Recent results of LHCb

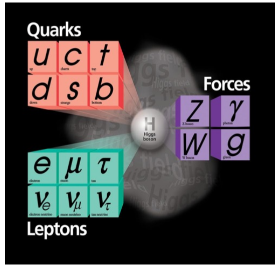
张艳席
北京大学

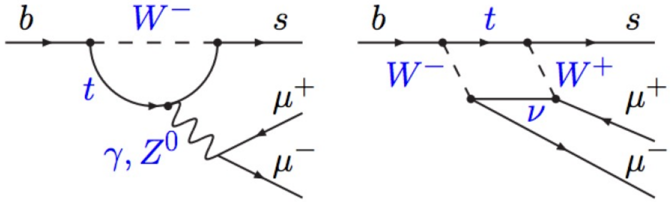
超级陶粲装置研讨会

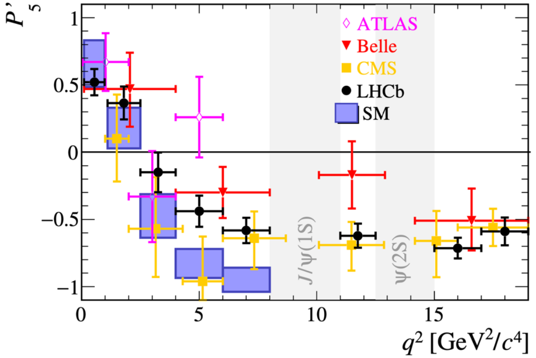
兰州大学，2024年7月

Outline

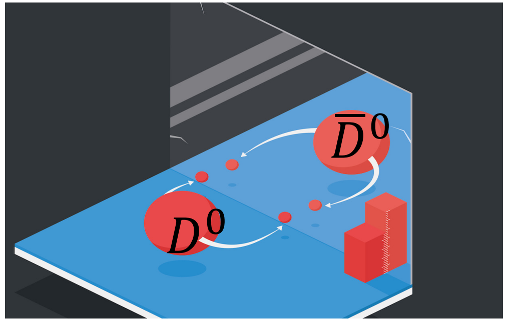
- LHCb and introduction
- Flavor anomalies
- CKM matrix
- Charm physics
- Hadron spectroscopy
- Summary

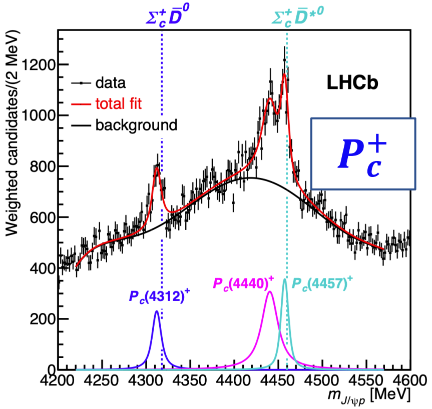






$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





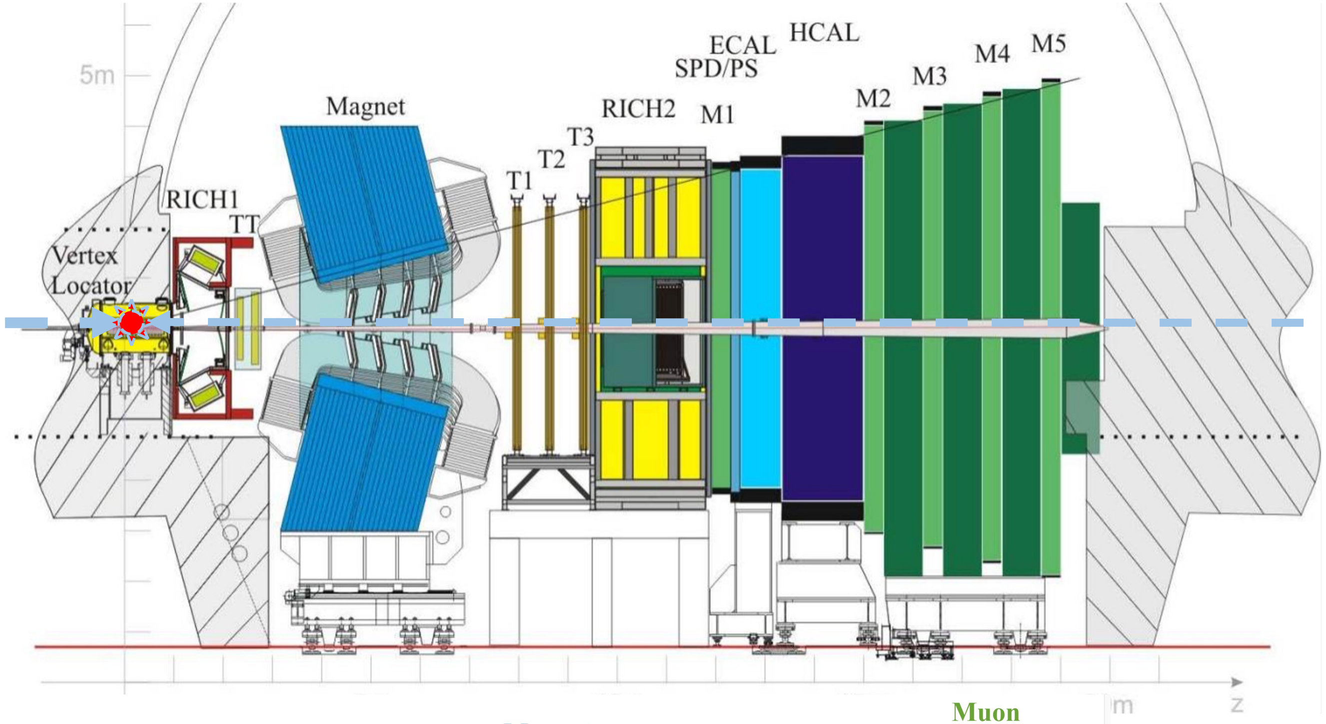
LHCb

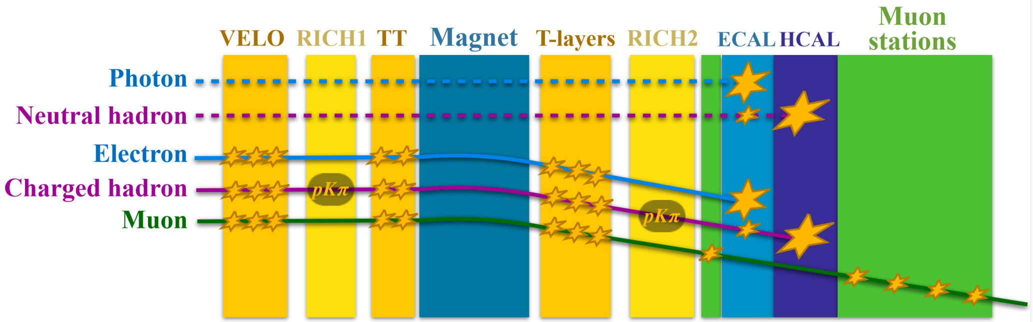
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Dedicated flavor experiment at CERN for b, c hadrons
- pp collisions at $\sqrt{s} = 7,\ 8, 13, 13.6$TeV, $\int \mathcal{L} = 10\ \text{fb}^{-1}$

$\sigma(b\bar{b}, 13\ \text{TeV}) \approx 0.5\ \mu\text{b}$

$\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$





- ✓ Excellent vertexing

  $\sigma_\tau \sim 45$ fs
- ✓ Hadron PID

  $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- ✓ Precise momentum measurement

  $\delta m_{B\to K\pi}/m_B \sim 0.005$

Flavor physics experiment

- Precise studies of SM flavor structure

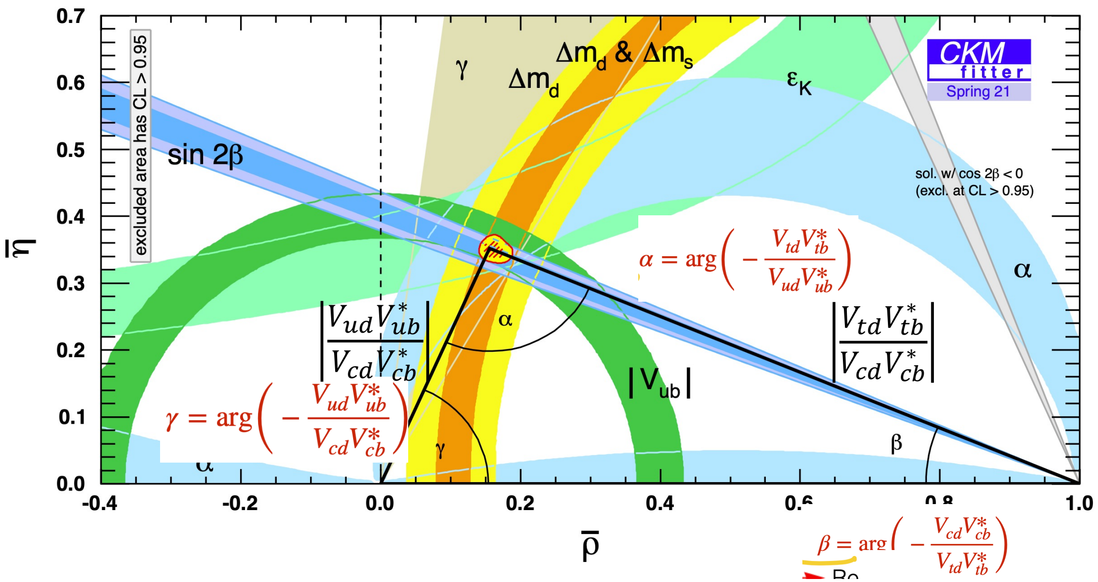
  Quark mixing matrix (CKM matrix)

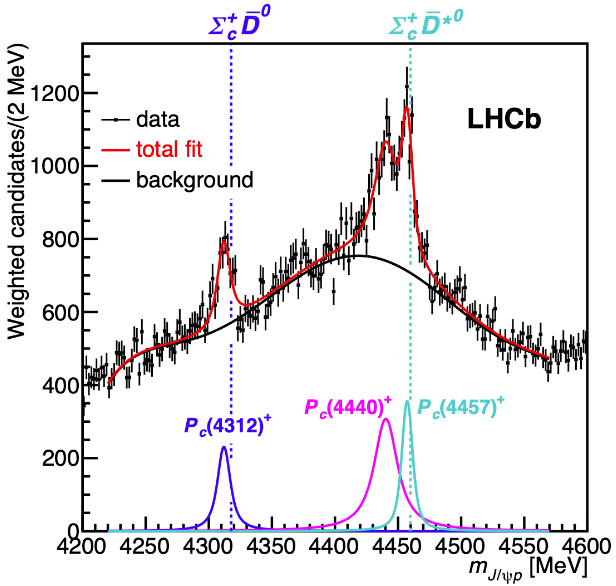
$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

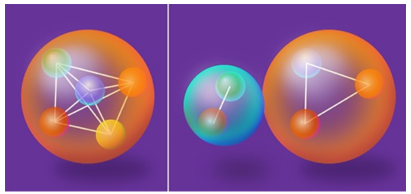
- Probe new physics through rare decay, FCNC, CP violation, CKM test

  Complementary to direct detection, possible to probe energy scales beyond collider energy

- Hadron physics

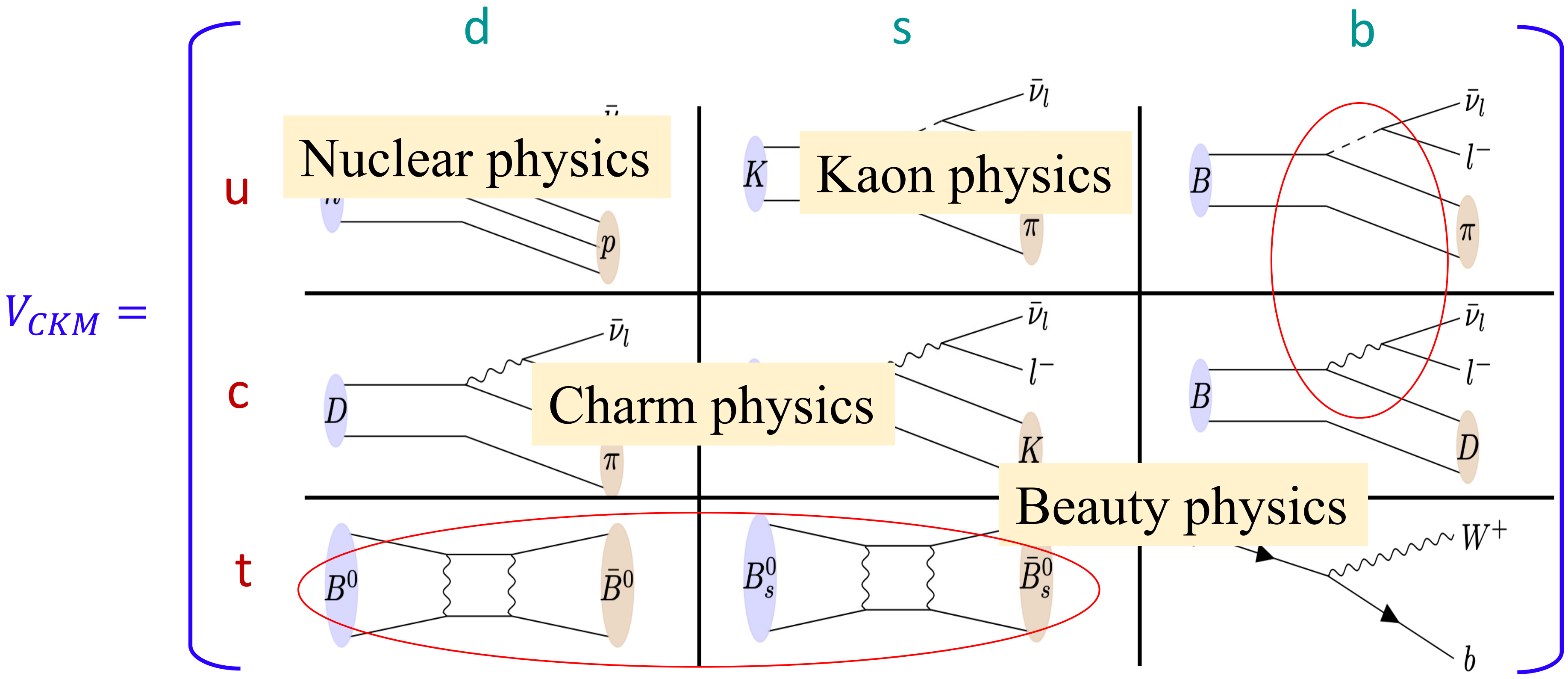






Measurements of CKM matrix

Quark mixing matrix



Complementarity between beauty and charm factories

CKM matrix parameterization

CP violation phase

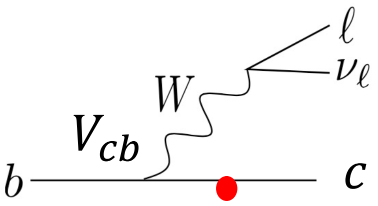
$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Standard parameterization: $\theta_{12}, \theta_{13}, \theta_{23}, \delta$, unitarity ensured

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterization: ρ, η, λ, A

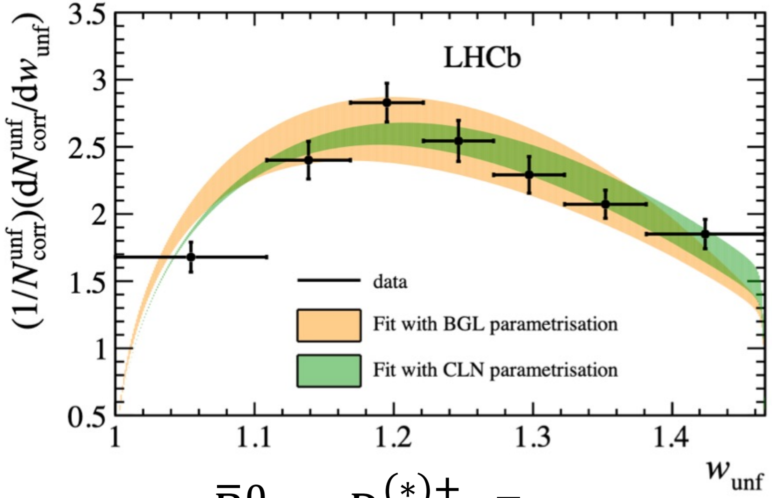
$|V_{cb}|$ at LHC



- $|V_{cb}| = A\lambda^2 \sim 4\times10^{-2}$, measured in $b \to c\mu\nu_\mu$ decays
- Measured by LHCb with $B \to D^{(*)}\mu\nu_\mu$, $\Lambda_b^0 \to \Lambda_c^+\mu^-\nu_\mu$ and $\bar{B}_s^0 \to D_s^{(*)+}\mu^-\nu_\mu$ decays
- Measuring decay rate, require external inputs of form factors (or parameterizations)

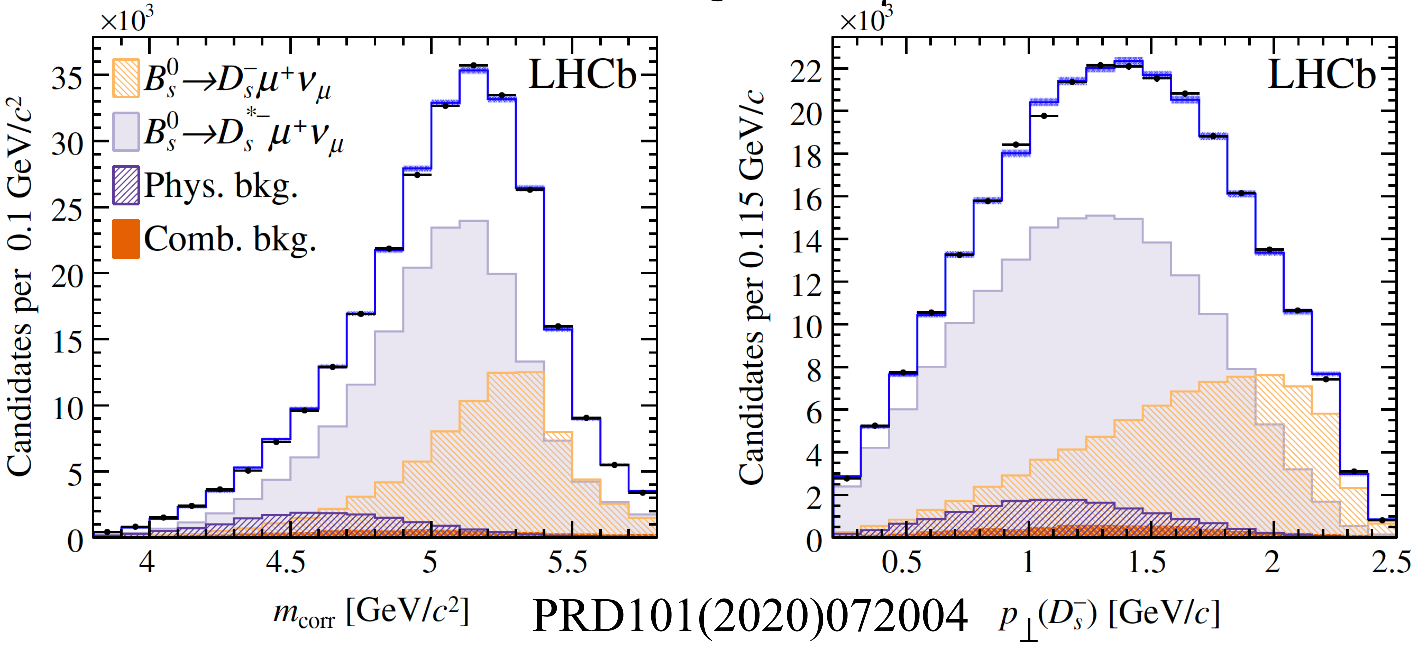
$$\frac{d^4\Gamma(B \to D^*\mu\nu)}{dw\,d\cos\theta_\mu\,d\cos\theta_D\,d\chi} = \frac{3m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4}\eta_{EW}^2 |V_{cb}|^2 |\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2$$

BGL, Phy.Rev.Lett.74(1995)4603
CLN, Nucl.Phys.B53(1998)0153



$\bar{B}_s^0 \to D_s^{(*)+}\mu^-\nu_\mu$

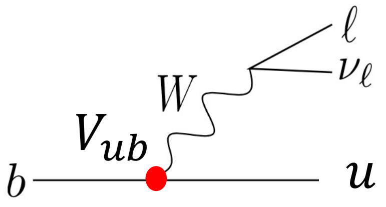
$\bar{B}_s^0 \to D_s^{(*)+}\mu^-\nu_\mu$



PRD101(2020)072004

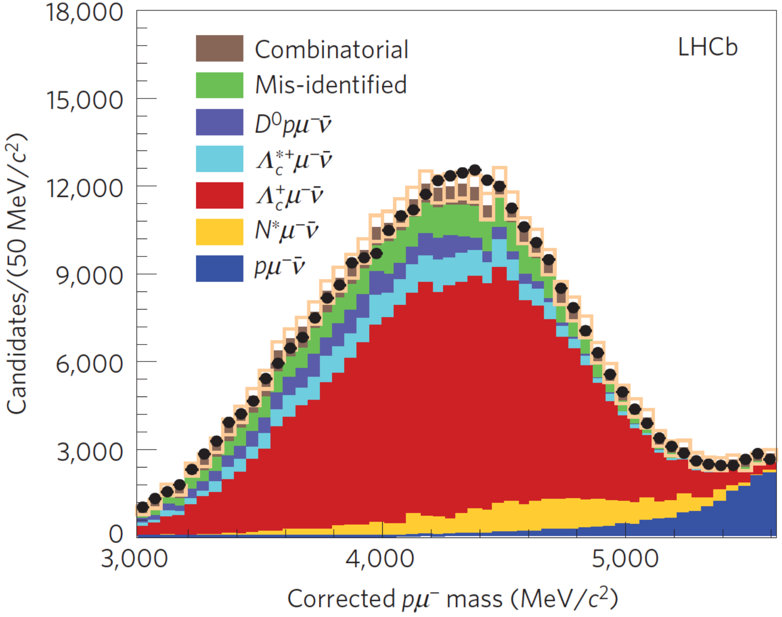
$|V_{ub}|$ at LHC

- $|V_{ub}| = |A\lambda^3(\rho - i\eta)| \sim 4{\times}10^{-3}$, related to four CKM parameters
- Measured with $b \to u\mu\nu_\mu$
- Results from LHCb with $\Lambda_b^0 \to p\mu^-\nu_\mu$ and $\bar{B}_s^0 \to K^+\mu^-\nu_\mu$ decays



$\Lambda_b^0 \to p\mu^-\nu_\mu$

High $q^2 > 15$ GeV

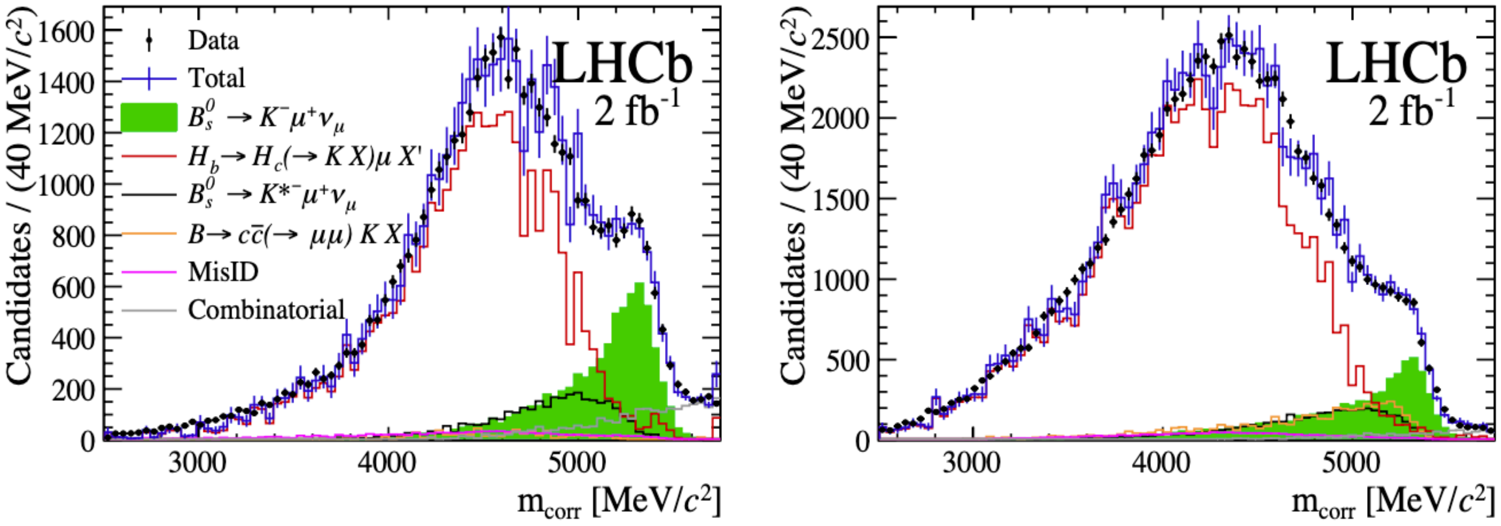


Nat.Phys.11(2015)743

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

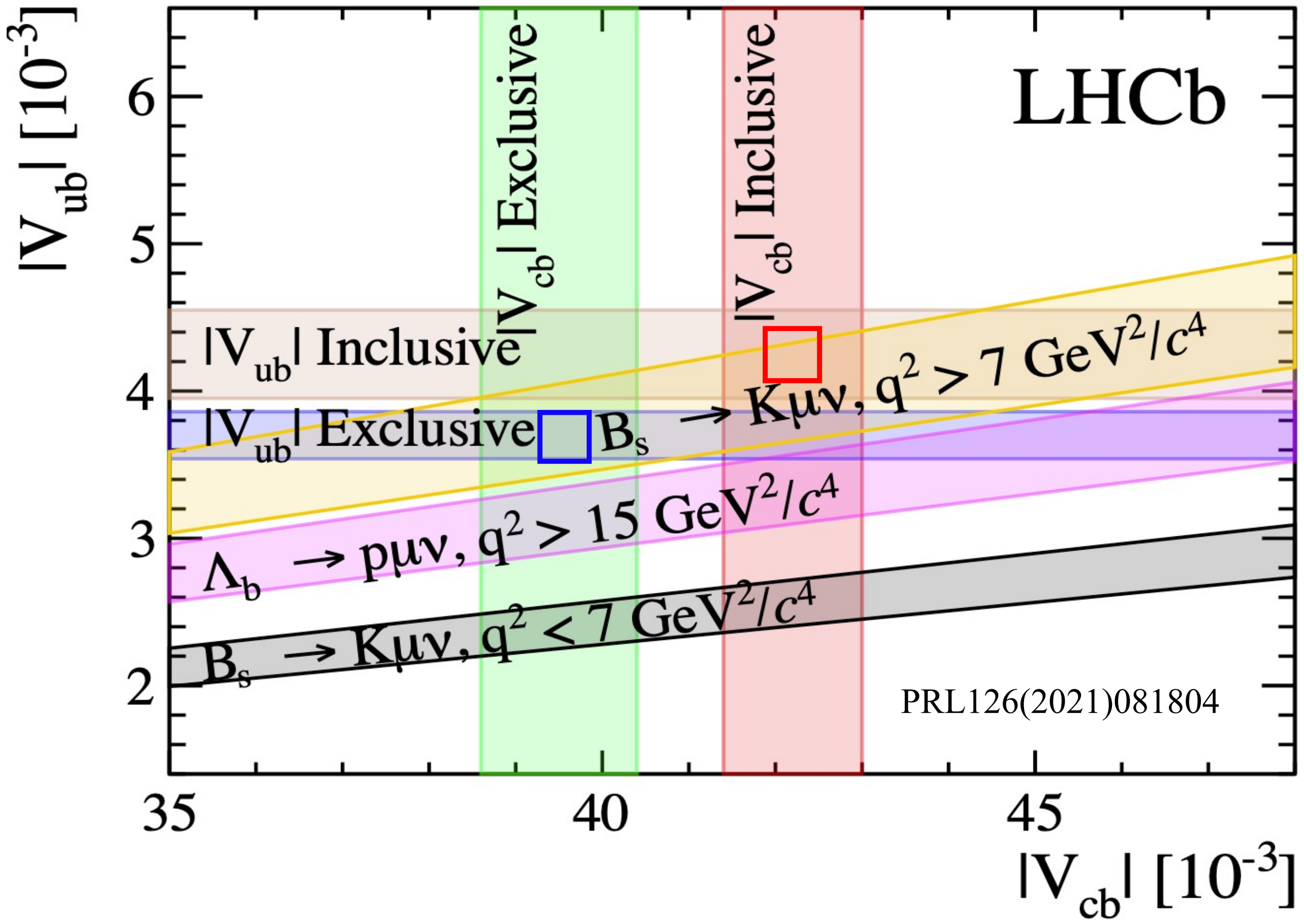
Low $q^2 < 7$ GeV

High $q^2 > 7$ GeV



PRL126(2021)081804

The V_{ub}, V_{cb} puzzle



$|V_{ub}/V_{cb}|$ by LHCb

LHCb PRL126(2021)081804

LHCb Nat.Phys.11(2015)743

LHCb PRL126(2021)081804

Tension between low-q^2 and high-q^2 due to form factors

Low q^2: light-cone sum rule
High q^2: lattice QCD

V_{td}, V_{ts}

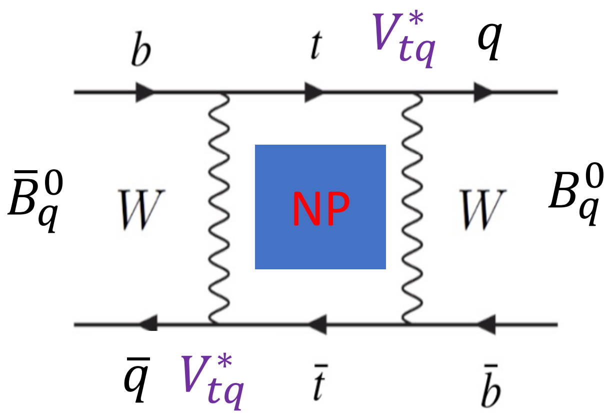
NaturePhysics18(2022)1
EPJC76(2016)412

- $\bar{B}^0_{(s)}$-$B^0_{(s)}$ oscillation with t-loops, allowed to measure $|V_{tq}|$

