Recent Experimental Progress on Heavy Flavour Physics

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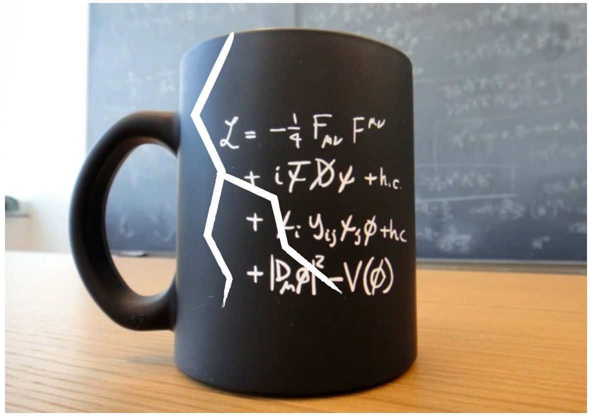
Role of flavour physics

- **Key open HEP questions**
  - Why antimatter disappear?
  - Any BSM physics and what is the form?

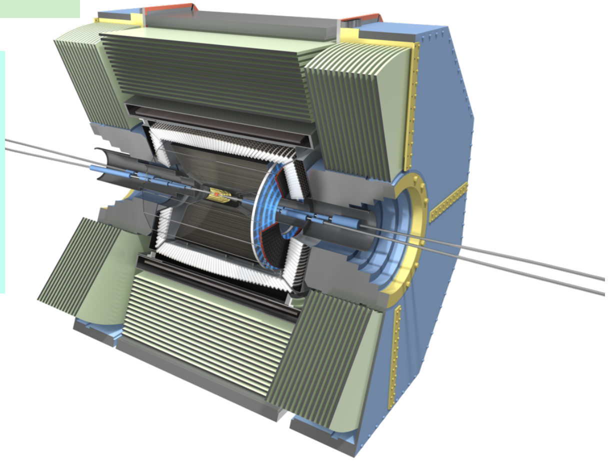


- **Precision study of flavour and CP violation can probe BSM physics**
  - Looking for new sources of CP violation
    - Precision flavour measurements to overconstrain CKM matrix
  - Looking for new phenomena in rare or forbidden decays
    - Flavour changing neutral current
    - Lepton flavour universality violation
    - Lepton flavour number violation

Experiments for HFP

Advantages of e^+e^- collider:
lower BKG, $B\bar{B}(D\bar{D})$ production in pair (can measure absolute BF, or polarization via quantum correlation), advantages in (semi)leptonic and neutral channels…

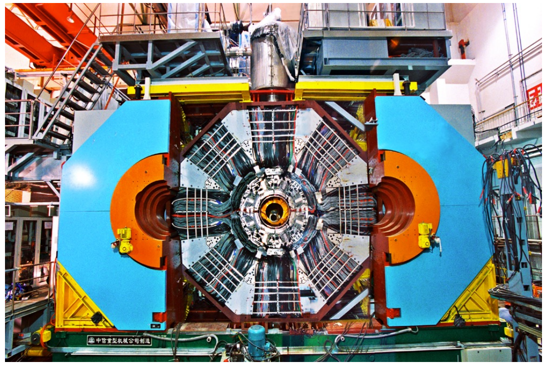
Belle II



around $\Upsilon(4S)$:

$\sim$**220** fb^{-1} up to Nov. 2021, <1/4 of the total Belle data

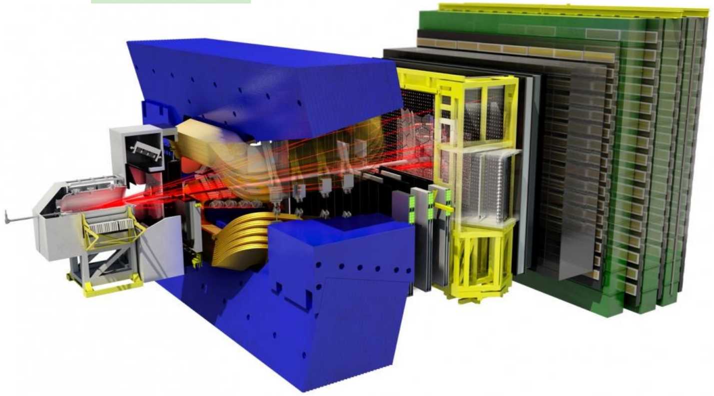
BES III



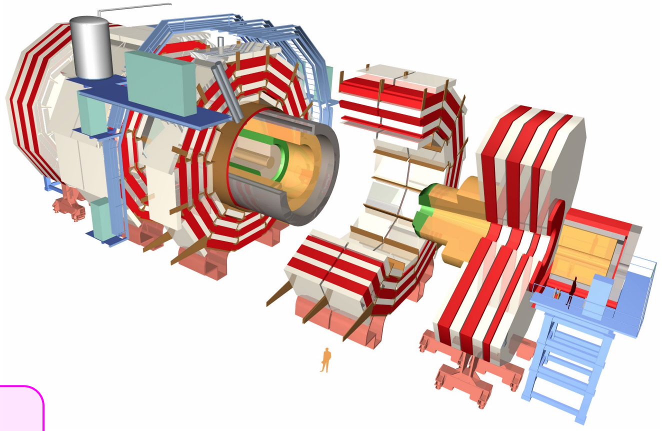
E ∈ (3.77, 4.95) GeV:

$\sim$**27** fb^{-1} up to Nov. 2021

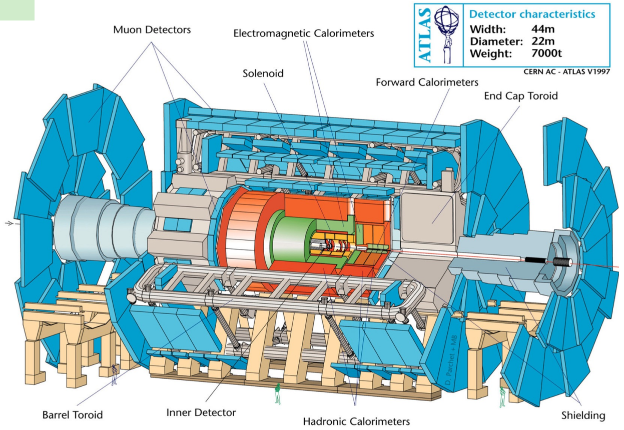
LHCb



CMS



ATLAS



Hadron collider: Large cross-section
LHCb: dedicated detector for flavour physics

CKM matrix

Precision measurement of CKM elements -- Test EW theory

CKM matrix elements are fundamental SM parameters that describe the mixing of quark fields due to weak interaction.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

B factories + LHCb + LQCD

Three generations of quark?

Unitary matrix?

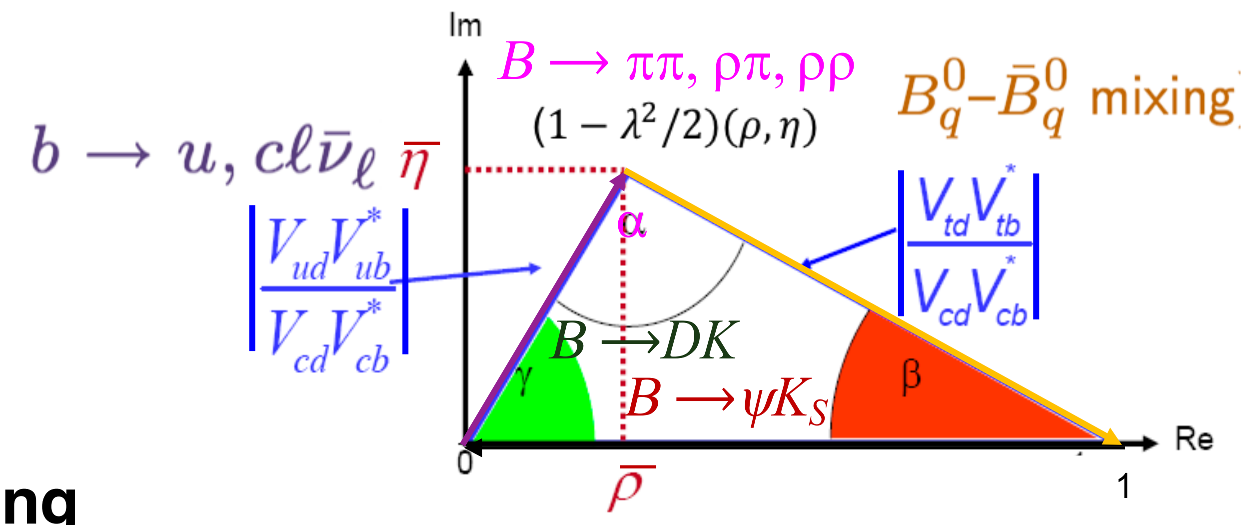
Expected precision < 2% at BESIII

- **Precision measurement of CKM matrix elements**
- **A precise test of SM model**
- **New physics beyond SM?**

How to measure

$$
\mathbf{V}_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & e^{-i\gamma}|V_{ub}| \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ e^{-i\beta}|V_{td}| & -e^{i\beta_s}|V_{ts}| & |V_{tb}| \end{pmatrix}
$$

db triangle $\quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



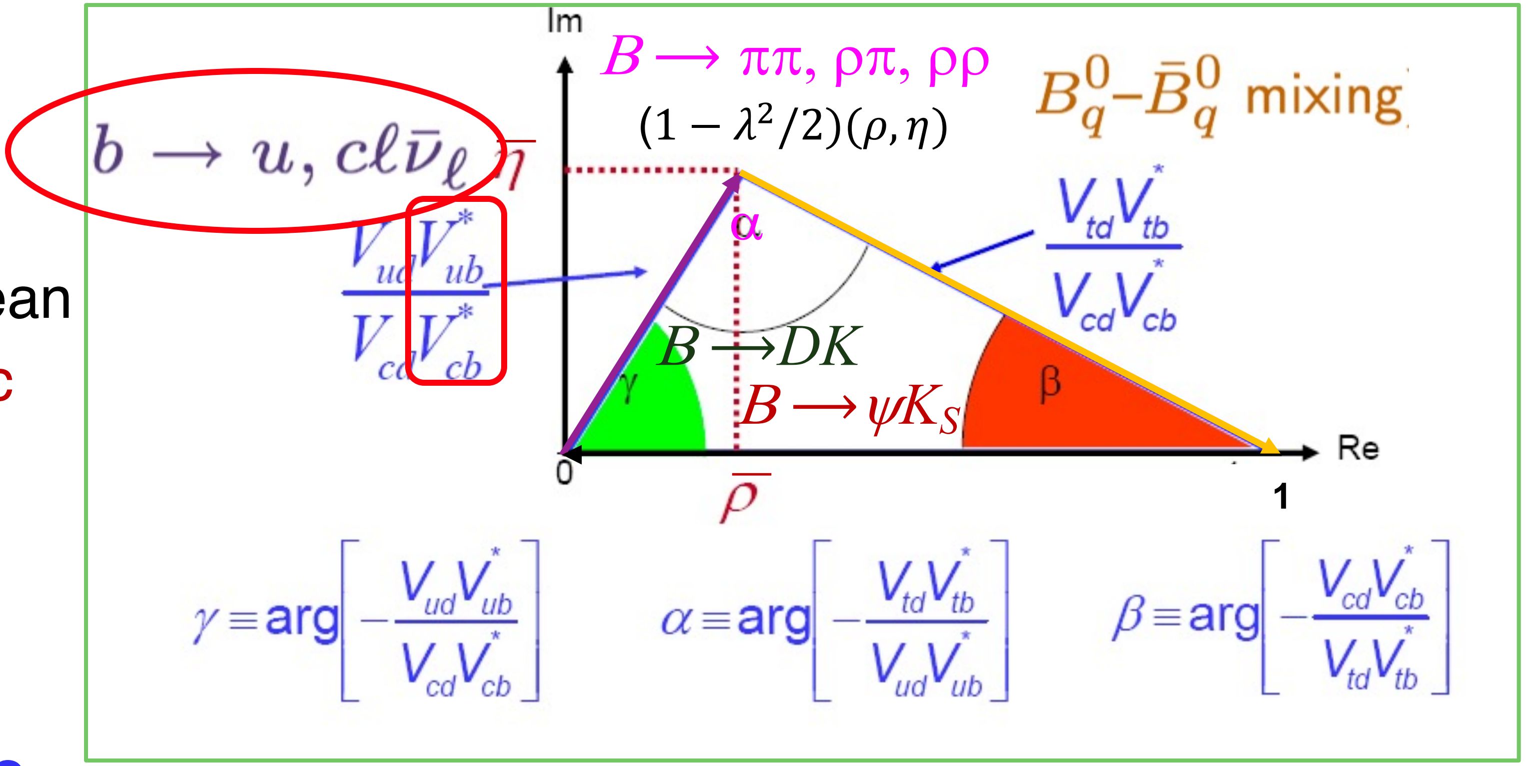
- **Test of Unitarity by measuring**
  - Angles (CP violating) and sides (CP conserving)

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

V_{ub}/V_{cb}

- V_{ub}/V_{cb} **is fundamental input to constrain SM**

- **Measure differential decay rates of:**
  - Inclusive semileptonic decays: theoretically clean
  - Exclusive (semi)leptonic decays: theoretical uncertainties



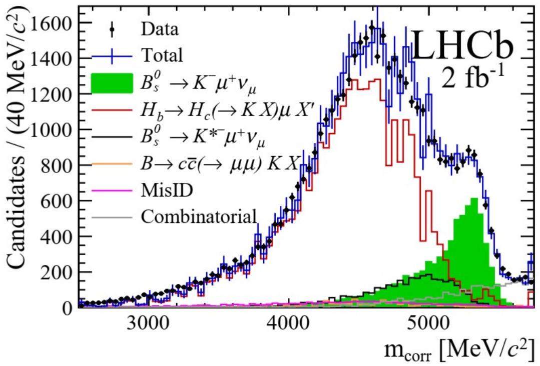
- **Large tenson between inclusive and exclusive determinations**

$\mathrm{V_{ub}/V_{cb}}$ in $B_s^0 \to K^-\mu^+\nu_\mu$

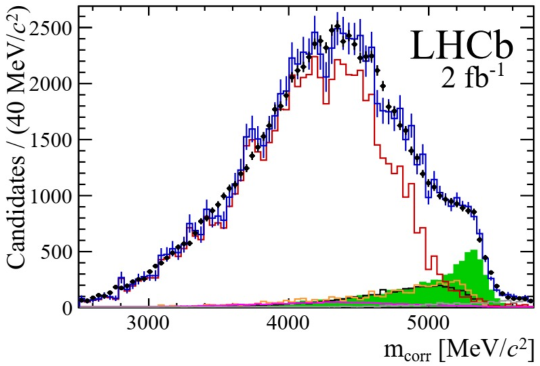
PRL 126 (2021) 081804

- **Measure** $\mathrm{R_{BF} = BF}(B_s^0 \to K^-\mu^+\nu_\mu)/\mathrm{BF}(B_s^0 \to D_s^-\mu^+\nu_\mu)$

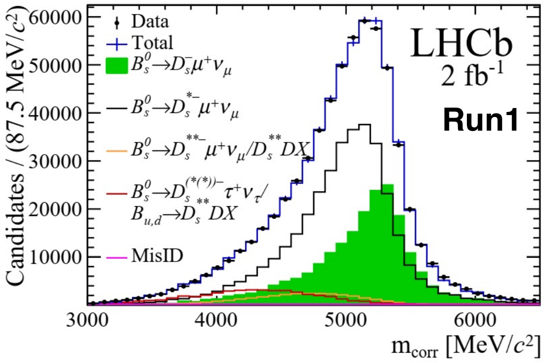
$B_s^0 \to K^-\mu^+\nu_\mu$ low q^2



$B_s^0 \to K^-\mu^+\nu_\mu$ high q^2



$B_s^0 \to D_s^-\mu^+\nu_\mu$



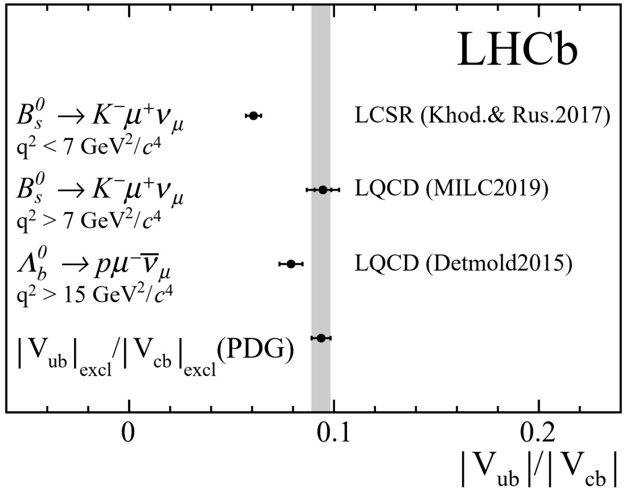
- **Determine** $|\mathrm{V_{ub}/V_{cb}}|$ **through** $\mathrm{R_{BF}} = |\mathrm{V_{ub}/V_{cb}}|^2(\mathrm{FF}_K/\mathrm{FF}_{D_s})$

Low q^2: LCSR $\mathrm{FF}_K = 4.14 \pm 0.38\ \mathrm{ps}^{-1}$

$\left|\frac{\mathrm{V_{ub}}}{\mathrm{V_{cb}}}\right|(\mathrm{low}) = 0.061 \pm 0.004$

High q^2: LQCD $\mathrm{FF}_K = 3.32 \pm 0.46\ \mathrm{ps}^{-1}$

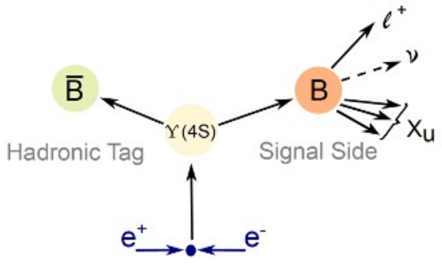
$\left|\frac{\mathrm{V_{ub}}}{\mathrm{V_{cb}}}\right|(\mathrm{high}) = 0.095 \pm 0.008$



Inclusive $B \to X_u \ell^+ \nu$

PRD 104 (2021) 012008

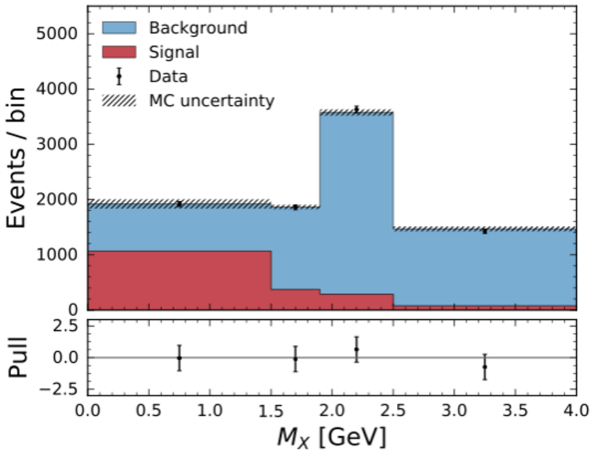
- **Full Belle dataset 711fb^{-1}**
  - Hadronic tagging with Neural Networks ($\varepsilon \sim 0.25\%$)
  - Measure partial BF in $E_\ell^B > 1$ GeV, and convert to **$|V_{ub}|$**

