Recent highlights from LHCb

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On behalf of the LHCb Collaboration

Corfu Summer Institute
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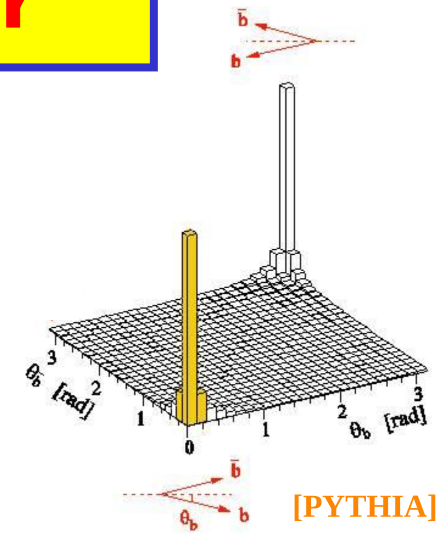
Outline

- General introduction to LHCb
- An update of mixing and CP-violation measurements
  - Unitarity triangle and update on the angle γ
  - Mixing and CP violation in charm
- New measurements in spectroscopy
- Rare decays and anomalies
  - Lepton universality
- The upgraded LHCb detector and outlook
- Summary

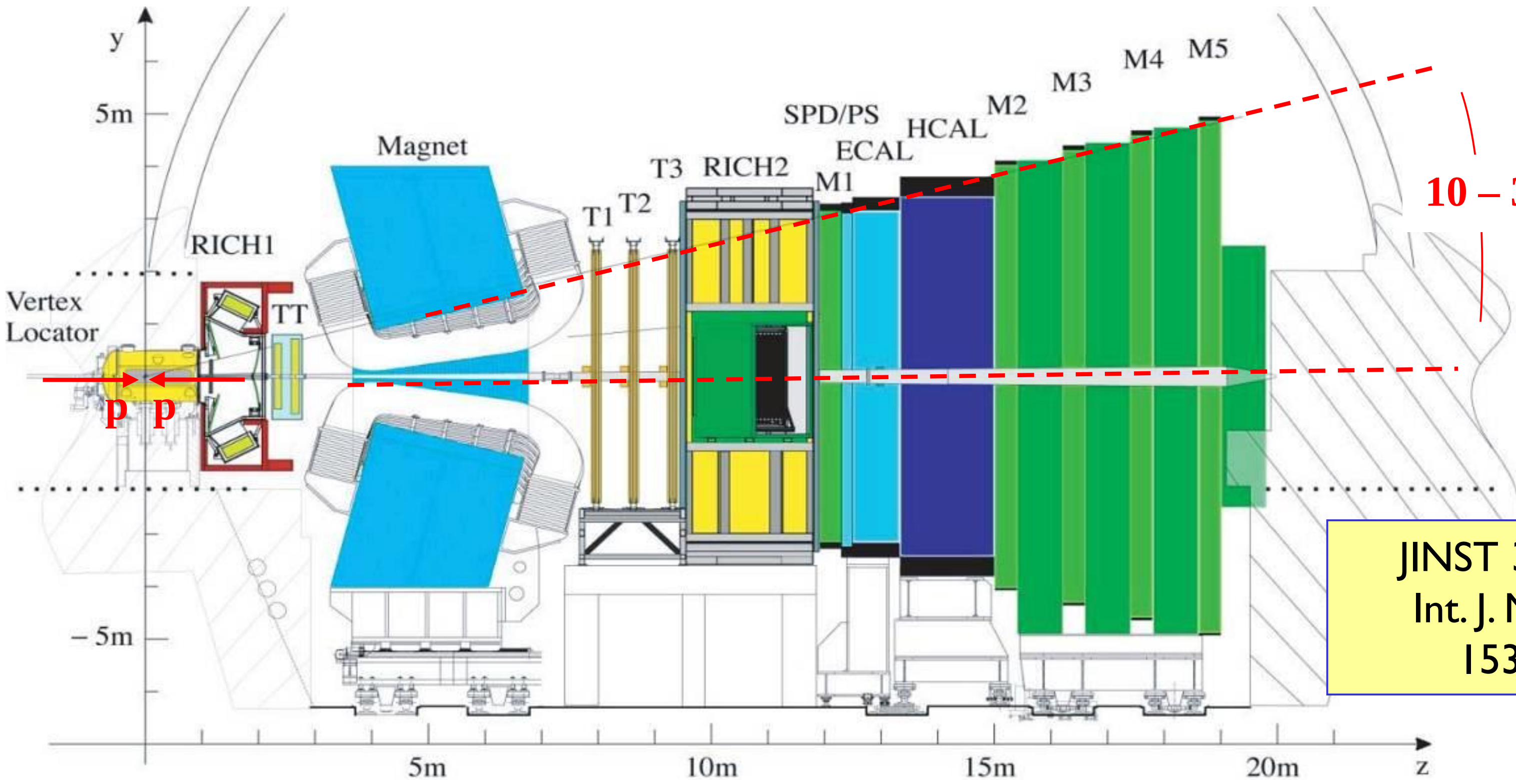
LHCb forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- bb cross-section = 154.3 ± 1.5 ± 14.3 μb at √s = 13 TeV in the LHCb acceptance 2< η < 5

PRL 118, 052002 (2017)



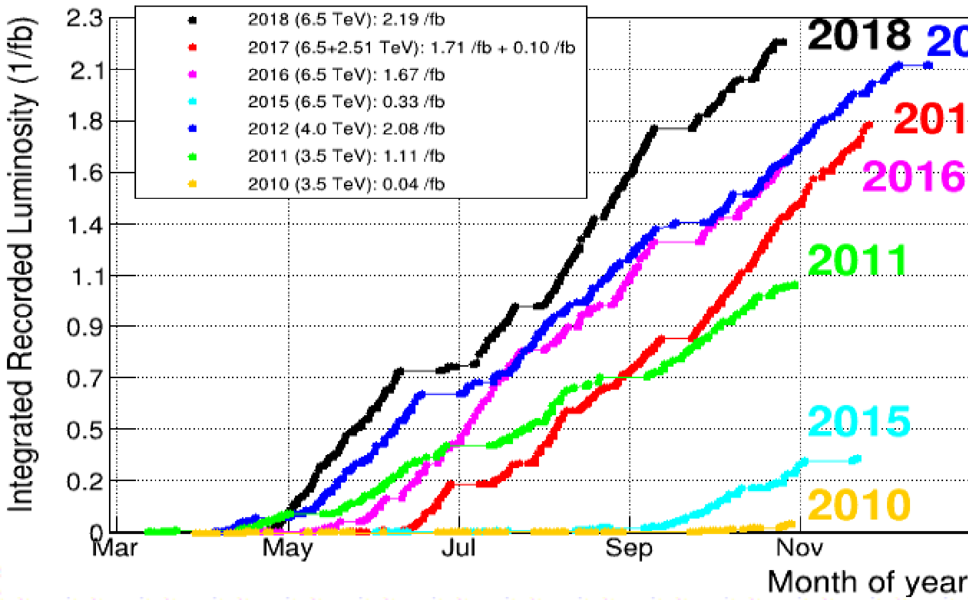
→ O(100,000) $b\bar{b}$ pairs produced/second at LHC Run 1&2 luminosities ($c\bar{c}$ x20 larger)

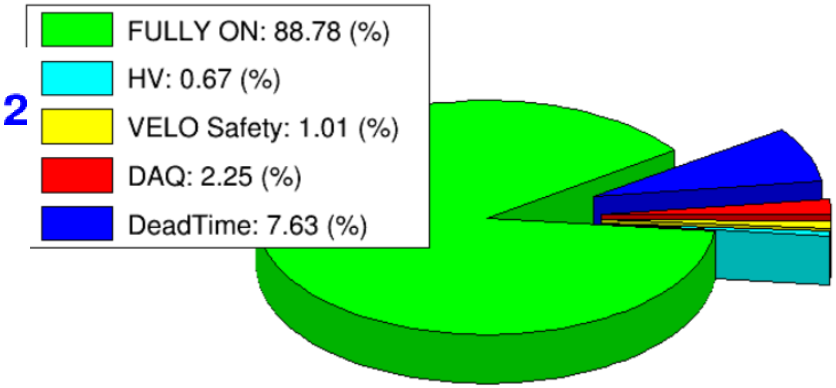


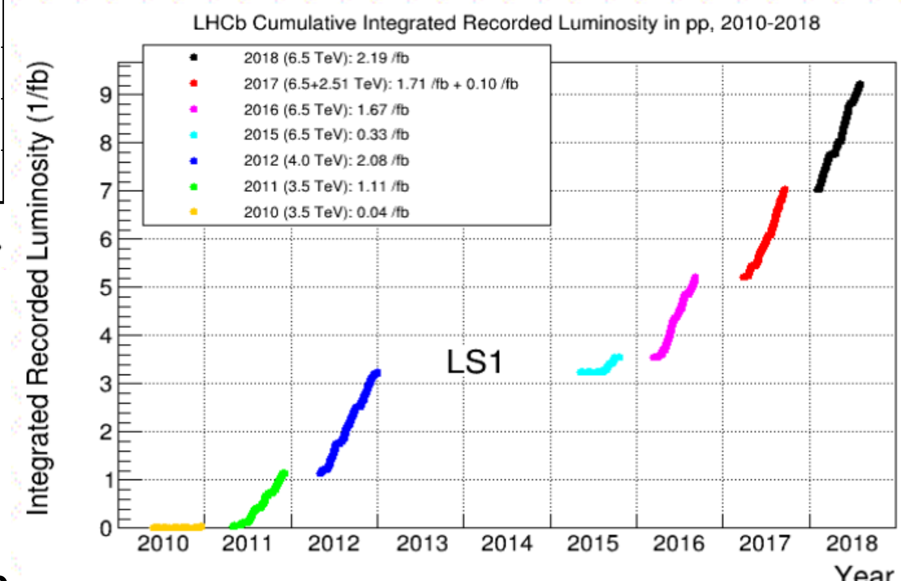
JINST 3:S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

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}







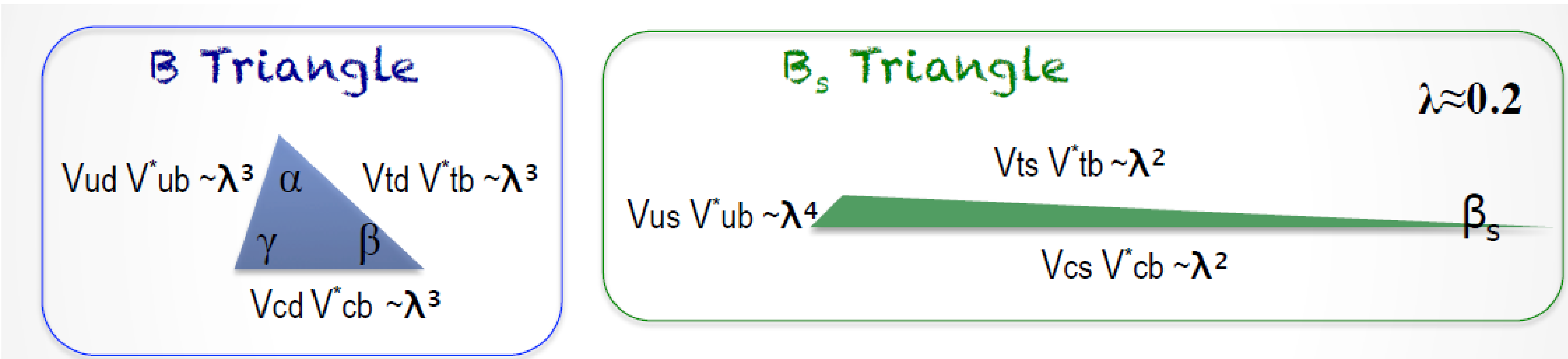
Run 1 & 2
$\mathcal{L}_{int} = 9$ fb^{-1}

CP-violation and mixing in beauty and charm

Unitarity triangles

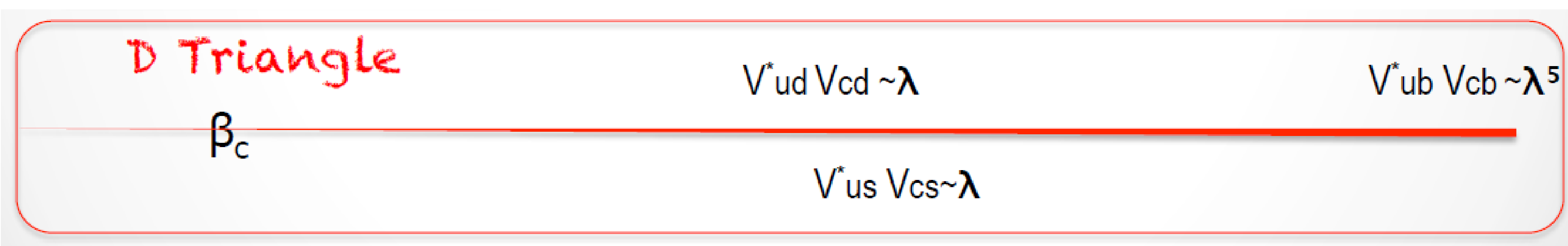
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Beauty system



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

- Charm system



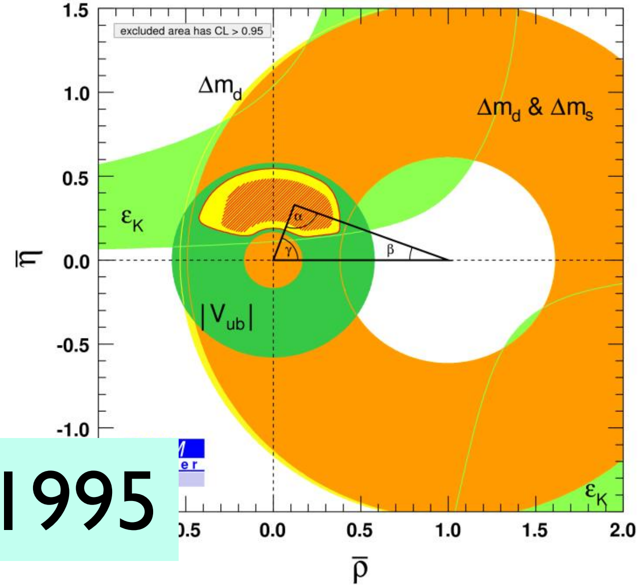
Charm system : angle $\beta_c \sim \lambda^4$

Diagrams from Jolanta Brodzicka

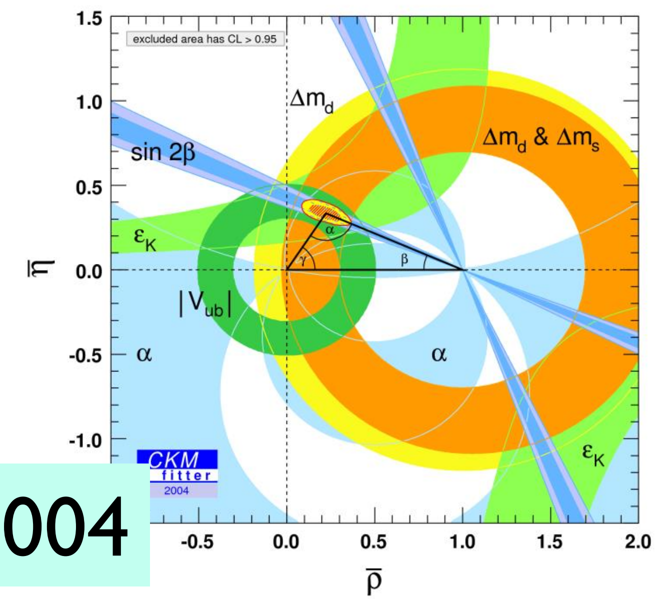
Unitarity Triangle measurements

- Amazing progress in the last 27 years; the SM remains intact, but a whole lot still to learn

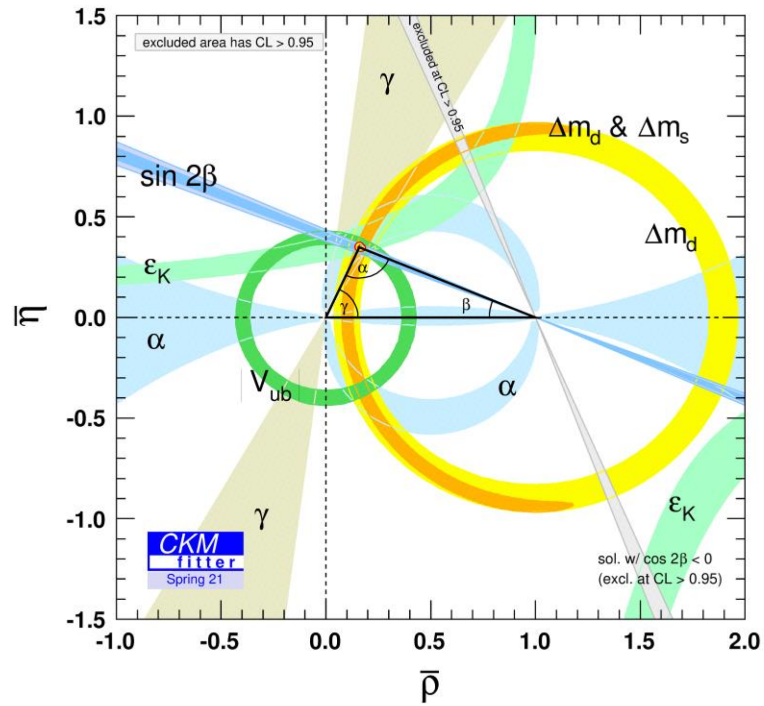
http://ckmfitter.in2p3.fr



1995



2004



Now (dominated by LHCb)

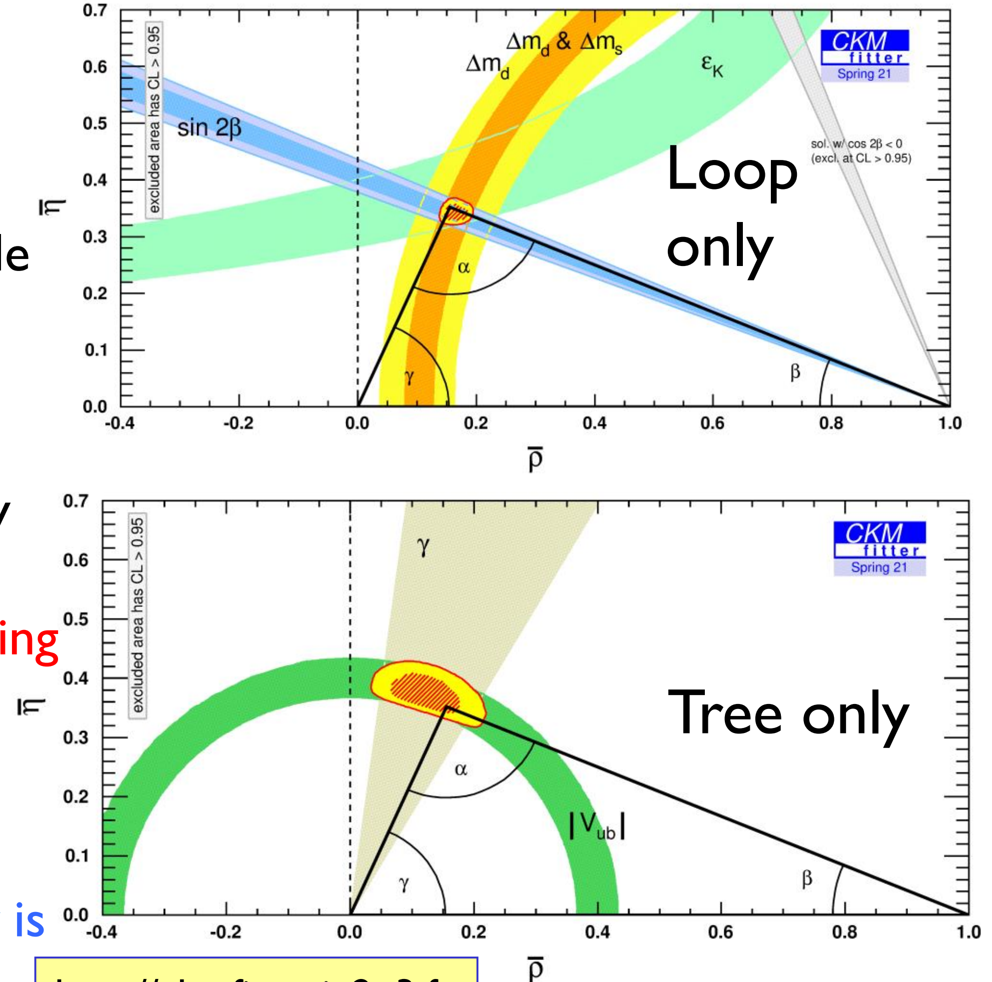
The angle γ (a key measurement)

- 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 (assuming no significant New Physics in tree decays)
- γ prediction in SM theoretically very clean JHEP 01 (2014) 051, PRD 92(3):033002 (2015)
- Determination from CKM fit excluding all direct measurements of γ

$$\gamma = (65.5^{+1.1}_{-2.7})^{\circ}$$

- Reaching degree level precision on γ is crucial

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



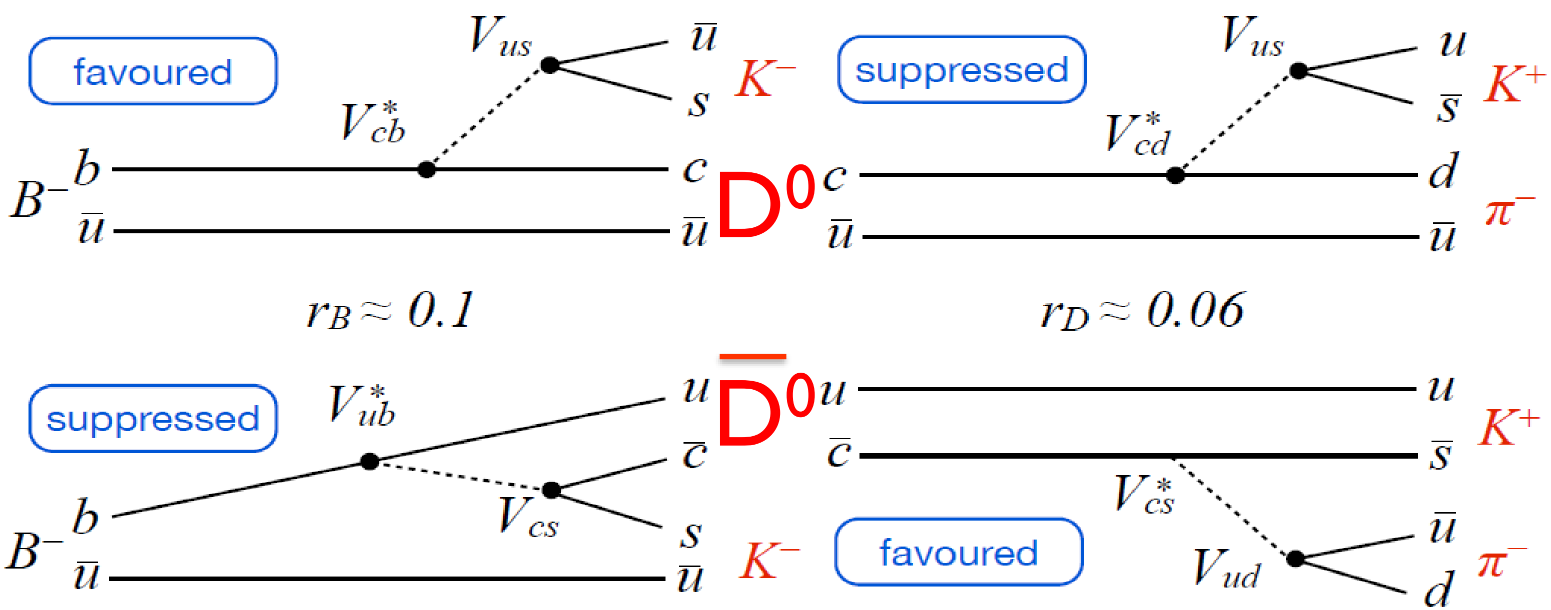
http://ckmfitter.in2p3.fr

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

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

(and charge conjugate mode $B^+ \rightarrow \overline{D}^0 K^+$) provides most precise measurement of γ

- 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 $\overline{D}^0$



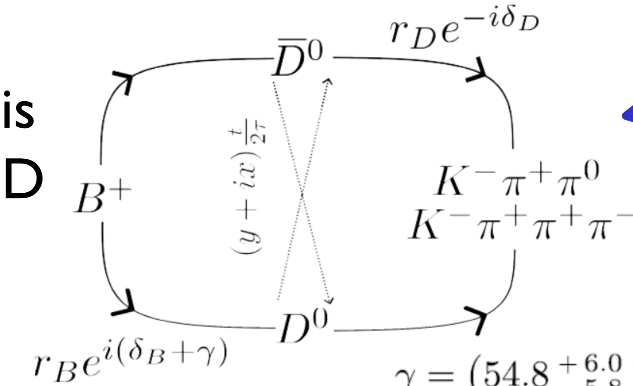
- Branching fraction for favoured B decay only ~10^{-4}
  - Measurements require high statistics

