第17届全国重味物理和CP破坏研讨会
2019.07.29-08.01，内蒙古大学

清華大學
TSINGHUA UNIVERSITY

LHCb overview and highlights

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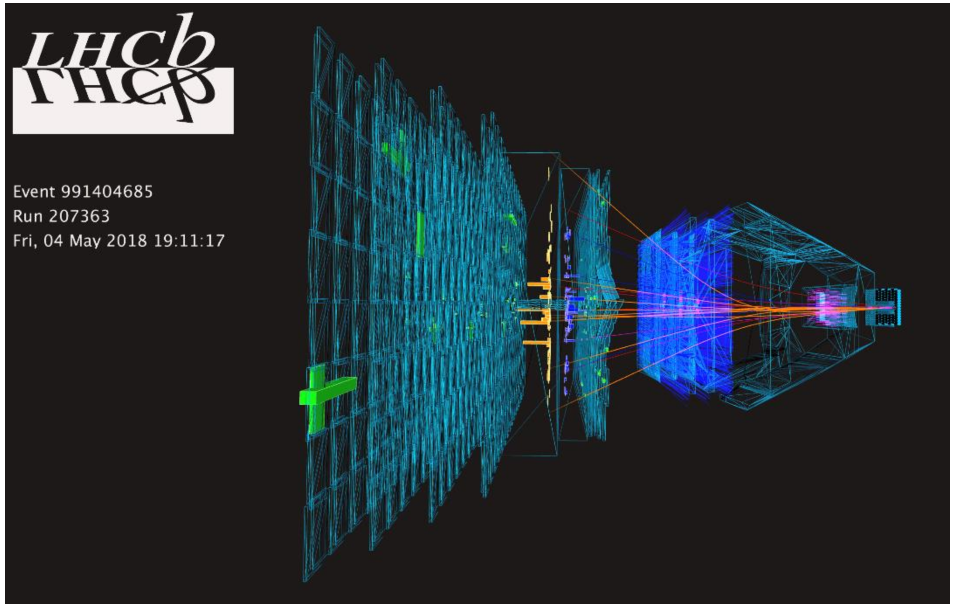
2019.07.29



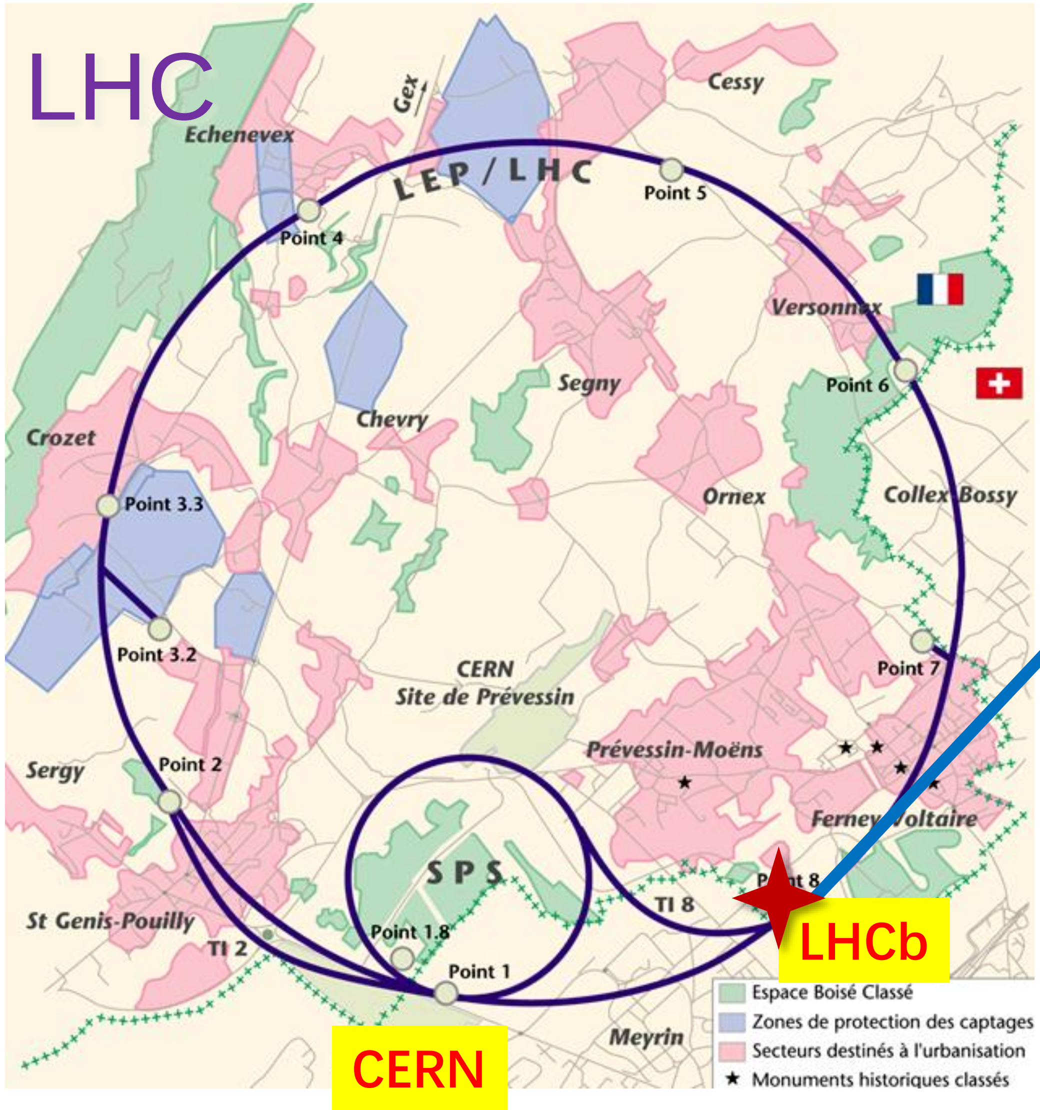
Outline

- ➢ **Introduction**
- ➢ **Highlights of CP violation and RD**
- ➢ **Highlights of hadron spectroscopy**
- ➢ **Prospect & summary**

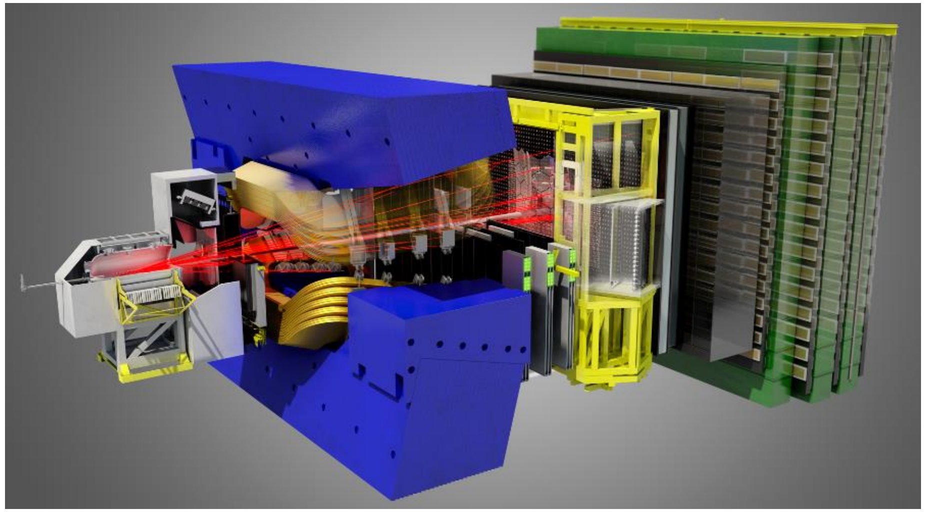
Other LHCb talks

- ✓ **Rare B decays at LHCb**
  Jibo He, 14:30-15:00, 29 July
- ✓ **Hadron spectroscopy and exotic states at LHCb**
  Hang Yin, 16:20-16:50, 29 July
- ✓ **CP violation in B decays at LHCb**
  Wenbin Qian, 9:00-9:30, 30 July
- ✓ **CP violation in charm decays at LHCb**
  Liang Sun, 9:30-10:00, 31 July
- ✓ **LHCb future upgrade and prospects**
  Jike Wang, 16:00-16:20, 31 July

The LHCb experiment



- A forward spectrometer at the LHC designed for the study of heavy flavour physics
  - Indirect searches for NP via precision measurement of b- and c-hadrons



- The LHCb collaboration
  - 1378 Members, from 79 institutes in 18 countries

LHCb China: from 2000 to 2019

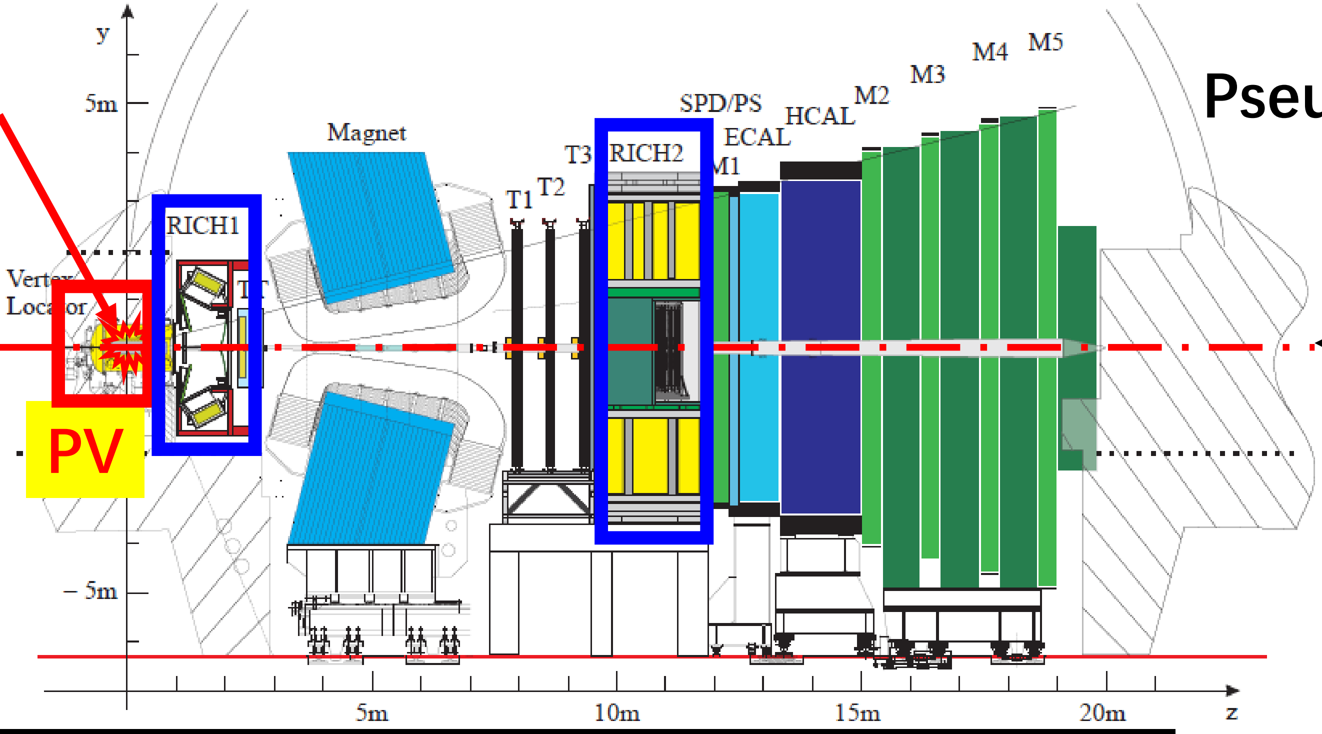
- 7 institutes：
  ~ 20 faculties + 10 postdocs + 50 students
  - 2000，Tsinghua（清华）, founded by Prof. Y. Gao
  - 2013，CCNU（华中师范）
  - 2015，UCAS（国科大）
  - 2016，Wuhan Univ（武大）
  - 2018，IHEP（高能所）
    SCNU（华南师大）
  - 2019，PKU (北大）

The LHCb detector

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

Collision point

Beam1



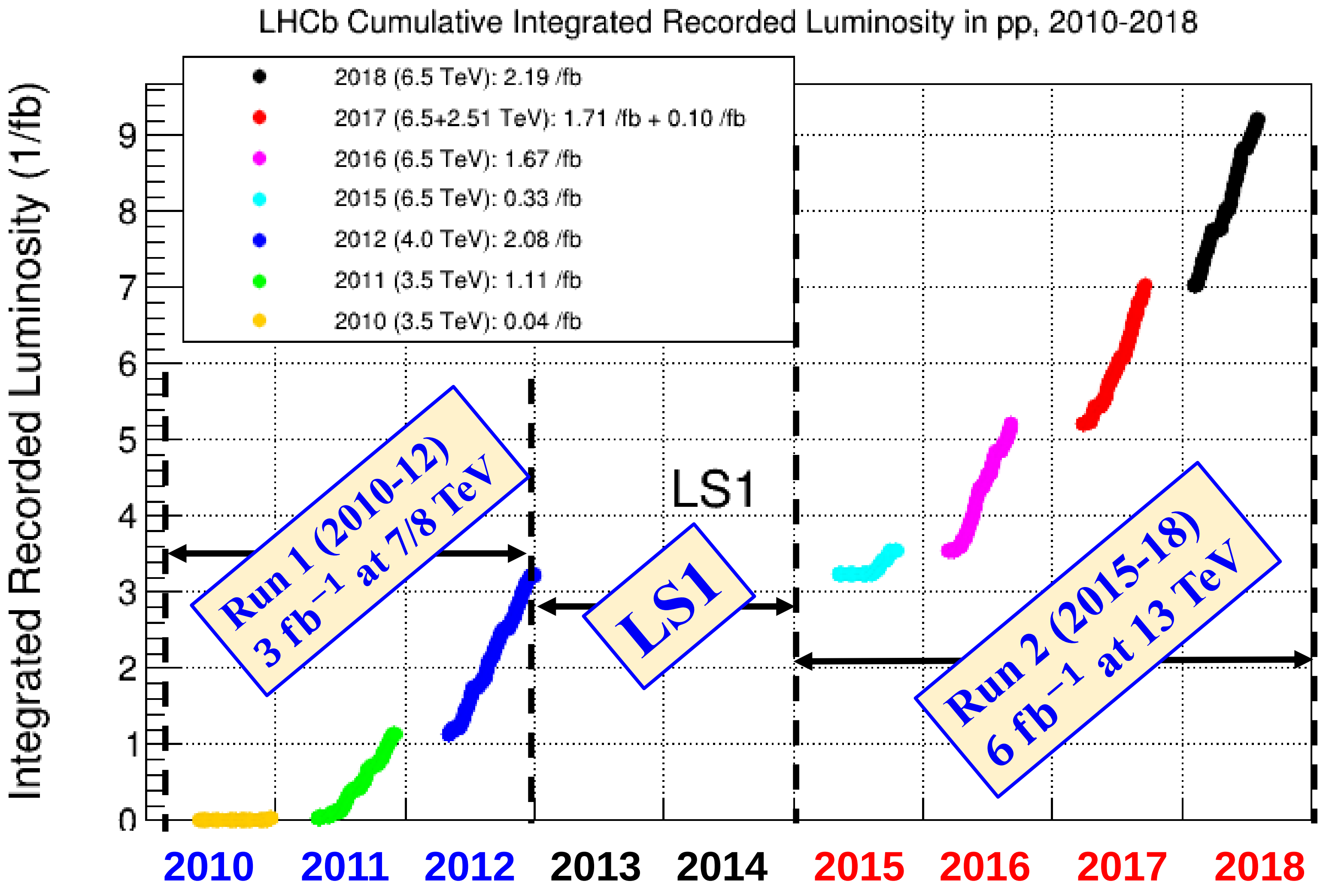
Beam2

Pseudorapidity coverage
$2 < \eta < 5$

Vertex:	$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
Time:	$\sigma_\tau = 45\ \mathrm{fs}$ for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

- Efficient trigger
- Efficient particle ID
- Good vertex and impact parameter resolution
- Excellent momentum resolution

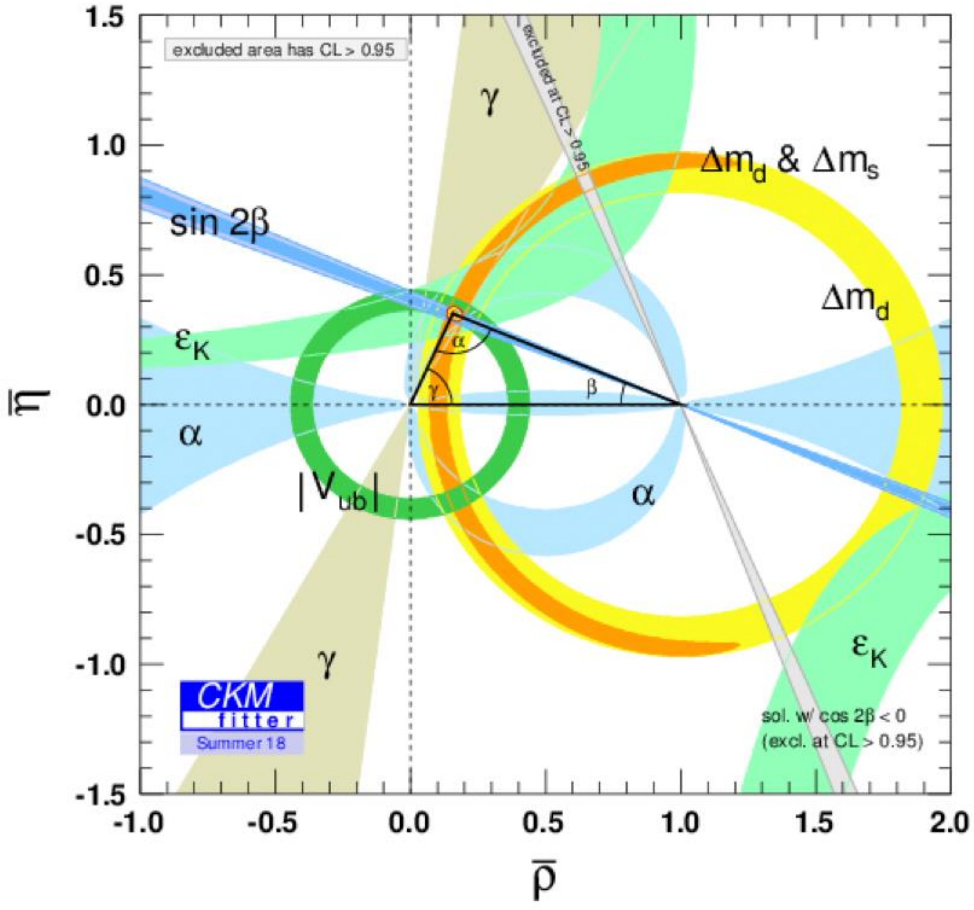
Data taking (run1+run2)



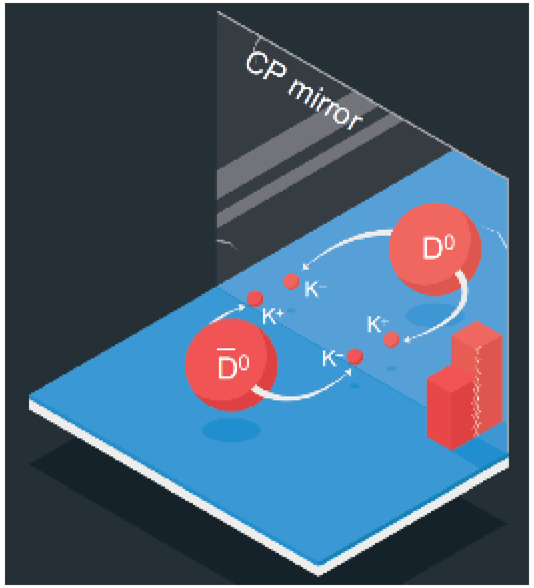
- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- Many impressive results have been achieved

More than 9 $\mathbf{fb^{-1}}$ accumulated in Run1+Run2

CP violation



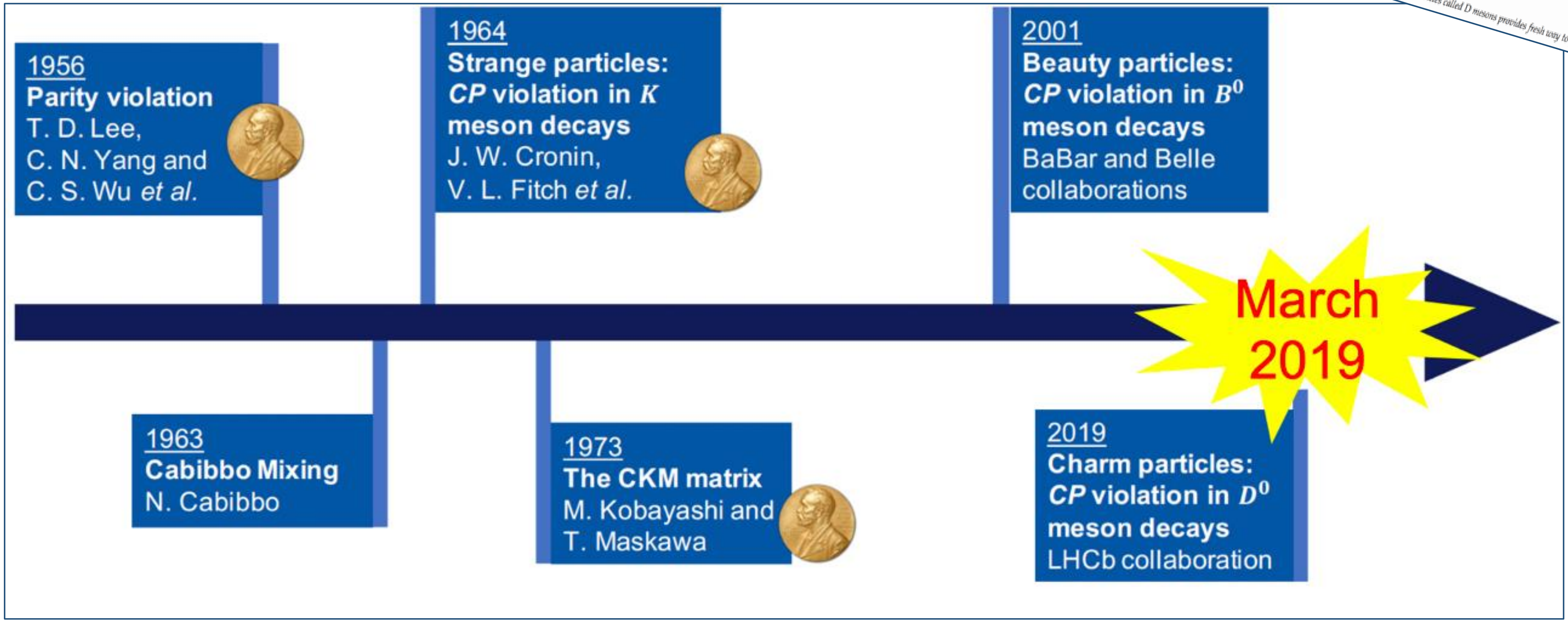
Discovery of CPV in charm sector



PRL122 (2019) 211803

Observation of CPV in charm

- Long awaited



Observation of CPV in D^0

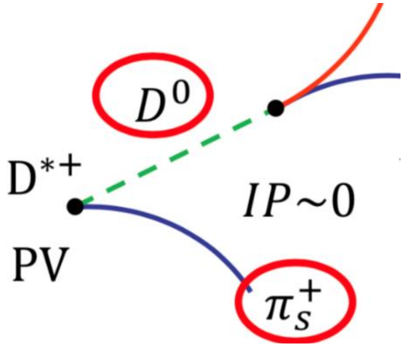
PRL122 (2019) 211803

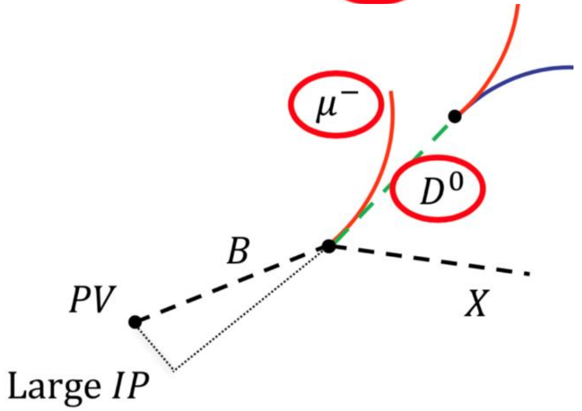
- SM expectation of A_{CP}^{dir} small, but "how small" is uncertain

$$A_{CP}^{dir} \equiv \frac{|A(D^0 \to f)|^2 - |A(\bar{D}^0 \to \bar{f})|^2}{|A(D^0 \to f)|^2 + |A(\bar{D}^0 \to \bar{f})|^2} \le O(10^{-3})$$

- Was not observed at LHCb until 2019 using full Run1+Run2 data

- $D^{*+} \to D^0\pi^+$ (π-tagged) and $B \to D^0\mu^- X$ (μ-tagged)





$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

Compatible with previous LHCb results and WA

LHCb combination (9 fb^{-1})

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

CP violation in charm observed at 5.3σ !