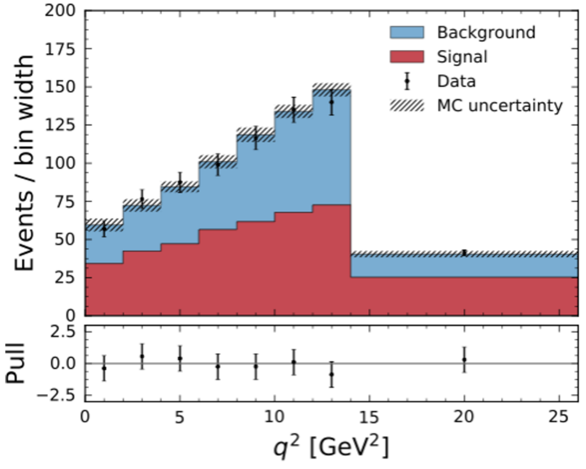


Can fully assign each final state particle to either the tag or signal side

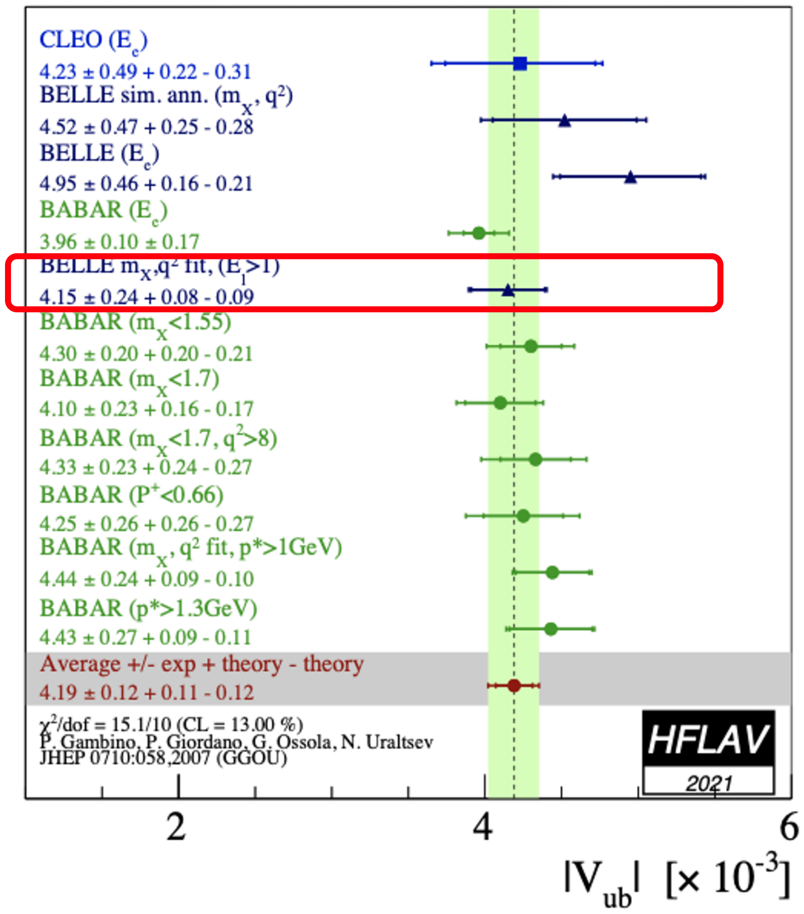
→ Allows to reconstruct X_u

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$



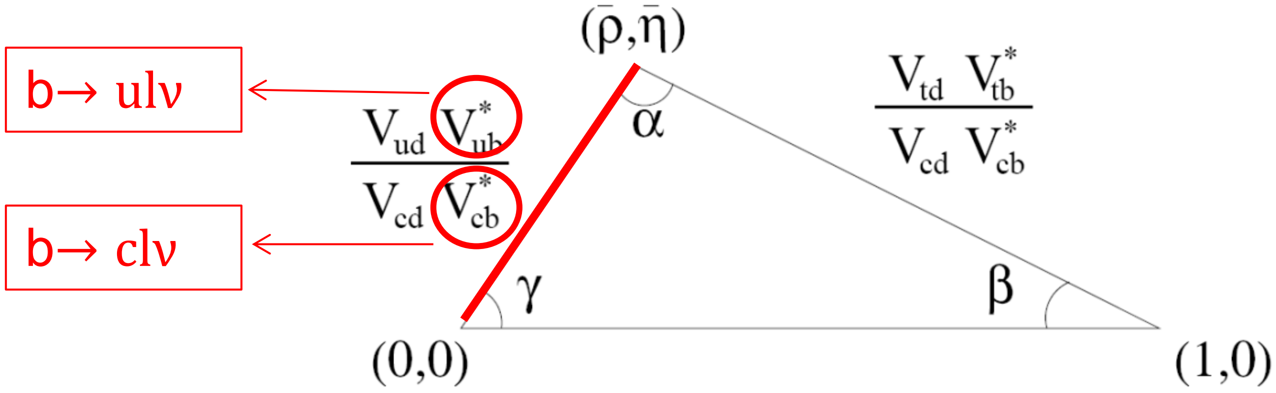


$\Delta\mathcal{B}(E_\ell^B > 1$ GeV $) = (1.59 \pm 0.07_{stat} \pm 0.16_{sys}) \times 10^{-3}$

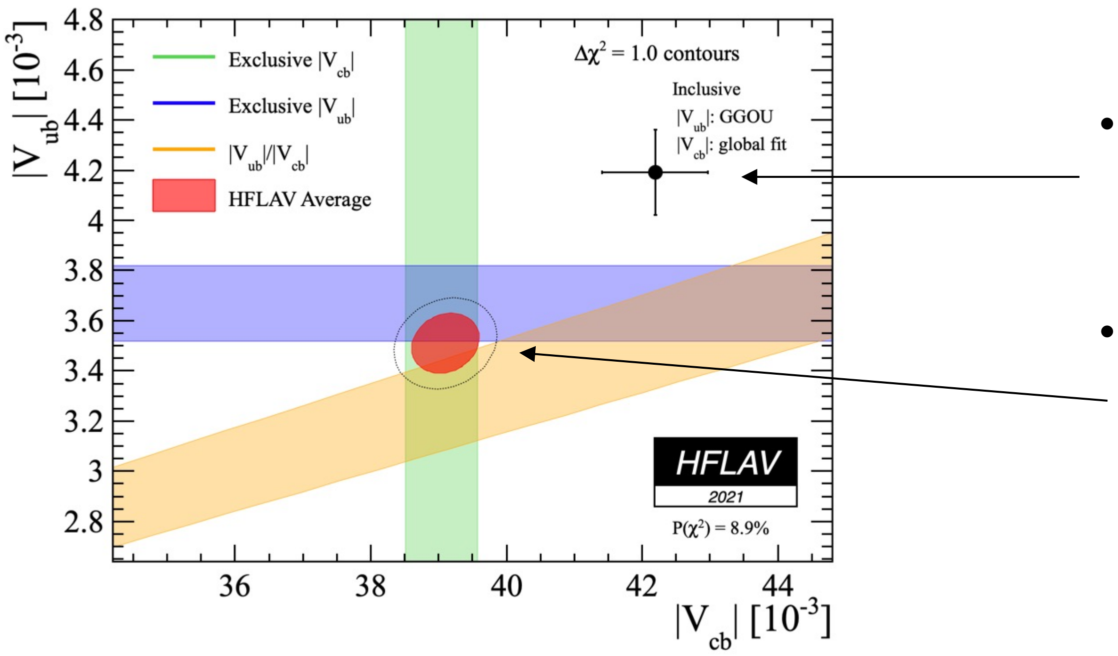


This work

V_{ub}/V_{cb} puzzle



- **Tension between inclusive and exclusive determinations**



- **Inclusive: high background**

  $|V_{ub}| = (4.19 \pm 0.17)\times10^{-3}$

  $|V_{cb}| = (42.19 \pm 0.78)\times10^{-3}$

- **Exclusive: need LQCD inputs**

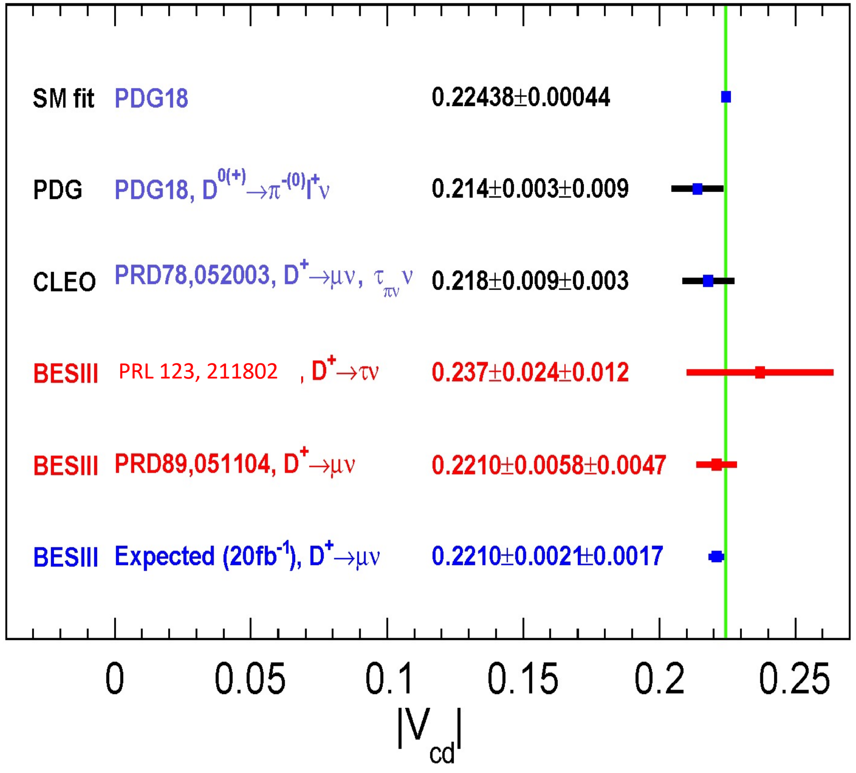
  $|V_{ub}| = (3.51 \pm 0.12)\times10^{-3}$

  $|V_{cb}| = (39.10 \pm 0.50)\times10^{-3}$

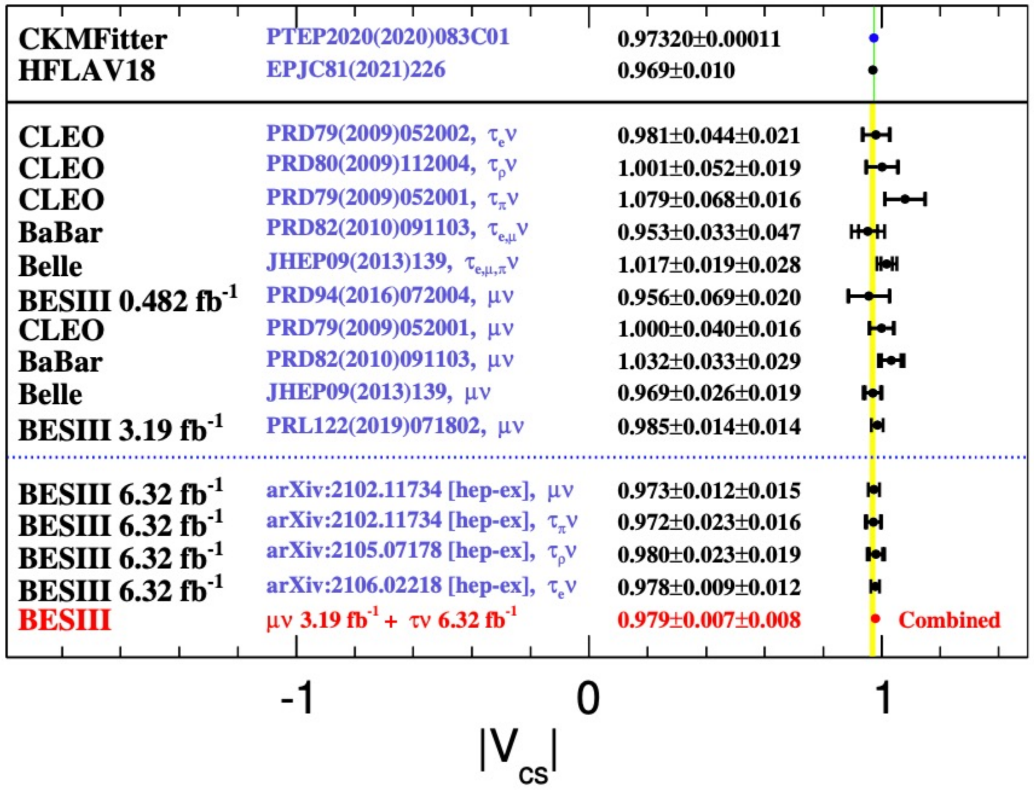
Extraction of $|V_{cd(s)}|$

Take f_D^{LQCD} as input：

$|V_{cd}|=(0.2210\pm0.0058\pm0.0047)$ ($\mu^+\nu$ mode)



- Input $f_{D_s^+} = 249.9 \pm 0.5$ MeV from LQCD calculations

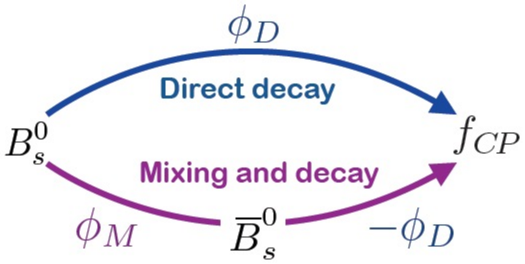


Most precise measurement

B_s^0 mixing phase ϕ_s

- **Mixing induced CPV phase of B_s^0:**

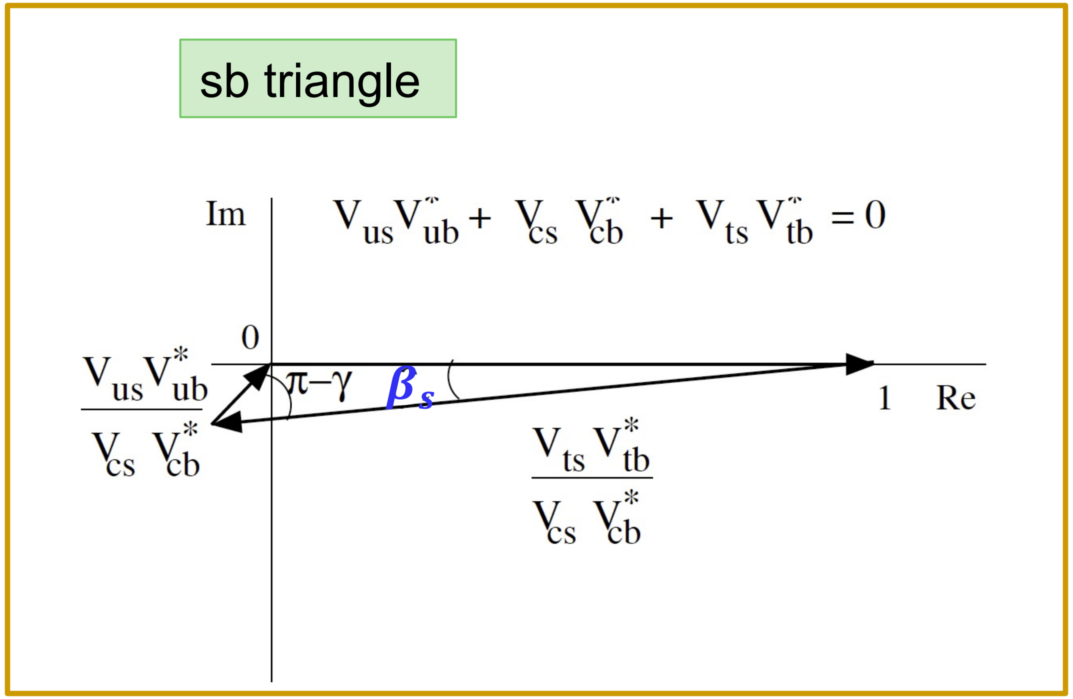
$$\phi_s = \phi_M - 2\phi_D$$



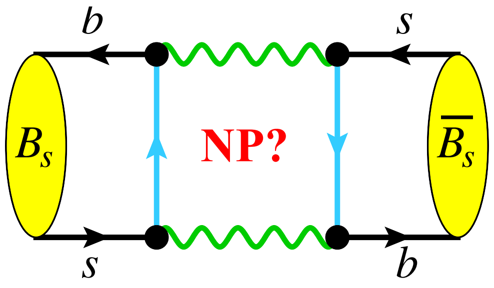
- **Value is precisely predicted**

$$\phi_s^{\rm SM} = -2\beta_s = -36.5^{+1.3}_{-1.2}\ \text{mrad}$$

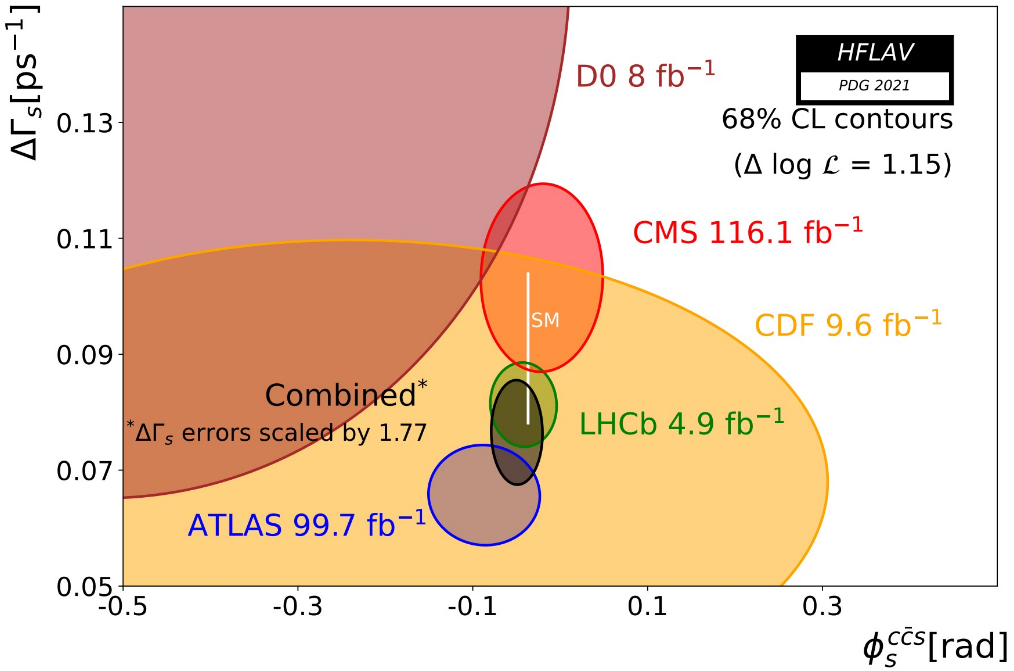
(Ignoring small penguin contribution)



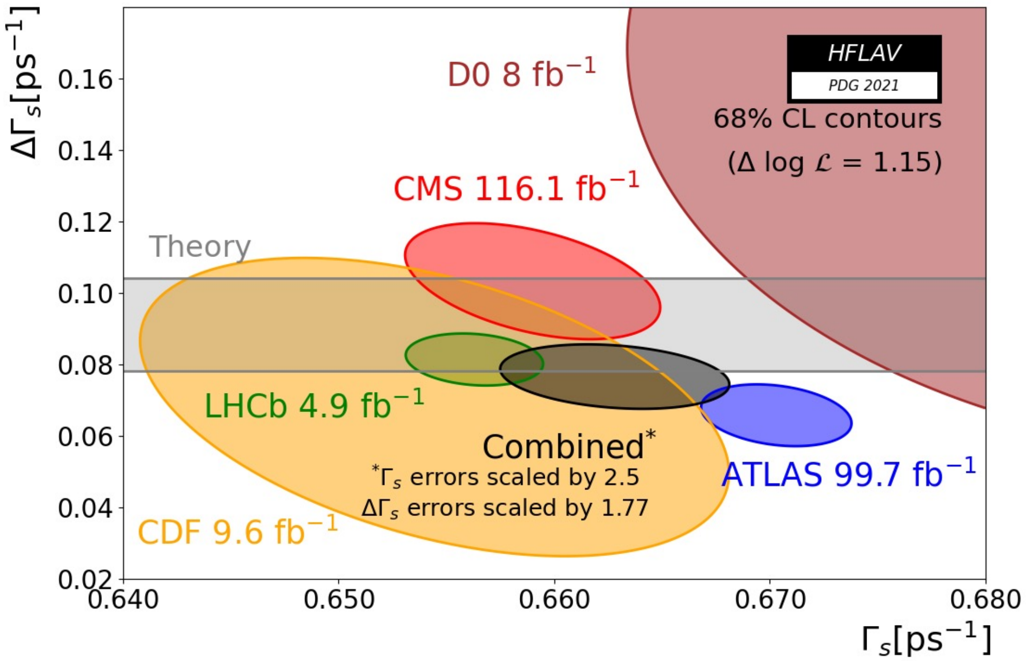
ϕ_s: sensitive to new physics in B_s^0 mixing.
Golden channel: $B_s^0 \to J/\psi\phi(\to K^+K^-)$



World average



Some tensons between measurements

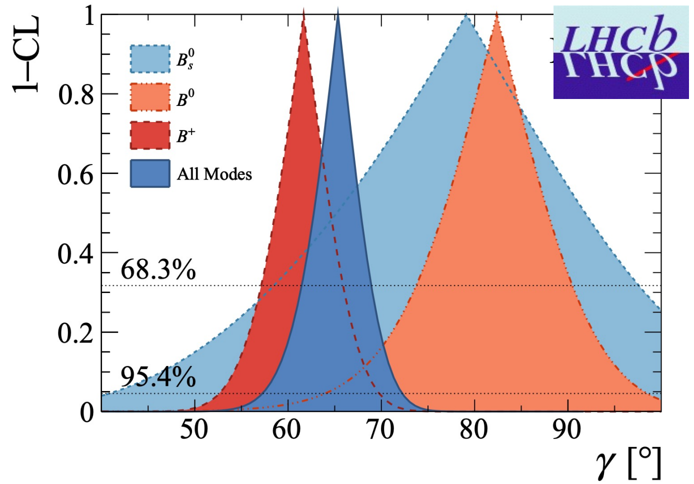


Collab.	Decay Modes	ϕ_s (mrad)	$\Delta\Gamma_s$ (ps^{-1})
ATLAS	$J/\psi K^+K^-$	-87 ± 41	0.0657 ± 0.0057
CMS	$J/\psi K^+K^-$	-21 ± 45	0.1032 ± 0.0106
LHCb	$J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$, $D_s^+D_s^-$	$\mathbf{-42 \pm 25}$	0.0813 ± 0.0048
HFLAV	Above+CDF+D0	-50 ± 19	0.082 ± 0.005
SM prediction from CKMfitter		$\mathbf{-37 \pm 1}$	0.091 ± 0.013

