Review of CP-violation and spectroscopy measurements at LHCb

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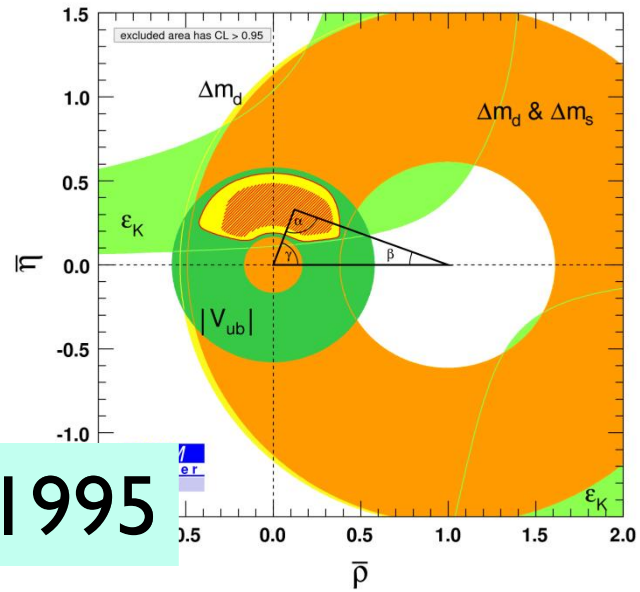
On behalf of the LHCb Collaboration

Corfu Summer Institute
2 September 2021

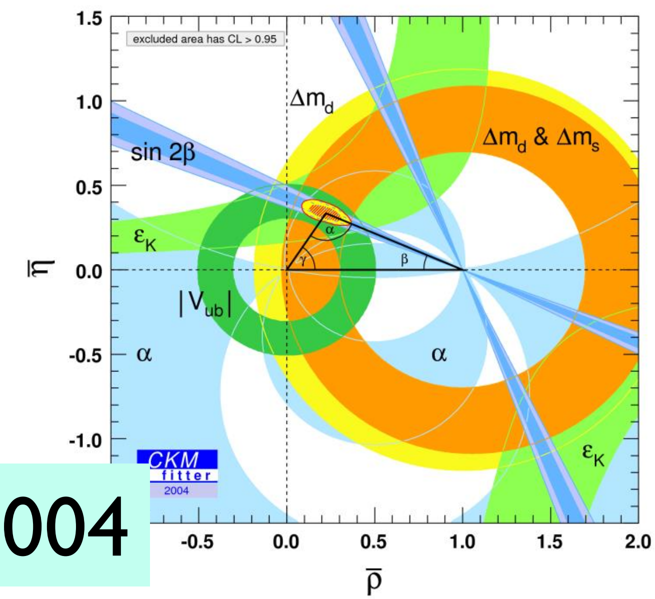
Outline

- General introduction
- An update of mixing and CP-violation measurements
  - New unitarity triangle measurements
  - Update on the angle γ
  - CP violation and mixing in charm
- New measurements in spectroscopy
- The upgraded LHCb detector and outlook
- Summary

Unitarity Triangle measurements



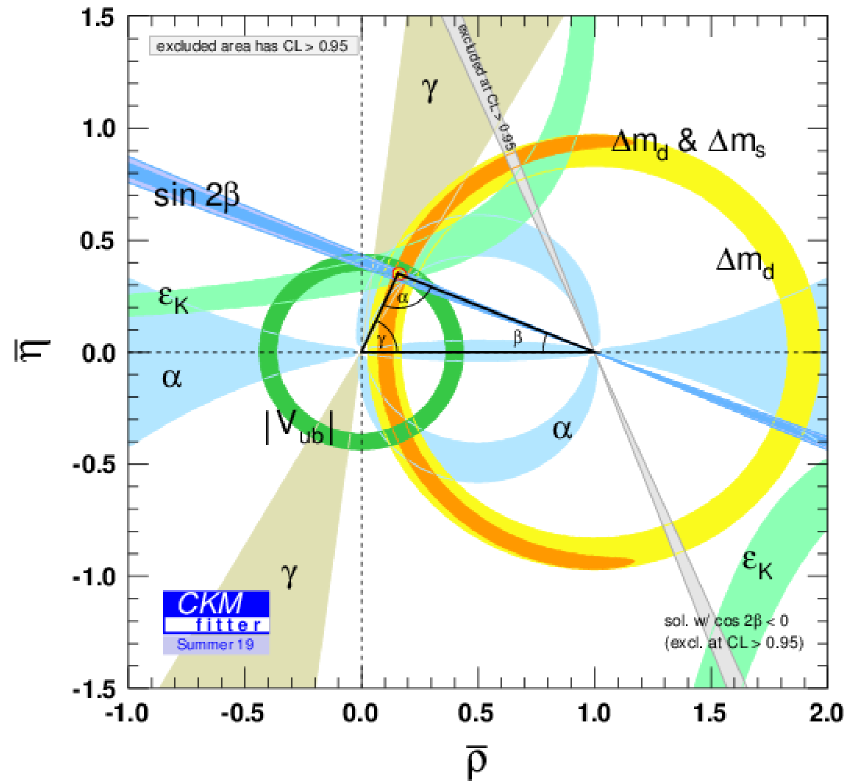
1995



2004

- Amazing progress in the last 26 years; the SM remains intact, but a whole lot still to learn

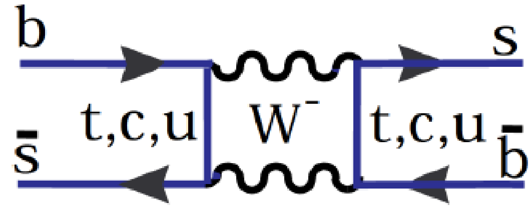
http://ckmfitter.in2p3.fr



Now (dominated by LHCb)

LHCb
Mixing and CP-violation in beauty and charm

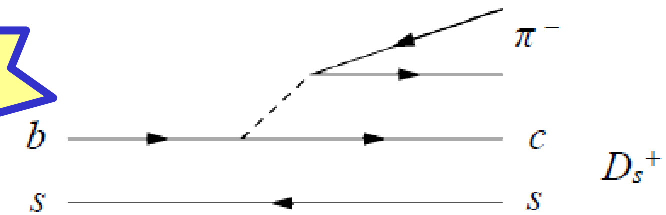
$B_{(s)}$ mixing at LHCb

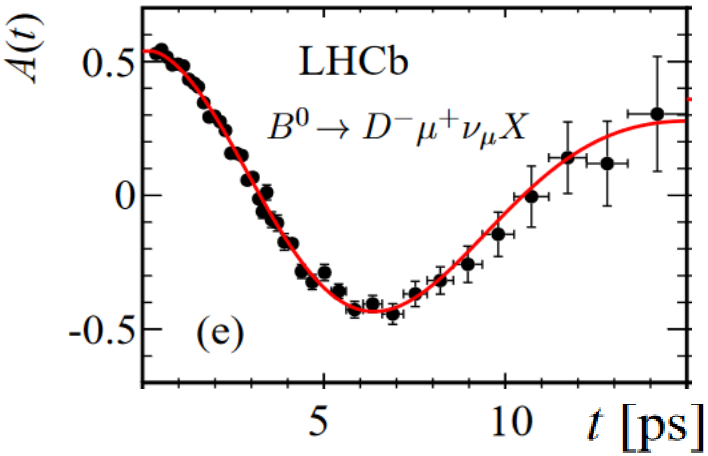


$$\frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow \overline{B}^0)}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow \overline{B}^0)}$$

Previous Workshop

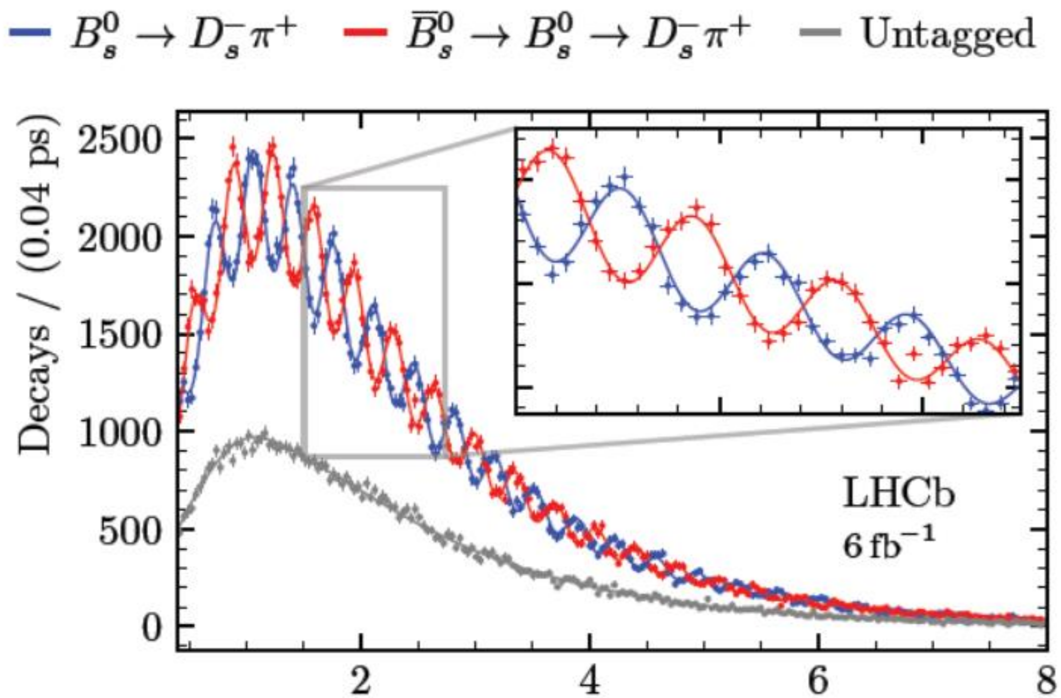
NEW





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

Eur. Phys. J. C76 (2016) 412



t [ps]

LHCb-PAPER-2021-005, arXiv:2104.04421

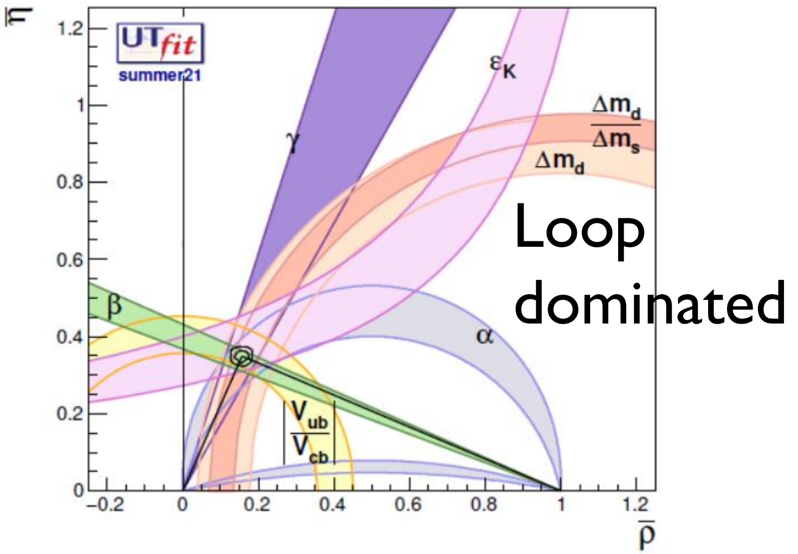
$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \mathrm{ps}^{-1}$

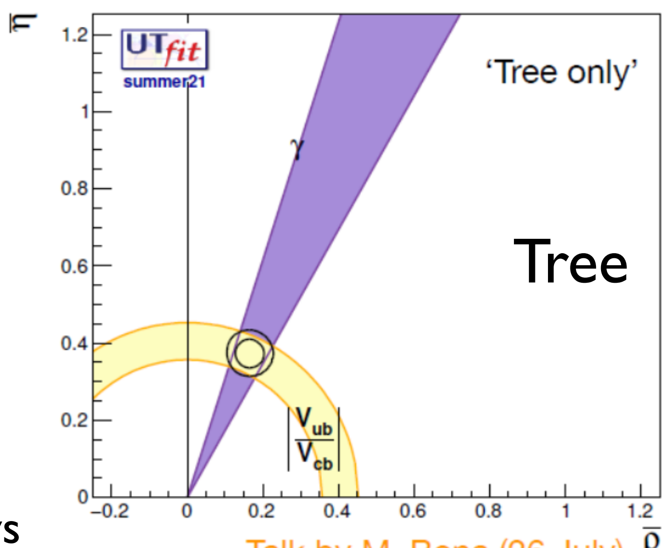
Mixing measurements dominated by LHCb

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 very clean

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



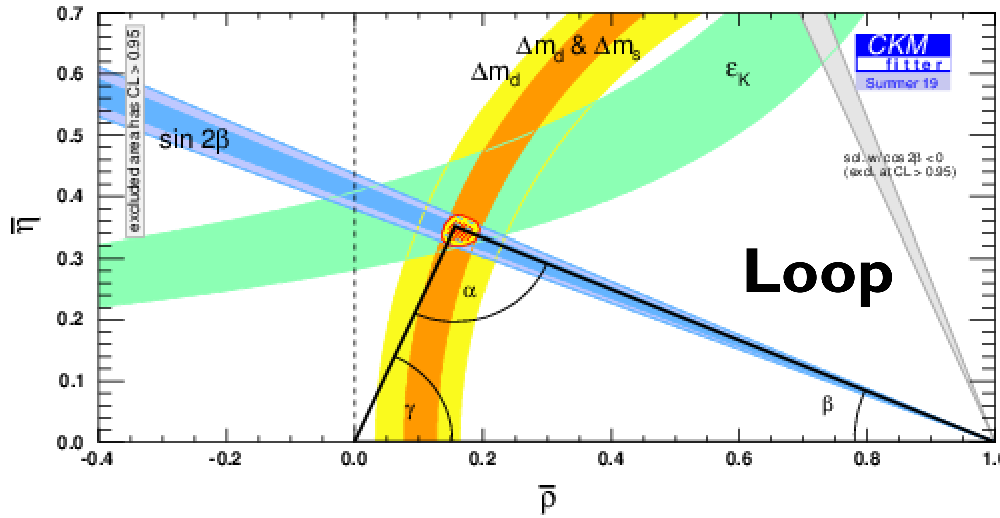


Talk by M. Bona (26 July)

* assuming no significant New Physics in tree decays

γ : indirect vs direct determinations

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



γ combination from all direct measurements from tree decays

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

(As of Summer 2019)

Determination from CKM fit excluding all direct measurements of γ

$$\gamma = (65.8^{+0.9}_{-1.3})^o$$

Reaching degree level precision from direct measurements is crucial

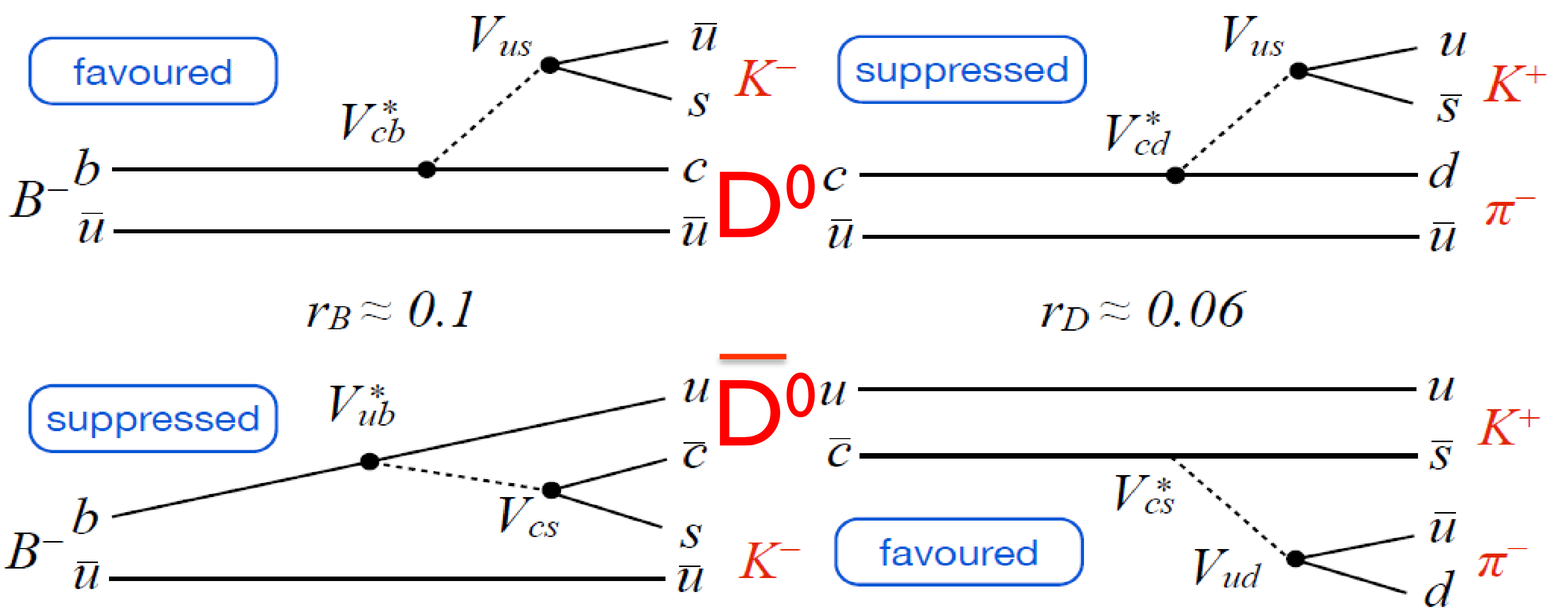
http://ckmfitter.in2p3.fr

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 $B^+ \to \overline{D}^0 K^+$)

