decays

A. Bertolin on behalf of the LHCb collaboration

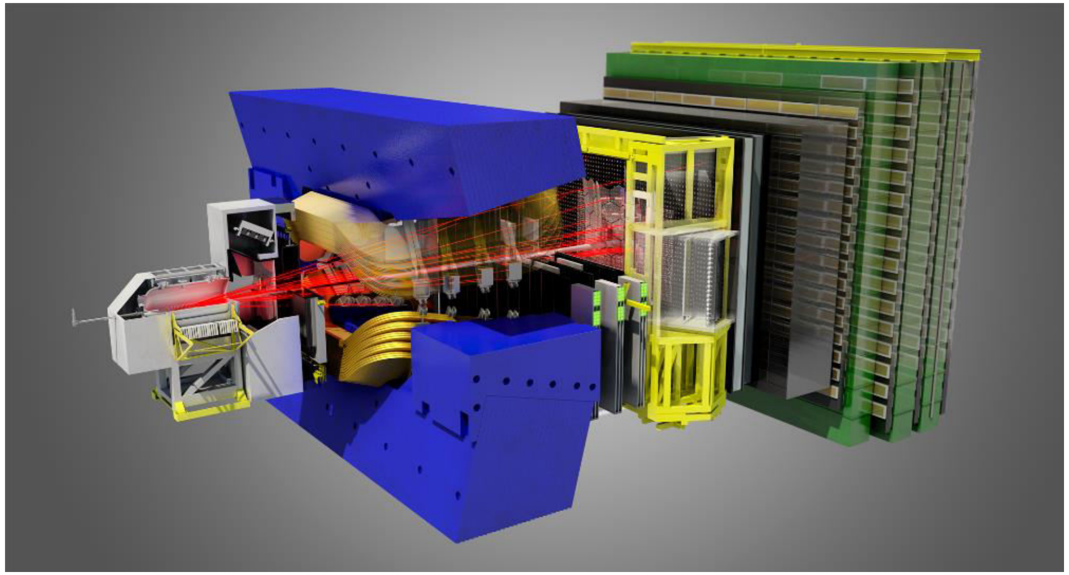


Outlook:

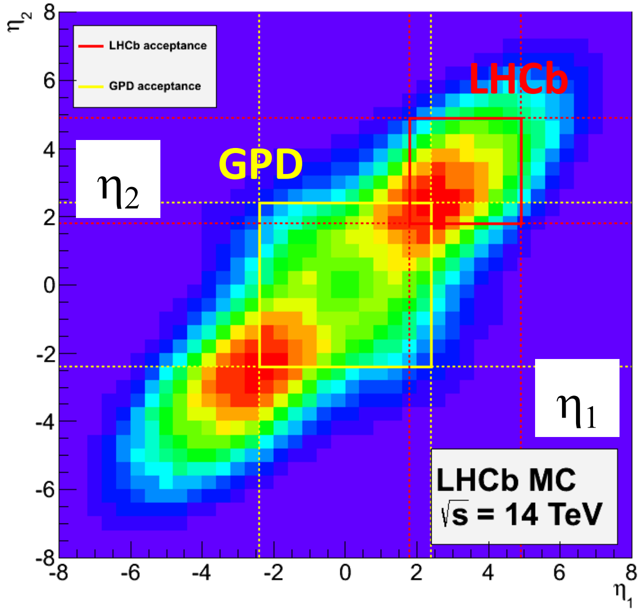
- short introduction to LHCb and γ
- LHCb γ results:
  - some representative measurements included LHCb γ combination
  - the γ combination results
- future prospects on γ
- take home message

LHCb: the detector and its performance so far

single-arm forward spectrometer at the LHC



b anti-b pairs produced



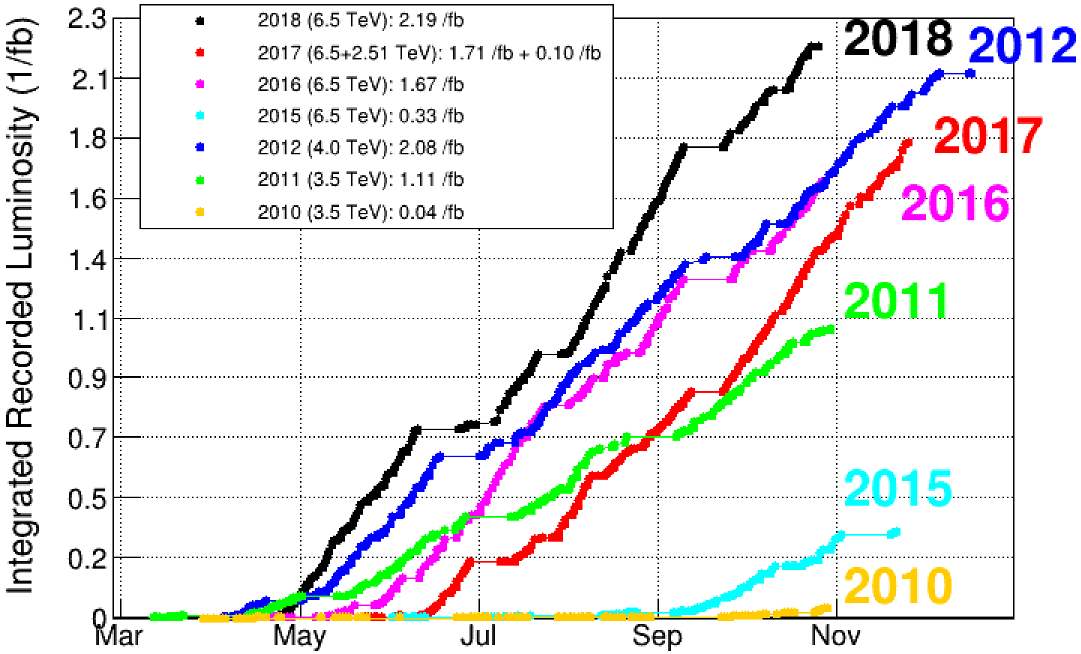
- detector paper:
  JINST 3 (2008) S08005
- Run 1 performance:
  Int. J. Mod. Phys. A30 (2015) 1530022
- Run 2 performance:
  JINST 14 (2019) P04013

optimized for beauty and charm physics at $2 < \eta < 5$

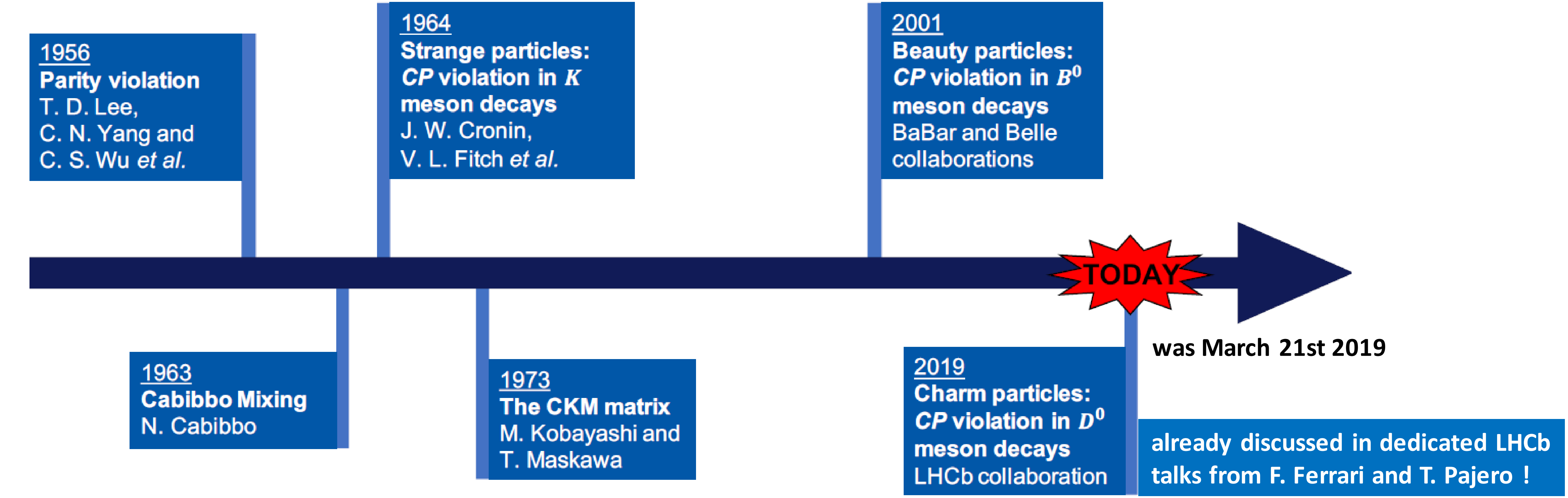
key points:

- momentum resolution
  ($\sigma(p)/p \approx 0.5$ % (low momentum) to 1 % @ 200 GeV/c)
- impact parameter resolution
  ($\sigma(IP) \approx 15$ μm at high p_T)
- primary and secondary vertices reco.
- decay time resolution ($\sigma(t) \approx 50$ fs)
- 'global' PID: e / μ / π / K
  (K id ≈ 95 % π mis-id ≈ 5 %, p < 100 GeV/c)
- γ and π^0 reconstruction

recorded lumi.:
2011→ 2012 (Run 1): 3.19 /fb
~ 3 10^{11} b anti-b pairs prod.
2015 → 2018 (Run 2): 5.9 /fb
~ 2 x 6 10^{11} b anti-b pairs prod.



CP violation: historical approach



BaBar: 2000-2008, 0.5 /ab $\quad \gamma = (69^{+17}_{-16})^\circ \quad$ PRD 87, 052015 (2013) “legacy paper”

Belle: 2000-2010, 0.8 /ab

so this presentation will focus on LHCb results, keeping in mind that a new player is coming into the game: Belle II

CP violation in the SM

CPV is one of the requirements for explaining the baryon asymmetry we observe today

a process must have been in place that took us from the equal amounts of matter - anti-matter produced in the Big Bang to the matter dominated Universe we are living in

in the SM charged current weak interactions between quarks are described by a matrix, V, 3 x 3, fulfilling V V* = I

⇔ 3 angles and 1 phase or 3 reals and 1 imaginary parameters

CKM matrix

$$V = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{pmatrix} d & s & b \\ 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5\left[1-2(\rho+i\eta)\right] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)\right] & -A\lambda^2+\frac{1}{2}A\lambda^4\left[1-2(\rho+i\eta)\right] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}\left(\lambda^6\right) \qquad \lambda \approx 0.22$$

$\rho + i\,\eta$ gives the **CKM phase**, only source of CPV in the SM quark sector

"intrinsic" connection between CPV in the beauty and charm sectors … however the imaginary part of:

