Review of Unitarity Triangle and spectroscopy measurements with LHCb

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On behalf of the LHCb Collaboration

September 3rd 2018

Outline

- General introduction
- A review of LHCb's measurements of the Unitarity Triangle parameters
  - The angle β
  - The triangle sides
  - The angle γ
- A review on measurements on spectroscopy
- The upgraded LHCb detector and outlook
- Summary

The CKM matrix

- The CKM matrix is unitary, and reduces to three rotation angles and one phase.
- The Wolfenstein parameterisation is commonly used to expand in orders of λ, the sine of the Cabibbo angle: $\lambda \sim 0.22$
- The imaginary term (phase) gives rise to CP violation in the SM

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(1-\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Measured magnitudes:

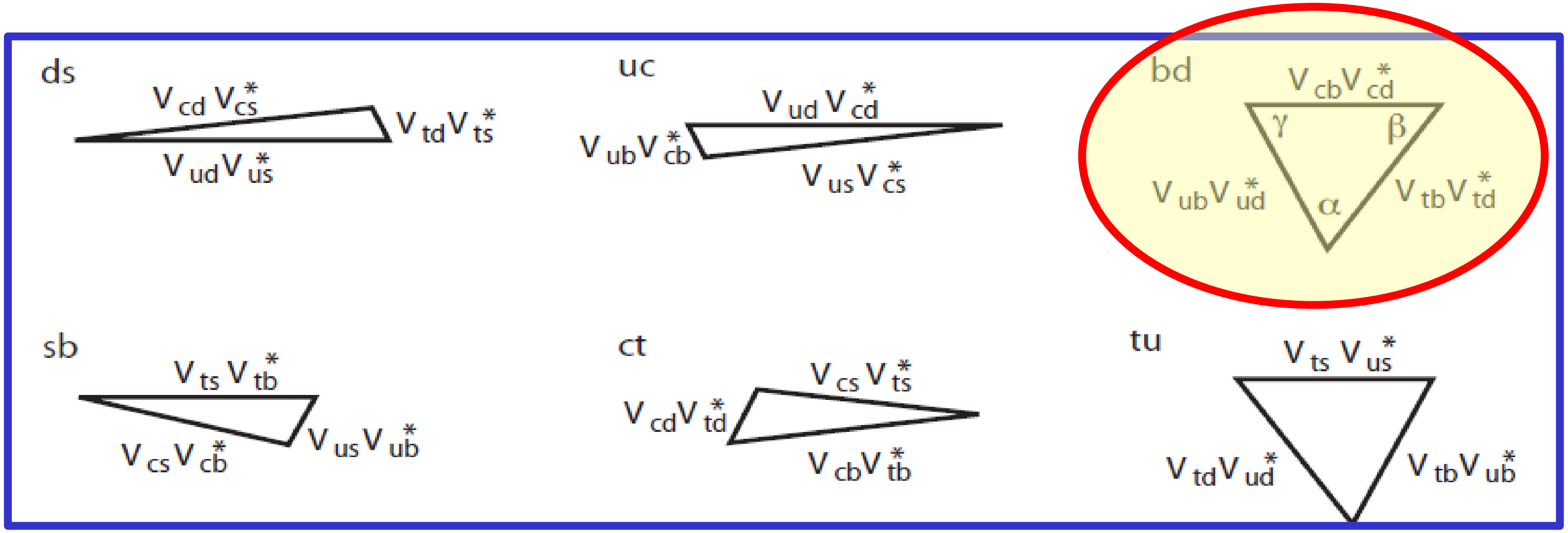
$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-ckm-matrix.pdf

The Unitarity Triangle

- 6 unitarity conditions of the CKM matrix
- Gives 6 triangles in the complex plane
- 2 of these triangles do not have a side which is much shorter than the other two:

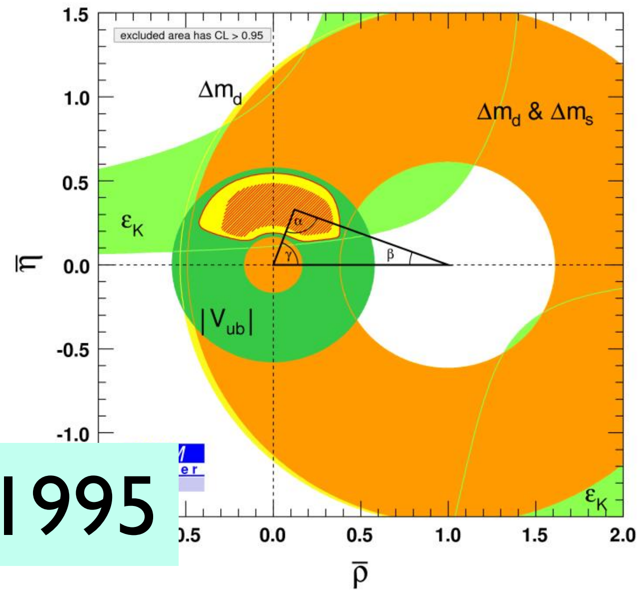
$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0$ $(V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}) = 0$



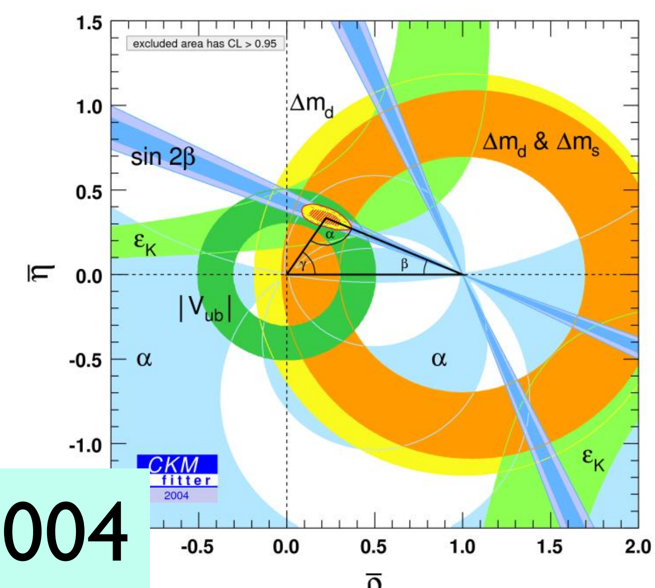
THE unitarity triangle

Unitarity triangle measurements

- Amazing progress in the last >20 years; the SM remains intact, but still a whole lot still to learn

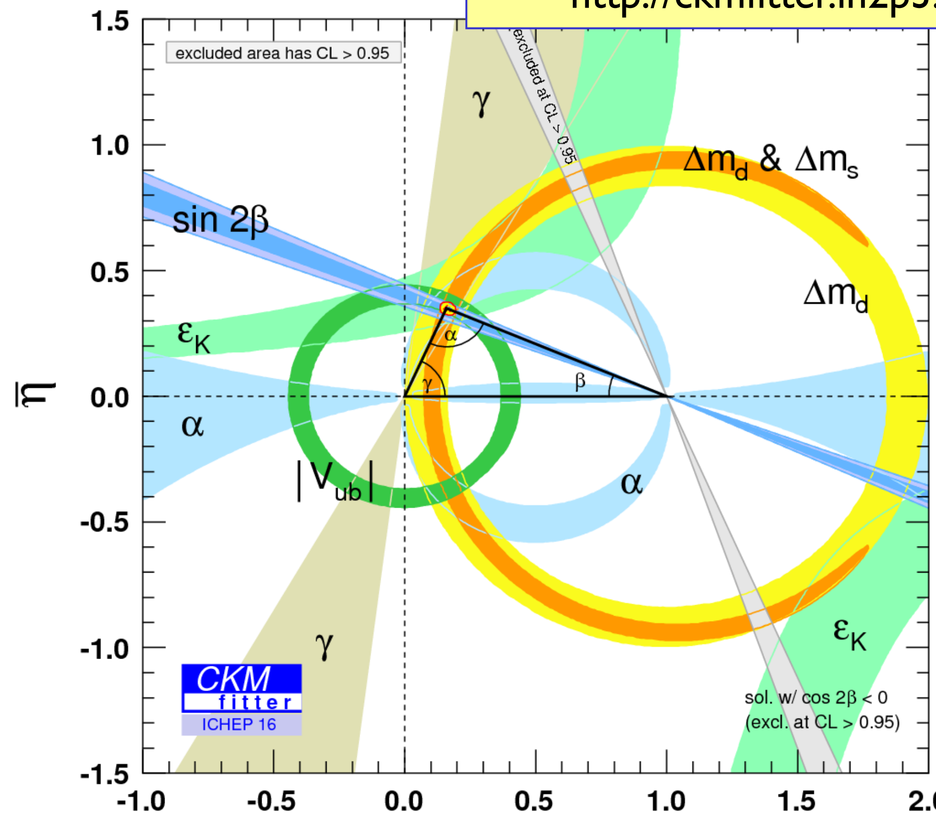


1995



2004

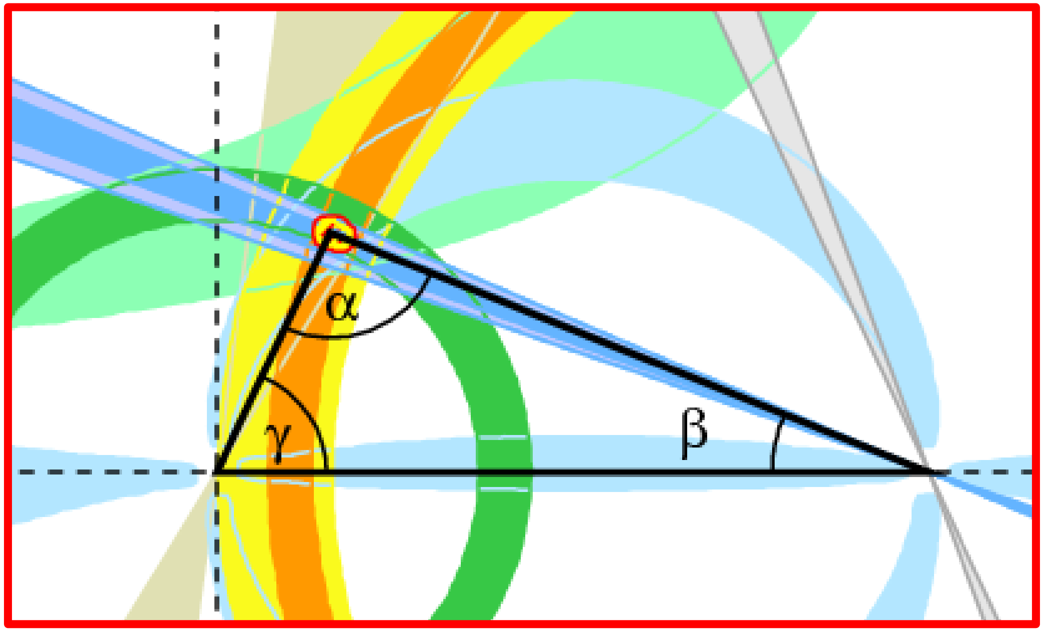
http://ckmfitter.in2p3.fr



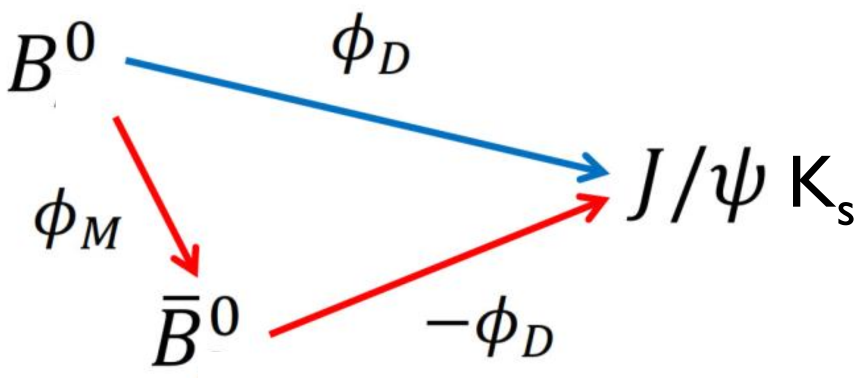
2016 (a 2018 update is imminent)

A review of LHCb Unitarity Triangle measurements

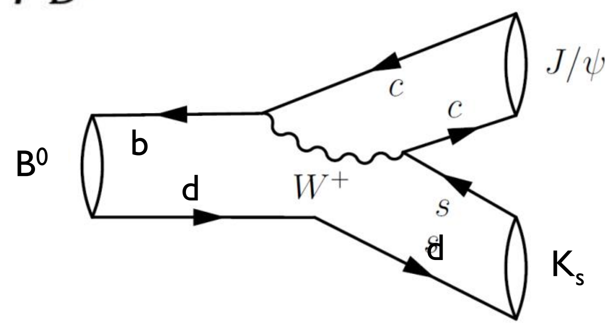
The angle β

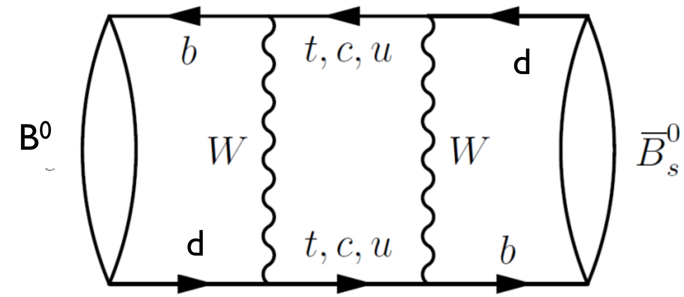


Measurement of angle β



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





- *Interference* between B^0 decay to $J/\psi K^0_S$ directly and via $B^0\,\overline{B}^0$ oscillation gives rise to a CP violating phase

$$\phi = \phi_{Mixing} - 2\,\phi_{Decay} = 2\beta$$

LHCb measurement of sin(2β)

sin(2β) from $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S) K^0_S$

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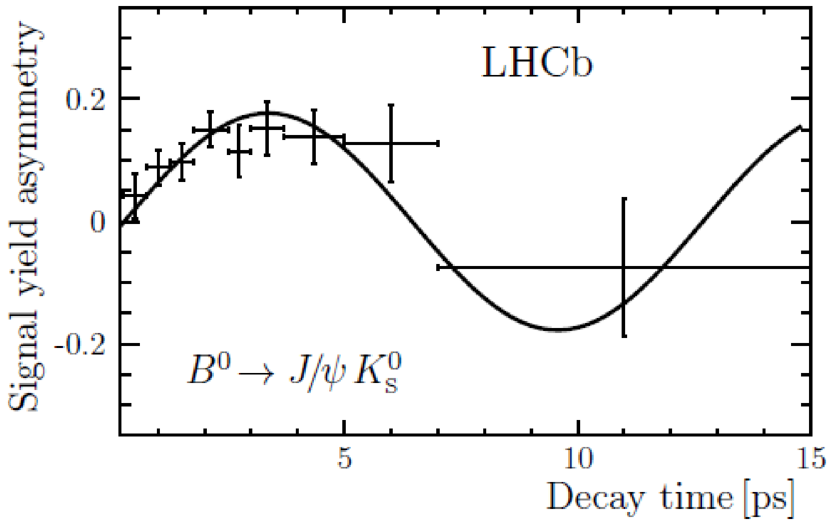
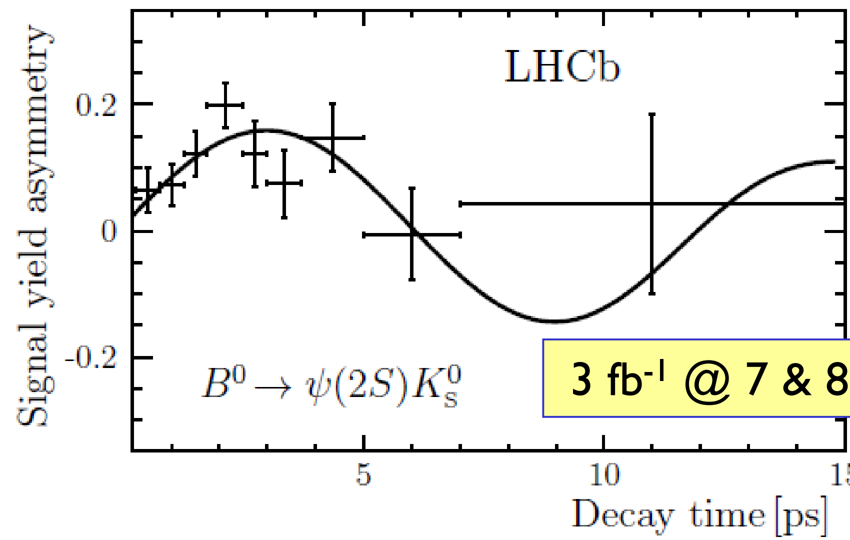
$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to [c\bar{c}]K^0_S) - \Gamma(B^0(t) \to [c\bar{c}]K^0_S)}{\Gamma(\overline{B}^0(t) \to [c\bar{c}]K^0_S) + \Gamma(B^0(t) \to [c\bar{c}]K^0_S)} \approx S \sin(\Delta m\, t) - C \cos(\Delta m\, t)$$

where S = sin(2β) assuming $C_{J/\psi KS}$ (≡ penguin contribution) = 0



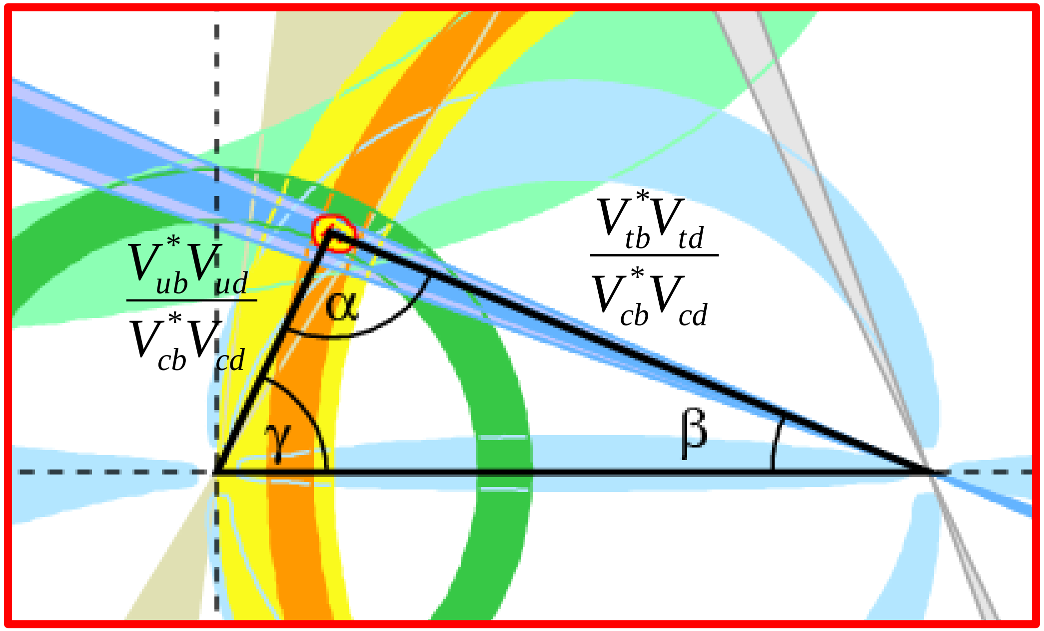


3 fb^{-1} @ 7 & 8TeV

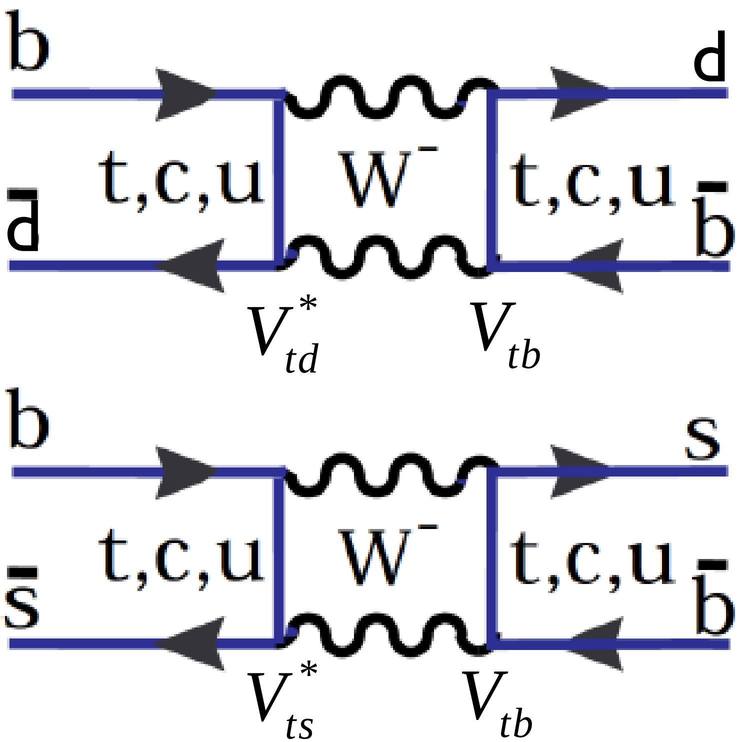
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

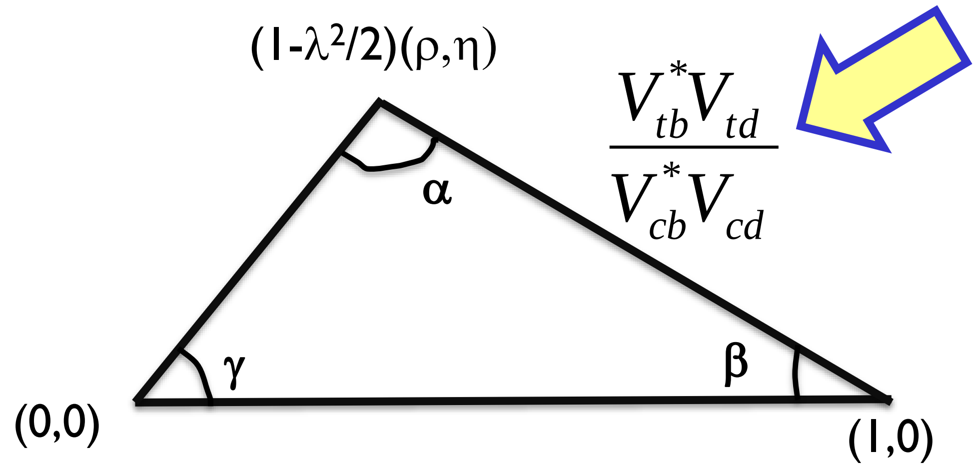
Competitive with Babar & Belle.
World average from all modes :
sin(2β) = 0.699 ± 0.017
(HFLAV Winter 2018)

The sides of the triangle



$B_{(s)}$ mixing for side opposite to γ





$$\Delta m_d = \frac{G_F}{6\pi^2} \cdot m_W^2 \cdot \eta_b \cdot S_0\left(\frac{m_t^2}{m_W^2}\right) \cdot m_{B_d} \cdot f_{B_d}^2 \cdot \hat{B}_{B_d} \cdot |V_{tb}|^2 |V_{td}|^2$$

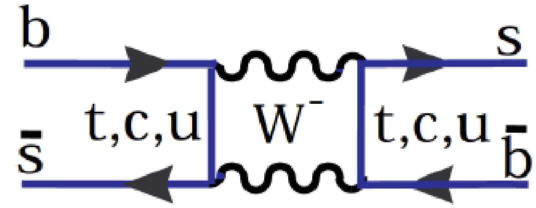
Fermi constant (G_F); W-boson mass (m_W); perturbative QCD (η_b); "Inami-Lim function" for box diagram (S_0); B_d mass (m_{B_d}); decay constant (f_{B_d}); "bag parameter" ($\hat{B}_{B_d}$)

