Overview of LHCb Run 2 Results

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On behalf of the LHCb collaboration

Virtual XXVII Cracow EPIPHANY
Conference on the future of particle physics
January 7th – 10th 2021

Outline

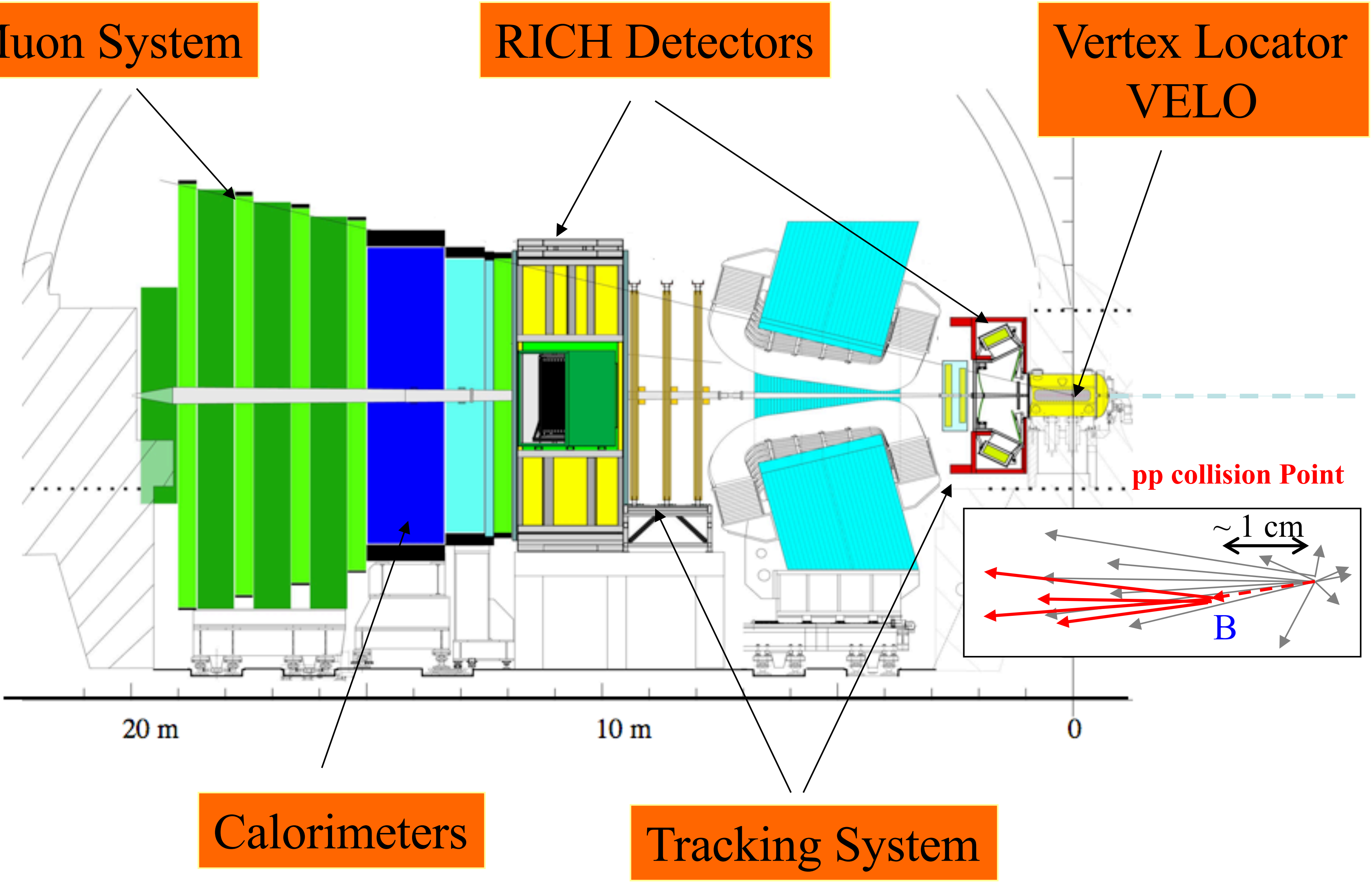
The LHC is a heavy flavour factory: Golden Age for precision studies and new measurements. Focus today on selection of recent LHCb results from Run 2

- Updates to γ
- The Kπ puzzle
- Rare decays: B → K*$\mu\mu$ and friends
- Spectroscopy

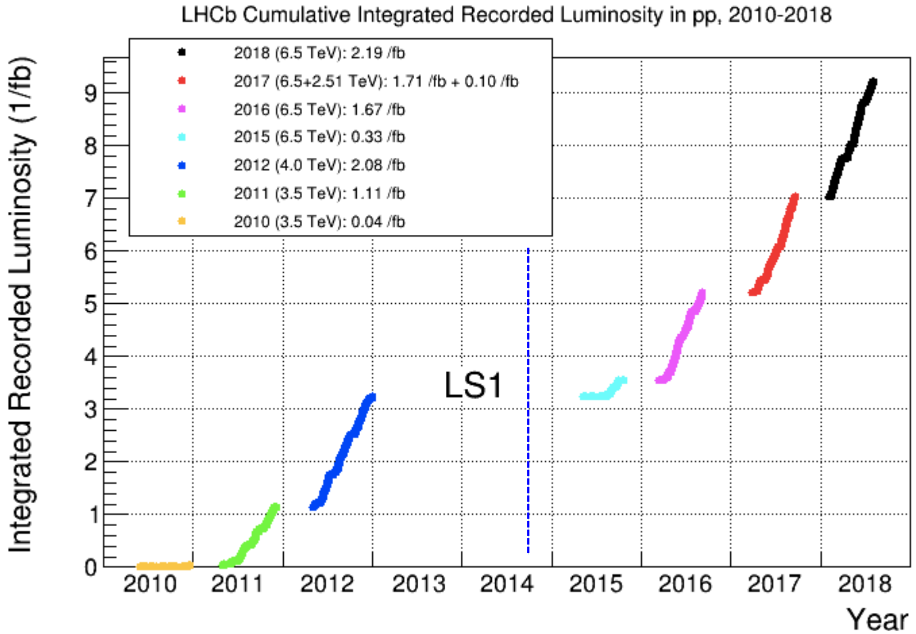
Other LHCb talks in this conference:

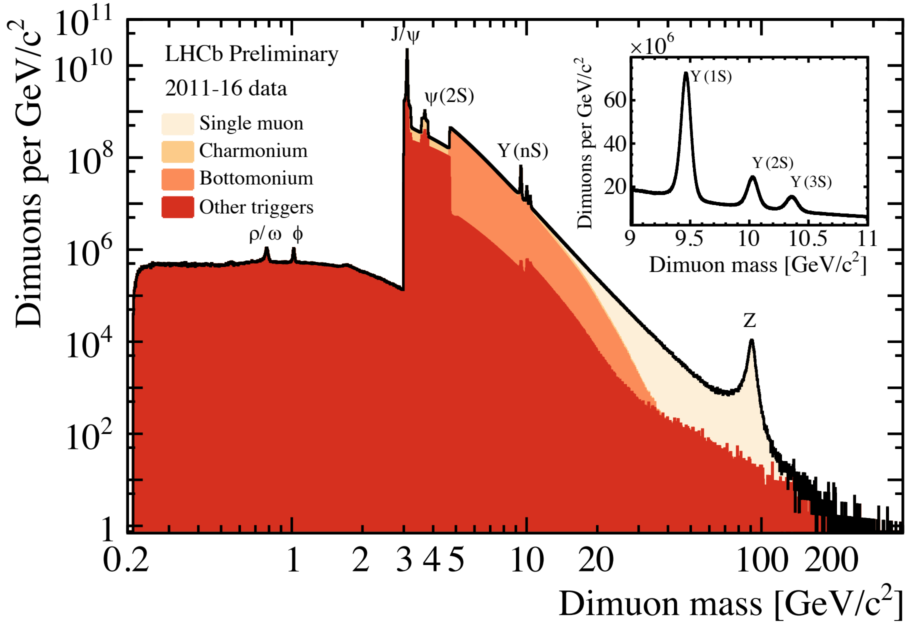
Angular observables in the B → K*$\mu\mu$ decay at LHCb, *J. Borsuk*
Mixing and CP violation in charm mesons, *B. Shields*
Spectroscopy in beauty decays at the LHCb experiment, *T Ovsiannikova*

The LHCb Detector



Introduction

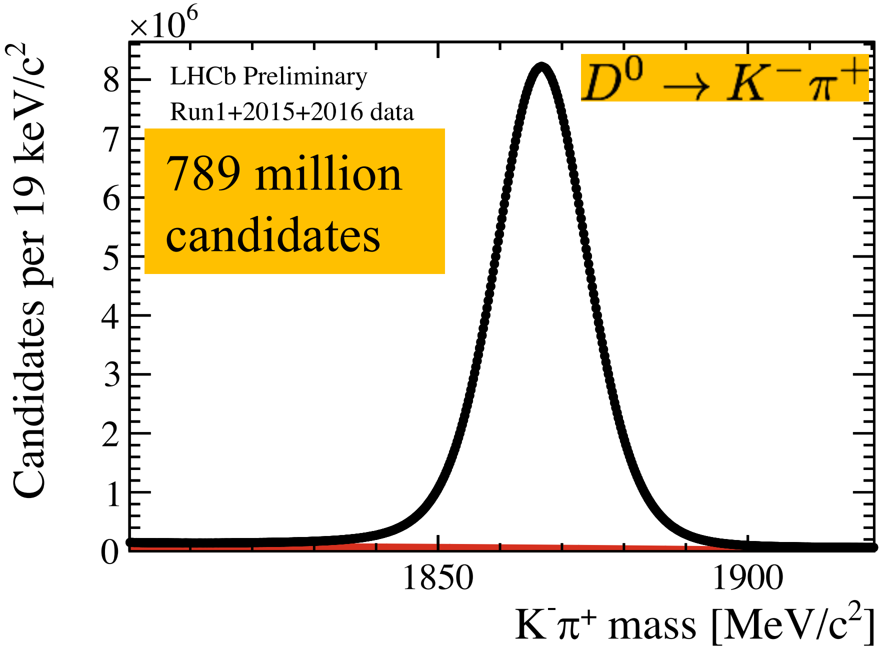




World largest heavy flavour dataset (9 fb^{-1}) collected during Run1+Run2

- Precision tracking
- Excellent PID using RICH
- Trigger for fully hadronic decays

Int.J.Mod.Phys. A30 (2015) no.07, 1530022

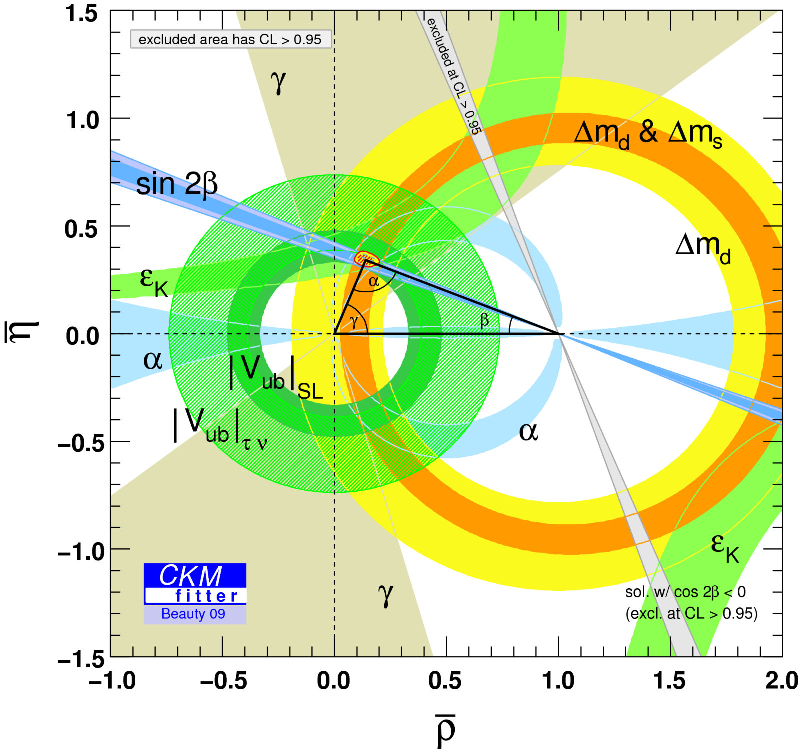


Precision CKM and CP measurements

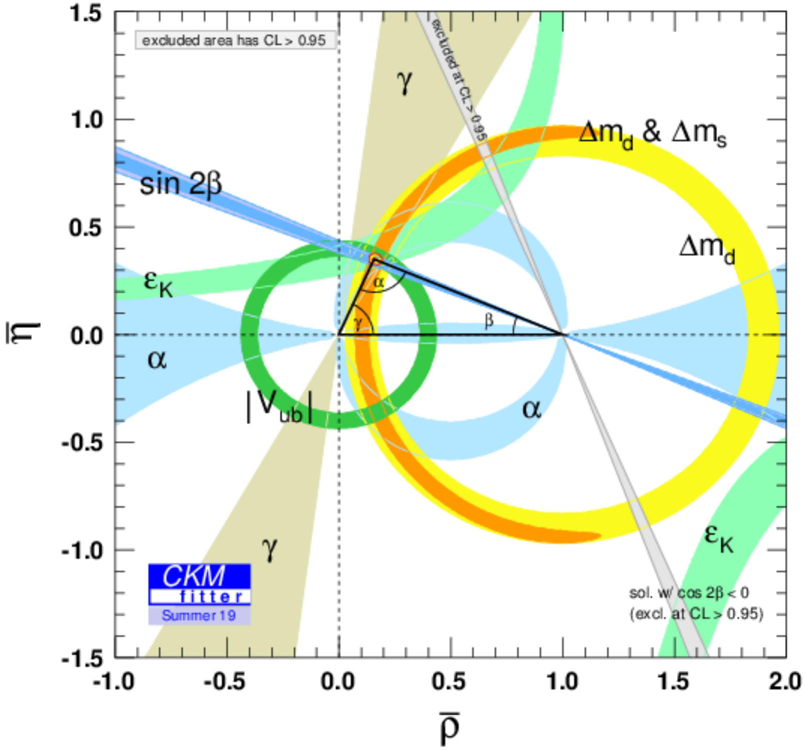
CKM evolution

Huge progress over the last decade in measurement of CKM parameters, largely driven experimentally by LHCb