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

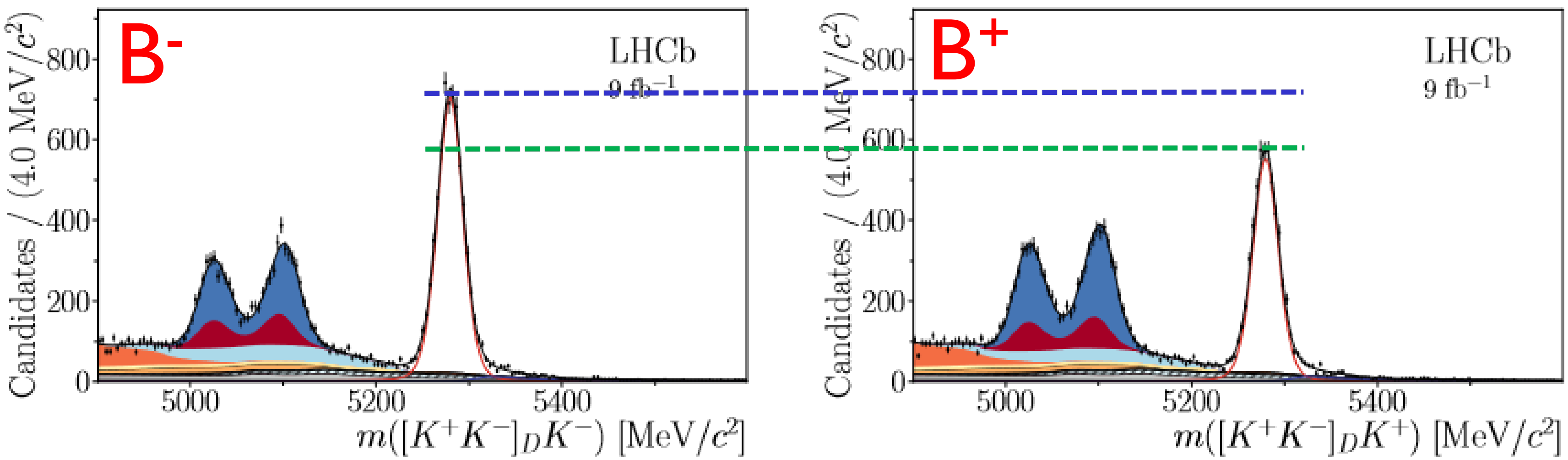


- Branching fraction for favoured B decay only ~10^{-4}
  - Measurements require high statistics

New GLW & ADS γ measurements

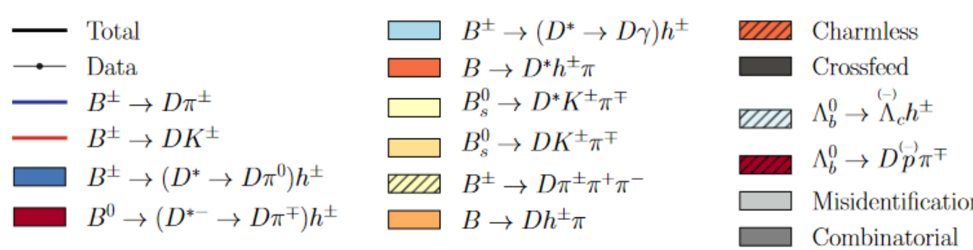
GLW : where D^0 and $\overline{D^0}$ decay to CP eigenstates

ADS : where D^0 and $\overline{D^0}$ decay to flavour-specific states



$$A_K^{CP} = \frac{\Gamma(B^- \to [hh]_D^0 K^-) - \Gamma(B^+ \to [hh]_D^0 K^+)}{\Gamma(B^- \to [hh]_D^0 K^-) + \Gamma(B^+ \to [hh]_D^0 K^+)}$$

JHEP 04 (2021) 081



LHCb combination from different modes

LHCb-CONF-2021-001

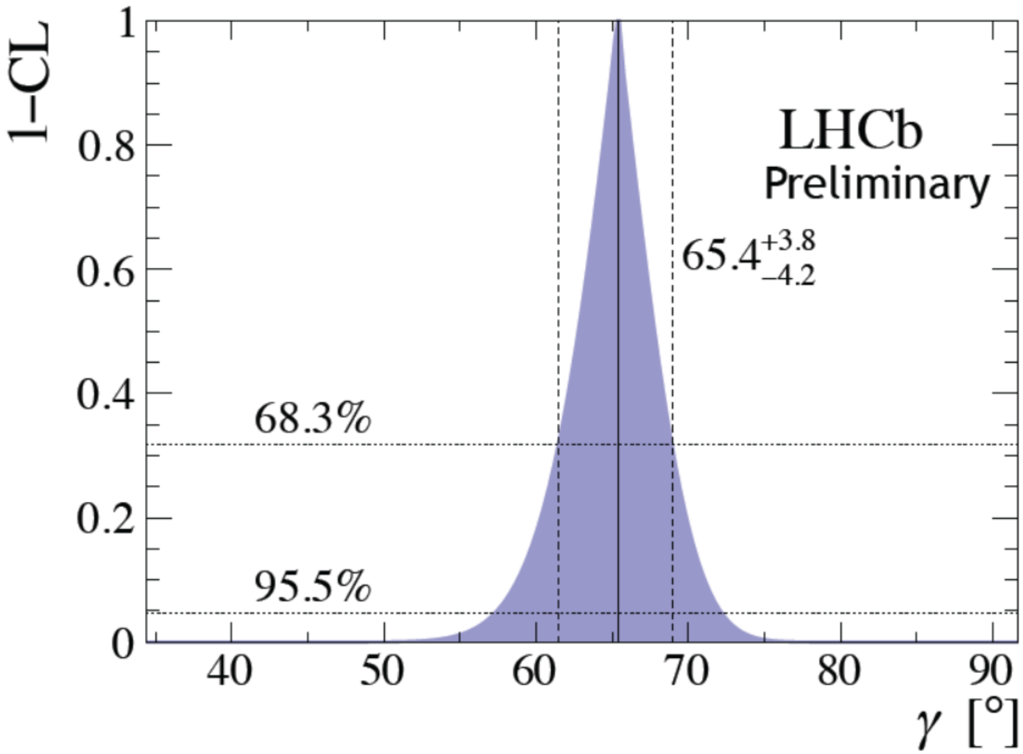
- The most recent combination includes the following modes:

B decay	D decay	Ref.	Dataset	Lumi (fb^{-1})	Status since Ref. [21]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[23]	Run 1&2	9	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1	3	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[25]	Run 1	3	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$	[22]	Run 2	9	**Updated**
$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$	[26]	Run 1&2	9	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[23]	Run 1&2	5	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[27]	Run 1&2	5	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[27]	Run 1&2	5	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[28]	Run 1	3	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	[29]	Run 1&2	5	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[29]	Run 1&2	5	**New**
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	[30]	Run 1	3	**Supersede**
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[31]	Run 1	3	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[32]	Run 1	3	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[33]	Run 1	3	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[34]	Run 1&2	9	**New**

D decay	Ref.	Dataset	Lumi (fb^{-1})	Status since Ref. [21]
$D \to h^+h^-$	[35–37]	Run 1&2	9	**New**
$D \to h^+h^-$	[38]	Run 1	3	**New**
$D \to h^+h^-$	[39]	Run 1&2	9	**New**
$D \to K^+\pi^-$	[40]	Run 1	3	**New**
$D \to K^+\pi^-$	[41]	Run 1&2	5	**New**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	[42]	Run 1	3	**New**
$D \to K_S^0\pi^+\pi^-$	[43, 44]	Run 1&2	9	**New**
$D \to K_S^0\pi^+\pi^-$	[45]	Run 1	1	**New**

LHCb combination from different modes

New LHCb average $\gamma = (65.4\ ^{+3.8}_{-4.2})^\circ$



Previous measurement from LHCb

$\gamma = (74.0^{+5.0}_{-5.8})^\circ$ LHCb-CONF-2018-002

LHCb dominates world average

Reminder of indirect constraint

$\gamma = (65.8^{+0.9}_{-1.3})^\circ$

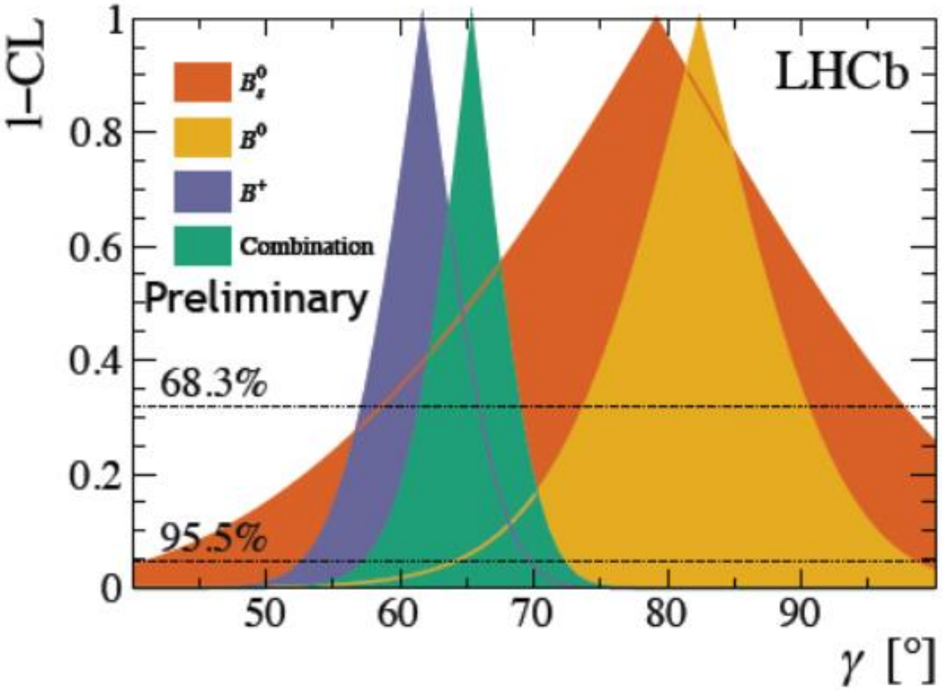
LHCb-CONF-2021-001

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

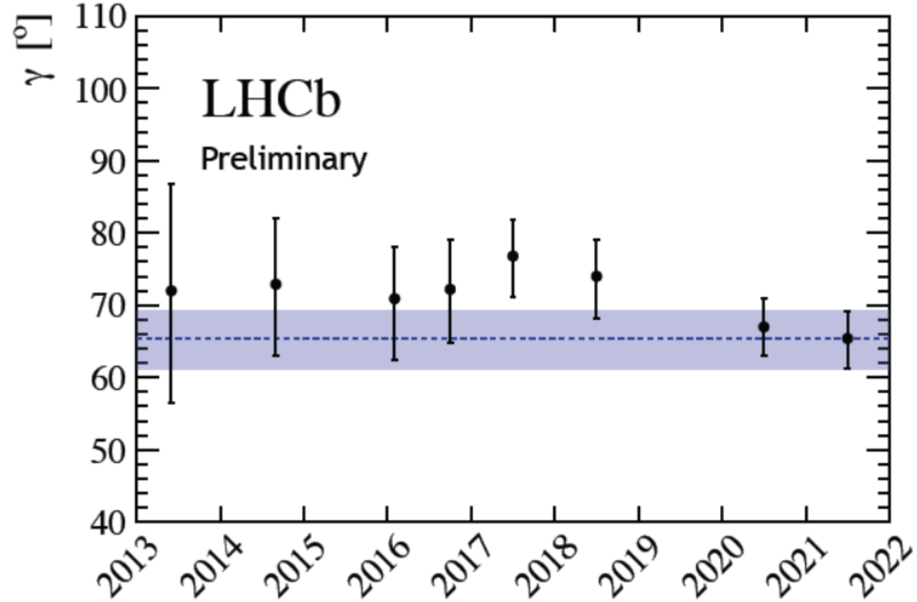
Belle: $\gamma = (73^{+15}_{-14})^\circ$ arXiv:1301.2033

Breakdowns and evolution of γ results

LHCb-CONF-2021-001



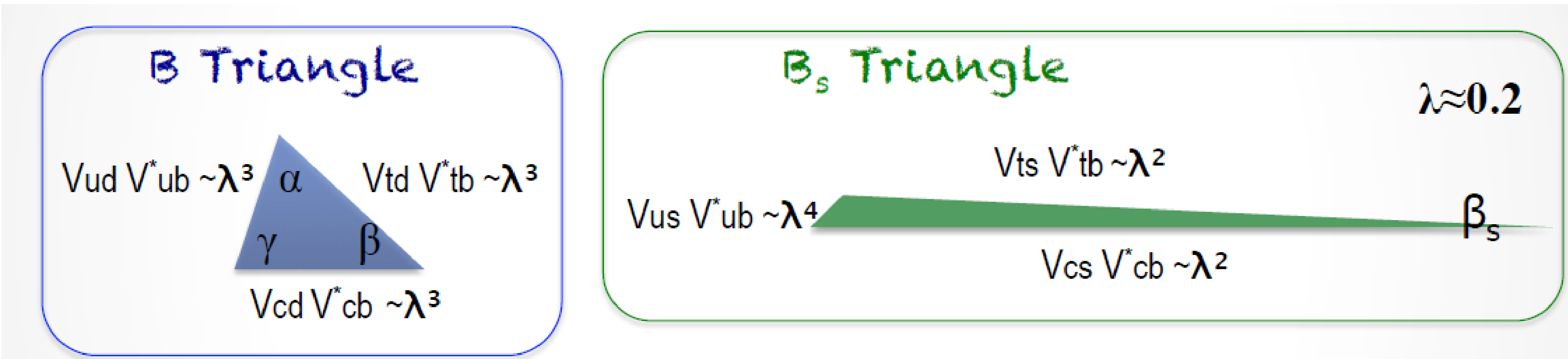
$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$



Combination	Value	68.3% CL	95.4% CL
B^+	61.7	[57.1, 65.9]	[52.6, 69.8]
B^0	82.0	[73.7, 90.5]	[64.0, 98.0]
B_s^0	79.0	[59.0, 98.0]	[41.0, 106.0]

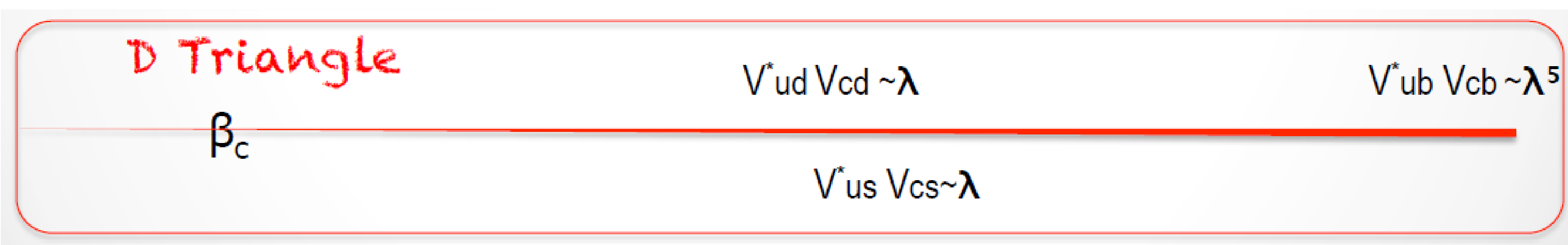
Beauty and Charm unitarity triangles

- Beauty system



B system : angles α, β, $\gamma \sim 1$ $\quad$ B_s system : angle $\beta_s \sim \lambda^2$

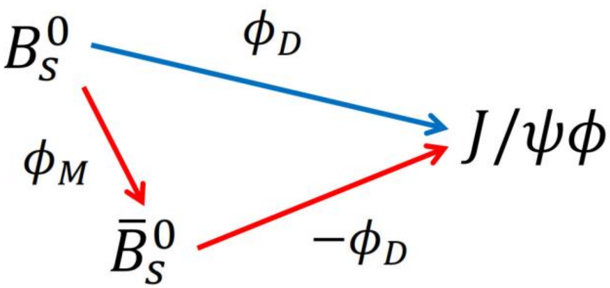
- Charm system

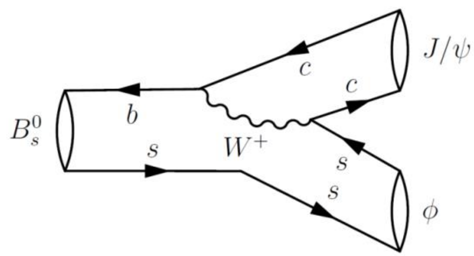


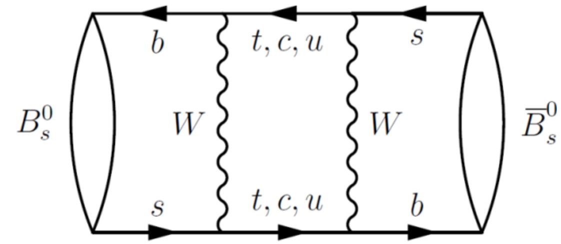
Charm system : angle $\beta_c \sim \lambda^4$