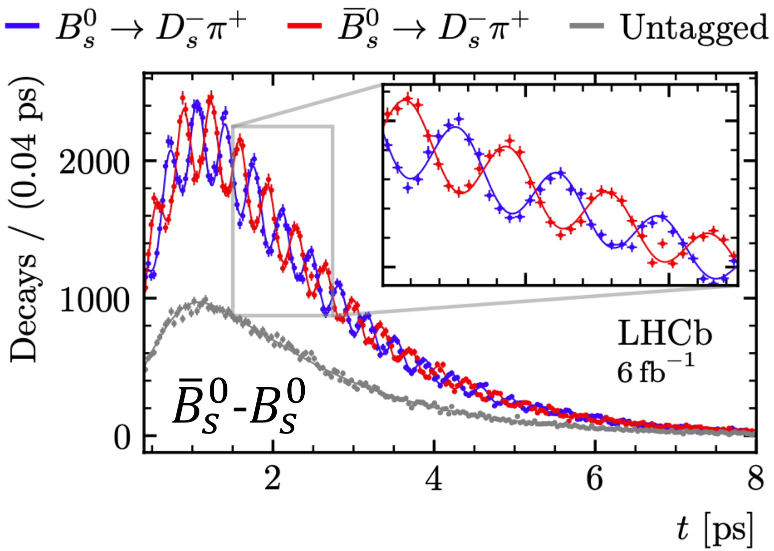
$$\left(B^0_q \to \frac{B^0_q}{\bar{B}^0_q}\right)(t) = \frac{e^{-\Gamma_q t}}{2}\left[\cosh\left(\frac{\Delta\Gamma_q}{2}t\right) \pm \cos(\Delta m_q t)\right]$$

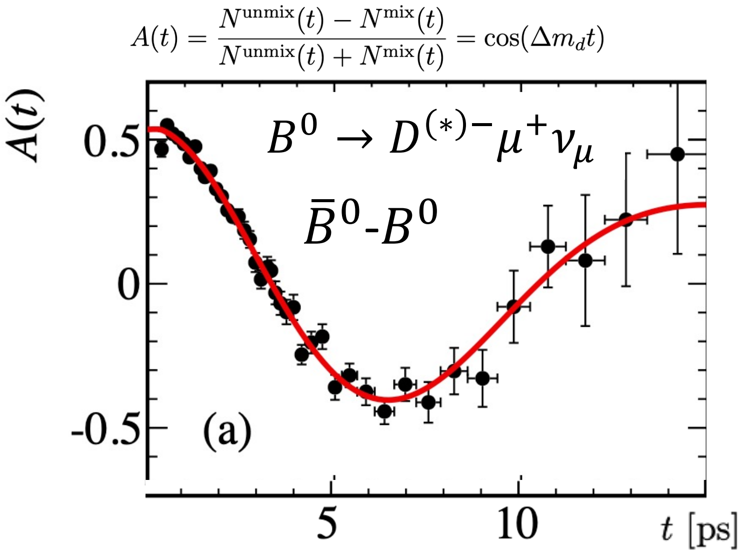
$$\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2$$

Flavor tagging is essential: $\epsilon(1-\omega)^2 \sim 5\%$ at LHCb



- LHCb measurements: $\Delta M_s = 17.7656 \pm 0.0057\ \text{ps}^{-1}$ $\Delta M_d = 0.5051 \pm 0.0023\ \text{ps}^{-1}$





Extraction of V_{tq} (PDG average)

Exp.   LatticeQCD

$$\left|\frac{V_{td}}{V_{ts}}\right| = (20.7 \pm 0.1 \pm 0.3)\times 10^{-2}$$

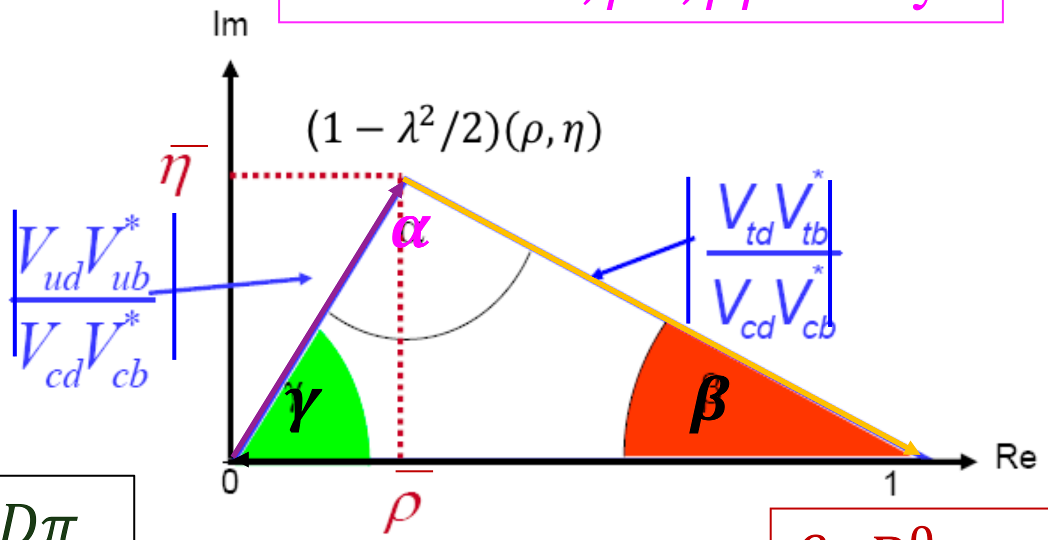
Consistent with global fit

Measurement of CKM matrix phases

Three angles of the Unitarity triangle

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

α: $B \to \pi\pi, \rho\pi, \rho\rho$ decays



γ: CPV in $B \to DK,\ D\pi$ decays

β: $B^0 \to \psi K_{S/L}$ decays, golden channel

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

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \approx \pi - \alpha - \beta$$

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \approx V_{td}^*$$

Measurement of angle β

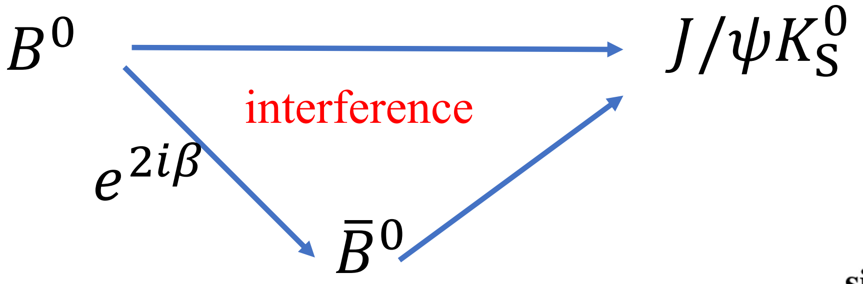
JHEP11(2017)170

- 2β: $B^0-\bar{B}^0$ mixing angle, extracted using interference between B^0 decay and $B^0-\bar{B}^0$ mixing

$$\mathcal{A}(\bar{B}^0 \to B^0) \propto (V_{td}^*)^2$$

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

- Golden mode: $B^0 \to \psi K^0_{S,L}$, weak phase in decay highly suppressed



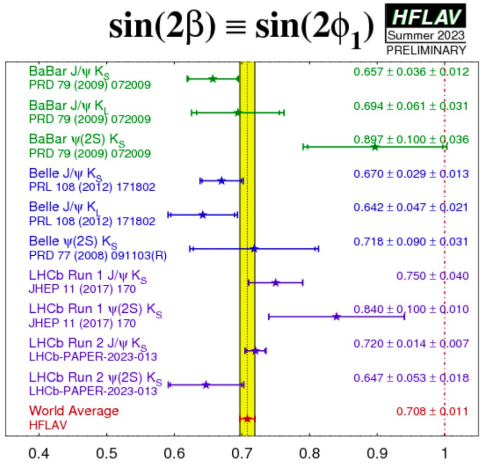
LHCb: $\sin 2\beta = 0.717 \pm 0.015$

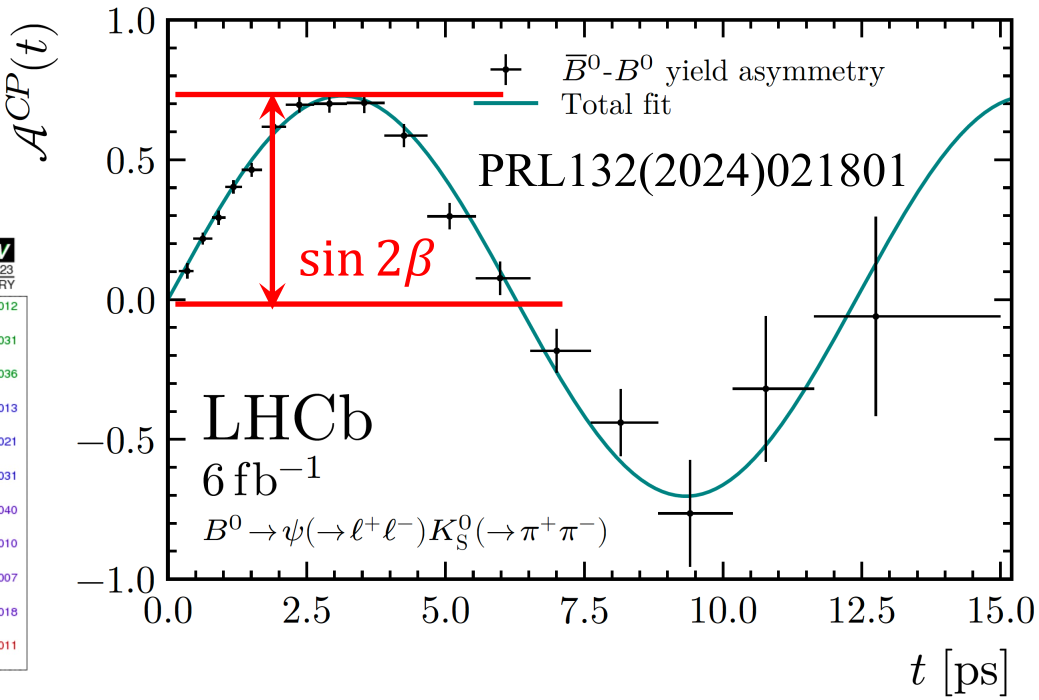
- β average:

$\beta = (22.5 \pm 0.4)^\circ$

Time dependent CP violation

$$A_{\rm CP}(t) = \frac{\Gamma_{\bar{B}^0\to f}(t)-\Gamma_{B^0\to f}(t)}{\Gamma_{\bar{B}^0\to f}(t)+\Gamma_{B^0\to f}(t)} = -\eta_f \sin 2\beta \sin(\Delta M_d t)$$





$\phi_s \equiv -2\beta_s$

PRL132 (2024) 051802

- Phase of $\bar{B}_s^0 - B_s^0$ mixing, $\beta_s \approx \arg[-V_{ts}^*]$

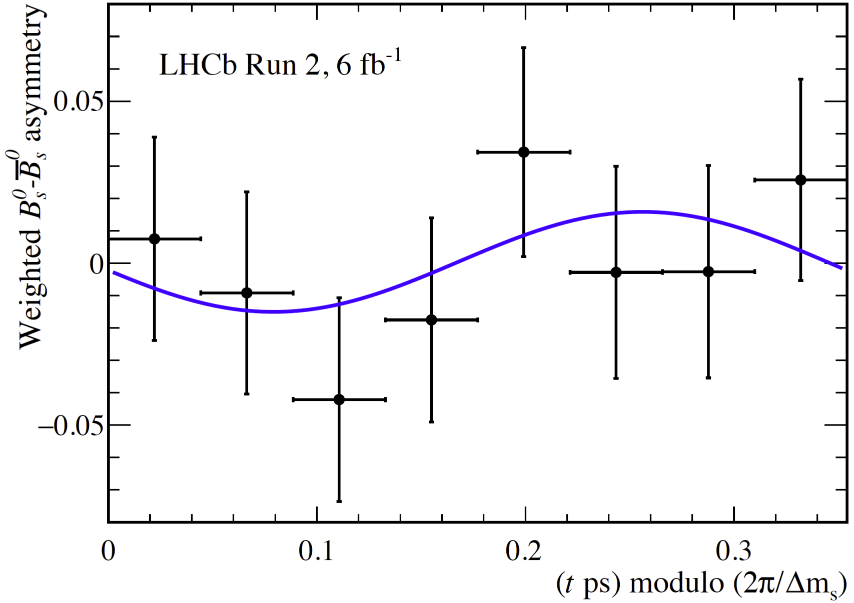
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

CKM global fit : $\phi_s = -37 \pm 1$ mrad, sensitive to NP

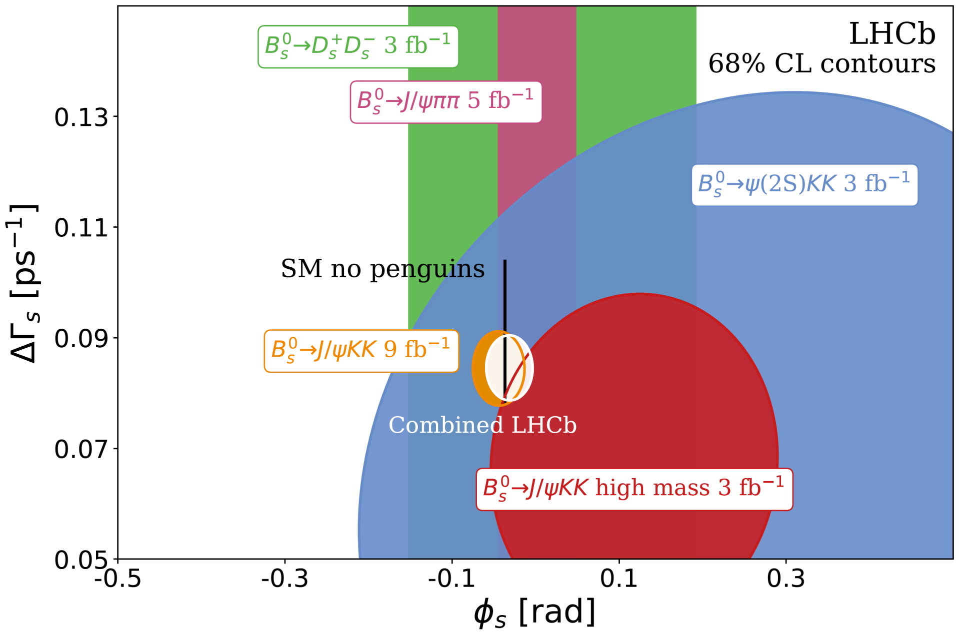
- Measured with time dependent CP asymmetry of $B_s^0 \to J/\psi\phi, J/\psi\pi^+\pi^-, D_s^+D_s^-$ decays

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

Gold mode: $B_s^0, \bar{B}_s^0 \to J/\psi\phi$

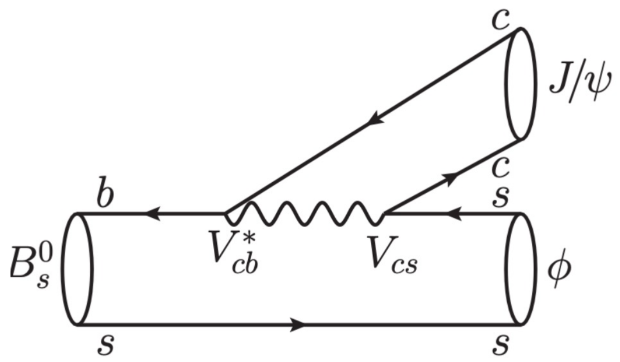


LHCb combination: $\phi_s = -44 \pm 20$ mrad

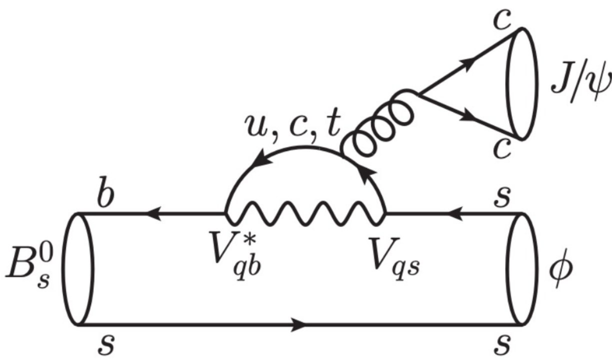


Penguin pollution

- Only effective mixing phase measured
  - ➢ Weak phase in mixing + decay
  - ➢ Theoretical uncertainty due to penguin pollution ($\sim 1°$) nonnegligible



Tree diagram
No weak phase



Penguin diagram
Weak phase $\propto V_{ts}$

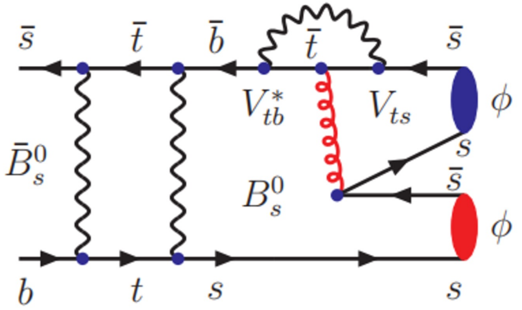
- $b \to \bar{s}ss$ FCNC decay: weak phases in mixing and decay cancel, effective mixing phase $\phi_s^{s\bar{s}s} \approx 0$

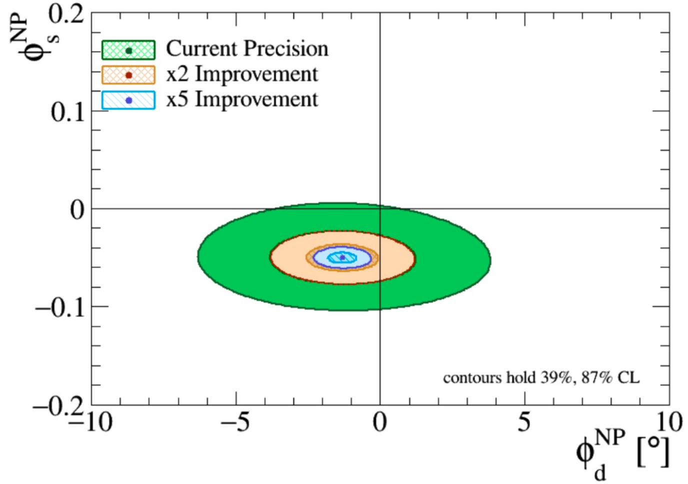
LHCb measurement with $B_s^0 \to \phi\phi$

$\phi_s^{s\bar{s}s}(B_s^0 \to \phi\phi) = -42 \pm 76$ mrad

PRL131(2023)171802

Very sensitive to NP in loops, but better precision needed





Measurement of angle γ

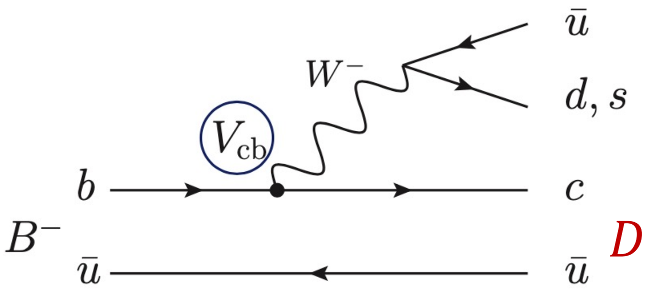
- γ directly related to phase of $\rho + i\eta$

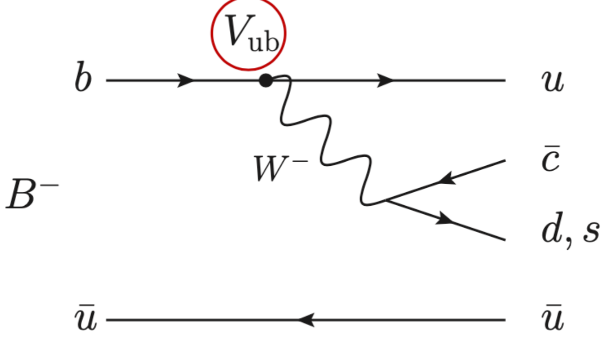
$$\gamma = \arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}] \approx \arg[V_{ub}^{*}]$$

- Measured with tree-level decays, theoretically clean observable ($\delta\gamma \sim 10^{-7}$)

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

Interference between $b \to c$ and $b \to u$ give rises to γ





$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

Essential inputs from charm facilities

- $\bar{D}$ and D to same final states to interfere

GLW: $f = KK, \pi\pi$ etc, CP eigenstates
PLB 253 (1991) 483, PLB 265 (1991) 172

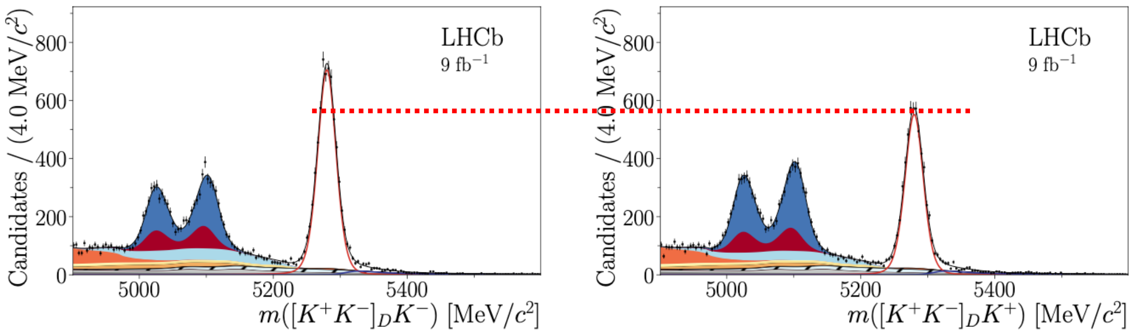
ADS: $f = K\pi, K3\pi$ etc, quasi-flavor-specific sates PRL 78 (1997) 3257

BPGGSZ: $f = K_s\pi\pi$ etc, self-conjugate multi-body
PRD 68 (2003) 054018

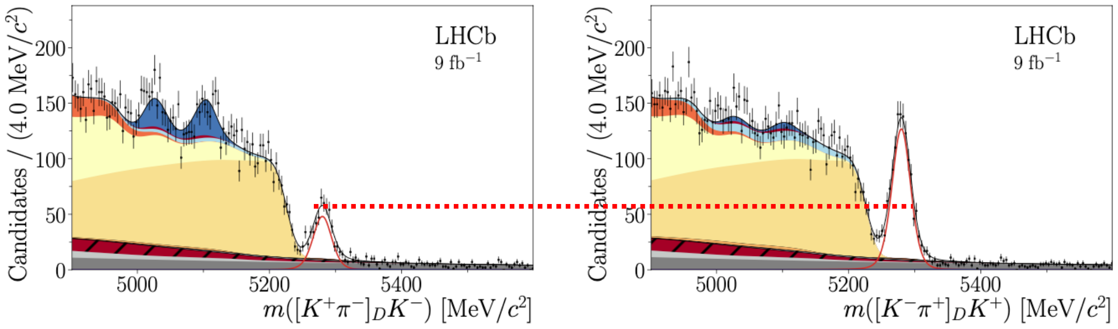
Measurements of γ

JHEP04(2021)081
JHEP12(2021)141

$B^{\pm} \to D^{(*)}K^{\pm}$, CP eigenstate of $D^{(*)} \to K^{+}K^{-}$



$B^{\pm} \to D^{(*)}K^{\pm}$, doubly Cabibbo suppressed decay of $D^{(*)} \to K^{\pm}\pi^{\pm}$



- γ combination

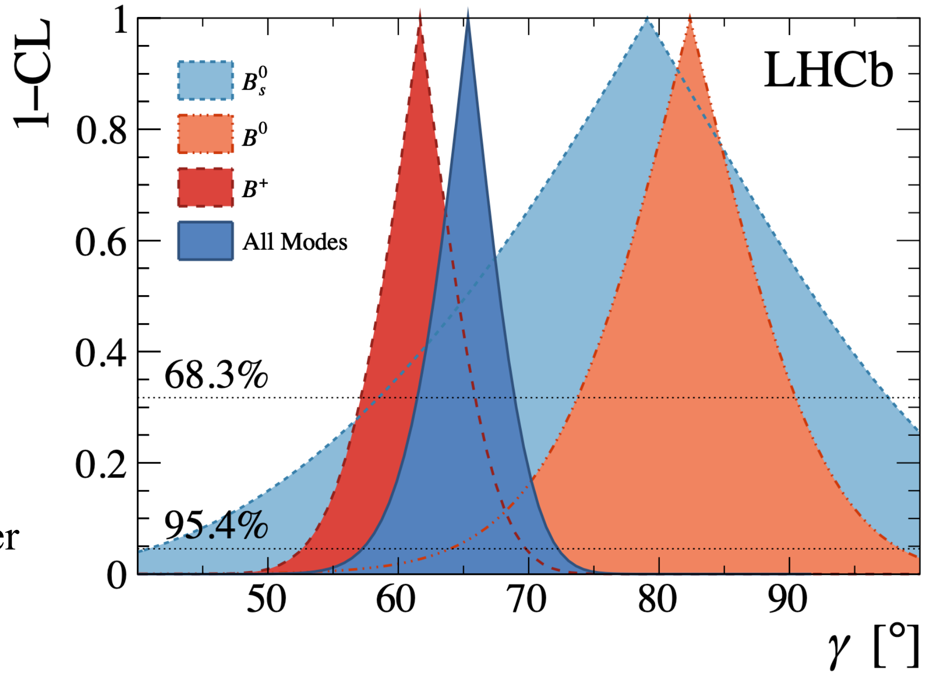
LHCb combination:

$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$

3× better than B-factories

Global fit (indirect meas.):

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



➢ Time-independent $B^{\pm} \to Dh^{\pm}$

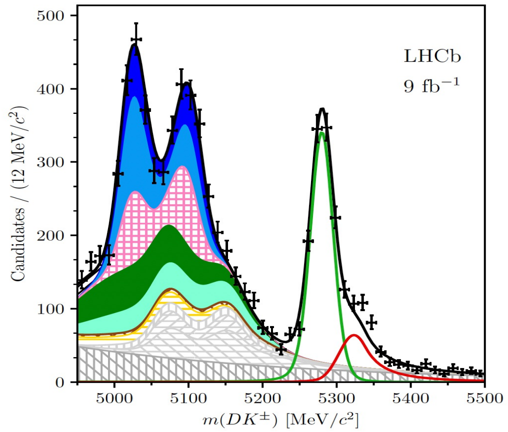
$D \to h^{+}h^{-}$
$D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$
$D \to h^{+}h^{-}\pi^{0}$
$D \to K_S^0 h^{+}h^{-}$
$D \to K_S^0 K^{\pm}\pi^{\mp}$

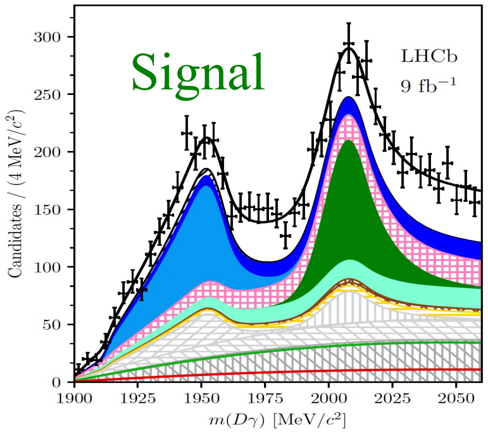
➢ Time-independent

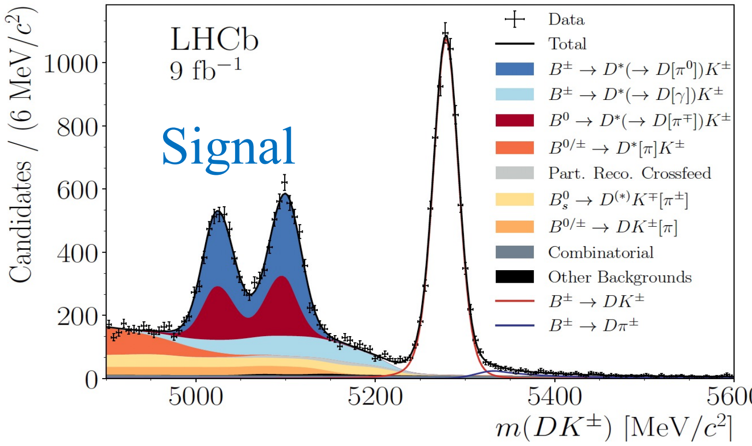
$B^0 \to D^{\mp}\pi^{\pm}$, $B_s^0 \to D_s^{\mp}K^{\pm}$

