CKM Physics and CPV in b decays at LHCb

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on behalf of the LHCb Collaboration

Snowmass, Oct. 2, 2020

Introduction

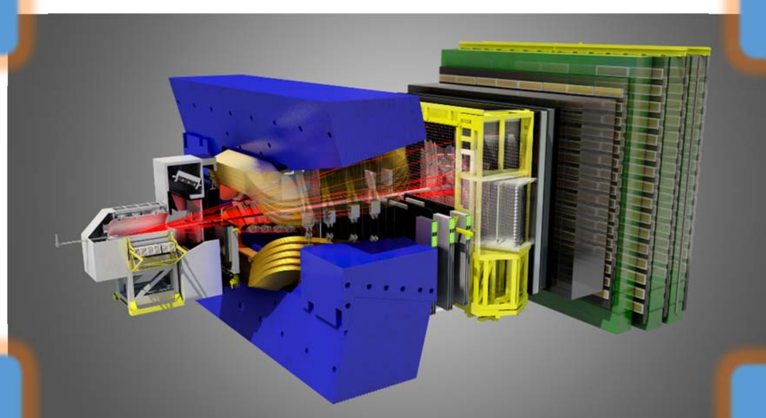
- ❑ **LHCb is a GPD**
- ❑ Focus on discovering **NP in b,c decays, but breadth of physics is staggering**.
  - ❑ Made possible by **highly flexible trigger**, **excellent SV capabilities** & **PID** (p, K, π μ, e).
  - ❑ Key strengths will be maintained (or improved) in Run 3 & Run 4 (2021 – 2030)

Lepton Universality

Hadron Spectroscopy (Conventional, exotic)

Charm physics

Rare decays (b, c, s)



Heavy Ions

CKM & CPV (b and c)

Fixed target

Forward, low q^2 QCD

Dark sectors

Electroweak (H, t, W, Z)

Key areas

- ❑ Weak phase γ
- ❑ B^0, B_s mixing, phases
- ❑ V_{ub} & V_{cb}
- ❑ A_{sl}
- ❑ CPV charmless B, Λ_b decays
- ❑ CPV in charm
- ❑ …

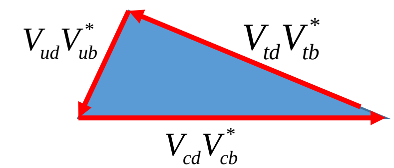
Each of these is a full program of measurements

CKM Physics

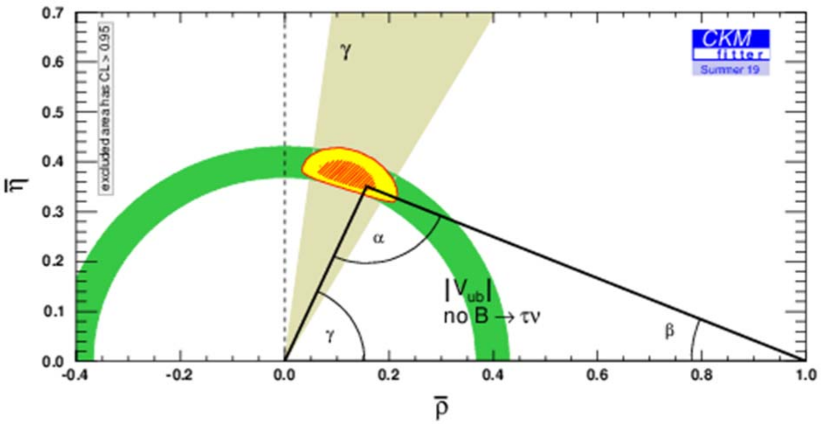
- **CKM matrix due to non-diagonal Higgs-quark Yukawa matrices**.
  - Precision test of this paradigm is a core goal of flavor physics.
  - Are 4 CKM parameters sufficient to describe all CC interactions, or **are additional phases (NP) needed?**

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

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

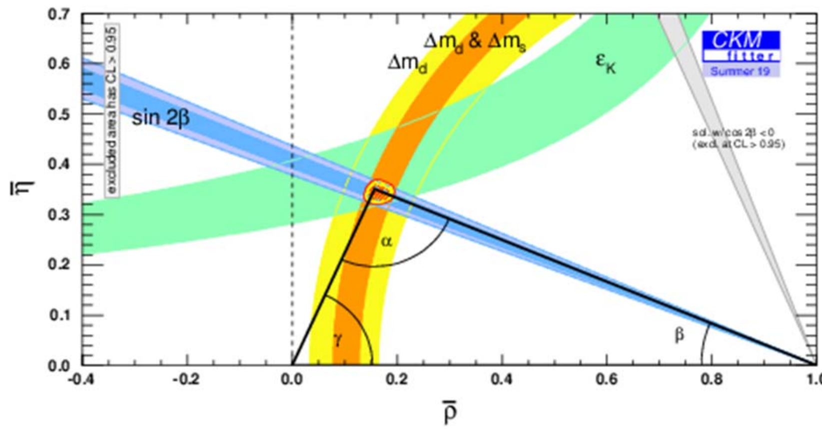


Tree-level processes only:
Don't expect NP to compete



- Weak phase γ from tree-level decays
- $|V_{ub}|$ and $|V_{cb}|$ from SL b-hadron decays