Diagrams from Jolanta Brodzicka

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 B^0 - $\overline{B}^0$ oscillation gives rise to a CP violating phase in the SM : a time-dependent measurement

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

- ϕ_S is expected to be very small in the SM and precisely predicted: $\phi_{SM} = -0.037 \pm 0.001$ rad (see eg Charles et al PRD84 (2011) 033005)

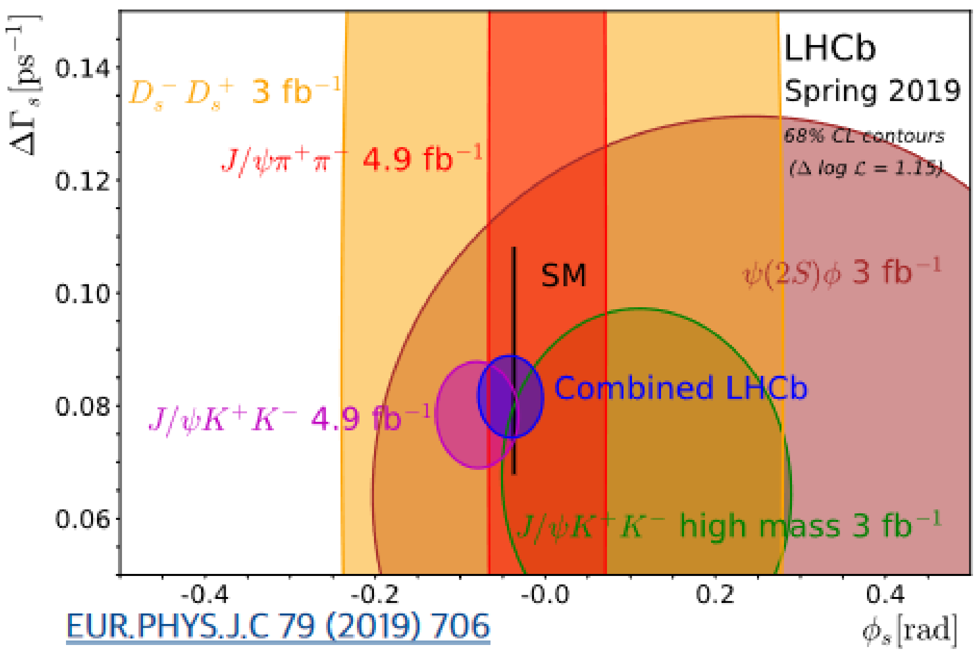
LHCb combination

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

- 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
- ϕ_S is 0.1σ from Standard Model and 1.6σ from zero

$\Delta\Gamma_S = 0.0813 \pm 0.0048\ \text{ps}^{-1}$

CP-violating phase: $\phi_S = -\,0.040 \pm 0.025$ rad



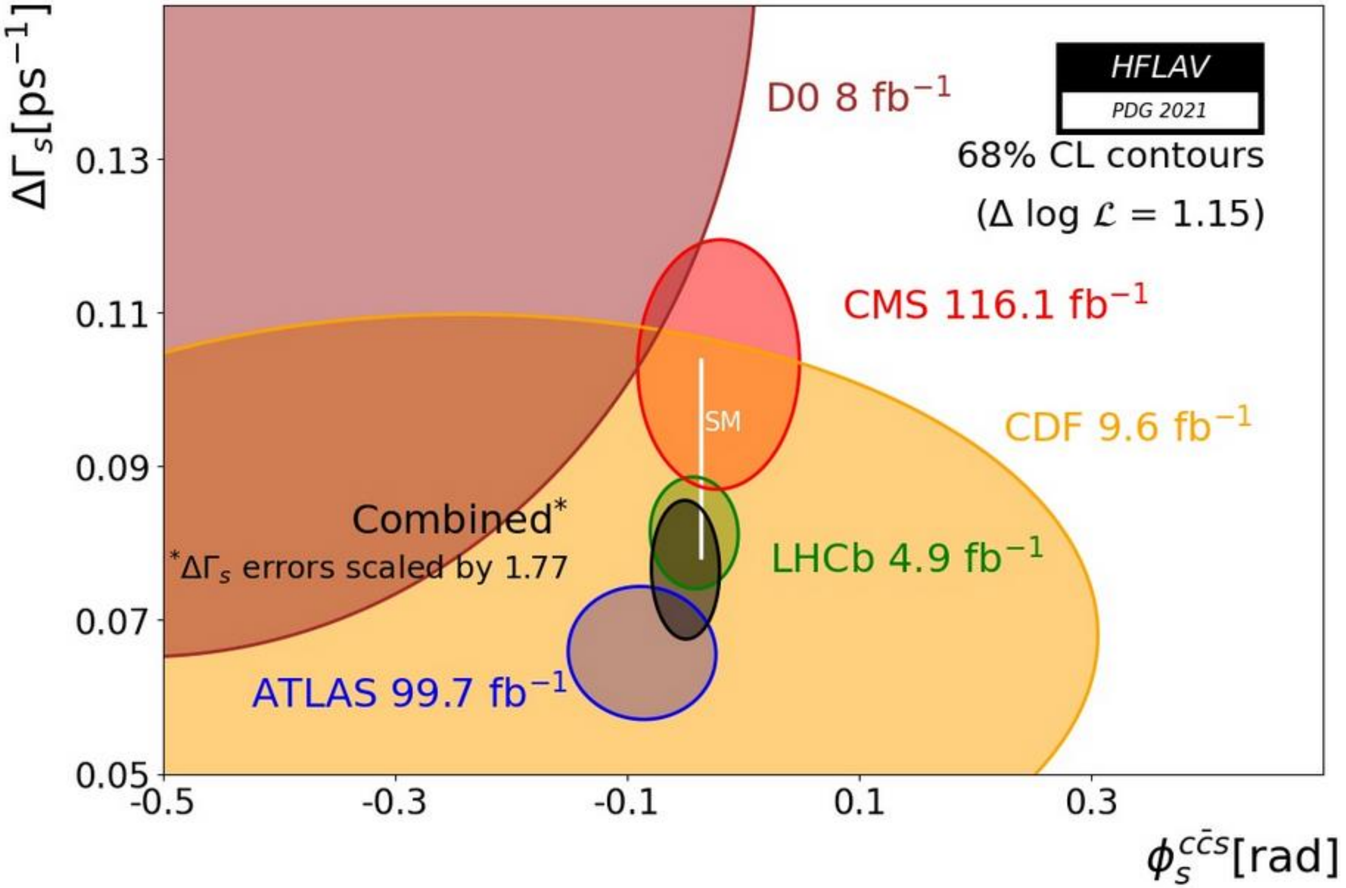
EUR.PHYS.J.C 79 (2019) 706

HFLAV combination all experiments

CP-violating phase:

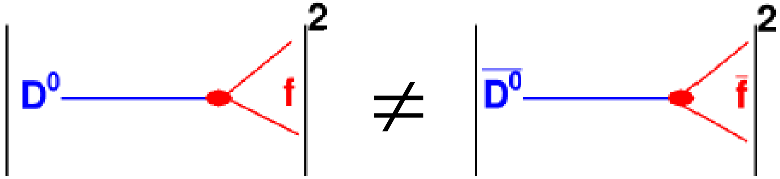
$\phi_S = -\,0.050 \pm 0.019$ rad

($\phi_s^{SM} = -0.037 \pm 0.001$ rad)



CP violation in charm

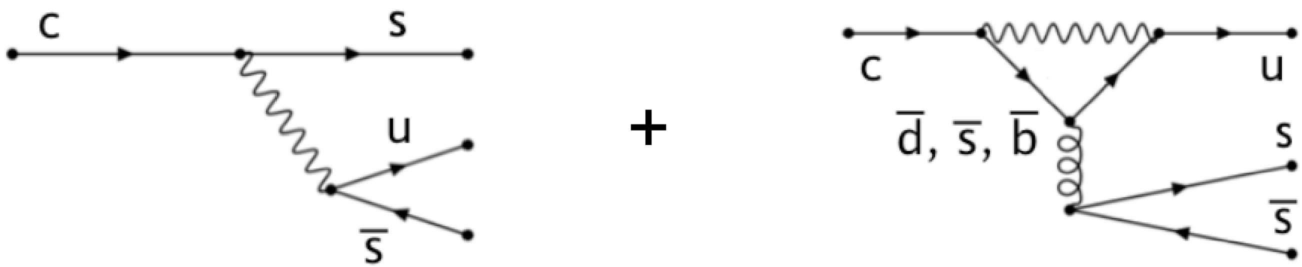
- Direct CP violation



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 $O(10^{-4}) \to O(10^{-3})$

Reminder of the "ΔA_{CP}" measurement

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

Phys. Rev. Lett. 122 (2019) 211803

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

includes physics and detector effects:

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

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

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

- To eliminate these contributions and cancel the systematics measure :

$$\Delta A_{CP} = A(K^-K^+) - A(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

Observation of CPV in charm decays

- Measurement performed with combined Run-1 and Run-2 data-set

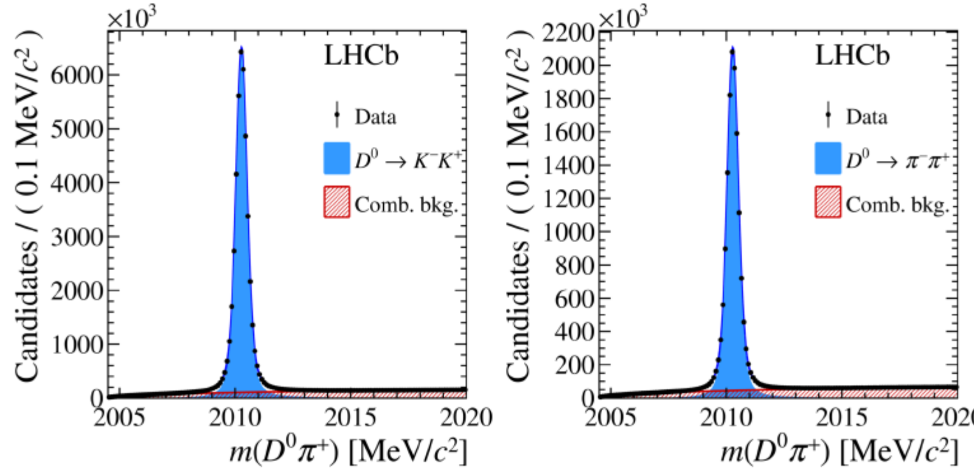
Phys. Rev. Lett. 122 (2019) 211803

ΔA_{CP} = [–15.4 ± 2.9] x 10^{-4}

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

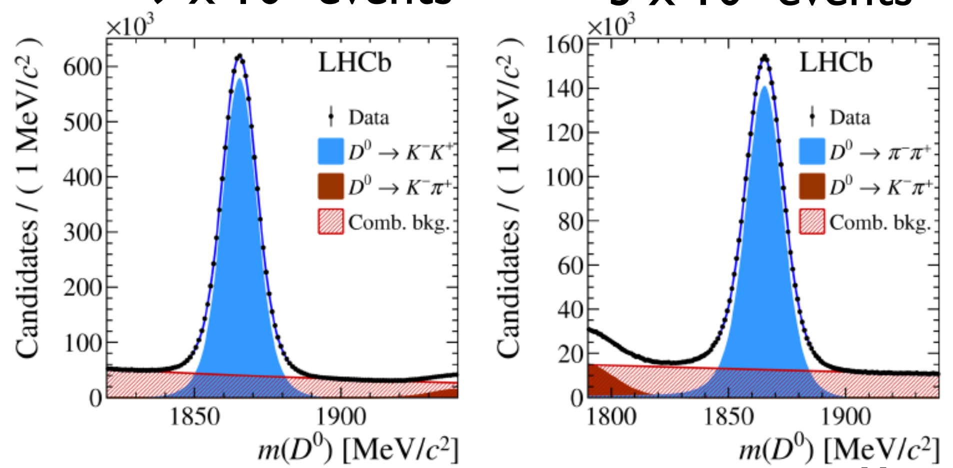
Prompt

44 x 10^6 events   14 x 10^6 events



Semi-leptonic

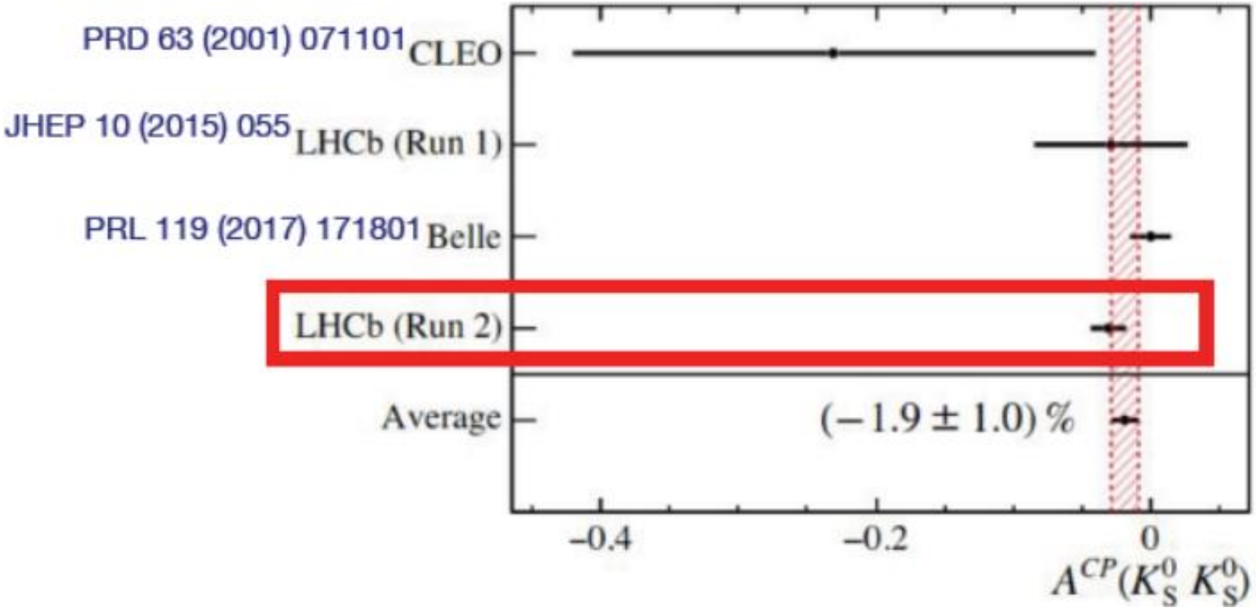
9 x 10^6 events   3 x 10^6 events



Charm CPV : more recent measurements

arXiv:2105.01565 (2021)

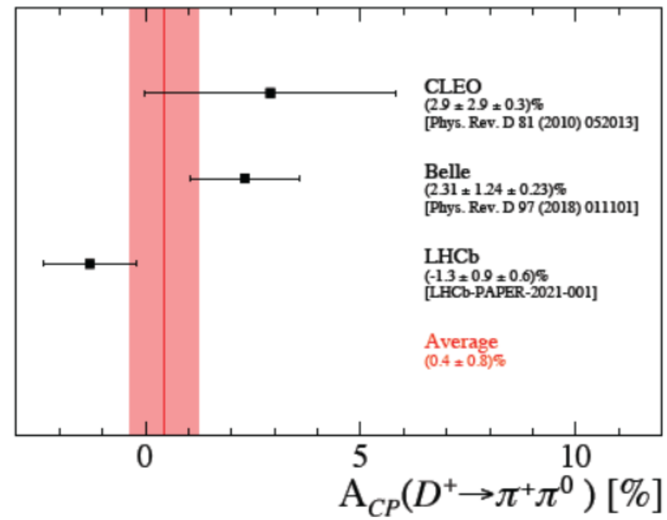
- Direct CPV : $A_{CP}(D^0 \rightarrow K^0_S K^0_S)$
- Use $D^0 \rightarrow K^+K^-$ channel as control for A_D & A_P
- $A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ [last uncertainity : CP violation of control channel]
- Consistent with no violation at the 2.4σ level



$A_{CP}(D^+{}_{(s)} \rightarrow h^+\pi^0, h^+\eta)$

JHEP 06 (2021) 019

$$\mathcal{A}_{CP}\left(D^+ \rightarrow \pi^+\pi^0\right) = (-1.3 \pm 0.9 \pm 0.6)\,\%,$$
$$\mathcal{A}_{CP}\left(D^+ \rightarrow K^+\pi^0\right) = (-3.2 \pm 4.7 \pm 2.1)\,\%,$$
$$\mathcal{A}_{CP}\left(D^+ \rightarrow \pi^+\eta\right) = (-0.2 \pm 0.8 \pm 0.4)\,\%,$$
$$\mathcal{A}_{CP}\left(D^+ \rightarrow K^+\eta\right) = (-6 \pm 10 \pm 4)\,\%,$$
$$\mathcal{A}_{CP}\left(D_s^+ \rightarrow K^+\pi^0\right) = (-0.8 \pm 3.9 \pm 1.2)\,\%,$$
$$\mathcal{A}_{CP}\left(D_s^+ \rightarrow \pi^+\eta\right) = (0.8 \pm 0.7 \pm 0.5)\,\%,$$
$$\mathcal{A}_{CP}\left(D_s^+ \rightarrow K^+\eta\right) = (0.9 \pm 3.7 \pm 1.1)\,\%,$$

