Review of CP-violation and spectroscopy measurements at LHCb

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Outline

- General introduction
- A review of CP-violation measurements
  - The unitarity triangle parameters
  - Angle β_s in the B_s system
  - CP violation in charm
- New 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

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

- l

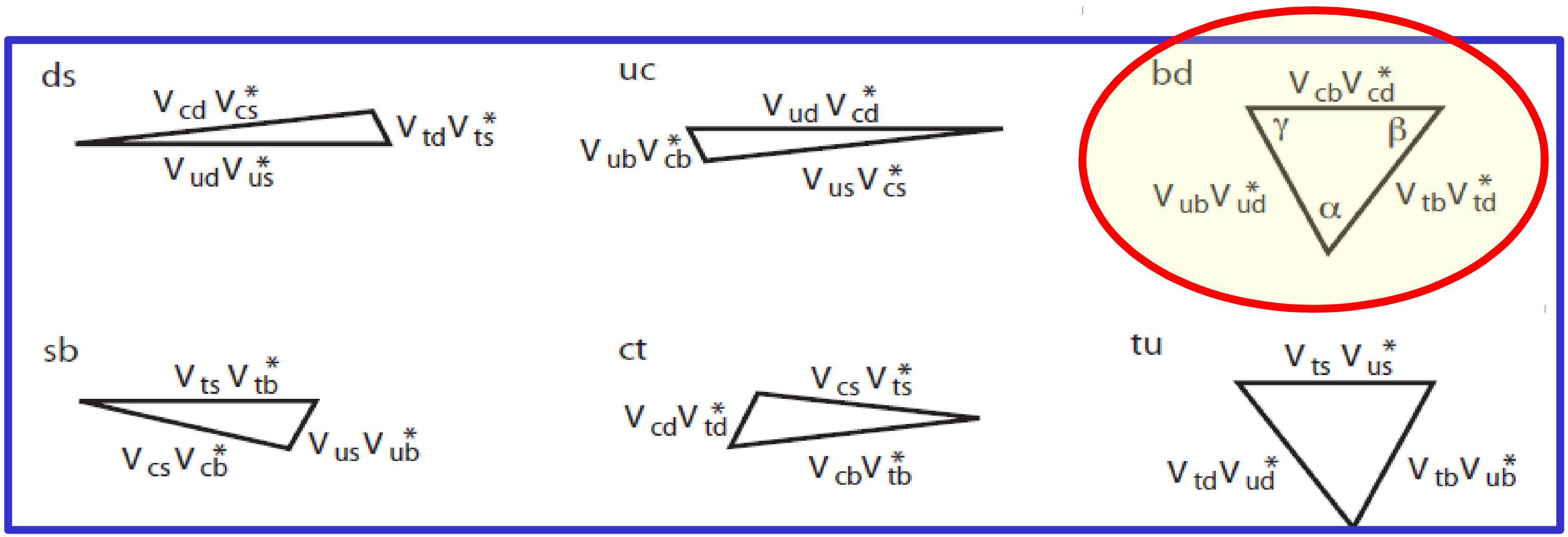
$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

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:

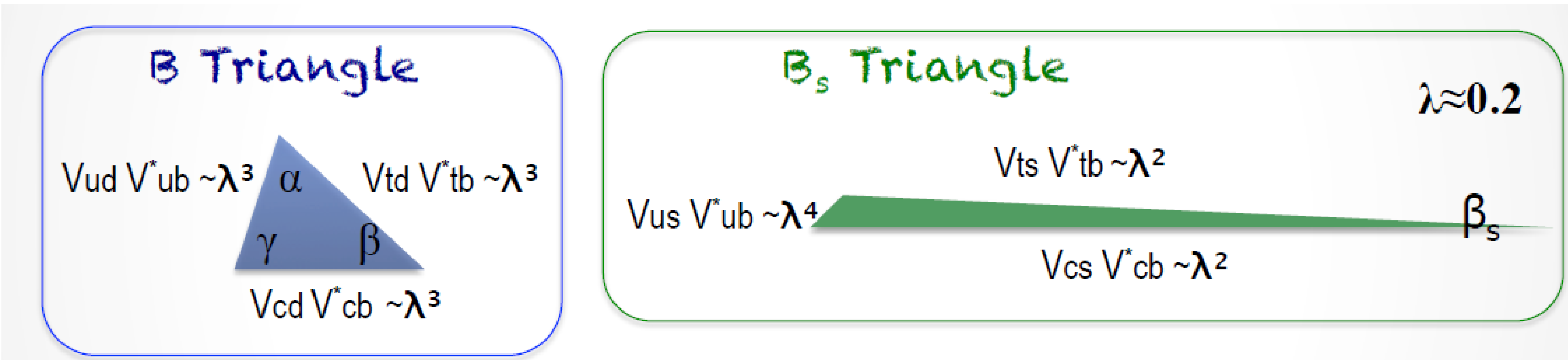
$$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0 \qquad (V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}) = 0$$



THE unitarit y triangle

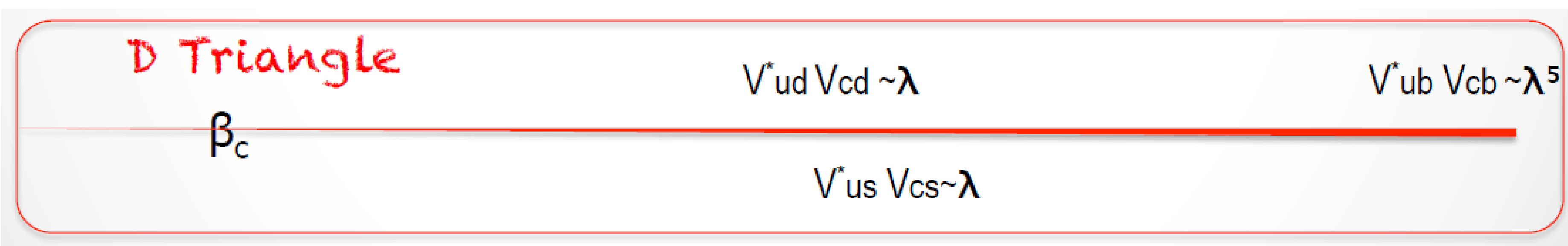
Beauty and Charm triangles

- Beauty system



B system : angles $\alpha, \beta, \gamma \sim 1$ B_s system : angle $\beta_s \sim \lambda^2$

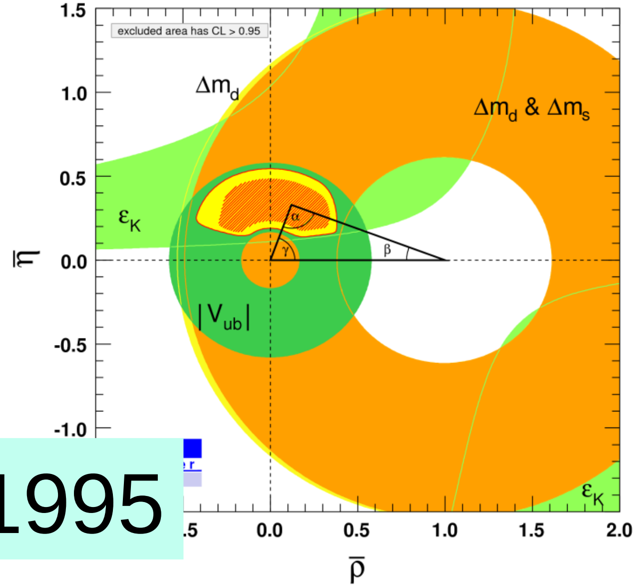
- Charm system



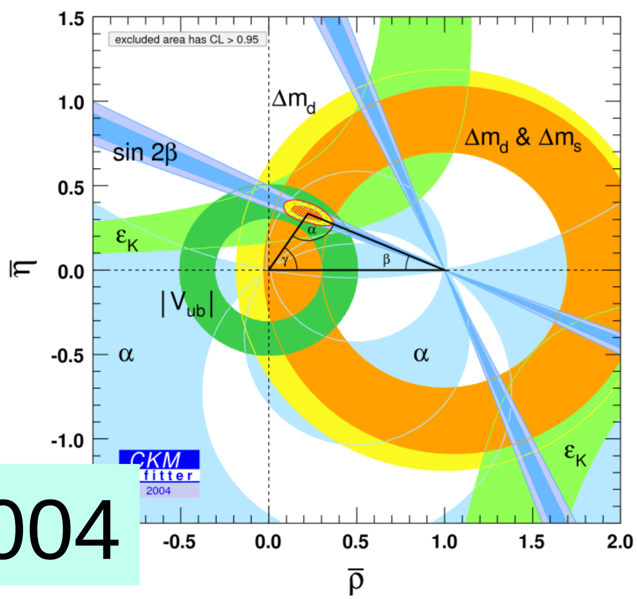
Charm system : angle $\beta_c \sim \lambda^4$

Diagrams from Jolanta Brodzicka

Unitarity Triangle measurements



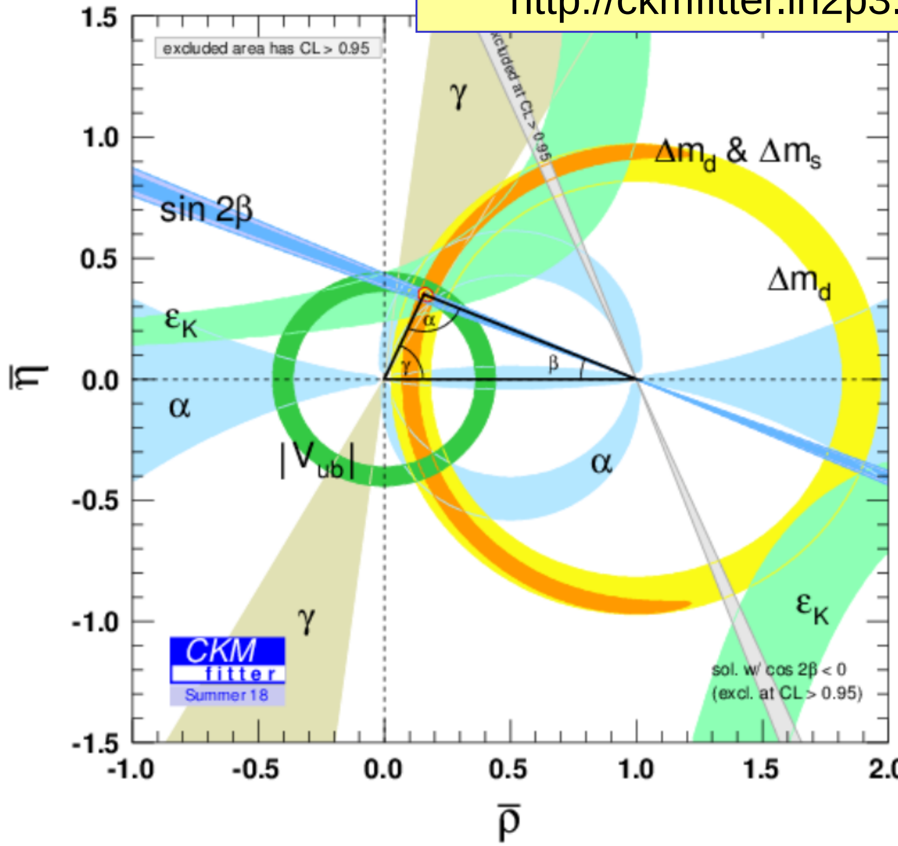
1995



2004

- Amazing progress in the last 25 years; the SM remains intact, but still a whole lot still to learn

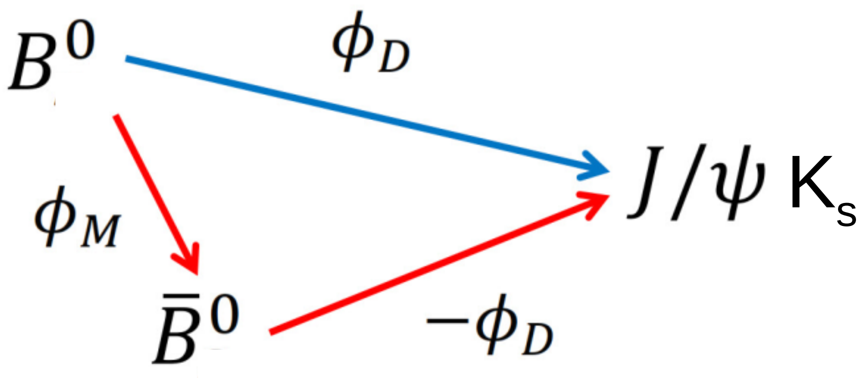
http://ckmfitter.in2p3.fr



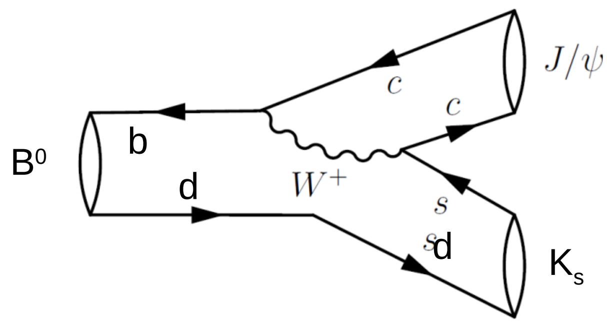
2019 (dominated by LHCb)

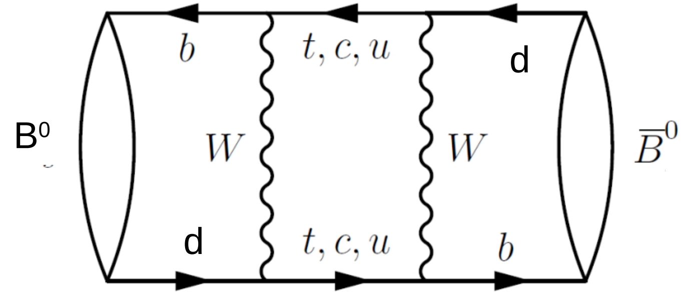
LHCb CP-violation and Unitarity Triangle measurements

Measurement of the 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 B^0 oscillation gives rise to a CP violating phase

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

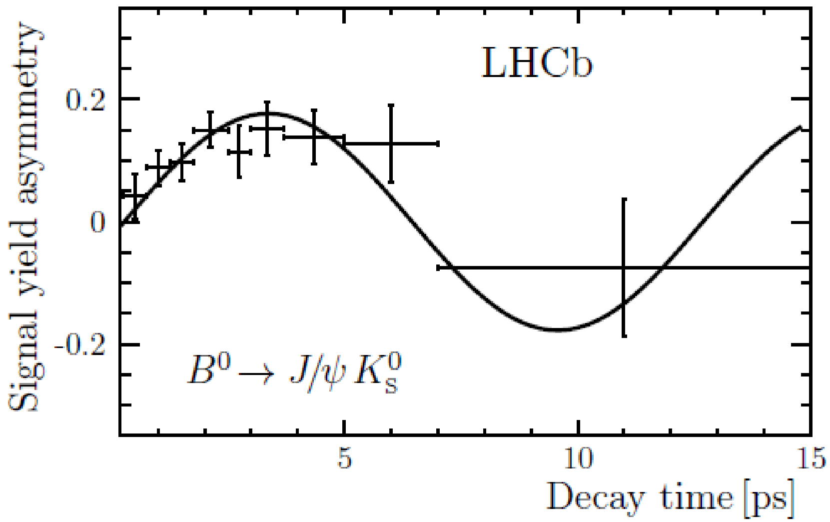
LHCb measurement of sin(2β)

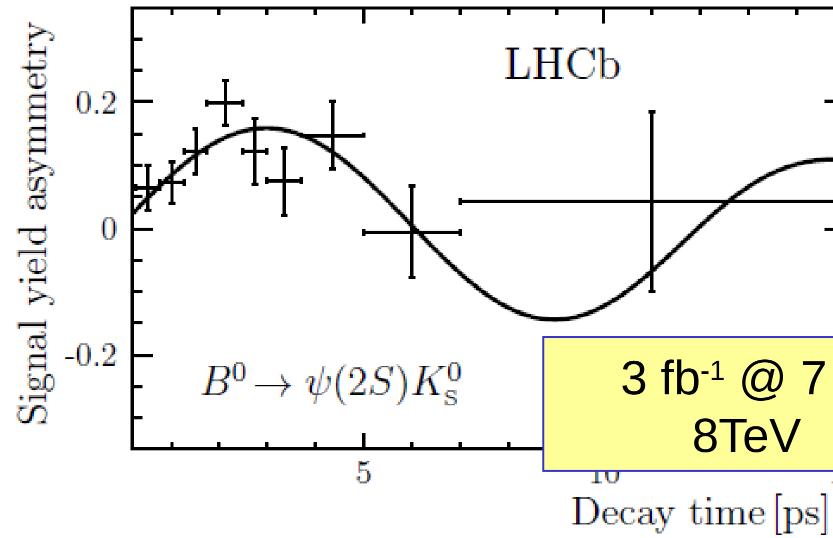
sin(2β) from $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S) K^0_S$

JHEP 11 (2017) 170

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

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





3 fb[-1] @ 7 & 8TeV

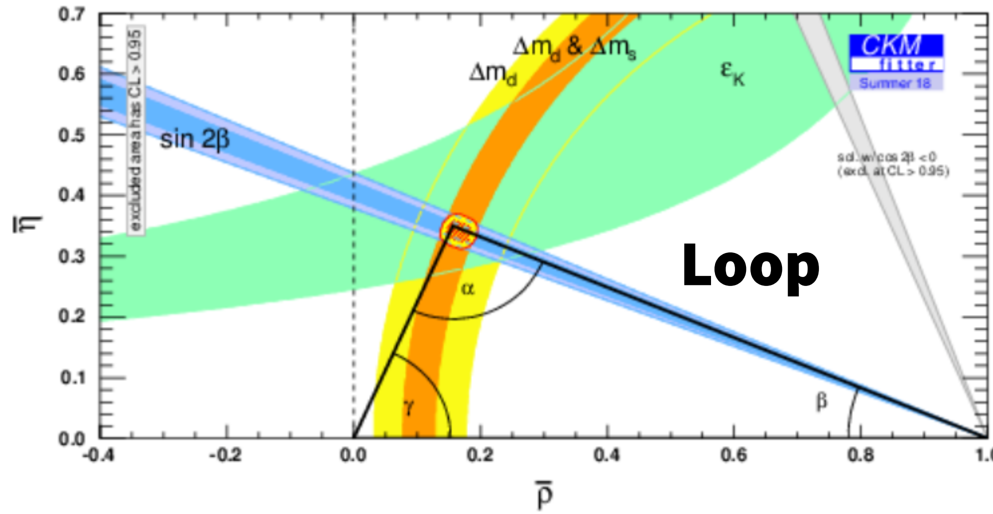
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

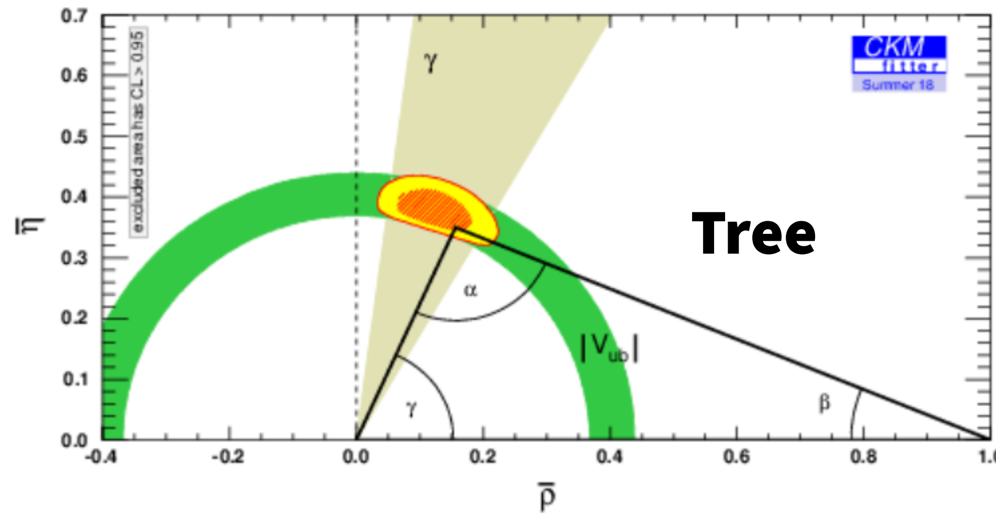
Competitive with Babar & Belle. HFLAV world average from all modes :

https://www.slac.stanford.edu/xorg/hflav/triangle/summer2018/

The angle γ (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





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

* assuming no significant New Physics in tree decays

http://ckmfitter.in2p3.fr

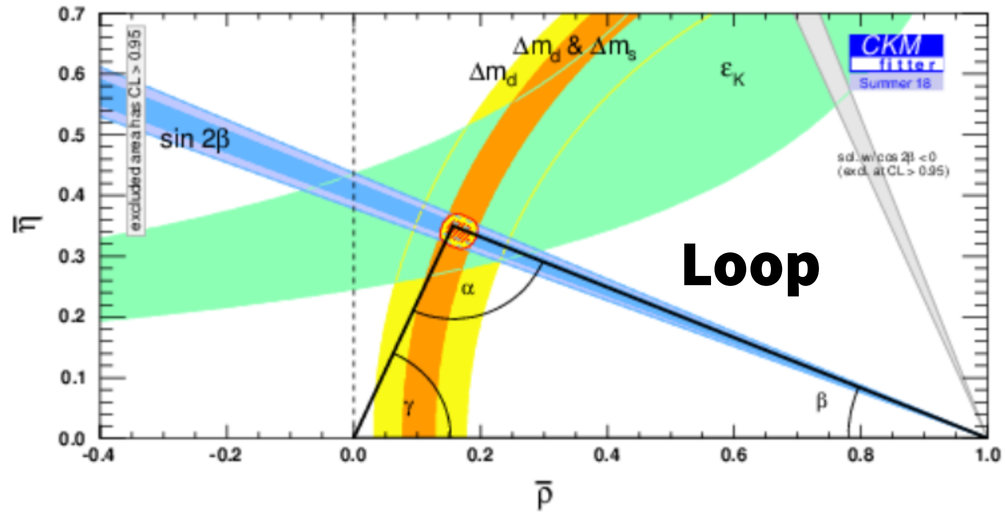
γ : indirect vs direct determinations

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

Combination of all direct measurements from tree decays

$$\gamma = (72.1^{+5.4}_{-5.7})$$

Reaching degree level precision from direct measurements is crucial



Determination from CKM fit excluding all direct measurements of γ

$$\gamma = (65.8^{+1.0}_{-1.7})$$

http://ckmfitter.in2p3.fr

Several methods to measure γ

- From $B^{\pm}$ (and $\overset{(-)}{B^0}$) decays : the "time-integrated",

  direct C[...] $B^{\pm} \to \overset{(-)}{D^0} K^{\pm}$

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

  - GLW

  Atwood, Dunietz & Soni PRL 78 (1997) 3257,

  Atwood, Dunietz & Soni PRD 63 (2001) 036005

  - ADS

  Giri, Gronau, Soffer & Zupan, PRD 68 (2003) 054018

  - GGSZ

- [...]TD) analysis

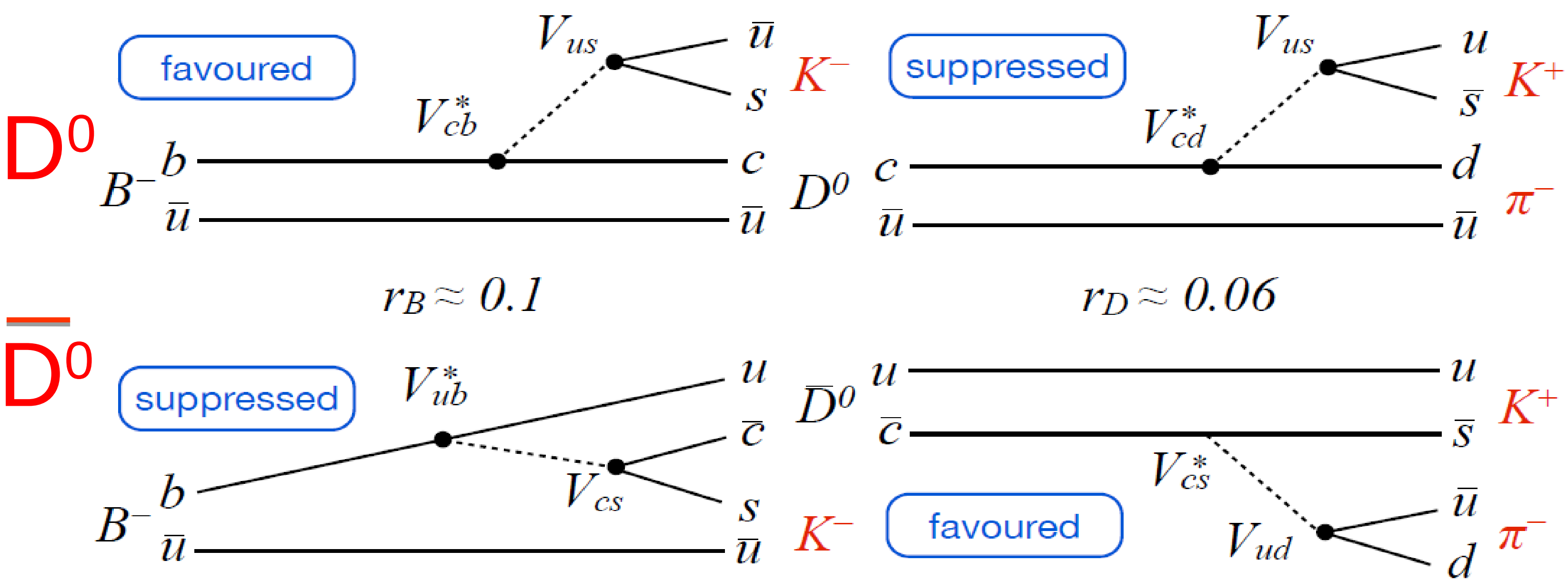
  Dunietz & Sachs Phys. Rev. D37(1988) 3186,
  R. Aleksan, I. Dunietz & B. Kayser, Z. Phys. C54 (1992) 653

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

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

(and charge conjugate mode $B^+ \to D^0 K^+$)

- Interference possible if D^0 and $\bar{D}^0$ decay to same final state
- Two possible decay paths to $K^+\pi^-$ final state via D^0 and $\bar{D}^0$

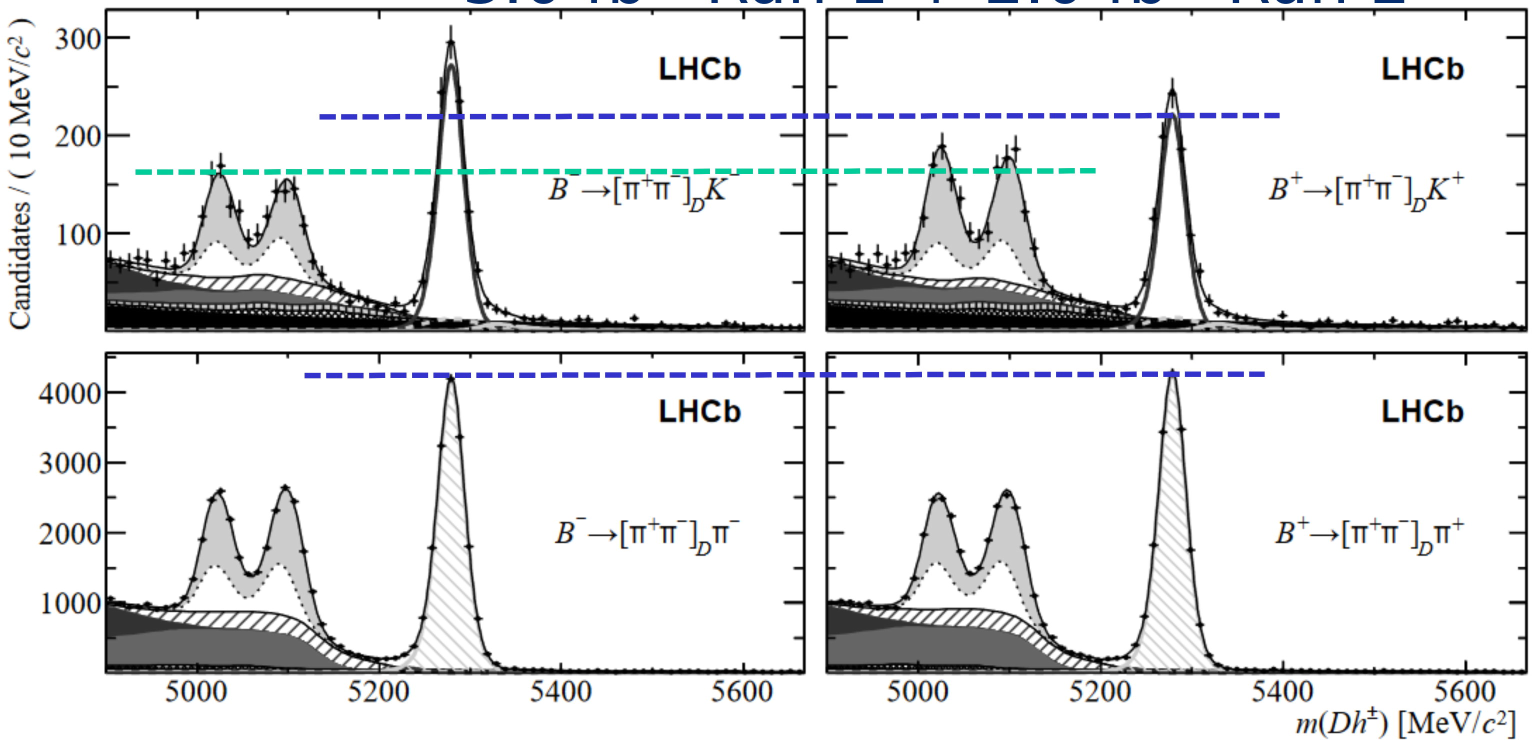


- Branching fraction for favoured B decay only $\sim 10^{-4}$
  - Measurements require high statistics

GLW: B→D$^{(*)}$(π π or KK) h (h = K, π)