Loop-level processes only:
NP **can compete** with SM



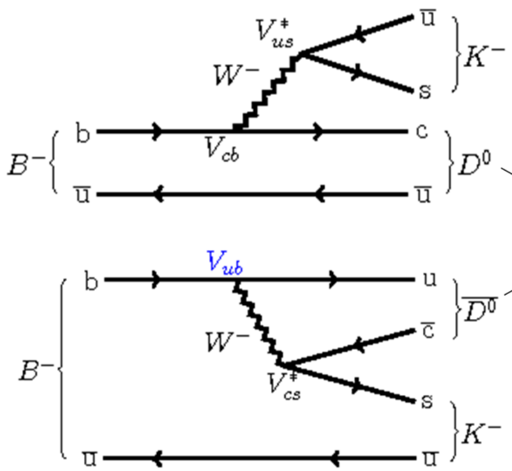
- B^0 & B_s mixing (Δm_d, Δm_s)
- CPV in $b \to c\bar{c}s$ (sin2β), $b \to u\bar{u}d$ (sin2α)

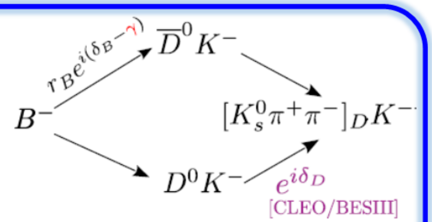
If CKM paradigm is correct, the apex must be the same in tree & loop-level processes.

Measurements of γ from LHCb

- ❑ Measure interference between two amplitudes that are of the same magnitude, **but have different weak and strong phases**

Time Integrated





D decay modes

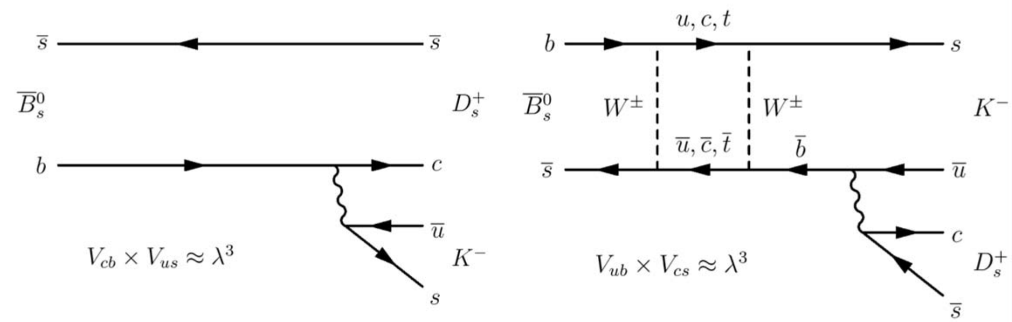
***GGSZ*: $K_S\pi^+\pi^-$**

$GLW: K^+K^-, \pi^+\pi^-$

$ADS: K^\pm\pi^\mp$

$\boldsymbol{B^- \to DK^-}$

Time Dependent



$\boldsymbol{B_S^0 \to D_S^+ K^-}$

Many other modes analyzed

- ❑ D modes: $K_S K^+\pi^-, K^+\pi^+\pi^-\pi^+, K^-\pi^+\pi^0$
- ❑ B: $B^0 \to DK^-\pi^+, B^- \to DK^-\pi^+\pi^-$
- ❑ B_S^0: $B_S^0 \to DK^-K^+$
- ❑ Λ_b^0: $\Lambda_b^0 \to DpK^-$

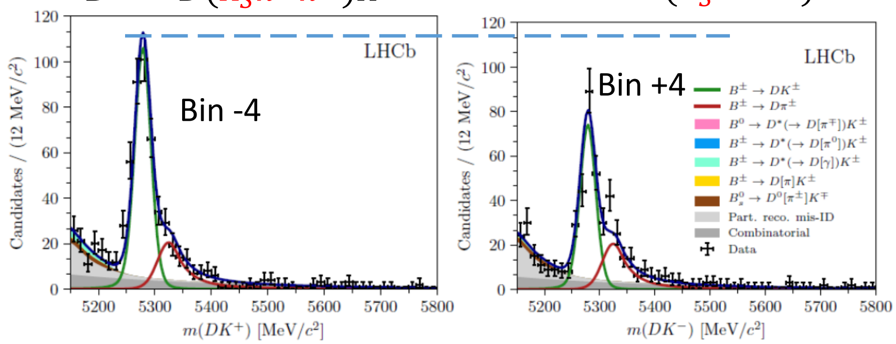
Other modes

- ❑ $\boldsymbol{B_S^0 \to D_S^+ K^-\pi^+\pi^-}$, $B_S^0 \to D_S^{*+}K^-$

Recent γ from LHCb

LHCb-PAPER-2020-019 (Preliminary)