$\sigma(\gamma) \sim 22^o$



$\sigma(\gamma) \sim 5.5^o$



Here focus on recent measurements of CKM angle γ and Δm_s using full LHCb dataset

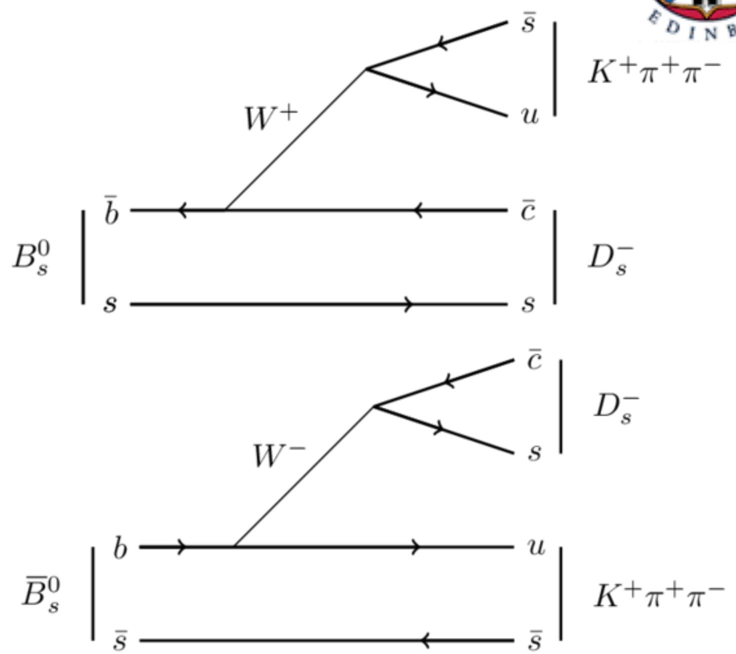
γ with $B_s \to D_s^- K^+ \pi^+ \pi^-$

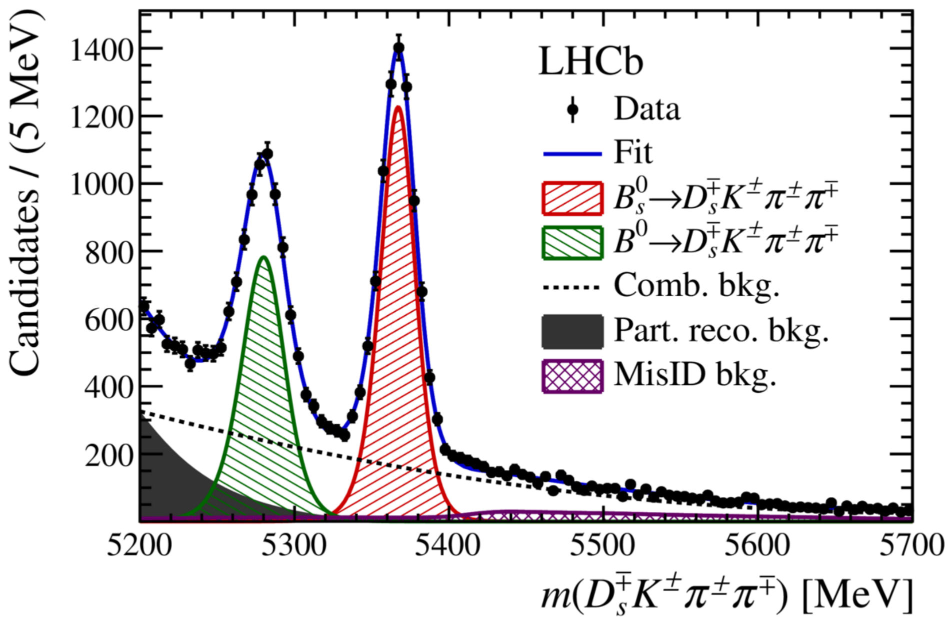
arXiv: 2011.12041

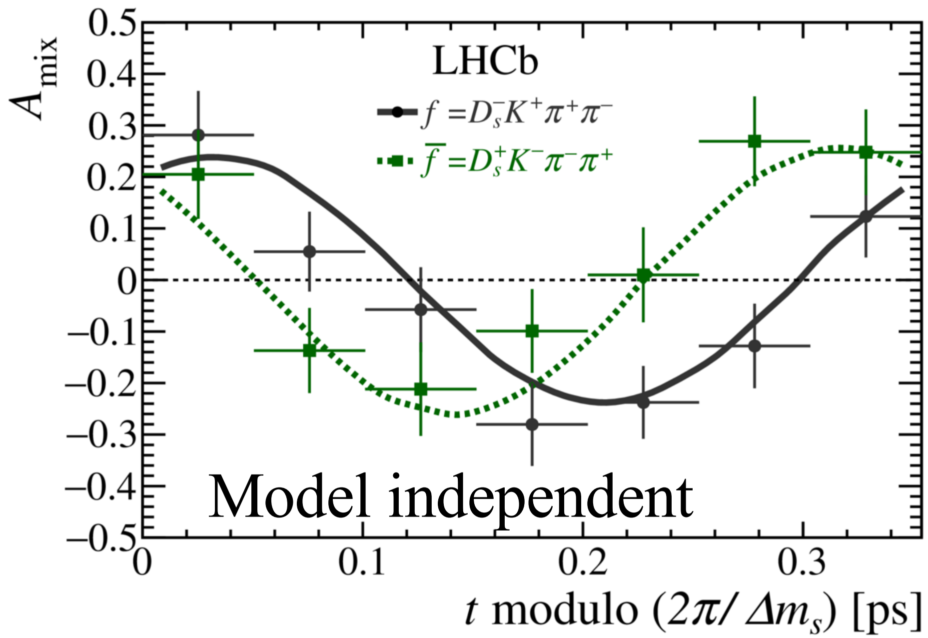
Interference between decays with/without mixing allows to measure γ-$2\beta_s$ via time dependent amplitude analysis

$\gamma = (44 \pm 12)^o$ Model dependent

$\gamma = (44^{+20}_{-13})^o$ Model independent







Δm_s with $B_s \to D_s^- \pi^+\pi^+\pi^-$

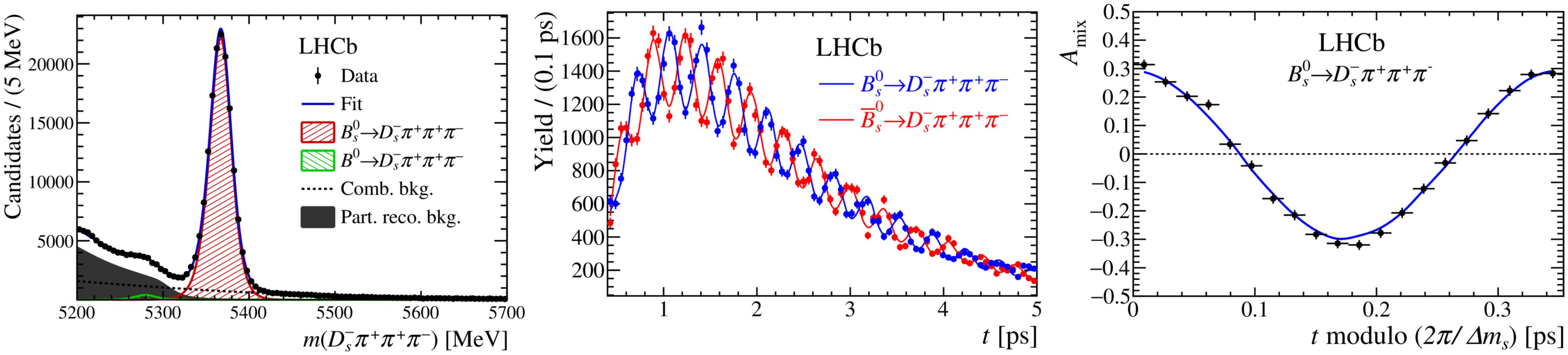
Flavour specific channel $B_s \to D_s^+ \pi^-\pi^+\pi^-$ used to calibrate decay time acceptance and flavour tagging

Has excellent decay time resolution (37 fs) and allows measurement of Δm_s

$$\Delta m_s = (17.757 \pm 0.007 \pm 0.008)\ \mathrm{ps}^{-1}$$

Most precise measurement to date

$$\Delta m_s = (17.756 \pm 0.02)\ \mathrm{ps}^{-1}\ \text{(PDG20)}$$



γ from $B^{\pm} \rightarrow D^0 h^{\pm}$, $D \rightarrow K_s hh$

Interference between $\bar{b} \rightarrow \bar{c}u\bar{s}$ and $\bar{b} \rightarrow \bar{u}c\bar{s}$ amplitudes gives access to γ [BPGGSZ, arXiv:2006.12404]

To determine γ need strong phase

Model independent approach

Bin data into regions of Dalitz

Use measurements of phase difference

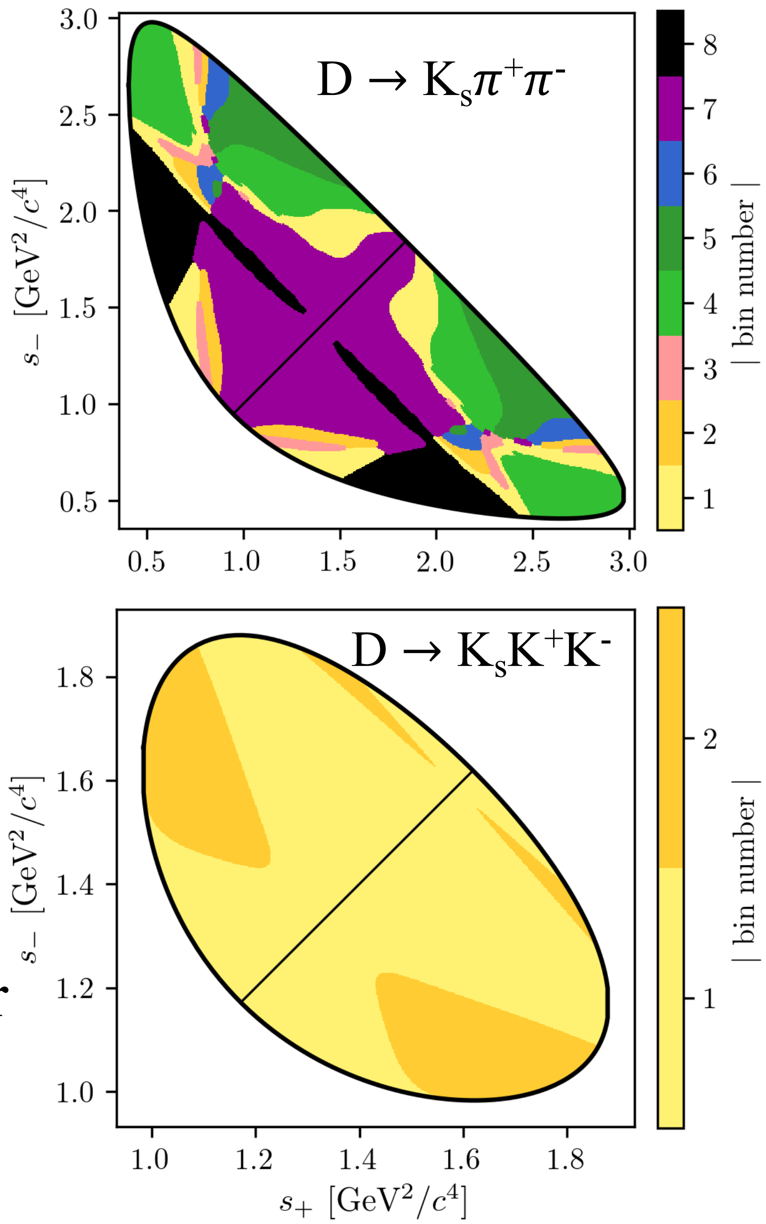
$$\delta_D = \arg(A(D^0)) - \arg(A(\overline{D}^0))$$