LHCb, EPJC 80 (2020) 601
ATLAS, EPJC 81 (2021) 342
CMS, PLB 816 (2021) 136188

LHC: pushing the frontier

And significant improvements in γ



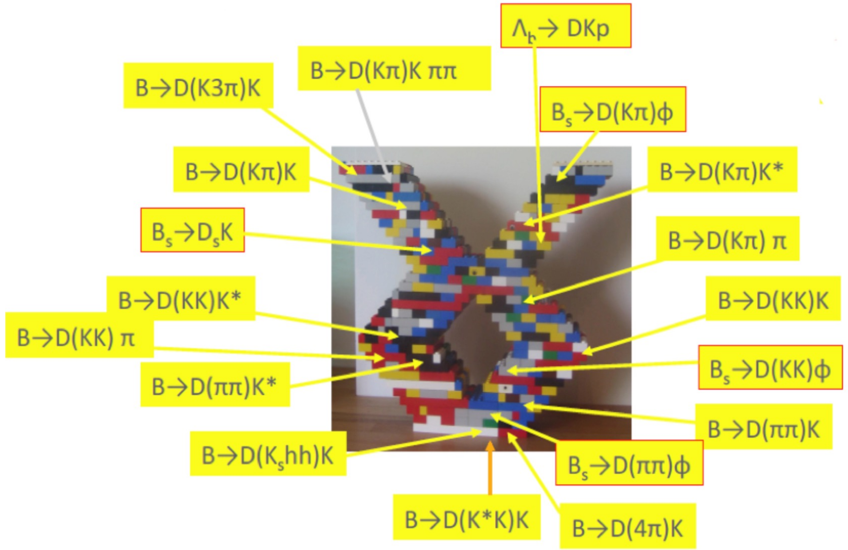
arXiv:2110.02350

LHCb:

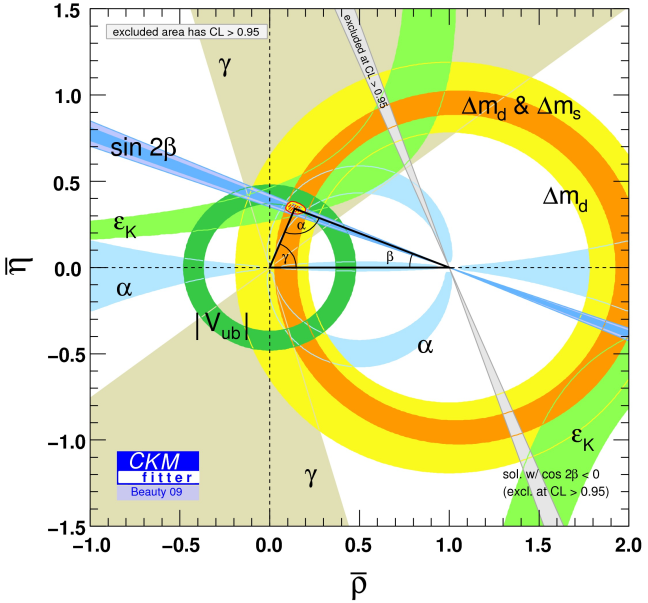
$\gamma = (65.4^{+3.8}_{-4.2})^\circ$

Previous WA:

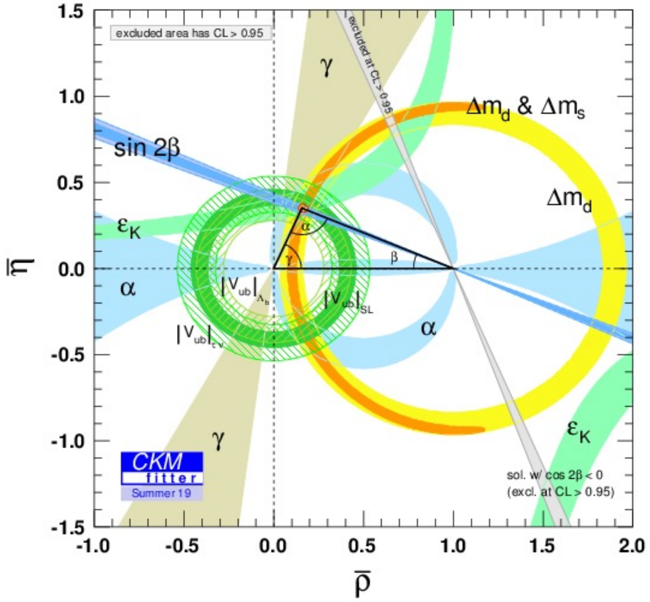
$\gamma = (73.5^{+4.2}_{-5.1})^\circ$



When LHC started



Current status



Anomalies

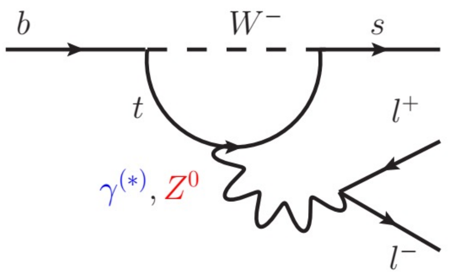
FCNC $b \to s\ell^+\ell^-$ decays

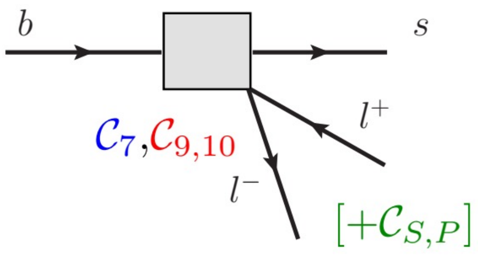
- **FCNC $b \to s\ell^+\ell^-$ decays described by effective Hamiltonian**

$$H = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i\, O_i + \frac{K}{\Lambda_{NP}^2} O_j^{(6)}$$

New physics can affect Wilson coefficients C_i and/or add new operators O_j

- **Sensitivity to Wilson coefficients**

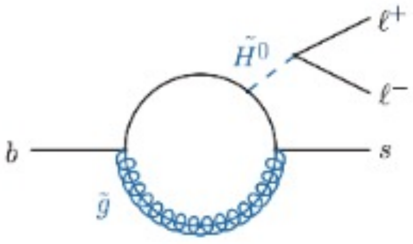


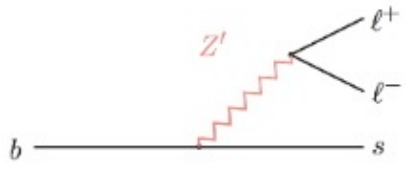


- $B^0_{(s)} \to l^+l^-$ $[\mathcal{C}_{10}, \mathcal{C}_S, \mathcal{C}_P]$
- $b \to sl^+l^-$ $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

7: photon penguin; 9,10: EW penguin; S,P: (pseudo-) scalar penguin

- **Theoretically clean probes of NP**
  - Pure leptonic decays
  - Special angular observables
  - Ratio between $e/\mu/\tau$



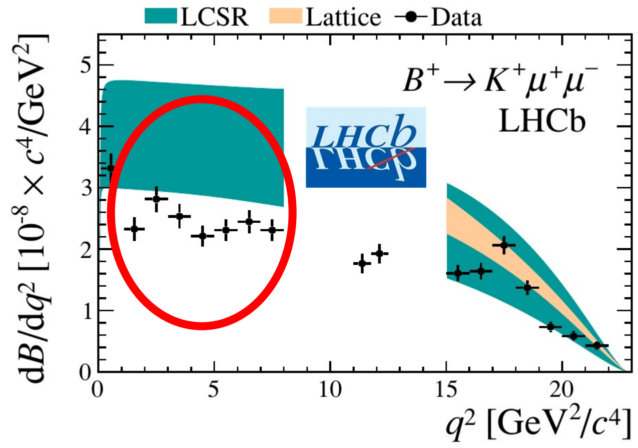


$b \to s\mu^+\mu^-$ branching fractions

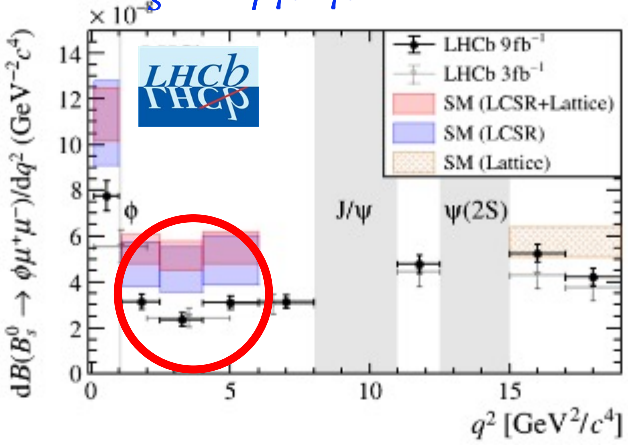
- **Measurements use the $J/\psi \to \mu^+\mu^-$ channels for normalization**
- **Measured values consistently below SM predictions**

Caveat: significant theory uncertainties from hadronic form factors

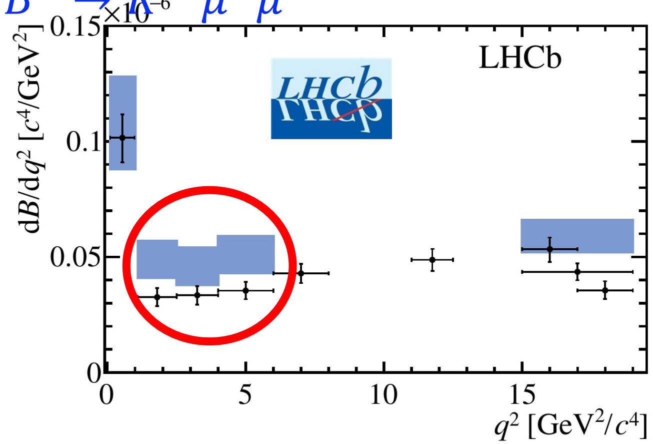
$B^+ \to K^+\mu^+\mu^-$ JHEP 06(2014)133



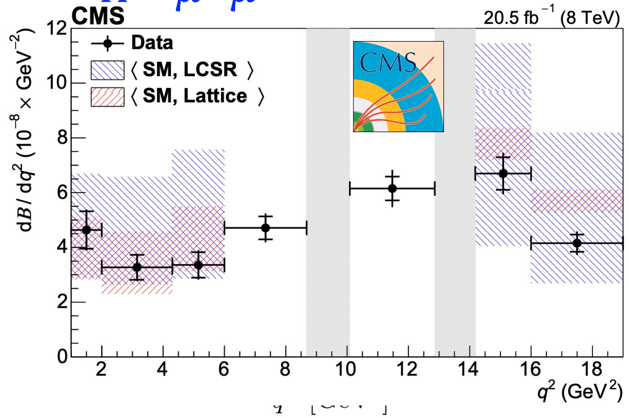
$B_s^0 \to \phi\mu^+\mu^-$ arXiv: 2105.14007



$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 04(2017)142



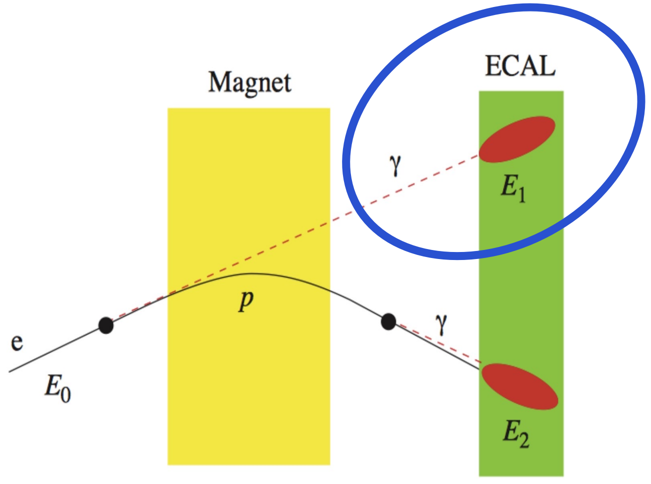
$B^0 \to K^{*0}\mu^+\mu^-$ Phys.Lett.B 753 (2016) 424



Lepton flavour universality test

$$R_{K^{(*)}} = \frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)} = \frac{B(B \to K^{(*)}\mu^+\mu^-)/B(B \to K^{(*)}J/\psi(\to \mu^+\mu^-))}{B(B \to K^{(*)}e^+e^-)/B(B \to K^{(*)}J/\psi(\to e^+e))}$$

- $R_{K^{(*)}} = 1.000 \pm 0.001$ in the SM, with uncertainties related to form factors largely cancelled
- Experimental challenge: electron reconstruction
- Double ratio technique



Electron Bremstrahlungs recovery

Lepton flavour universality test

- Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:
  - Test of LFU in $\Lambda_b^0 \to pK^-\ell^+\ell^-$ with Run1+2016 data

$$R_{pK}(0.1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.86^{+0.14}_{-0.11} \pm 0.05$$

JHEP 05 (2020) 040

  - Test of LFU in $B^0 \to K^{*0}\ell^+\ell^-$ with Run1 data

JHEP 08 (2017) 055

$$R_{K^{*0}}(0.045 < q^2 < 1.1\ \mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.05$$ (2.1-2.3σ from SM)

$$R_{K^{*0}}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$$ (2.4-2.5σ from SM)

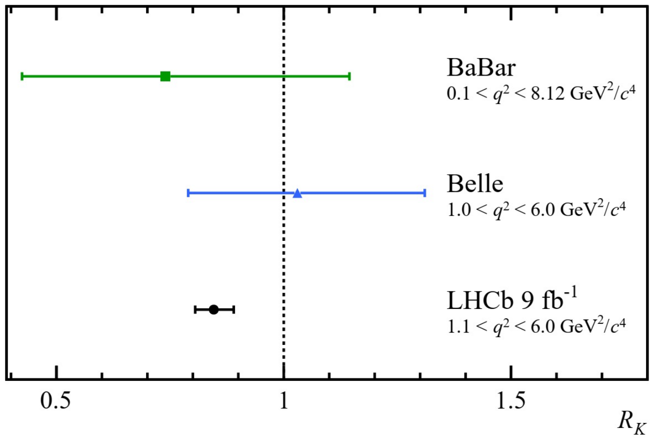
  - Test of LFU in $B^+ \to K^+\ell^+\ell^-$ with full Run1+Run2 sample

$$R_{K^+}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.846^{+0.042\ +0.013}_{-0.039\ -0.012}$$

(3.1σ from SM)

arXiv:2105.14007

BaBar: Phys. Rev. D86 (2012) 032012
Belle: JHEP 03 (2021) 105



Results from K_s^0 channels

- New result with full Run1+Run2 sample

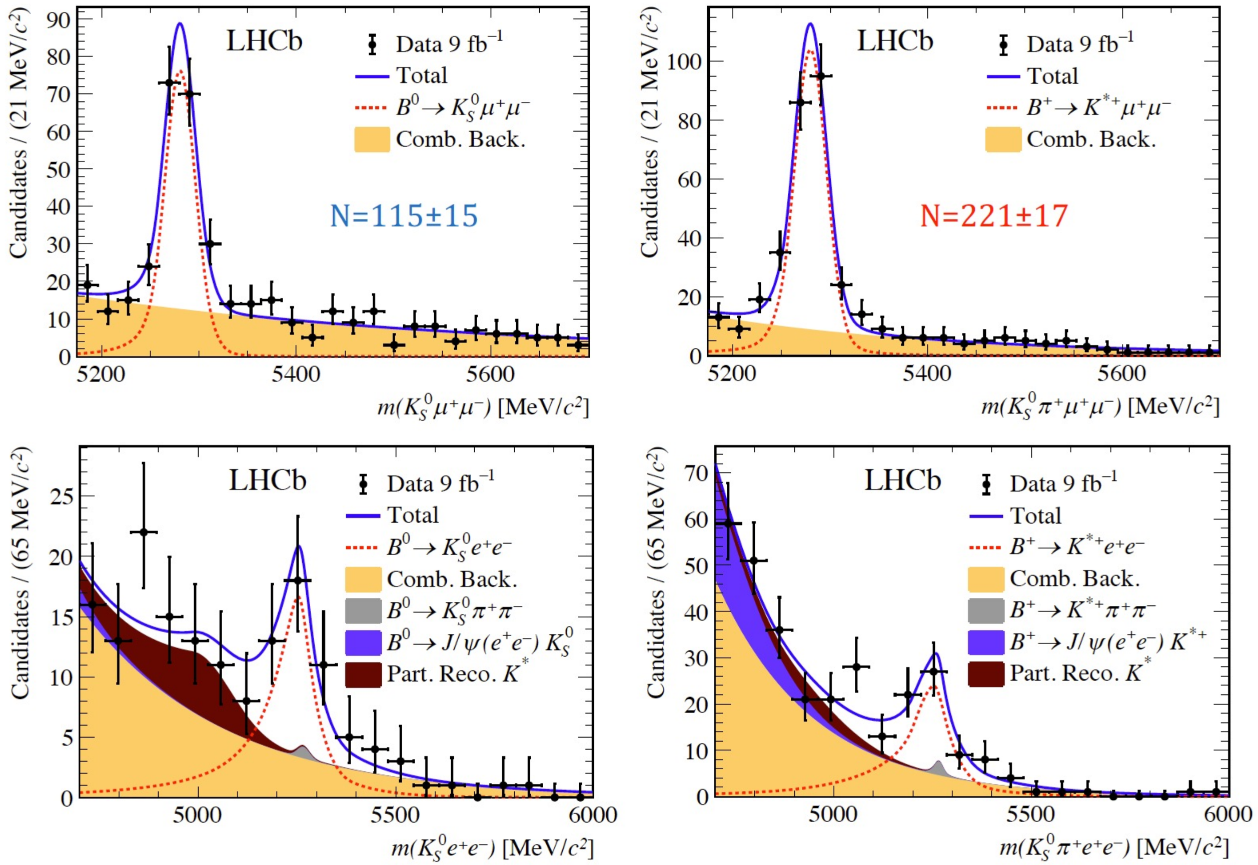
LHCb-PAPER-2021-038

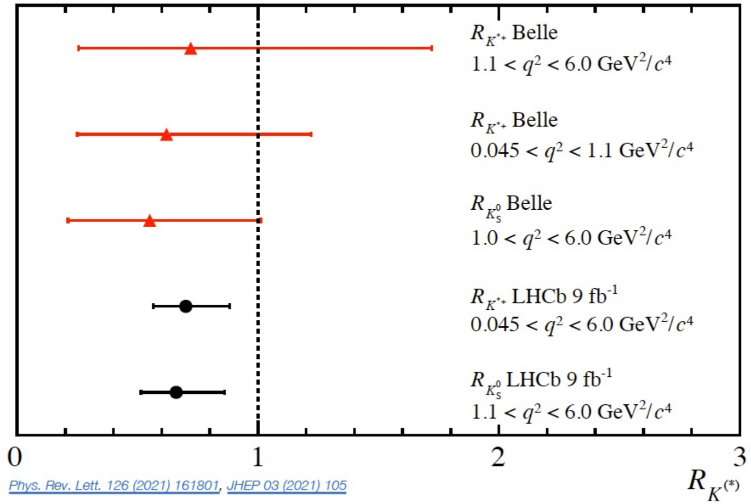
$$R_{K_S^0}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.66^{+0.20}_{-0.13}{}^{+0.02}_{-0.04}$$

(1.5σ from SM)

$$R_{K^{*+}}(0.045 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.70^{+0.18}_{-0.13}{}^{+0.03}_{-0.04}$$

(1.4σ from SM)



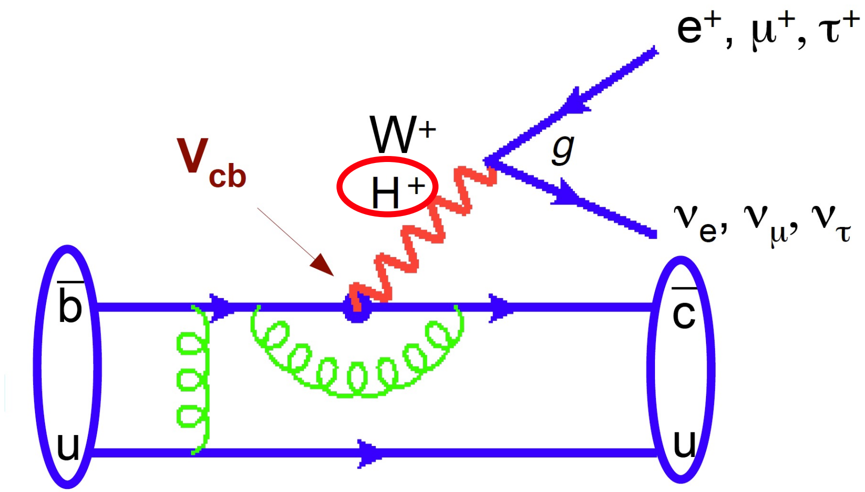


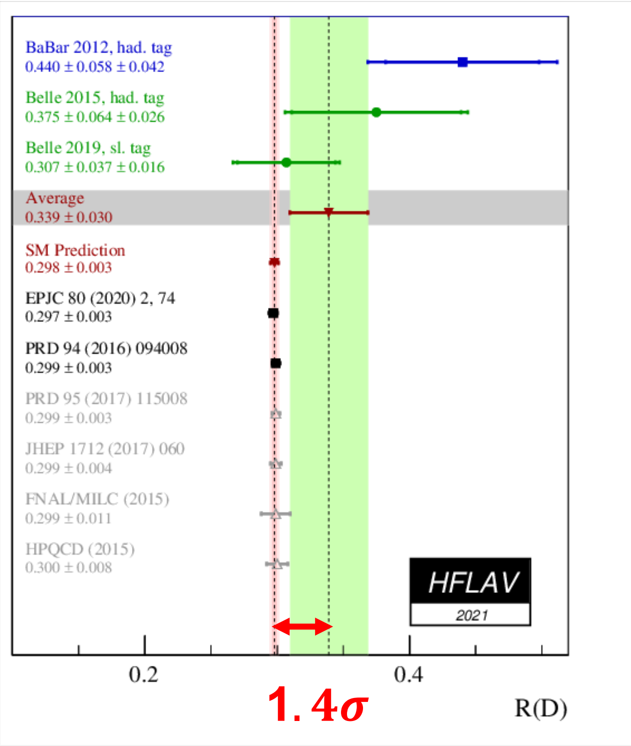
Caution: Needs Belle2/CMS confirmation and Looking forward to LHCb's electron efficiency validation from $\phi \to e^+e^- / \phi \to \mu^+\mu^-$