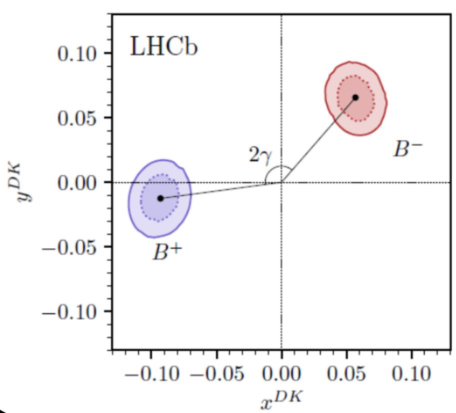
$B^+ \to D(K_S\pi^+\pi^-)K^+$ $B^- \to D(K_S\pi^+\pi^-)K^-$



- Yields across D Dalitz depend on γ, r_B^{DK}, δ_B^{DK} and $\delta_D(\mathcal{D})$

$$x_\pm^{DK} \equiv r_B^{DK}\cos(\delta_B^{DK} \pm \gamma) \quad \text{and} \quad y_\pm^{DK} \equiv r_B^{DK}\sin(\delta_B^{DK} \pm \gamma).$$

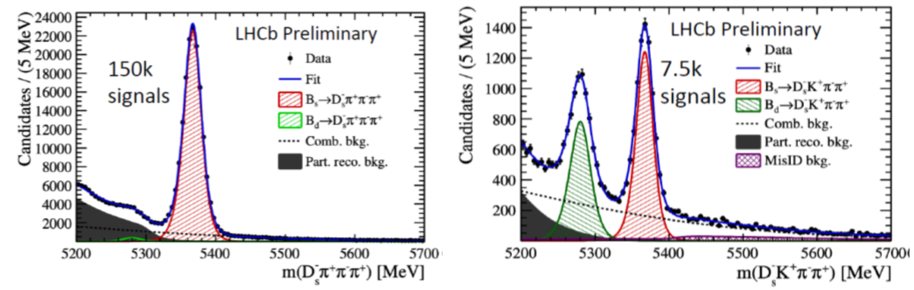
- $\langle\cos\delta_D\rangle_i$, $\langle\sin\delta_D\rangle_i$ from CLEO-c / BESIII



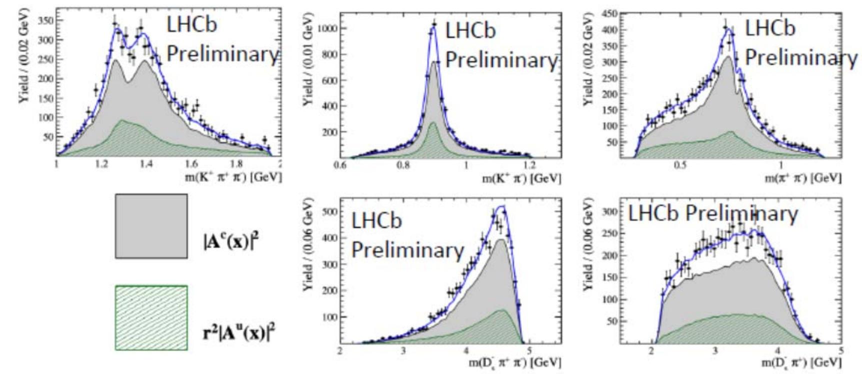
Full Run 1 + Run 2

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$

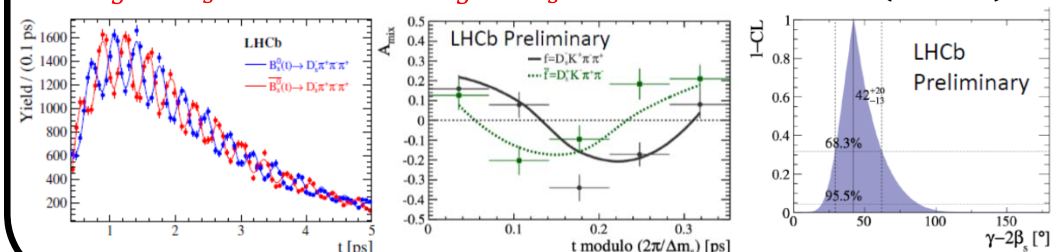
LHCb-PAPER-2020-030 (Preliminary) $B_S^0 \to D_S^+K^-\pi^+\pi^-$



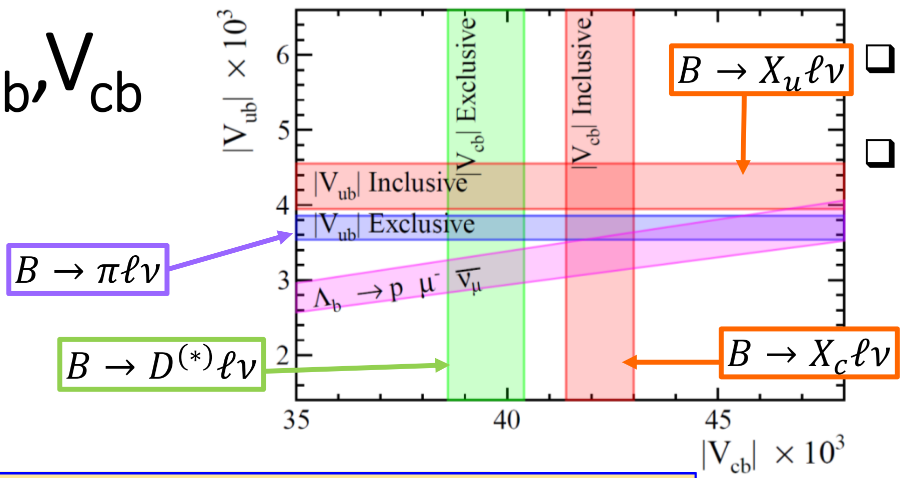
Strong phase varies over the 5D Dalitz plot