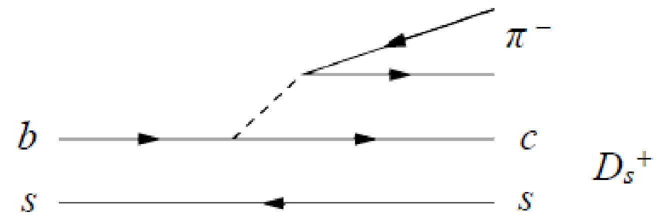
- Mixing loop dominated by the top
- Length of side from ratio of B_d and B_s : mixing frequencies extracted with input from lattice QCD (systematics cancel)

$$\left|\frac{V^*_{tb}V_{td}}{V^*_{cb}V_{cd}}\right| \approx \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

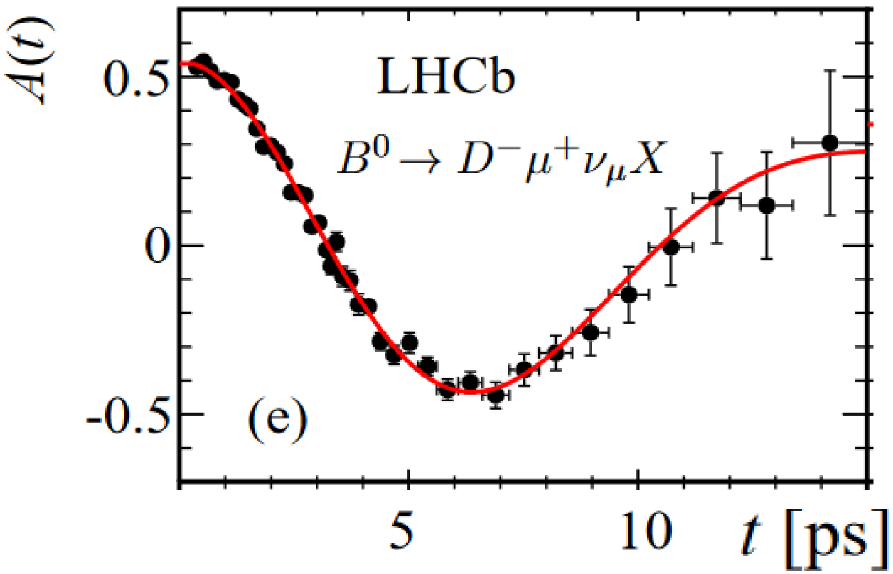
$$\frac{|V_{td}|}{|V_{ts}|} \sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

$B_{(s)}$ mixing at LHCb





$$\frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}$$

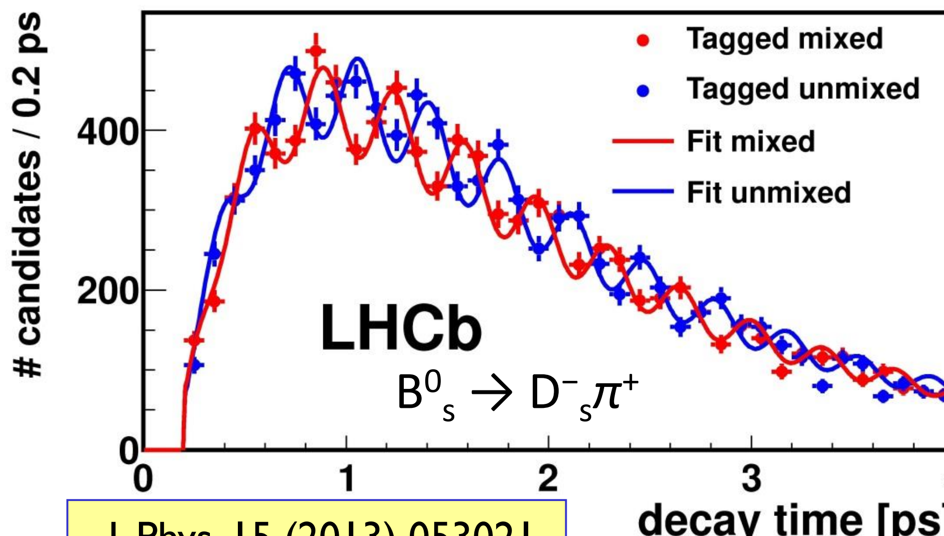


$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\,\text{ns}^{-1}$

Eur. Phys. J. C76 (2016) 412

$|V_{td}/V_{ts}| = 0.210 \pm 0.001 \pm 0.008.$

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-ckm-matrix.pdf



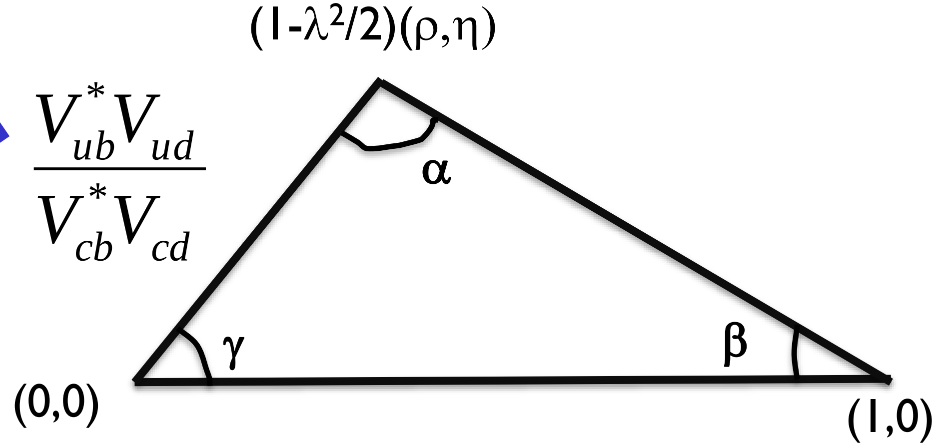
J. Phys. 15 (2013) 053021

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \text{ps}^{-1}$

Mixing measurements now dominated by LHCb (L-QCD systematics to be improved)

$|V_{ub}|$ measurement for side opposite to β

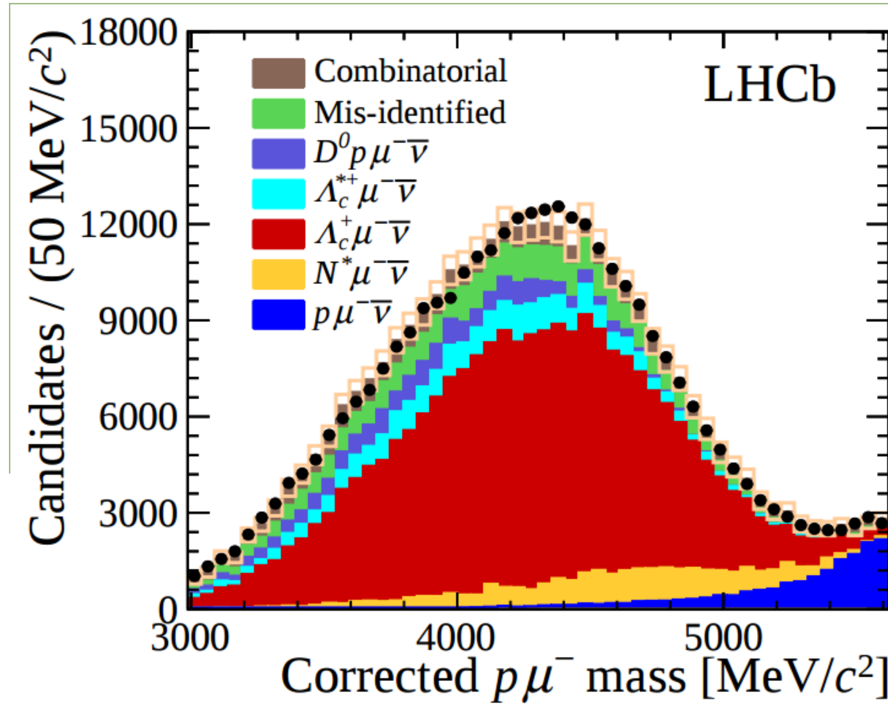
$$\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}}$$



- Closure test of UT mainly limited by $|V_{ub}|$
- Side opposite to β proportional to $|V_{ub}|$ / $|V_{cb}|$
- V_{ud} and V_{cd} very well known. $|V_{cb}|$ known to better than 3%
- $|V_{ub}|^2$ is directly proportional to the decay rate $B \rightarrow X_u l\nu$ and is then calculated using HQET

LHCb measurement of $|V_{ub}|$

- $|V_{ub}| / |V_{cb}|$ difficult at hadron colliders due to presence of neutrino
- LHCb measures $\Lambda_b \rightarrow p\, \mu^- \nu$ (the $B^0 \rightarrow \pi^- \mu^+ \nu$ channel is extremely difficult)
- The measurement relies on $\Lambda_b \rightarrow p$ form factors from the lattice)



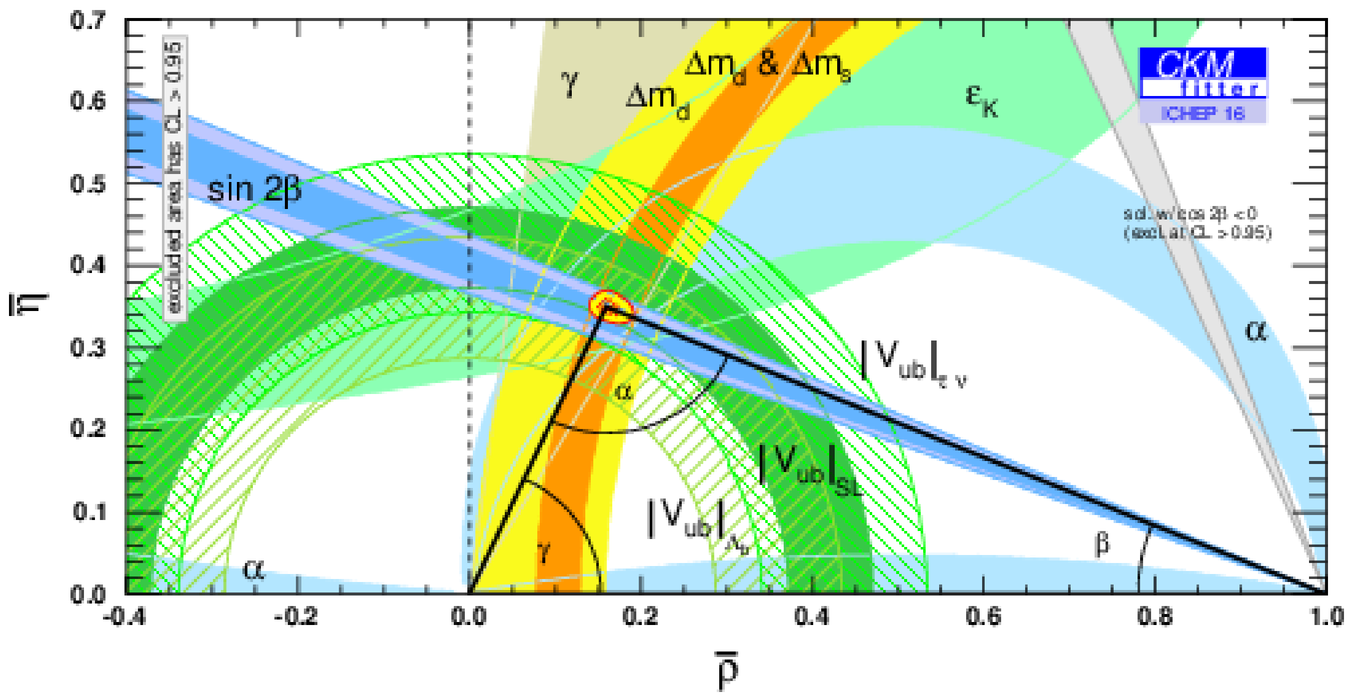
$$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06\ (|V_{cb}|)) \times 10^{-3}$$

Nature Physics 10 (2015) 1038

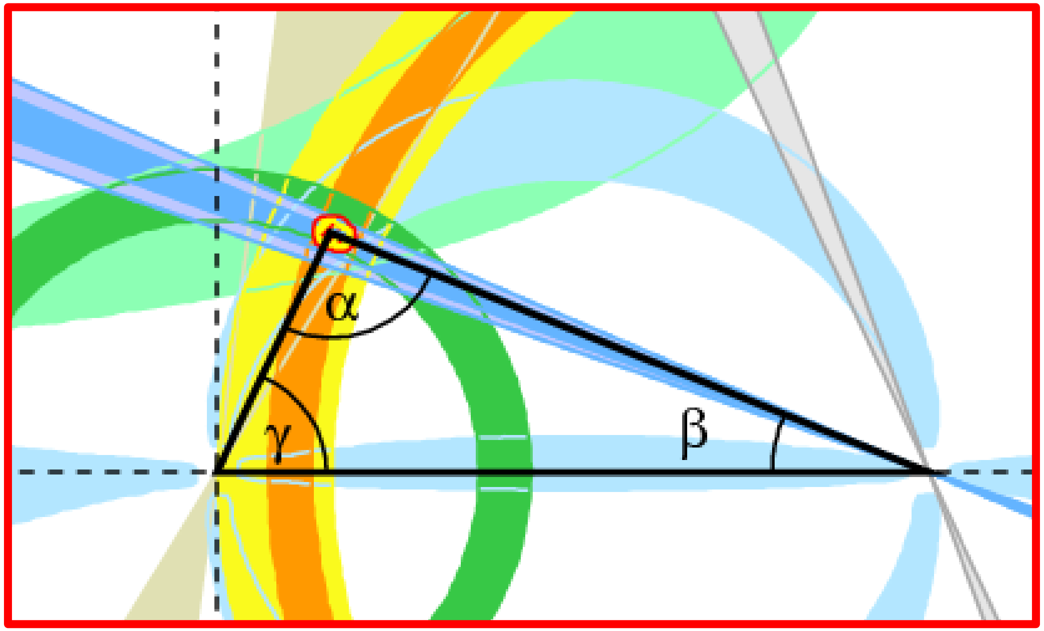
Tension between B-factory inclusive and exclusive $|V_{ub}|$ measurements limit the precision on UT side. World averages:

$$|V_{ub}| = (4.49 \pm 0.15 \, {}^{+\,0.16}_{-\,0.17} \pm 0.17) \times 10^{-3} \quad \text{(inclusive)}$$
$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{(exclusive)}$$
$$|V_{ub}| = (3.94 \pm 0.36) \times 10^{-3} \quad \text{(average)}$$

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-ckm-matrix.pdf



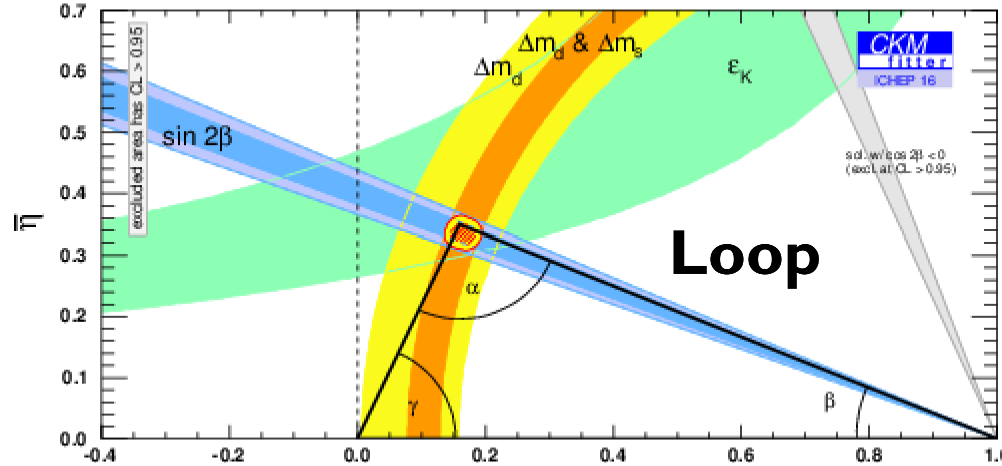
The angle γ

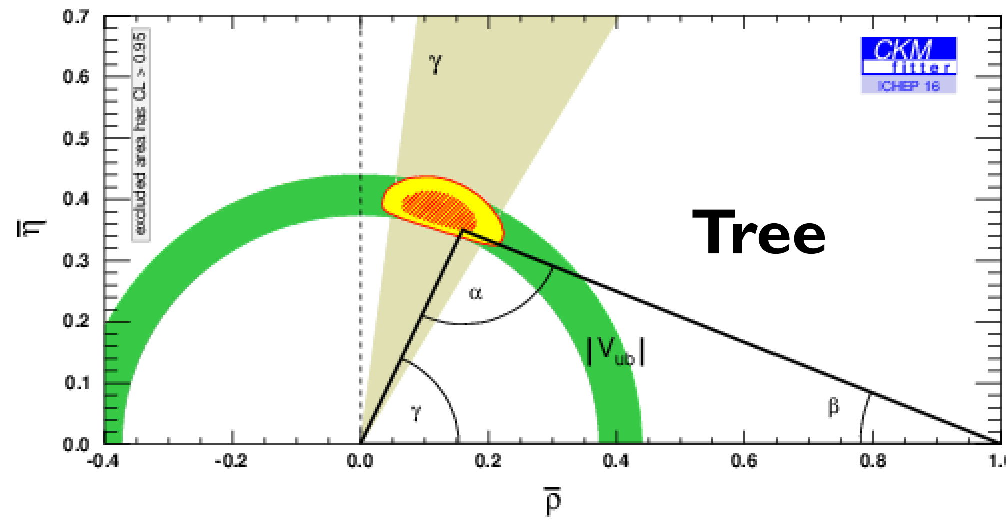


γ – why this is a key measurement

- Loop processes are very sensitive to the presence of New Physics
- Constraints on the triangle apex largely come from loop decay measurements
- Large uncertainty on γ, the only angle accessible at tree level : forms a SM benchmark*
- γ measurement theoretically very clean

JHEP 01 (2014) 051, PRD 92(3):033002 (2015)



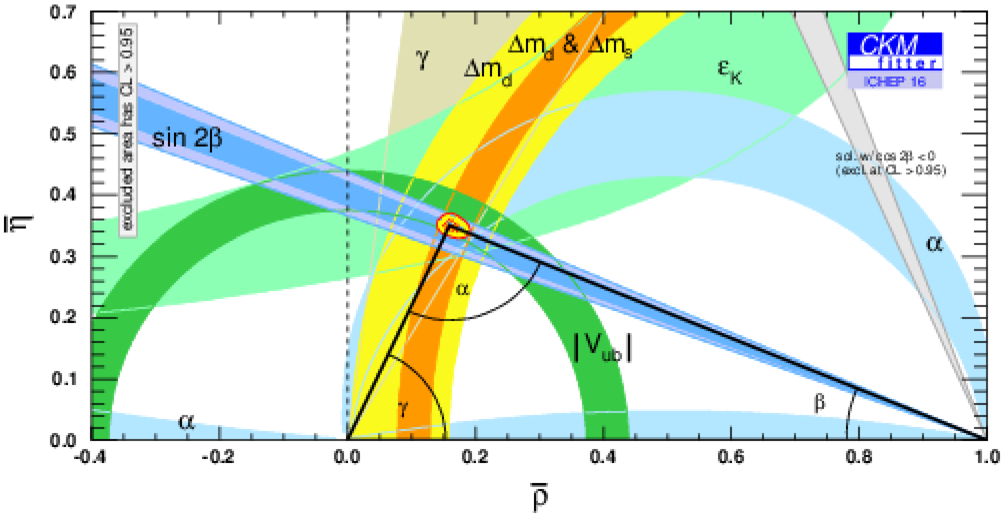


* assuming no significant New Physics in tree decays

http://ckmfitter.in2p3.fr

γ : indirect vs direct determinations

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



Combination of all direct measurements from tree decays (summer 2016)

$$\gamma = (72.1^{+5.4}_{-5.8})^\circ$$

Determination from CKM fit excluding all direct measurements of γ

$$\gamma = (65.3^{+1.0}_{-2.5})^\circ$$

http://ckmfitter.in2p3.fr

Reaching degree level precision from direct measurements is crucial

Uncertainties from LQCD, expect to reduce over the next decade

Several methods to measure γ

- From $B^{\pm}$ (and $\overset{(-)}{B}{}^0$) decays : the "time-integrated", direct CP-violation modes $B^{\pm} \to \overset{(-)}{D}{}^0 K^{\pm}$
  - GLW

    Gronau & London, PLB 253 (1991) 483,
    Gronau & Wyler PLB 265 (1991) 172
  - ADS

    Atwood, Dunietz & Soni PRL 78 (1997) 3257,
    Atwood, Dunietz & Soni PRD 63 (2001) 036005
  - GGSZ

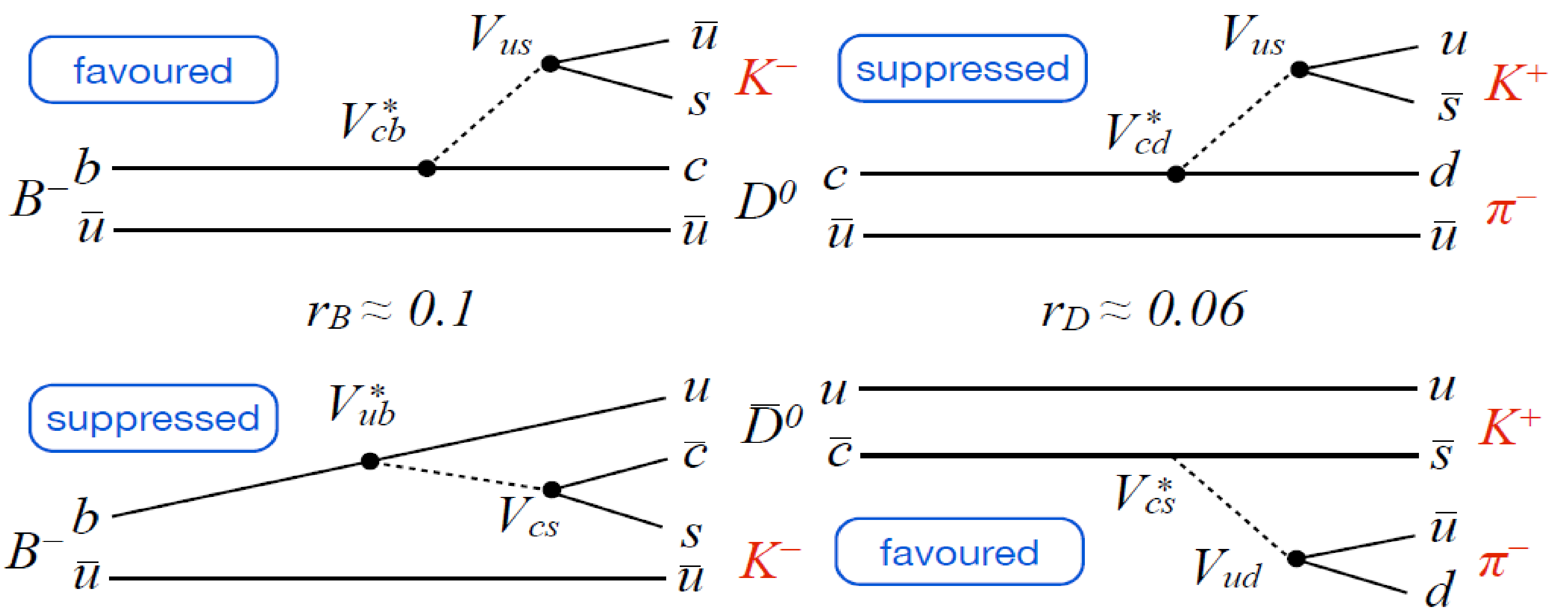
    Giri, Gronau, Soffer & Zupan, PRD 68 (2003) 054018
- $B_s^0 \to D_s K$ time-dependent (TD) analysis

  Dunietz & Sachs Phys. Rev. D37(1988) 3186,
  R. Aleksan, I. Dunietz & B. Kayser, Z. Phys. C54 (1992) 653

