Recent highlights from the LHCb experiment

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14th workshop on TeV Physics, Nanjing, China

TeV Workshop and Myself

- 1st TeV Workshop in Tsinghua Univ. (2005)
  - Volunteer to serve in the workshop
  - Made THE most important decision in my life

仰望星空派

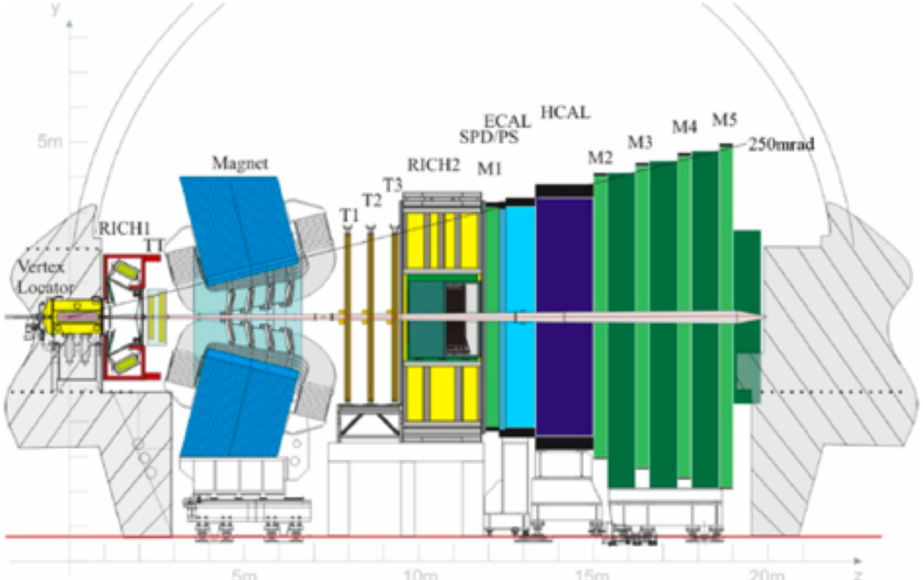
Outline on recent highlights

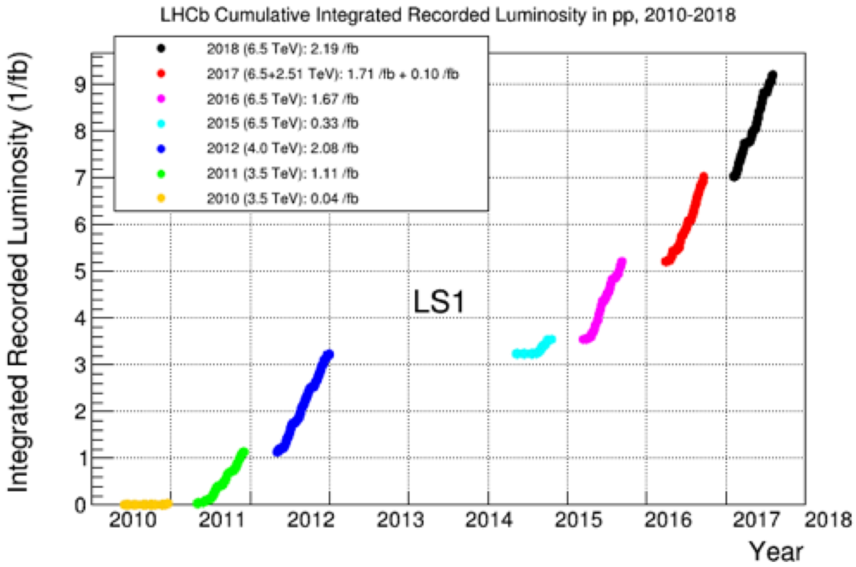
- CP violation measurements
- Spectroscopy and exotic studies
- Rare decays and lepton universality test
- Conclusion

LHCb detector and operation status

- Dedicated for flavor physics studies
  - Excellent primary and secondary vertex measurements;
  - Very good PID performance on K/π/p

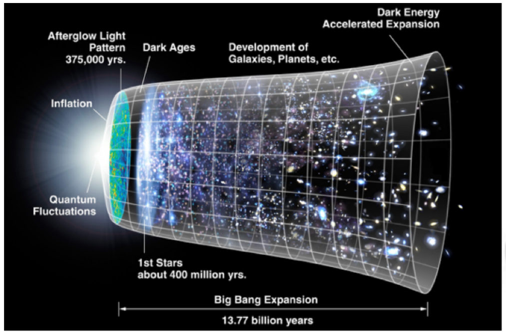
- Wonderful performance with the LHCb detector:
  - 3 fb^{-1} pp data at 7 and 8 TeV
  - 6 fb^{-1} data at 13 TeV





Many interesting results from LHCb at the beginning of 2019
Not all are covered here

CP violation measurements



Understand matter antimatter asymmetry in Universe

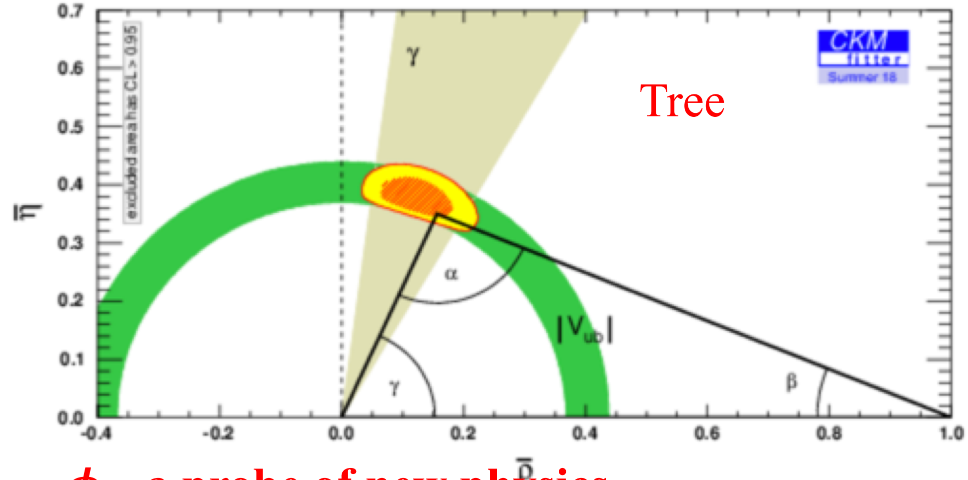
Search for new sources of CPV through precision measurement

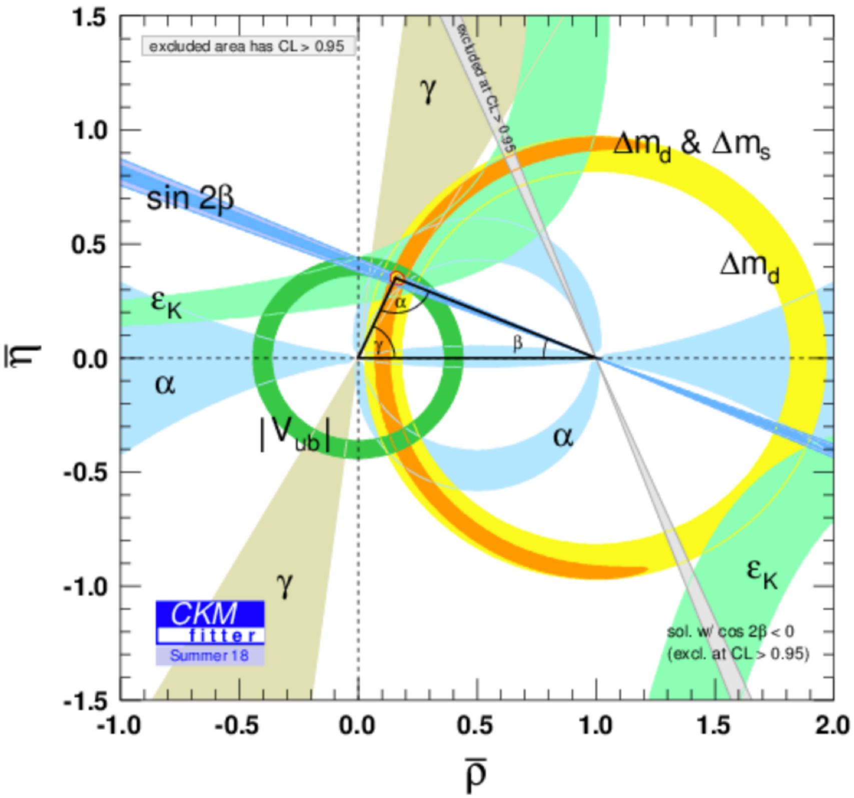
Global fit

CKMfitter 2018 updates

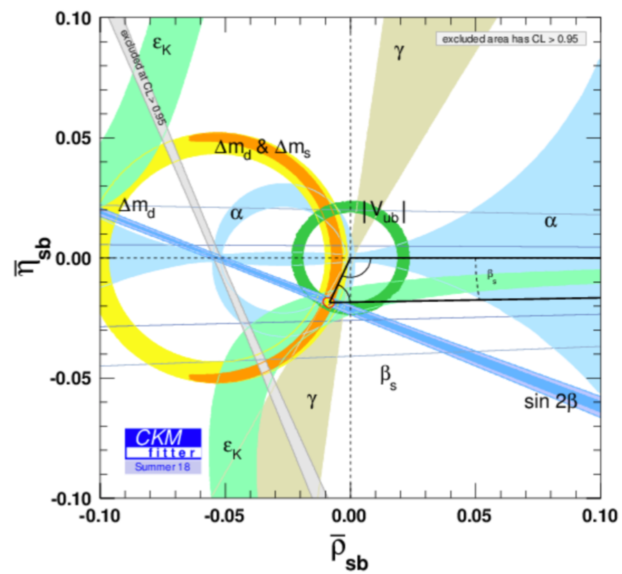
- CPV in SM described by CKM mechanism
- Precision measurements ⇨ global fit

SM baseline，γ least precise measurement



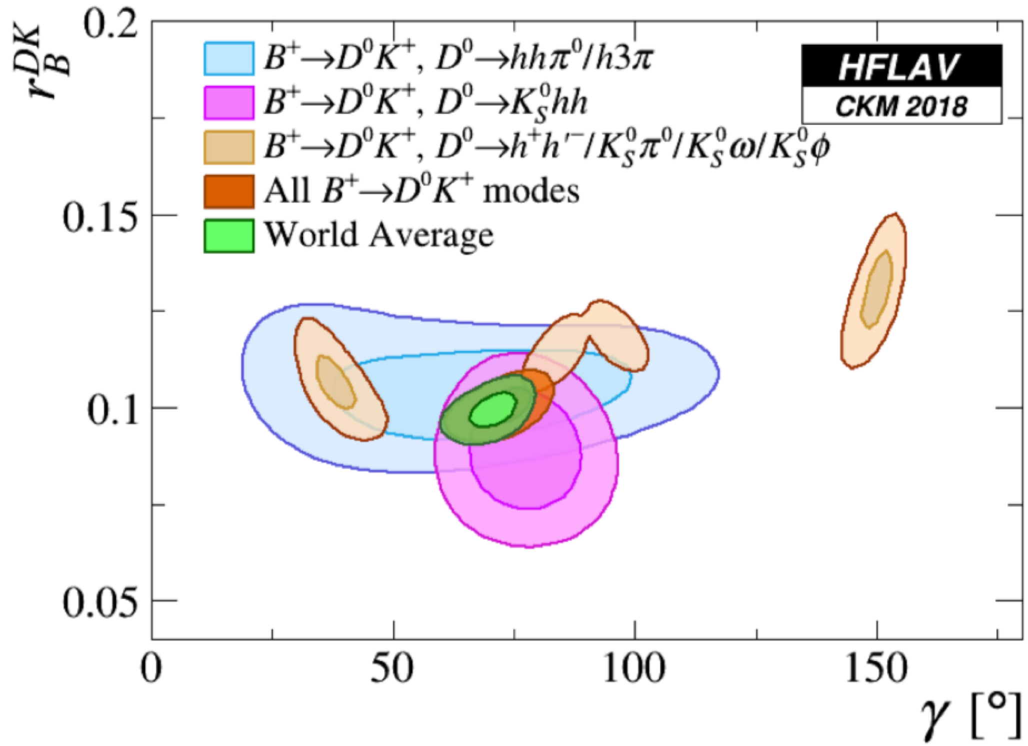


ϕ_s, a probe of new physics



γ in a nutshell

- Tree-level γ： sensitive channels ($B \to D^{(*)}h(h)$ etc.) with small BFs, need to combined them to achieve best sensitivity
- Theoretical uncertainties small: strong interaction parameters determined directly from experiment using a global fit



- LHCb dominants current sensitivity

Direct: $\gamma = (73.5^{+4.3}_{-5.0})^\circ$

VS

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

New Physics?