from CLEO, Phys.Rev.D 82 (2010) 112006

And important new inputs from BES3 this year

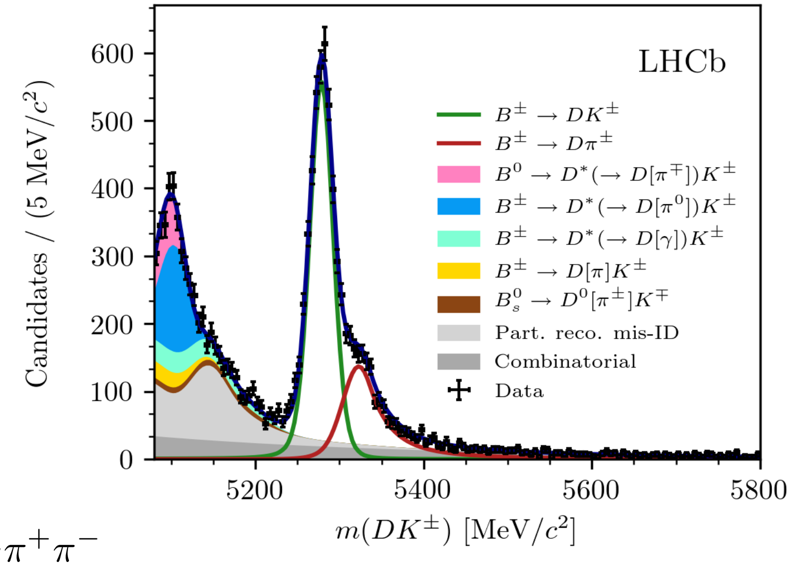
PRL 124 (2020) 241802

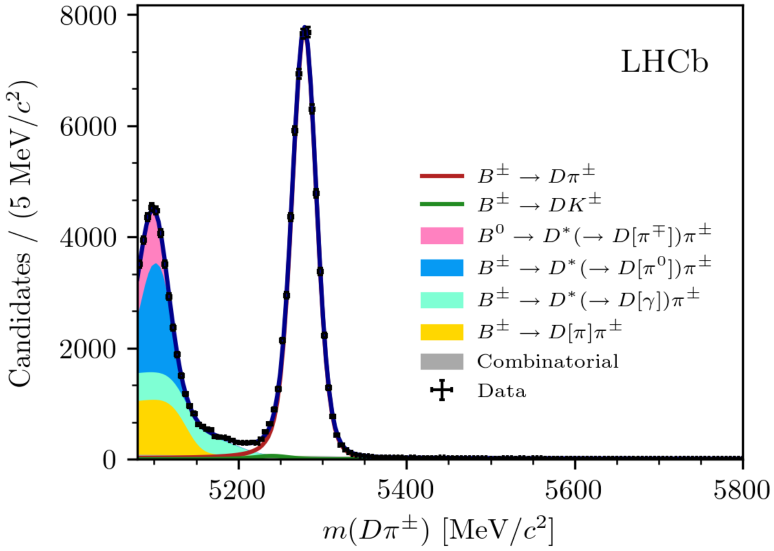
PRD 102 (2020) 052008)



γ from $B^{\pm} \rightarrow D^0 h^{\pm}$, $D \rightarrow K_s hh$

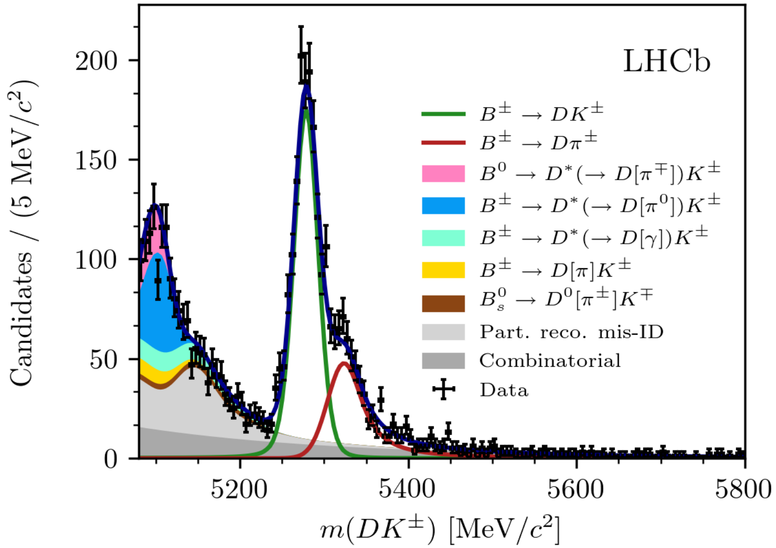
arXiv: 12010.08483

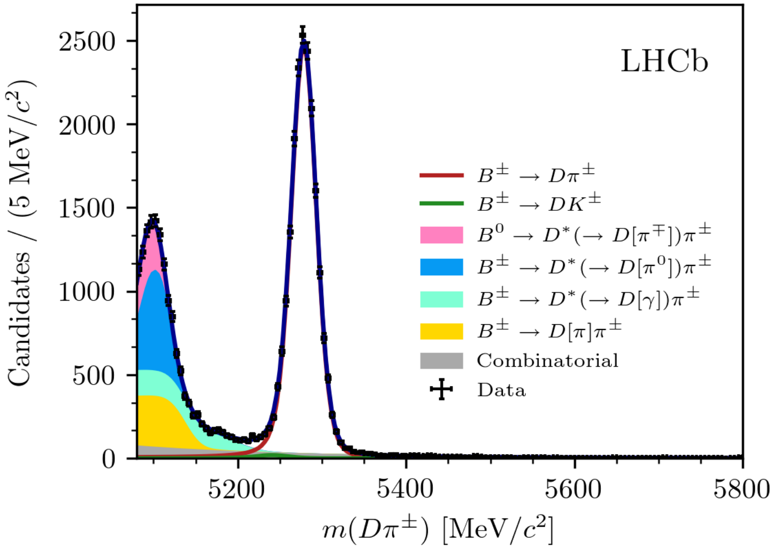




K_s decay in VELO

$D \rightarrow K_S\pi^+\pi^-$



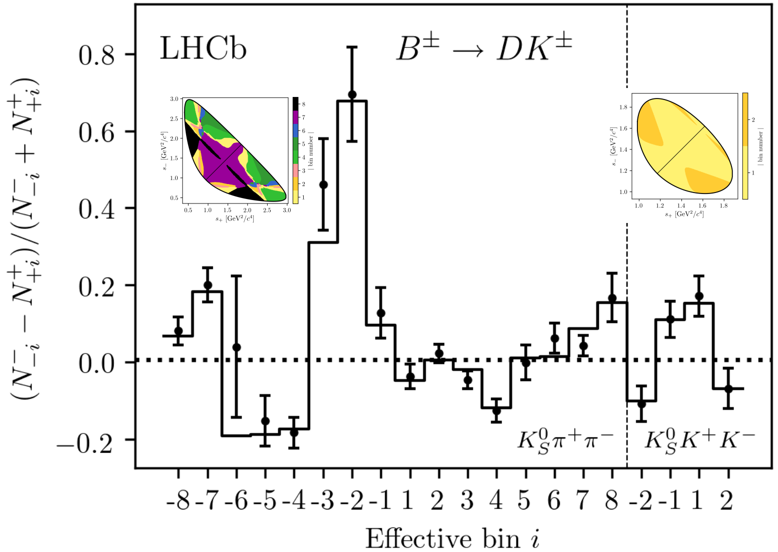


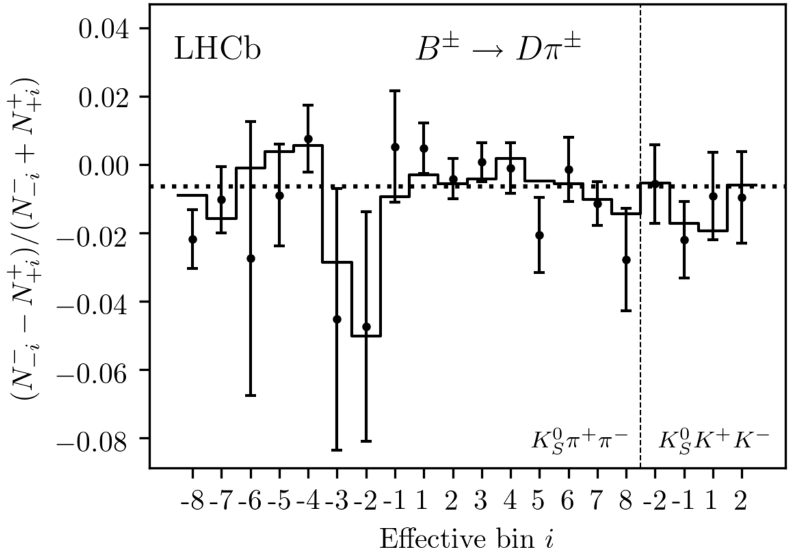
K_s decay after VELO

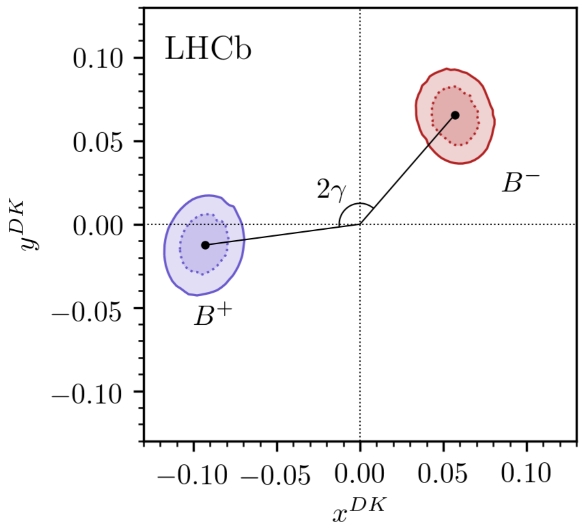
Very clear signals observed: CP observables extracted from fit in bins

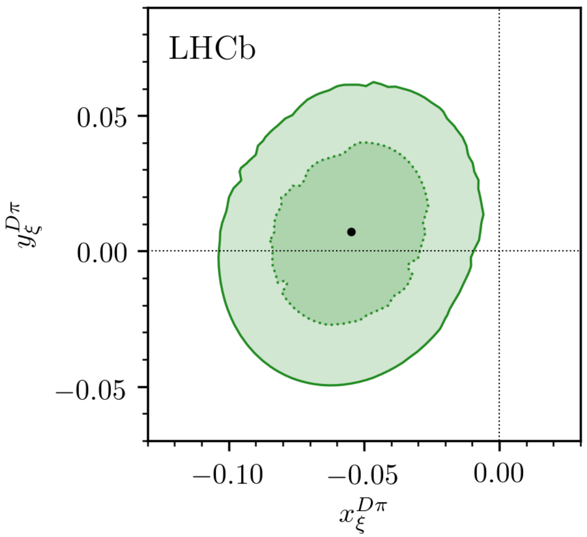
γ from $B^{\pm} \rightarrow D^0 h^{\pm}$, $D \rightarrow K_s hh$