$B_S^0 \to D_S^+\pi^-\pi^+\pi^-$ $B_S^0 \to D_S^+K^-\pi^+\pi^-$ $\gamma = (42^{+20}_{-15})^\circ$



V_{ub},V_{cb}



- ❑ LHCb has unique opportunity to probe $|V_{qb}|$ in SL B_s and Λ_b decays.
  - ❑ Heavier *s* spectator (in B_s) advantageous theoretically.
- ❑ **Exclusive $|V_{cb}|$**: Form factors (FF) needed from theory

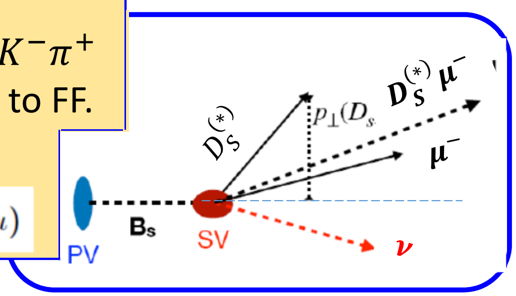
$$\frac{d\Gamma(B \to D\mu\nu)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 \eta_{EW}^2 |V_{cb}|^2 (w^2-1)^{3/2} |\mathcal{G}(w)|^2$$

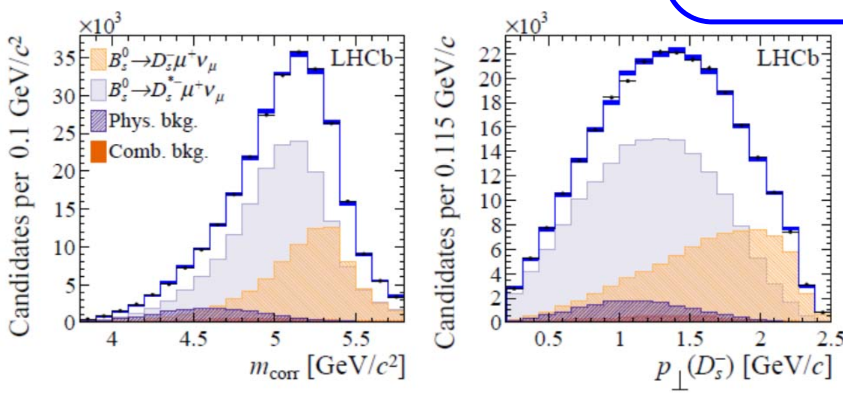
Measured

LHCb, PRD101, 072004 (2020)

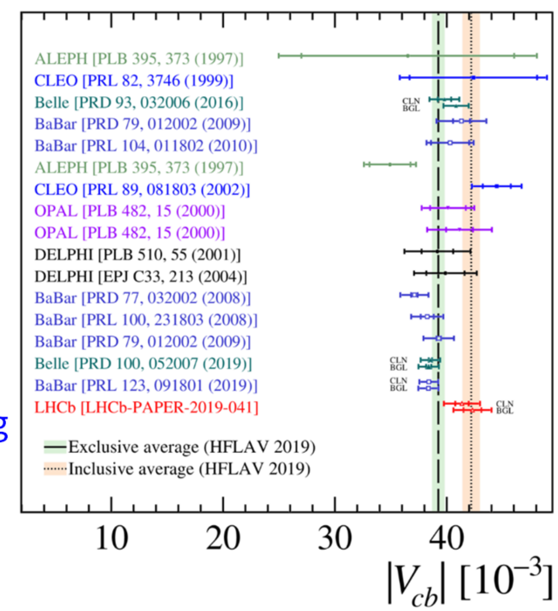
- ❑ **$|V_{cb}|$** with $B_s^0 \to D_s^{(*)+}\mu\nu$, $D_s^+ \to K^+K^-\pi^+$
- ❑ $p_\perp(D_s)$ correlated with *w*. Sensitivity to FF.
- ❑ 2D fit in corrected mass and $p_\perp(D_s)$