New : γ from $B^{\pm} \to D\,[K^-\pi^+\pi^+\pi^-]\,h^{\pm}$ decays

- Large benefits from binned analysis
- Measure observables in 4 bins of D decay phase space

arXiv: 1909.10196

- Use full Run 1 and Run 2 dataset
- Largest CP violation observed

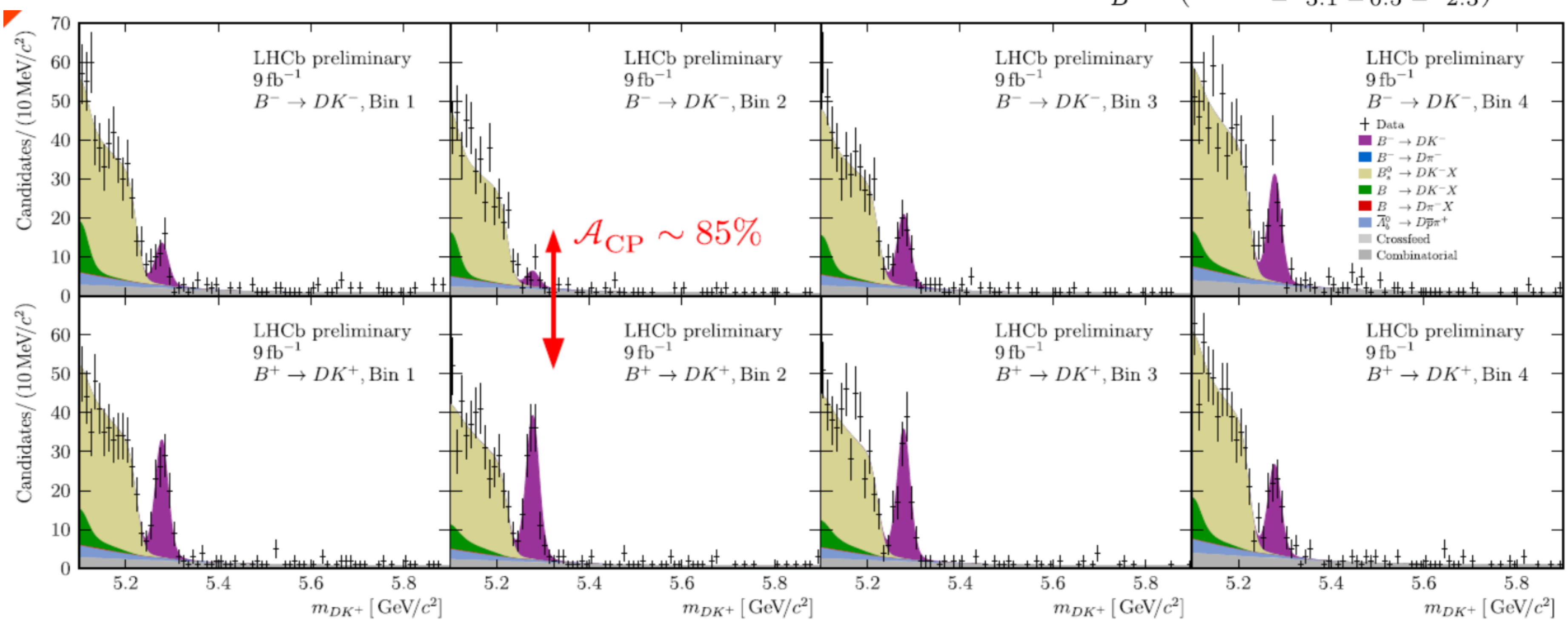


NEW

$$\gamma = (54.8\,^{+6.0}_{-5.8}\,^{+0.6}_{-0.6}\,^{+6.7}_{-4.3})^\circ$$

$$\delta_B^K = (134.6\,^{+6.0}_{-6.0}\,^{+0.7}_{-0.7}\,^{+8.6}_{-8.7})^\circ$$

$$r_B^K = (94.6\,^{+3.1}_{-3.1}\,^{+0.5}_{-0.5}\,^{+3.0}_{-2.3}) \times 10^{-3}$$



New : γ from $B^{\pm} \to D\,[h^{\pm} h'^{\mp} \pi^0]\, h^{\pm}$ decays

arXiv: 2112.10617

NEW

- π^0 reconstruction is challenging at LHCb
- Measure observables in 3 D decay channels

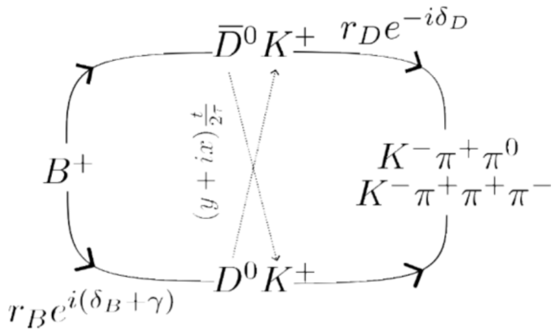
  – $D \to K^{\pm}\pi^{\mp}\pi^0$

  – $D \to \pi^+\pi^-\pi^0$

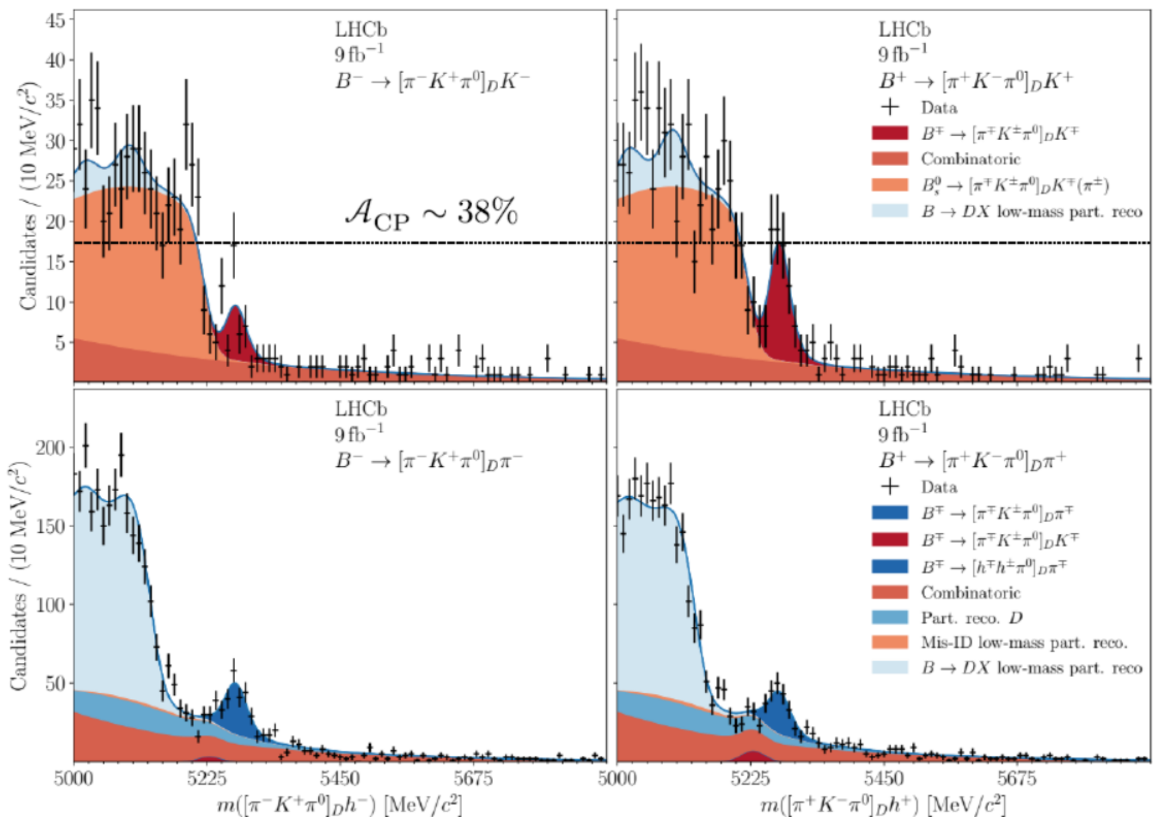
  – $D \to K^+K^-\pi^0$

and two B decays $B^+ \to DK^+$ & $B^+ \to D\pi^+$

- Gives total of 11 CP violating observables
- Use full Run 1 and Run 2 dataset



$$\gamma = (56^{+24}_{-19})^\circ,$$
$$\delta_B = (122^{+19}_{-23})^\circ,$$
$$r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$$



LHCb combination from different modes

JHEP 12 (2021) 141

- The most recent combination includes many decay modes :

B decay	D decay	Data set
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	Run 1
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&15/16
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1&15/16
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&15/16
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1&15/16
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	Run 1
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	Run 1
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	Run 1&2

D decay	Observable(s)	Data set
$D^0 \to h^+h^-$	ΔA_{CP}	Run 1&2
$D^0 \to h^+h^-$	y_{CP}	Run 1
$D^0 \to h^+h^-$	ΔY	Run 1&2
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1&15/16
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x, y	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	Run 1&2

LHCb combination from the different modes

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

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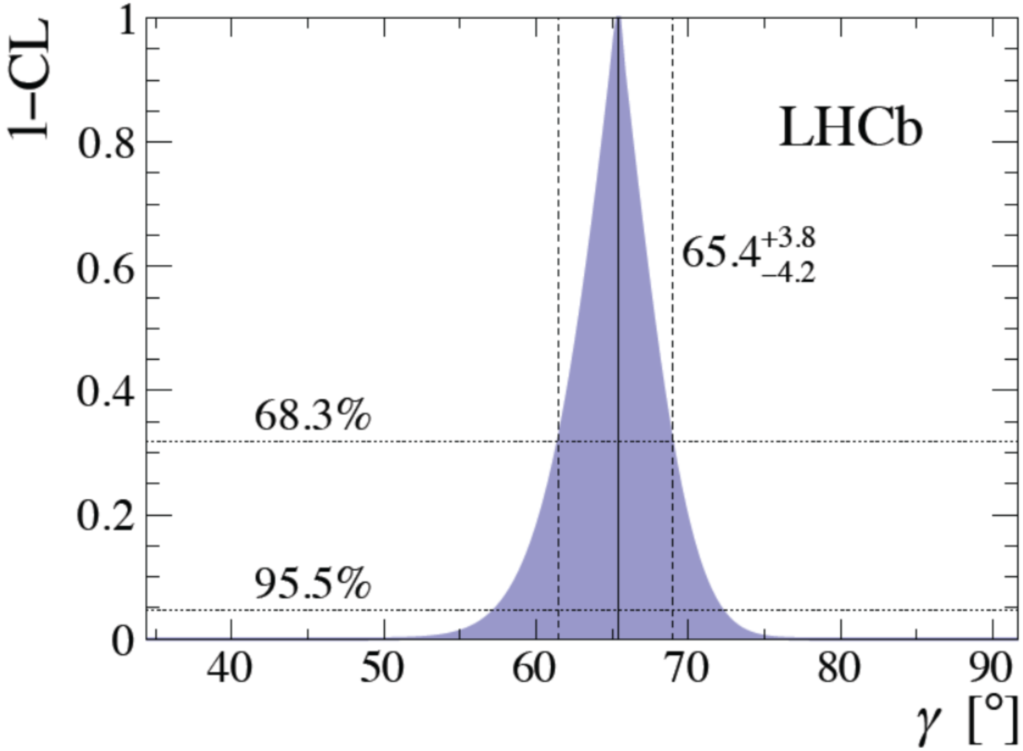

LHCb dominates world average

Reminder of indirect constraint, mainly from loops

$\gamma = (65.5^{+1.1}_{-2.7})^{o}$

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

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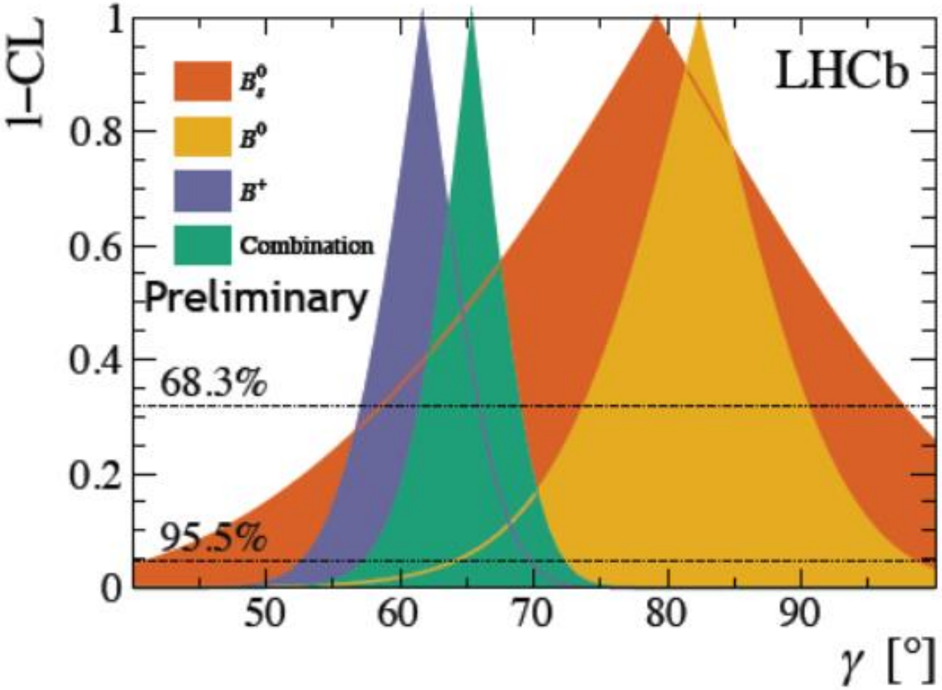
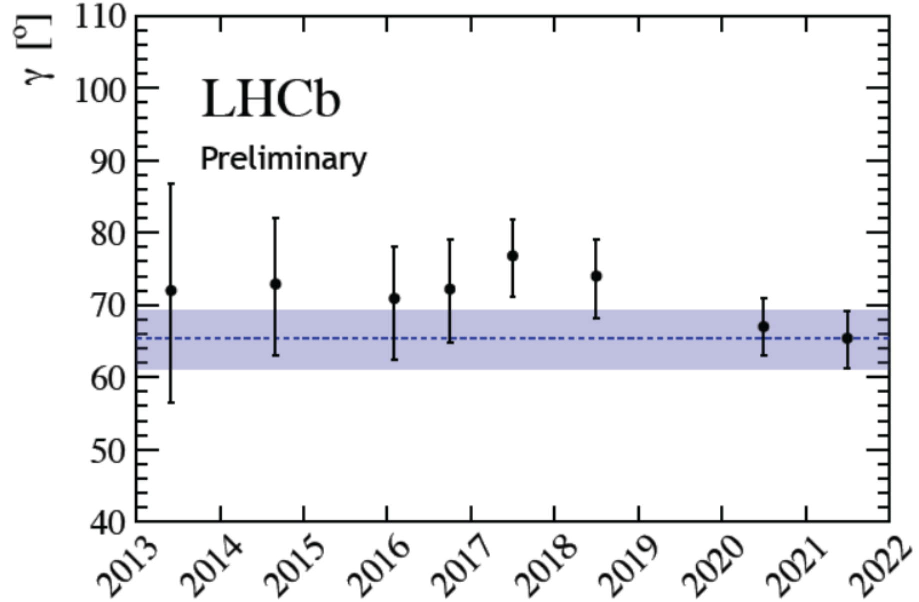


$$\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$$

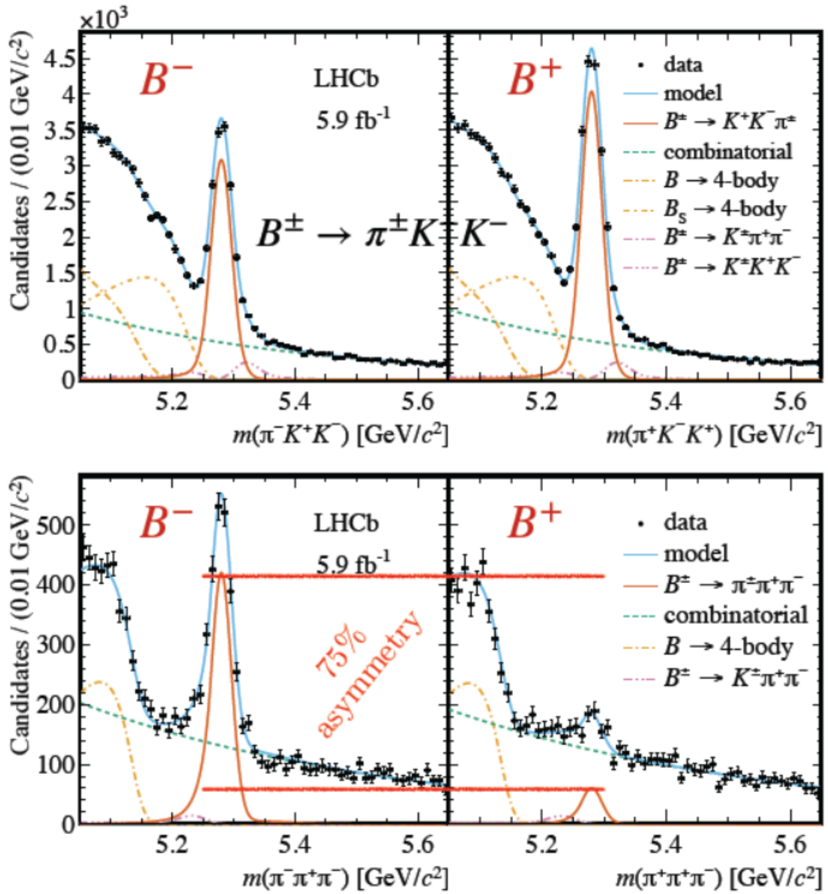


CP violation in $B^\pm \to h^\pm h^+ h^-$

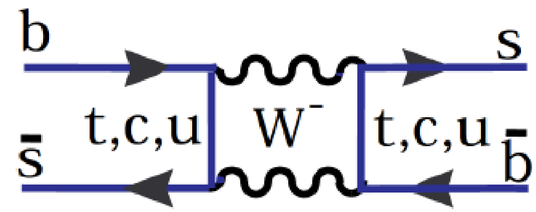
NEW

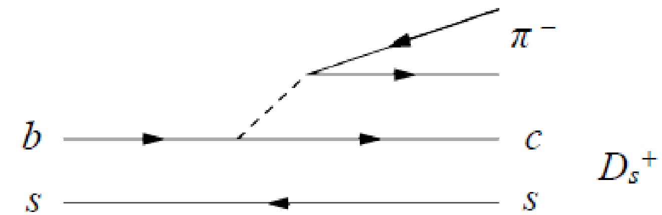
LHCb-PAPER-2021-049/050

- CPV observed in four decay channels:
  - $B^\pm \to K^\pm\pi^+\pi^-$, $B^\pm \to K^\pm K^+K^-$
    $B^\pm \to \pi^\pm\pi^+\pi^-$, $B^\pm \to \pi^\pm K^+K^-$
- Large and interesting localised CP-asymmetries observed
- The biggest difference is observed for the $B^\pm\to\pi^\pm \pi^+\pi^-$ and $B^\pm\to\pi^\pm K^+K^-$ decays (14 σ)
- However the CP asymmetry of $B^\pm\to K^\pm\pi^+\pi^-$ decays compatible with zero
- Hard to know what this all means. Possible information about the relation between decay channels eg $\pi\pi \leftrightarrow KK$ rescattering



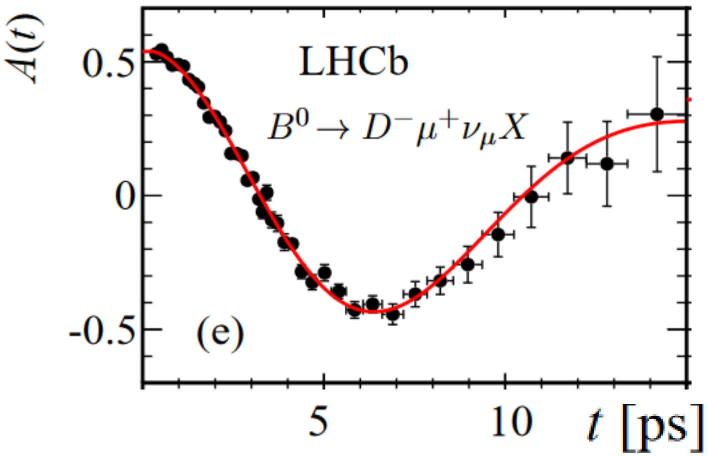
$B_{(s)}$ mixing at LHCb





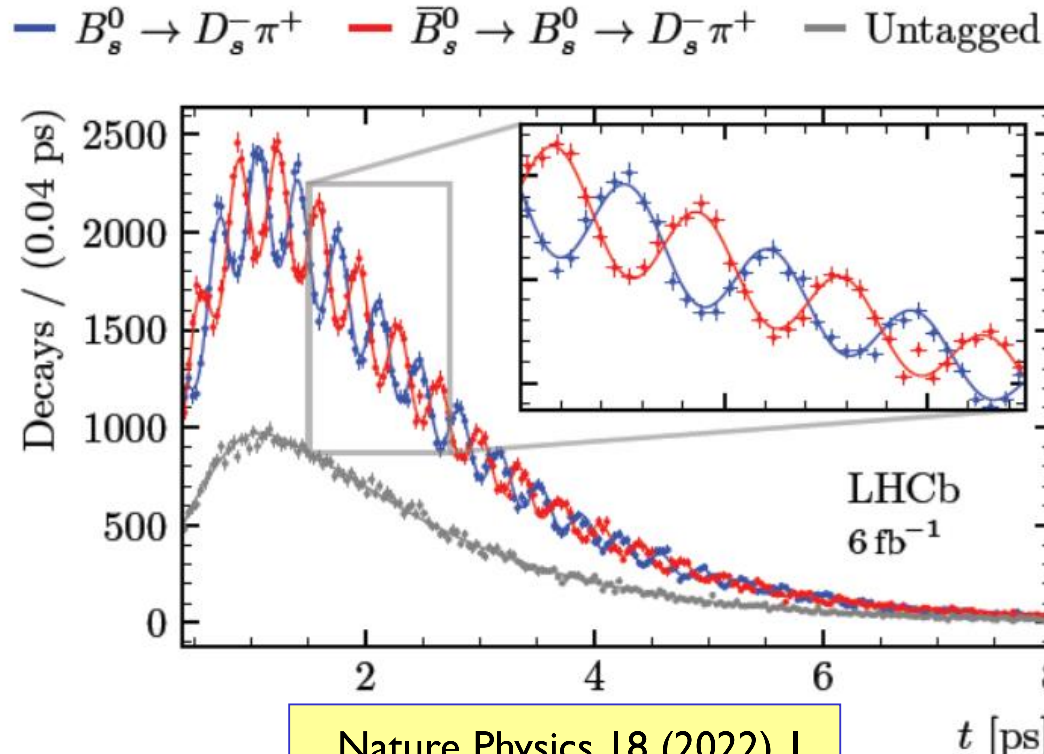
Previous Workshop

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



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

Eur. Phys. J. C76 (2016) 412



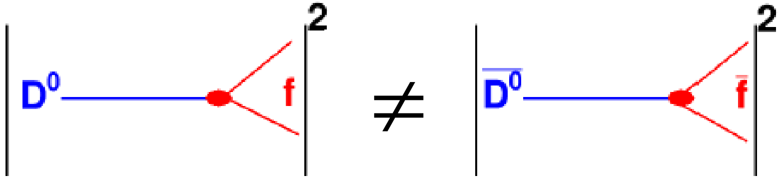
Nature Physics 18 (2022) 1

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

Mixing measurements dominated by LHCb

CP violation in charm

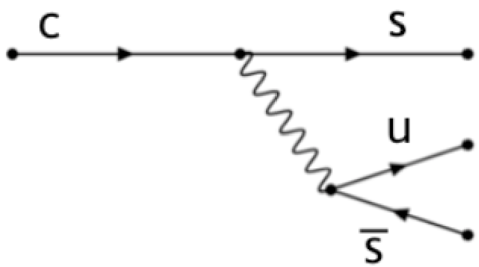
- Direct CP violation



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



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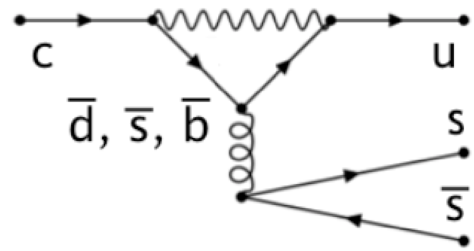


- SM prediction is very small $O(10^{-4}) \to O(10^{-3})$

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 Run1 and Run 2 data-set

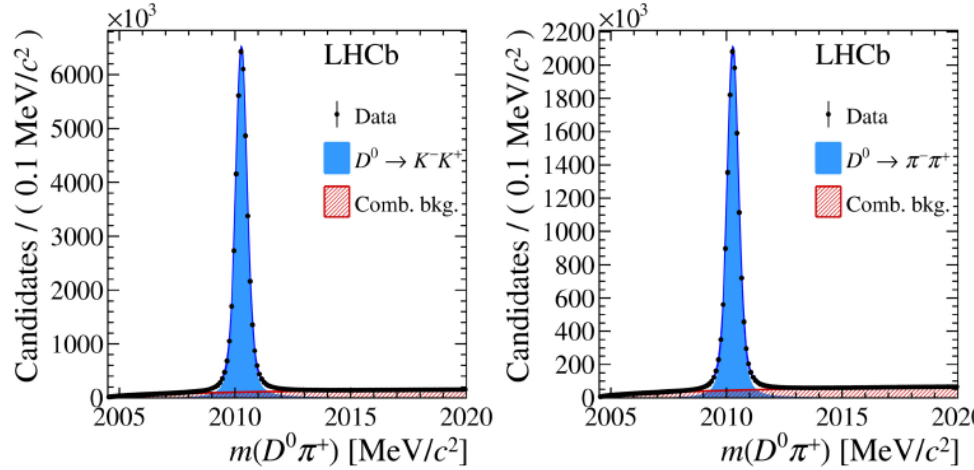
Phys. Rev. Lett. 122 (2019) 211803

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

- The first measurement of CPV in the charm system (5.3σ) !
- However this doesn't pin down the channel which the CP violation is in

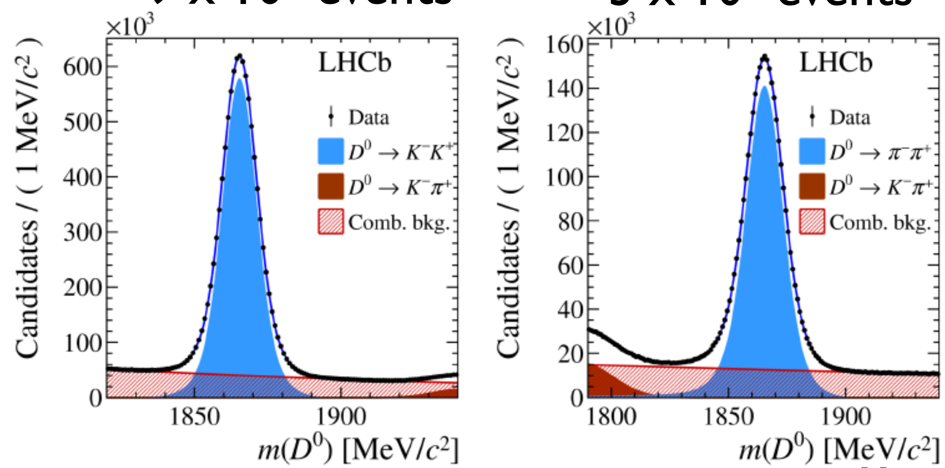
Prompt

44×10^6 events — 14×10^6 events



Semi-leptonic

9×10^6 events — 3×10^6 events



CP violation in a *specific* charm hadron decay

LHCb-PAPER-2022-024 (in preparation)

NEW

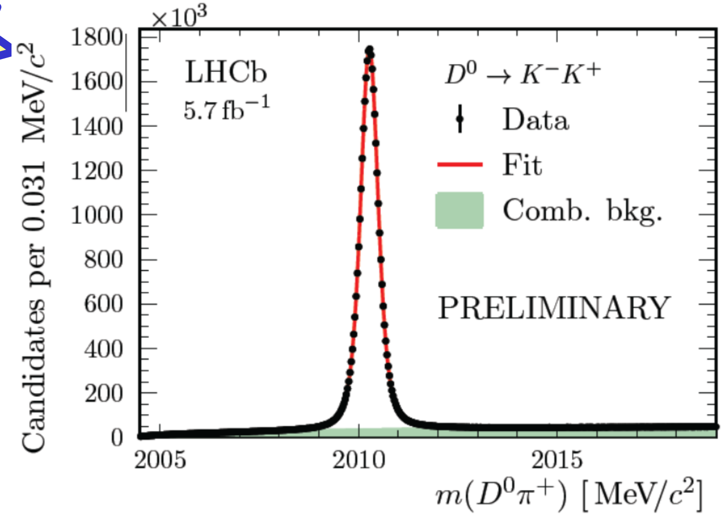
- New measurement of $A_{CP}(K^-K^+)$:

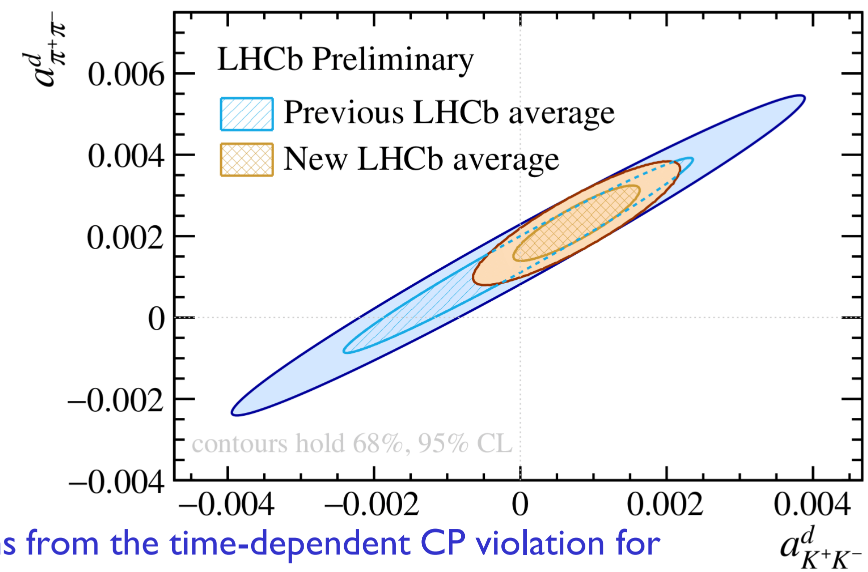
$$A_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

then determine the direct CP asymmetries in $\pi^-\pi^+$ from ΔA_{CP}

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4} \quad *$$

- First evidence in a single channel (3.8σ in $D^0 \to \pi^-\pi^+$) for direct CP violation (1.4σ in $D^0 \to K^-K^+$)
- Yet unclear if consistent with SM or new dynamics in charm decays





* An aside : The A_{CP}'s are time-integrated, but contributions from the time-dependent CP violation for charm mixing have been subtracted in $a^d_{K^-K^+}$ and $a^d_{\pi^-\pi^+}$.