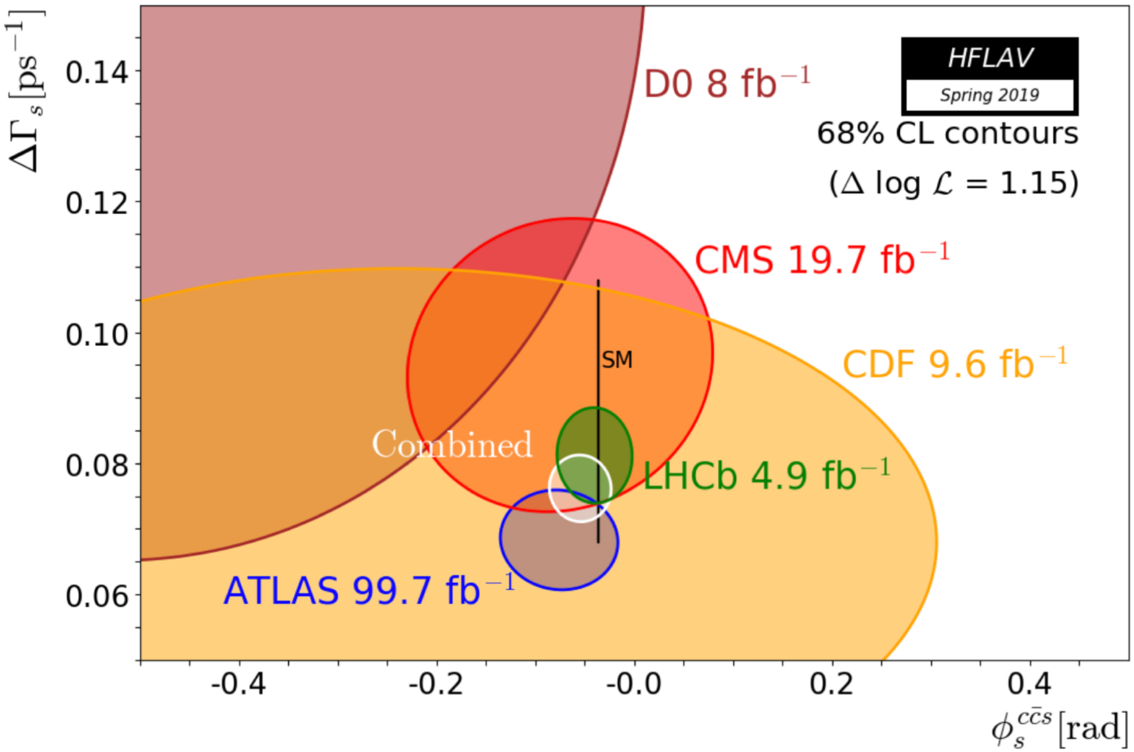
ϕ_s updates

ATLAS-CONF-2019-009
LHCb-PAPER-2019-013
LHCb-PAPER-2019-003

- B physics now attracts more interests from GPD
- We have three important updates recently: one from ATLAS ($B_s^0 \to J/\psi\ \phi$) and two from LHCb ($B_s^0 \to J/\psi\ \phi$ and $B_s^0 \to J/\psi \pi^+\pi^-$)
- Interesting to see that ATLAS begins to play very important role in the game

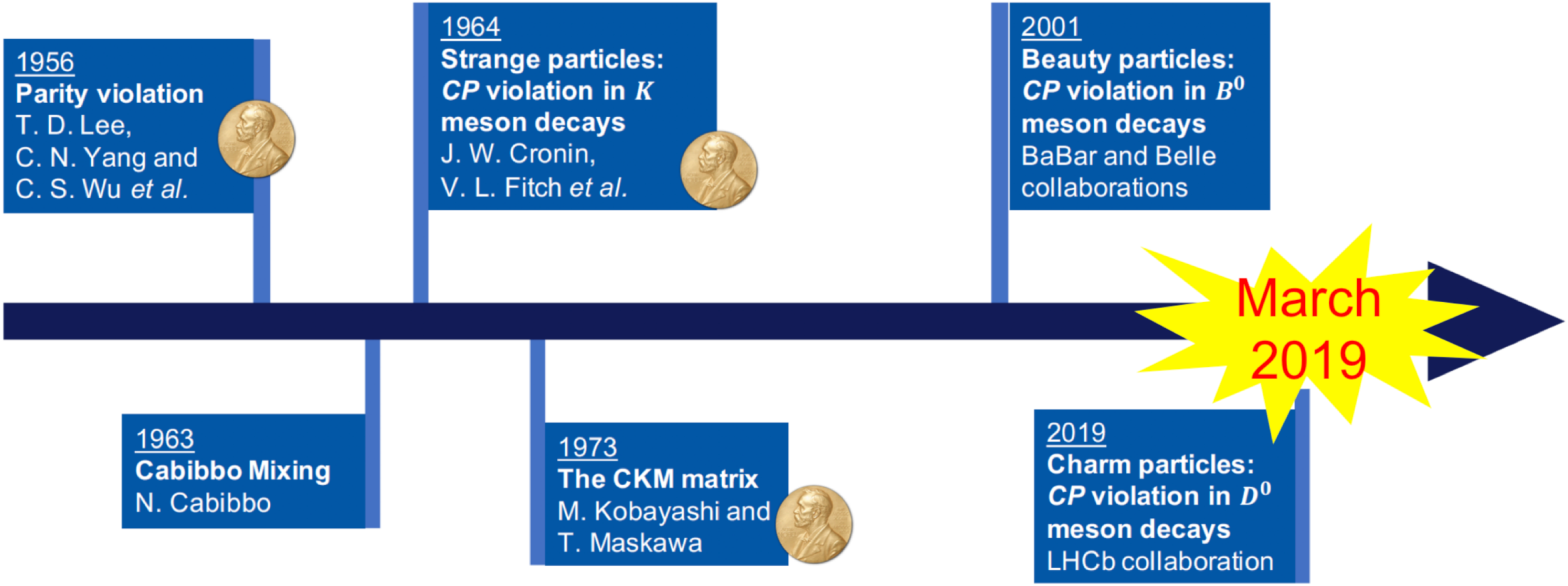
[CKMFitter, PRD 84 (2011) 033005]

- World average: $\phi_s = -0.054 \pm 0.020$ rad vs -0.0370 ± 0.0006 rad from prediction



Observation of CPV in charm decays

LHCb-PAPER-2019-006



A. Carbone, CERN seminar, March 19, 2019

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

CP violation in charm observed at 5.3σ

What we do

LHCb-PAPER-2019-006

- Time-integrated CP asymmetry:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}, f = K^+K^- \text{and } f = \pi^+\pi^-$$

- Difference on CP asymmetry between the two channels

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$

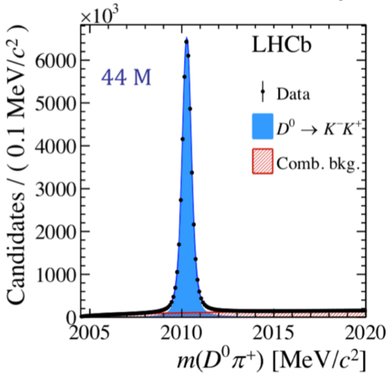
- What does it mean

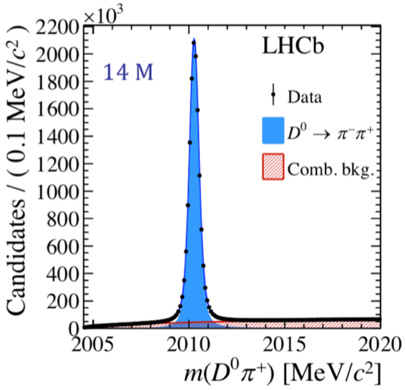
Average of proper time — negligible

$$\Delta A_{CP} = \left[a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)\right]\left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{ind}$$

Relative difference of proper tim

- We use $D^0, \overline{D^0}$ from flavor tagged process $D^{*-} \to D^0\pi^-$, $B \to D^0\mu^-X$
- How many D^0 in LHCb
  - More than 1 billion D^0 reconstructed in LHCb
  - 44(π)+9(μ) M $D^0 \to KK$ and 14+3 M $D^0 \to \pi^+\pi^-$ for 6 fb^{-1} data
  - free of background





CPV measurements in charm decays

LHCb-PAPER-2019-006

Run 2

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

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

Run 1

$$\Delta A_{CP} = (+14 \pm 16(\text{stat}) \pm 8\,(\text{syst}))\times 10^{-4}$$

μ-tagged Run 1 (3 fb^{-1})

Phys. Rev. Lett. 116 (2016)

$$\Delta A_{CP} = (-10 \pm 8\,(\text{stat}) \pm 3\,(\text{syst}))\times 10^{-4}$$

π-tagged Run 1 (3 fb^{-1})

JHEP 07 041 (2014)

Combined

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

π-tagged (6 fb^{-1}) — LHCb-PAPER-2019-006

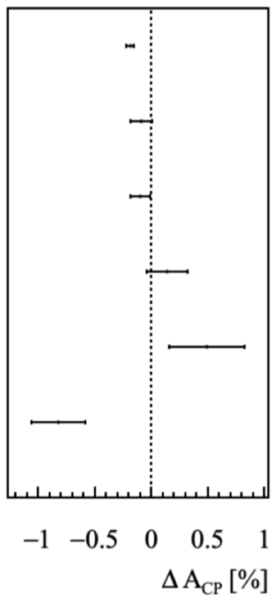
μ-tagged (6 fb^{-1}) — LHCb-PAPER-2019-006

π-tagged (3 fb^{-1}) — Phys. Rev. Lett. 116 (2016)

μ-tagged (3 fb^{-1}) — JHEP 07 041 (2014)

μ-tagged (1 fb^{-1}) — Phys. Lett. B723 33 (2013)

π-tagged (0.62 fb^{-1}) — Phys. Rev. Lett. 108 (2012)

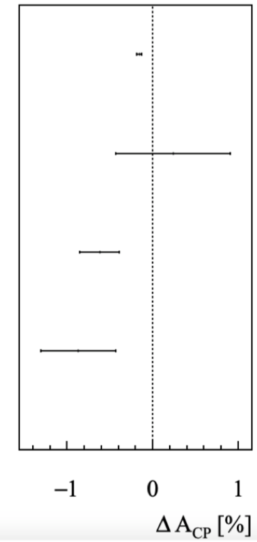


9 fb^{-1} $\sqrt{s}$ = 7,13 TeV pp — LHCb [LHCb-PAPER-2019-006]

385.8 fb^{-1} $\Upsilon(4S)$ — BaBar [Phys. Rev. Lett. 100, 061803(2008)]

9.7 fb^{-1} $\sqrt{s}$ = 1.96 TeV $p\bar{p}$ — CDF [Phys.Rev.Lett. 109 111801 (2012)]

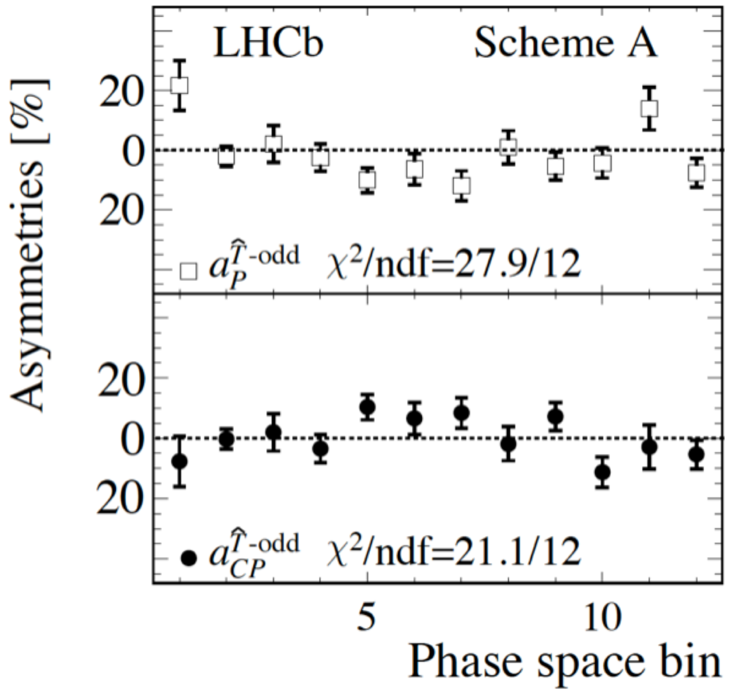
976 fb^{-1} fb^{-1} $\Upsilon(4S)$ — Belle Preliminary [arXiv:1212.1975]