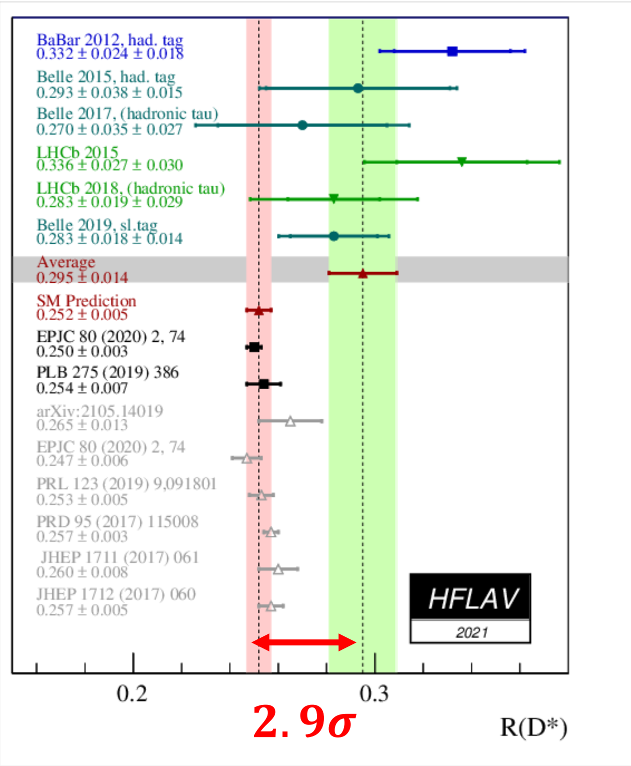
R_D and R_{D^*}

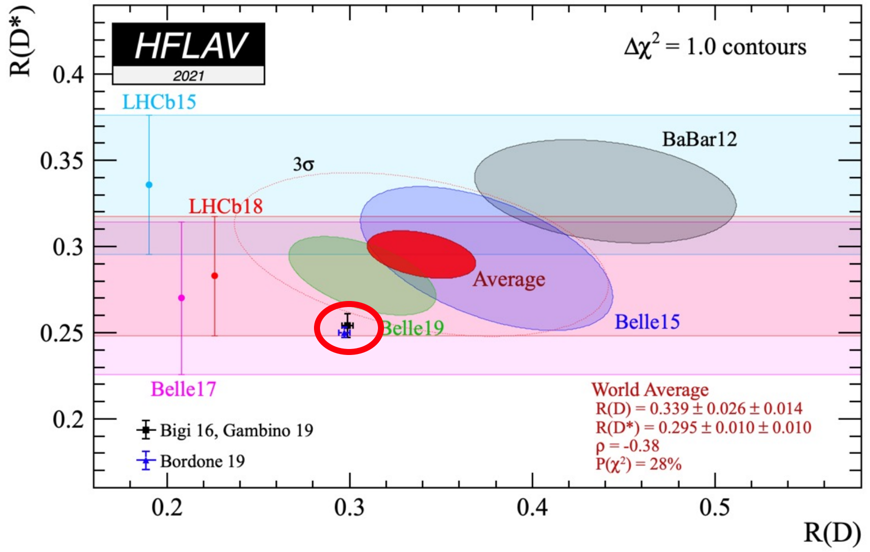
- Measured by BarBar, Belle and LHCb
- Tension between measurements and SM predictions

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}l\bar{\nu}_l)}$$









3.4σ

(with R_D&R_{D^*} correlation considered)

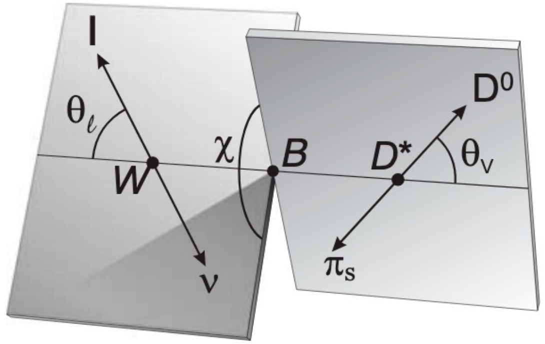
$\bar{B} \to D^* l \bar{\nu}$ angular analysis

- **Interpretation to Belle data [PRD 100 (2019) 052007]**
- **One dimensional fit to $\bar{B} \to D^* e(\mu)\bar{\nu}$ angular variables to test LFU**

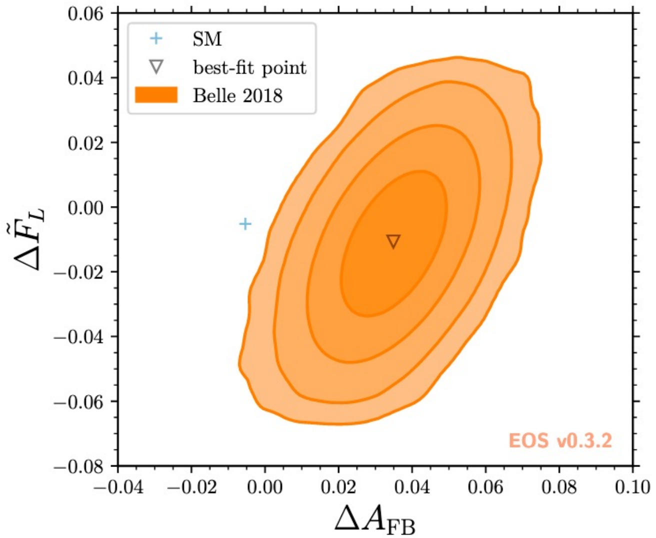
$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\cos\theta_\ell} = \frac{1}{2} + \langle A_{\rm FB}^{(\ell)}\rangle \cos\theta_\ell + \frac{1}{4}\left(1 - 3\langle \widetilde{F}_L^{(\ell)}\rangle\right)\frac{3\cos^2\theta_\ell - 1}{2},$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\cos\theta_D} = \frac{3}{4}\left(1 - \langle F_L^{(\ell)}\rangle\right)\sin^2\theta_D + \frac{3}{2}\langle F_L^{(\ell)}\rangle \cos^2\theta_D,$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\chi} = \frac{1}{2\pi} + \frac{2}{3\pi}\langle S_3^{(\ell)}\rangle \cos 2\chi + \frac{2}{3\pi}\langle S_9^{(\ell)}\rangle \sin 2\chi,$$



- **A 4σ tension between fit result & SM prediction** arXiv: 2104.02094

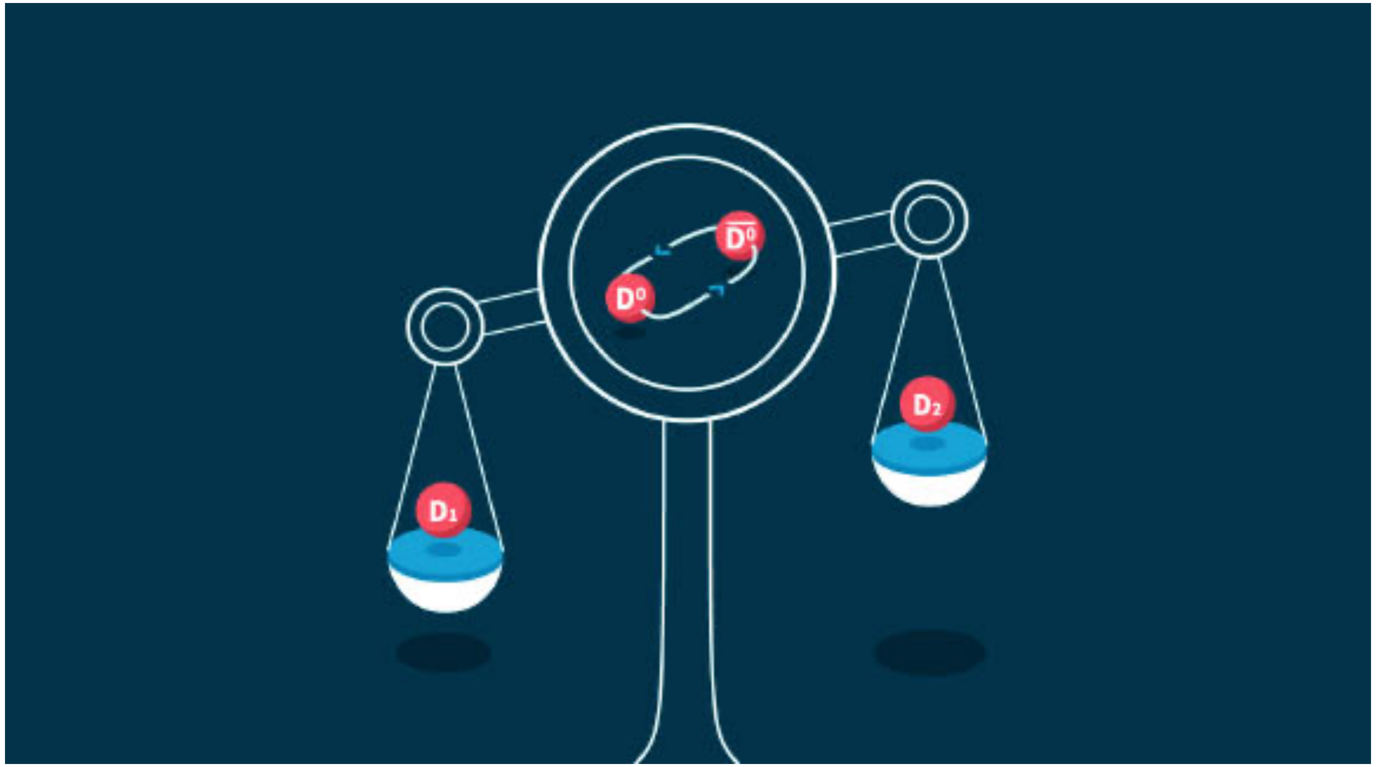


- **Most of the tension arises from muon mode**

$$< A_{FB}^{\mu} >_{\rm SM} = 0.198 \pm 0.012$$
$$< A_{FB}^{\mu} >_{\rm fit} = 0.2300 \pm 0.0059$$

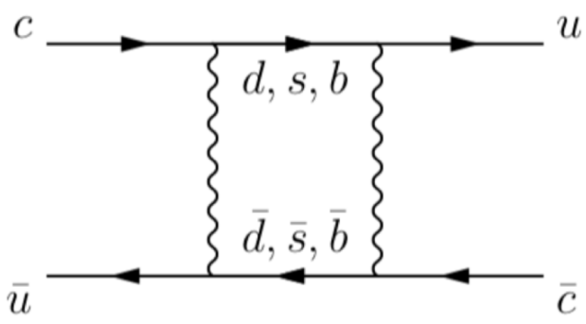
- **Indicate a potential interest of angular analysis of $b \to c l \nu$ process**

Charm mixing



$D^0 - \bar{D}^0$ mixing

- **After many effort, D^0-$\bar{D}^0$ oscillation was observed**
- **But mass difference and CP-violation poorly known**

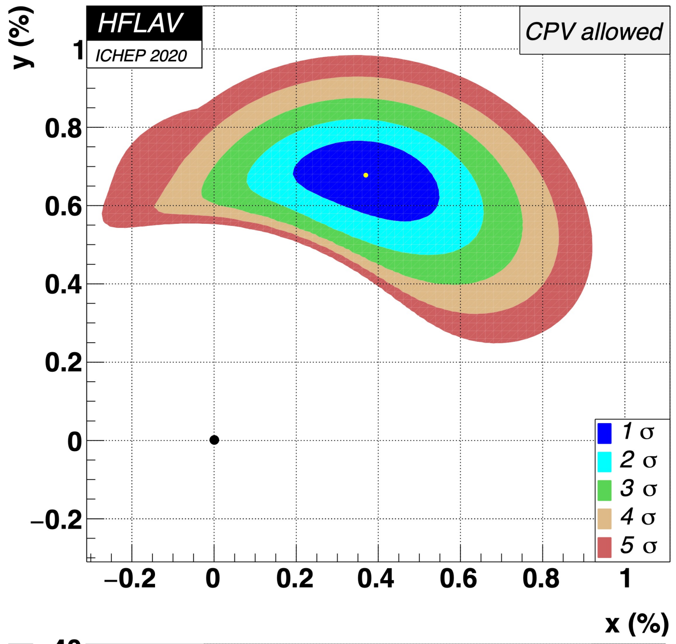


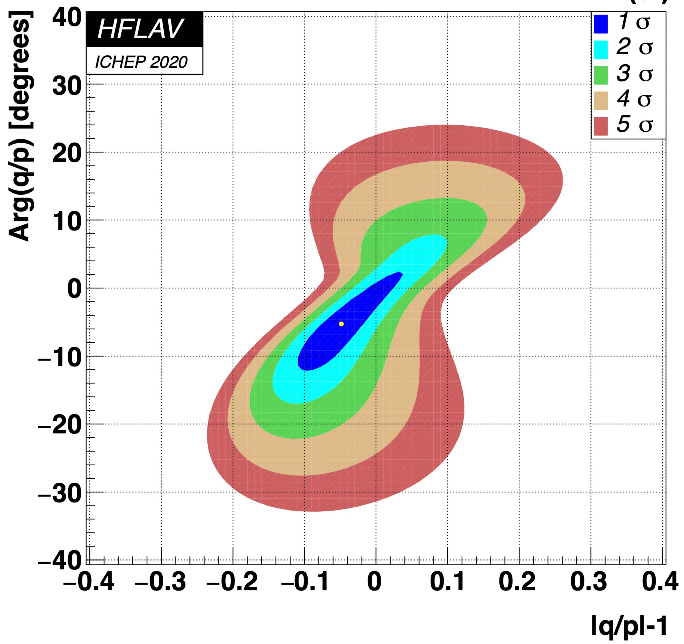
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = \left(0.68^{+0.06}_{-0.07}\right)\% \neq 0$$

$$x = \frac{m_1 - m_2}{\Gamma} = (0.37 \pm 0.12)\%$$

World average (WA)





- **Mainly used for new physics search**

Expect in SM: $|x| \lesssim |y| \sim$ $10^{-6} - 10^{-3}$ (short distance), $10^{-3} - 10^{-2}$ (long distance)

- If obtain $|x| >> |y|$ or *CPV* $\Rightarrow$ New Physics

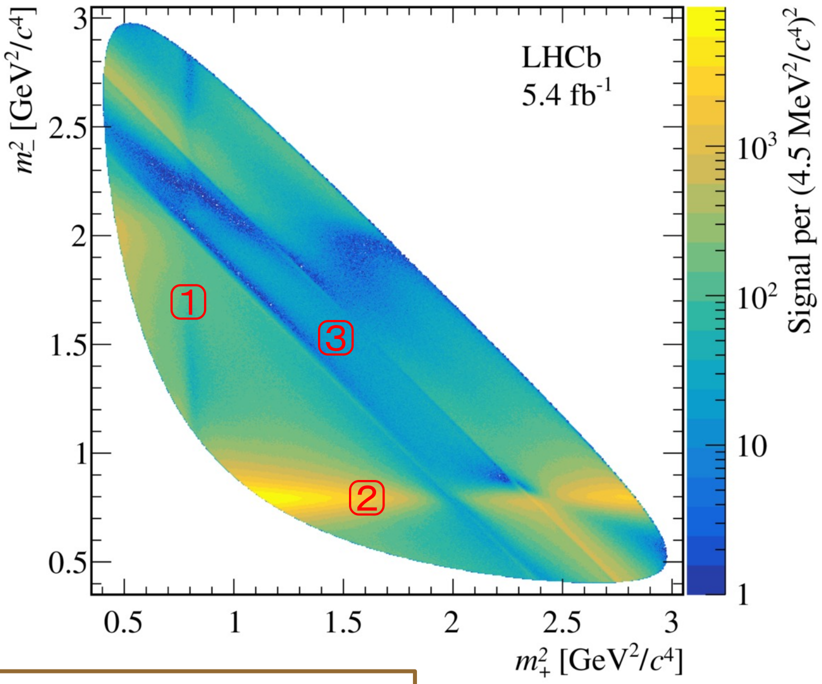
$D^0 \to K_S^0\pi^+\pi^-$ decays for mixing measurement

- **Different decays identified through Dalitz plot**

①
- $D^0 \xrightarrow{\text{DCS}} K^{*+}\pi^- \to K_S^0\pi^+\pi^-$
- $D^0 \xrightarrow{\text{mix}} \bar{D}^0 \xrightarrow{\text{CF}} K^{*+}\pi^- \to K_S^0\pi^+\pi^-$

②
- $D^0 \xrightarrow{\text{CF}} K^{*-}\pi^+ \to K_S^0\pi^+\pi^-$

③
- $D^0 \xrightarrow{\text{CP}} K_S^0\rho^0 \to K_S^0\pi^+\pi^-$



Interference bwt resonances probes x and y

$$R(\overline{D}^0(t) \to f) \approx |\mathcal{A}_f|^2 \left|\frac{p}{q}\right|^2 e^{-\bar{\Gamma}t}\left\{|\lambda|^2 + [yRe(\lambda) + xIm(\lambda)](\bar{\Gamma}t) + \frac{1}{4}(x^2+y^2)(\bar{\Gamma}t)^2\right\}$$

Two methods:

(1) Amplitude model fit to the Dalitz-plot and t

L.M.Zhang et. al. (Belle) PRL 99 (2007) 131803

T.Peng et. al. (Belle) PRD 89, 091103 (2014)

(2) "Bin-flip" method

R.Aaij et. al. (LHCb) PRL 127 (2021) 111801

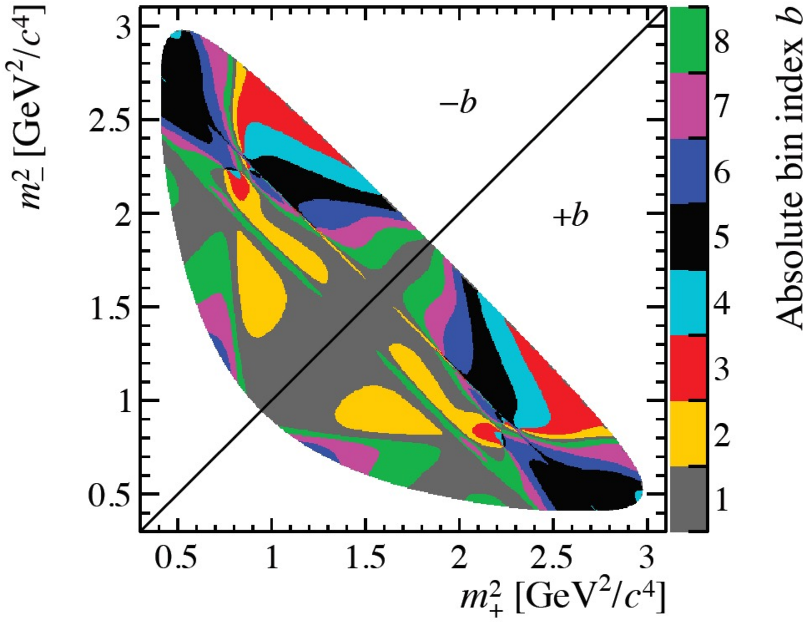
$D^0 \to K_S^0\pi^+\pi^-$ decays for mixing measurement

- **Different decays identified through Dalitz plot**

① $\begin{cases} D^0 \xrightarrow{\text{DCS}} K^{*+}\pi^- \to K_S^0\pi^+\pi^- \\ D^0 \xrightarrow{\text{mix}} \bar{D}^0 \xrightarrow{\text{CF}} K^{*+}\pi^- \to K_S^0\pi^+\pi^- \end{cases}$

② $D^0 \xrightarrow{\text{CF}} K^{*-}\pi^+ \to K_S^0\pi^+\pi^-$

③ $D^0 \xrightarrow{\text{CP}} K_S^0\rho^0 \to K_S^0\pi^+\pi^-$



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R.Aaij et. al. (LHCb) PRL 127 (2021) 111801

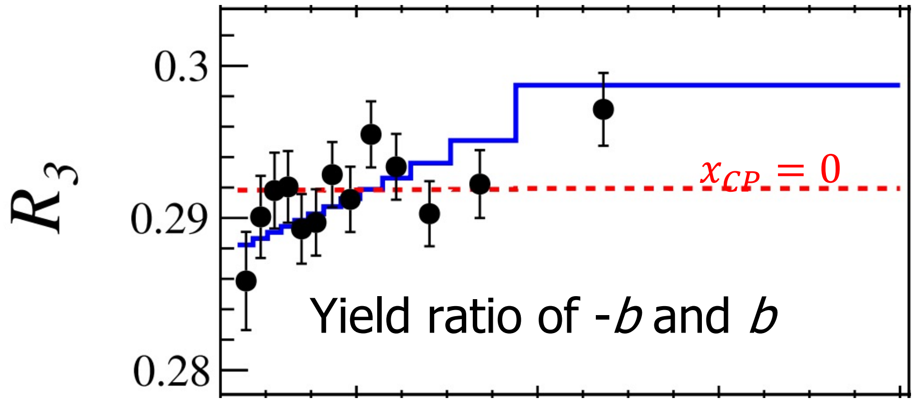
Result and WA

- **Bin-Flip method** PRD 99, 012007 (2019)
- **First measurement of $x > 0$ for 7σ**