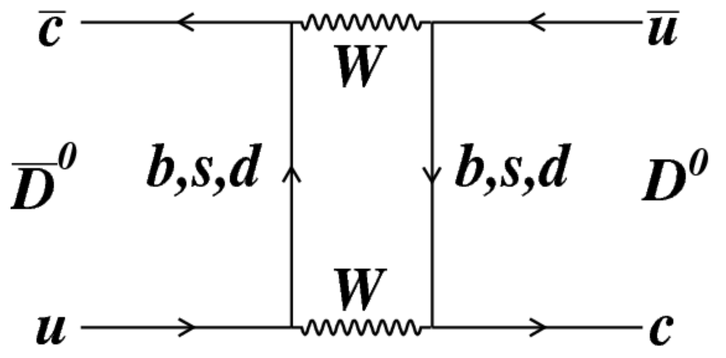
Oscillation of charm mesons in $D^0 \to K_s^0\pi^+\pi^-$

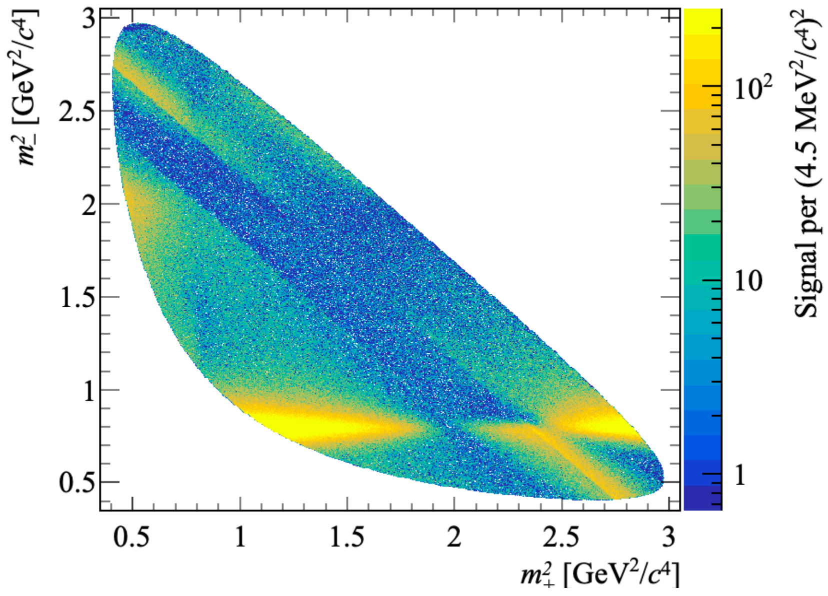
PRL122 (2019) 231802

Oscillation of charm mesons in $D^0 \to K_S^0\pi^+\pi^-$

PRL122 (2019) 231802

- D^0 and $\bar{D}^0$ can oscillate between each other
  - Mass eigenstates $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle$ with $m_{1,2}$ ($\Gamma_{1,2}$) mass (width) of $D_{1,2}$
  - Mixing parameters: $x \equiv \frac{m_1 - m_2}{\Gamma}$ $y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma}$ $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$
    - x determines the oscillation rate
  - CPV can occur in the mixing
    - Oscillation rates differ for D^0 and $\bar{D}^0$
- x is small in SM, but NP can enhance x and CPV
- LHCb Run1 tagged $D^0 \to K_S^0\pi^+\pi^-$
  - 1.3M (prompt) + 1M (secondary)





Oscillation of charm mesons in $D^0 \to K_S^0 \pi^+ \pi^-$

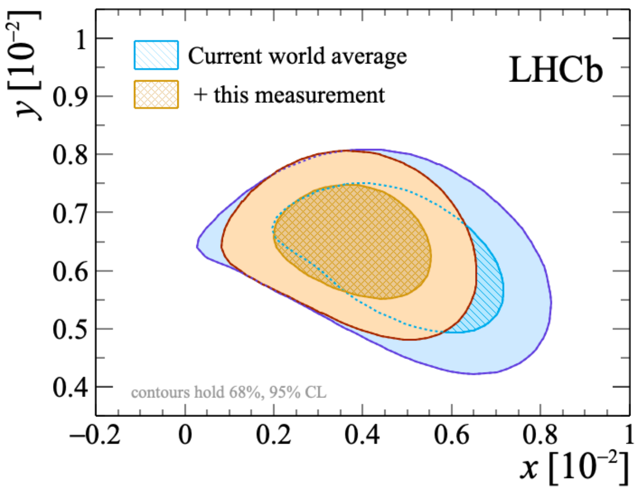
PRL122 (2019) 231802

- Model independent analysis (bin-flip method)
  - To void efficiency modelling

PRD99 (2019) 012007

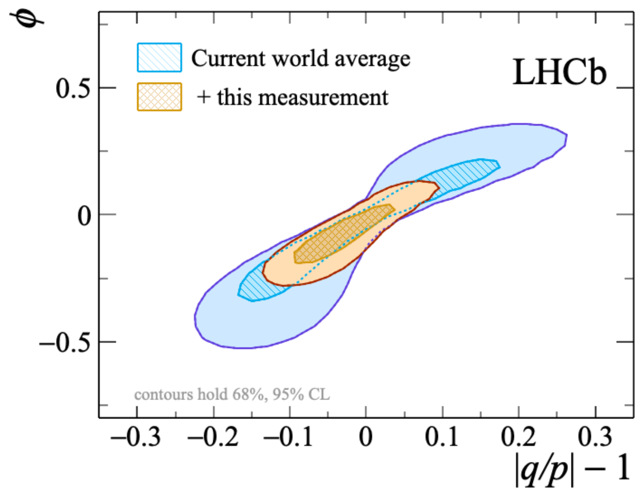
- Results

$$x_{CP} = (2.7 \pm 1.6 \pm 0.4) \times 10^{-3}$$
$$\Delta x = (-0.53 \pm 0.70 \pm 0.22) \times 10^{-3}$$
$$y_{CP} = (7.4 \pm 3.6 \pm 1.1) \times 10^{-3}$$
$$\Delta y = (0.6 \pm 1.6 \pm 0.3) \times 10^{-3}$$



- Most precise determination of the mass difference x from a single experiment
- New world average (assume CP symmetry in mixing and interference)

$$x_{CP} = \left(3.9^{+1.1}_{-1.2}\right) \times 10^{-3}$$



First evidence of mass difference between D^0 mass eigenvalues

CPV parameter A_Γ in $D^0 \to K^+K^-, \pi^+\pi^-$

LHCb-CONF-2019-001

CPV parameter A_Γ in $D^0 \to K^+K^-(\pi^+\pi^-)$

LHCb-CONF-2019-001

- The asymmetry of $D^0 \to f(= K^+K^- \text{ or } \pi^+\pi^-)$ decay rates is sensitive to CPV in charm mesons

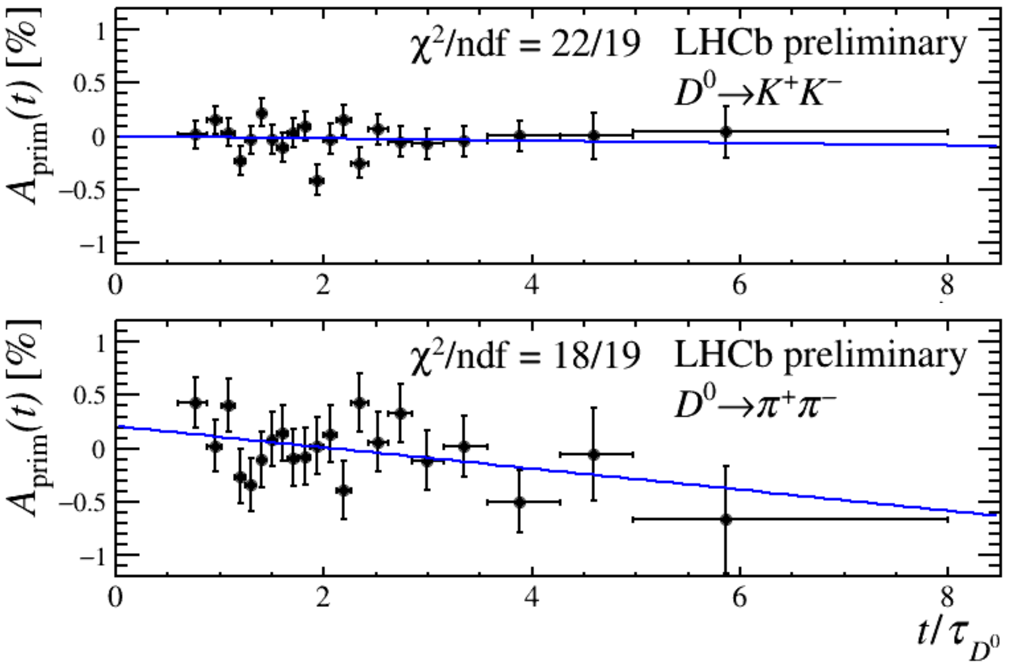
$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\bar{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\bar{D}^0 \to f,t)} \approx A_{CP}^{\text{decay}}(f) - A_\Gamma(f)\frac{t}{\tau_{D^0}}$$

- A_Γ probes CPV in mixing and interference
- Can be extracted by a linear fit to A_{CP} in bins of D^0 decay time
- $A_\Gamma^{\text{SM}} \approx 3 \times 10^{-5}$ [arXiv:1812.07638]

CPV parameter A_Γ in $D^0 \to K^+K^-(\pi^+\pi^-)$

LHCb-CONF-2019-001

- $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ samples from $D^{*+} \to D^0\pi^+$ in 2015-2016 data ($1.9\ \mathrm{fb}^{-1}$)



- Results

$$A_\Gamma(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$
$$A_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$

$$\Delta A_\Gamma \equiv A_\Gamma(K^+K^-) - A_\Gamma(\pi^+\pi^-)$$
$$= (-10.1 \pm 7.8 \pm 0.5) \times 10^{-4}$$
$$A_\Gamma(K^+K^- + \pi^+\pi^-) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4}$$

- Combined with the Run1 result

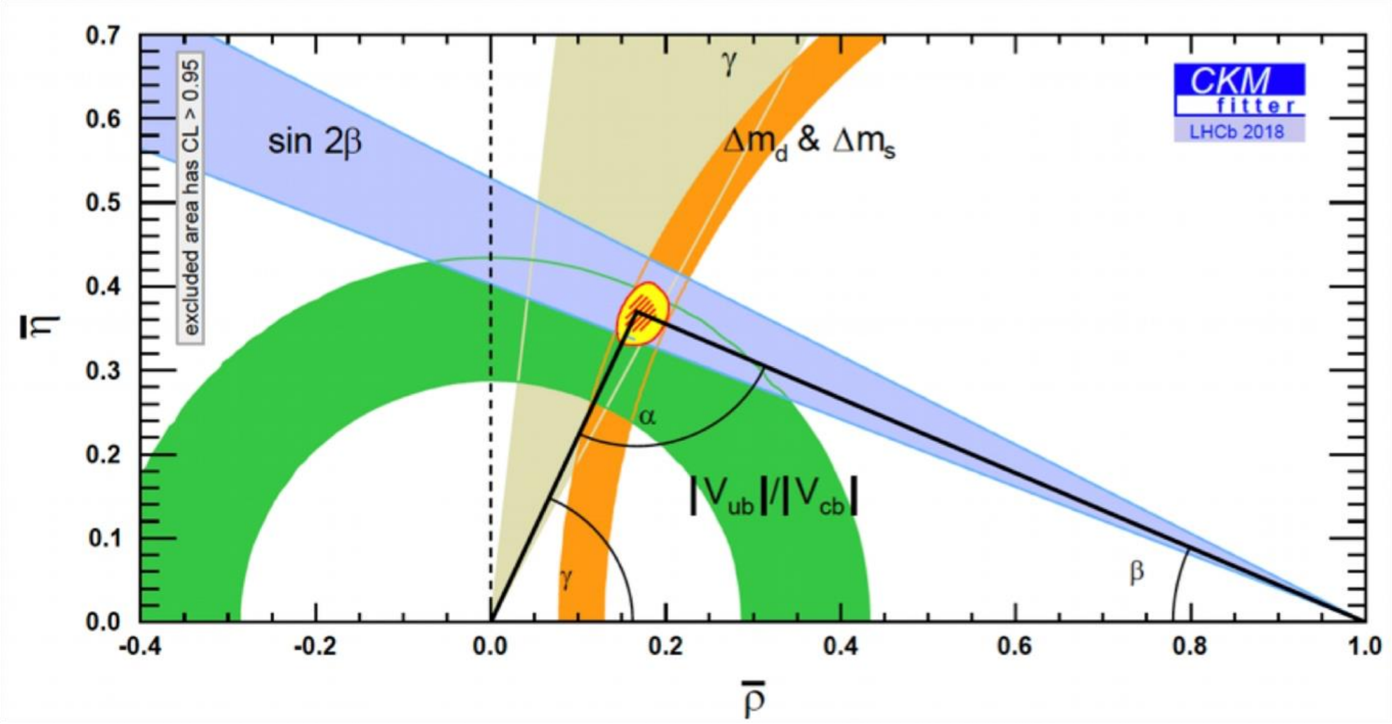
$$\Delta A_\Gamma = (-8.6 \pm 5.0 \pm 0.5) \times 10^{-4}$$
$$A_\Gamma(K^+K^- + \pi^+\pi^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}$$

Consistent with SM
More data needed

ϕ_s measurement

arXiv:1903.05530

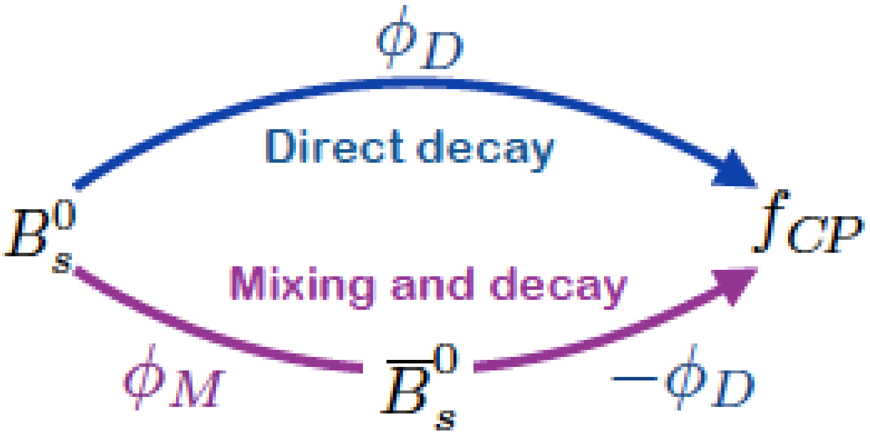
arXiv:1906.08356



$B_s^0 - \overline{B}_s^0$ mixing phase ϕ_s in $b \to c\bar{c}s$ decays

CP phase sensitive to new physics

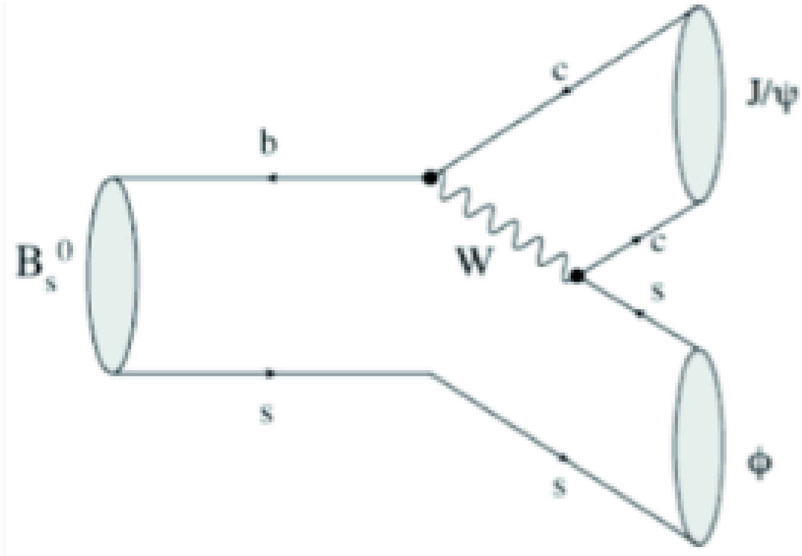
$$\phi_s = \phi_M - 2\phi_D$$



Tree-dominated decay

- Large signal yield
- Clean SM expectation

$\phi_s \approx -2\beta_s = -36.8^{+9.6}_{-6.8}$ mrad (CKM fitter)



LHCb uses $B_s^0 \to J/\psi K^+ K^-, J/\psi \pi^+ \pi^-$

ϕ_s in $b \to c\bar{c}s$ decays

arXiv:1903.05530

arXiv:1906.08356

LHCb combination (7/8/13 TeV, 4.9 fb^{-1})

$\phi_s = -41 \pm 25$ mrad

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

ATLAS combination (7/8/13 TeV, 100 fb^{-1})

$\phi_s = -76 \pm 34 \pm 19$ mrad

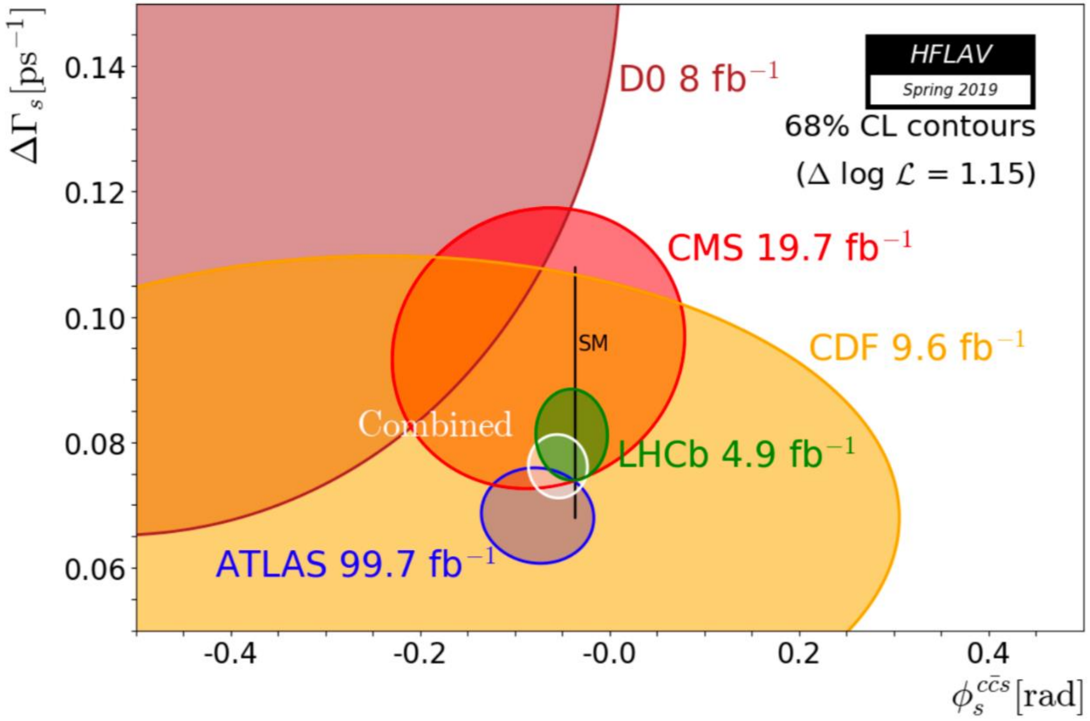
$\Delta\Gamma_s = 0.068 \pm 0.004 \pm 0.003$ ps^{-1}

[ATLAS-CONF-2019-019]