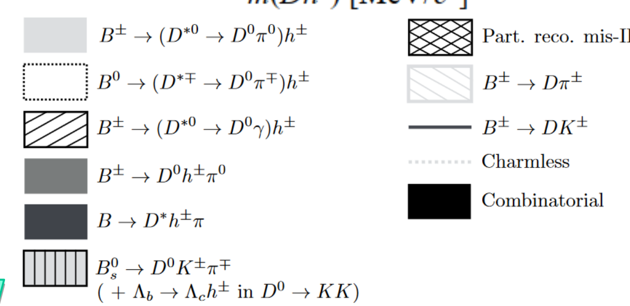
Method where D^0 and $\overline{D}^0$ decay to CP eigenstates

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



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

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



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

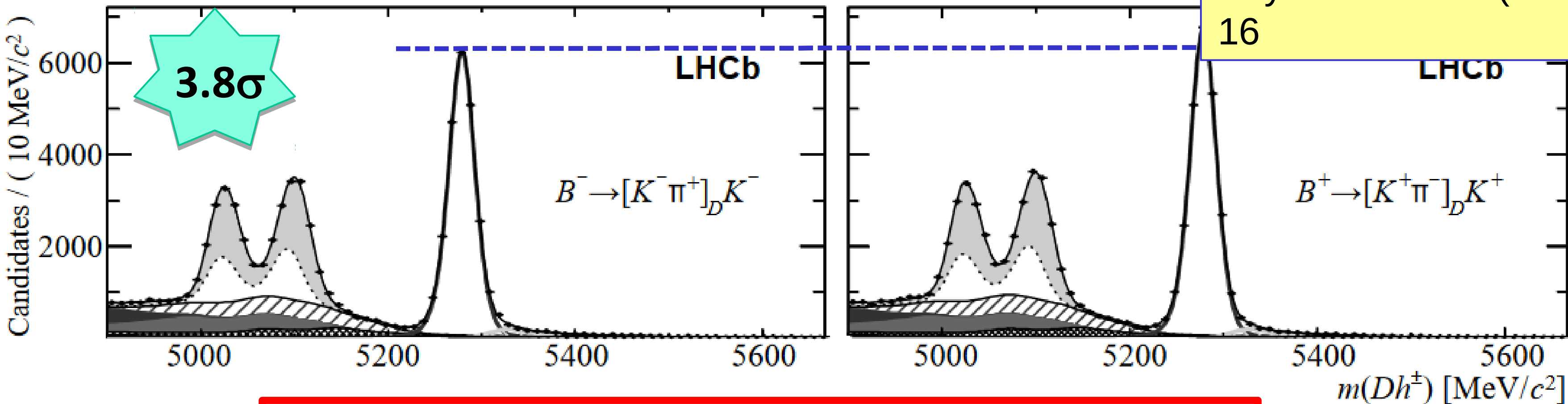
At the level of >5σ

ADS : $B \to D^{(*)}(K\pi)h$ $(h = K, \pi)$

Method where D^0 and $\overline{D^0}$ decay into flavour-specific final states

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

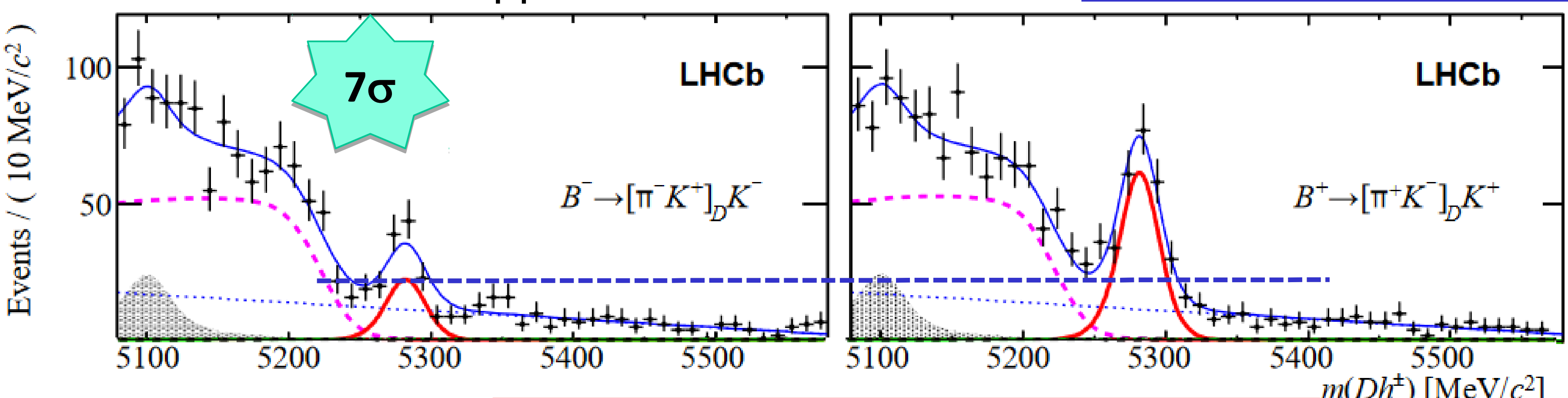
Phys Lett B 777 (2018) 16



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

Cabibbo suppressed : 3.0 fb-1 Run 1

Phys Lett B 760 (2016) 117

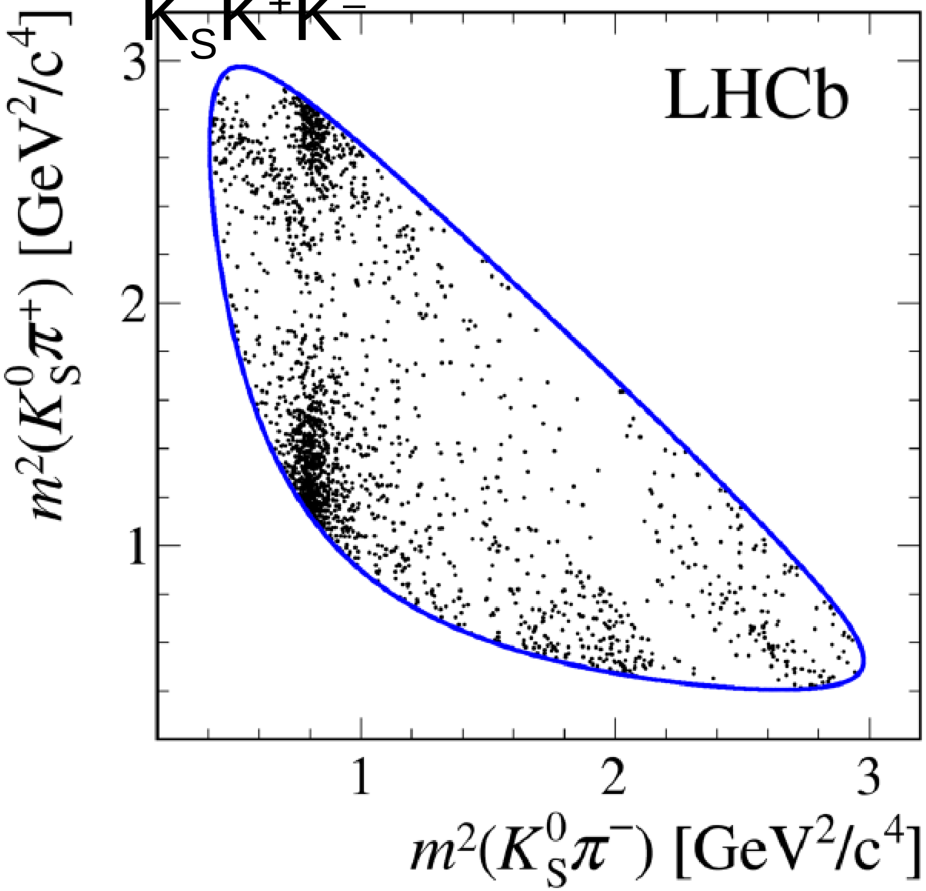


$$A_{\mathrm{ADS}(K)}^{\pi K} = -0.403 \pm 0.056 \pm 0.011$$

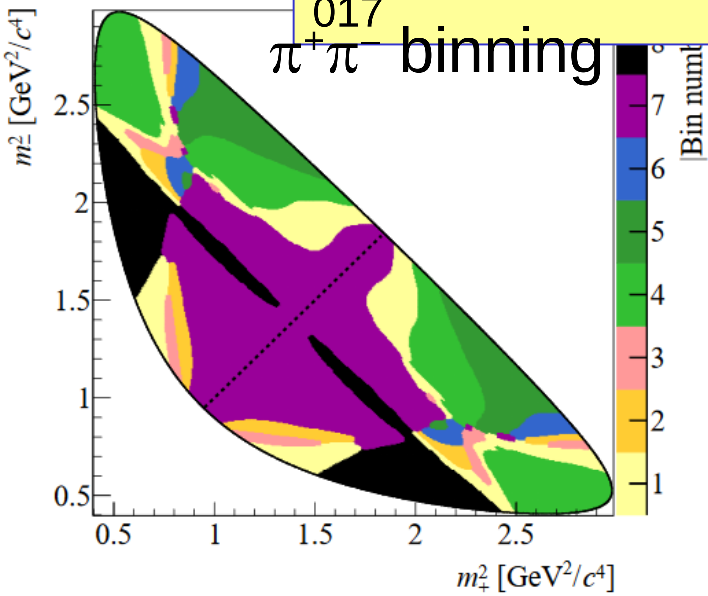
Model-independent GGSZ analysis

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

LHCb-PAPER-2018-017



$\pi^+\pi^-$ binning



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

Model-independent GGSZ analysis

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

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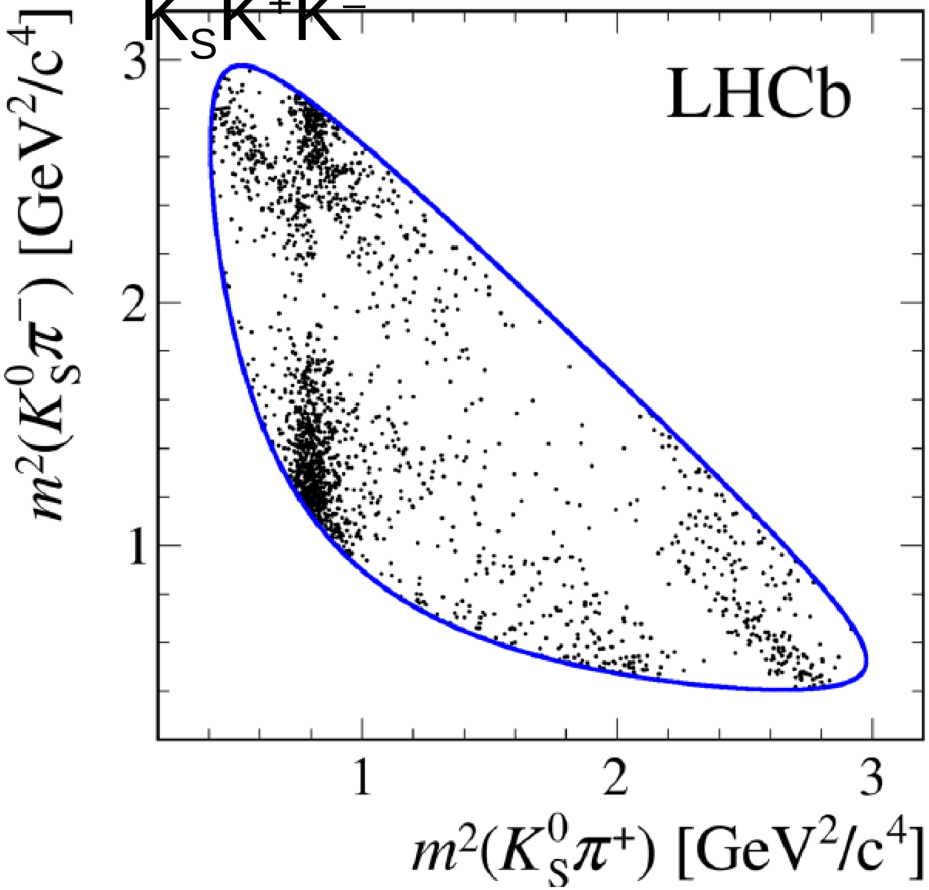
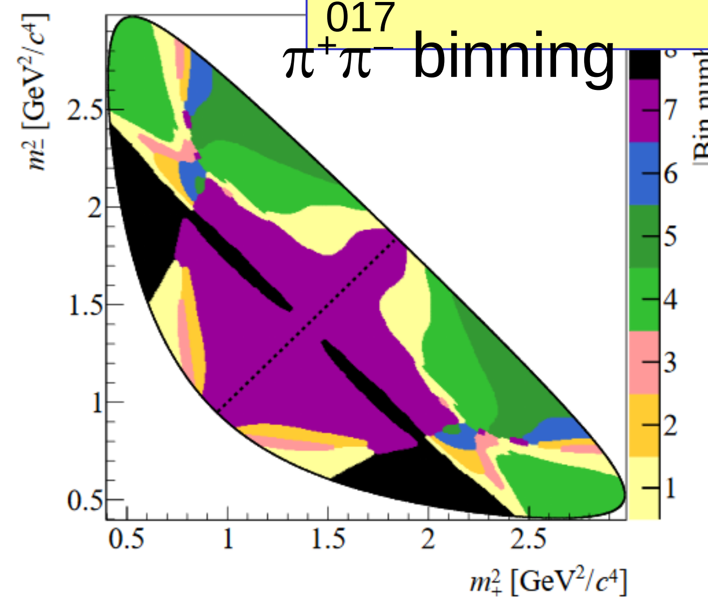


$\pi^+\pi^-$ binning



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

Combination from different modes

- The most recent combination includes the following

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	Most recent
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	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	Most recent
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	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	Most recent

† 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

LHCb average :

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

Dominates HFLAV average :

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

Reminder of indirect constraint

$$\gamma = (65.8^{+1.0}_{-1.7})$$

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

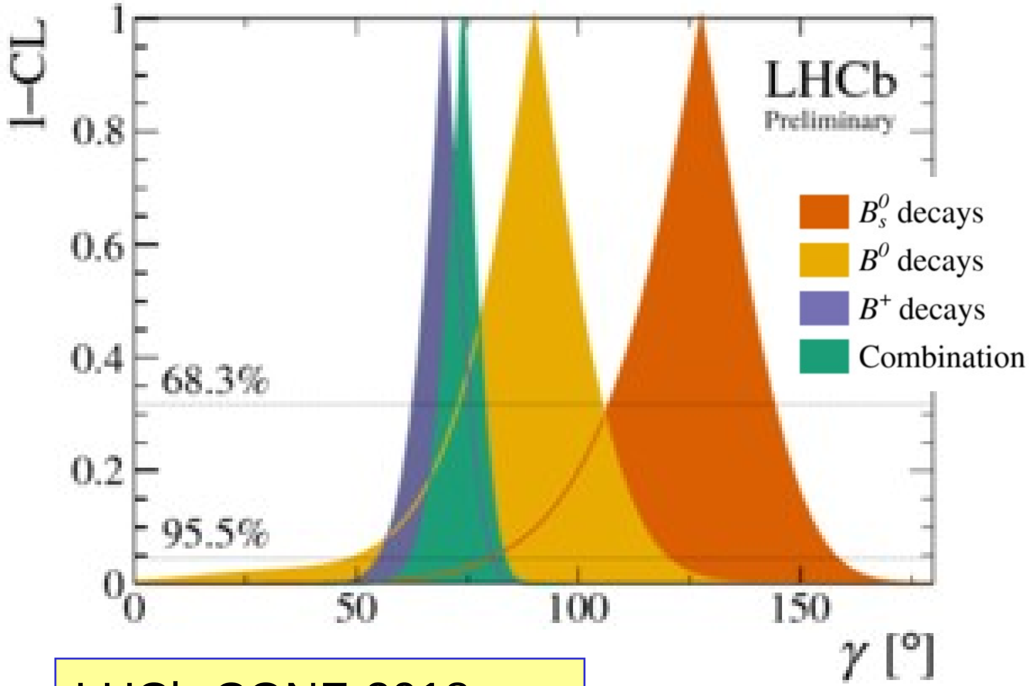
PRD 87 (2013) 052015

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

arXiv:1301.2033

LHCb combination from different modes

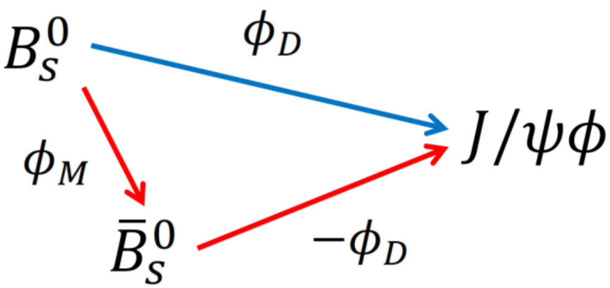
LHCb average $\gamma = (74.0^{+5.0}_{-5.8})^\circ$

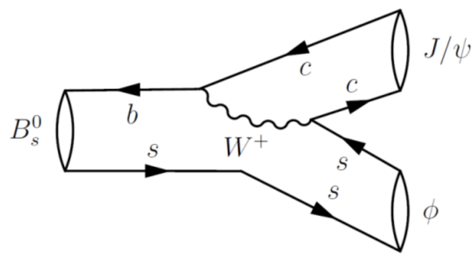


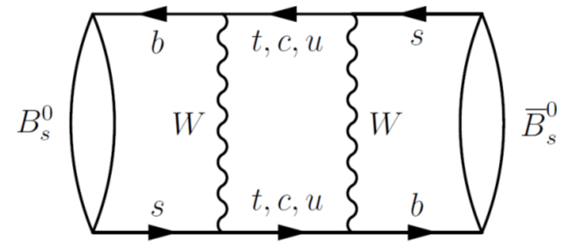
LHCb-CONF-2018-002

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

B_s weak mixing phase ϕ_s in $B_s \to J/\psi\ \phi$







- "Golden mode" for this study is $B_s \to J/\psi\ \phi\ (\to K^+K^-)$
- Analogue of 2β (phase of B^0 mixing) but in the B_s system

- *Interference* between B^0 decay to $J/\psi\phi$ directly and via $\bar{B}^0$ - B^0 oscillation gives rise to a CP violating phase in the SM

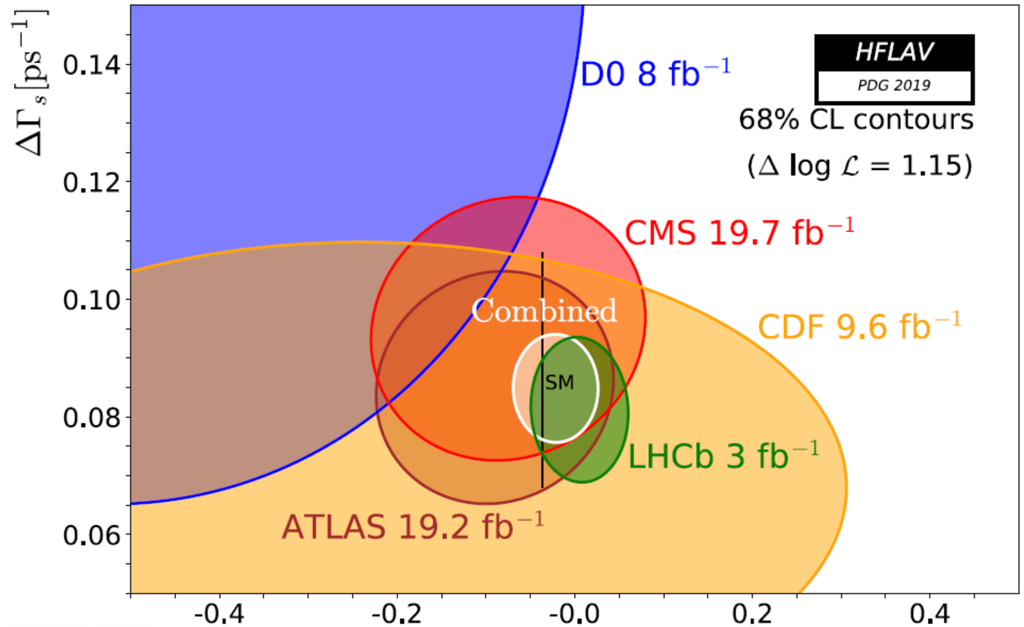
  $\phi_S = \phi_{Mixing} - 2\ \phi_{Decay} = -2\beta_s$

- ϕ_S is expected to be very small in the SM and precisely predicted: $\phi_{SM} = -0.036 \pm 0.002$ (see eg Charles et al PRD84 (2011) 033005)

Status of ϕ_s before Spring 2019

- World average dominated by LHCb

- Results consistent with SM-based global fits to data, but still room for NP



[HFLAV]

ϕ_S [rad]

ϕ_S^{exp} = – 0.020 ± 0.031 rad

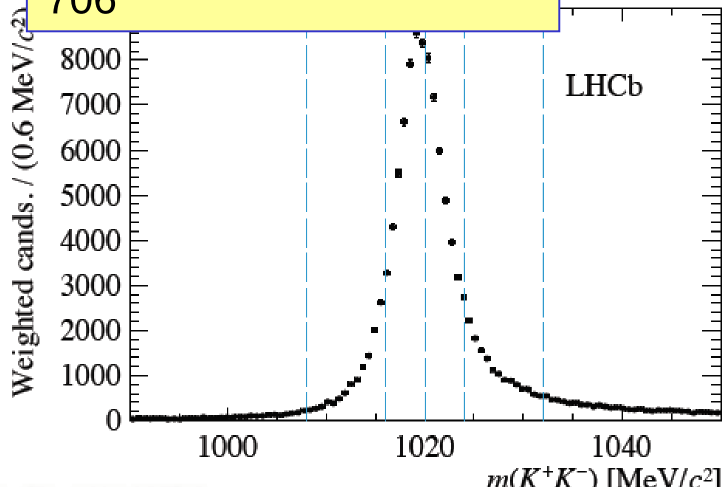
ϕ_{SM} = – 0.036 ± 0.002 rad

LHCb : 3 fb^{-1} PLB 736 (2014) 186

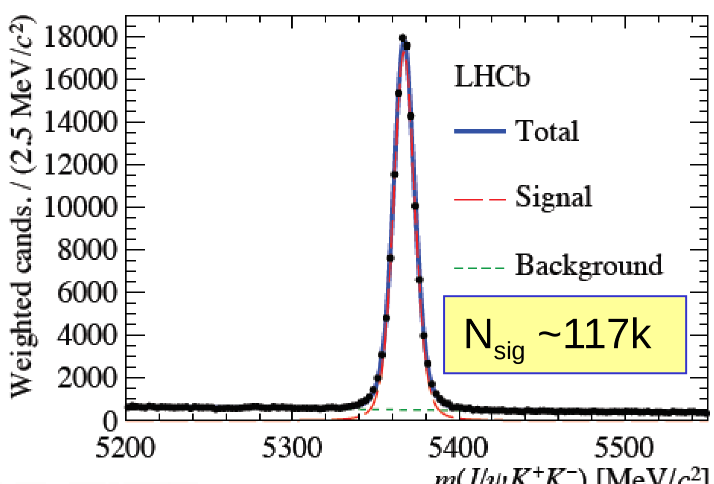
NEW : Add Run-II LHCb measurements with 2015 (0.3 fb^{-1}) and 2016 (1.6 fb^{-1}) datasets

- $B_s \to J/\psi\ K^+K^-$

Eur. Phys. J. C 79 (2019) 706



[arXiv:1906.08356]

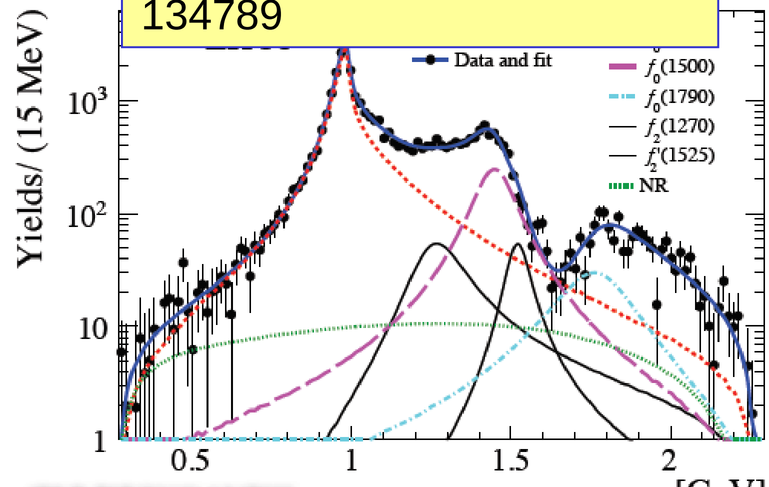


N_{sig} ~117k

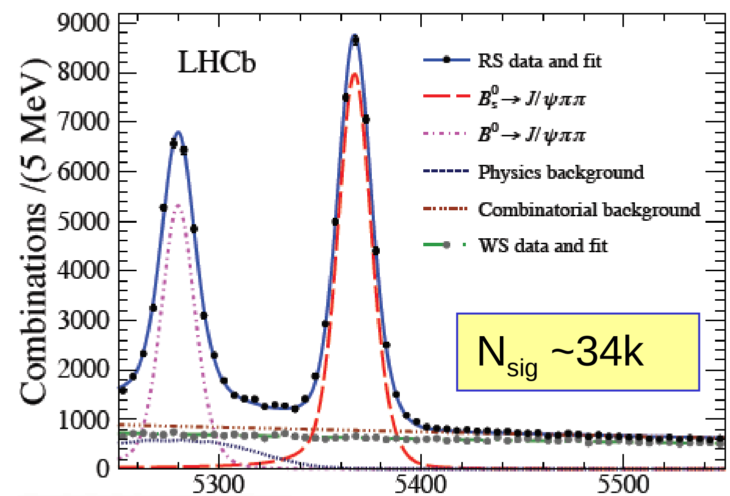
[arXiv:1906.08356]

- $B_s \to J/\psi\ \pi^+\pi^-$

Phys. Lett. B 797 (2019) 134789



[PLB 797(2019) 134789]



N_{sig} ~34k

[PLB 797(2019) 134789]

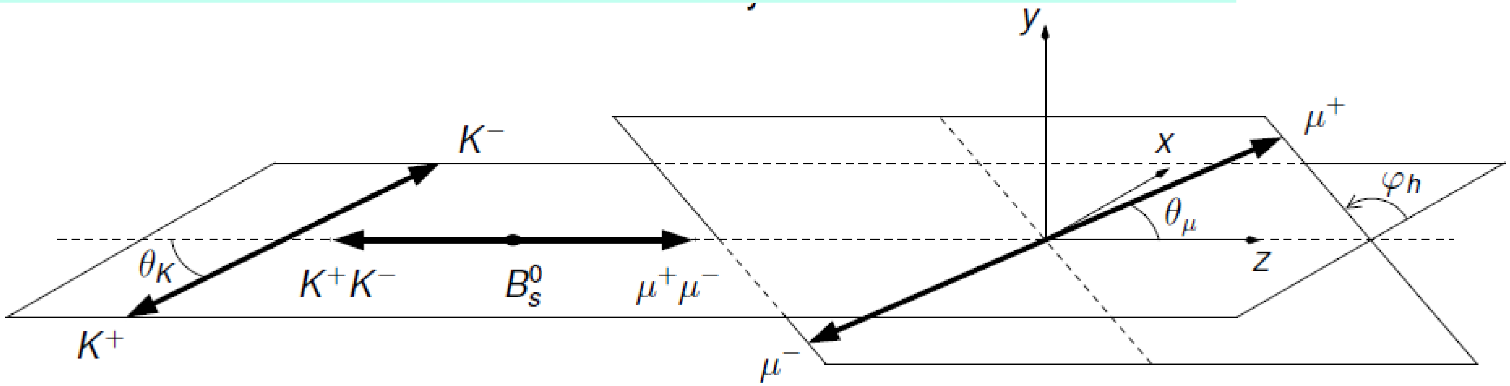
$B_s \to J/\psi\, \phi$ analysis

- ϕ is a vector meson (spin 1)

Eur. Phys. J. C 79 (2019) 706

- Vector-vector final state: mixture of CP-odd and CP-even components

Need to perform $B_s \to J/\Psi\, \phi$ angular analysis



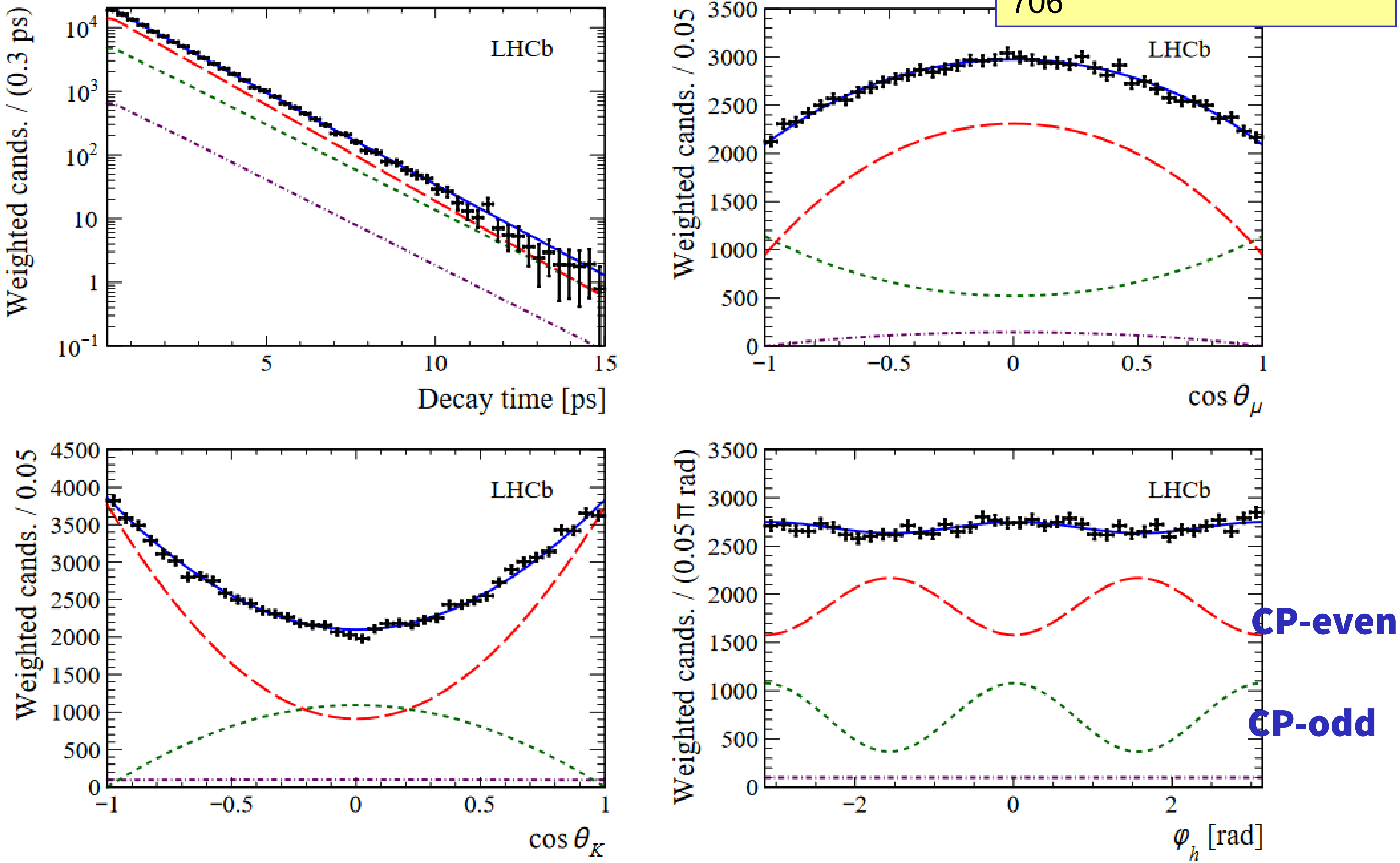
- Good tagging performance of $\bar{B}_s$ & B_s is important