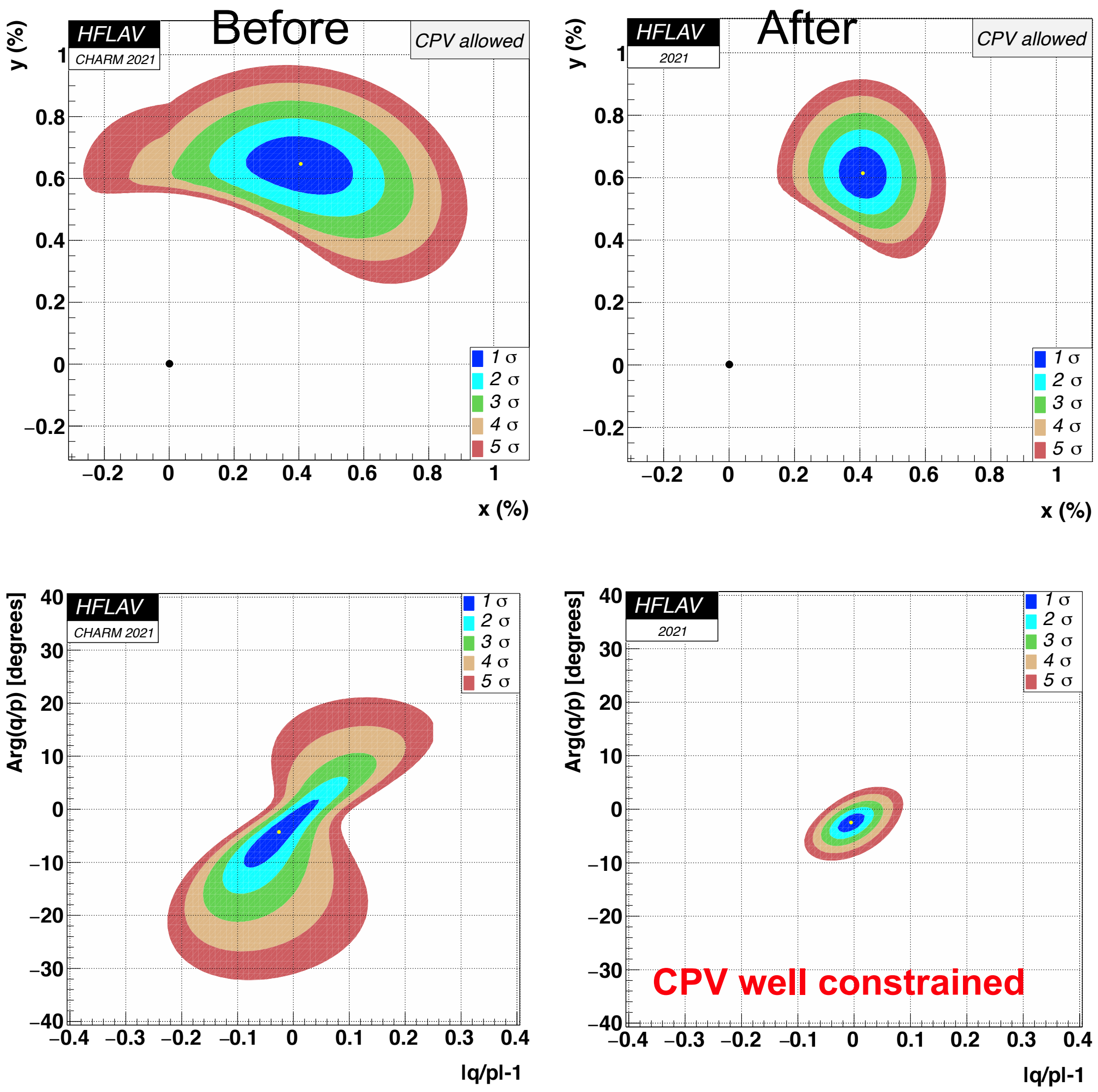
PRL 127 (2021) 111801

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

30.6M signal events



Huge impact on WA of x and CPV !

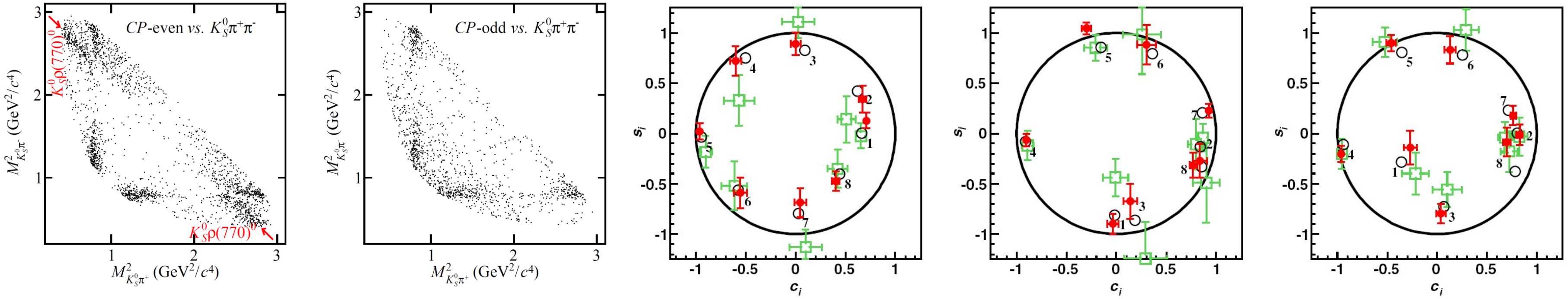


Quantum entangled $D^0 D^0$ Strong phase measurements

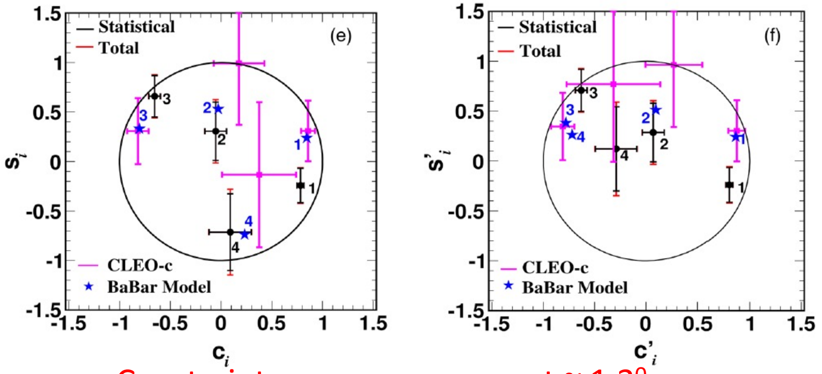
$2.93\ \mathrm{fb}^{-1}@E_{cm} = 3.773\ \mathrm{GeV}$
$e^+e^- \to \psi(3770) \to D\bar{D}$

- **Important for measurements of γ angle and $D^0 - \bar{D}^0$ mixing**
  - $D \to K^0_{S/L}\pi^+\pi^-$ PRL 124 (2020)241802

Constraint on γ measurement ~ 0.9^0



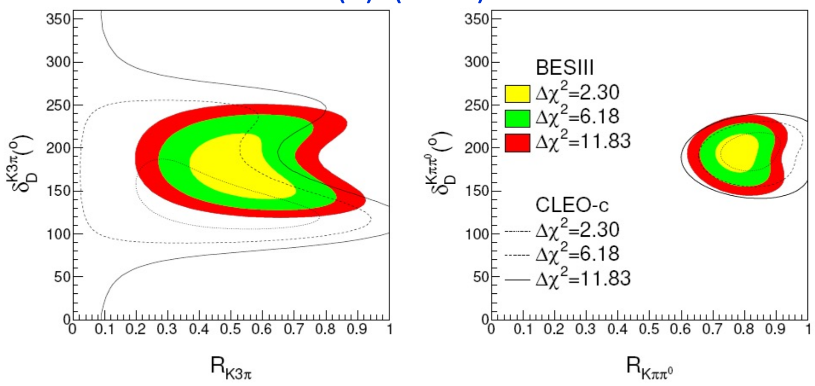
- $D \to K^0_{S/L}K^+K^-$ PRD102(2020)052008



Constraint on γ measurement ~ 1.3^0

- $D \to K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$

JHEP 2021 (5) (2021) 164

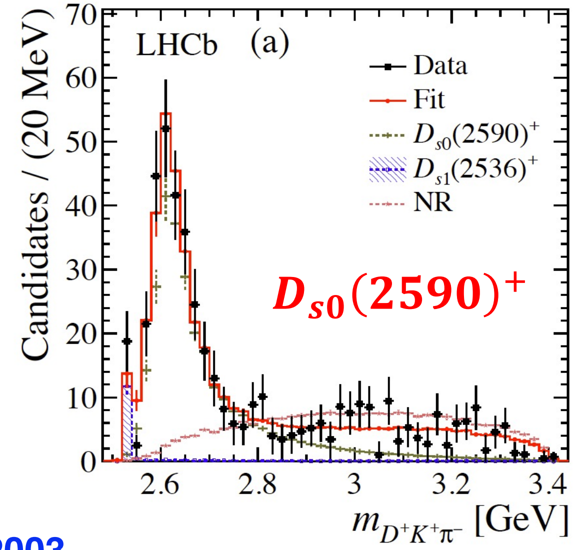


Constraint on γ measurement ~ 6^0

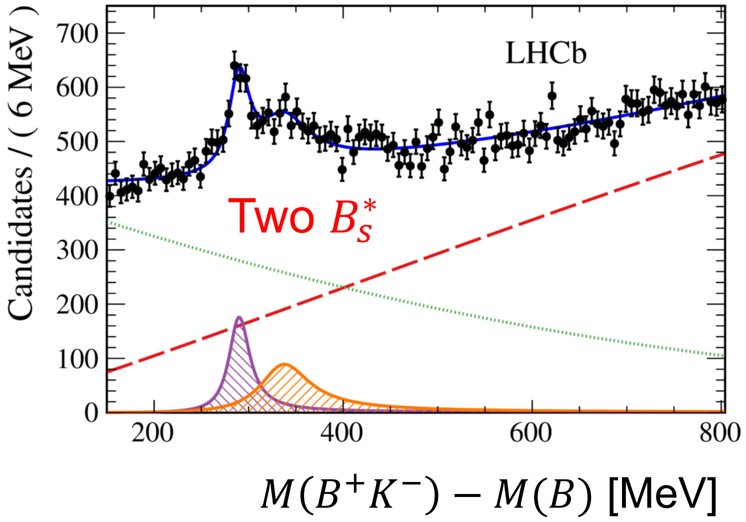
Hadron spectroscopy

New conventional hadrons

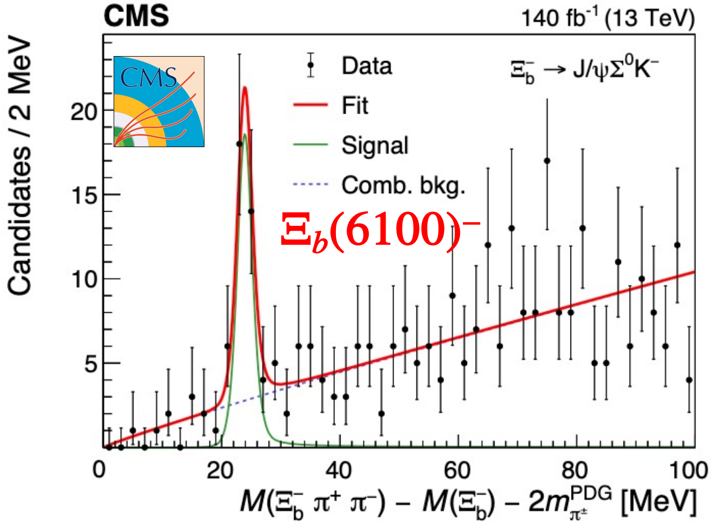
PRL126 (2021) 122002



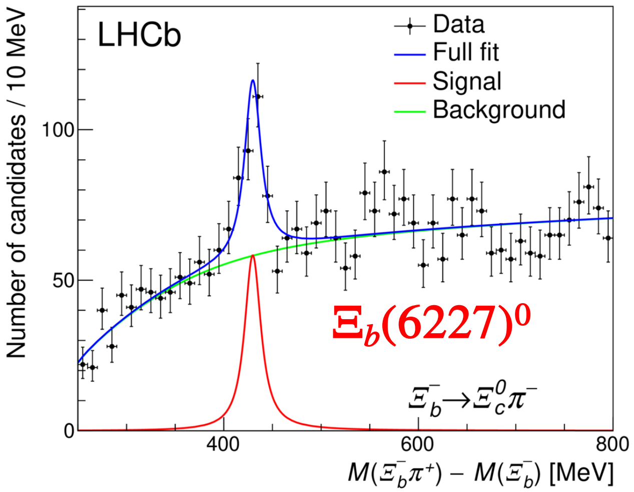
EPJC 81 (2021) 601



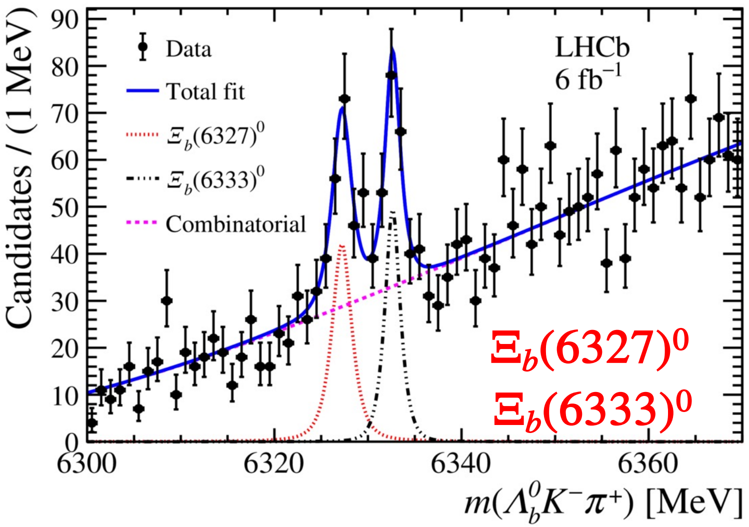
PRL 126 (2021) 252003



PRD103 (2021) 012004

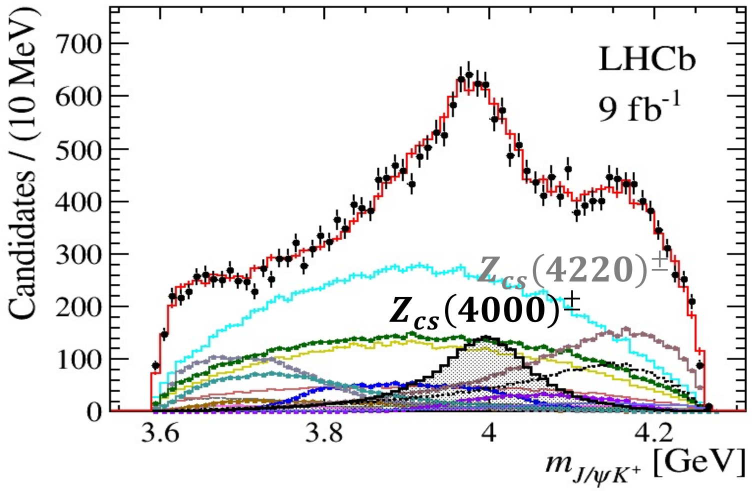


arXiv:2110.04497

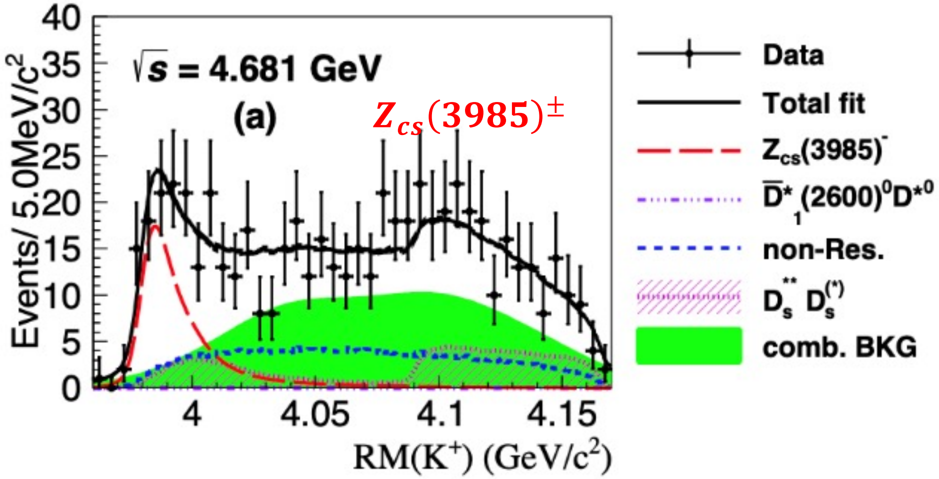


Hidden-charm tetra(penta)-quarks

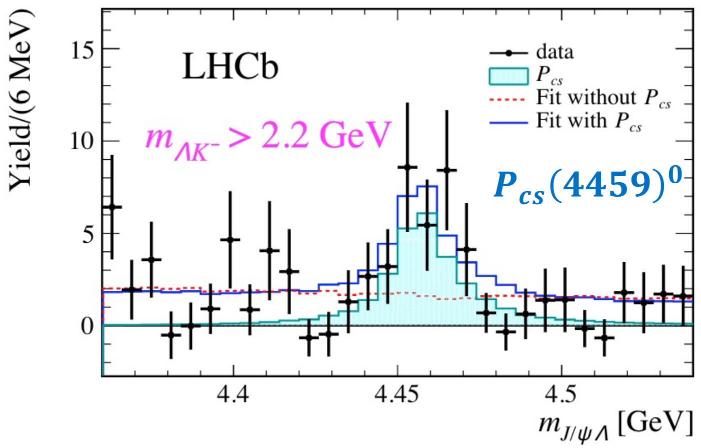
PRL 127 (2021) 082001



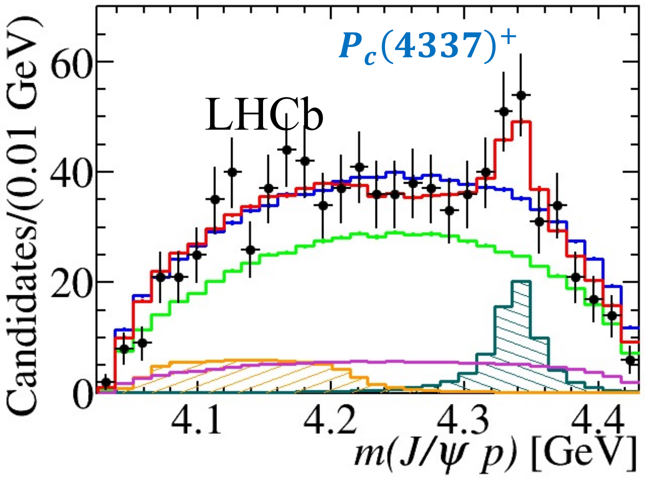
PRL 126 (2021) 102001



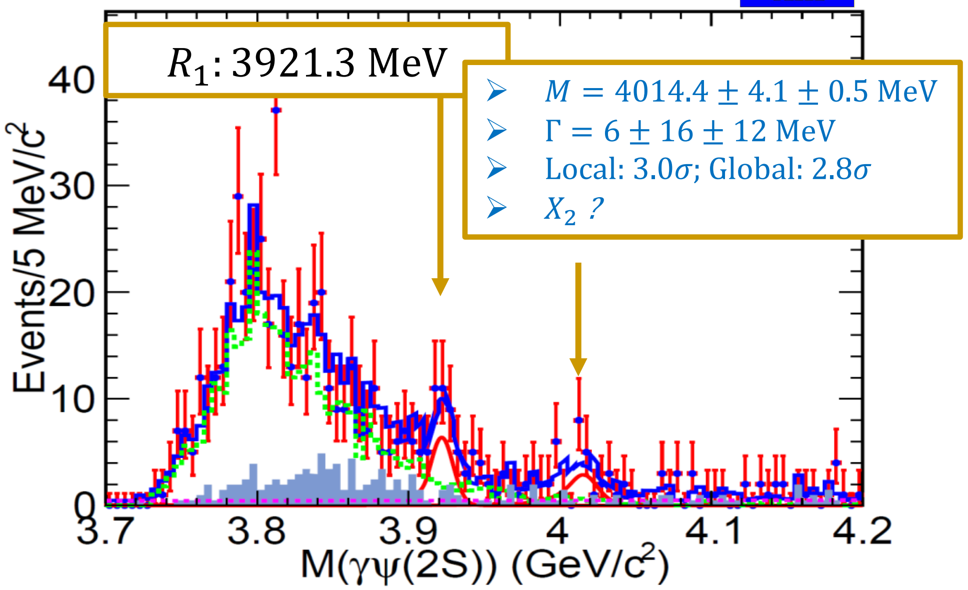
Science Bulletin 66 (2021) 1278



arXiv:2108.04720



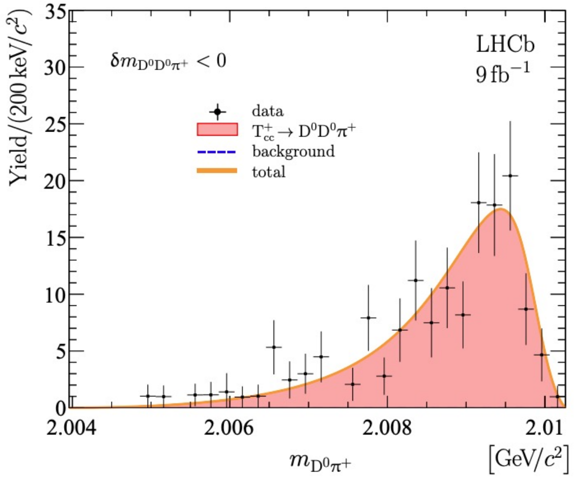
arXiv:2105.06605

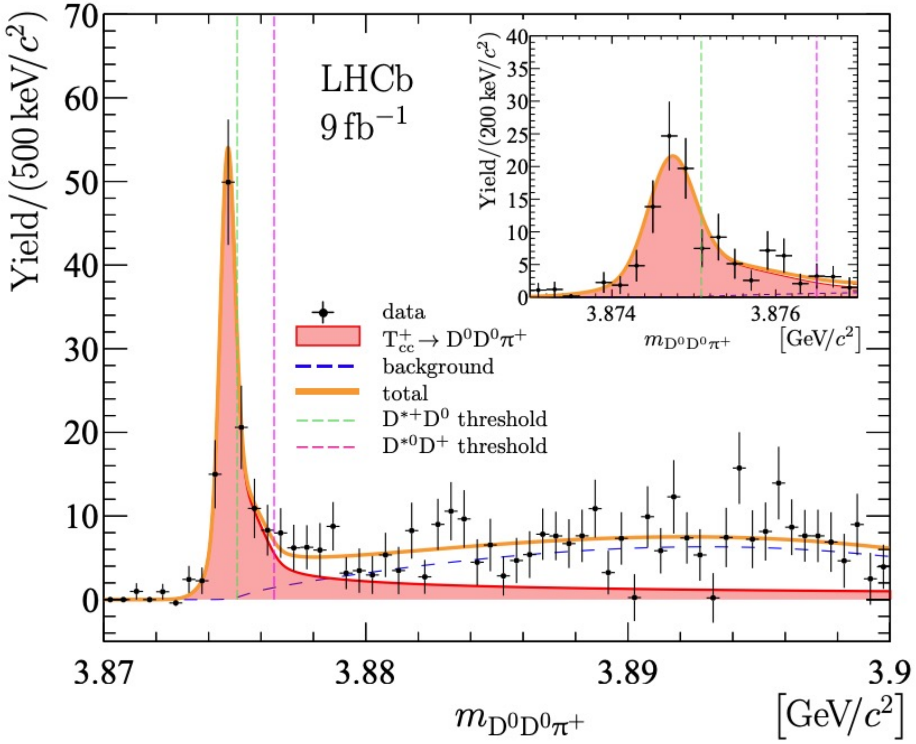


$T_{cc}^{+}\ (cc\bar{u}\bar{d})$

arXiv:2109.01056, arXiv:2109.01038

- **Significant peak in the $D^0D^0\pi^+$ mass**
  - Slightly below the $D^{*+}D^0$ threshold:
  - Consist with decay via an off-shell D^{*+}