D^0 mixing parameters

- Mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$
- $x = (m_1 - m_2)/\Gamma$; $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, $\phi = \arg(q/p)$

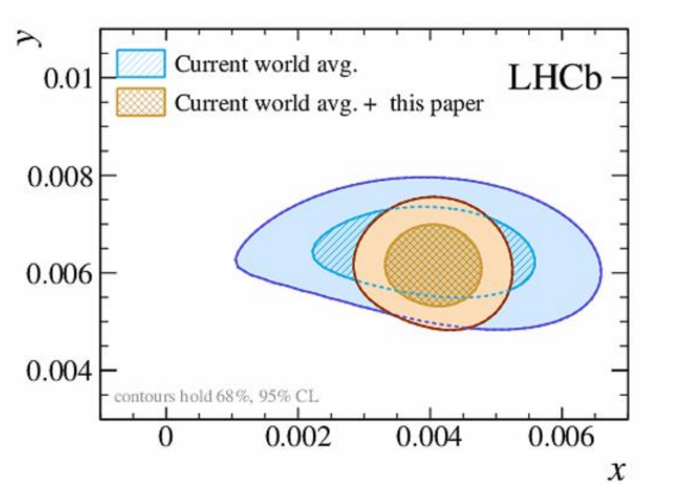
  Up to 2021, mixing parameters were measured only at ~3σ (HFLAV)

Recall from previous Workshop

- Analysis of tagged $\overset{(-)}{D}{}^0 \to K_S^0\, \pi^+ \pi^-$ decays
- First observation with a significance of more than 7 standard deviations of the mass difference between mass eigenstates $|D_{1,2}\rangle$

PRL127 (2021) 111801

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



$m_1 - m_2 = 6.4 \times 10^{-6}$ eV = 1×10^{-38} g = 0.00000000000000000000000000000000000001 grams !!

Charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$

NEW

PRD 105 (2022) 092013

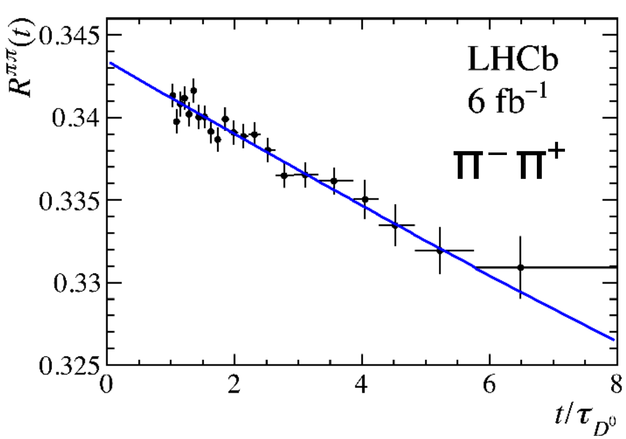
- Study the D^0 meson decays into K^-K^+, $\pi^-\pi^+$ and $K^-\pi^+$
- The decay $D^0 \to K^-\pi^+$ is a CP-mixed state with $\tau(D^0 \to K^-\pi^+) \approx 1/\Gamma$; the decay $D^0 \to f$ is a CP-even state with $\tau(D^0 \to f) < \tau(D^0 \to K^-\pi^+)$

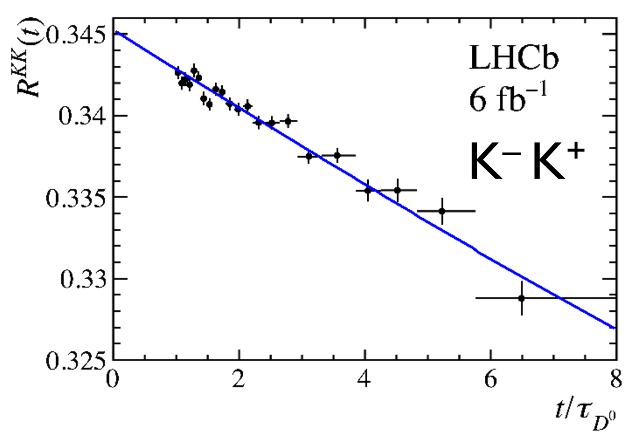
$$f = KK, \pi\pi$$

- Measure ratio :

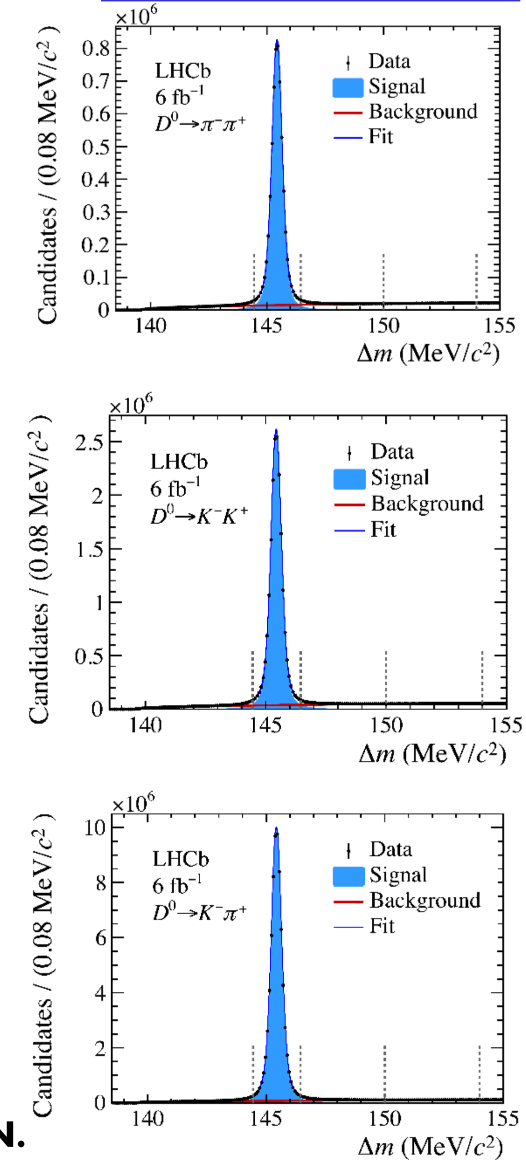
$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^f - y_{CP}^{K\pi})\, t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+,t)}$$

$y_{CP}^{K\pi} \approx -0.4 \times 10^{-3}$





$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$



D^0 mixing parameter $y_{CP} - y_{CP}^{K\pi}$

PRD 105 (2022) 092013

- Measure ratio :

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^f - y_{CP}^{K\pi})\, t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+,t)}$$

$y_{CP}^{K\pi} \approx -0.4 \times 10^{-3}$

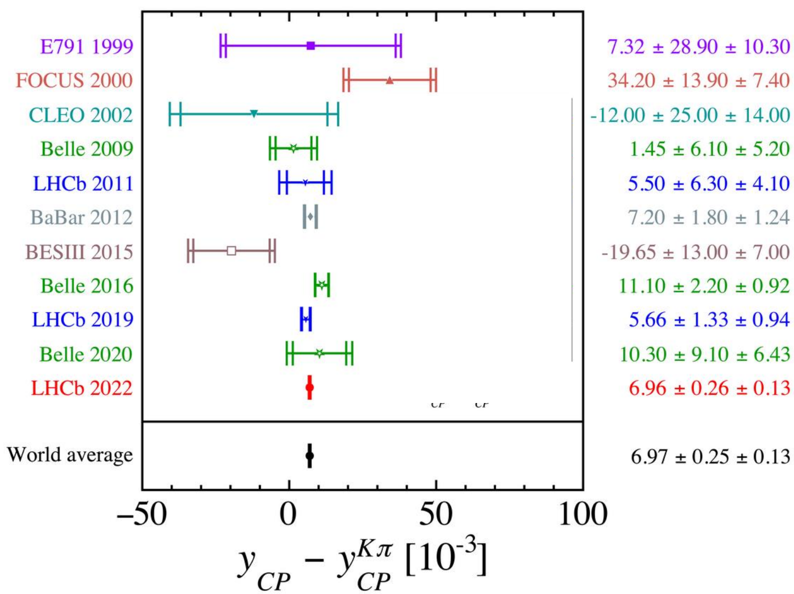
$f = KK, \pi\pi$

$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$

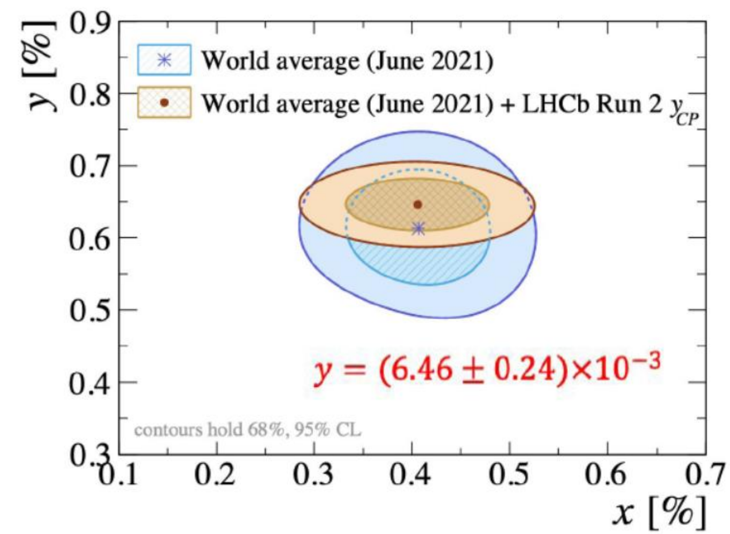
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

- Combine :

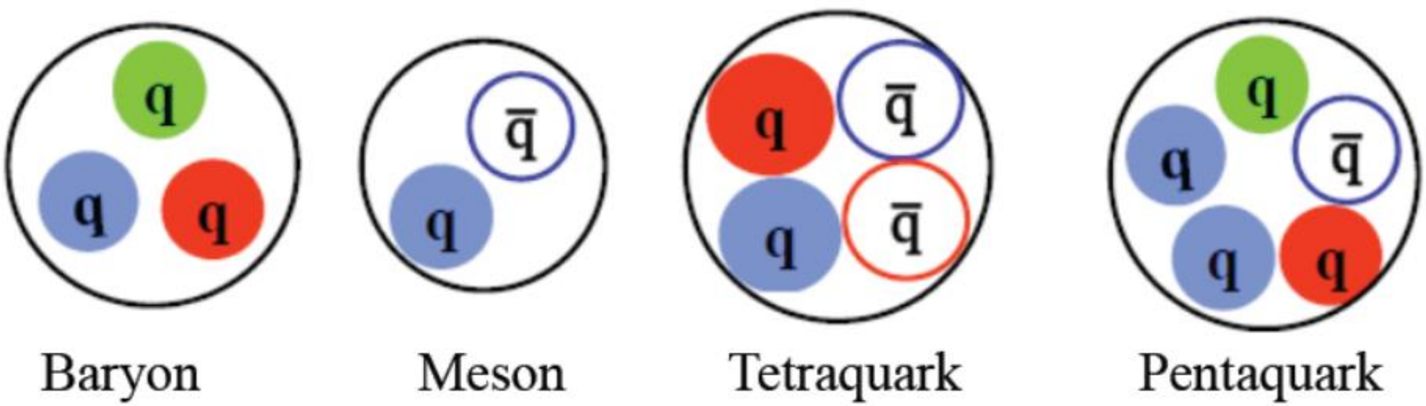
$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$



This measurement is ***four times*** more precise than the previous world average value.



New (exotic) spectroscopy measurements

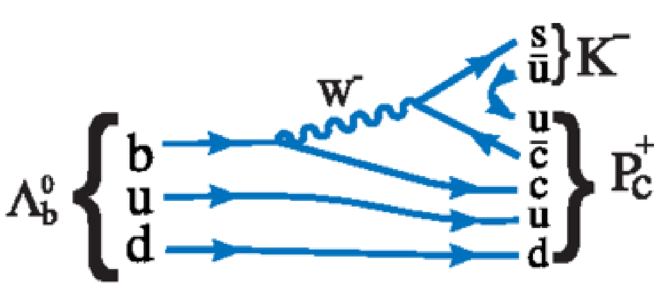


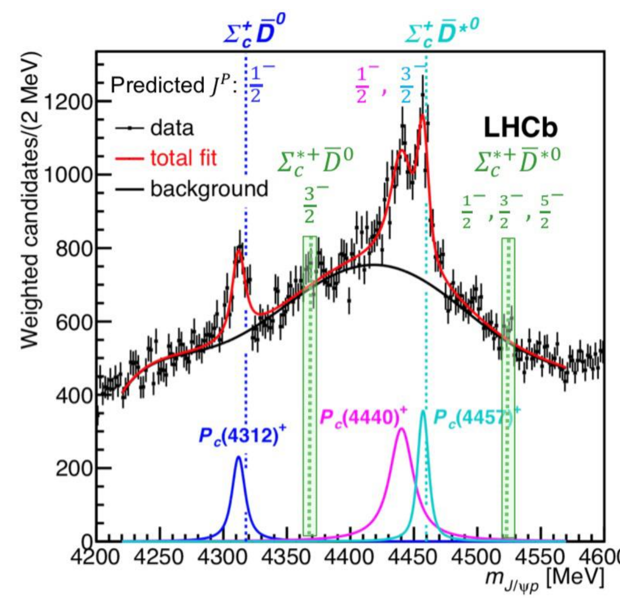
Reminder: tetra/pentaquark discoveries

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

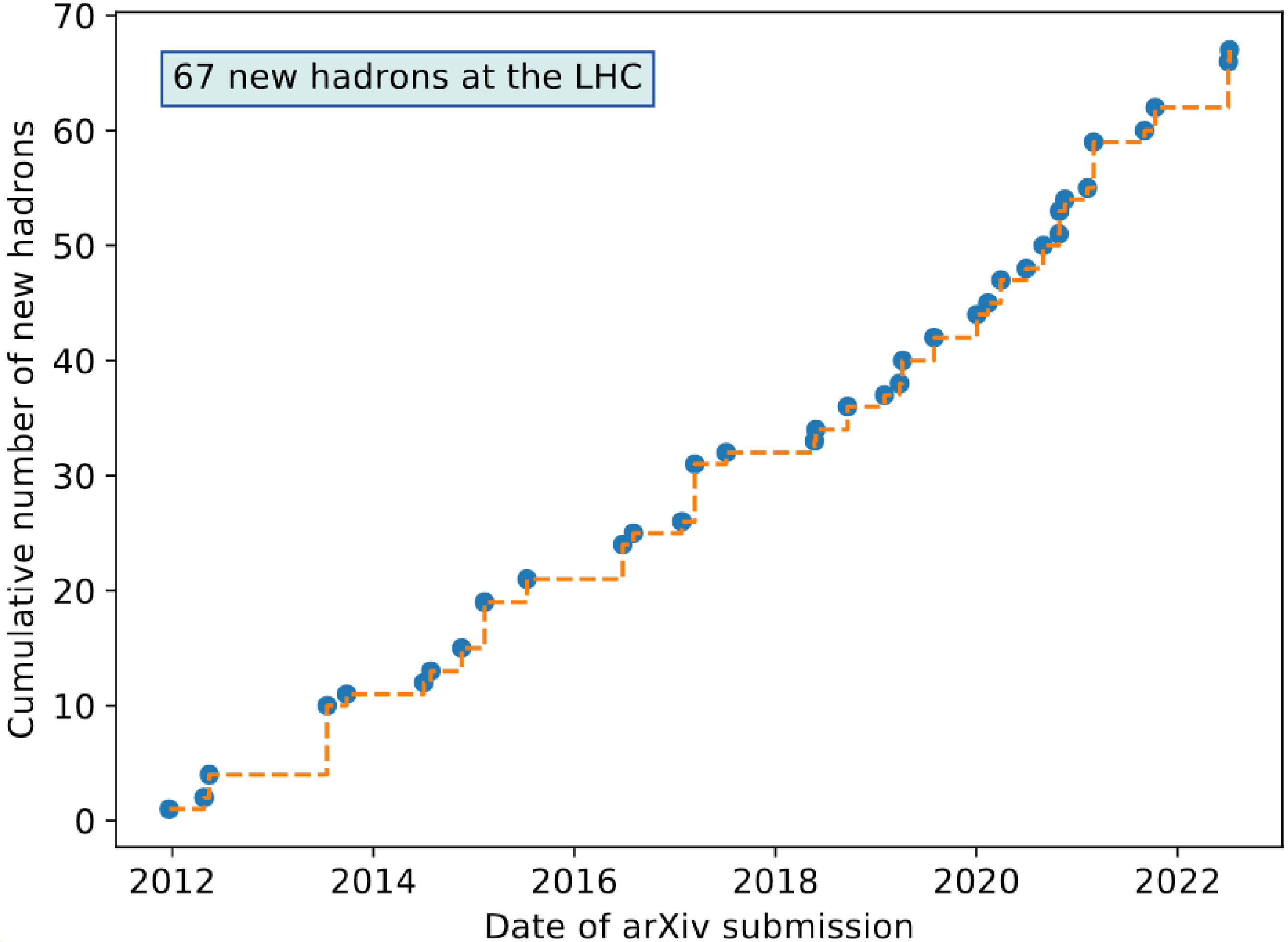
PRL 115 (2015) 072001, PRL 122 (2019) 222001

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





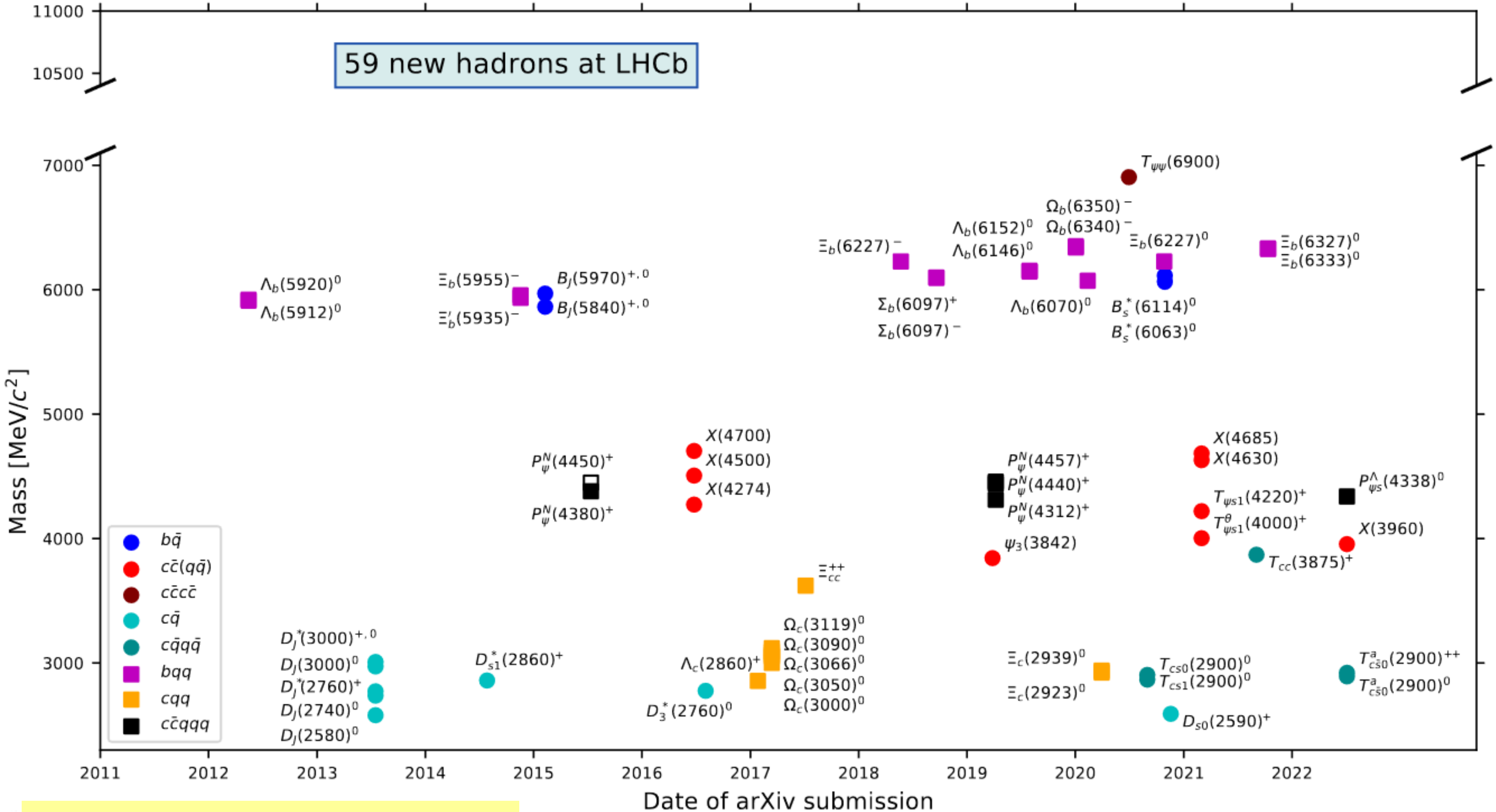
New hadron discoveries at the LHC



With thanks to Patrick Koppenburg

LHCb-FIGURE-2021-001 (update)

New hadron discoveries at LHCb



With thanks to Patrick Koppenburg
LHCb-FIGURE-2021-001 (update)

Need for a new naming scheme (proposal)

T.Gershon/LHCb : arXiv:2206.15233

- Currently no PDG rule for :
  - exotic mesons with s, c, b quantum numbers
  - no extension for pentaquark states
- Idea of the proposal :
  - *T* for tetra, *P* for penta
  - **Superscript**: based on existing symbols, to indicate isospin, parity and G-parity
  - **Subscript**: heavy quark content

T states, zero net S, C, B

(P,G)	$I=0$	$I=1$
$(-,-)$	ω	π
$(-,+)$	η	ρ
$(+,+)$	f	b
$(+,-)$	h	a

T states, non-zero net S, C, B

(P)	$I=0$	$I=\frac{1}{2}$	$I=1$
$(-)$	η	τ	π
$(+)$	f	θ	a

P states

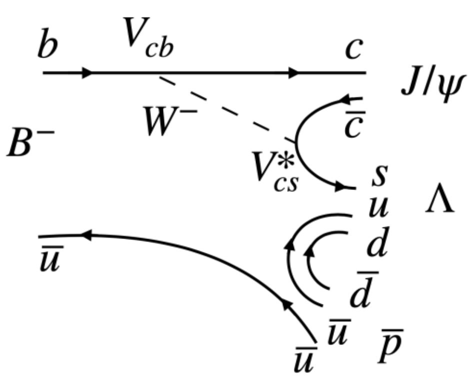
$I=0$	$I=\frac{1}{2}$	$I=1$	$I=\frac{3}{2}$
Λ	N	Σ	Δ

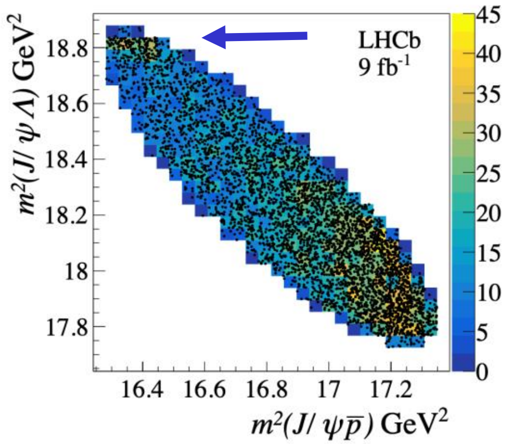
Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G=1^-$	$T_{\psi}(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^{\theta}_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_{\psi}(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^{\Lambda}_{\psi s}(4459)^0$

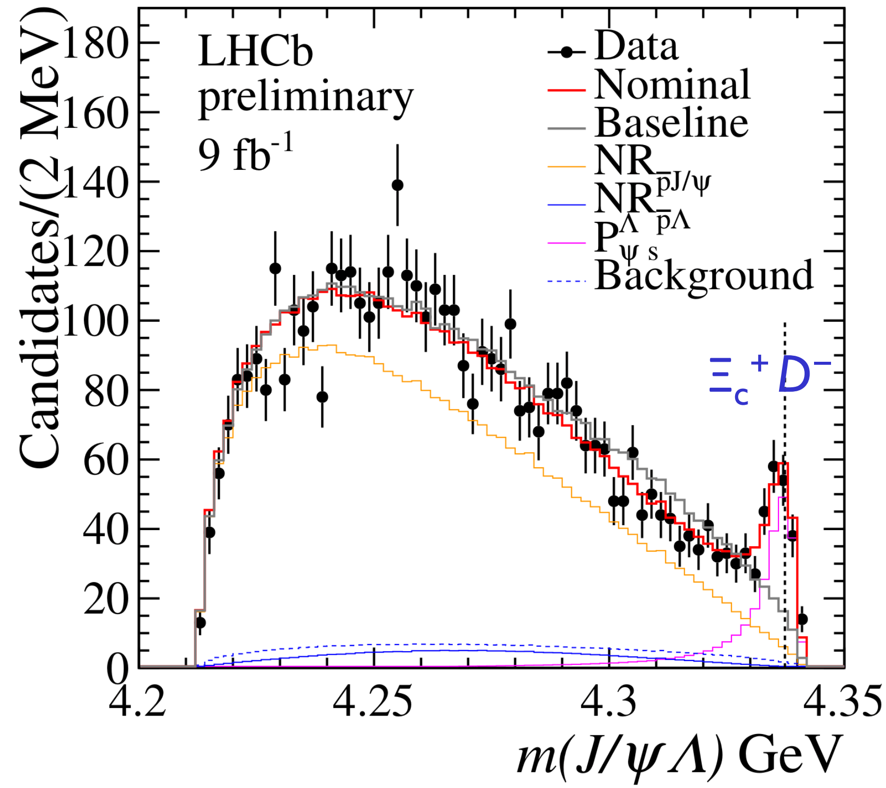
Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda p$ decays