Dalitz bins



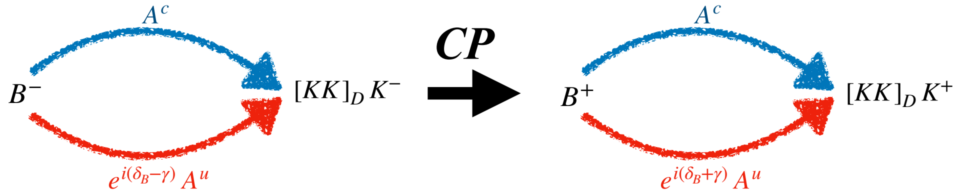


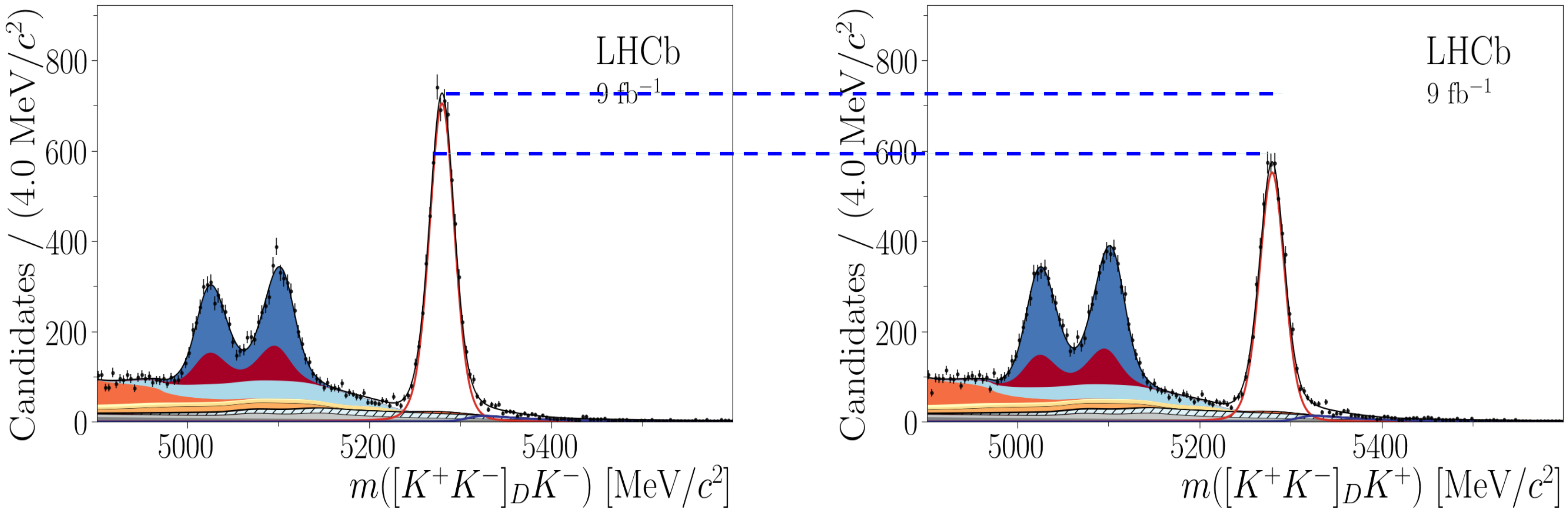




$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$
$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$
$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$
$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$
$$\delta_B^{D\pi^\pm} = (291^{+24}_{-26})^\circ.$$

γ in $B^+ \to D^{(*)} h^+$, $h = \pi, K$



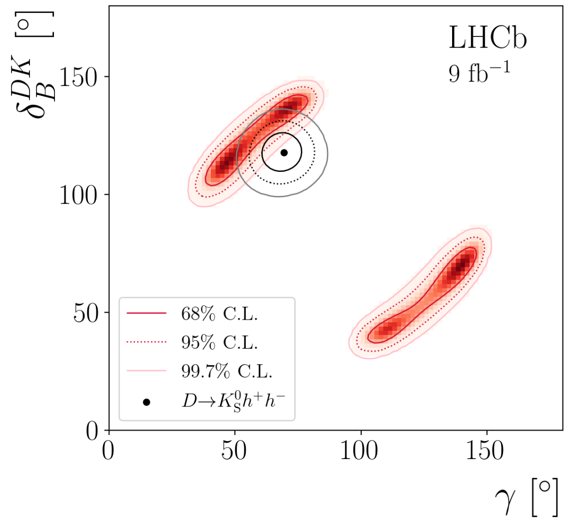


arXiv: 2012.09903

Update to full Run 1+2 dataset

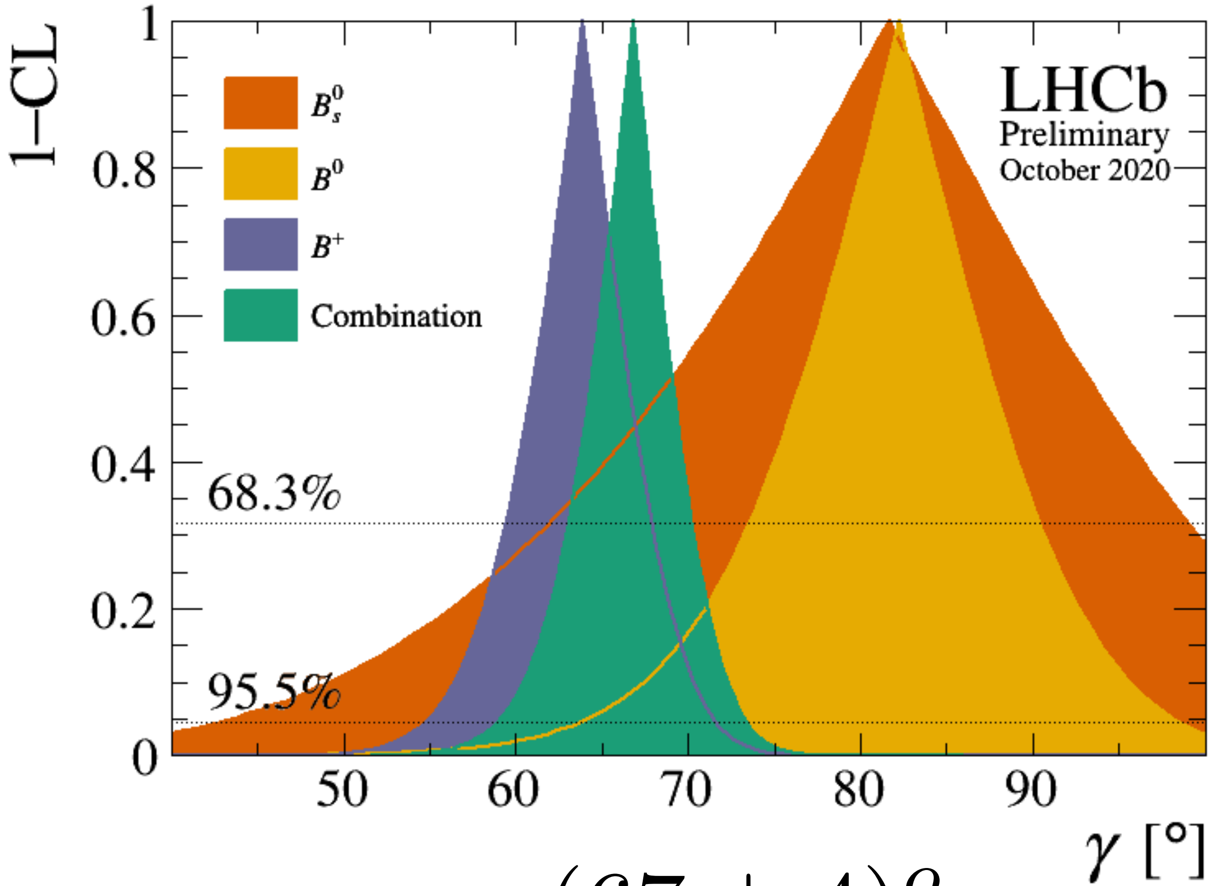
28 observable from $B^+ \to D^{(*)} h^+$, $h = \pi, K$ modes

9 parameters determined including γ



LHCb γ combination

LHCb-CONF-2020-003



$$\gamma = (67 \pm 4)^o$$

- Excellent agreement with indirect determinations
- Experimental precision on α and γ now comparable
- LHCb goal for γ achieved + more to come, e.g. $B_s \rightarrow D_s K$ with Run 2 data

The Kπ puzzle

Isospin symmetry expect

$$A_{CP}(B^0 \to K^+\pi^-) = A_{CP}(B^+ \to K^+\pi^0)$$

But Babar and Belle measured these asymmetries to be different at more than 5σ: The 'Kπ puzzle'

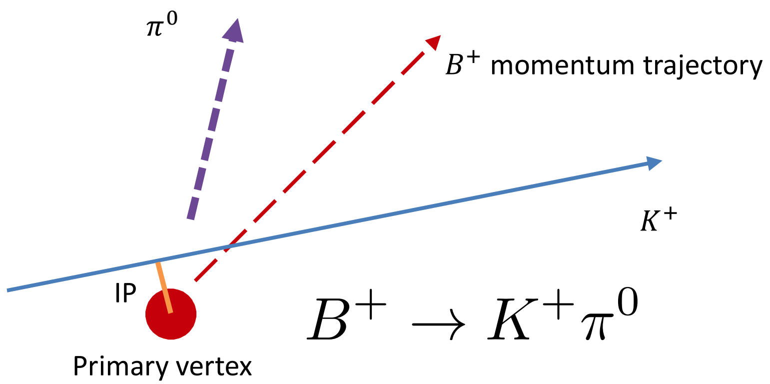
$$A_{CP}(B^0 \to K^+\pi^-) = -0.084 \pm 0.004$$
$$A_{CP}(B^+ \to K^+\pi^0) = 0.040 \pm 0.021$$

PDG

$B^+ \to K^+\pi^0$ challenging topology at hadron collider

- Single displaced track: no vertex
- Many π^0 from PV: bad combinatorics

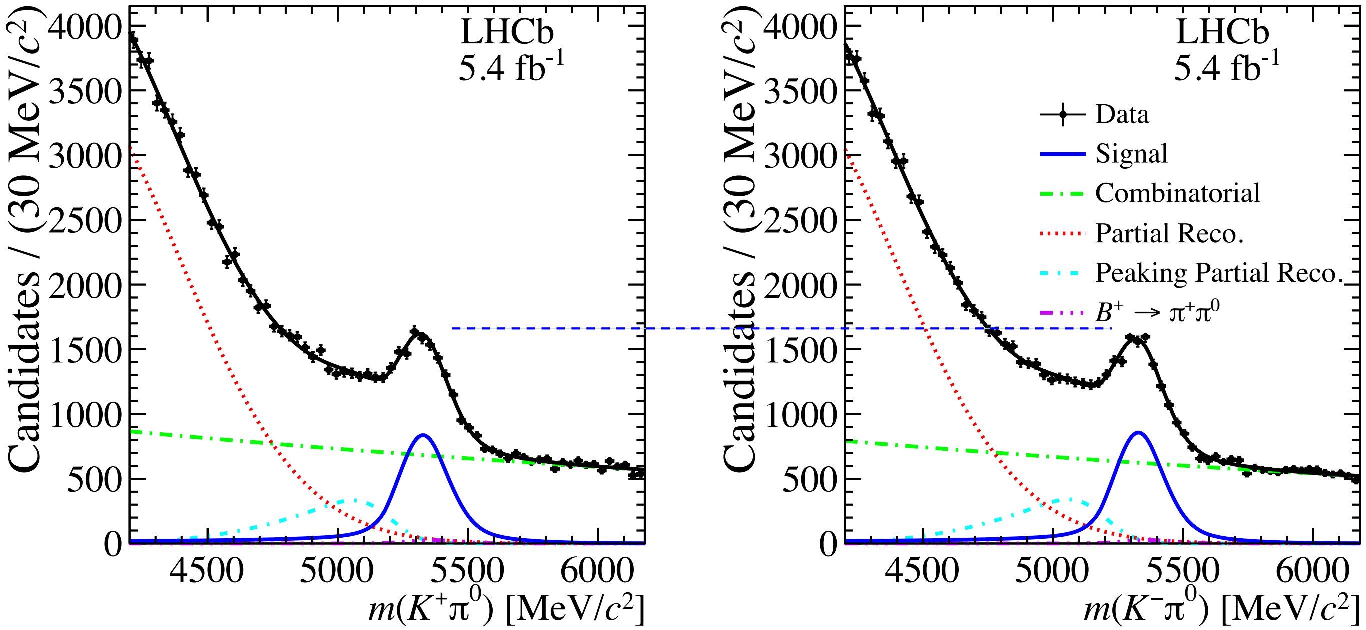
arXiv: 2012.12789



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

Run 2 dedicated trigger implemented
Offline analysis exploiting displacement and isolation topologies

The Kπ puzzle



Around 16k candidates selected

Use $B^+ \to J/\psi\, K^+$ as control channel to cancel detection/production asymmetries