Unitarized Breit-Wigner function (more appropriate close to threshold)

Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\ \mathrm{keV}/c^2$
$\lvert g \rvert$	$3 \times 10^4\ \mathrm{GeV}$ (fixed)

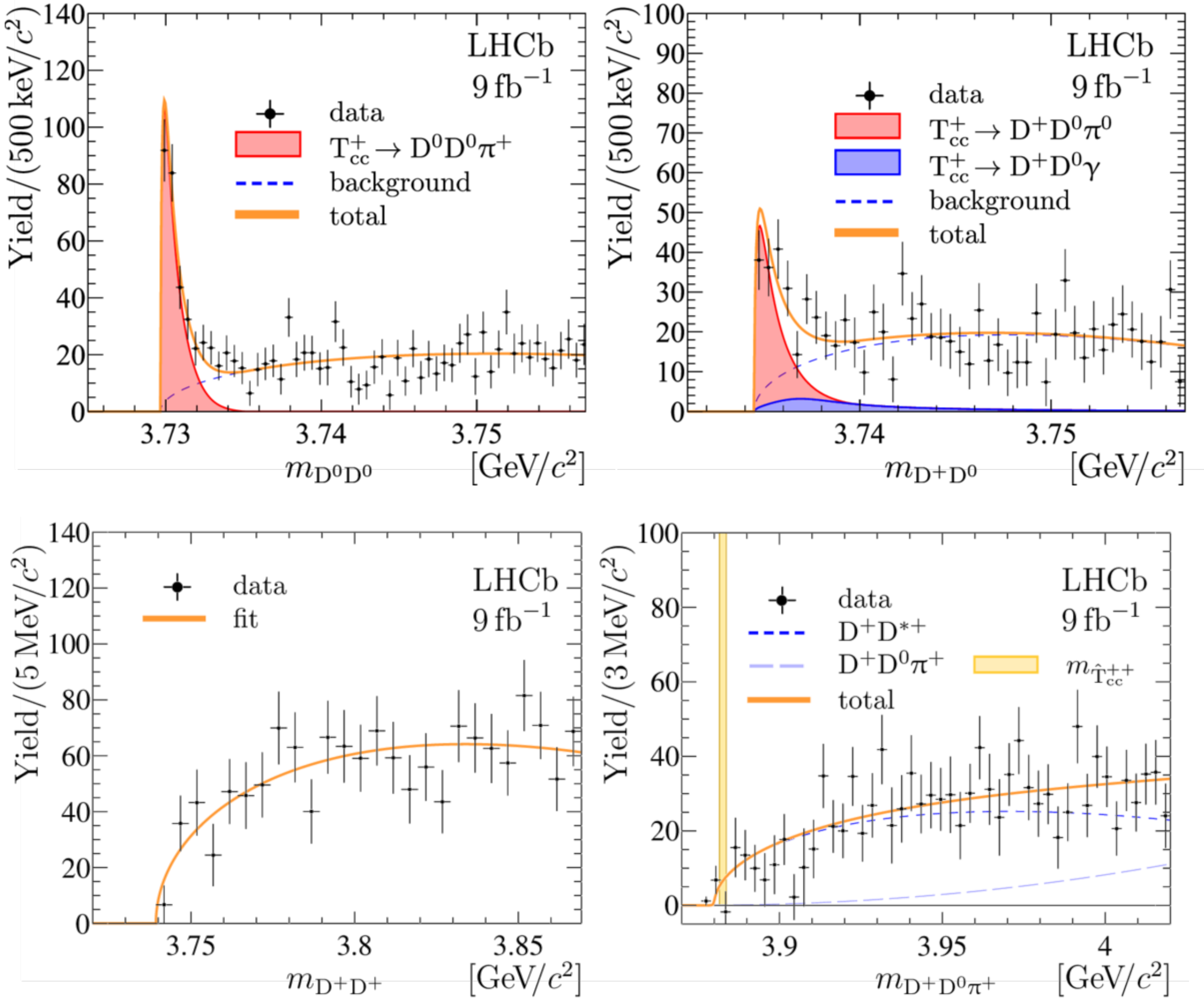
$T_{cc}^{+}\ (cc\bar{u}\bar{d})$

arXiv:2109.01056, arXiv:2109.01038

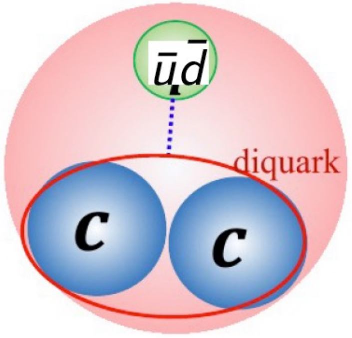
❑ Consist with $J^P = 1^+$ isoscalar

- ❑ Contribute to D^0D^0 and D^0D^+ (π/γ is missing)

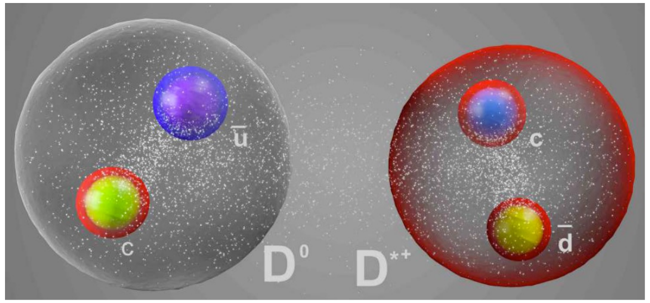
- ❑ No peaks in $D^+D^0\pi^+$ and D^+D^+
  => T_{cc}^{++} not found
  => Support that T_{cc}^{+} is an isoscalar



?



?



Answer: To find the predicted deep-bounded $bb\bar{u}\bar{d}$?

Future

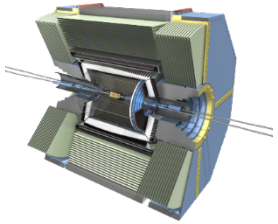
2018 2021 2025 2027 2030 2035

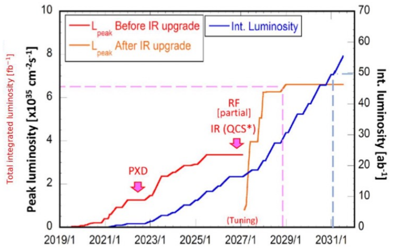
220fb^{-1}

50 ab^{-1}

Belle II

$\approx 55\times10^{9}$ $B\bar{B}$ pairs





9 fb^{-1}

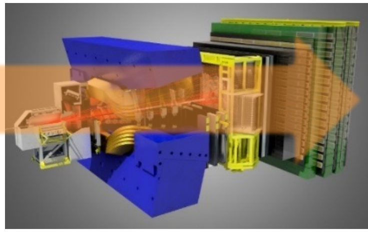
~23 fb^{-1}

~50 fb^{-1}

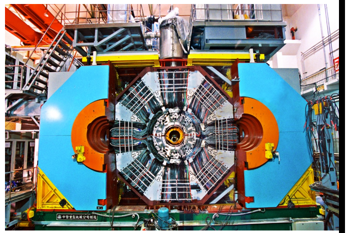
300 fb^{-1}

LHCb → **LHCb Upgrade 1** → **Phase I** (May/2022-Dec/2024) → **Phase 1b Upgrade** → **Phase 1b** → **Phase 2 Upgrade** (proposed) → **Phase 2**

$\approx 3\times10^{12}$ $b\bar{b}$ pairs



BES III



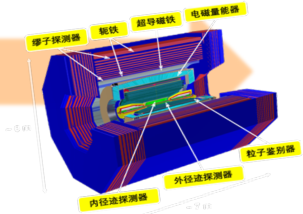
Continue to run for 5-10 years

Increase E_{cm}=> 5.6 GeV

Prepare → **Construction?** → **STCF?**

E_{cm} = 2-7 GeV

L_{peak}= 0.5~1.0 x10^{35}/cm^{2}s



Summary

- CP violation in quark sector is measured with higher precision and broadly consistent with the CKM picture
  - Hint of leptonic CP violation at T2K experiment

- A few anomalies in $b \to s\ell^+\ell^-$ transitions persist, such as hints of LFUV
  - Any connection with the anomaly in muon g-2?

- Many new type of exotic hadrons are observed, molecule vs tightly bounded?

- Exciting opportunities expected with Belle-II, BESIII and upgraded LHCb detector (50 fb^{-1}), its phase-2 upgrade (300 fb^{-1}), and ATLAS & CMS B physics programs at HL-LHC

Backup

Data taking plans at BES-III and Belle-II

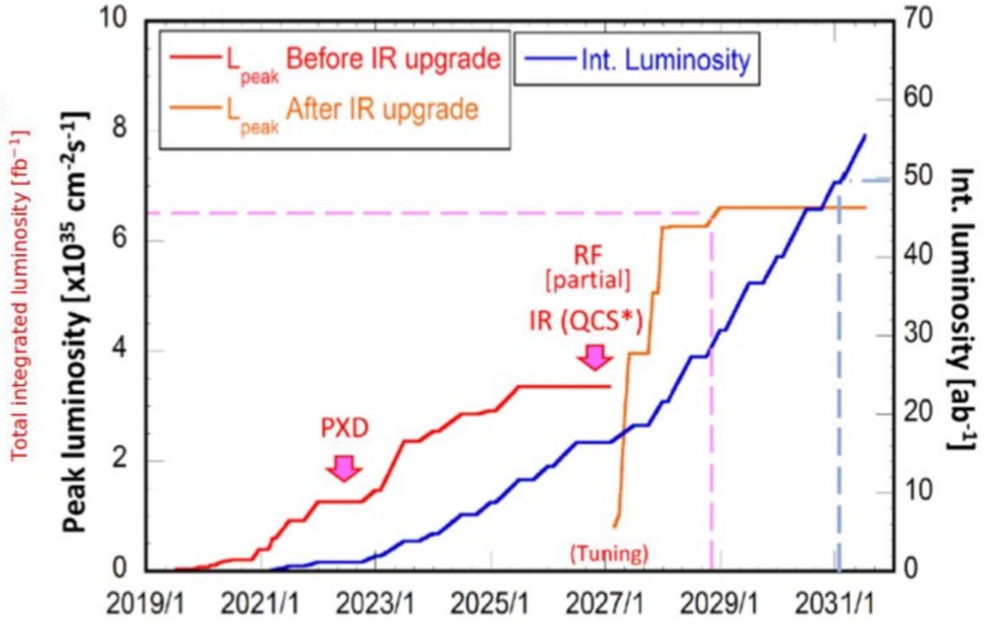
BES III

Energy	Current data	Expected final data
1.8 - 2.0 GeV	N/A	0.1 fb^{-1} (fine scan)
2.0 - 3.1 GeV	Fine scan (20 energy points)	Complete scan (additional points)
$\psi(3686)$ peak	4.0 fb^{-1}	4.5 fb^{-1} (3.0 billion)
$\psi(3770)$ peak	2.9 fb^{-1}	20.0 fb^{-1}
4.180 GeV	3.2 fb^{-1}	6 fb^{-1}
4.0 - 4.6 GeV	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$
4.6 - 4.9 GeV	6.3 fb^{-1}	15 fb^{-1} at different $\sqrt{s}$
4.74 GeV	0.15 fb^{-1}	1.0 fb^{-1}
4.91 GeV	0.2 fb^{-1}	1.0 fb^{-1}
4.95 GeV	0.15 fb^{-1}	1.0 fb^{-1}

*The blue texts indicate the newly taking data after 2019.

[See also BESIII white paper: CPC 44 (2020) 4, 040001]

Belle II

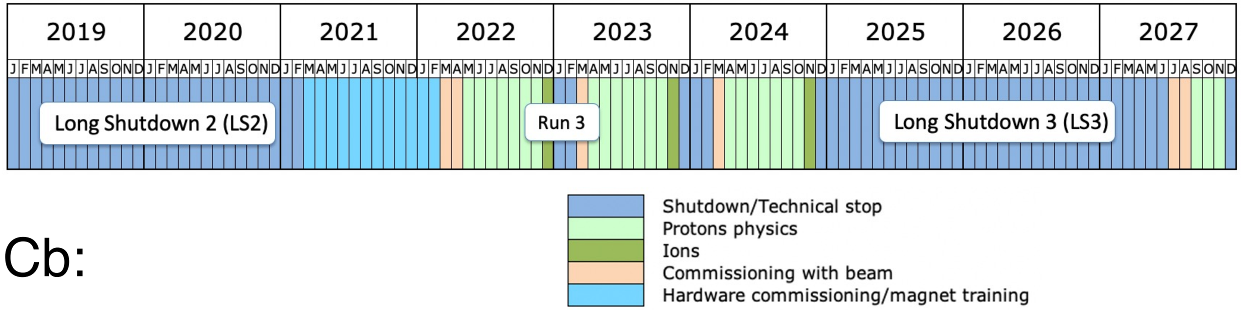


Current data (around $\Upsilon(4S)$): 220 fb^{-1}

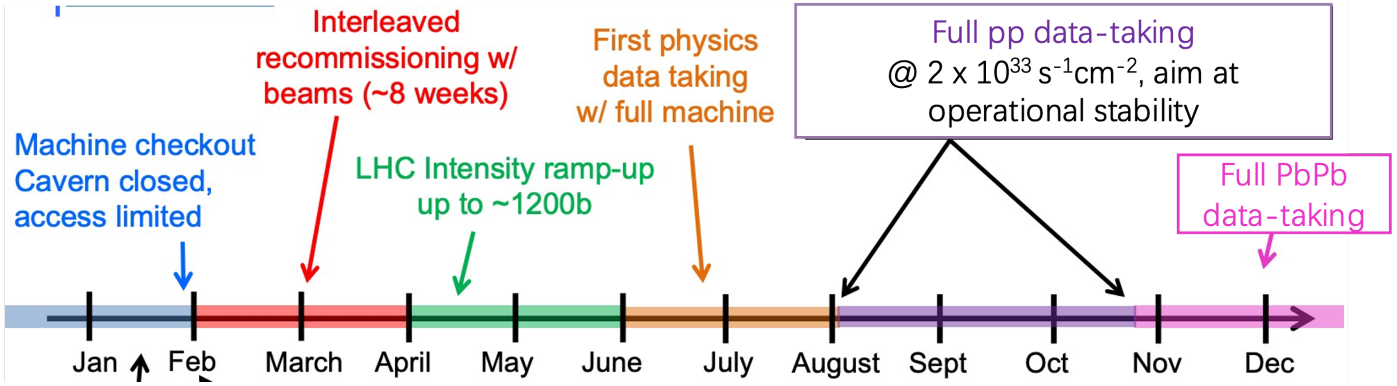
Required data: 50 ab^{-1}

LHC Run 3 data-taking plan

- LHC Run3: Recommissioning with beam @ 5th May, 2022, End @ Dec, 2024



- LHCb:
  - $\mathcal{L} = 2{\times}10^{33}\,s^{-1}cm^{-2}$
  - Full software trigger and read-out system @ 40 MHz
  - New tracking detectors
  - Data-taking plan



Best run parameters for Run3

	2022	2023	2024
Beam energy [TeV]		6.8	
Collisions at IP1/5(ATLAS/CMS) & IP2/IP8 (ALICE/LHCb)		2736/2736 & 2250/2376	
Bunch length [ns]	1.2	1.2	1.2
Bunch charge [10^{11}]	1.4	1.8	1.8
Time in pp[10^6 s]*		~ 6	
Time in PbPb [10^6 s]*		~ 1.2	
LHCb lumi* [fb^{-1}]	<10	<10	<10
CMS/ATLAS lumi* [fb^{-1}]	<70	<100	<100

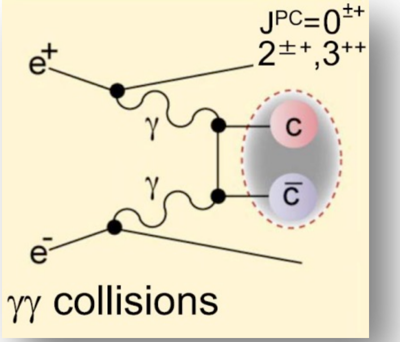
* From LHC Programme Coordination (LPC)

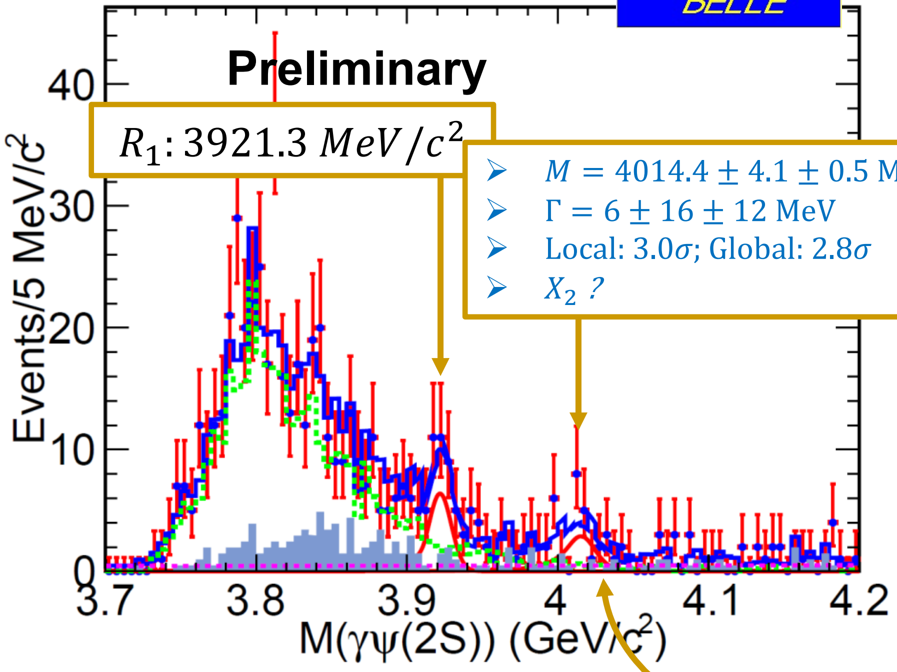
$\gamma\gamma \to \gamma\psi(2S)$ at Belle

980 fb^{-1}

- **First measurement on $\gamma\gamma\to\gamma\psi(2S)$**
- R_1 **near** $3.92\ GeV/c^2$**:** 4.0σ, **good candidate of** $X(3915)/Z(3930)$
- R_2 **near** $4.01\ GeV/c^2$**: New state!**
  - Study on look-elsewhere effect show a global significance of 2.8
  - The predicted 2^{++} partner of $X(3872)$?