$V_{cd} \propto \lambda^5$

$V_{ub} \propto \lambda^3$

expect CPV suppression in charm w.r.t beauty …

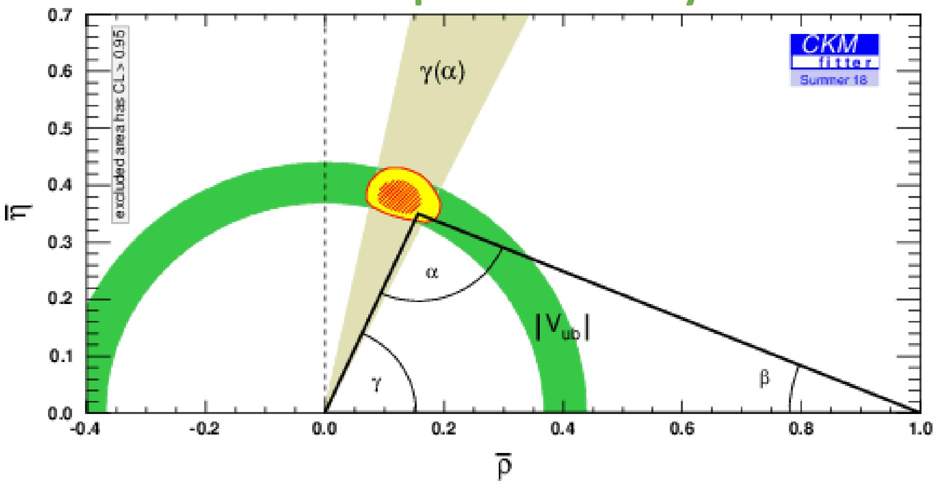
CP violation and γ

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

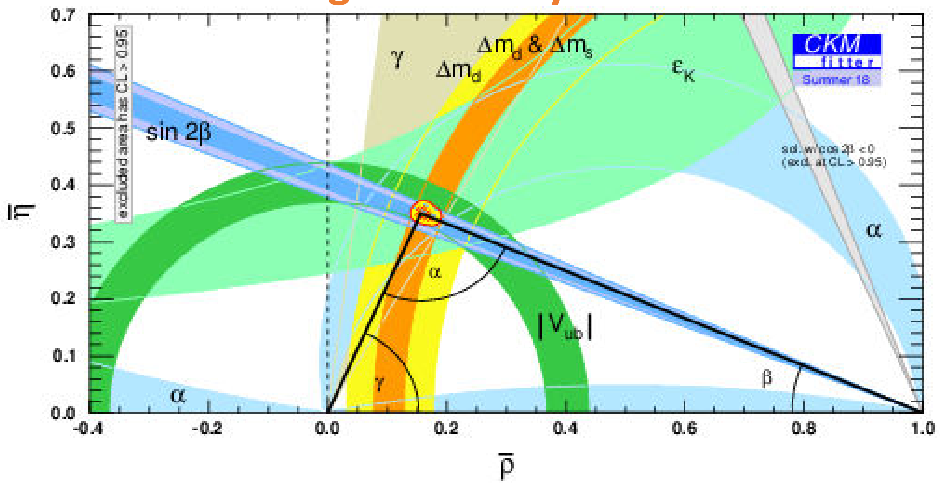
unitary condition relevant for beauty decays

can be represented as a triangle in a complex plane, with angles α, β and γ

tree processes only



global analysis



http://ckmfitter.in2p3.fr/www/results/plots_summer18/ckm_res_summer18.html

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

a.k.a. ϕ_3

- only CKM angle easily accessible in tree-level decays
- assuming no new physics in tree-level decays, has negligible theoretical uncertainty i.e. achievable accuracy dominated by experiments

any disagreement between tree-level determinations and the value inferred from global CKM fits would indicate physics beyond the SM … due for example to new particles / mediators being exchanged in loops …

… however the present γ uncertainty from **tree processes only** is not small enough, desirable to reduce it to look for new physics effects starting from solid grounds !

JHEP12 (2016) 087

γ can be determined by exploiting the interference between
- $b \to cW$ (V_{cb}), favoured
- $b \to uW$ (V_{ub}), suppressed

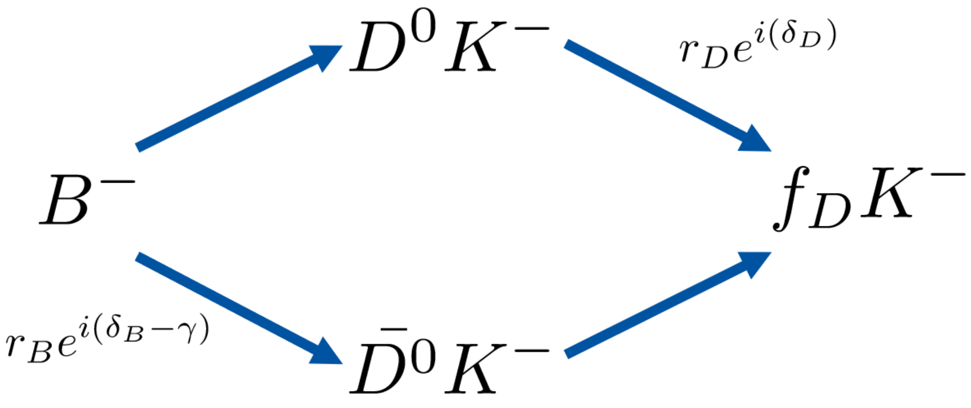
transition amplitudes

$$A_{sup}/A_{fav} = r^X_B \, e^{i(\delta^X_B \pm \gamma)}$$

(– is for b-quark, + for anti-b)

where r^X_B and δ^X_B are the ratio and the strong phase differences between the V_{cb} and V_{ub} transition amplitudes for the specific final state X
these are also simultaneously determined

charm parameters can also get involved



golden mode for illustration purposes

❑ which/typical B meson final states (h=K,π) ?

$B^+ \to D h^+$

$B^+ \to D h^+ \pi^- \pi^+$

$B^0 \to D K^{*0}$

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

where D is a neutral charm meson mixture of the D^0 anti-D^0 flavor eigenstates

❑ which/typical D meson final states ?

CP-eigenstates, $D \to K^+ K^-$ and $D \to \pi^+ \pi^-$, Gronau-London-Wyler (**GLW**) method

non CP-eigenstates, $D^0 \to \pi^- K^+$, Atwood-Dunietz-Soni (**ADS**)

self-conjugate multibody D meson decay, like $K^0_s \pi^+ \pi^-$, with the D-Dalitz plot distributions, Giri-Grossman-Soffer-Zupan (**GGSZ**)

however due to the small branching ratios the most precise way to determine γ is through a combination of measurements from analyses of many decay modes

LHCb γ combination: inputs

B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S \pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV.

latest LHCb result on γ

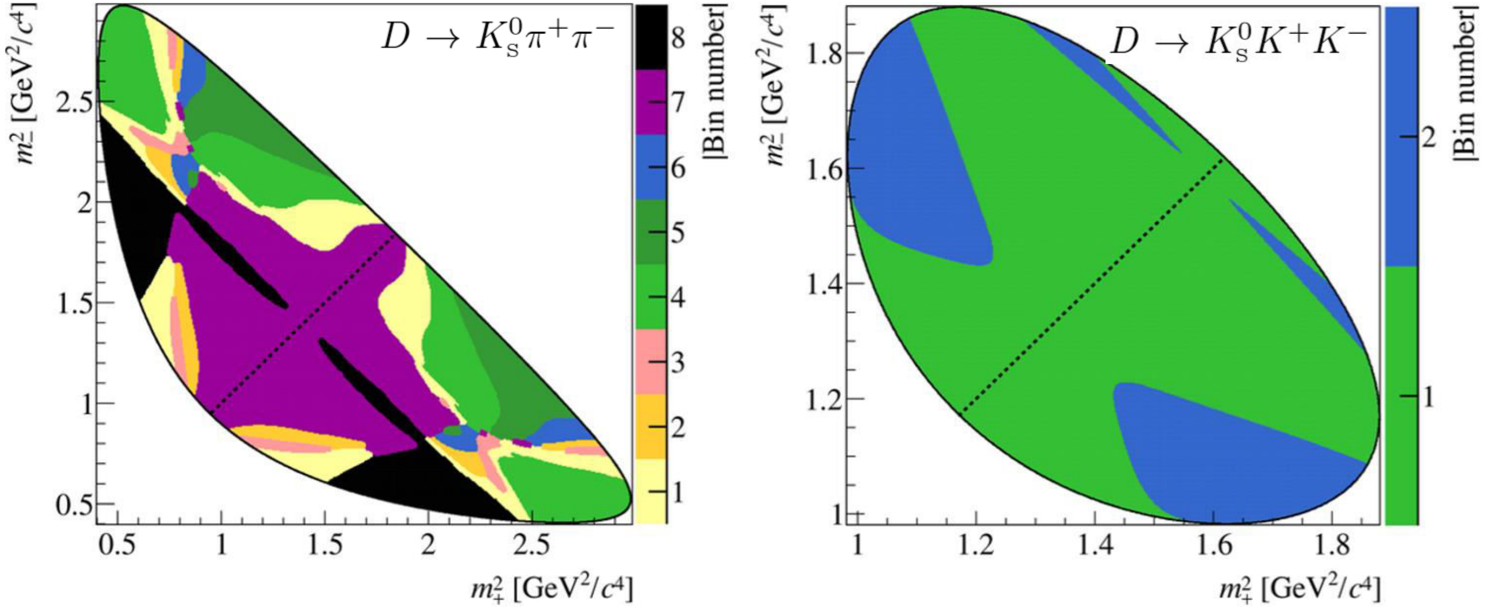
recent result

large sensitivity, very different analysis technique

LHCb γ combination: $B^+ \to D K^+$ ($D \to K^0_s h^+ h^-$) input

- sensitivity to γ obtained comparing the D-Dalitz plot distribution for reconstructed B^+ and B^-
- $D \to K^0_s h^+ h^-$ where h=K, π
- $B^- \to D K^-$ decay amplitude:

$$A_B(m_-^2, m_+^2) \propto \underbrace{A_D(m_-^2, m_+^2)}_{\text{favored}} + r_B e^{i(\delta_B - \gamma)} \underbrace{A_{\bar{D}}(m_-^2, m_+^2)}_{\text{suppressed}}$$



- 'optimal binning' scheme: bins have been chosen to optimize the statistical sensitivity to γ
- strong-phase difference between the D^0 and anti-D^0 amplitudes at a given point in the Dalitz plot directly measured by the CLEO collaboration exploiting quantum-correlated pairs produced at the $\psi(3770)$ resonance ($c_{\pm i}$, $s_{\pm i}$)

$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma) \quad \text{and} \quad y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