New γ measurements with $B^+ \to D^{*0}K^+$ with $D^0 \to K_S^0\pi^+\pi^-$

- Fully reconstructed $D^{*0} \to D^0\gamma/\pi^0$
- Partially reconstructed $D^{*0} \to D^0$

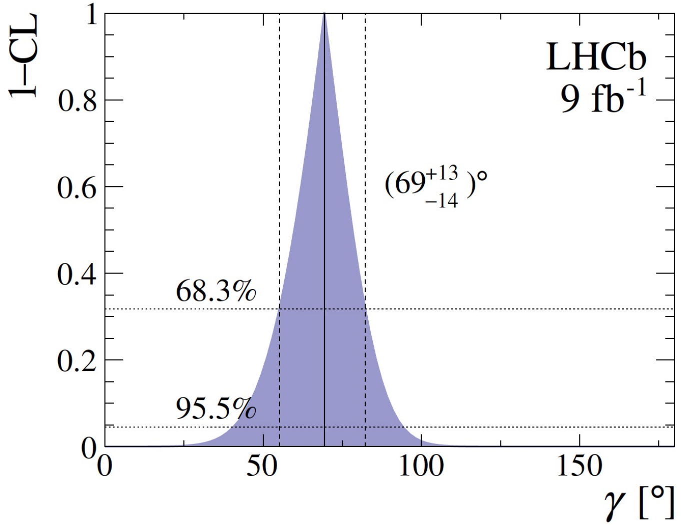




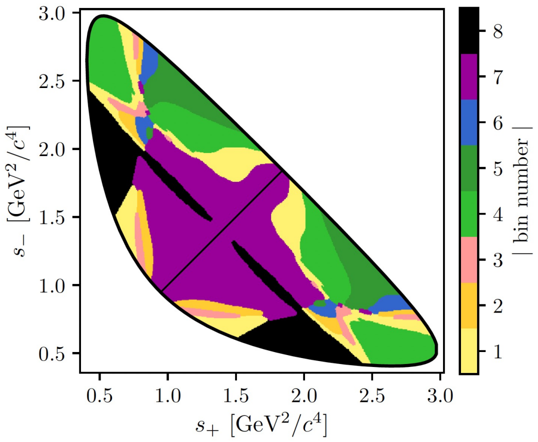


JHEP12(2023)013

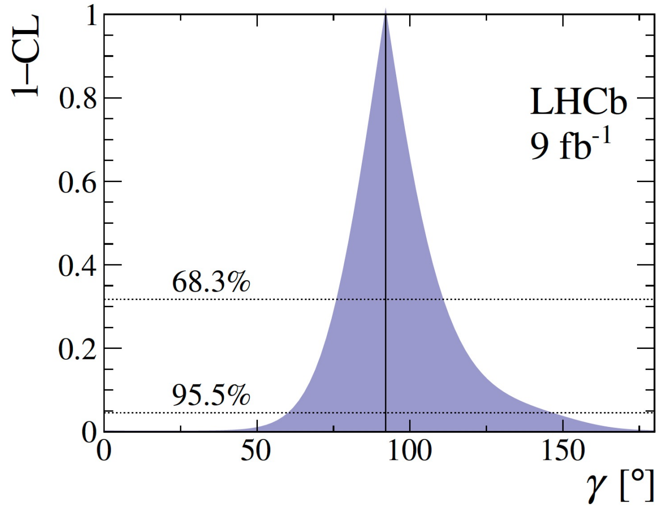
$\gamma = (69^{+13}_{-14})^\circ$



Strong phase from BESIII and CLEO

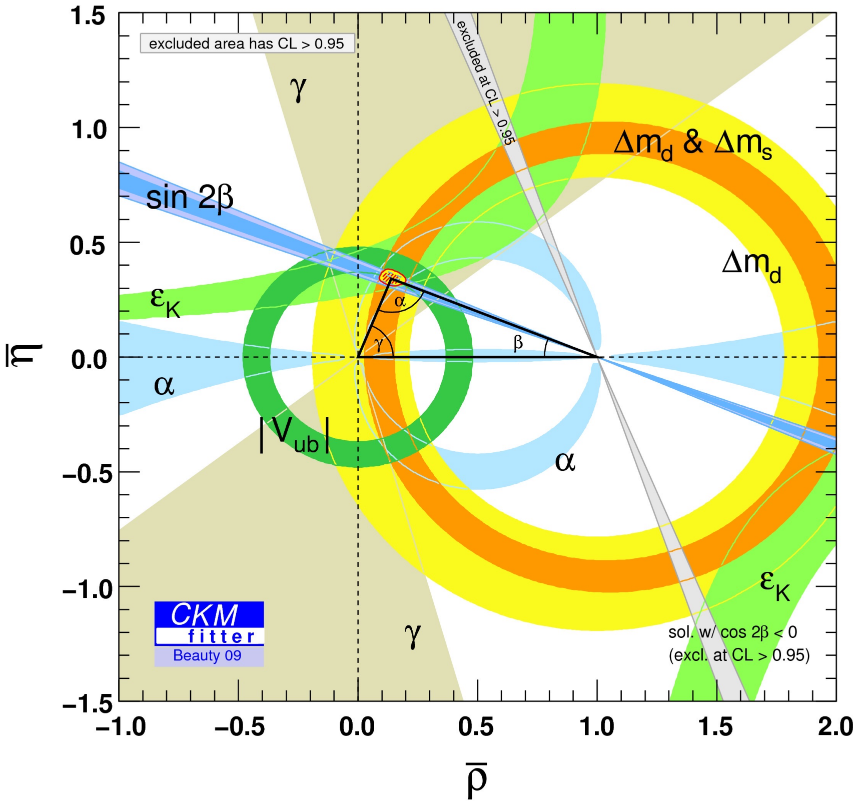


JHEP02(2024)118 $\gamma = (69^{+21}_{-17})^\circ$

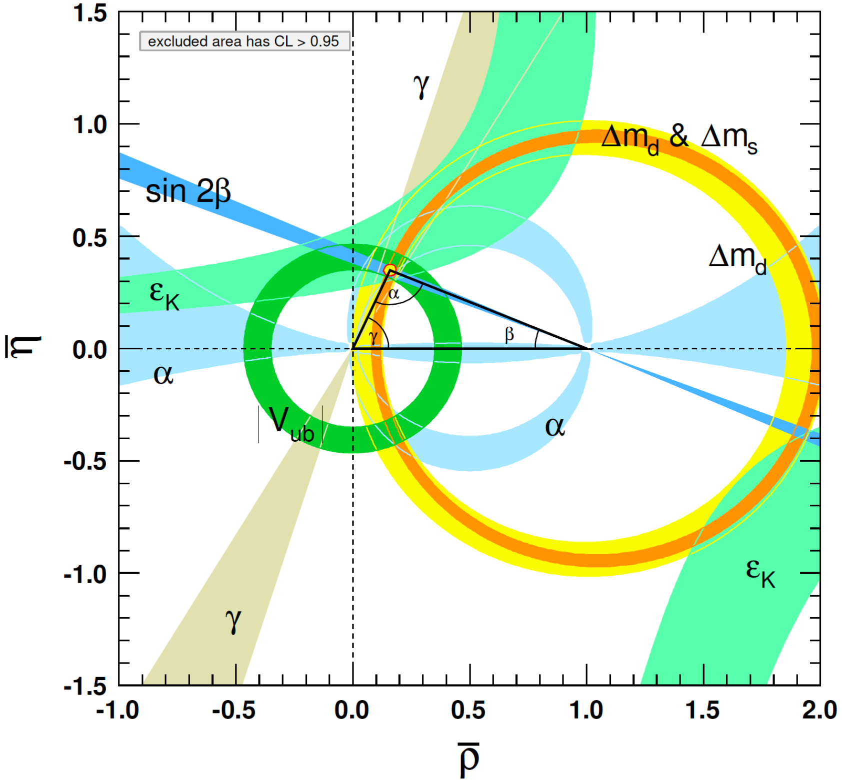


Global analysis of CKM mechanism (4 parameters)

When LHC started



Current status



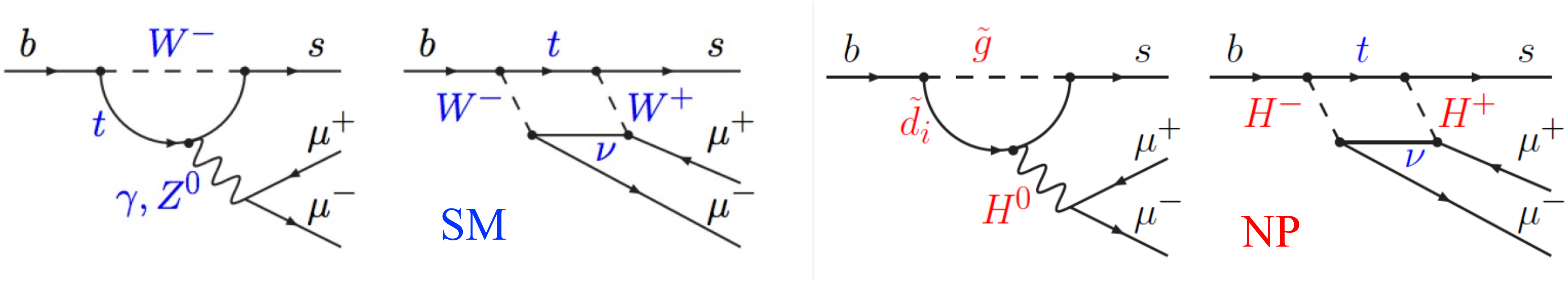
$A = 0.826^{+0.018}_{-0.015}$ $\lambda = 0.22500 \pm 0.00067$ $\bar{\rho} = 0.159 \pm 0.010$ $\bar{\eta} = 0.348 \pm 0.010$

$$\alpha + \beta + \gamma = (173 \pm 6)^\circ$$

Flavor anomalies in semi-leptonic decays

$b \to s l^+ l^-$ decays

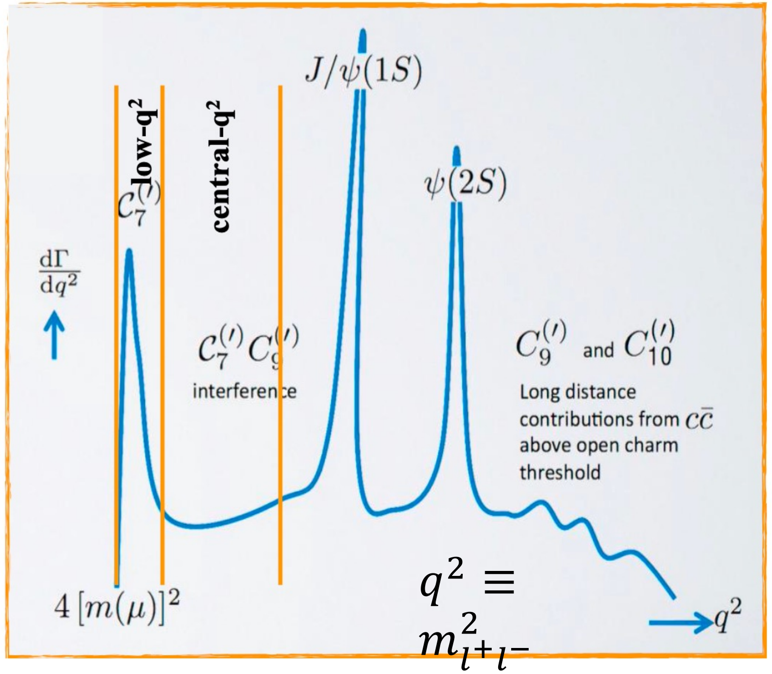
- $b \to s l^+ l^-$ mediated by FCNC loops, SM clean observables, sensitive to BSM physics



Effective Theory:

$$\mathcal{H}_{\text{WET}} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i^{(\prime)}(\mu) \mathcal{O}_i^{(\prime)}(\mu)$$

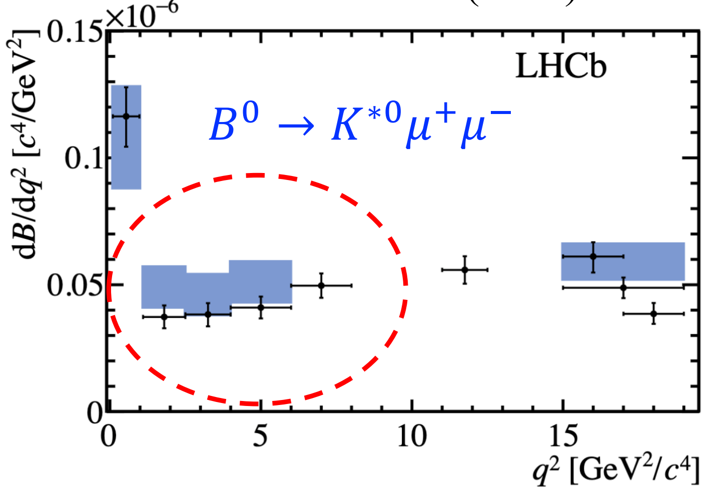
$b \to s l^+ l^-$ probing Wilson coefficients:
C_7, C_9, C_{10}



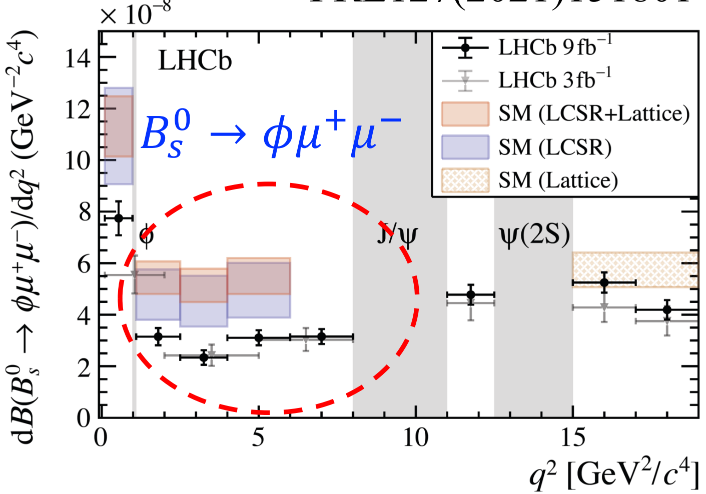
Flavor anomalies in $b \to s l^+ l^-$ decays

- Anomalous tensions with SM in differential rate

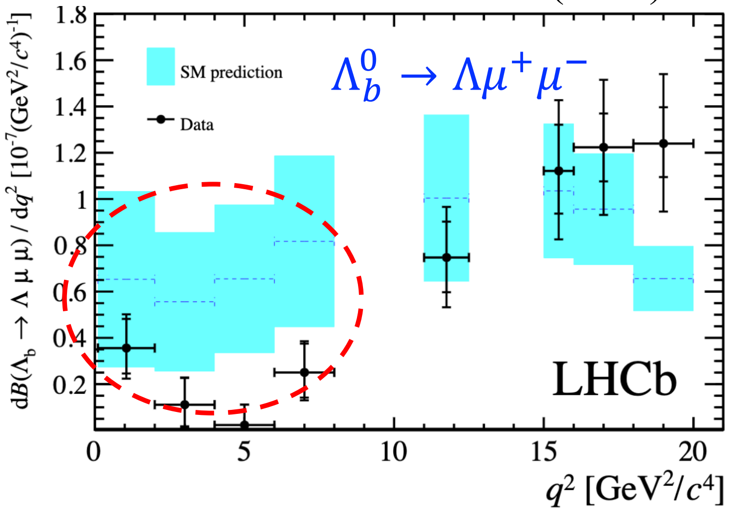
JHEP04(2017)142



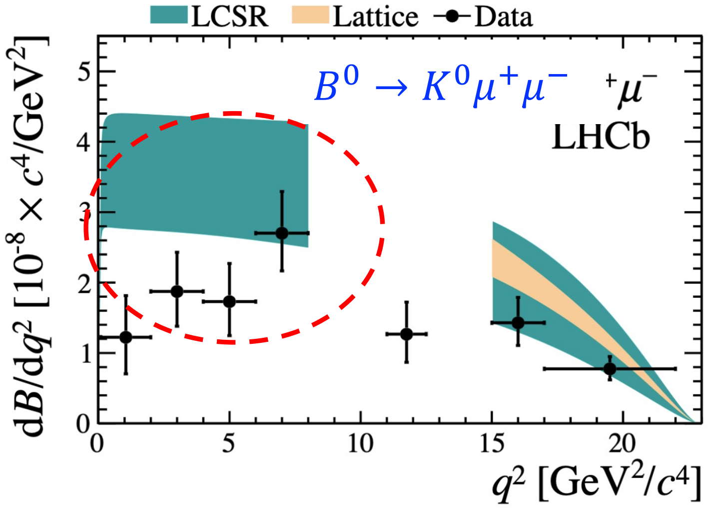
PRL127(2021)151801

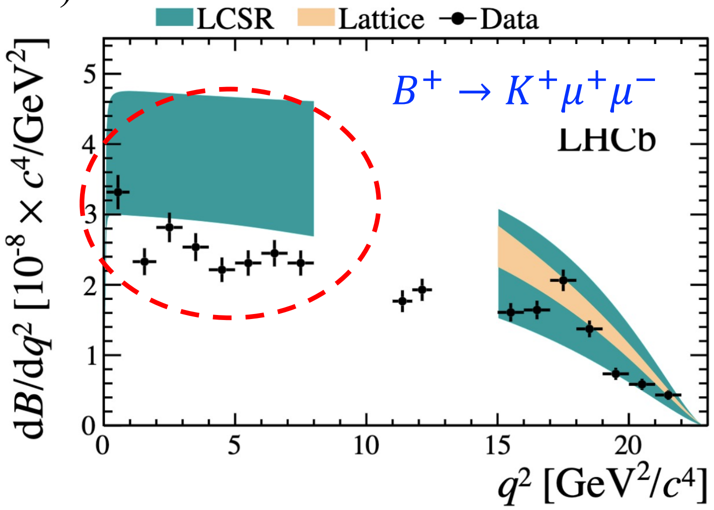


JHEP06(2015)115

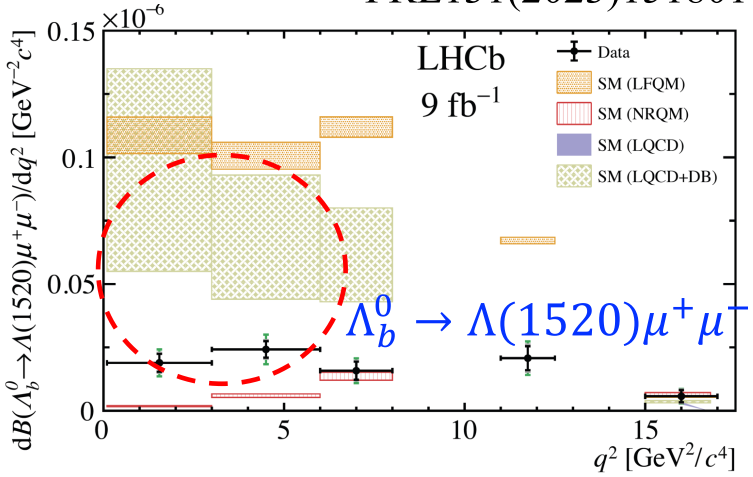


JHEP06(2014)133



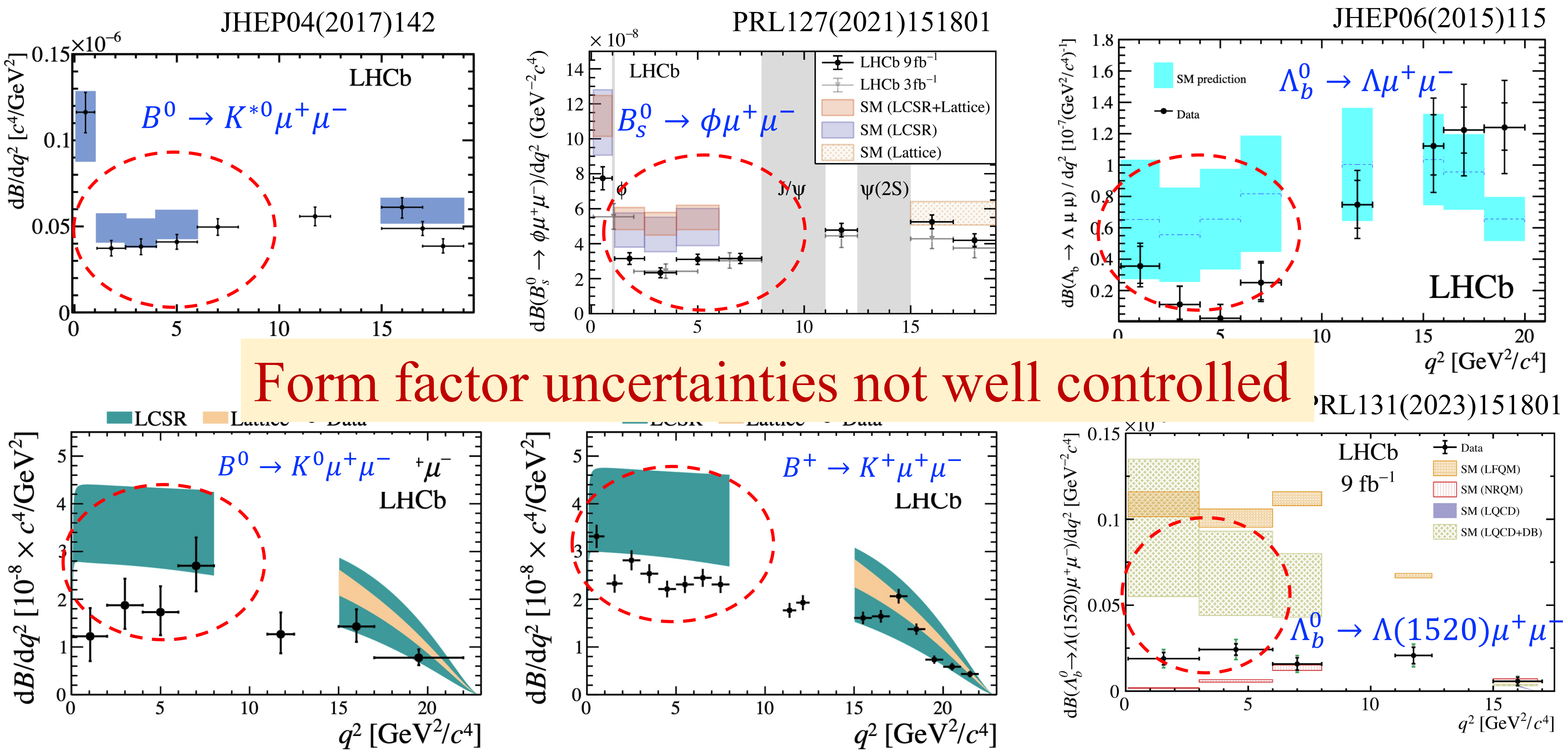


PRL131(2023)151801

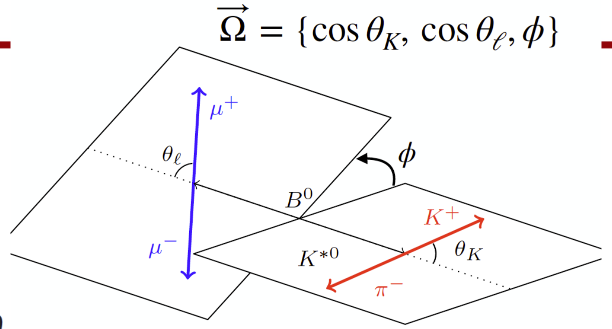


Flavor anomalies in $b \to s l^+ l^-$ decays

- Anomalous tensions with SM in differential rate



Angular analysis in q^2



- Detailed information to test SM calculations

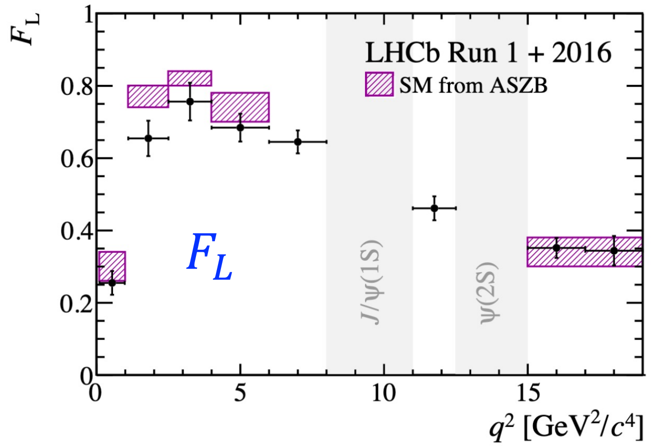
Angular distribution for $B^0 \to K^* l^+ l^-$ decay (CP averaged):

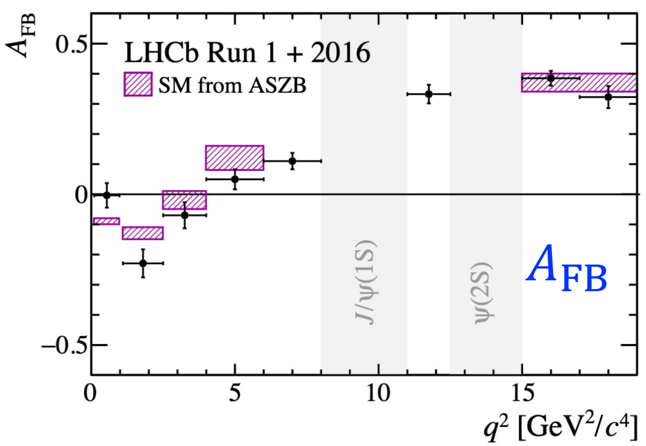
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}}\Bigg|_P = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \frac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_l$$
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_{\rm FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

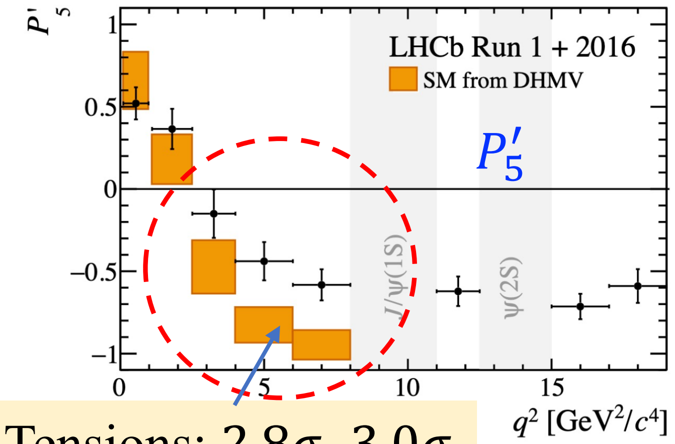
F_L: longitudinal polarization, $A_{\rm FB}$ forward-backward asymmetry

PRL 125 (2020) 011802

Cleaner observables: $P_i' = S_i'/\sqrt{F_L(1-F_L)}$







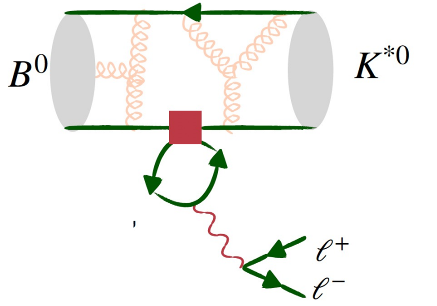
Tensions: 2.8σ, 3.0σ

Understanding nonlocal contributions

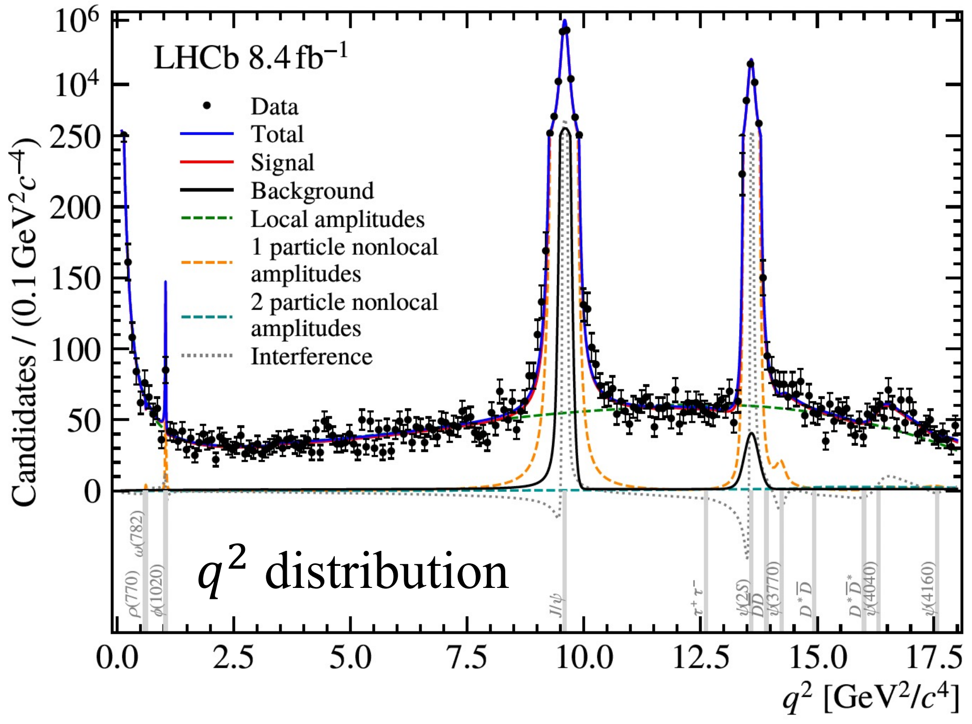
- $b \to s l^+ l^-$ measurements polluted by nonlocal ($\omega\rho, \phi, \psi, D\bar{D}\ldots$) effects
- Amplitude analysis to separate local and nonlocal contributions