$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

stat syst ext

Consistent with previous measurements + more precise. Reinforces Kπ puzzle

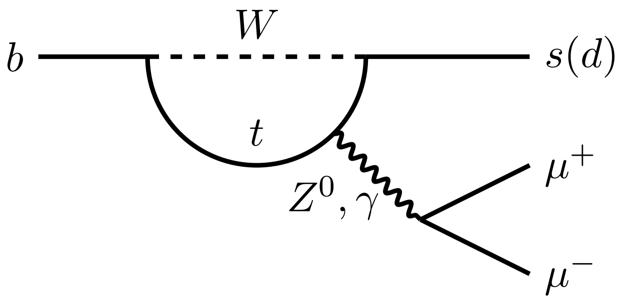
New WA $\Delta A_{CP}(K\pi) = 0.115 \pm 0.014$ 8σ from zero

Rare decays

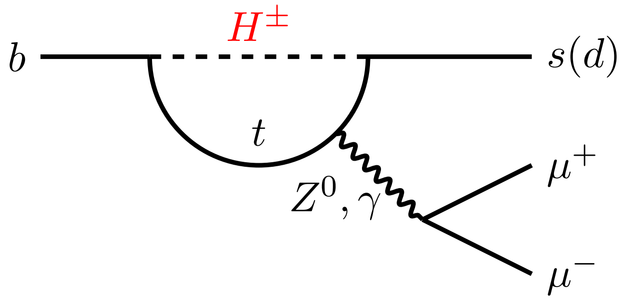
Electroweak Penguins

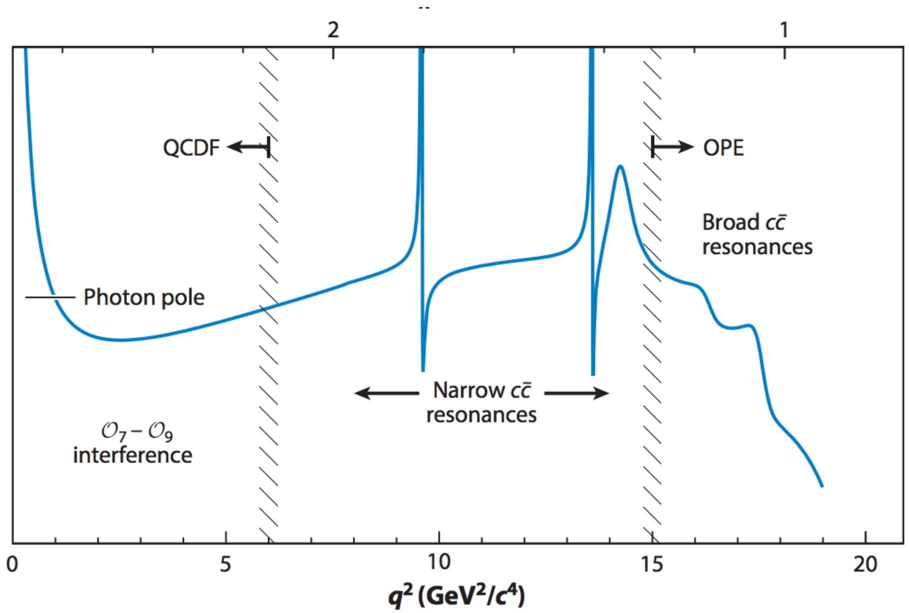
Branching ratios and angular distribution sensitive to New Particles in the loop

SM penguin diagram



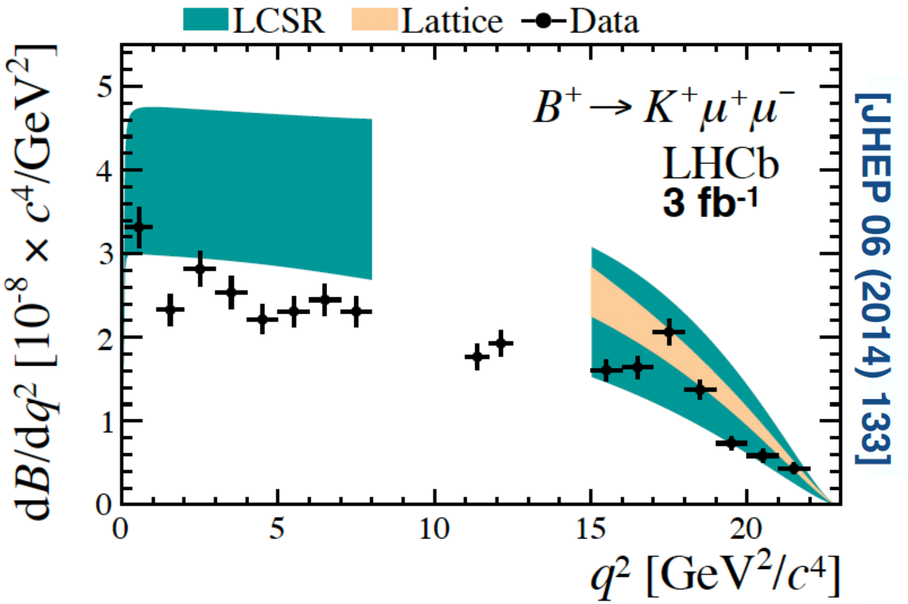
NP penguin diagram

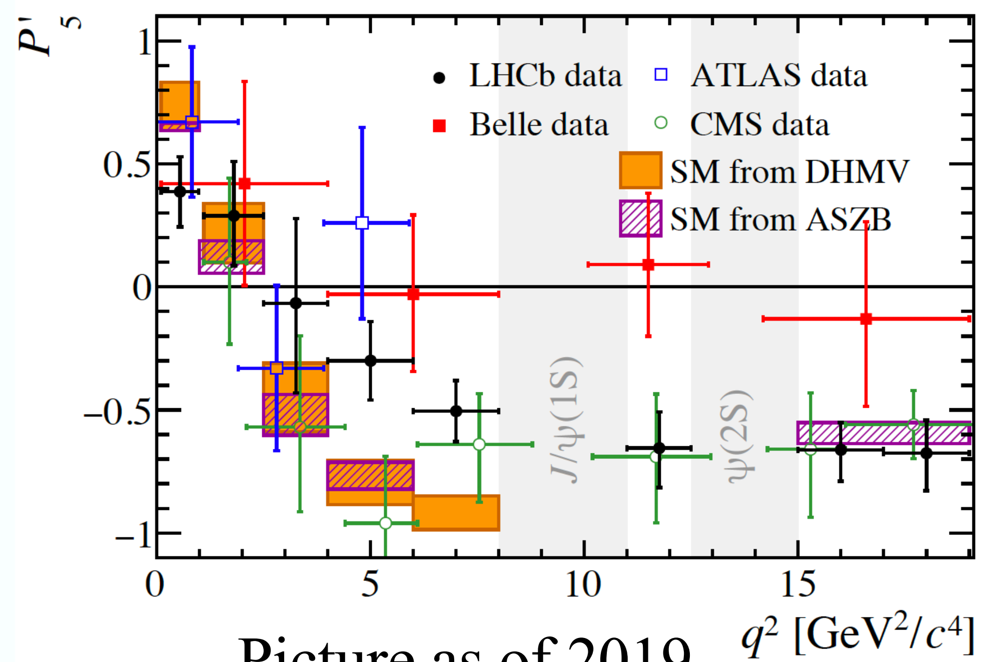




Different regions of dilepton mass allow to probe new physics in different Wilson coefficients

Electroweak Penguins: Recap





Picture as of 2019

Long-standing anomalies from Run 1 in electroweak penguin decays

Muon BF for many modes low compared to SM predictions

LHCb Angular analysis of $B^0 \to K^*\mu\mu$ shows tension in P_5' variable

Data points to new physics in Wilson coefficients C_9 (vector coupling) or C_9+C_{10} (axial vector)

Parallel hints of LFU violation (R_K, R_{K*})

Angular analysis of $B \to K^* \mu^+ \mu^-$

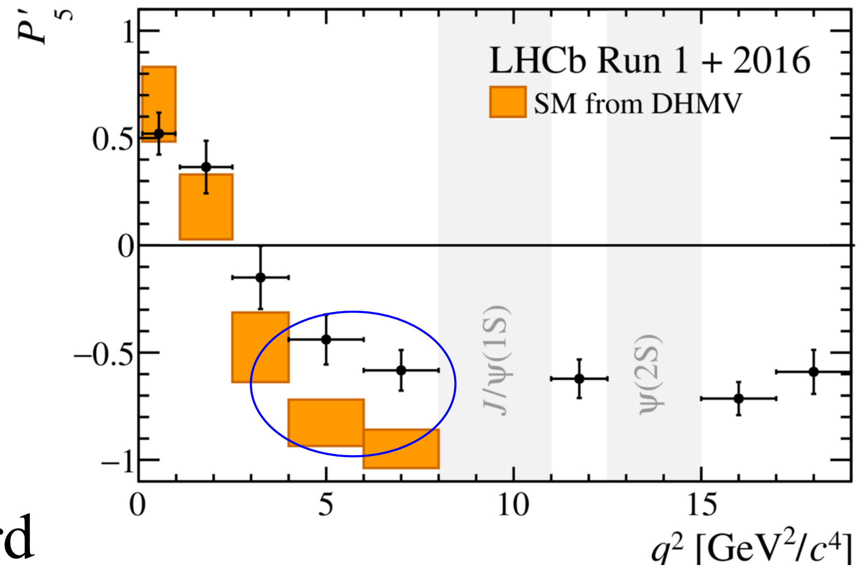
PRL 125 (2020) 011802

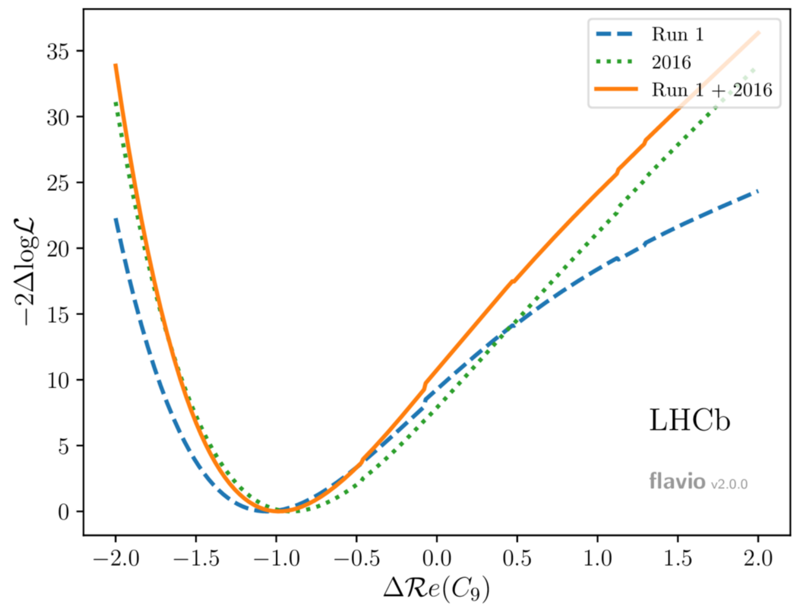
Update to Run 1 result including data from 2016

Local tensions at 2.5 and 2.9σ with Standard Model in P'_5

Fits using the FLAVIO package give 3.3σ discrepancy with Standard Model for Re(C_9)