The time-integrated mode: $B^- \rightarrow D^0 K^-$

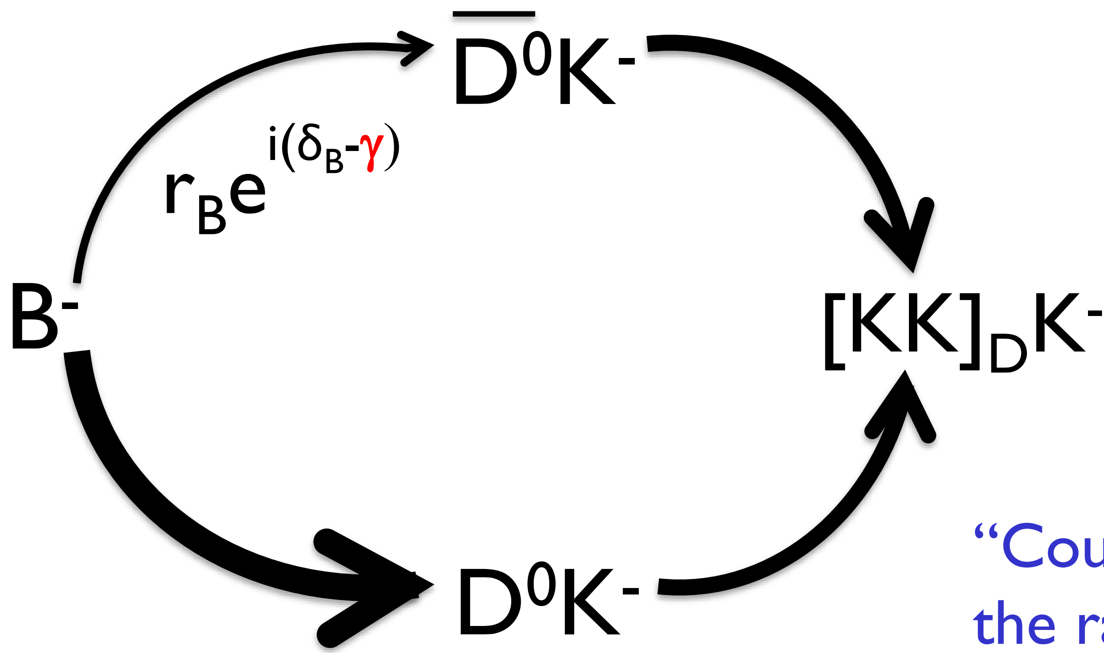
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

(and charge conjugate mode $B^+ \rightarrow \overline{D}^0 K^+$)



- Interference possible if $\overline{D}^0$ and D^0 decay to same final state
- Branching fraction for favoured B decay only ~10^{-4}
  - Measurements require high statistics

"GLW" method



- Method where D^0 and $\overline{D}^0$ decay to CP eigenstates
- Eigenstates are equally accessible to D^0 and $\overline{D}^0$
- Only 2 hadronic parameters r_B, δ_B to be determined alongside γ (r_B ~0.1)

"Counting experiment" : observe the rate of B^- vs. B^+ decays

Weak phase changes sign for equiv B^+ diagram, thickness of arrows indicate relative strengths

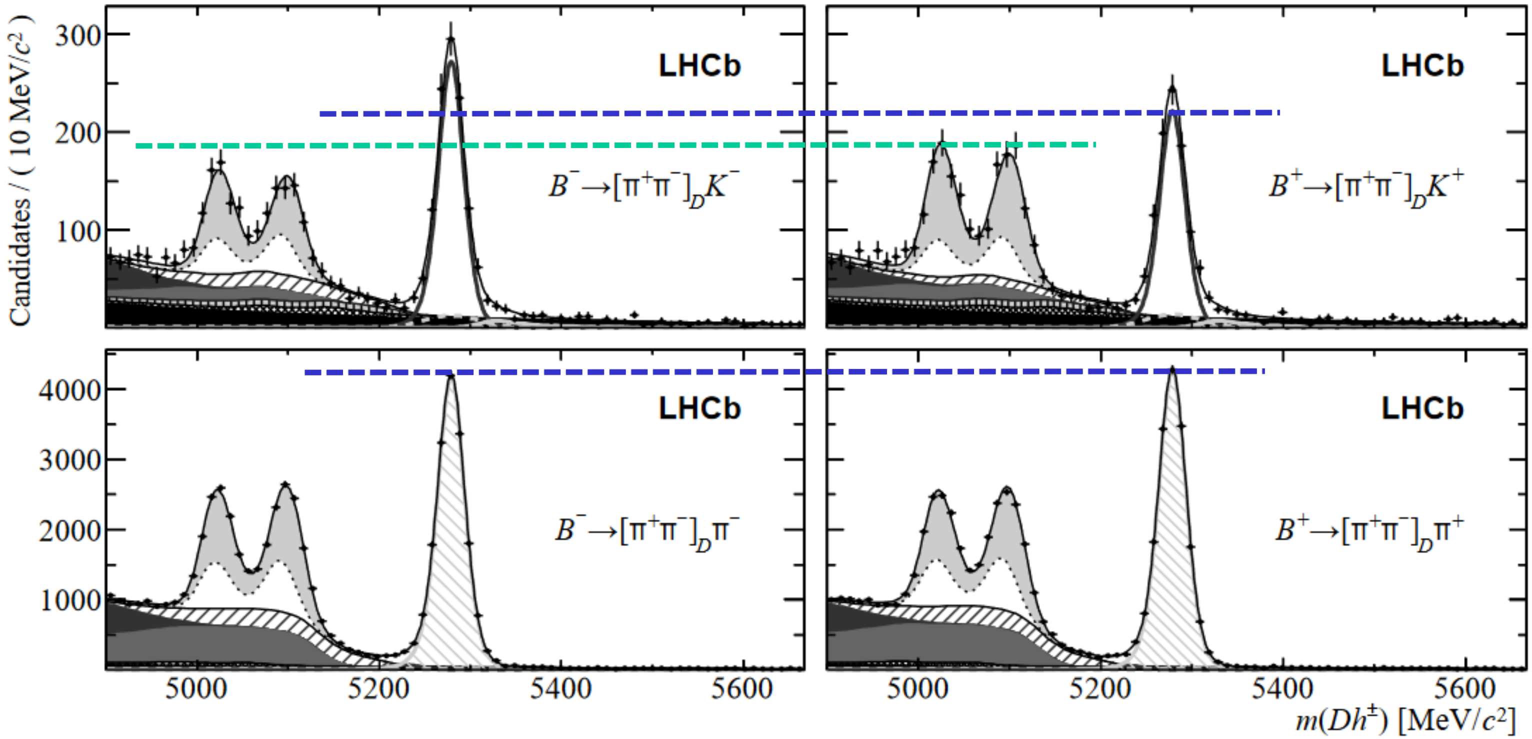
$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ - 1)\sin(\delta_B)\sin(\gamma)$$

$$\frac{N(B\to[KK]_D K)\times\Gamma(D\to K\pi)}{N(B\to[K\pi]_D K)\times\Gamma(D\to KK)} = R_{CP+} = 1 + r_B^2 + 2r_B(2F_+ - 1)\cos(\delta_B)\cos(\gamma)$$

For CP+ eigenstates e.g KK, π π , $F_+ = 1$

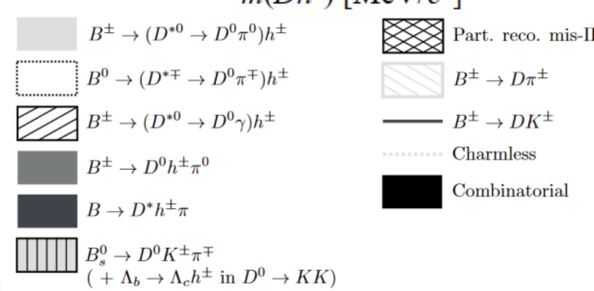
B→D(*)(π π or KK)h   (where h = K, π)

3.0 fb^{-1} Run 1 + 2.0 fb^{-1} Run 2 results



$$A_K^{\pi\pi} = +0.115 \pm 0.025 \text{ (stat)} \pm 0.007 \text{ (syst)}$$

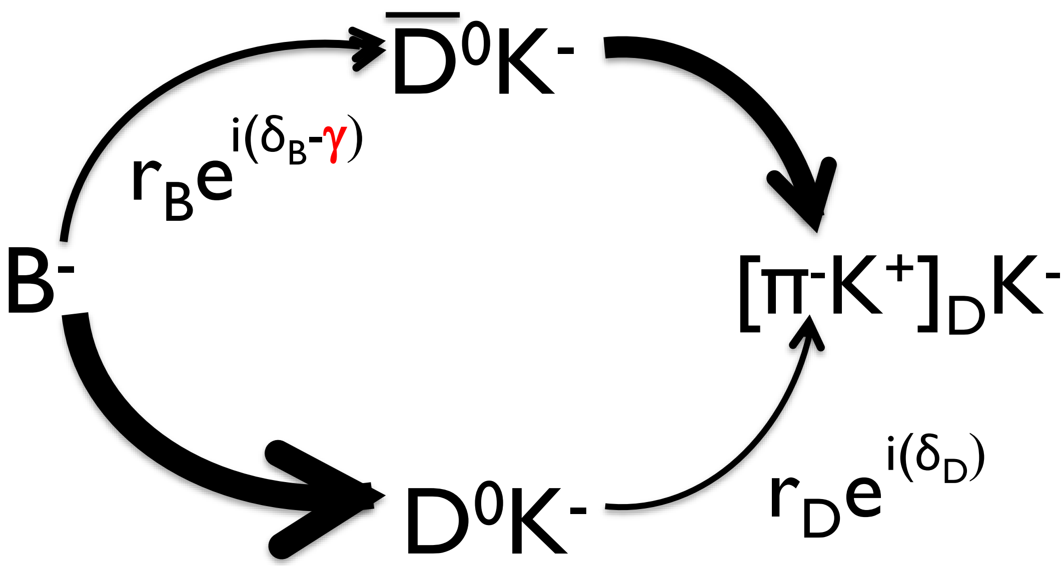
$$A_K^{KK} = +0.126 \pm 0.014 \text{ (stat)} \pm 0.002 \text{ (syst)}$$



Phys Lett B 760 (2016) 117 &
Phys Lett B 777 (2018) 16

At the level of >5σ in some modes

"ADS" method



Weak phase changes sign for equivalent B^+ diagram

- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- r_B, δ_B hadronic parameters again to be determined alongside γ ($r_B \sim 0.1$)
- Additional two parameters r_D, δ_D . External inputs from charm mixing measurements ($r_D \sim 0.06$)

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2r_Br_D \sin(\delta_B+\delta_D)\sin(\gamma)$$

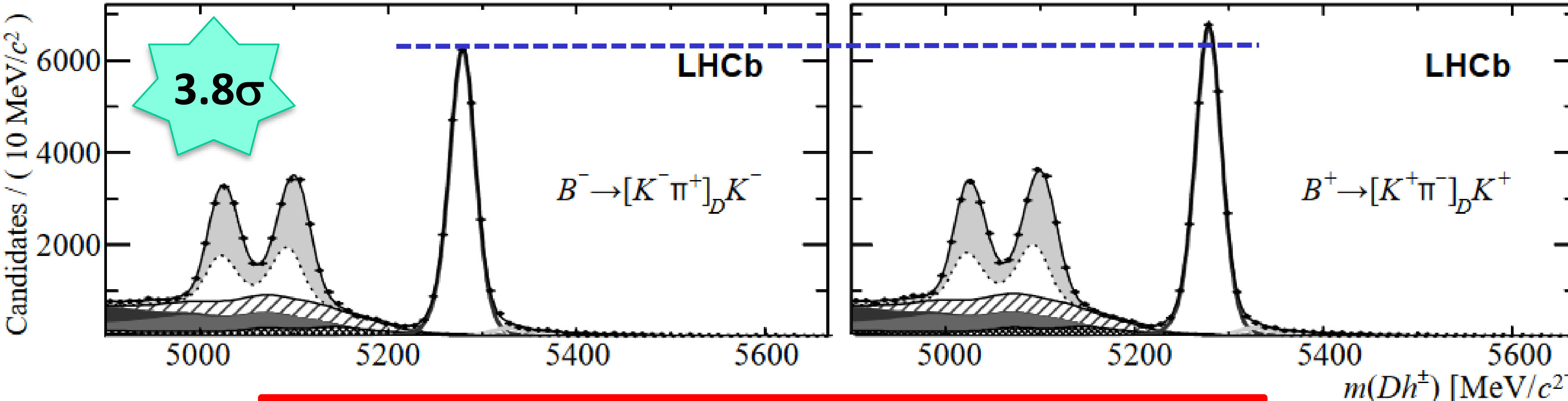
$$\frac{N(B^\pm \rightarrow [\pi^\pm K^\mp]_D K^\pm)}{N(B^\pm \rightarrow [K^\pm \pi^\mp]_D K^\pm)} = R_{ADS} = r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B+\delta_D)\cos(\gamma)$$

Again, a counting experiment : observing the rate of B^- vs. B^+ decays

$B \rightarrow D^{(*)}(K\pi)h$ (where $h = K, \pi$)

Cabibbo favoured : 3.0 fb^{-1} Run 1 + 2.0 fb^{-1} Run 2

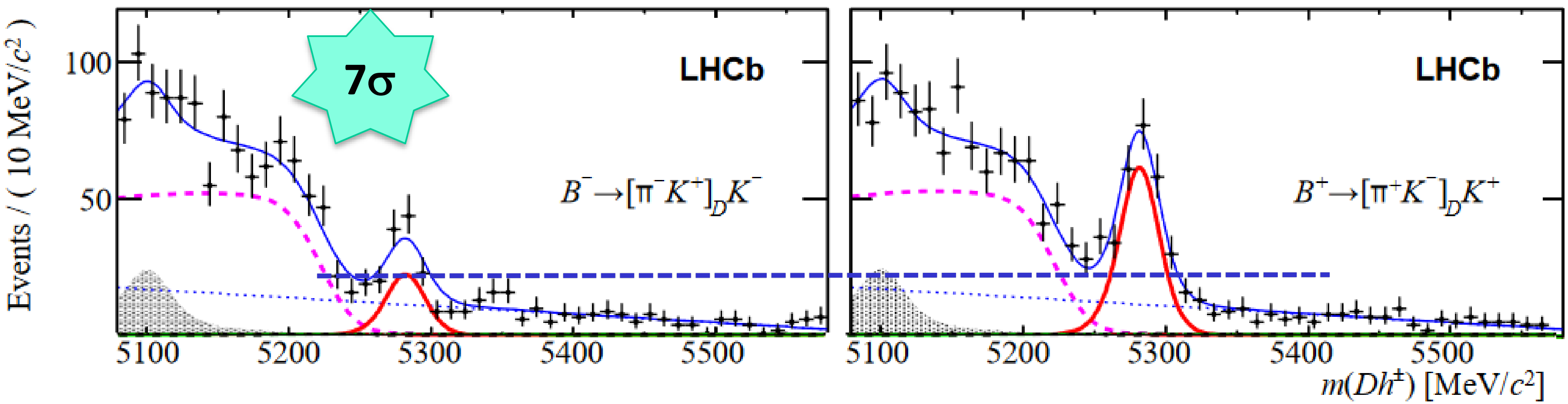
Phys Lett B 777 (2018) 16



$$A_K^{K\pi} = -0.019 \pm 0.005 \text{ (stat)} \pm 0.002 \text{ (syst)}$$

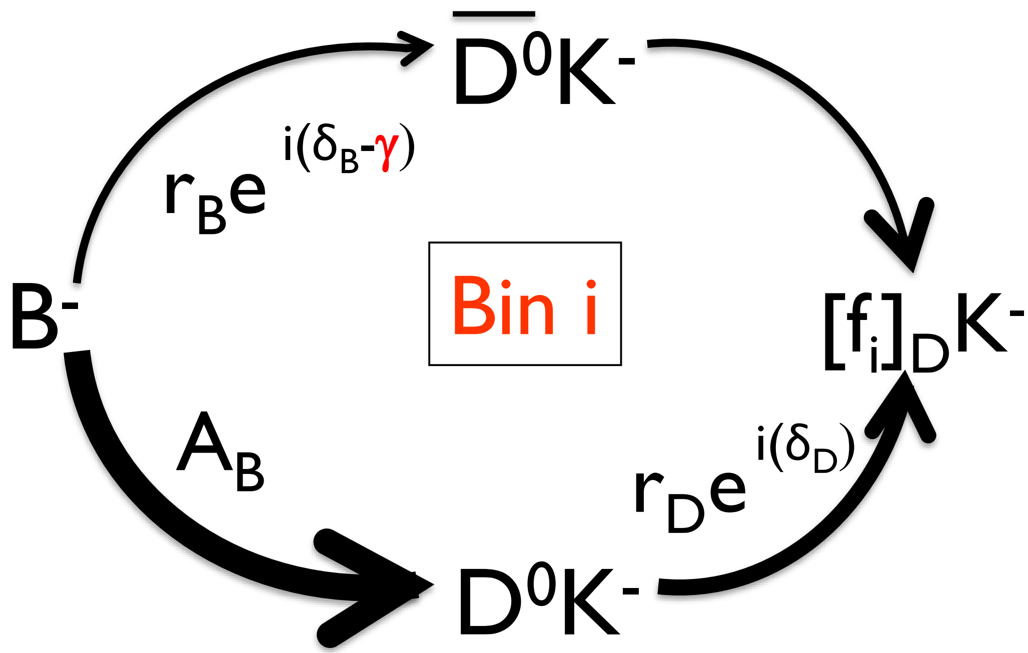
Cabibbo suppressed : 3.0 fb^{-1} Run 1

Phys Lett B 760 (2016) 117



$$A_{\mathrm{ADS}(K)}^{\pi K} = -0.403 \pm 0.056 \pm 0.011$$

"GGSZ" method



Weak phase changes sign for equiv B^+ diagram

- 3-body final D states e.g. $D \rightarrow K^0_S\, \pi\pi$
- Dalitz plot analysis : a counting experiment in bins of phase space, where r_D and δ_D vary

- GGSZ observables (rate as function of Dalitz position)

$$d\Gamma_{B^\pm}(x) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\Big[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\,\underbrace{\cos(\delta_{D(\pm,\mp)})}_{c_i} + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\,\underbrace{\sin(\delta_{D(\pm,\mp)})}_{s_i}\Big]$$

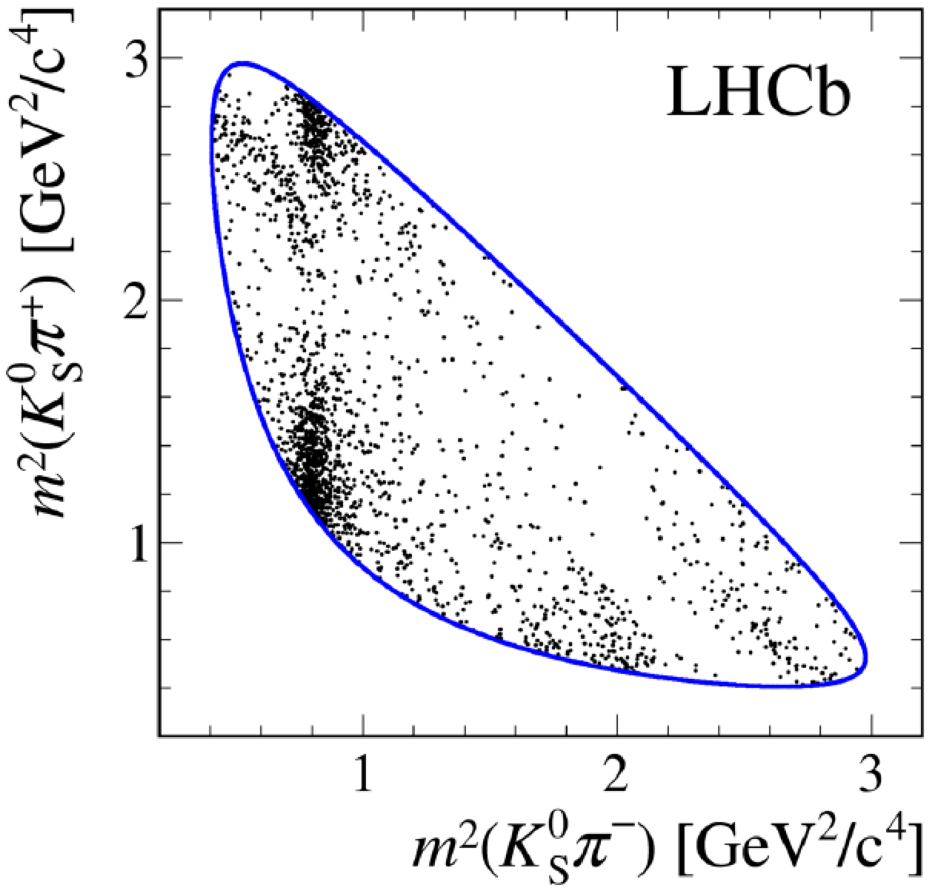
c_i and s_i measured from Q-C D decays at CLEO-c

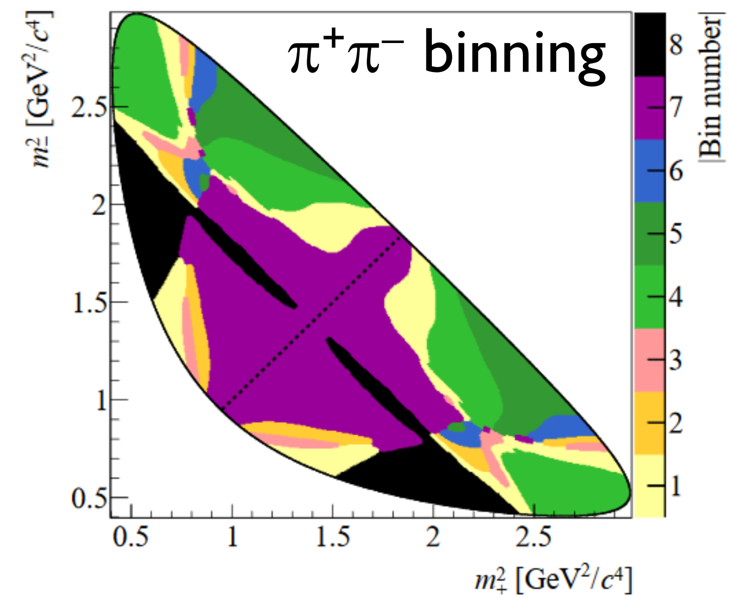
arXiv:1010.2817

New model-independent GGSZ analysis

- CP observables measured in $B^{\pm} \rightarrow DK^{\pm}$ decays with $D \rightarrow K_S\pi^+\pi^-$ and $D \rightarrow K_SK^+K^-$