$$m_{corr} = \sqrt{m^2(D_s\mu) + p_\perp^2(D_s\mu)} + p_\perp(D_s\mu)$$

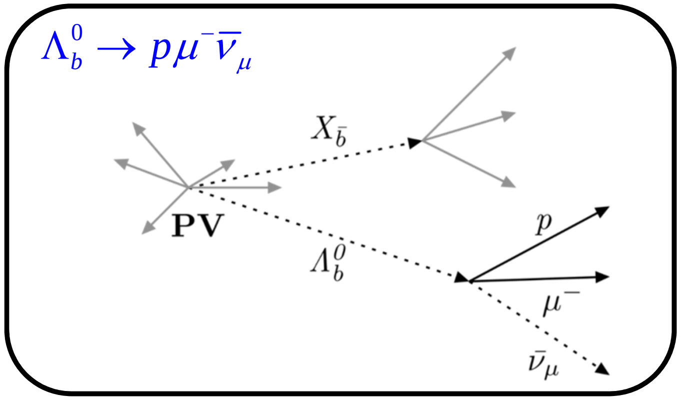


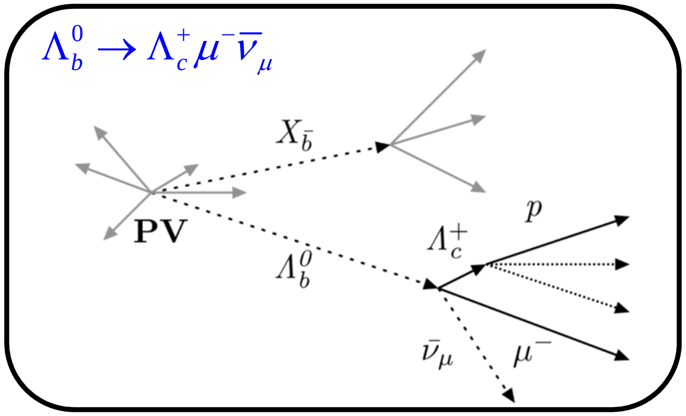


- ❑ First m'ment of $|V_{cb}|$ at a hadron collider
- ❑ Consistent with both $|V_{cb}|_{excl}$ and $|V_{cb}|_{incl}$.
- ❑ Work ongoing with $|V_{cb}|$ using $\Lambda_b \to \Lambda_c \mu\nu$, $B^0 \to D^*\mu\nu$



V_{ub} / V_{cb}



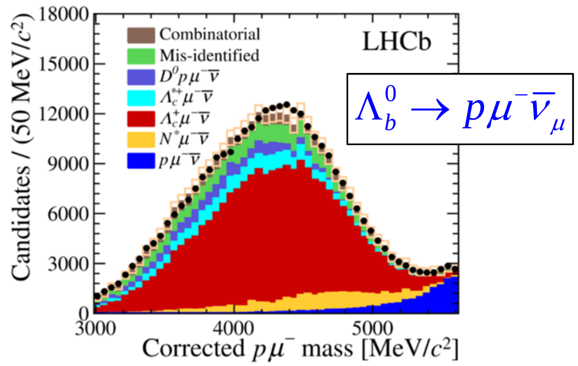


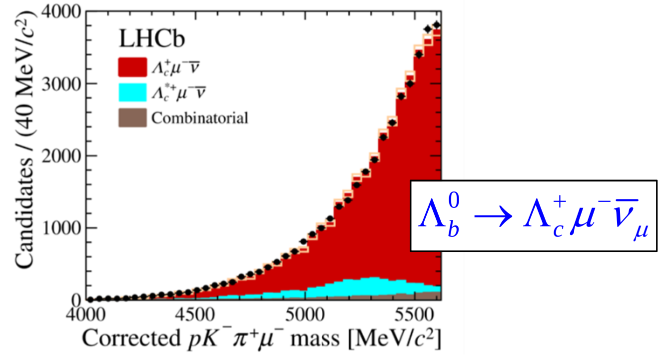
LHCb, Nature Physics 11 (2015) 743

- Exploit large samples of Λ_b baryons produced in LHCb.

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\rm FF}$$

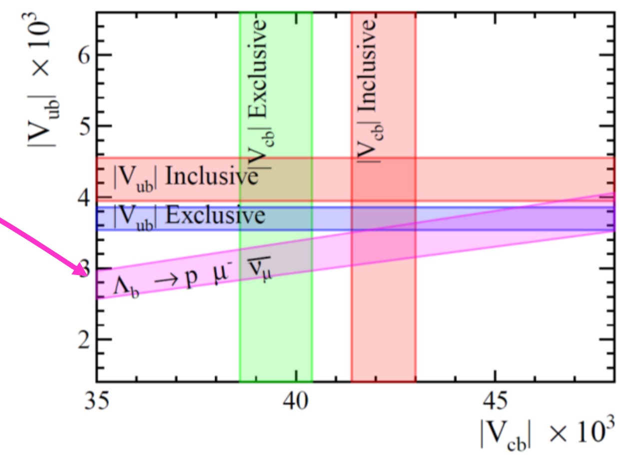
R_{FF} is the ratio of form factors, from LQCD, R_{FF} = 0.68±0.07
Detmold et. al, PRD92 (2015) 034503





$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

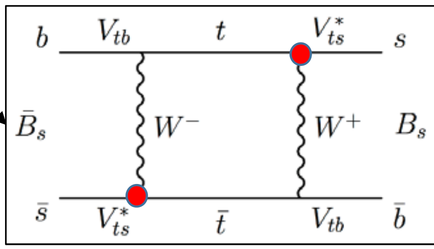
- **First measurement of V_{ub} at a hadron collider!**
- **This is just the beginning…**
  Ongoing work with $B_s \to K\mu\nu$, $B^- \to \rho^0\mu^-\nu$, and $B(B_c \to D^0\mu\nu)$