HFLAV average

$\phi_s = -55 \pm 21$ mrad

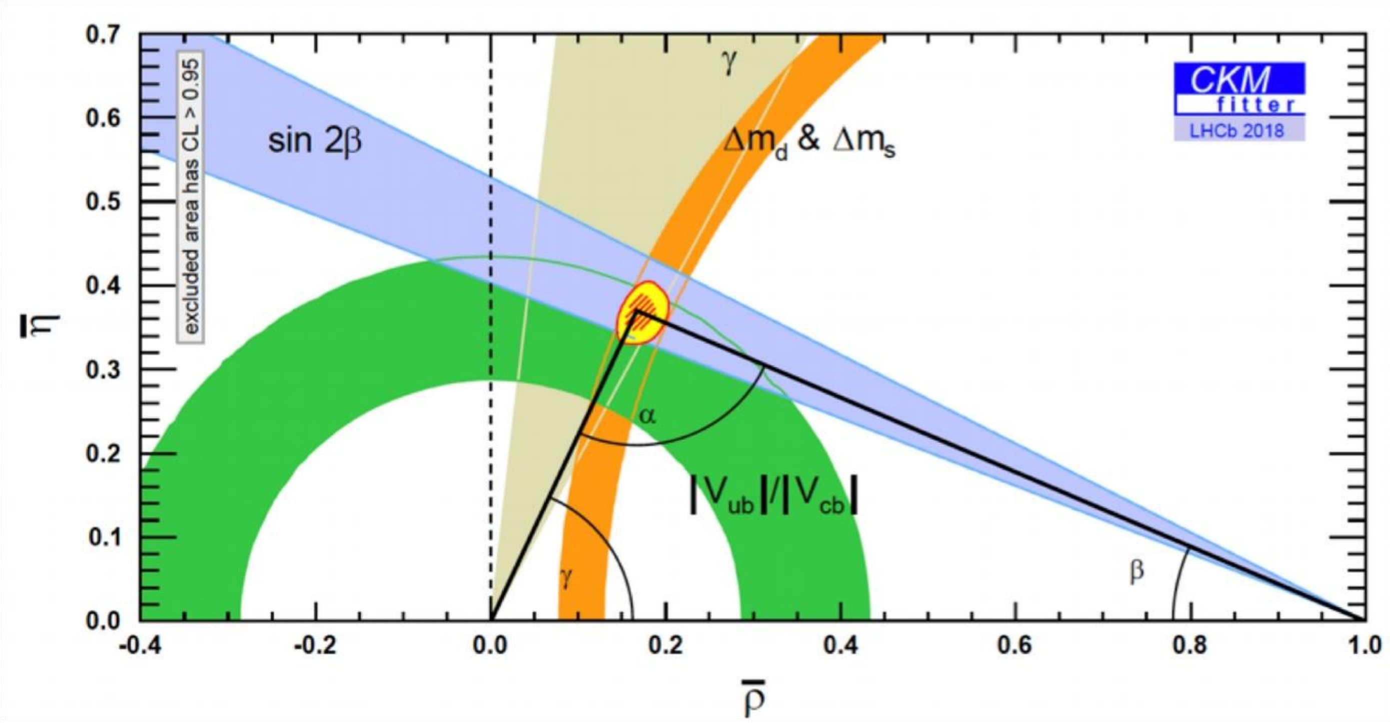
$\Delta\Gamma_s = 0.0762 \pm 0.0033$ ps^{-1}



γ measurement

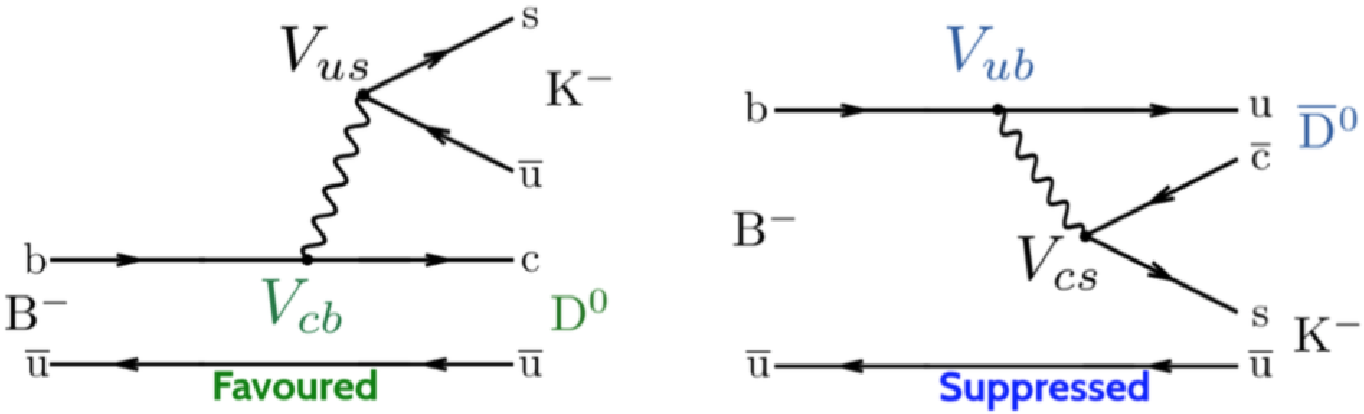
LHCb-CONF-2018-002

arXiv:1906.08297



$$\gamma = -\arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

- The least well-known angle of the CKM Unitarity Triangle
- Can be measured in the interference between $b \to c$ (Cabibbo favored) and $b - u$ (Cabibbo suppressed) transitions, e.g.

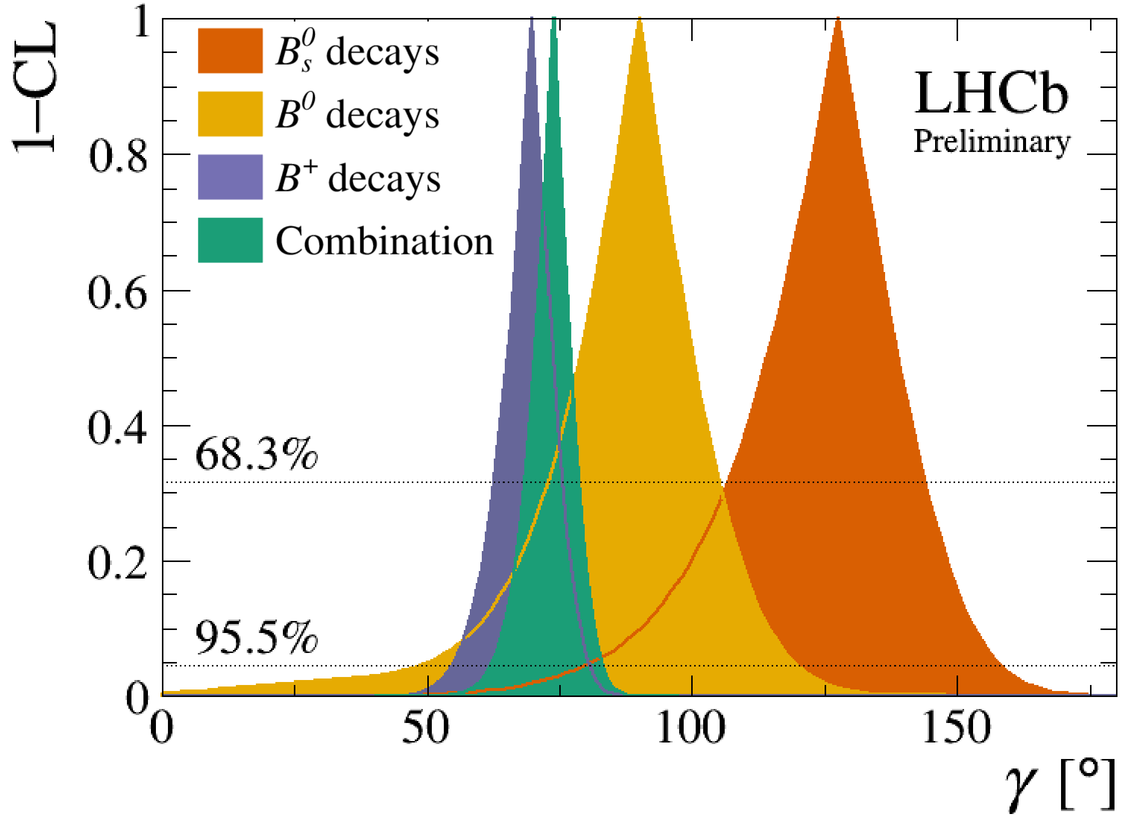


Many decay modes combined to achieve the ultimate precision due to small yields ($\mathcal{B} \approx 10^{-7}$) and small interference effects ($\sim 10\%$)

Combination of γ

LHCb-CONF-2018-002

- Tension (2σ) between B^+ and B_s^0 results
- Tension (2σ) direct measurements and indirect constraints from UT



Run1: 3 fb^{-1} (2011+2012)
Run2: 2 fb^{-1} (2015+2015)

B decay	D decay	Method	Ref.	Dataset[†]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ	[17]	Run 1
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ	[18]	Run 2
$B^+ \to DK^+$	$D \to K_S^0 K^+\pi^-$	GLS	[19]	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ	[24]	Run 1
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1

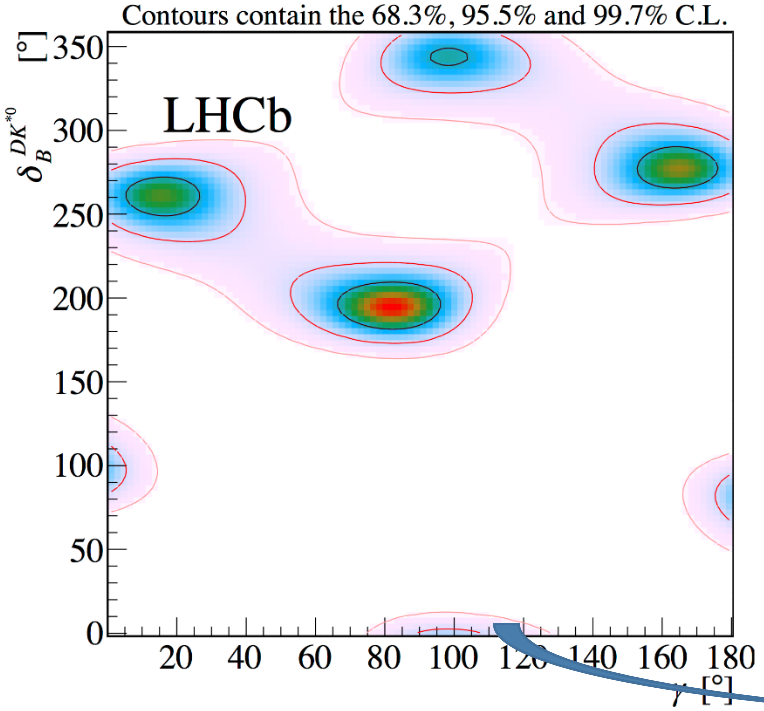
$$\gamma(\mathbf{LHCb}) = \left(74.0^{+5.0}_{-5.8}\right)^\circ$$

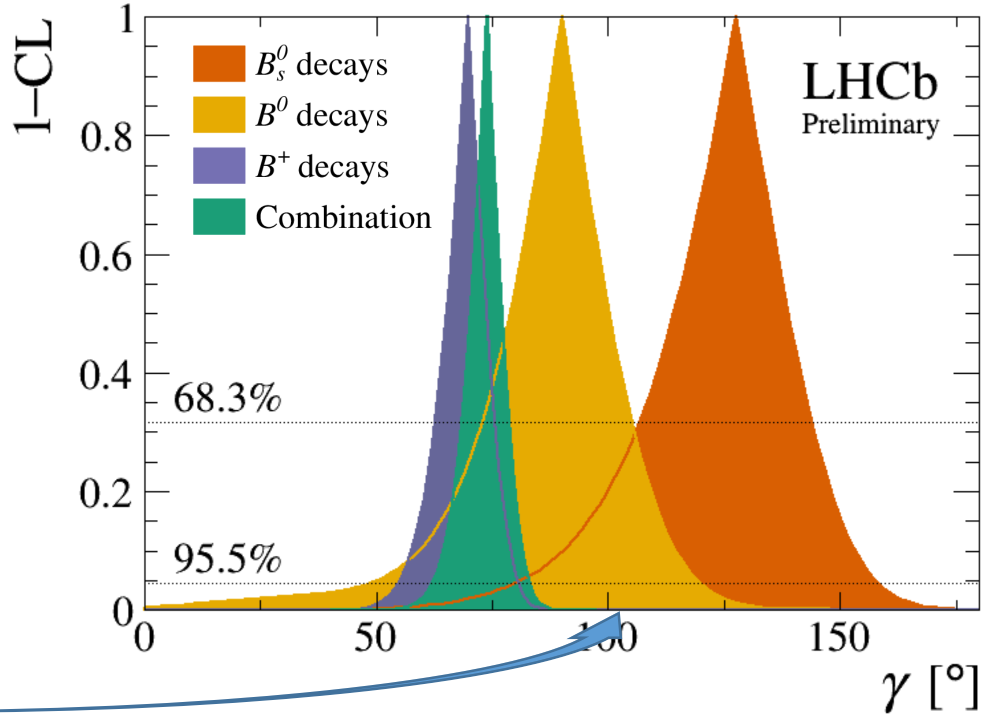
$$\gamma(\mathbf{HFLAV}) = \left(71.1^{+4.6}_{-5.3}\right)^\circ$$
$$\gamma(\mathbf{CKM\ fitter}) = \left(65.8^{+1.0}_{-1.7}\right)^\circ$$

γ in $B^0 \to DK^{*0}$

arXiv:1906.08297

- Latest measurement in $B^0 \to DK^{*0}$ with $D \to K\pi, KK, \pi\pi, K3\pi, 4\pi$ in Run1 (3 fb^{-1})+Run2 (1.9 fb^{-1})



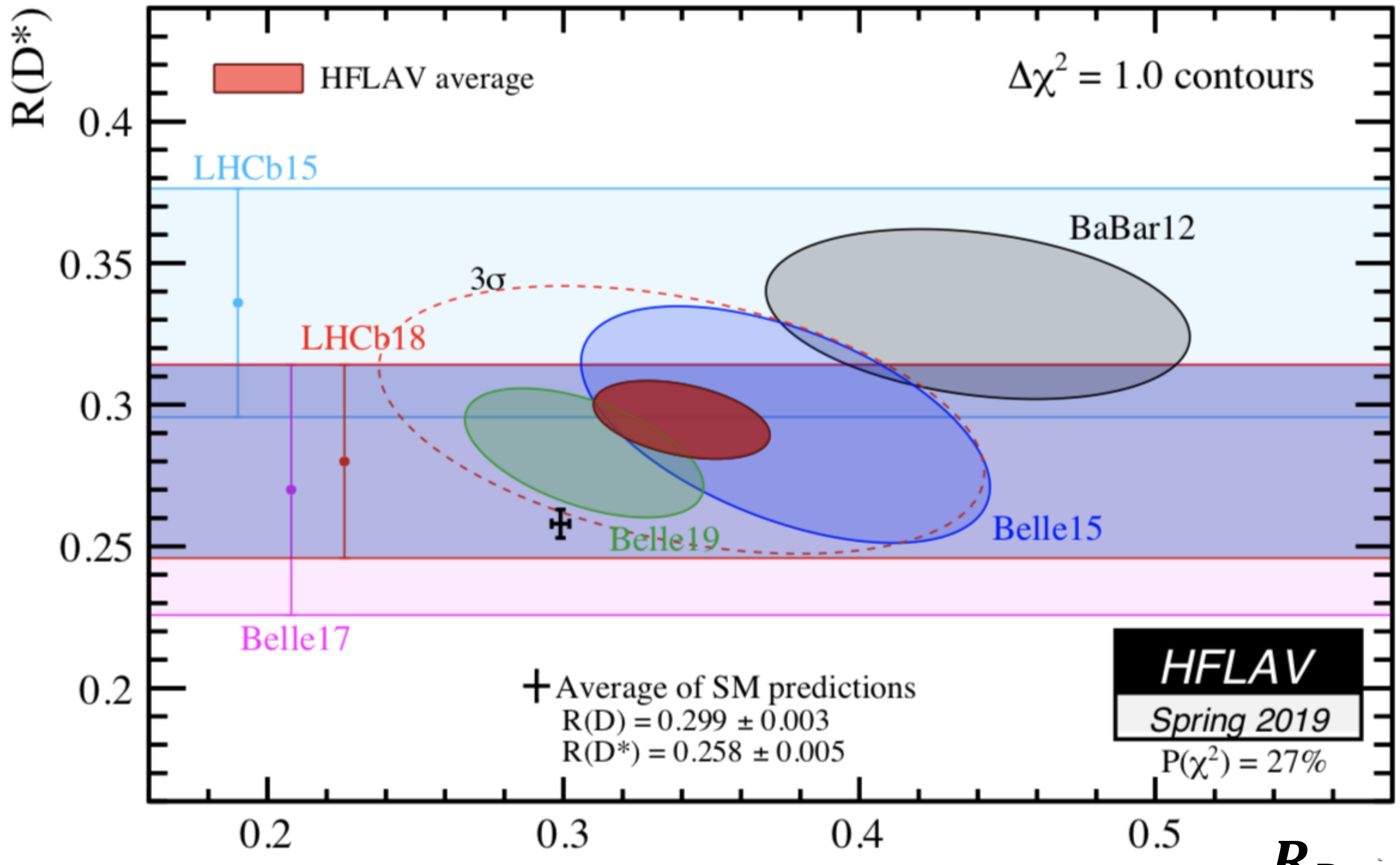


Provide powerful constraint when combined

BESIII measurements on strong phase parameters in D decays important

Lepton flavour anomalies in b-hadron decays

Latest world average of R_D and R_{D^*}

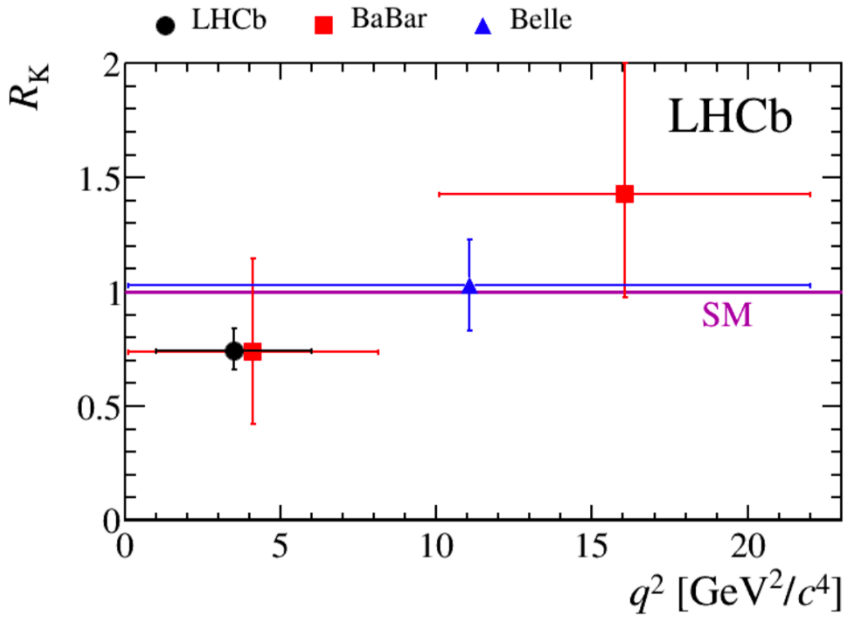


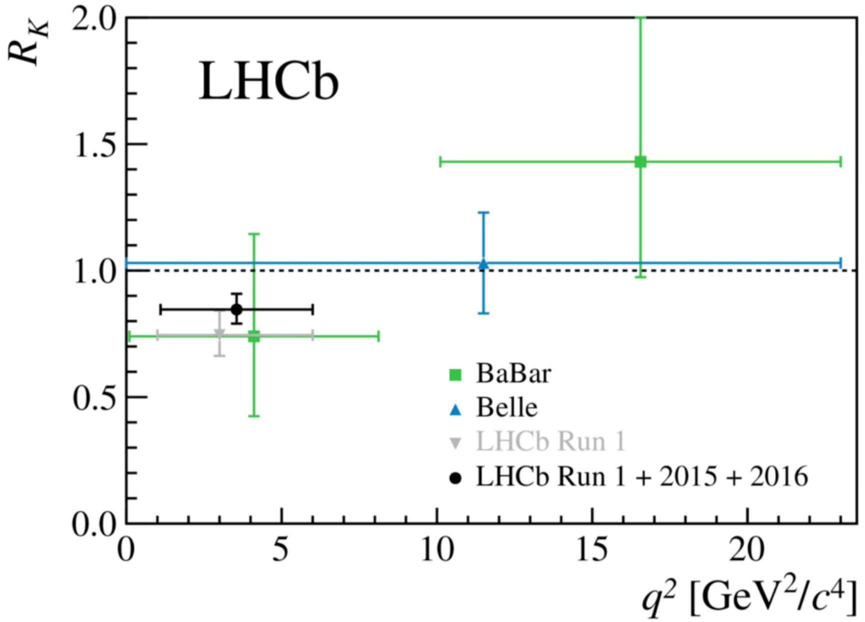
R_D

Update of R_K

PRL 122 (2019) 191801

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$





$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ PRL 113 (2014) 151601

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

$1 < q^2 < 6\ \mathrm{GeV}^2/c^4$

Run1: 2.6σ

Run1+2015+2016: 2.5σ

Hadron spectroscopy

Doubly charmed baryons

arXiv:1905.02421

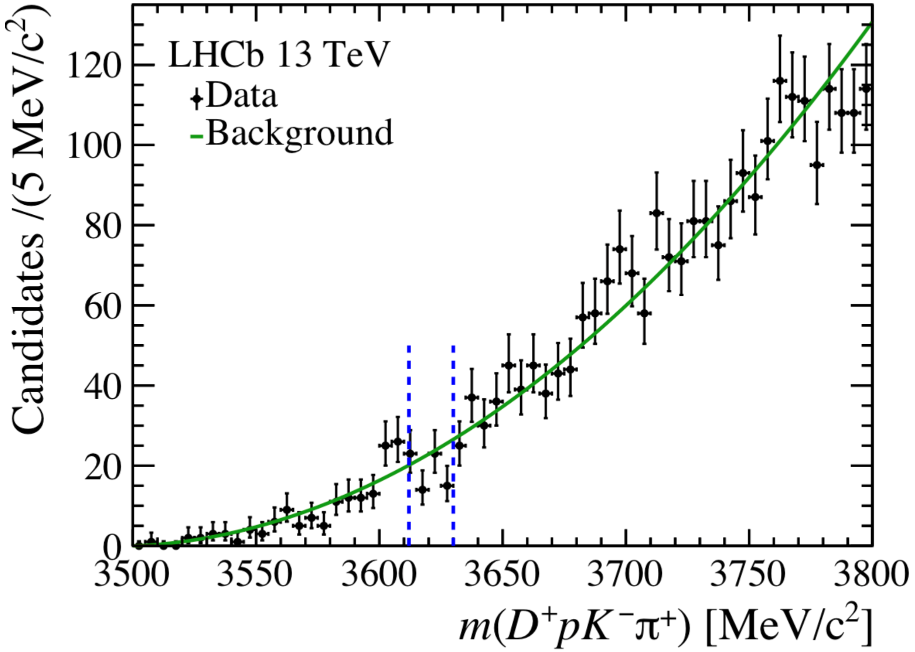
- Three ground states: $\Xi_{cc}^{++}(ccu), \Xi_{cc}^{+}(ccd)$ and $\Omega_{cc}^{+}(ccs)$
  - Ξ_{cc}^{++} observed, searches for others are ongoing
  - Lifetime measured: $\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022} \pm 0.014$ ps