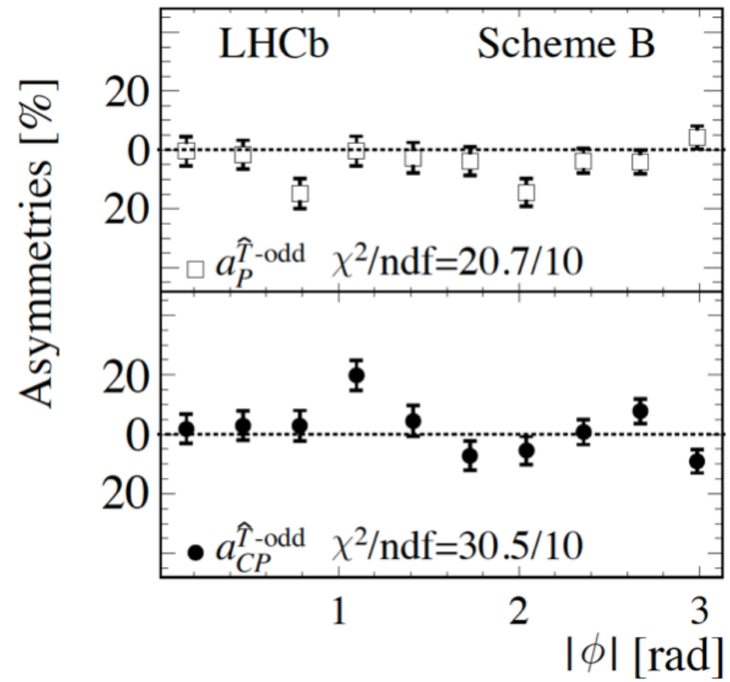
The next CPV

Nature Physics 13 (2017) 391

- CPV has not yet been found in baryon decays
- We saw first evidence of 3.3σ 2 years ago in $\Lambda_b \to p3\pi$ using triple products



Binning based on resonant structures, e.g. ρ(770), N*, Δ++



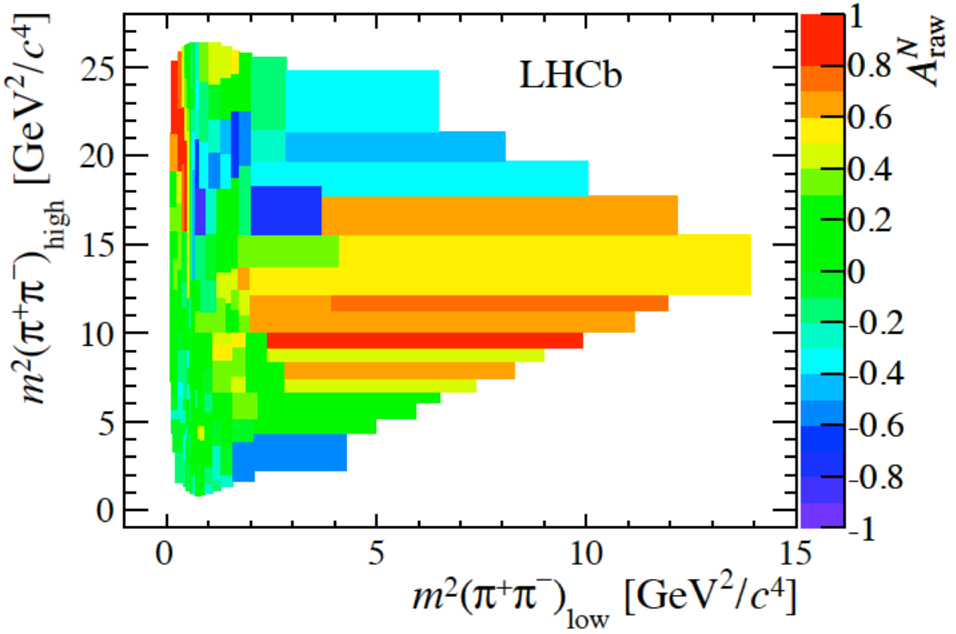
Binning based on ϕ angle

- Searches are performed extensively in LHCb, including $\Lambda_b \to p3\pi$, $\Lambda_b \to pK_S\pi$ (a CPV as large as 20% is predicted in arXiv:1412.1899)

CPV in charmless B decays

PRL 112 (2014) 011081
PRL 111 (2013) 101801
PRD 90 (2014) 112004

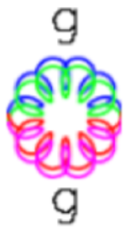
- Interesting CPV pattern seen on Dalitz plot of $B \to h'^{+}h^{+}h^{-}, h = K, \pi$
- Dalitz plot analysis needed to shed more light on understanding nature of these CPV

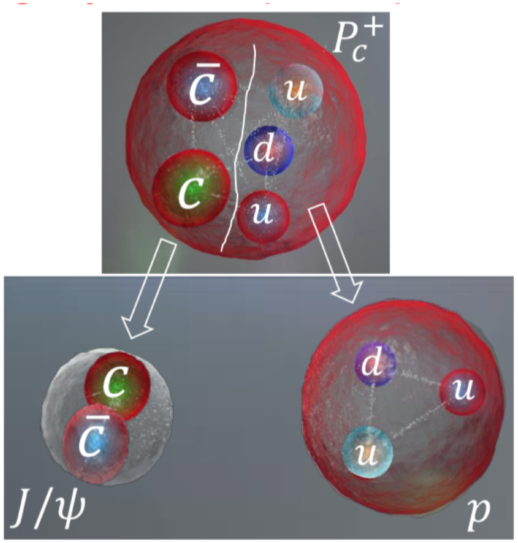


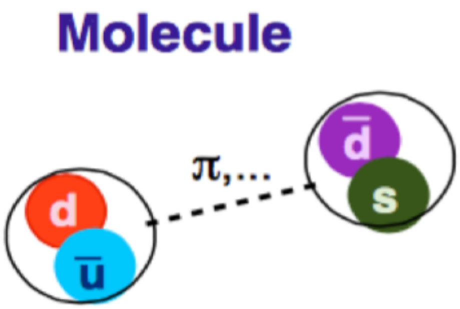
- LHCb has published amplitude analyses of $B_s^0 \to K_S\pi^+\pi^-$ (PRL 120 (2017) 261801) and $B_s^0 \to K_S K^{\pm}\pi^{\mp}$ (arXiv:1902.07955)
- Soon to come: amplitude analyses of $B^+ \to \pi^+\pi^+\pi^-$ and $B^+ \to \pi^+K^+K^-$, with much larger statistics than previous B-factory analyses and thus more interesting results

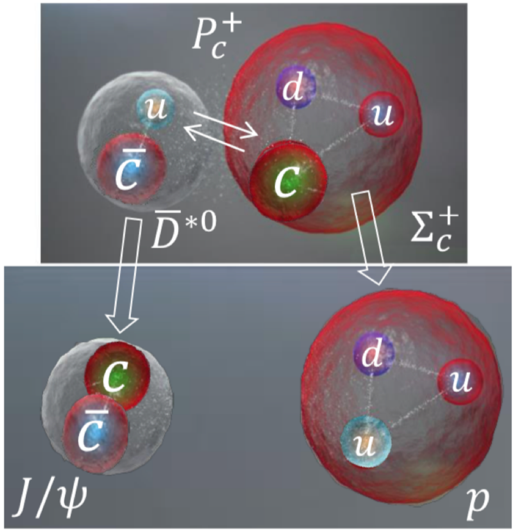
Spectroscopy and excited state searches

Understanding QCD at low-energy





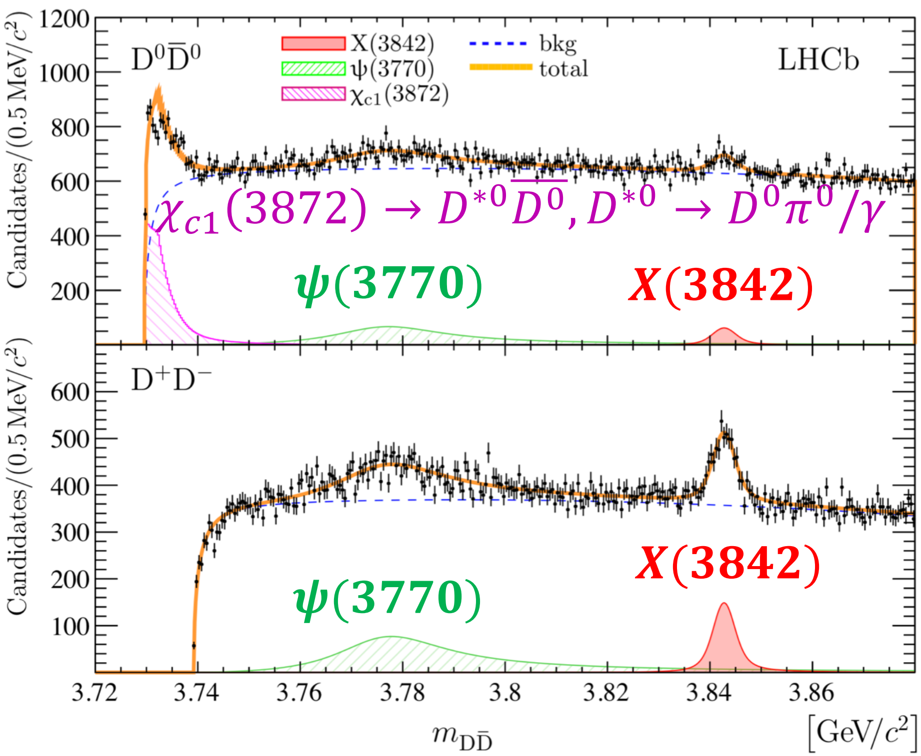


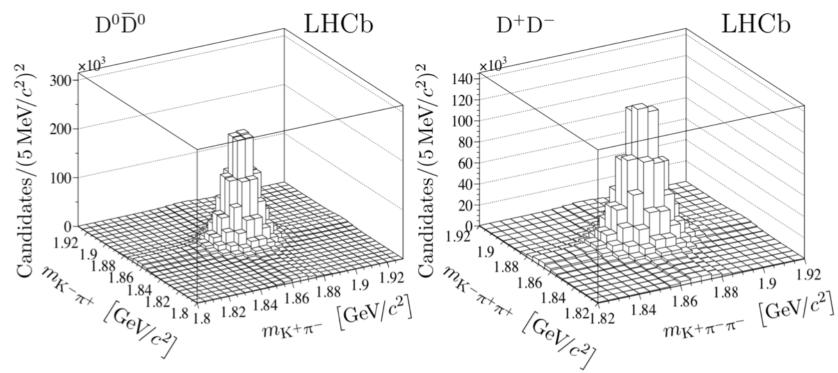


Spectroscopy above $D\bar{D}$ threshold (1)

LHCb-PAPER-2019-005

- Large and pure D samples at LHCb for spectroscopy studies





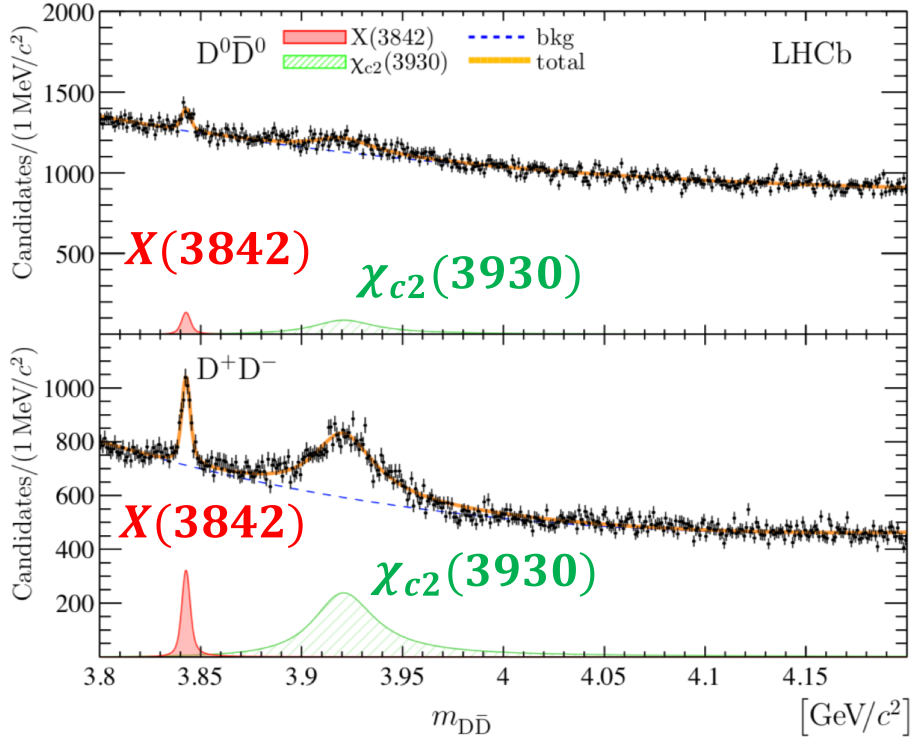
ψ(3770)