NEW

LHCb-PAPER-2022-031 (in preparation)







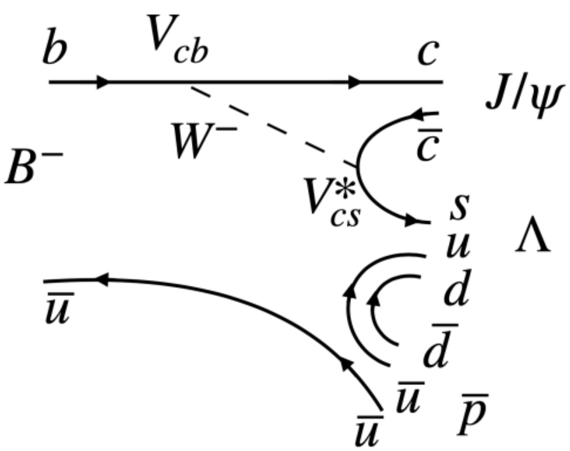
- Study of $B^- \to J/\psi\Lambda\bar{p}$ decays
- Observe $P^{\Lambda}_{\psi s}$ $(J/\psi\Lambda)$ pentaquark with strange quark content $c\bar{c}uds$ close to $\Xi_c^+D^-$ threshold (with $>10\sigma$ significance)
- $m(P^{\Lambda}_{\psi s}(J/\psi\Lambda)) = 4338.2 \pm 0.7 \pm 0.4$ MeV
  $\Gamma(P^{\Lambda}_{\psi s}(J/\psi\Lambda)) = 7.0 \pm 1.2 \pm 1.3$ MeV
- Spin ½ is assigned. $J^P = ½^+$ preferred

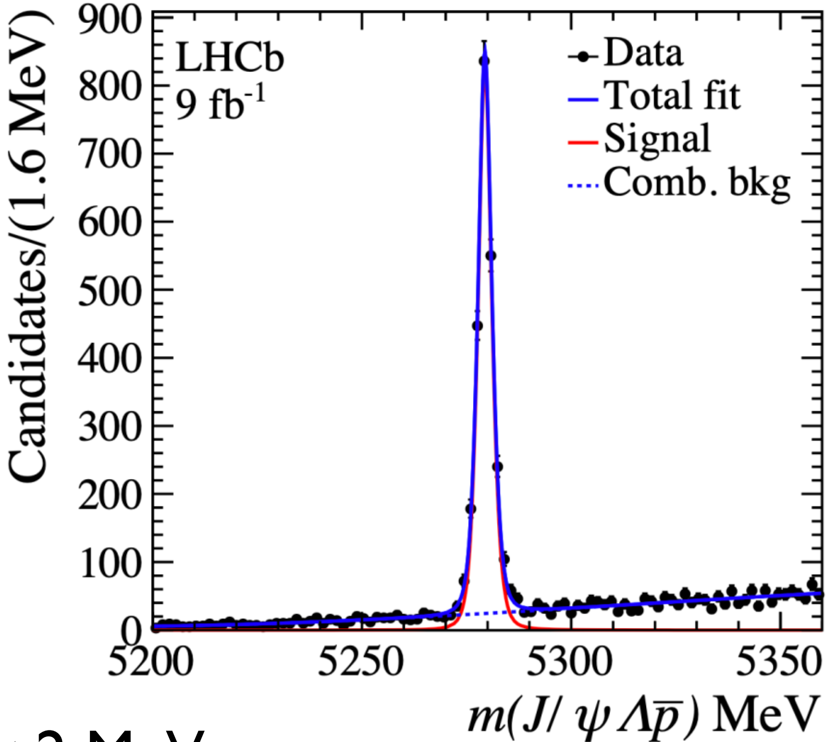
This is the first observation of a strange pentaquark

An interesting aside – B mass measurement

LHCb-PAPER-2022-031 (in preparation)

NEW





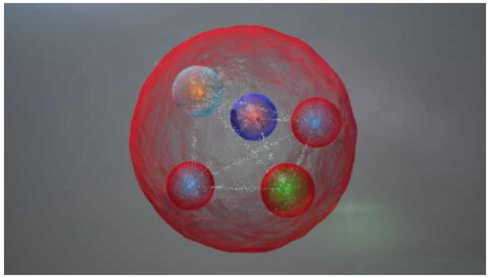
- Small Q-value ≈ 128 MeV.
- Resolution on $m(J/\psi\Lambda\bar{p})$ $\sigma \approx 2$ MeV
- Leads to the most precise B^- mass measurement

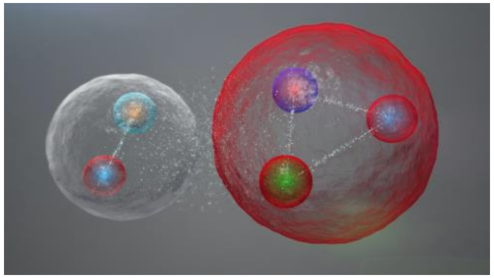
$m(B^-) = 5279.44 \pm 0.05$ (stat) ± 0.07 (syst) MeV

Nature of pentaquarks ?

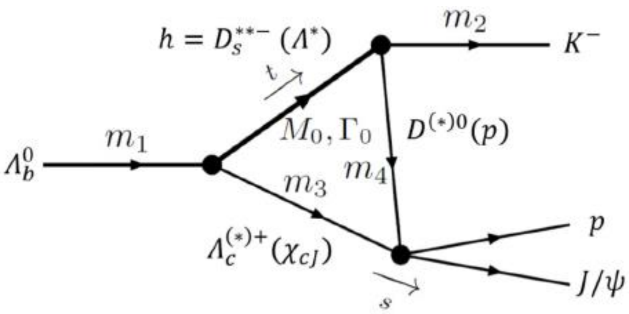
Possible models describing the observed pentaquark states :

- Tightly bounded states?
- Meson-baryon molecules?





- Re-scattering effects?

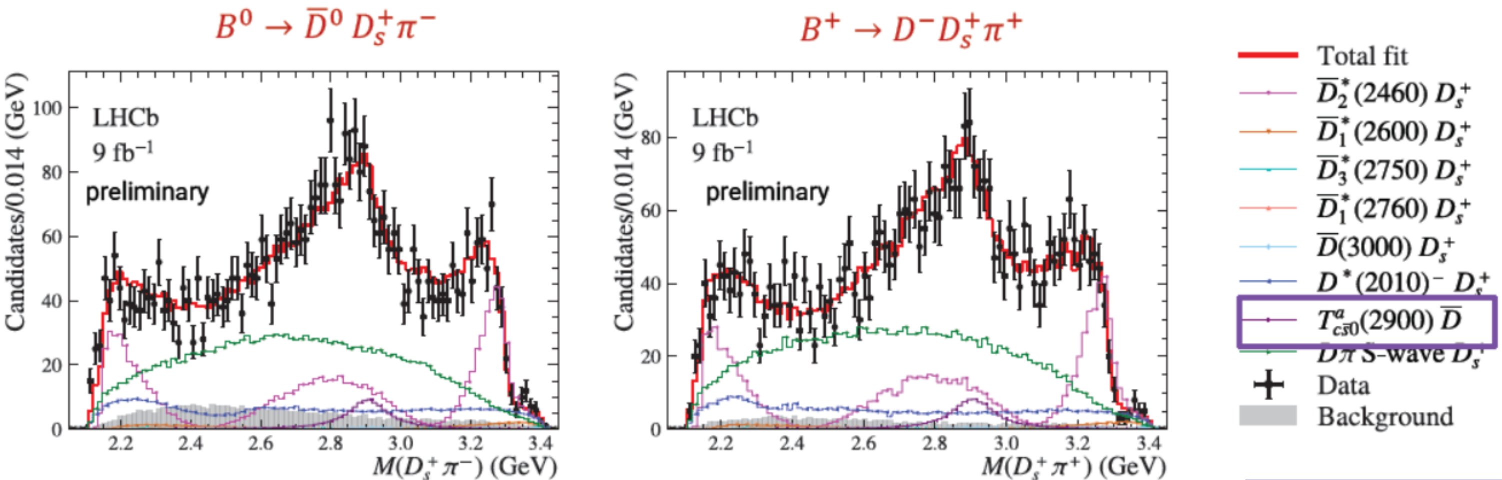


- Molecular-state model likely favoured when bound mesons and baryons form narrow resonances just below mass thresholds
- More work needed

Recent 4-quark states from LHCb

NEW

- Observation of isospin triplet $[c\bar{s}u\bar{d}]$ 4-quark states in $D_s^+\pi^-$ mass spectrum in $B^0 \to \bar{D}^0 D_s^+\pi^-$ and $B^+ \to D^- D_s^+\pi^+$ decays



LHCb-PAPER-2022-026/027 (in preparation)

$$M = 2.908 \pm 0.011 \pm 0.020\,\mathrm{GeV}$$

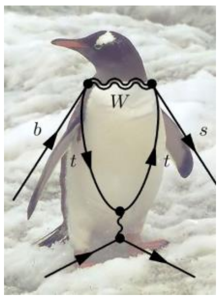
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\mathrm{GeV}$$

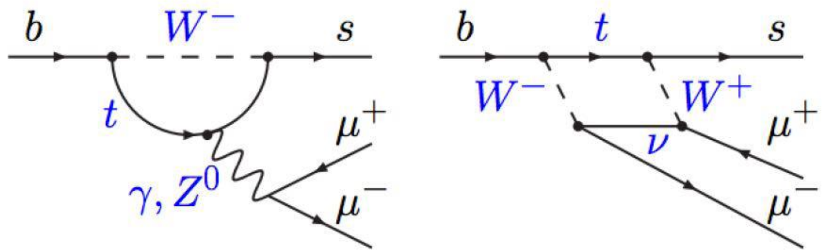
$m(D_s^+\pi^-)$ well described by adding $J^P=0^+$ tetraquark states $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$ in both channels (7.5 σ)

Rare decays and lepton universality

Rare decays : why interesting

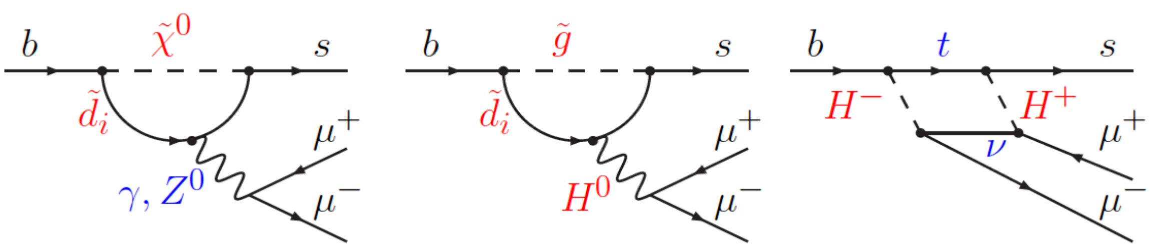
- In the SM, processes involving flavour changing neutral currents (FCNCs) are forbidden at tree level but can occur at loop level (penguin and box)





$b \to s\ell^+\ell^-$ transitions (BF 10^{-6} to 10^{-10})

- New particles too heavy to be produced directly, can give sizeable effects when exchanged in a loop



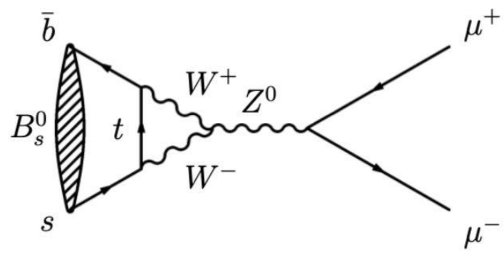
- This "indirect" approach to New Physics searches is complementary to that of ATLAS/ CMS

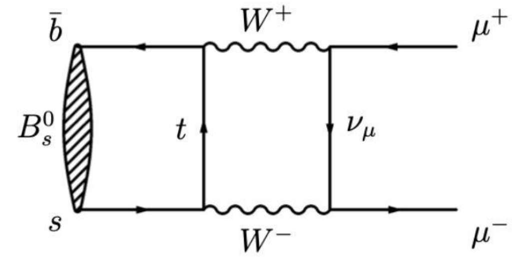
$B_{(s)} \rightarrow \mu^+\mu^-$

- Very suppressed loop decay in the SM
- CKM ($|V_{ts}|^2$ for B_S) and helicity suppressed ~ $(m_\mu/m_b)^2$
- Theoretically "clean" → 4% prediction :

  $\mathcal{B}(B^0_S \rightarrow \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$

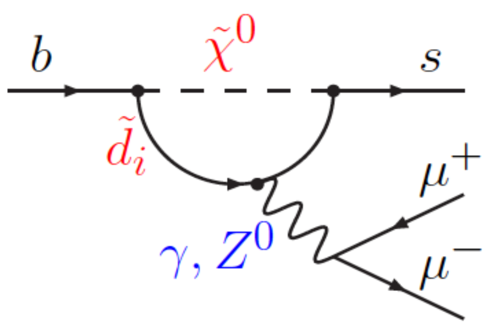
  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \times 10^{-10}$



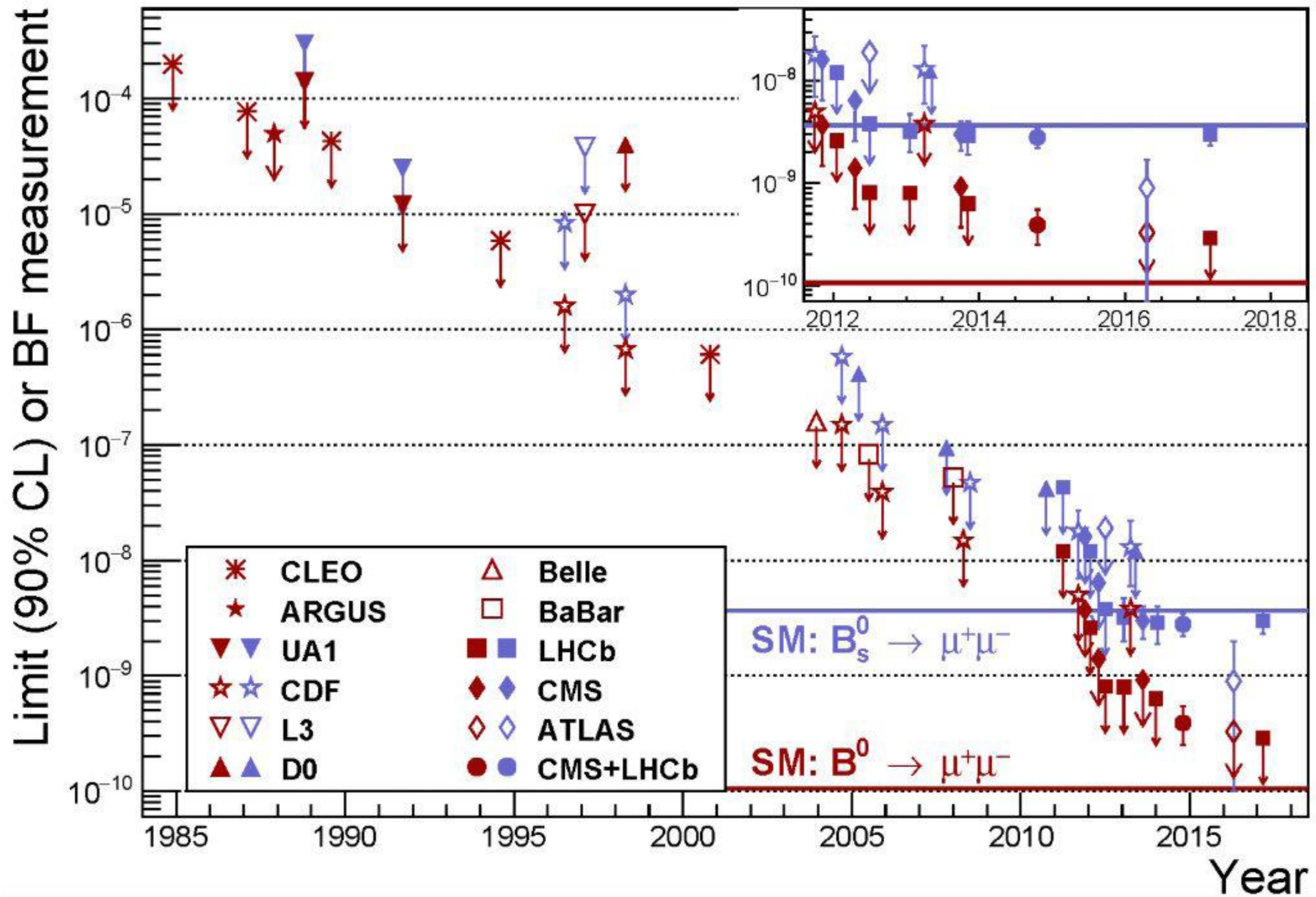


Bobeth et al. PRL 112 (2014) 101801
Beneke et al. JHEP 10 (2019) 232

- NP theories can predict significantly higher values for the branching ratios
- Very clean experimental signature
- Also studied by ATLAS & CMS

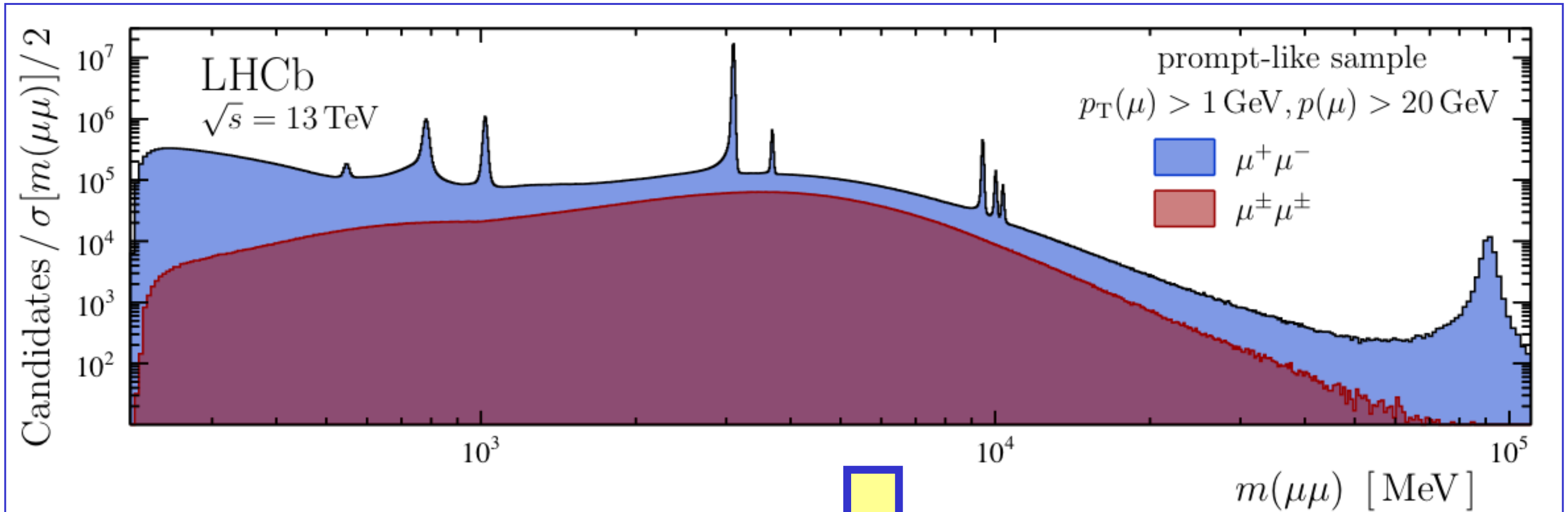


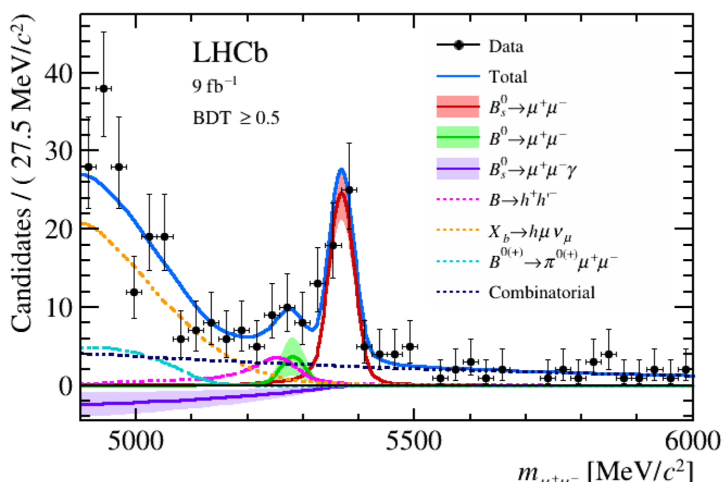
35 years of effort !



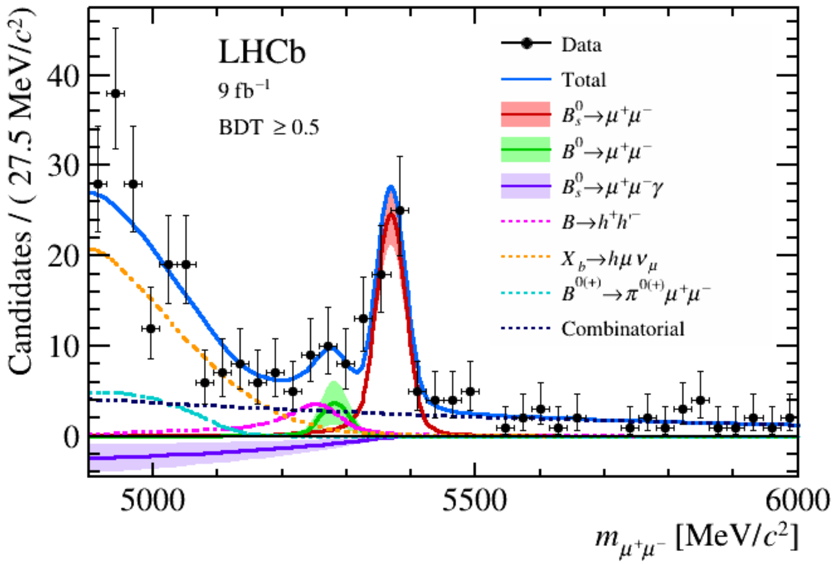
A needle in a haystack

PRL 120 (2018) 061801





$B_{(s)} \to \mu^+\mu^-$ latest result



Phys Rev D 105 (2022) 012010
Phys. Rev. Lett. 128, 041801

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09\ ^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11}) \times 10^{-9}\ (10\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.20\ ^{+0.83}_{-0.74} \pm 0.14) \times 10^{-10}\ (< 2.6 \times 10^{-10} @ 95\%CL)$$

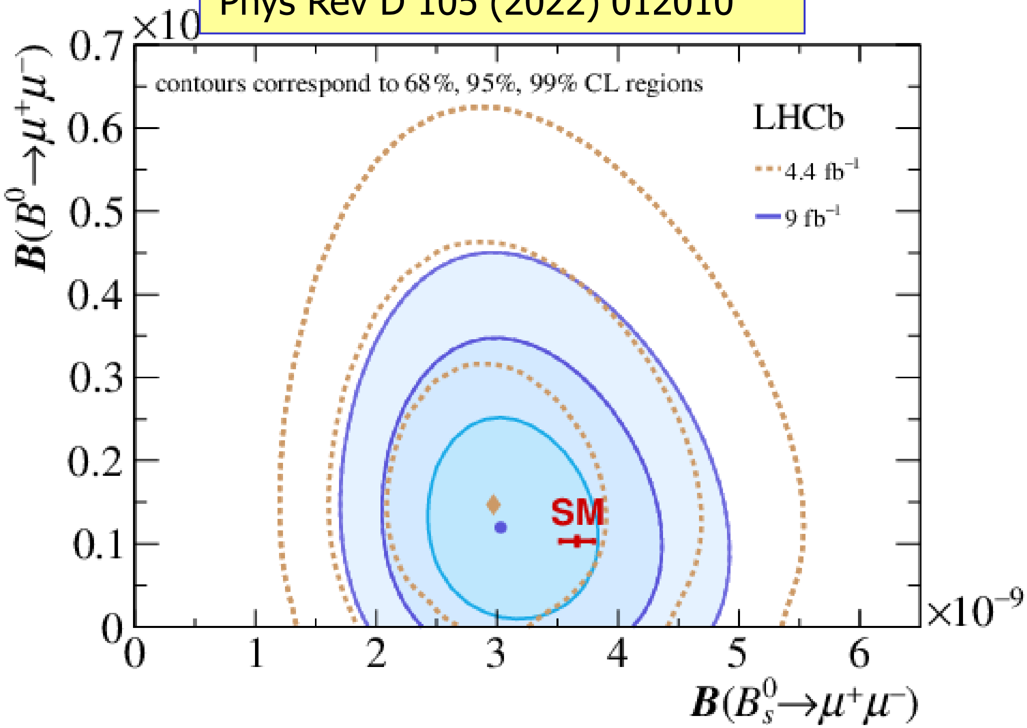
- $B_S{}^0 \to \mu^+\mu^-$ found with significance >10 sigma
  - But no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7 sigma)
- Result dominated by statistical uncertainty
- Latest CMS results

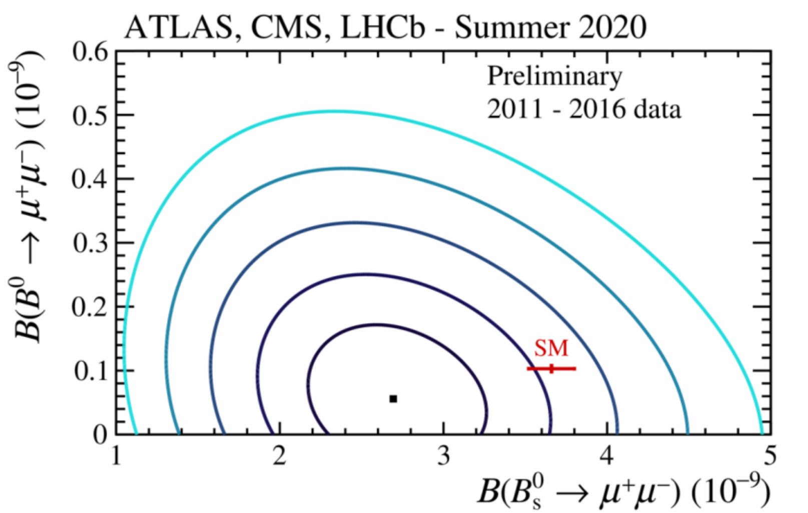
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (f_s/f_u)\right] \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\text{stat})\ ^{+0.08}_{-0.09}\ (\text{syst})\right] \times 10^{-10}$$

$B_{(s)} \to \mu^+\mu^-$ latest result and LHC combination

Phys Rev D 105 (2022) 012010





LHCb-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049

LHCb

$$\mathcal{B}(B^0{}_s \to \mu^+\mu^-) = (3.09\ {}^{+0.46}_{-0.43}\ {}^{+0.15}_{-0.11}) \times 10^{-9} \quad (10\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.20\ {}^{+0.83}_{-0.74} \pm 0.14) \times 10^{-10}$$

Combination 2.1σ below SM prediction

Effective B_s lifetime

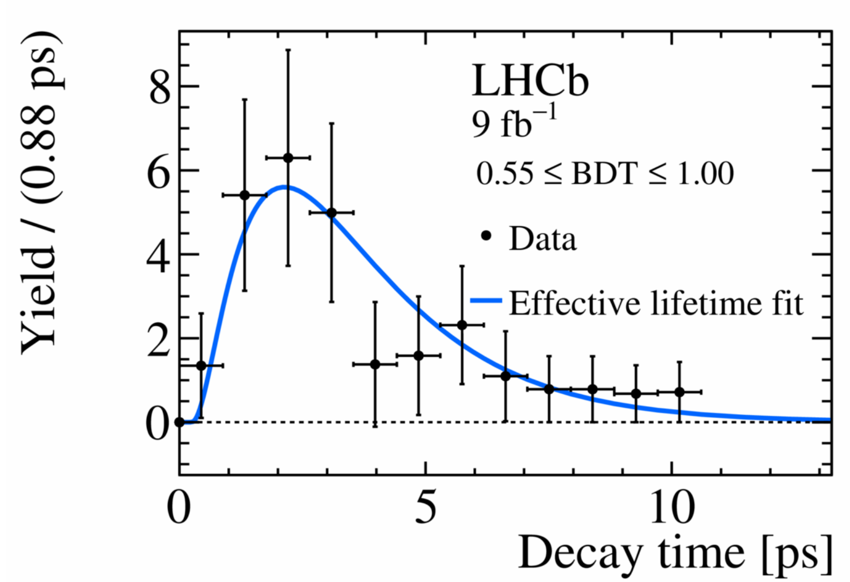
Phys Rev D 105 (2022) 012010
Phys. Rev. Lett. 128, 041801

- For B_S mesons, there is a sizeable difference between the decay widths $\Delta\Gamma_S$ of the light and heavy mass eigenstates ($\Delta\Gamma_S$ = 0.085 ± 0.004 ps^{-1}) PDG

- In the SM, the B_S system evolves with the lifetime of the heavy mass eigenstate (since CP odd).