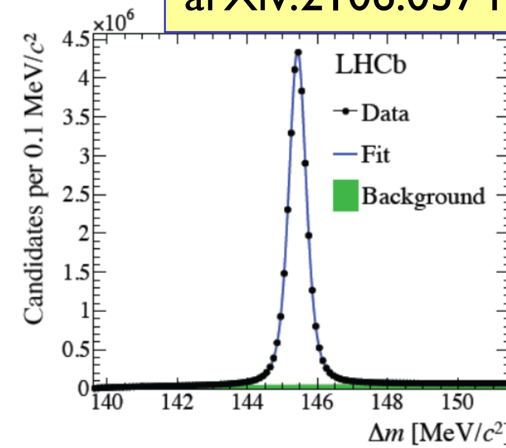


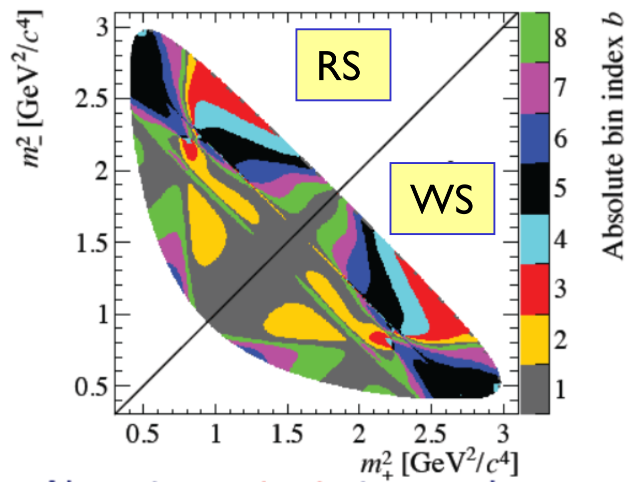
- All compatible with no CP violation
- More data needed !
- Note that LHCb is now regularly extracting measurements with neutrals in the final state (K_sK_s and h^0h^+)

D^0 mixing parameters in $D^0 \rightarrow K_S^0 \pi^+\pi^-$

- Mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$
- $x = (m_1 - m_2)/\Gamma$; $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, $\phi = \arg(q/p)$
  until now x measured only at ~3σ (HFLAV)
- 30.6×10^6 of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with very small background. $\overline{D}$ or D flavour tagging using $D^* \rightarrow D\pi$ decays
- Use the bin-flip method
  - Measure ratios between D^0 and $\overline{D^0}$ candidates in symmetric bins of Dalitz plot $m^2(K_S^0\pi^-)$ vs $m^2(K_S^0\pi^+)$
  - 2 (flavour) x 16 (Dalitz bin) x 13 (decay time bin) subsamples
  - In each bin, strong-phase difference approx. constant for D^0 and $\overline{D^0}$ amplitudes (input from CLEOc and BESIII)

arXiv:2106.03744





$$m_\pm^2 \equiv \begin{cases} m^2(K_S^0\pi^\pm) & \text{for } D^0 \rightarrow K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^\mp) & \text{for } \overline{D}^0 \rightarrow K_S^0\pi^+\pi^- \end{cases}$$

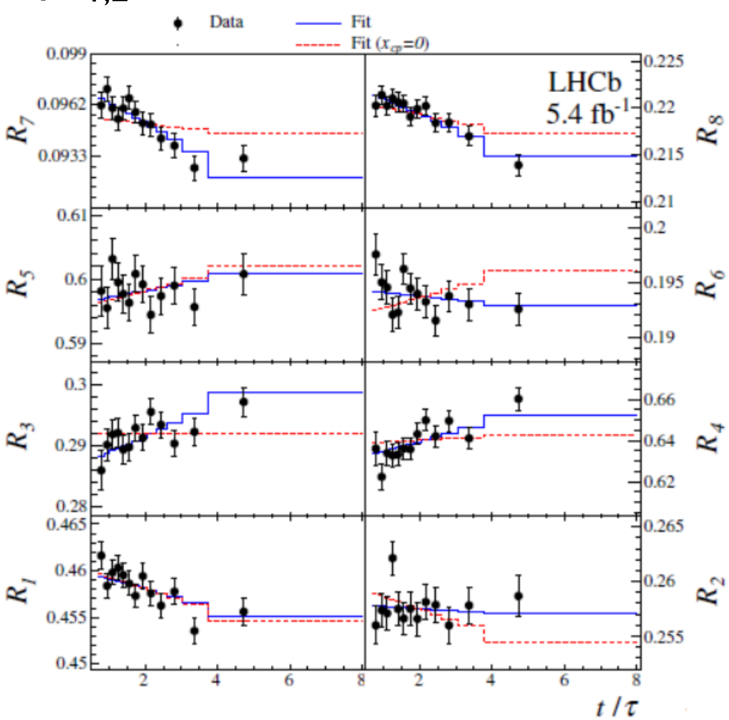
D^0 mixing parameters in $D^0 \to K_S^0 \pi^+\pi^-$

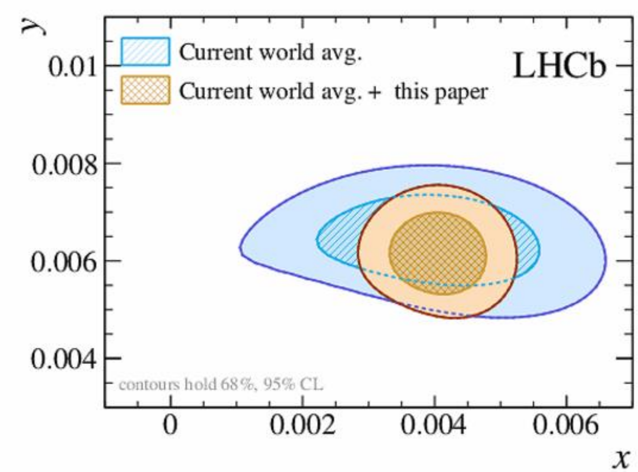
- Plot Ratio R_i : asymmetry for Dalitz bin *i* in bins of decay time
  - Deviations from constant values are due to mixing

arXiv:2106.03744

- First observation with a significance of more than 7 standard deviations of the mass difference between mass eigenstates $|D_{1,2}\rangle$

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3}$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$



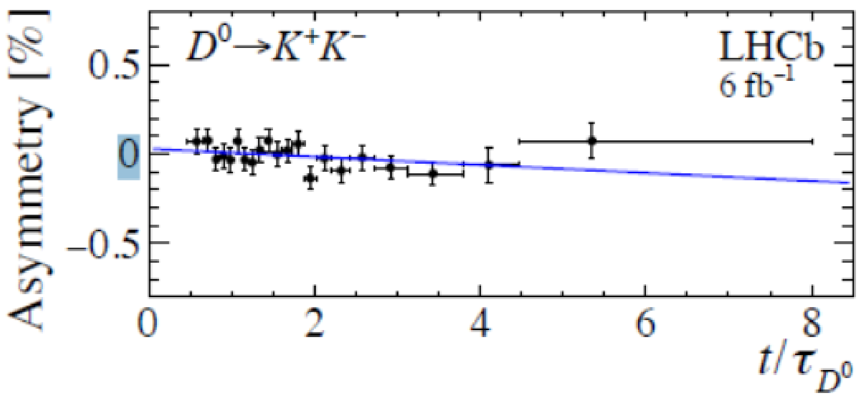


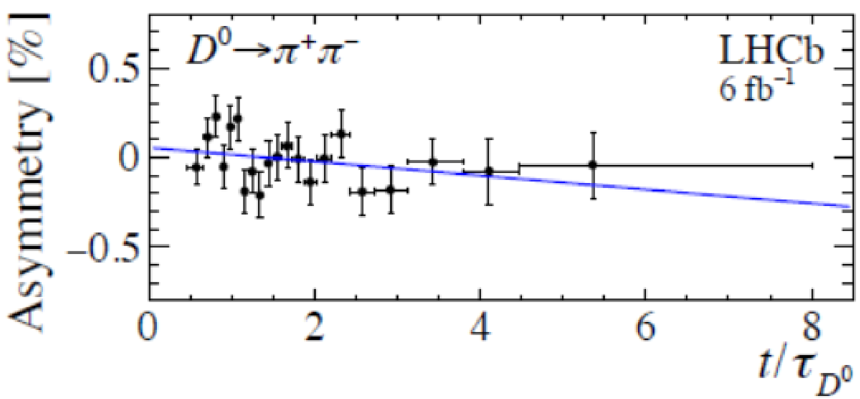
m_1-m_2 = 6.4x10^{-6} eV = 1x10^{-38}g = 0.00000000000000000000000000000000000001 grams !!

ΔY in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

arXiv:2105.09889

- ΔY is the slope of the time-dependent asymmetry of the decay rates of D^0 and $\overline{D}^0$ mesons
- It is a measure of CP violation in mixing and interference
- Strategy: measure asymmetry in bins of decay time and measure the linear slope





$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$

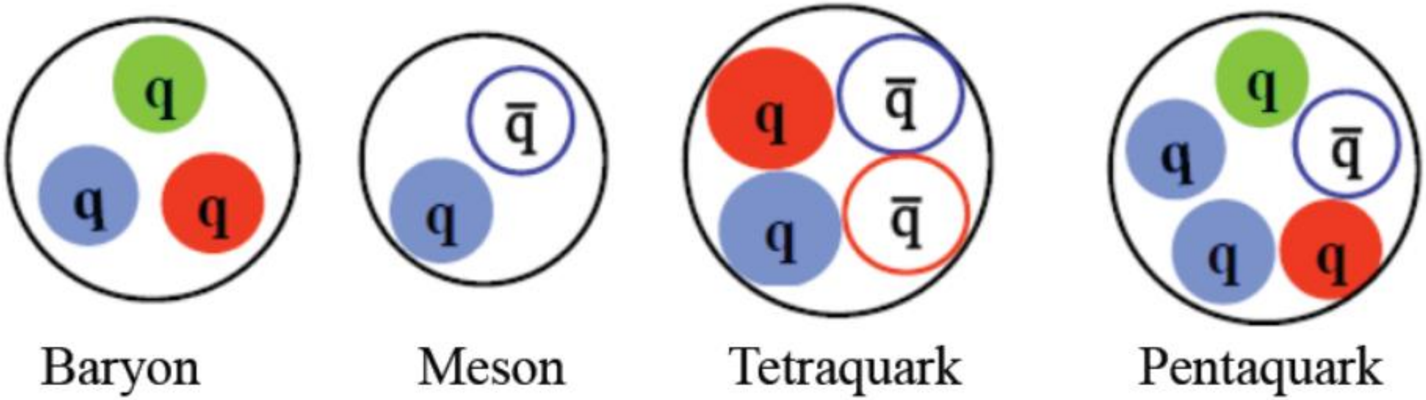
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

Combining

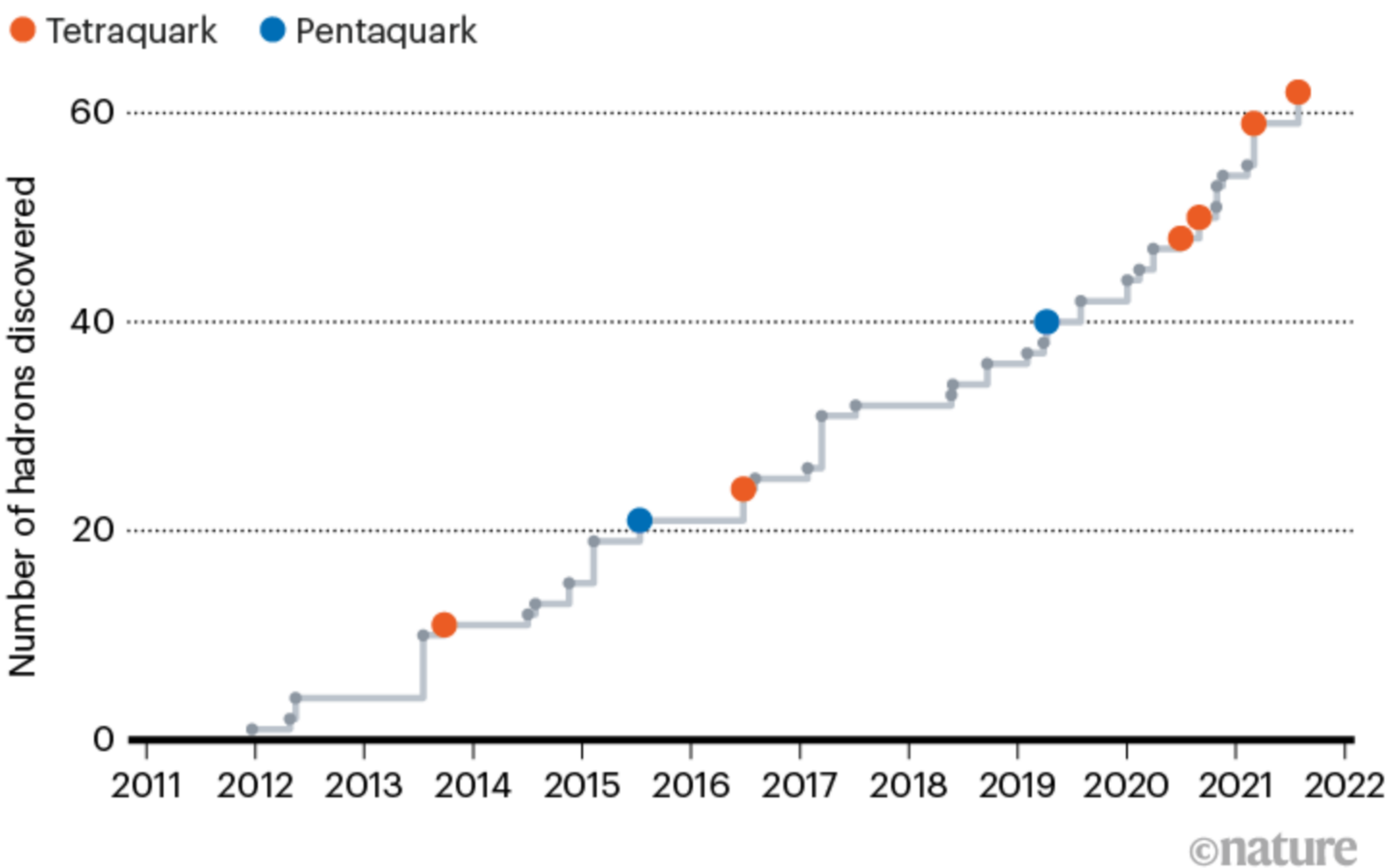
$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

- Compatible with 0 within 2σ
- This result improves by nearly a factor 2 the precision of the previous world average

LHCb new (exotic) spectroscopy measurements

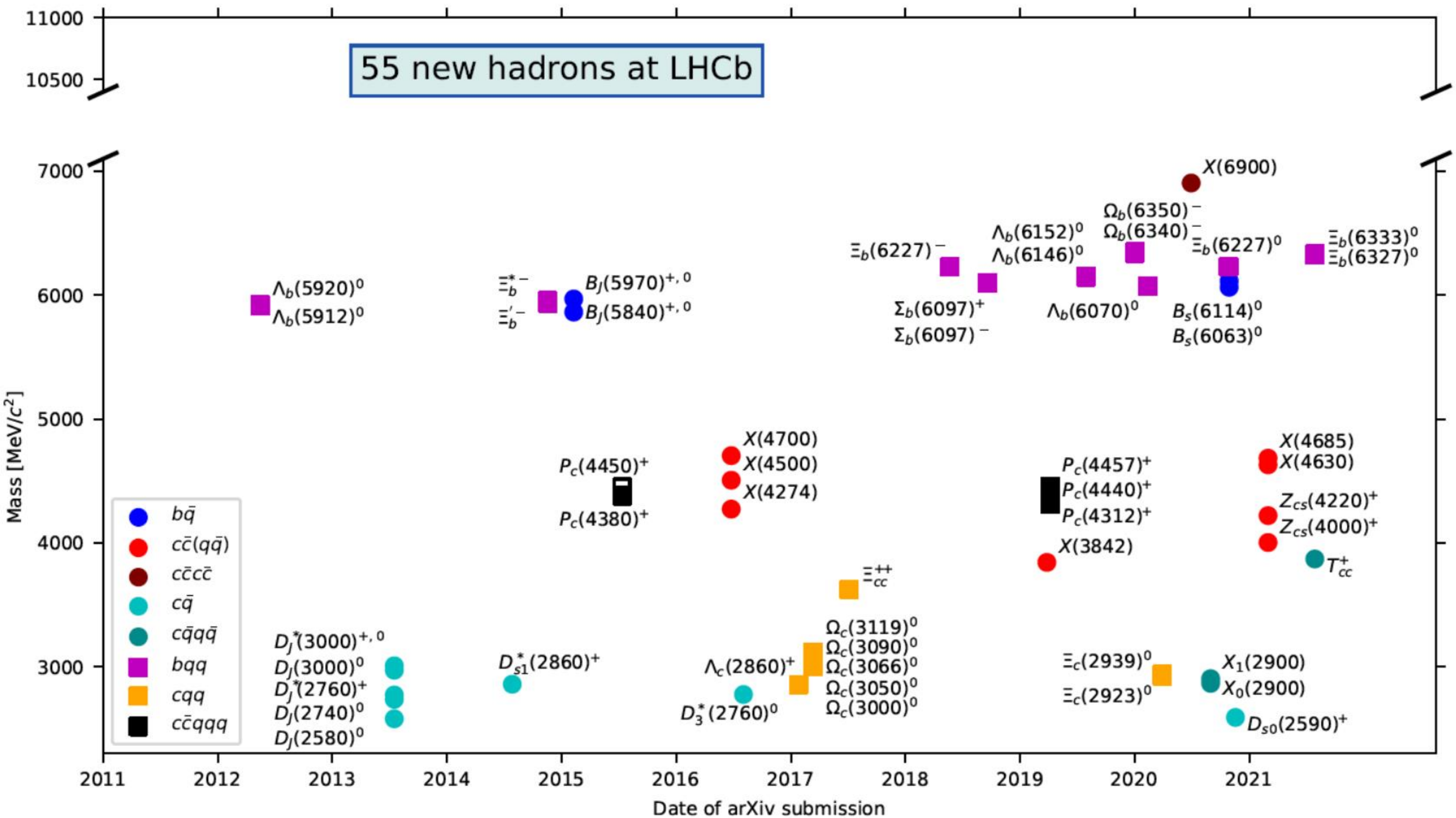


New hadron discoveries at the LHC



With thanks to Partick Koppenberg

New hadron discoveries at LHCb



With thanks to Partick Koppenberg

Pentaquark discovery by LHCb

- Discovery of X(3872) - now $\chi_{c1}(3872)$ - by Belle in 2003 started new era in exotic spectroscopy
- First observation of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ as narrow resonances in the mass spectrum of (J/ψ p) in $\Lambda_b \rightarrow (J/\psi\ p)\ K^-$ decays

PRL 115 (2015) 072001

- Consistent with $c\bar{c}uud$ pentaquarks : allowed by QCD, but not observed in 50 years of searching.