Category	$\epsilon_{\text{tag}}(\%)$	D^2	$\epsilon_{\text{tag}} D^2(\%)$
OS only	11.4	0.078	0.88 ± 0.04
SSK only	42.6	0.032	1.38 ± 0.30
OS & SSK	23.8	0.104	2.47 ± 0.15
Total	77.8	0.061	4.73 ± 0.34

new

$B_s \to J/\psi\ \phi$: fit projections

Eur. Phys. J. C 79 (2019) 706



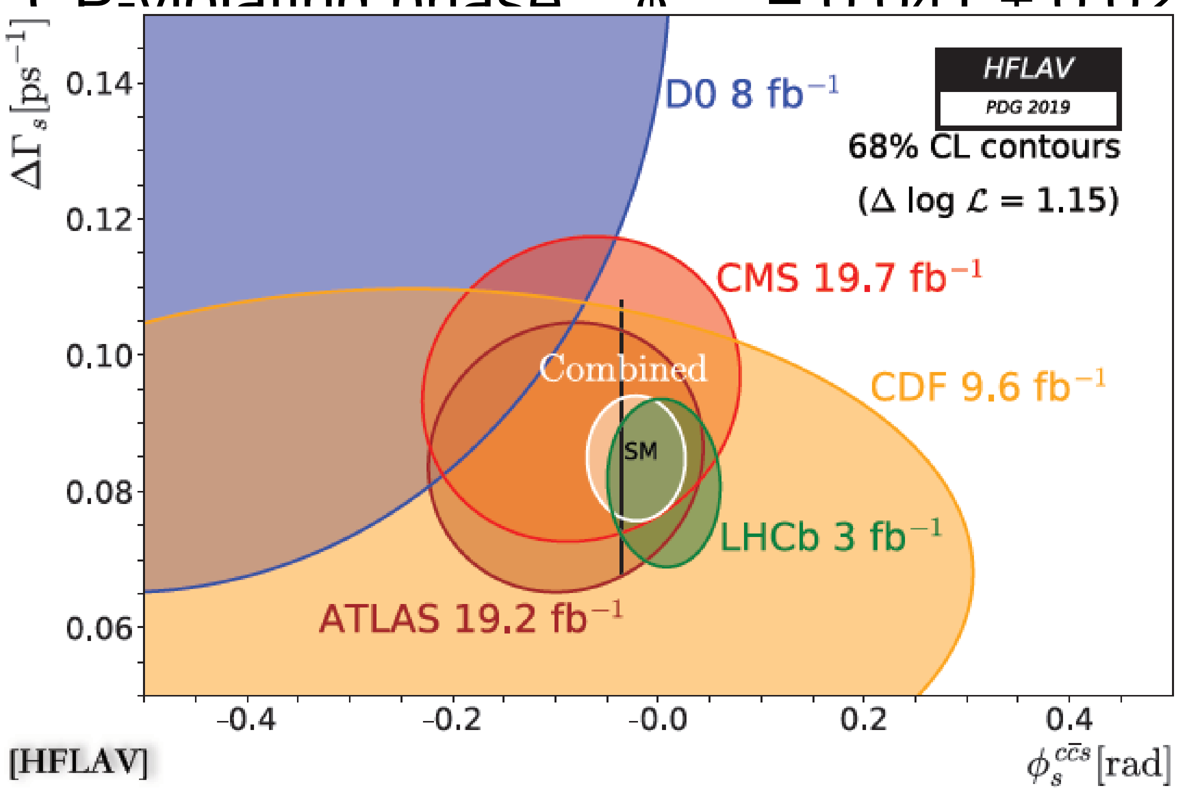
Results and new LHCb combination

- ϕ_s fitted value correlated with $\Delta\Gamma_s$ = width diff. of the B_s mass eigenstates $\rightarrow$ plot as contours in (ϕ_s *vs* $\Delta\Gamma_s$) plane

$\Delta\Gamma_s$ = 0.0816 ± 0.0048 ps^{-1}

CP-violating phase: ϕ_s = – 0.041 ± 0.025 rad

BEFORE

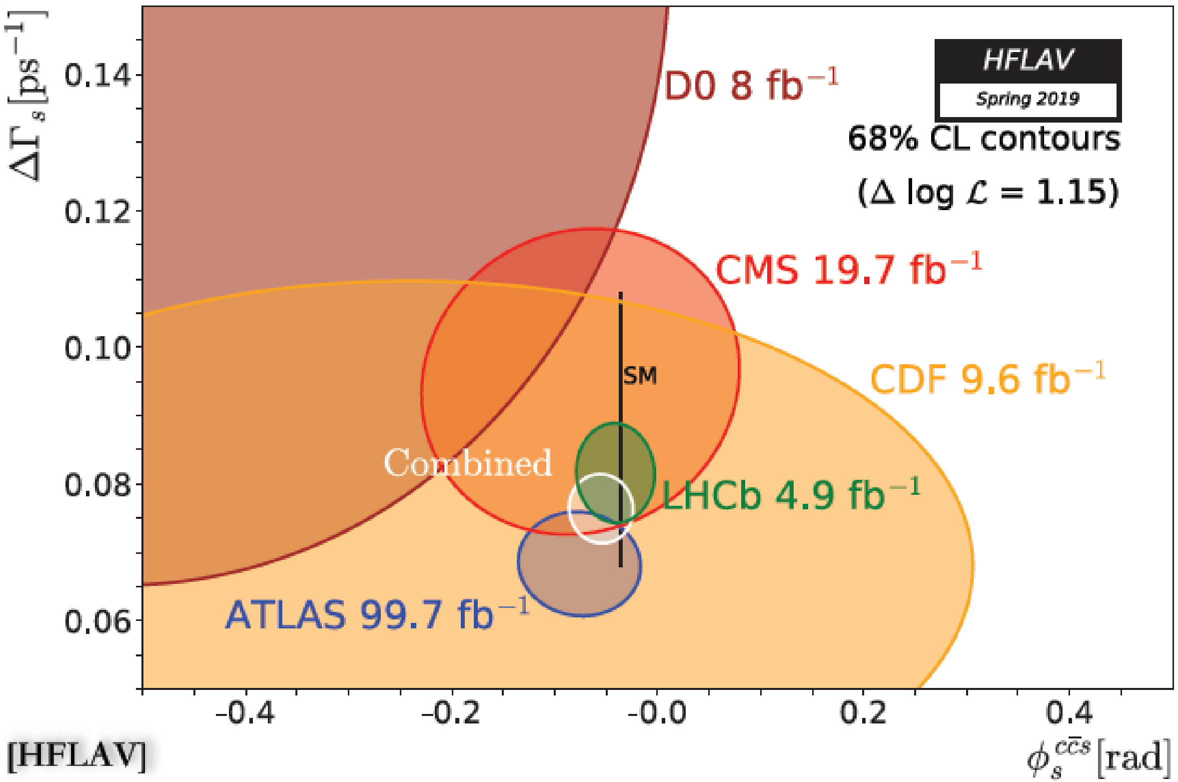


HFLAV combination

$\Delta\Gamma_s = 0.0764 \pm 0.0024\ \mathrm{ps}^{-1}$

CP-violating phase: $\phi_s = -\,0.055 \pm 0.021$ rad

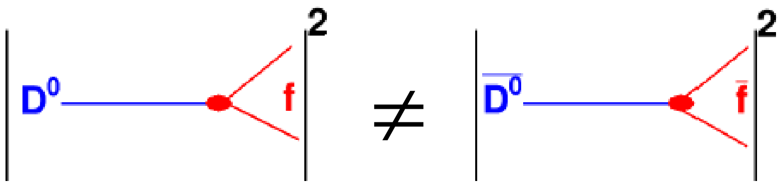
AFTER



[HFLAV]

CP violation in charm

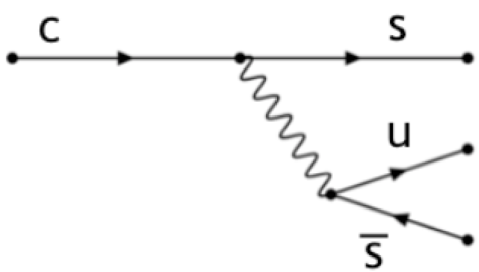
- Direct CP violation



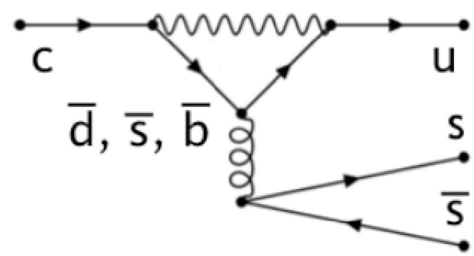
Measure asymmetry

$$A(D \to f) = \frac{N(D\to f) - N(\bar{D}\to \bar{f})}{N(D\to f) + N(\bar{D}\to \bar{f})}$$

- Most promising channels are *Cabibbo-suppressed* (CS) decays where CPV may arise from the *interference* between the **tree** and the **penguin** amplitudes



+



- SM prediction is very small $O(10^{-4}) \to O(10^{-3})$

The ΔA_{CP} measurement

- Tag D^0 and $\overline{D}^0$ via "*prompt*" and "*semileptonic*" decays:
  - Prompt: coming from primary vertex, *i.e.* $D^{*\pm} \rightarrow \overset{(-)}{D^0}\, \pi^{\pm}_{soft}$
  - Semileptonic: coming from B-decays, *i.e.* $B^{\pm} \rightarrow \overset{(-)}{D^0}\, \mu^{\pm} X$
- Th… (A) in Cabibbo-suppressed … π) defined as

$$A(D \rightarrow f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}$$

includes physics and detector effects:

Detection asymmetry from π^+_{soft} or μ^+

Production asymmetry from D^{*+} or B decays

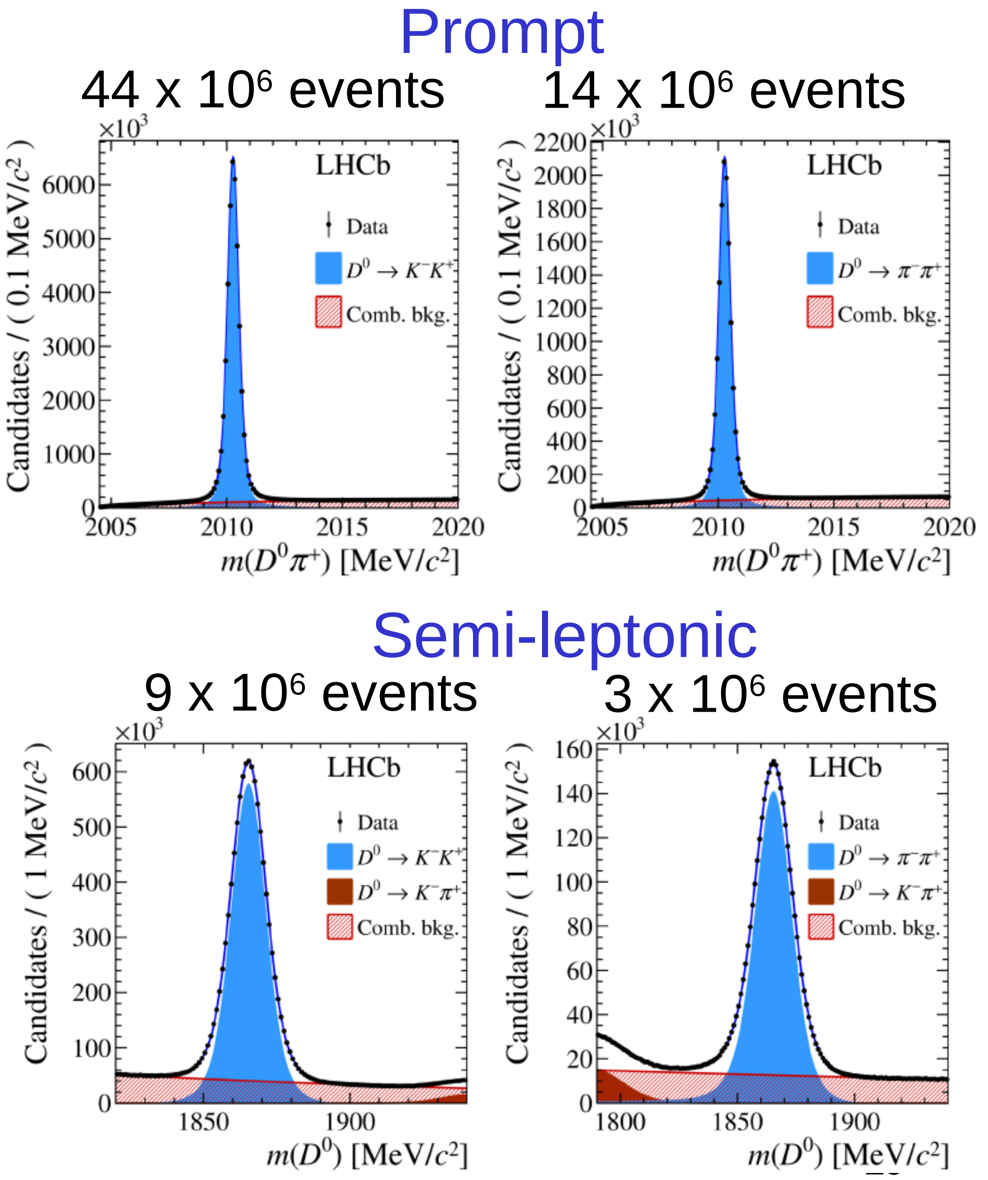
$$A = A_{CP} + A_D + A_P$$

- To eliminate these contributions and cancel the systematics measure :

ΔA_{CP} measurement : fits and yields

- Measurement performed with almost full Run-2 data- set (5.9/fb)
- Get the raw asymmetries from fits to the m(D^0 π^+_{soft}) or m(D^0) distributions

[Phys. Rev. Lett. 122, 211803]



Observation of CPV in charm decays

- Run-2 results alone :

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

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

- Add in the Run-1 result gives :

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

- A 5.3σ measurement of CPV in the charm system !

- This opens a completely new window for the study of CP violation

LHCb new spectroscopy measurements

Corfu Workshop as of last year …

- Reported an unexpected narrow resonance in the mass spectrum of (J/ψ p) in $\Lambda_b \rightarrow$ (J/ψ p) K^- decays
- First observed in 2015→ LHC Run 1 data : 3 fb^{-1}
- Consistent with pentaquarks: allowed by QCD, but not observed in 50 years of searching.

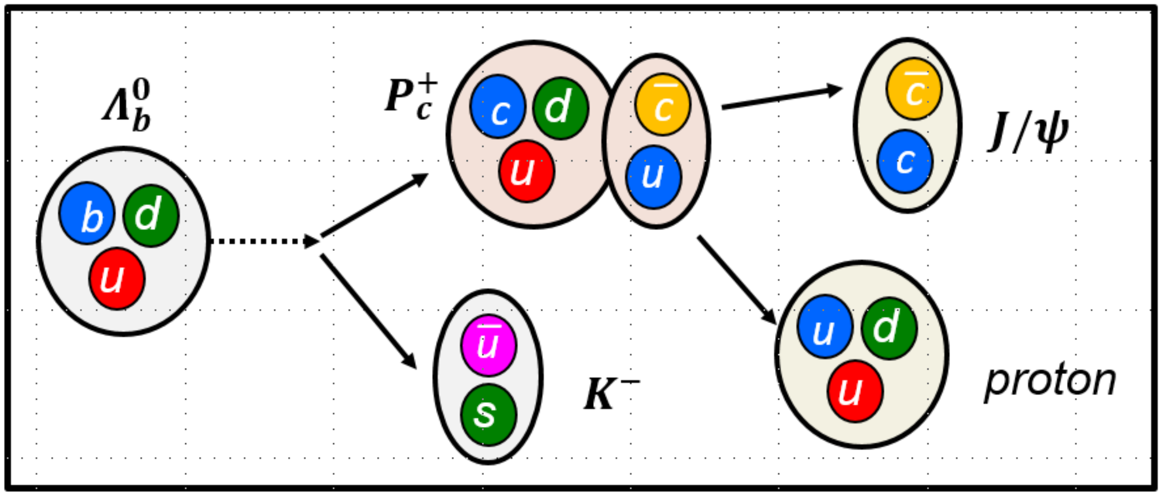
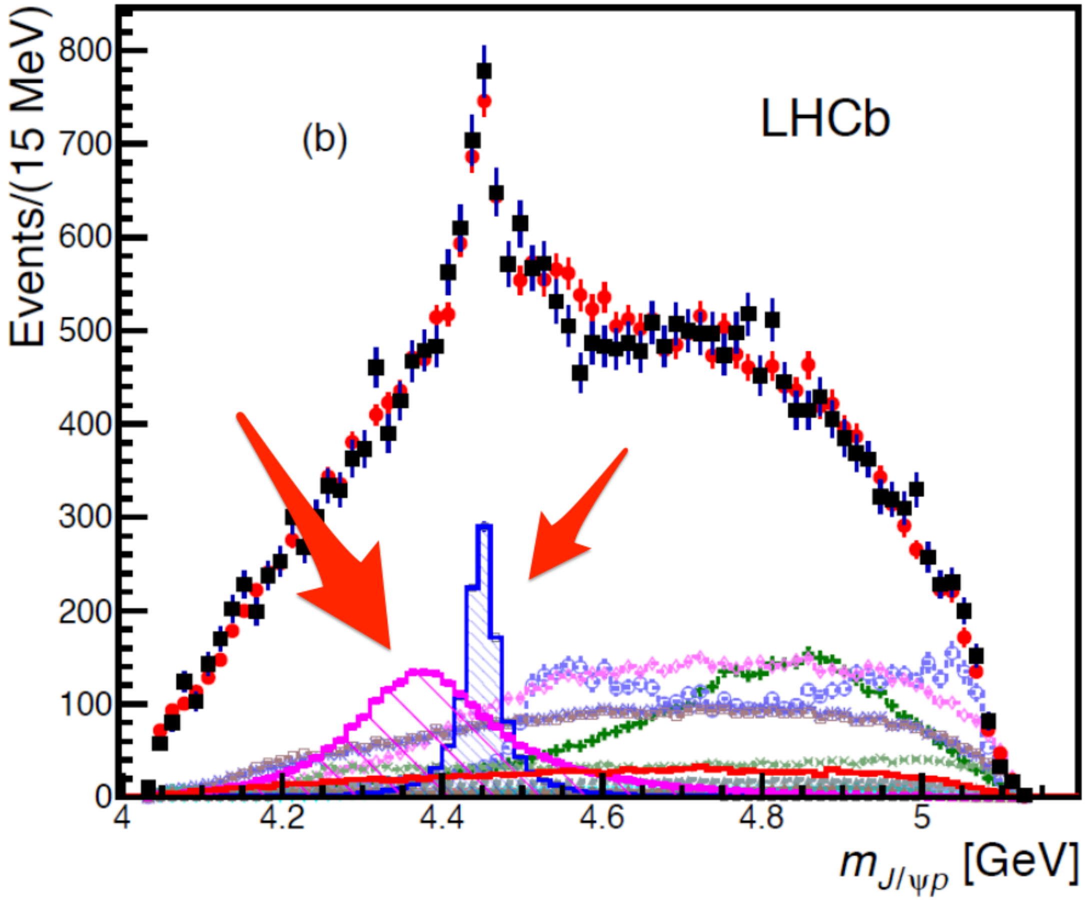
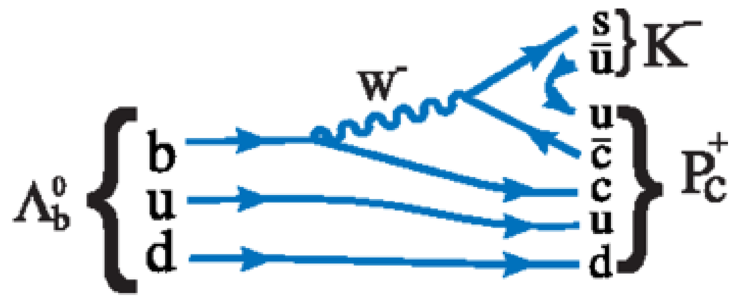


Diagram from Liming Zhang

Pentaquarks – 2015 reminder



PRL 115 (2015) 072001



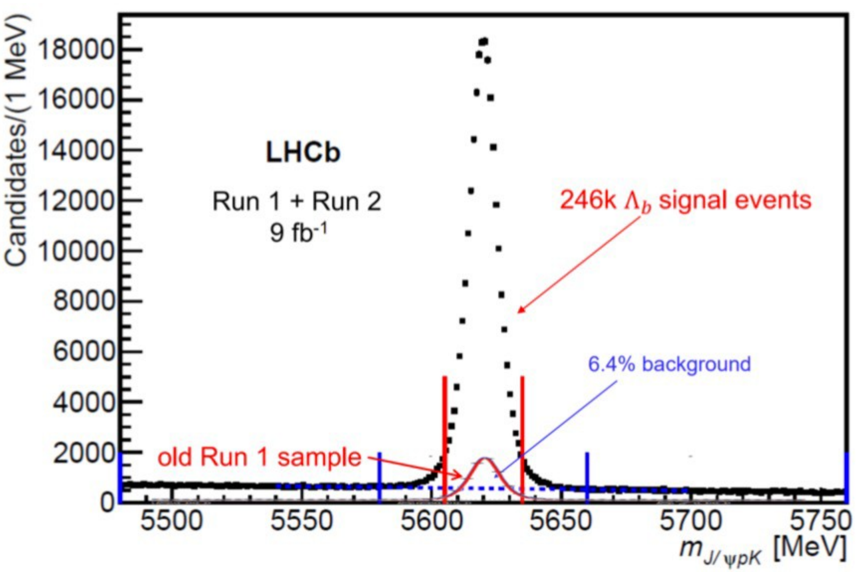
P_c^+(4380): M = 4380±8±29 MeV , Γ = 205±18±86 MeV — 9 σ

P_c^+(4450): M = 4449.8±1.7±2.5 MeV , Γ = 39±5±19 MeV — 12 σ

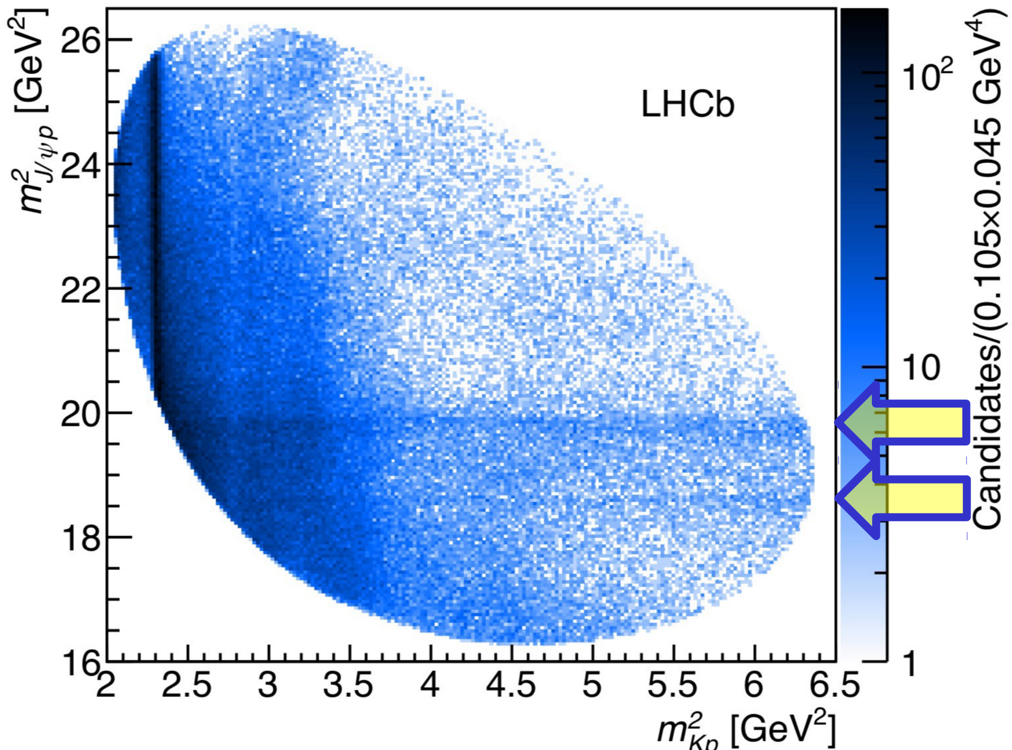
New Run I and II analysis

PRL 122 (2019) 222001

- 9.5x more data than used in Run-I
- Improvements in the data selection (2x), integrated luminosity (3x) and cross section (13 TeV vs 7-8 TeV)



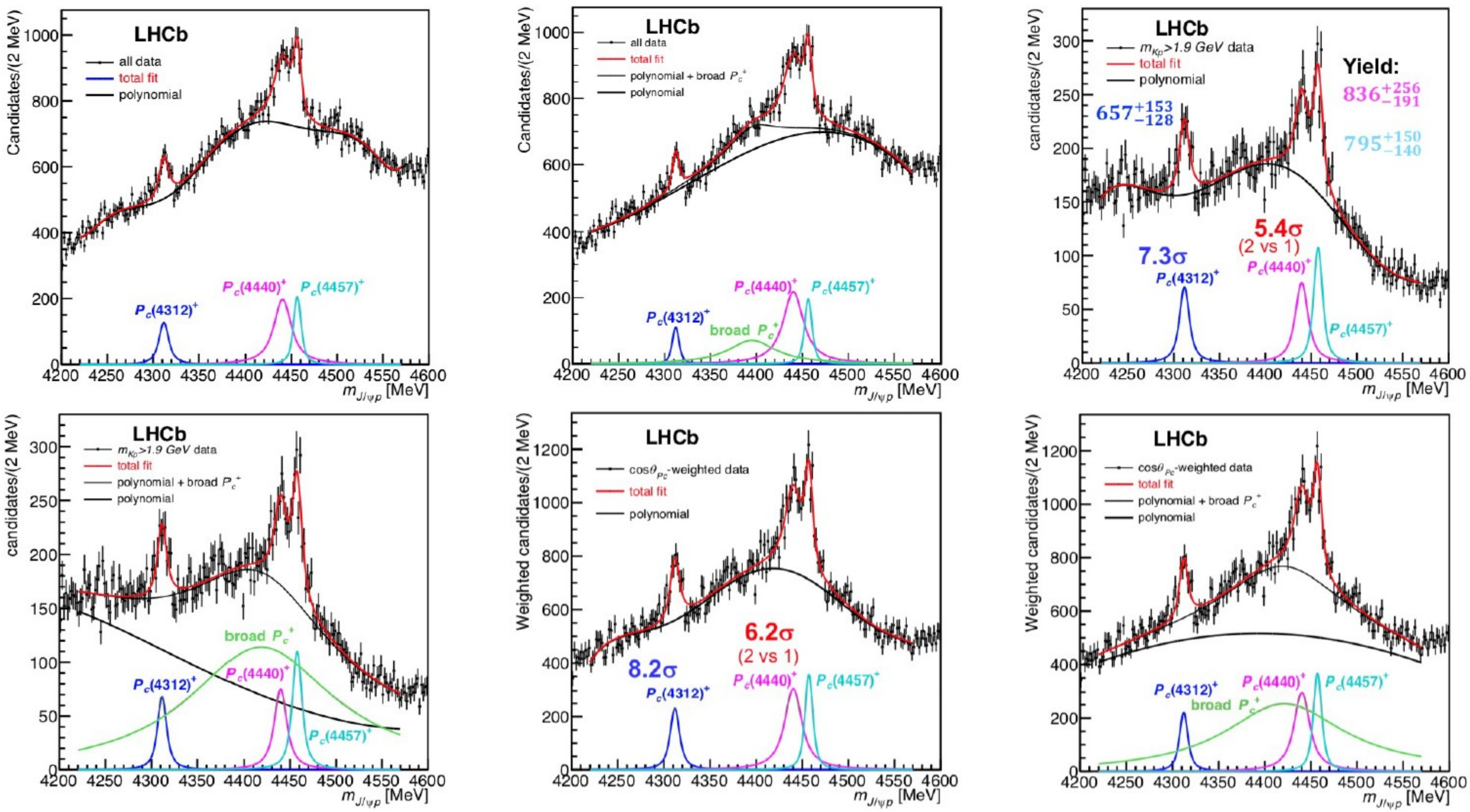
$\Lambda_b \to$ (J/ψ pK) mass



Fits to data

PRL 122 (2019) 222001

- Confirms the peaking structure at ~4450 MeV



Fits to data

PRL 122 (2019) 222001

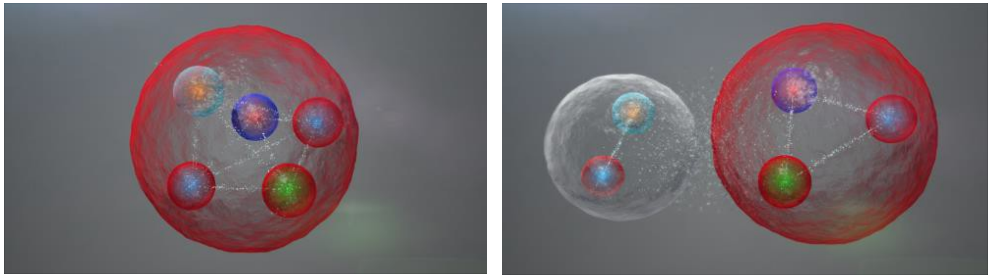
- The previously observed $P_c^+(4450)$ is now superseded by the $P_c^+(4440)$ and $P_c^+(4457)$
- New state $P_c^+(4312)$
- The broad $P_c^+(4380)$ state is neither excluded nor confirmed by current analysis
- Updated amplitude analysis required to identify the states

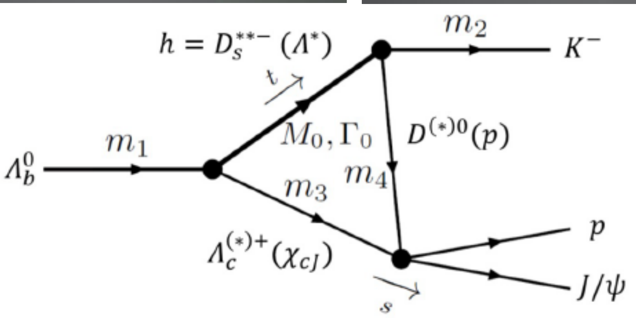
State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

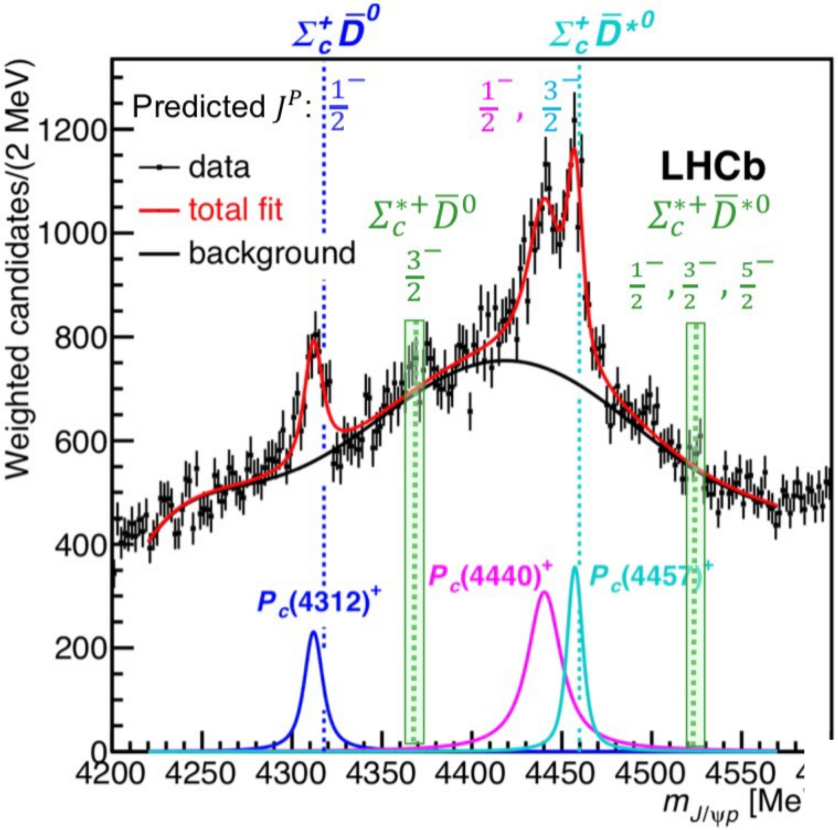
Nature of pentaquarks ?