		$m_{\psi(3770)}$ [MeV/c^2]
Shamov and Todyshev	[58]	3779.8 ± 0.6
PDG average	[39]	3778.1 ± 1.2
PDG fit	[39]	3773.13 ± 0.35
This analysis		$3778.1 \pm 0.7 \pm 0.6$

- Modeled with a relativistic multi-channel P-wave BW
- Width Gaussian constrained to PDG value of 27.2 ± 1.0 MeV
- Mass similar to Shamov and Todyshev obtained from e^+e^-data and PDG average, but different from PDG fit

Spectroscopy above $D\bar{D}$ threshold (2)

LHCb-PAPER-2019-005



$X(3842)$

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}\,,$$

- New resonance decaying to both $D^0\overline{D^0}$ and D^+D^-
- Narrow width and mass suggest it to be $\psi_3(1^3D_3)$ with $J^{PC} = 3^{--}$

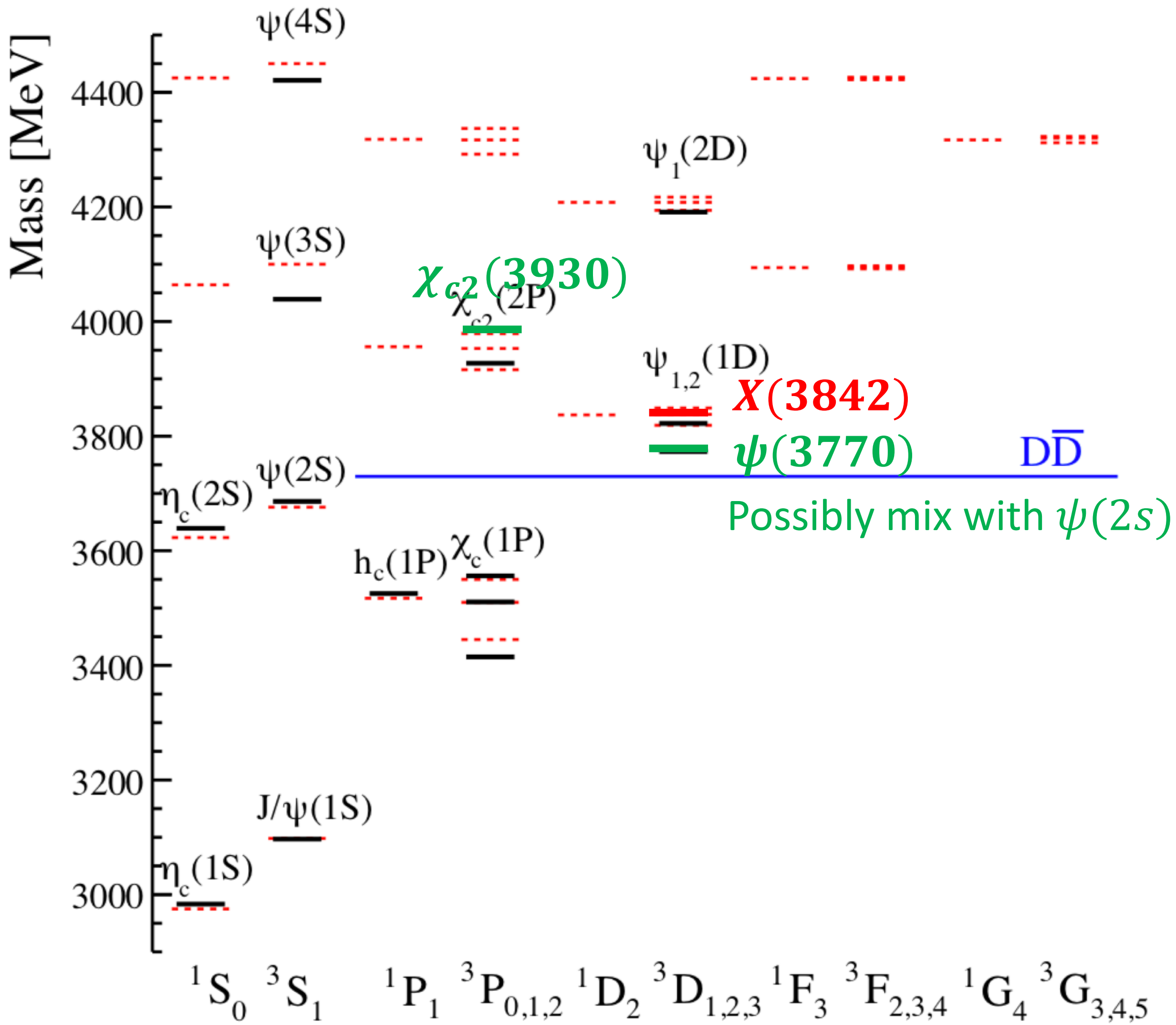
$\chi_{c2}(3930)$

		$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle	[17]	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$
BaBar	[18]	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$
This analysis		$3921.9 \pm 0.6 \pm 0.2$	$36.6 \pm 1.9 \pm 0.9$

- Mass 2σ lower than current world average
- Width 2 σ higher
- Mass now even closer to $X(3915) \to J/\psi\omega$, further study needed to see if they are two different states or the same one

Spectroscopy above $D\bar{D}$ threshold (3)

LHCb-PAPER-2019-005



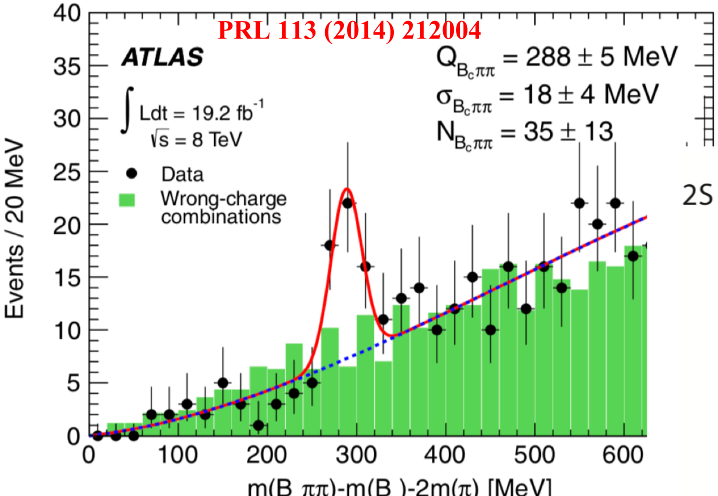
Olsen, Skwarnicki, Zieminska, Rev. Mod. Phys. 90, 015003 (2018); arXiv: 1708.04012

B_c excited states

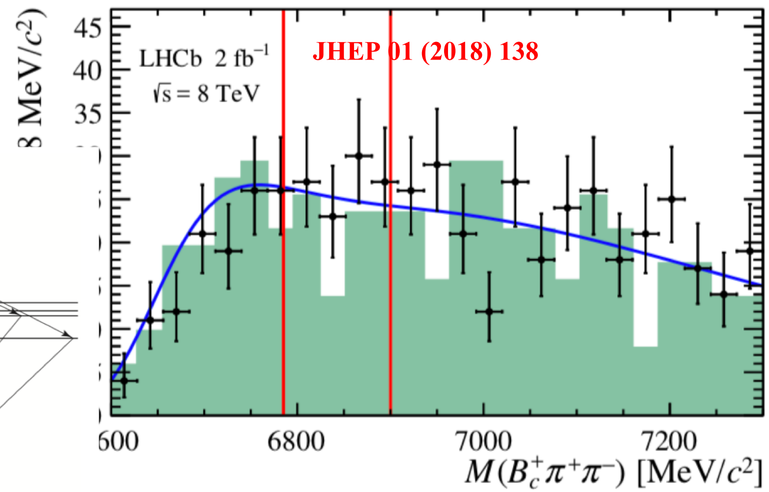
LHCb-PAPER-2019-007

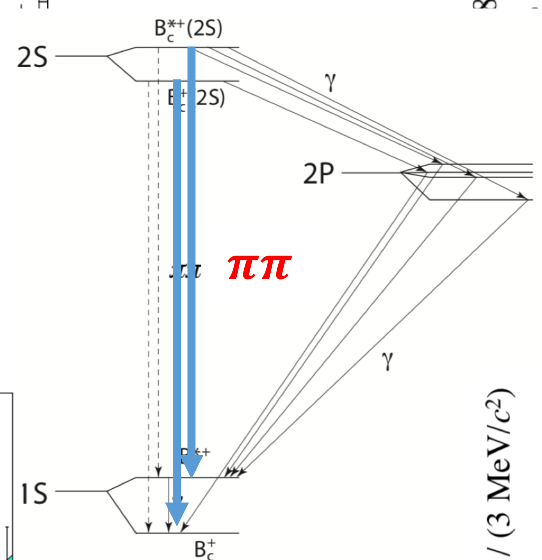
- B_c excited states below BD threshold can only decay to B_c
- Controversy over excited state searches; now clear and consistent picture over different η range

ATLAS: 6800~6900 MeV, single peak, large width

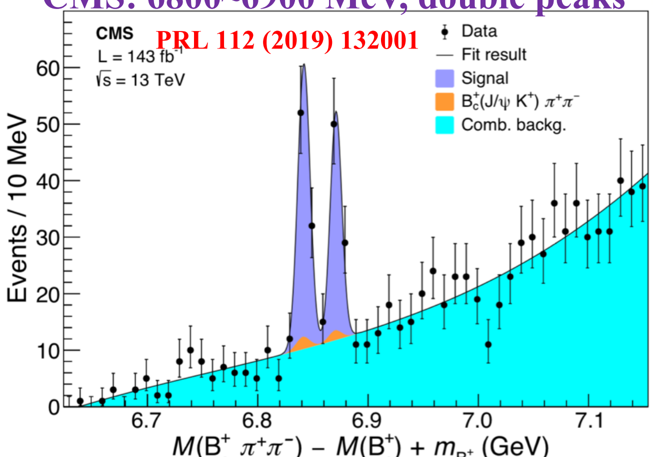


LHCb: nothing for 2 fb^{-1} data

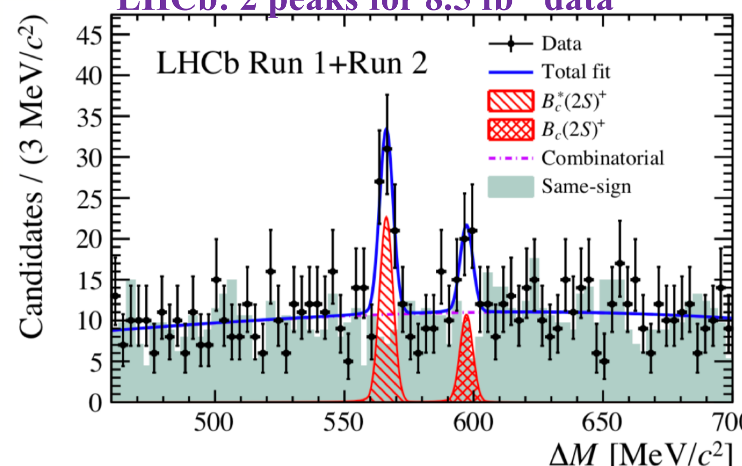




CMS: 6800~6900 MeV, double peaks



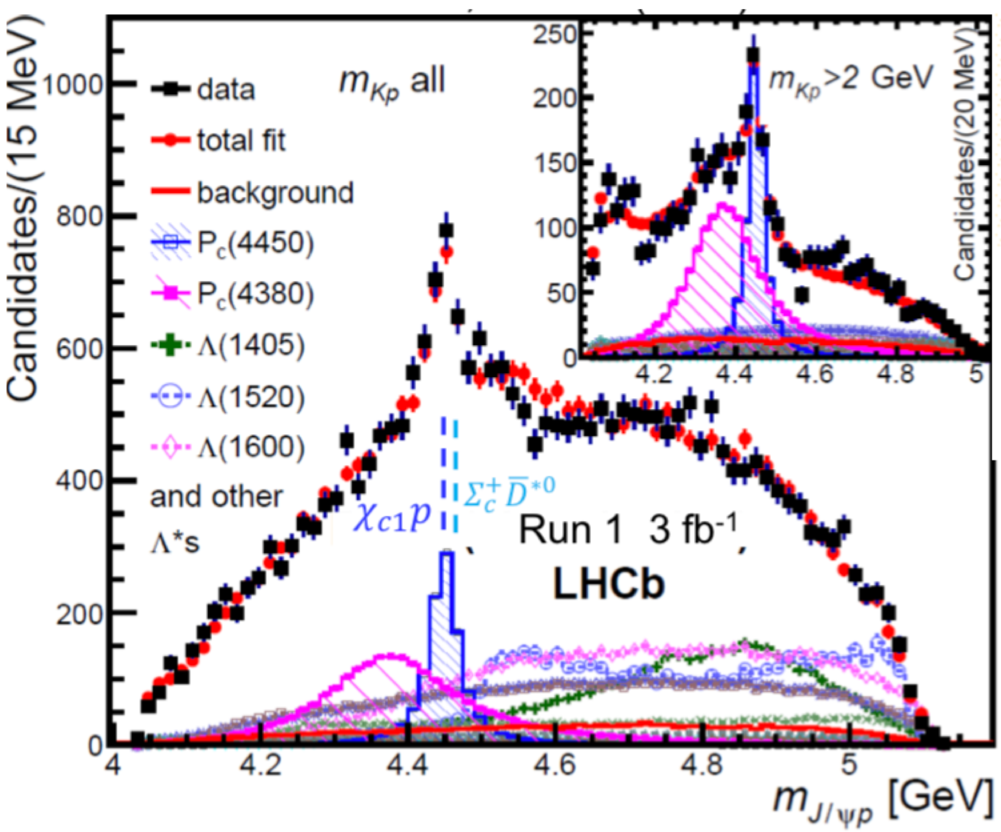
LHCb: 2 peaks for 8.5 fb^{-1} data



Pentaquark states

PRL 115 (2015) 072001
LHCb-PAPER-2019-014

- Pentaquark states observed in Run 1 data (3 fb^{-1})