Resonant parameters	$J=0$	$J=2$
M_1	$3921.3 \pm 2.4 \pm 1.6$	
Γ_1	$0.0 \pm 5.3 \pm 2.0$	
Γ_1^{UL}	11.5	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$8.2 \pm 2.3 \pm 0.9$	$1.6 \pm 0.5 \pm 0.2$
M_2	$4014.4 \pm 4.1 \pm 0.5$	
Γ_2	$6 \pm 16 \pm 12$	
Γ_2^{UL}	39.3	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$5.3 \pm 2.7 \pm 2.5$	$1.1 \pm 0.5 \pm 0.5$
$\Gamma_{\gamma\gamma}^{\text{UL}}\mathcal{B}(R_2 \to \gamma\psi(2S))$	12.8	2.6
$M_{X(3915)}$	3918.4 (fixed)	
$\Gamma_{X(3915)}$	20 (fixed)	
$\Gamma_{\gamma\gamma}\mathcal{B}(X(3915) \to \gamma\psi(2S))$	$10.9 \pm 3.1 \pm 1.2$	$2.2 \pm 0.6 \pm 0.2$
$M_{Z(3930)}$	—	3922.2 (fixed)
$\Gamma_{Z(3930)}$	—	35 (fixed)
$\Gamma_{\gamma\gamma}\mathcal{B}(Z(3930) \to \gamma\psi(2S))$	—	$2.4 \pm 0.7 \pm 0.4$





R_1: 3921.3 MeV/c^2

- $M = 4014.4 \pm 4.1 \pm 0.5\ \text{MeV}/c^2$
- $\Gamma = 6 \pm 16 \pm 12$ MeV
- Local: 3.0σ; Global: 2.8σ
- X_2 ?

F.K. Guo, PRD88, 054007 (2013)

V_C	$I(J^{PC})$	States	Thresholds	Masses ($\Lambda = 0.5$ GeV)	Masses ($\Lambda = 1$ GeV)	Measurements
C_{0X}	$0(1^{++})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$	3875.87	3871.68 (input)	3871.68 (input)	3871.68 ± 0.17 [34]
	$0(2^{++})$	$D^*\bar{D}^*$	4017.3	4012^{+4}_{-5}	4012^{+5}_{-12}	?

X.L. Wang, B.S. Gao, W.J. Zhu, et al., Belle Collaboration, arXiv:2105.06605

$K\pi$ puzzle confirmed

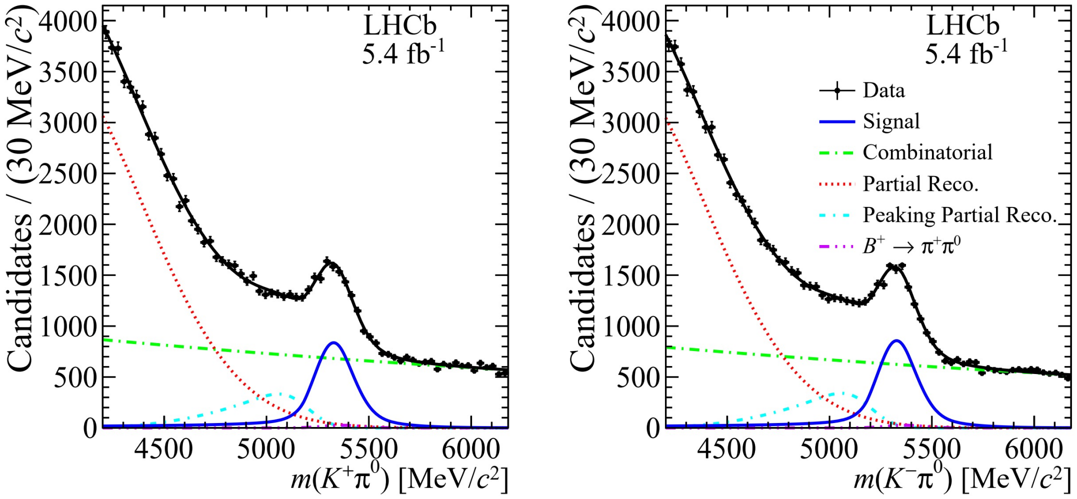
PRL 126 (2021) 091802

- **Anomaly in CP asymmetries of $B \to K\pi$ decays**

  $\Delta A_{\mathrm{CP}}(K\pi) = A_{\mathrm{CP}}(K^+\pi^0) - A_{\mathrm{CP}}(K^+\pi^-) \approx 0.124 \pm 0.021$

  $\Delta A_{\mathrm{CP}}(K\pi) \approx 0$ expected based on isospin symmetry. 5.5σ discrepancy!

- **Most precise $A_{CP}(K^+\pi^0)$ with LHCb Run2 data**



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

WA: $A_{\mathrm{CP}}(K^+\pi^0) = 0.040 \pm 0.021$ ➡ $A_{\mathrm{CP}}(K^+\pi^0) = 0.031 \pm 0.013$

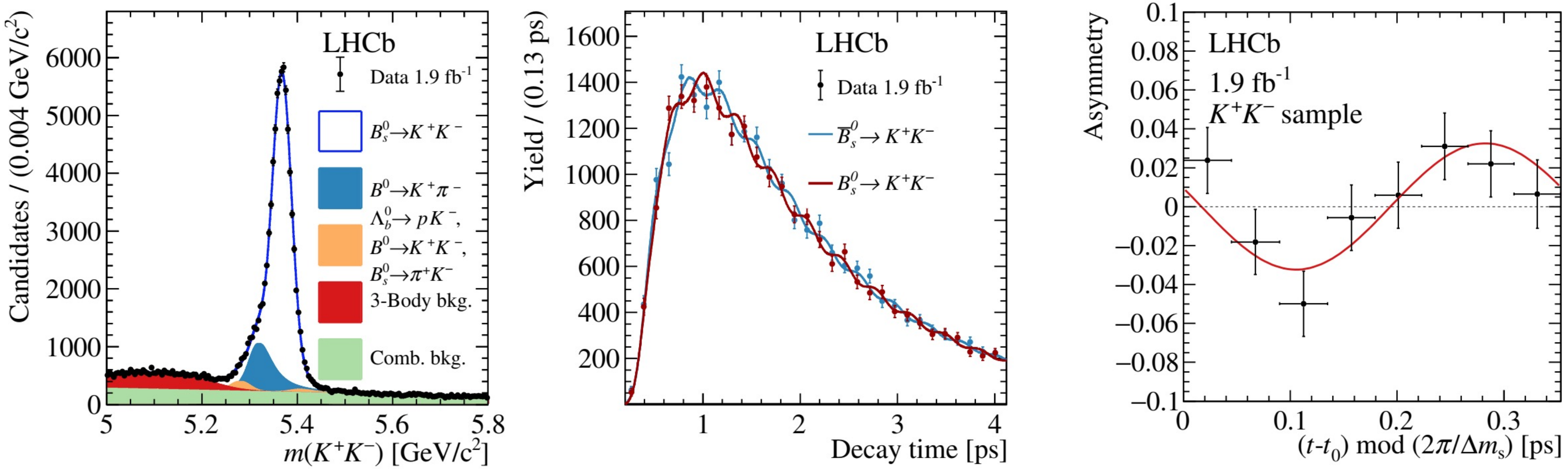
$\boldsymbol{\Delta A_{CP}(K\pi) = 0.115 \pm 0.014}$ **(8σ from zero)**

CPV in $B_s^0 \to K^+K^-$

JHEP 03 (2021) 075

- Flavour-tagged time-dependent analysis with 2015+2016 data

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_s^0\to f}(t) - \Gamma_{B_s^0\to f}(t)}{\Gamma_{\bar{B}_s^0\to f}(t) + \Gamma_{B_s^0\to f}(t)} = \frac{-C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$



$S_{KK} = 0.123 \pm 0.034 \pm 0.015$

$C_{KK} = 0.164 \pm 0.034 \pm 0.014$

$A_{KK}^{\Delta} = -0.83 \pm 0.05 \pm 0.09$

First observation of time-dependent CP violation in B_s^0 decays!

$B_s^0 \to \phi\mu^+\mu^-$ angular analysis

arXiv:2107.13428

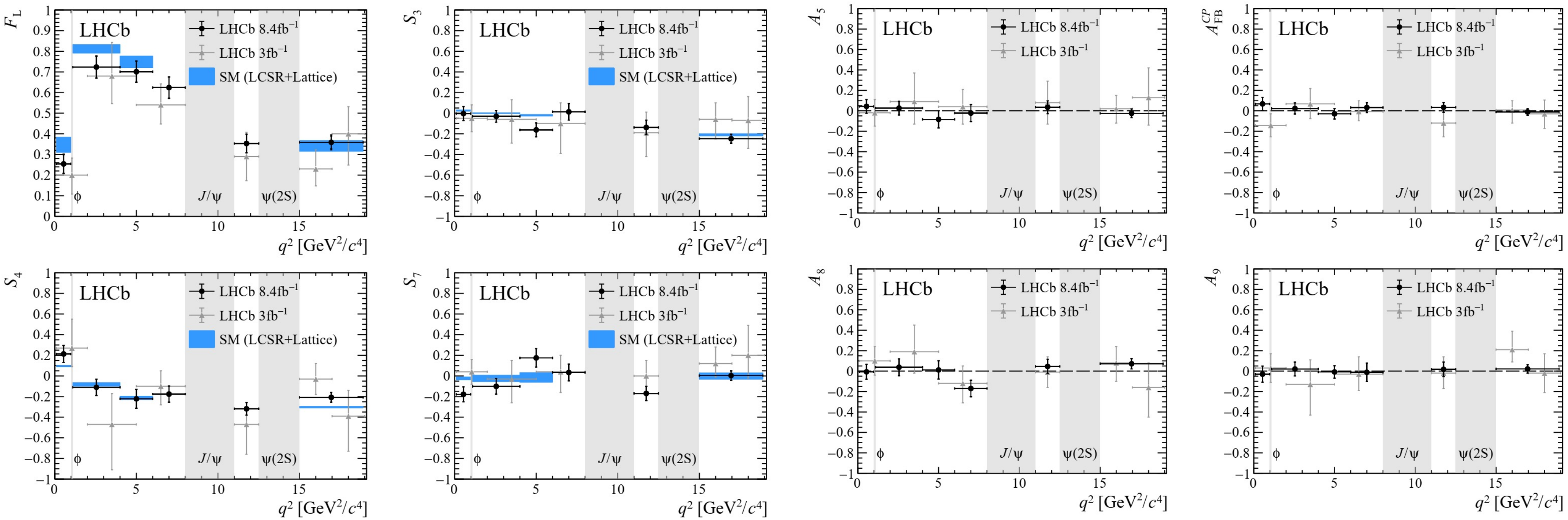
- **Untagged angular observables**

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K(1+\tfrac{1}{3}\cos 2\theta_l) + F_{\mathrm{L}}\cos^2\theta_K(1-\cos 2\theta_l) + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + A_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{\mathrm{FB}}^{CP}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\phi + A_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big],$$

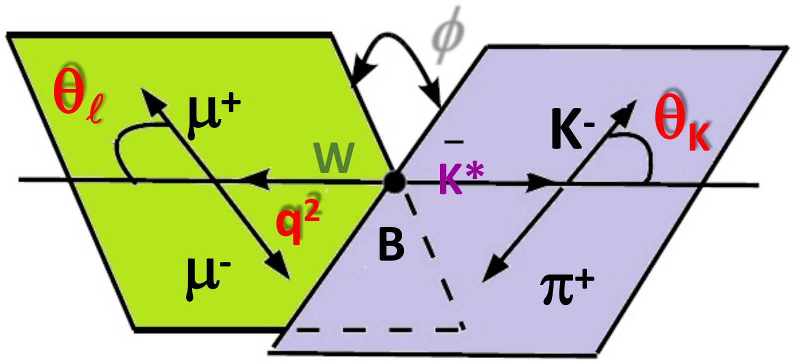
- **Results in general consistent with SM expectations**

CP average: F_L, S_3, S_4, S_7

CP asymmetries: $A_{FB}^{CP}, A_5, A_8, A_9$



Angular analysis: $B^0 \to K^{*0}\mu^+\mu^-$



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

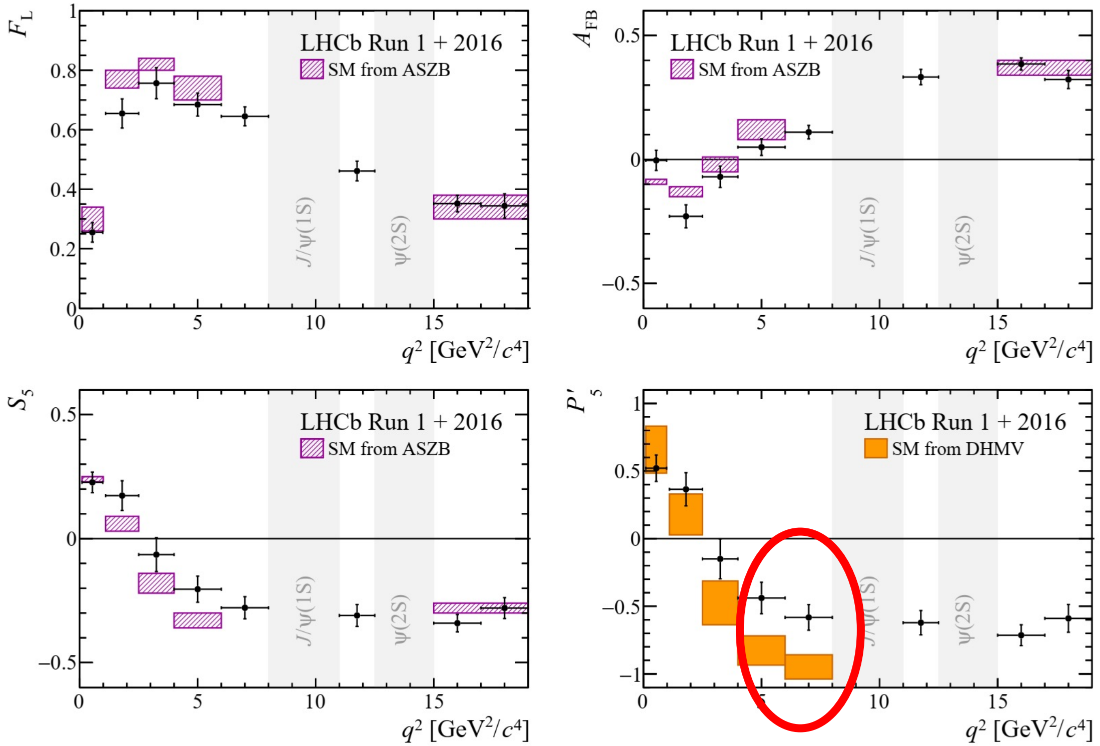
- **8 independent CP-averaged observables: F_L, A_{FB}, $S_{3,4,5,7,8,9}$**
- **Form factors cancel at leading order: $P'_i = S_i/\sqrt{F_L(1-F_L)}$**

Update on $B^0 \to K^{*0}\mu^+\mu^-$

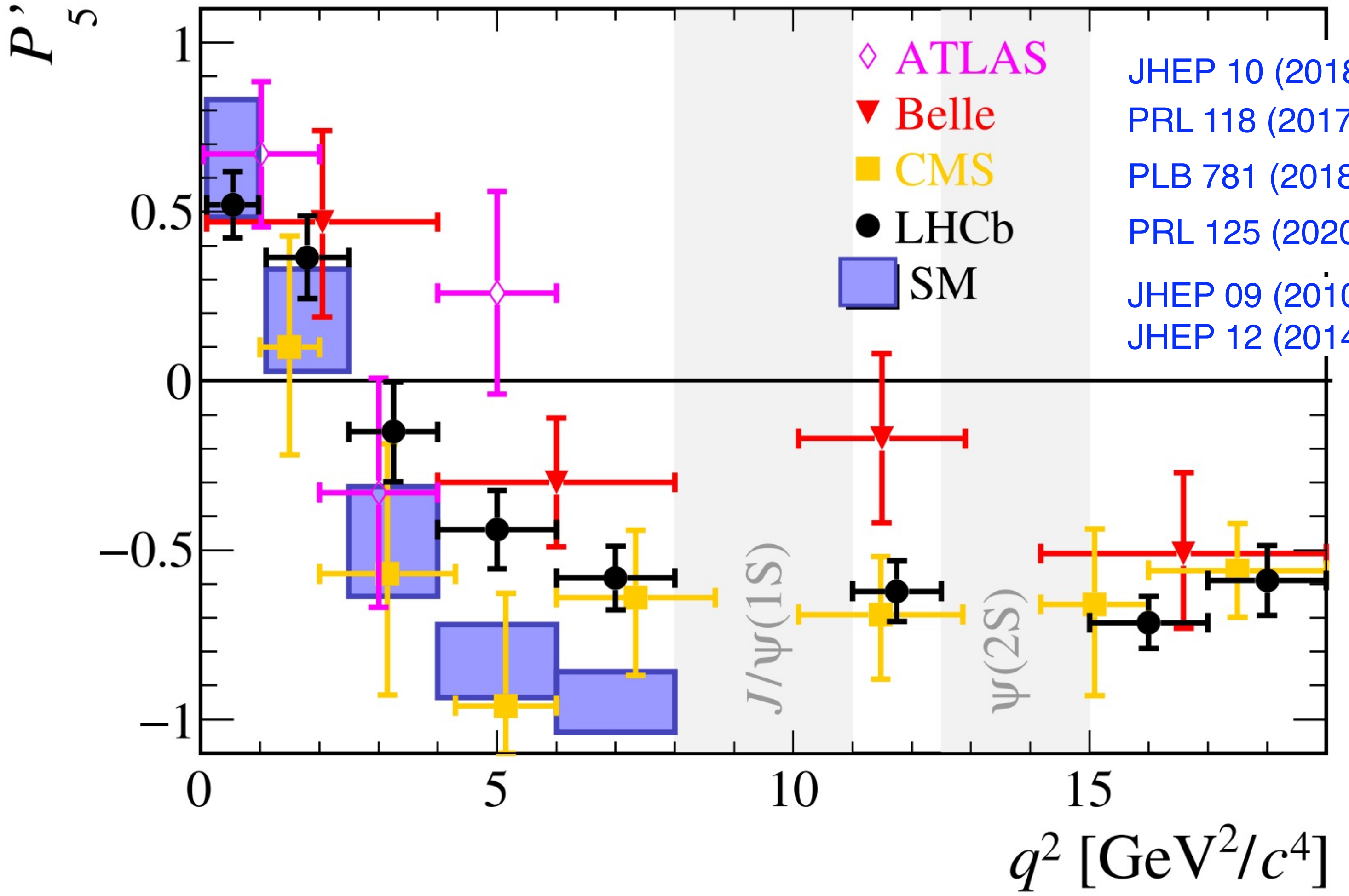
PRL 125 (2020) 011802

- Tension of P_5' with SM seen in Run 1 result persists with new data

	Run 1	Run1+2016
$4.0 < q^2 < 6.0\ \mathrm{GeV}^2$	2.8σ	2.5σ
$6.0 < q^2 < 8.0\ \mathrm{GeV}^2$	3.0σ	2.9σ



P'_5 comparison



JHEP 10 (2018) 047
PRL 118 (2017) 111801
PLB 781 (2018) 517
PRL 125 (2020) 011802
JHEP 09 (2010) 089
JHEP 12 (2014) 125

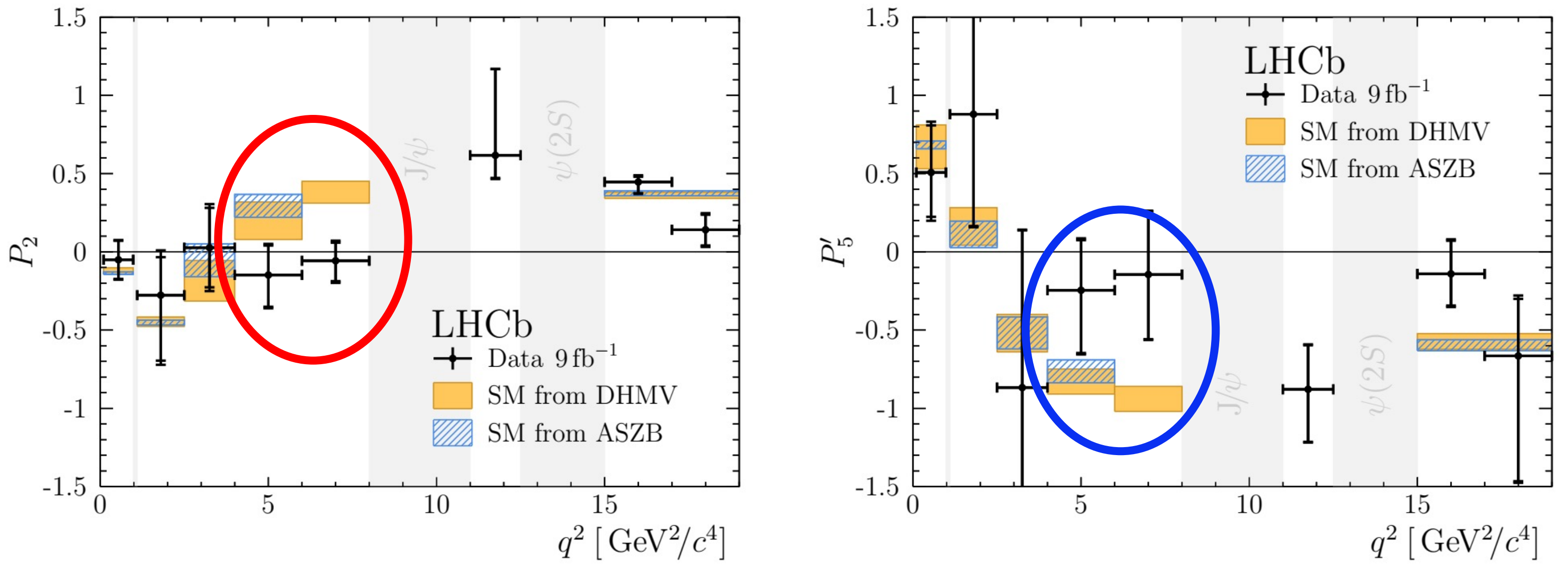
$B^+ \to K^{*+}\mu^+\mu^-$

PRL 126 (2021) 161802

- First analysis of $B^+ \to K^{*+}\mu^+\mu^-$ using full Run1+Run2 sample

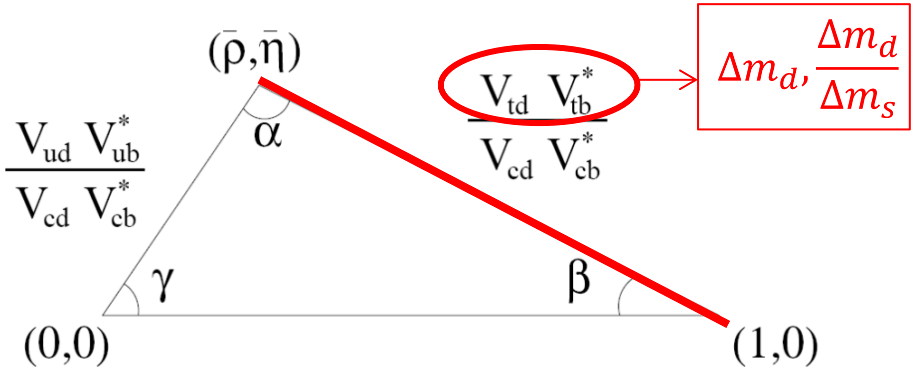
  P'_5: pattern consistent with that seen in $B^0 \to K^{*0}\mu^+\mu^-$