Possible models describing the observed pentaquark states :

- Tightly bounded states
- Re-scattering models





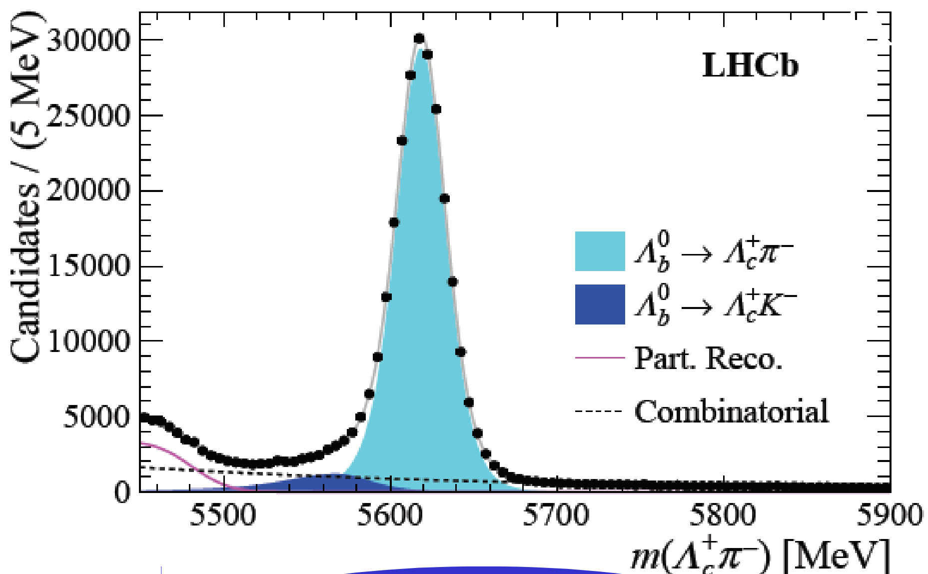


- Molecular-state model favoured : bound mesons and baryons are expected to form narrow resonances just below mass thresholds
- More work needed

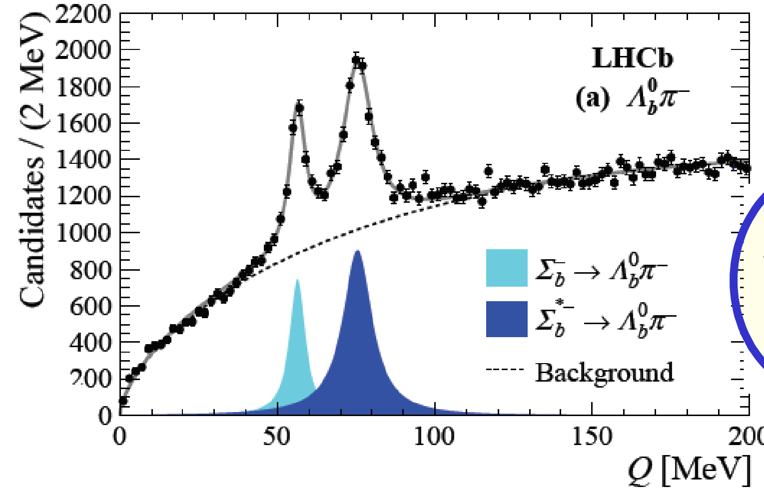
New : Σ_b and Σ_b^* spectroscopy

PRL122 (2019) 012001

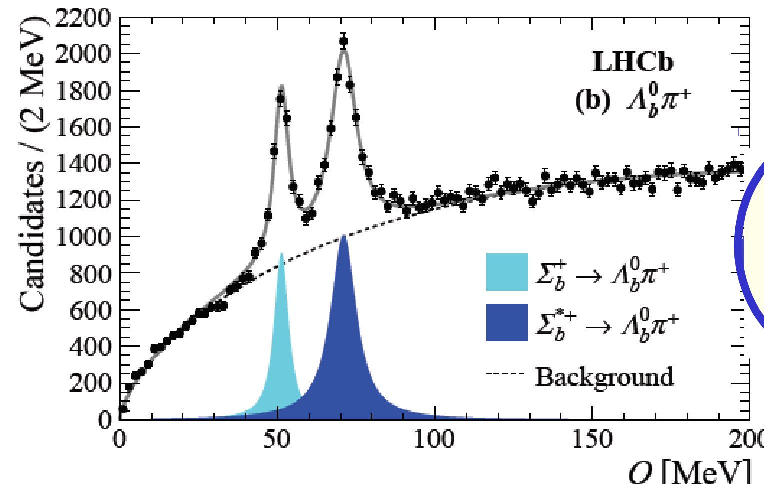
- Study the $\Lambda_b\,\pi^{\pm}$ spectrum where $\Lambda_b \rightarrow \Lambda_c^+\,\pi^-$ and $\Lambda_c^+ \rightarrow p\,K\,\pi$
- Find (234,270 ± 900) Λ_b candidates in 3 fb^{-1} (Run



$\Lambda_c^+\,\pi^-$ mass (Λ_b^+)



$\Lambda_b\,\pi^-$ mass



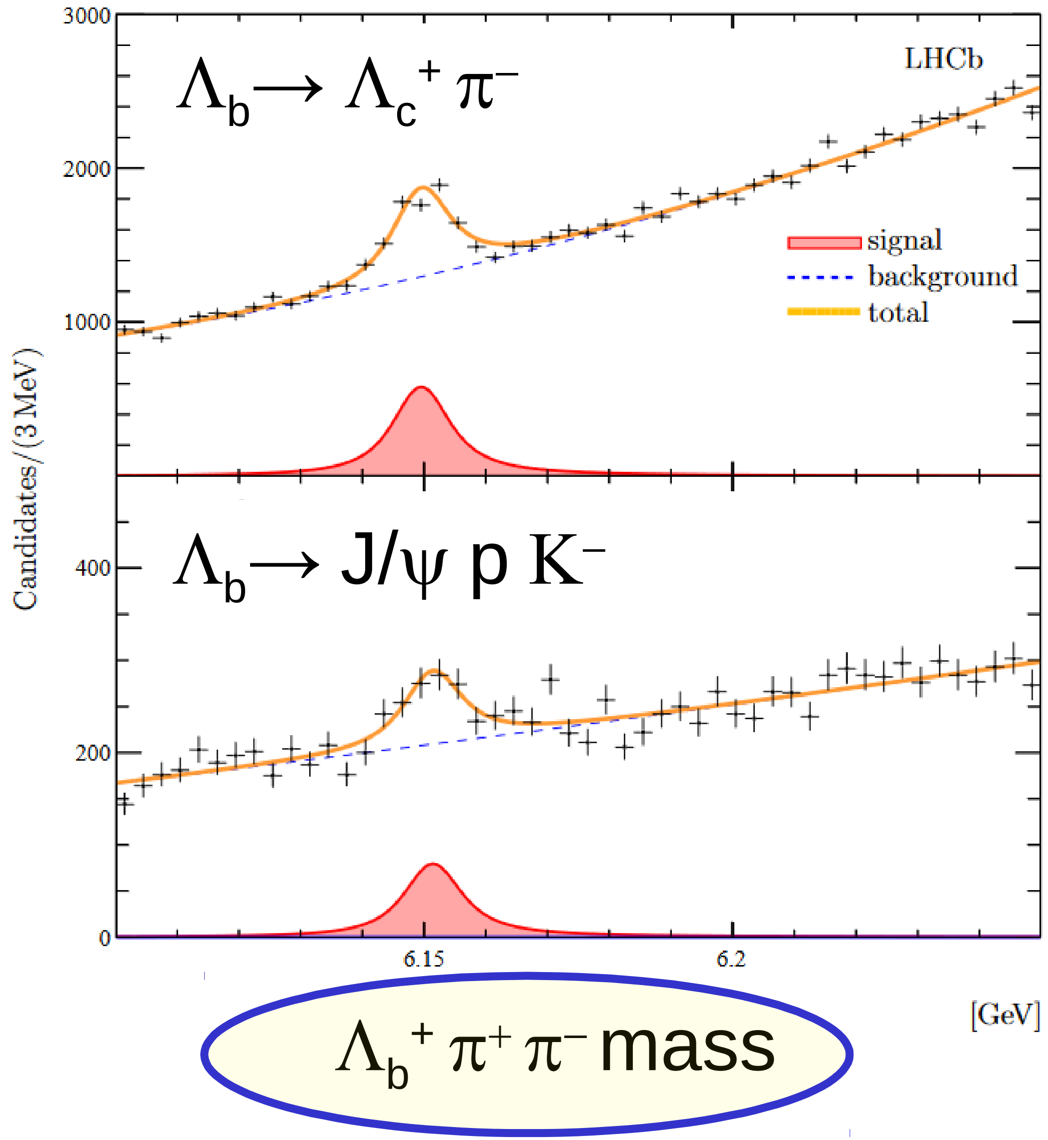
$\Lambda_b\,\pi^+$ mass

Σ_b and Σ_b^* resonances

Λ_b excitations in $(\Lambda_b\, \pi^+ \pi^-)$

arXiv:1907.13598

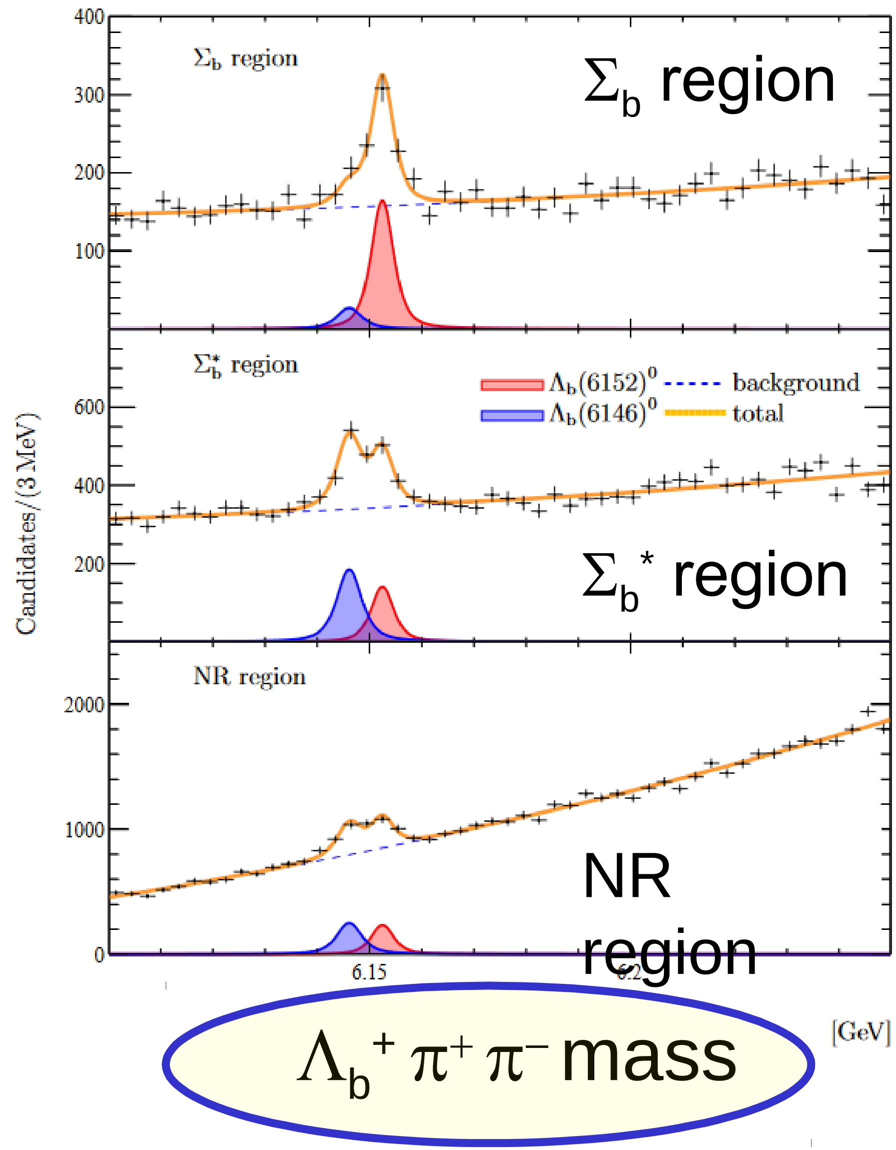
- Study excitations by adding $\pi^+\pi^-$ to the Λ_b
- Λ_b reconstructed in $\Lambda_b \to \Lambda_c^+ \pi^-$, and also add in $\Lambda_b \to J/\psi\, p\, K^-$
- Structure seen around 6.15 GeV/c²



Λ_b excitations in ($\Lambda_b\ \pi^+\pi^-$)

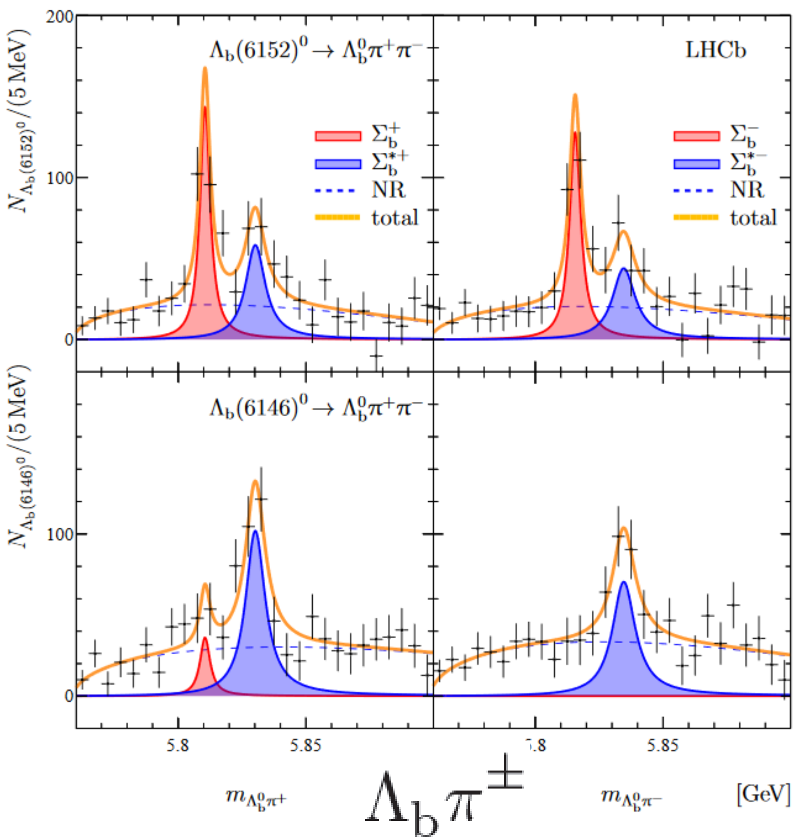
arXiv:1907.13598

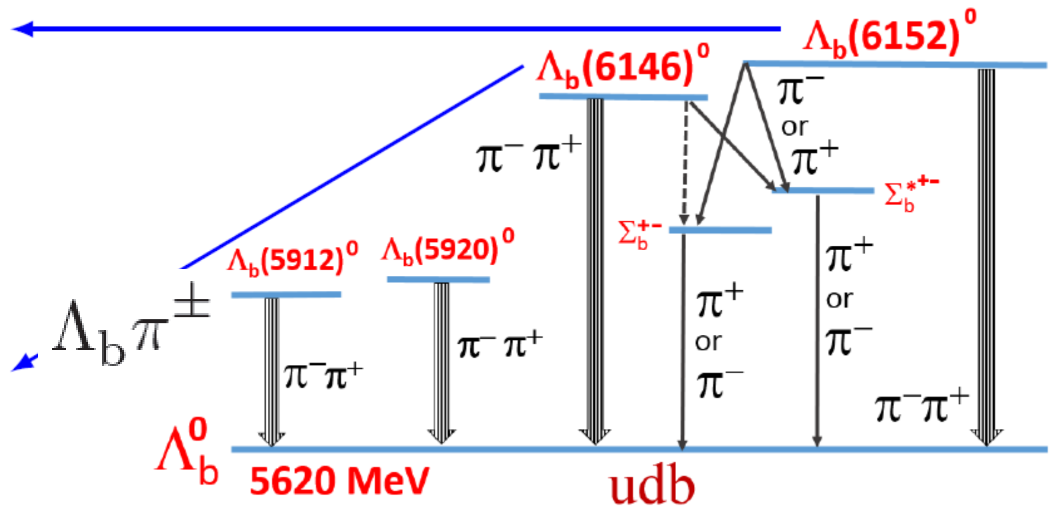
- Study excitations by adding $\pi^+\pi^-$ to the Λ_b
- Λ_b reconstructed in $\Lambda_b \rightarrow \Lambda_c^+\pi^-$, and also add in $\Lambda_b \rightarrow J/\psi\ p\ K^-$
- Structure seen around 6.15 GeV/c²
- Investigate substructure of the decays where $X \rightarrow \Sigma_b^{(*)}\pi \rightarrow \Lambda_b\ \pi^+\pi^-$



Observation of two new Λ_b excitations

arXiv:1907.13598





$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\text{ MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\text{ MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\text{ MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\text{ MeV},$$

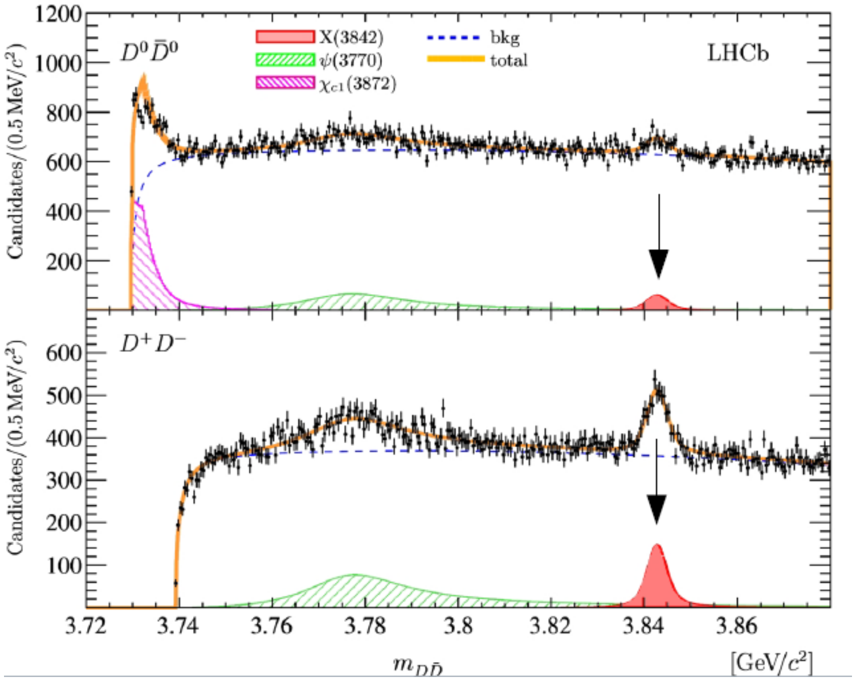
- Very rich spectroscopy in the Λ_b & $\Sigma_b^{(*)}$ systems !

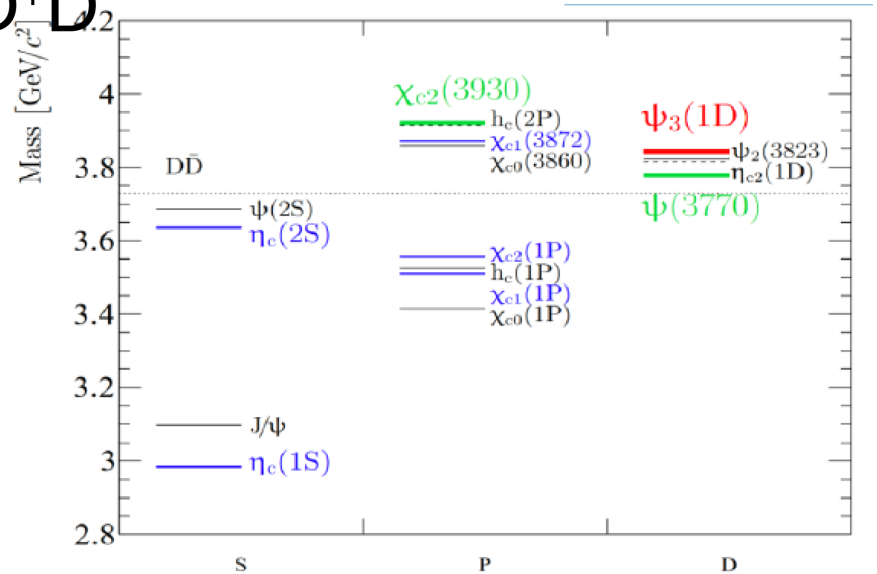
Observation of new state in DD spectrum

- Use full Run1+Run2 dataset

JHEP 07 (2019) 035

→ new narrow state observed in the invariant mass spectra of $D^0\bar{D}^0$ and D^+D^-





$M_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12$ MeV/c²

$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35$ MeV

The upgraded LHCb detector and outlook

LHCb Upgrade planning

Install Upgrade I

Consolidation

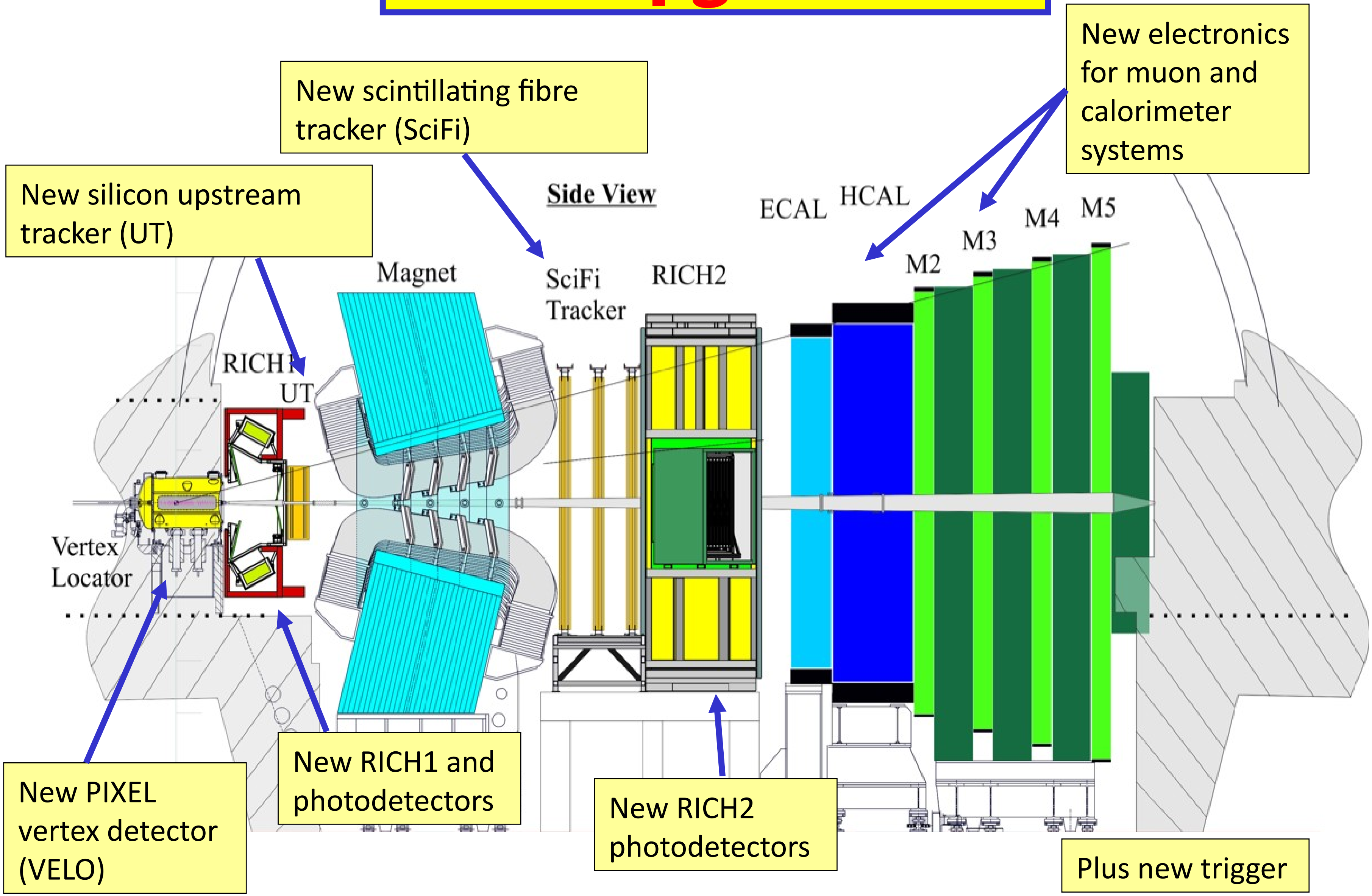
Upgrade II

Luminosity 4×10^{32} $cm^{-2}s^{-1}$
~1.1 visible interactions/crossing
~9 fb^{-1} collected

Luminosity 2×10^{33} $cm^{-2}s^{-1}$
~5.5 visible interactions/crossing
Up to 50 fb^{-1} collected

Luminosity 2×10^{34} $cm^{-2}s^{-1}$
~55 visible interactions/crossing
300 fb^{-1} collected