- Define the $B^0_S \rightarrow \mu^+\mu^-$ effective lifetime as

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\Gamma(B_s(t) \to \mu^+\mu^-)\mathrm{d}t}{\int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)\mathrm{d}t}$$



- LHCb measure $\tau_{\mu+\mu-}$ ($B_S(t) \rightarrow \mu^+\mu^-$) = (2.07 ± 0.29 ± 0.03) ps.

SM values $\tau_L = 1.423 \pm 0.005$ ps and $\tau_H = 1.620 \pm 0.007$ ps

Consistency at 2.2σ and 1.5σ

Search for $B_{(s)} \to e^+e^-$

- Standard Model predicts :

  Beneke et al. JHEP 10 (2019) 232

  - $\mathcal{B}(B_s \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$
  - $\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$

- CKM and helicity super-suppressed decay : out of reach from the experimental point of view

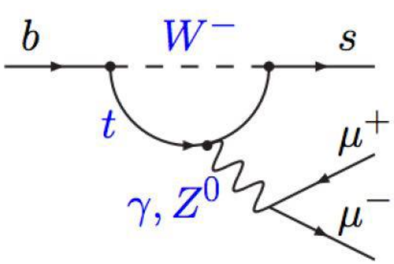
- LHCb measurement based on Run1 and partial Run 2 (4 fb^{-1}). $\mathcal{B}$ measured relative to $B^+ \to K^+ J/\psi(\to e^+e^-)$

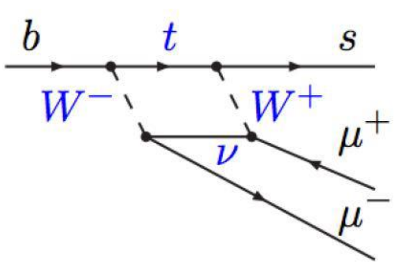
  PRL 124 (2020) 211802

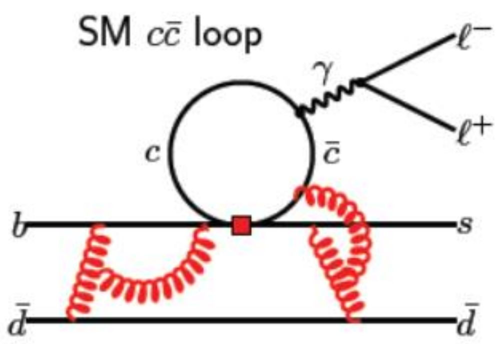
  - $\mathcal{B}(B_s \to e^+e^-) < 9.4 \times 10^{-9}$ @ 90%CL
  - $\mathcal{B}(B^0 \to e^+e^-) < 2.5 \times 10^{-9}$ @ 90%CL

$b \to s\,\ell^+\ell^-$ transitions

- Study $B \to h\,\mu^+\mu^-$ transitions with hadron h = K, K^*, ϕ . . .
- Same loop diagrams, different spectator quarks
- Rates, angular distributions and asymmetries are sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical predictions.



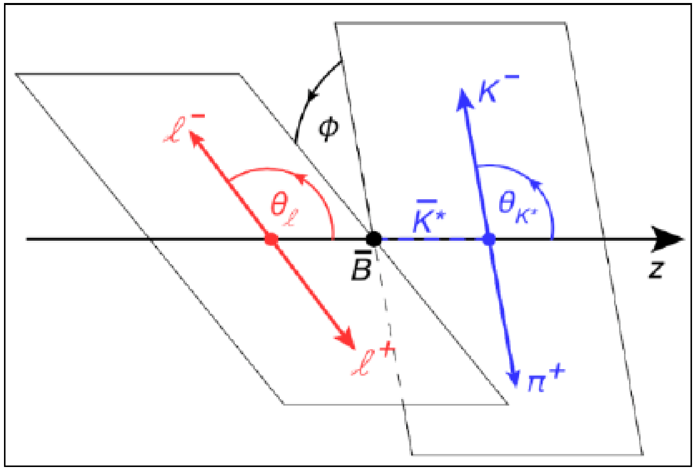




$B^0 \to K^{*0}\mu^+\mu^-$: 4-body angular observables

- The $B^0 \to K^{*0}\mu^+\mu^-$ differential decay rate can be described by 3 angles and di-muon invariant mass squared (q^2)
- Rich structure of physics observables in the angular coefficients (as functions of q^2)
- Form angular coefficients which are robust against form-factor uncertainties (e.g. P'_5)

Descotes-Genonet al., JHEP 01 (2013) 048

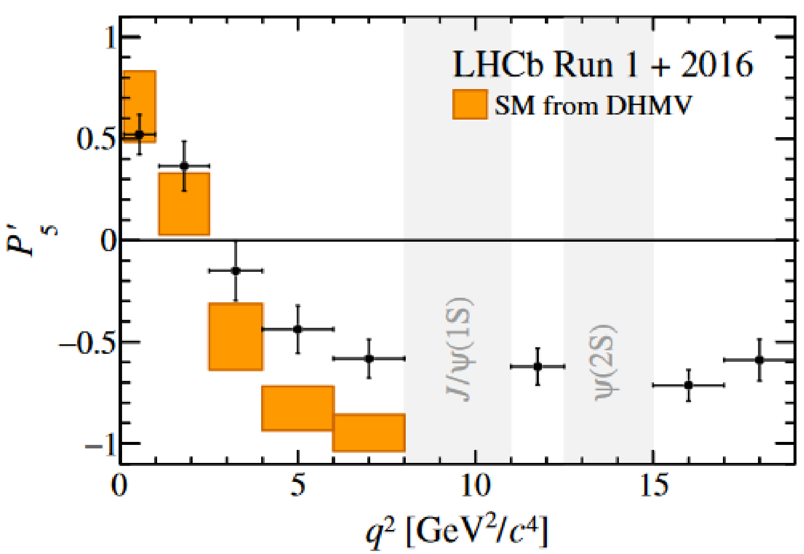


$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$\sqrt{F_L(1-F_L)}P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

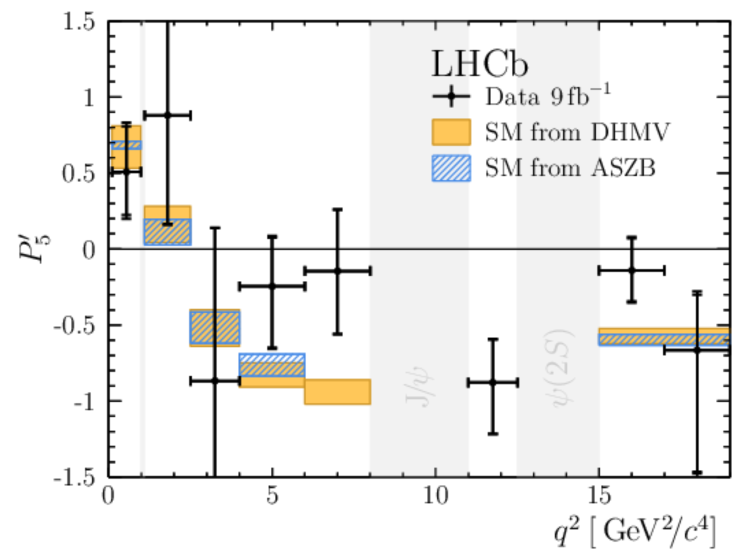
Measurement of P'$_5$ angular coefficient

- Anomaly in P'$_5$ found in $B^0 \to K^{*0}\mu^+\mu^-$ for $4 < q^2 < 8$ GeV^2
- P'$_5$ local tension of 2.5σ and 2.9σ in q^2 bins of [4.0, 6.0] and [6.0, 8.0] GeV^2 $\to$ Global analysis finds a deviation of 3.3σ
- Also observed also in B^+ isospin partner decay
- Some deviation from SM predictions also in other angular observables
- Results are intriguing, however extent of hadronic contributions still matter of debate (particularly regarding charm-quark loops)

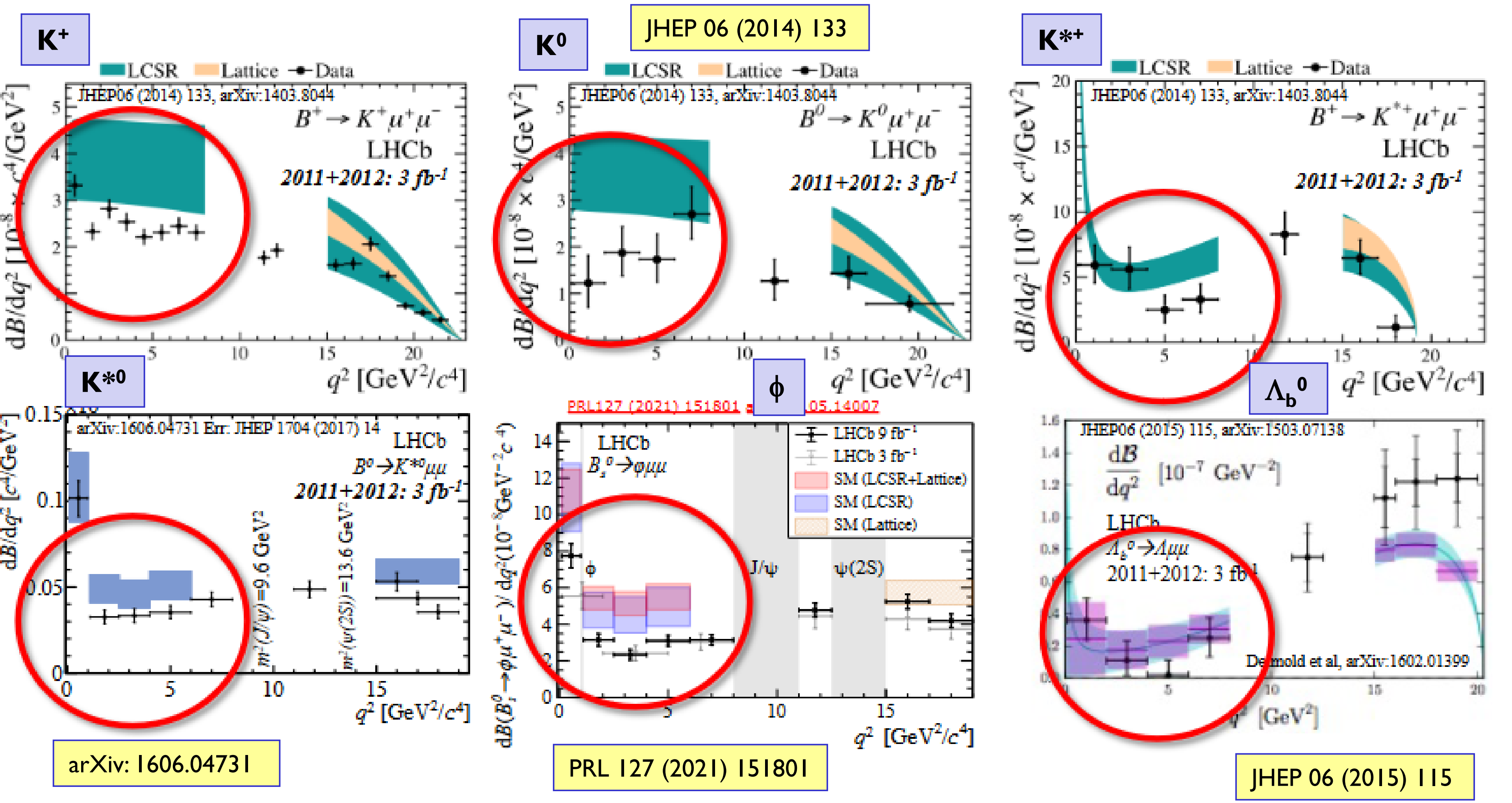
$B^0 \to K^{*0}\mu^+\mu^-$ PRL 125 (2020) 011802



$B^+ \to K^{*+}\mu^+\mu^-$ PRL 126 (2021) 161802



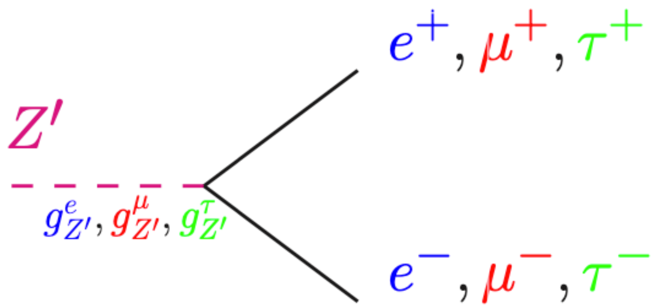
Semi-leptonic differential branching fractions

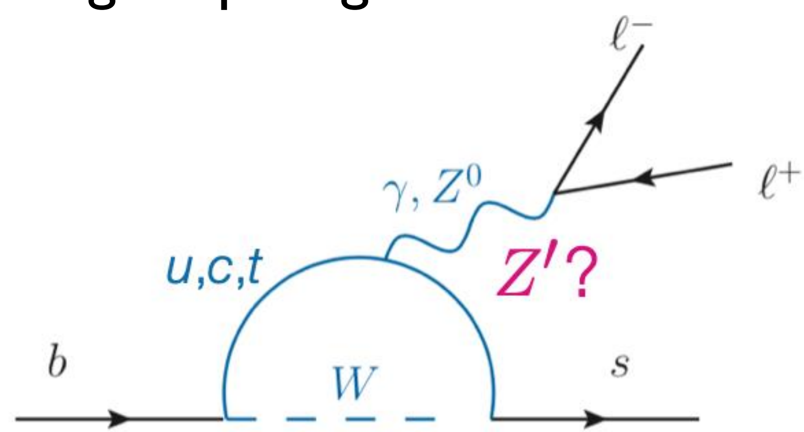


- All semi-leptonic BF's lower than SM expectations at low q^2 (~1 to 4σ) [comparison limited due to large theory uncertainties from form factors]

Lepton Flavour Universality (LFU)

- LFU is a cornerstone of the SM : charged leptons (e, μ , τ) couple in a universal way to the SM gauge bosons
- If NP couples in a non-universal way to the three lepton families, then we might see differences in rates of rare decays involving different lepton pairs (e.g. e/μ or μ/τ)
- Hence - LFU is tested in $b \rightarrow s\ \ell^+\ell^-$ transitions. These are FCNC's with amplitudes involving loop diagrams





Several R-ratio measurements

- Compare the rates of $B \to X_s e^+ e^-$ and $B \to X_s \mu^+ \mu^-$
  [*where B is* B^+, B^0, B^0_s , Λ^0_b and X_s is K^+, K^{*0}, ϕ , pK . . .]
- This allows precise testing of lepton flavour universality
- We can construct the ratio :

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B_q \to X_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B_q \to X_s e^+ e^-)}{dq^2} dq^2} = 1 \pm \mathcal{O}(1\,\%)$$

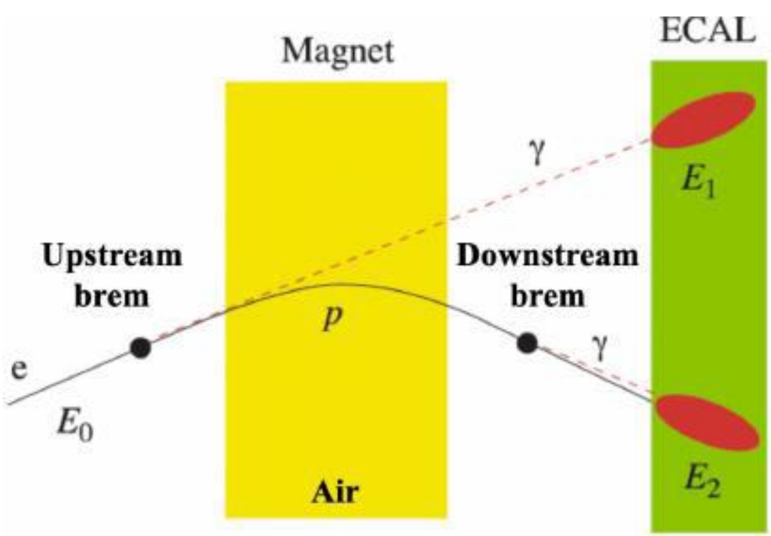
- Small theoretical uncertainties because hadronic uncertainties cancel
- This ratio is unity in the SM, neglecting lepton masses, with QED corrections at the % level

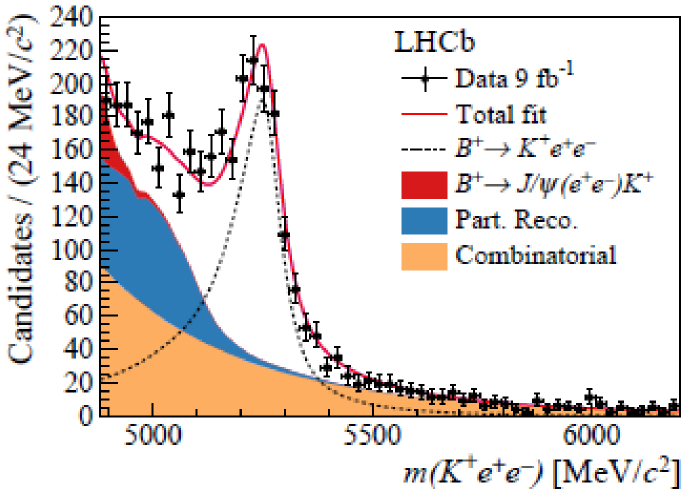
- Five different ratios published so far by LHCb:
  $X_s = K^+$, K^0_S, K^{*0}, K^{*+} and pK^-

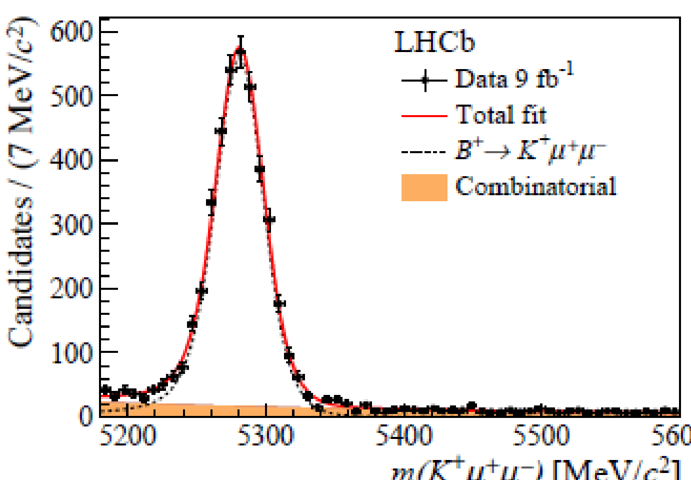
This might seem easy, but actually rather challenging

Nat Phys18 (2022) 277

- Lower efficiency of electron trigger
- Electrons emit bremsstrahlung, resulting in degraded momentum and mass resolution
- Attempt to recover the energy of the emitted photons :
  - Some energy missed
  - Some energy mis-attributed







Experimental strategy

- Actually measure double ratios which significantly reduce systematic uncertainties:

$$R_X = \frac{\mathcal{B}\left(B_q \to X_s \mu^+ \mu^-\right)}{\mathcal{B}\left(B_q \to X_s J/\psi(\mu^+ \mu^-)\right)} \cdot \frac{\mathcal{B}\left(B_q \to X_s J/\psi(e^+ e^-)\right)}{\mathcal{B}\left(B_q \to X_s e^+ e^-\right)}$$

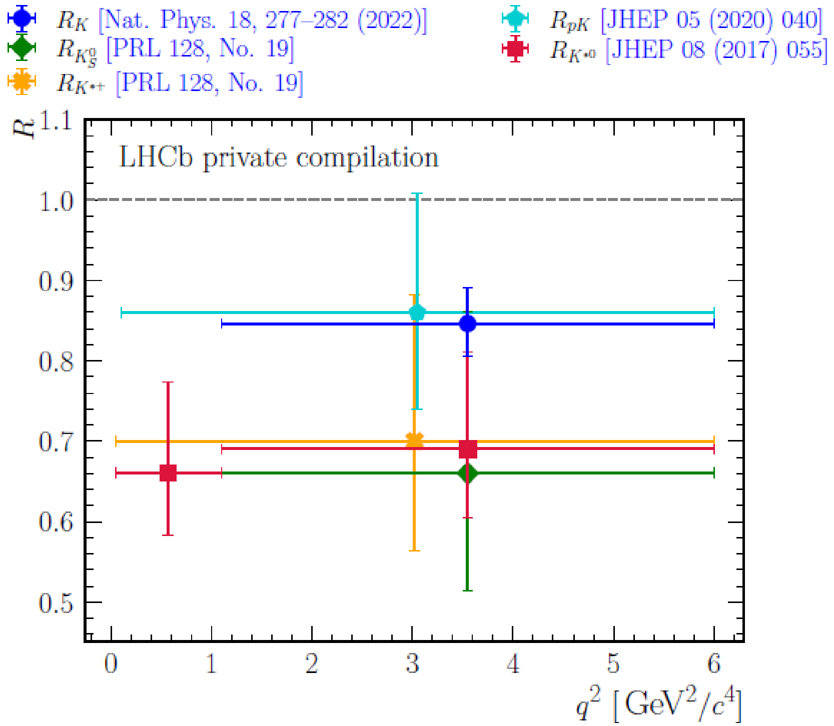
- Ratios determined using yields and efficiencies
  - Yields extracted from fits to the data
  - As cross-checks the ratios

$$R_{J/\psi} = \frac{\mathcal{B}\left(B_q \to X_s J/\psi(\mu^+ \mu^-)\right)}{\mathcal{B}\left(B_q \to X_s J/\psi(e^+ e^-)\right)}$$

are compatible with unity to 0.4%

X_s	$r_{J/\psi}$	$R_{\psi(2S)}$
K^+	0.981 ± 0.020	0.997 ± 0.011
K^{*+}	0.965 ± 0.032	1.017 ± 0.050
K^0_s	0.977 ± 0.028	1.014 ± 0.036
K^{*0}	1.043 ± 0.045	within 1σ from 1
pK^-	0.96 ± 0.05	within 1σ from 1

LFU results : R_x



R_K (9/fb) 3.1 σ from SM

$R_{K^{*+}}$ (9/fb) 1.4 σ **NEW**

R_{K0s} (9/fb) 1.5 σ **NEW**

$R_{K^{*0}}$ low-q^2 (3/fb) 2.1 σ

$R_{K^{*0}}$ central-q^2 (3/fb) 2.4 σ

R_{pK} (5/fb) <1 σ

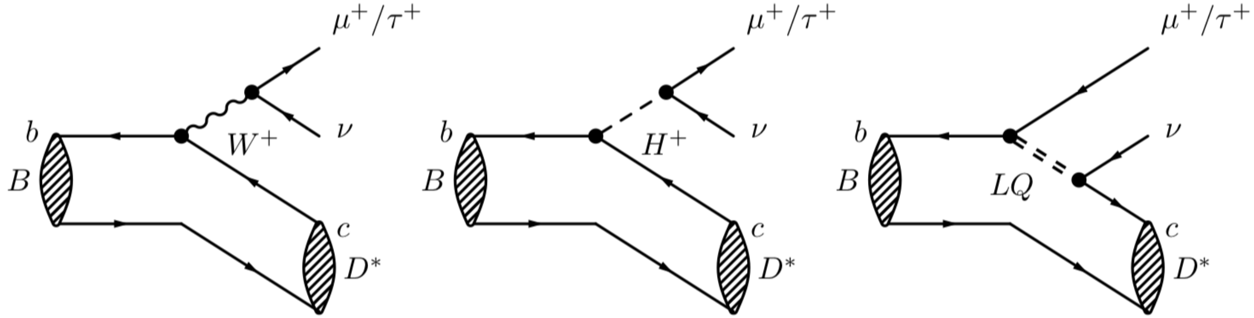
- All measurements have values less than unity
- The puzzle persists → we eagerly await Belle-II & CMS results
- LHCb is now focused on completing a combined analysis of RK & RK* with the Run 1+2 dataset. This work has led to a deeper understanding of systematics which will be reflected in the final result.