LHCb-PAPER-2018-017

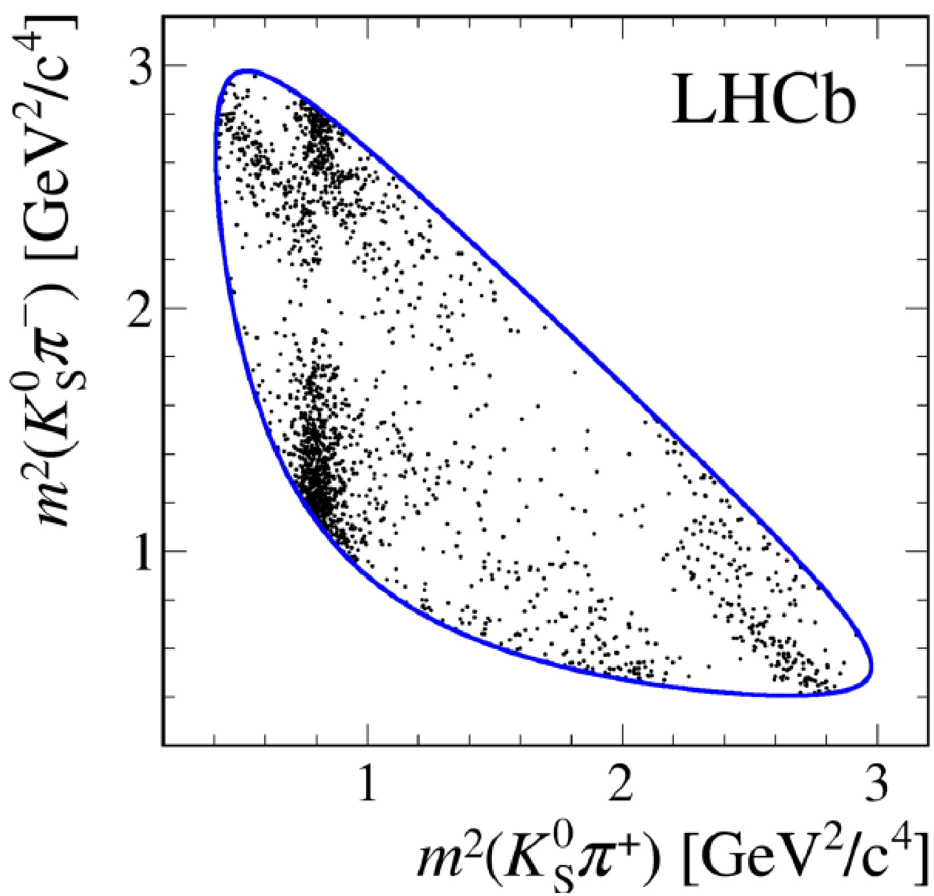




- Divide up Dalitz space into 2N symmetric bins, chosen to optimise sensitivity to γ

New model-independent GGSZ analysis

- CP observables measured in $B^\pm \to DK^\pm$ decays with $D \to K_S\pi^+\pi^-$ and $D \to K_SK^+K^-$



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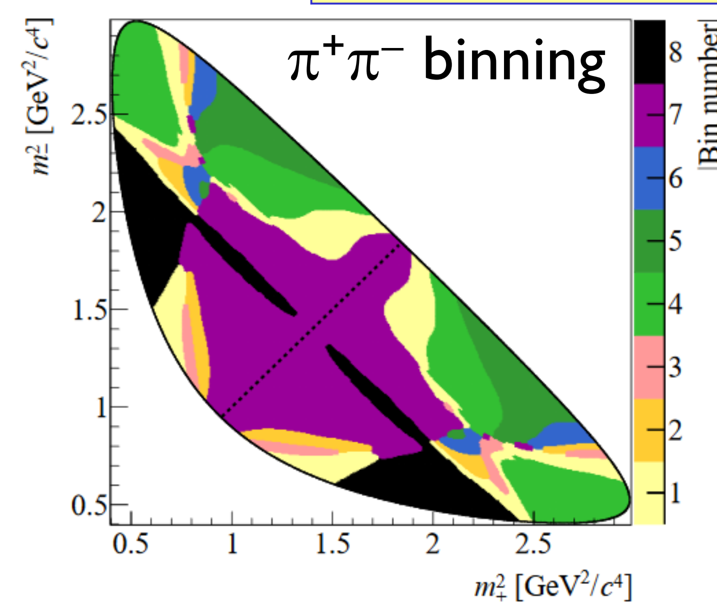
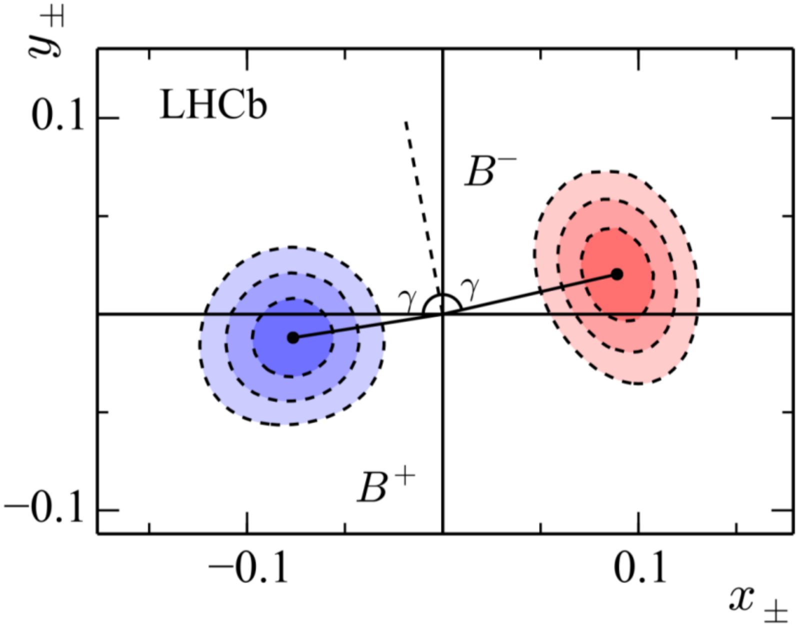
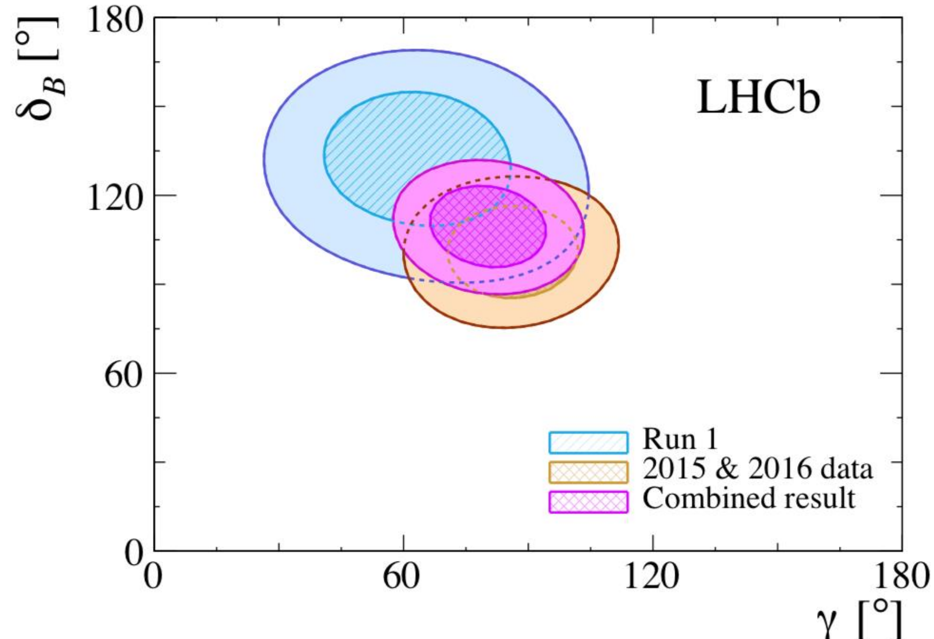


- Divide up Dalitz space into 2N symmetric bins, chosen to optimise sensitivity to γ

New model-independent GGSZ analysis

LHCb-PAPER-2018-017





LHCb GGSZ only

$$\gamma = 80^\circ\,^{+10^\circ}_{-9^\circ}\ \left(^{+19^\circ}_{-18^\circ}\right),$$

$$r_B = 0.080\,^{+0.011}_{-0.011}\ \left(^{+0.022}_{-0.023}\right),$$

$$\delta_B = 110^\circ\,^{+10^\circ}_{-10^\circ}\ \left(^{+19^\circ}_{-20^\circ}\right).$$

The most precise determination of γ from a single analysis

Combination from different modes

- The most recent combination includes the following modes:

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
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	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.

LHCb-CONF-2018-002

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

Dominates HFLAV average :

$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

Indirect constraints are:

$$\gamma = (65.3^{+1.0}_{-2.5})^\circ \ (\sim 2\sigma)$$

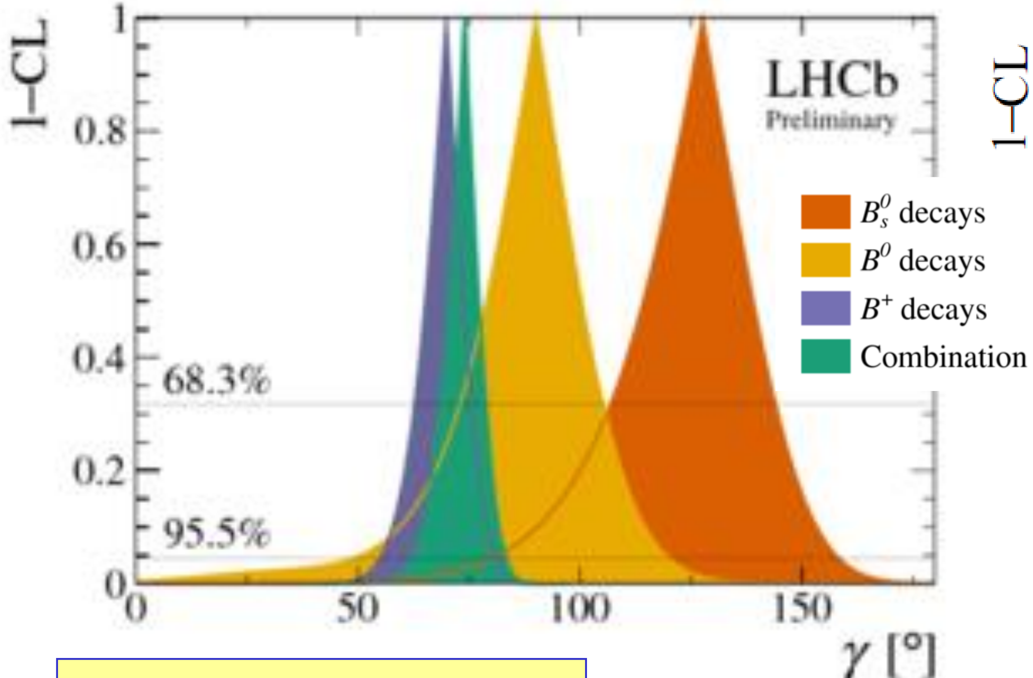
BaBar : $\gamma = (69^{+17}_{-16})^\circ$ PRD 87 (2013) 052015

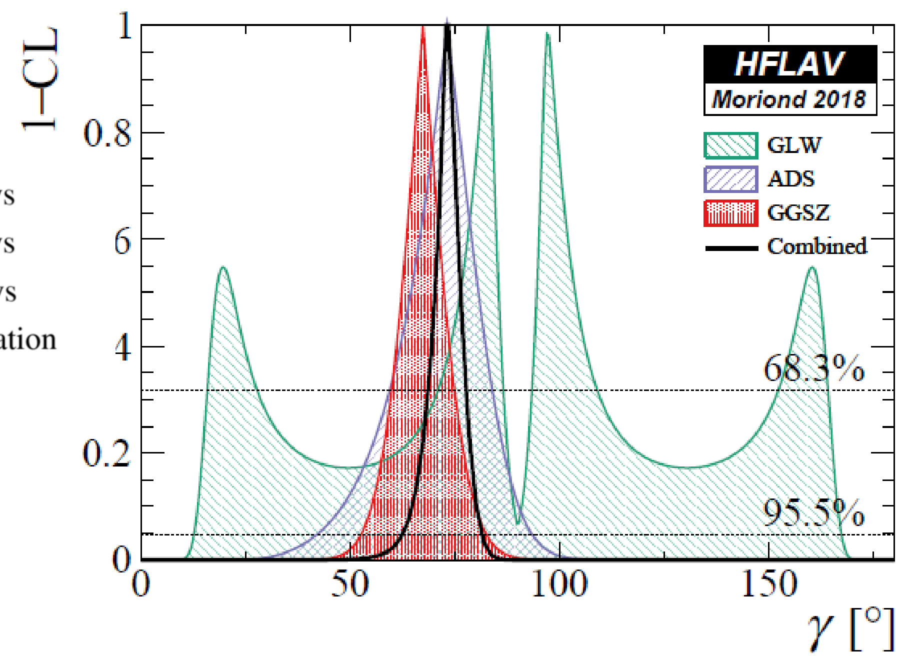
Belle: $\gamma = (73^{+15}_{-14})^\circ$ arXiv:1301.2033

LHCb combination from different modes

LHCb average $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$

HFLAV world average (spring update) $\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$



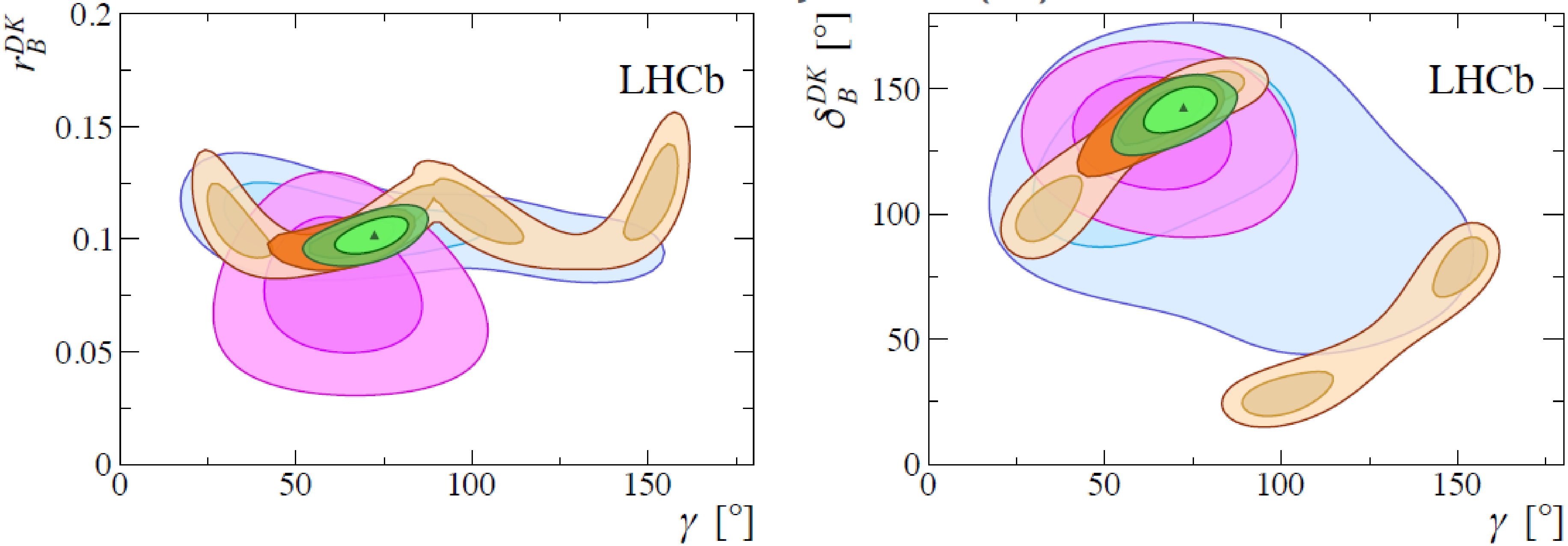


LHCb-CONF-2018-002

- Comparison between B^0_s and $B^{\pm}$ initial states ~ 2 sigma
- More B_s channels under study ($B_s \rightarrow D_s^{(*)}K^{(*)}$, $B_s \rightarrow D\phi$)

Evolution of γ precision

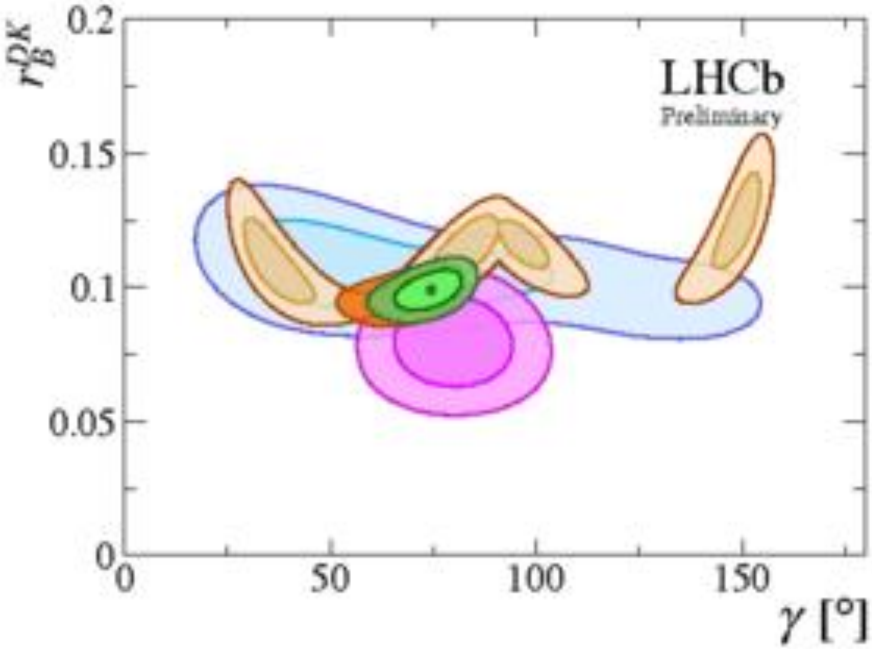
Nov 2016 JHEP 12 (16) 087

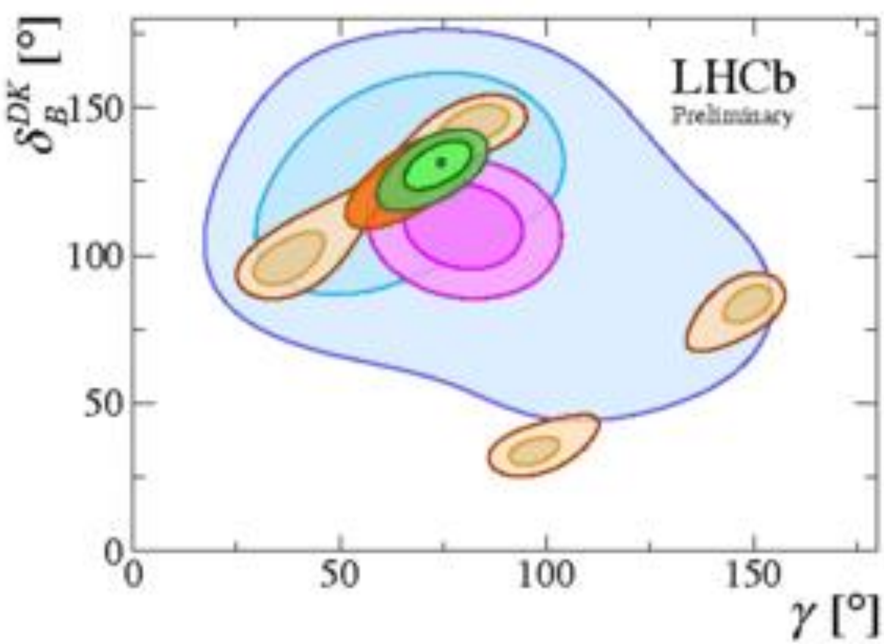


- It is necessary to pursue different B decays to provide crosschecks
- Current measurements still dominated by statistical uncertainties

Evolution of γ precision

Spring 2018 LHCb-CONF-2018-002



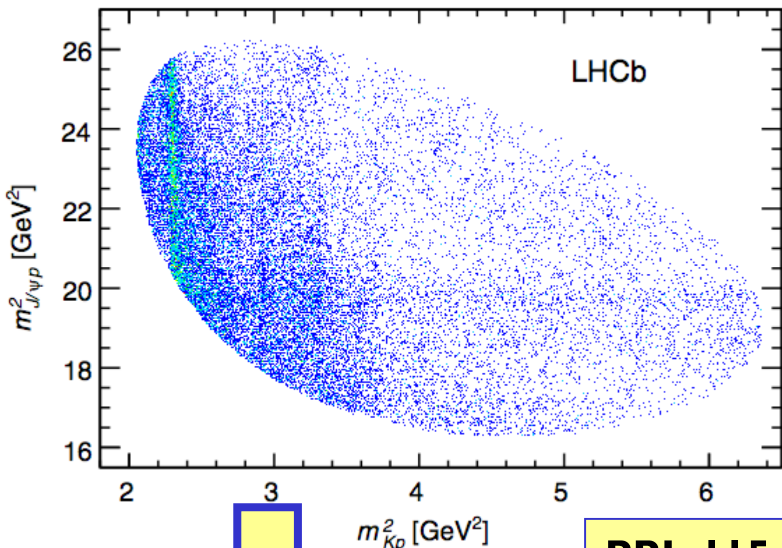


- It is necessary to pursue different B decays to provide crosschecks
- Current measurements still dominated by statistical uncertainties

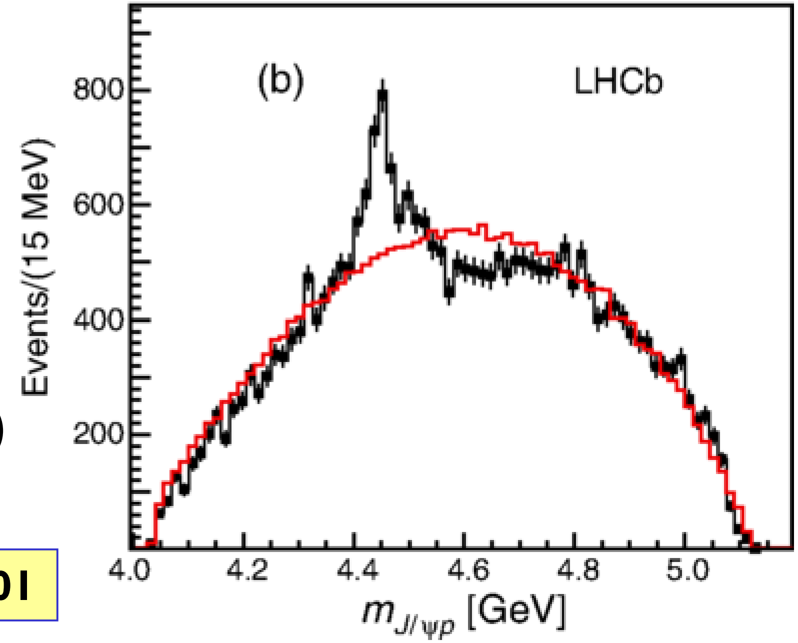
A review of LHCb spectroscopy measurements