  Dedicated form factor ($f(q^2)$) for each component

  Direct access to Wilson coefficients

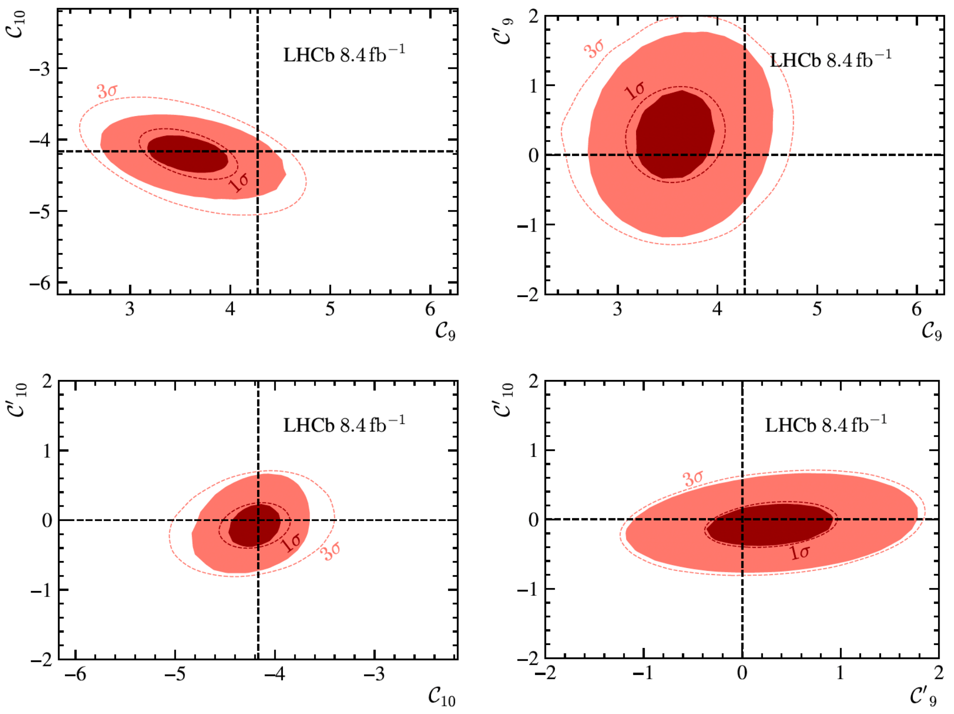


arXiv:2405.17347

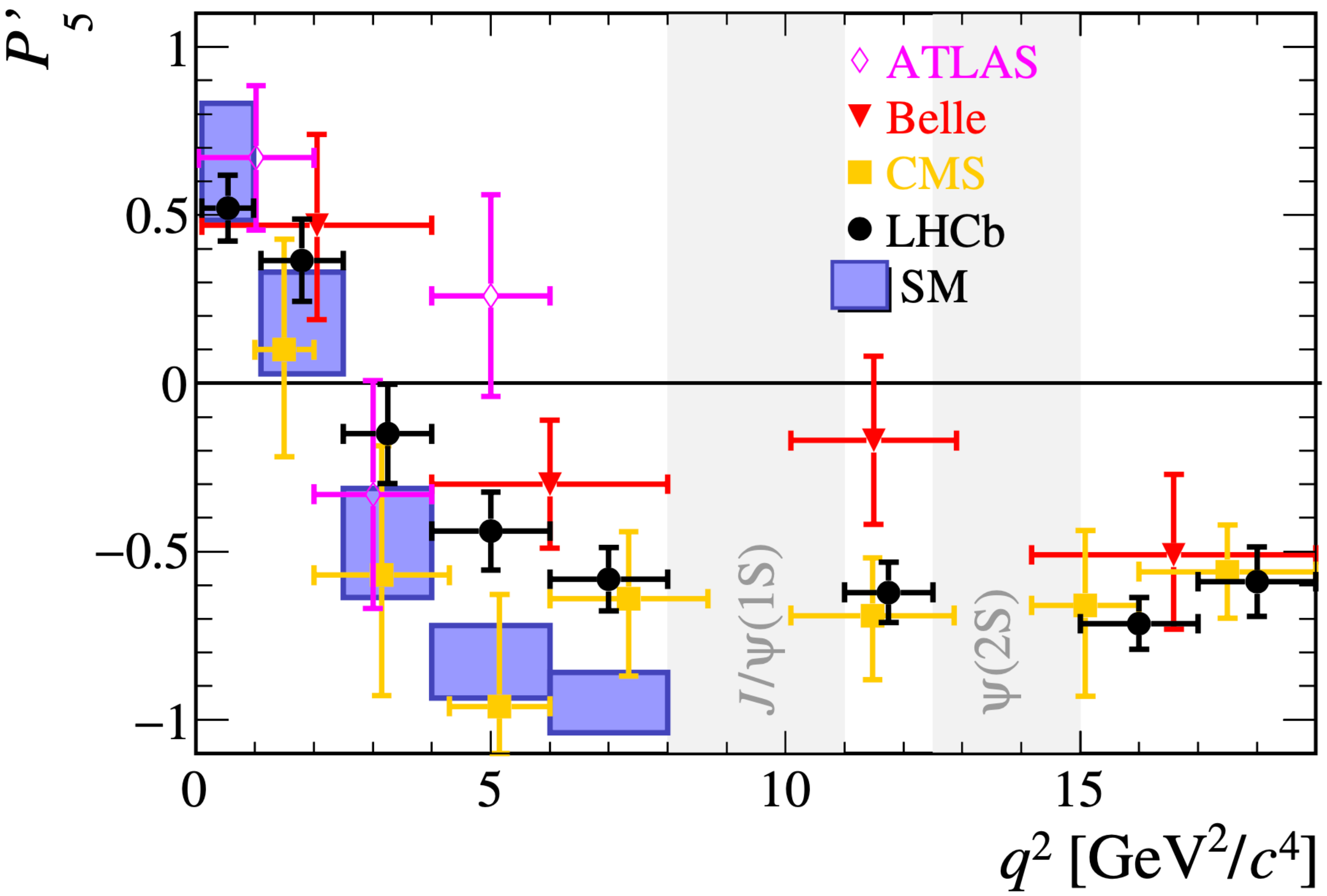


q^2 distribution

$\mathcal{C}_9$: 2.1σ deviation from SM



Gaining experimental precisions



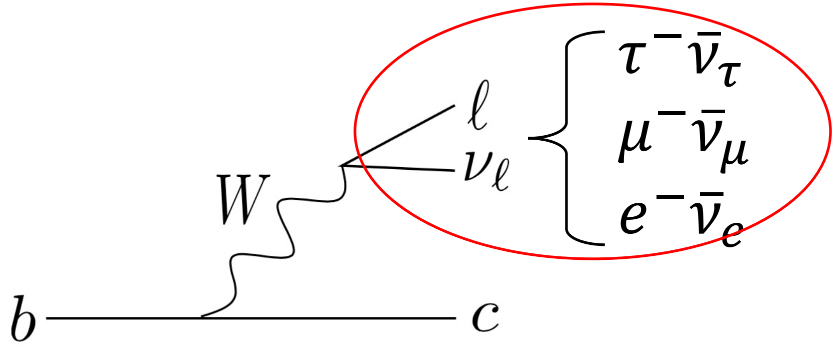
Combined deviations: 3.3 σ

$D \to \pi/\rho\ l^+ l^-$?

JHEP 10 (2018) 047, PLB 753 (2016) 424

Lepton flavor anomalies in charged currents

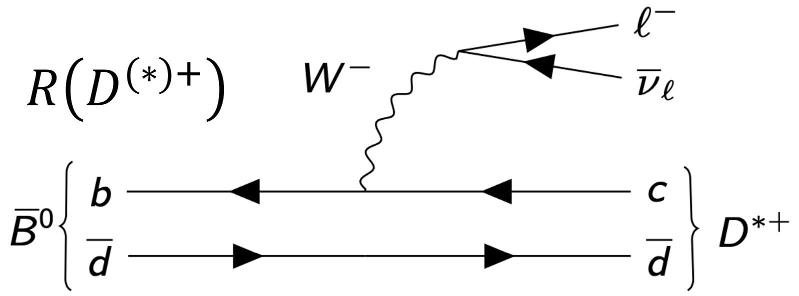
SM $W^{\pm}$ couples equally to three generations of fermions, tested through $R(H_c)$ data



$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \nu_\mu)}$$

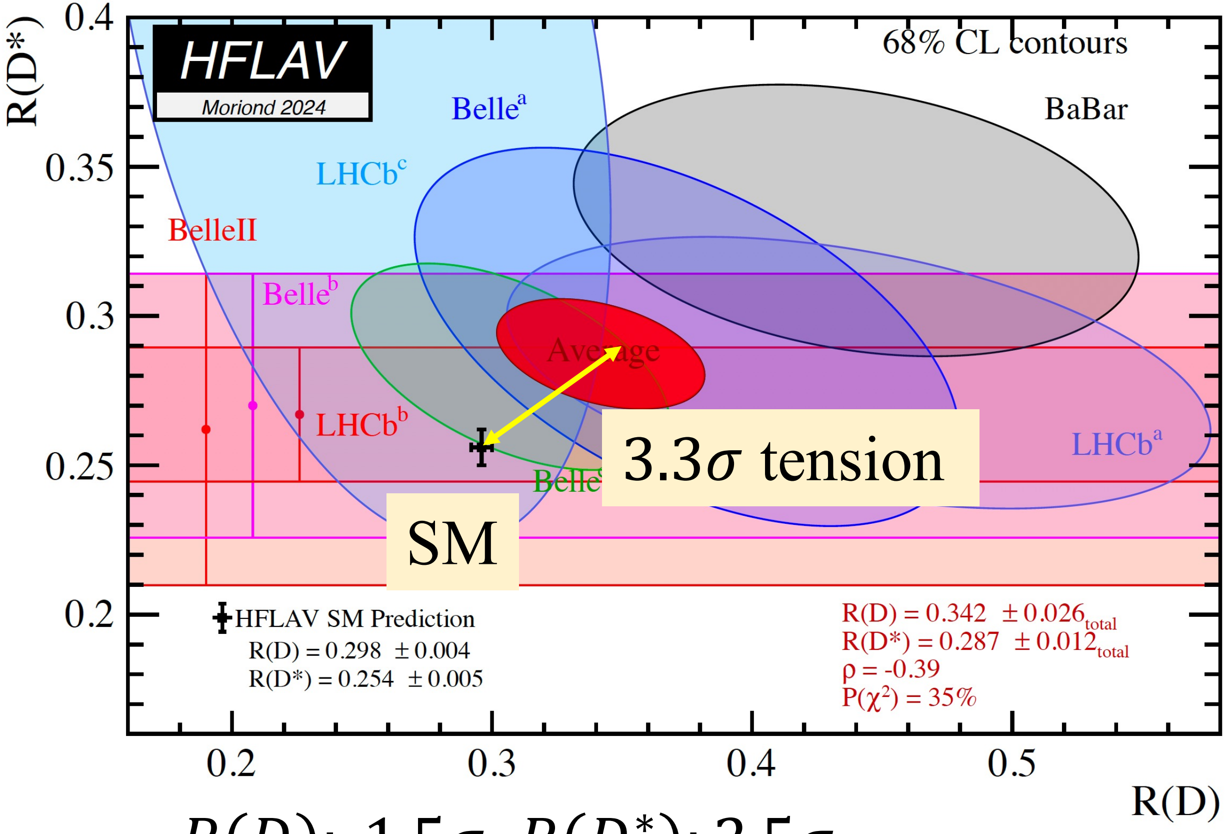
$H_c = D^{(*)+}, D^0, D_s^+, \Lambda_c^+, J/\psi \ldots$

$R(D^{(*)+})$



$R(D^{(*)})$ with $\tau \to \mu\nu\nu, \tau \to 3\pi\nu$

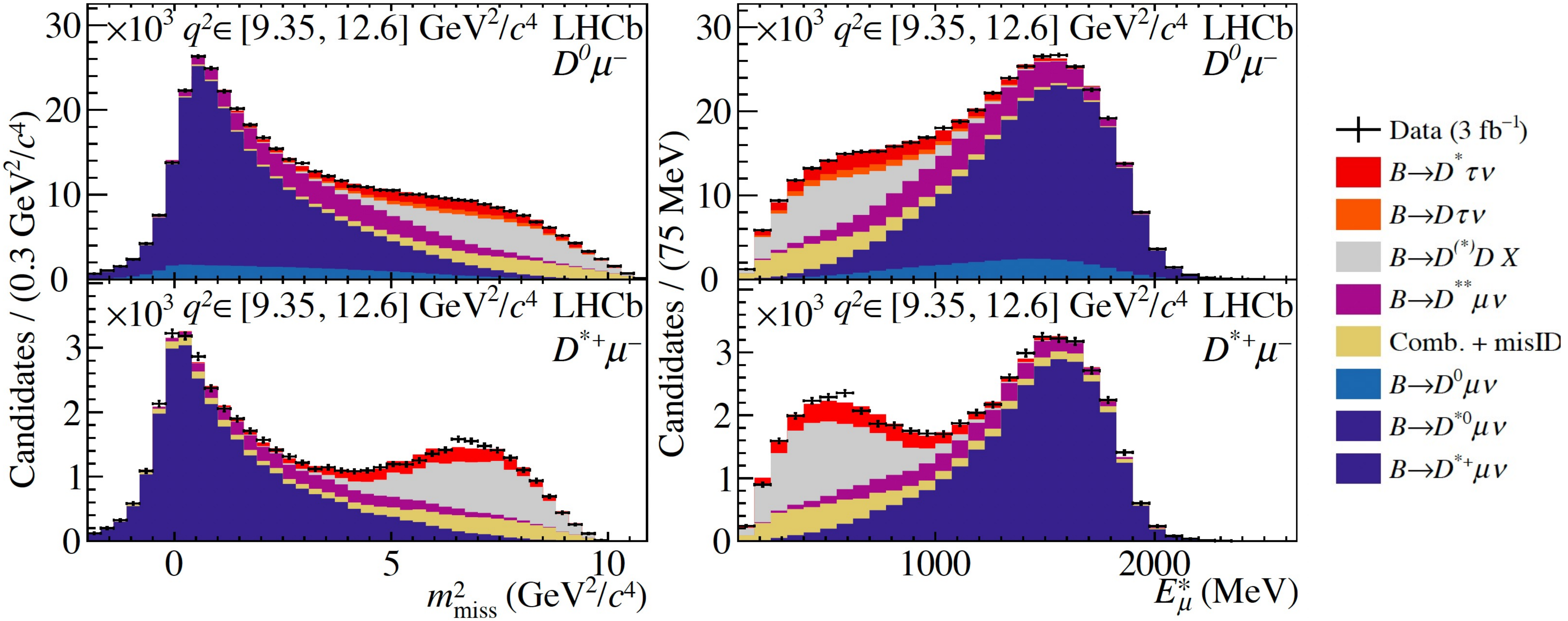
PRL131(2023)111802
PRD108(2023) 012018
arXiv:2406.03387



$R(D)$: 1.5σ, $R(D^*)$: 2.5σ

$R\left(D^{(*)}\right)$ signal extraction

PRL131(2023)111802



Better knowledge of D^{**} helps to reduce systematics

D^{*-} longitudinal polarization ($F_L^{D^*}$) in $B^0 \to D^{*-}\tau^+\nu_\tau$ decay

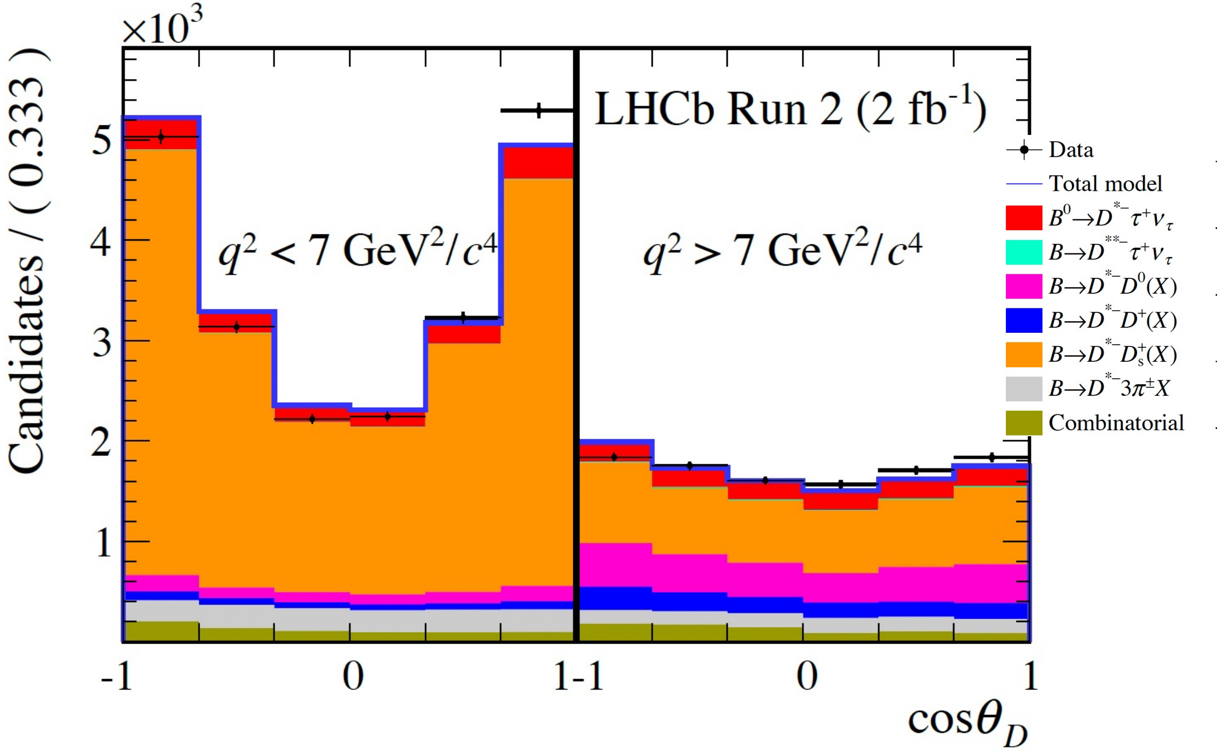
- $F_L^{D^*}$: additional information to understand the anomaly

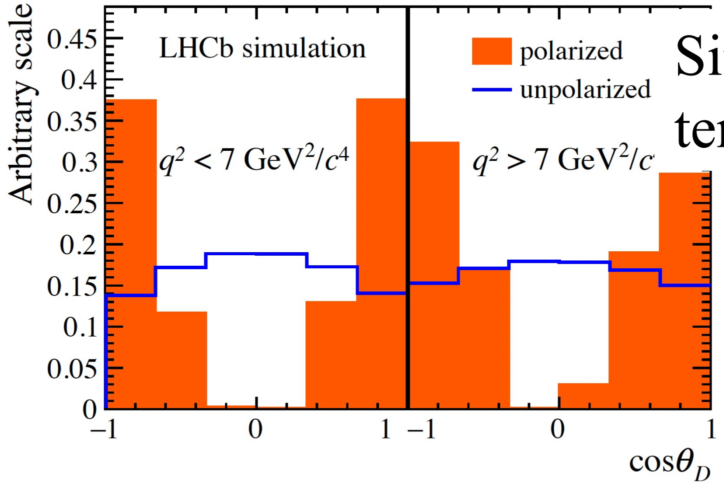
arXiv:2311.05224

$$\frac{d^2\Gamma}{dq^2 d\cos\theta} \propto 1 - F_L(q^2) + [3F_L(q^2) - 1]\cos^2\theta, \qquad \theta: \bar{D}^{*-} \text{ helicity angle}$$

- Measured with polarized/unpolarized template fits (4D: $\cos\theta$, q^2, t_τ, D_s^+-veto)

Performed in two separate q^2 bins





Simulated signal templates

$F_L^{D^*} = 0.41 \pm 0.06 \pm 0.03$

consistent with

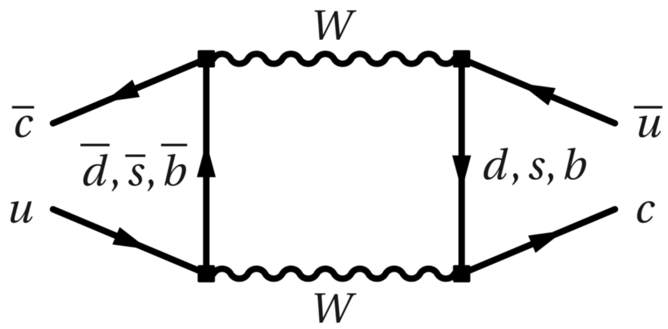
SM : $F_L^{D^*} = 0.441 \pm 0.006$

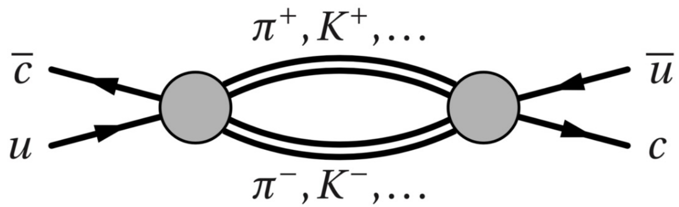
[PRD98(2018)095018]

Charm physics

Charm mixing and CP violation

- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix ($< \lambda^4 \sim 0.1\%$)
- Oscillation and CPV ($\lesssim 10^{-3}$) tiny in the SM, room for BSM
- Long distance contribution comparable/larger than short distance





Breakthroughs by LHCb thanks to huge statistics:

First observation of CPV in $D^0 \to h^+h^-$ decays

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ [PRL(2019)211803]

Evidence of CPV in $D^0 \to \pi^+\pi^-$ decay

$A_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1)\times 10^{-4}$ (3.8σ) [PRL(2023)211803]

CP violation measurements

- Energy test of D^0 and $\overline{D}^0$ samples: average distance between two candidates

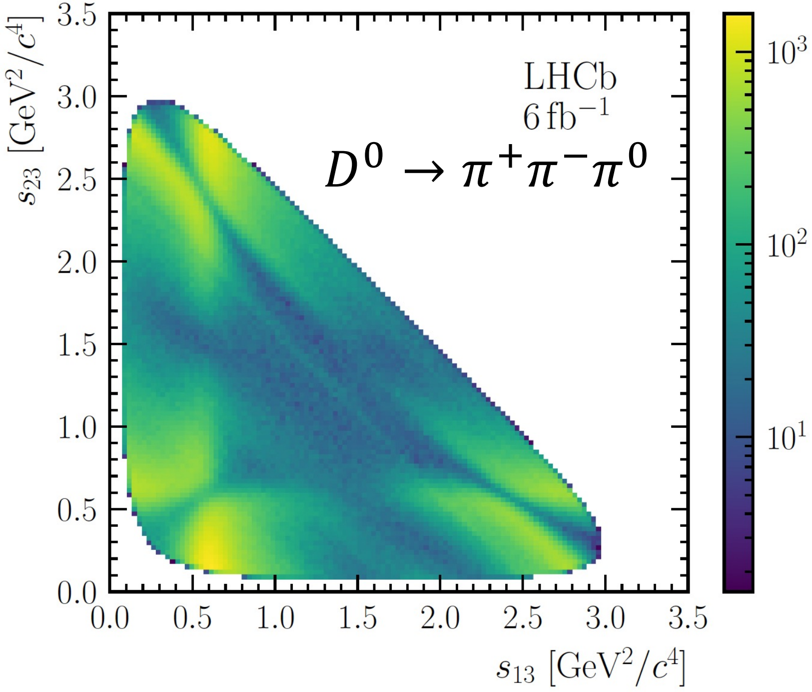
$$T = \frac{1}{2}\frac{1}{n(n-1)}\sum_{i\neq j}^{n}\psi_{ij} + \frac{1}{2}\frac{1}{\overline{n}(\overline{n}-1)}\sum_{i\neq j}^{\overline{n}}\psi_{ij} - \frac{1}{n\overline{n}}\sum_{i,j}^{n,\overline{n}}\psi_{ij},$$