$P_c(4380)^+$: $4380 \pm 8 \pm 29$ MeV
$205 \pm 18 \pm 86$ MeV **8.4%**

$P_c(4450)^+$: $4449.8 \pm 1.7 \pm 2.5$ MeV
$39 \pm 5 \pm 19$ MeV **4.1%**

Massive production

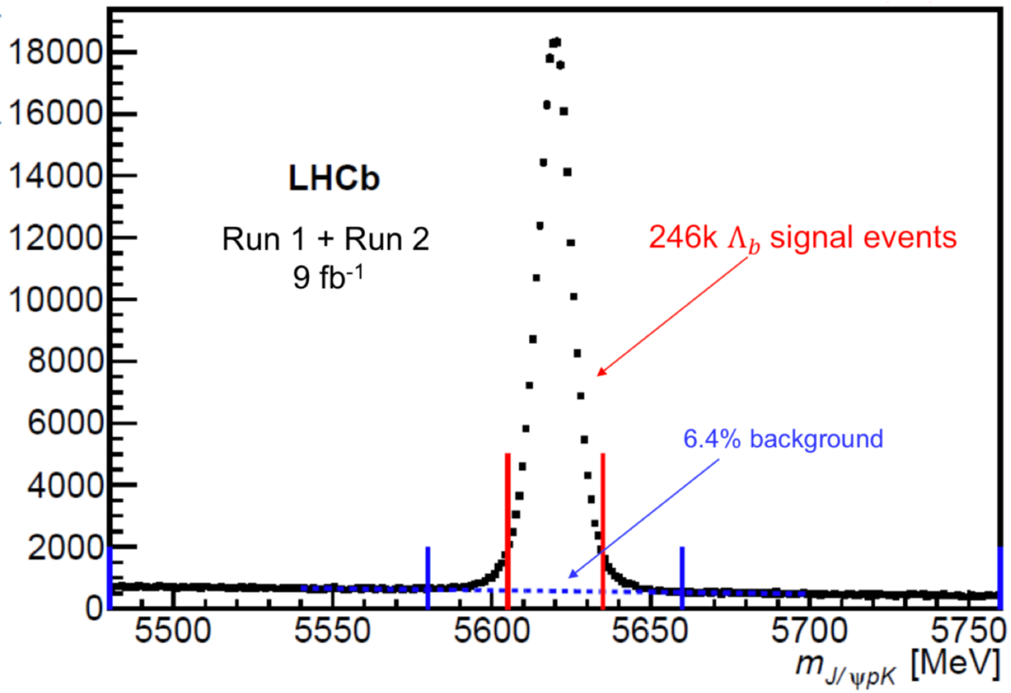
$J^P = (3/2^-, 5/2^+)$
aso possible $(3/2^+, 5/2^-)$, $(5/2^+, 3/2^-)$

27k $\Lambda_b \to J/\psi p K^-$ signal events
5.4% background

Now we have 6 fb^{-1} more data with twice larger cross-section

New data sample

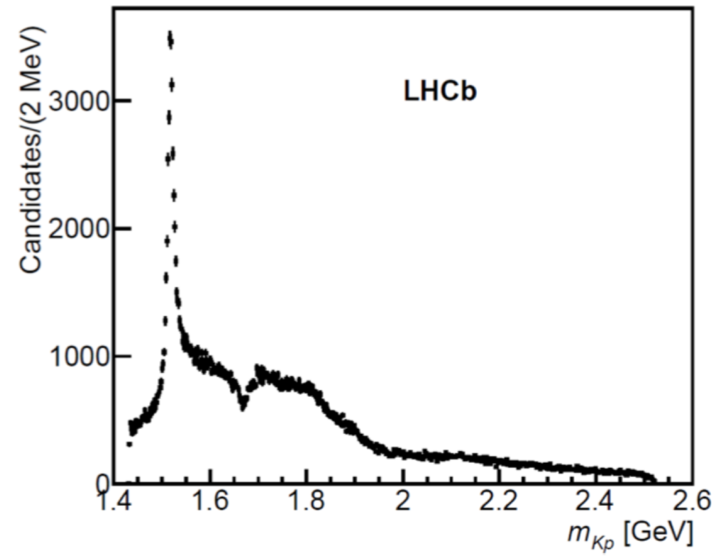
PRL 115 (2015) 072001
LHCb-PAPER-2019-014

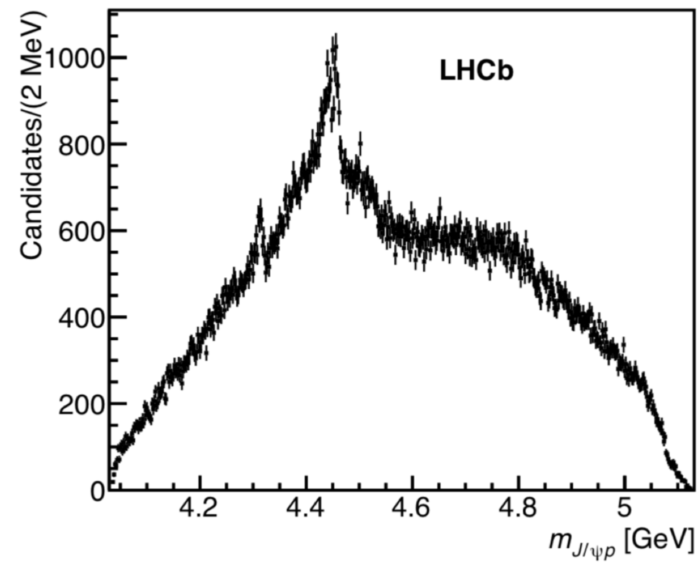


VS

27k $\Lambda_b \to J/\psi p K^-$ signal events
5.4% background

9X more data with slightly increased background

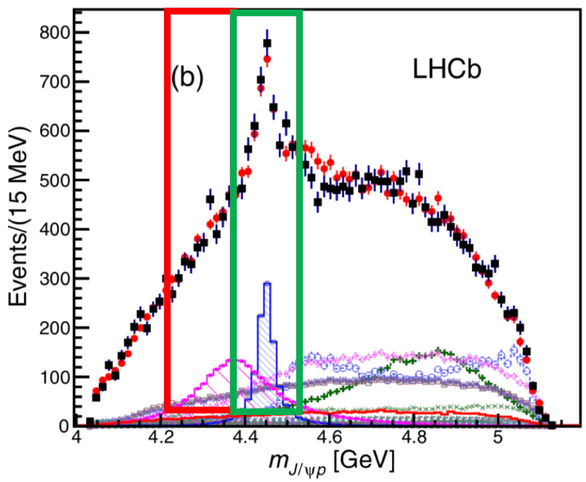




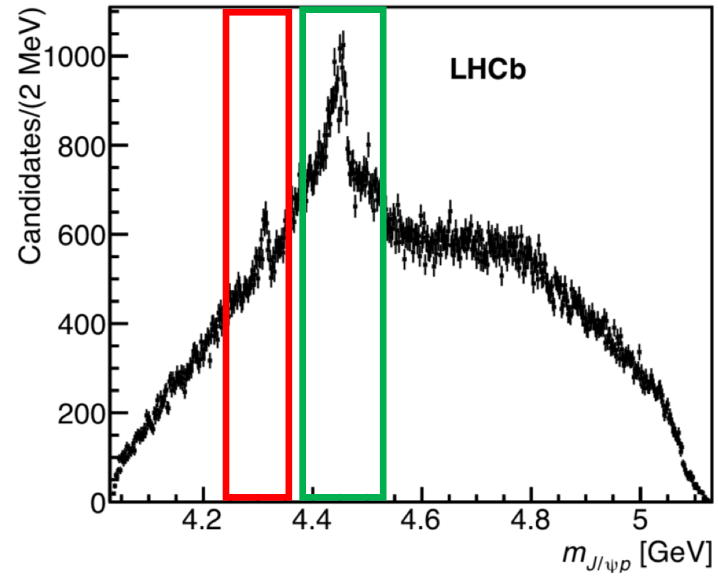
A closer look

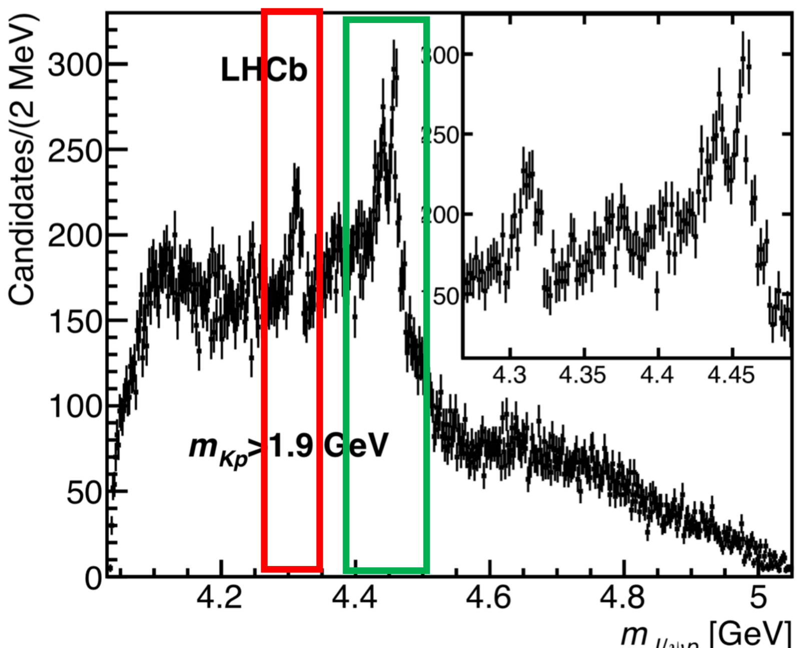
PRL 115 (2015) 072001
LHCb-PAPER-2019-014