Best fit give shift in C_9 of $-0.99^{+0.25}_{-0.21}$





Angular analysis of $B^+ \to K^{*+} \mu^+ \mu^-$

Sensitive to the same physics as $B^0 \to K^* \mu^+ \mu^-$

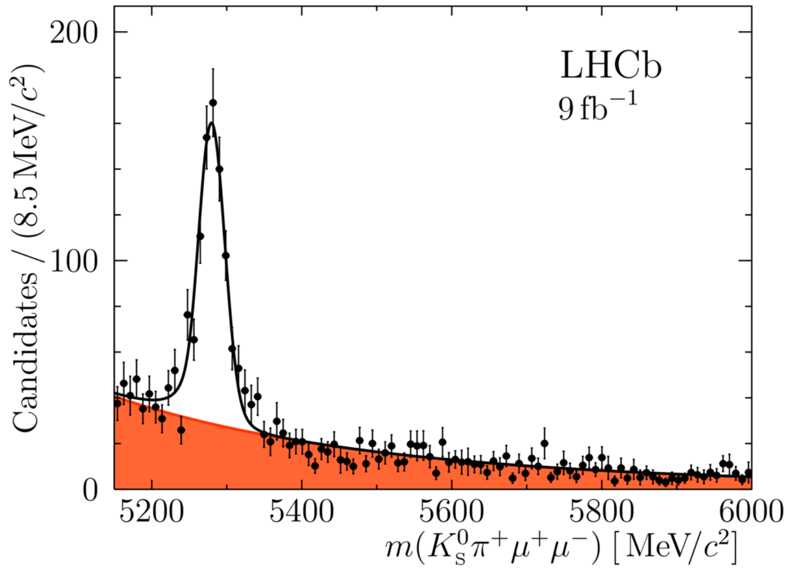
Smaller dataset (737 events) in Run 1+2

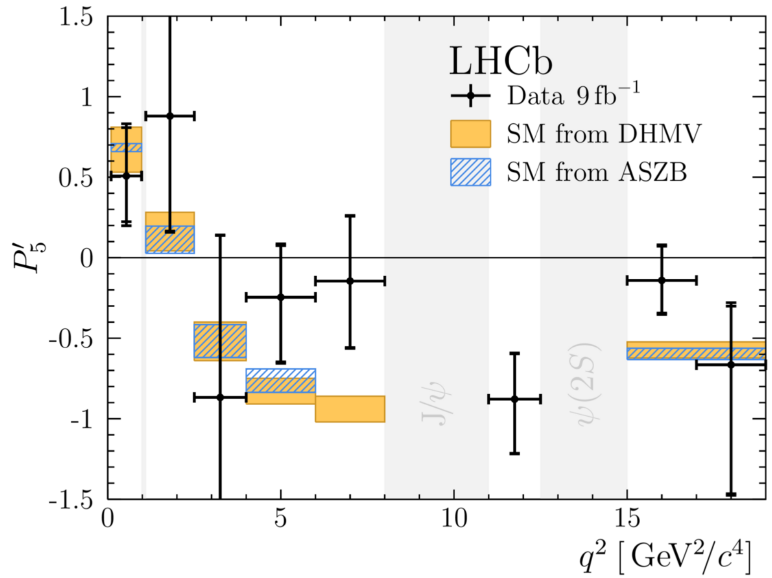
4-d fit to extract angular observables

Similar tensions seen as for $B^0 \to K^* \mu^+ \mu^-$ in P'_5

Favour shift with respect to SM of $Re(C_9) = -1.9$. Tension with SM is 3 σ

arXiv:2012.13241



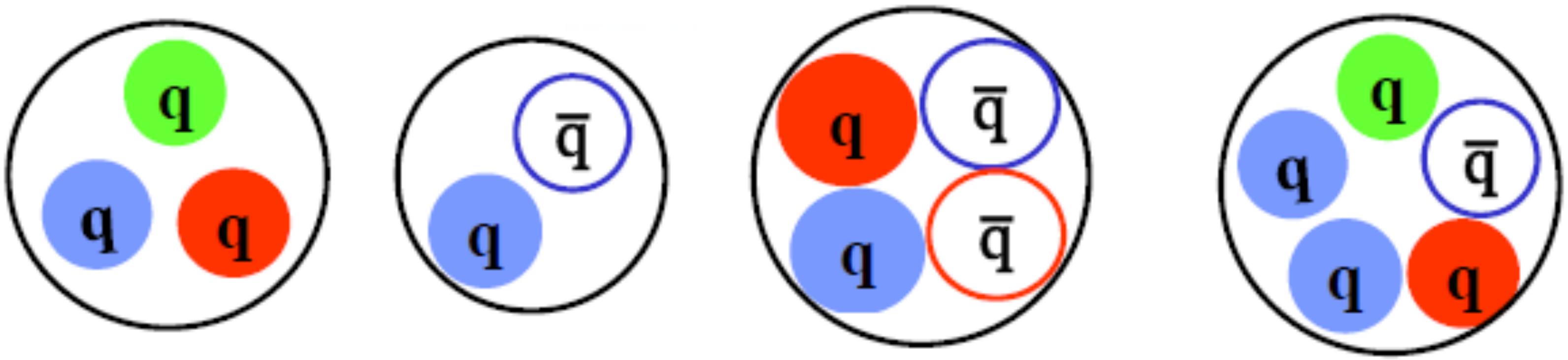


Spectroscopy

Spectroscopy

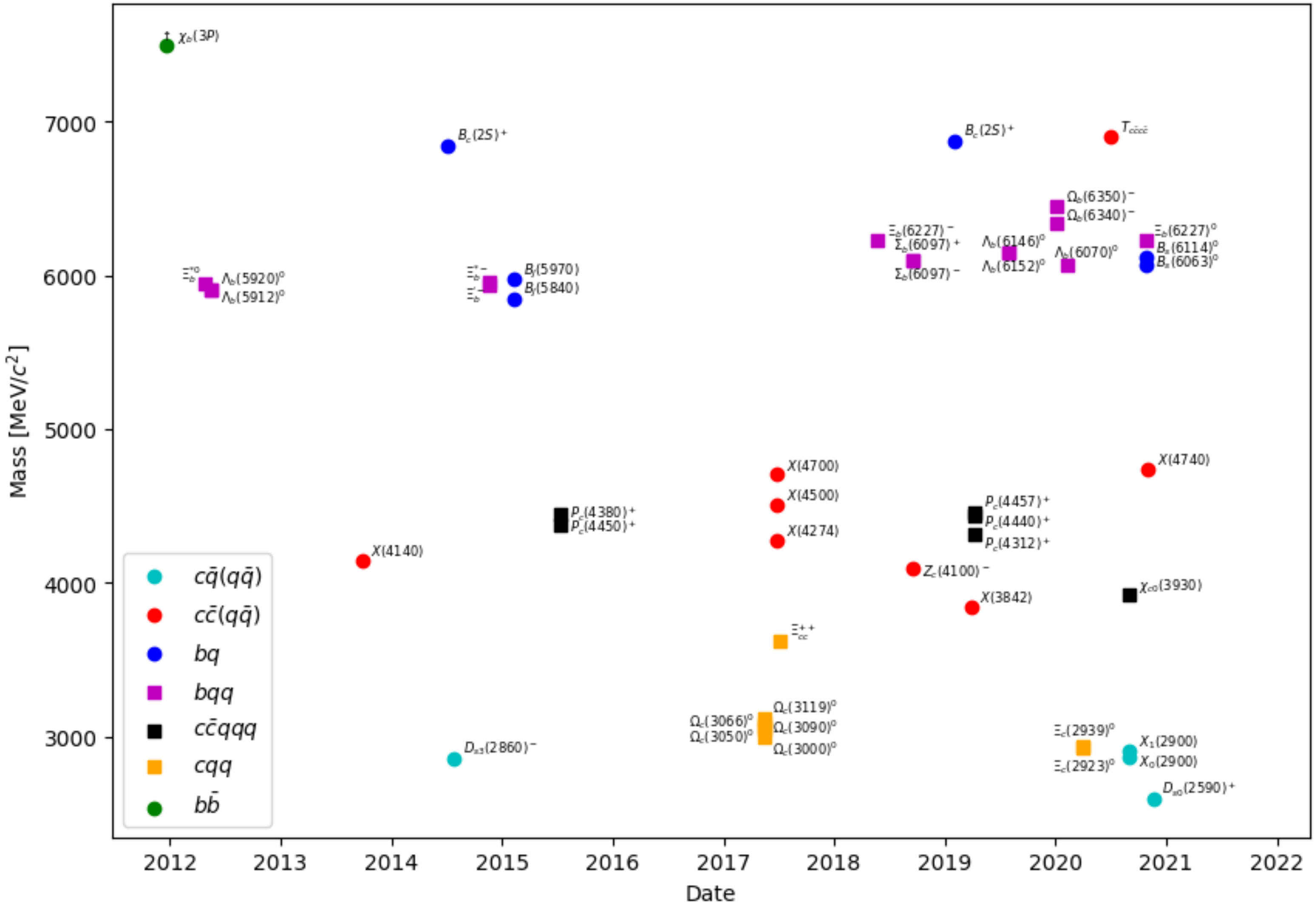
Studies of spectrum of hadronic resonances tests predictions of quark model and QCD

- Map out conventional states with two or three quarks
- Look for exotic states: tetraquarks, pentaquarks
- Study dynamics: diquarks, molecules
-



Spectroscopy

https://www.nikhef.nl/~pkoppenb/particles.html

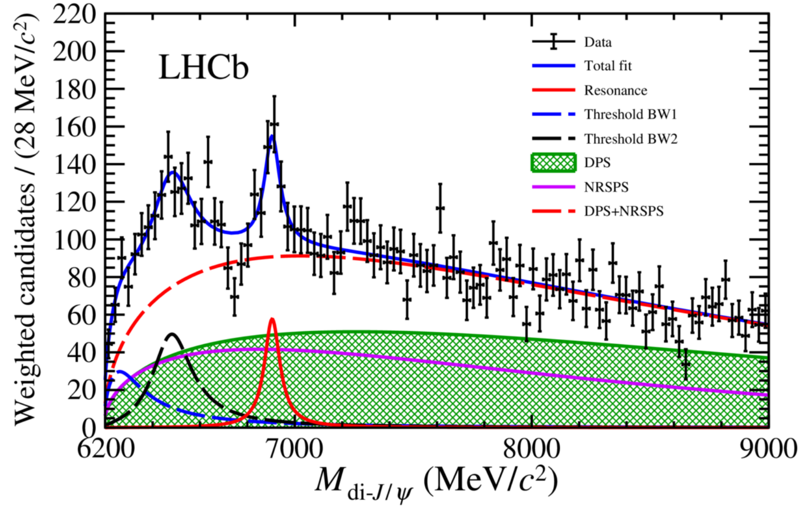


Large datasets collected at LHC led to new golden age for spectroscopy
Many new states discovered, 80 % by LHCb

X(6900) in $J/\psi J/\psi$ final state

Science Bulletin, Vol 65, Issue 23, 2020

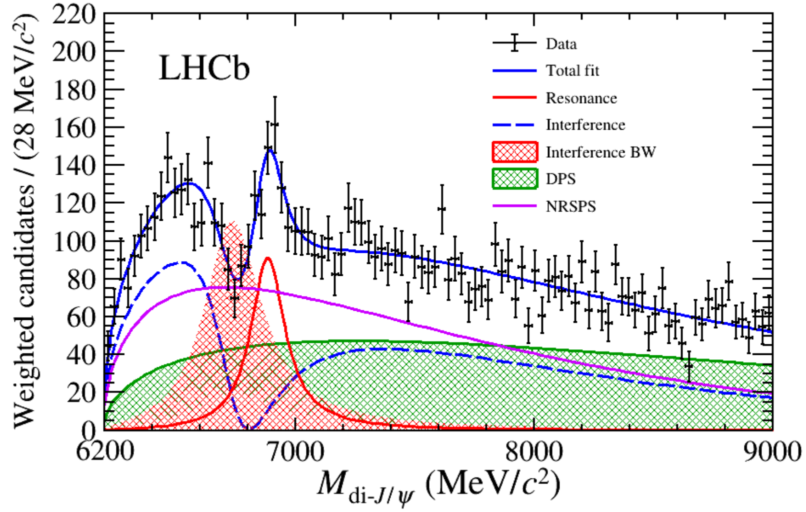
- Study $J/\psi J/\psi$ system with full dataset
- DPS + NRSPS do not describe data well
- Adding resonance, X(6900) improves fit
  - Significance > 5σ in models considered



Model 1: No interference between NRSPS and BW

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$$

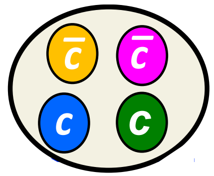


Model 2: Interference between NRSPS and broad BW

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}$$

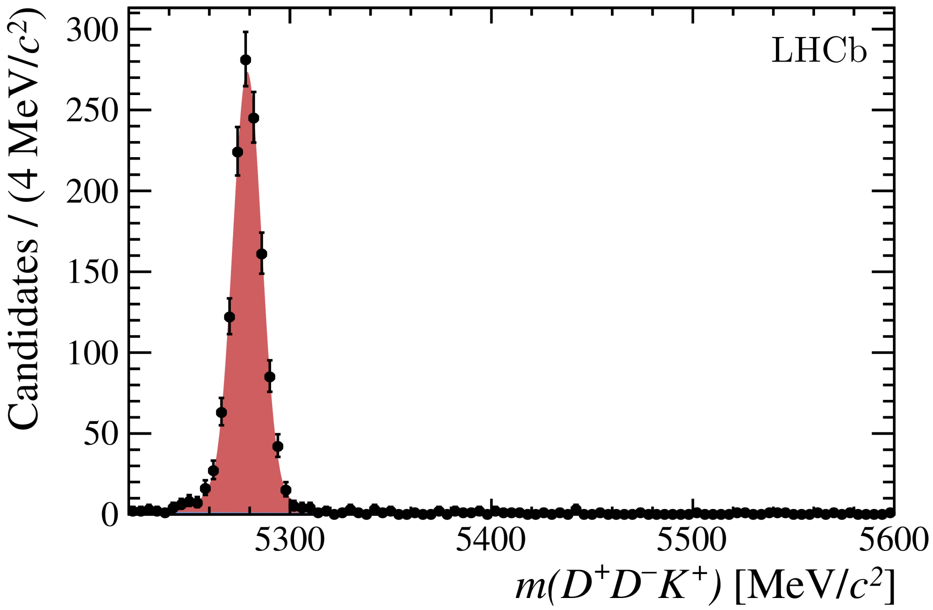
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$$