D^0 decay — $\overline{D}^0$ decay — D^0 and $\overline{D}^0$

$$\psi_{ij} = e^{-d_{ij}^2/2\delta}$$

d_{ij}: phase-space distance

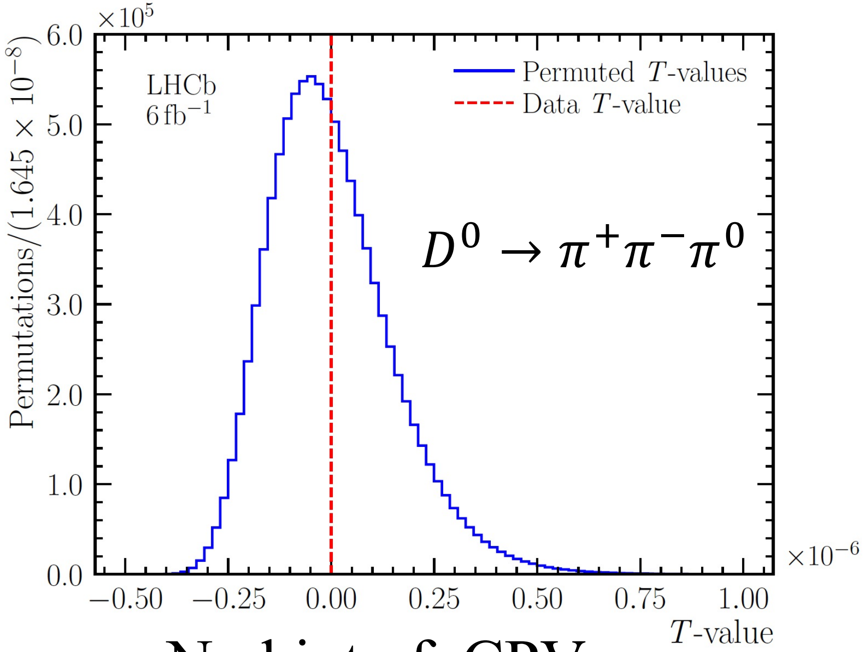
δ optimized to be best sensitive



JHEP 09 (2023) 129

≈ 2.5 M signals

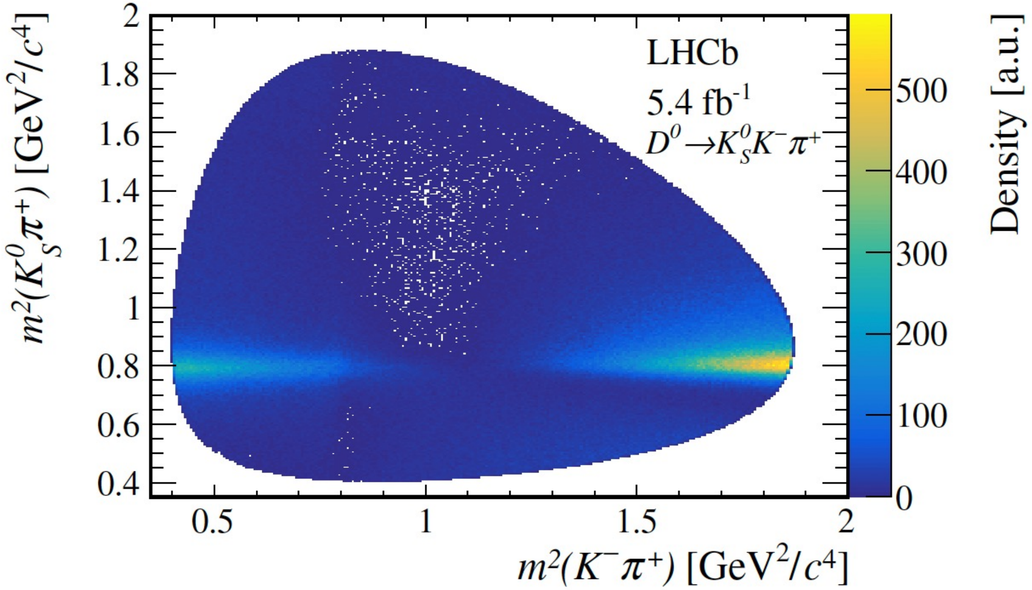
Sensitive to 1° weak phase

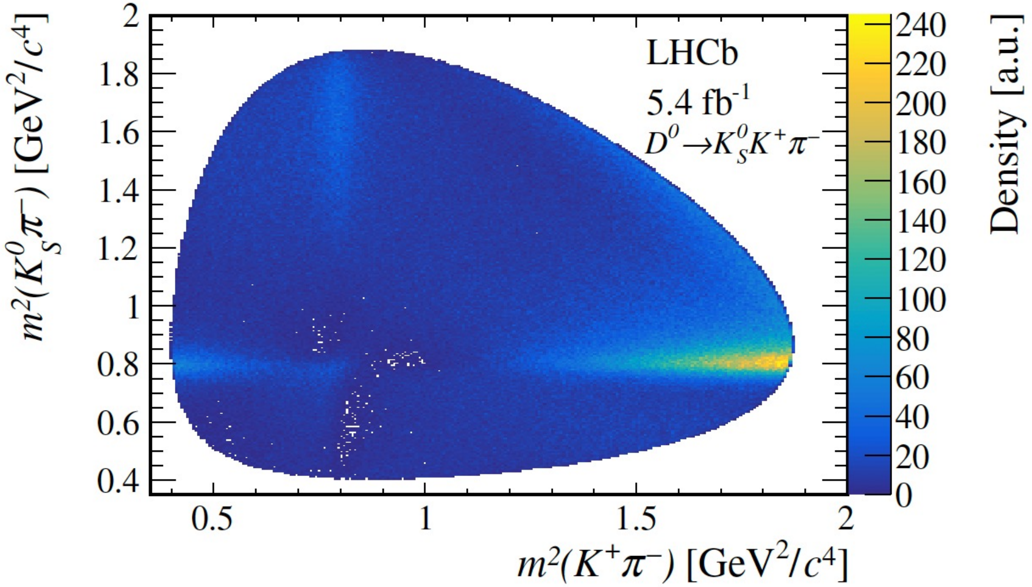


No hint of CPV

CP violation of $D^0 \to K_S^0 K\pi$ decays

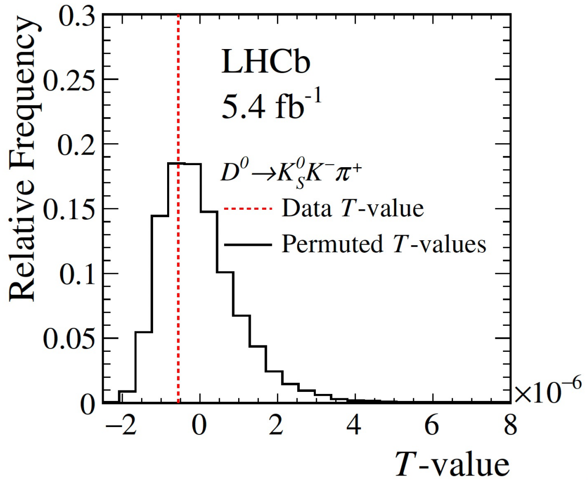
JHEP 03 (2024) 107



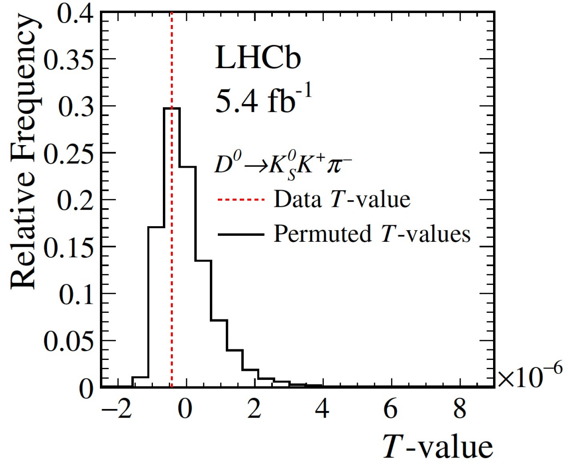


$D^0 \to K_S^0 K^- \pi^+$, 0.95 M signals

$D^0 \to K_S^0 K^+ \pi^-$, 0.62 M signals

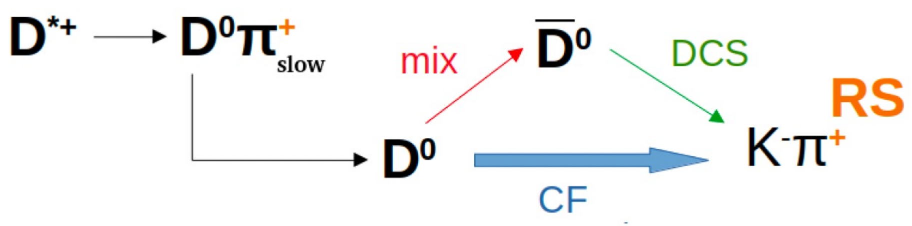


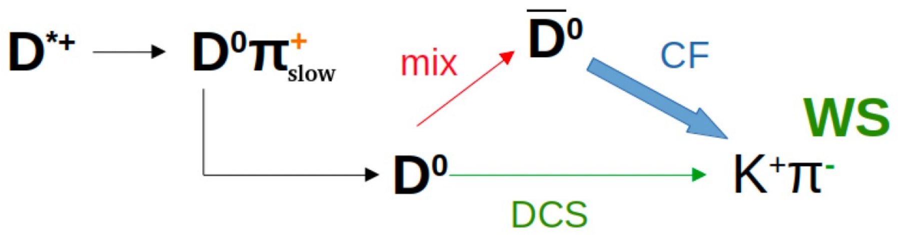
No hint of CPV



D^0 time-dependent CP violation

- Interference between mixing and decay for favored RS and suppressed WS decays





Tim-dependent ratio between WS and RS: $R^{+}_{K\pi}(t) \equiv \dfrac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)}$ $\quad R^{-}_{K\pi}(t) \equiv \dfrac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$

DCS over CF amplitude

$$R^{\pm}_{K\pi}(t) \approx \boxed{R_{K\pi}}(1 \pm A_{K\pi}) + R_{K\pi}(1 \pm A_{K\pi})(c_{K\pi} \pm \Delta c_{K\pi})\left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

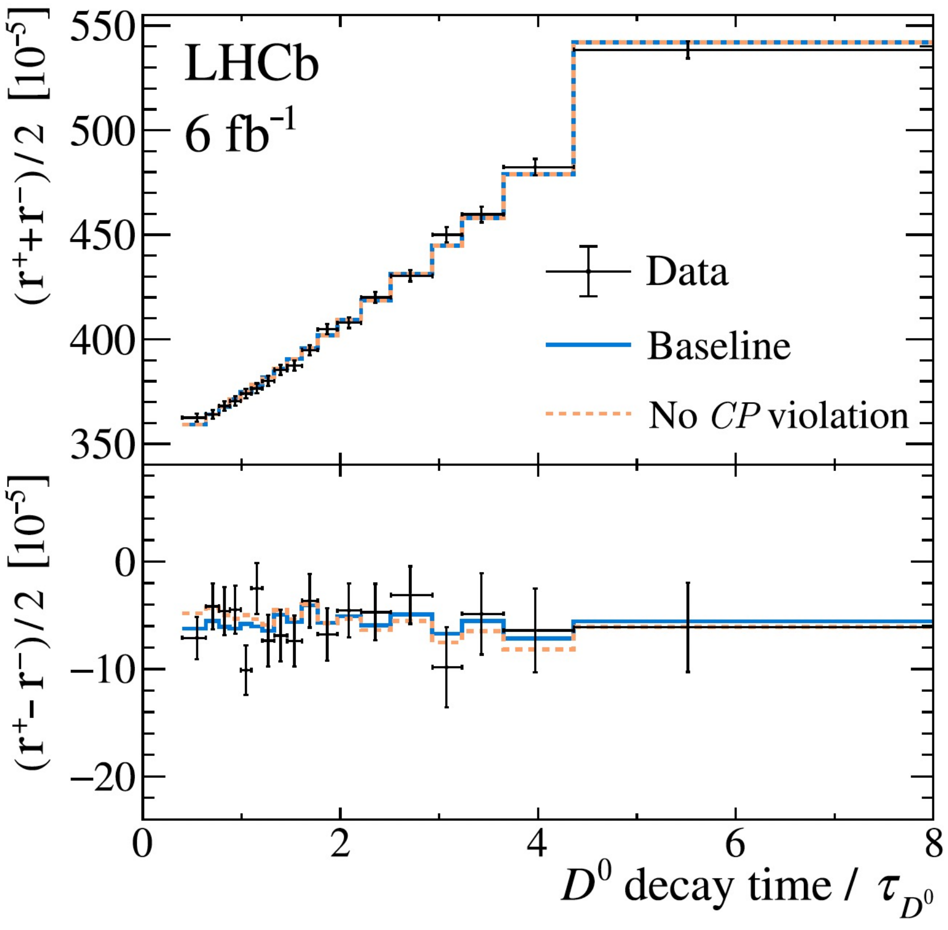
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

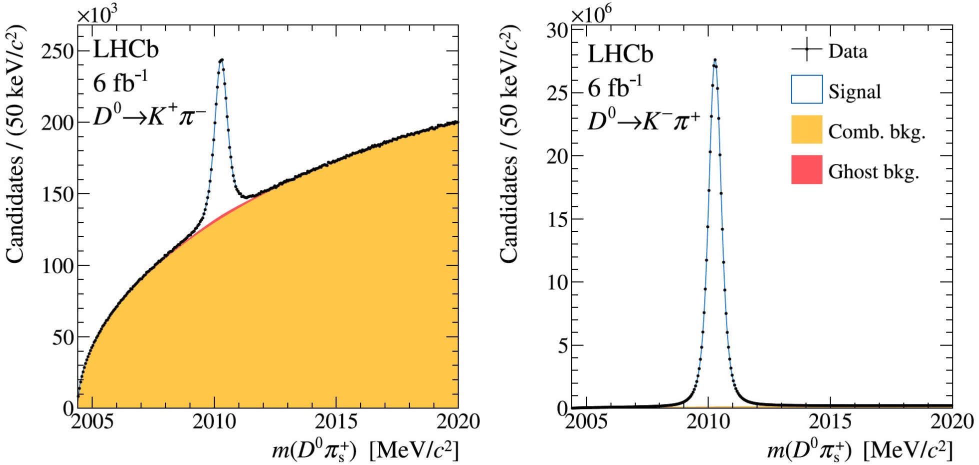
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

$D^0 \to K\pi$ time-dependent CP violation

LHCb-PAPER-2024-008

- Measured with yields: RS ~400 M, WS ~1.6 M





No sign of CP violation

$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

Mixing parameter
Evidence of non 0

No CPV

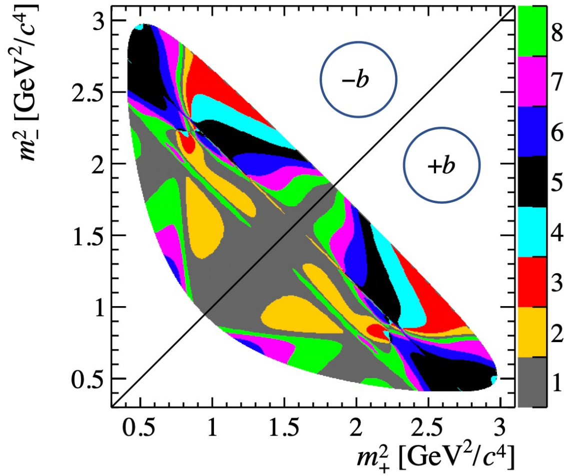
$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

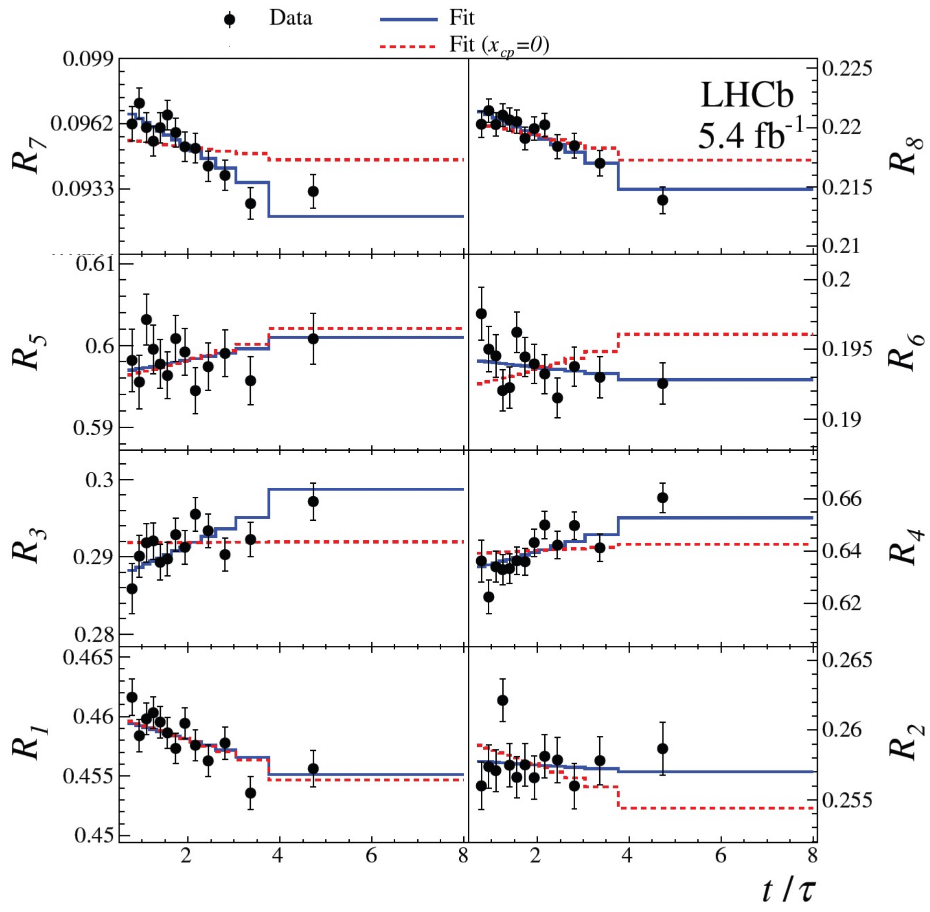
$$c_{K\pi} \approx y_{12} \cos\phi_f^\Gamma \cos\Delta_f + x_{12} \cos\phi_f^M \sin\Delta_f$$

Mixing parameters with $D^0 \to K_S^0\pi^+\pi^-$ decay

PRL127(2021)111801
PRD108(2023)052005

- Ratio of time-dependent decay rate between flipped bins, $m_{K_S^0\pi^+} \leftrightarrow m_{K_S^0\pi^-}$, sensitive to mixing parameters
  - ➢ Known strong phases of D^0 decay, varying across bins



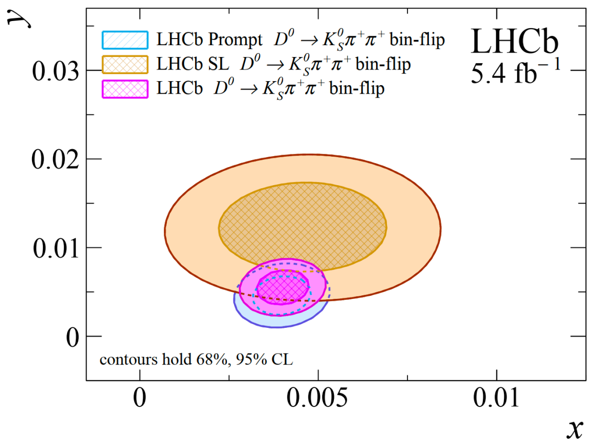


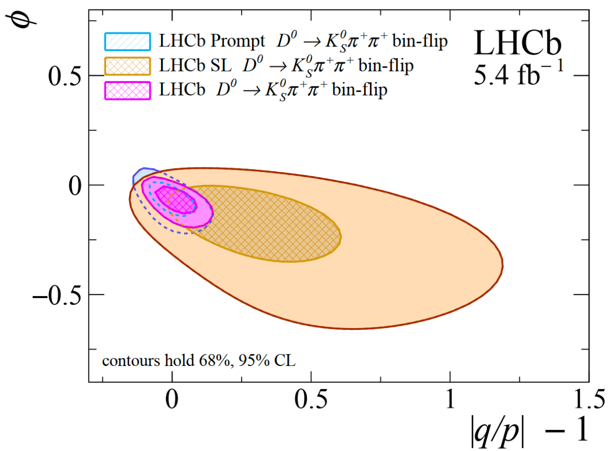
First observation of non-zero $x \equiv \Delta M/\Gamma$

Dominating global fit of D^0 mixing parameters:

$$x = (4.0 \pm 0.5)\times 10^{-3}, \quad y = (5.5 \pm 1.3)\times 10^{-3}$$

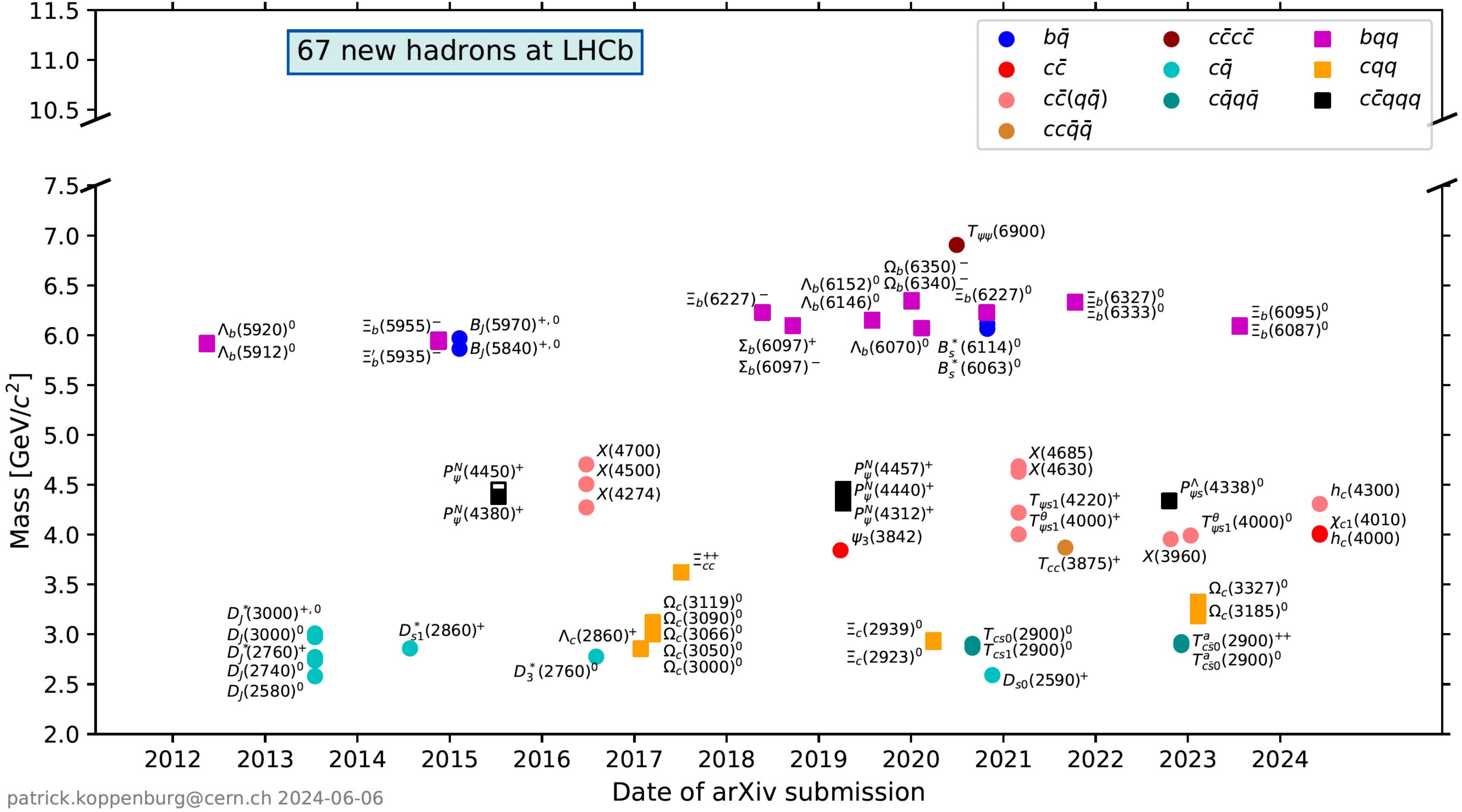
$$|q/p| = 1.012^{+0.050}_{-0.048}, \quad \phi = -0.061^{+0.037}_{-0.044}$$



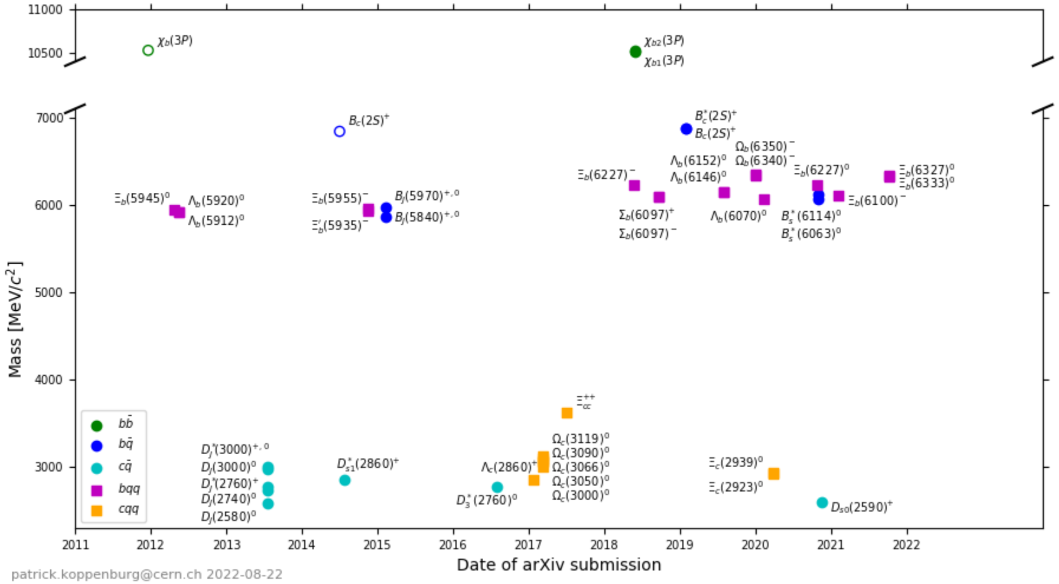


QCD: hadron spectroscopy

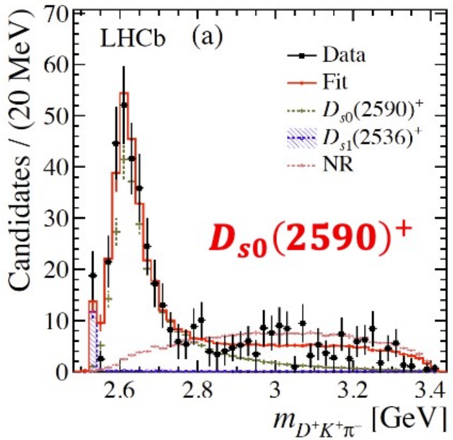
New states observed at LHCb



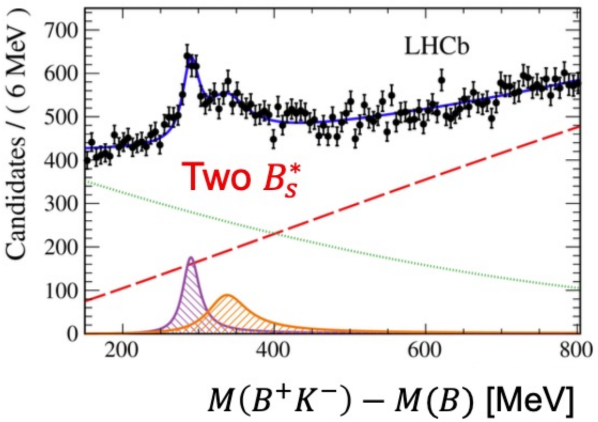
Hadrons: conventional



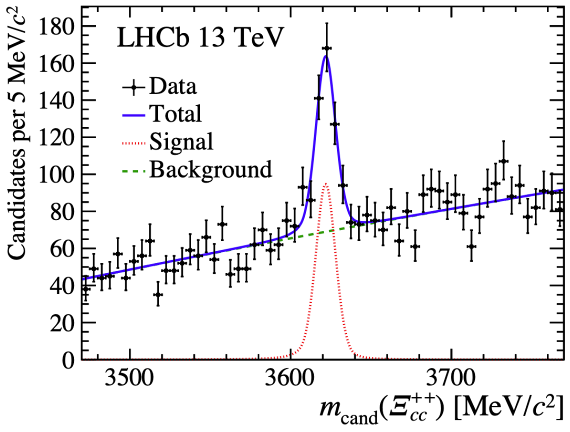
PRL126 (2021) 122002



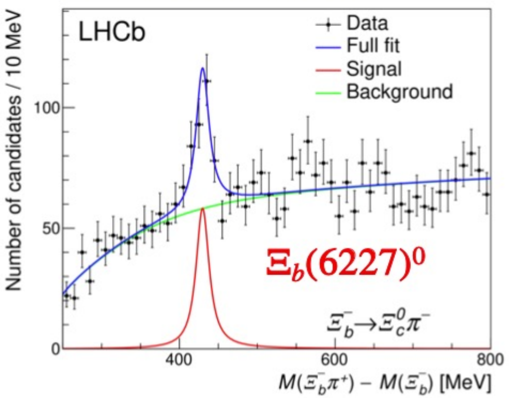
EPJC 81 (2021) 601



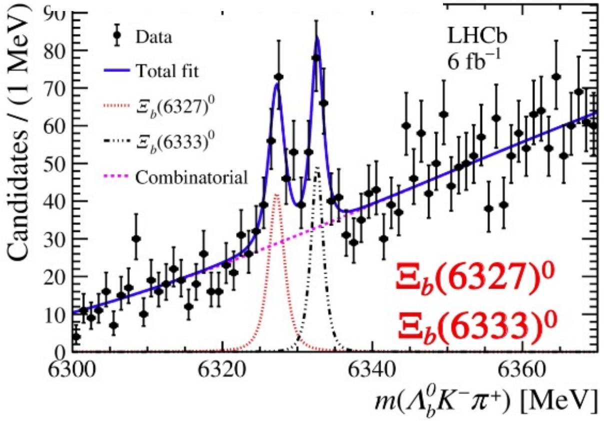
PRL 119 (2017) 112001



PRD103 (2021) 012004

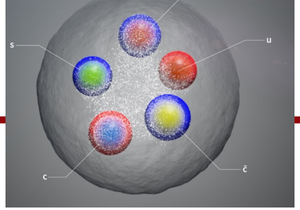
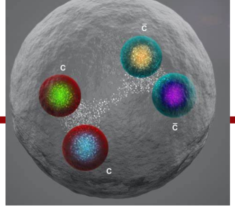


PRL 128 (2022) 162001



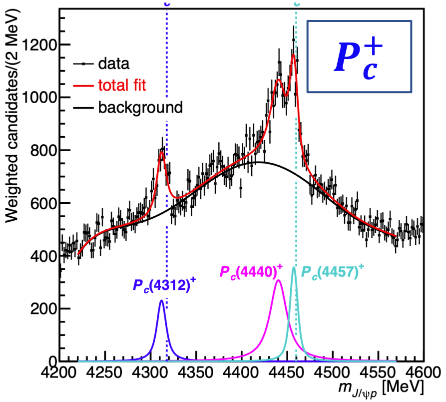
Hadrons: exotic

Expanding of “exotic” zoo

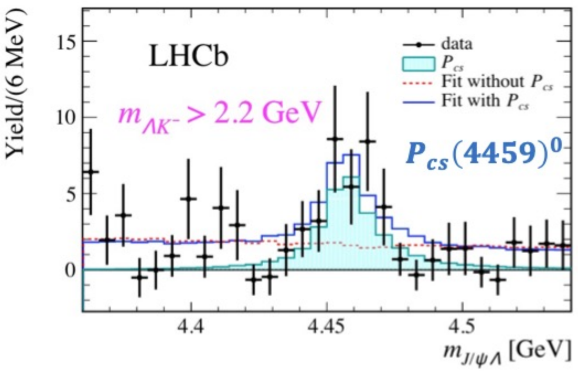



Pentaquarks:

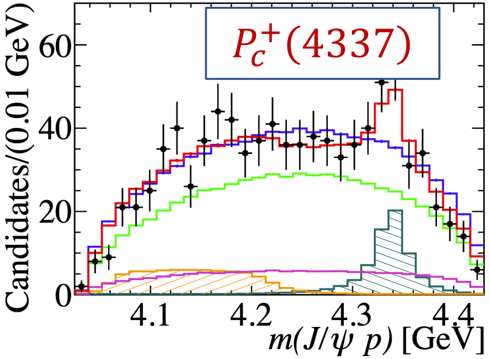
PRL 122 (2019) 22001



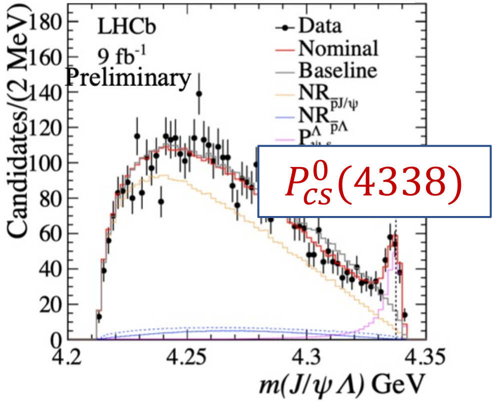
Science Bulletin 66 (2021) 1278



PRL 122 (2019) 22001

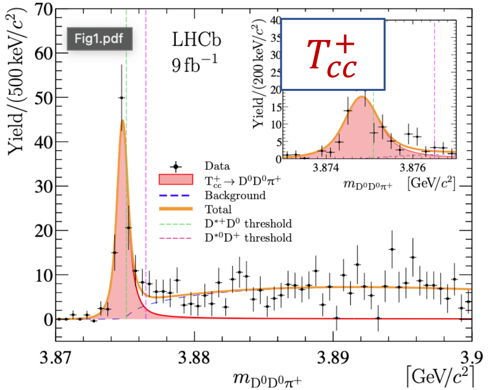


PRL 131 (2023) 031901

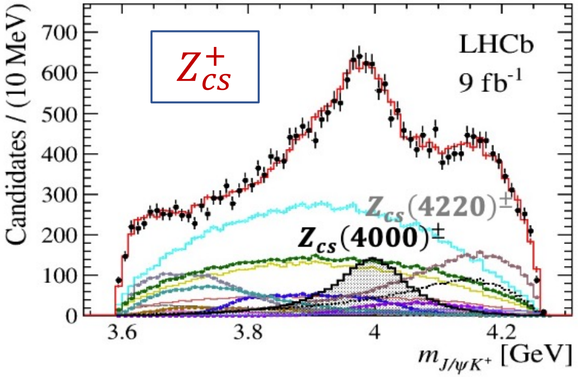


Tetraquarks:

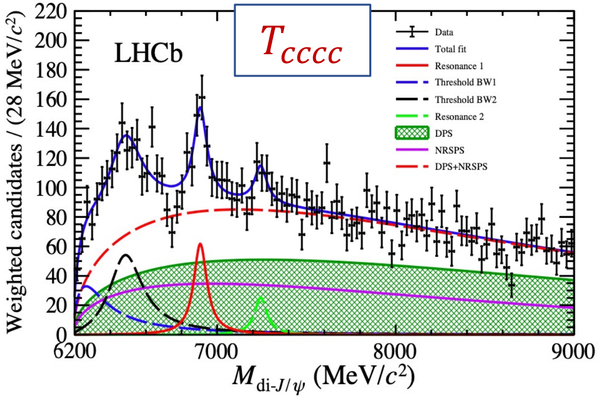
Nature Physics 18 (2021) 751



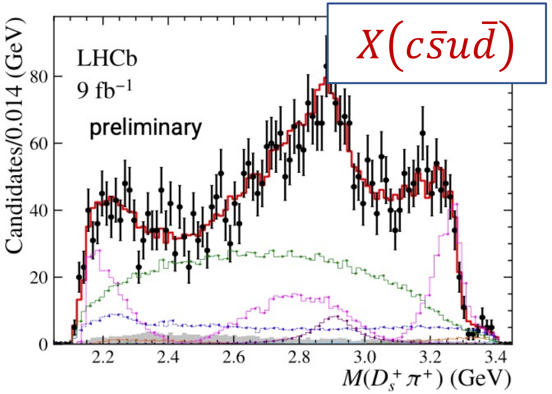
PRL 127 (2021) 082001



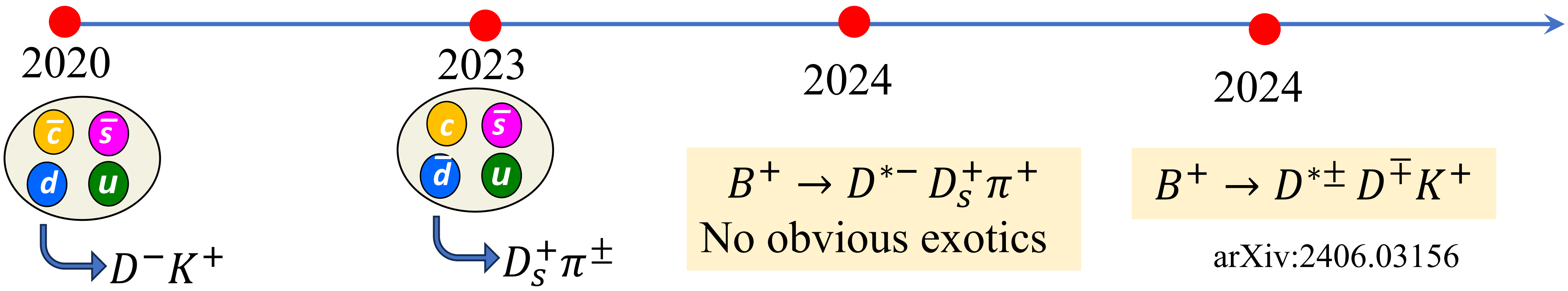
Science Bulletin 65 (2020) 1983



PRL 131 (2023) 041902



Study of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays



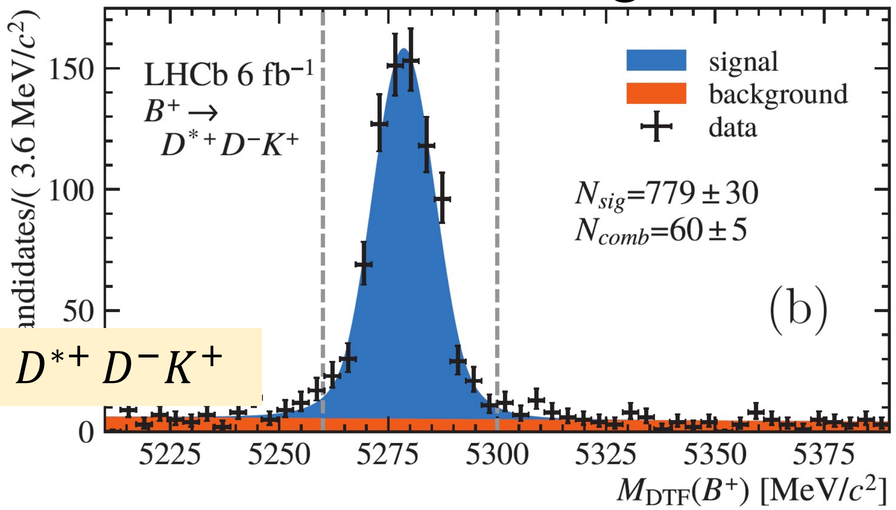
$B^+ \to D^{*-} D_s^+ \pi^+$
No obvious exotics

$B^+ \to D^{*\pm} D^{\mp} K^+$

arXiv:2406.03156

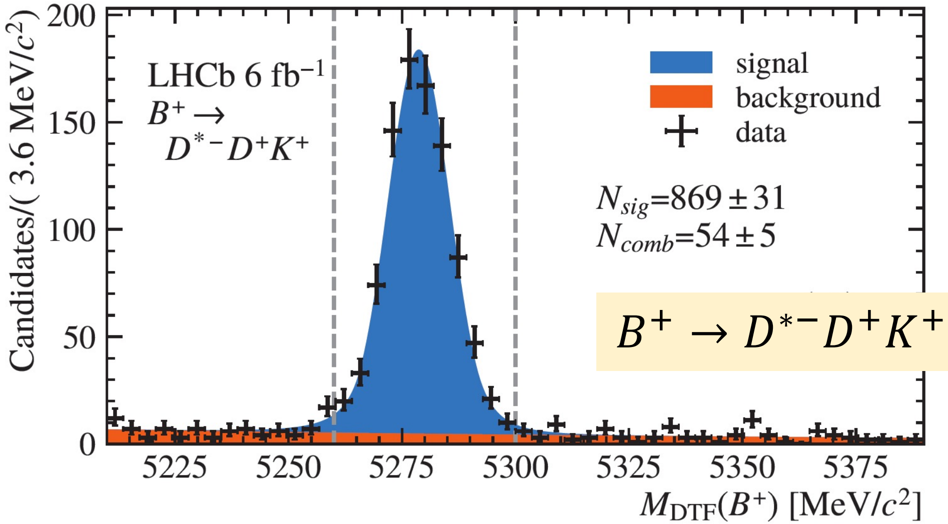
$B^+ \to D^{*\pm} D^{\mp} K^+$ topology similar to $B^+ \to D^- D^+ K^+$ decays

About 1700 signals



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

About 1700 signals



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

$B^+ \to D^{*\pm} D^{\mp} K^+$ amplitude analysis

arXiv:2406.03156

- Joint fit to $B^+ \to D^{*+} D^- K^+$ and $B^+ \to D^{*-} D^+ K^+$ decays
- Possible resonance compositions

Charmonium(-like): $R \to D^{*+}D^-$ and $R \to D^{*-}D^+$ amplitudes linked by C-parity

C-even: $\mathcal{A}_R(D^{*+}D^-) = \mathcal{A}_R(D^{*-}D^+)$ C-odd: $\mathcal{A}_R(D^{*+}D^-) = -\mathcal{A}_R(D^{*-}D^+)$ Measuring C-parity

Open charm tetraquarks: $T_{\bar{c}\bar{s}} \to D^{(*)-}K^+$ or $T_{c\bar{s}} \to D^{(*)+}K^+$

- Significant components:

Component	$J^{P(C)}$	Fit fraction(%) $B^+ \to D^{*+}D^-K^+$	Fit fraction(%) $B^+ \to D^{*-}D^+K^+$	Branching fraction $(\times 10^{-4})$
$\mathrm{EFF}_{1^{++}}$	1^{++}	$10.9^{+2.3}_{-1.2}{}^{+1.6}_{-2.1}$	$9.9^{+2.1}_{-1.0}{}^{+1.4}_{-1.9}$	$0.74^{+0.16}_{-0.08}{}^{+0.11}_{-0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4^{+0.5}_{-1.0}{}^{+1.9}_{-0.7}$	$3.1^{+0.5}_{-0.9}{}^{+1.7}_{-0.6}$	$0.23^{+0.04}_{-0.07}{}^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)^\dagger$	2^{++}	$1.8^{+0.5}_{-0.4}{}^{+0.6}_{-1.2}$	$1.7^{+0.5}_{-0.4}{}^{+0.6}_{-1.1}$	$0.12^{+0.03}_{-0.03}{}^{+0.04}_{-0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1^{+1.0}_{-0.8}{}^{+1.5}_{-0.8}$	$4.6^{+0.9}_{-0.7}{}^{+1.4}_{-0.7}$	$0.35^{+0.07}_{-0.05}{}^{+0.10}_{-0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1^{+1.6}_{-0.9}{}^{+1.3}_{-1.6}$	$9.1^{+1.4}_{-0.8}{}^{+1.2}_{-1.4}$	$0.69^{+0.11}_{-0.06}{}^{+0.09}_{-0.11} \pm 0.06$
$\psi(4040)^\dagger$	1^{--}	$2.8^{+0.5}_{-0.4}{}^{+0.5}_{-0.5}$	$2.6^{+0.5}_{-0.4}{}^{+0.4}_{-0.5}$	$0.19^{+0.04}_{-0.03}{}^{+0.03}_{-0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2^{+0.2}_{-0.5}{}^{+0.2}_{-0.2}$	$1.1^{+0.2}_{-0.5}{}^{+0.2}_{-0.2}$	$0.08^{+0.01}_{-0.03}{}^{+0.02}_{-0.01} \pm 0.01$
$T^*_{\bar{c}\bar{s}0}(2900)^{0\,\dagger}$	0^+	$6.5^{+0.9}_{-1.2}{}^{+1.3}_{-1.6}$	–	$0.45^{+0.06}_{-0.08}{}^{+0.09}_{-0.10} \pm 0.04$
$T^*_{\bar{c}\bar{s}1}(2900)^{0\,\dagger}$	1^-	$5.5^{+1.1}_{-1.5}{}^{+2.4}_{-1.6}$	–	$0.38^{+0.07}_{-0.10}{}^{+0.16}_{-0.11} \pm 0.03$

(New) $R \to D^{*\pm}D^{\mp}$ states, only conventional J^{PC} Charmonium or tetraquarks?

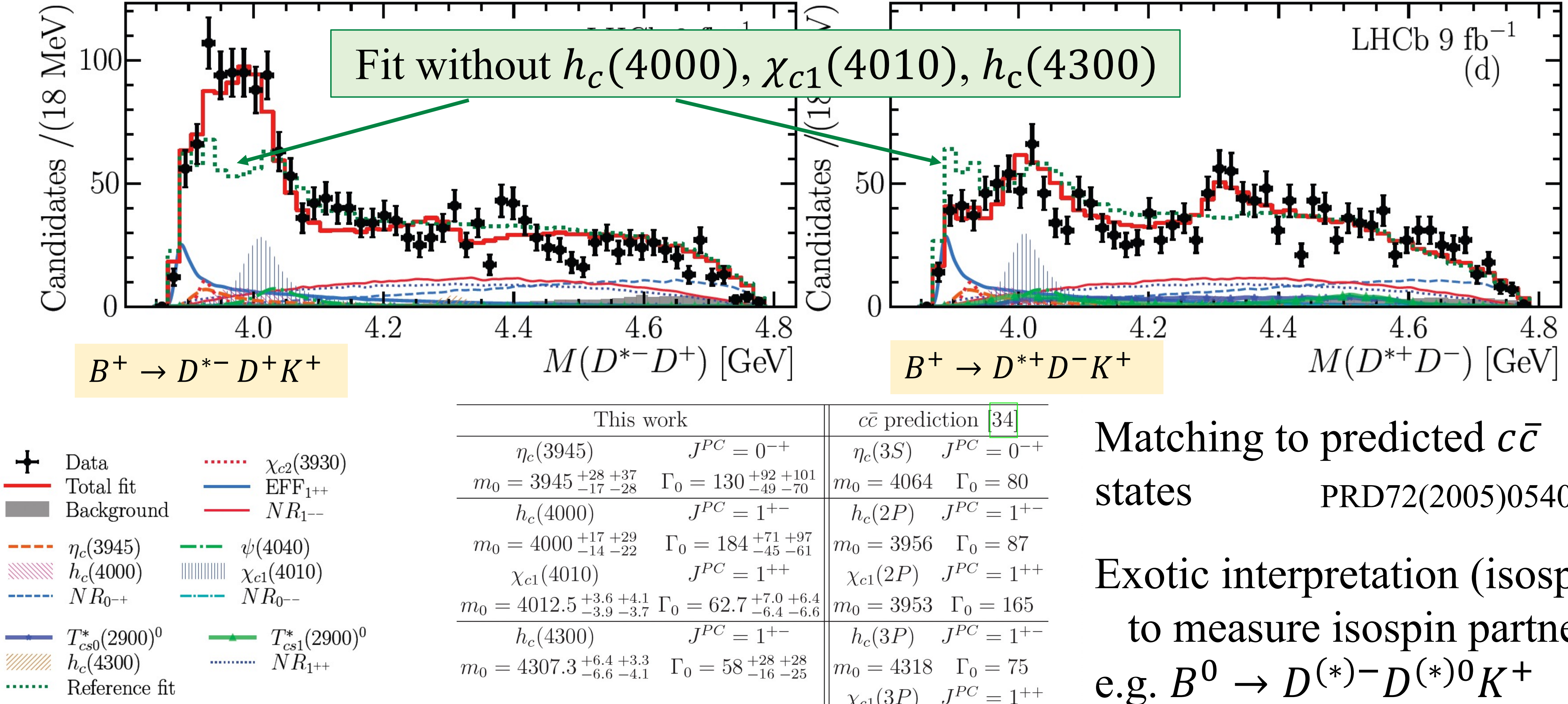
Rediscover $T_{c\bar{s}0} \to D^-K^+$

+ 4 non-resonant contributions with ≈ 50% fraction

Charmonium-like states

arXiv:2406.03156

- Different $m(D^{*\pm} D^{\mp})$ distributions due to interference of two C-parities



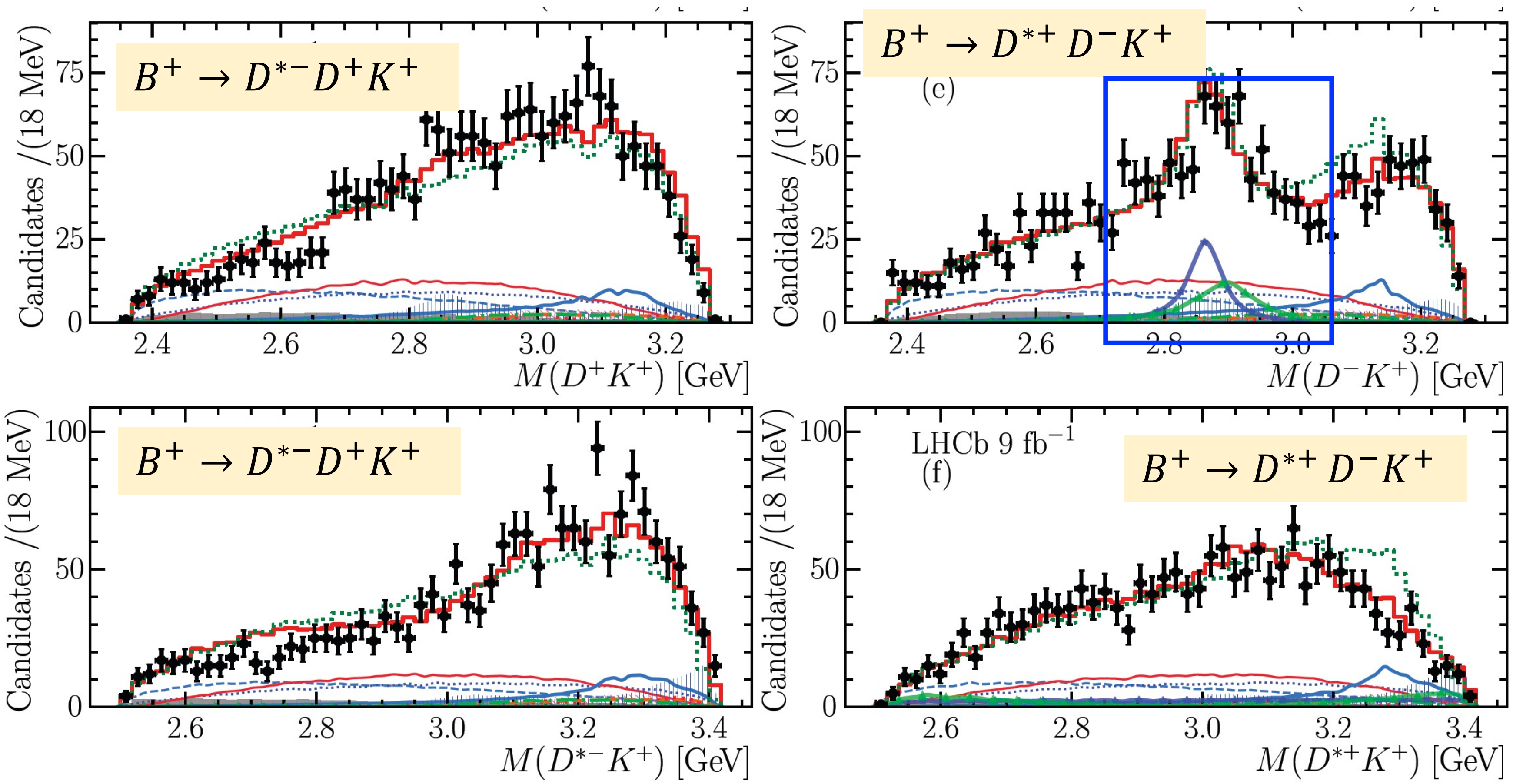
This work		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 3956$	$\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$	$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$	$m_0 = 3953$	$\Gamma_0 = 165$
$h_c(4300)$	$J^{PC} = 1^{+-}$	$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$	$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4317$	$\Gamma_0 = 39$

Matching to predicted $c\bar{c}$ states PRD72(2005)054026

Exotic interpretation (isospin): to measure isospin partners e.g. $B^0 \to D^{(*)-} D^{(*)0} K^+$

Open charm tetraquarks

arXiv:2406.03156



Statistical significance

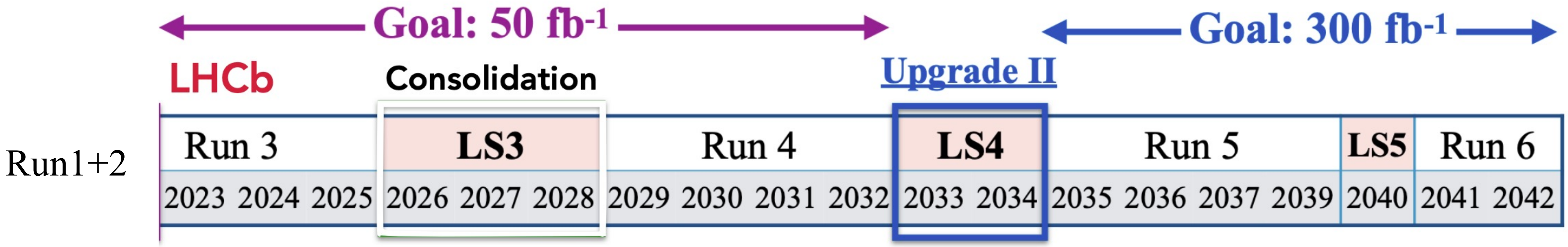
$T^*_{cs0}(2900)^0$: 11σ

$T^*_{cs1}(2900)^0$: 9.2σ

No obvious structure in $D^{*\pm}K^+$ and D^+K^+ spectra

Future prospects

LHC(b) timeline



$\mathcal{L} = 4 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$

1.1 visible interactions / crossing

8 fb^{-1} collected

$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$

5.5 visible interactions / crossing

50 fb^{-1} collected

$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

55 visible interactions / crossing

300 fb^{-1} collected

LHCb Upgrade II sensitivities

CERN Yellow Rep.Monogr. 7 (2019) 867

Table 10.1: Summary of prospects for future measurements of selected flavour observables. The projected LHCb sensitivities take no account of potent detector improvements, apart from in the trigger. Unless indicated otherwise the Belle-II sensitivies are taken from Ref. [568].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0\to\mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c l^- \bar{\nu}_l$ LUV studies					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	
A_Γ $(\approx x\sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

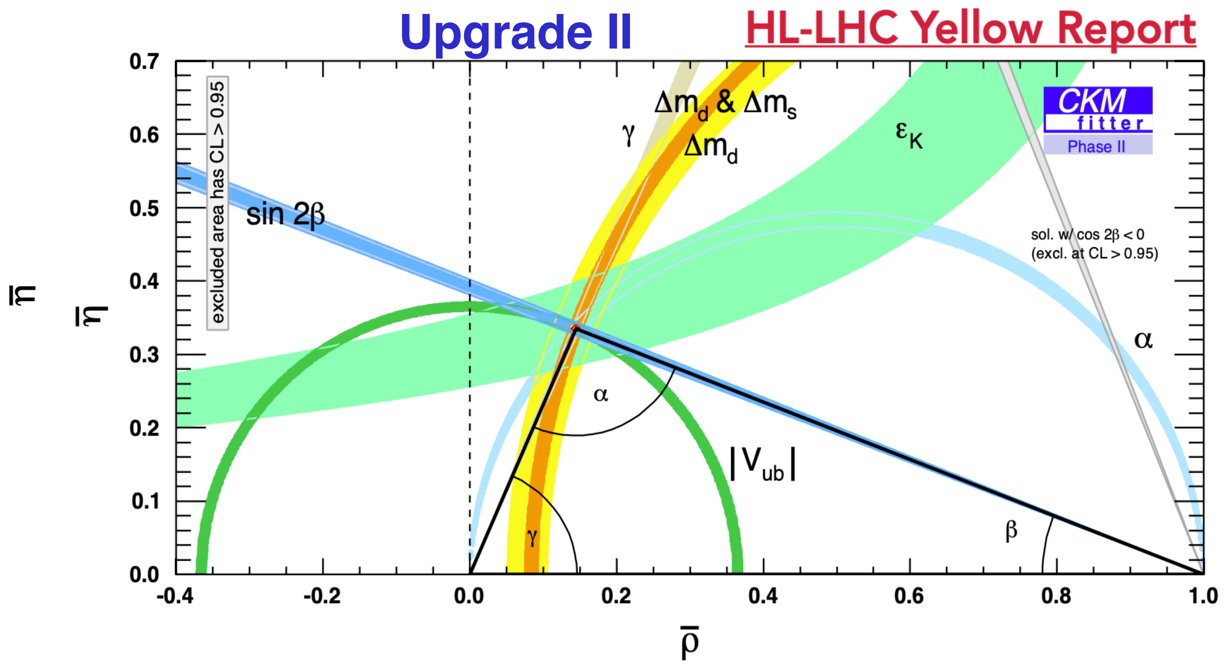
Uncertainty reduced by factor ~10

1% level precision

High precision charm physics

Summary

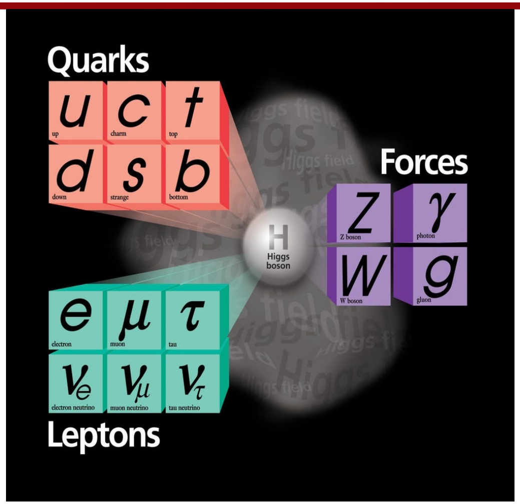
- LHC pushes flavor physics to new frontier
  - ➢ Precision measurements of CKM matrix: $\beta, \gamma, V_{qb}, \phi_s$
  - ➢ $b \to sl^+l^-$: anomalies or underestimated QCD effects?
  - ➢ Charm mixing/CPV reachable
  - ➢ Ongoing excitement for hadron spectroscopy



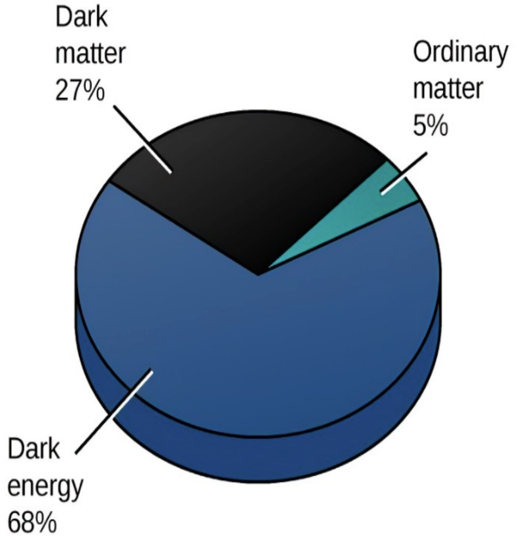
Backup slides

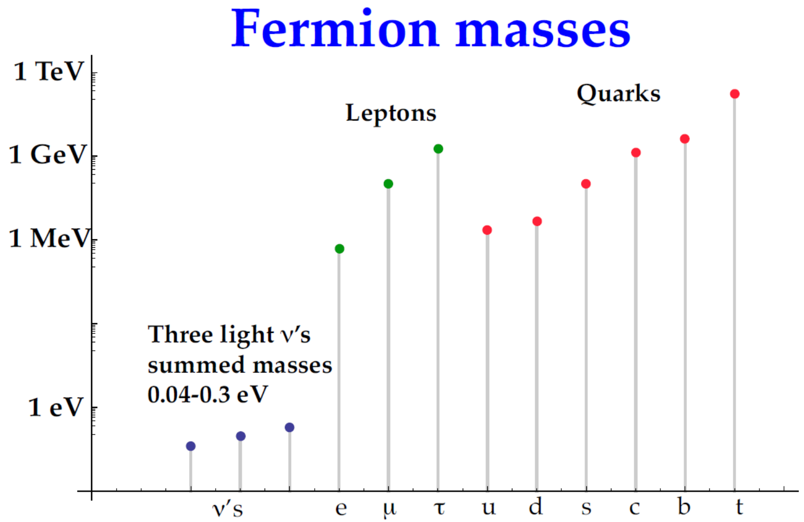
Introduction

- The **Standard Model** (SM): remarkably successful at describing **particles of nature** and **interactions between them**



- But answered questions/observations
  - Dark matter, dark energy
  - Baryon Asymmetry in the Universe (BAU): $n_{\mathrm{B}}/n_{\overline{\mathrm{B}}} \gg 1$
  - Quark/lepton family structure and masses
  - …





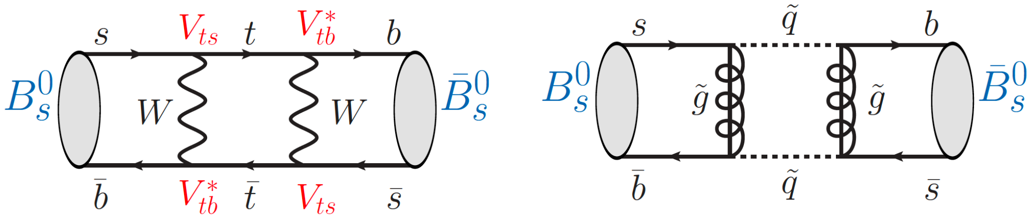
Must there be New Physics (NP)

Flavor physics

- Most SM parameters related to flavor structure

  Yukawa couplings (9), Quark mixing (4), Gauge couplings (3), Higgs potential (2)