Pentaquarks

Observed in 2015→ LHC Run 1 data : 3 fb^{-1}

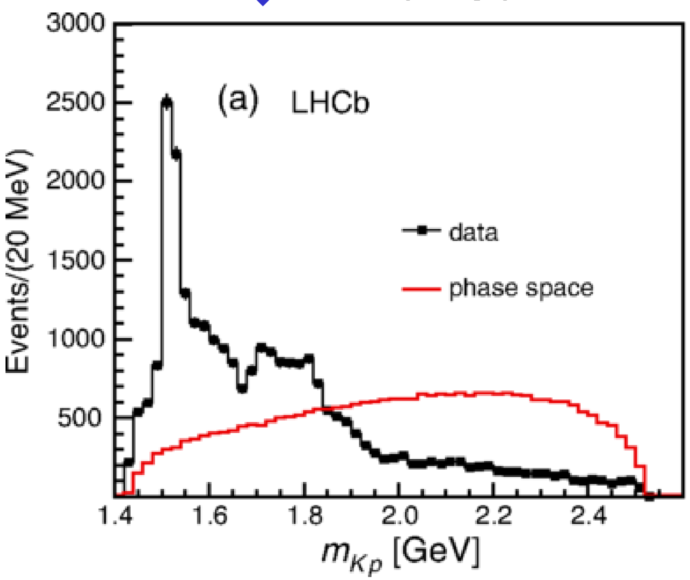


$m(J/\psi\ p)$



$m(K\ p)$

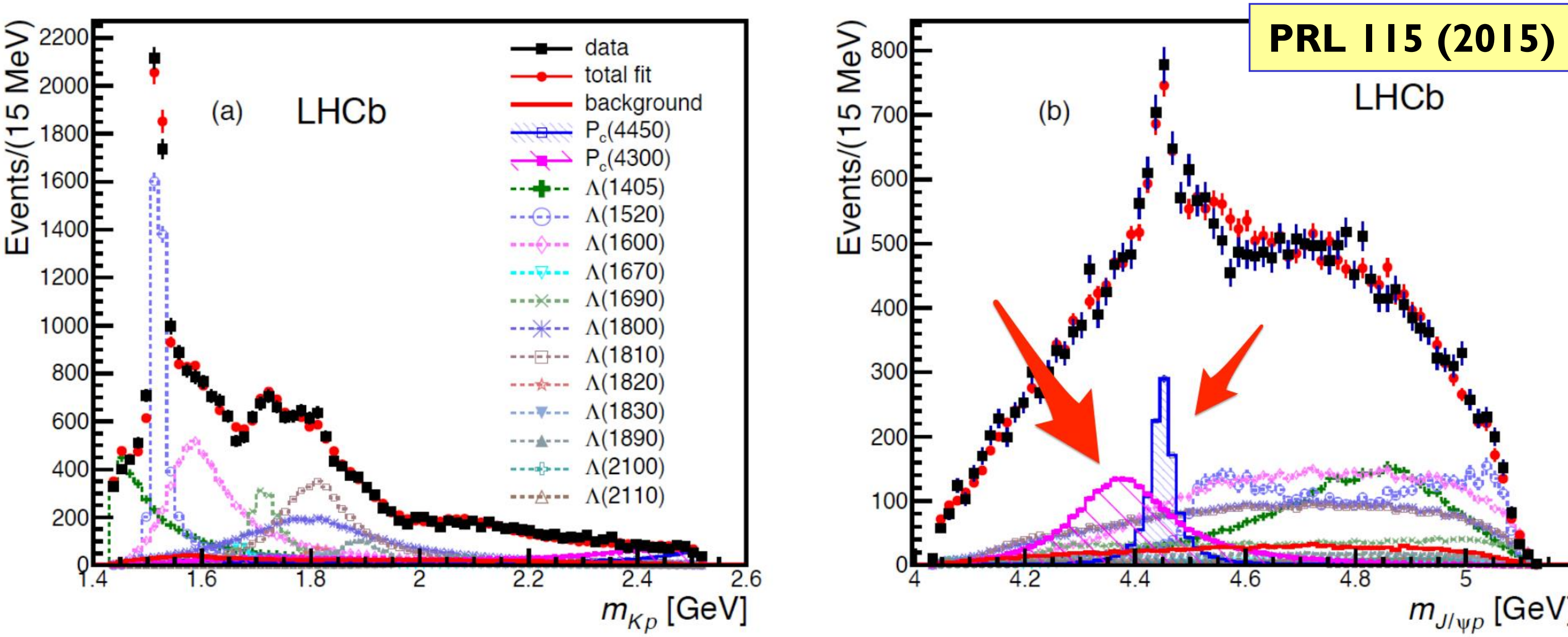
PRL 115 (2015) 072001

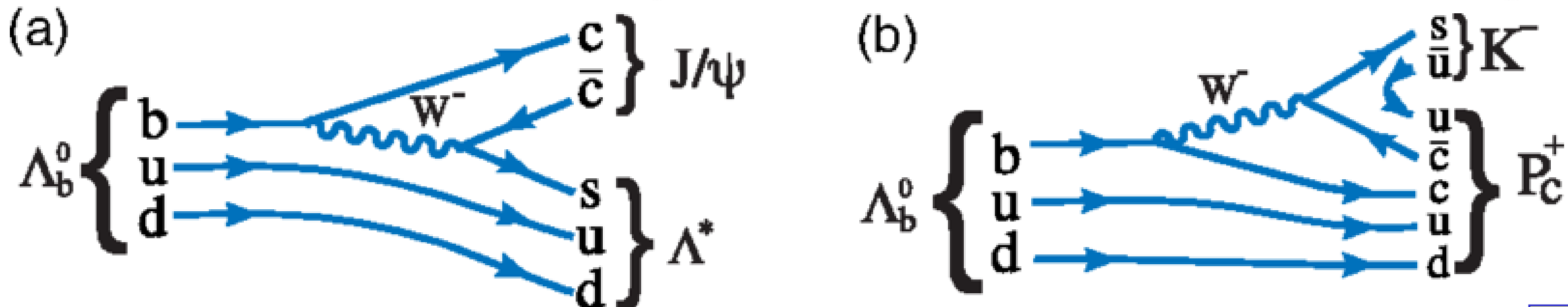


- Observation of unexpected narrow resonance in mass spectrum of $(J/\psi\ p)$ in $\Lambda_b \to (J/\psi\ p)\ K^-$ decays
- Consistent with pentaquarks: allowed by QCD, but not observed in 50 years of searching.

Pentaquarks – full amplitude analysis

PRL 115 (2015) 072001





$P_c^+(4380)$: M = 4380±8±29 MeV , Γ = 205±18±86 MeV

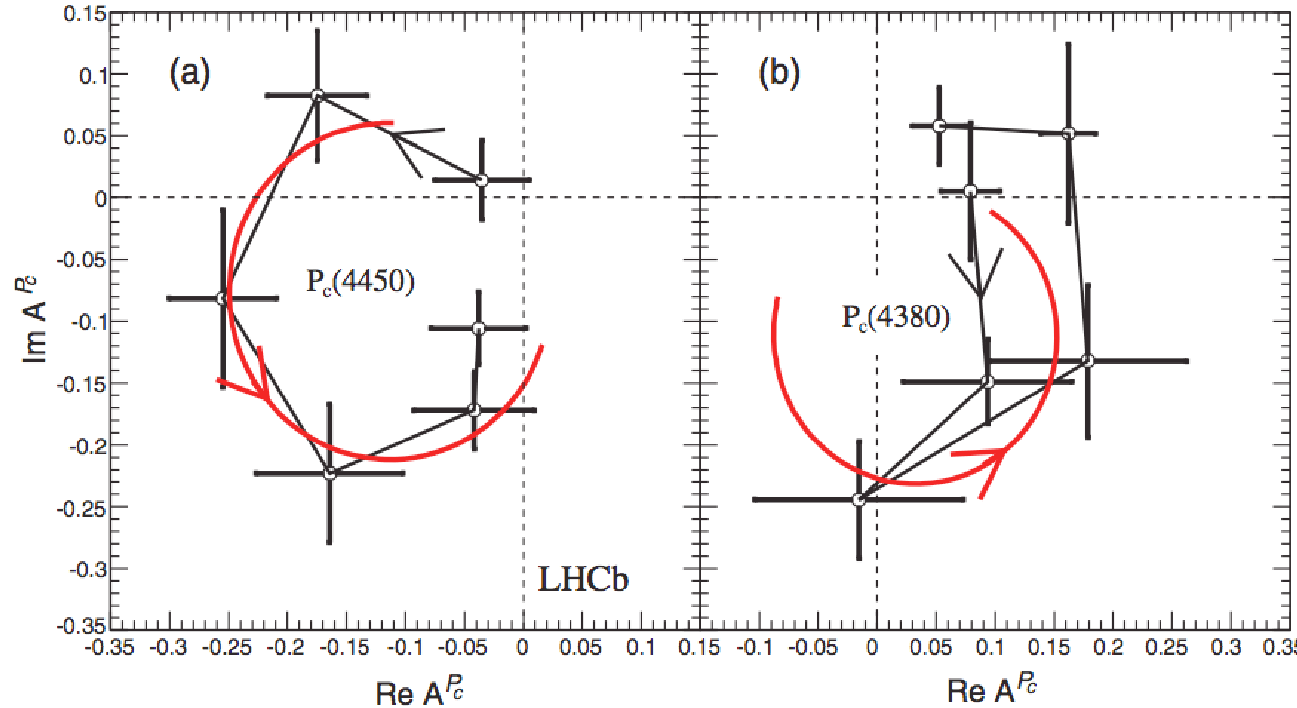
$P_c^+(4450)$: M = 4449.8±1.7±2.5 MeV , Γ = 39±5±19 MeV

9 σ

12 σ

Pentaquarks J^P assignments

Argand diagram



- The preferred J^P assignments are of opposite parity, with $P_c^+(4380)$ having $3/2^-$ and the $P_c^+(4450)$ having $5/2^+$
- Good evidence for the resonant character of $P_c^+(4450)$ Too large errors for $P_c^+(4380)$: hard to make a definitive conclusion. More data to follow.

PRL 115 (2015) 072001

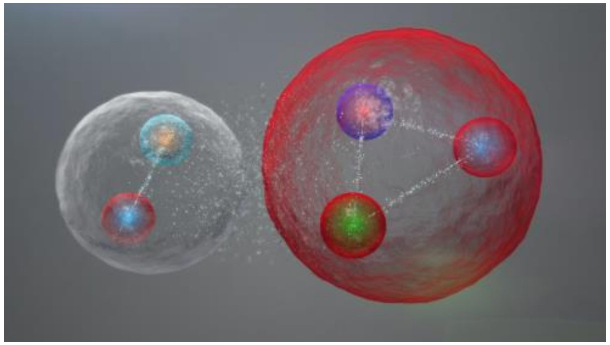
Nature of pentaquarks ?

Possible models describing the observed pentaquark states :

- Meson-baryon molecules

  ("friends in separate bedrooms")

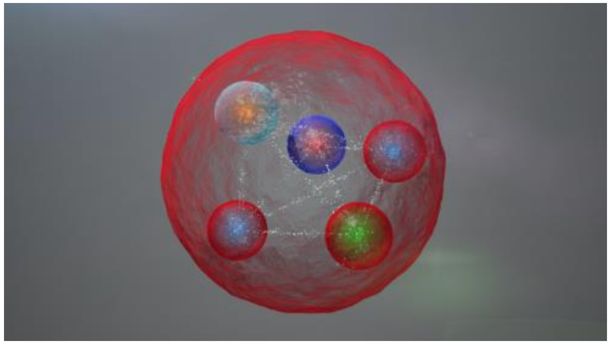
  - PRL 115 (2015) 122001
  - PRL 115 (2015) 172001
  - PRD 92 (2015) 094003



- Tightly bounded states

  ("5 in a bed")

  - PLB 749 (2015) 289
  - PLB 749 (2015) 454
  - JHEP 12 (2015) 128



Pentaquarks in $\Lambda_b \to (J/\psi\ p)\pi^-$

- Search for additional Pentaquark candidates in other production channels
- $\Lambda_b \to (J/\psi\ p)\ \pi^-$ (Cabbibo suppressed ≈ 15 times smaller statistics)
- Contributions from:

  $N^* \to p\pi^-$

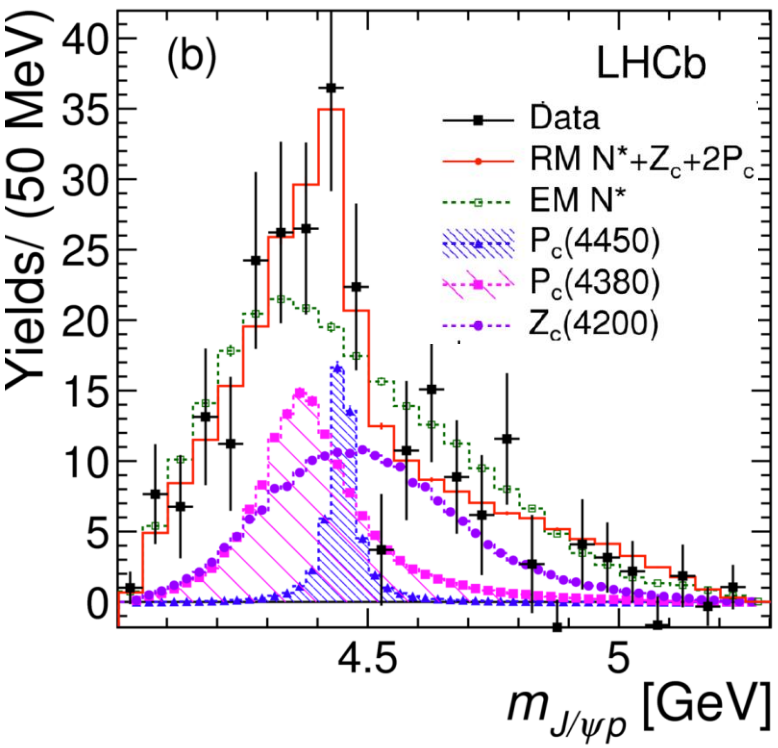
  $P_c(4380)^+ \to J/\psi\ p$

  $P_c(4450)^+ \to J/\psi\ p$

  $Z_c(4200)^- \to J/\psi\ \pi^-$

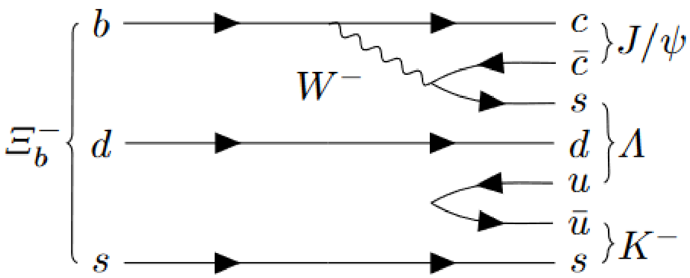
- Fit with 2 pentaquarks + $Z_c(4200)$ tetraquark : favoured by 3σ compared to no exotic contributions

PRL 115 (2015) 072001



Another possible pentaquark mode

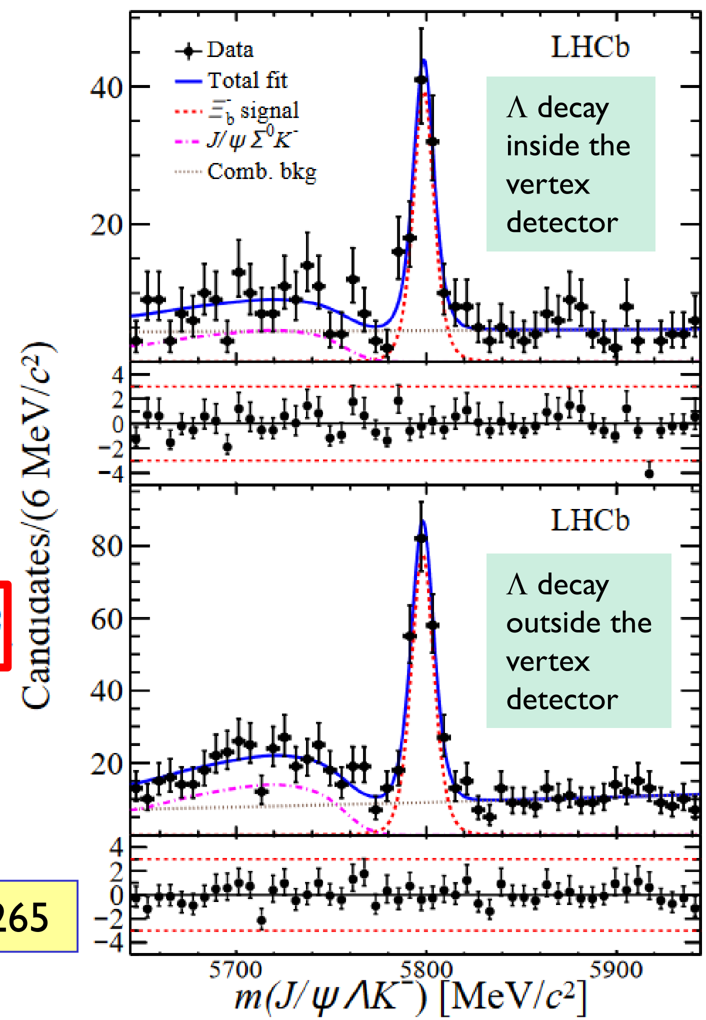
- Can look for udsc̄c pentaquark in $\Xi_b^-(bds) \rightarrow J/\psi \Lambda K^-$



- Observation of Ξ_b^- in Run I data (~300 candidates)

$$M(\Xi_b^-) - M(\Lambda_b^0) = 177.08 \pm 0.47\ (\text{stat}) \pm 0.16\ (\text{syst})\ \text{MeV}/c^2$$

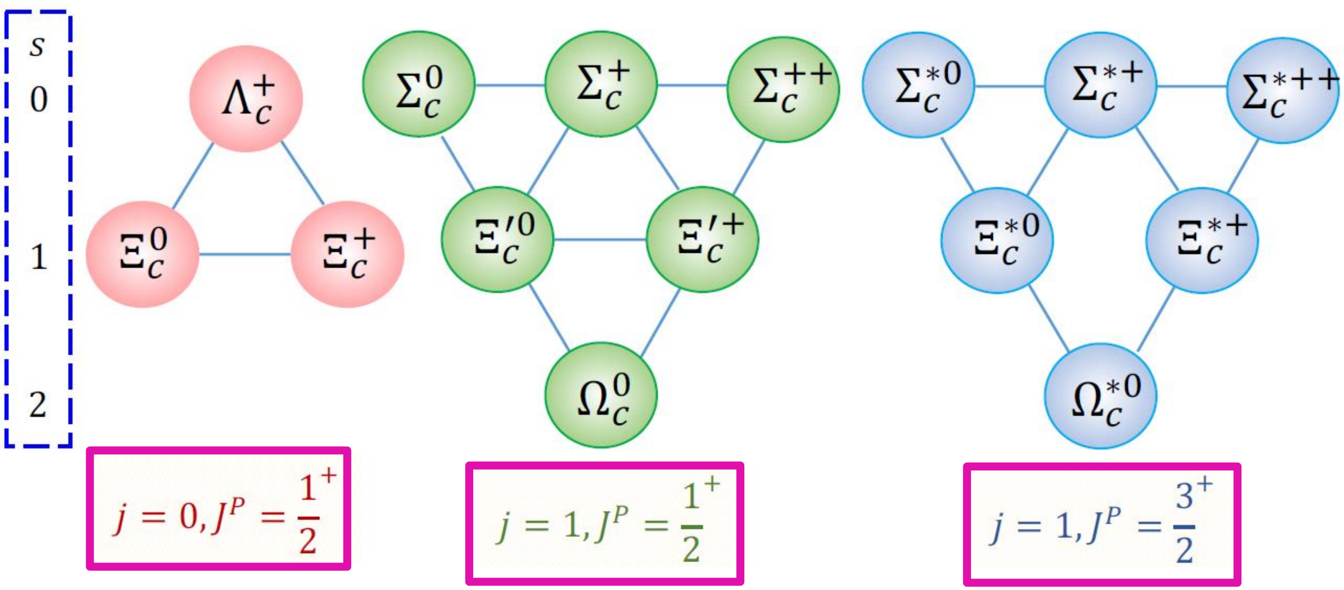
- Amplitude analysis with Run II data to follow



Phys. Lett. B 772 (2017) 265

Observation of Ω_c excited states

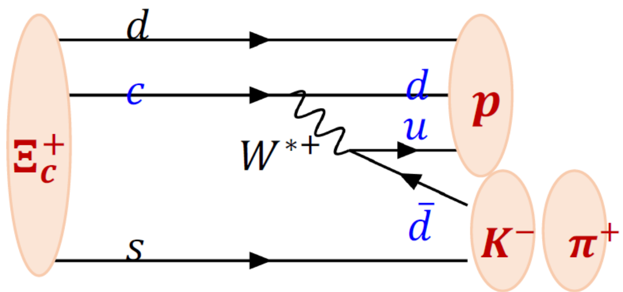
- Single charmed baryons predicted to form SU(3) $3 \otimes 3 = \bar{3} \oplus 6$ baryon multiplets (Jaffe, Phys. Rep. 409 (2005) 1)
- All ground states have been observed, as have excited states Λ_c, Σ_c and Ξ_c

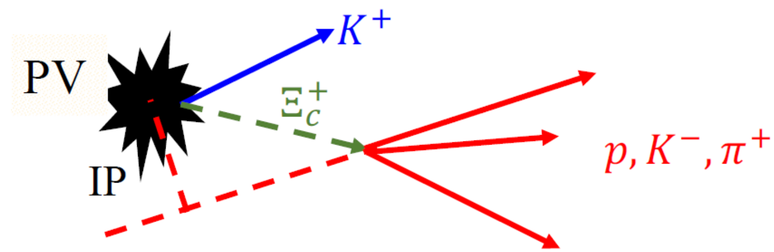


- LHCb: 3 fb^{-1} Run I + 0.3 fb^{-1} Run II pp collisions data

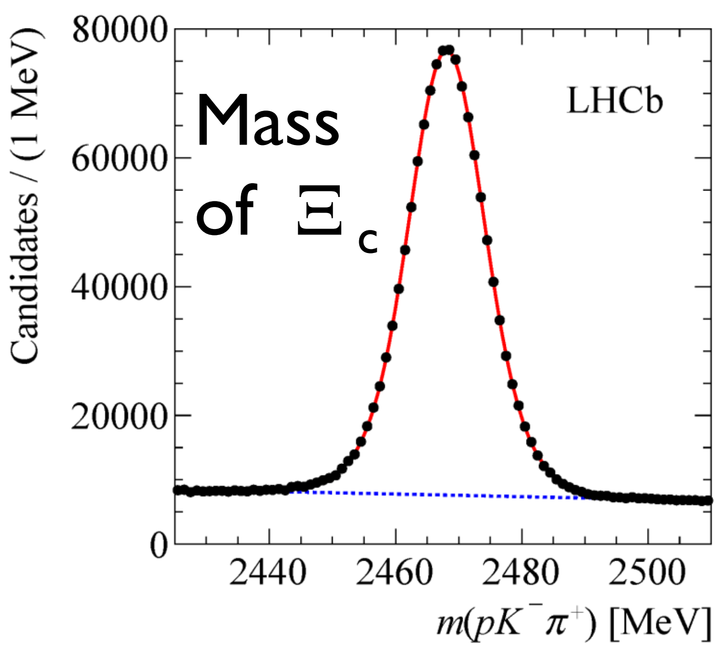
Observation of five new narrow Ω_c^0 excited states

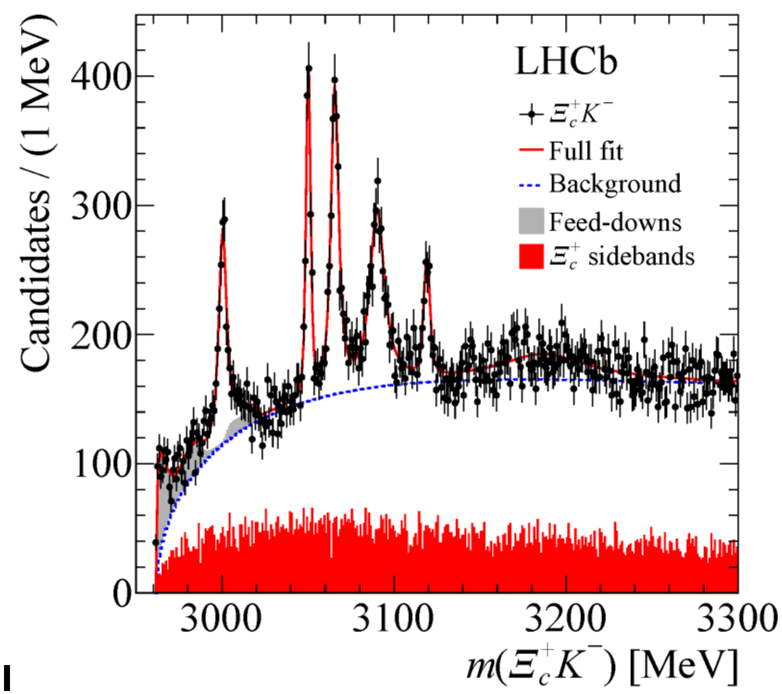
- Decay : Ω_c^{0*} (css) $\rightarrow \Xi_c^+$ (csu) K^- ; Ξ_c^+ (csu) $\rightarrow pK^-\pi^+$