PRL 121 (2018) 052002

- No signal is observed in $\Xi_{cc}^{++} \to D^+ pK^-\pi^+$

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)}$$

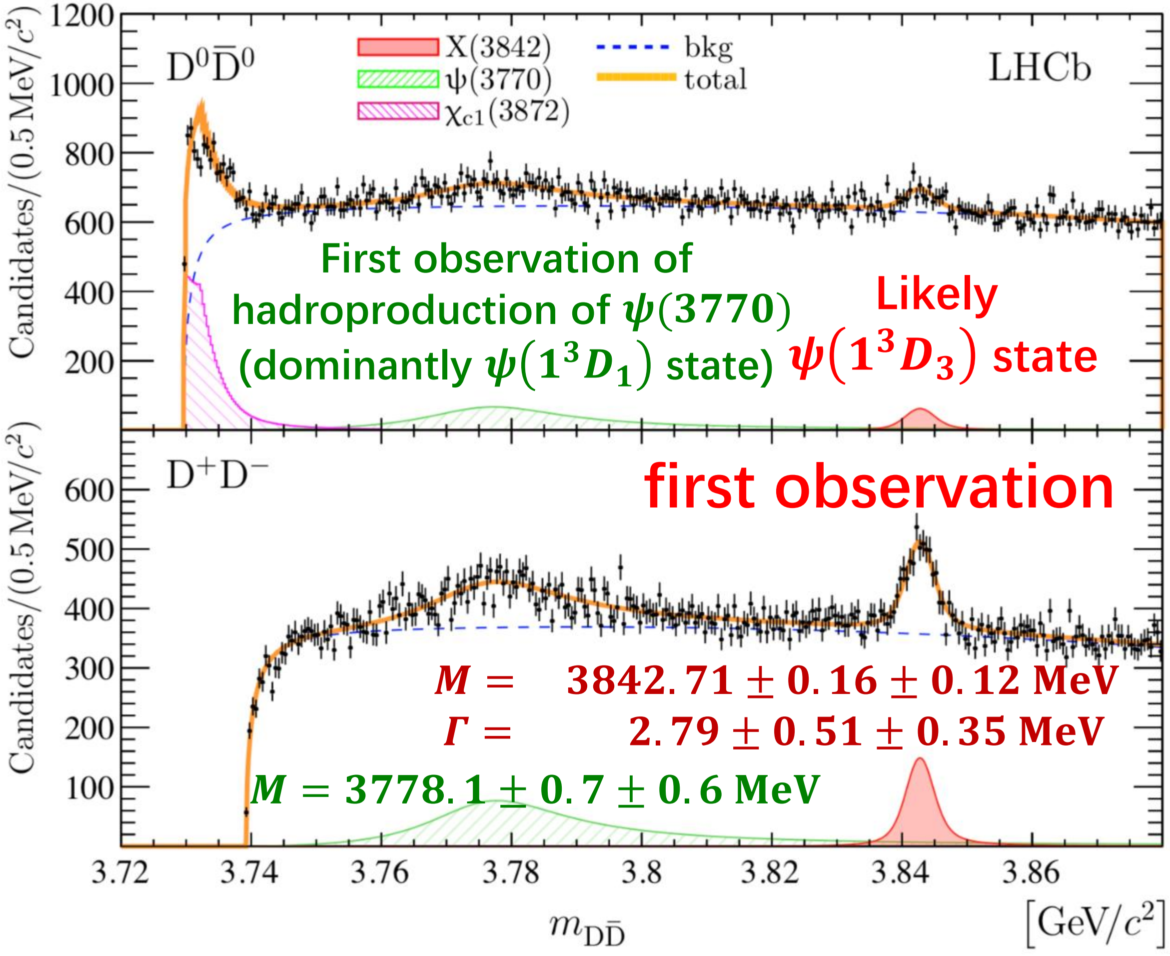
$$\mathcal{R} < 1.7\ (2.1) \times 10^{-2} \text{ at } 90\%\ (95\%) \text{ CL}$$

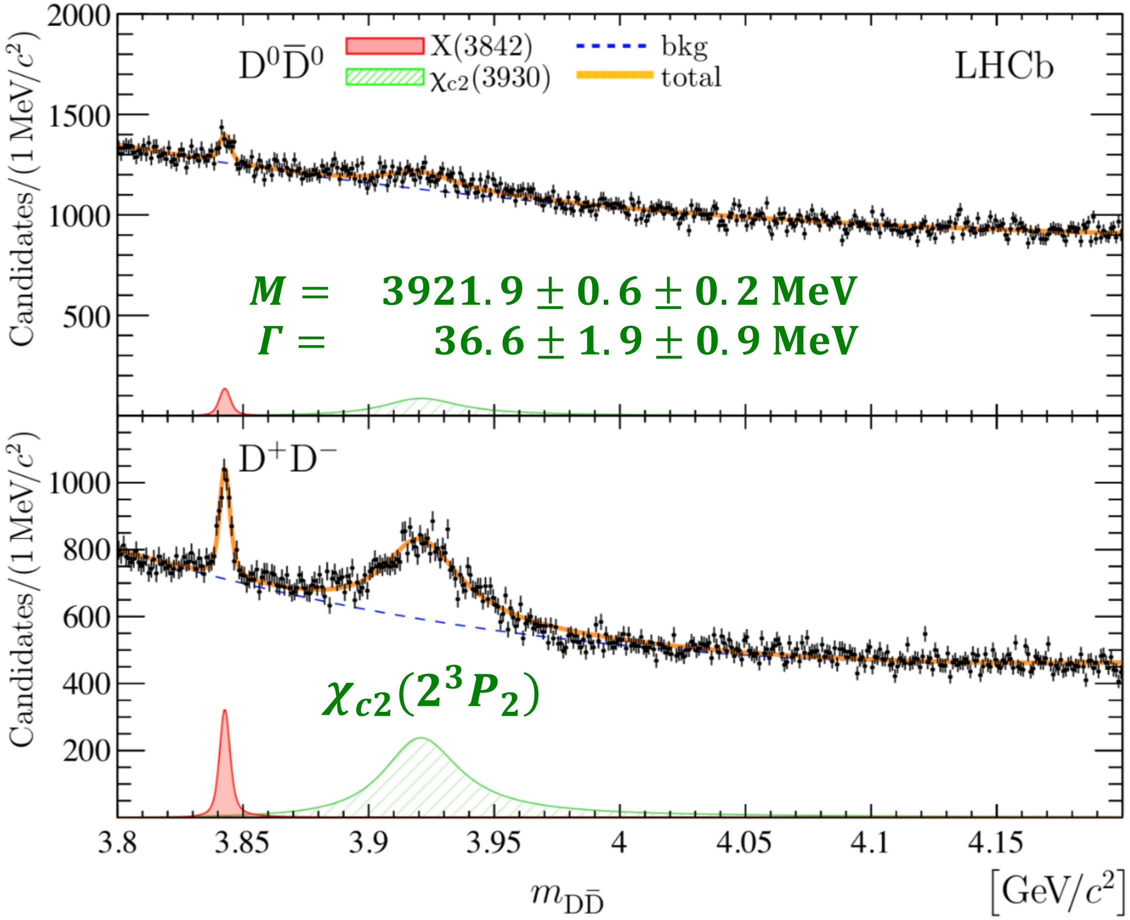


Observation of $X(3842)$ in $m(D\bar{D})$

JHEP07(2019)035

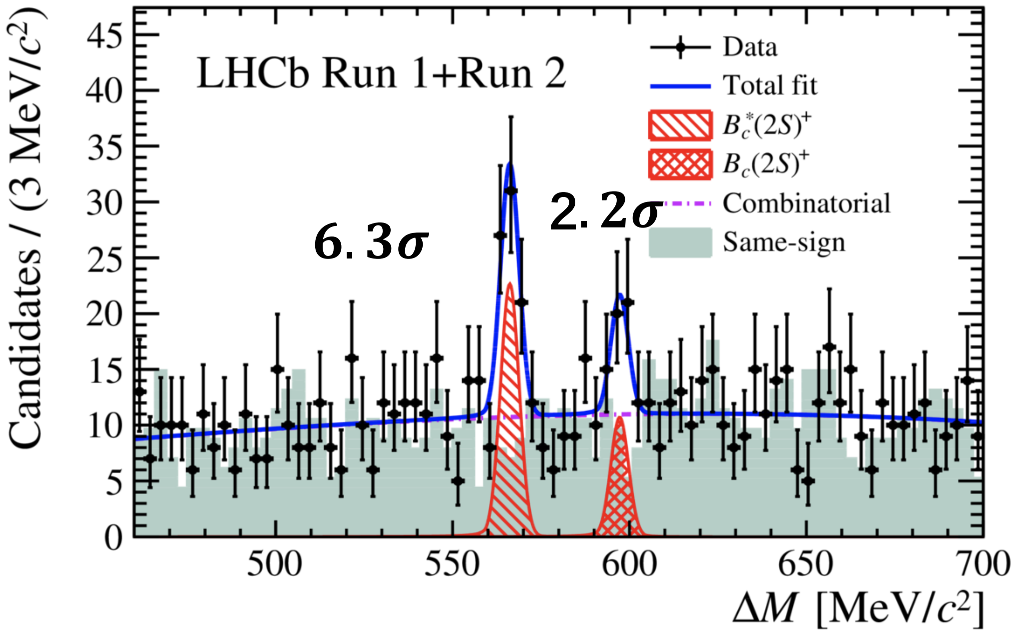
- First observation of $X(3842)$, probably $\psi(1^3D_3)$
- First observation of hadroproduced $\psi(3770)$ and $\chi_{c2}(3930)$





Observation of excited B_c^+

LHCb: PRL 122 (2019) 232001

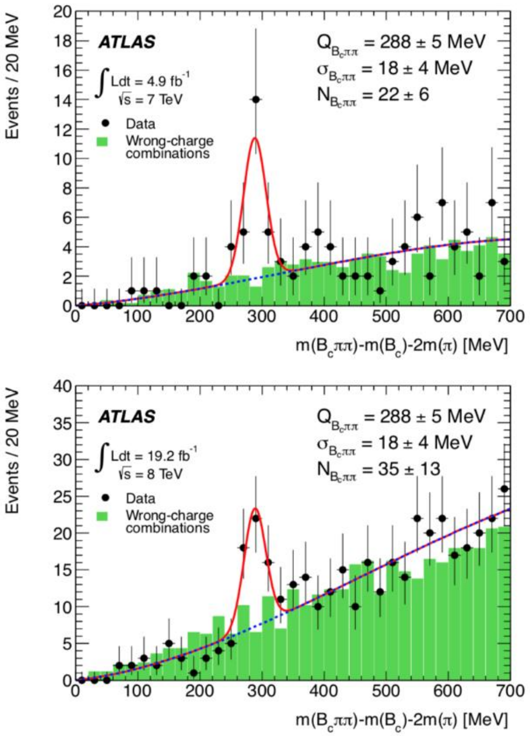


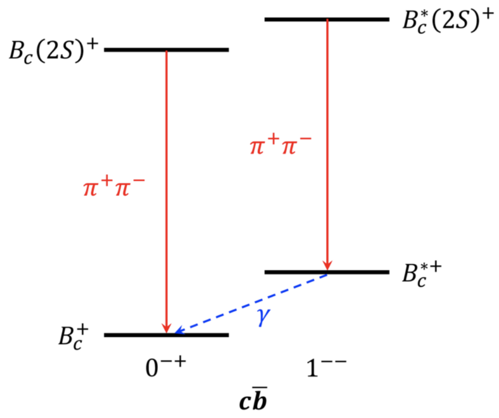
$$M = 6841.2 \pm 0.6\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.8\,(B_c^+)\ \text{MeV}/c^2$$

$$M = 6872.1 \pm 1.3\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.8\,(B_c^+)\ \text{MeV}/c^2$$

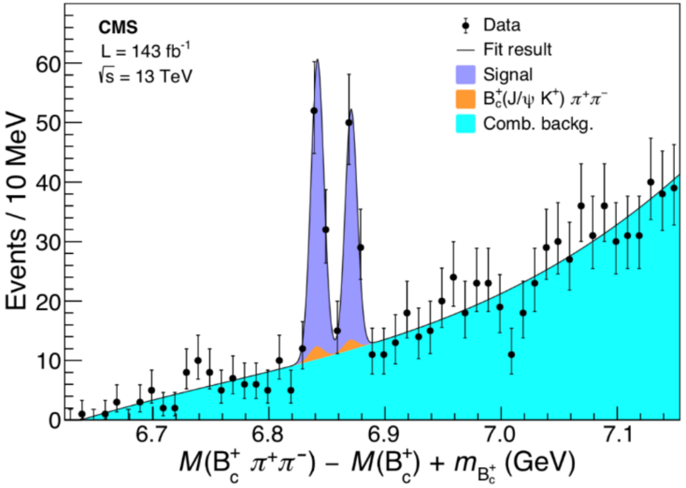
ATLAS: Phys.Rev.Lett.113(2014)212004

$$6842 \pm 4 \pm 5\ \text{MeV}$$





CMS: Phys.Rev.Lett.122(2019)132001



$$6871.0 \pm 1.2\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 0.8\,(B_c^+)\ \text{MeV}$$

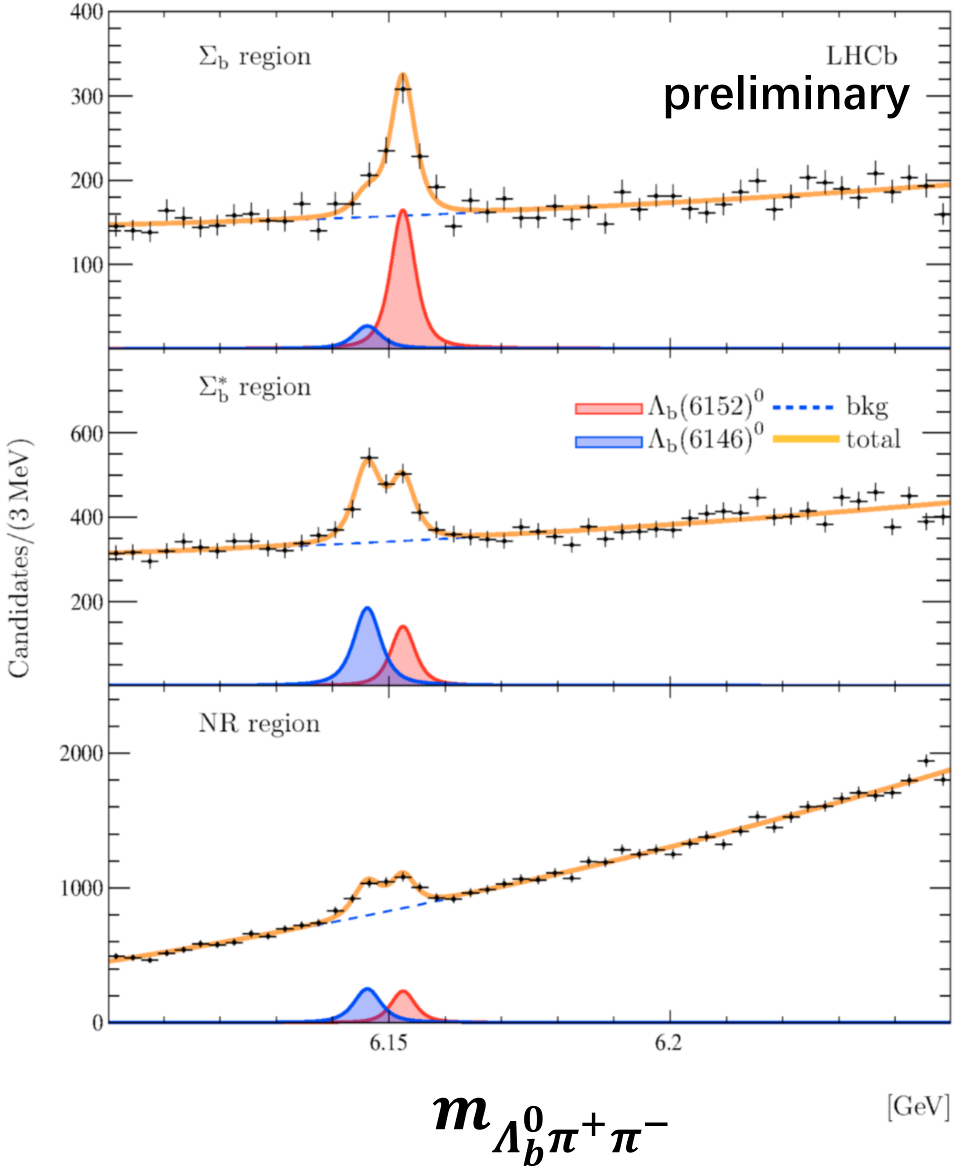
Excited Λ_b^0 in $\Lambda_b^0\pi^+\pi^-$

- Full Run1+Run2 dataset
- Λ_b^0 reconstructed in $\Lambda_c^+\pi^-$ and $J/\psi p K^-$
- Two new resonances around 6.15 GeV
- Mass and mass-splitting agree with expectation for $\Lambda_b(1D)^0$ doublet

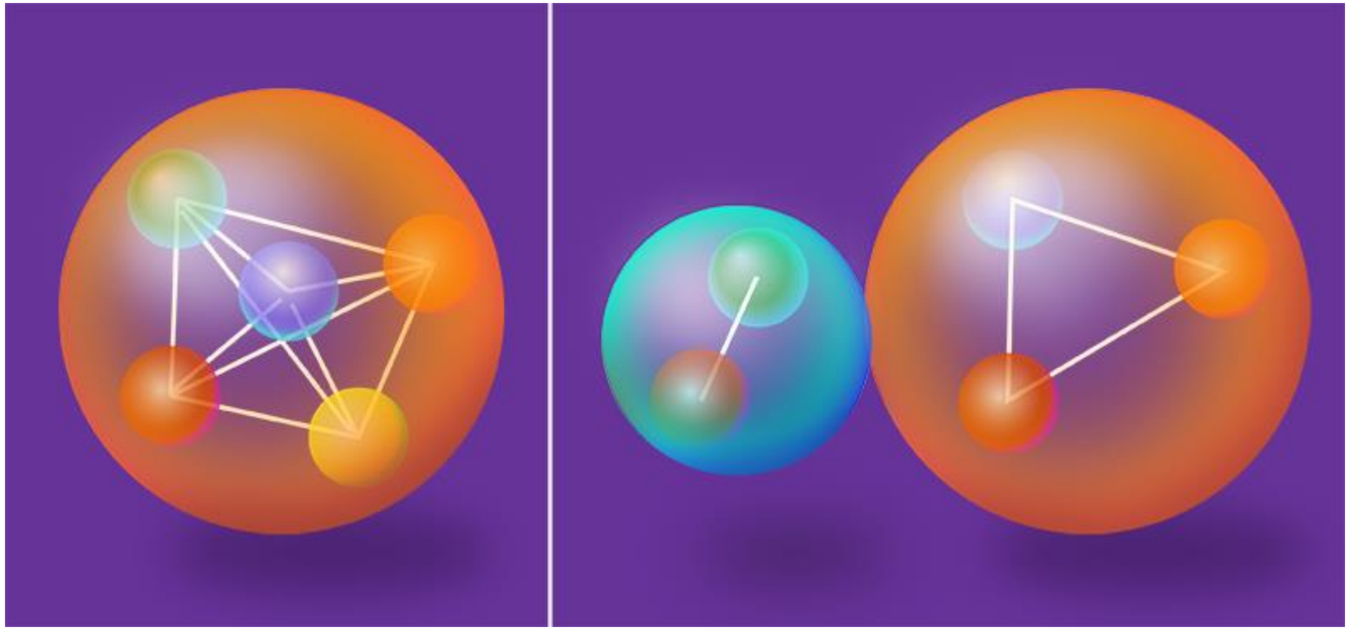
preliminary

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

LHCb-PAPER-2019-025 in preparation



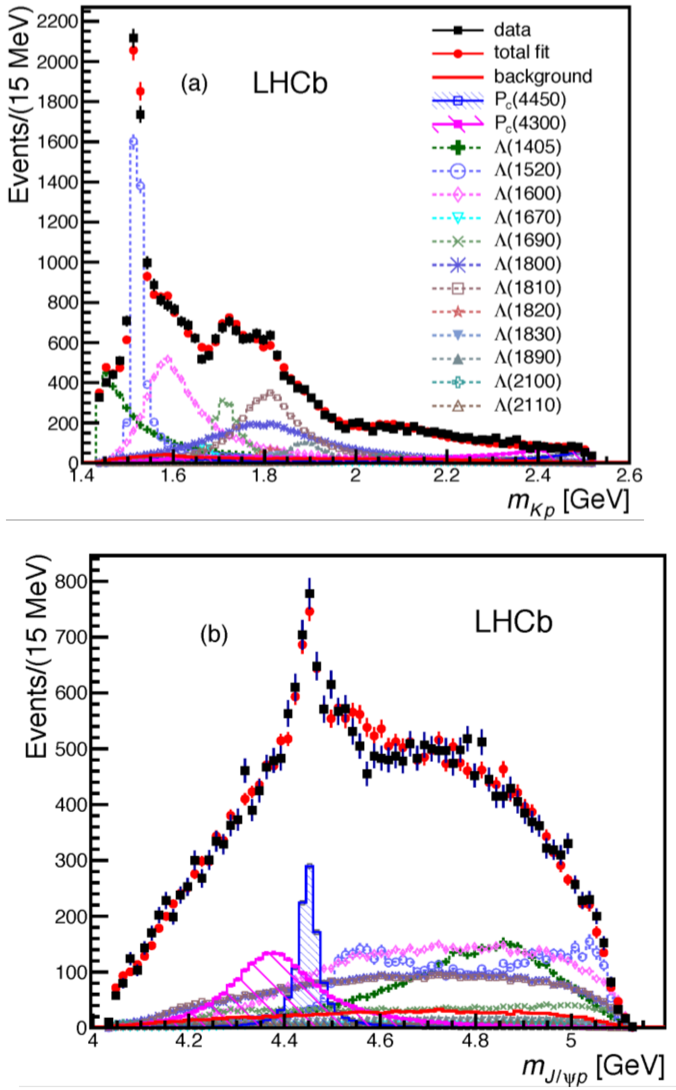
Pentaquarks



Observation of pentaquarks

PRL 115 (2015) 072001

- Two P_c^+ states observed in full amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays
- Planned to update the results with full dataset
  - To determine the J^P quantum numbers
  - To better determine other properties



Resonance	Mass (MeV)	Width (MeV)	Fraction (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$

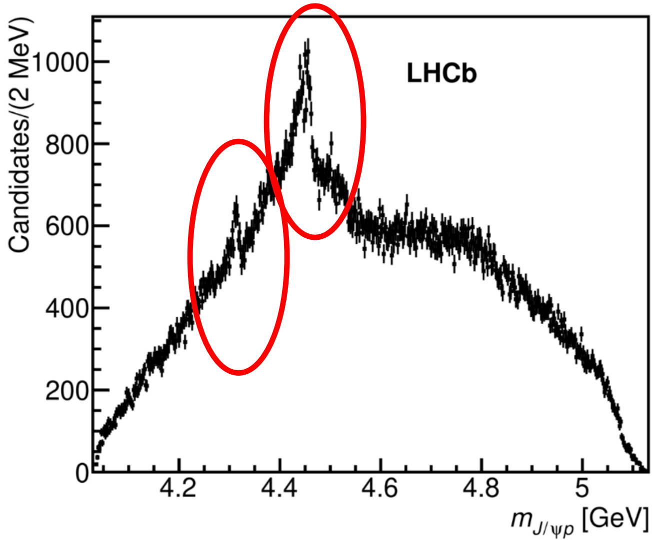
$$\mathcal{B}(\Lambda_b^0 \to P_c(4380)^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c(4450)^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5}$$