LFU studies in $B^0 \to D^{(*)-}\tau^+\nu_\tau$ decays

- Different class of decays (tree-level charged current with V_{cb} suppression)
- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\%$, the problem is the background.
- Lepton-universality ratio R(D*) :

$$R(D^*) = \frac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- may be sensitive to any NP model coupling preferentially to third generation leptons



- Ratios predicted theoretically at ~1%:

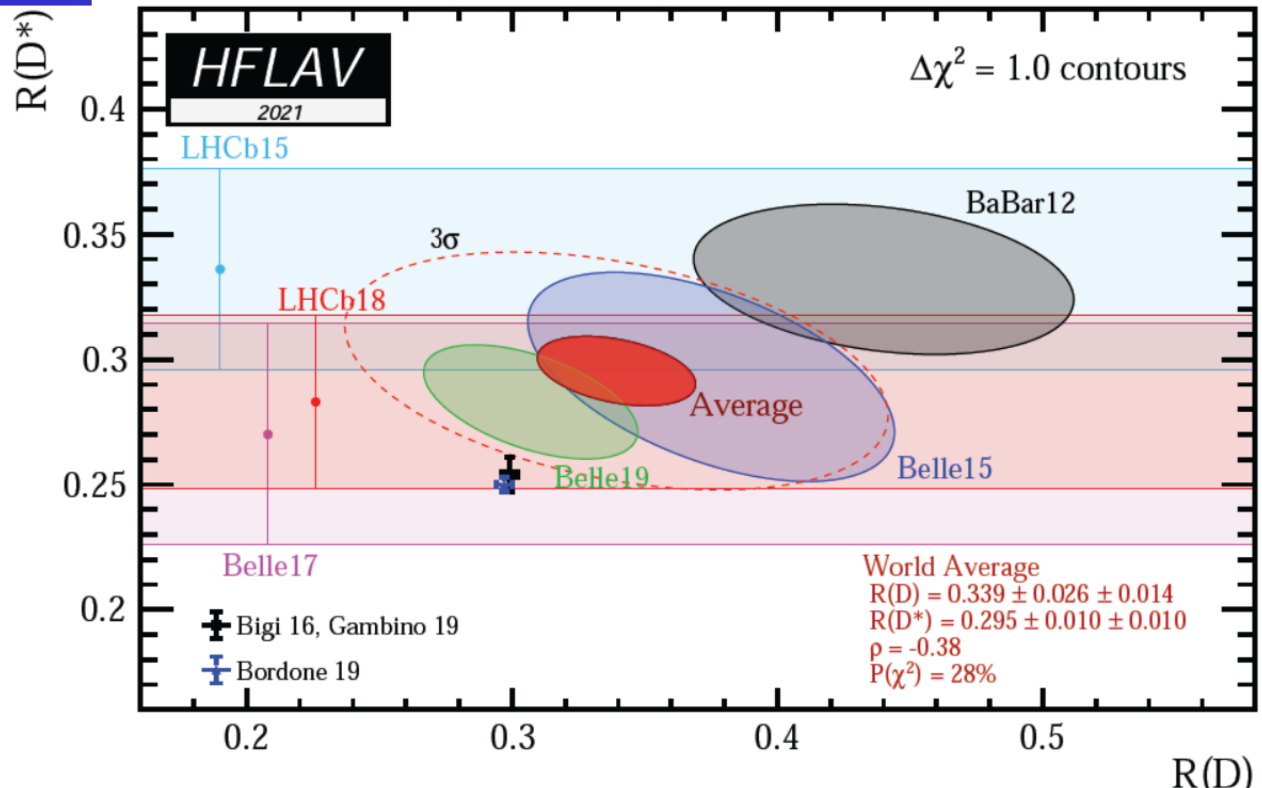
  $R(D)_{SM} = 0.299 \pm 0.003$ $R(D^*)_{SM} = 0.258 \pm 0.005$

- Anomolies first observed by Belle and BaBar

HFLAV 2019 average of theoretical predictions

$R(D)$ vs $R(D^*)$

- All experiments see an excess wrt SM predictions
- Combining R(D)/R(D*) average ~3.4 σ tension with SM



- Intriguing as anomaly occurs in a tree-level SM process

- New LHCb result

$R(\Lambda_c) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059(\text{ext})$

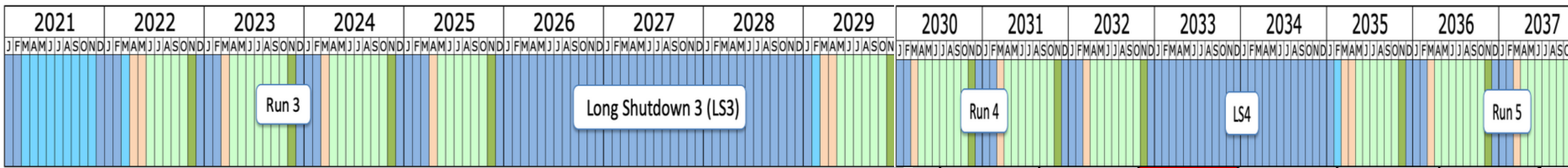
arxiv:2201:03497

Measurement is consistent with SM (~1σ “low”) [SM=0.324±0.004].

The upgraded LHCb detector and outlook

LHCb Upgrade planning

WE ARE HERE



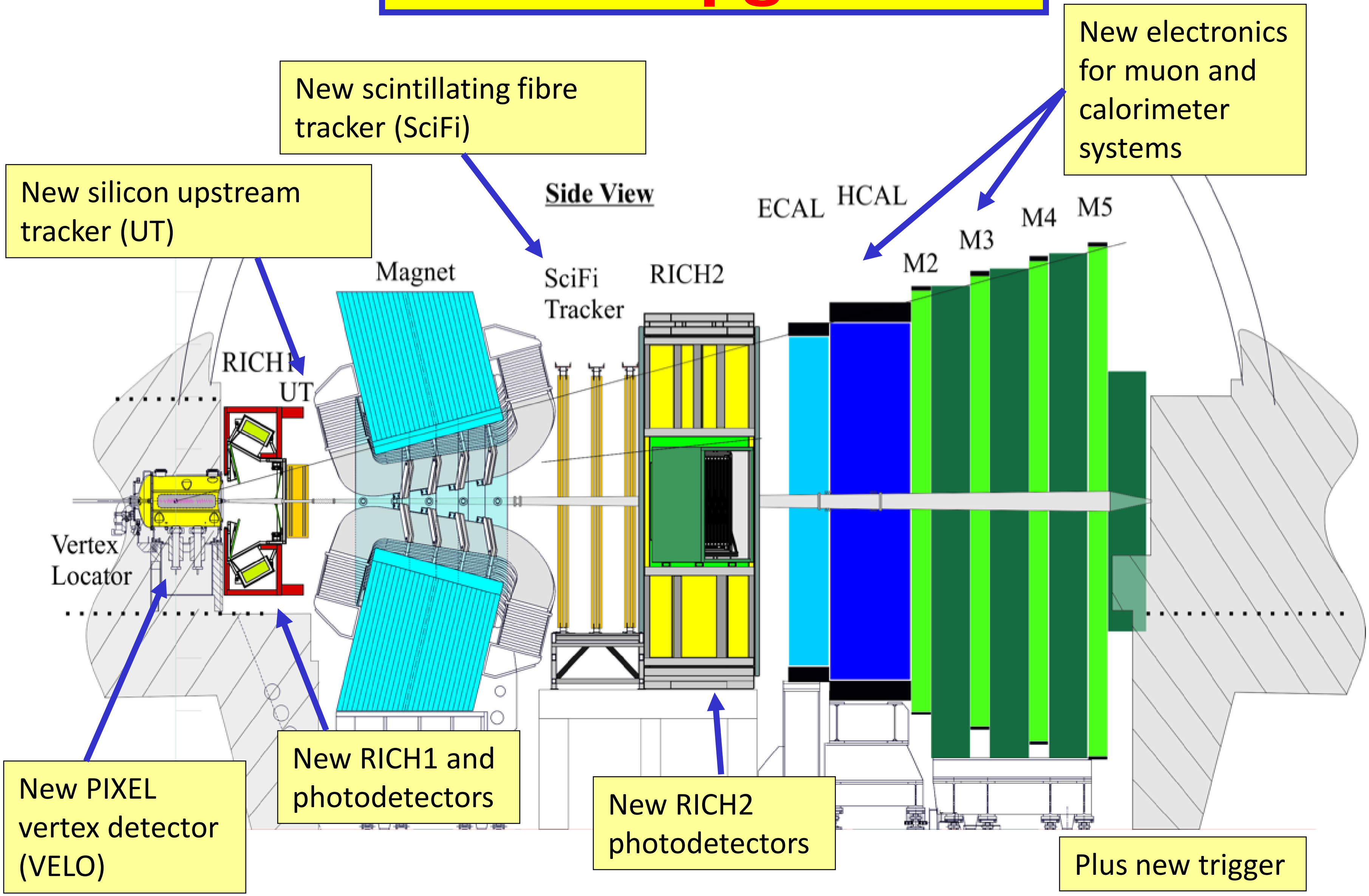
LHCb 40 MHz **UPGRADE I**	$L = 2 \times 10^{33}$	**LHCb** **Consolidate: UPGRADE Ib**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb** **UPGRADE II**	$L = 1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS **Phase I Upgr**	$L = 2 \times 10^{34}$	**ATLAS** **Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$		**HL-LHC** $L = 5 \times 10^{34}$
CMS **Phase I Upgr**	$300\ fb^{-1}$	**CMS** **Phase II UPGRADE**			$3000\ fb^{-1}$
Bell e II	$5\ ab^{-1}$	$L = 6 \times 10^{35}$	$50\ ab^{-1}$		

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

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

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

LHCb Upgrade I



Construction & Installation – Upgrade I

SciFi tracker

RICH 2

UT stave

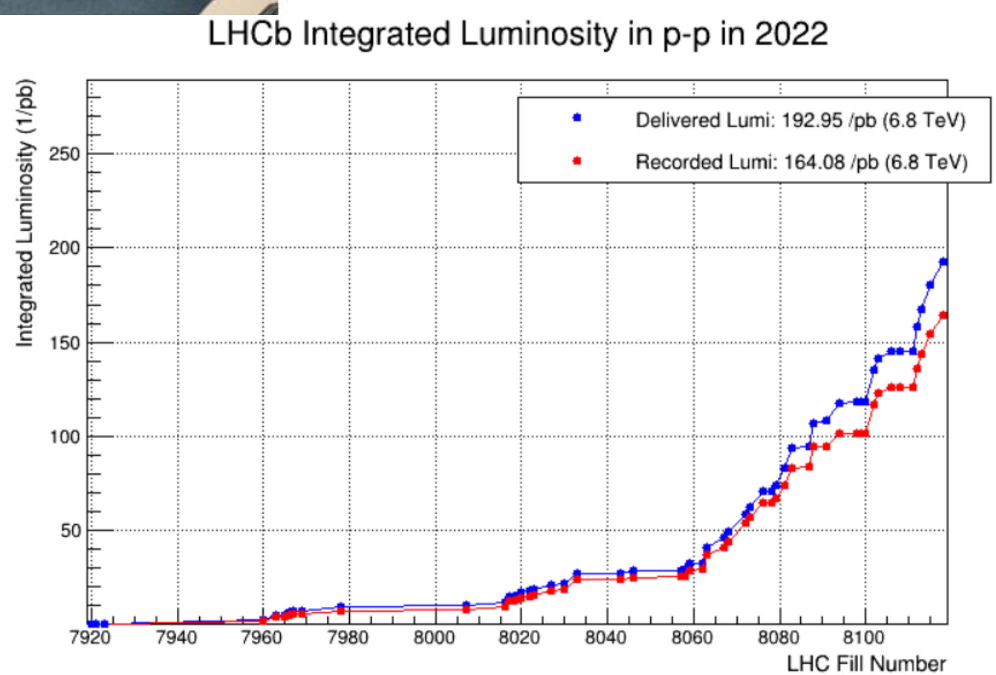
July 5th 2022 - 16:47

DETECTOR LATEST POSTS

First collisions at the world-record energy for a brand-new LHCb detector

JUL 5, 2022 ADMIN

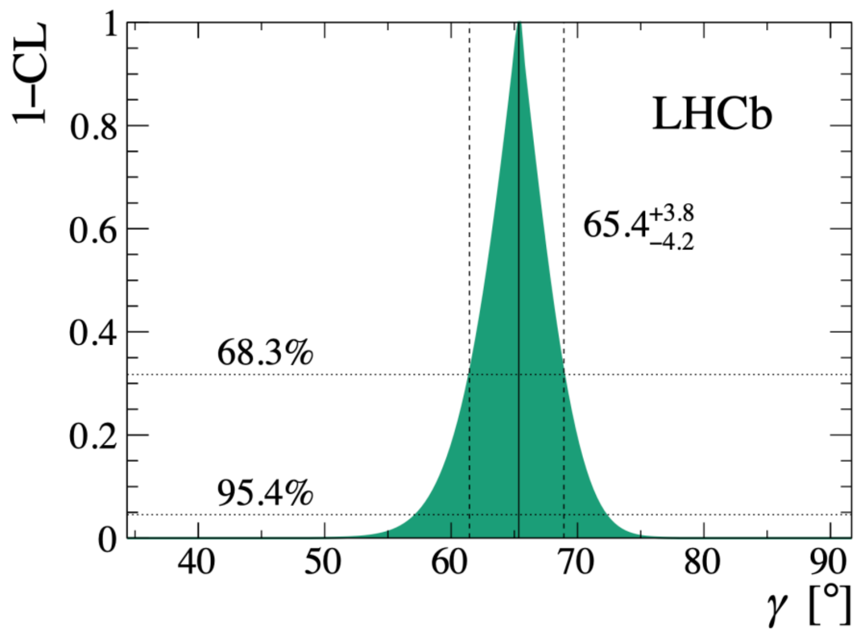
Start of LHC Run 3. Today, at 16:47, protons collided again at LHCb after a 3.5 year break known as Long Shutdown 2 (LS2). During...



γ prospects : Run II → Upgrade I

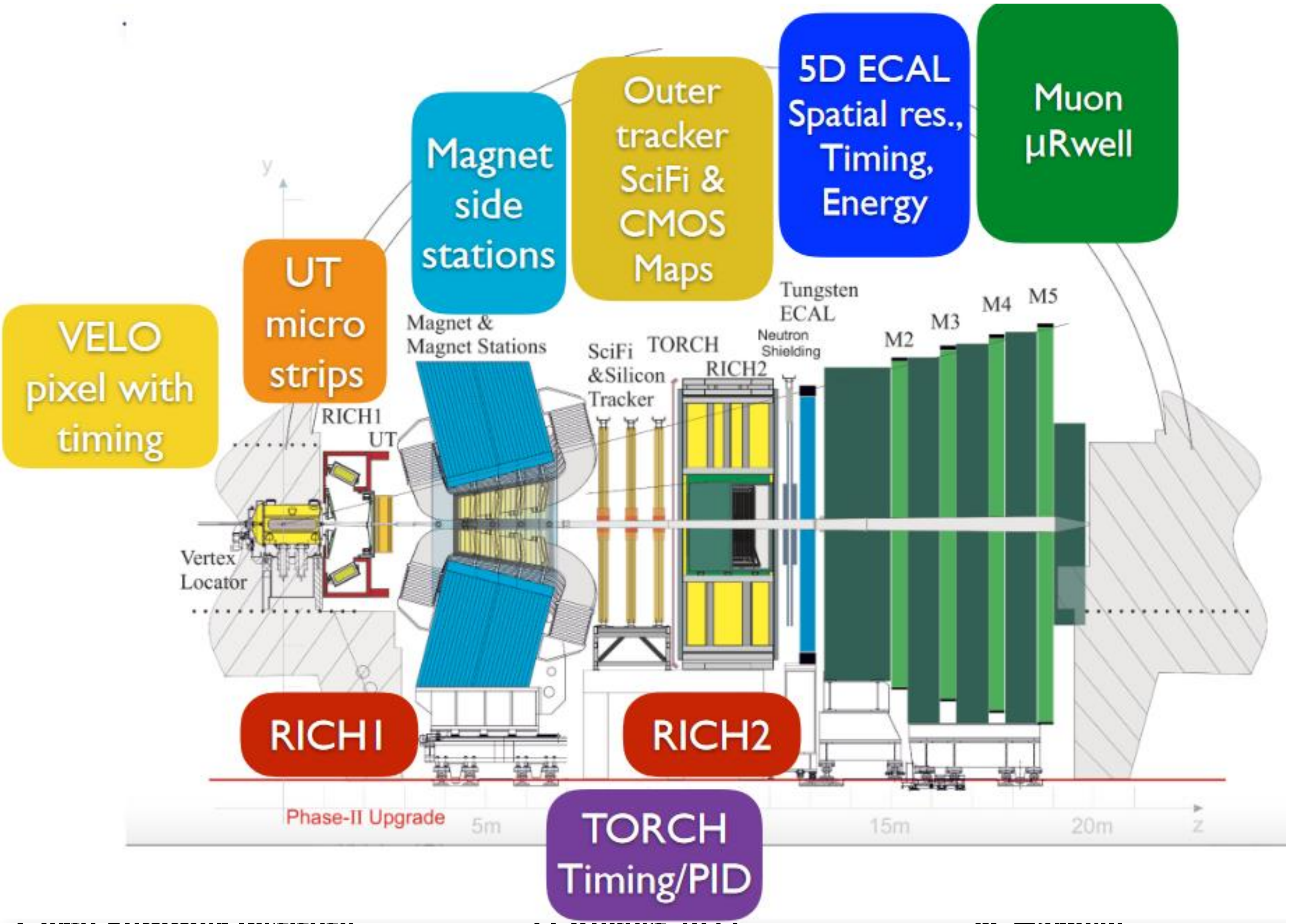
- Post Run II target of 4° almost surpassed (~9 fb^{-1}) and analyses still in progress
- LHCb Upgrade I : target 0.9° (~50 fb^{-1})

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



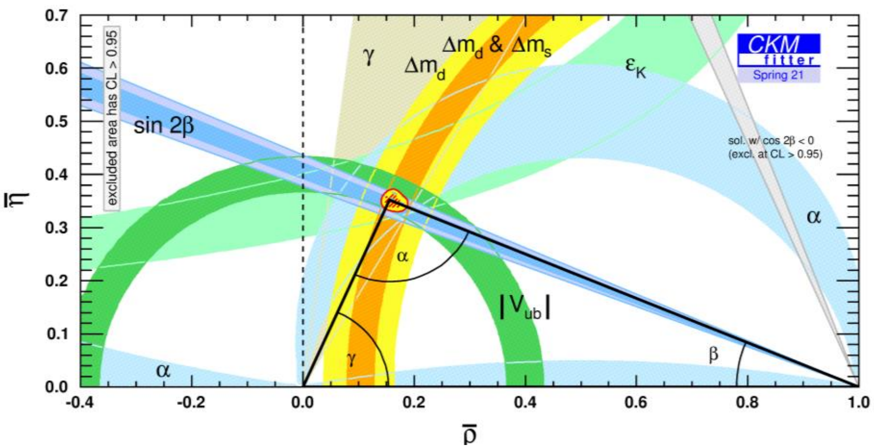
EPJC (2013) 73:2373

… and beyond 2035 : Upgrade II



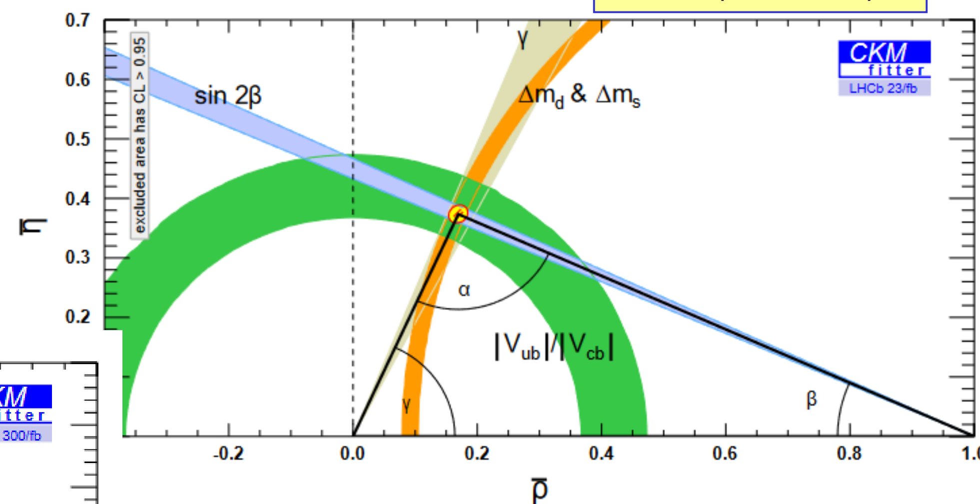
Evolution of the Unitarity Triangle

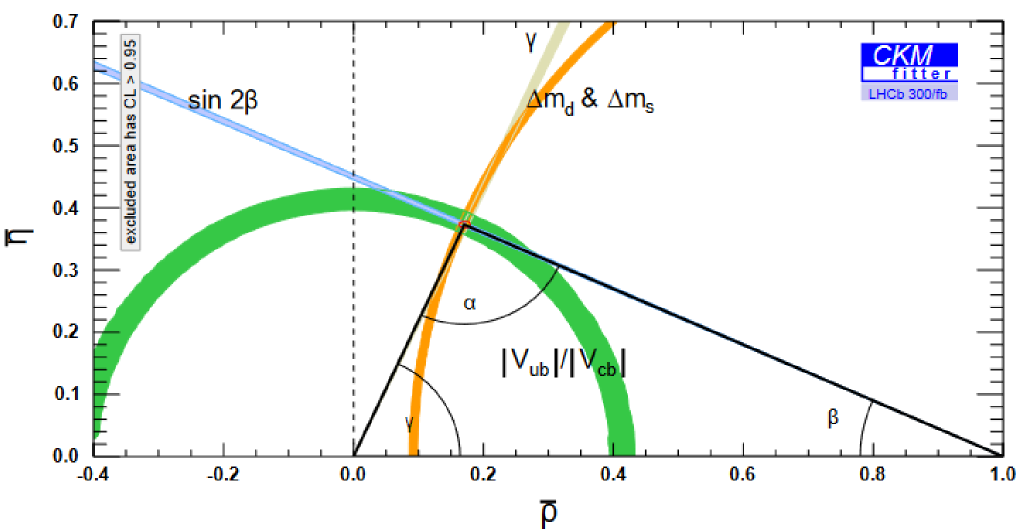
LHCb : 2021
Run 2 (~9 fb^{-1})



LHCB-PUB-2018-009

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. We now even need a new naming system !
- Many rare-decay results show good compatibility with the SM, however hints of LFU violation persist. This has generated a lot of theoretical interest. We eagerly await confirmation …
- Still a lot of room for New Physics, but higher precision required
  → preparing for LHCb Upgrades beyond 2022 and the decade afterwards! Very much looking forward to Belle-II results.

Spare Slides

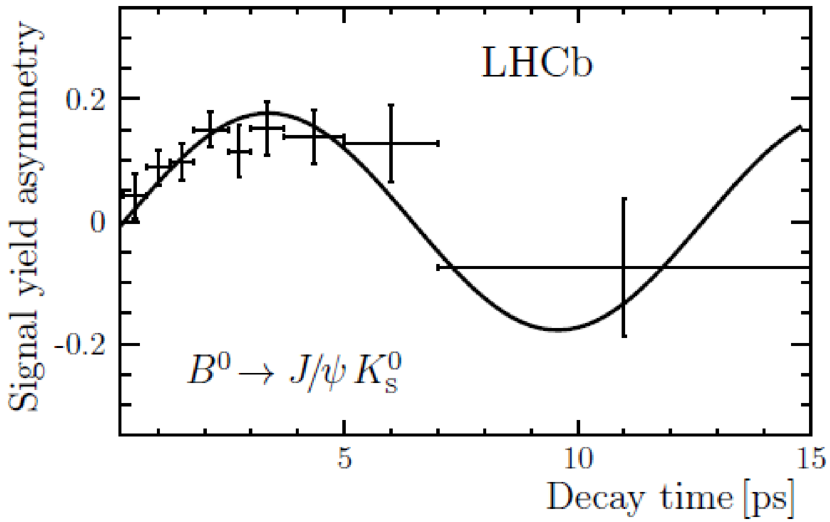
LHCb measurement of sin(2β)

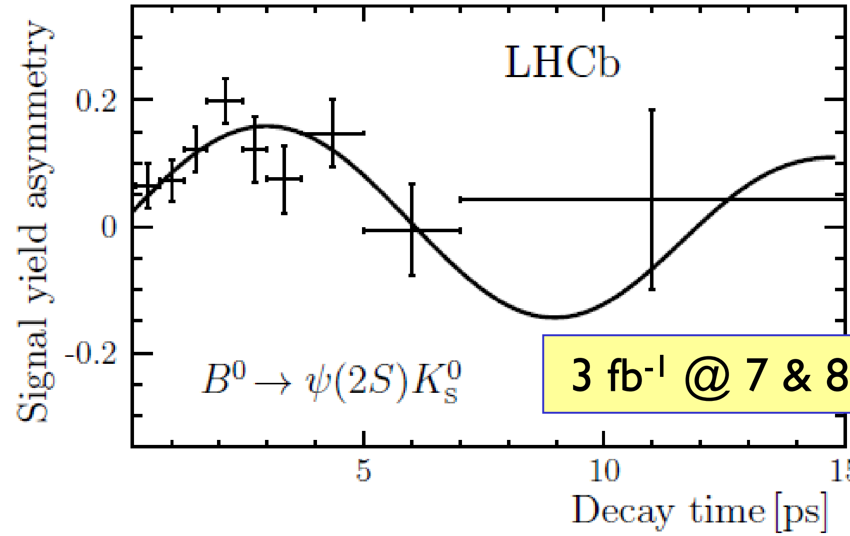
sin(2β) from $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S) K^0_S$

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

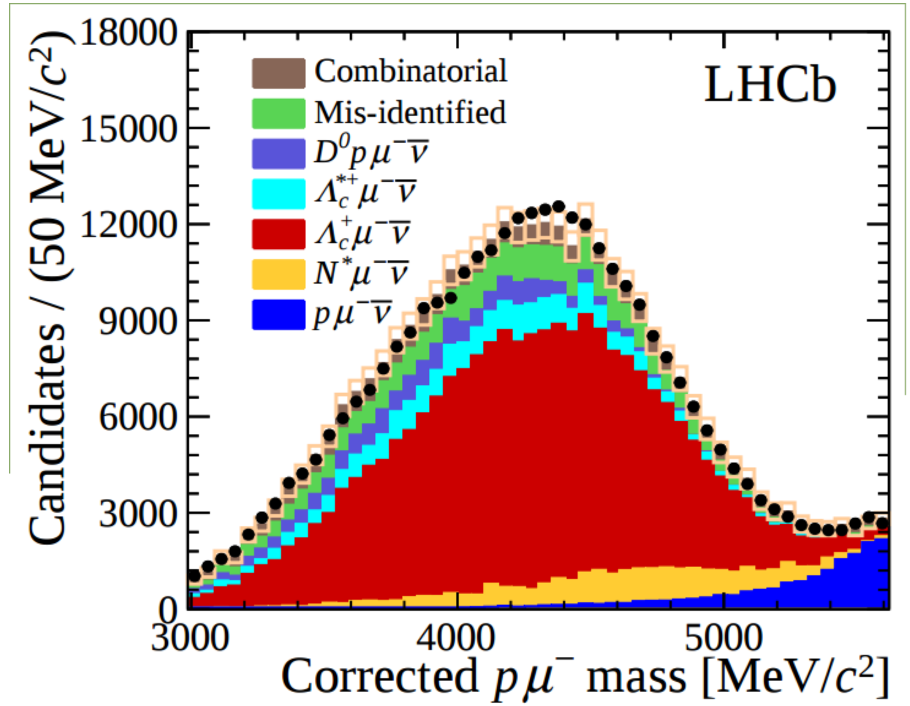
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