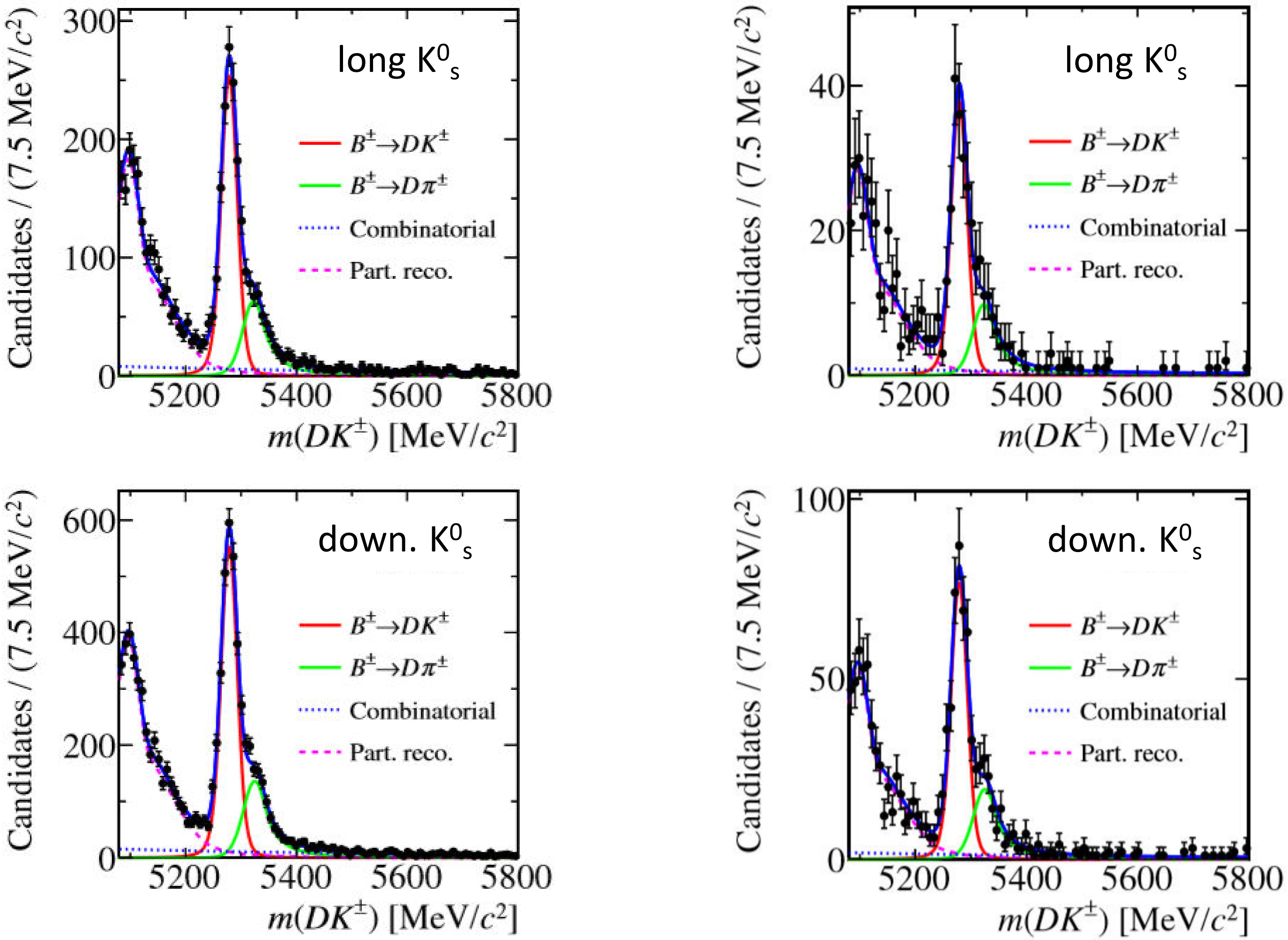
$$N^+_{\pm i} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

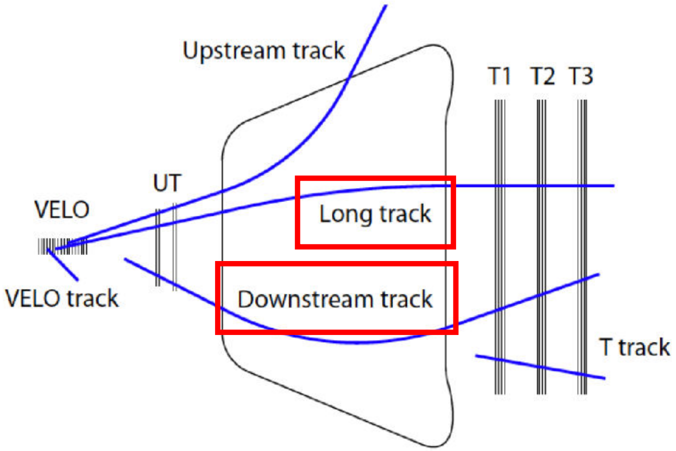
$$N^-_{\pm i} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$

LHCb γ combination: $B^+ \to D K^+$ ($D \to K^0_s h^+ h^-$) input (cont.)

$K^0_s \pi^+ \pi^-$

$K^0_s K^+ K^-$





long and down(stream) are different $K^0_s \to \pi^+ \pi^-$ “categories”, with different reconstruction efficiencies

2015 → 2016 data	$B^- \to DK^-$		$B^+ \to DK^+$	
	Long	Downstream	Long	Downstream
$D \to K^0_S\pi^+\pi^-$	602 ± 26	$1\,315 \pm 39$	606 ± 26	$1\,334 \pm 39$
$D \to K^0_S K^+K^-$	92 ± 10	189 ± 15	82 ± 10	193 ± 15

LHCb γ combination: $B^+ \to D K^+$ ($D \to K^0_s h^+ h^-$) input (cont.)

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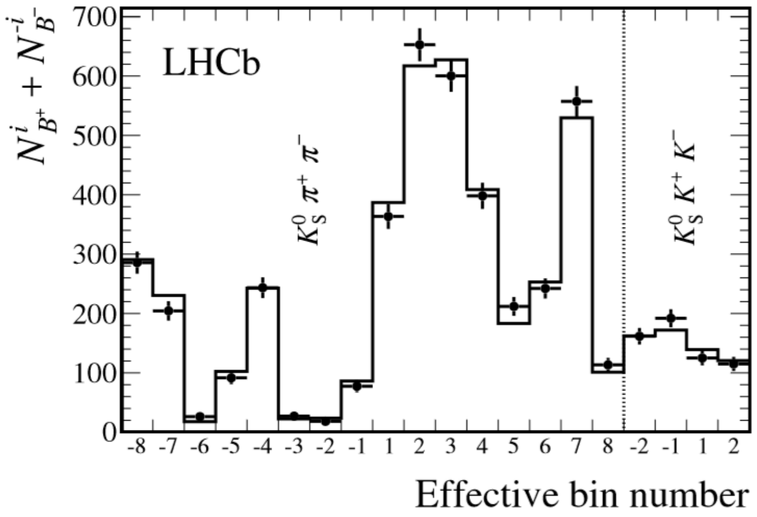
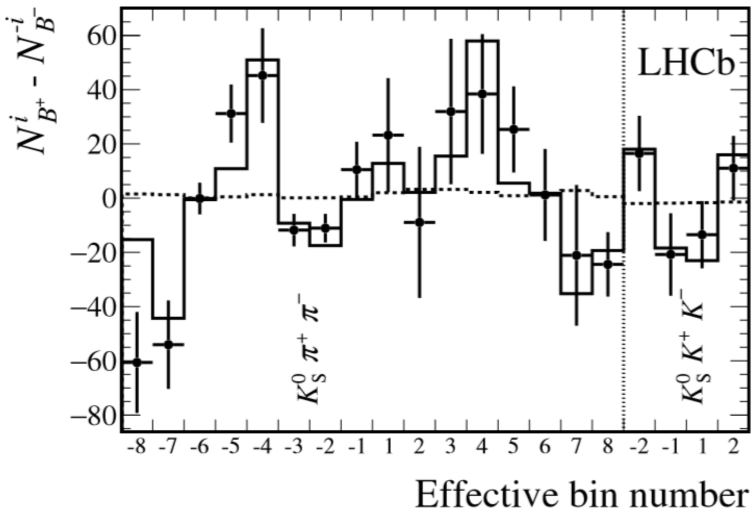
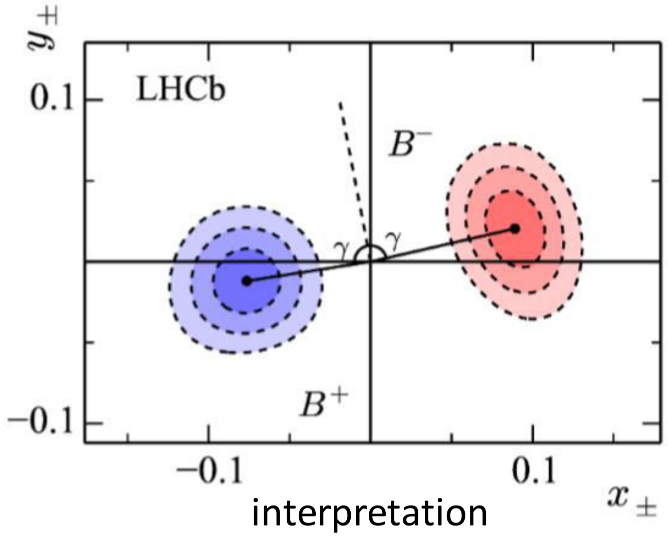




- dots: data
- horizontal dotted line: expectation with no CPV
- continuous line: expectation with central values of $x_\pm$ $y_\pm$



interpretation

$$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2}$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2}$$

CLEO input
PRD 82 (2010) 112006

2015 → 2016 data:

$$\gamma = (87^{+11}_{-12})^\circ$$

up to a two fold ambiguity resolved using the constraint $\gamma \in [0^o, 180^o]$

- most precise determination of γ from a single analysis
- statistically limited but more data have yet to come (2017 → 2018)
- have to pay attention also to the CLEO input uncertainty

LHCb γ combination: $B^+ \to D K^{*+}$ (2,4-body D) input

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- sensitivity to γ obtained from the interference observed by reconstructing the D meson in final states accessible to both D^0 and anti-D^0
- 2-body and 4-body D decay modes ($h^+ h^-$, $h^+ \pi^- \pi^+ \pi^-$ where h=K, π)
- 12 CP observables are measured, for illustration purposes 4 are given below:

$$A_{KK} = \frac{\Gamma(B^- \to D(K^+K^-)K^{*-}) - \Gamma(B^+ \to D(K^+K^-)K^{*+})}{\Gamma(B^- \to D(K^+K^-)K^{*-}) + \Gamma(B^+ \to D(K^+K^-)K^{*+})}$$

$= A_{\pi\pi}$ defined with a K to π swap

equality holds as long as / if direct CP violation in D decays is small: true

$$R_{KK} = \frac{\Gamma(B^- \to D(K^+K^-)K^{*-}) + \Gamma(B^+ \to D(K^+K^-)K^{*+})}{\Gamma(B^- \to D(K^-\pi^+)K^{*-}) + \Gamma(B^+ \to D(K^+\pi^-)K^{*+})} \times \frac{\mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(D^0 \to K^+K^-)}$$

$= R_{\pi\pi}$ defined with a K to π swap

$A_{KK} = A_{\pi\pi} \equiv A_{CP+}$

$R_{KK} = R_{\pi\pi} \equiv R_{CP+}$

$$A_{CP+} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma}$$

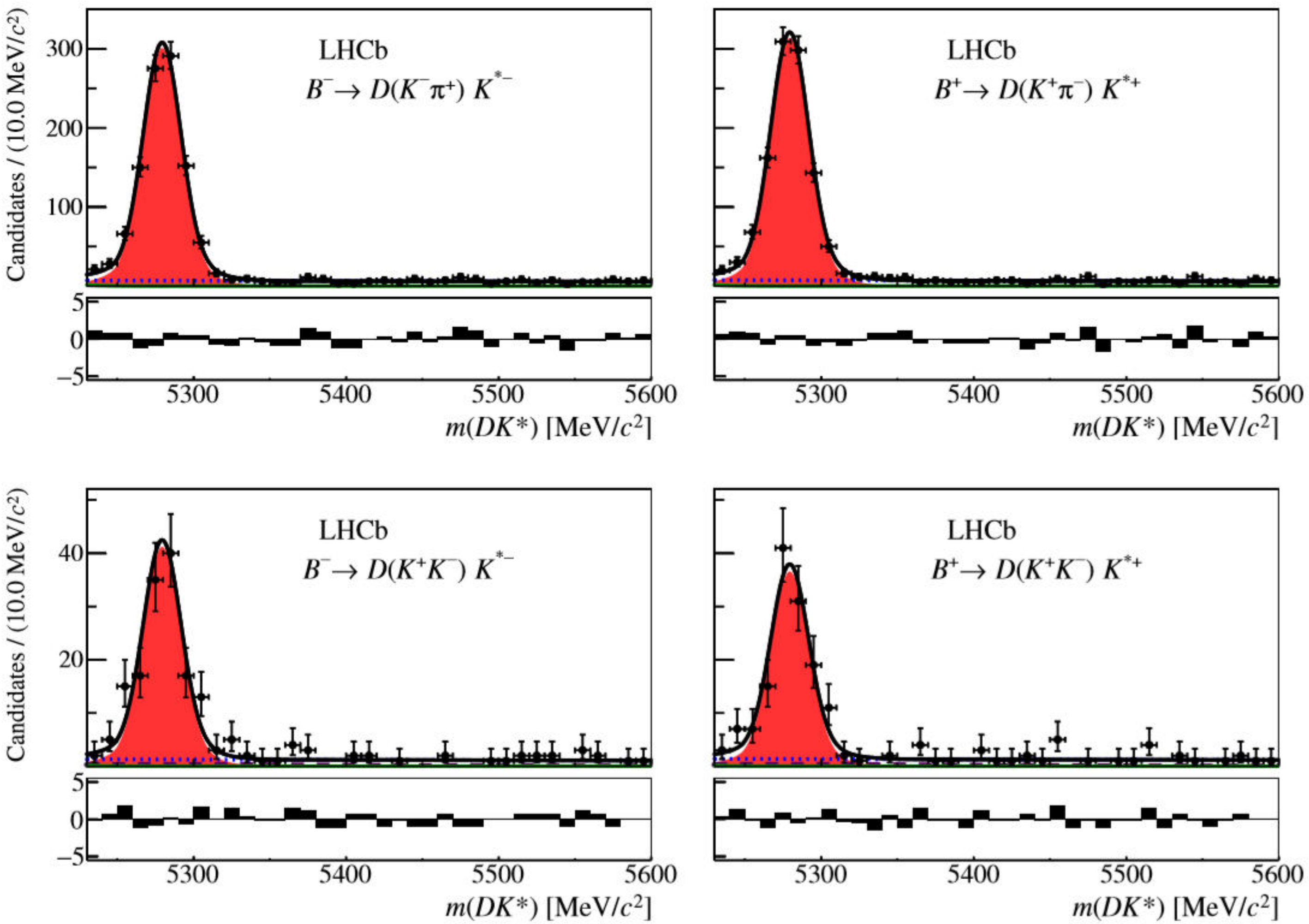
$$R_{CP+} = 1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma$$