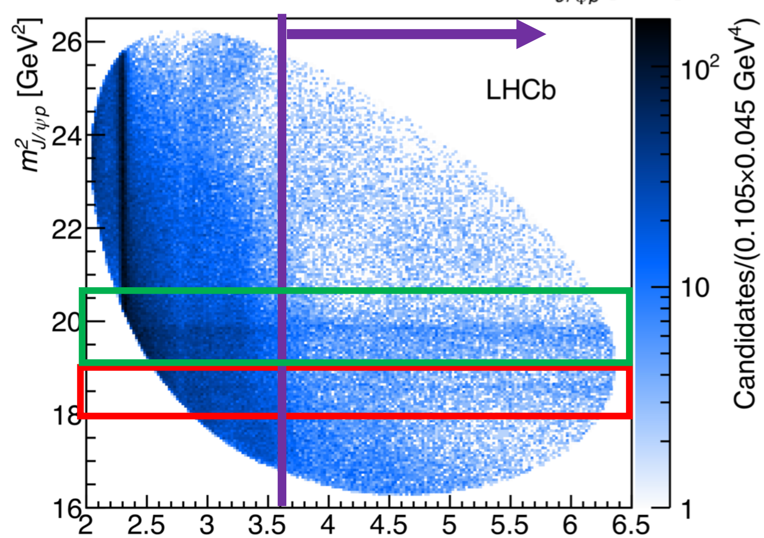
Run 1



Run 1 + Run 2





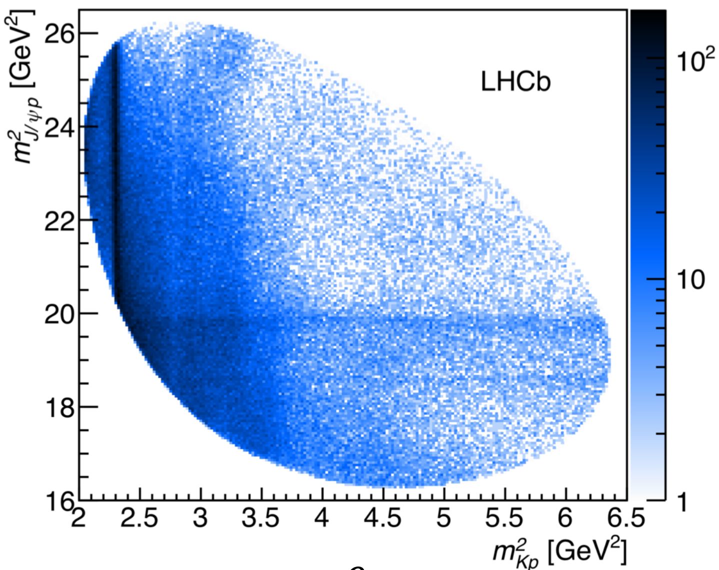


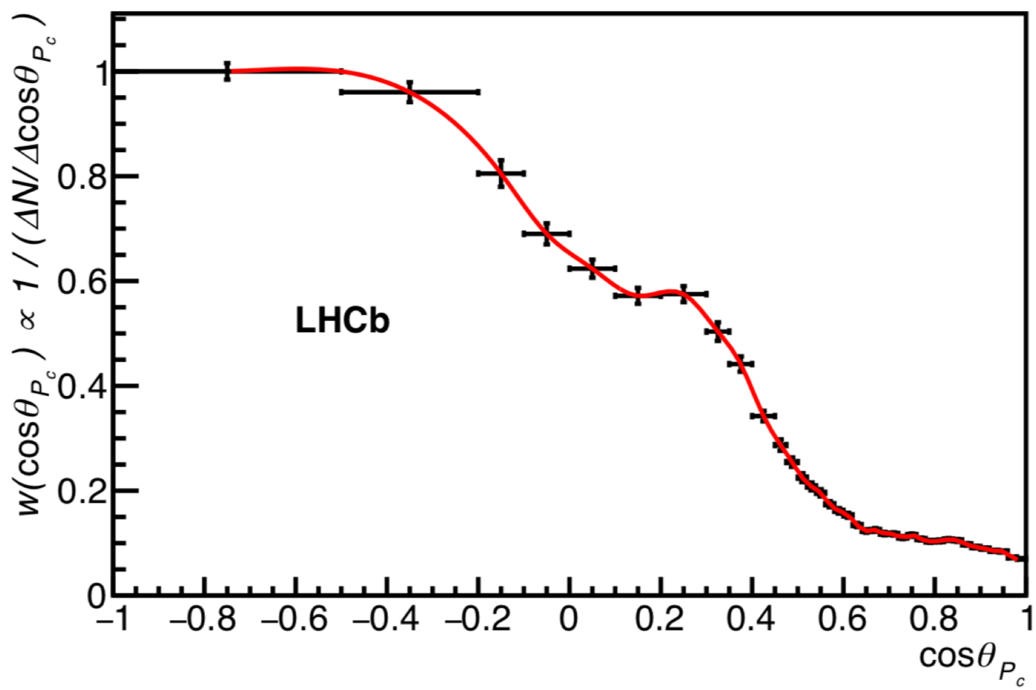
1.9 GeV

Analysis strategy

PRL 115 (2015) 072001
LHCb-PAPER-2019-014

- Amplitude analysis not needed for discovery since resonances are narrow; a 1D analysis is used
- But clearly a full amplitude analysis is needed to precisely determine resonant quantum number
- 1D Analysis not sensitive to broad resonance (i.e. $P_c(4380)^+$)
- $\cos\theta_{PC}$ dependent weight applied to increase sensitivity; though signal significant without weight





$\cos\theta_{PC}$

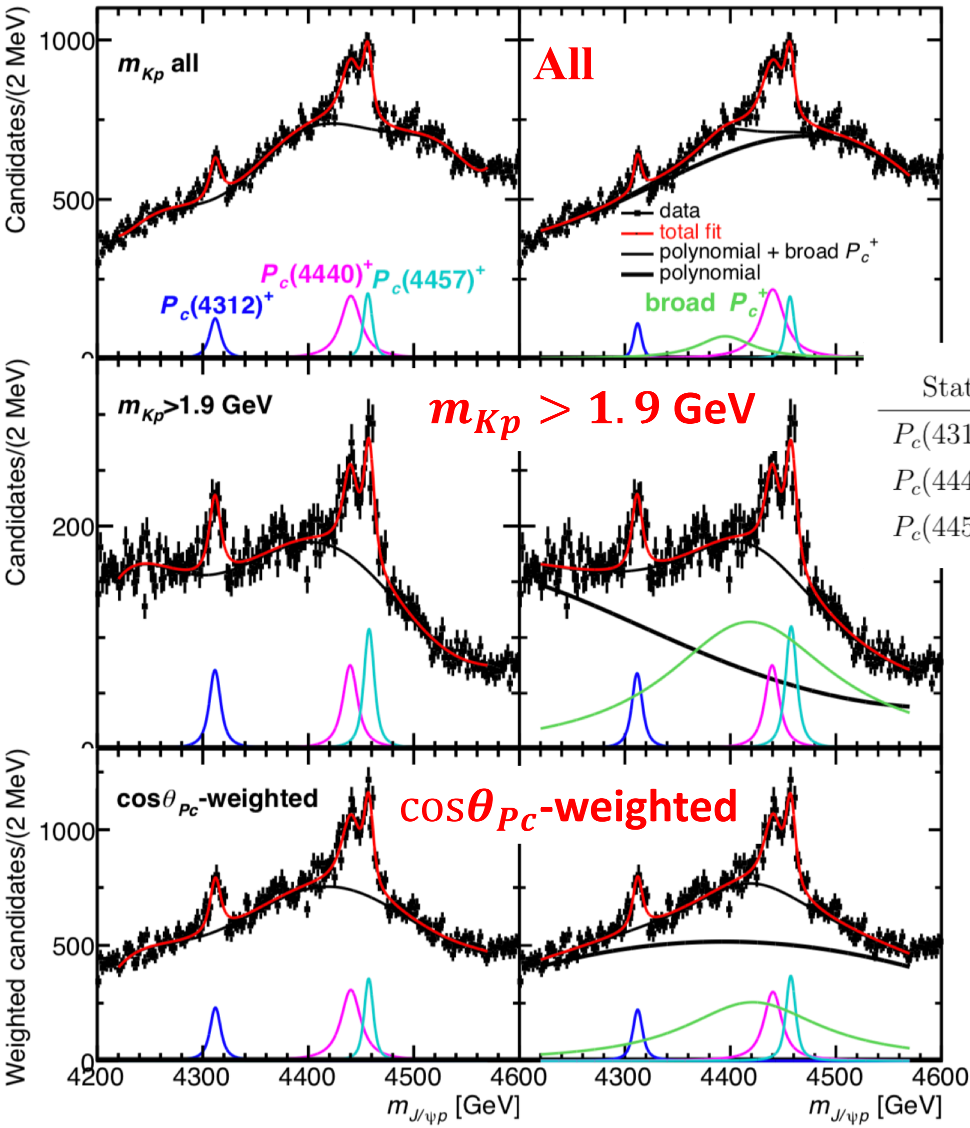
+1 ⟷ −1

weights

~0.1   +1

Resonant parameter determination

PRL 115 (2015) 072001
LHCb-PAPER-2019-014



- RBW function convoluted with resolution (2-3 MeV) to describe signal;
- Different background scenario considered: polynomial, polynomial + broad P_c^+ etc

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

- Large systematic uncertainties from with or without interference
- Relative contribution differ from amplitude analysis; need a proper amplitude analysis

What do we have now

PRL 115 (2015) 072001
LHCb-PAPER-2019-014

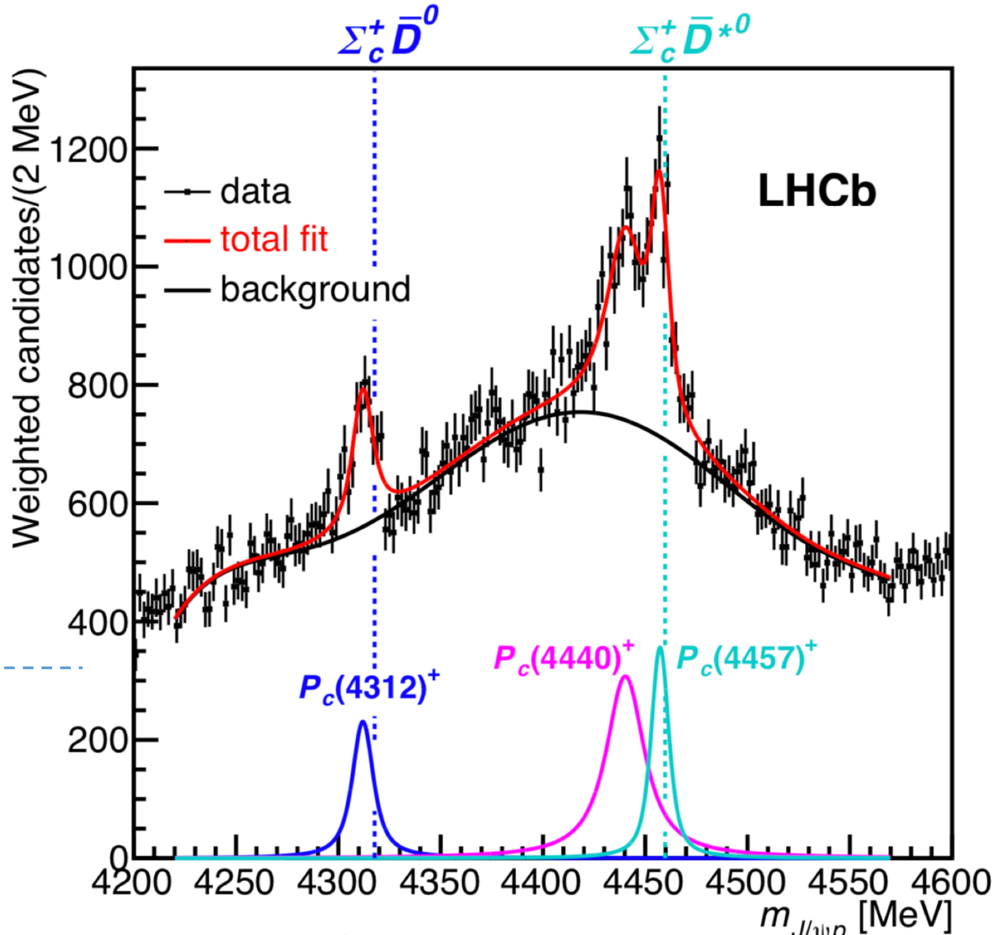
$P_c(4450)^+: 4449.8 \pm 1.7 \pm 2.5$ MeV
$39 \pm \ \ 5 \pm 19$ MeV

$P_c(4440)^+: 4440.3 \pm 1.3^{+4.1}_{-4.7}$ MeV
$20.6 \pm 4.9^{+8.7}_{-10.1}$ MeV