- Decay well separated from primary vertex $\tau(\Xi_c) \approx 45$ ps





LHCb, PRL 118 (2017) 182001

Masses and widths

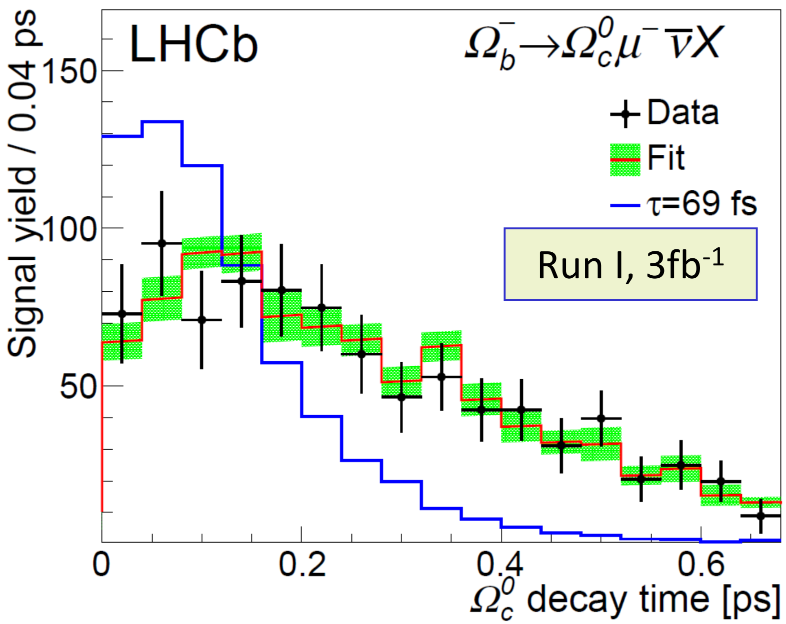
LHCb, PRL 118 (2017) 182001

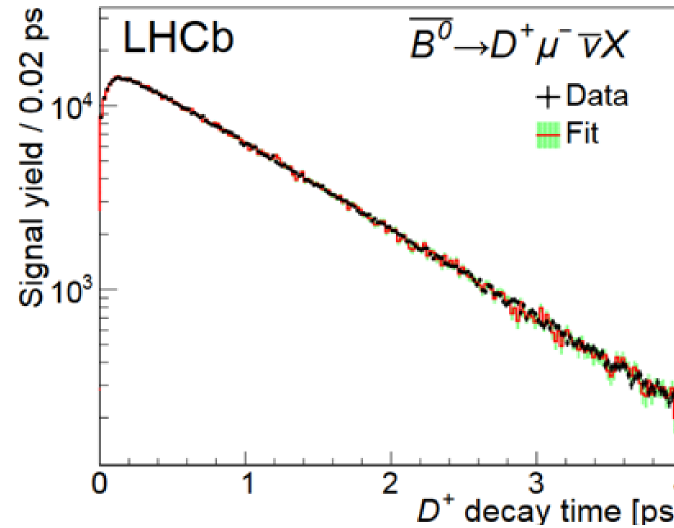
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		$< 1.2\,\text{MeV}, 95\%$ CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		$< 2.6\,\text{MeV}, 95\%$ CL
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

- 5 narrow states & evidence for 6th broader state at high mass
- Assignment of J^P states in the quark model (see backup slides)
  (M. Karliner, J.L. Rosner, PR D95, 114012 (2017))
- Suggestion the 2 narrowest states might be pentaquarks ?
  (Michał Praszałowicz et al Phys.Rev. D96 (2017) 014009)
- Confirmation of states awaits spin-parity assignments (coming)

The puzzle of the $\Omega_c^{\pm}$ lifetime

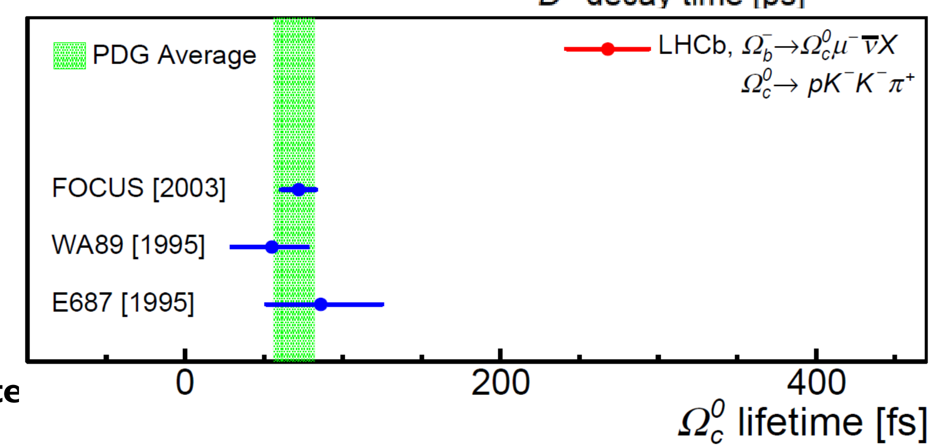
- Via the decay $\Omega_b^{\pm} \rightarrow \Omega_c^0 \mu^{\pm} \nu_\mu X$ then $\Omega_c^0 \rightarrow pK^-K^-\pi^+$ [Ω_c^0 is (css)]
- Measured relative to that of D^+ meson decays (reduce systematics)
- Lifetime ~4 times greater than previous experiments, which have ~10 times less statistics





$\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2$ fs

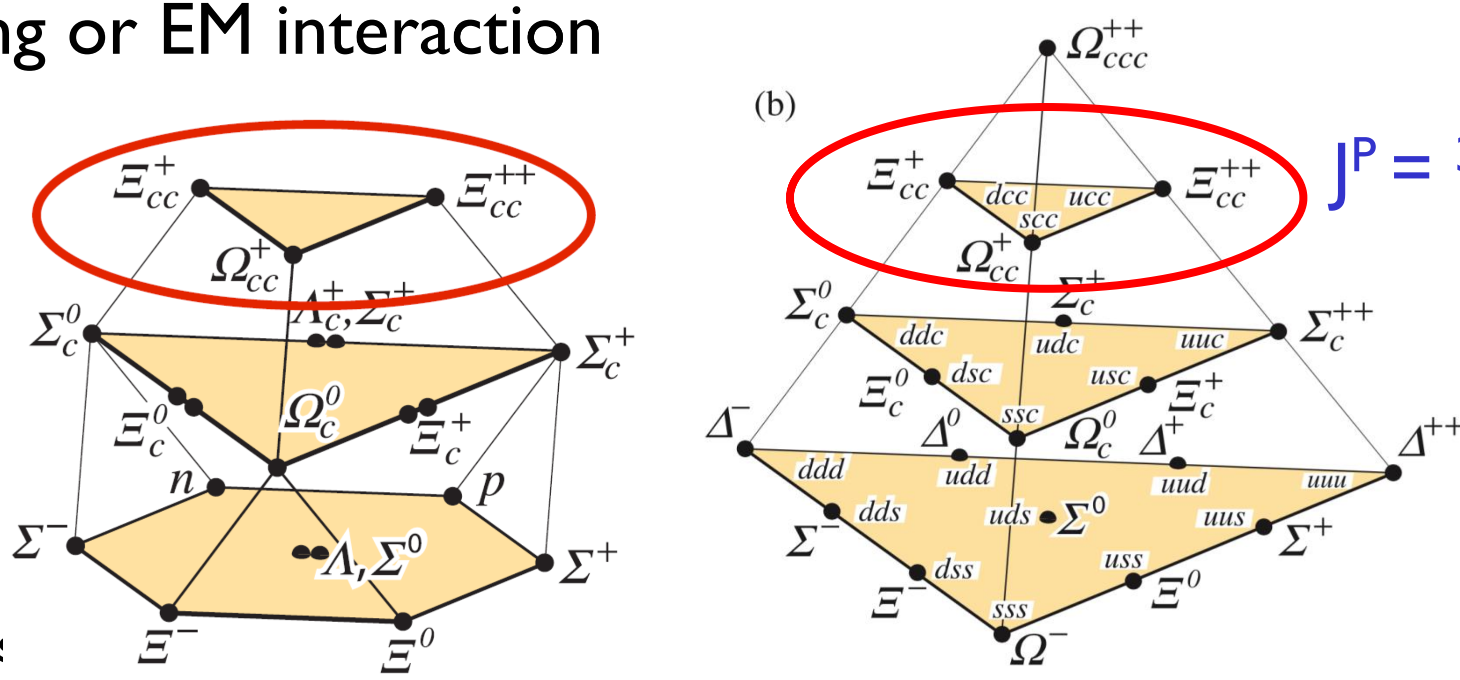
arXiv:1807.02024



Search for the doubly charmed baryon Ξ_{cc}^{++}

- The quark model predicts three weakly decaying $C = 2$ $J^P = ½^+$ states: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, and $\Omega_{cc}^{+}(ccs)$
- $J^P = ½^+$ states decay weakly with a c quark decaying to lighter quarks
- $J^P = {}^3/_2{}^+$ states expected to decay to $½^+$ states via strong or EM interaction

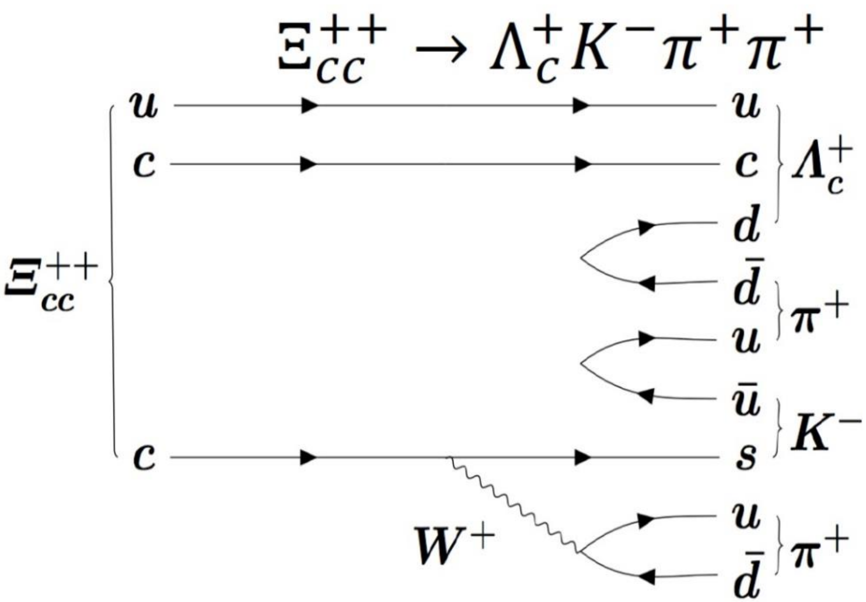
$J^P = {}^1/_2{}^+$

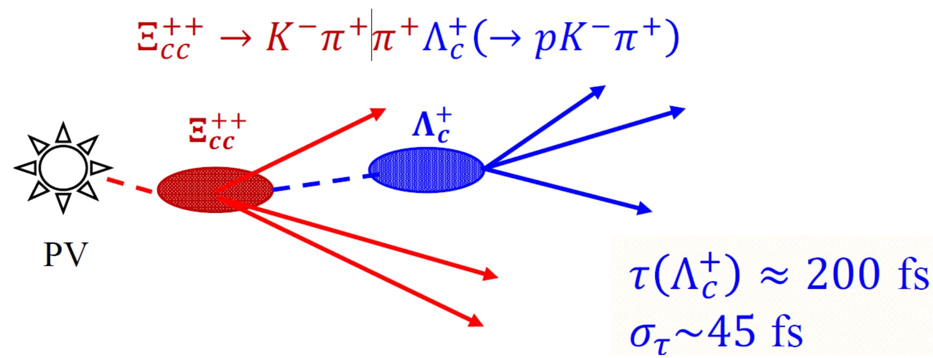


$J^P = {}^3/_2{}^+$

Decay mode of Ξ_{cc}^{++}

- Search in decay mode : $\Xi_{cc}^{++} \rightarrow \Lambda_c K^- \pi^+ \pi^+$ Branching fraction can be significant (10%) (Yu et al., arXiv:1703.09086)
- Run 2 data sample: $\sqrt{s}$=13 TeV, ~1.7 fb^{-1}





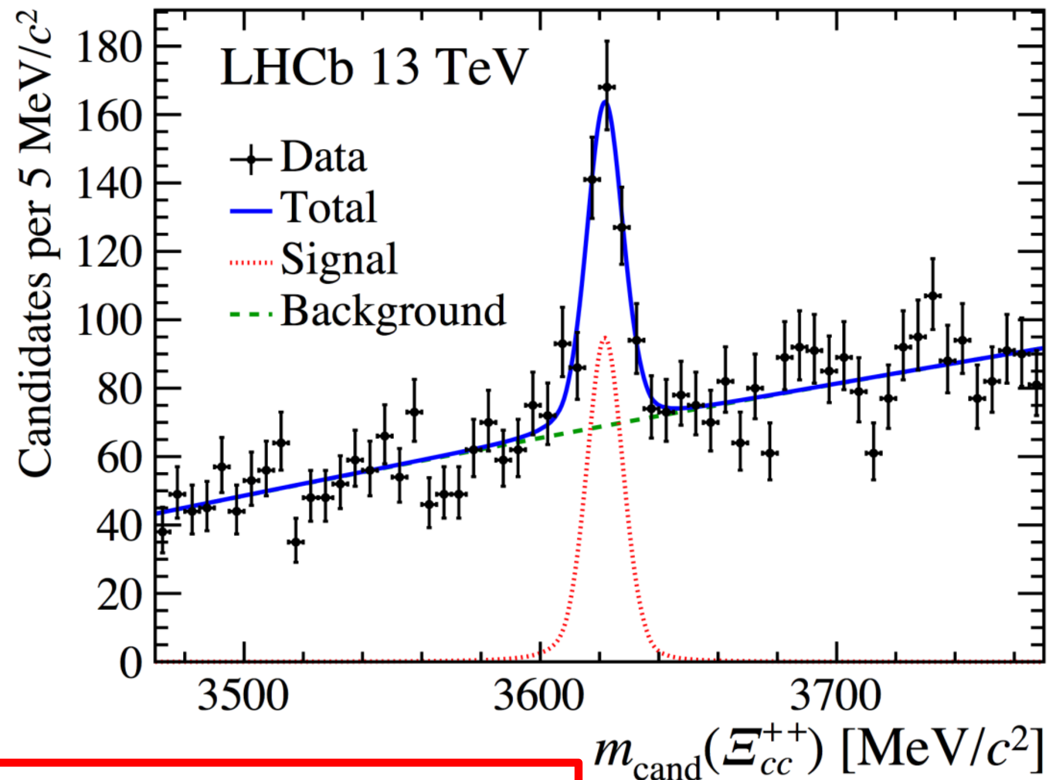
Observation of Ξ_{cc}^{++}

PRL 119 (2017) 112001

- Ξ^{++} is Λ_c-mass corrected :

$$m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$$

- Signal yield: 313 ± 33 events
- Width 6.6±0.8 MeV, consistent with resolution
- Local significance > 12σ



$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$

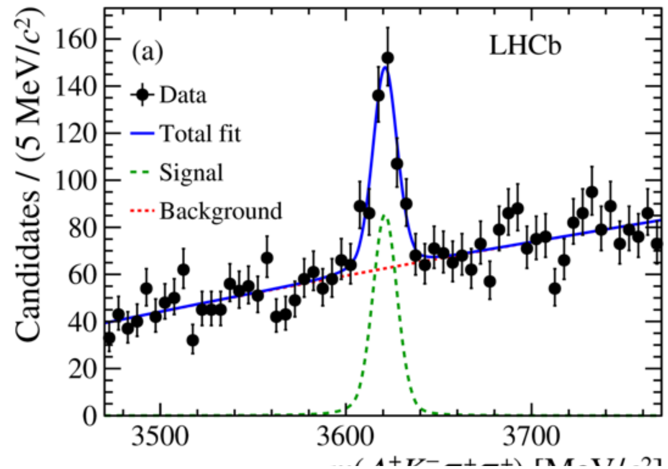
Ξ_{cc}^{++} new result : lifetime measurement

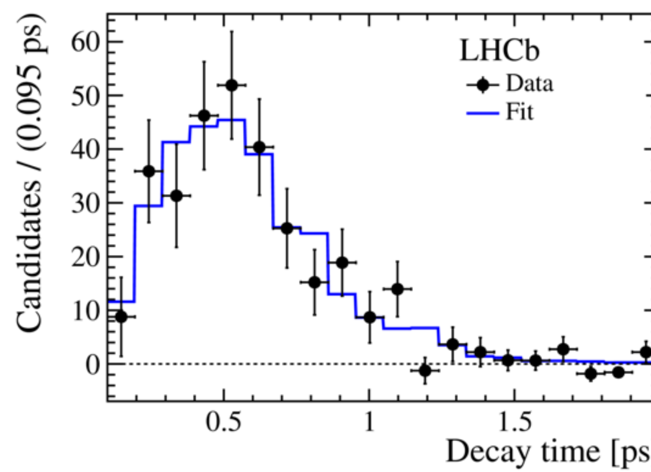
Phys. Rev. Lett. 121, 052002 (2018)

- Analysis of 1.7 fb^{-1} sample of Run 2 data, using $\Lambda^0_b \to \Lambda_c^+ K^- \pi^+ \pi^+$ control mode to measure the Ξ_{cc}^{++} lifetime with respect to that of Λ^0_b
- Lifetime result :

$$\tau(\Xi_{cc}^{+}) = (256^{+24}_{-22} \pm 14)\,\mathrm{fs}$$

- Confirms that Ξ_{cc}^{++} is a weakly decaying baryon.



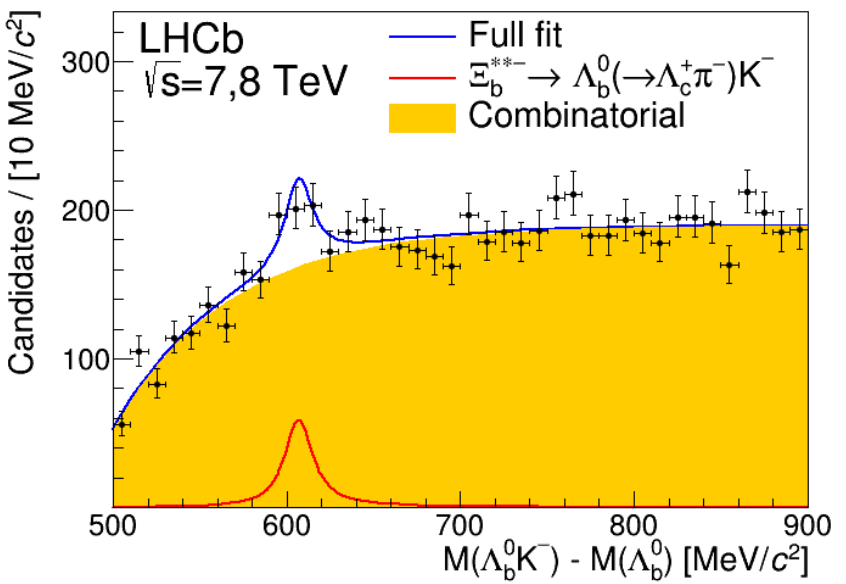


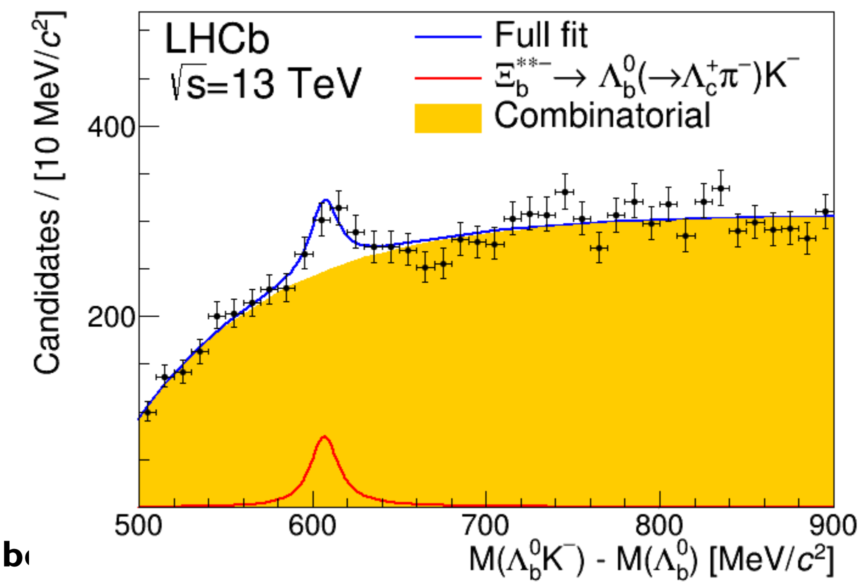
Observation of a new Ξ_b^{**-} resonance

- Seen both in $\Xi_b^{**-} \rightarrow \Lambda_b^0 K^-$ & $\Xi_b^{**-} \rightarrow \Xi_b^0 \pi^-$ decays
- J^P not yet measured
- Measure with hadronic mode $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$

$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})\ \mathrm{MeV}/c^2,$$
$$\Gamma = 18.1 \pm 5.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst})\ \mathrm{MeV}/c^2,$$
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst}) \pm 0.2(\Lambda_b^0)\ \mathrm{MeV}/c^2.$$