r, δ and γ as defined previously

k: dilution factor for non $K^*(892)^- \to K_s^0 \pi^-$ contributions

LHCb γ combination: $B^+ \to D K^{*+}$ (2,4-body D) input (cont.)

$K^{*+} \to K^0_s \pi^-$



2011 → 2016 data

Decay mode	B^- yield	B^+ yield
$B^\pm \to D(K^\pm\pi^\mp)K^{*\pm}$	996 ± 34	1035 ± 35
$B^\pm \to D(K^+K^-)K^{*\pm}$	134 ± 14	121 ± 13
$B^\pm \to D(\pi^+\pi^-)K^{*\pm}$	45 ± 10	33 ± 9
$B^\pm \to D(K^\mp\pi^\pm)K^{*\pm}$	1.6 ± 1.9	19 ± 7
$B^\pm \to D(K^\pm\pi^\mp\pi^+\pi^-)K^{*\pm}$	556 ± 26	588 ± 27
$B^\pm \to D(\pi^+\pi^-\pi^+\pi^-)K^{*\pm}$	59 ± 10	56 ± 10
$B^\pm \to D(K^\mp\pi^\pm\pi^-\pi^+)K^{*\pm}$	3 ± 5	10 ± 6

- 7 D decay modes
- 2 B meson charges
- $K^0_s \to \pi^- \pi^+$ has 2 categories with different reco. eff.
- 2 data taking periods (11 → 12, 15 → 16)

⇒ 56 B meson mass fits

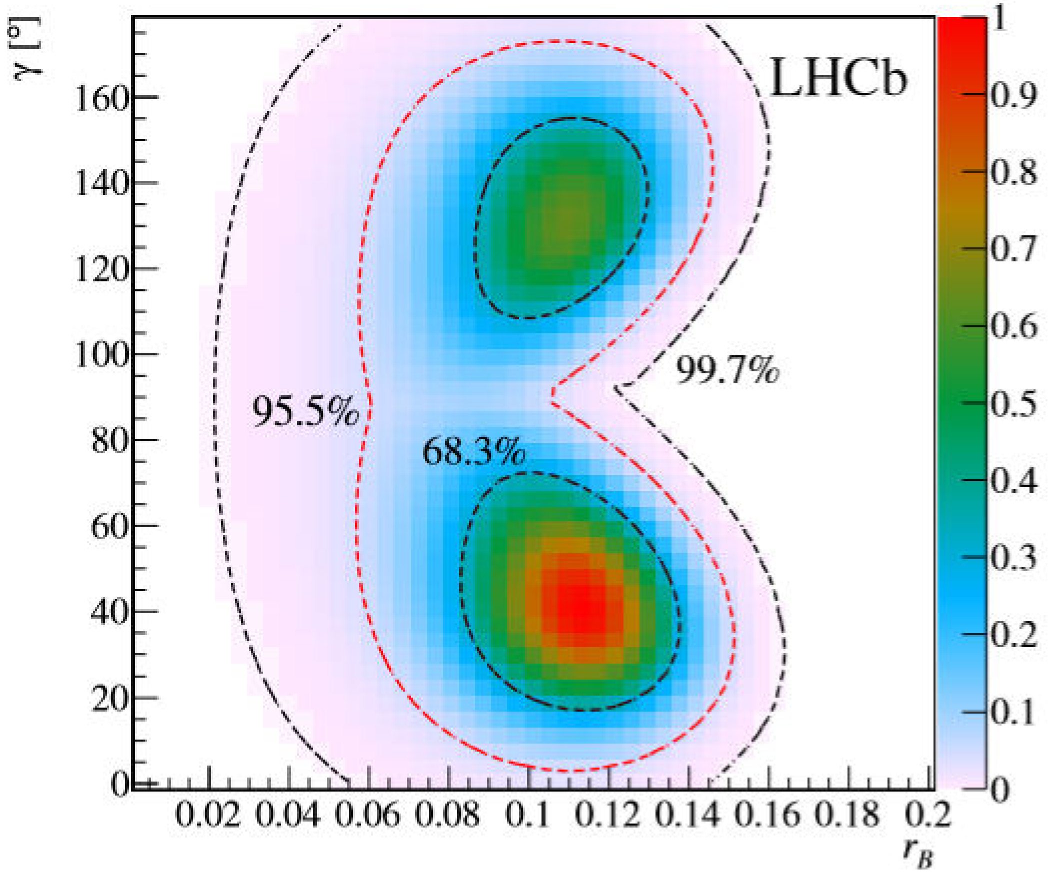
⇒ 12 CP observables (after efficiency corrections)

LHCb γ combination: $B^+ \to D K^{*+}$ (2,4-body D) input (cont.)

numerical results for the 12 CP observables (2011 → 2016 data):

$$A_{K\pi} = -0.004 \pm 0.023 \pm 0.008$$
$$A_{KK} = 0.06 \pm 0.07 \pm 0.01$$
$$A_{\pi\pi} = 0.15 \pm 0.13 \pm 0.02$$
$$R_{KK} = 1.22 \pm 0.09 \pm 0.01$$
$$R_{\pi\pi} = 1.08 \pm 0.14 \pm 0.03$$
$$R^+_{K\pi} = 0.020 \pm 0.006 \pm 0.001$$
$$R^-_{K\pi} = 0.002 \pm 0.004 \pm 0.001$$
$$A_{K\pi\pi\pi} = -0.013 \pm 0.031 \pm 0.009$$
$$A_{\pi\pi\pi\pi} = 0.02 \pm 0.11 \pm 0.01$$
$$R_{\pi\pi\pi\pi} = 1.08 \pm 0.13 \pm 0.03$$
$$R^+_{K\pi\pi\pi} = 0.016 \pm 0.007 \pm 0.003$$
$$R^-_{K\pi\pi\pi} = 0.006 \pm 0.006 \pm 0.004$$

interpretation



- $B^+ \to D K^{*+}$ alone has a limited sensitivity to γ
- results are consistent with $\gamma \sim 70^\circ$ and $r_B \sim 0.1$
- statistically limited but more data have yet to come (2017 → 2018)
- valuable in constraining γ

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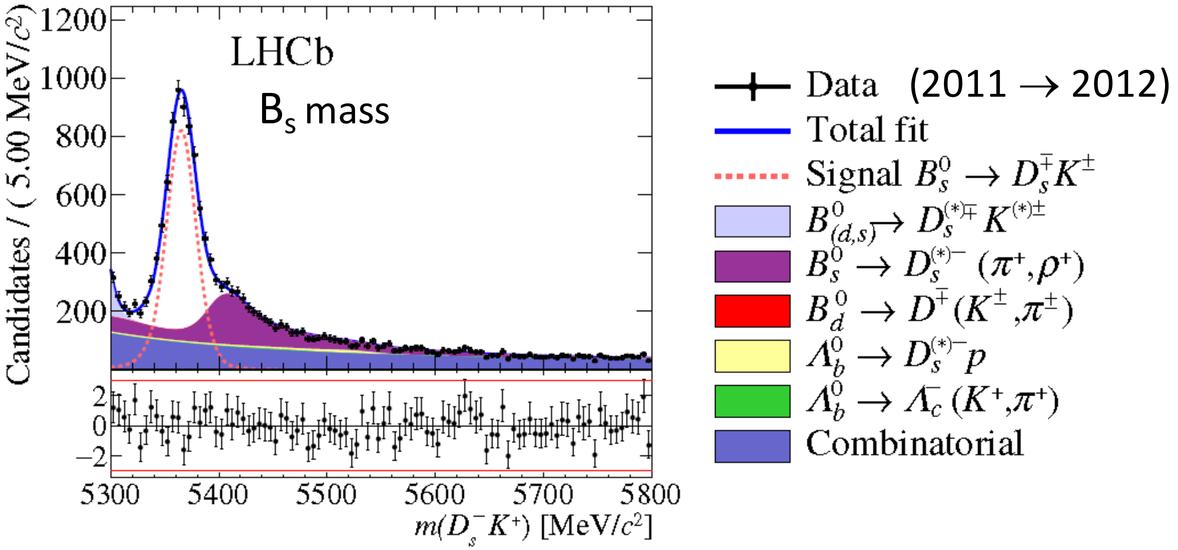
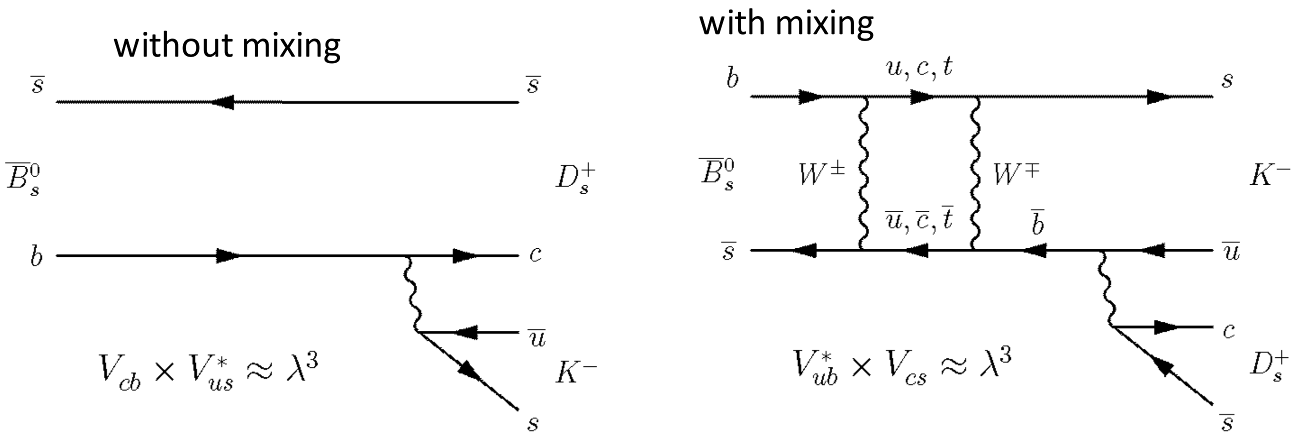
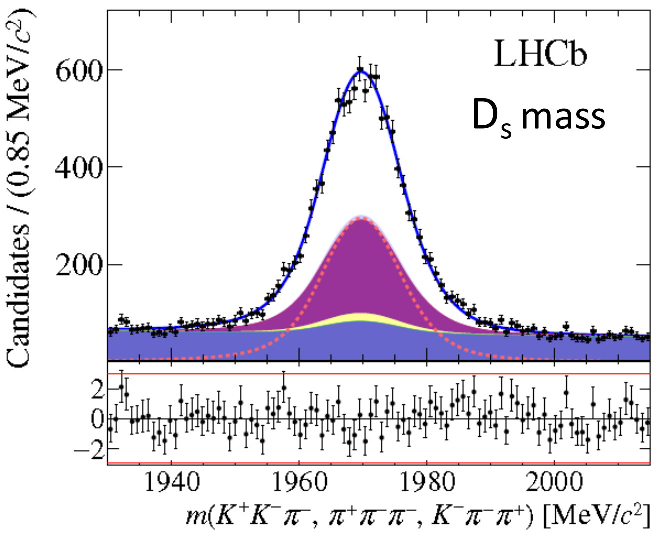
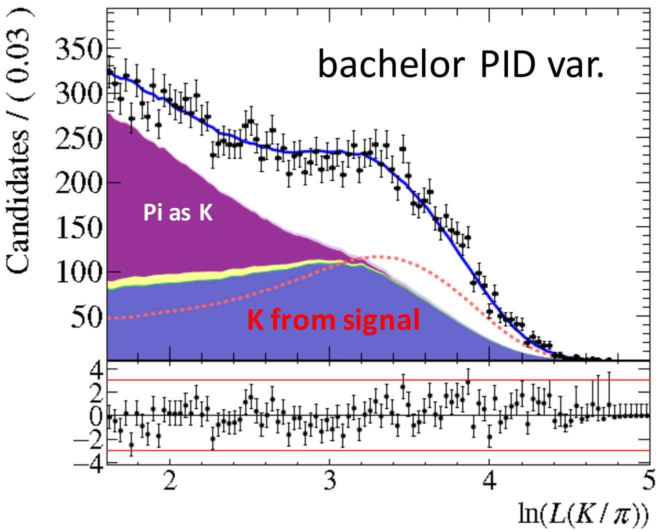
- sensitivity to γ from interference of decay amplitudes with and without mixing