$P_c(4457)^+: 4457.3 \pm 0.6^{+4.1}_{-1.7}$ MeV
$6.4 \pm 2.0^{+5.7}_{-1.9}$ MeV

A new resonance

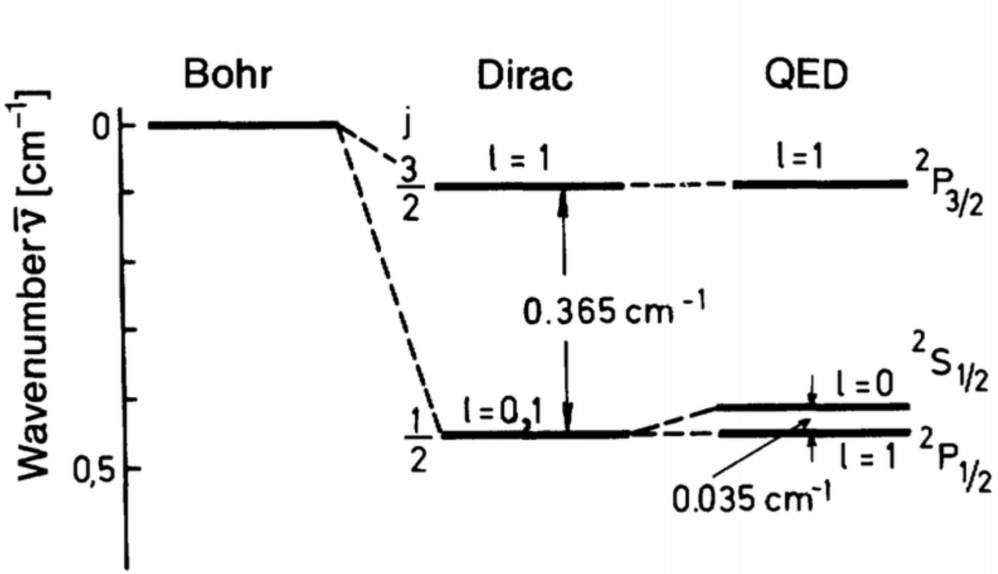
$P_c(4312)^+: 4311.9 \pm 0.7^{+6.8}_{-0.6}$ MeV
$9.8 \pm 2.7^{+3.7}_{-4.5}$ MeV



- No J^P determined; one could possibly be the missing $J^p = \frac{1}{2^-}$, amplitude analysis needed
- Resonant close to $\Sigma_c^+\overline{D^0}$ and $\Sigma_c^+\overline{D^{*0}}$ threshold hopefully can give more hints on their nature
- One notable thing: Chinese researchers (J. J Wu, B. S. Zou et al.) predict resonant at similar location long before the discovery

Rare decays and lepton universality test

Discrepancies indicate new physics

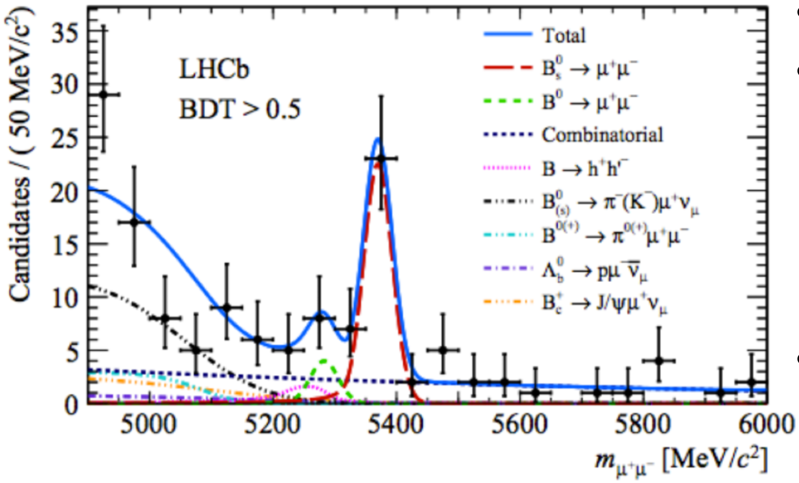


Lamb shift: a QED effect in Quantum mechanism

$B_s^0 \to \mu^+\mu^-$ status

PRL 118 (2017) 191801
Nature 522 (2015) 68
arXiv: 1812.03017

- Highly suppressed FCNC mode, sensitive to new physics



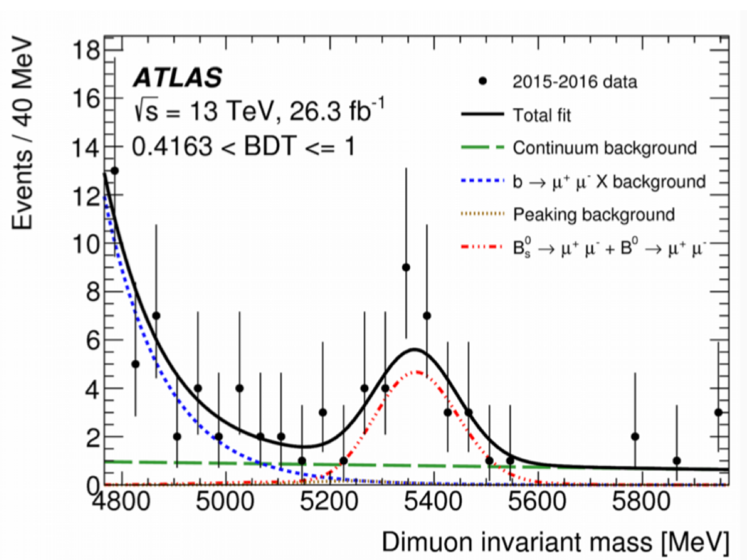
- Joint discovery from CMS+LHCb Run 1 combination
- First single experiment discovery using 1.4 fb^{-1} Run 2 data + Run 1 data

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9} \quad 7.8\sigma$$

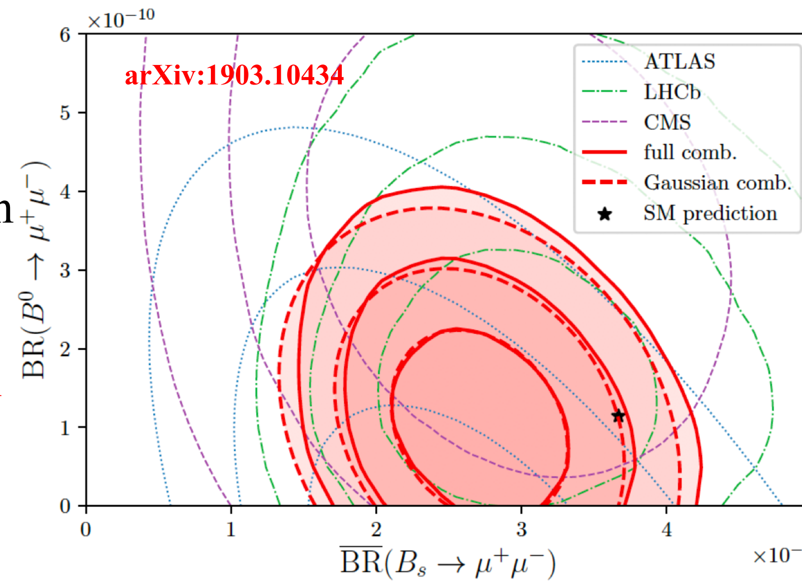
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}\right) \times 10^{-10} \quad 1.6\sigma$$

- ATLAS updates with Run 1 + 2015-2016 data

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9} \quad 4.6\sigma$$



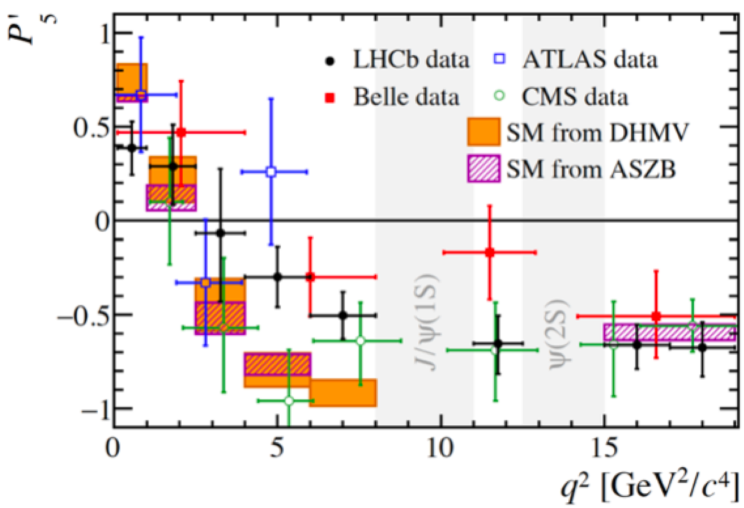
Naïve combination for all LHC experiment; ~2σ tension



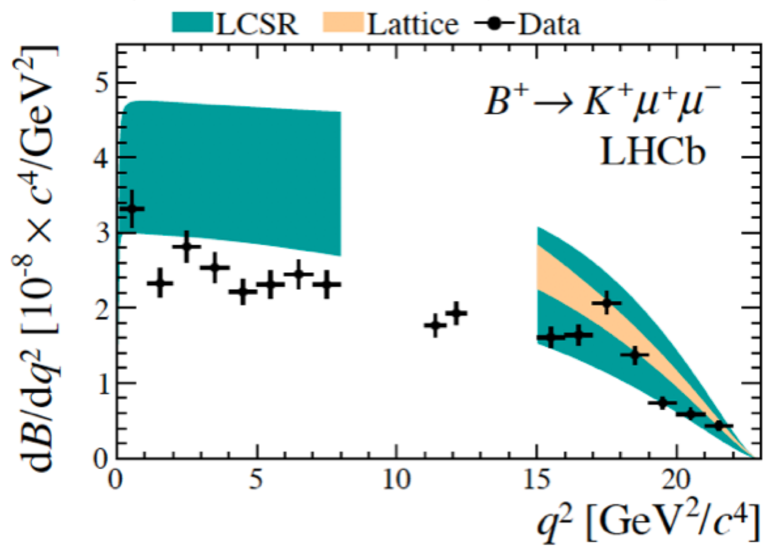
Tensions in rare sector

- Tensions with the SM seen in $b \to s l^+ l^-$ and $b \to c l \nu$
  - Branching fraction of exclusive $b \to s\, \mu^+ \mu^-$ decays
  - Angular analysis of $B^0 \to K^{*0} \mu^+ \mu^-$
  - Lepton universality tests of R_{K,K^*,D,D^*}
- Exceed all around 2-3σ, but seems to be consistent in global fits

Angular observables of $B^0 \to K^* \mu\mu$



Branching fraction of many b→sll processes



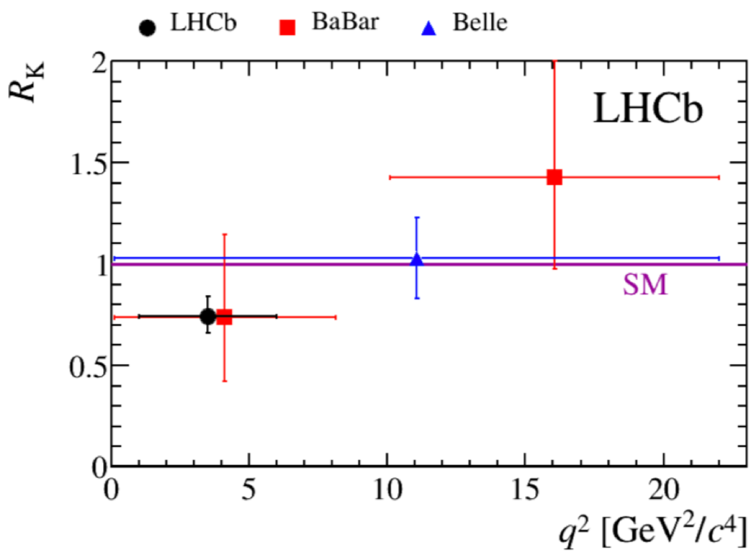
R_K updates

PRL 113 (2014) 151601
LHCb-PAPER-2019-009

$$R_K = \frac{\mathrm{Br}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}(B^+ \to K^+e^+e^-)}$$

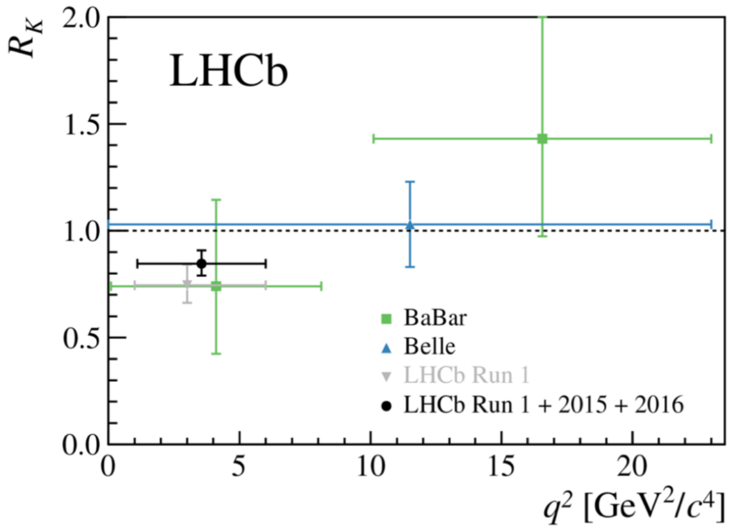
- We saw 2.6σ tension from LHCb previous measurements;
- Now add 2015+2016 data (similar statistic): more precise but significance similar + central value moves closer to SM