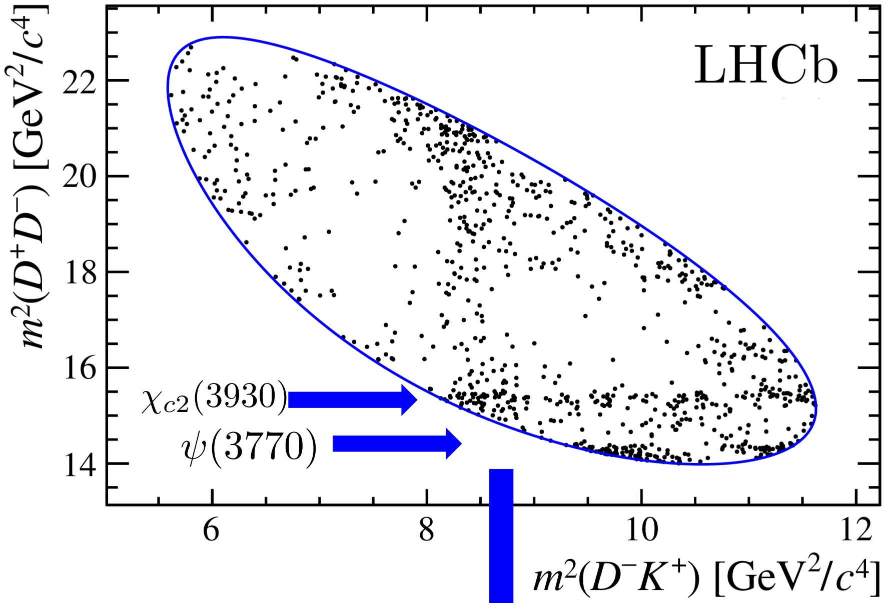
Candidate for fully charmed tetraquark

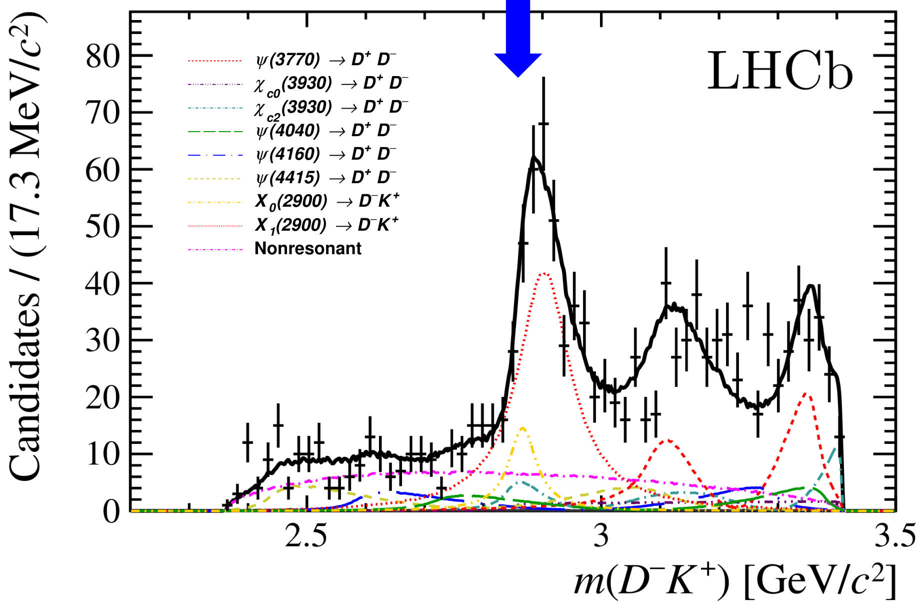


Amplitude analysis of $B^+ \to D^+D^-K^+$

PRD 102 (2020) 242001







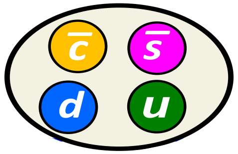
Around 1300 candidates selected in full Run 1+2 dataset

Full amplitude analysis performed

Significant enhancement seen in $m(D^-K^+)$ around ~ 2900 MeV

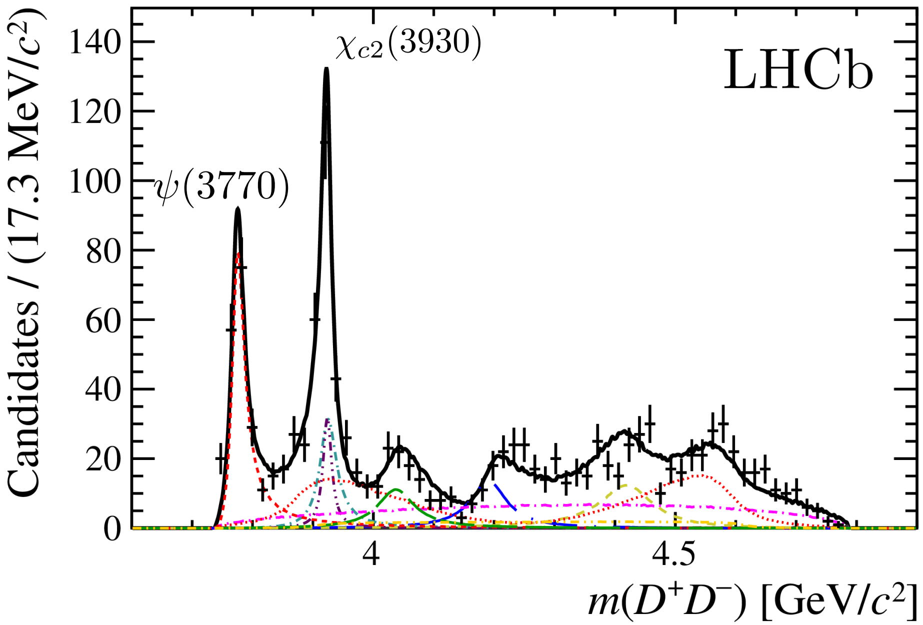
Amplitude analysis of $B^+ \to D^+D^-K^+$

Data well described by two states $X_0(2900)$ and $X_1(2900)$ with high significance



Conclusion supported by model independent analysis
PRL 125 (2020) 242001)

Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$



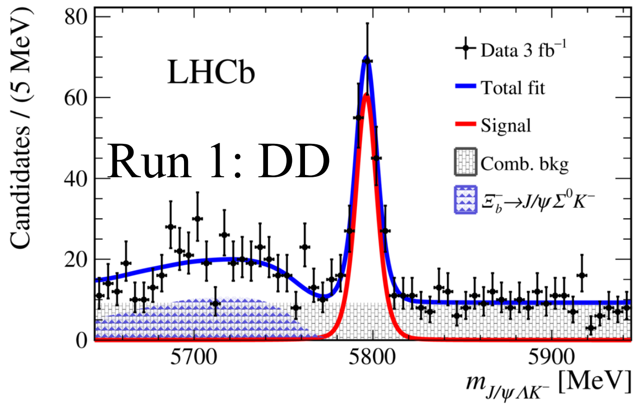
Amplitudes analysis also requires both a spin 0 and spin 2 state decaying to D^+D^- in the mass region around 3930MeV

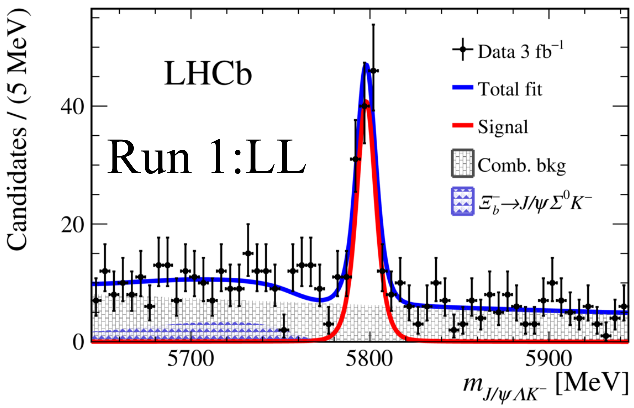
Deepens puzzle of what states are present in this region

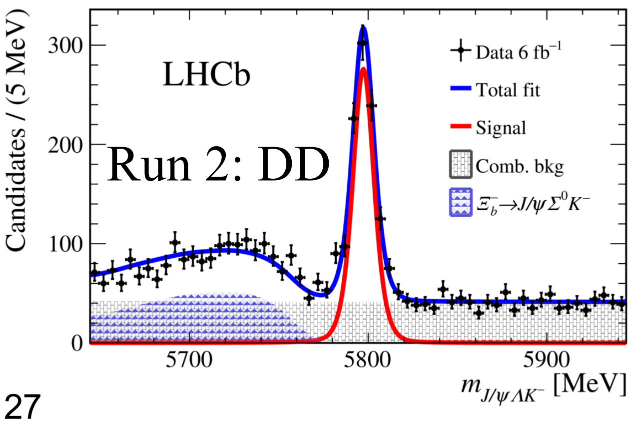
Evidence for a $J/\psi\Lambda$ resonance

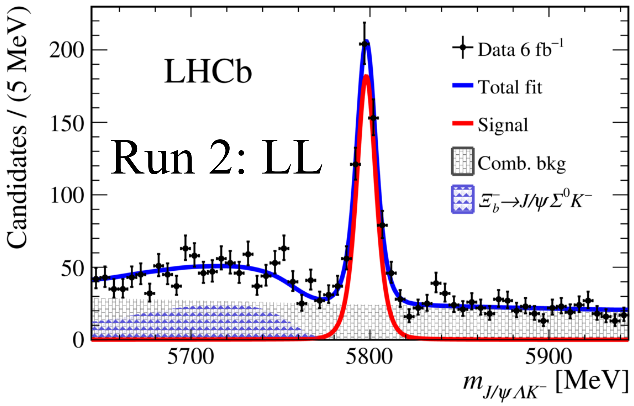
Hidden-charm pentaquark with strangeness predicted in $\Xi_b \to J/\psi\Lambda K$ decays
(JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203)

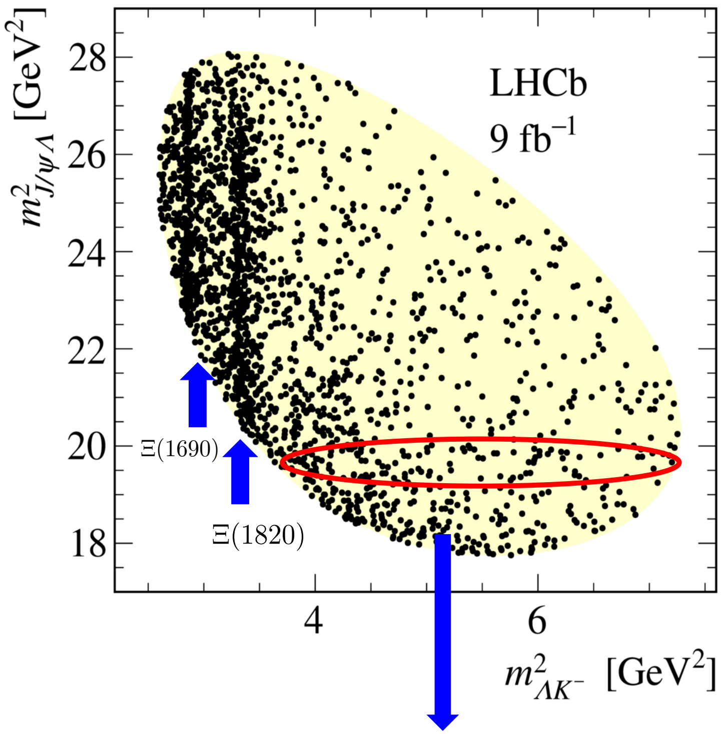
- Full Run 1+ Run 2 dataset
- LL events: decays in VELO
- DD event: decays after vertex detector