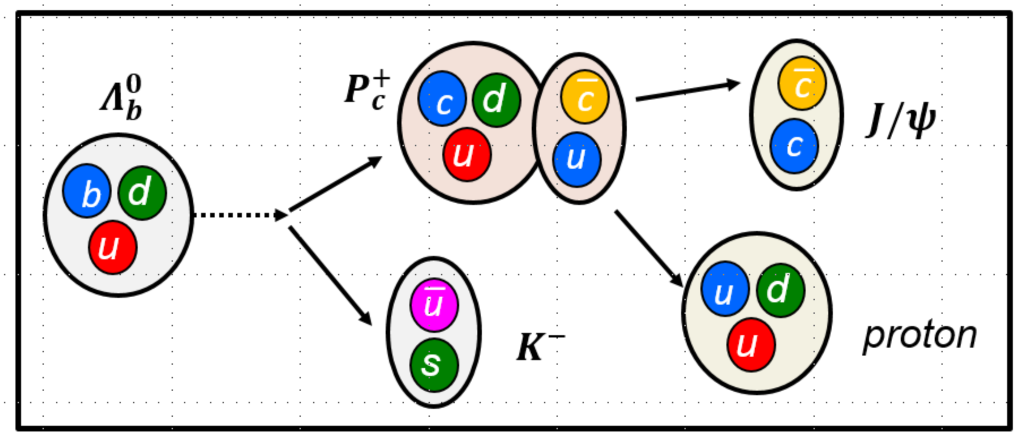
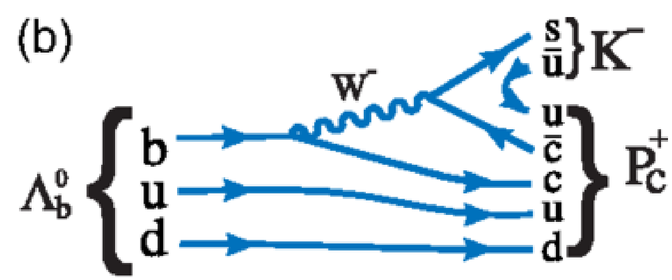


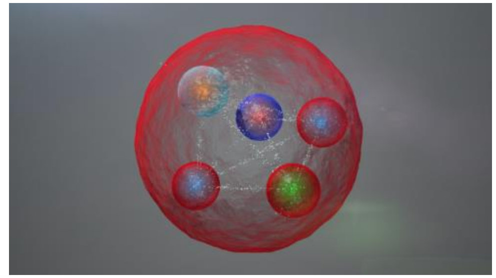
Diagram from Liming Zhang

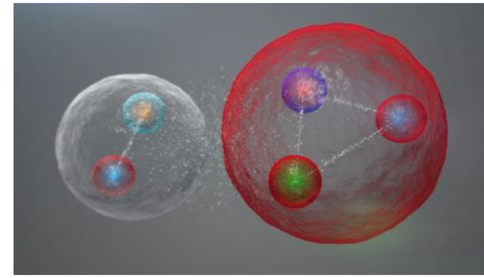


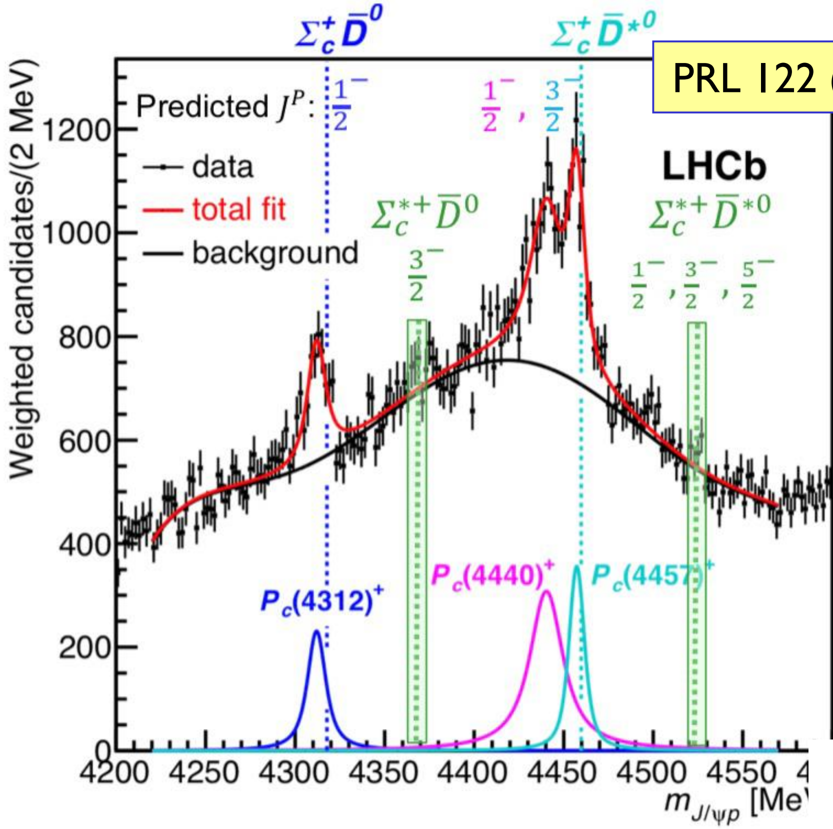
Nature of pentaquarks ?

Possible models describing the observed pentaquark states :

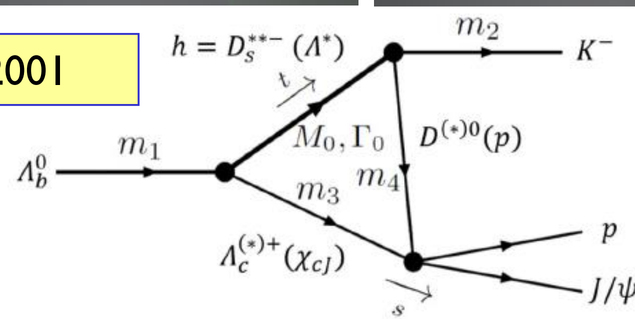
- Tightly bounded states
- Re-scattering models
- Meson-baryon molecules







PRL 122 (2019) 222001

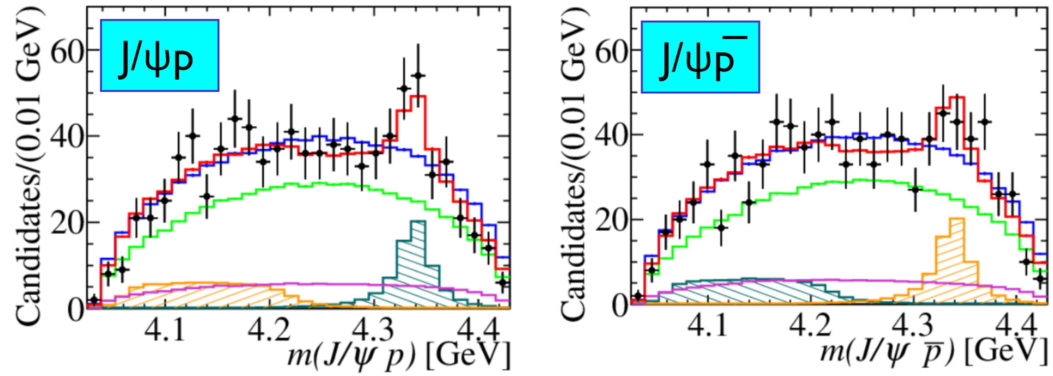


- Molecular-state model favoured : bound mesons and baryons are expected to form narrow resonances just below mass thresholds
- More work needed

Evidence for more pentaquark states

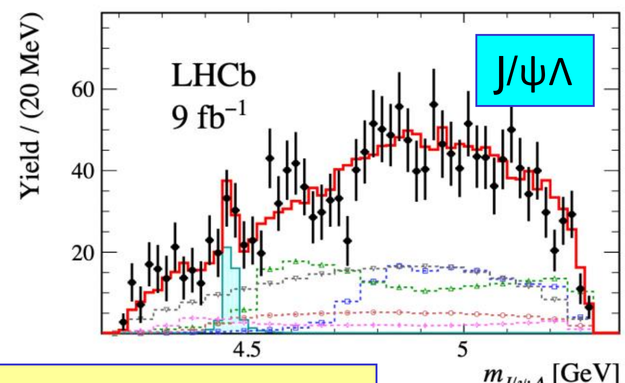
arXiv:2108.04720

- Amplitude analysis using 800 $B_s^0 \rightarrow J/\psi p\bar{p}$ decays
- Observe additional structure in $J/\psi p$ and $J/\psi \bar{p}$ spectra
- Significance of 3.1σ to 3.7σ depending on J^P assignment
- Evidence for new $P_c(4337)^+$ state consistent with another $(c\bar{c}uud)$ pentaquark



	M[MeV]	Γ[MeV]
$P_c(4337)^+$	$4337^{+7}_{-4} \pm 2$	$29^{+26}_{-12} \pm 14$
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$

- Amplitude analysis using 1750 $\Xi^-_b \rightarrow J/\psi \Lambda K^-$ decays
- Observe structure in $J/\psi\Lambda$ spectrum
- Evidence for new $P_{cs}(4459)^0$ state with significance of 3.1σ
- Consistent with $(c\bar{c}uds)$ pentaquark



Sci.Bull.66(2021)1278

New doubly charmed tetraquark T_{cc}^{+}

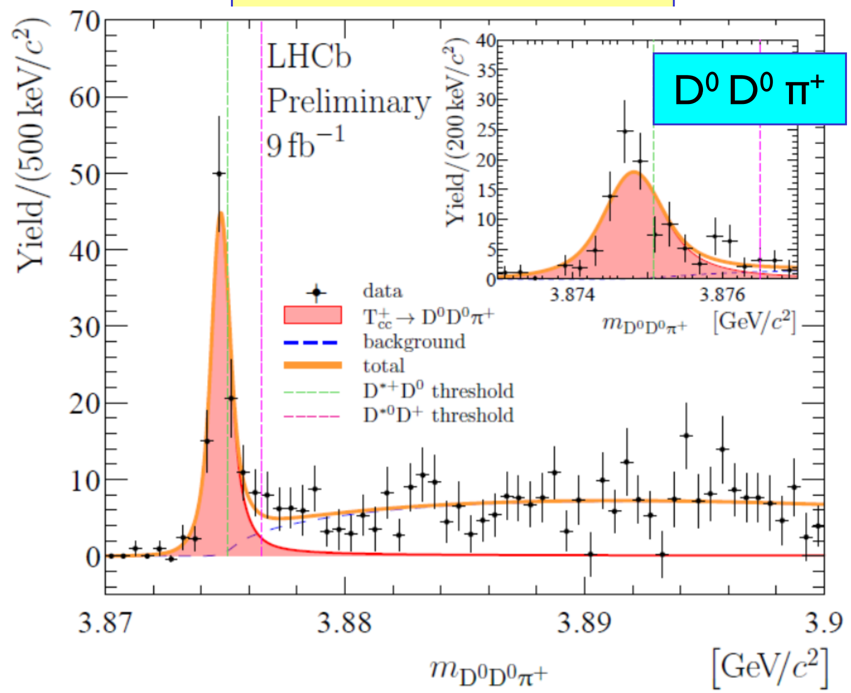
LHCb-PAPER-2021-031

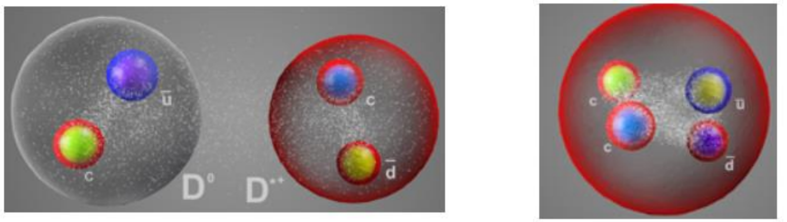
- Study $D^0 D^0 \pi^+$ mass spectrum near $D^{*+}D^0$ and $D^{*0}D^+$ thresholds

$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

- Very narrow state in $D^0D^0 \pi^+$ mass spectrum consistent with $cc\bar{u}\bar{d}$ tetraquark, with significance 10σ . Manifestly exotic state.
- Very close to $D^{*+}D^0$ mass thresholds

δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV

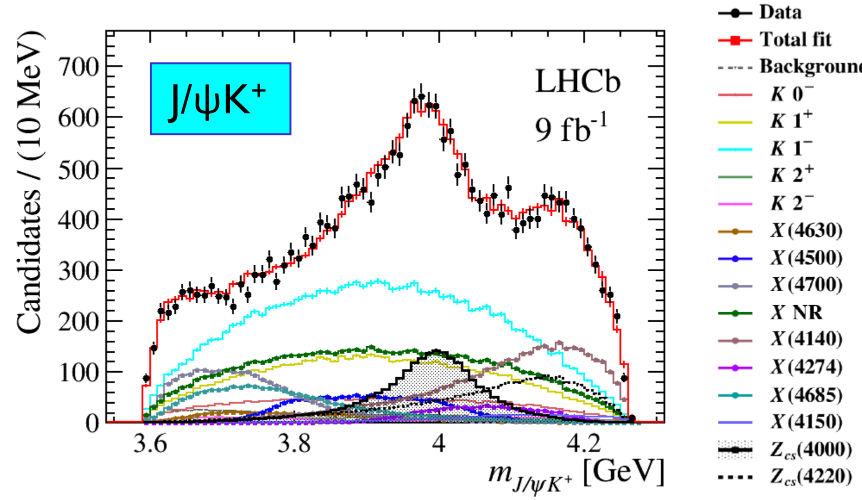




- Possible evidence for molecular bound state, but jury still out.