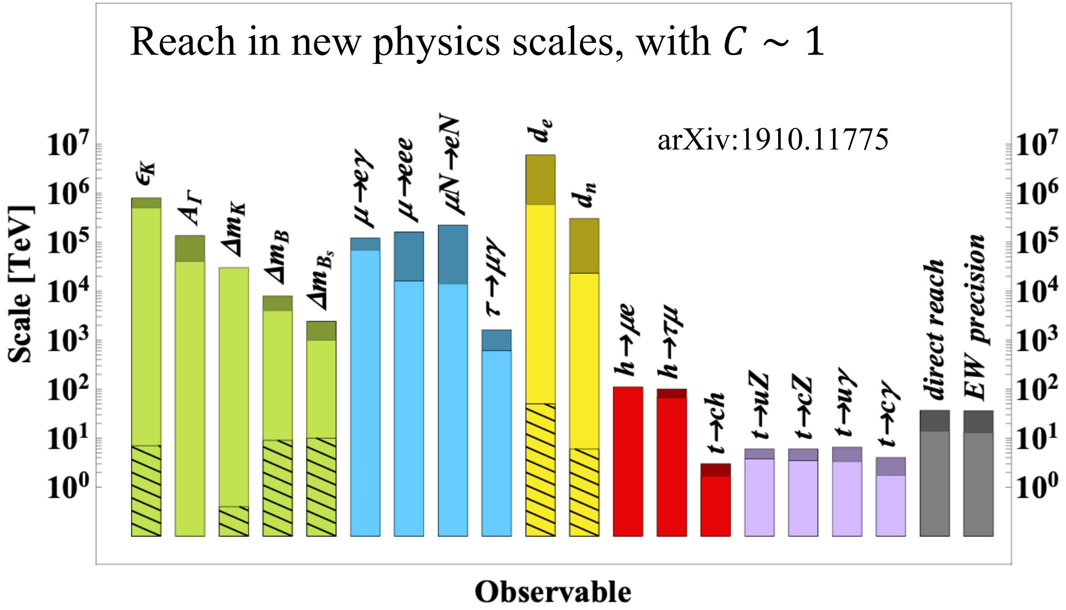
- General idea of flavor physics for NP
  - ➢ Possible new physics enters in (low-energy) quantum loops
  - ➢ Deviations w.r.t SM → possible new physics



Complementary to direct detection of BSM particles/forces, possible to probe energy scales beyond collider energy

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C_5}{\Lambda_M}\mathscr{O}^{(5)} + \sum_a \frac{C_6^a}{\Lambda^2}\mathscr{O}_a^{(6)} + \cdots$$

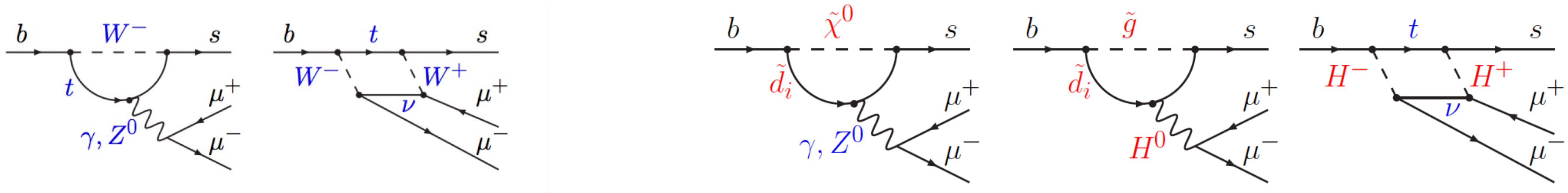
$$\delta_{\text{NP}} \sim C_{n+4}/\Lambda^n, \quad \Lambda^n \sim C_{n+4}/\delta_{SM}$$



CP violation, mixing, (forbidden) rare decays, lepton flavor universality/violation, EDM…

Quark flavor physics

- SM rare/forbidden decays, may be enhanced/allowed by new physics



E.g.: Flavor Changing Neutral Current (FCNC), $b \to s$…

- Charge conjugation-Parity (CP) violation
  - One of the Sakharov conditions to explain BAU
  - Incorporated in SM by CKM matrix, **quark flavor eigenstates = mixing of mass eigenstates**

$$V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitary matrix
- Four parameters: 3 mixing angle and 1 phase which generates CPV

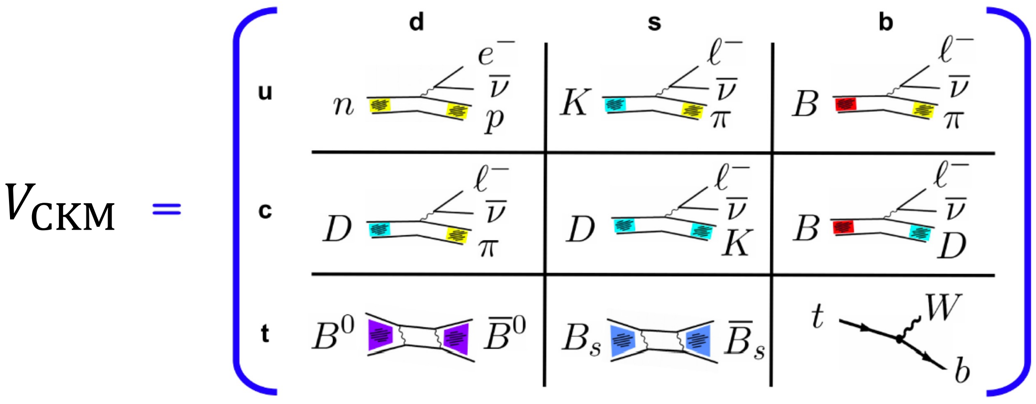
- Is CKM the only source of CPV? No, CPV from CKM far below that required for BAU

BAU from CKM $J_Y = J_{\text{CP}} \frac{(m_t^2 - m_c^2)}{v^2/2} \frac{(m_t^2 - m_u^2)}{v^2/2} \frac{(m_c^2 - m_u^2)}{v^2/2} \frac{(m_b^2 - m_s^2)}{v^2/2} \frac{(m_b^2 - m_d^2)}{v^2/2} \frac{(m_s^2 - m_d^2)}{v^2/2} \simeq \mathcal{O}(10^{-22})$ $\ll 10^{-10}$

Search for new source of CPV

- Consistency test of CKM mechanism

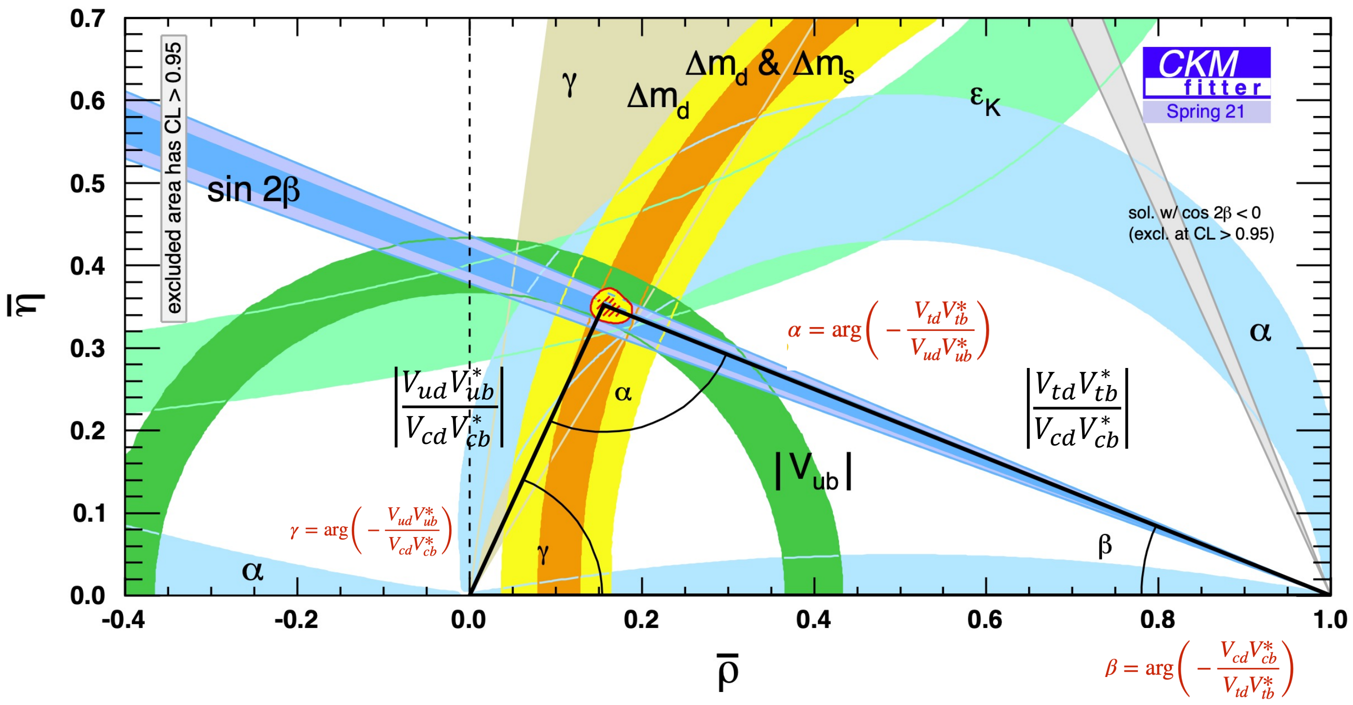
  4 parameters determine all quark mixings



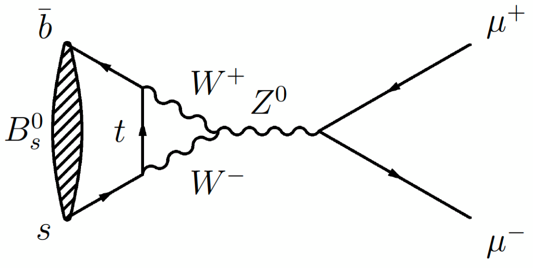
- Unitarity of 3×3 V_{CKM} → 6 triangles in complex plane

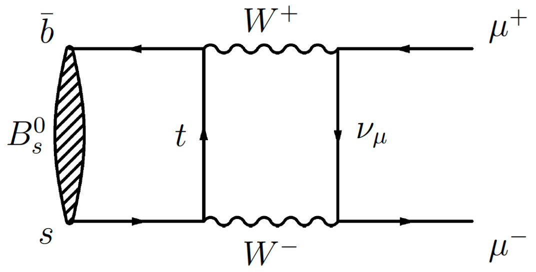
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\Rightarrow \alpha + \beta + \gamma = 180°$$



$B \to l^+ l^-$ decay





$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\lambda) \mathcal{O}_i(\lambda)$$

Wilson coefficients

Local operators

$$\mathcal{O}_9^{(\prime)} = (\bar{s} P_{\mathrm{L(R)}} b)\,(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{s} P_{\mathrm{L(R)}} b)\,(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

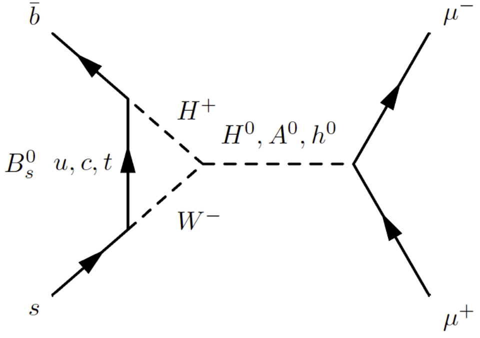
SM prediction:

$$\mathscr{B}(B_q^0 \to \mu^+\mu^-)_{\mathrm{SM}} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{\mathrm{SM}} V_{tb} V_{tq}^*|^2 f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1}{1-y_q}$$

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.03 \pm 0.05) \times 10^{-10}$$

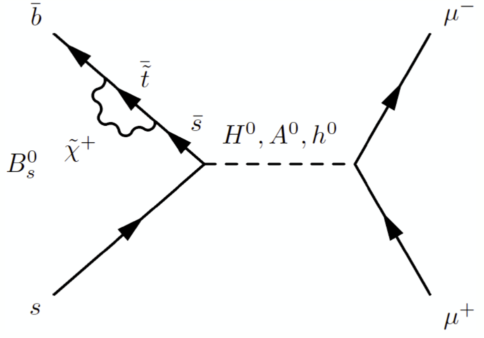
BSM models

2HDM



$\mathcal{B} \propto \tan^4\beta$

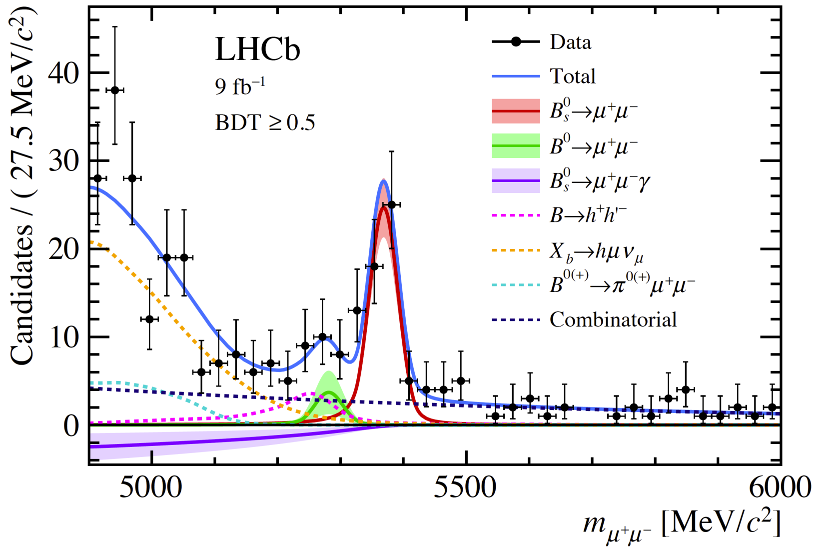
SUSY



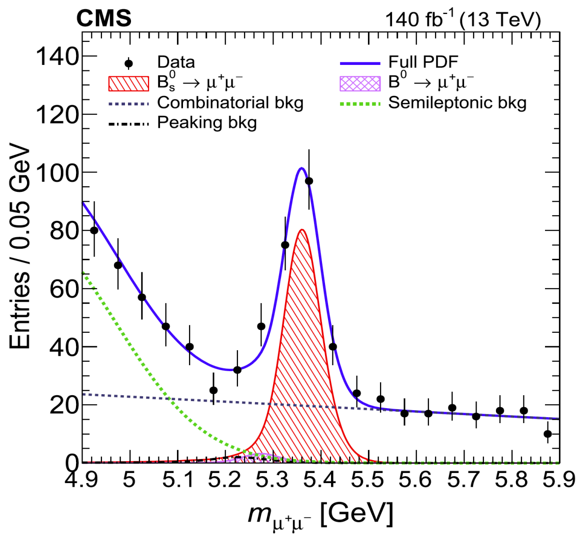
$\mathcal{B} \propto \tan^6\beta$

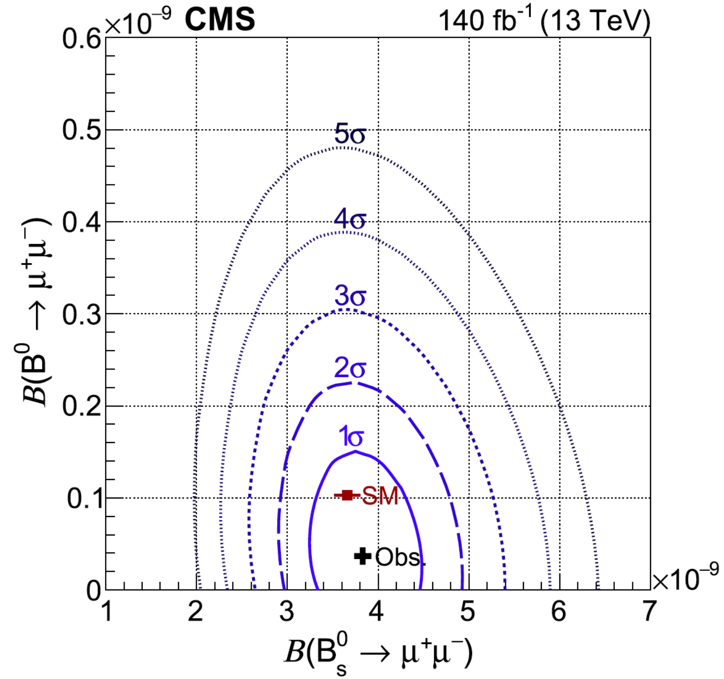
$B \to l^+l^-$ decay: experimental

PRL128(2022)041801



PLB842(2023)137955





LHCb+CMS data

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.48}_{-0.43})\times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9\times 10^{-10} @ \text{ 95 CL}$$

Precision reaching SM calculations, further reduced in Run3 and beyond

Future prospects:

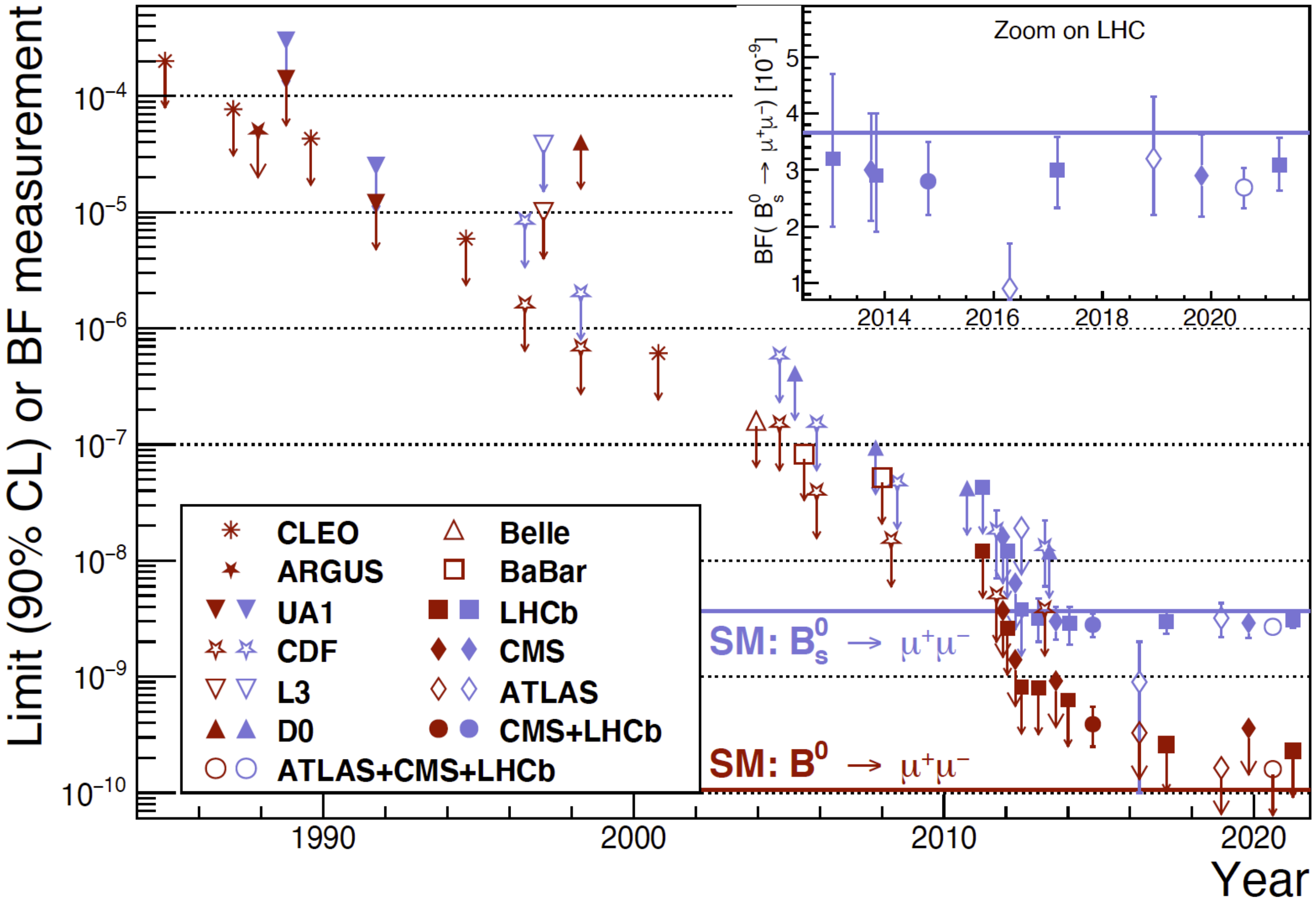
$B_q^0 \to e^+e^-, \tau^+\tau^-$ decays?

$$\mathcal{B}(B_q^0 \to l^+l^-) \propto m_l^2$$

Related measurements:

$D^0 \to l^+l^-, K_S^0 \to l^+l^-$

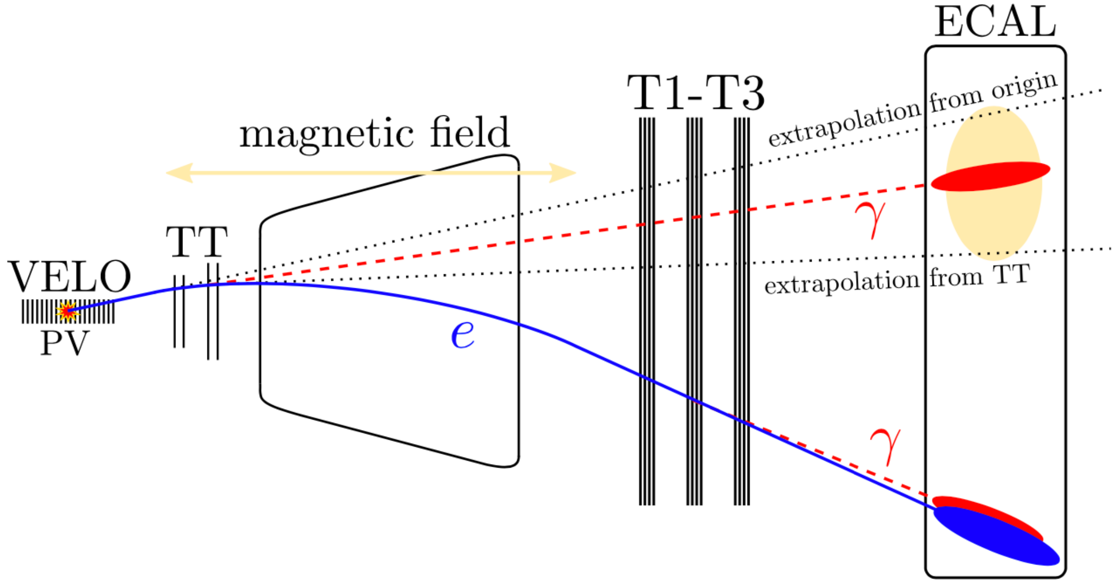
History of $B \to \mu^+\mu^-$

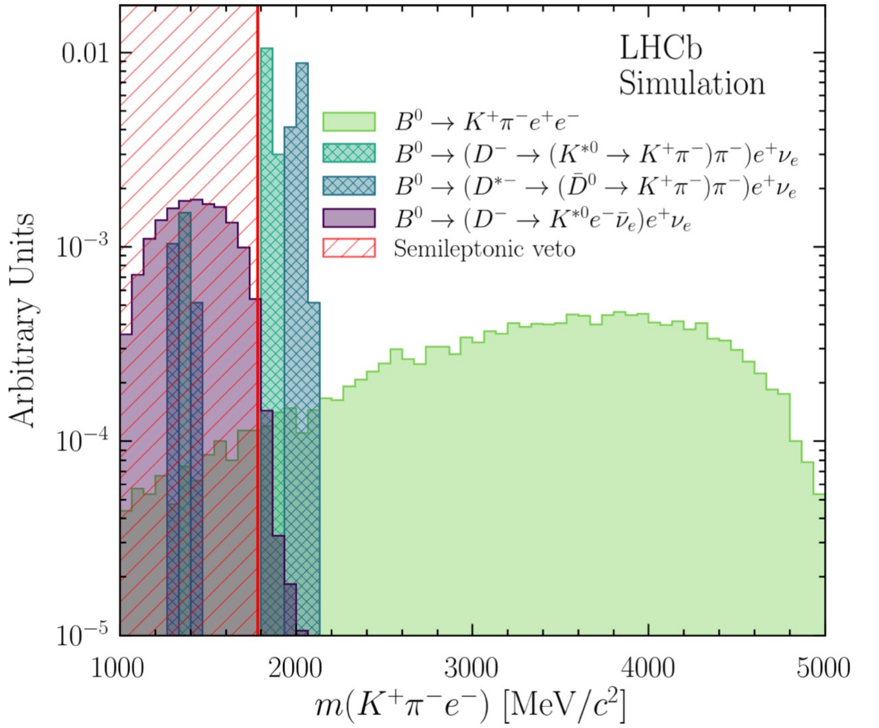


Run3+4 (2030, 50 fb-1) projections

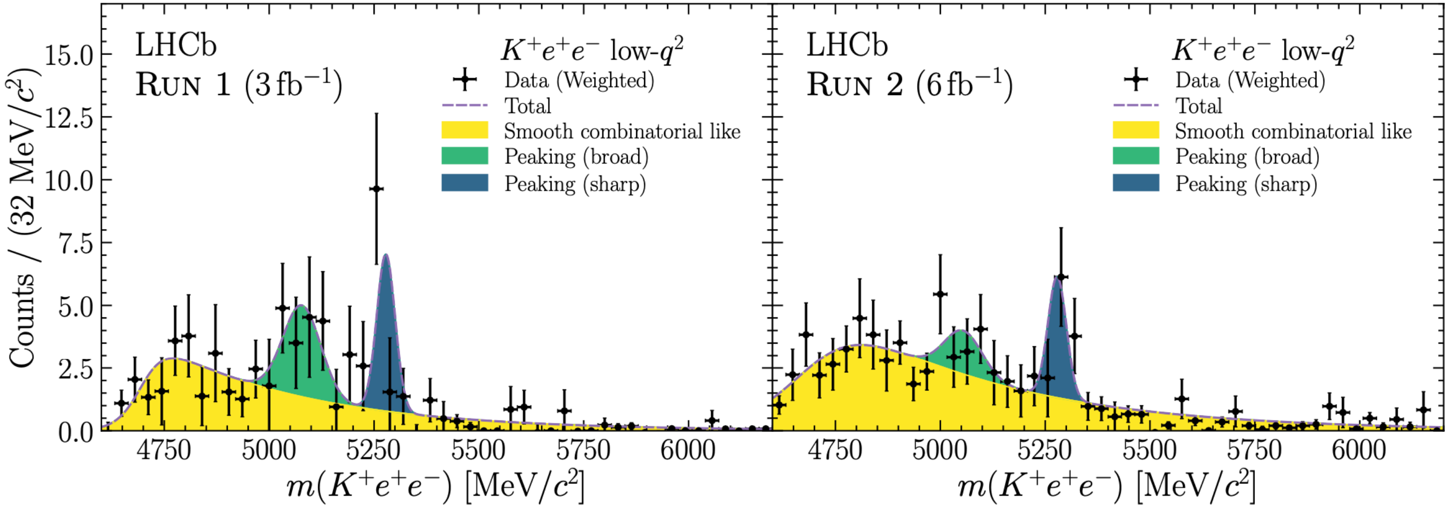
Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [213]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [243, 257]	4°	0.9°	negligible
	γ ($B_s^0 \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Bremsstrahlung recovery and misID