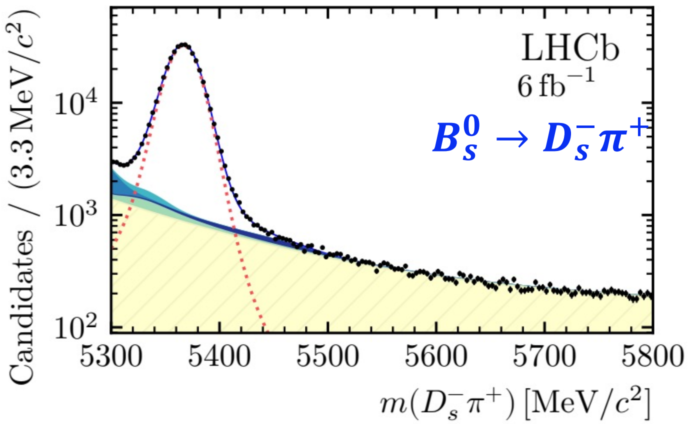
  $P_2 = \frac{2}{3}A_{FB}/(1 - F_L)$: tension of 3.0σ with SM in $6.0 < q^2 < 8.0\ \mathrm{GeV}^2$



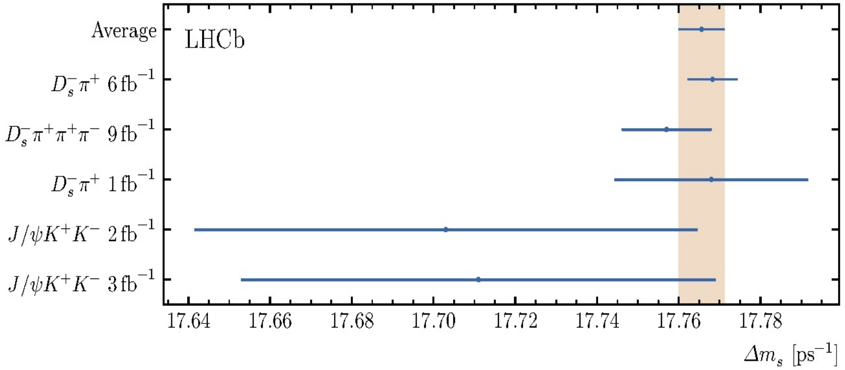
Improvement on Δm_s

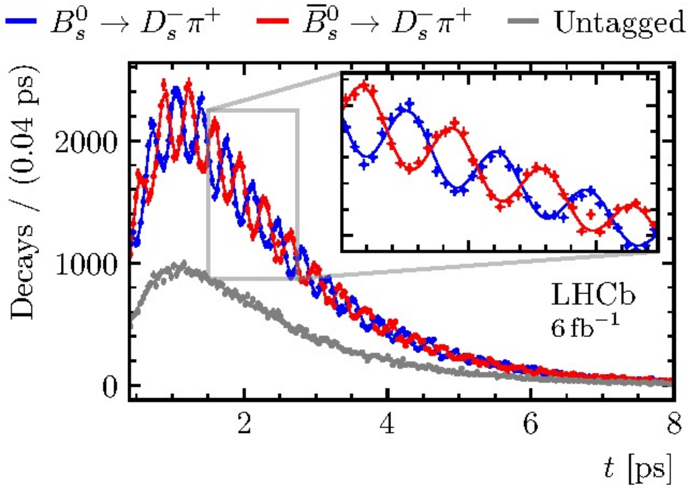
arXiv:2104.04421





- **Run2 analysis of $B_s^0 \to D_s^- \pi^+$**
- **LHCb combination**





$$\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}$$

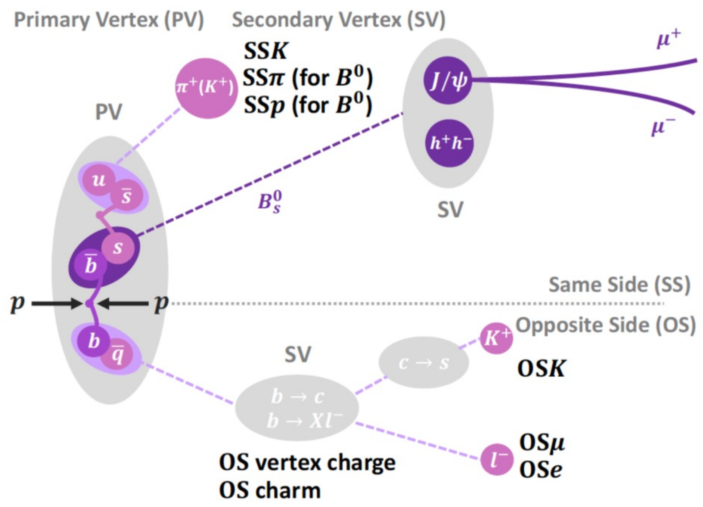
SM prediction: $\Delta m_s = 18.4^{+0.7}_{-1.2} \text{ ps}^{-1}$

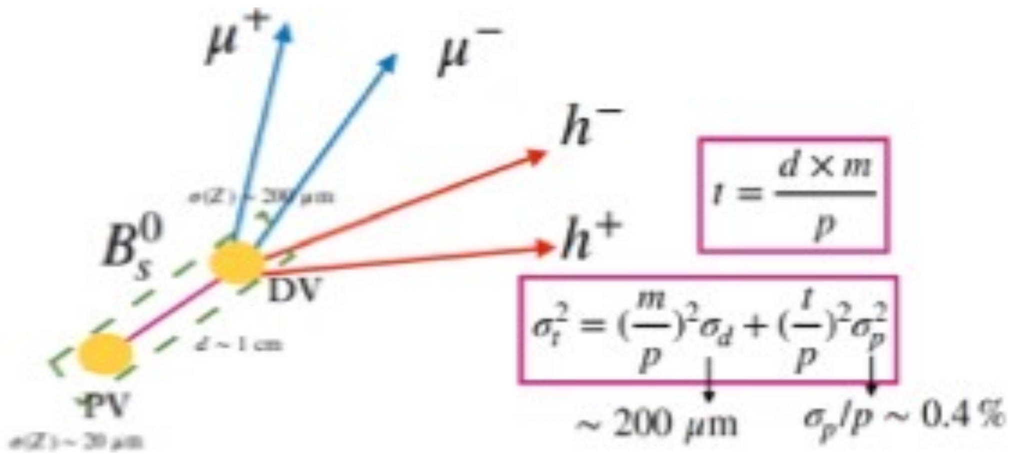
$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \cos(\Delta m_s t)\right]$$

Luzio, Kirk, Lenz, JHEP 12 (2019) 009

Time-dependent flavour tagged analysis

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_s{}^0 \to f}(t) - \Gamma_{B_s{}^0 \to f}(t)}{\Gamma_{\bar{B}_s{}^0 \to f}(t) + \Gamma_{B_s{}^0 \to f}(t)} \approx -\eta_f \sin\phi_s \sin(\Delta m_s t)$$



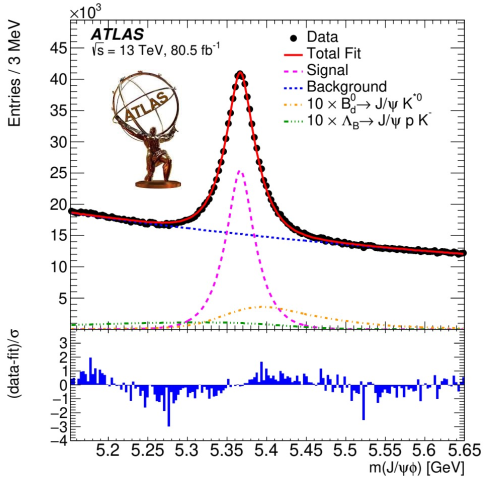


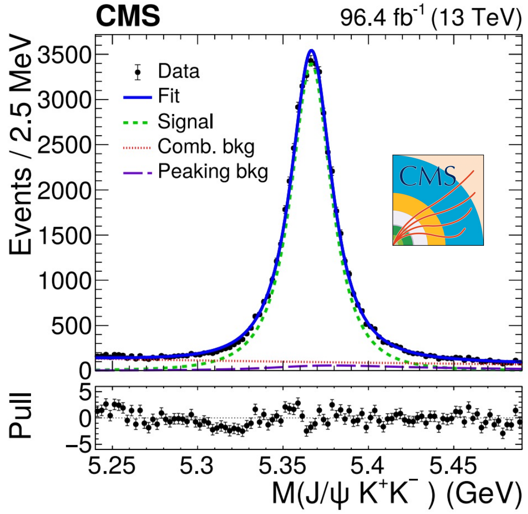
	N(signal)	Luminosity (fb^{-1})	tagging power	σ_t	features
ATLAS	453 570	80.5	1.75%	70 fs	new Inner B-Layers improve σ_t
CMS	48500	96.4	~10% (in muon tagger)	75 fs	new DNN OS muon tagger
LHCb	117 000	1.9	4.73%	45 fs	excellent K/π separation & vertex reconstruction

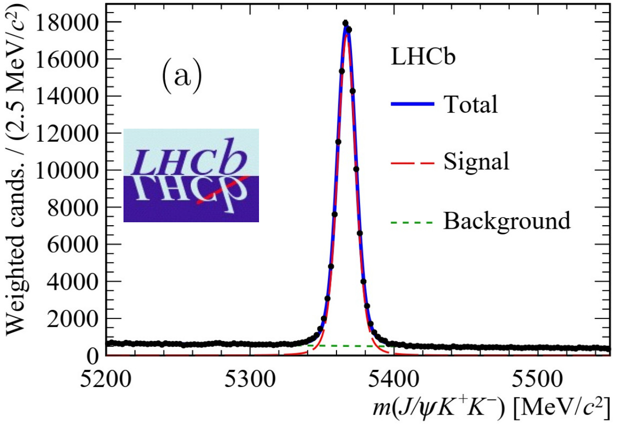
$B_s^0 \to J/\psi\phi$ analyses

LHCb, EPJC 80 (2020) 601
ATLAS, EPJC 81 (2021) 342
CMS, PLB 816 (2021) 136188

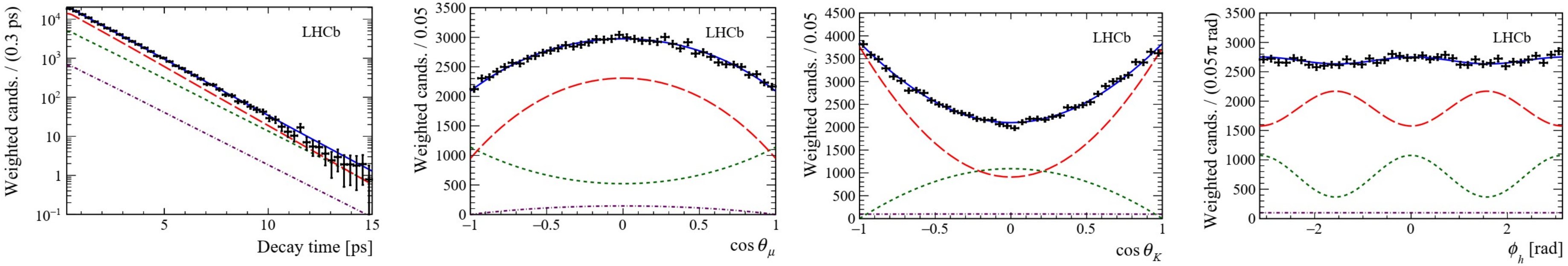
- **Signal reconstruction & selection**







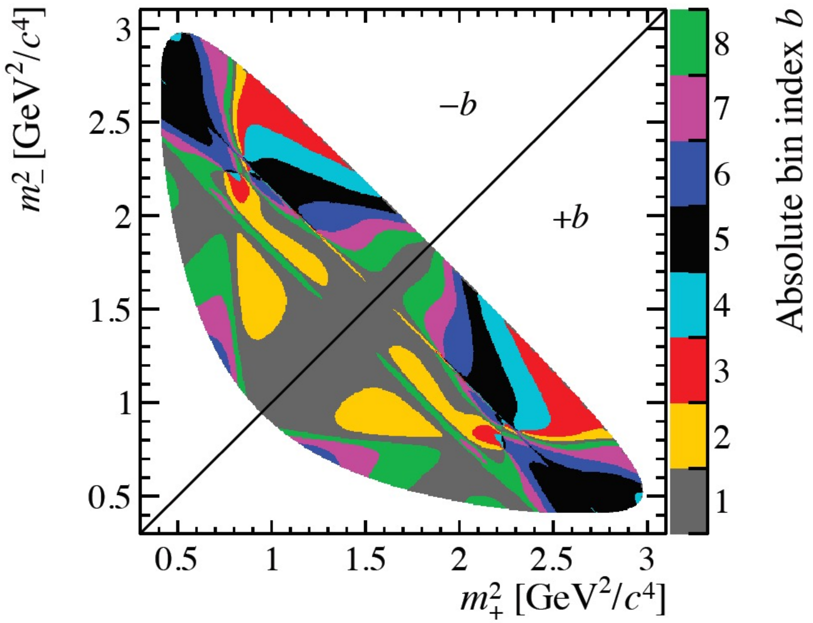
- **Tagged 4-dimensional time-angular fit**



Bin-Flip

PRD 99, 012007 (2019)

- **"Bin-Flip" method: time-dependent yield ratio between –b and b bin**
  - Most detector effects cancel
  - Fix $\boldsymbol{X_b = (C_b, S_b)}$ parameters from CLEO+BES results

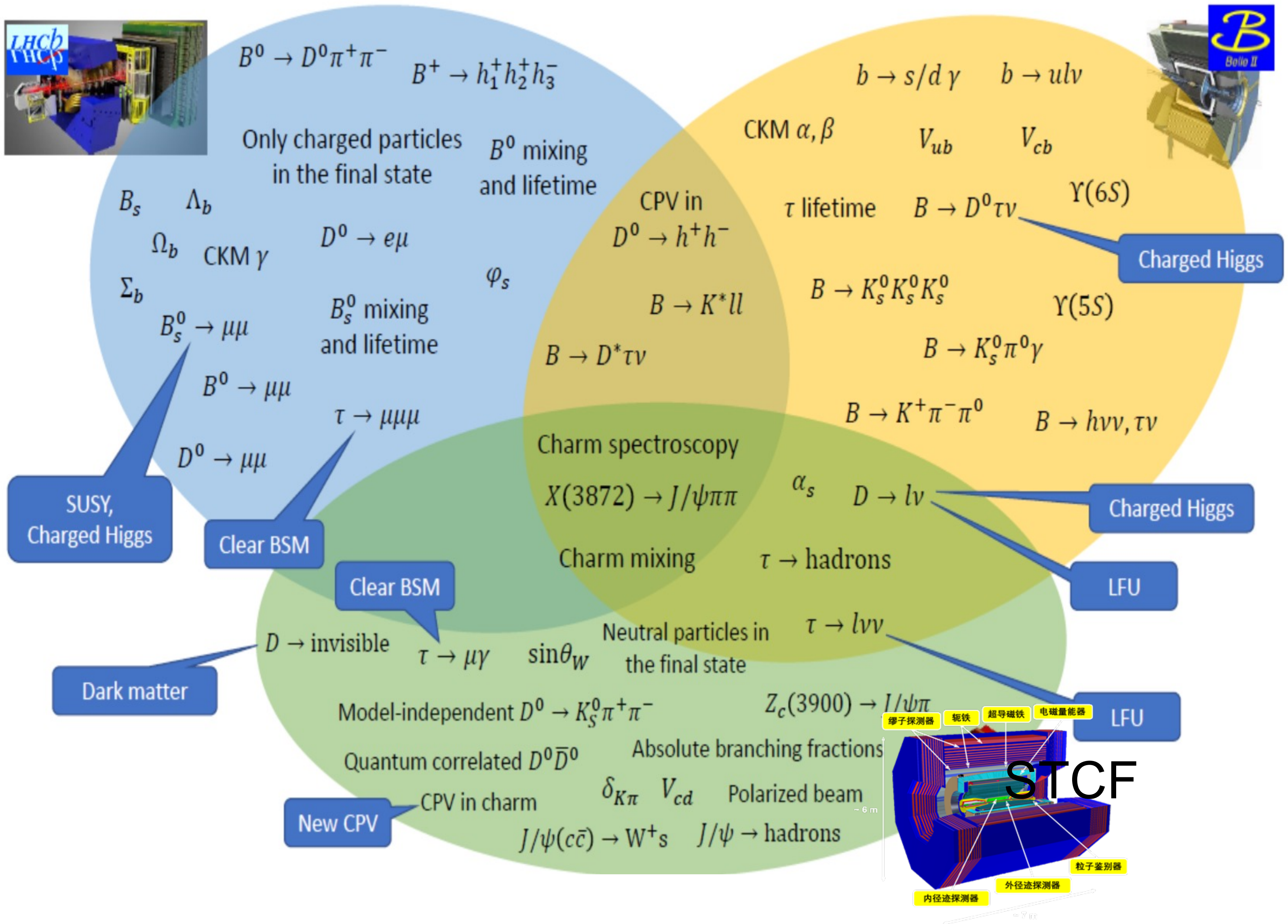


$$R_{bj}^{\pm} \approx \frac{r_b + r_b\frac{\langle t^2\rangle_j}{4}\mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2\rangle_j}{4}|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \mathrm{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{\langle t^2\rangle_j}{4}\mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b\frac{\langle t^2\rangle_j}{4}|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \mathrm{Re}[X_b(z_{CP} \pm \Delta z)]}.$$

Fit parameters:
4 mixing+CPV + r_b

$\boldsymbol{z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)}$
$\boldsymbol{x_{CP} \equiv -\mathrm{Im}(z_{CP})}$
$\boldsymbol{y_{CP} \equiv -\mathrm{Re}(z_{CP})}$
$\boldsymbol{\Delta x \equiv -Im(\Delta z)}$
$\boldsymbol{\Delta y \equiv -\mathrm{Re}(\Delta z)}$
If CP-conservation, q/p=1
$\boldsymbol{\Delta x = \Delta y = \Delta z = 0}$
$\boldsymbol{x_{CP} = x \;\; y_{CP} = y}$

互补与协同



LHCb
$B^0 \to D^0\pi^+\pi^-$
$B^+ \to h_1^+h_2^+h_3^-$
Only charged particles in the final state
B^0 mixing and lifetime
B_s
Λ_b
Ω_b
CKM γ
$D^0 \to e\mu$
φ_s
Σ_b
$B_s^0 \to \mu\mu$
B_s^0 mixing and lifetime
$B^0 \to \mu\mu$
$\tau \to \mu\mu\mu$
$D^0 \to \mu\mu$
SUSY, Charged Higgs
Clear BSM
Belle II
$b \to s/d\,\gamma$
$b \to ul\nu$
CKM α, β
V_{ub}
V_{cb}
τ lifetime
$B \to D^0\tau\nu$
$\Upsilon(6S)$
Charged Higgs
CPV in $D^0 \to h^+h^-$
$B \to K^*ll$
$B \to K_S^0K_S^0K_S^0$
$\Upsilon(5S)$
$B \to K_S^0\pi^0\gamma$
$B \to D^*\tau\nu$
$B \to K^+\pi^-\pi^0$
$B \to h\nu\nu, \tau\nu$
Charm spectroscopy
$X(3872) \to J/\psi\pi\pi$
α_s
$D \to l\nu$
Charged Higgs
Charm mixing
$\tau \to$ hadrons
LFU
Clear BSM
$D \to$ invisible
$\tau \to \mu\gamma$
$\sin\theta_W$
Neutral particles in the final state
$\tau \to l\nu\nu$
Dark matter
LFU
Model-independent $D^0 \to K_S^0\pi^+\pi^-$
$Z_c(3900) \to J/\psi\pi$
Quantum correlated $D^0\bar{D}^0$
Absolute branching fractions
New CPV
CPV in charm
$\delta_{K\pi}$
V_{cd}
Polarized beam
$J/\psi(c\bar{c}) \to W^+s$
$J/\psi \to$ hadrons
缪子探测器
轭铁
超导磁铁
电磁量能器
STCF
粒子鉴别器
外径迹探测器
内径迹探测器