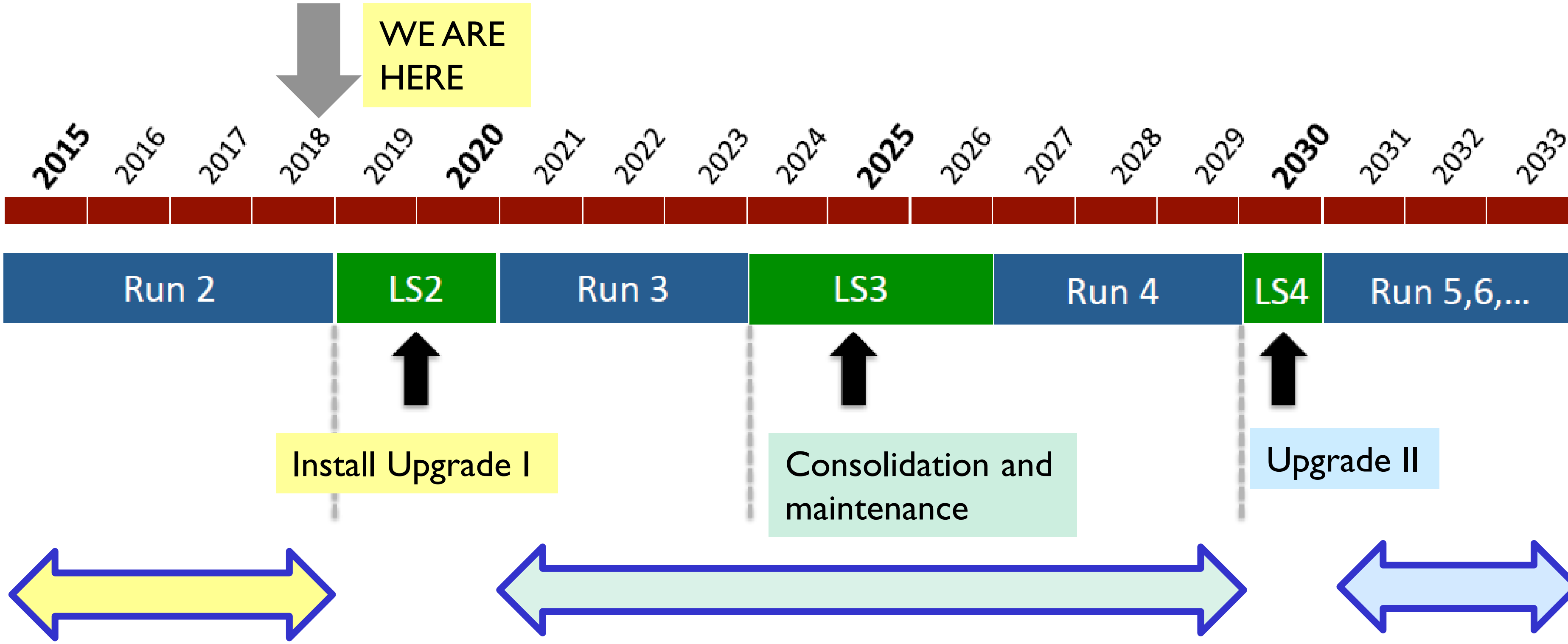
arXiv:1805.09418





The upgraded LHCb detector and outlook

LHCb Upgrade planning

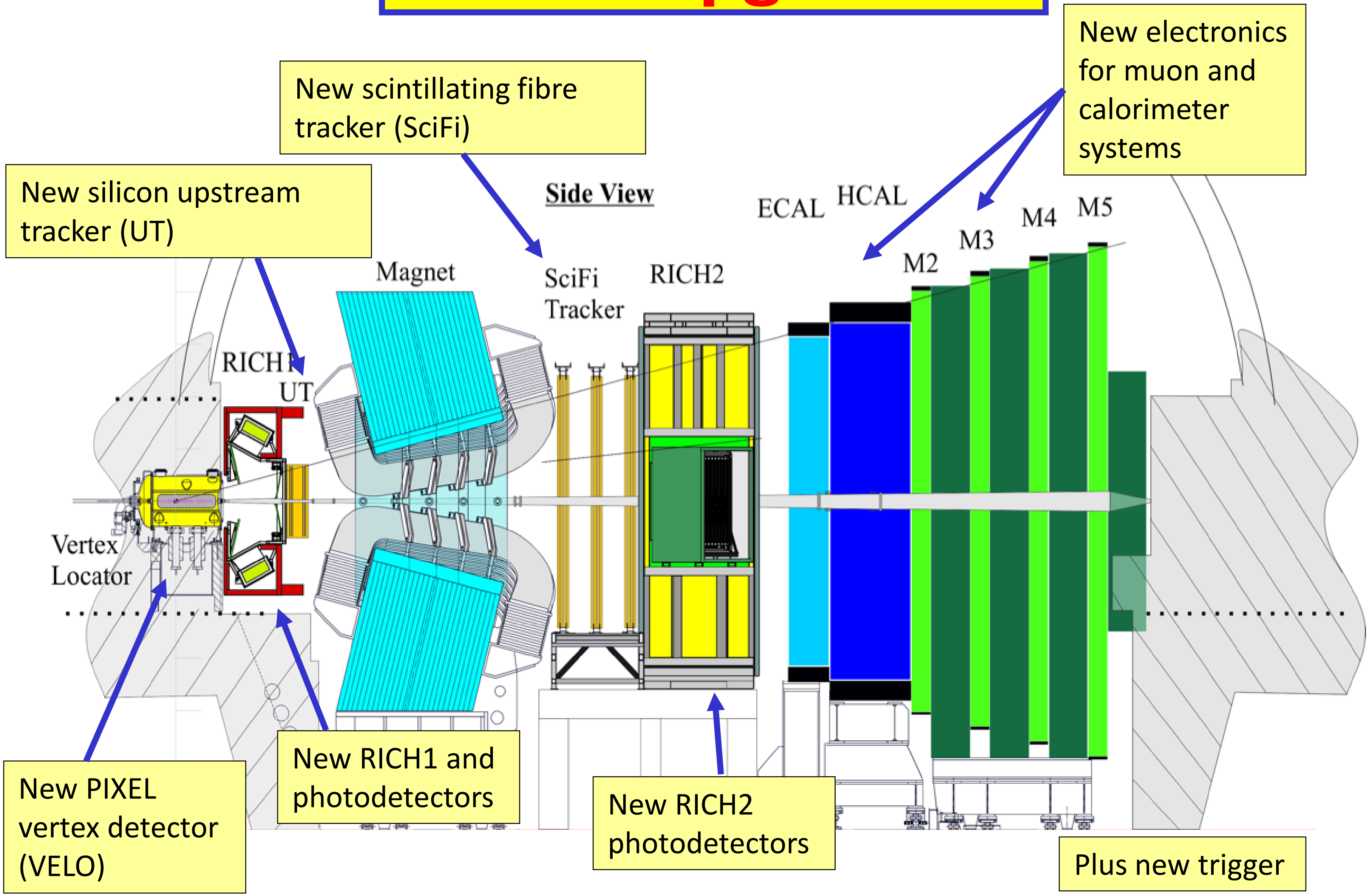


Luminosity 4x10^{32} cm^{-2}s^{-1}
~1.1 visible interactions/crossing
Up to10 fb^{-1} collected

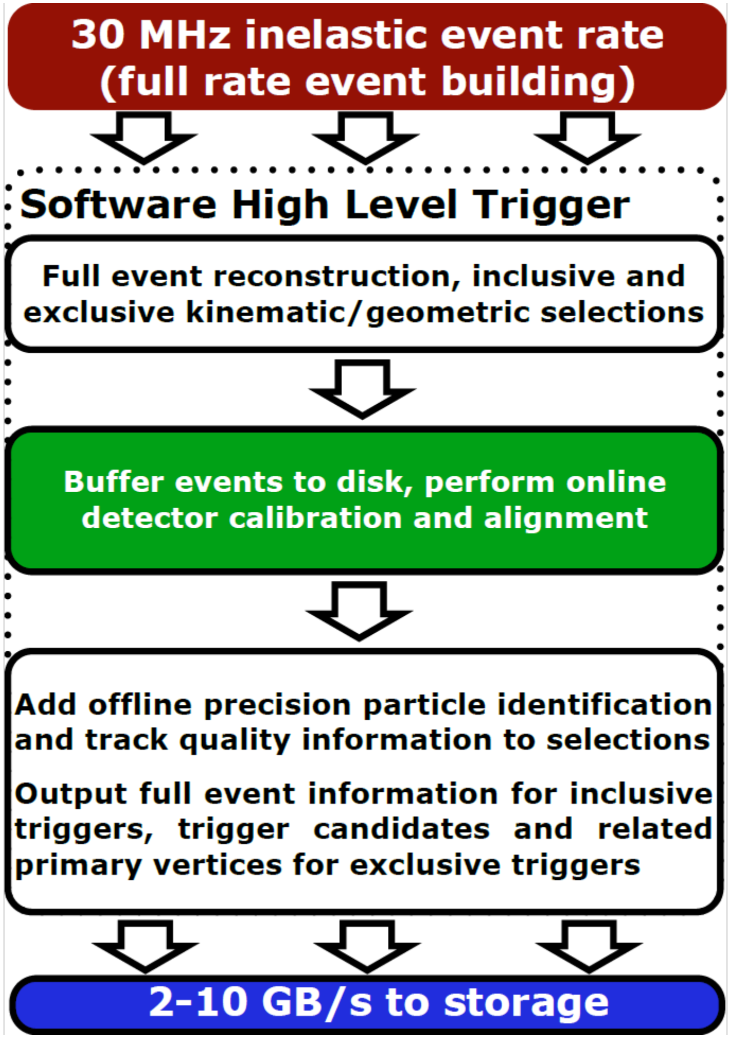
Luminosity 2x10^{33} cm^{-2}s^{-1}
~5.5 visible interactions/crossing
Up to 50 fb^{-1} collected

Luminosity 2x10^{34} cm^{-2}s^{-1}
~55 visible interactions/crossing
300 fb^{-1} collected

LHCb Upgrade I



LHCb Upgrade I trigger system



- Trigger-less readout and full software trigger
  - Process data at machine clock (40 MHz crossings and 30 MHz of visible interactions)
  - No L0 (hardware) bottleneck
- No further offline processing
  - Run II is already a critical testbed for this technology (turbo mode)

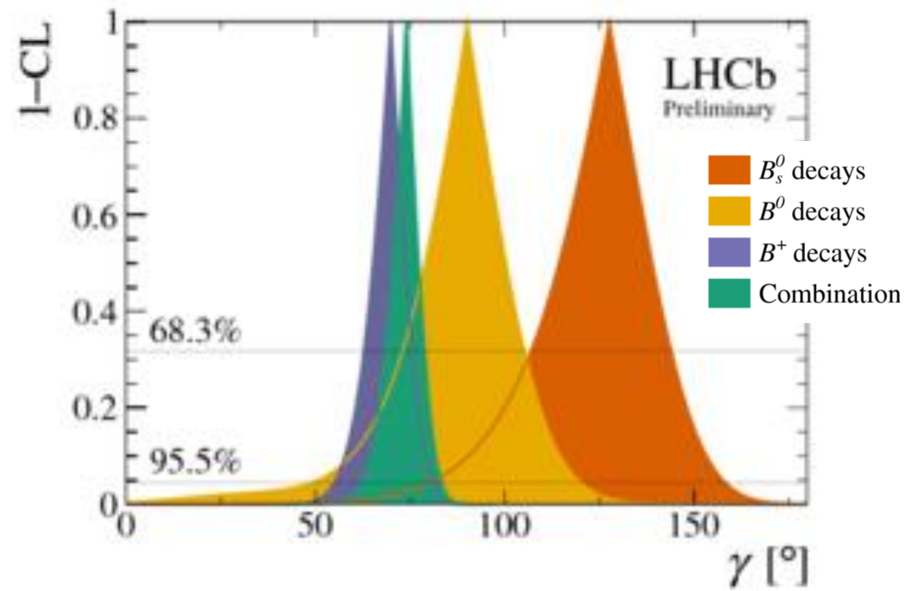
γ prospects : Run 1 & 2 → Upgrade

- Run 1 target of 8° surpassed : (analyses now mostly complete)

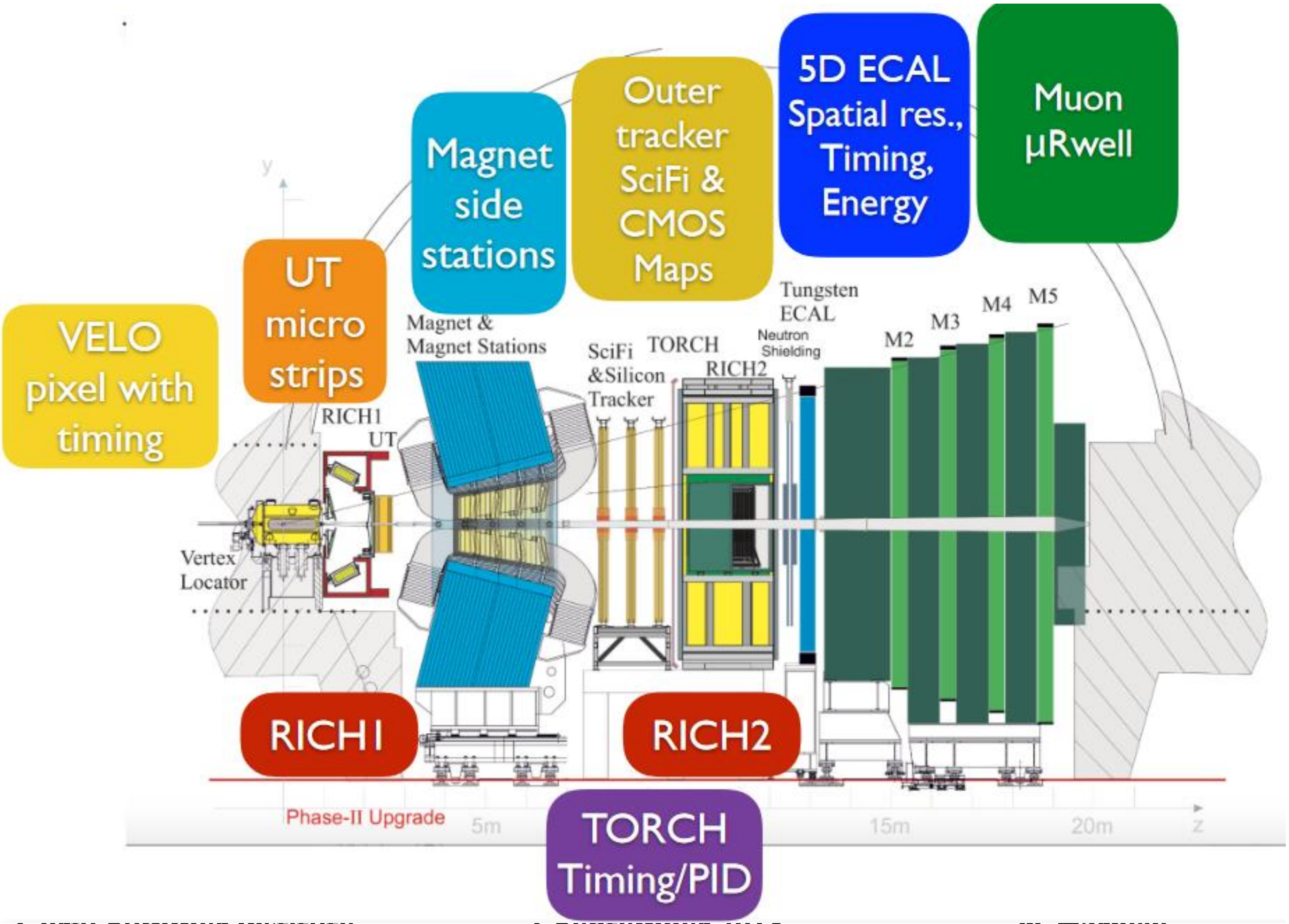
$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

- Run 2 data incoming
- Run 2 : target <4° (~10 fb^{-1})
- LHCb Upgrade : target 0.9° (~50 fb^{-1})

EPJC (2013) 73:2373

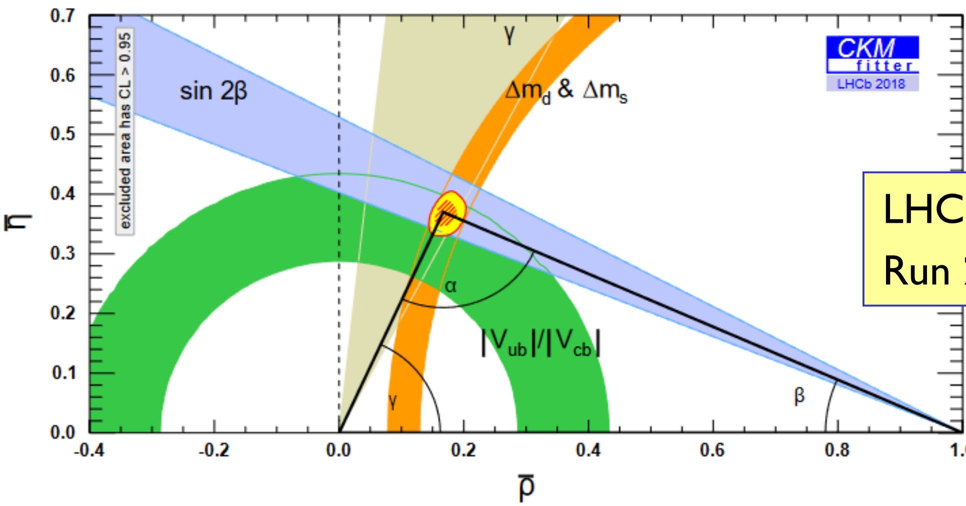


… and beyond 2026 : Upgrade II



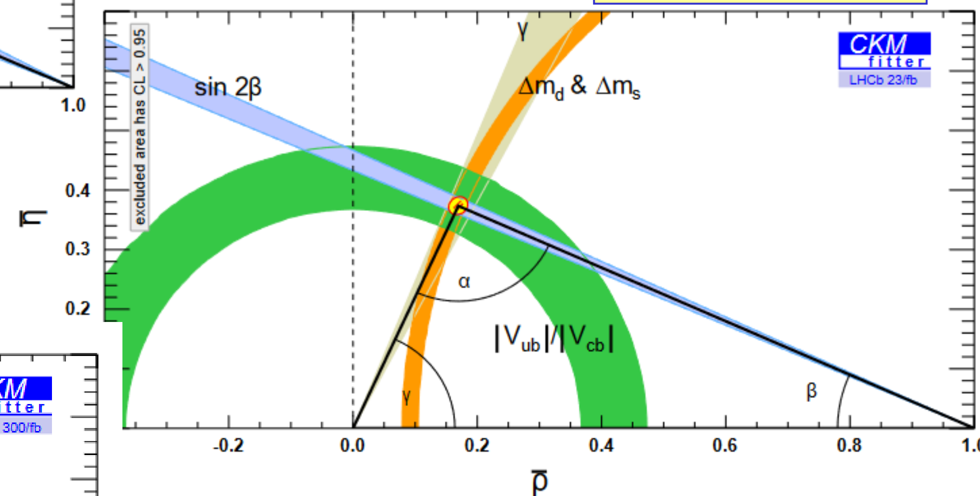
Evolution of the Unitarity Triangle

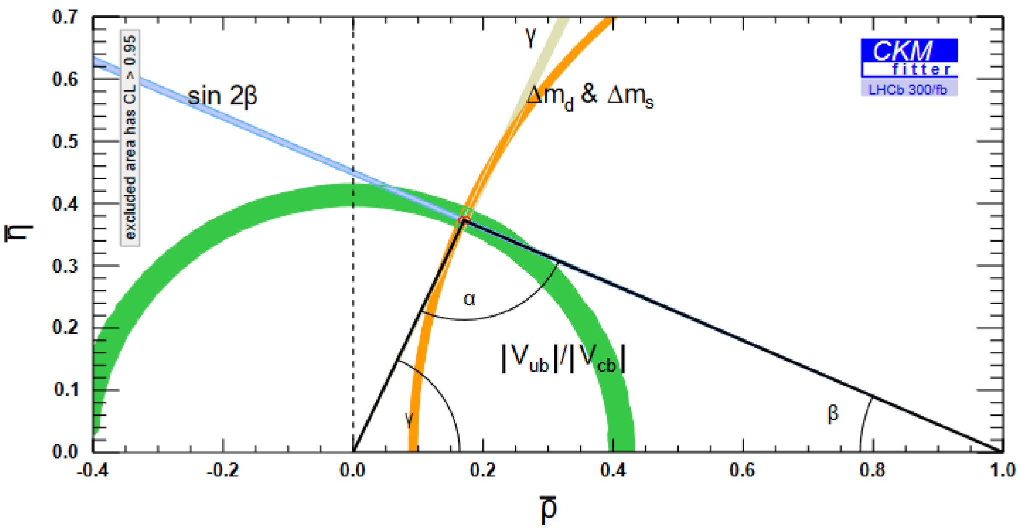
LHCB-PUB-2018-009



LHCb : 2018
Run 2

LHCb Upgrade I
2025 (23 fb^{-1})





LHCb Upgrade II
2035 (300 fb^{-1})

Summary and Outlook

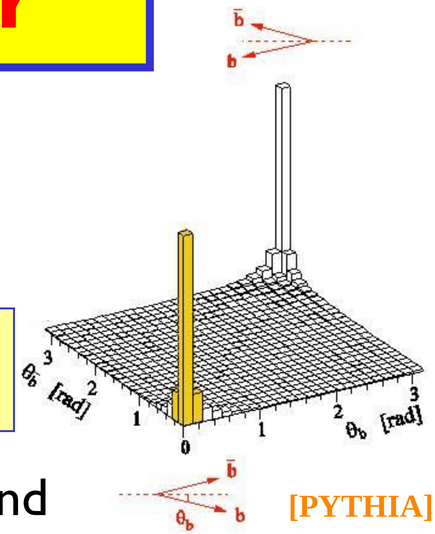
- The LHCb experiment is performing spectacularly well
- So far all Unitarity Triangle measurements are in good agreement with the Standard Model
  $\rightarrow$ new physics is becoming constrained in the flavour sector
- LHCb is a fantastic platform for spectroscopy measurements: charm baryonic resonance formation was not even in LHCb's original physics portfolio.
- Up to 2018 we anticipate up to 10 fb^{-1} of data at $\sqrt{s}$ =13 TeV, where 7-8 fb^{-1} was expected
- Still much room for new physics, but higher precision required
  $\rightarrow$ preparing for LHCb Upgrades beyond 2020 and the decade afterwards!

Spare Slides

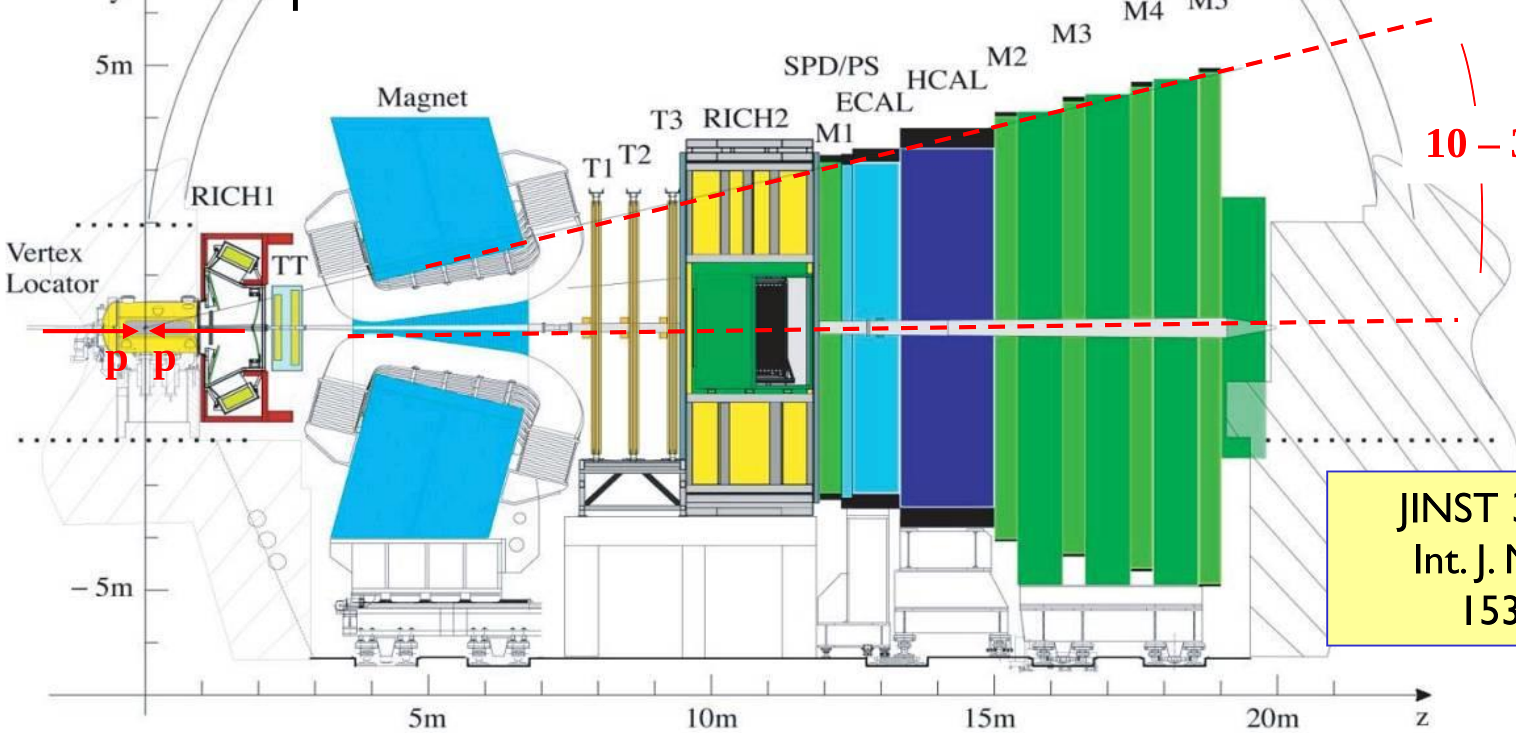
LHCb forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 72.0 ± 0.3 ± 6.8 μb at $\sqrt{s}$ = 7 TeV
  in the LHCb acceptance 2< η < 5
  At $\sqrt{s}$ = 13 TeV : 154.3 ± 1.5 ± 14.3 μb