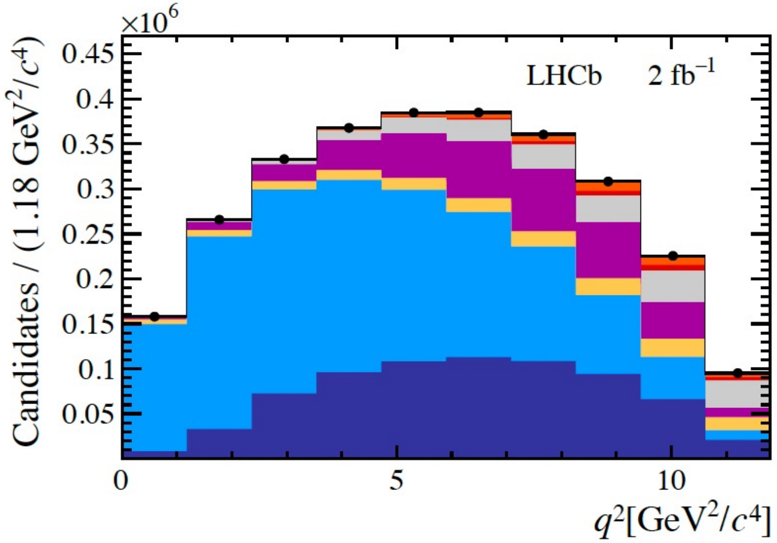


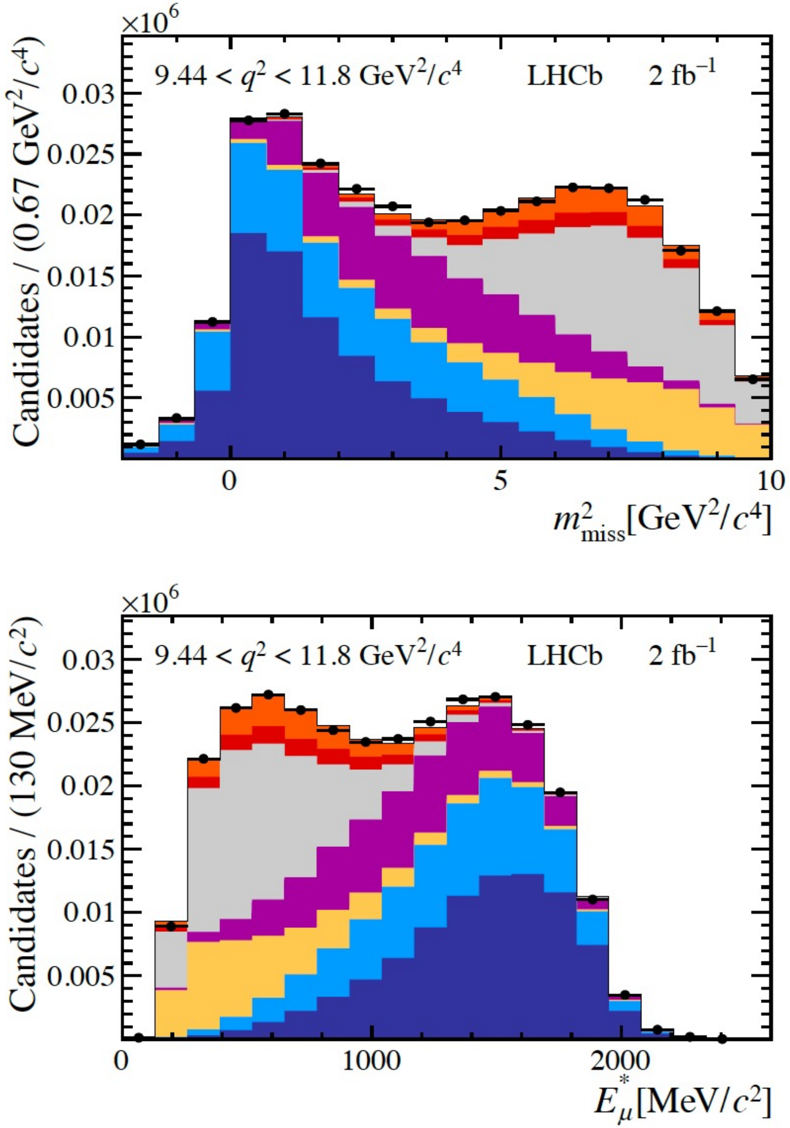


Background of hadronic decays ($B \to Khh$) are peaking

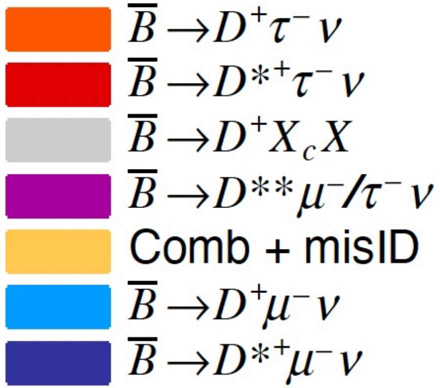


$R(D^+)$ and $R(D^{*+})$ with $D^{*+} \to D^+\pi^0$

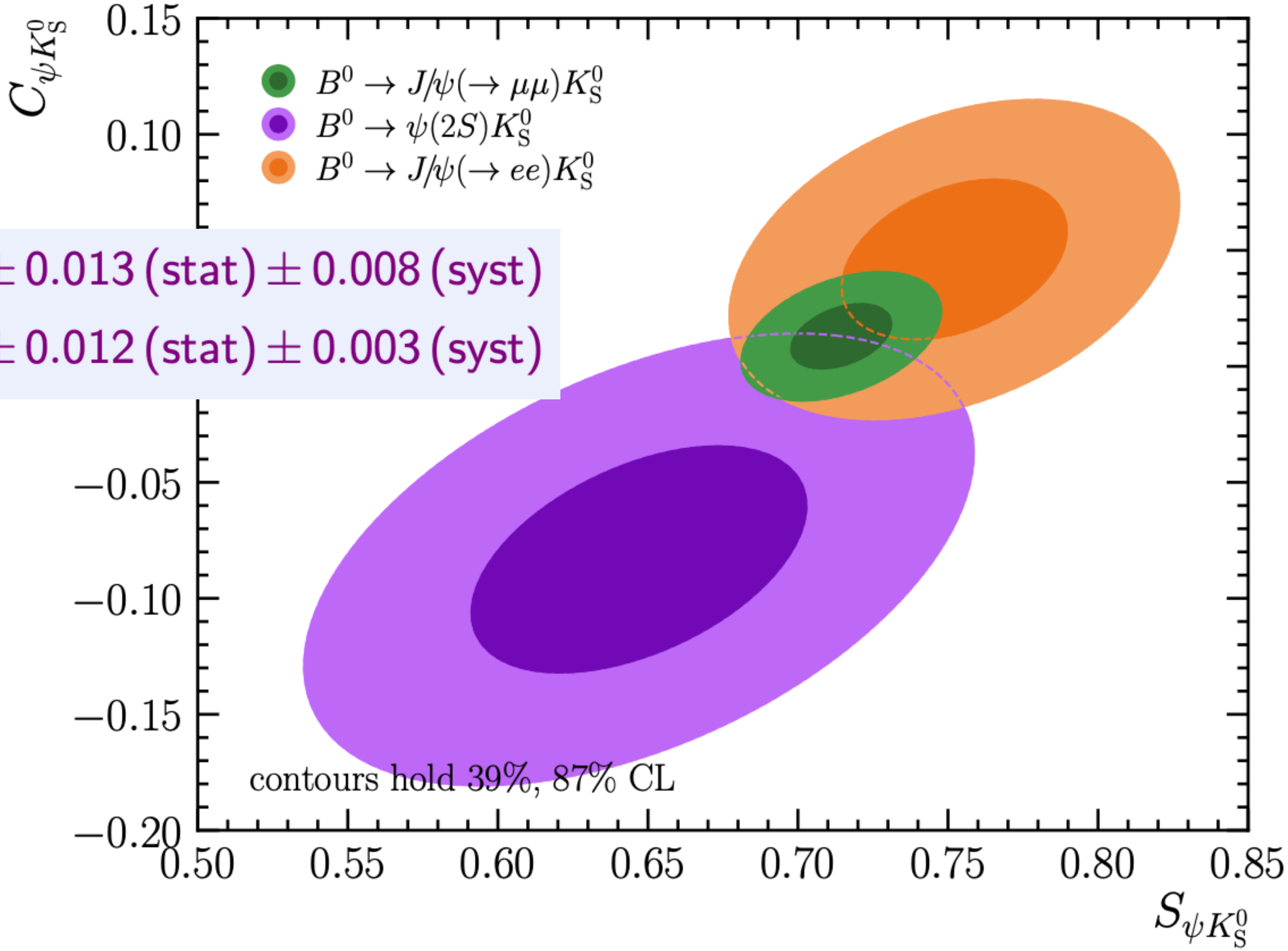




arXiv:2406.033871



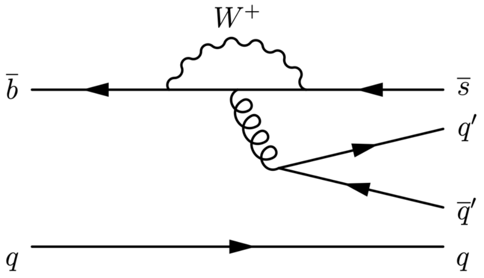
$\sin 2\beta$



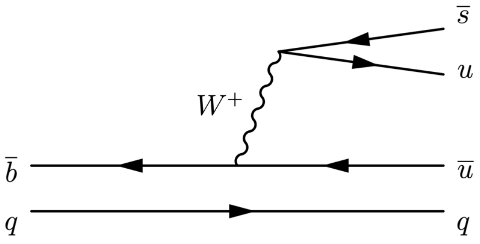
$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$

$K - \pi$ puzzle

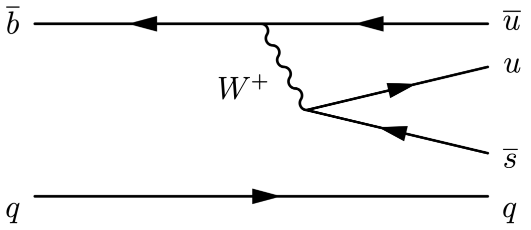
Considering all possible diagrams



P **(color suppressed)**



T



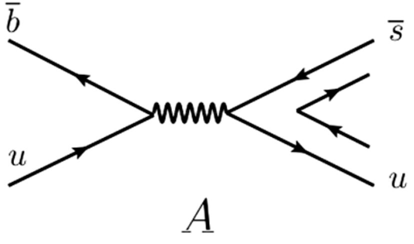
$\boldsymbol{T_c}$ **(color suppressed)**

$B^0 \to K^+\pi^-: P + T$

$B^+ \to K^+\pi^0: P + T + T_c$

$B^0 \to K^0\pi^0: P + T_c$

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



Weak annihilation

New equation

$$\mathcal{A}^{CP}(K^+\pi^-)+\mathcal{A}^{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}^{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^0)}\frac{\tau_0}{\tau_+}+\mathcal{A}^{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

CPV in $\Lambda_b^0 \to DpK^-$ decays

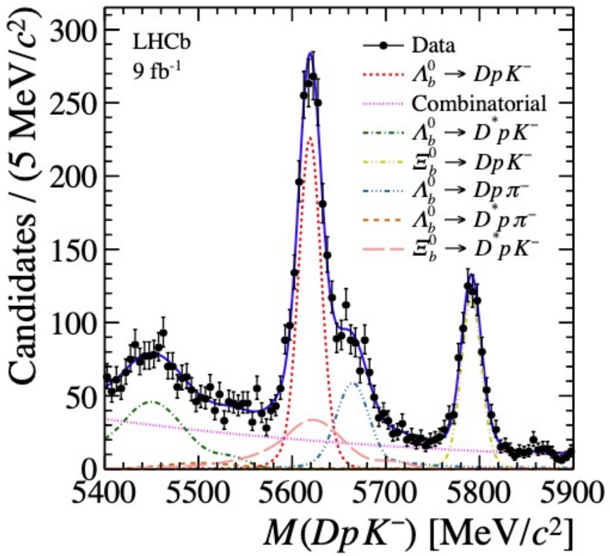
arXiv:2109.02621

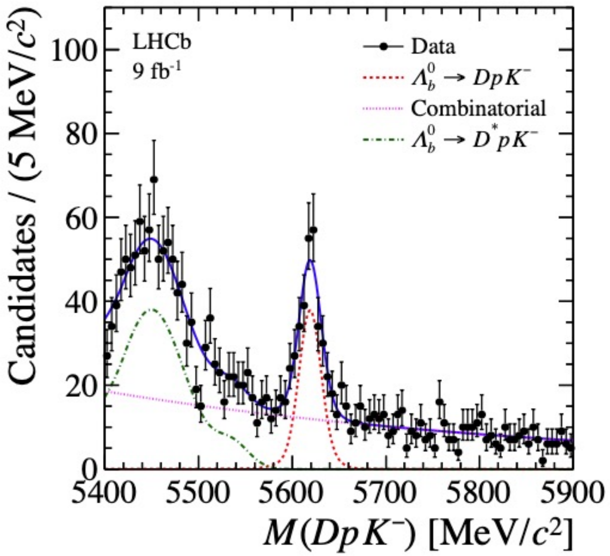
- A new channel sensitive to γ angle

Favored ($b \to c$)
$\Lambda_b^0 \to [K^-\pi^+]_D pK^-$

Suppressed ($b \to u$)
$\Lambda_b^0 \to [K^+\pi^-]_D pK^-$

No relative color suppression





$$R \equiv \frac{\mathcal{B}([K^-\pi^+]_D pK^-)}{\mathcal{B}([K^+\pi^-]_D pK^-)} = 7.1 \pm 0.8^{+0.4}_{-0.3}$$

$$A_{\mathrm{CP}}([K^+\pi^-]_D pK^-) = 0.12 \pm 0.09^{+0.02}_{-0.03}$$

Interference and CP may be large

CPV in $\Xi_b^- \to pK^-K^-$ decays

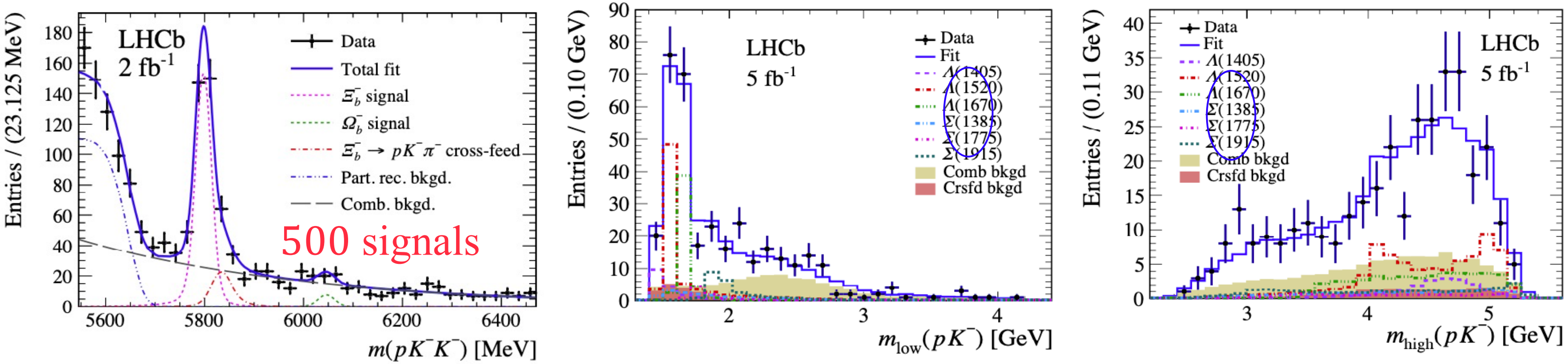
PRD 104 (2021) 052010

- Charmless $b \to s$ transition, CPV as for $B \to hhh$ in mesons?
- Amplitude analysis with 6 resonances

Mass spectrum

$m_{\text{low}}(pK^-)$

$m_{\text{high}}(pK^-)$



Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

No evidence of CPV

$$\mathcal{B}\left(\Xi_b^- \to pK^-K^-\right) = (2.3 \pm 0.9) \times 10^{-6}$$

Magnitude similar to $\mathcal{B}(B \to 3h)$

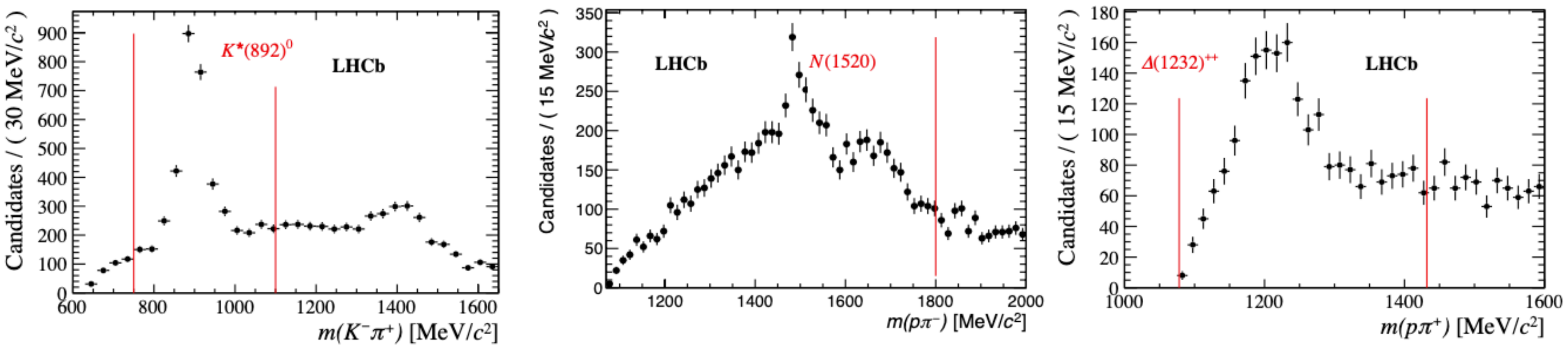
CPV in $\Xi_b^0, \Lambda_b^0 \to phhh$ decays

EPJC 79 (2019) 745

- Six decay modes from 0.5-10K signals (3 fb^{-1})
- Abundant resonant structures

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+\pi^-$ $\Lambda_b^0 \to pK^-K^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$ $\Lambda_b^0 \to pK^-K^+K^-$

Example: $\Lambda_b^0 \to pK^-\pi^+\pi^-$



- Global and local A_{CP} around resonances studied, relative to CKM favored modes

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (-17 \pm 11 \pm 1)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\,\%$$

- With experimental precision of $\geq 1\%$ no evidence of A_{CP} found.
- Baryon A_{CP} small compared to mesons

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

PRD 102 (2020) 051101

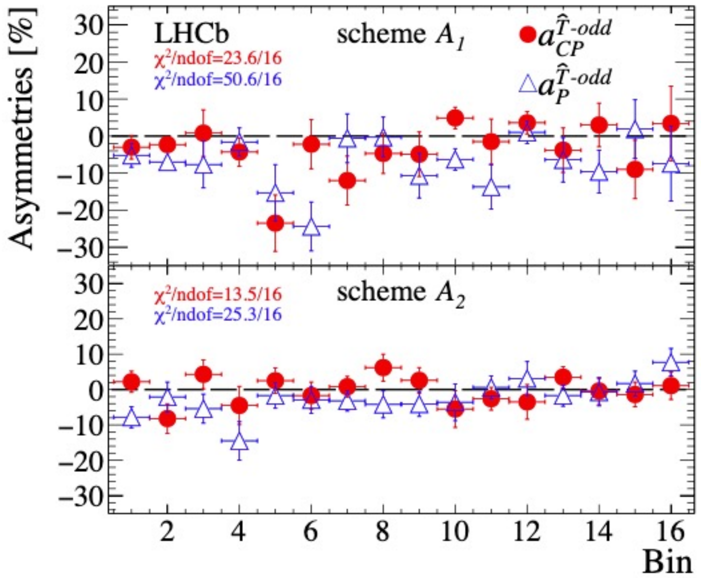
- Triple product $C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi^-_{\text{fast}}} \times p_{\pi^+})$, $\bar{C}_{\hat{T}} \equiv \vec{P}_p \cdot (\vec{p}_{\pi^+_{\text{fast}}} \times p_{\pi^-})$
- Triple product asymmetry: $A_{\hat{T}} = \langle C_{\hat{T}} \rangle$, $\bar{A}_{\hat{T}} = \langle -\bar{C}_{\hat{T}} \rangle$

CP violating: $a_{\text{CP}} = (A_{\hat{T}} - \bar{A}_{\hat{T}})/2 = (-0.7 \pm 0.7 \pm 0.2)\%$. No hint of CPV

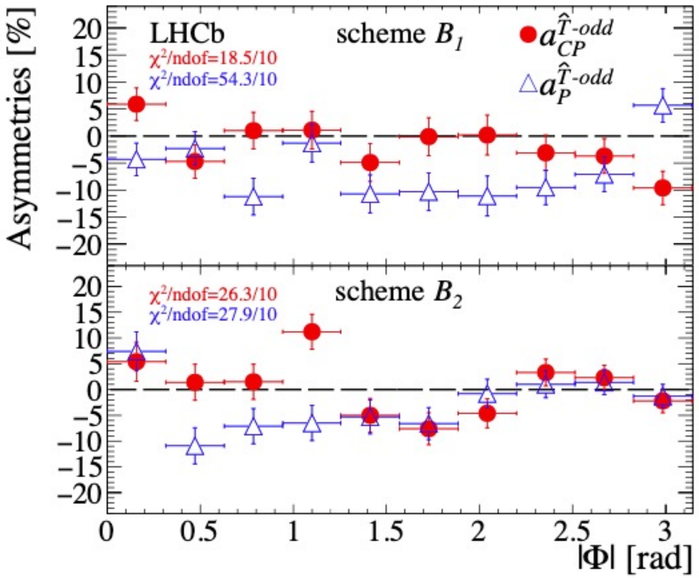
Parity violation observed: $a_{\text{P}} = (A_{\hat{T}} + \bar{A}_{\hat{T}})/2 = (-4.0 \pm 0.7 \pm 0.2)\%$

No CPV of triple product asymmetry in phase space either

Binning according to N^{*+}/Δ^{++} resoances



Φ: angle between $\vec{p}_p \times \vec{p}_{\pi^-_{\text{fast}}}$ and $\vec{p}_{\pi^+} \times \vec{p}_{\pi^-_{\text{slow}}}$



Charm mixing

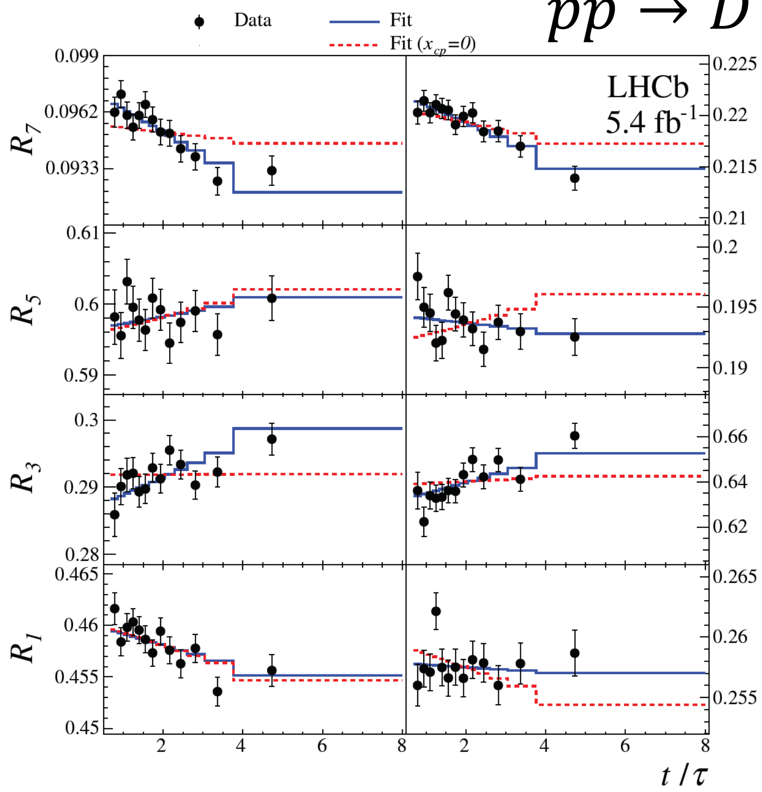
$$R_b^{\pm}(t) \approx r_b - \sqrt{r_b}[(1-r_b)c_b y - (1+r_b)s_b x]\Gamma t$$

PRL127(2021)111801
PRD108(2023)052005

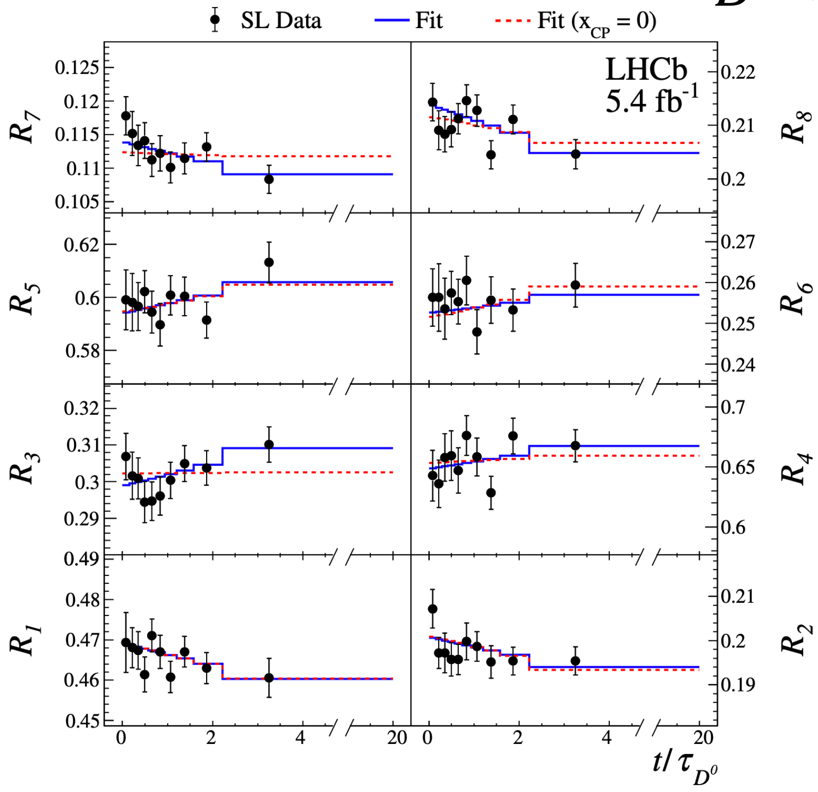
c_b, s_b: $D^0 \to K_S^0\pi^+\pi^-$ strong phases

$x = \Delta M/\Gamma, y = \Delta\Gamma/2\Gamma$

$pp \to D^{*+}$

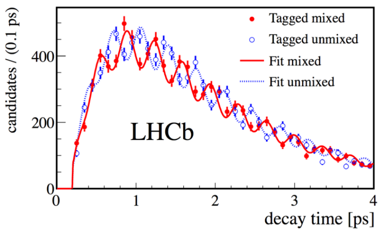


$B \to D^{*+}$

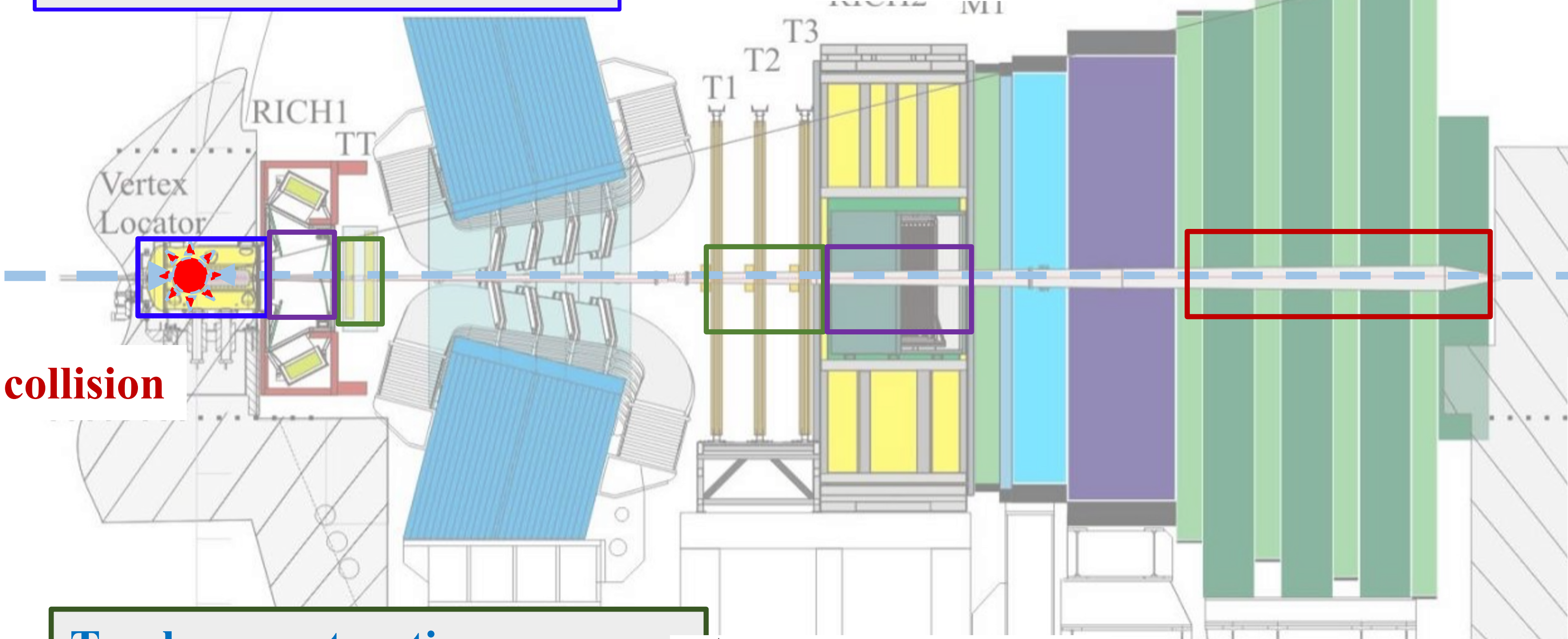


LHCb detector

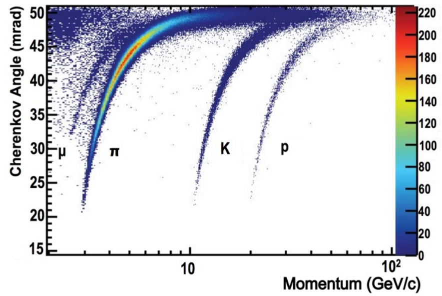
Vertex reconstruction
- Large boost
- $\sigma_{\mathrm{IP}} \sim 20\ \mu\mathrm{m}$
- $\sigma_{\tau} \sim 45$ fs w.r.t. $\tau_B \approx 1.5$ ps



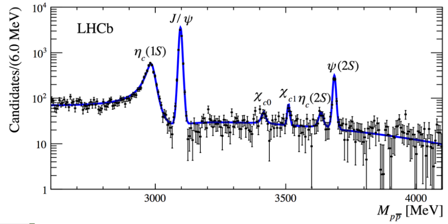
Muon identification
- $\epsilon(\mu \to \mu) \sim 97\%$
- MisID rate $(\pi \to \mu) \sim 1 - 3\%$



***pp* collision**



Track reconstruction
- $\epsilon(\mathrm{Tracking}) \sim 96\%$
- $\delta p/p \sim 0.5\%$-1% (5-200 GeV)
- $\epsilon(m_{J/\psi}) \approx 15$ MeV



Hadron identification
- $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- MisID rate $(\pi \to K/p) < 5\%$