CP Violation in Loops: ϕ_s

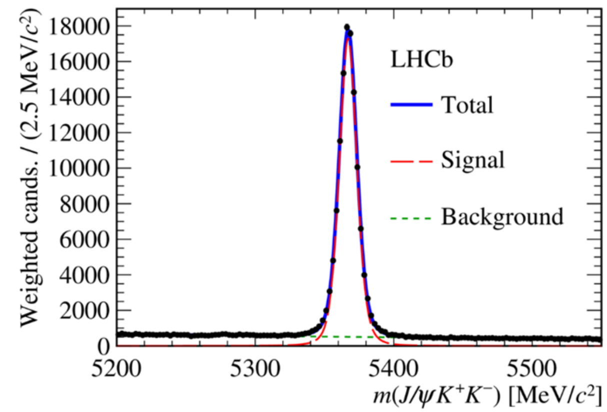
- **New particles could participate in the loop.**

$\bar{B}_s$



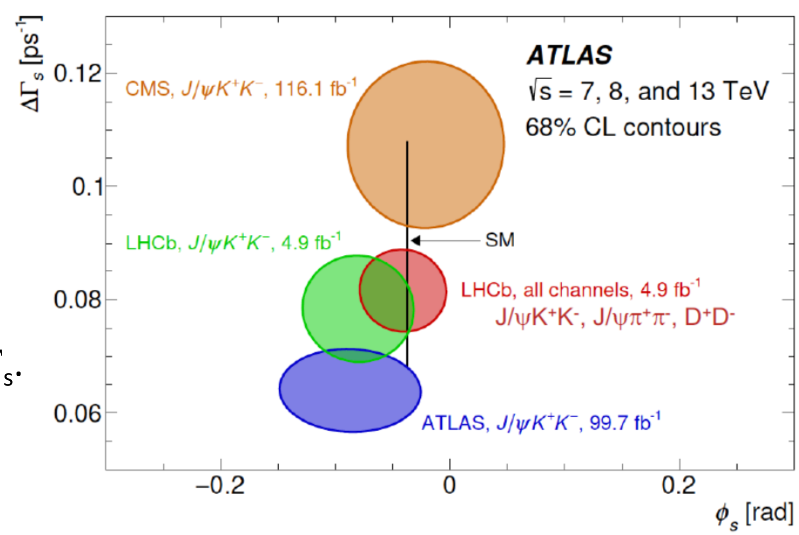
f = States accessible to B_s and $\bar{B}_s$ via $\bar{b} \rightarrow \bar{c}c\bar{s}$,
$J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$, $D_s^+D_s^-$

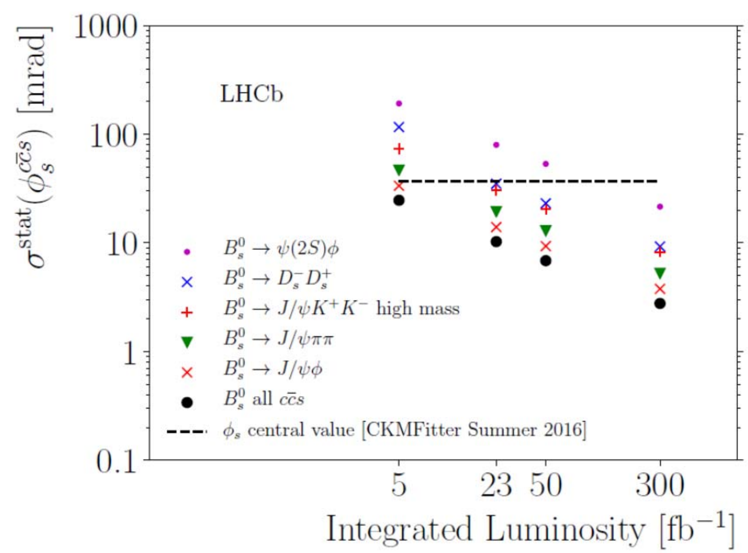
- CKM phase from V_{ts}
- **SM prediction: -35.4 ± 1.2 mrad**
- NP could alter this!



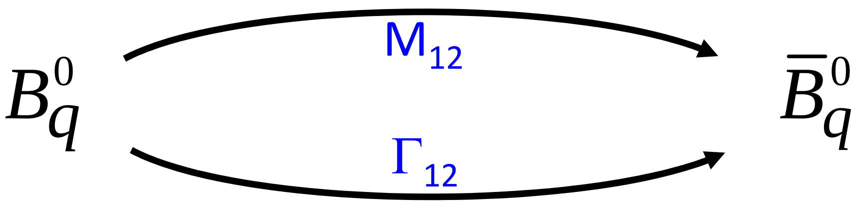
$B_s \rightarrow J/\psi h^+h^-$ decay amplitudes depends on ϕ_s and includes CP even and CP odd terms.

→Fit determines $\Delta\Gamma_s$.