More observations of new tetraquark states

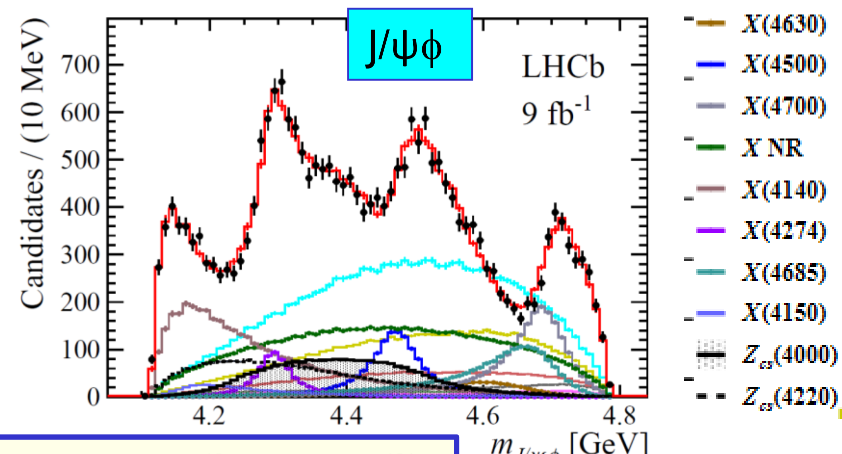
- $B^+ \to J/\psi \phi K^+$ sample
- Observe structure in $J/\psi K$
- Observation of two new $c\bar{c}u\bar{s}$ tetraquark states $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$
- Significance of 15σ and 6σ respectively, 1^+ assignment



Phys. Rev. Lett. 127 (2021) 082001

$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$

- $B^+ \to J/\psi \phi K^+$ sample
- Observe structure in $J/\psi \phi$
- Observation of two new $c\bar{c}s\bar{s}$ tetraquark states X(4630) and X(4685) as well as previously confirmed states
- Significance of 5.5σ and 15σ respectively



$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$

The upgraded LHCb detector and outlook

LHCb Upgrade planning

WE ARE HERE

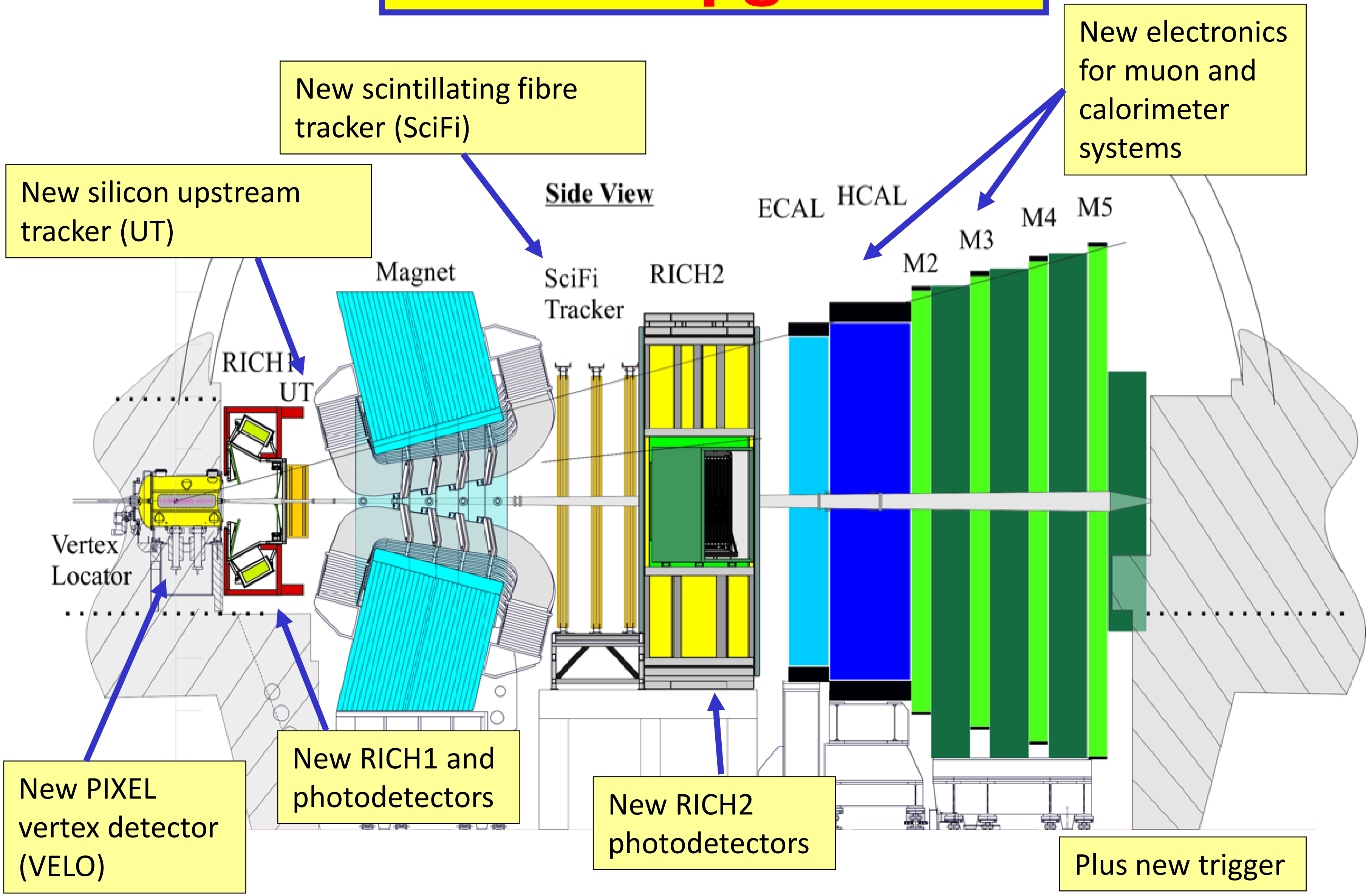
2020–2021	2022–2024	2025–2027	2028–2030	2031–2032	2033–203+
2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031 2032	2033 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz **UPGRADE I**	*L = 2 x 10*^{33}	**LHCb** **Consolidate: UPGRADE Ib**	*L = 2 x 10*^{33} *50 fb*$^{-1}$	**LHCb** **UPGRADE II**	*L=1-2x 10*^{34} *300 fb*$^{-1}$
ATLAS **Phase I Upgr**	*L = 2 x 10*^{34}	**ATLAS** **Phase II UPGRADE**	**HL-LHC** *L = 5 x 10*^{34}		**HL-LHC** *L = 5 x 10*^{34}
CMS **Phase I Upgr**	*300 fb*$^{-1}$	**CMS** **Phase II UPGRADE**			*3000 fb*$^{-1}$
Belle II	*5 ab*$^{-1}$	*L = 6 x 10*^{35}	*50 ab*$^{-1}$		

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



Construction & Installation – Upgrade I

SciFi tracker

RICH 2

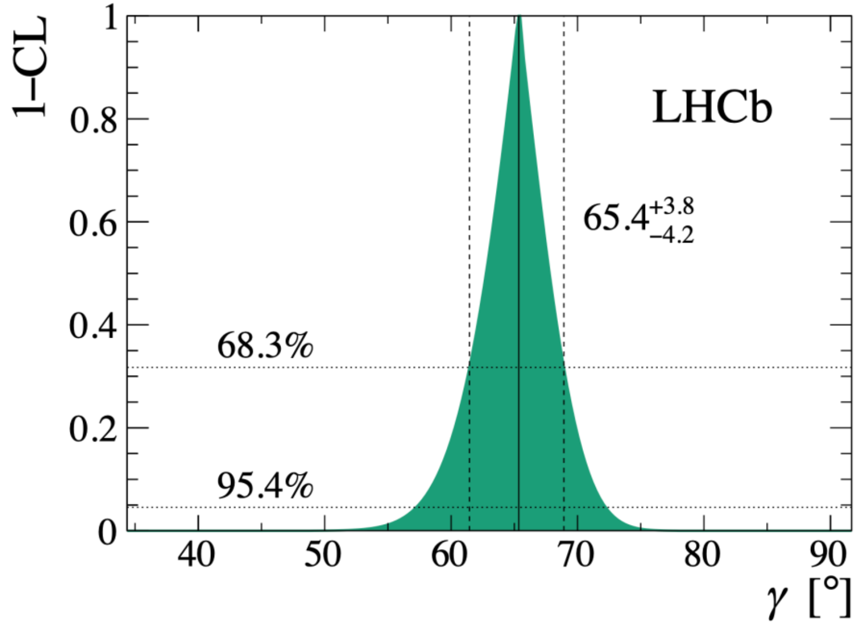
UT stave

γ prospects : Run II → Upgrade I

- Post Run II target of 4° almost surpassed (~9 fb^{-1}) and analyses still in progress

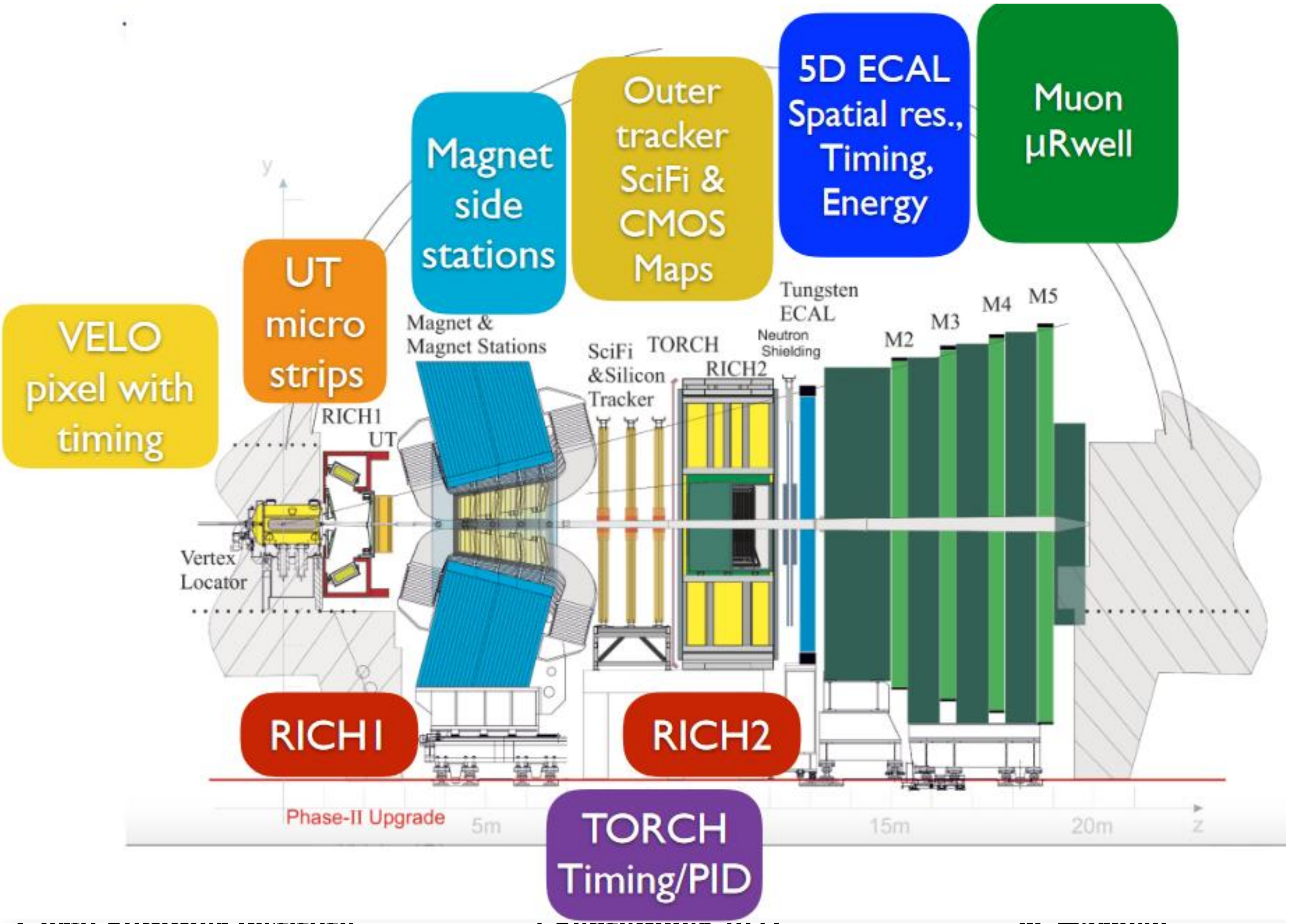
- LHCb Upgrade I : target 0.9° (~50 fb^{-1})

$$\gamma = (65.4\ ^{+3.8}_{-4.2})^{\circ}$$



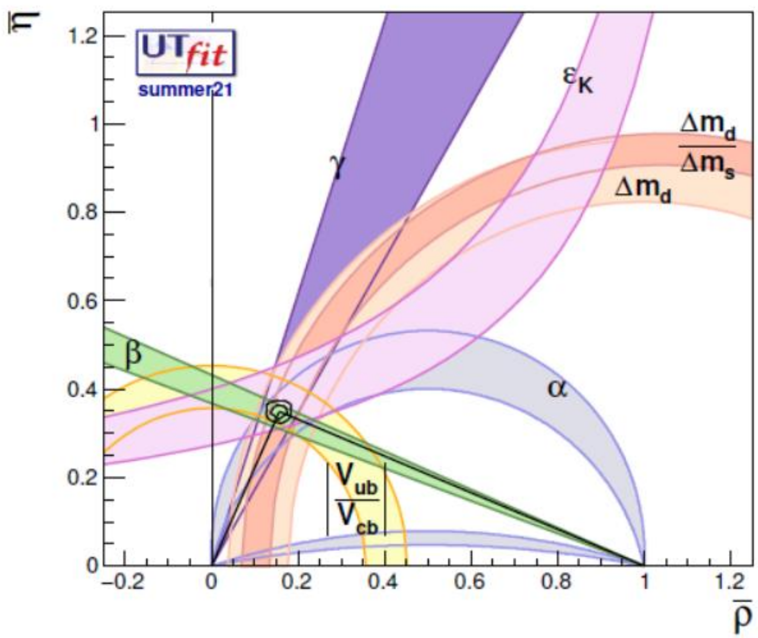
EPJC (2013) 73:2373

… and beyond 2030 : Upgrade II



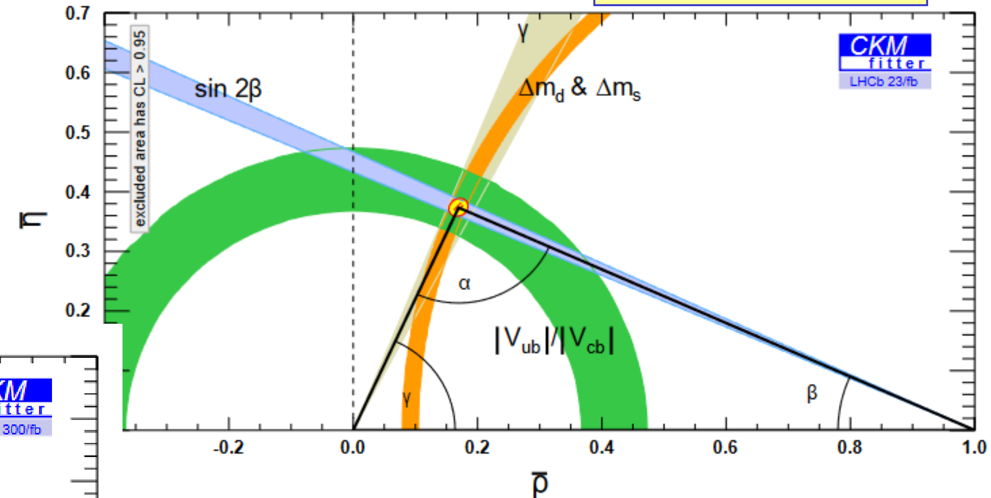
Evolution of the Unitarity Triangle

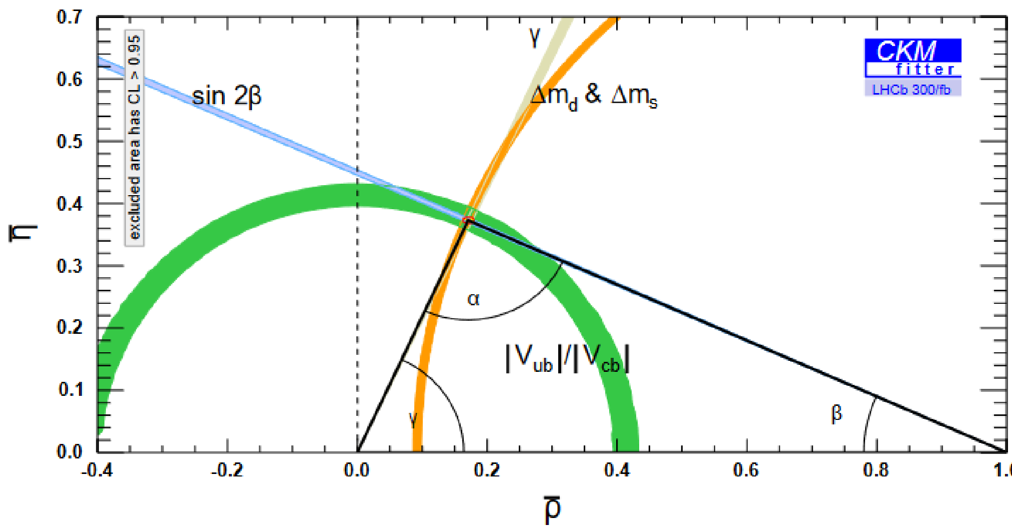
LHCB-PUB-2018-009



LHCb : 2021
Run 2 (~9 fb^{-1})

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.

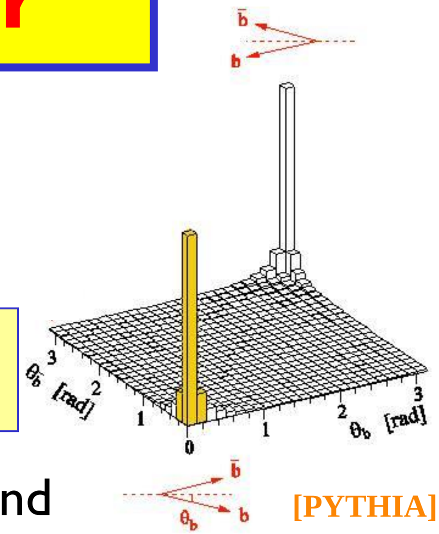
- Still much room for New Physics, but higher precision required
  → preparing for LHCb Upgrades beyond 2022 and the decade afterwards!