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 $\Lambda_b \to p\,\mu^-\,\nu$ (the $B^0 \to \pi^-\,\mu^+\,\nu$ channel is extremely difficult)
- The measurement relies on $\Lambda_b \to p$ form factors from the lattice)



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

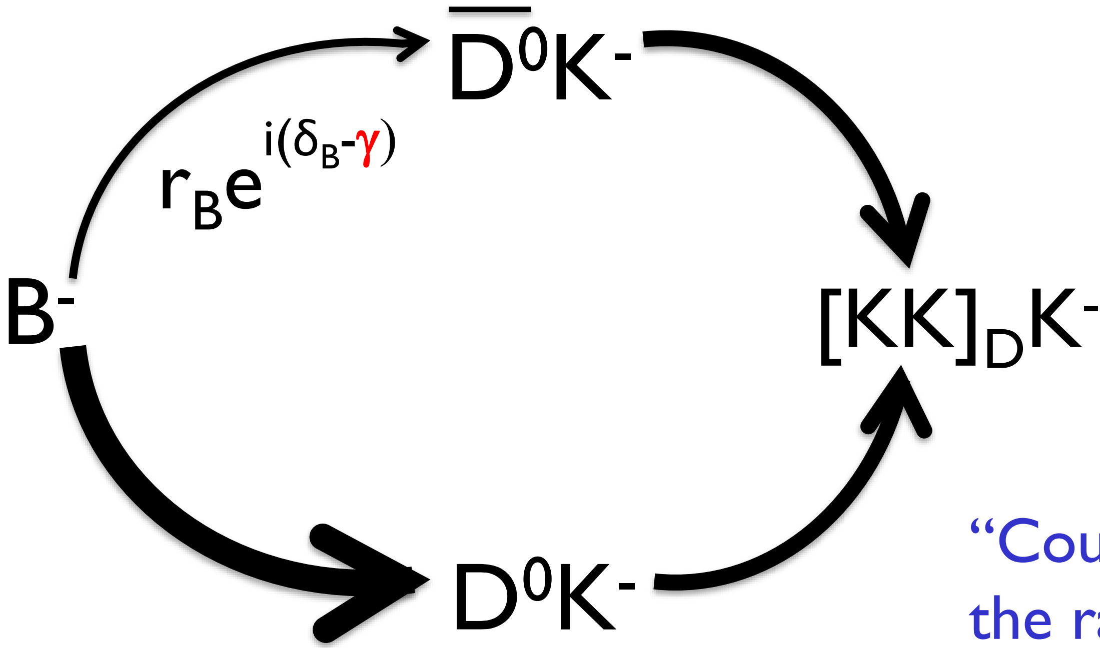
Nature Physics 10 (2015) 1038

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 $\bar{D}^0$ 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 ($r_B \sim 0.1$)

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

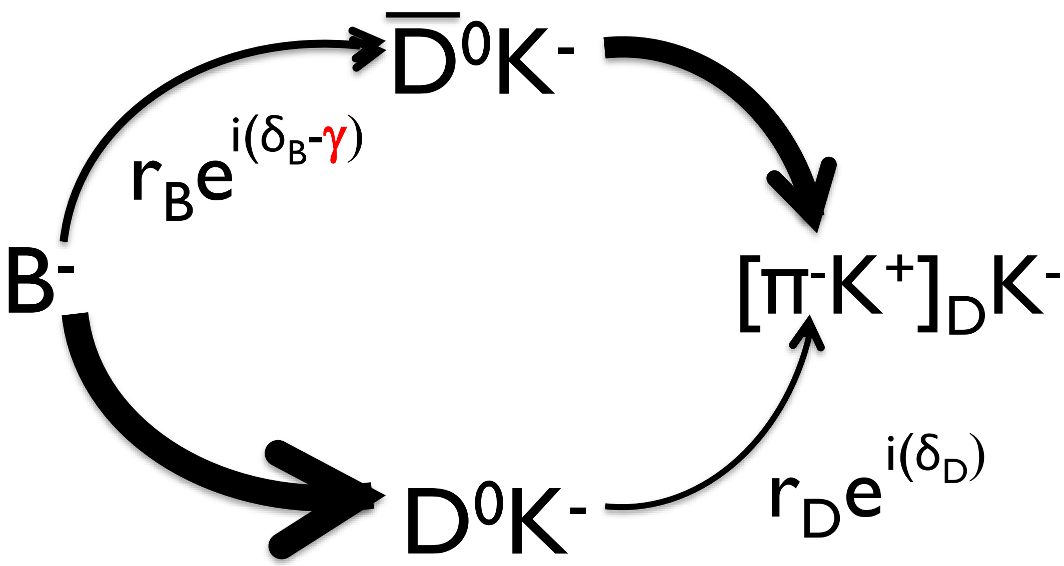
Weak phase changes sign for equiv B^+ diagram, thickness of arrows indicate relative strengths

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

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

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

"ADS" method



Weak phase changes sign for equivalent B^+ diagram

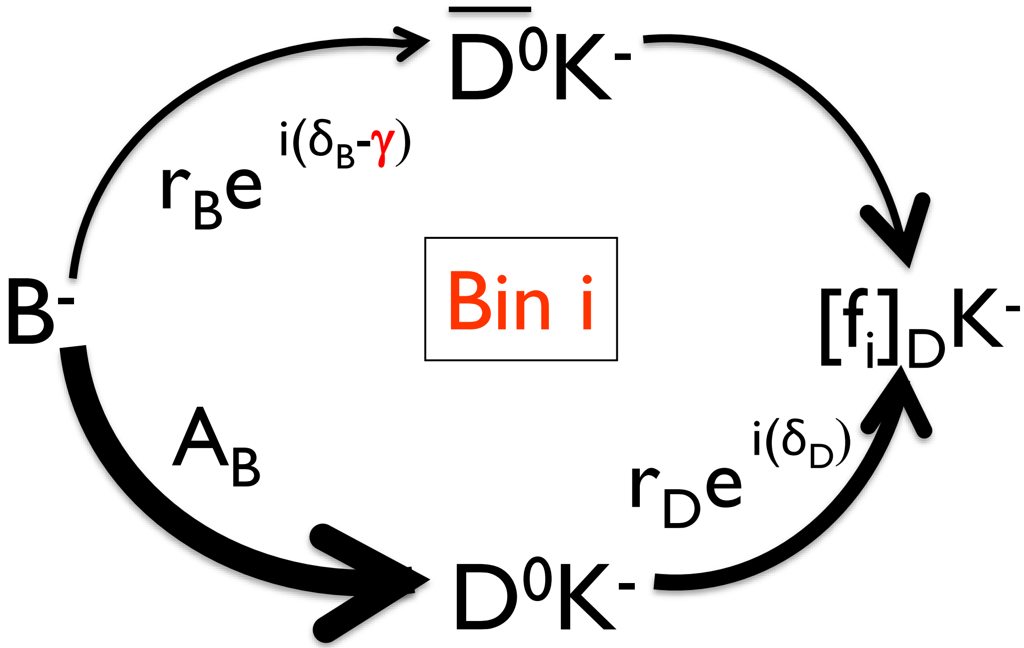
- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- r_B, δ_B hadronic parameters again to be determined alongside γ ($r_B \sim 0.1$)
- Additional two parameters r_D, δ_D . External inputs from charm mixing measurements ($r_D \sim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

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

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

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, where r_D and δ_D vary

- GGSZ observables (rate as function of Dalitz position)

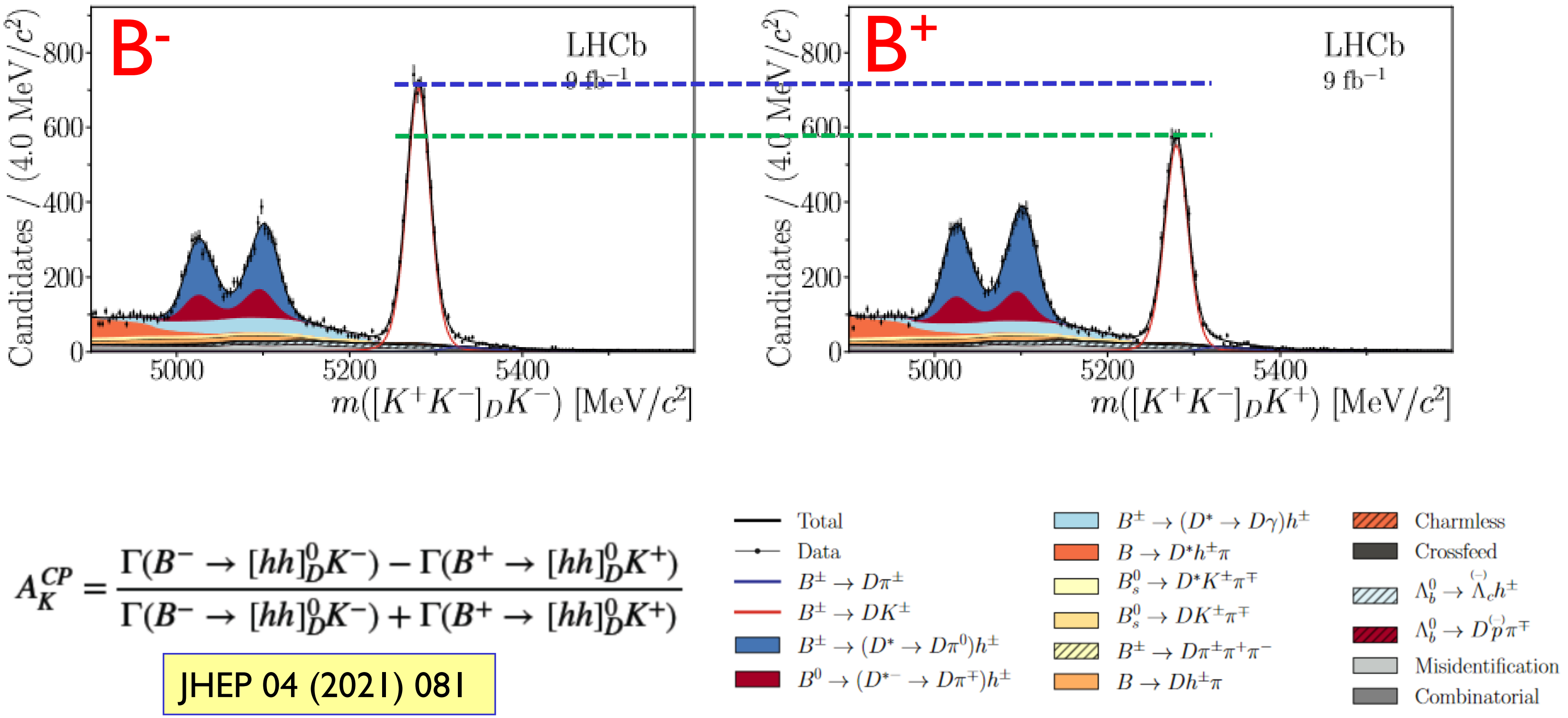
$$d\Gamma_{B\pm}(\mathrm{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\big[\underbrace{r_B\cos(\delta_B\pm\gamma)}_{x_\pm}\underbrace{\cos(\delta_{D(\pm,\mp)})}_{c_i} + \underbrace{r_B\sin(\delta_B\pm\gamma)}_{y_\pm}\underbrace{\sin(\delta_{D(\pm,\mp)})}_{s_i}\big]$$

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

arXiv:1010.2817

New 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



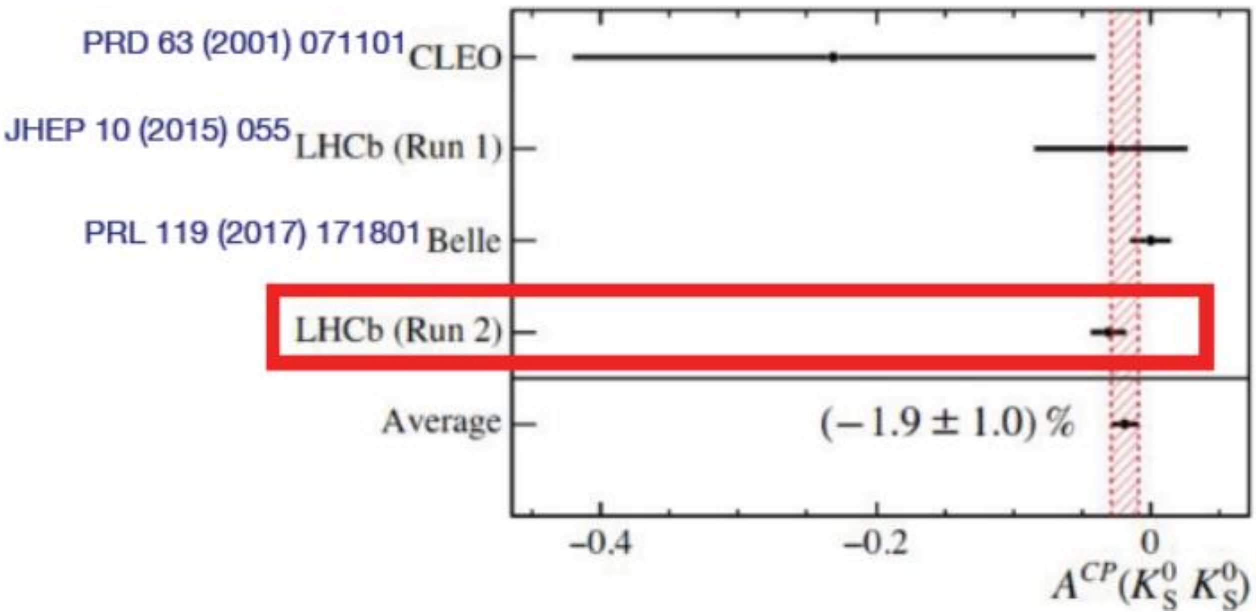
$$A_K^{CP} = \frac{\Gamma(B^- \to [hh]_D^0 K^-) - \Gamma(B^+ \to [hh]_D^0 K^+)}{\Gamma(B^- \to [hh]_D^0 K^-) + \Gamma(B^+ \to [hh]_D^0 K^+)}$$

JHEP 04 (2021) 081

Charm CPV : more recent measurements

arXiv:2105.01565 (2021)

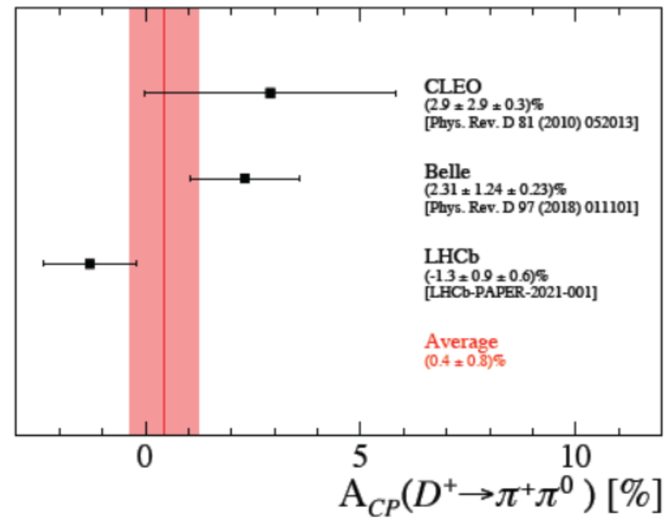
- Direct CPV : $A_{CP}(D^0 \rightarrow K^0_s K^0_s)$
- Use $D^0 \rightarrow K^+K^-$ channel as control for A_D & A_P
- $A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ [last uncertainity : CP violation of control channel]
- Consistent with no violation at the 2.4σ level



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

JHEP 06 (2021) 019

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

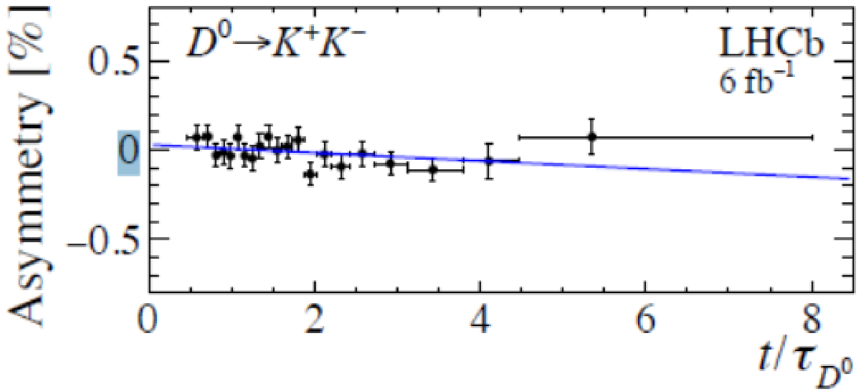


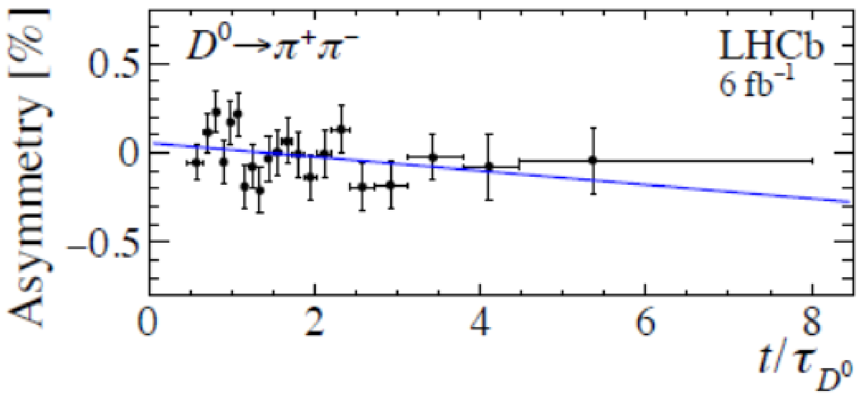
- All compatible with no CP violation
- More data needed !
- Note that LHCb is now regularly extracting measurements with neutrals in the final state (K_sK_s and h^0h^+)

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

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

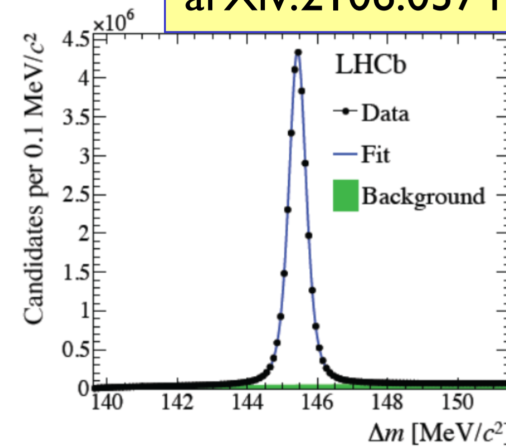
- Compatible with 0 within 2σ
- This result improves by nearly a factor 2 the precision of the previous world average

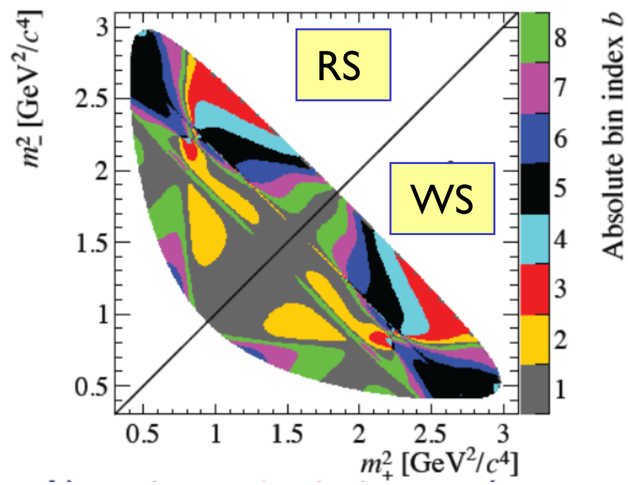
D^0 mixing parameters in $D^0 \to K_S^0\, \pi^+\pi^-$

- 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 $D^0 \to K_S^0\, \pi^+ \pi^-$ decays with very small background. $\overline{D}$ or D flavour tagging using $D^* \to D\, \pi$ 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





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

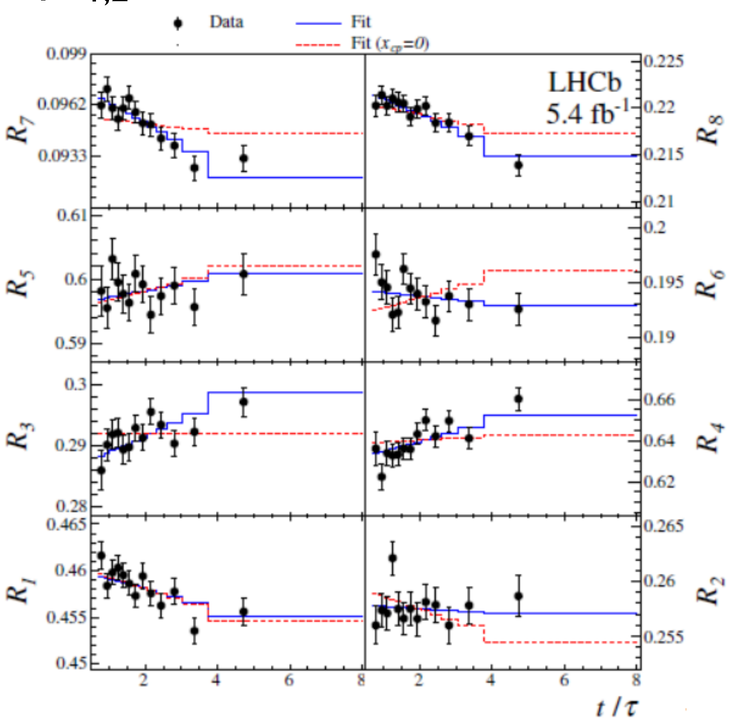
D^0 mixing parameters in $D^0 \to K_S^0 \pi^+\pi^-$

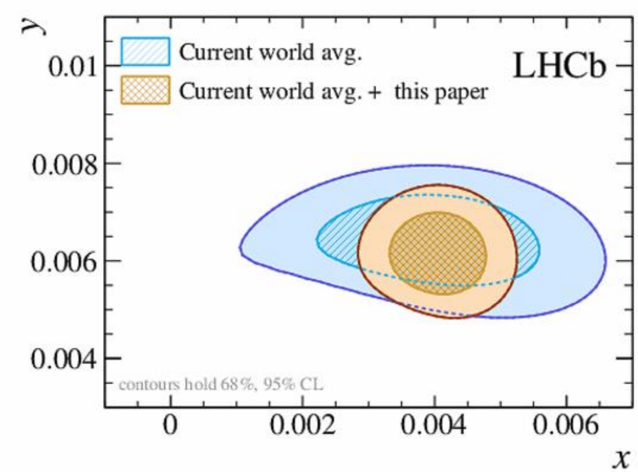
- Plot Ratio R_i : asymmetry for Dalitz bin *i* in bins of decay time
  - Deviations from constant values are due to mixing

PRL127 (2021) 111801

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

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





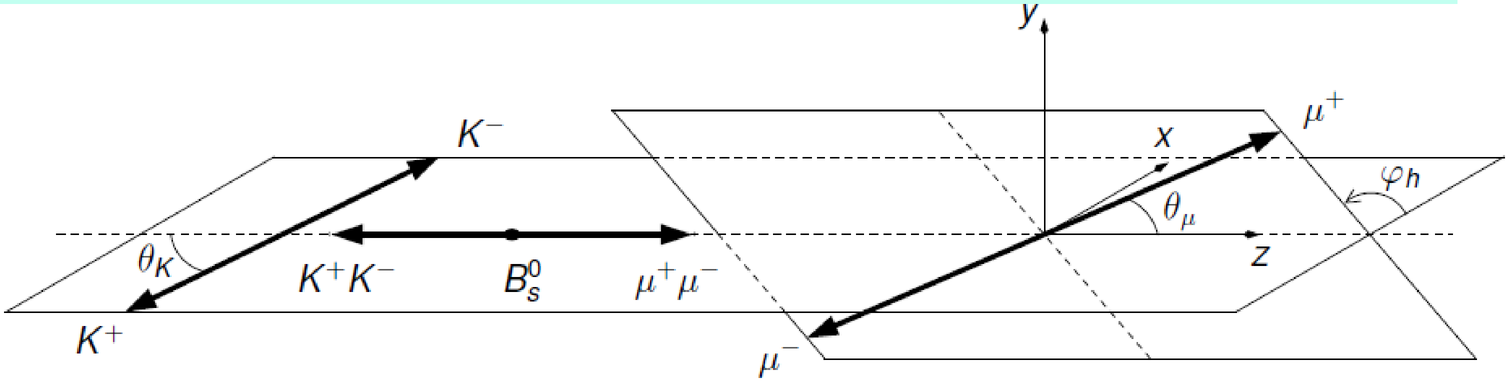
m_1-m_2 = 6.4x10^{-6} eV = 1x10^{-38}g = 0.00000000000000000000000000000000000001 grams !!