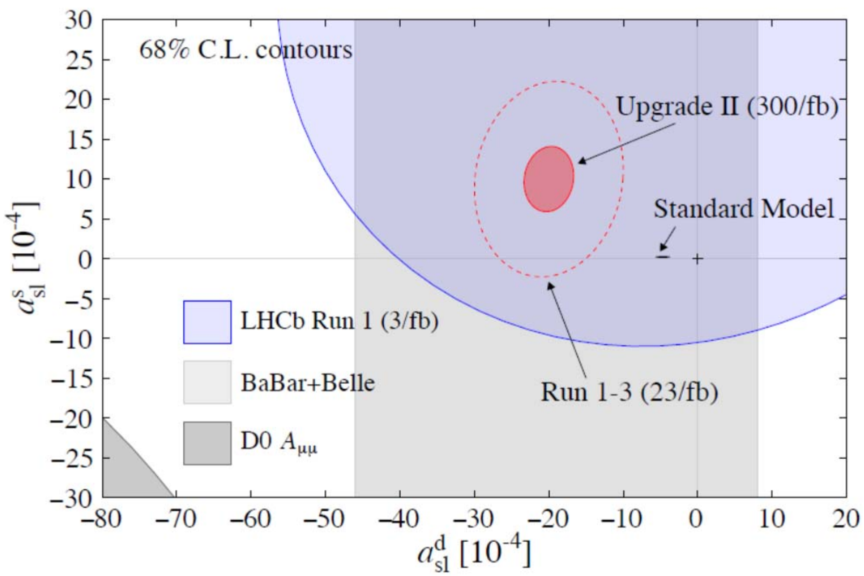
Mixing asymmetry: A_{sl}



M_{12} : Off-shell contribution (top quark loop)

Γ_{12} : On-shell contributions (e.g. $b \to c\bar{c}s$)

- ❑ **The interference between M_{12} and Γ_{12} gives CP violation in the mixing.**
- ❑ **Isolate by choosing a flavor-specific final state → SL decays**



$$a_{sl}^q = \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \overline{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \overline{f})} \approx \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_{12}^q \qquad \phi_{12}^q = \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

$$\frac{N(D_q^-\mu^+) - N(D_q^+\mu^-)}{N(D_q^-\mu^+) + N(D_q^+\mu^-)} = \frac{a_{\rm fs}}{2} + \left(\frac{a_{\rm fs}}{2} - a_{\rm prod}\right) \frac{\int_0^\infty {\rm d}t\, e^{-\Gamma t} \cos(\Delta m\, t)}{\int_0^\infty {\rm d}t\, e^{-\Gamma t} \cosh(\frac{1}{2}\Delta\Gamma\, t)}$$

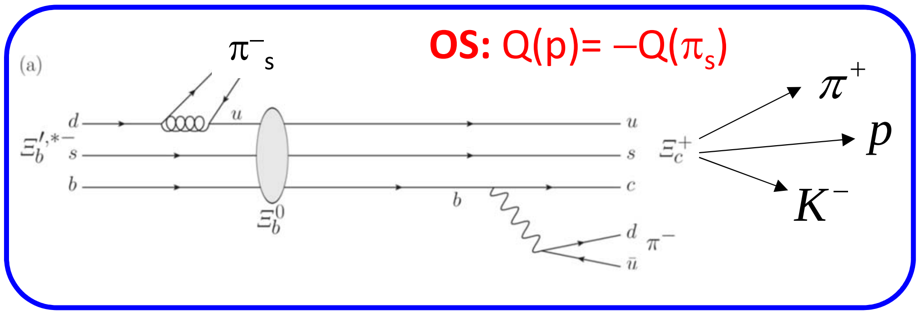
- o B_s: ($\Delta m_s \approx 18$ ps^{-1}) >> ($\Gamma_s \approx 0.7$ ps^{-1})
  → can neglect this term
- o B_d: ($\Delta m_d \approx 0.5$ ps^{-1}) ≈ ($\Gamma_d \approx 0.7$ ps^{-1})
  → cannot neglect this term,
  must fit decay time spectrum

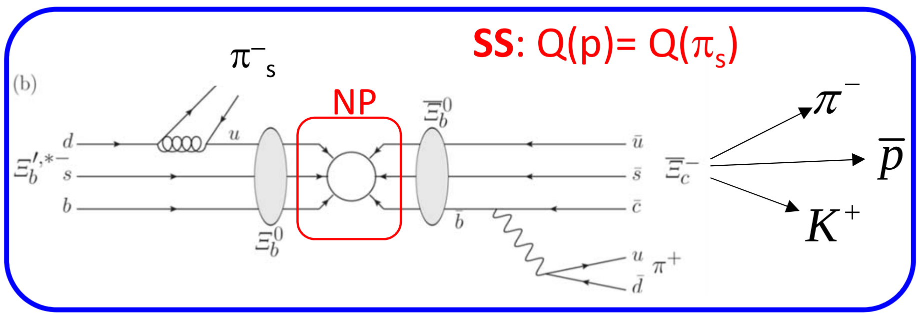
Baryon number violation

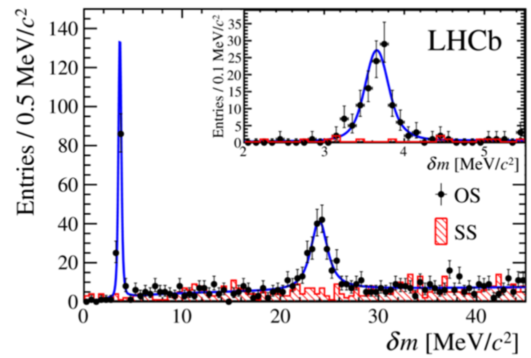
- **BNV** is a key ingredient to account for the matter-antimatter asymmetry of the Universe.
- Certain NP six-fermion operators can generate BNV w/o affecting the nucleon lifetimes.
  - Such operators could generate Ξ_b^0 oscillations.
  - Idea: Look for WS Ξ_b^0 decays in tagged $\Xi_b^{(\prime,*)-} \rightarrow \Xi_b^0\pi^-$ decays