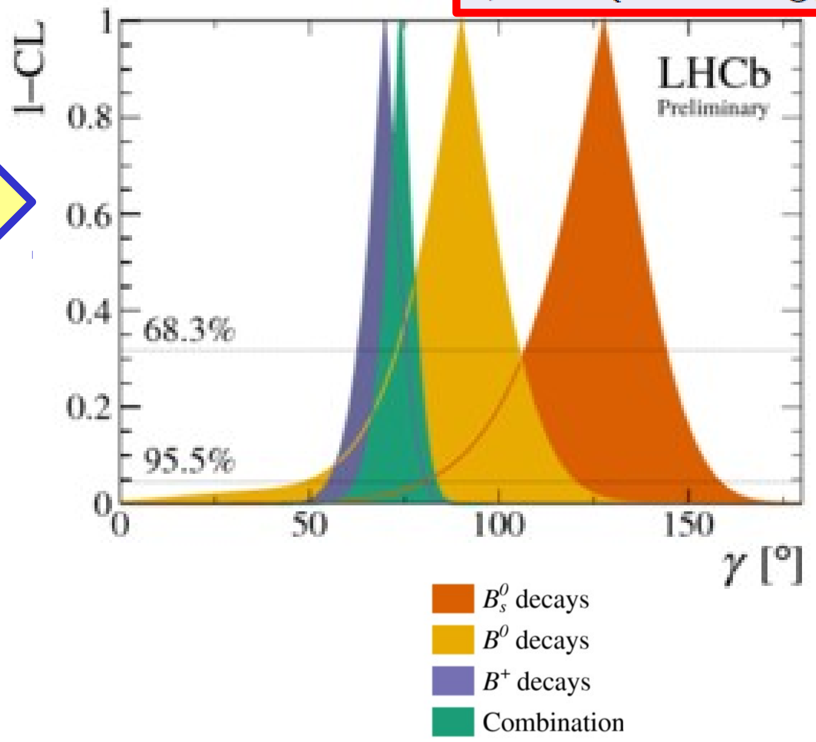
LHCb Upgrade I



γ prospects : Run 1 & II → Upgrade

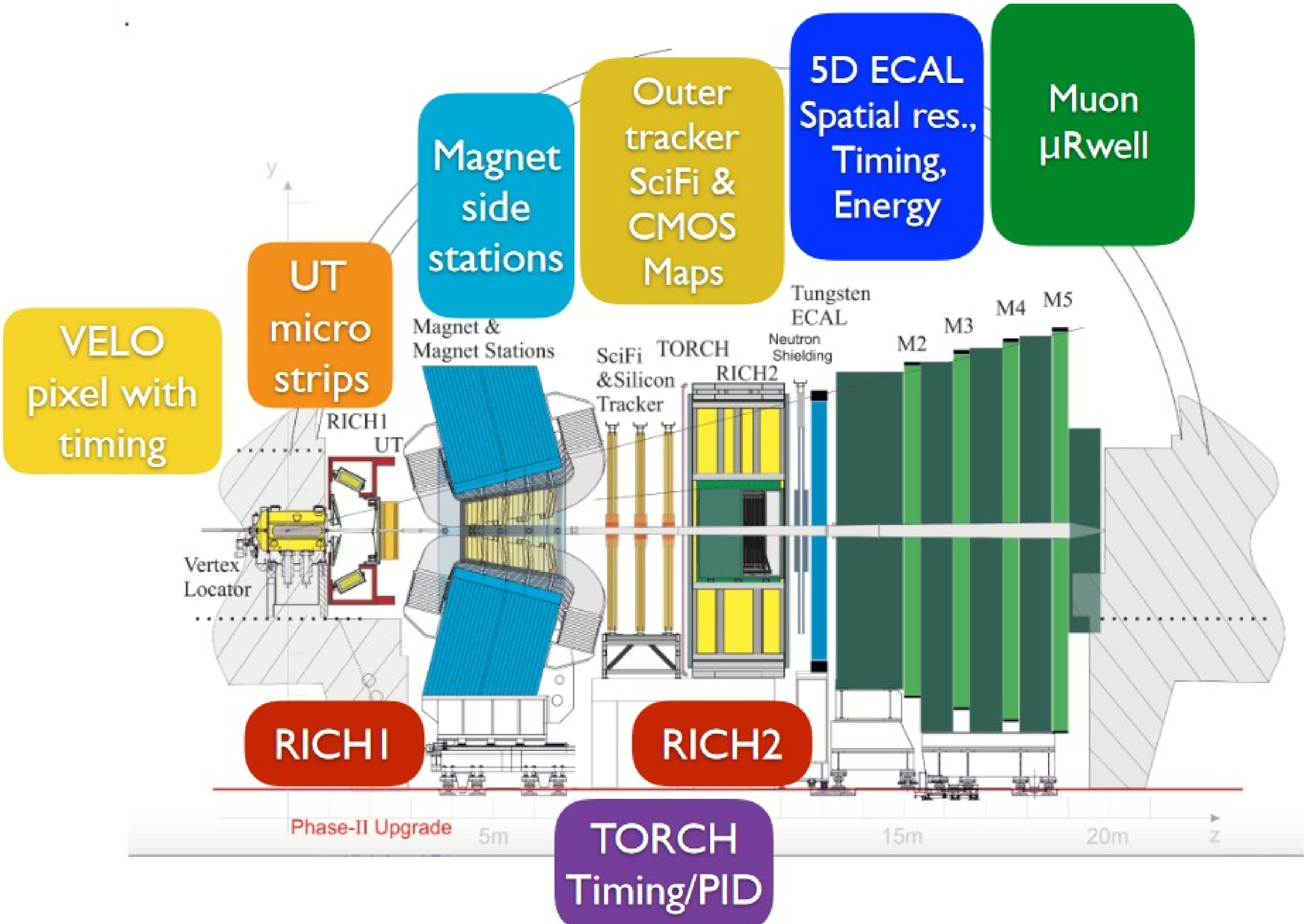
- Run 1 target of 8° surpassed : (analyses now essentially complete)
- Run II data well into analysis :
  target <4°(~9 fb^{-1})
- LHCb Upgrade :
  target 0.9°(~50 fb^{-1})

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



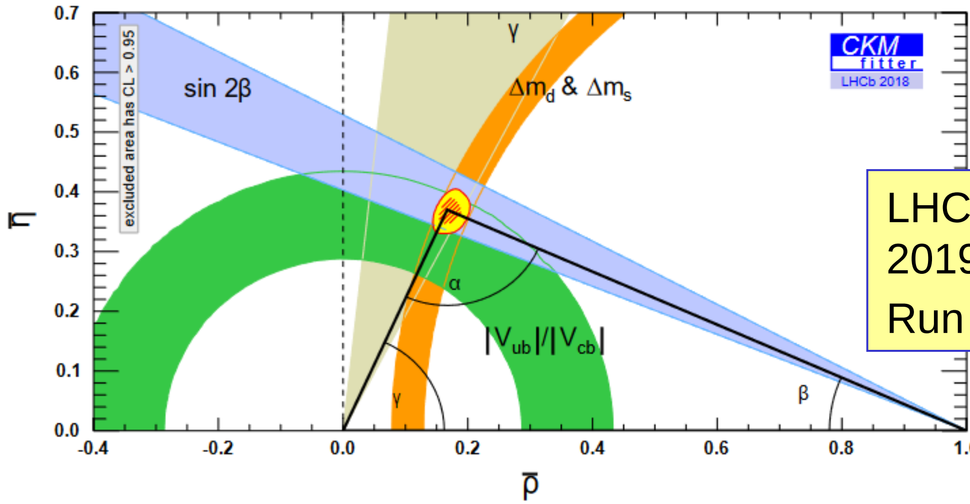
EPJC (2013) 73:2373

… and beyond 2026 : Upgrade II



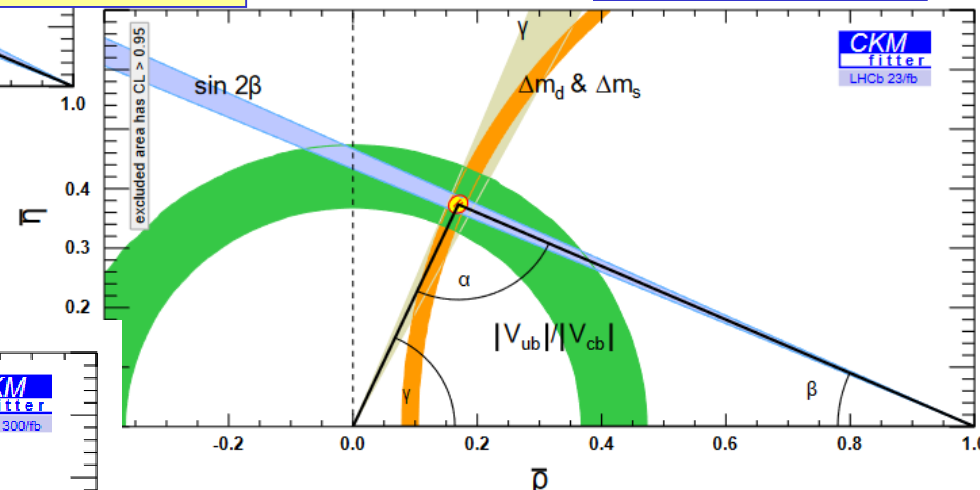
Evolution of the Unitarity Triangle

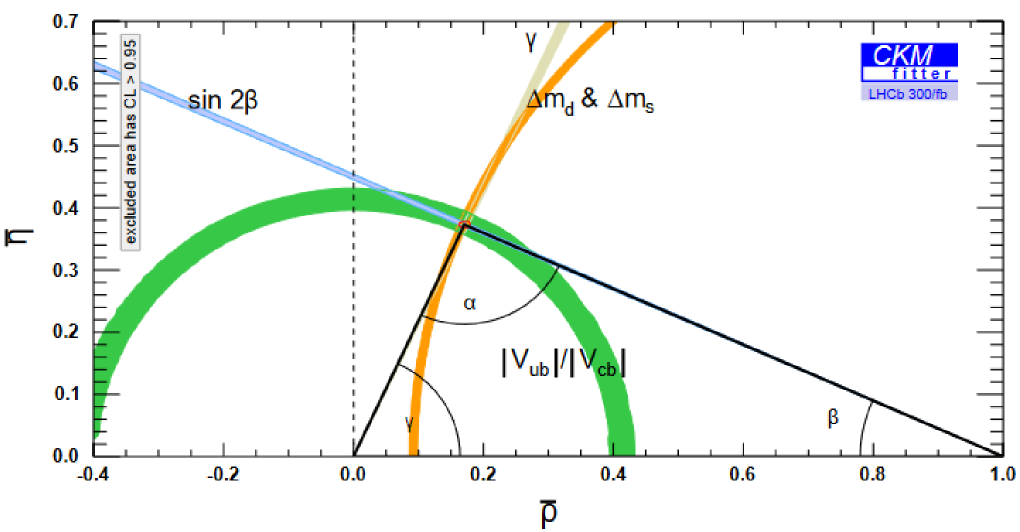
LHCB-PUB-2018-009



LHCb : 2019 Run 2

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





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

Summary and Outlook

- The LHCb experiment has performed spectacularly well :
  → ~9 fb^{-1} of recorded data up to $\sqrt{s}$ =13 TeV
- So far all Unitarity Triangle measurements are consistent with the Standard Model
  → New Physics is becoming constrained
- LHCb is a fantastic platform for spectroscopy measurements: many measurements were never foreseen in LHCb's original physics portfolio.
- Still much room for New Physics, but higher precision required

→ preparing for LHCb Upgrades beyond 2020 and the decade
afterwards!

Spare Slides

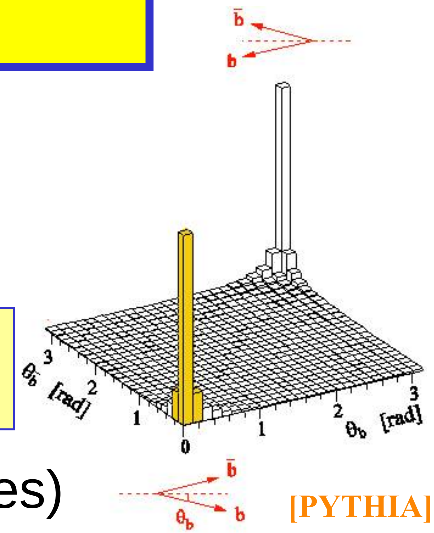
LHCb forward spectrometer

- 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 √s = 7 TeV

  in the LHCb acceptance 2< η < 5

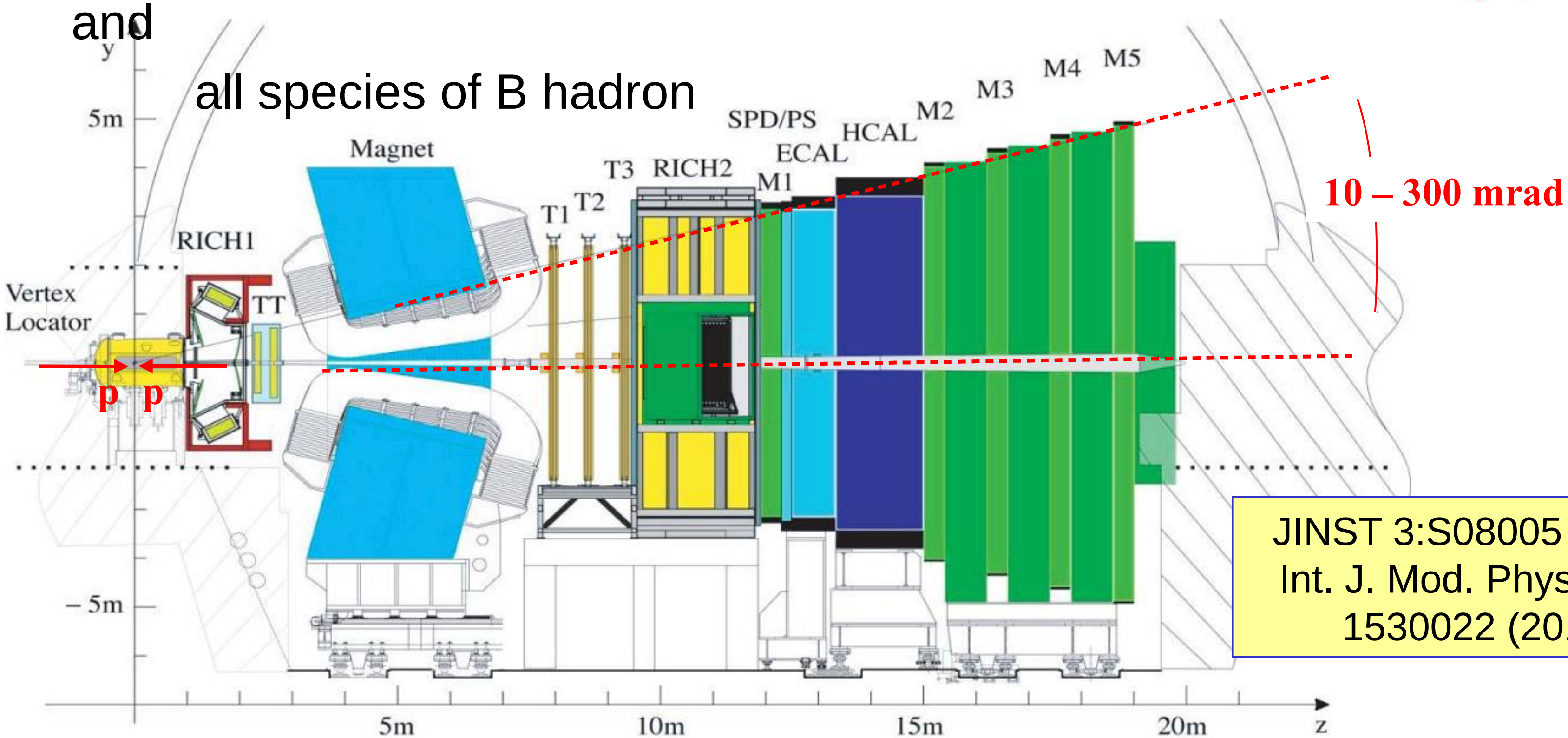
  At √s = 13 TeV : 154.3 ± 1.5 ± 14.3 μb

PRL 118, 052002 (2017)



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

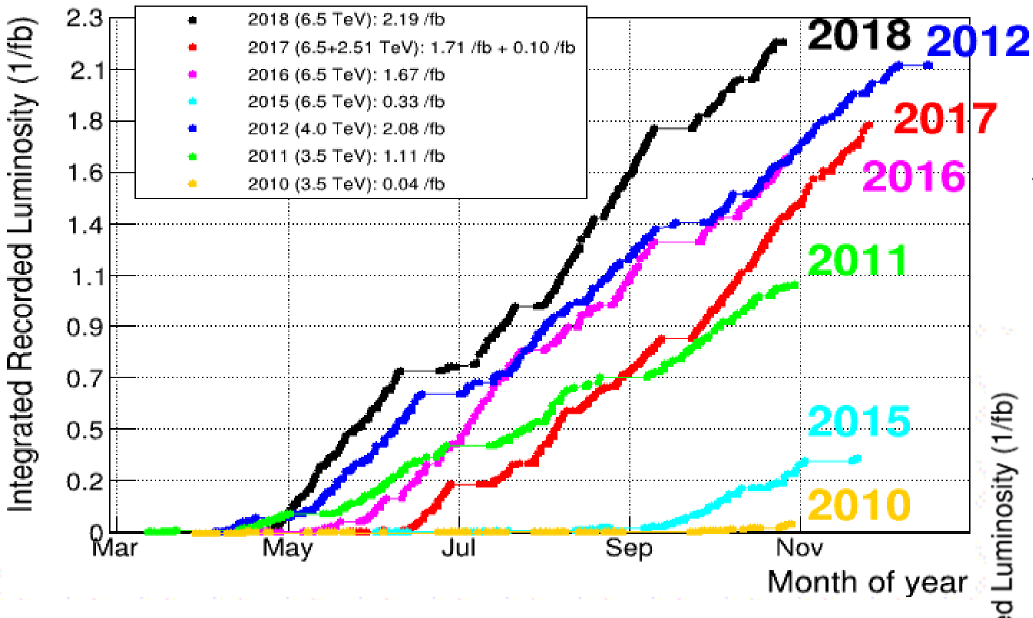
all species of B hadron

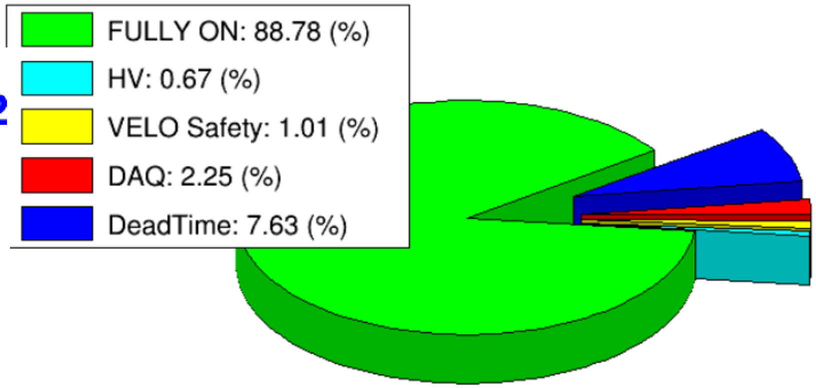


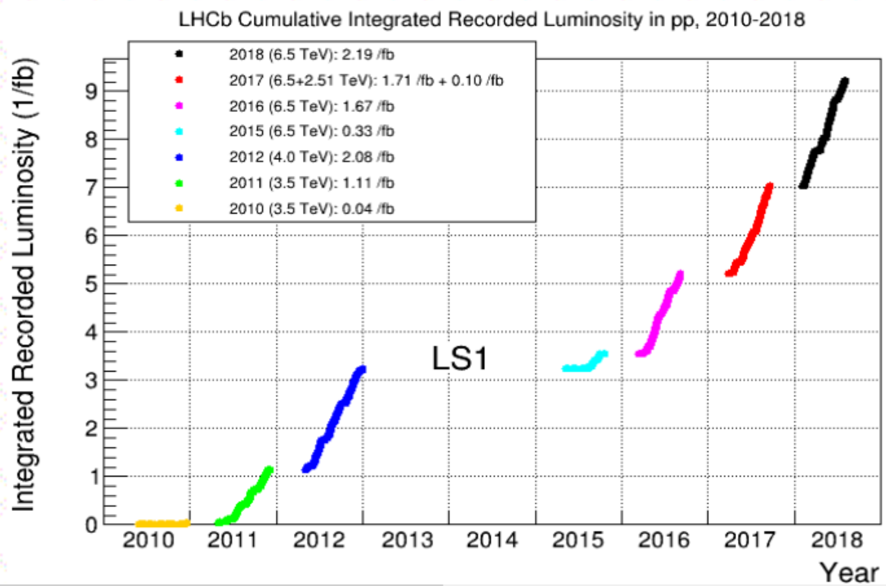
JINST 3:S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb data taking

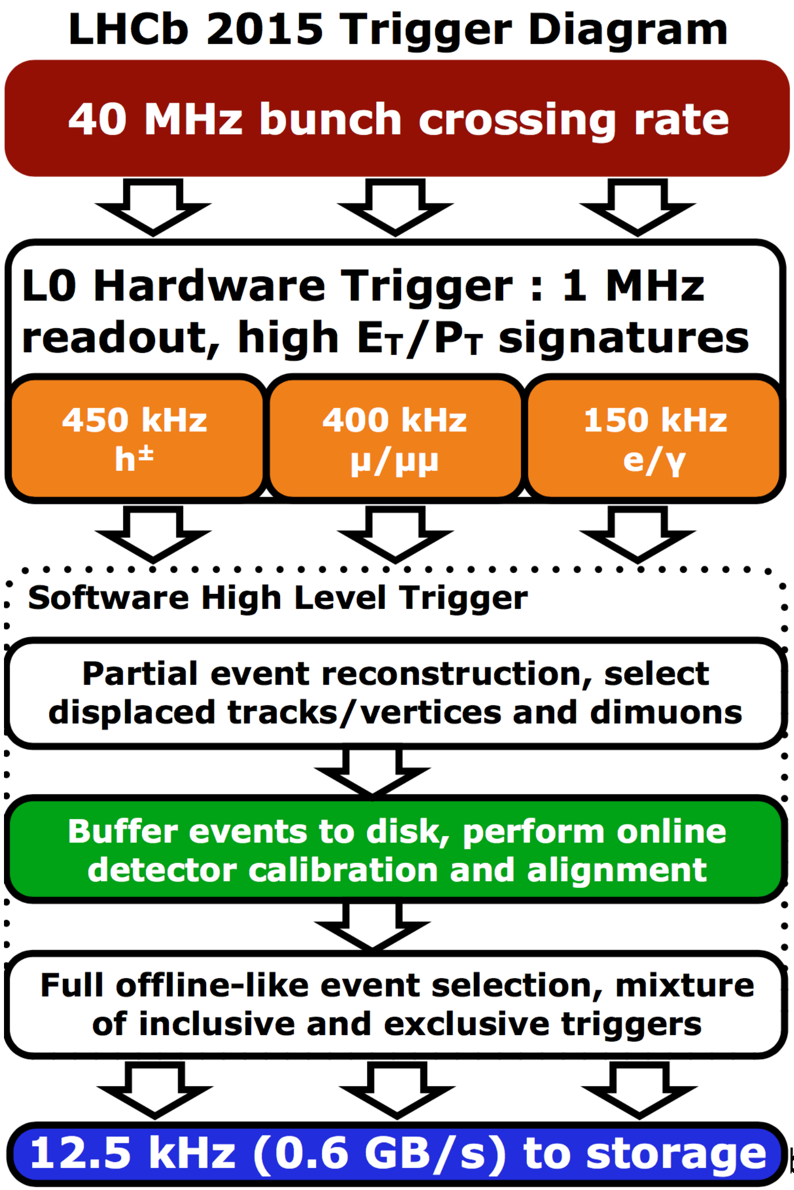
- Design luminosity = 2×10^{32} $cm^{-2} s^{-1}$ (50 times less than ATLAS/CMS). Typical running luminosity ~4×10^{32} $cm^{-2} s^{-1}$





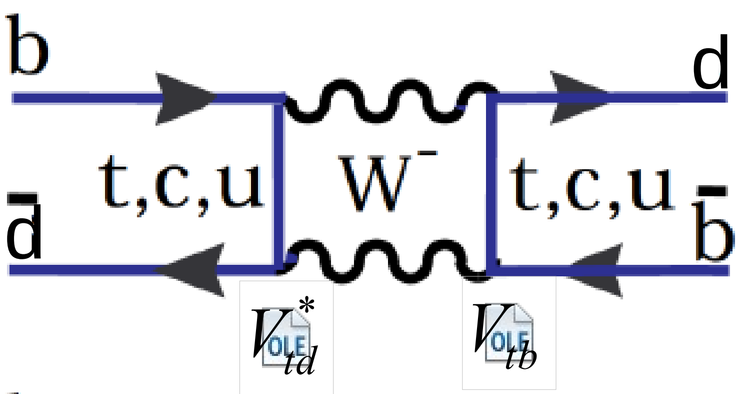


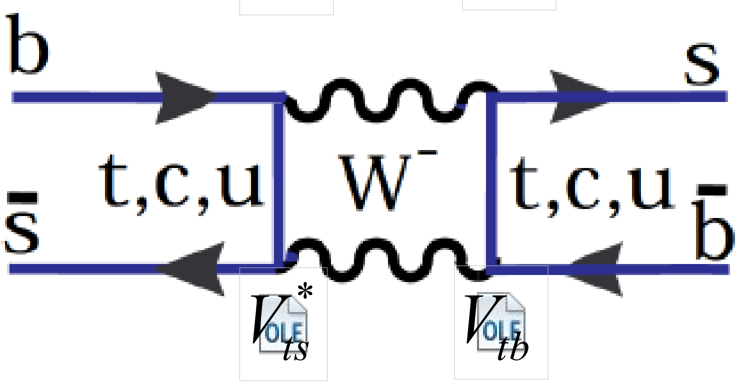
LHCb Run 2 trigger

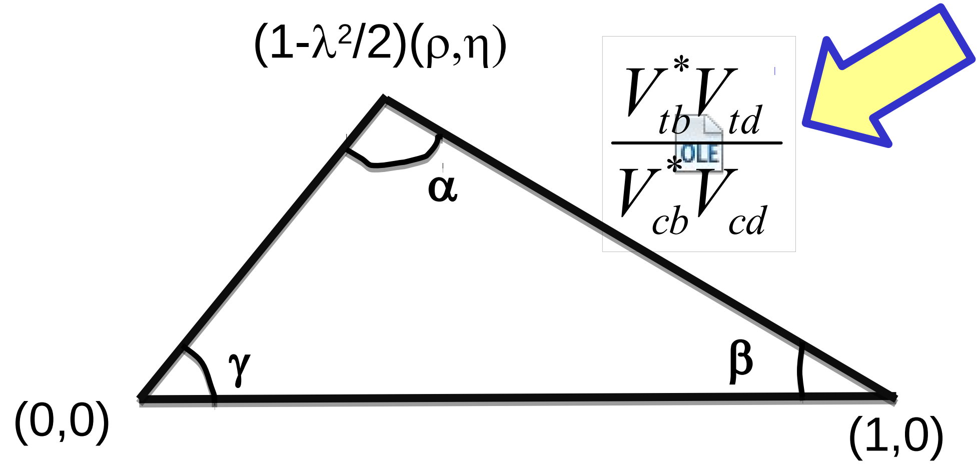


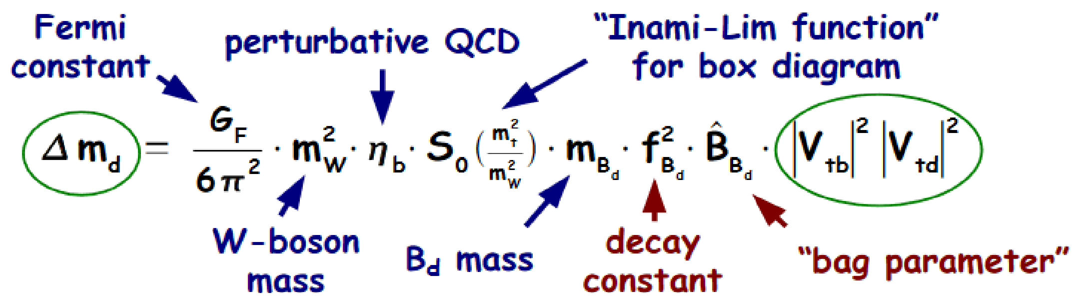
- After LHCb's hardware trigger, events are buffered.
- LHCb's automated real-time alignment and calibration runs :
  - Full detector alignment and calibration in minutes.
- Full event reconstruction in software trigger
  - Exclusive decay modes and calibration modes fully reconstructed,
  - Results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

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









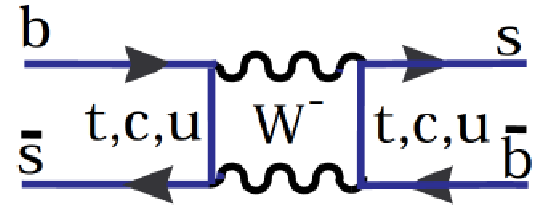
$$\Delta m_d = \frac{G_F}{6\pi^2} \cdot m_W^2 \cdot \eta_b \cdot S_0\left(\frac{m_t^2}{m_W^2}\right) \cdot m_{B_d} \cdot f_{B_d}^2 \cdot \hat{B}_{B_d} \cdot |V_{tb}|^2 |V_{td}|^2$$

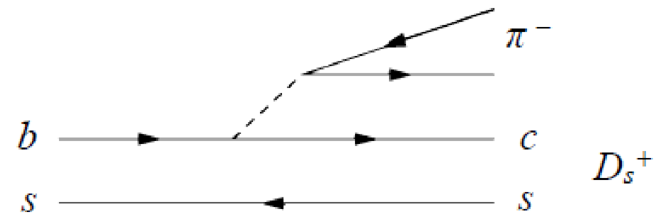
- Mixing loop dominated by the top
- Length of side from ratio of B_d and B_s : mixing frequencies extracted with input from lattice QCD (systematics cancel)

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

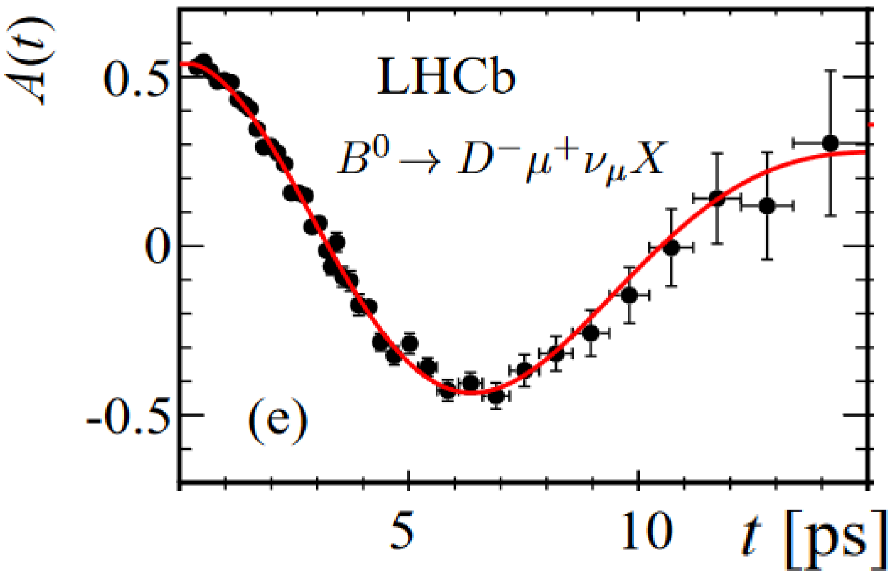
$$\sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