$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$



2.5σ

$$R_K = 0.846\ ^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}$$



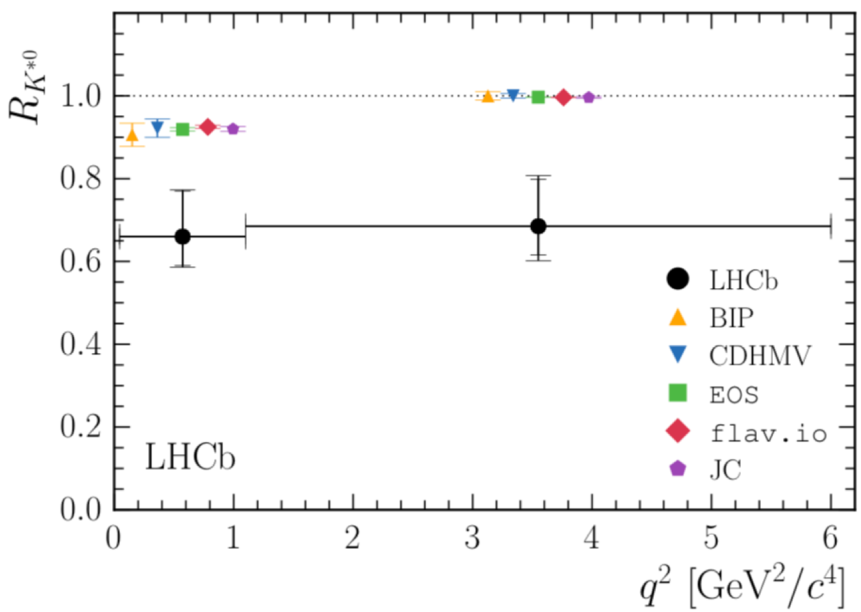
R_{K^*} updates from Belle

JHEP 08 (2017) 055
arXiv: 1904.02440

$$R_K = \frac{\mathrm{Br}(B^{0/+} \to K^* \mu^+ \mu^-)}{\mathrm{Br}(B^{0/+} \to K^* e^+ e^-)}$$

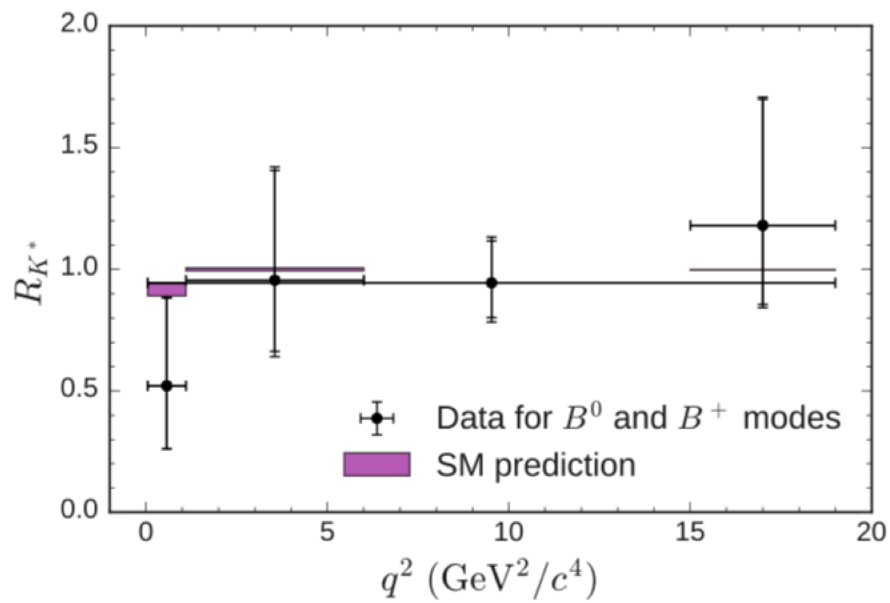
- LHCb has performed measurements with 3 fb^{-1} data and saw more than 2σ in both bins
- Belle has performed analysis with both B^0 and B^+; consistent with SM with large uncertainties

$$R_{K^{*0}} = \begin{cases} 0.66 \, ^{+\,0.11}_{-\,0.07} \, (\mathrm{stat}) \pm 0.03 \, (\mathrm{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \mathrm{GeV}^2/c^4 \, , \\ 0.69 \, ^{+\,0.11}_{-\,0.07} \, (\mathrm{stat}) \pm 0.05 \, (\mathrm{syst}) & \text{for } 1.1 < q^2 < 6.0 \ \mathrm{GeV}^2/c^4 \, . \end{cases}$$



Ref: arXiv: 1904.02440

q^2 in GeV$^2/c^4$	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+[illegible]}_{-0.26} \pm 0.05$	$0.46^{+[illegible]}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$



$R_{D^{(*)}}$ updates from Belle

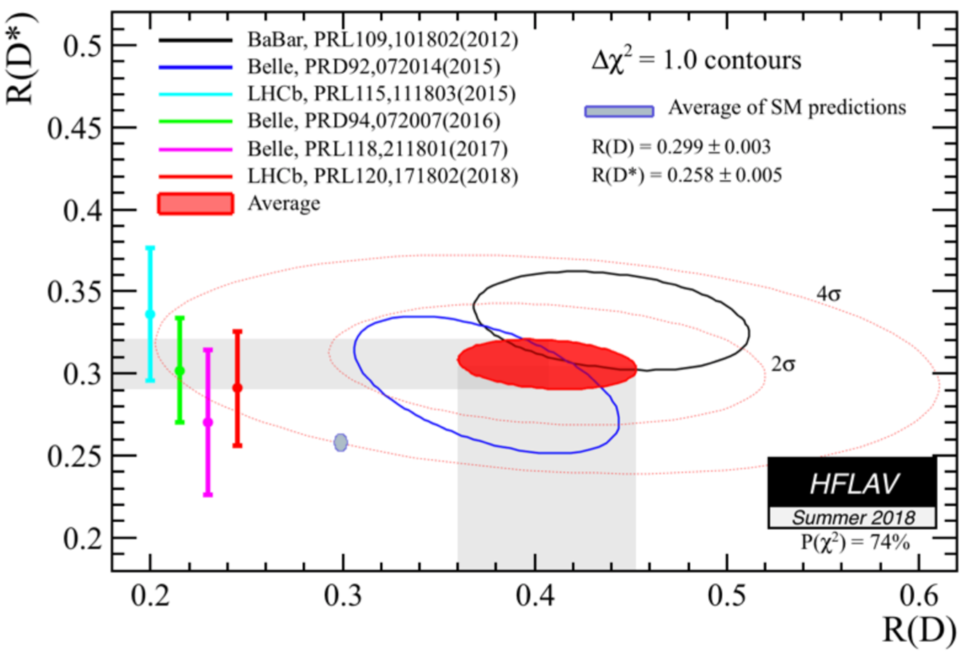
JHEP 08 (2017) 055
arXiv: 1904.02440

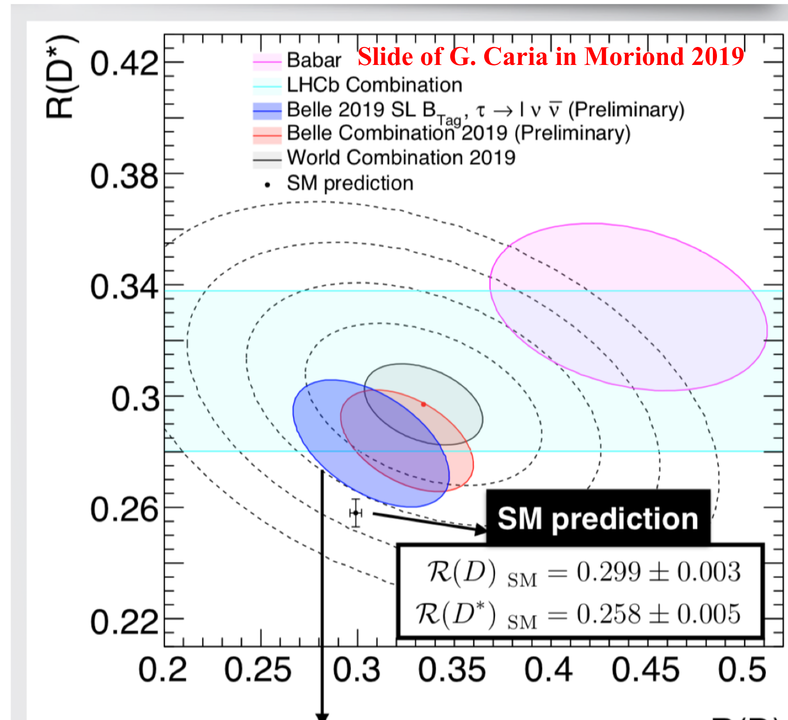
$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau^-\overline{\nu_\tau})}{Br(B \to D^{(*)}l^-\overline{\nu_l})}$$

3.8σ tension with SM

- Update semileptonic tag mode; compatible with SM within **1.2σ**
- Average of Belle compatible with SM within **2σ**
- **World average: 3.8σ to 3.1σ**

R(D*) = 0.306 ± 0.013 ± 0.007
R(D) = 0.407 ± 0.039 ± 0.024



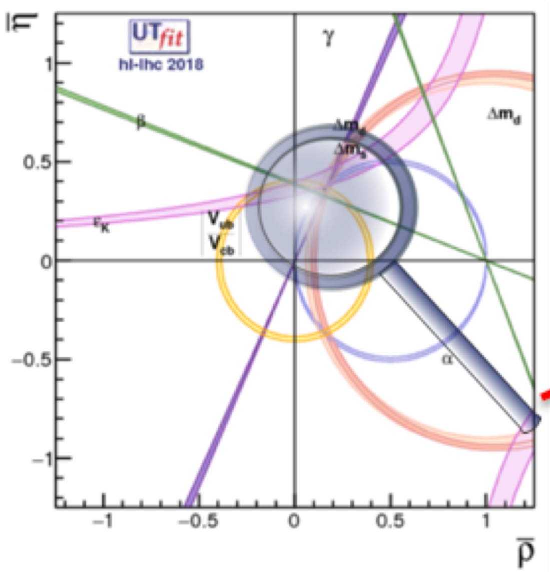


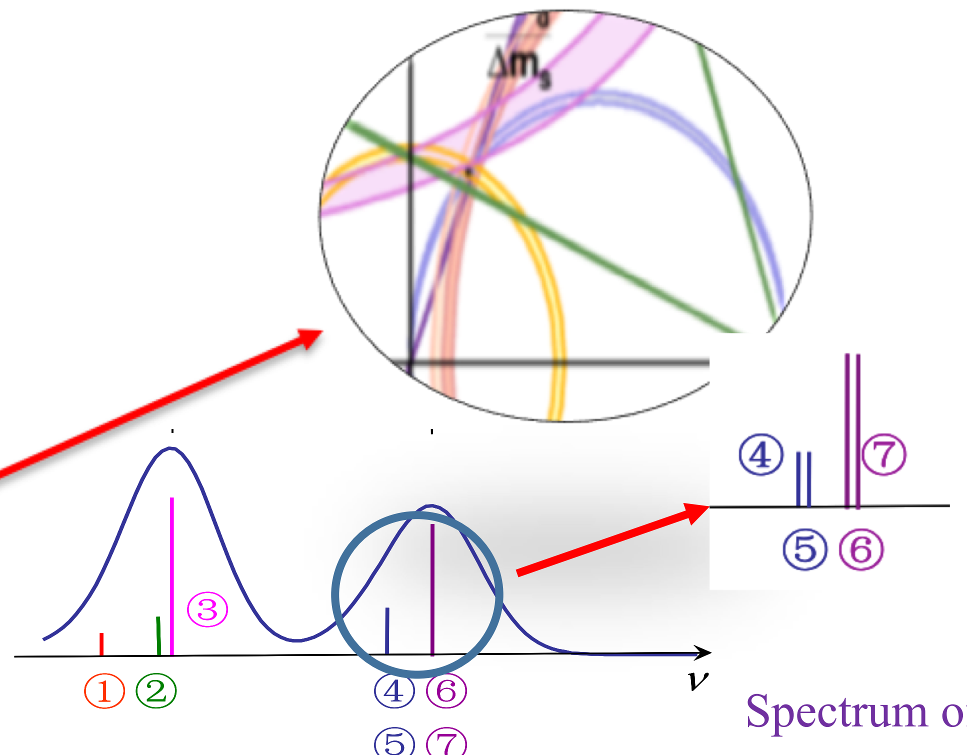
This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Conclusion

- LHCb: a wonderful apparatus and collaboration
- Many excited results at the beginning of 2019 from LHCb, including new pentaquark states and observation of CPV in charm decays
- One of the key goals of LHCb is to search for New physics through precision measurements. New physics may appear anywhere, maybe in flavor sector in year 202x





Spectrum of H_α