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

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

- ϕ is a vector meson (spin 1)
- Vector-vector final state: mixture of CP-odd and CP-even components

Need to perform time-dependent $B_s \rightarrow J/\Psi\ \phi$ 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

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

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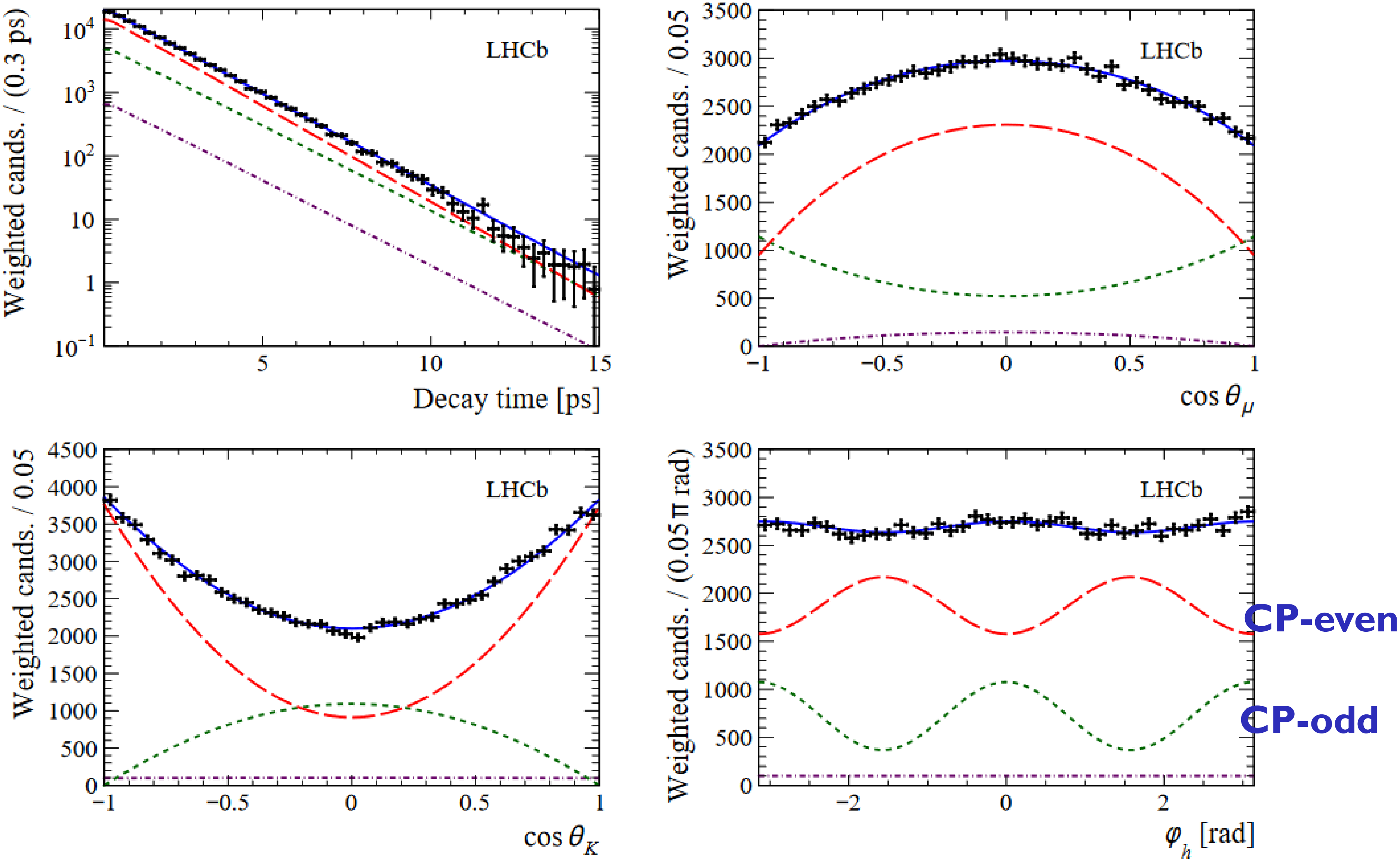
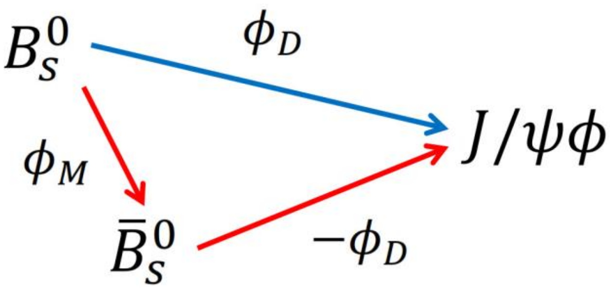
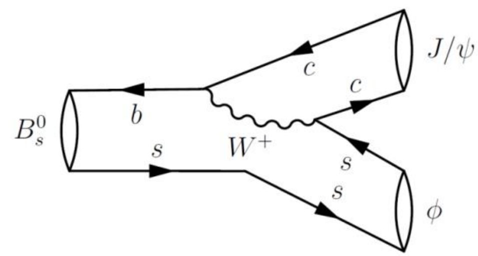
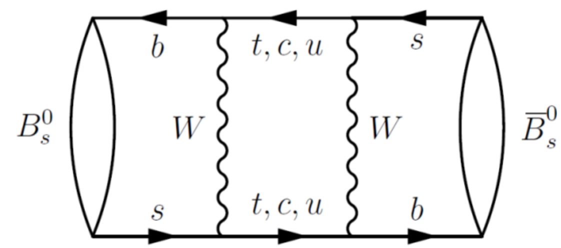


B_s weak mixing phase ϕ_s in $B_s \to J/\psi\ \phi$







- "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 - $\bar{B}^0$ 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)

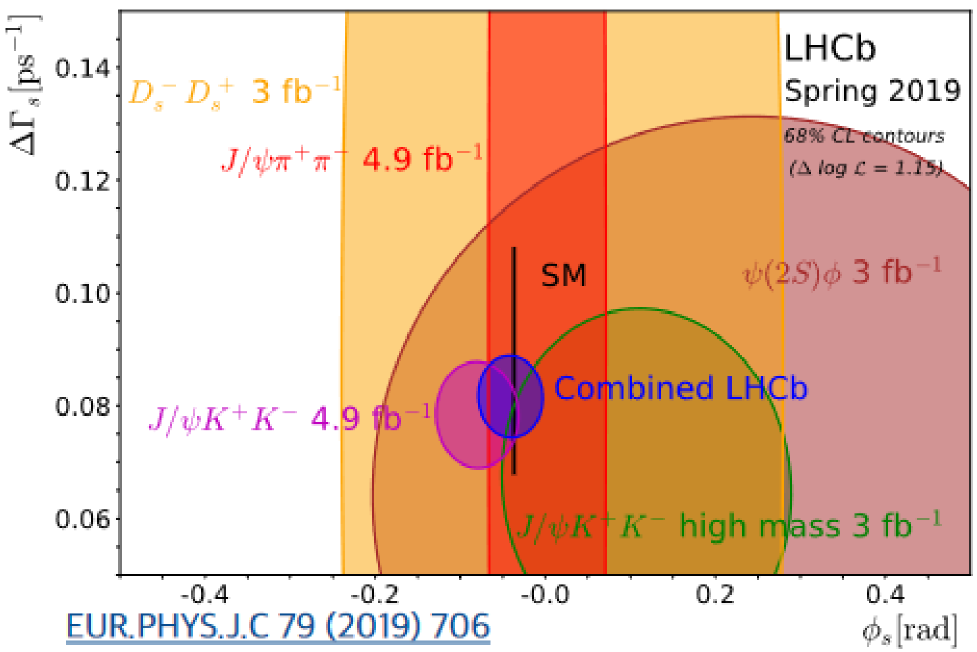
LHCb combination

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

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

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



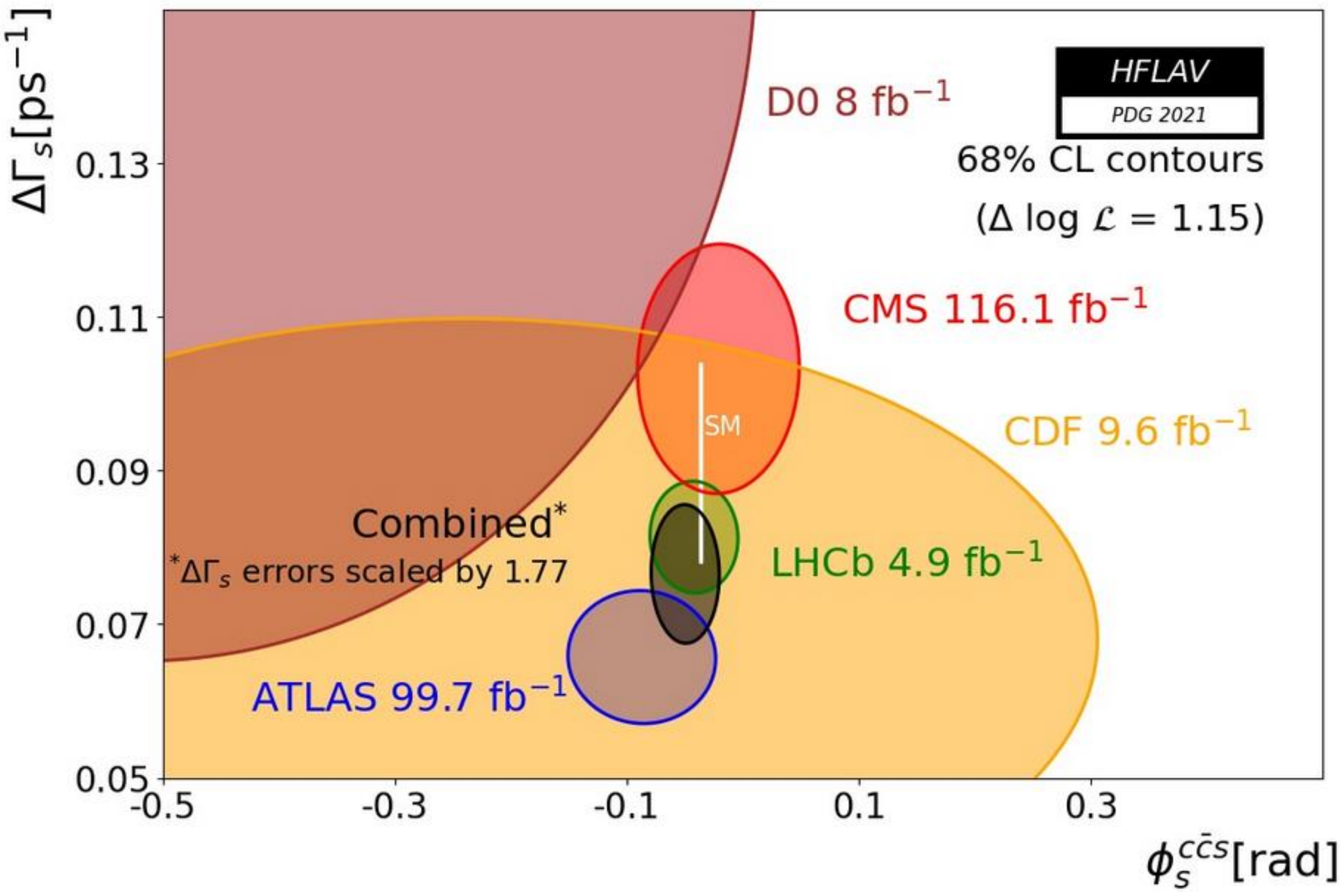
EUR.PHYS.J.C 79 (2019) 706

HFLAV combination all experiments

CP-violating phase:

$\phi_s = -0.050 \pm 0.019$ rad

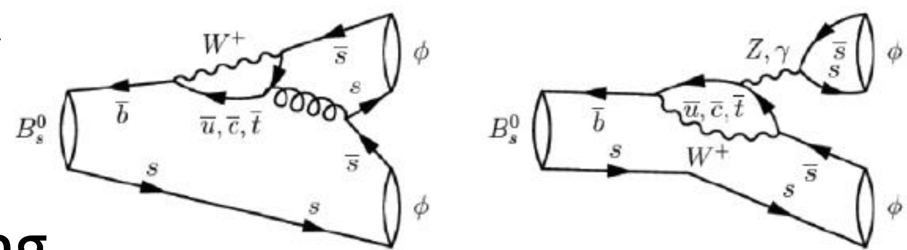
($\phi_s^{SM} = -0.037 \pm 0.001$ rad)



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

LHCb-PAPER-2019-019

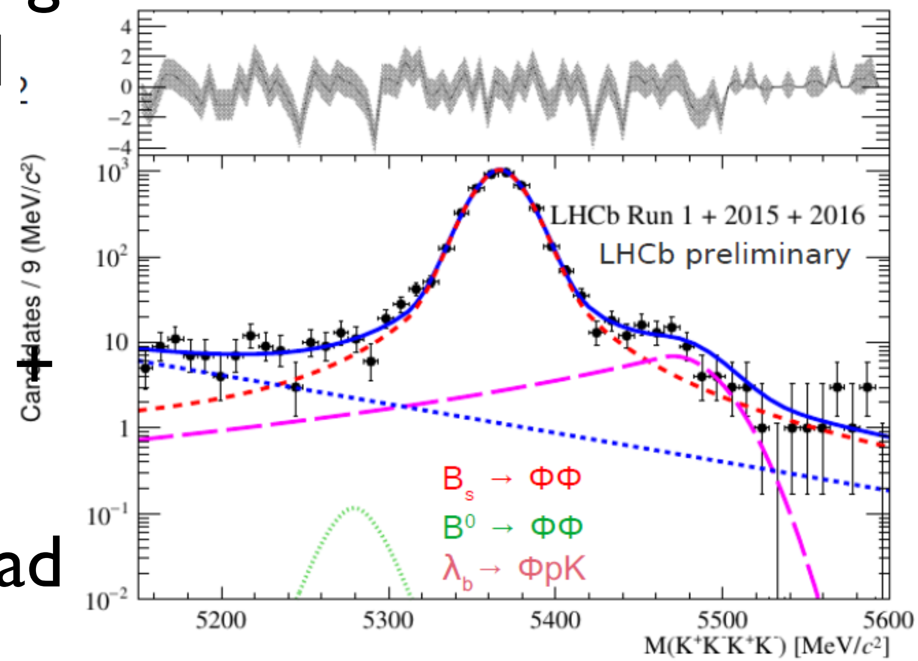
- Enhanced sensitivity to NP since decay is dominated by penguin loop



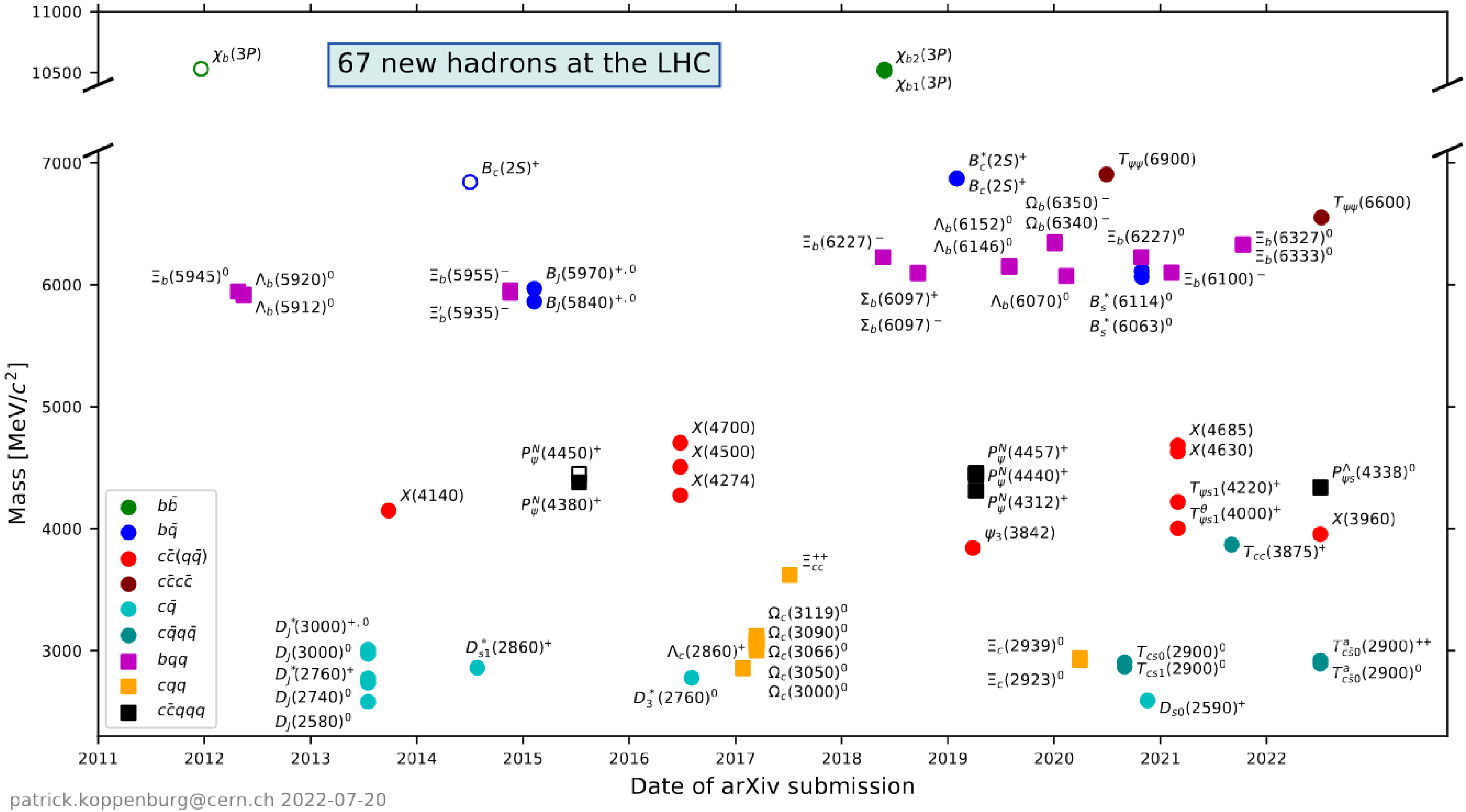
- SM prediction of CP violating phase is small < 20 mrad

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

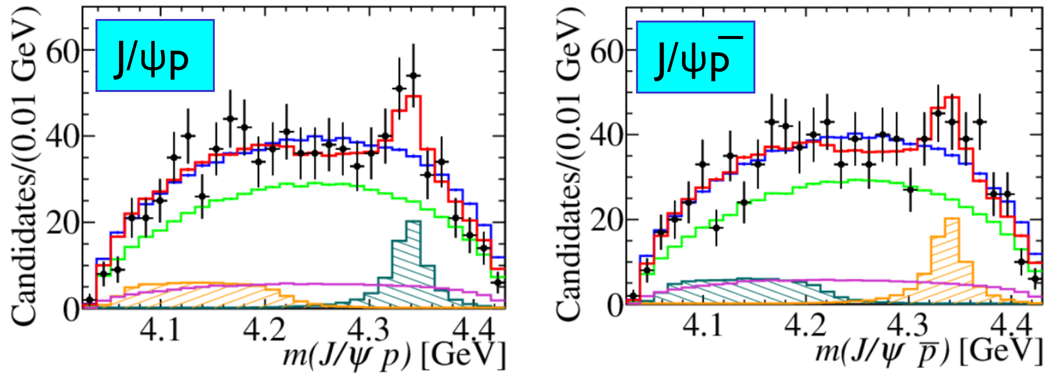


With thanks to Patrick Koppenburg

Evidence for more pentaquark states

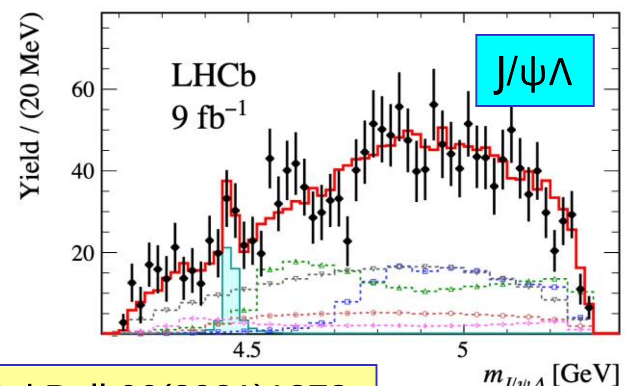
- Amplitude analysis using 800 $B_s^0 \to J/\psi p\bar{p}$ decays
- Observe additional structure in $J/\psi p$ and $J/\psi\bar{p}$ spectra
- Significance of 3.1σ to 3.7σ depending on J^P assignment
- Evidence for new $P_c(4337)^+$ state consistent with another ($c\bar{c}uud$) pentaquark

arXiv:2108.04720



	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 $\Xi^-_b \to J/\psi\Lambda K^-$ 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



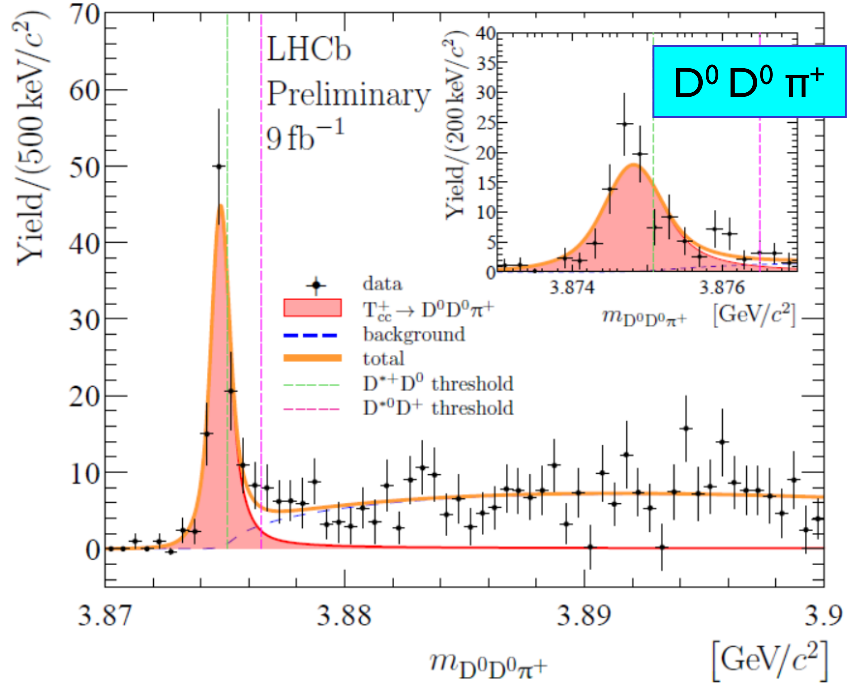
Sci.Bull.66(2021)1278

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

LHCb-PAPER-2021-031

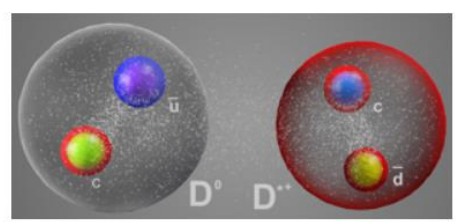
- Study $D^0 D^0 \pi^+$ mass spectrum near $D^{*+}D^0$ and $D^{*0}D^+$ thresholds

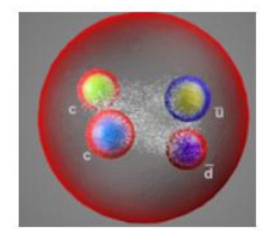
$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$



- 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

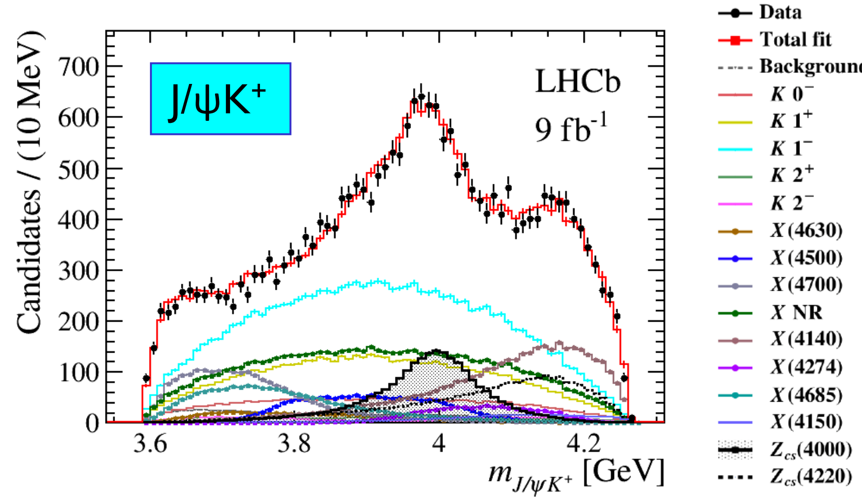




- Possible evidence for molecular bound state, but jury still out.

More observations of new tetraquark states

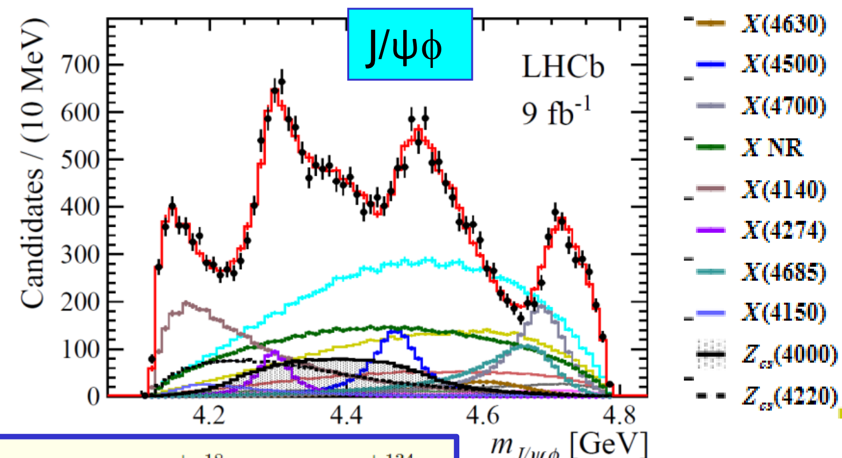
- $B^+ \to J/\psi\phi K^+$ sample
- Observe structure in $J/\psi K$
- Observation of two new $c\bar{c}u\bar{s}$ tetraquark states $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$
- Significance of 15σ and 6σ respectively, 1^+ assignment



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

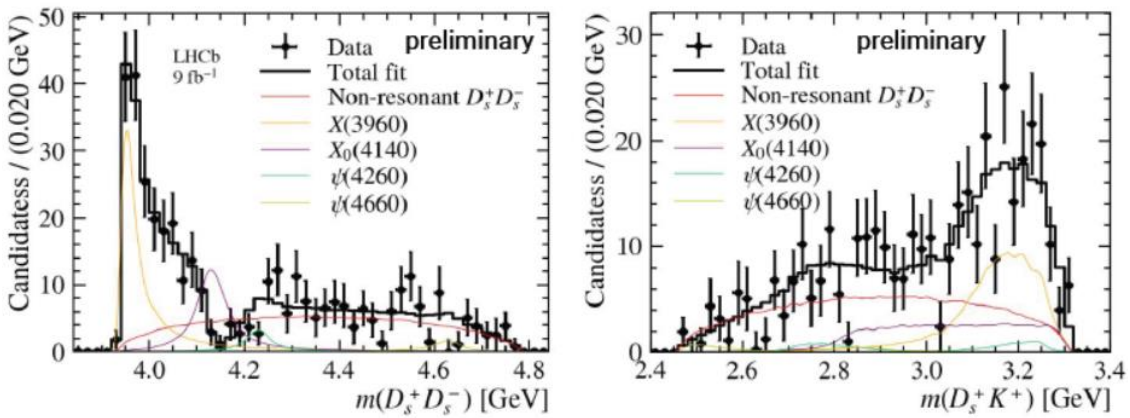


$X(4630)$	5.5 (5.7)	$4626 \pm 16 ^{+\,18}_{-110}$	$174 \pm 27 ^{+134}_{-\,73}$
$X(4685)$	15 (15)	$4684 \pm 7 ^{+13}_{-16}$	$126 \pm 15 ^{+37}_{-41}$

Latest 4-quark states from LHCb

NEW

- Observation of X(3960) in $D_s^+D_s^-$ mass spectrum near threshold Quark content: $[c\bar{c}s\bar{s}]$
- Question whether X(3960) could be the $X_{c0}(3930)$?
- Determination of the properties needs more work



LHCb-PAPER-2022-026 (in preparation)
LHCb-PAPER-2022-027 (in preparation)

$$M_0 = 3955 \pm 6 \pm 11 \text{ MeV}$$

$$\Gamma_0 = 48 \pm 17 \pm 10 \text{ MeV}$$