- time dependent analysis
- requiring flavor tagging

time-dependent-decay rates

$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right],$$

$$\frac{d\Gamma_{\overline{B}_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right]$$

CP parameters related to r_B δ_B $(\gamma - 2\beta_s)$

LHCb γ combination: $B^0_s \to D_s K$ input (cont.)

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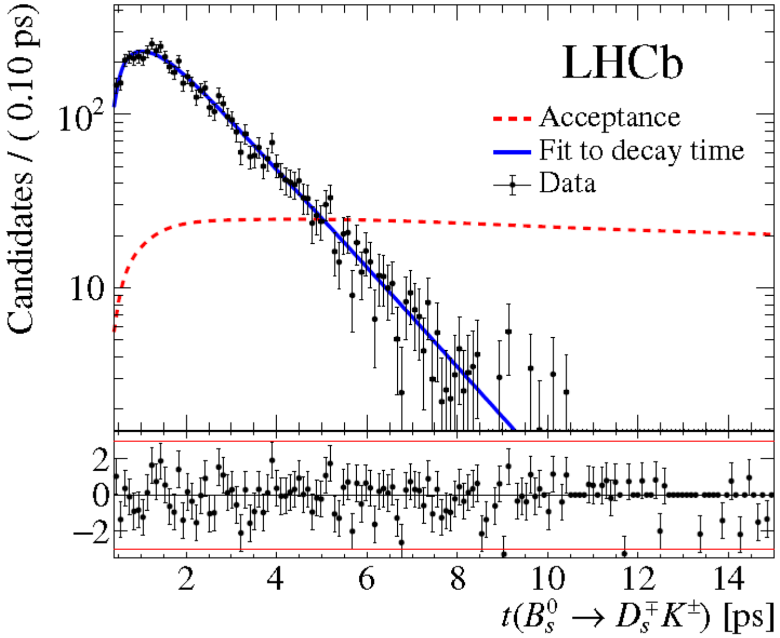


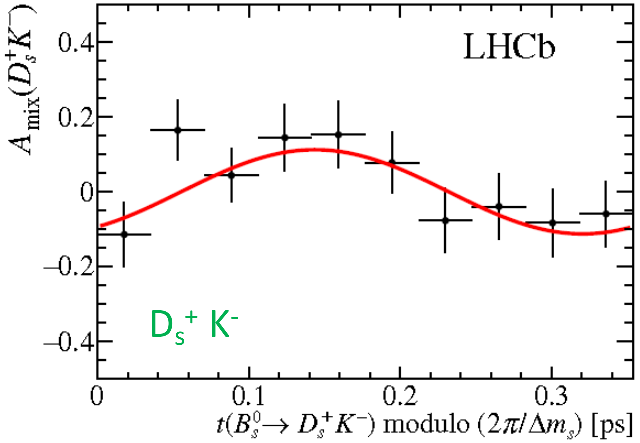
red dashed curve: time acceptance obtained from $B_s \to D_s$ Pi DATA, corrected for the $B_s \to D_s K$ to $B_s \to D_s$ Pi MC time acceptance ratio (small)

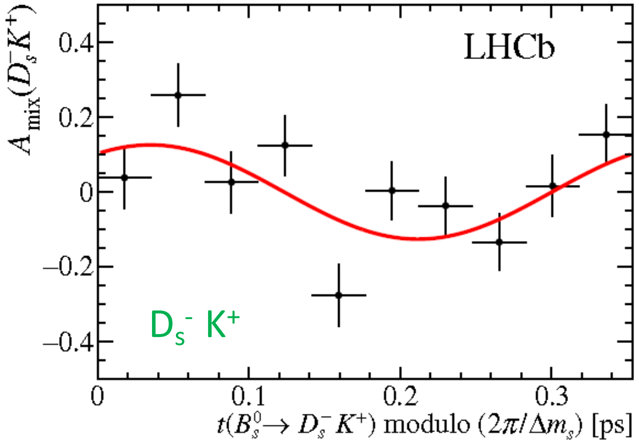
blue curve: fit to the decay time distribution

$$
\begin{aligned}
C_f &= 0.73 \pm 0.14 \pm 0.05 \\
A_f^{\Delta\Gamma} &= 0.39 \pm 0.28 \pm 0.15 \\
A_{\bar{f}}^{\Delta\Gamma} &= 0.31 \pm 0.28 \pm 0.15 \\
S_f &= -0.52 \pm 0.20 \pm 0.07 \\
S_{\bar{f}} &= -0.49 \pm 0.20 \pm 0.07
\end{aligned}
$$

$C_f = - C_{fbar}$
no CPV in:
- decay
- mixing

CPV only in the interference





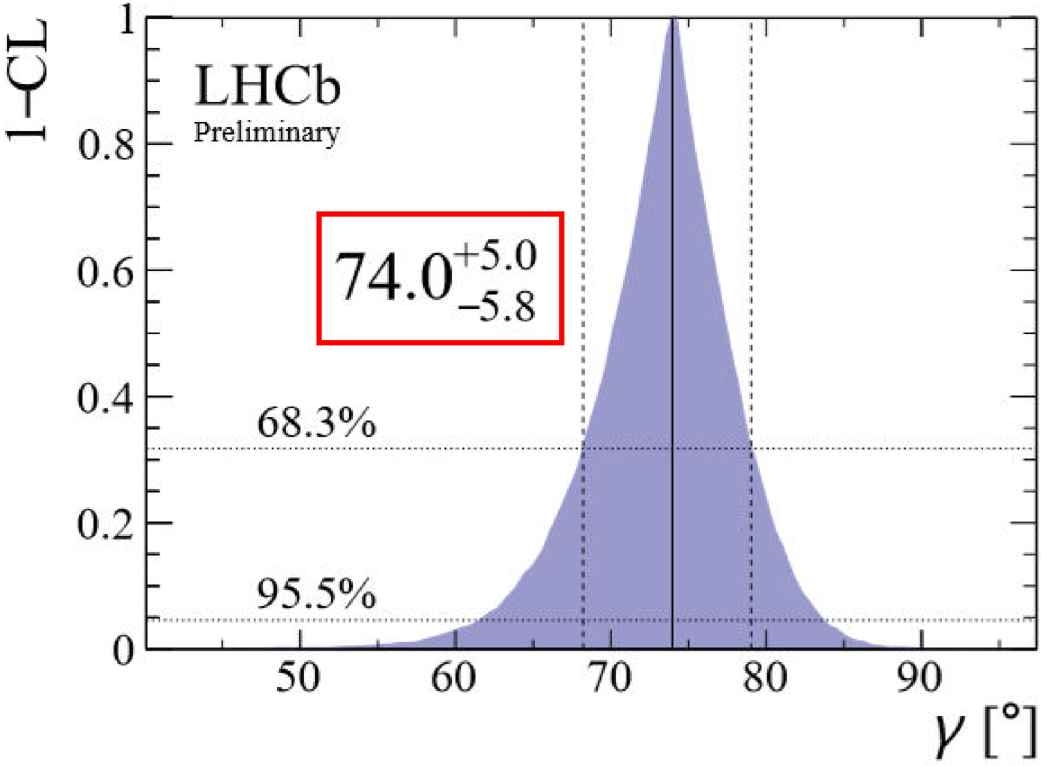
folded asymmetry plots for $D_s^+ K^-$ and $D_s^- K^+$
red curve: fit result
CP violation: non trivial phase difference for t = 0 ps

- strictly speaking probing $\gamma - 2\beta_s$, using in addition $\phi_s = -2\beta_s$ and ϕ_s from HFAG
- 2011 $\to$ 2012 data

$$\gamma = (128\,^{+17}_{-22})^\circ$$

- most precise determination of γ from a B_s meson decay
- statistically limited but more data have yet to come (2015 $\to$ 2018)

- 98 observables
- 40 free parameters
- fit quality:
  - given the χ^2 value at the best fit point and the n.d.f. the fit probability is 69.9 %
  - the fraction of pseudoexperiments which are generated from the best fit point and have a χ^2 larger than that found in data is (69.6±0.5) %
- main results: γ (common free parameter) and r_B δ_B for every "B"



parameters of interest

Quantity	Value	68.3% CL	95.5% CL
γ [°]	74.0	[68.2, 79.0]	[61.6, 83.7]
r_B^{DK}	0.0989	[0.0939, 0.1040]	[0.0891, 0.1087]
δ_B^{DK} [°]	131.2	[125.3, 136.3]	[118.3, 140.9]
$r_B^{D^*K^+}$	0.191	[0.153, 0.236]	[0.121, 0.287]
$\delta_B^{D^*K^+}$ [°]	331.6	[321.4, 339.8]	[309, 346]
$r_B^{DK^{*+}}$	0.092	[0.059, 0.110]	[0.034, 0.126]
$\delta_B^{DK^{*+}}$ [°]	40	[20, 132]	[5, 155]
$r_B^{DK^{*0}}$	0.221	[0.174, 0.265]	[0.123, 0.309]
$\delta_B^{DK^{*0}}$ [°]	187	[167, 210]	[148, 239]
$r_B^{DK\pi\pi}$	0.081	[0.054, 0.106]	[0.000, 0.125]
$\delta_B^{DK\pi\pi}$ [°]	351.4	[314.0, 359.8]	[180, 360]
$r_B^{D_s^\mp K^\pm}$	0.301	[0.215, 0.391]	[0.14, 0.49]
$\delta_B^{D_s^\mp K^\pm}$ [°]	355	[339, 372]	[321, 390]
$\delta_B^{D^\mp\pi^\pm}$ [°]	17	[0, 46]	[0, 76]