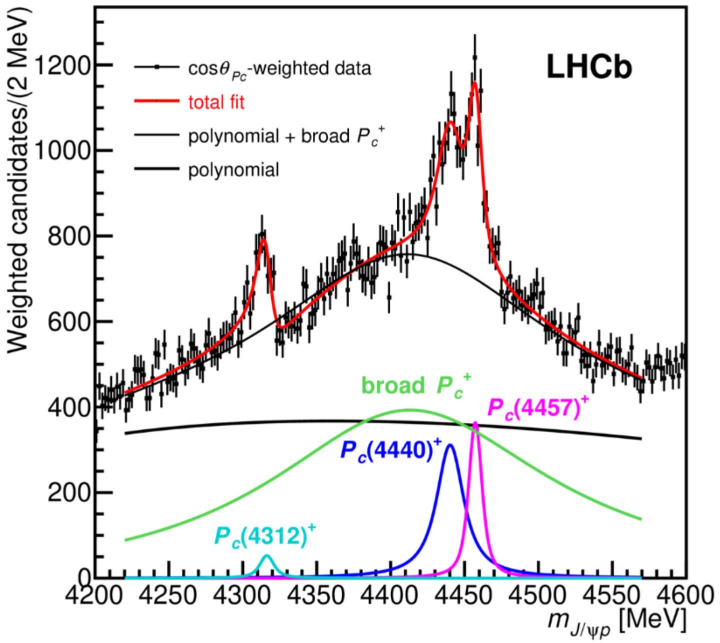
Chin. Phys. C40 (2016) 011001

Observation of new pentaquarks

PRL122 (2019) 222001

- Full Run1+Run2 → 9x $\Lambda_b^0 \to J/\psi p K^-$ signals
- Fit with Run1 model gives results **consistent** with those of Run1, however, fine structures appears with larger sample
  - $P_c(4450)^+$ splits into two substructures
  - A new narrow peak at around 4312 MeV
- One dimensional fit done
  - J^P and confirmation of $P_c(4380)^+$ need 6D amplitude analysis



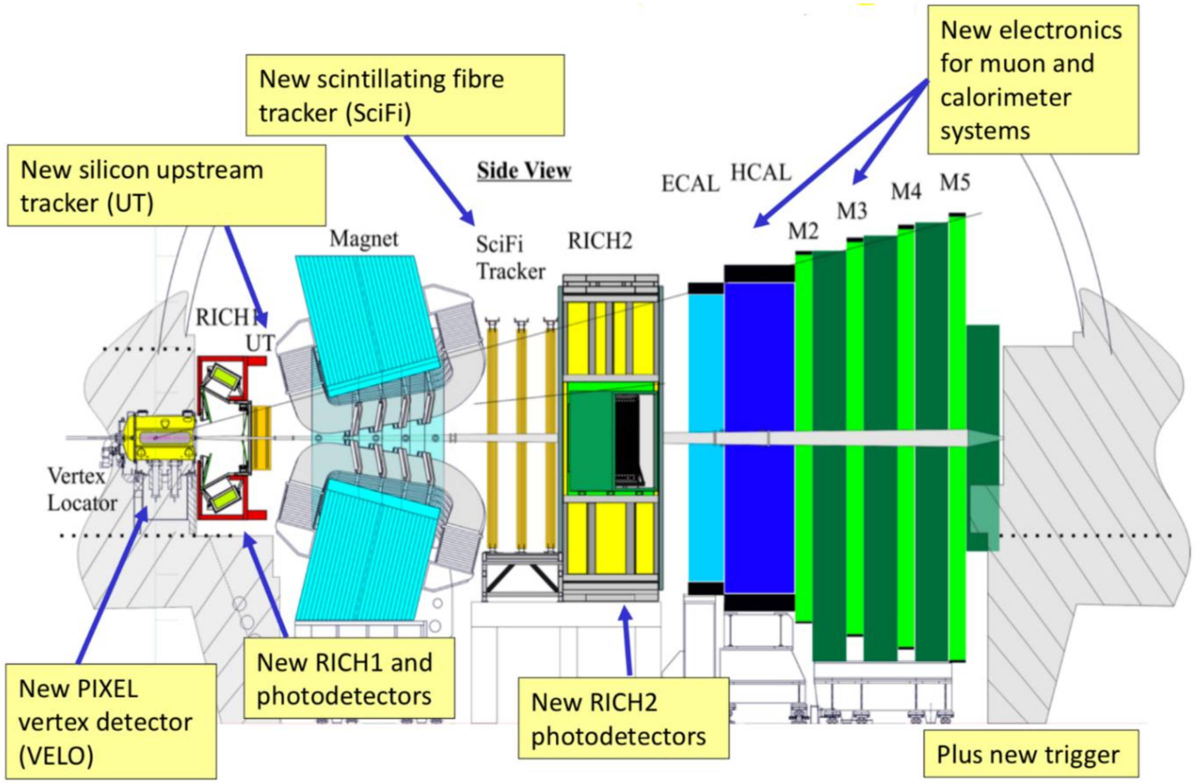


State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

Prospects

LHCb Upgrade (2019-2020)

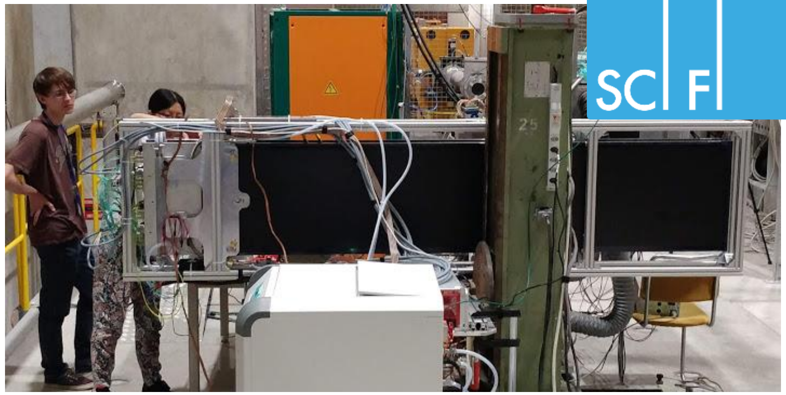
[LHCB-TDR-017]

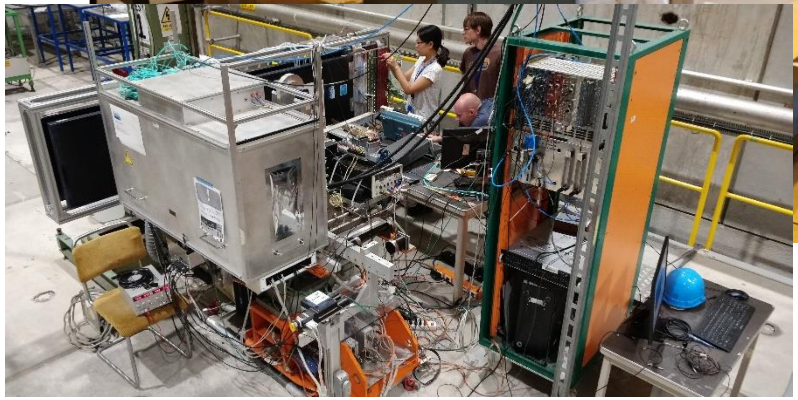


CERN-LHCC-2012-007

- **Increase luminosity to $2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$**
  - 5 times larger than current maximum instantaneous luminosity
- **All sub-detectors read out at 40 MHz for a full software trigger**
  - Record with 10 GB/s
- **All subdetector apart from muon and calorimeter systems will be fully replaced**

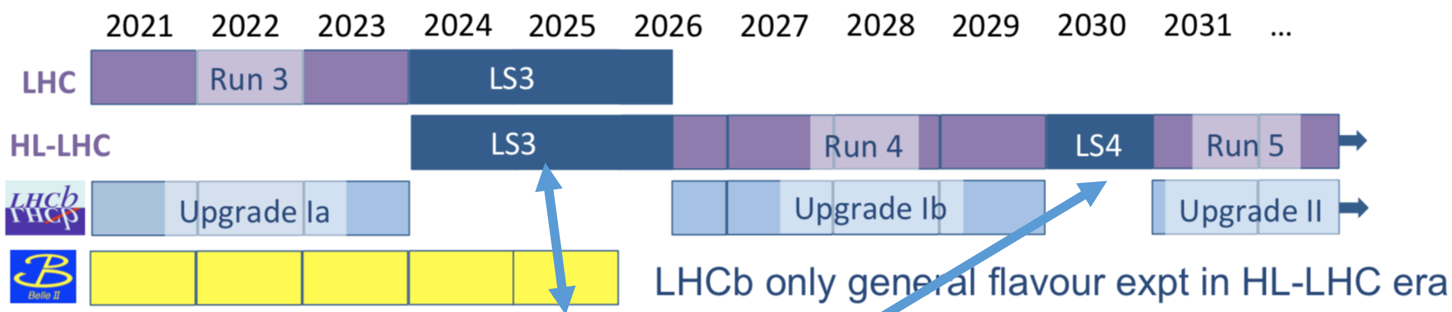
Scintillating Fibre (SciFi) tracker installation





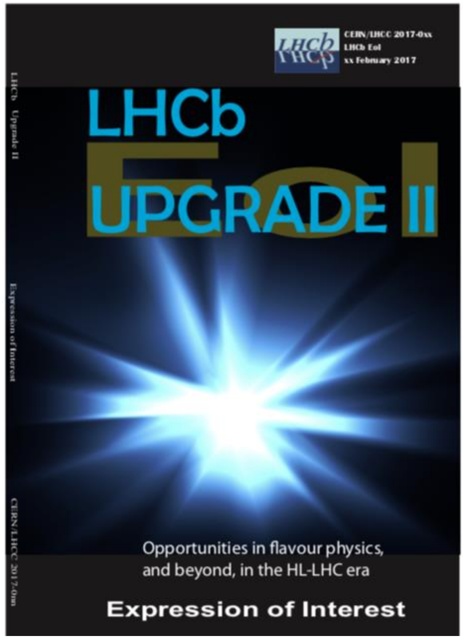
LHCb Upgrade 2

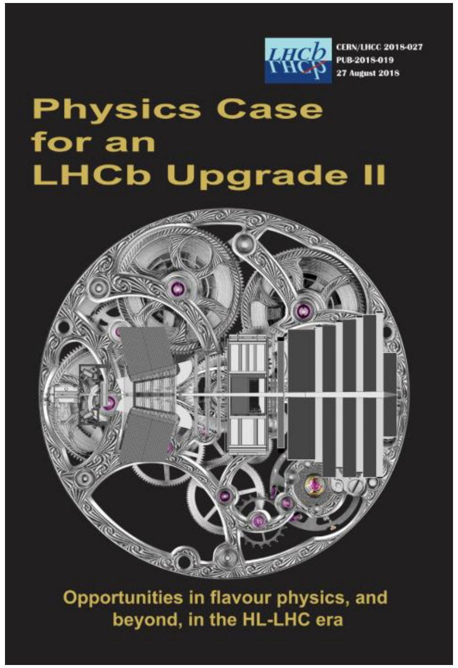
- Upgrade 2 proposed to take full profit of HL-LHC
  - $\mathcal{L} = 1 - 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, 10 times larger than Upgrade 1
  - Aiming at $300\ \mathrm{fb}^{-1}$ after Run5



- Consolidate in LS3
- Major upgrade in LS4

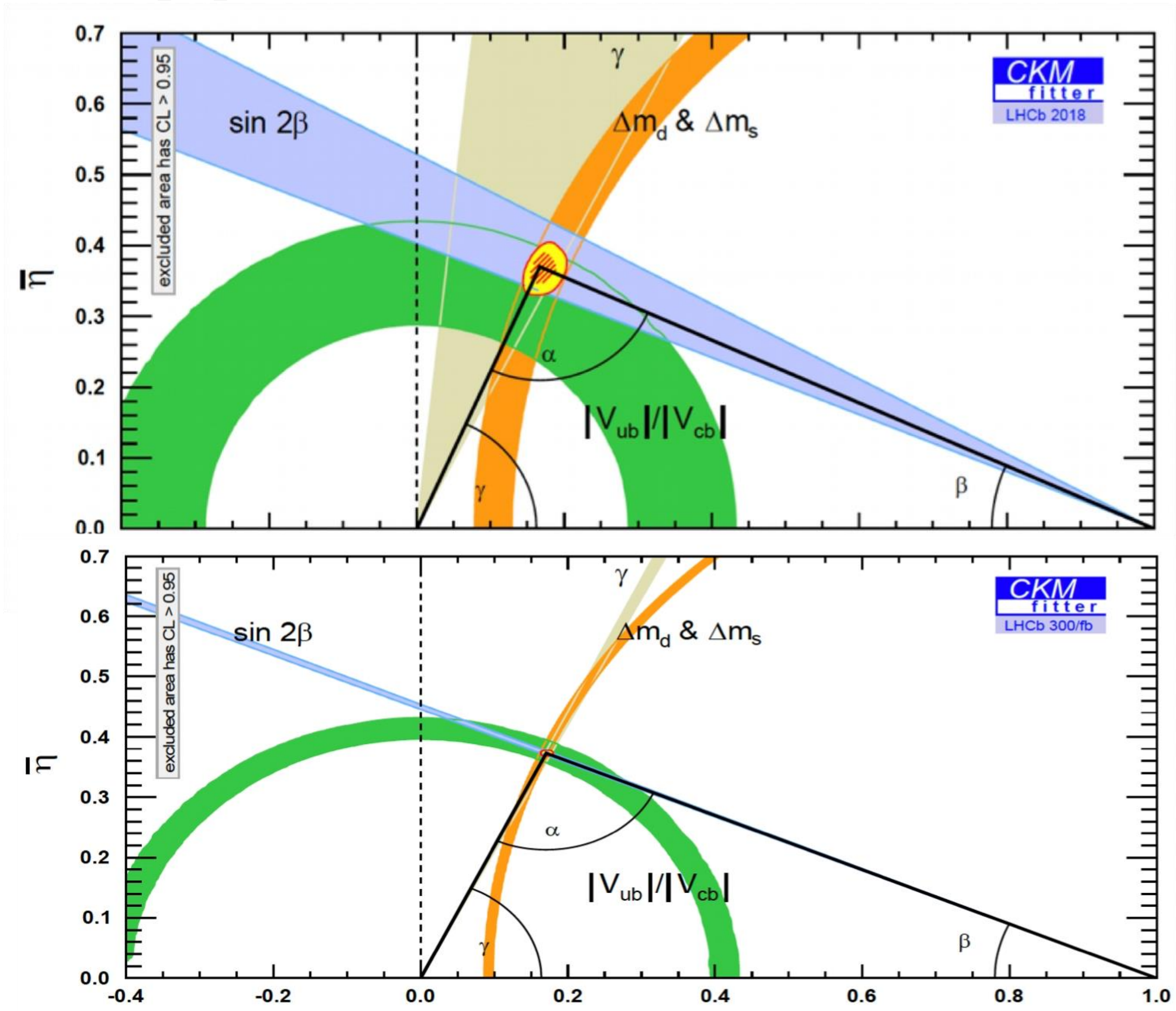
- EOI submitted in 2017 (CERN-LHCC-2017-003)
- Physics document submitted in 2018 (arXiv:1808.08865)

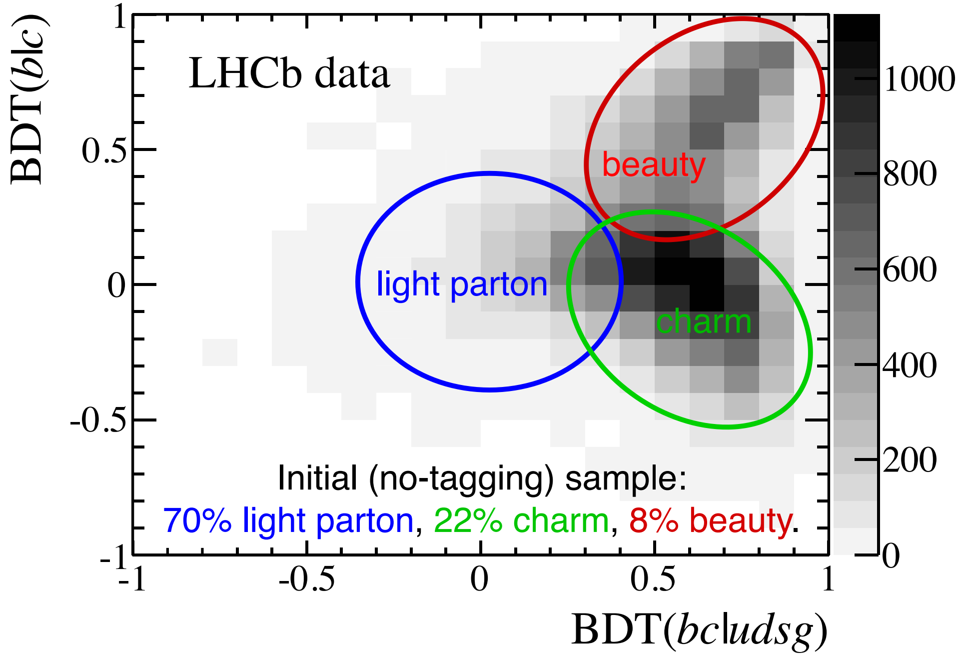


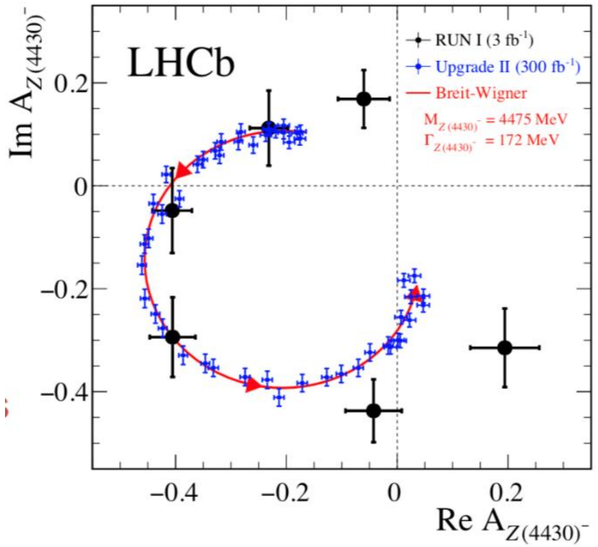


Opportunities

arXiv:1808.08865

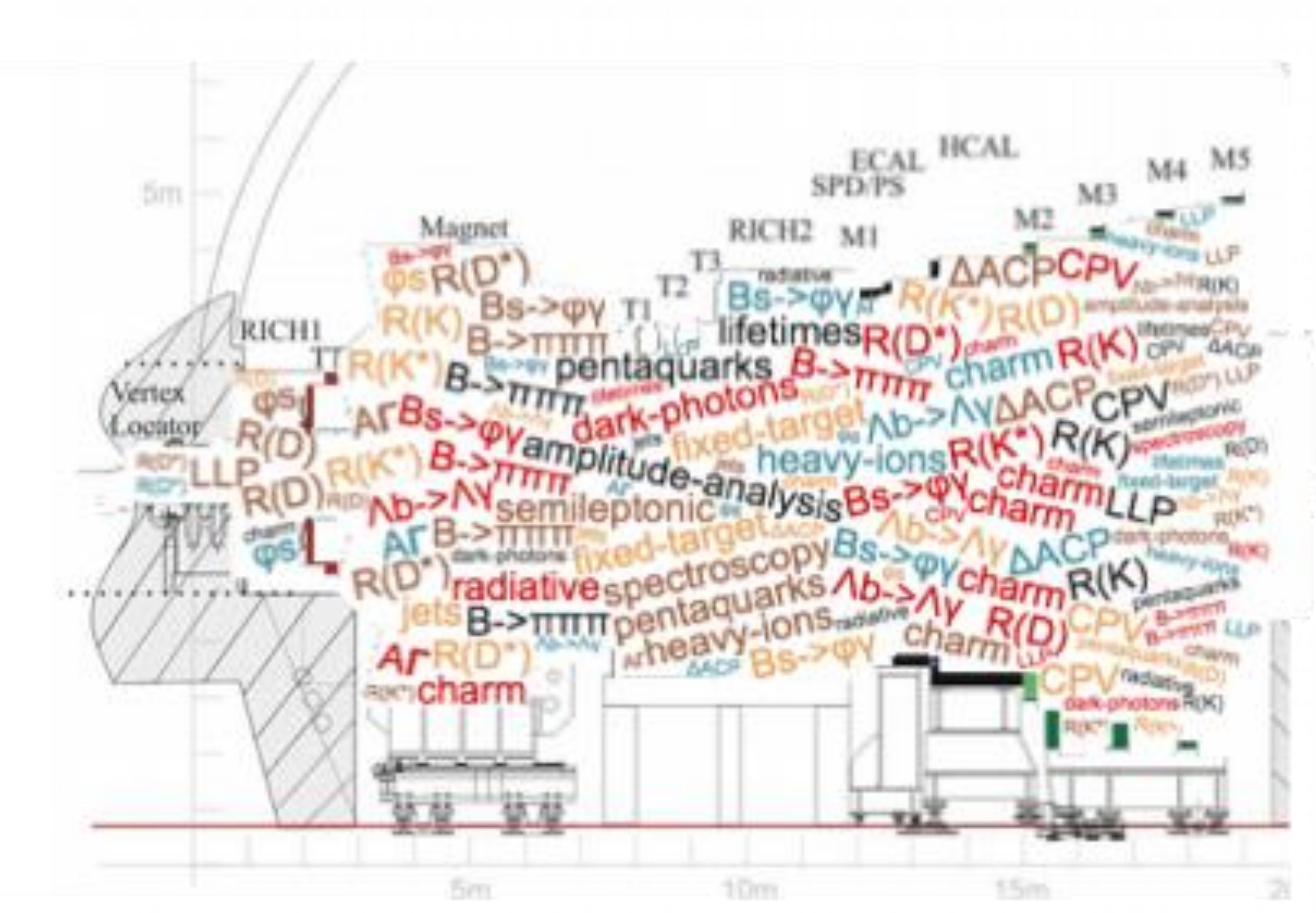






Summary and outlook

- LHCb has been operated well in run1+run2 and produced nice results in both flavour physics and QCD (including spectroscopy)
- LHCb Upgrade is under construction
  - Expect to accumulate data of $50\ \mathrm{fb}^{-1}$ after Run4 (2029)
- LHCb Upgrade2 proposed and R&D started
  - Expect to accumulate data of $300\ \mathrm{fb}^{-1}$ after Run5 (around 2035)
- Stay tuned for new results from LHCb

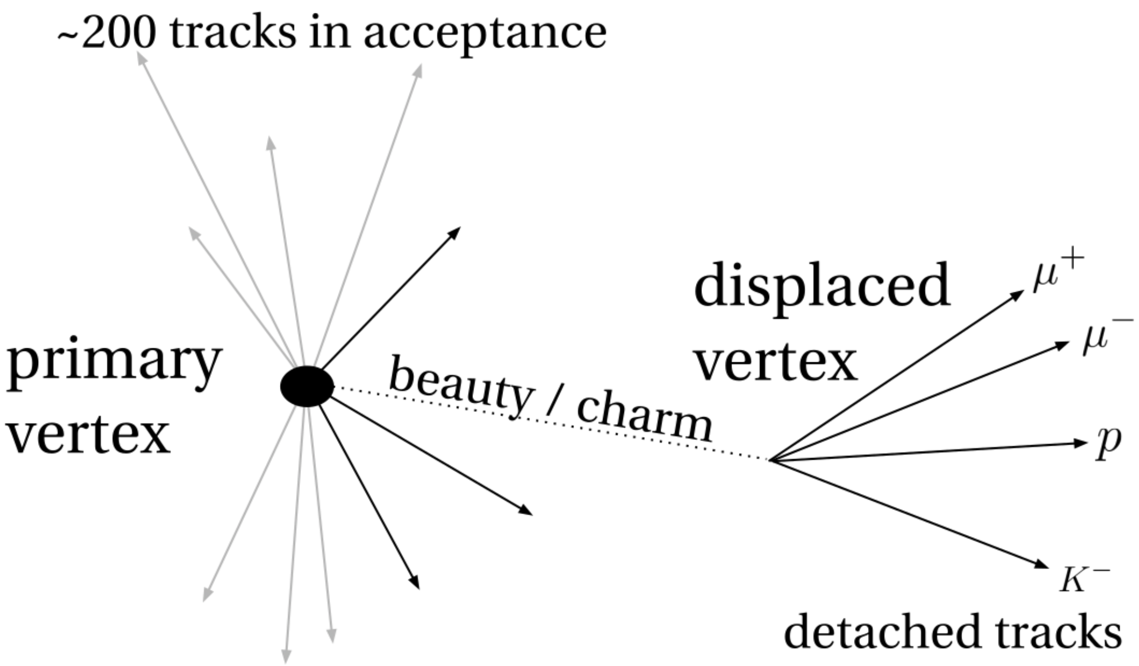


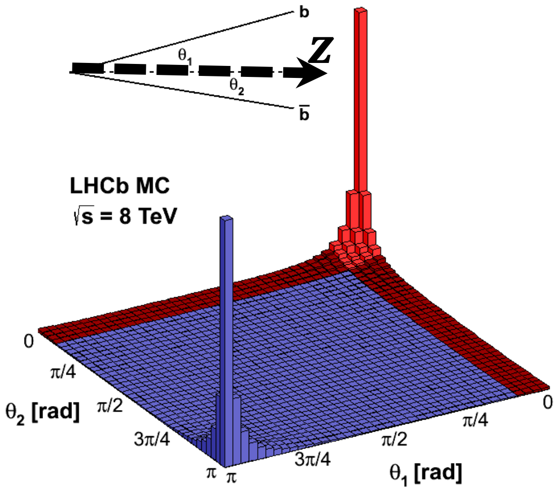
Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
pentaquarks
dark-photons
fixed-target
heavy-ions
amplitude-analysis
semileptonic
spectroscopy
radiative
lifetimes
charm
LLP
CPV
ΔACP

Thank you!