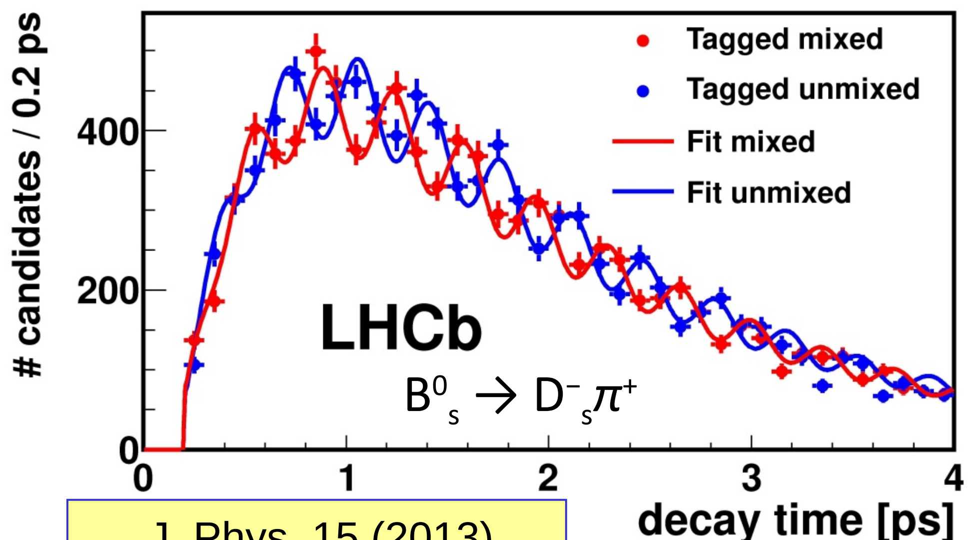
$B_{(s)}$ mixing at LHCb





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





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

Eur. Phys. J. C76 (2016) 412

J. Phys. 15 (2013) 053021

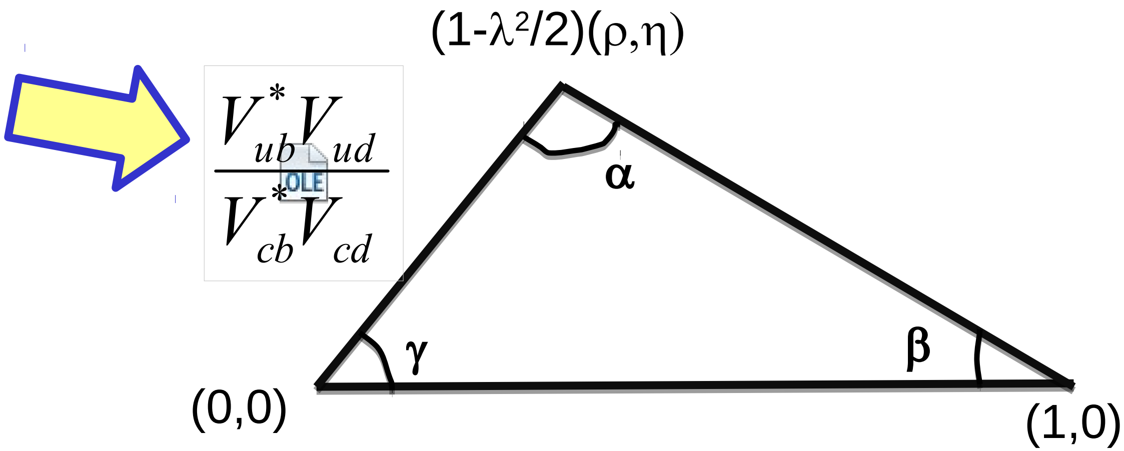
$\ldots .023 \pm 0.006\ \text{ps}^{-1}$

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

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

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

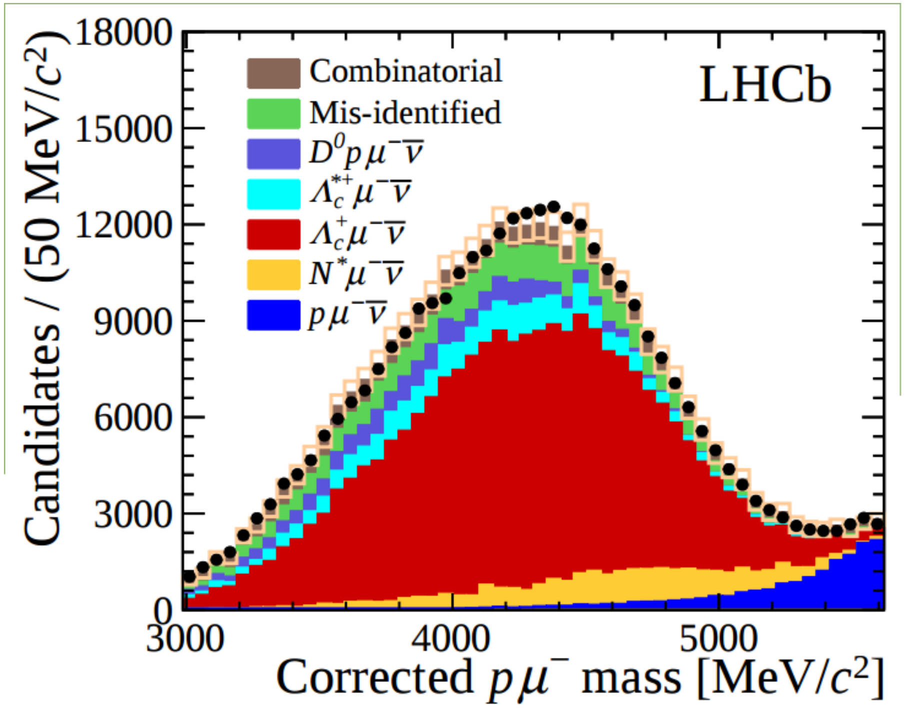
$|V_{ub}|$ measurement for side opposite to β



- 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

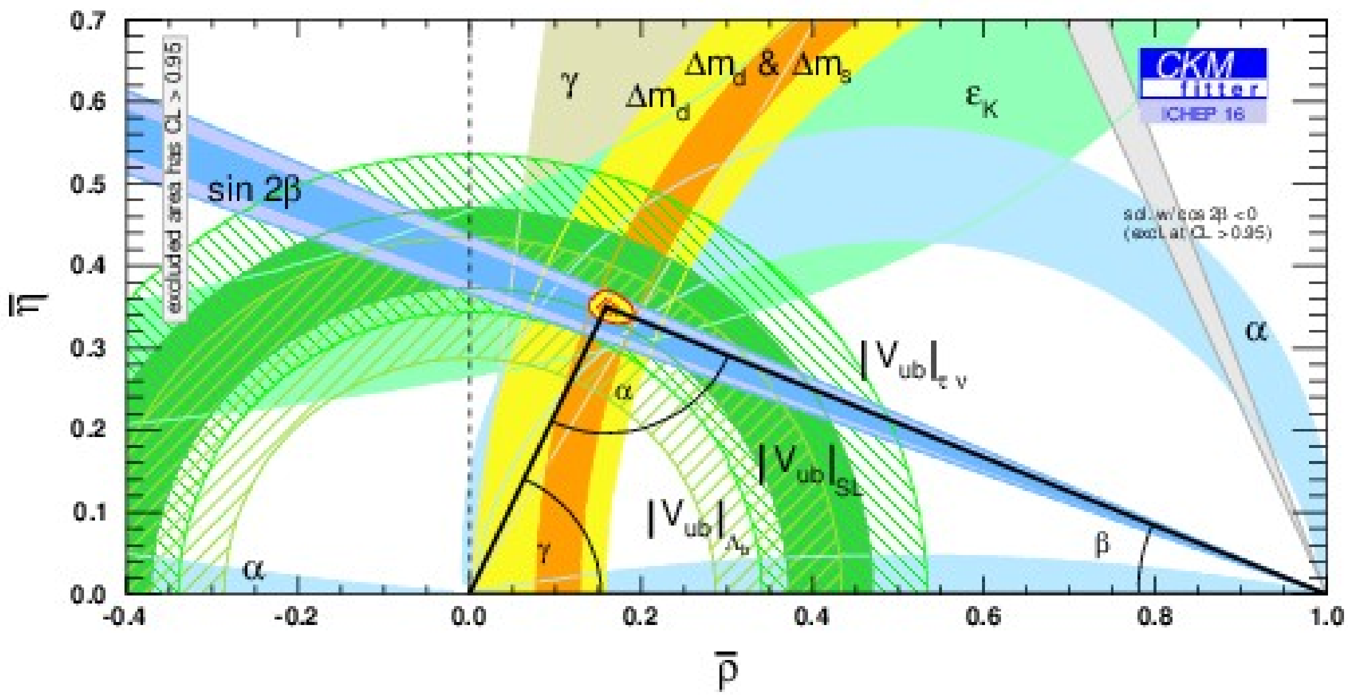
Tension between B-factory inclusive and exclusive $|V_{ub}|$ measurements limit the precision on UT side. World avera

$$|V_{ub}| = (4.49 \pm 0.15 \, {}^{+\,0.16}_{-\,0.17} \pm 0.17) \times 10^{-3} \quad \text{(inclusive)}$$

$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{(exclusive)}$$

$$|V_{ub}| = (3.94 \pm 0.36) \times 10^{-3} \quad \text{(average)}$$

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



Measurement of α

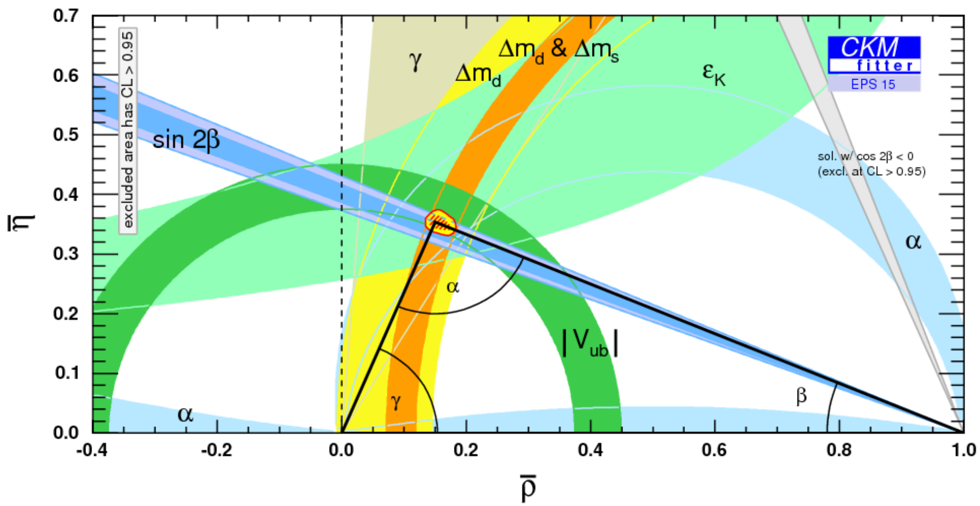
- Constraints on α from $B \to \pi\pi$, $\rho\pi$ and $\rho\rho$ (Babar and Belle)
- $\alpha = (87.6\ ^{+3.5}_{-3.3})°$ world average measurement
- Compared to the prediction from the global CKM fit (not including the α -related measurements)

$$\alpha = (90.6\ ^{+3.9}_{-1.1})$$

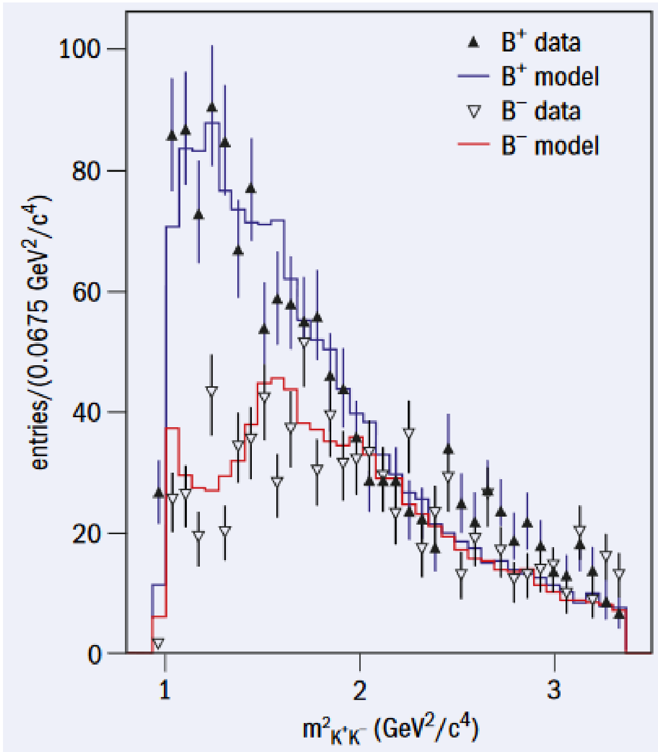
http://ckmfitter.in2p3.fr

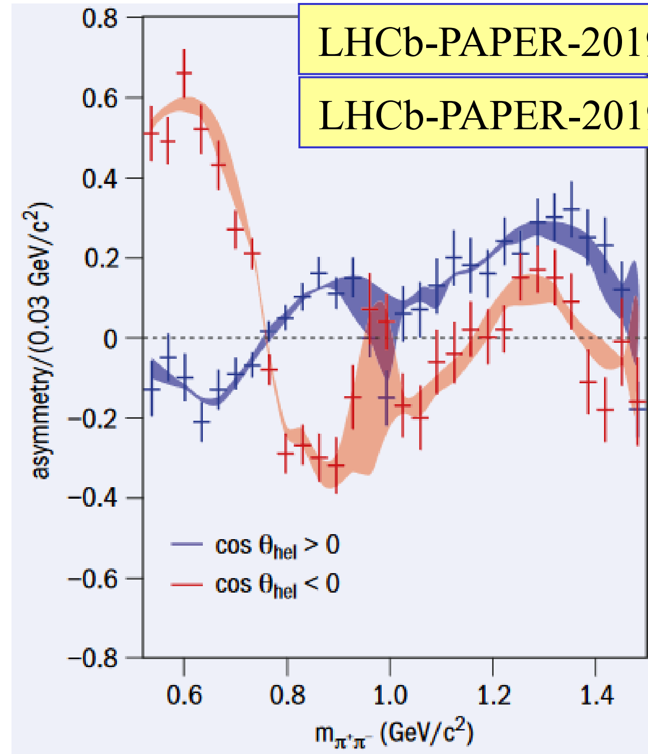
$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

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



CP violation in 3-body $B^{\pm}$ decays



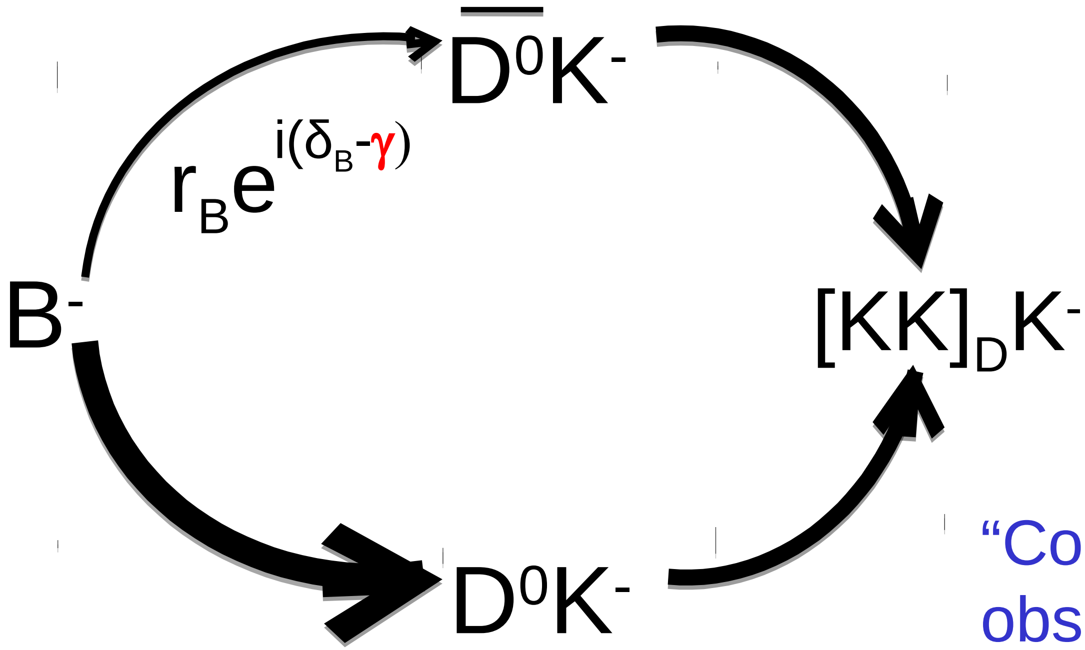


LHCb-PAPER-2019-017

LHCb-PAPER-2019-018

- Yields of $B^{+} \rightarrow \pi^{+} K^{+} K^{-}$ and $B^{-} \rightarrow \pi^{-} K^{-} K^{+}$ show a striking asymmetry in the region of phase space dominated by re-scattering effects.
- CP asymmetry between $B^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$ and $B^{-} \rightarrow \pi^{-}\pi^{-}\pi^{+}$ decays in a region of phase space including the $\rho(770)^{0}$ and $f_2(1270)$, divided according to whether the cosine of the helicity angle is positive (blue) or negative (red). The bands indicate the spreads of the isobar, K-matrix and quasi-model-independent models.

"GLW" method



- Method where D^0 and $\bar{D}^0$ decay to CP eigenstates
- Eigenstates are equally accessible to D^0 and $\bar{D}^0$
- 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

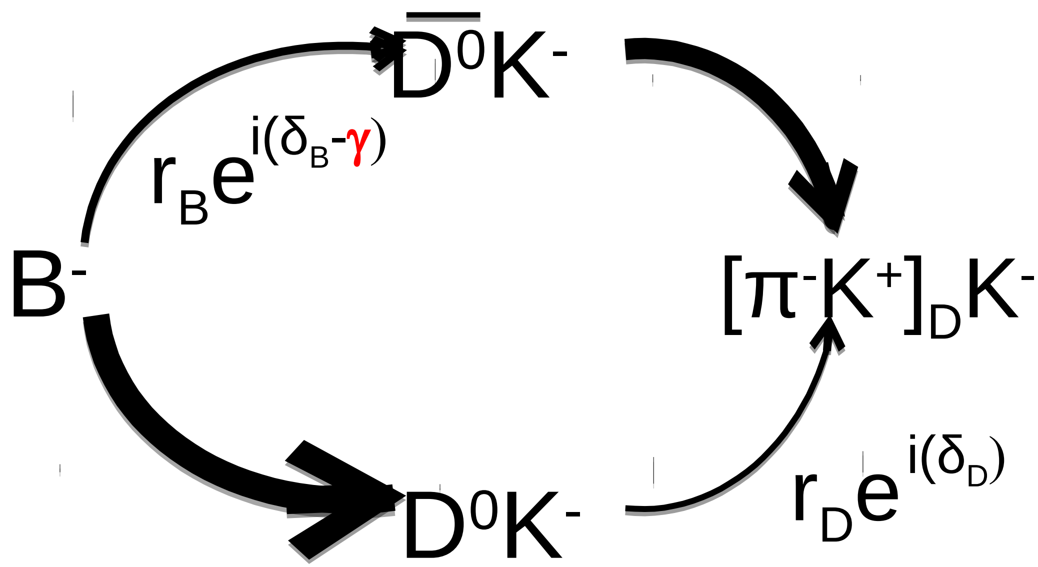
Weak phase changes sign for equiv B^+ diagram, thickness of arrows indicate relative strengths

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

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

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

"ADS" method



Weak phase changes sign for equivalent B^+ diagram

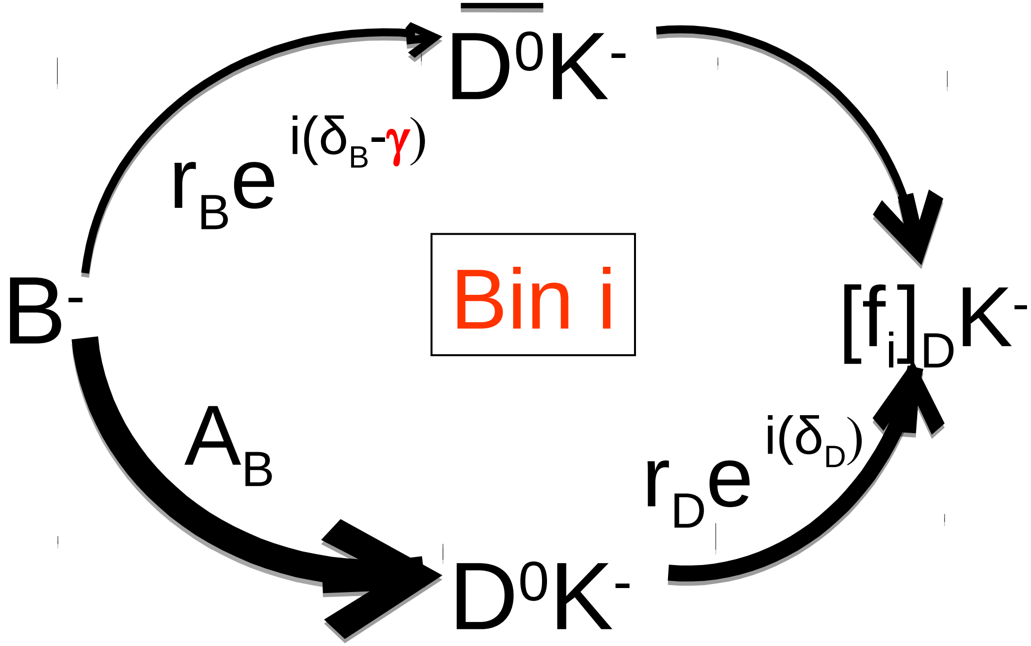
- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- r_B, δ_B hadronic parameters again to be determined alongside γ ($r_B \sim 0.1$)
- Additional two parameters r_D, δ_D .

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

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

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

“GGSZ” method



Weak phase changes sign for equiv B^+ diagram

- 3-body final D states e.g. $D \to K^0_S \pi\pi$
- Dalitz plot analysis : a counting experiment in bins of phase space

- GGSZ observables (rate as function of Dalitz position)

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

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

arXiv:1010.2817

New model-independent GGSZ analysis

017

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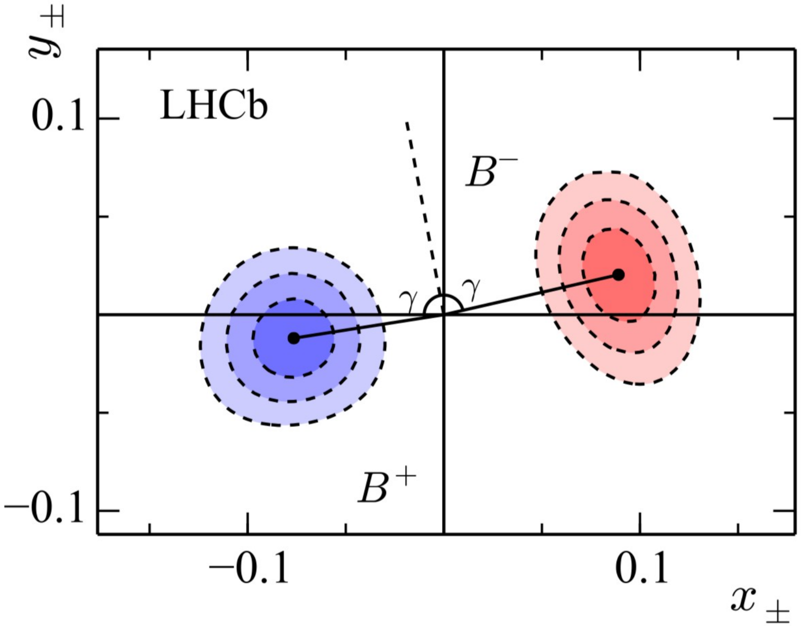
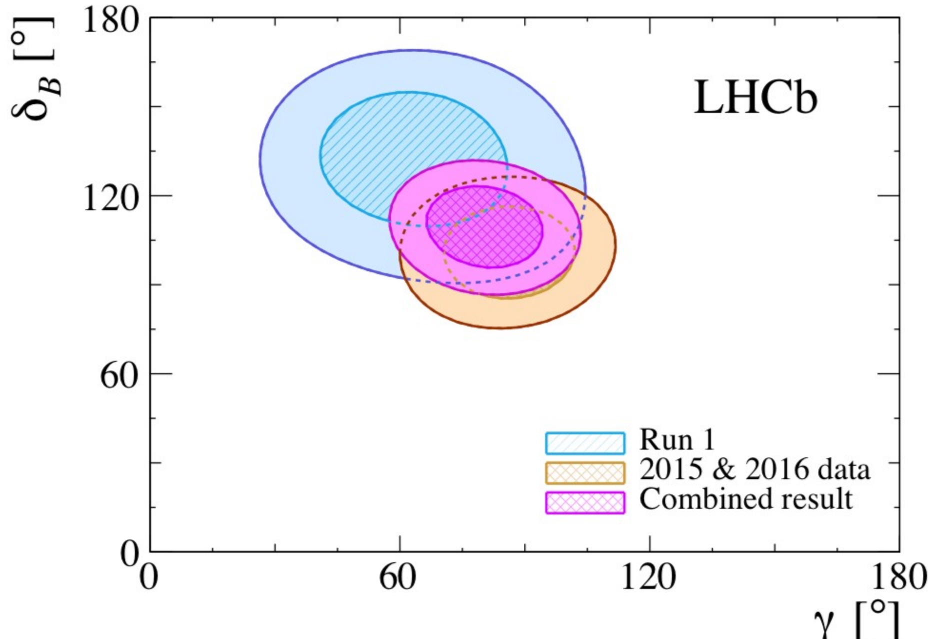




$$\gamma = 80^\circ\,^{+10^\circ}_{-9^\circ}\,\left(^{+19^\circ}_{-18^\circ}\right),$$

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

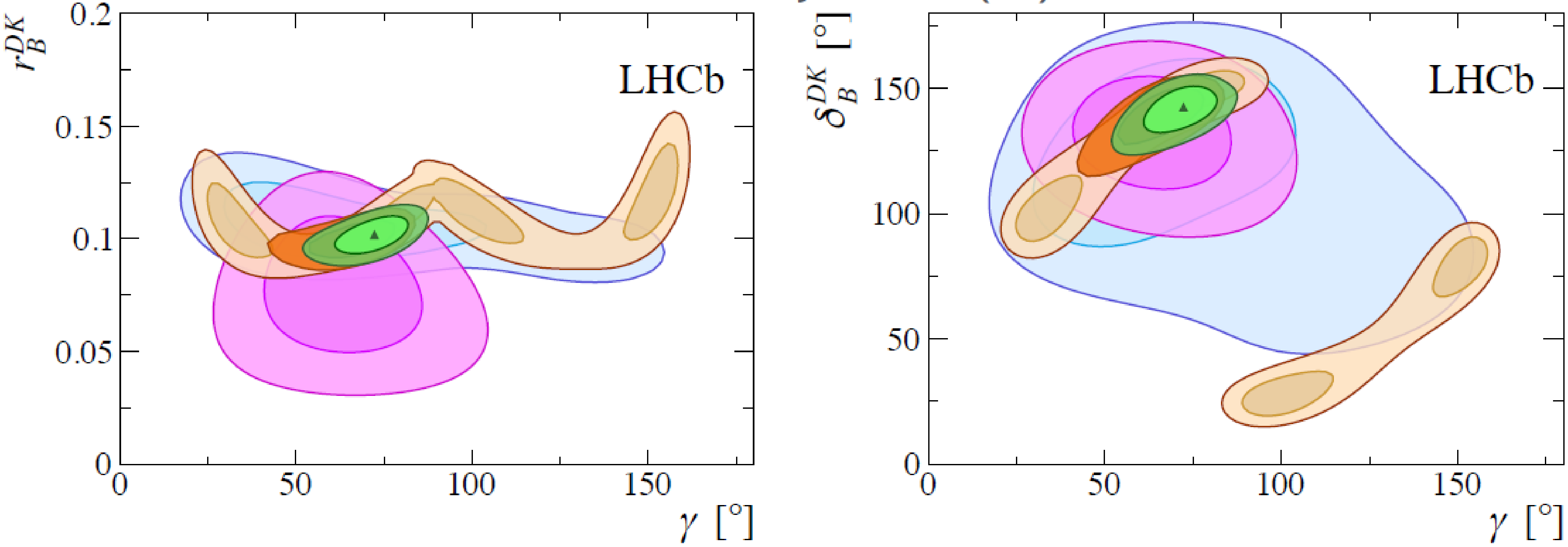
$$\delta_B = 110^\circ\,^{+10^\circ}_{-10^\circ}\,\left(^{+19^\circ}_{-20^\circ}\right).$$