Possible structure? Elucidate with amplitude analysis

arXiv: 2012.10380

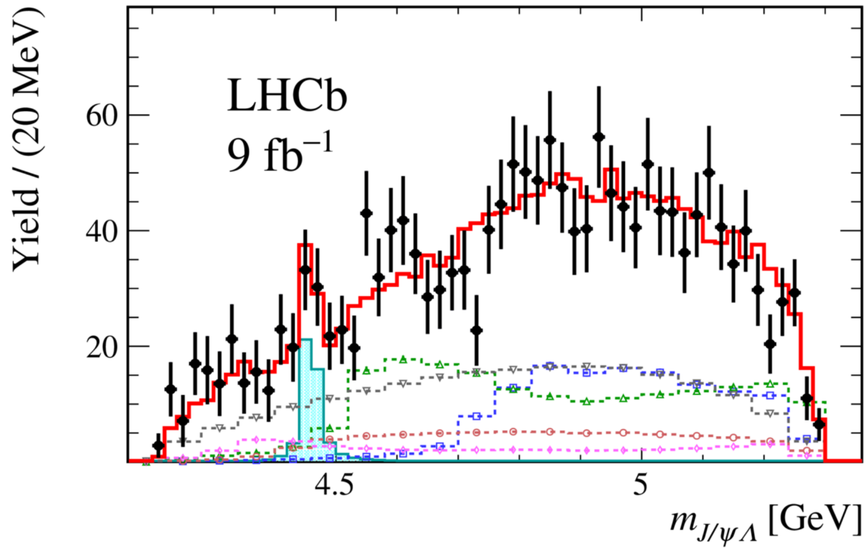
Evidence for a J/ψΛ resonance

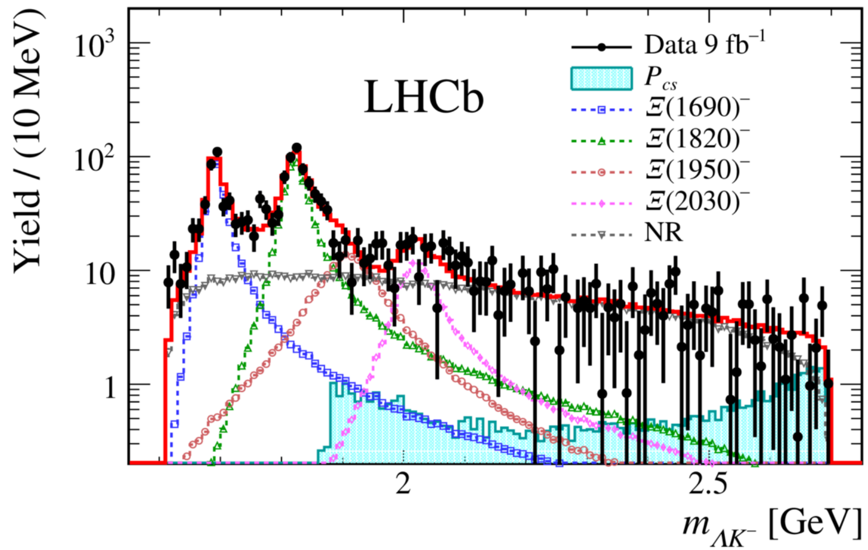
Allowing for systematic uncertainties + LEE 3.1σ evidence for a P^0_{cs} state

Measurements of Ξ^* mass and width consistent with PDG

Masses determined with significantly higher precision

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2}_{-2.6}\,^{+6.7}_{-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2}_{-6.2}\,^{+6.9}_{-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8}_{-3.5}\,^{+49.9}_{-9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8}_{-1.8}\,^{+3.8}_{-4.1}$
NR	–	–	$35.8\,^{+4.6}_{-6.4}\,^{+10.3}_{-11.2}$





Beyond Flavour

Beyond flavour

LHCb has also demonstrated its capabilities beyond flavour in forward Electroweak physics + direct searches

e.g. search for dark photons decaying to a dimuon pair

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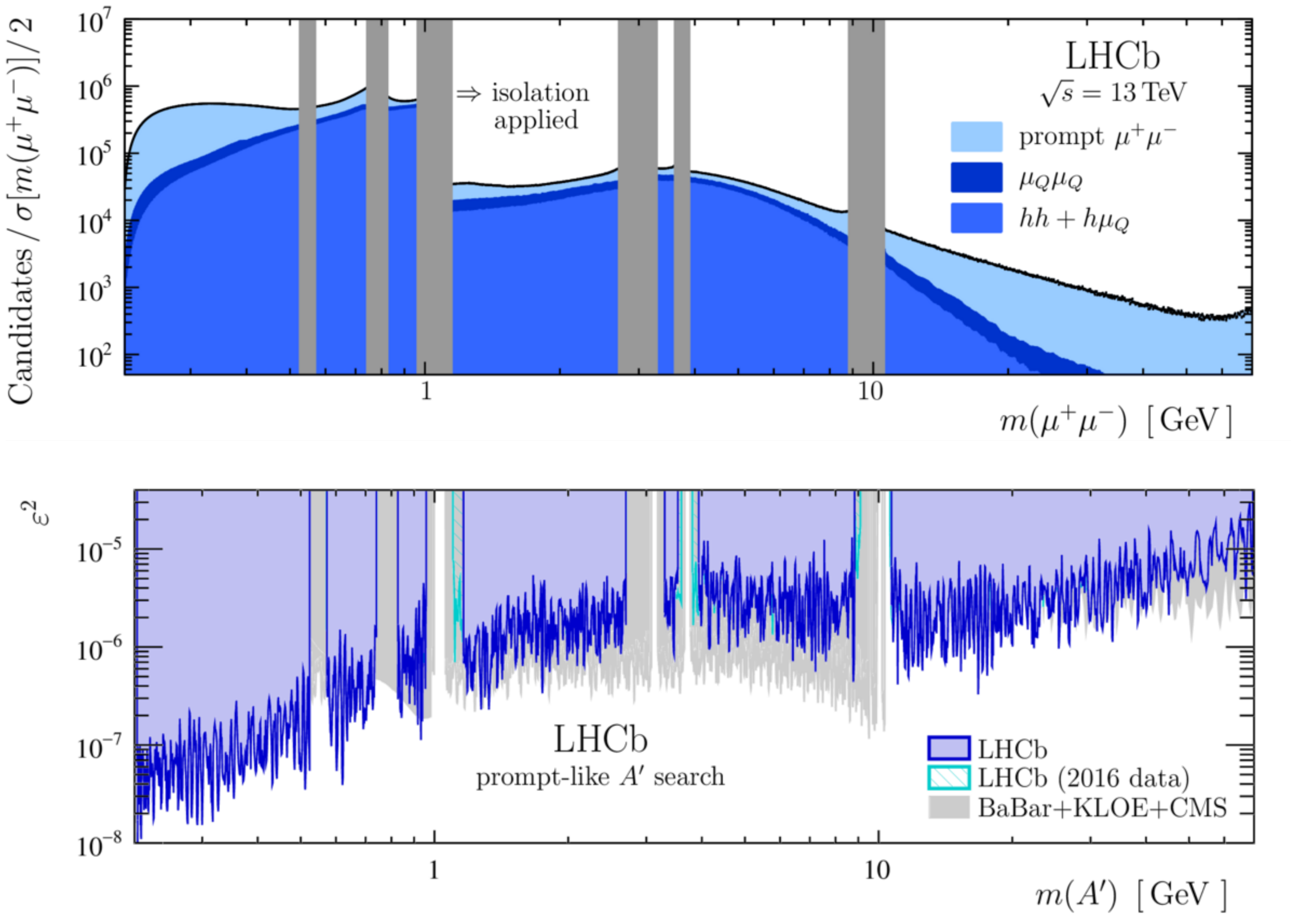
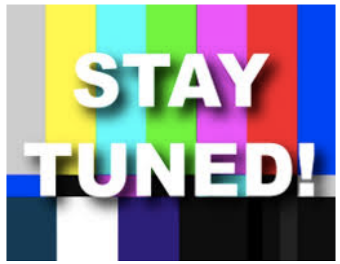


The future

The Future

A lot of important results over next couple of years updating either Run 1 results or results only including a fraction of Run 2 data

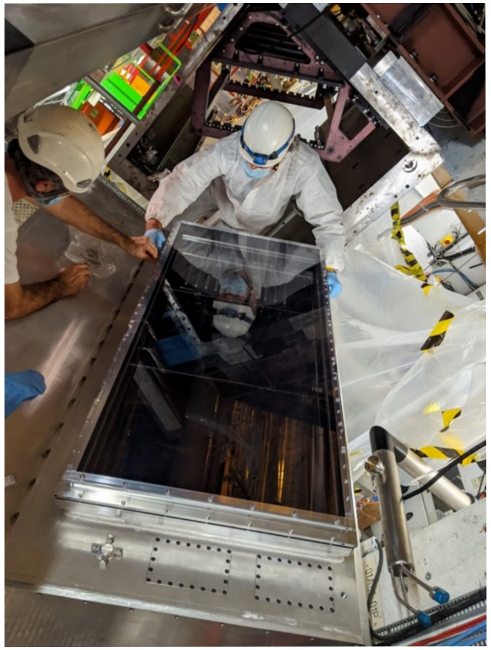
- γ with $B_s \rightarrow D_s^+ K^-$, Δm_s with $B_s \rightarrow D_s^+ \pi^-$
- Angular analysis of $K^* \mu^+ \mu^-$ with full dataset
- R_K with full dataset
- $B_s \rightarrow \mu^+ \mu^-$ with full dataset
- CP violation in B_s mixing (ϕ_s)
- Unique measurements in proton-lead/fixed-target mode
- m_W
- More new states ?



The Future

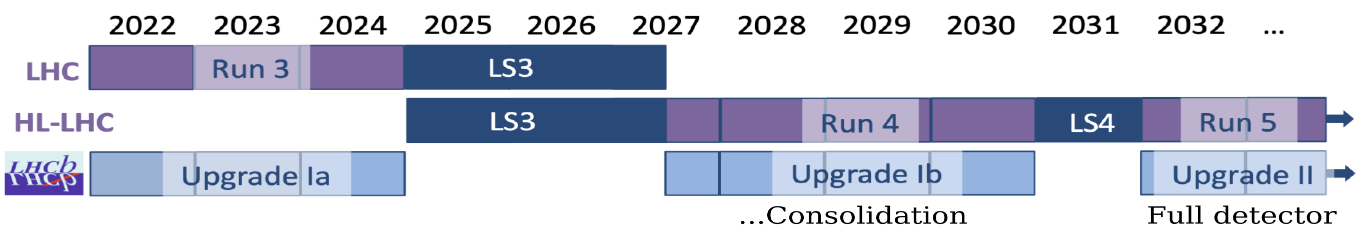
Major upgrade to LHCb for Run 3:

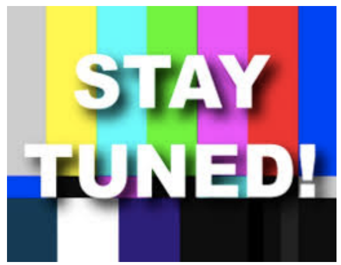
- Collect 50 fb^{-1} in Run 3/Run4
- Run at luminosity of up to 2×10^{33} cm^2 s^{-1}
- 40 MHz readout of detector
- Full software trigger (gain factor two for hadronic channels by removing L0 trigger)
- SMOG2 for fixed target running
- Installation progressing despite the difficulties of the pandemic



Summary

- Many important results from LHCb Run 2 dataset over last year
  - Improved precision on γ to 4°
  - Anomalies in $K^*\mu^+\mu^-$ continue
  - New conventional and exotic hadrons
- A lot more results to come from Run 1+2 dataset over the next couple of years
- From 2022 LHCb upgrade will increase dataset by factor 5-10 depending on mode
- Plans progressing for phase-2 upgrade in to fully exploit heavy flavour potential of high luminosity LHC in 2030s. Aims to collect 300 fb^{-1}





Backup

γ combination: inputs

B decay	D decay	Method	Ref.	Dataset	Status since Ref. [3]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[16]	Run 1+2	**Updated**
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[24]	Run 1	As before
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[25]	Run 1	As before
$B^+ \to Dh^+$	$D \to K^0_S h^+h^-$	BPGGSZ	[17]	Run 1+2	**Updated**
$B^+ \to Dh^+$	$D \to K^0_S K^\pm\pi^\mp$	GLS	[20]	Run 1+2	**Updated**
$B^+ \to D^*h^+$	$D \to h^+h^-$	GLW/ADS	[16]	Run 1+2	**Updated**
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[26]	Run 1+2(*)	As before
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[26]	Run 1+2(*)	As before
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[27]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1+2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[21]	Run 1+2(*)	**New**
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[22]	Run 1	**Superseded**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	BPGGSZ	[28]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^\pm \to K^\mp\pi^\pm\pi^\pm$	TD	[29]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^\pm_s \to h^\pm h^\mp\pi^\pm$	TD	[30]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^\pm\pi^\mp$	$D^\pm_s \to h^\pm h^\mp\pi^\pm$	TD	[23]	Run 1+2	**New**