Backup

Heavy flavour in pp collisions at LHCb





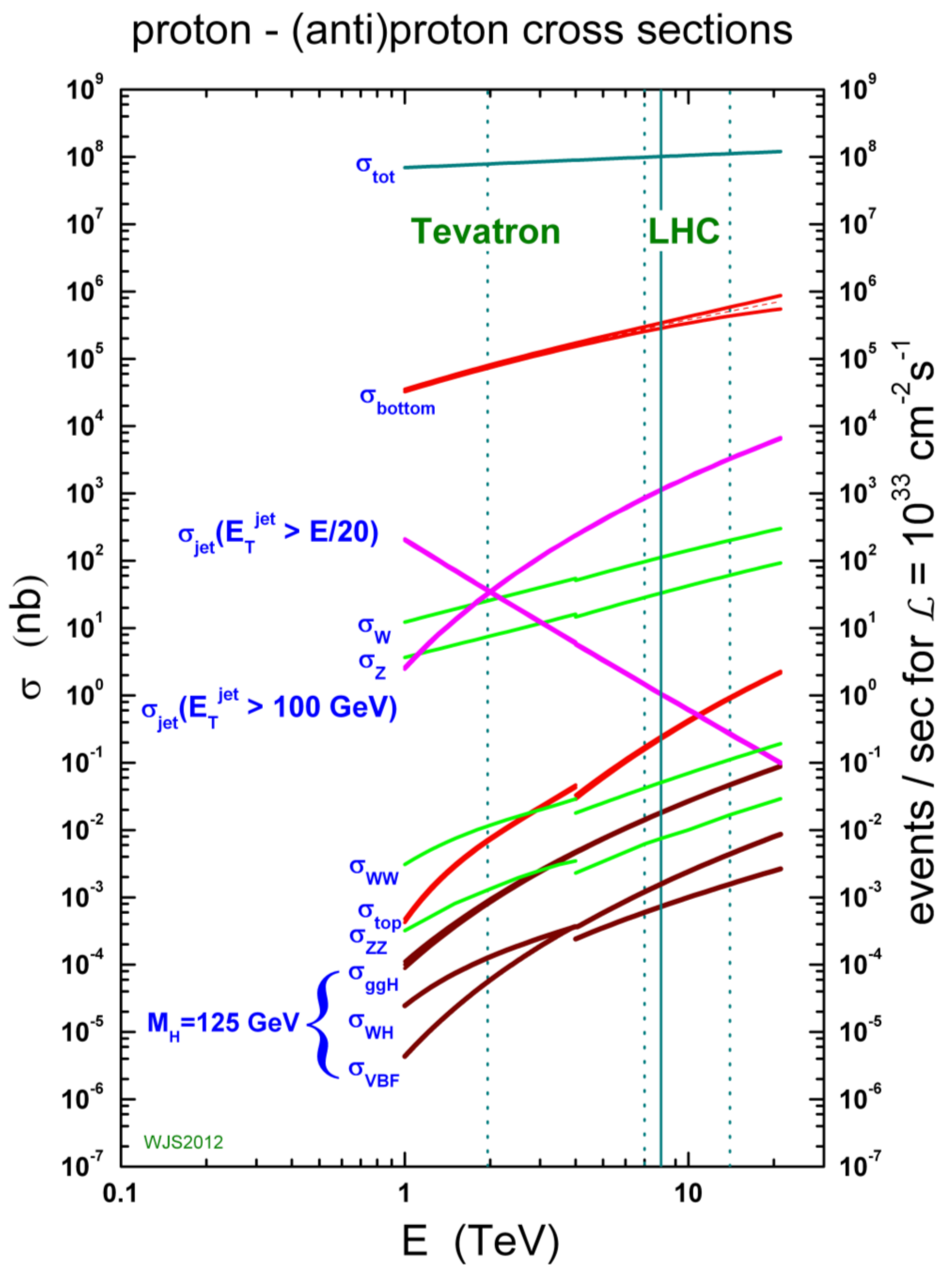
Large $b\bar{b}$ $(c\bar{c})$ cross-sections at the LHC

$$\sigma(b\bar{b}X) \sim 0.2\% \times \sigma_{pp}^{\text{inesl}},$$
$$\sim 10^{11}\ b\text{-hadrons per fb}^{-1}$$

$$\sigma(c\bar{c}X) \sim 4\% \times \sigma_{pp}^{\text{inesl}},$$
$$\sim 10^{12}\ c\text{-hadrons per fb}^{-1}$$

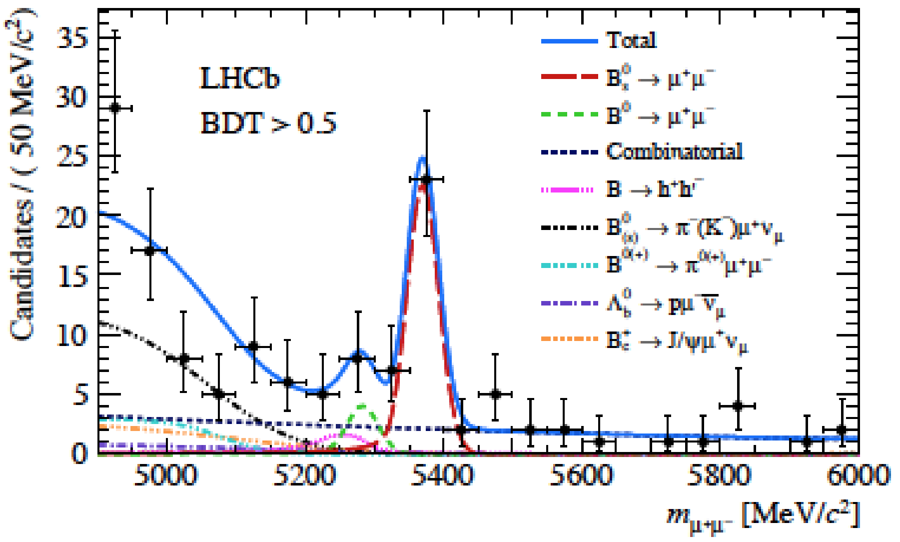
All species of heavy flavour hadrons:

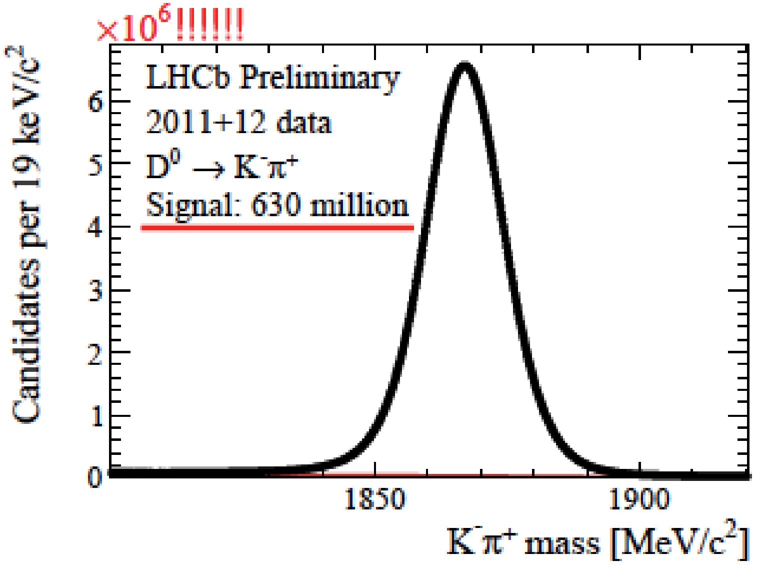
$B^0, B_s^0, B^{\pm}, B_c^{+}, \Lambda_b^0,$
$D^0, D^{\pm}, D_s^{\pm}, \Lambda_c^{\pm}, \Xi_{cc}^{++}, P_c^{+},$
$J/\psi, \Upsilon(\text{n}S), \ldots$



Two extremes of LHCb trigger

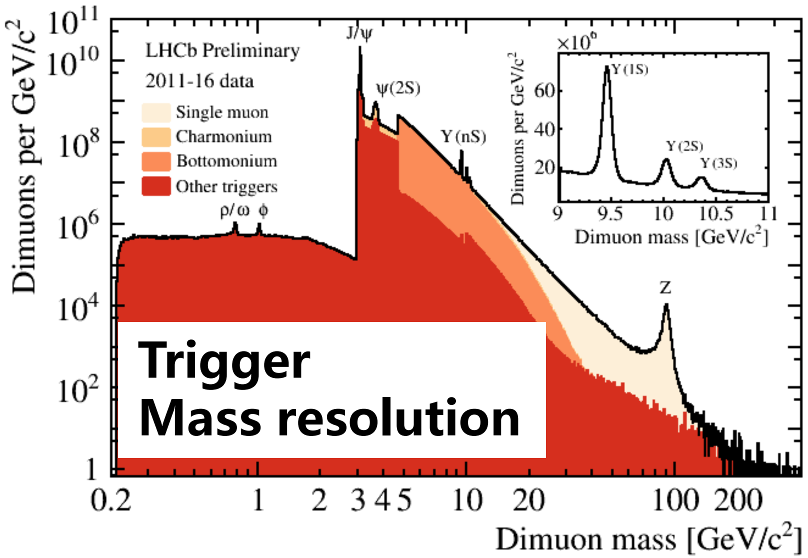
- The LHCb trigger has to cover two extremes, e.g.

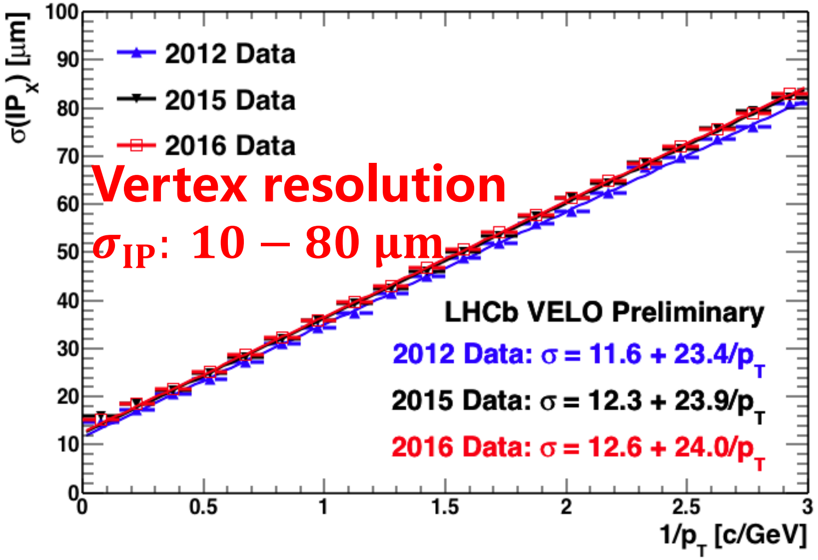


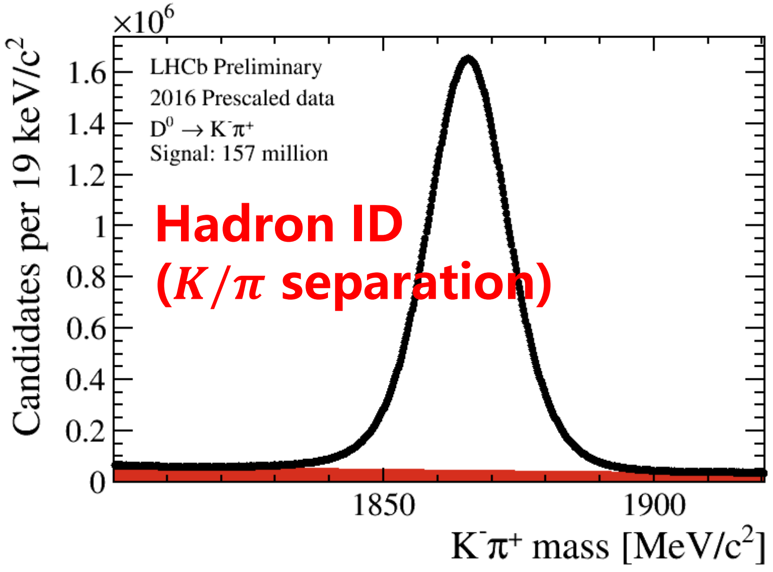


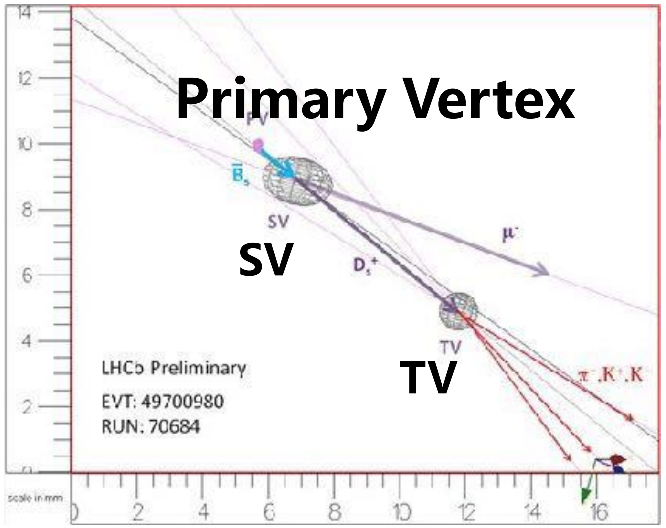
- High efficiency to collect rare decays like $B_s^0 \to \mu\mu$[1]
- High purity for enormous charm signals like $D^0 \to K\pi$[2]

Pros of hadron spectroscopy at LHCb





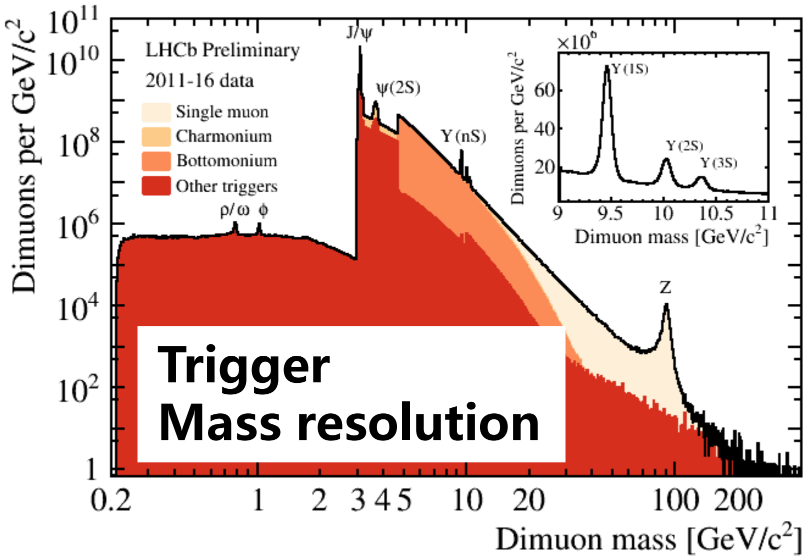


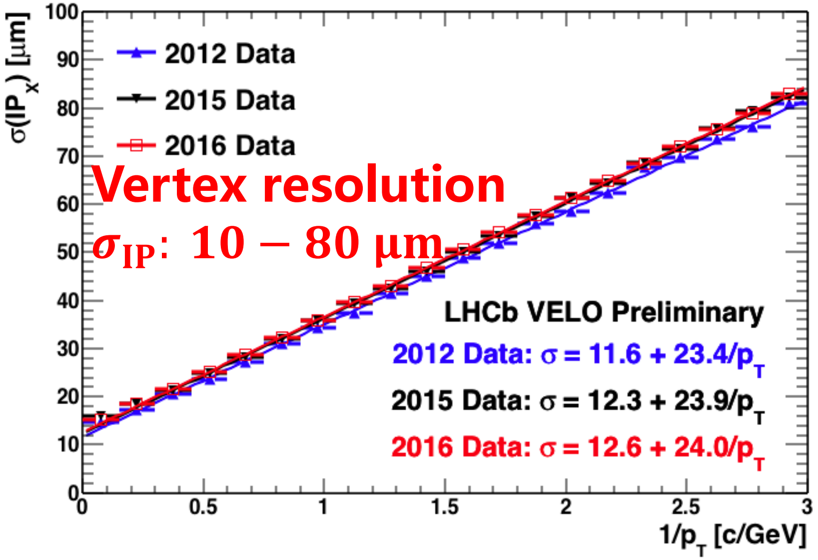


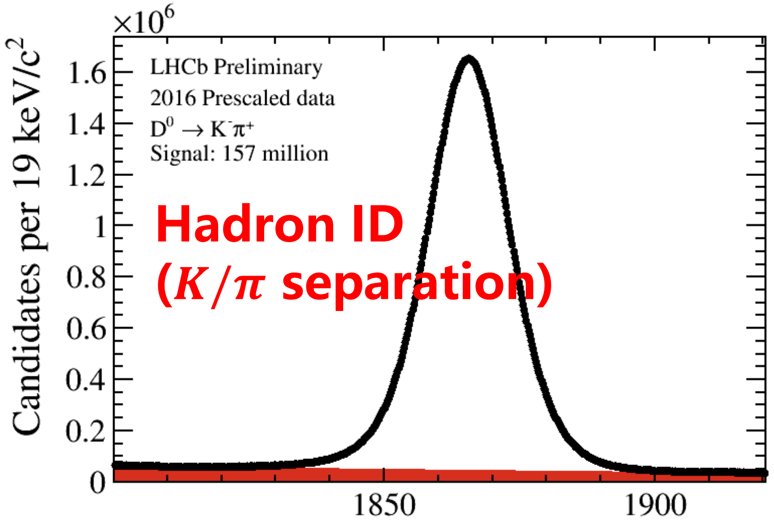
- **Large production cross-section**
- **Efficient trigger**
- **Vertex locator with high precision**
- **High precision tracking system**
- **Powerful hadron identification**
- **Efficient muon system**

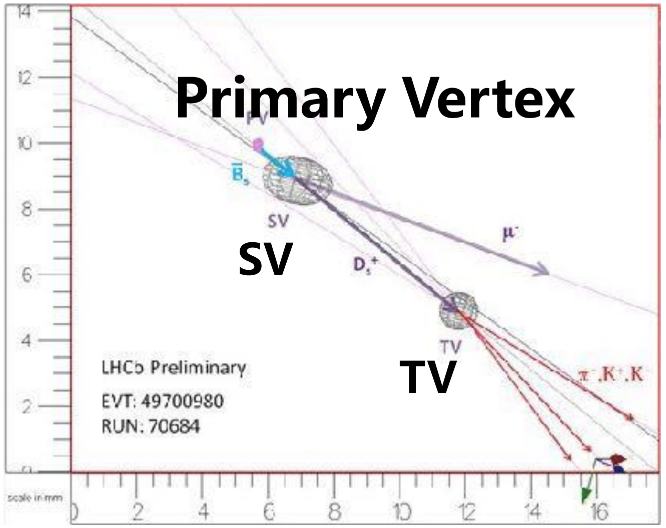
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2016
https://twiki.cern.ch/twiki/bin/view/LHCb/ConferencePlots

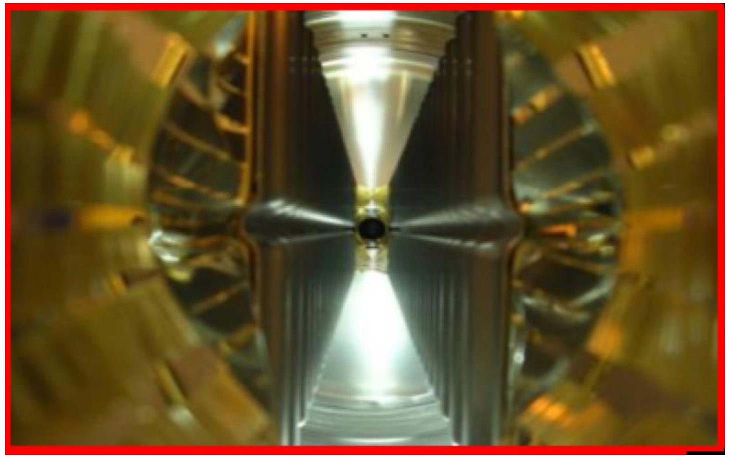
Pros of hadron spectroscopy at LHCb



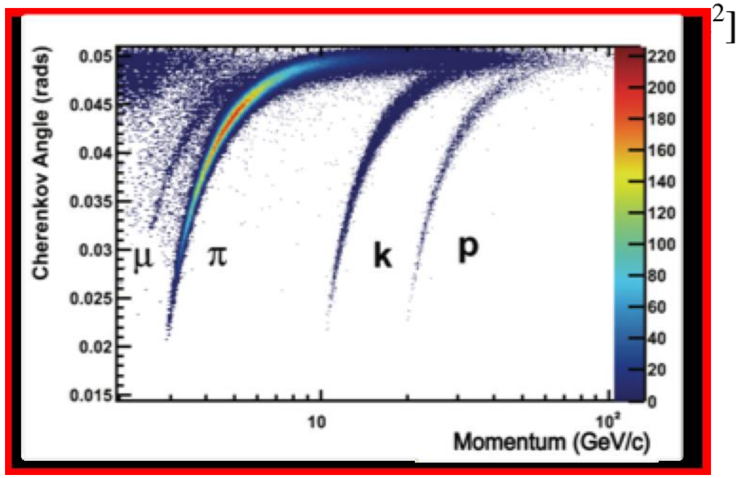








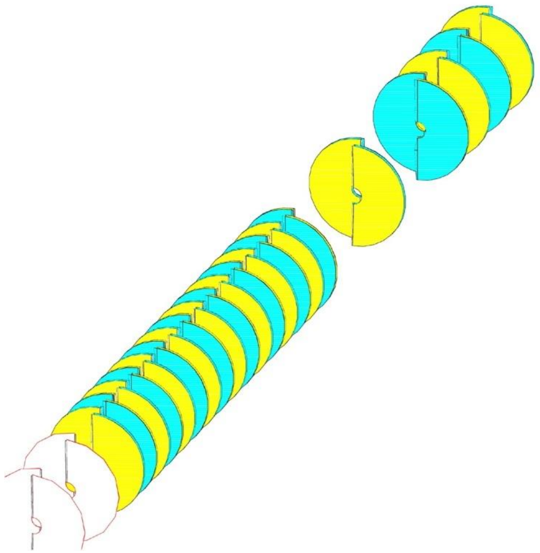
Closest distance between the beam and the VELO is around 0.5 cm