LHCb, PRL 119 (2017) 181807

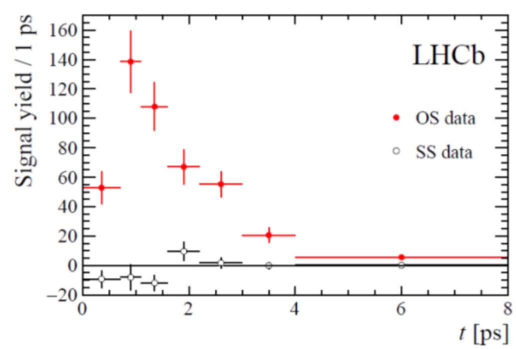
$$R(t) \equiv \frac{P_{X\to\overline{X}}(t)}{P_{X\to X}(t)} = \tan^2(t/\tau_{\rm mix}) \simeq \frac{t^2}{\tau^2_{\rm mix}} \equiv (\omega t)^2$$

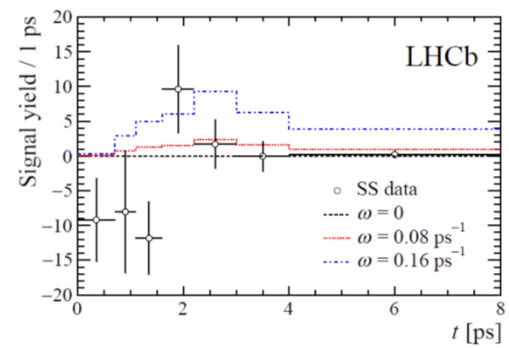






- ~450 $\Xi_b^{(\prime,*)-}$ signal in 3 fb^{-1} at $\sqrt{s}$=7, 8 TeV
- Estimate ≈**40K** (**400K**) in 30 (300) fb^{-1} at $\sqrt{s}$ = 13 or 14 TeV





- **No evidence of BNV, ω < 0.08 ps^{-1} (τ_{mix} > 13 ps) at 95% CL**
- **Constrains certain NP operators giving rise to BNV**

Summary

- The LHCb upgrade will p**robe for NP in b,c decays to an unprecedented precision**.
- Due to the flexible (fully software) trigger, we will be able to quickly adjust to new information that may come along.

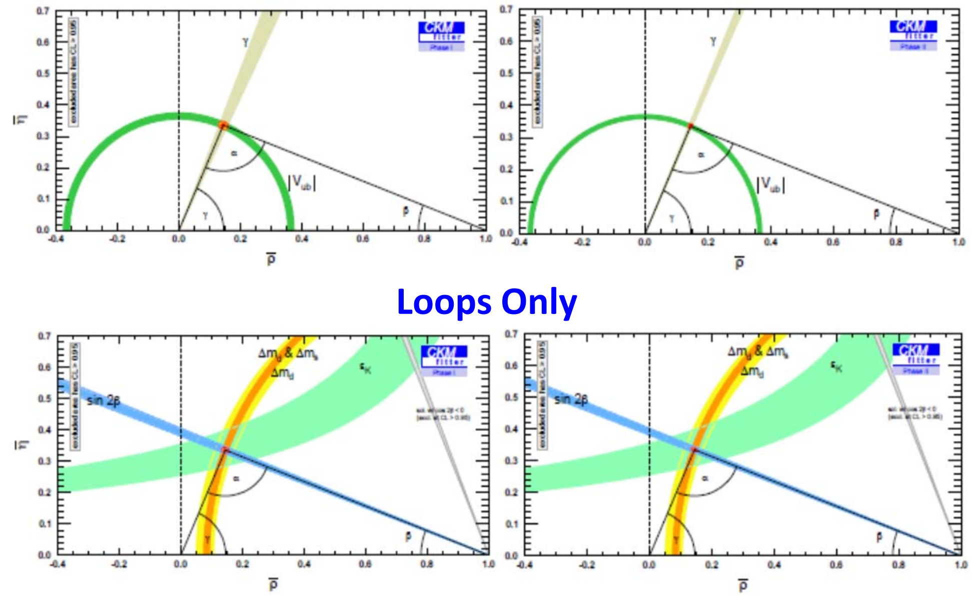
LHCb-PUB-2018-009: Physics Case for an LHCb Upgrade II

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	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% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	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}	–

23 fb^{-1} LHCb
50 ab^{-1} Belle II

Trees Only

300 fb^{-1} LHCb
50 ab^{-1} Belle II



arXiv:1812.076382

Ultra-precise test of the CKM paradigm:
Does $(\rho,\eta)_{Tree} = (\rho,\eta)_{Loop}$?