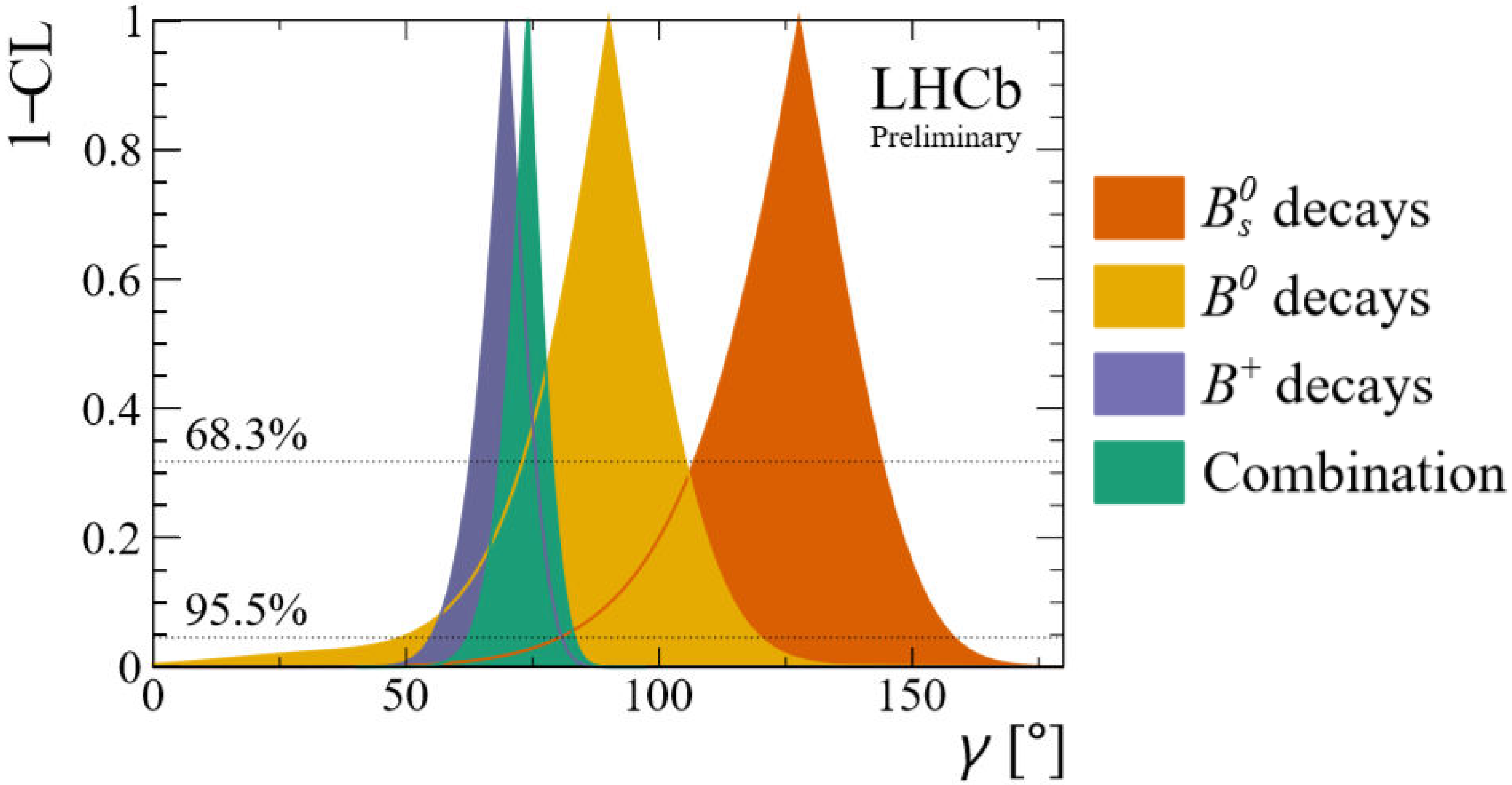
LHCb γ combination: remark on "auxiliary" inputs

Decay	Parameters	Source
D^0–$\bar{D}^0$-mixing	x_D, y_D	HLFAV
$D \to K^+\pi^-$	$r_D^{K\pi}$, $\delta_D^{K\pi}$	HLFAV
$D \to h^+h^-$	$A_{CP}^{\rm dir}(KK)$, $A_{CP}^{\rm dir}(\pi\pi)$	HLFAV
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$, $r_D^{K3\pi}$	CLEO+LHCb
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{\pi\pi\pi\pi}$	CLEO
$D \to K\pi\pi^0$	$\delta_D^{K2\pi}$, $\kappa_D^{K2\pi}$, $r_D^{K2\pi}$	CLEO+LHCb
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}$, $F_{KK\pi^0}$	CLEO
$D \to K^0_S K^+\pi^-$	$\delta_D^{K_SK\pi}$, $\kappa_D^{K_SK\pi}$, $r_D^{K_SK\pi}$	CLEO
$D \to K^0_S K^+\pi^-$	$r_D^{K_SK\pi}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_B^{DK^{*0}}$, $\bar{R}_B^{DK^{*0}}$, $\bar{\Delta}_B^{DK^{*0}}$	LHCb
$B^+ \to DK^{*+}$	$\kappa_B^{DK^{*+}}$	LHCb
$B^0_s \to D_s^\mp K^\pm$	ϕ_s	HFLAV
$B^0 \to D^\mp\pi^\pm$	β	HFLAV
$B^0 \to D^\mp\pi^\pm$	$r_B^{D^\mp\pi^\pm}$	See text

- there are some
- whenever possible these are taken from data
  - whenever possible from LHCb data !
- Gaussian constrained in the combination
  - allowing them to float roughly doubles the uncertainty on γ

LHCb γ combination: contribution of the different inputs to the final result

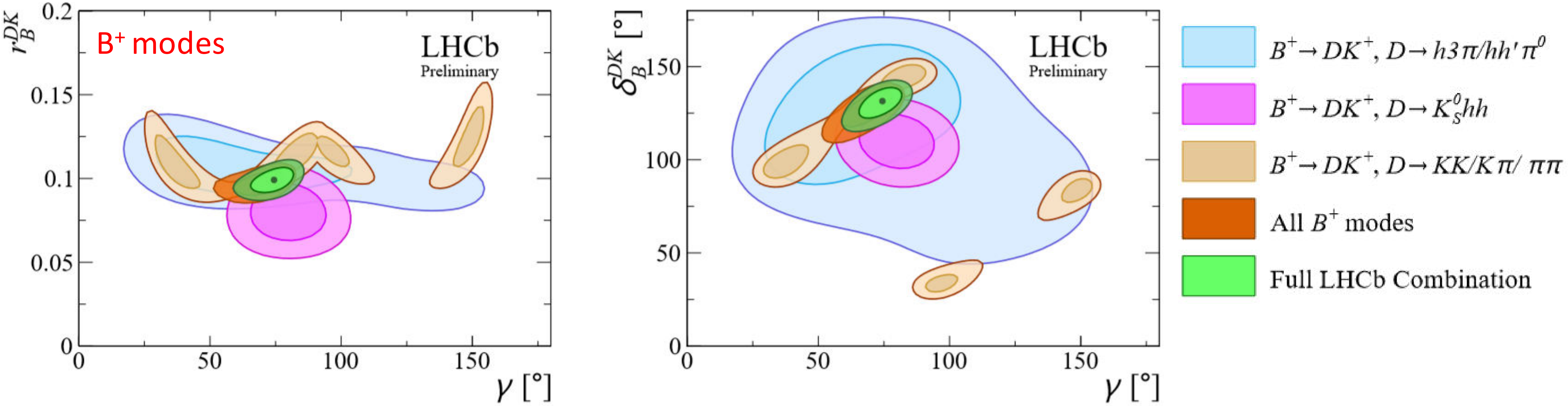
LHCb-CONF-2018-002



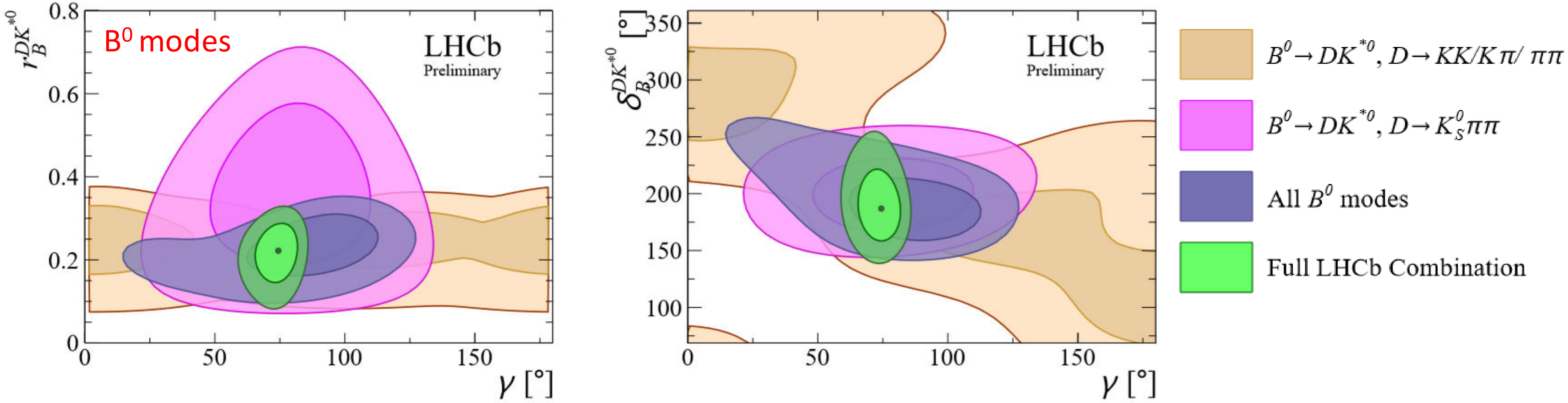
B decay	D decay	Method
$B^+ \to DK^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^+$	$D \to h^+h^-$	ADS
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K_S^0K^+\pi^-$	GLS
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD

- allows to probe the stability / strength of the final result on γ
- B^+ are clearly driving the final result
- B^0 and B^0_s (a single measurement but with r=0.301 !), subdominant, have almost the same weight
- … what about $B_c^{\pm} \to D_s^{\pm} D/\overline{D}$? small production rate but large, O(1), ratio of interfering amplitudes (PRD 65 034016)

LHCb γ combination: contribution of the different inputs to the final result (cont.)