LHCb GGSZ only

The most precise determination of γ from a single analysis

Evolution of γ precision

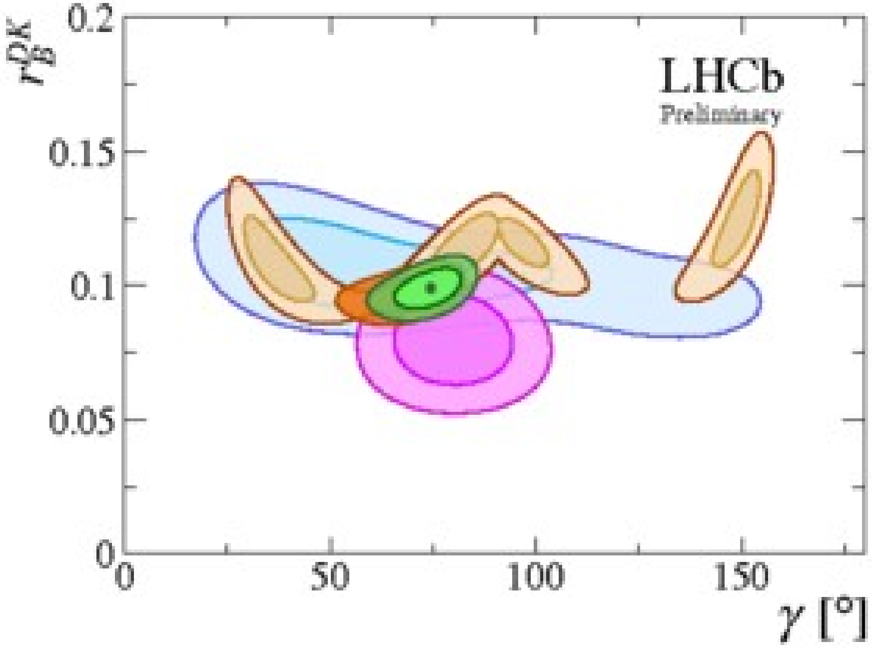
Nov 2016 JHEP 12 (16) 087

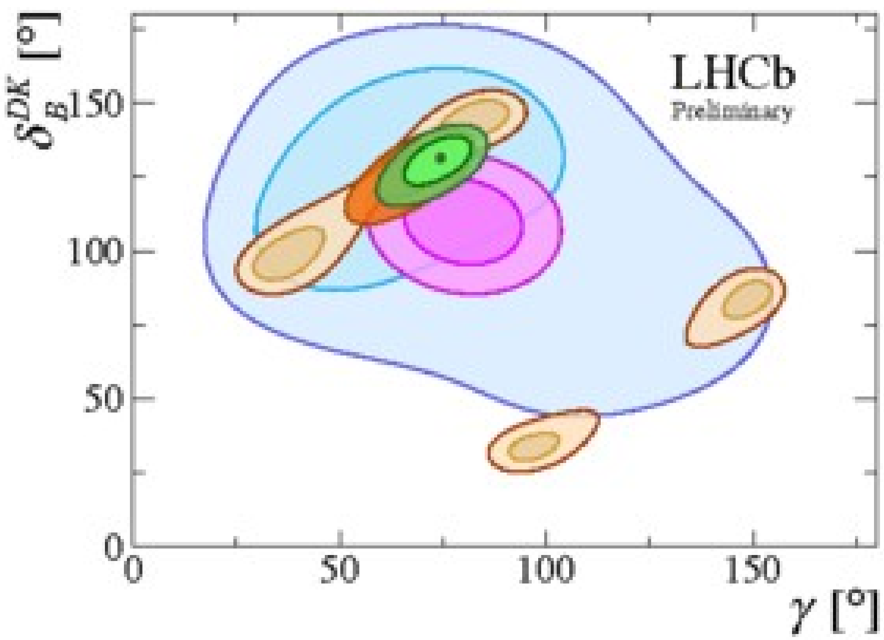


- It is necessary to pursue different B decays to provide crosschecks
- Current measurements still dominated by statistical uncertainties

Evolution of γ precision

Spring 2018   LHCb-CONF-2018-002





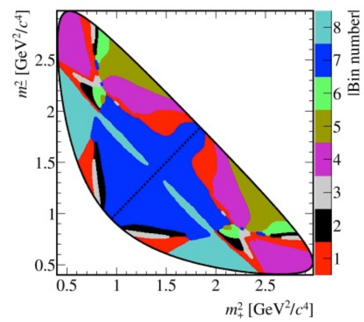
- It is necessary to pursue different B decays to provide crosschecks
- Current measurements still dominated by statistical uncertainties

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

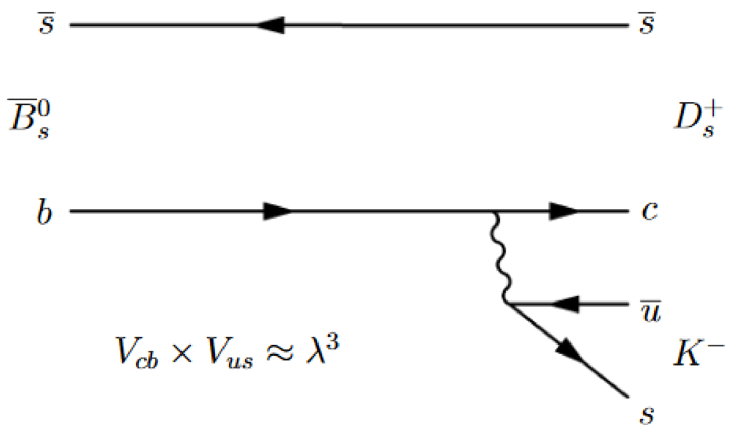


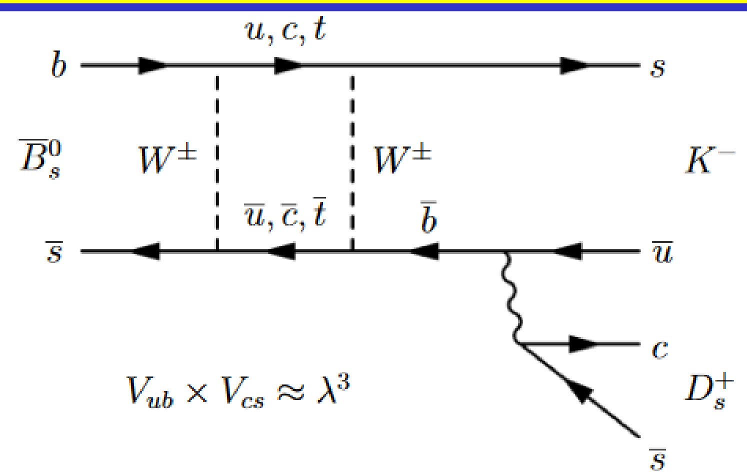
- Use CLEO data to measure average values of r_D and δ_D in p

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 $\overline{B}^0$ 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)

Phys. Rev. (2013) 112010

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

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

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

$B^0 \to \overline{D}_s^+ K^-$ 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.

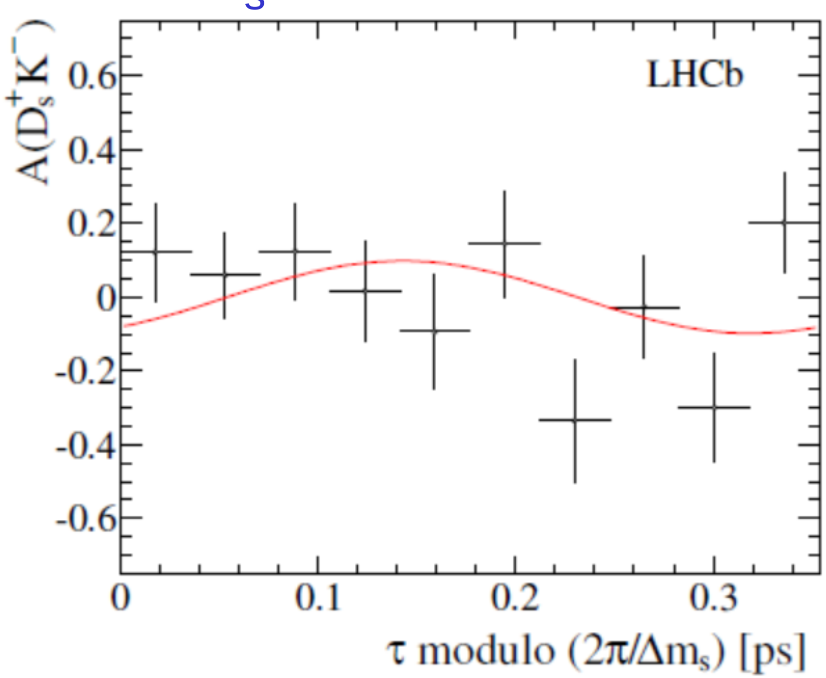
$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2}$$

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

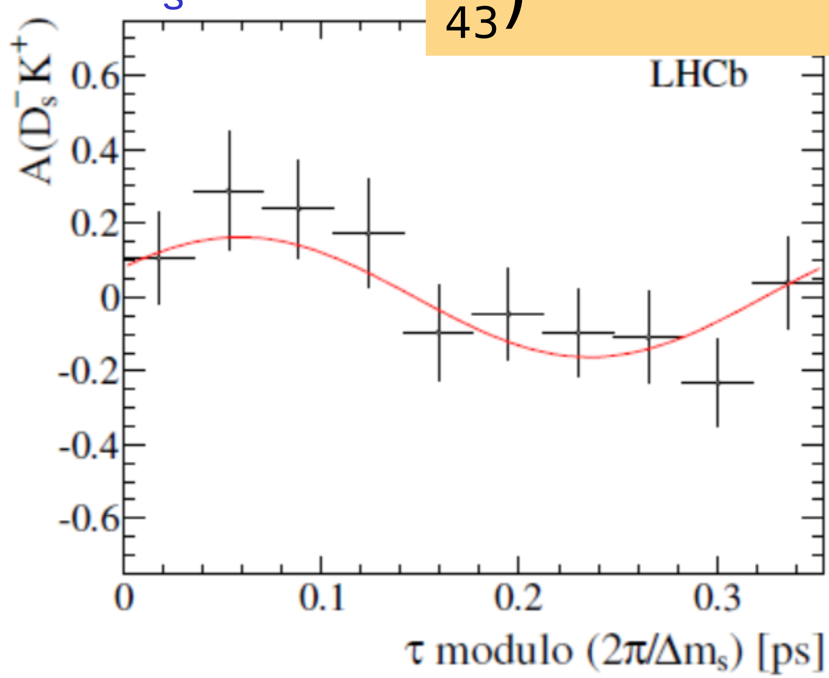
- Measure folded asymmetry distributions:

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

$D^+_s K^-$



$D^-_s K^+$

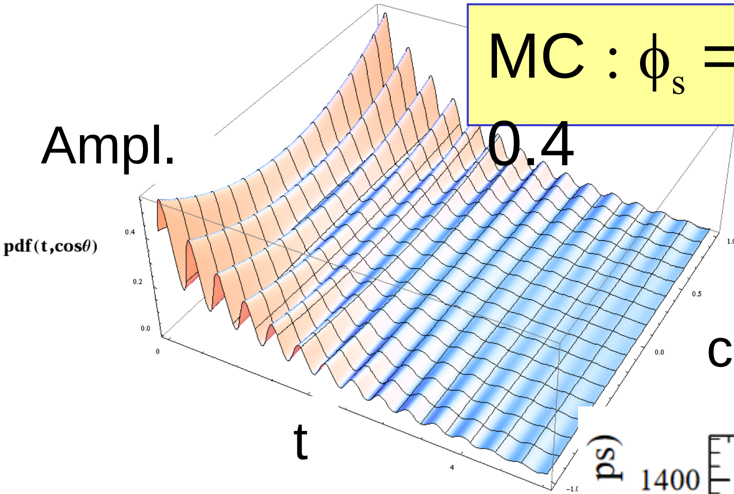


“Visualizing” the effect of ϕ_s in $B_s \to J/\psi\ \phi$

- Amplitude of asymmetry $\propto \sin \phi_s$
- Frequency is the same as in B_s mixing

MC : ϕ_s = 0.4

Ampl.

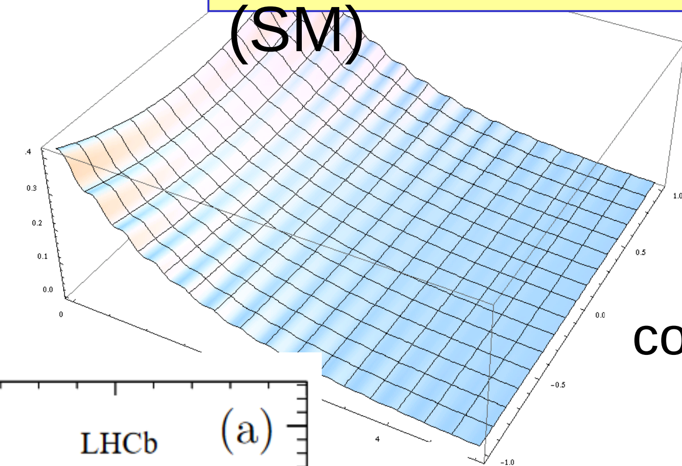


cos θ

t

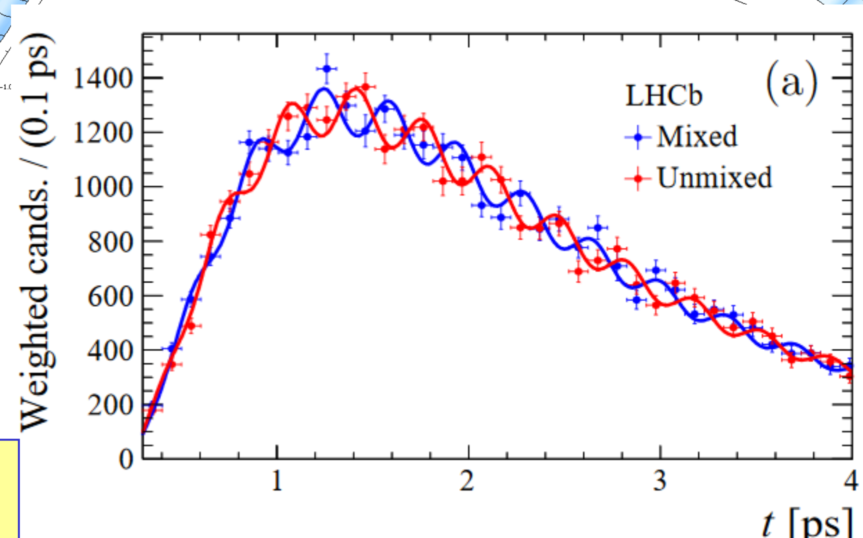
MC : ϕ_s = 0.04 (SM)

Ampl.



cos θ

t



DATA

$B_S^0 \to D_S^- \pi^+$ decays

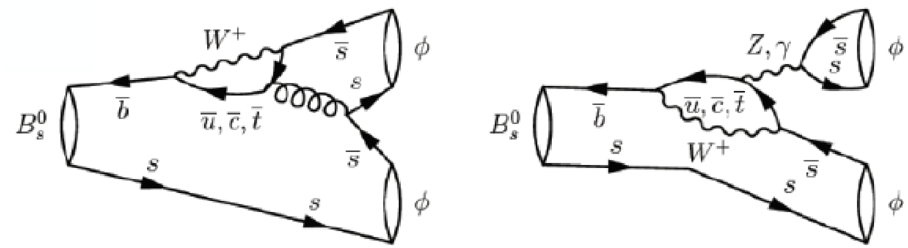
Eur. Phys. J. C 79 (2019) 706

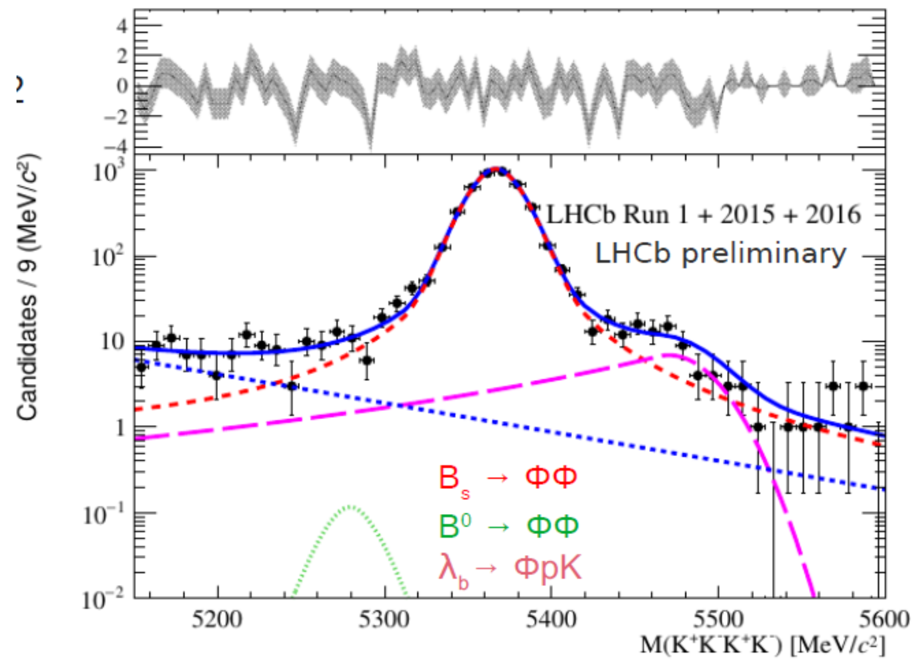
Measurement of CP violation in $B_s \to \phi\phi$

LHCb-PAPER-2019-019

- Enhanced sensitivity to NP since decay is dominated by penguin loop
- SM prediction of CP violating phase is small
  <

  arXiv:0810.0249
  Phys.Rev.D80:114026,2009
- Perform time-dependent angular analysis, Run1data + 2 fb^{-1} Run 2

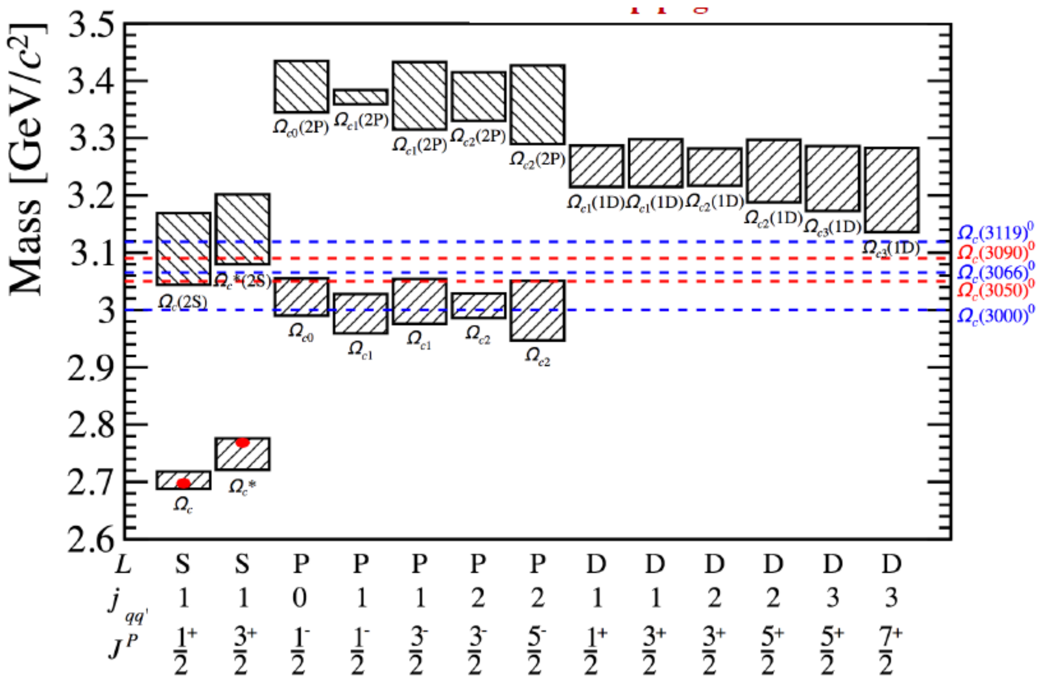


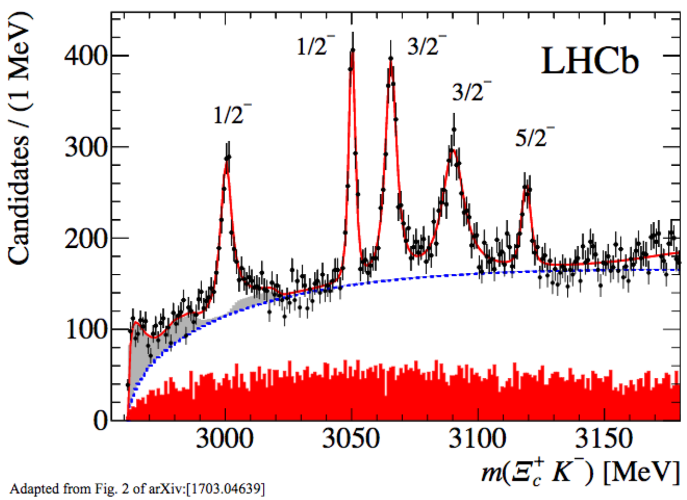


- $|\Phi_{sss}| = -73 \pm 115 \pm 27$

Possible assignment of excited Ω_c states

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



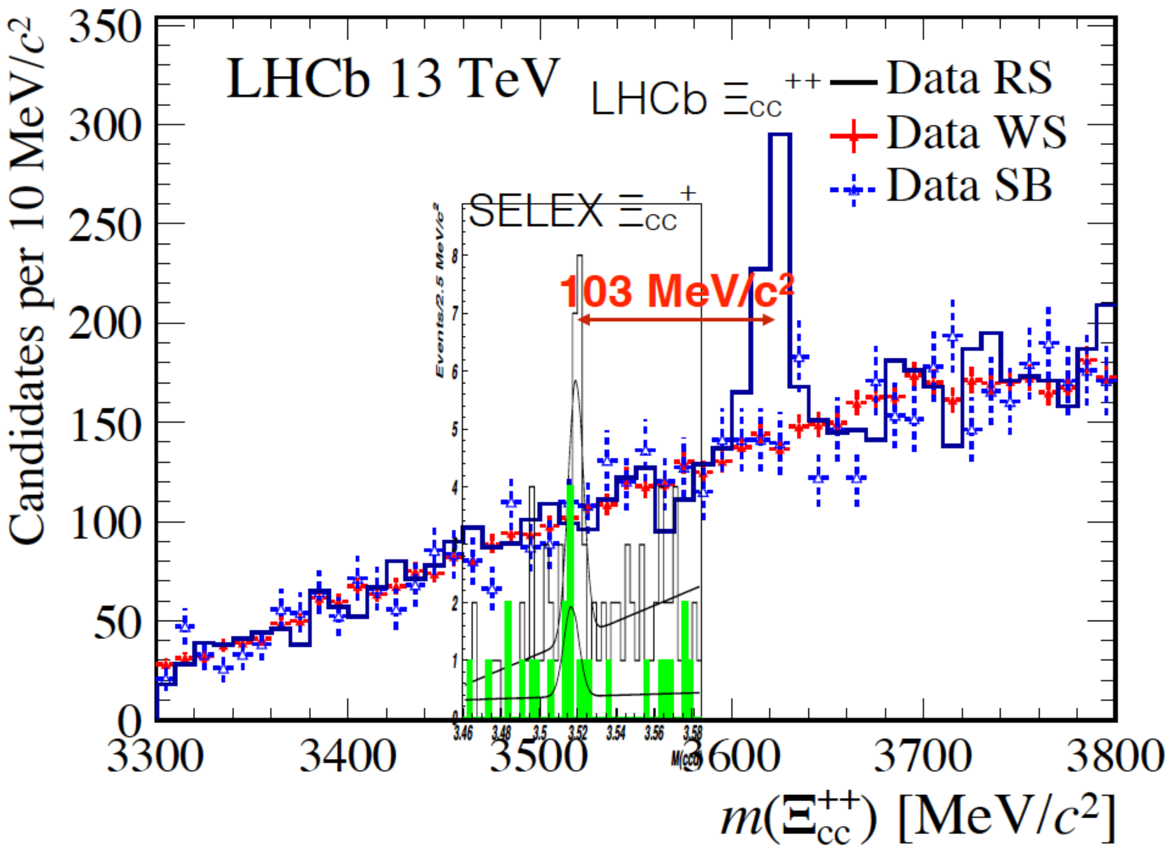


Adapted from Fig. 2 of arXiv:[1703.04639]

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

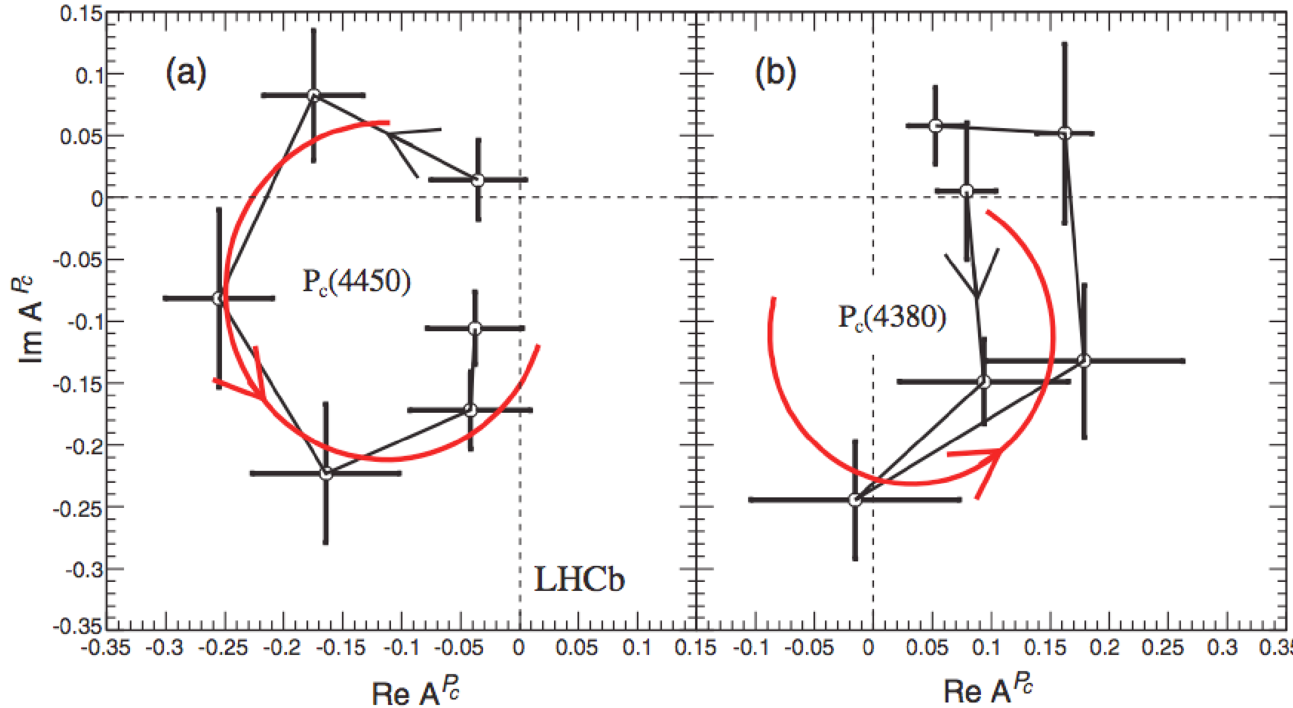
Comparisons with SELEX

- 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



Previous pentaquark J^P assignments

Argand diagram



- Preferred J^P assignments 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.