Spare Slides

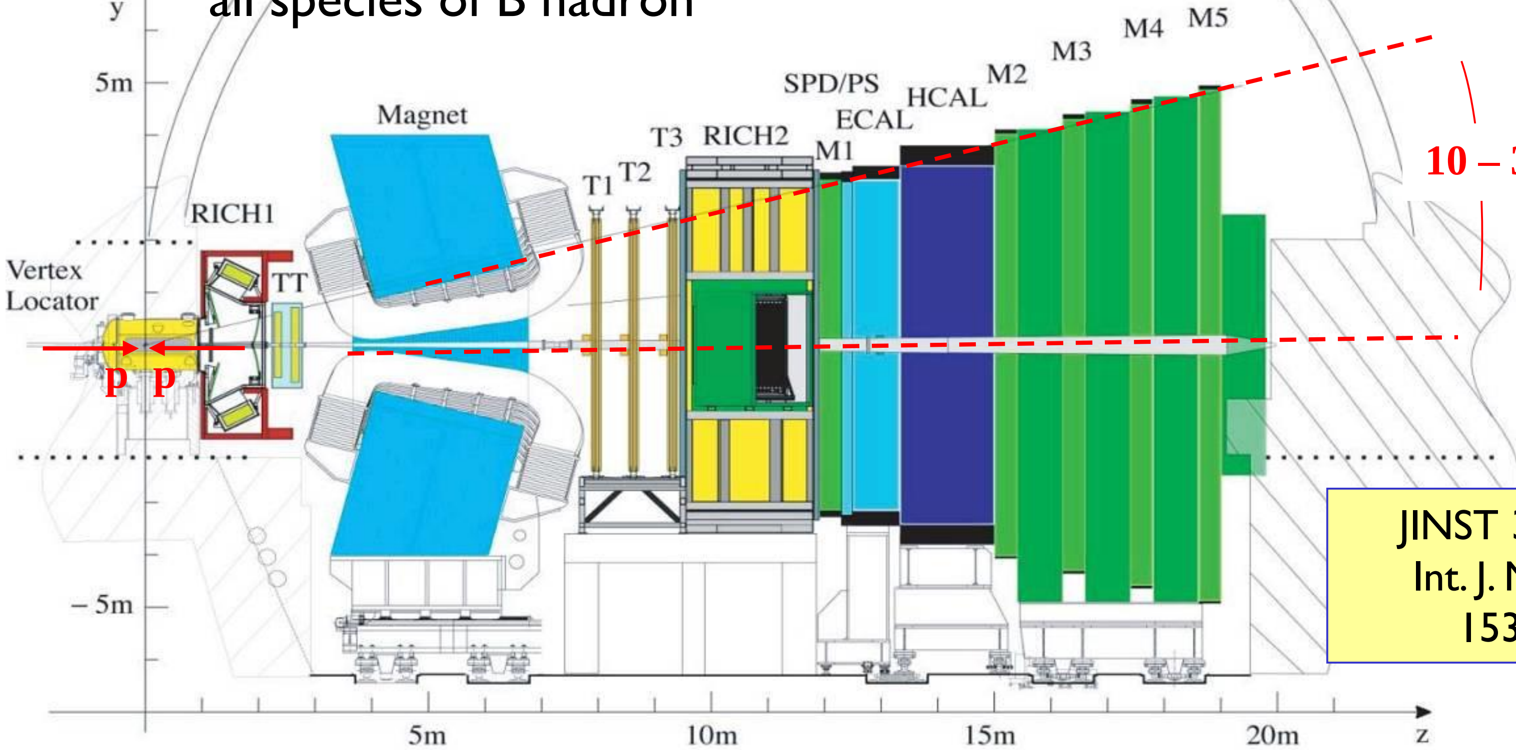
LHCb forward spectrometer

- 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 $2 < \eta < 5$
  At $\sqrt{s}$ = 13 TeV : 154.3 ± 1.5 ± 14.3 μb

PRL 118, 052002 (2017)



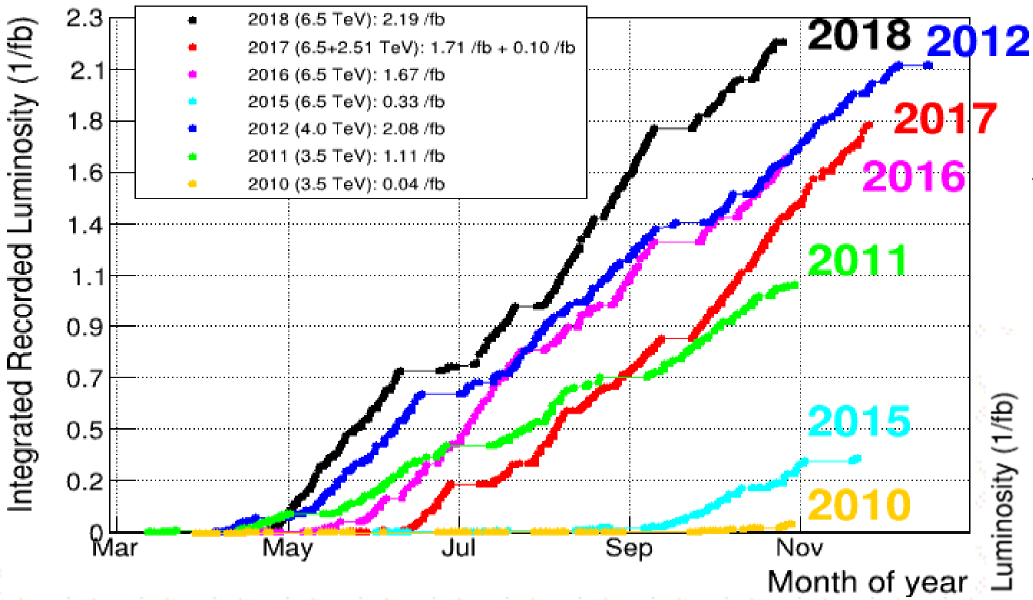
→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories) and all species of B hadron

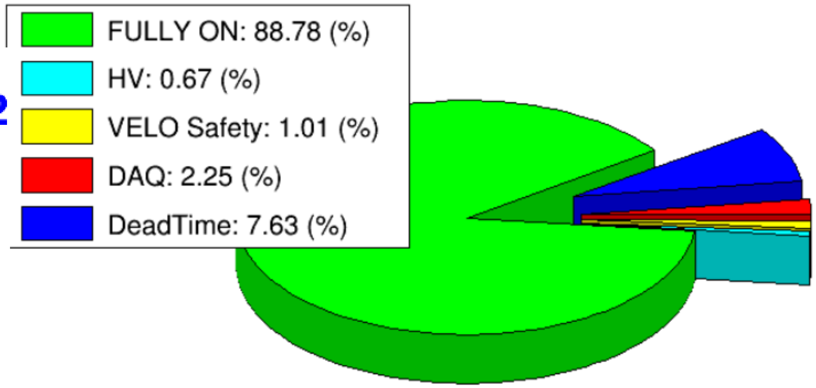


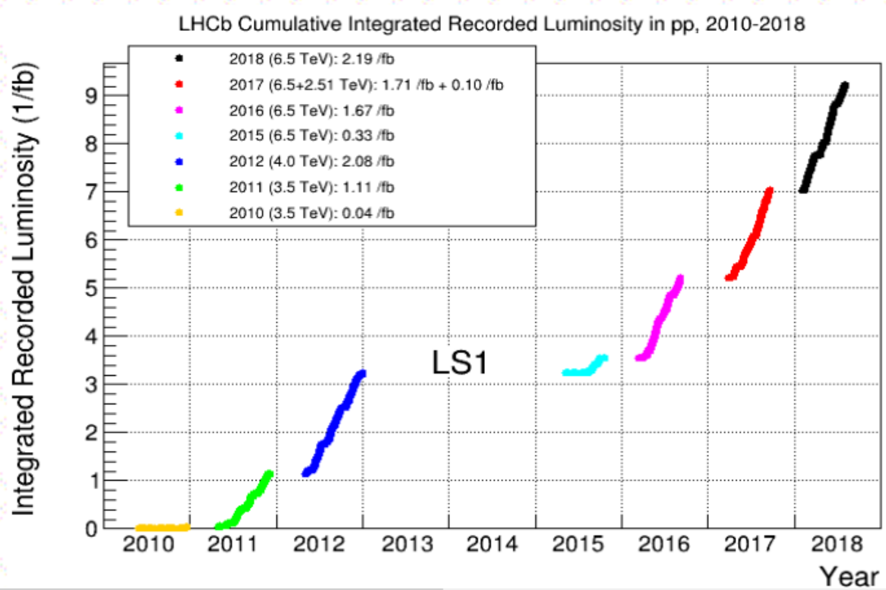
JINST 3:S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb data taking

- 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}







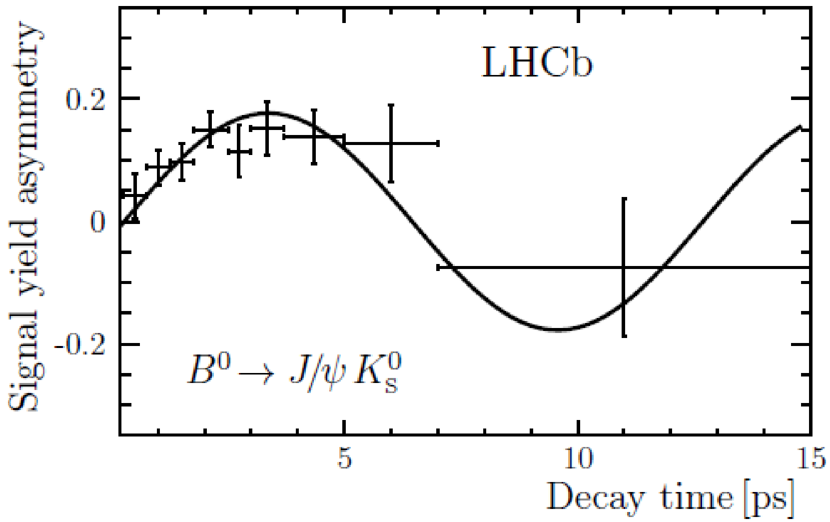
LHCb measurement of sin(2β)

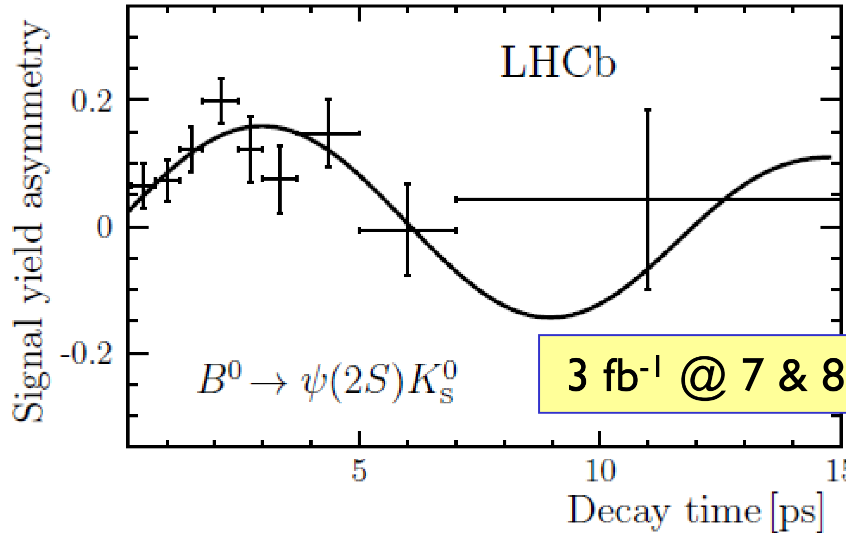
sin(2β) from $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S) K^0_S$

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) = 0





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

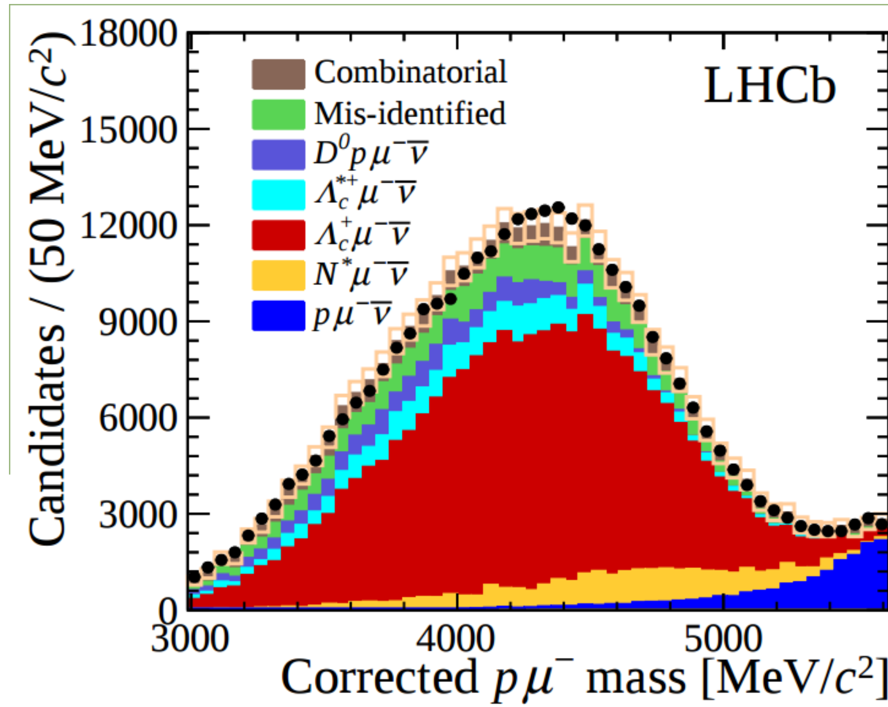
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

Competitive with Babar & Belle.
HFLAV world average from all modes :
sin(2β) = 0.695 ± 0.019

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

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)



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

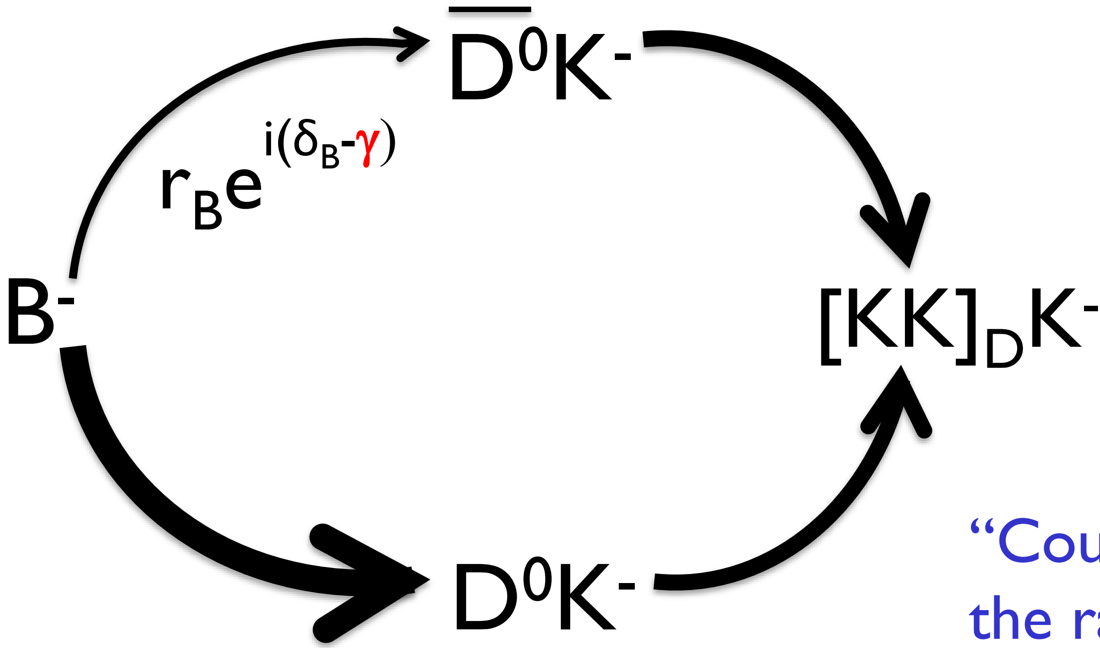
Nature Physics 10 (2015) 1038

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

"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 ($r_B \sim 0.1$)