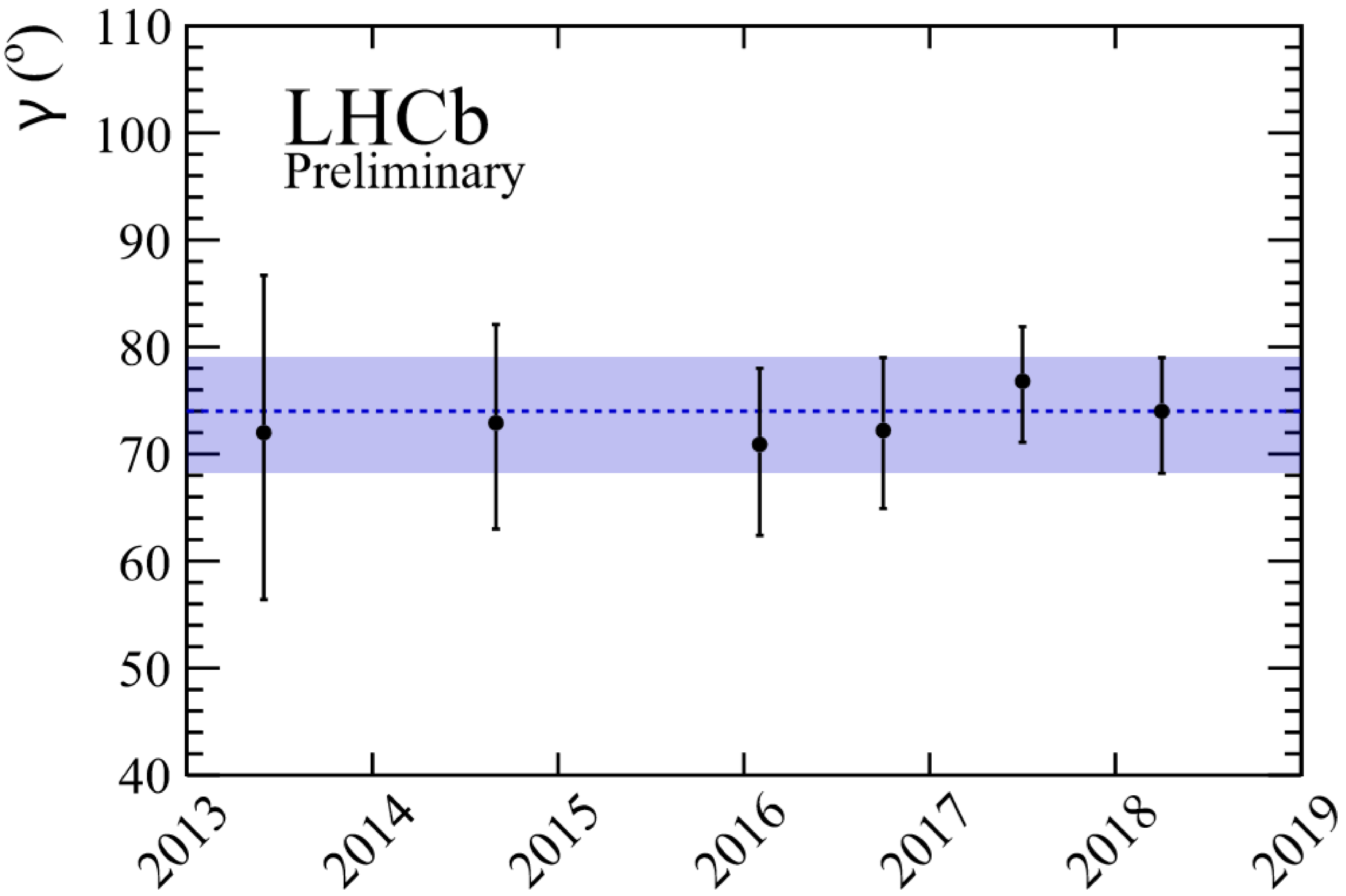


- less precise channels help solving many fold ambiguities of the most precise ones !



- multiple input channels allow to shrinks uncertainty !

LHCb γ combination: story so far

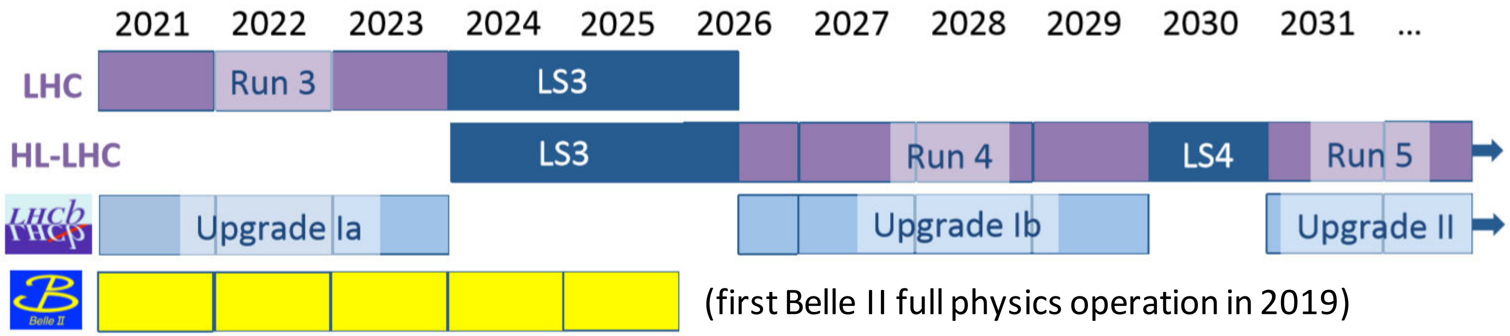


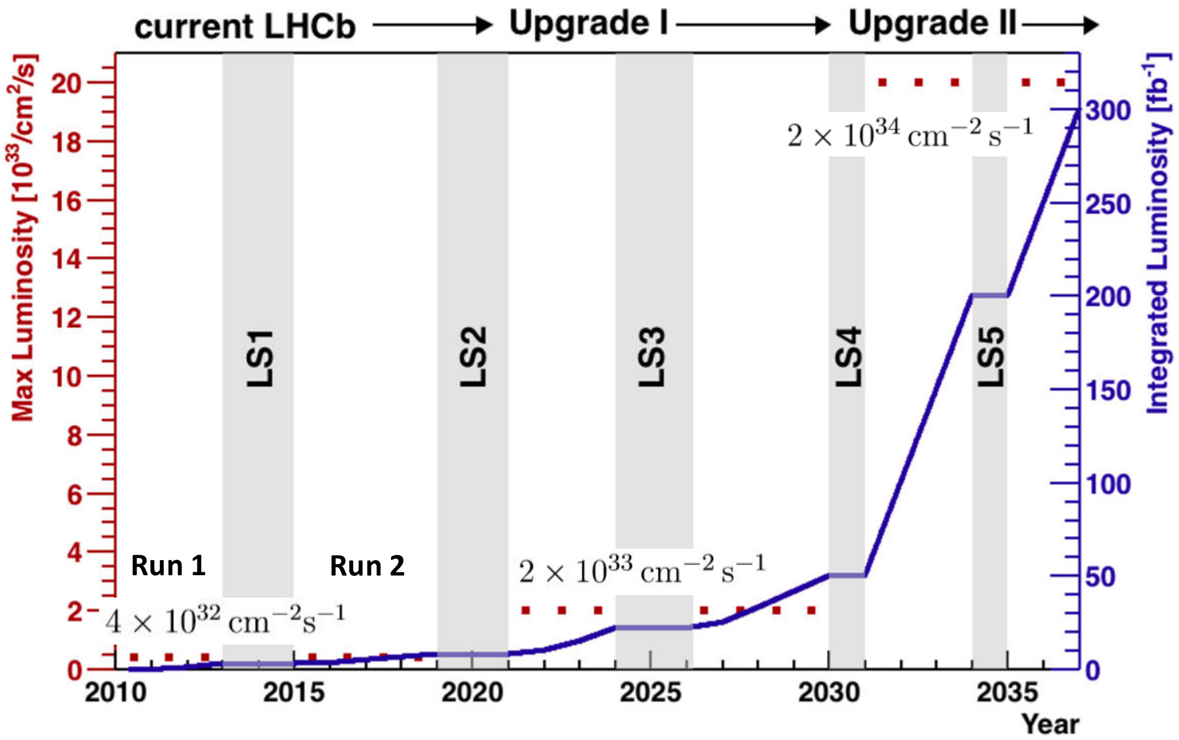
- stable
- uncertainties nicely shrinking

LHCb γ combination: what's next ?

CERN-LHCC-2018-027 or
LHCB-PUB-2018-009 or
https://arxiv.org/abs/1808.08865

- first of all not all the LHCb inputs are using the 3.2 + 5.9 /fb data sample collected up to 2018 expect improvements on a "short" time scale
- but an upgrade program is in place with fresh data starting to arrive from 2021



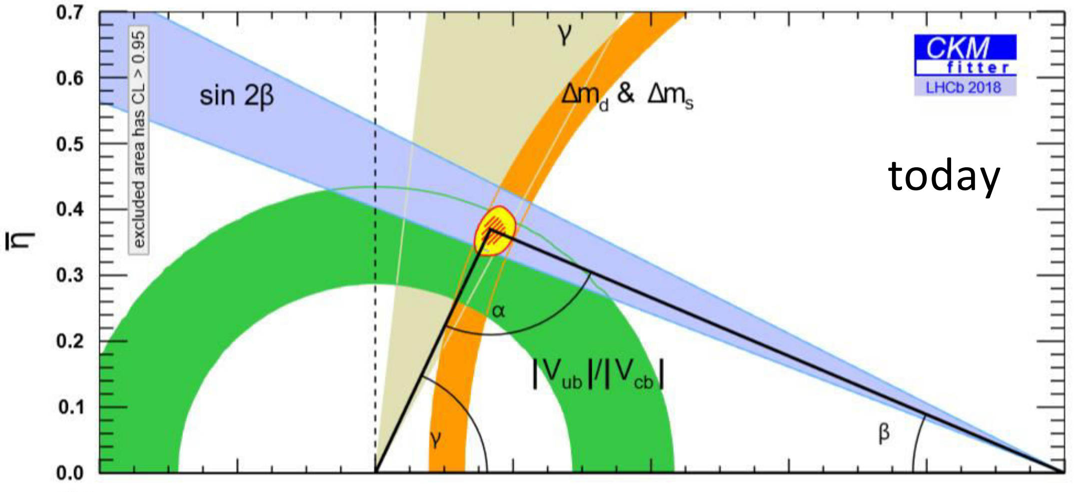


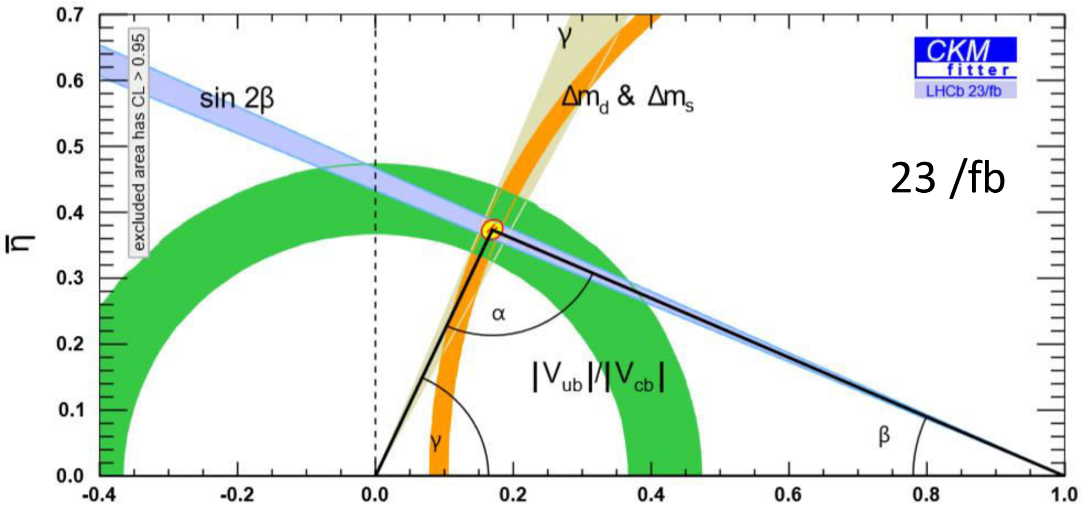
- up to now (the end of 2018):
  3.2 + 5.9 /fb
- by the end of Upgrade Ia (2024):
  23 /fb
- by the end of Upgrade Ia+Ib (2030):
  50 /fb
- by the end of Upgrade II (2037):
  300 /fb