PRL 115 (2015) 072001

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:

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

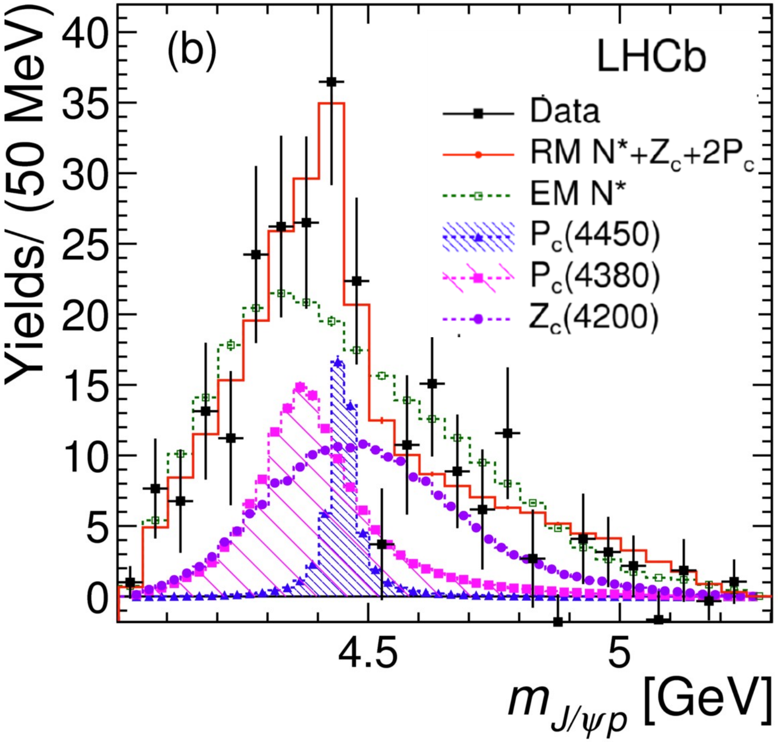
$P_c(4380)^+ \to J/\psi\ p$

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

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

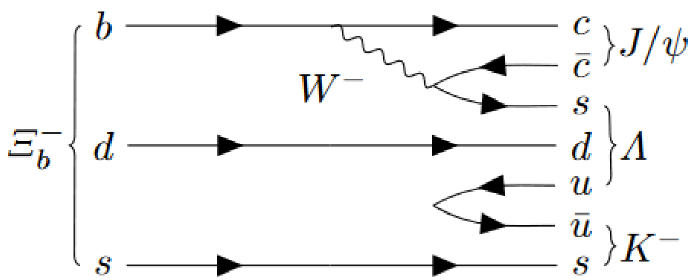
- Fit with 2 pentaquarks + Z_c(4200) tetraquark : favoured by 3σ compared to no exotic contributions

PRL 115 (2015) 072001



Another possible pentaquark mode

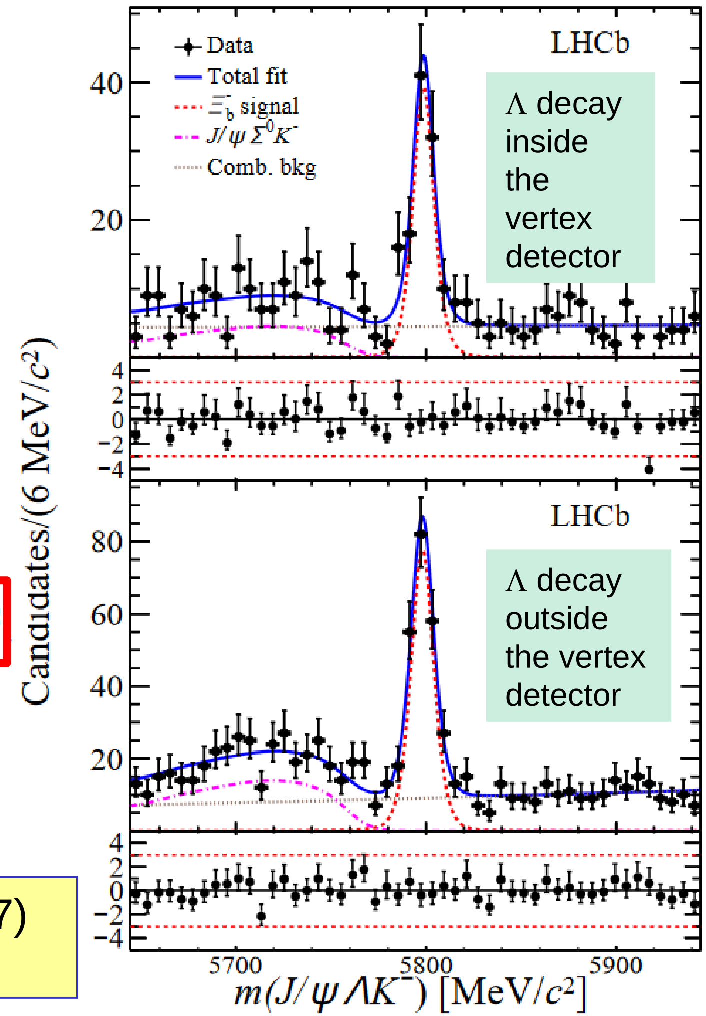
- Can look for udscc pentaquark in $\Xi_b^-(bds) \rightarrow J/\psi \Lambda K^-$



  - 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

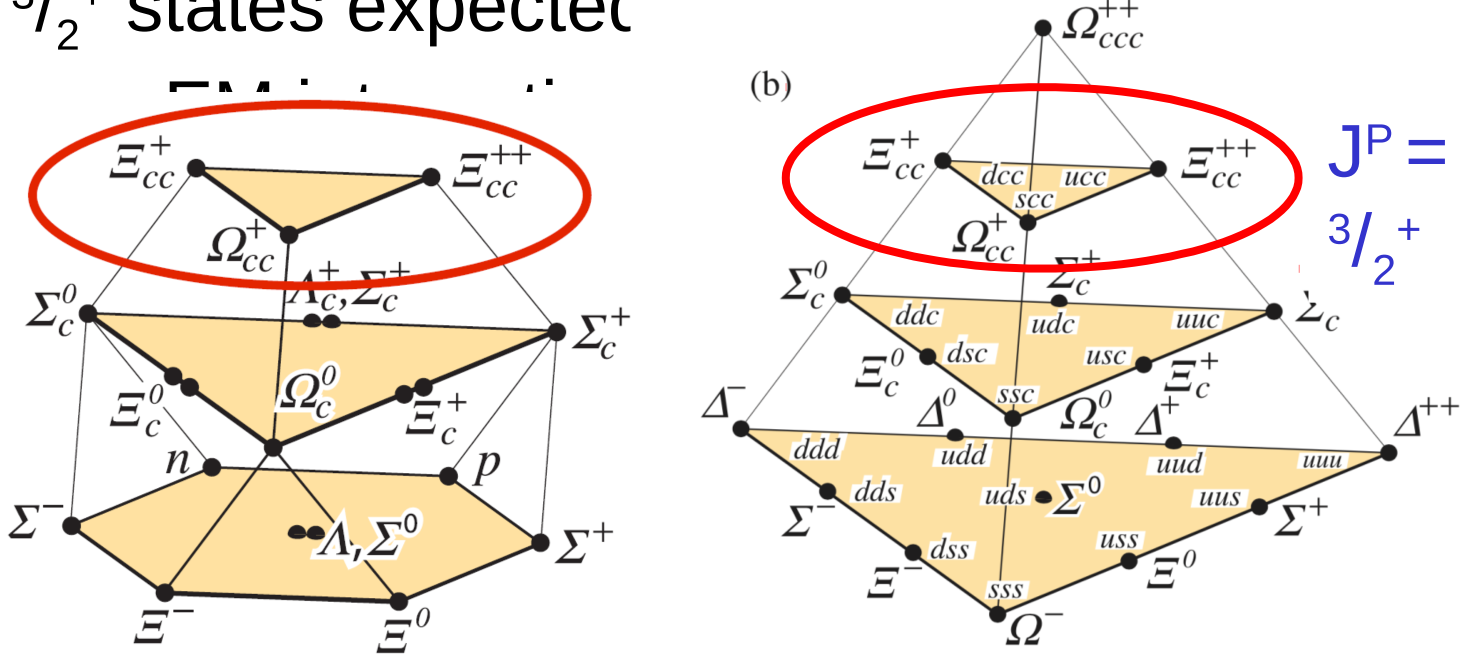


Phys. Lett. B 772 (2017) 265

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

- The quark model predicts three weakly decaying $C = 2$ $J^P = ½^+$ states: Ξ_{cc}^{+} (ccd), Ξ_{cc}^{++} (ccu), and Ω_{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 stron… EM i…

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

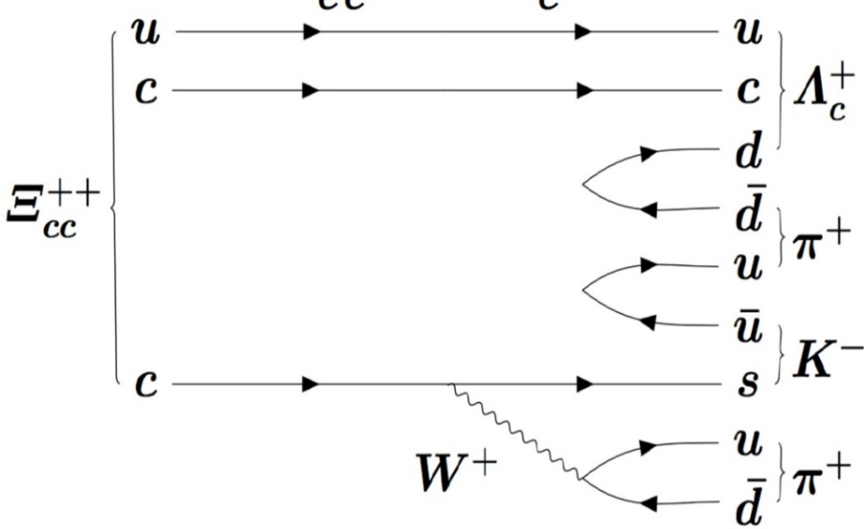


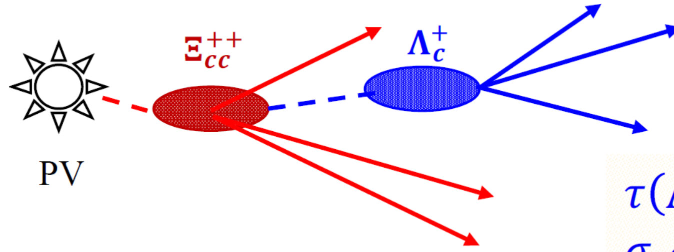
$J^P = {}^3/_2{}^+$

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}

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





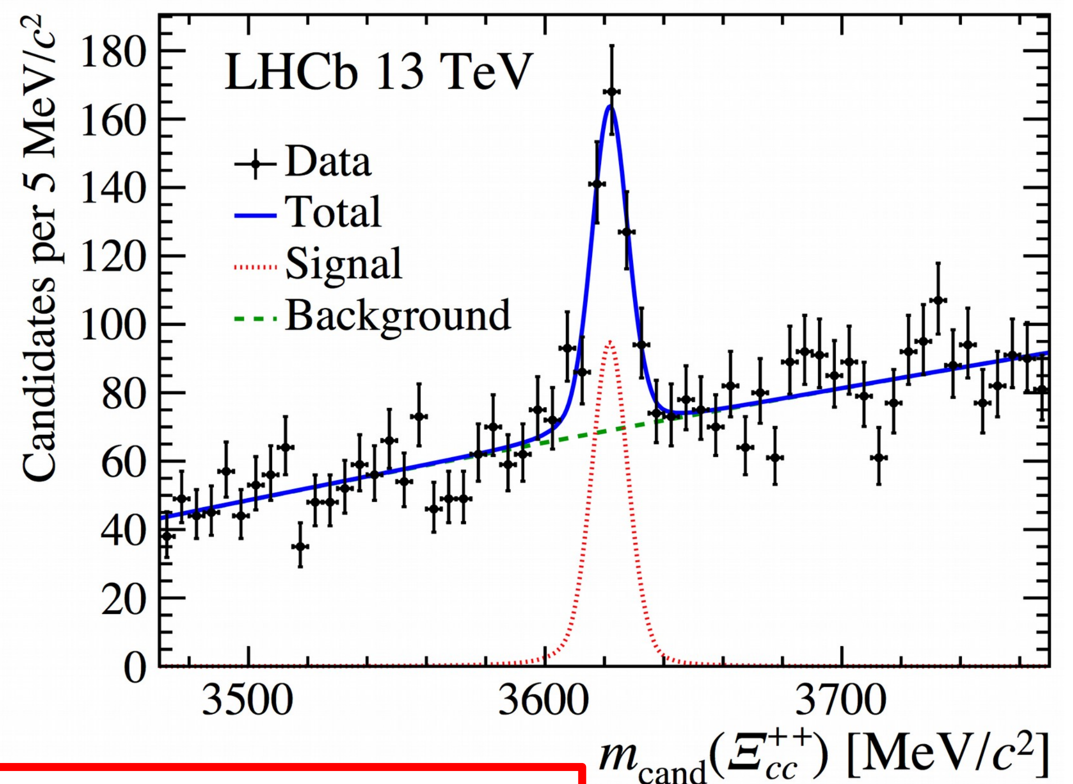
Observation of Ξ_{cc}^{++}

PRL 119 (2017) 112001

- Ξ^{++} is mass-corrected for Λ_c :

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

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



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

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

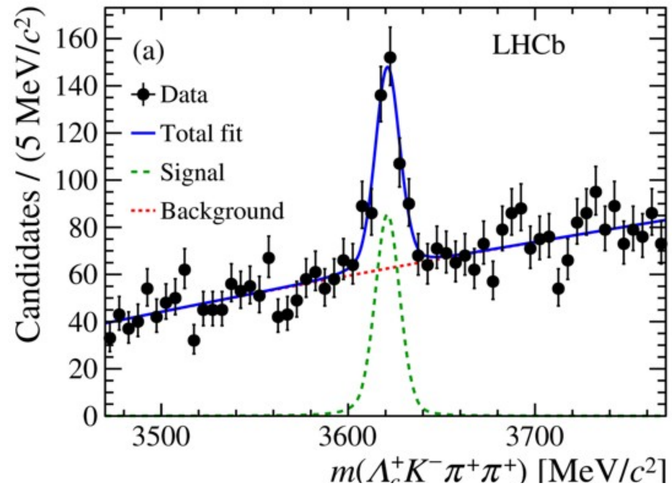
Ξ_{cc}^{++} lifetime measurement

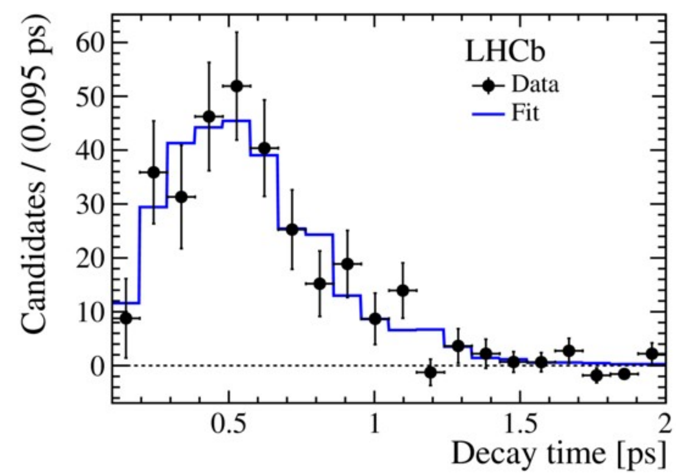
Phys. Rev. Lett. 121, 052002 (2018)

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

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

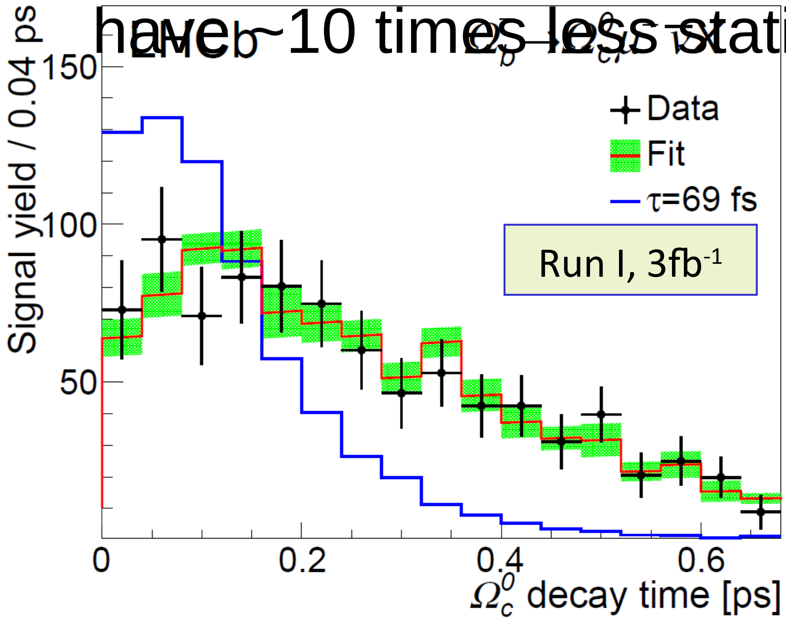
- Confirms that Ξ_{cc}^{++} is a weakly decaying baryon.

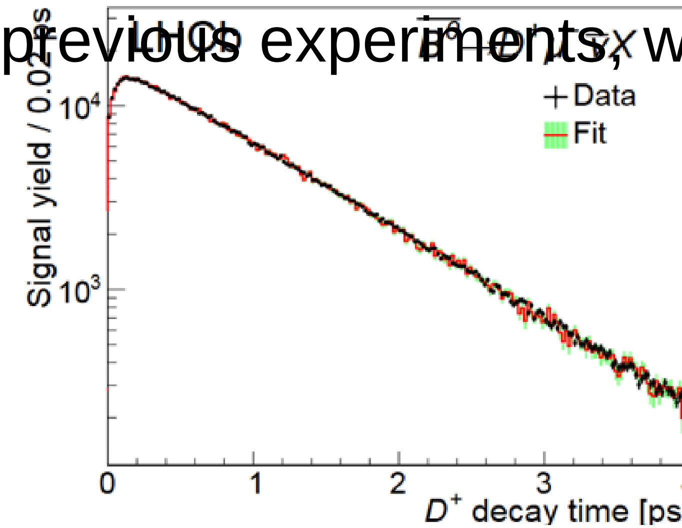




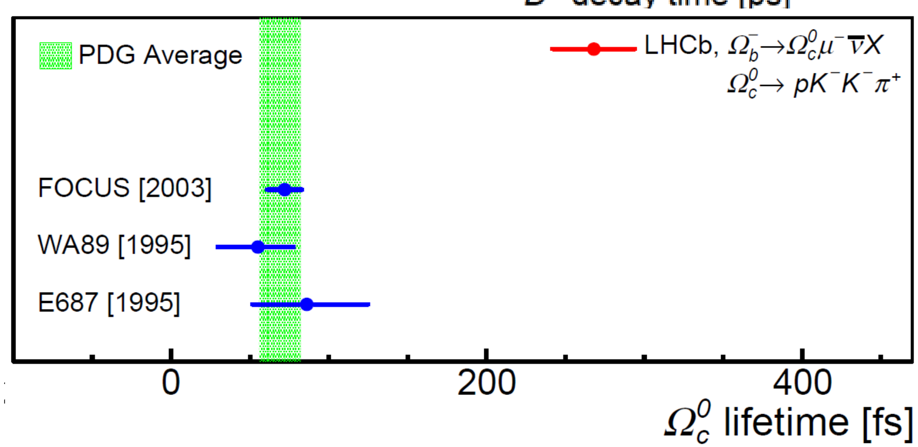
The puzzle of the $\Omega_c^{\pm}$ lifetime

- Via the decay $\Omega_b^{\pm} \to \Omega_c^0 \mu^{\pm} \nu_\mu X$ then $\Omega_c^0 \to pK^-K^-\pi^+$ [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





$\tau(\Omega_c^0) = 268\pm24\pm10\pm2$ fs



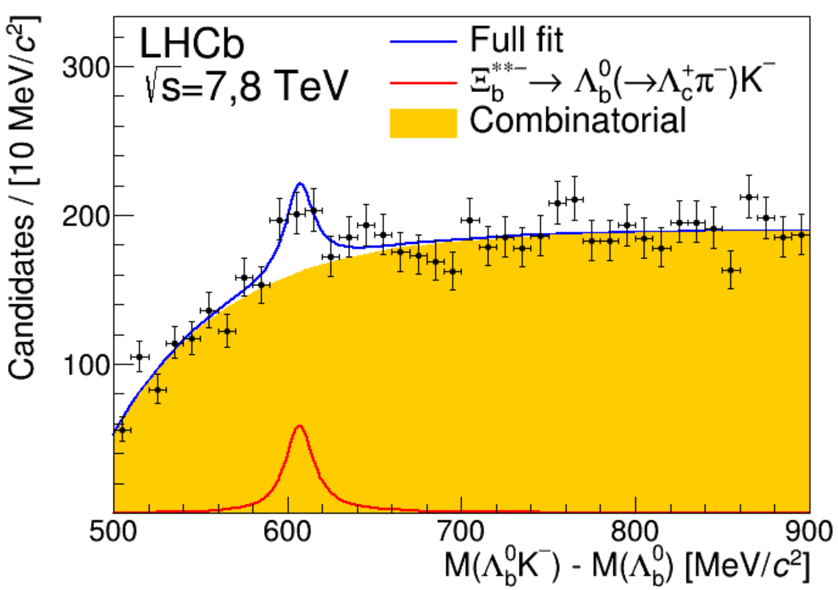
arXiv:1807.02024

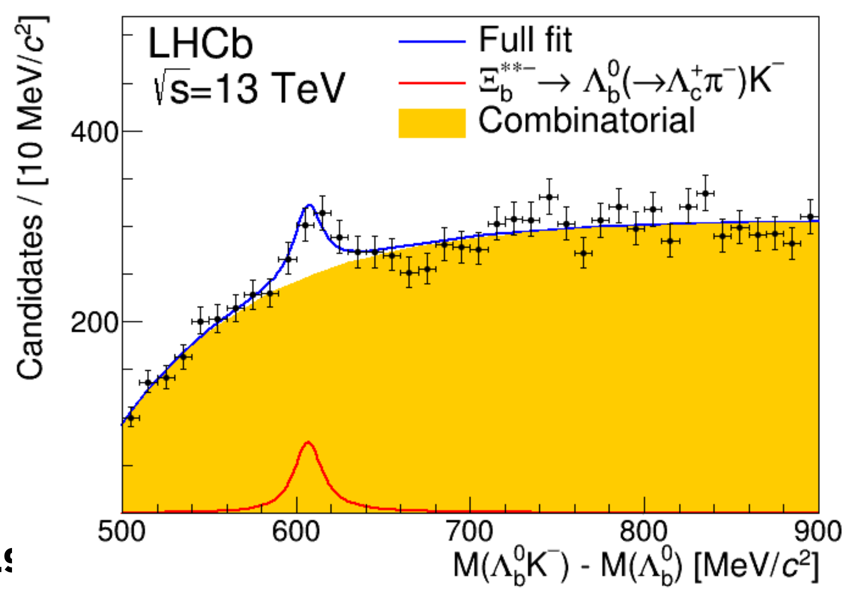
Observation of a new Ξ_b^{**-} resonance

- Seen both in $\Xi_b^{**-} \to \Lambda_b^0 K^-$ & $\Xi_b^{**-} \to \Xi_b^0 \pi^-$ decays
- J^P not yet measured

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

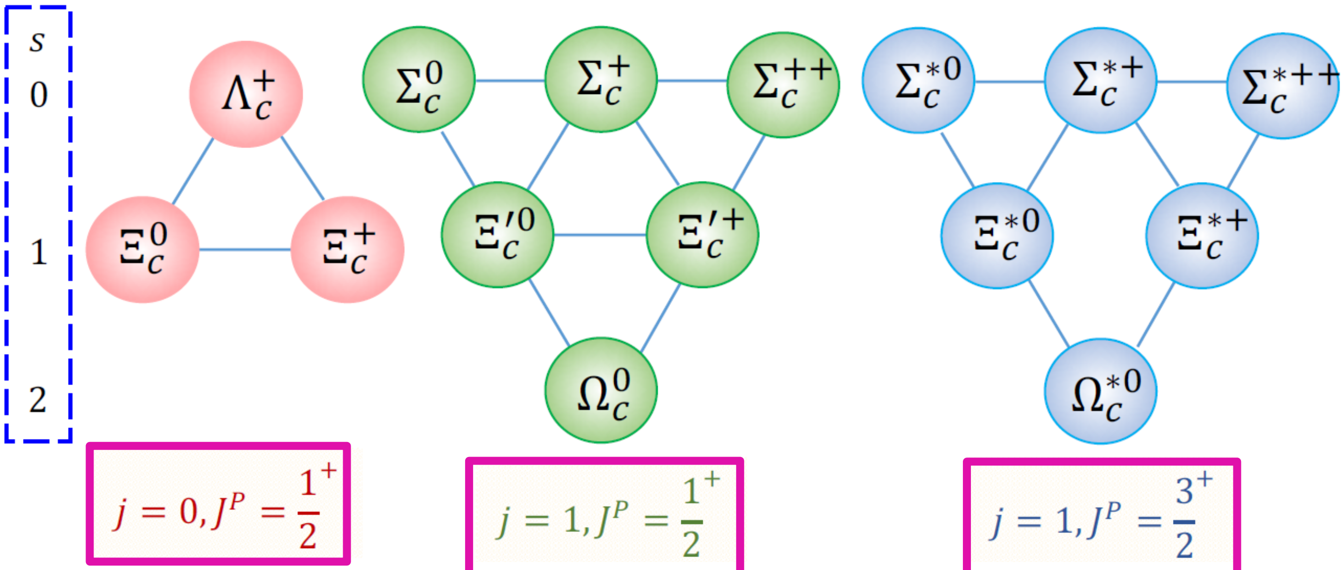
arXiv:1805.09418





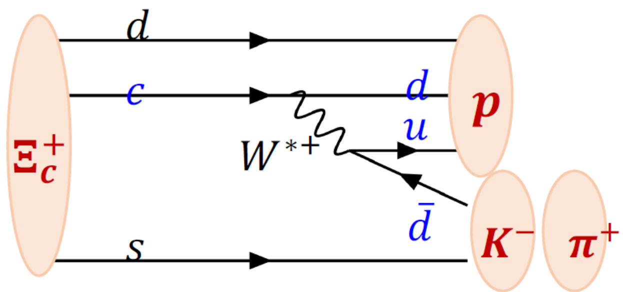
Observation of Ω_c excited states

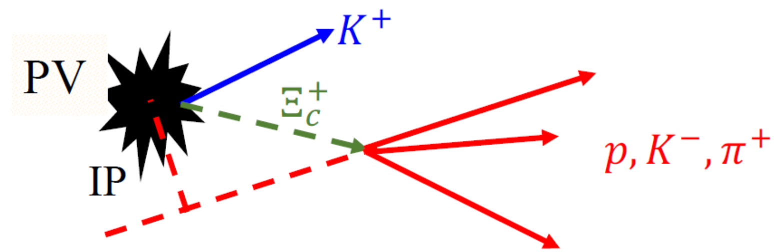
- Single charmed baryons predicted to form SU(3)
  $3 \otimes \bar{3} = 3 \oplus 6$ baryon multiplets (Jaffe, Phys. Rep. 409 (2005) 1)
- All ground states have been observed, as have excited states Λ, Σ and Ξ



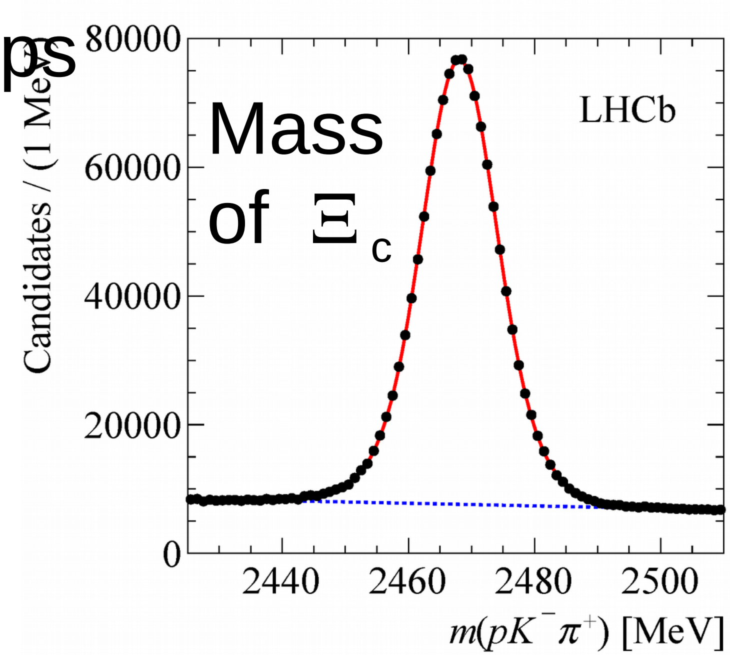
Observation of five new narrow Ω_c^0 excited states

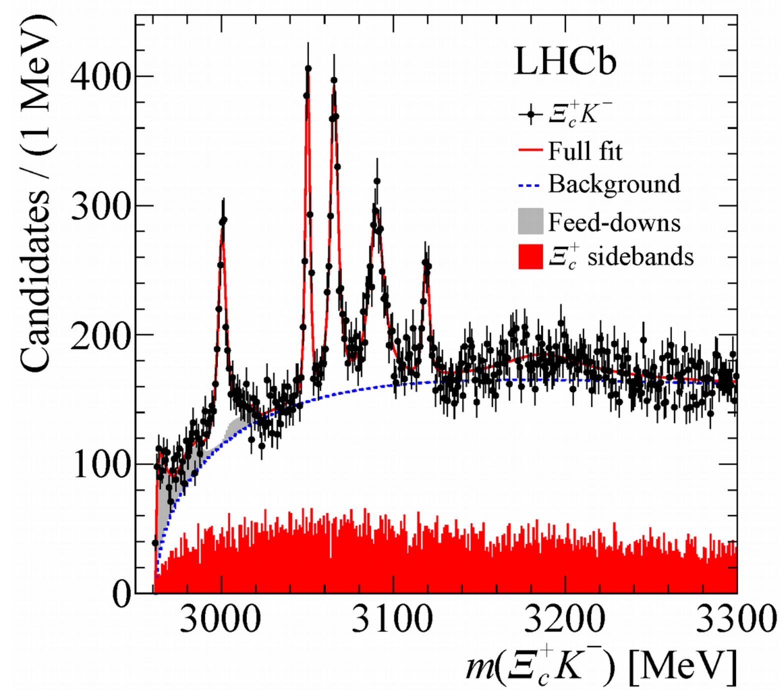
- Decay : Ω_c^{0*} (css) $\rightarrow \Xi_c^+$ (csu) K^- ; Ξ_c^+ (csu) $\rightarrow pK^-\pi^+$





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





LHCb, PRL 118 (2017) 182001

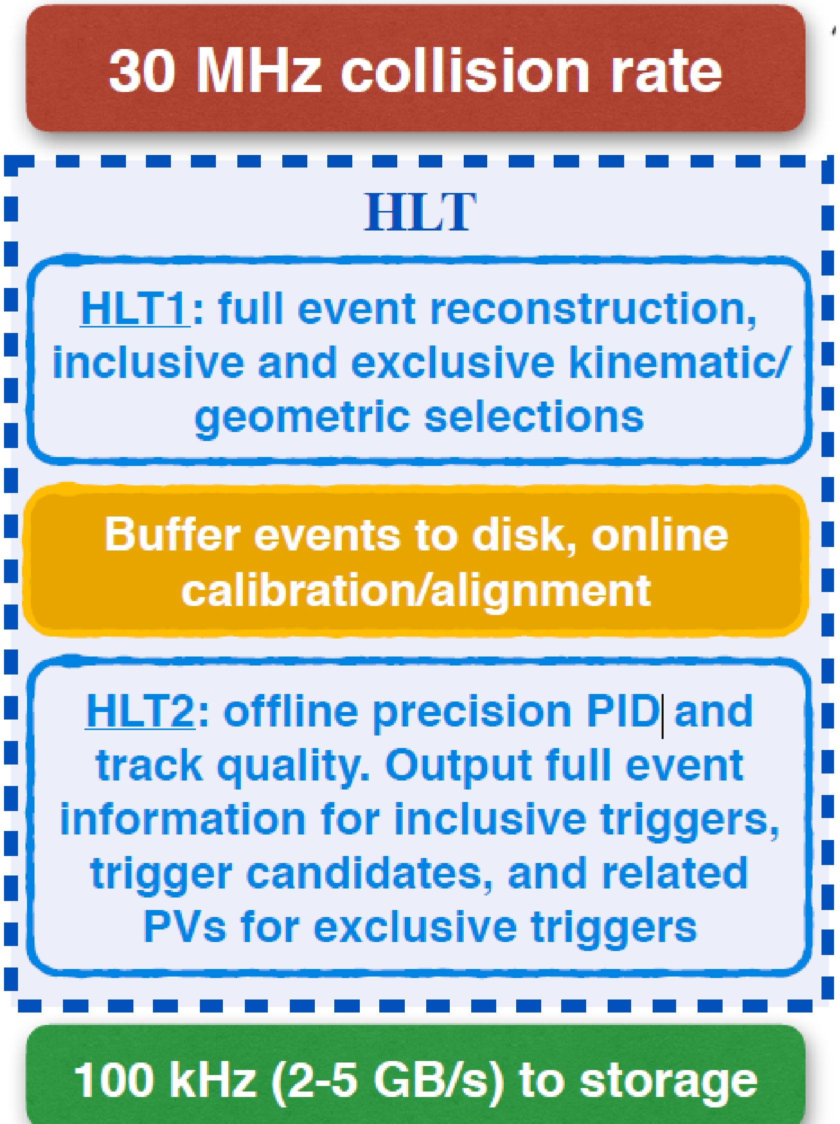
Masses and widths

LHCb, PRL 118 (2017) 182001

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

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 was already a critical test-bed for this technology (turbo mode)