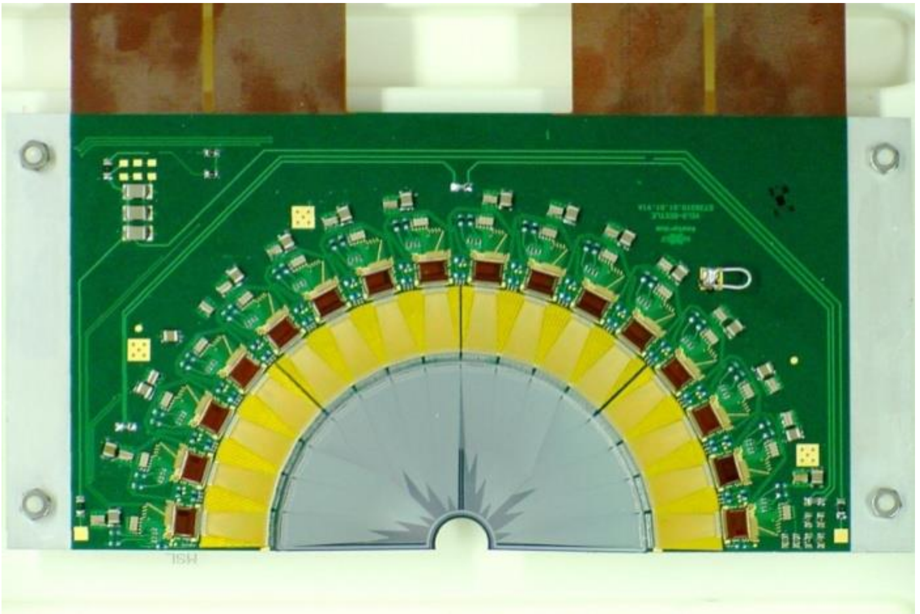


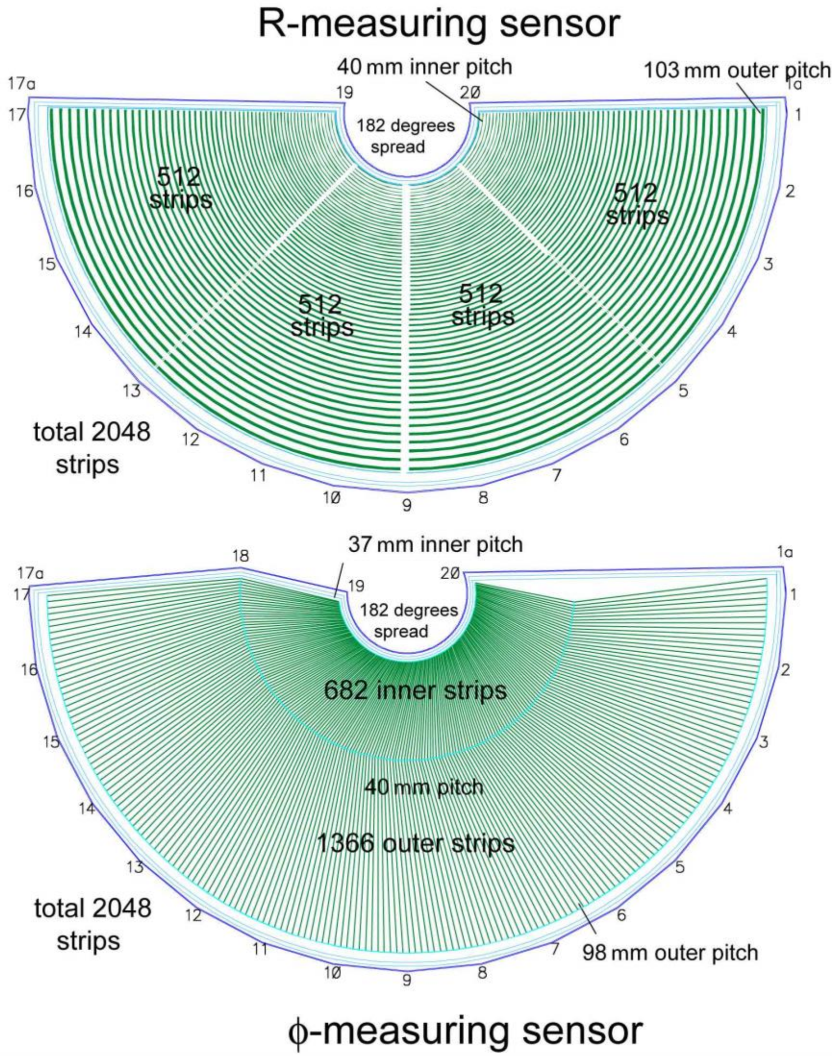
Well identified with $p \in 2 - 100$ GeV/c

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2016
https://twiki.cern.ch/twiki/bin/view/LHCb/ConferencePlots

Vertex Locator





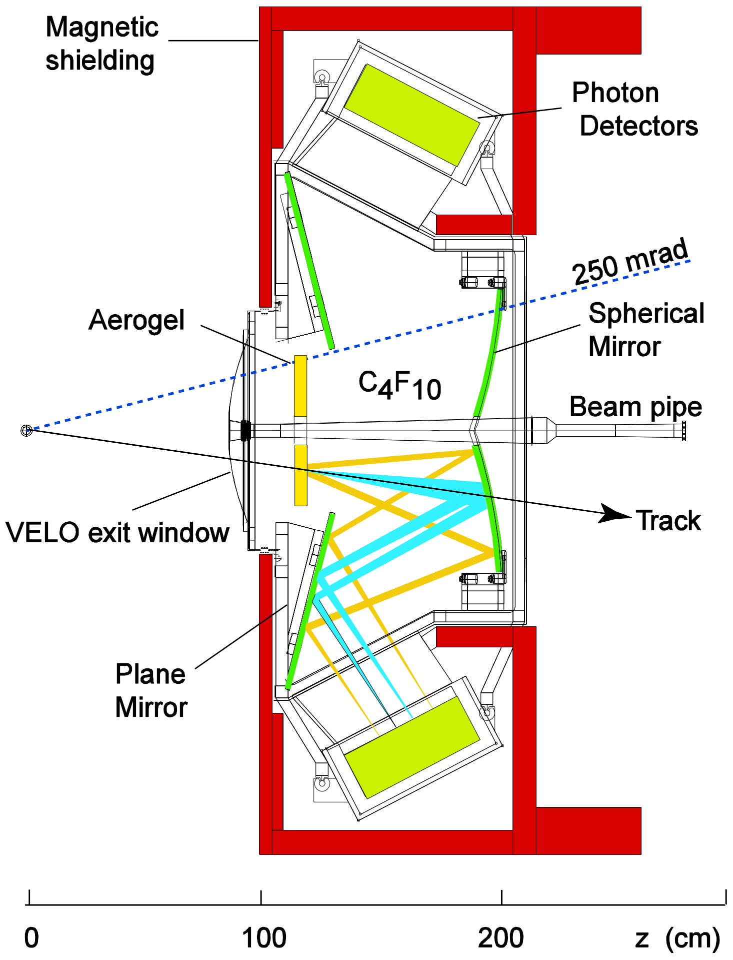


200 μm n-on-n Si short strips
double metal layer for readout
with Beetle chip (1/4 μm CMOS)

total 172 k channels
occupancy < 1%

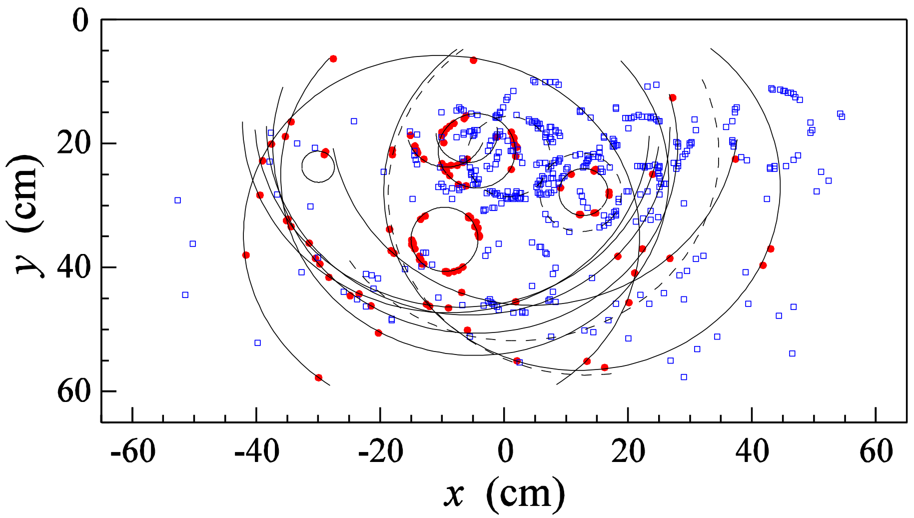
They have to be placed in secondary vacuum → complex mechanics

RICH detector

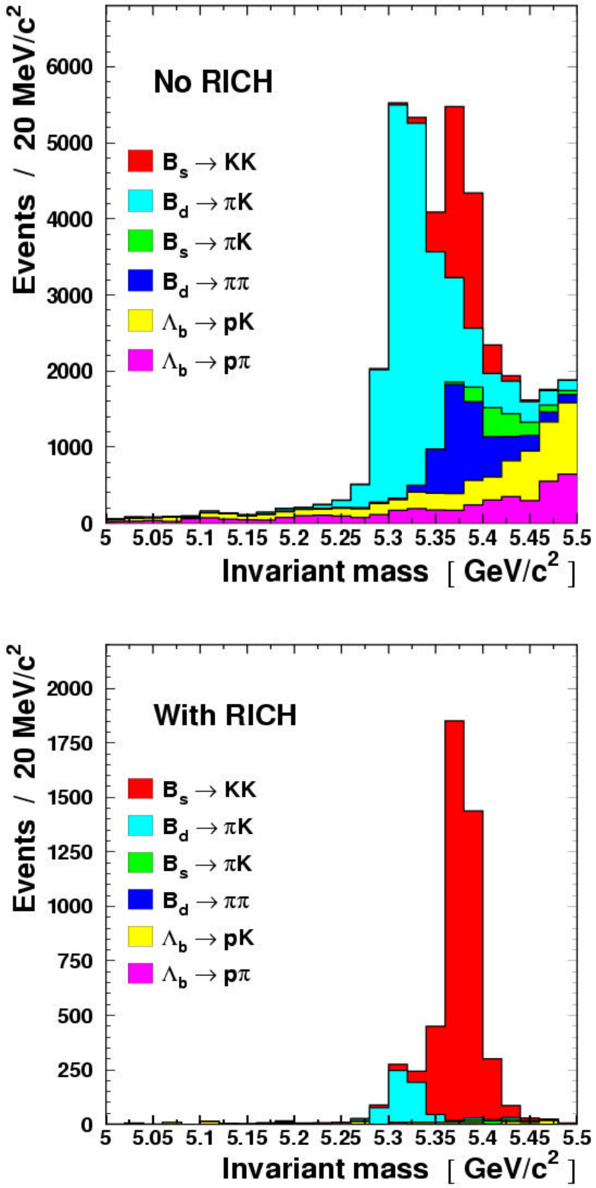


Use Cherenkov rings to identify charged particles, especially hadrons and muons

Typical event in the RICH1 photon detectors



Performance of particle ID



Origin of LHCb: 1995

LHC-B

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

… dedicated to the study of CPV and other rare phenomena in the decays of Beauty particles.

… precise measurements of the CKM angles…

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Key measurements listed in 2009

Roadmap for selected key measurements of LHCb

LHCb-PUB-2009-029
16 February 2010

1 Introduction **1**
1.1 Key measurements 3
1.2 The LHCb trigger 4

2 The tree-level determination of γ **8**

3 Charmless charged two-body B decays **58**

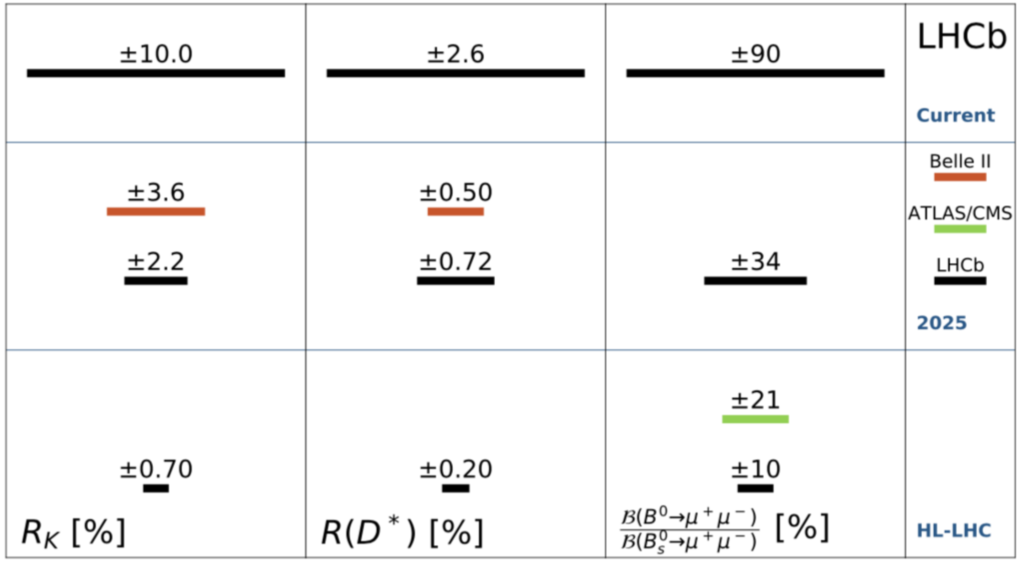
4 Measurement of mixing-induced CP violation in $B_s^0 \to J/\psi\phi$ **150**

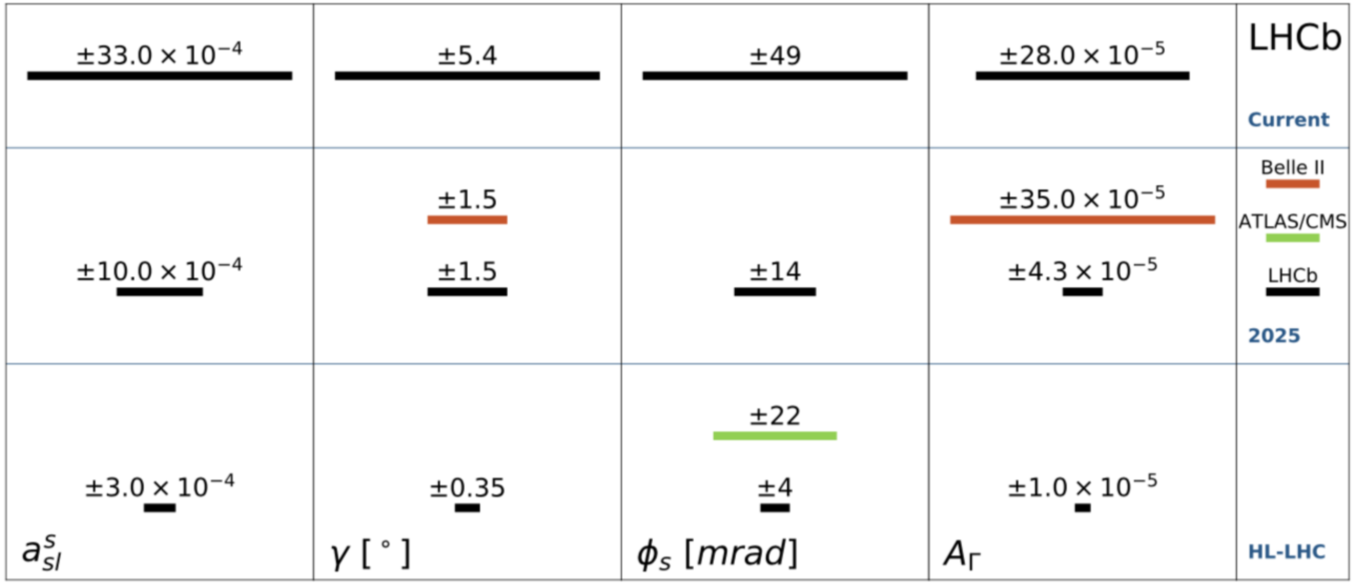
5 Analysis of the decay $B_s^0 \to \mu^+\mu^-$ **229**

6 Analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ **275**

7 Analysis of $B_s^0 \to \phi\gamma$ and other radiative B decays **313**

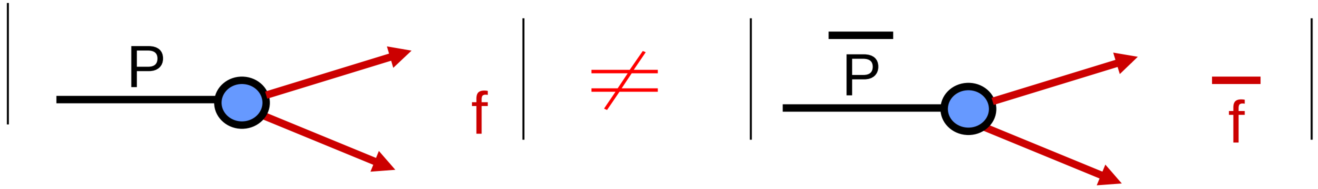
Physics cases: RD and CPV





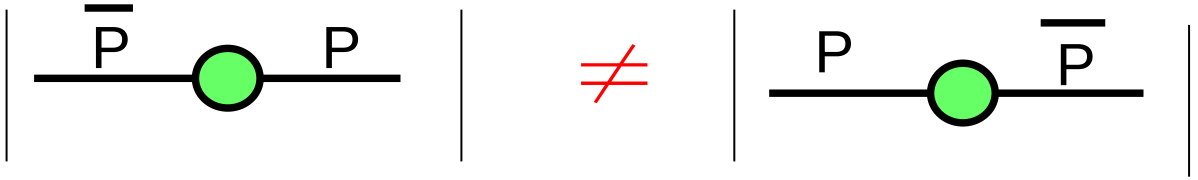
Classification of CPV

CP in decay (Interference of 2 or more complex amplitudes)

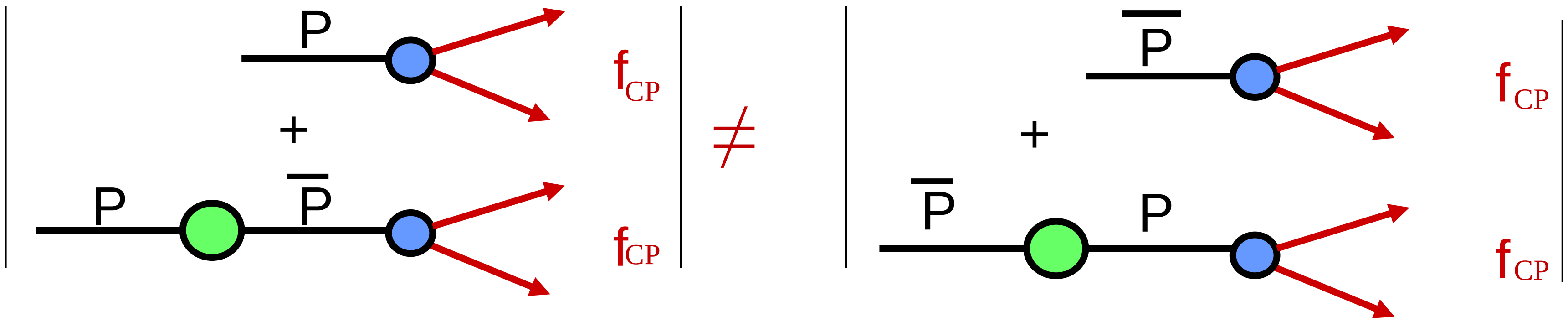


This observation

CP in mixing ("indirect CP")



CP in interference between mixing and decay ("Mixing induced CP")