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

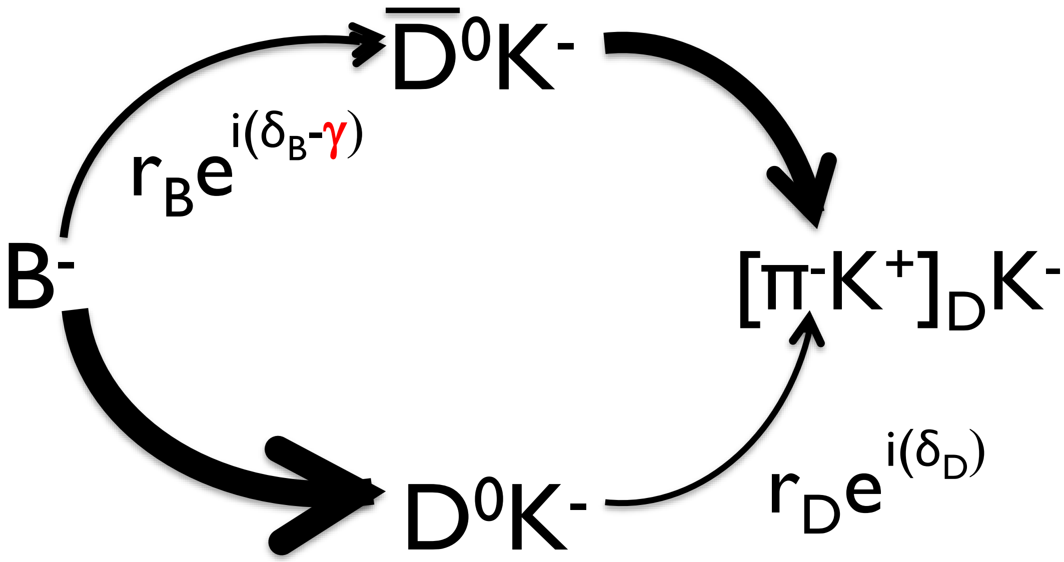
Weak phase changes sign for equiv B^+ diagram, thickness of arrows indicate relative strengths

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

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

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

"ADS" method



Weak phase changes sign for equivalent B^+ diagram

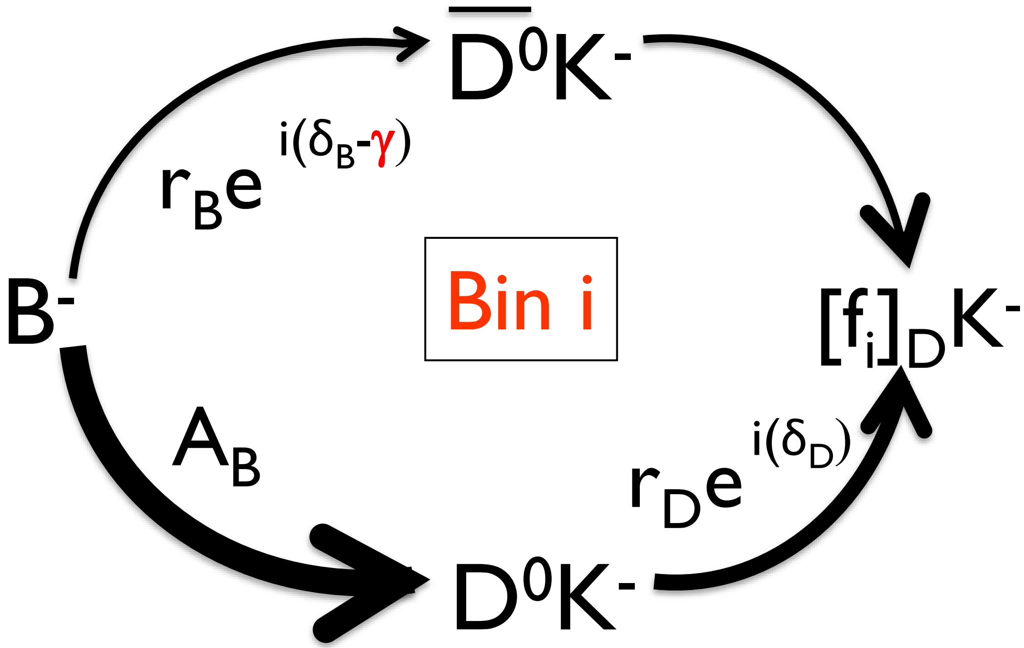
- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- r_B, δ_B hadronic parameters again to be determined alongside γ ($r_B \sim 0.1$)
- Additional two parameters r_D, δ_D . External inputs from charm mixing measurements ($r_D \sim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

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

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

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. $D \rightarrow K^0_S\,\pi\pi$
- 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)

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

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

arXiv:1010.2817

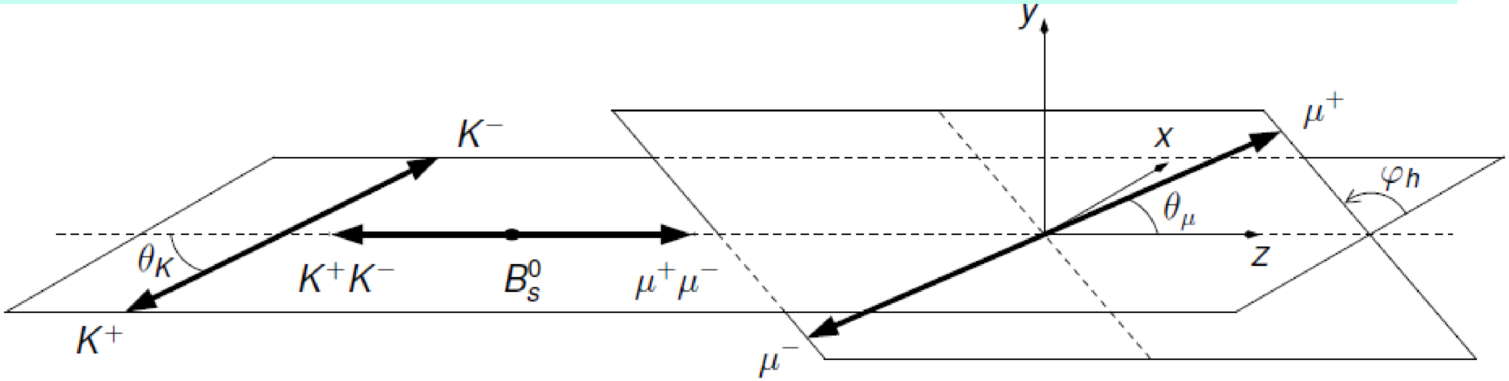
$B_s \to J/\psi\ \phi$ analysis

- 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 time-dependent $B_s \to J/\Psi\ \phi$ angular analysis

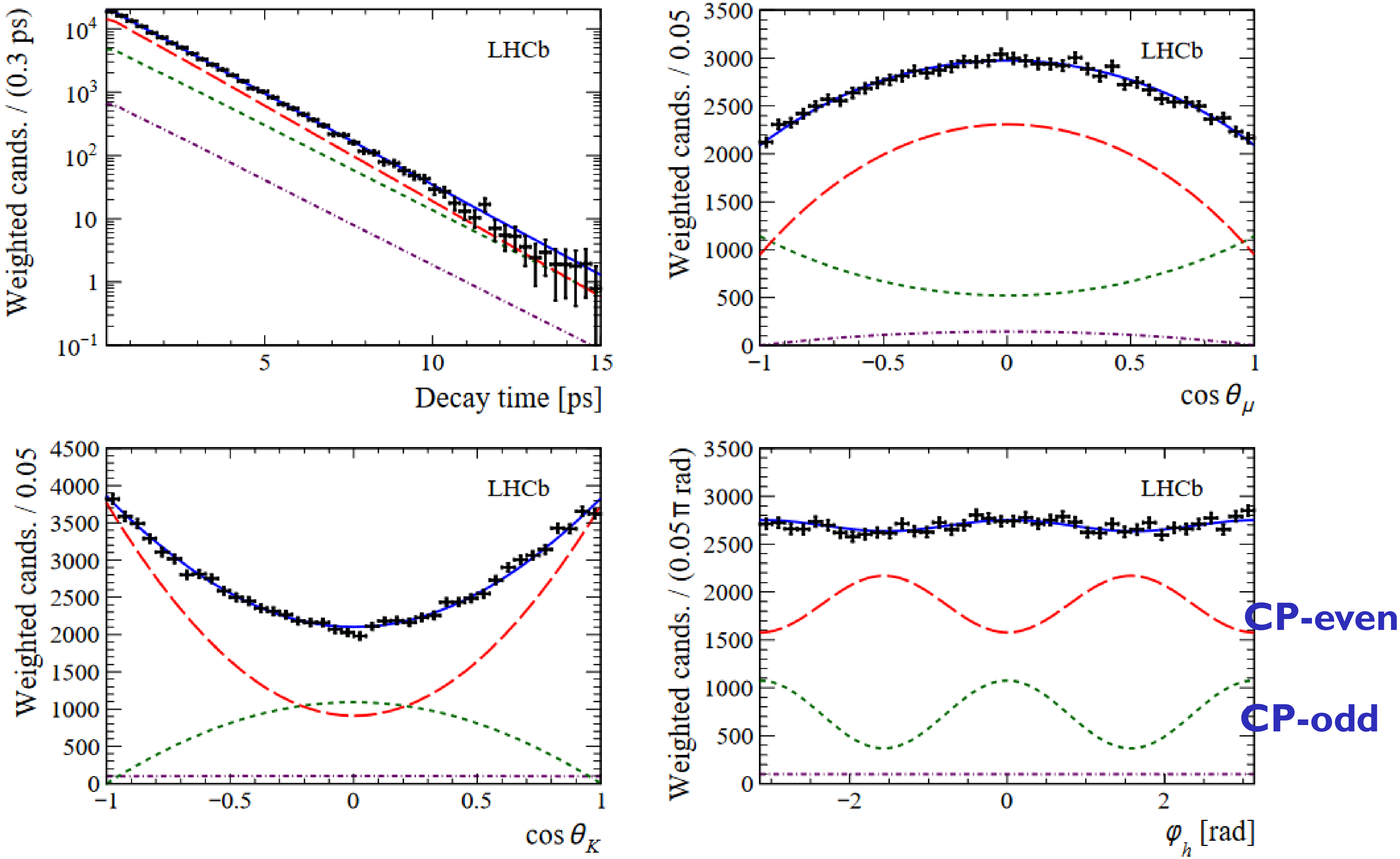


- Good tagging performance of B_s & $\overline{B}_s$ is important

Category	$\epsilon_{tag}(\%)$	D^2	$\epsilon_{tag}D^2(\%)$
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

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

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



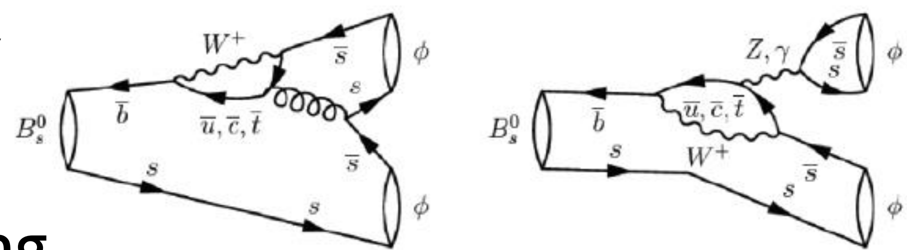
Measurement of CP violation in $B_s \to \phi\,\phi$

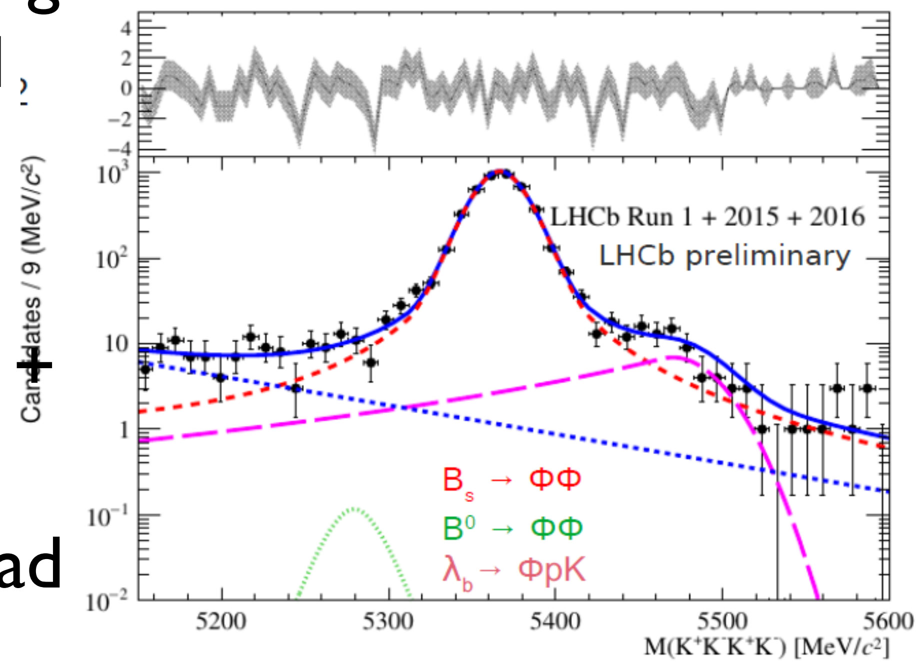
LHCb-PAPER-2019-019

- Enhanced sensitivity to NP since decay is dominated by penguin loop
- SM prediction of CP violating phase is small < 20 mrad

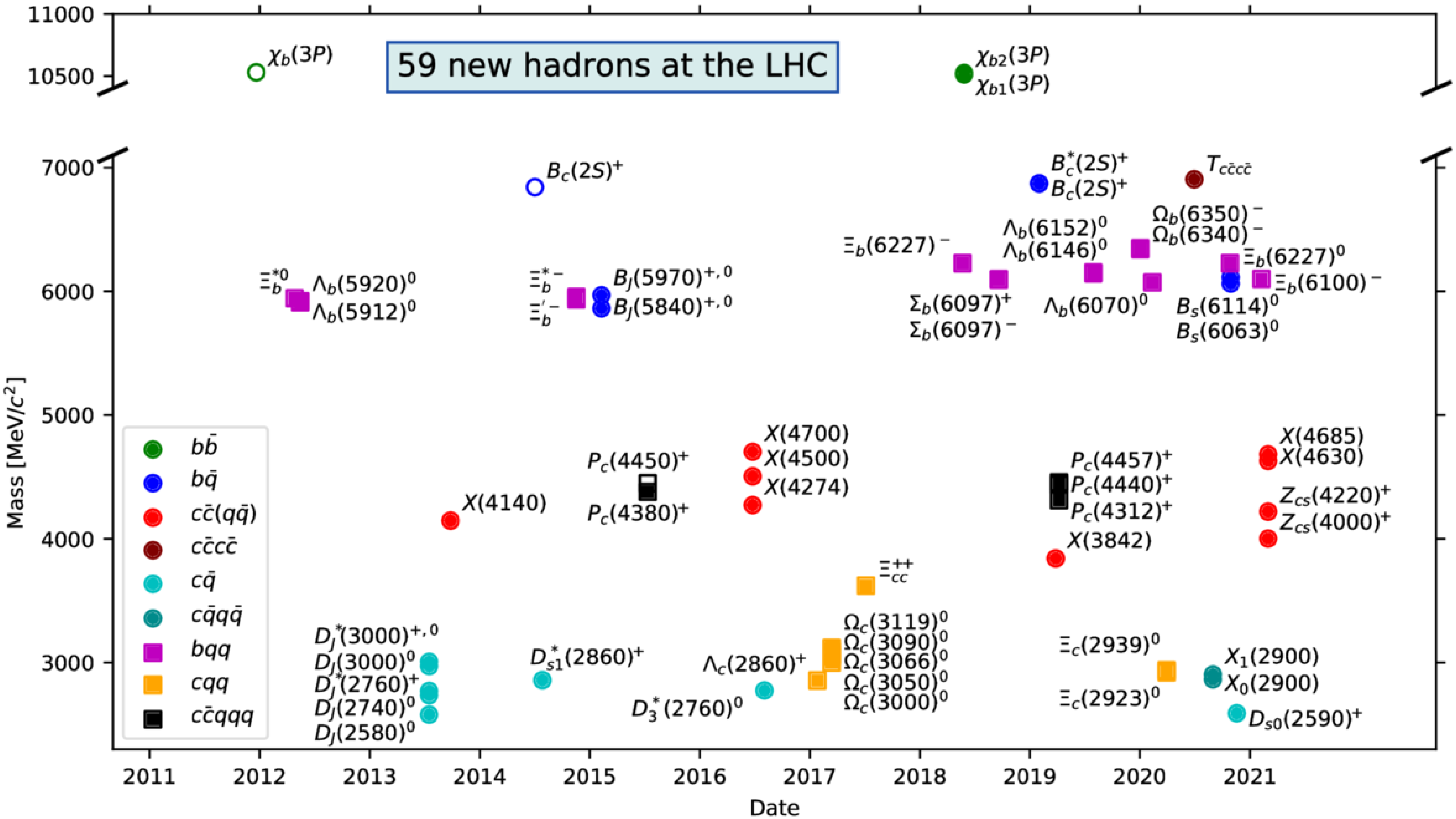
arXiv:0810.0249
Phys.Rev.D80:114026,2009

- Perform time-dependent angular analysis, Run1 data + 2 fb^{-1} Run 2
- $|\Phi_{sss}| = -73 \pm 115 \pm 27$ mrad





New hadron discoveries at the LHC



With thanks to Partick Koppenberg