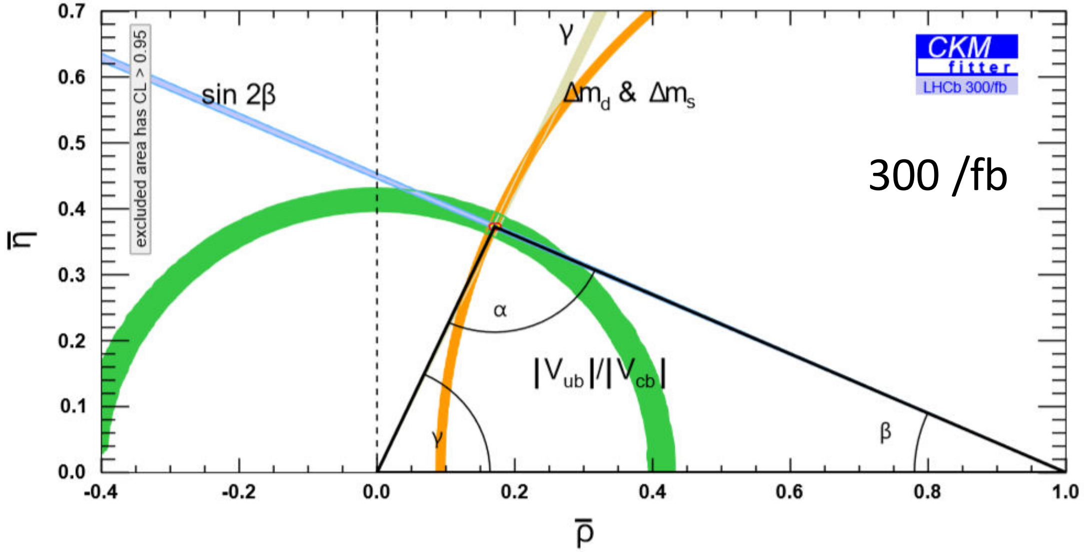
so **PROVIDED** the performances of the LHCb detector can be kept as good as in Run 2 ...
(see "LHCb upgrade status and progress" from S. Gambetta)

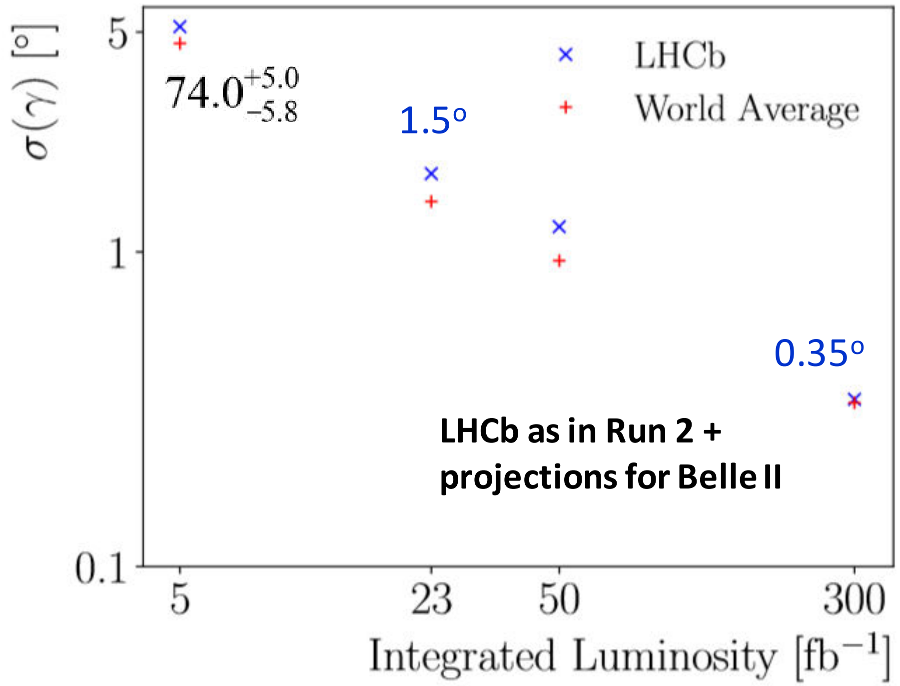
LHCb γ combination: what's next ? (cont.)

CERN-LHCC-2018-027 or
LHCB-PUB-2018-009 or
https://arxiv.org/abs/1808.08865



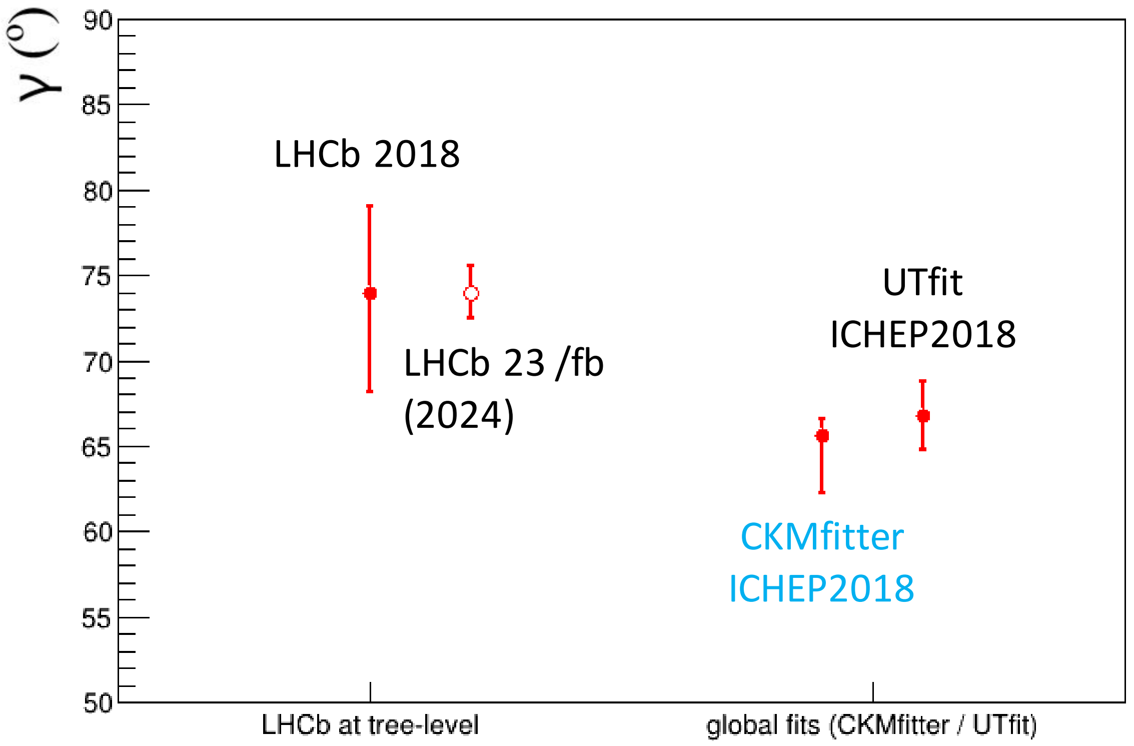






as in Run 2 == currently used strategies, does not include improvements from other approaches / new channels / …

LHCb γ combination: take home message



- 2018 LHCb γ combination:

$$74.0^{+5.0}_{-5.8}$$

CKMfitter: $65.64\,^{+0.97}_{-3.42}$

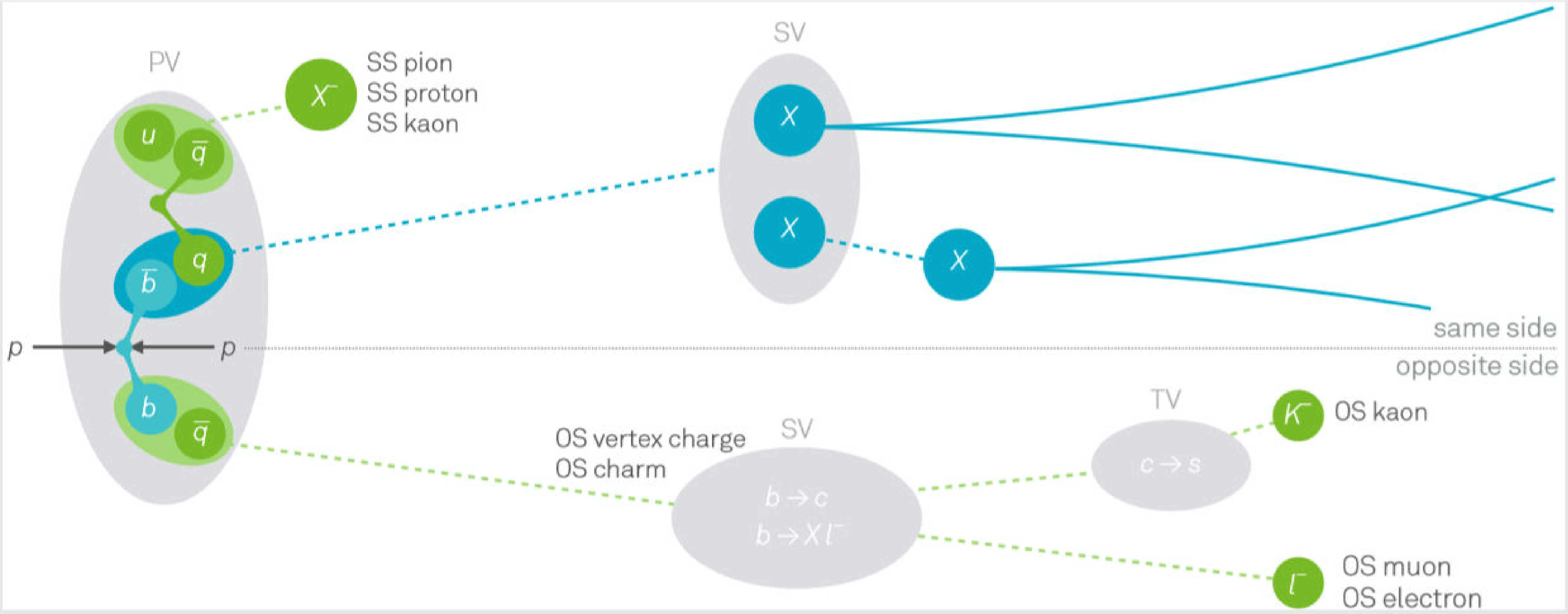
- 16 input measurements that can cross check each other
- present uncertainty is not yet what we need
- on a "short term" time scale:
  - extend all measurements to Run 1 + Run 2 data
  - add new channels … some are really about to come !
- on a "long term" time scale:
  - fresh data from 2021
  - more new channels ?
  - current projections indicate that with 23 /fb we could reach a 1.5° accuracy, similar to the present global fit
- if the accuracy of the external inputs will not limit the LHCb measurement could reach a 0.35° uncertainty with 300 /fb

- LHCb alone is doing well, with very significant improvements w.r.t. BaBar and Belle, and has excellent potentialities
- Belle II will also be able to push towards a reduction of the γ uncertainty, expect the same sensitivity

so stay tuned for more updates and comparisons between tree-level and global fits
only time will tell us if we will have surprises from these …

Backup material

Flavor tagging



Tagging performances

CERN-LHCC-2018-027 or
LHCB-PUB-2018-009 or
https://arxiv.org/abs/1808.08865