ΔA_{CP} strategy

$$A_{raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$$

Detection asymmetry , zero for symmetric $f = h^+h^-$

$$A_{raw}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_T(f)$$

Physical CP asymmetry

Production and detection asymmetry related to D^0 flavour tagging

If D^0 kinematics are similar for the two modes (after proper weighting),

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

Signal samples

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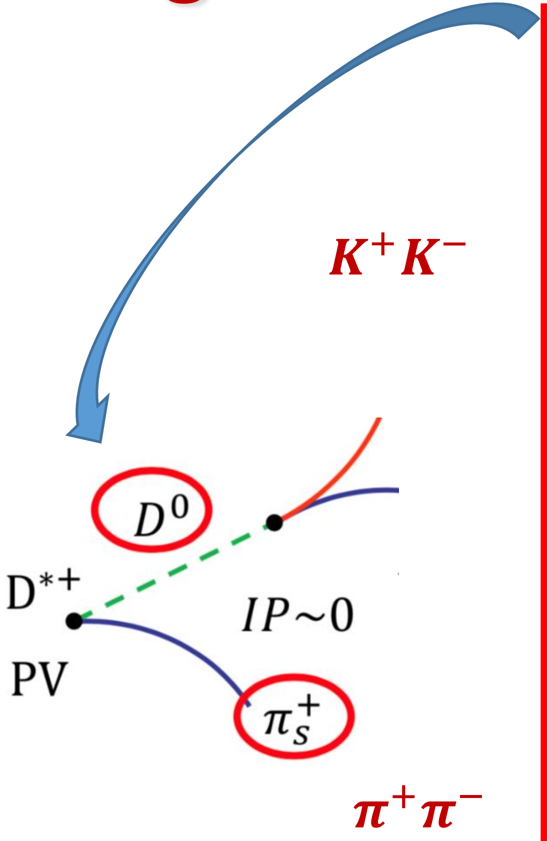
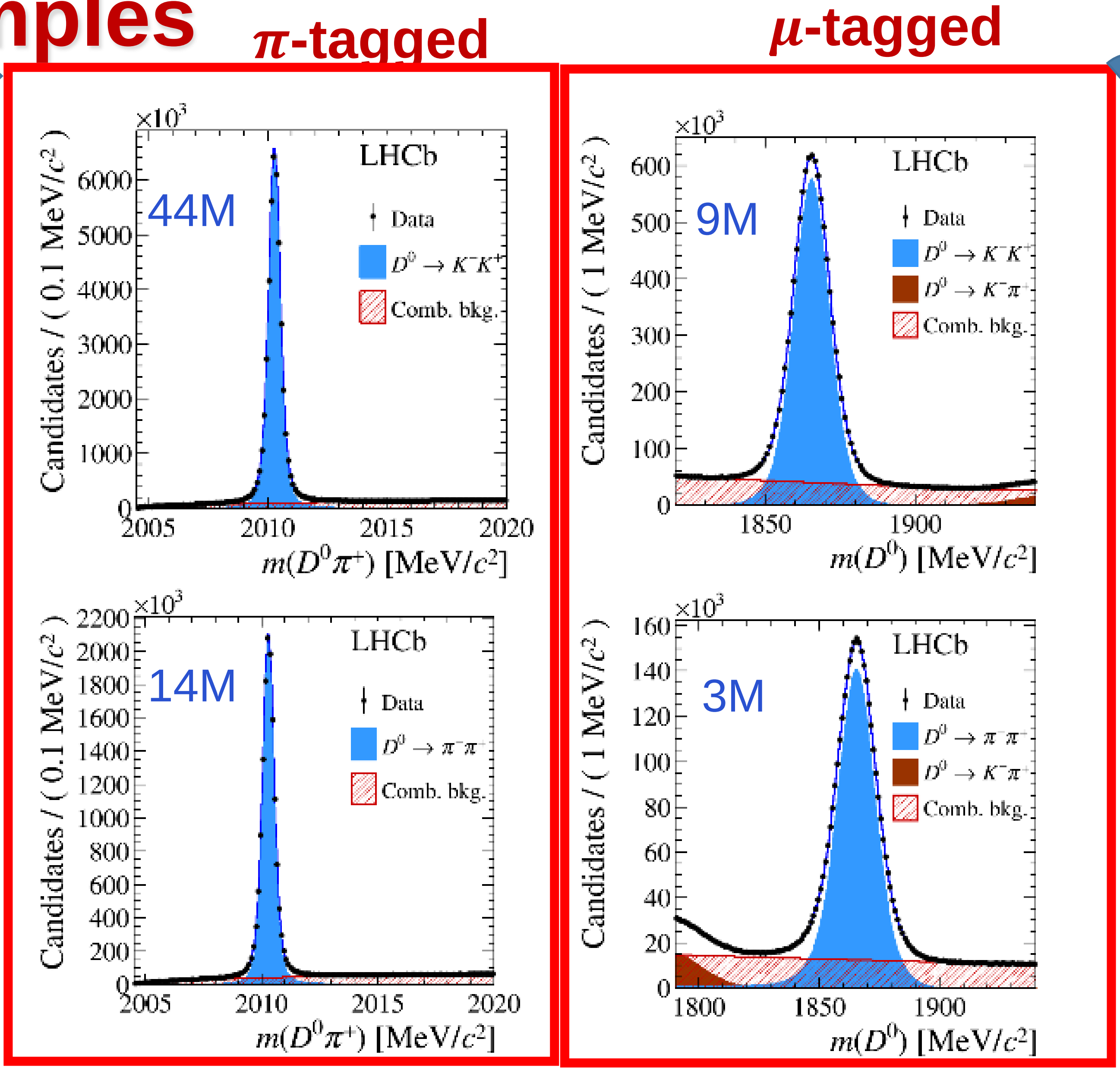
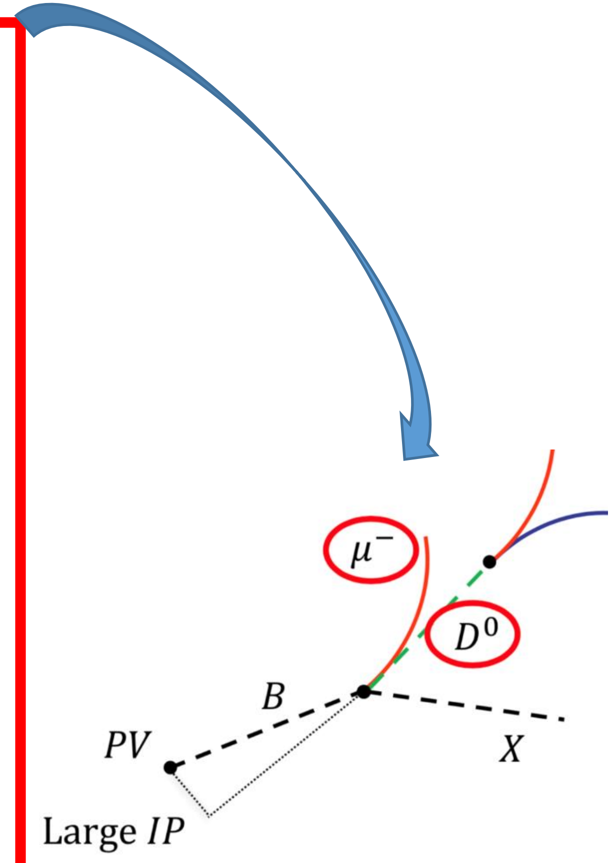






Results

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

Compatible with previous LHCb results and WA

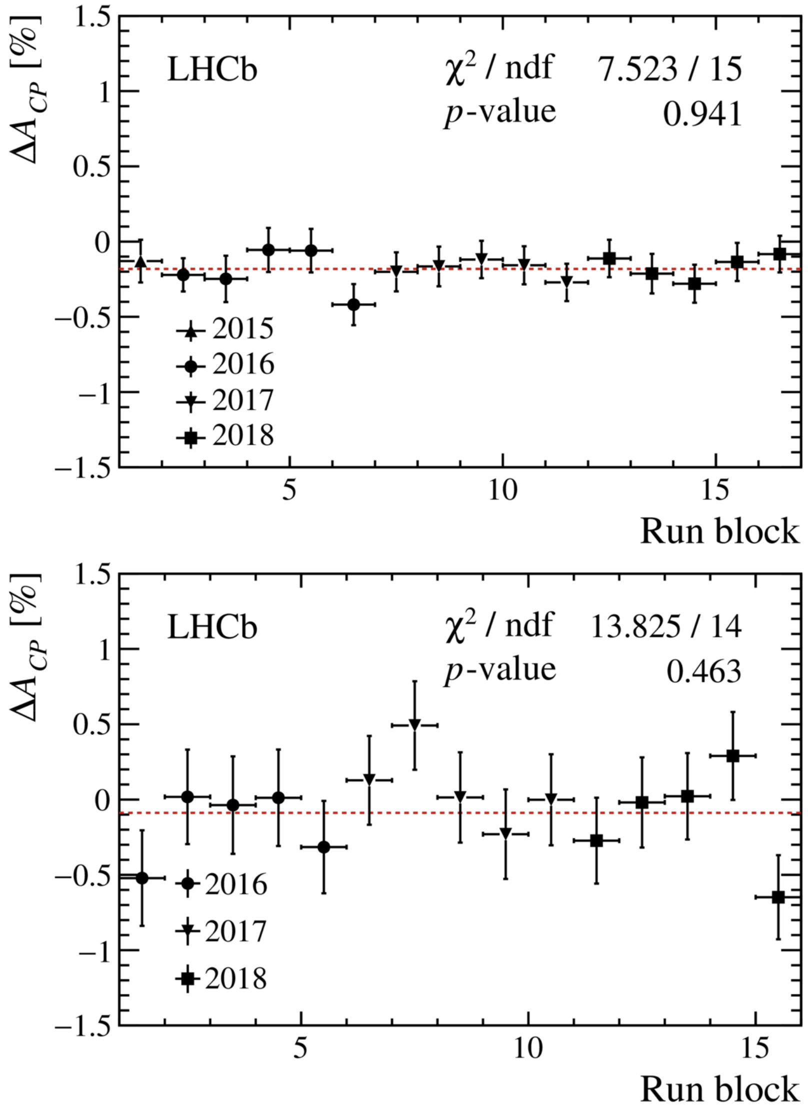
LHCb combination (9 fb^{-1})

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

CP violation in charm observed at 5.3σ !

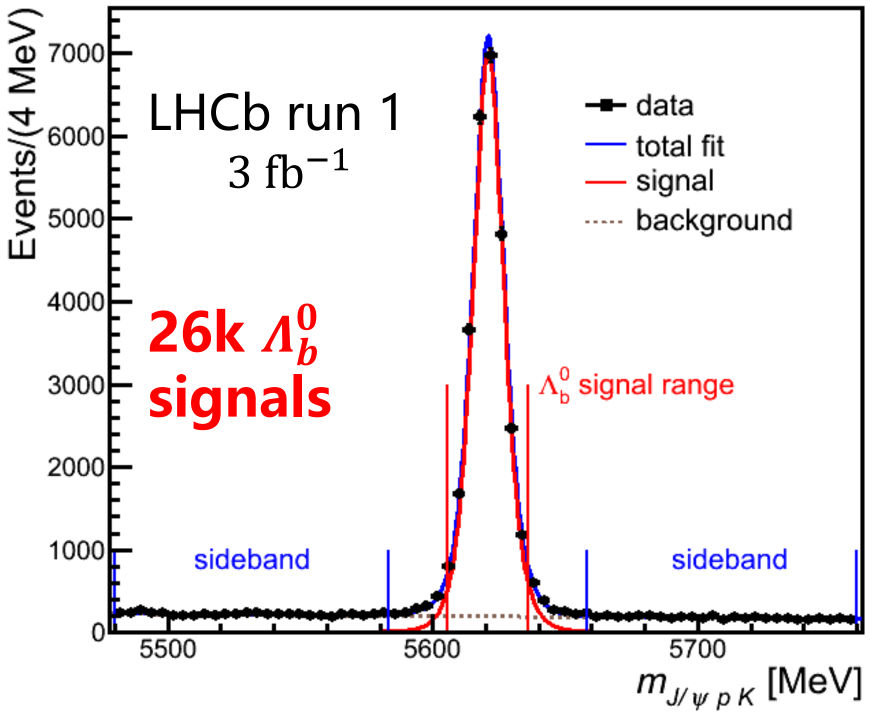
At the upper end of the SM expectations

Consistency checks



New $\Lambda_b^0 \to J/\psi p K^-$ sample

Signal yield is 9x more than



5.4% background in $\pm 2\sigma$

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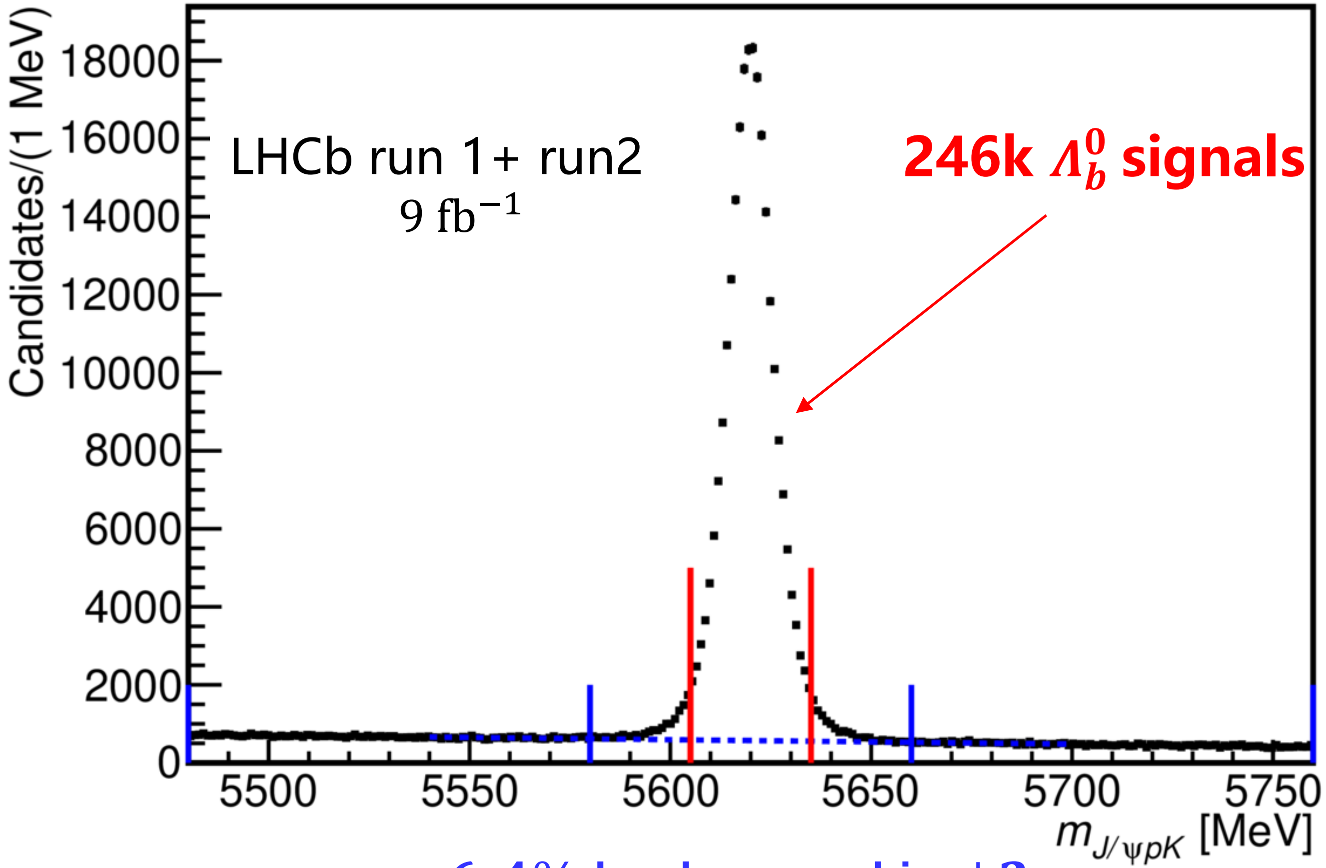

6.4% background in $\pm 2\sigma$

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Data consistency check

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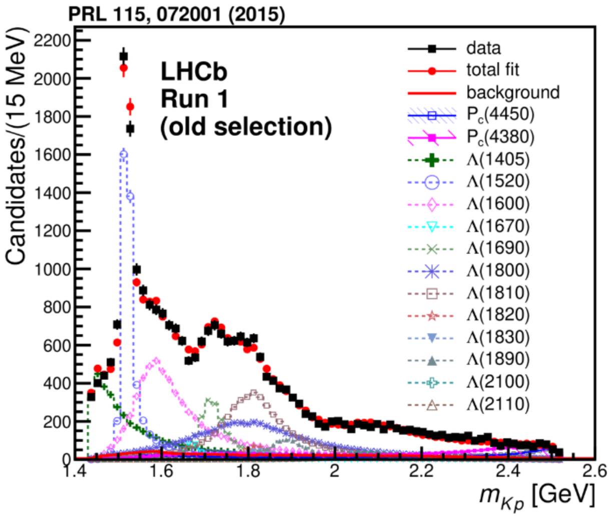
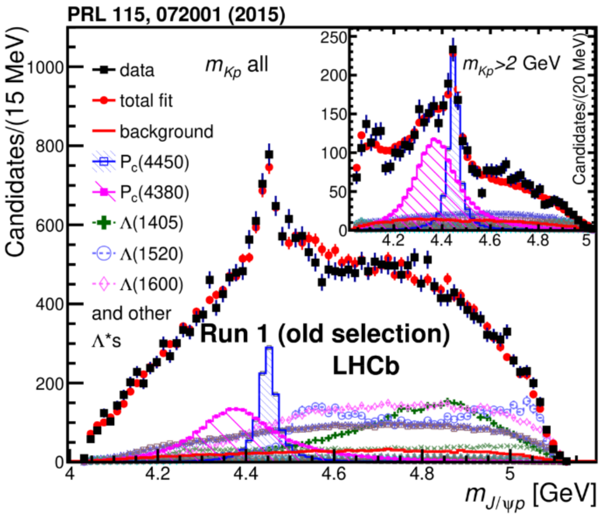
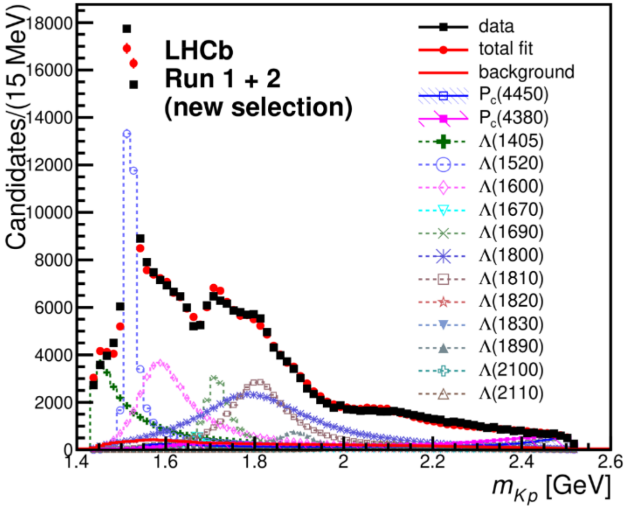
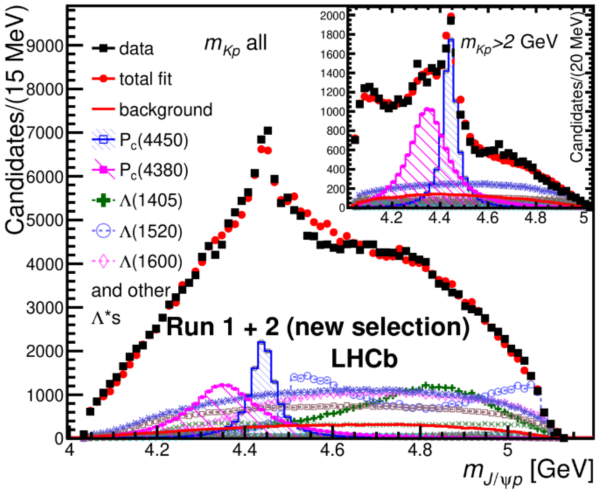
$\Lambda_b^0 \to J/\psi \Lambda^*(\to K^- p)$

$\Lambda_b^0 \to K^- P_c^+(\to J/\psi p)$









6D amplitude analysis fit to masses and decay angles

- **Fit with the same amplitude model to the full data sample**
  - It gives parameters of $P_c(4450)^+$ and $P_c(4380)^+$ that are **consistent** with the run1 results

- **However, more could be different …**

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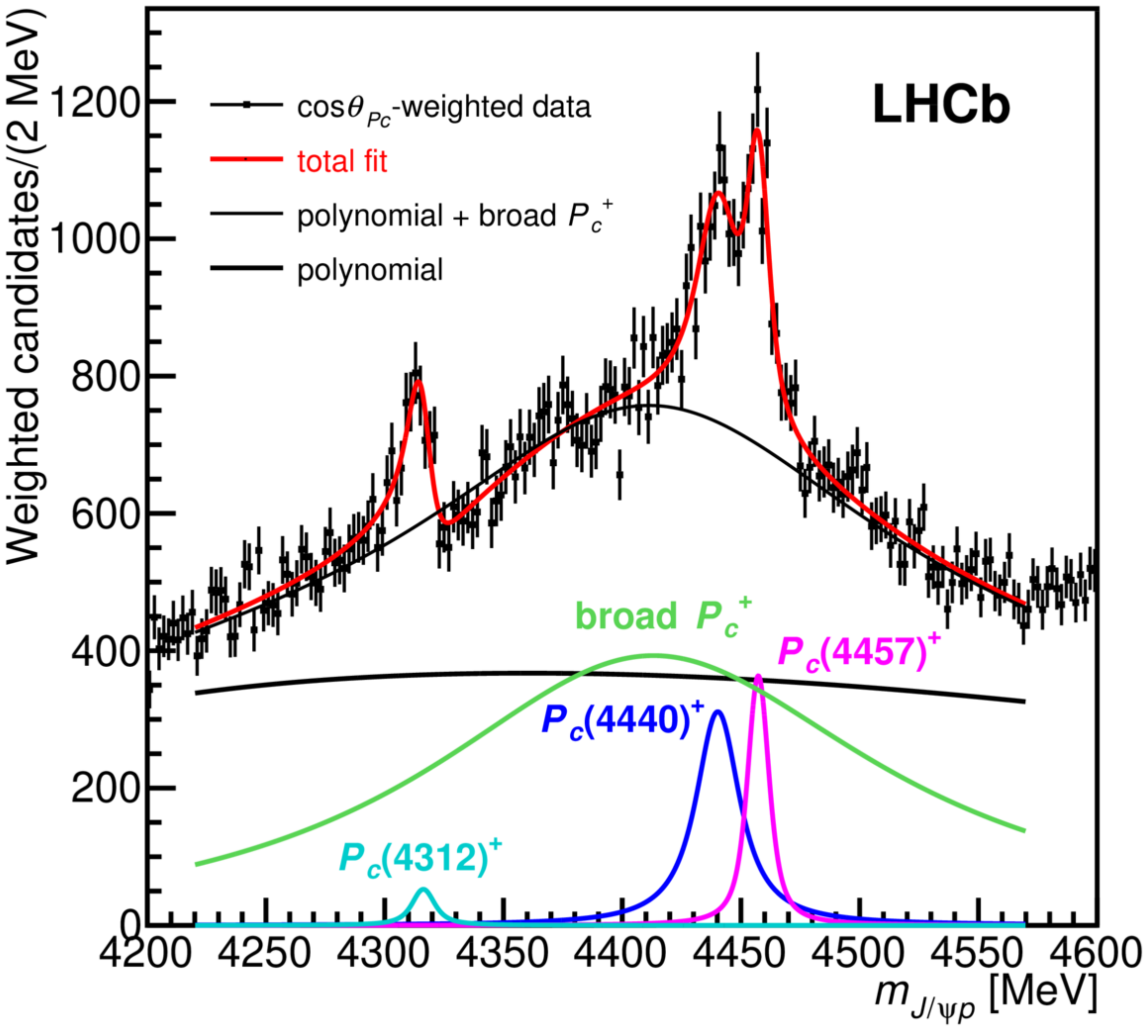
Fits with interferences

- No interferences considered for nominal fits
- Fits with coherent sum between various BW amplitudes, including the broad P_c^+ state with the same J^P are also tried
- No significant evidence for interferences
  - but it provides the source of the largest systematic uncertainty on the mass and width determinations.

Example of the fit with interference:
$P_c(4312)^+$ interfering with the broad P_c^+



Results

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To determine the relative P_c^+ production rates, fit inclusive $m(J/\psi p)$ obtained with $1/\varepsilon$ event-weights, where ε is the efficiency parameterization in 6D Λ_b^0 decay phase-space (masses and angles)

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi\, p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)}$$

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Further information needs the amplitude analysis of the $\Lambda^0 \to J/\psi p K^-$ decay