PRL 118, 052002 (2017)



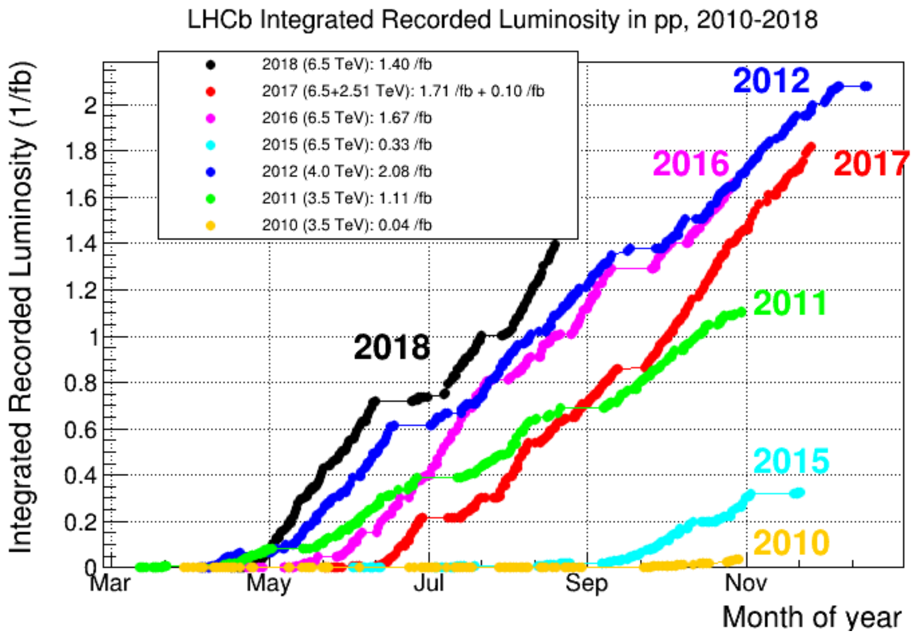
→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories) and all species of B hadron

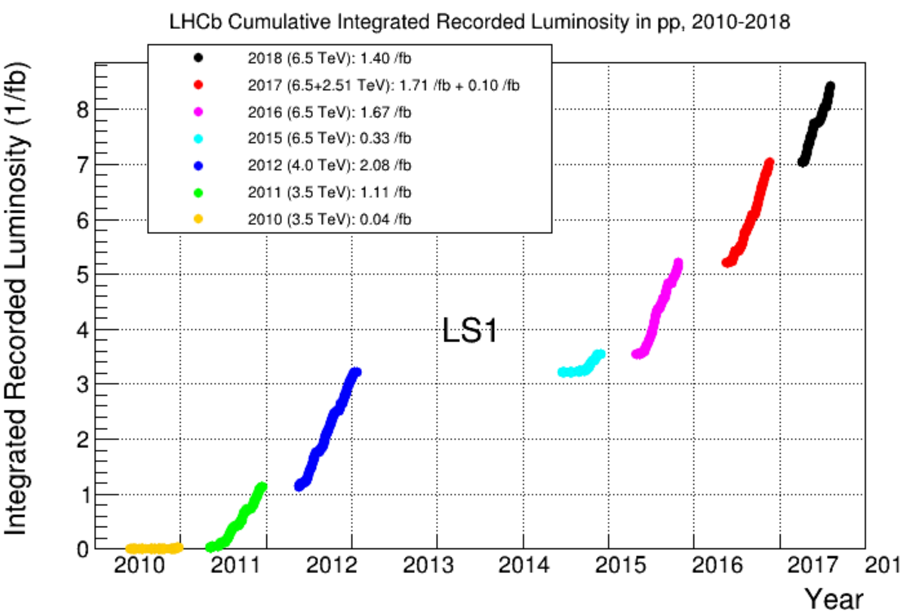


JINST 3:S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

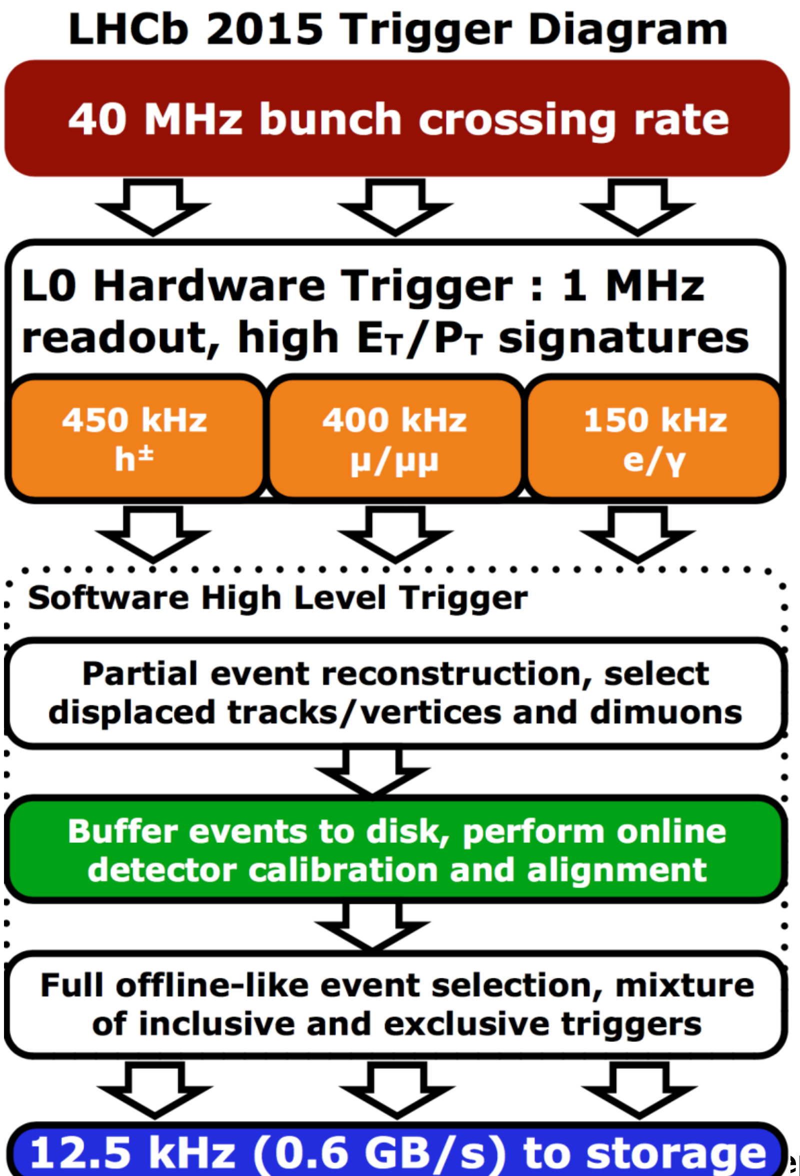
LHCb data taking

- Nominal luminosity = 2 × 10^{32} cm^{-2} s^{-1} (50 times less than ATLAS/CMS) : moreover, LHCb learned to run at >2 times this





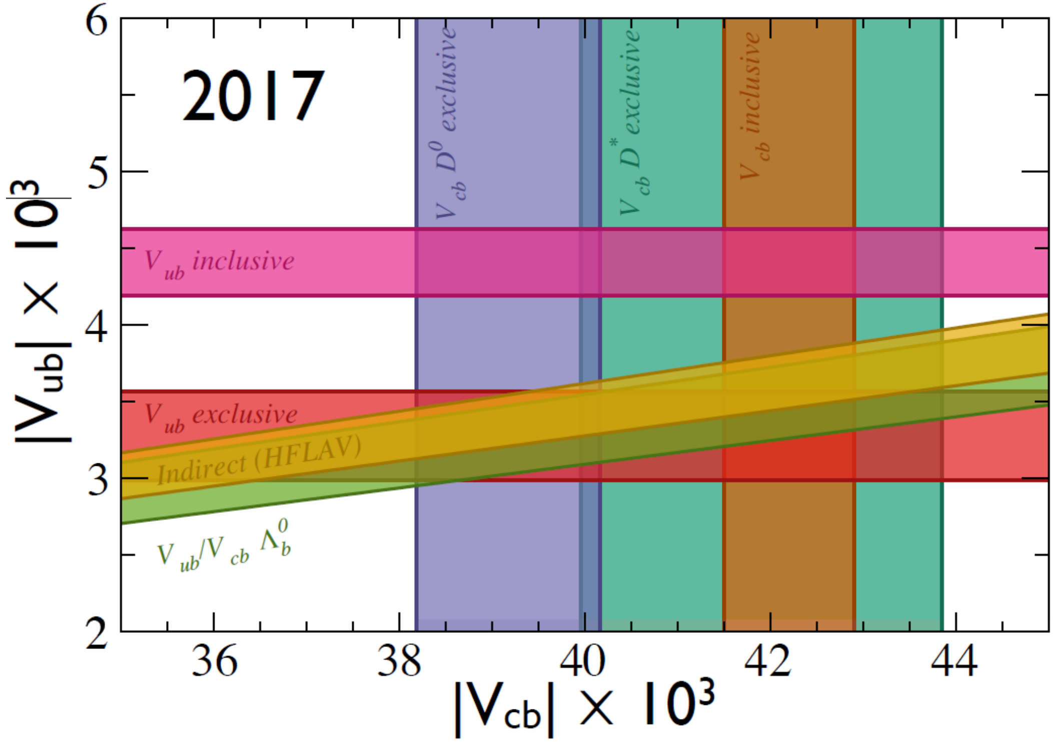
LHCb Run 2 trigger



- After LHCb's hardware trigger, events are buffered.
- LHCb's automated real-time alignment and calibration runs :
  - Full detector alignment and calibration in minutes.
- Full event reconstruction in software trigger
  - Exclusive decay modes and calibration modes fully reconstructed,
  - Results stored and used as basis for analysis.
- See LHCb-PROC-2015-011

Inclusive vs exclusive measurements of $|V_{ub}|$

- Babar & Belle drive the current measurements of $|V_{ub}|$ which have an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement : $B^0/B^+ \rightarrow X_u \mu^+ \nu$



Grinstein, Kobach, PLB771 (17) 359
Bigi, Gambino,Schacht, PLB 769 (17) 441

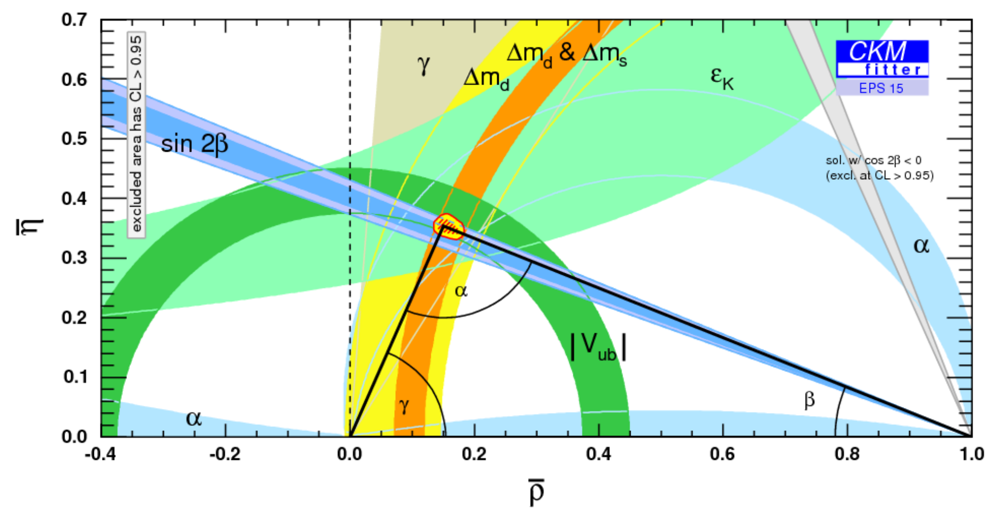
Measurement of α

- Constraints on α from B→π π, ρπ and ρρ (Babar and Belle)
- $\alpha = (87.6\ ^{+3.5}_{-3.3})^\circ$ world average measurement
- Compared to the prediction from the global CKM fit (not including the α -related measurements)
  $\alpha = (90.6\ ^{+3.9}_{-1.1})^\circ$

http://ckmfitter.in2p3.fr

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

- As yet there has been no LHCb 'standalone' measurement of α
- LHCb can provide useful input to B-factories measurements to constrain alpha.

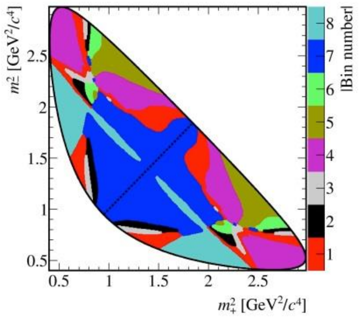


Two methods for accessing D decay information

Two ways to deal with the varying r_D , δ_D

Model dependent	**Model independent**

- r_D and δ_D determined from flavour tagged decays (eg Babar/Belle) via amplitude model
- Systematic uncertainties due to model hard to quantify

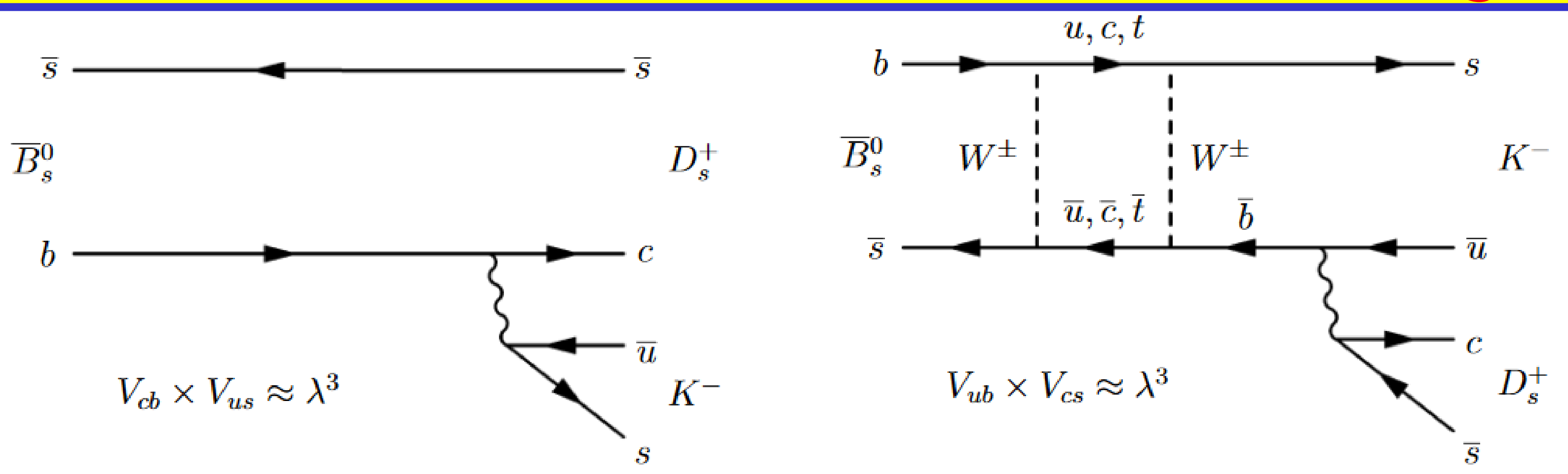


- Use CLEO data to measure average values of r_D and δ_D in pre-defined bins

PRD 82 (2010) 112006

- Direct phase information, uncertainties on which can be propagated

Time dependent analysis : $\overline{B}^0 \rightarrow D_s^+ K^-$



- *Interference* between $\overline{B}^0$ decay to $D_s^+K^-$ directly and via $B^0\ \overline{B}^0$ oscillation gives a CP violating phase

  $\phi = \phi_{Decay} - \phi_{Mixing} = (\gamma - 2\beta_S)$

β_S is (small) mixing phase, $\phi_s = -2\beta_S = 0.01 \pm 0.07 \pm 0.01$ (syst) rad.

Phys. Rev. (2013) 112010

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

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

JHEP 11 (2014) 060, Phys. Rev. (2013) 112010

$B^0 \rightarrow \bar{D}_s^+ K^-$ continued

JHEP 11 (2014) 060

- Only 1 fb^{-1} of data published so far. The full Run-I 3 fb^{-1} measurement is expected towards the end of this year.

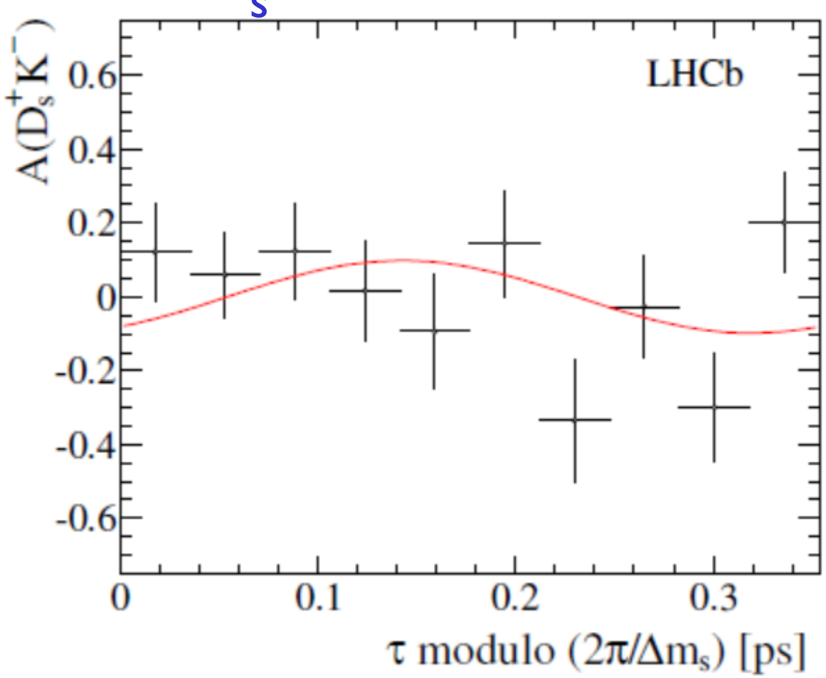
$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,,\quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,,\quad C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2}$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,,\quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,.$$

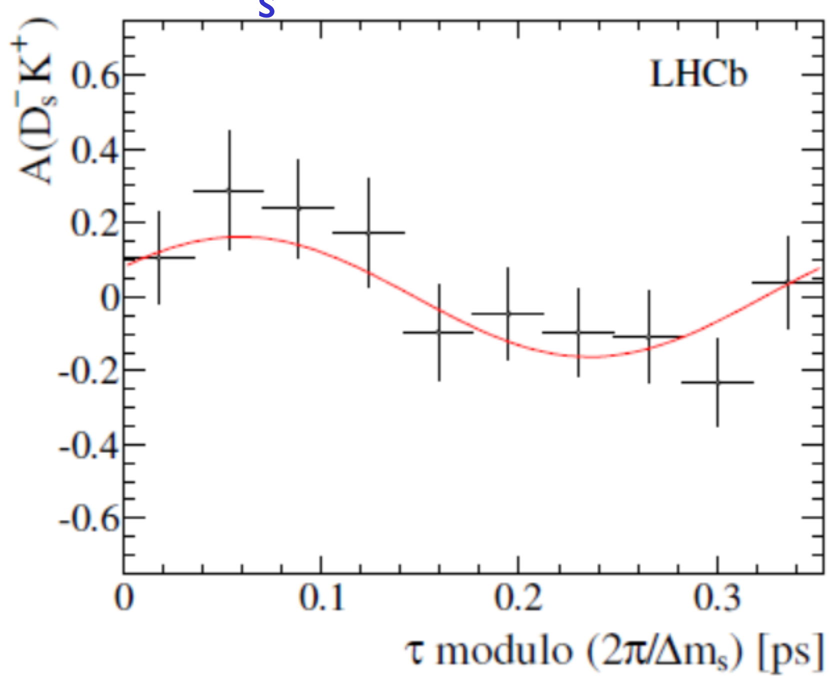
- Measure folded asymmetry distributions:

$\gamma = (115^{+28}_{-43})^o$

$D^+_s K^-$

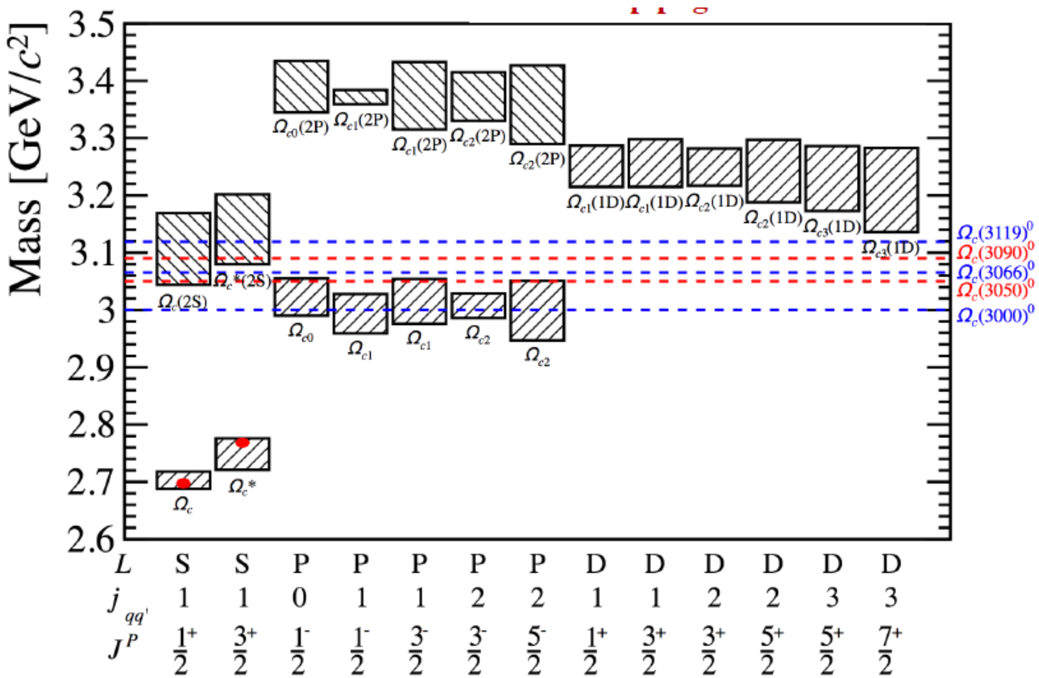


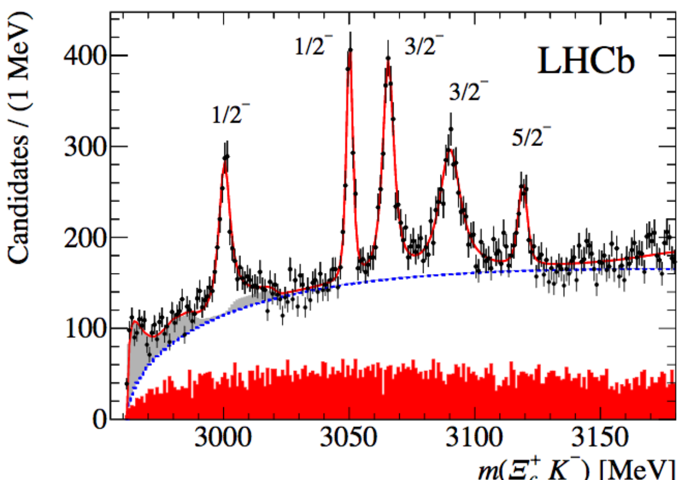
$D^-_s K^+$



Possible assignment of excited Ω_c states

- Matching between observed peaks and predictions requires spin-parity information





Adapted from Fig. 2 of arXiv:[1703.04639]

M. Karliner, J.L. Rosner, PR D95, 114012 (2017)

Comparisons with SELEX

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to p D^+ K^-$ decays
- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV