

# Flavor Physics Highlights

Selection of Recent Physics results with a view on  
the search for footprints of New Physics

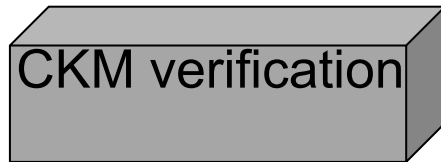
## *Brookhaven Forum*

*September 26, 2019  
Hassan Jawahery  
University of Maryland*

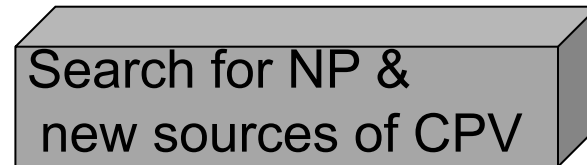


# Much of the Flavor Physics today is focused on the search for footprints of New Physics (NP):

1980's- 2000's -B factories



Today- LHC, SuperKEKB, Rare Kaon exp,...



- It is (so far) our sole source of observed CP Violation effects
- Provides access to very high energy scales through Flavor Changing Neutral Current processes (FCNC)

Flavor puzzle: Interpreting the current data in the language of effective field theory,

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{C_i}{\Lambda_i^2} + \dots$$

*Isidori, Nir, Perez*

Operator	Bounds on $\Lambda$ [TeV] ( $C = 1$ )		Bounds on $C$ ( $\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	$9.8 \times 10^2$	$1.6 \times 10^4$	$9.0 \times 10^{-7}$	$3.4 \times 10^{-9}$	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	$1.8 \times 10^4$	$3.2 \times 10^5$	$6.9 \times 10^{-9}$	$2.6 \times 10^{-11}$	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	$1.2 \times 10^3$	$2.9 \times 10^3$	$5.6 \times 10^{-7}$	$1.0 \times 10^{-7}$	$\Delta m_D;  q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$6.2 \times 10^3$	$1.5 \times 10^4$	$5.7 \times 10^{-8}$	$1.1 \times 10^{-8}$	$\Delta m_D;  q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	$6.6 \times 10^2$	$9.3 \times 10^2$	$2.3 \times 10^{-6}$	$1.1 \times 10^{-6}$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	$2.5 \times 10^3$	$3.6 \times 10^3$	$3.9 \times 10^{-7}$	$1.9 \times 10^{-7}$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	$1.4 \times 10^2$	$2.5 \times 10^2$	$5.0 \times 10^{-5}$	$1.7 \times 10^{-5}$	$\Delta m_{B_s}; S_{\psi \phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	$4.8 \times 10^2$	$8.3 \times 10^2$	$8.8 \times 10^{-6}$	$2.9 \times 10^{-6}$	$\Delta m_{B_s}; S_{\psi \phi}$

# Some of the Recent advances

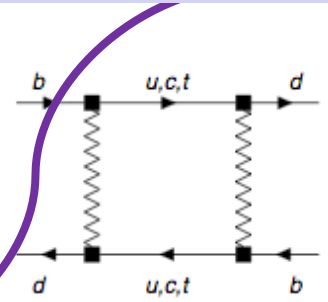
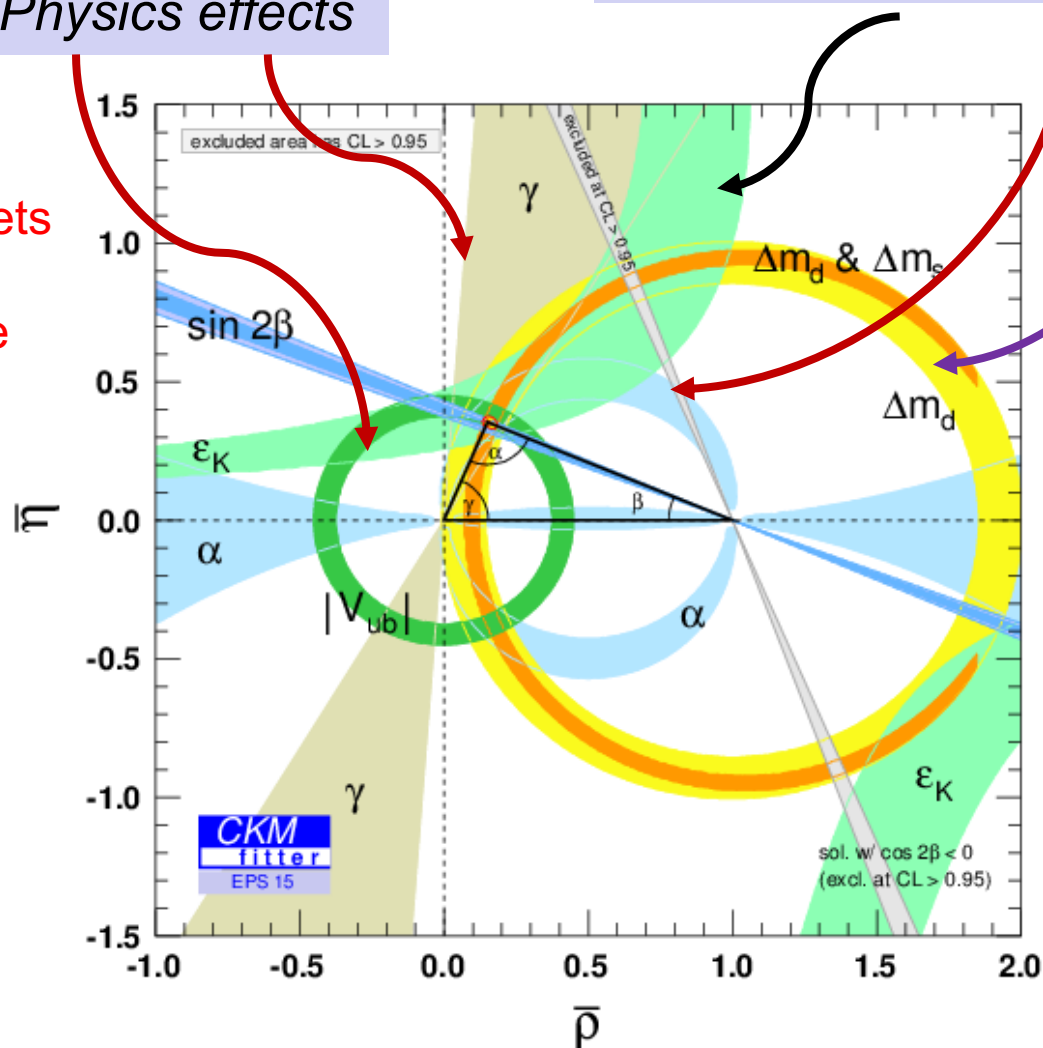
- The CKM picture continues to be sharpened:
  - Improved precision of Unitarity angle  $\gamma$
  - Improved measurements of time-dependent CPV in  $B_s^0$ :  $\phi_s$
- B-Anomalies: a few measurements are in tension with SM
  - Tests of Lepton Flavor Universality in B decays involving charged and neutral currents
- A new source of CPV found: **Charm Decays**
  - The quark sector (K, D, B hadrons) remains the sole source of CPV
- Era of Super-Flavor Experiments has arrived:
  - Belle-II had its first physics run (**March-June, 2019**)
  - LHCb upgrade I (50 fb<sup>-1</sup>) being installed: **2019-2020**
  - LHCb upgrade II (300 fb<sup>-1</sup>) in conception/design (**→2030**)

# Sharpening the CKM picture

tree level processes:  $V_{ub}$  &  $\gamma$   
Free of New Physics effects

Observables involving loop diagrams  
( $K^0$  and  $B^0$  oscillations) are sensitive  
to New Physics

Any Inconsistency  
between the two sets  
of measurements  
could be due to the  
influence of New  
Physics effects



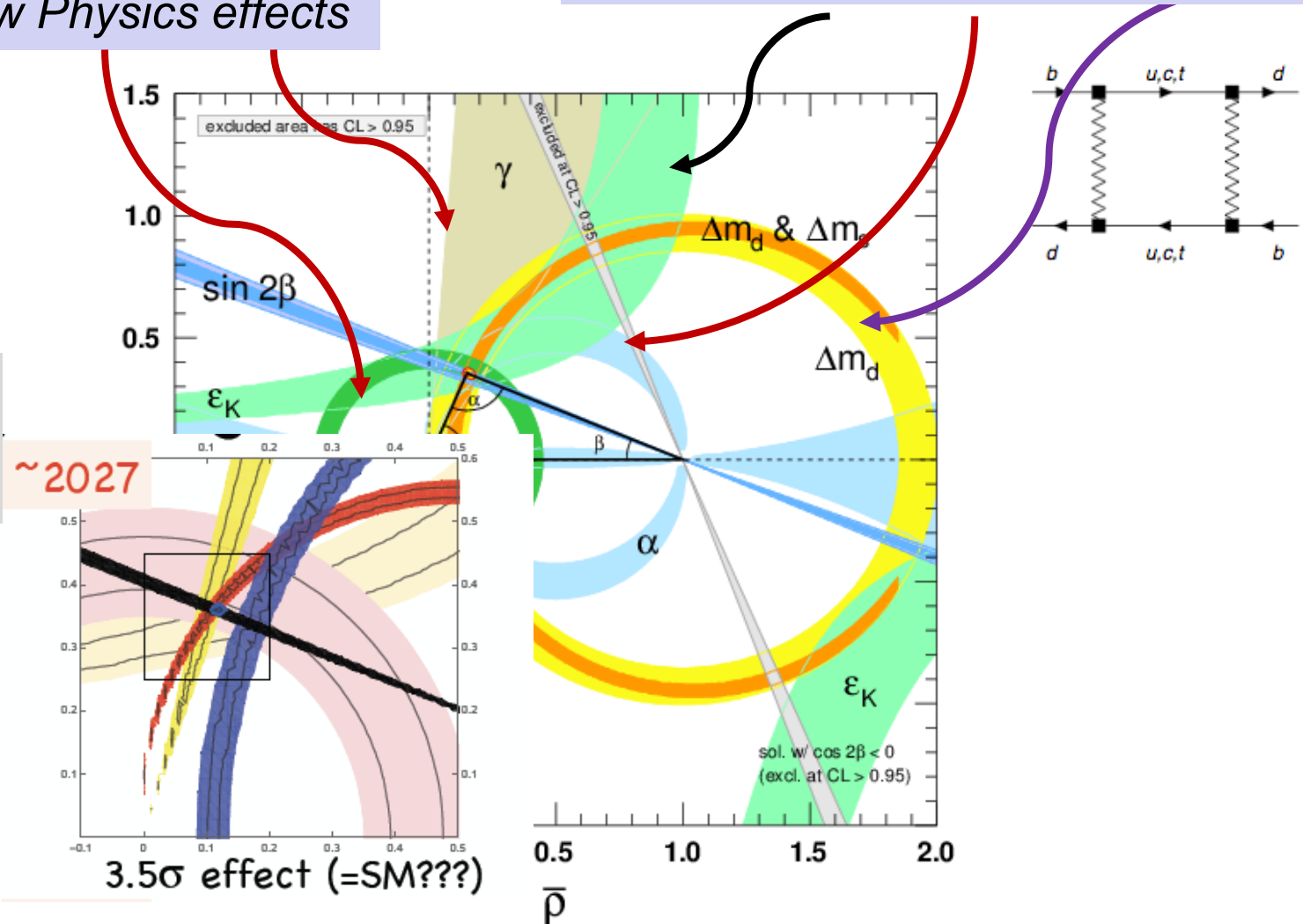
# Sharpening the CKM picture

tree level processes:  $V_{ub}$  &  $\gamma$   
Free of New Physics effects

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( $K^0$  and  $B^0$  oscillations) are sensitive  
to New Physics

Adapted from  
Emi Kou  
FPCP 2019)

If the central  
value remains  
exactly the  
same (though  
unlikely)...



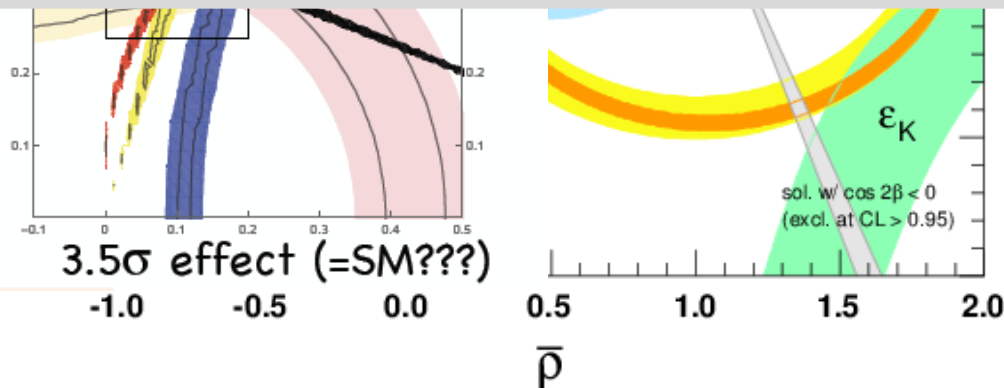
# Sharpening the CKM picture

## Recent progress :

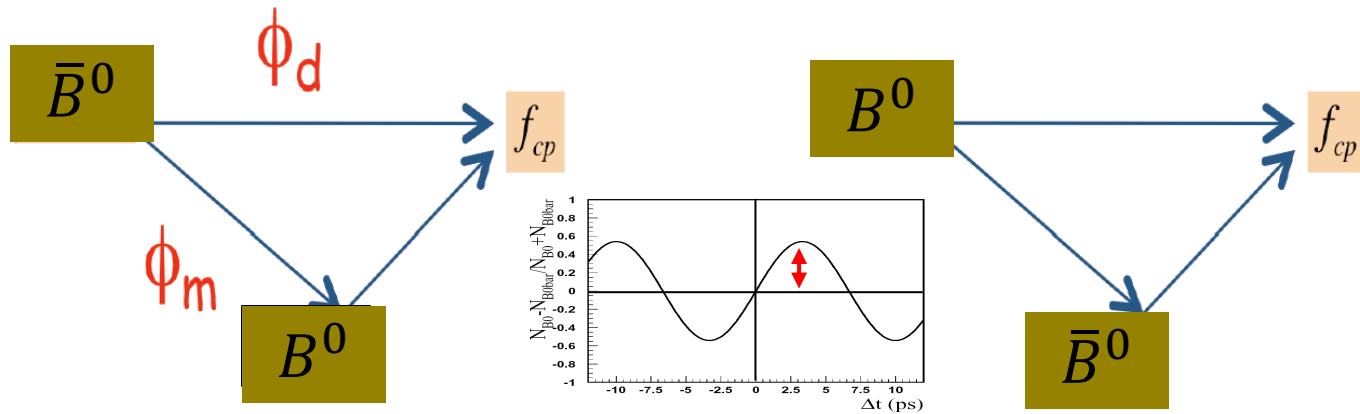
- Improved measurements of  $\gamma$  at LHCb
- Improved measurements of  $\varphi_S$  at ATLAS and LHCb
- Improved  $|V_{cb}|$  and  $|V_{ub}|$  measurements. Persistent tension between measurements using exclusive and inclusive decays. New measurements of  $|V_{cb}|$  at Belle and BaBar.  $|V_{ub}|$  measurement at LHCb using  $\Lambda_b$  decays

exactly the same (though unlikely)...

Emi Kou- FPCP 2019)

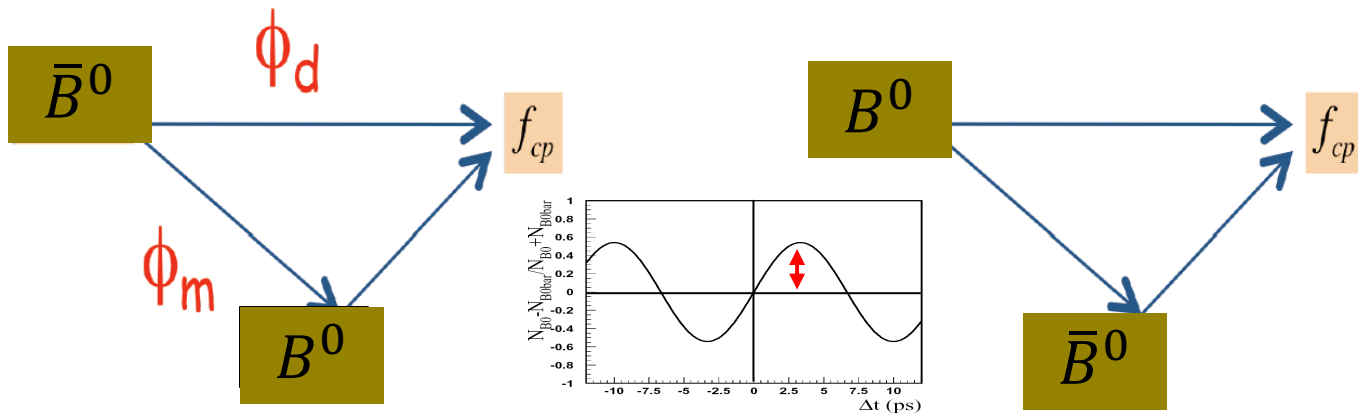


# Reminder: How we access the CKM phase



$$A_{cp}(t) = \frac{\Gamma(B^0(t) \rightarrow f_{cp}) - \Gamma(\bar{B}^0(t) \rightarrow f_{cp})}{\Gamma(B^0(t) \rightarrow f_{cp}) + \Gamma(\bar{B}^0(t) \rightarrow f_{cp})} = \sin 2(\varphi_m - \varphi_d) \sin \Delta m t$$

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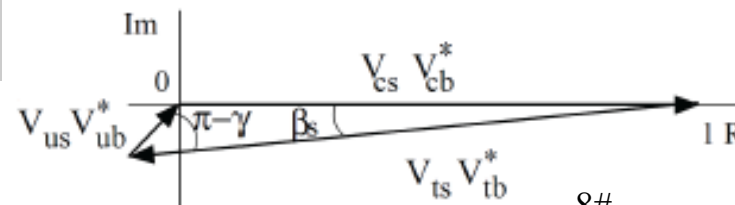
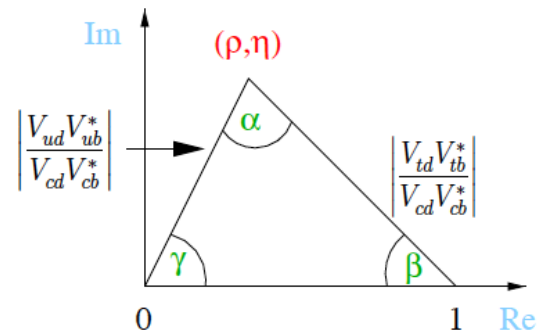


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With careful set up of the initial and final states:

$$B_d \rightarrow J/\psi K_s^0 :: \quad \beta \propto \arg(V_{td}^*) \sim 24^\circ$$

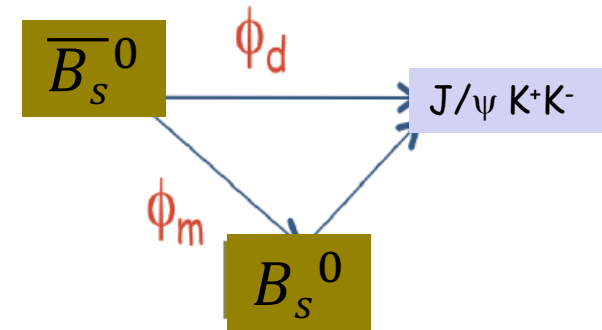
$$B_s \rightarrow J/\psi K^+ K^- :: \quad \varphi_s (= -2\beta_s) \propto \arg(V_{ts}^*) \sim 1^\circ$$





# Improved measurements of $\phi_s = -2\arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$

- From Time-dependent CPV in:
- $B_S^0 \rightarrow J/\psi K^+K^-$  [ $\phi \rightarrow K^+K^-$ , s-wave ( $K^+K^-$ )]
- $B_S^0 \rightarrow J/\psi K^+K^-$  -high-mass region
- $B_S^0 \rightarrow J/\psi \pi^+ \pi^-$
- $B_S^0 \rightarrow \psi(2s) K^+K^-$

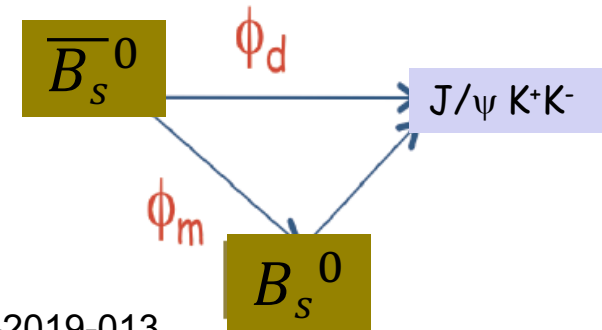
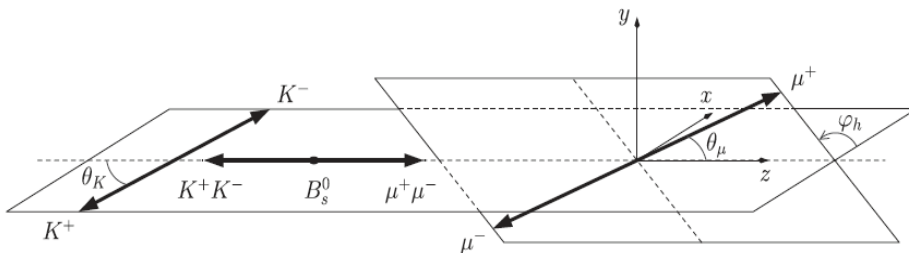


$$\phi_s^{SM} = -36.8^{+1.0}_{-0.8} \text{ mrad}$$

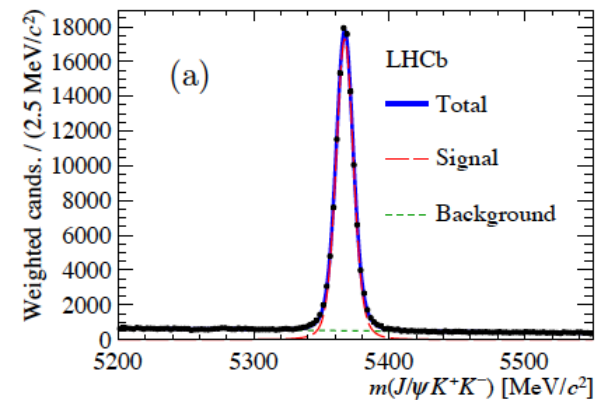
From CKM fit

# Improved measurements of $\phi_s = -2\arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$

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- $B_S^0 \rightarrow J/\psi K^+K^-$  -high-mass region
- $B_S^0 \rightarrow J/\psi \pi^+ \pi^-$
- $B_S^0 \rightarrow \psi(2s) K^+K^-$
- Mixture of CP odd & CP even states-  
Angular analysis required to extract CPV info.



LHCb-paper-2019-013

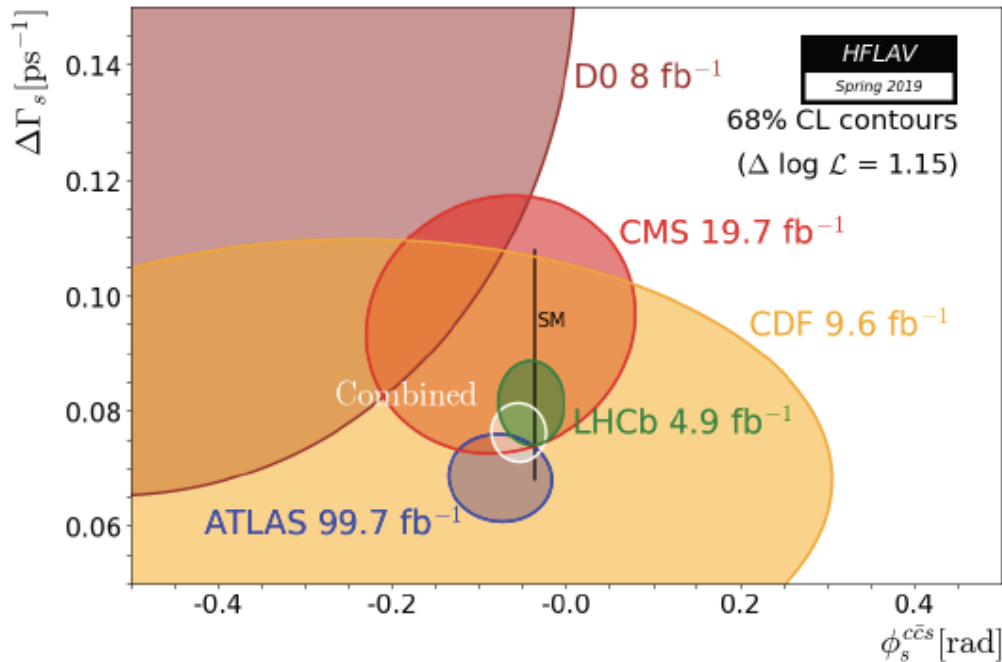


➤ Observables:  $\phi_s$   
 $\Delta\Gamma = \Gamma_H - \Gamma_L$ ,  
 $\Delta m = m_H - m_L$

The decay is described in terms of four helicity amplitudes

# Improved measurements of $\phi_s = -2\arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$

## Recent major improvements from ATLAS and LHCb



### ATLAS

$$\phi_s = -76 \pm 39 \text{ mrad}$$

$$\Delta\Gamma_s = 0.068 \pm 0.005 \text{ ps}^{-1}$$

### LHCb

$$\phi_s = -41 \pm 25 \text{ mrad}$$

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

### HFLAV average

$$\phi_s = -55 \pm 21 \text{ mrad}$$

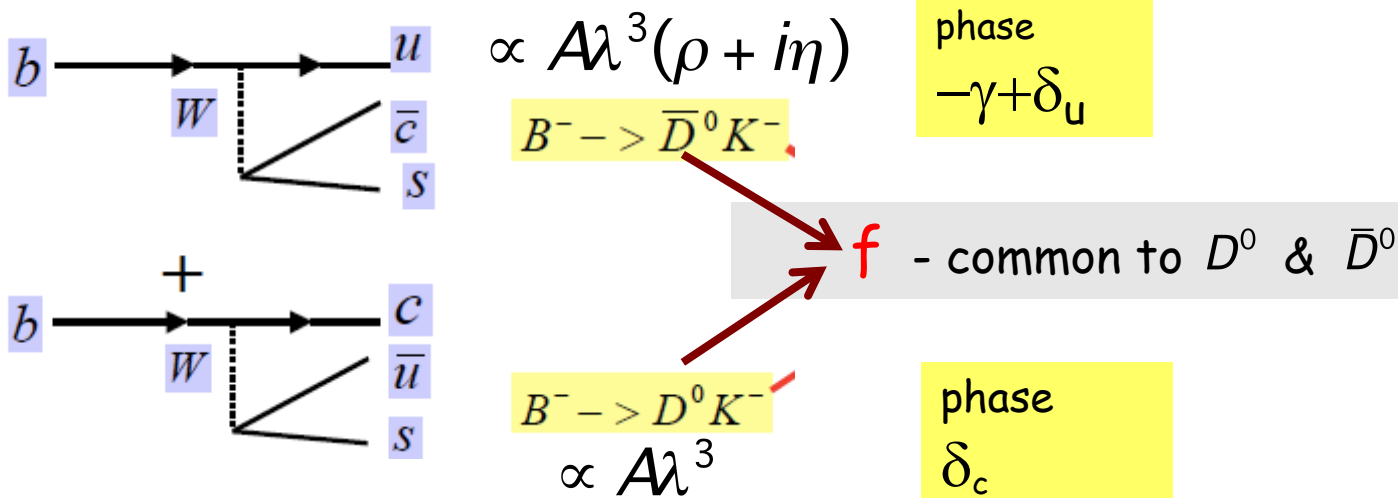
$$\Delta\Gamma_s = 0.0764 \pm 0.0024 \text{ ps}^{-1}$$

Consistent with SM- but a long way to reach the theory precision

$$\phi_s^{SM} = -36.8^{+1.0}_{-0.8} \text{ mrad}$$

# Improved Measurement of $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$

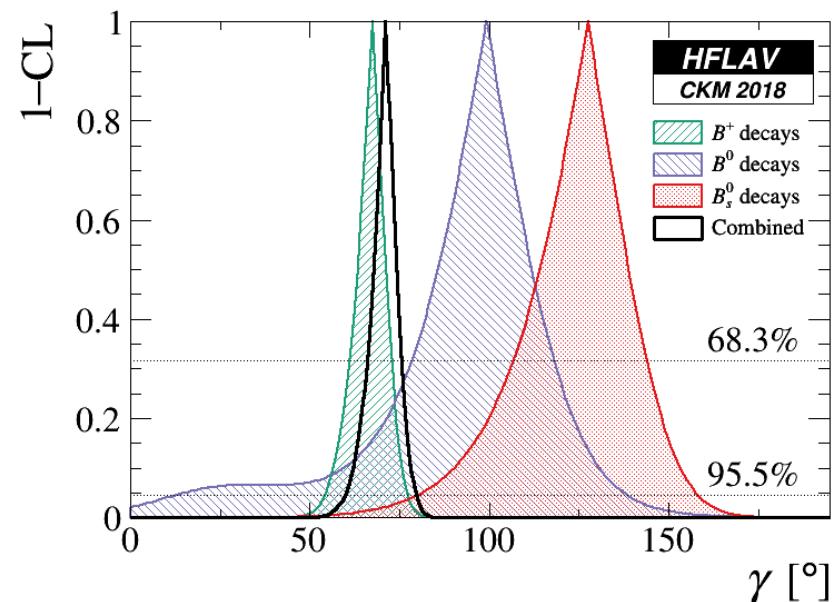
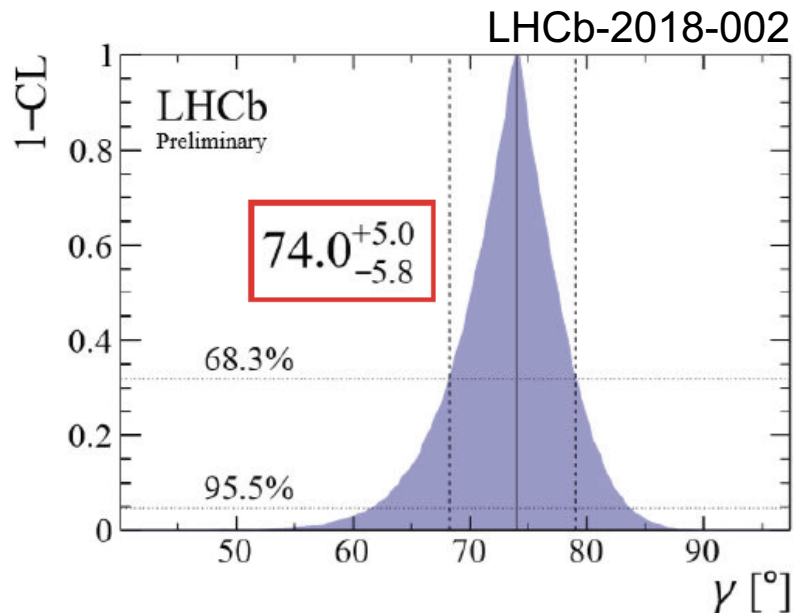
Yet another interferometer but w/o mixing:  
Interference of tree level  $b \rightarrow c$  &  $b \rightarrow u$  amplitudes



$$A[B^- \rightarrow (D \rightarrow f)K^-] = A_c A_f e^{i(\delta_c + \delta_f)} + A_u A_{\bar{f}} e^{i(\delta_u + \delta_{\bar{f}} - \gamma)}$$

# Improved Measurement of $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

Most significant recent advances have come from LHCb Analysis of Run 1 and part of Run 2 data.



BaBar:

$$\gamma = (69^{+17}_{-16})^\circ$$

Belle:

$$\gamma = (73^{+13}_{-15})^\circ$$

LHCb:

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

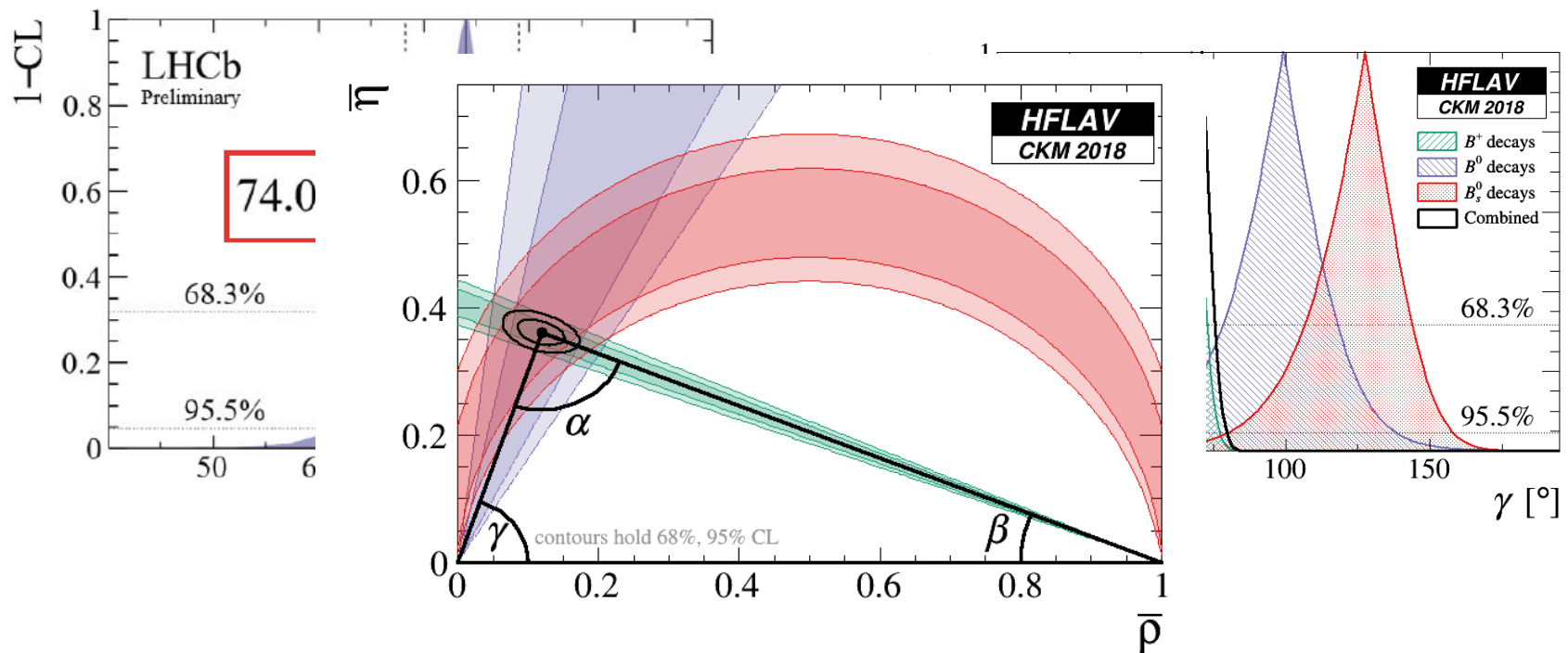
combined:

$$\gamma = (71.0^{+4.6}_{-5.3})^\circ$$

# Improved Measurement of $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

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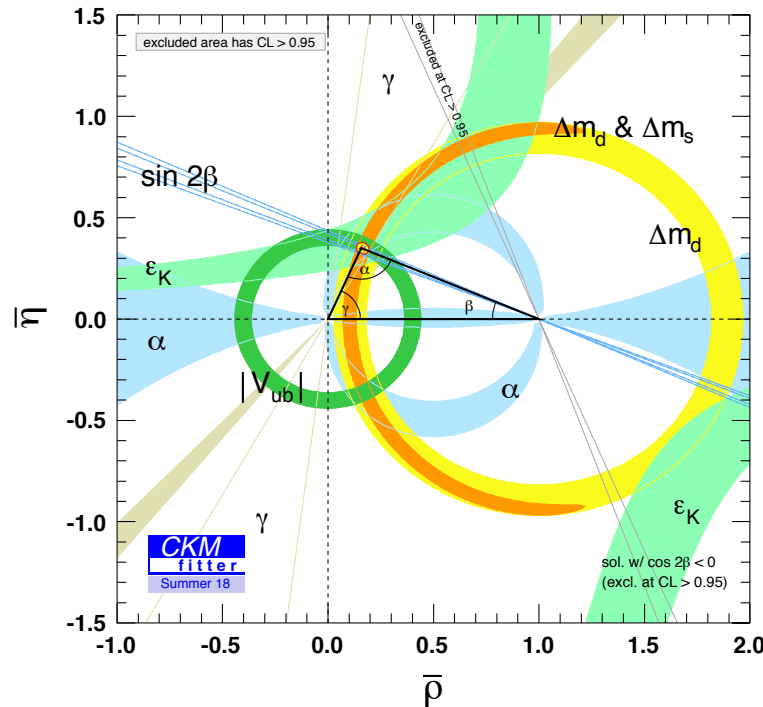
combined:  
 $\gamma = (71.0^{+4.6}_{-5.3})^\circ$



Still the less well measured angle of CKM unitarity triangle-  
 Super-flavor experiments aim for  $<1^\circ$  accuracy

# Status of CKM (2018)

The CKM picture in 2019:  
Still no major inconsistency



Direct (deg)

$$\alpha = 86.4^{+4.5}_{-4.3}$$

$$\beta = 22.14^{+0.69}_{-0.67}$$

$$\gamma = 71^{+4.6}_{-5.3}$$

CKM fit (deg)

$$91.9^{+3.0}_{-1.2}$$

$$23.90^{+1.2}_{-1.2}$$

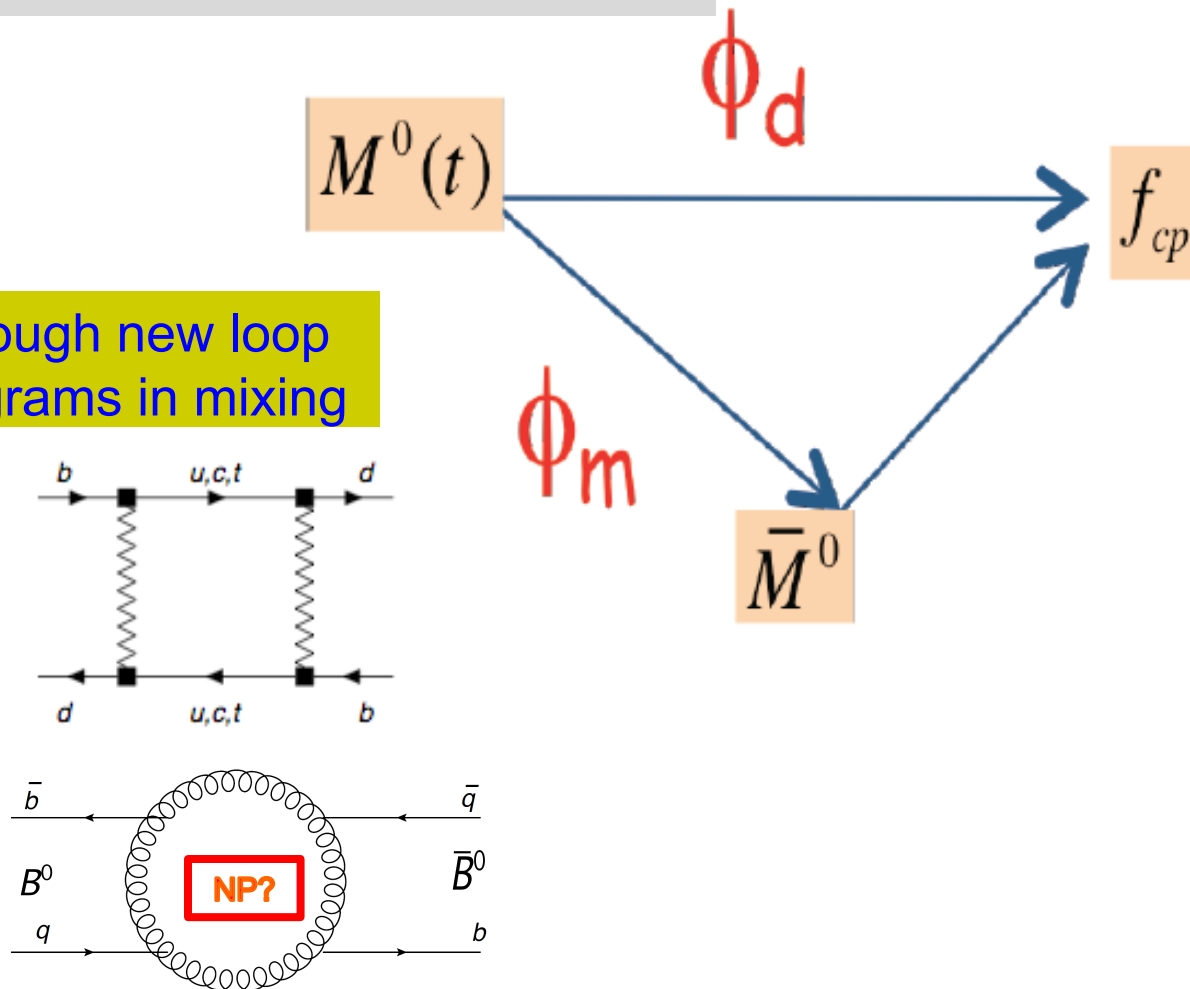
$$65.81^{+0.99}_{-1.66}$$

Implication for New Physics effects?

# New Physics Through Mixing

New Physics may affect either leg of the interferometer

Through new loop diagrams in mixing



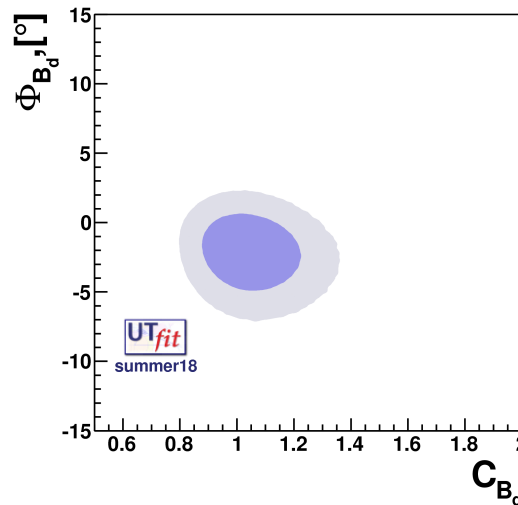
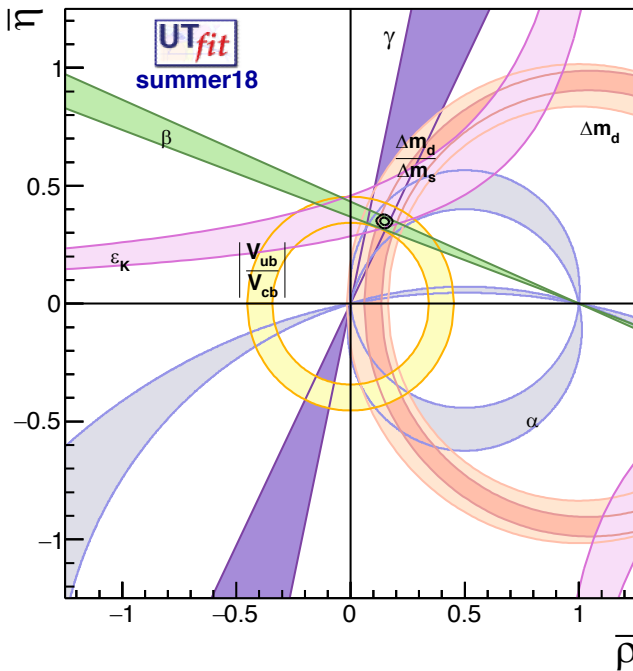


# New Physics Through Mixing

Fit the data allowing departure from SM in  $B^0$  mixing amplitude

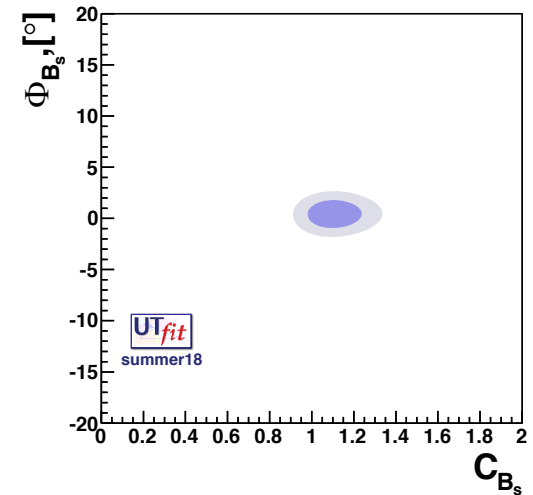
$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\text{eff}}^{\text{full}} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\text{eff}}^{\text{SM}} | \bar{B}_q^0 \rangle},$$

From the **UT<sub>fit</sub>**



$$C_{B_d} = 1.05 \pm 0.11$$

$$\varphi_{B_d} = -2.0 \pm 1.8$$

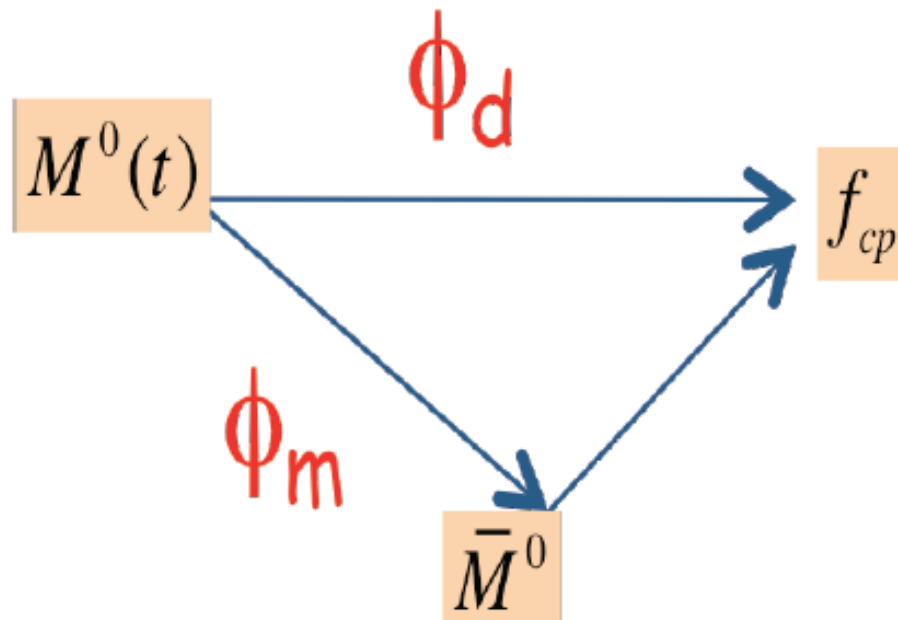


$$C_{B_s} = 1.110 \pm 0.090$$

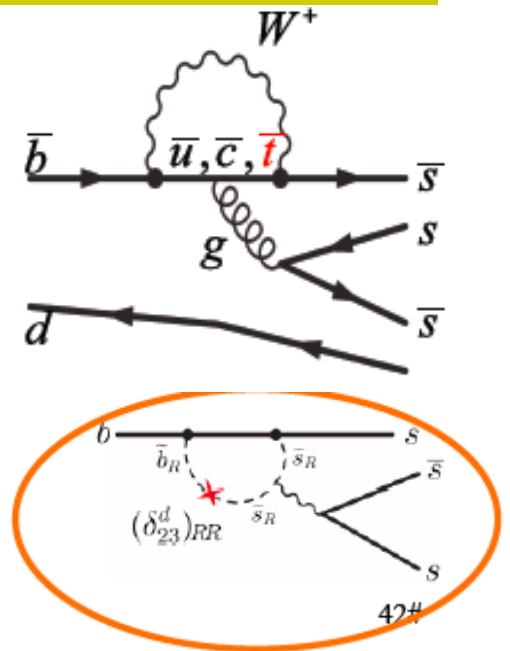
$$\varphi_{B_s} = 0.42 \pm 0.89$$

**Consistent With SM**

# New Physics Through Decay



Through new loop diagrams in the decay amplitude:



New Physics loops can lead to deviation of CPV from  $\sin 2\beta$

# Penguin dominated $B^0$ decays:

## Measurements of " $\sin 2\beta$ ", " $\phi_s$ "

New addition from  $B_s^0$  to this program

$\phi_s$  from  $B_s^0 \rightarrow \phi\phi$  (penguin dominated process)-Analog of  $B_d^0 \rightarrow \phi K_s$

$$\phi_s = -73 \pm 115 \pm 27 \text{ (mrad)}$$

$$\lambda = 0.99 \pm 0.05 \pm 0.01$$

Consistent with SM:

$$\phi_s^{SM} = -36.8^{+1.0}_{-0.8} \text{ mrad}$$

Naïve average of " $\sin 2\beta$ "\_penguins:

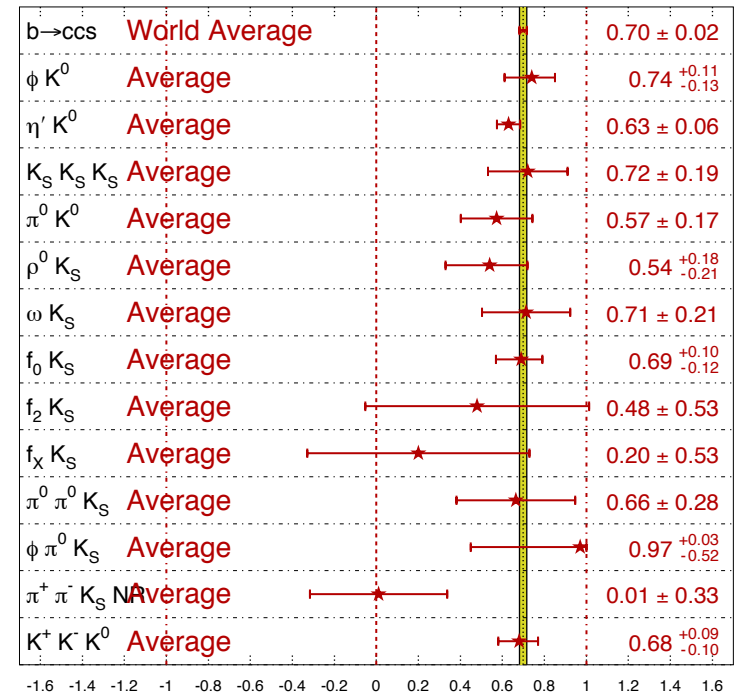
$$0.648 \pm 0.038$$

From ( $b \rightarrow ccs$ ):

$$0.70 \pm 0.02$$

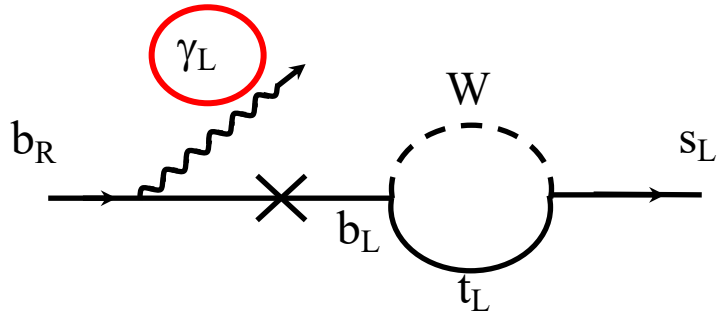
$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$

**HFLAV**  
Summer 2018  
PRELIMINARY

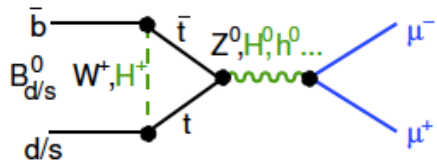


Current results are consistent with SM.  
Caution: theoretical uncertainties are not well defined.

# Footprint of New Physics in FCNC Processes

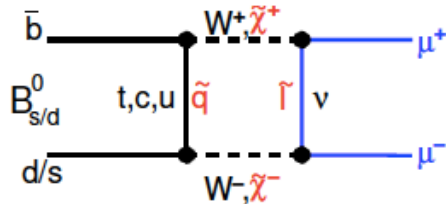


- Offers several observables sensitive to NP: Rate, CPV, polarization of photon (Soni et al)
- All measurements consistent with SM- Precision measurements expected from Belle-II and LHCb

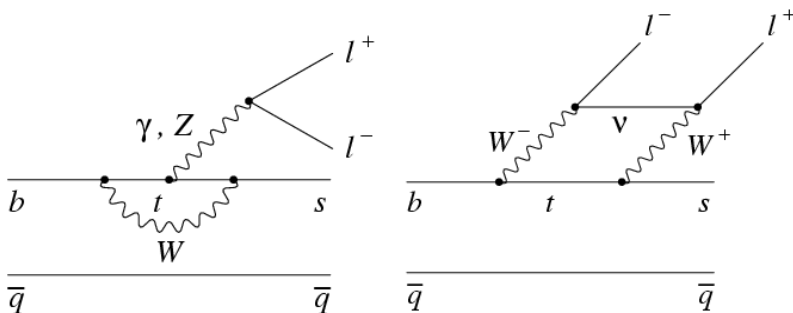


$$SM : Br(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

PRL 112, 101801



Finally seen (LHCb, CMS & ATLAS) – consistent with SM – sets severe constraints on BSM



- Precision of observables significantly improved with the LHCb data
  - Angular distributions & Lepton Flavor Universality tests are in tension with SM

# Tests of Lepton Flavor Universality (LFU)

Lepton Flavor Universality (LFU) is enshrined in the SM:

The three lepton flavors couple with equal strength to gauge bosons. Interaction outcomes differ only due to the effects of lepton masses .

✓ Current Data – some very precise- is mostly consistent with LFU.

Observable	Measurement	Expected
$\frac{B(Z \rightarrow \mu^+ \mu^-)}{B(Z \rightarrow e^+ e^-)}$	$1.0009 \pm 0.0028$	1.0
$\frac{B(Z \rightarrow \tau^+ \tau^-)}{B(Z \rightarrow e^+ e^-)}$	$1.0019 \pm 0.0032$	1.0
$R^W(\tau\mu e) = \frac{2 \times B(W^\pm \rightarrow \tau^\pm \bar{\nu}_\tau)}{B(W^\pm \rightarrow e^\pm \bar{\nu}_e) + B(W^\pm \rightarrow \mu^\pm \bar{\nu}_\mu)}$	$1.077 \pm 0.026$	0.999
$R(K_{\mu e}) = \frac{\Gamma(K^+ \rightarrow e^+ \nu)}{\Gamma(K^+ \rightarrow \mu^+ \nu)}$	$(2.488 \pm 0.009) \times 10^{-5}$	$(2.472 \pm 0.001) \times 10^{-5}$
$R(\pi_{\mu e}) = \frac{\Gamma(\pi^+ \rightarrow e^+ \nu)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu)}$	$(1.230 \pm 0.004) \times 10^{-4}$	$(1.2354 \pm 0.0002) \times 10^{-4}$
$(g_\mu/g_e)_\pi$	$1.0021 \pm 0.0015$	1.0
$(g_\mu/g_e)_\tau$ (from $R(\tau_{\mu e}) = \frac{B(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau)}{B(\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau)}$ )	$1.0018 \pm 0.0014$	1.0
$(g_\tau/g_\mu)$ (from $R(\tau_{\mu e}) = \frac{B(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau)}{B(\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau)}$ )	$1.0011 \pm 0.0015$	1.0
$(g_\tau/g_\mu)$ (from $R(\tau_{K\mu}) = \frac{B(\tau^+ \rightarrow K^+ \nu_\tau)}{B(K^+ \rightarrow \mu^+ \nu_\mu)}$ )	$0.9850 \pm 0.0054$	1.0
$R(Ds_{\tau\mu}) = \frac{\Gamma(D_s^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)}$	$(10.9^{+1.3}_{-1.2}) \times 10^{-2}$	$(8.65^{+1.65}_{-1.43}) \times 10^{-2}$
$R(\Upsilon(1S)_{\tau\mu}) = \frac{\Gamma(\Upsilon(1S) \rightarrow \tau^+ \tau^-)}{\Gamma(\Upsilon(1S) \rightarrow \mu^+ \mu^-)}$	$1.005 \pm 0.0255$	0.992
$R(D^*)_{e\mu} = B(\bar{B}^0 \rightarrow D^{*-} e^+ \bar{\nu}_e) / B(\bar{B}^0 \rightarrow D^{*-} \mu^+ \bar{\nu}_\mu)$	$1.01 \pm 0.03$	1.0
$R(D) = B(\bar{B}^0 \rightarrow D^0 \tau^- \bar{\nu}_\tau) / B(\bar{B}^0 \rightarrow D^0 \mu^- \bar{\nu}_\mu)$	$0.440 \pm 0.42$	$0.299 \pm 0.003$
$R(D^*) = B(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / B(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$	$0.332 \pm 0.182$	$0.258 \pm 0.003$
$R(J/\psi) = B(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau) / B(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$	$0.71 \pm 0.25$	$0.297 \pm 0.007$

➤ Hints of non-LFU effects in the 3<sup>rd</sup> generation first emerged at BaBar

>2 $\sigma$  effects in  $B \rightarrow K^{(*)} \ell^+ \ell^-$

# Tests of Lepton Flavor Universality in $B \rightarrow K^{(*)} \ell^+ \ell^-$

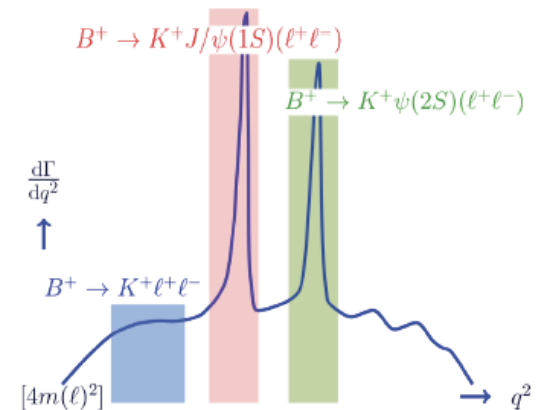
$\mu$  vs  $e$

# Tests of Lepton Flavor Universality: $B \rightarrow K^{(*)} \ell^+ \ell^-$

$$R_H = \frac{\int \frac{d\Gamma(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H e^+ e^-)}{dq^2} dq^2}$$

Within SM:  $R_{K^{(*)}} = 1 + O(<1\%)$

- Measurements performed in  $q^2$  bins
- Region of  $q^2 < 6 \text{ GeV}^2$  avoids charmonium resonances & has clean theoretical predictions
- Resonance regions provide powerful checks on the analysis



- LHCb and recent Belle Measurements performed as

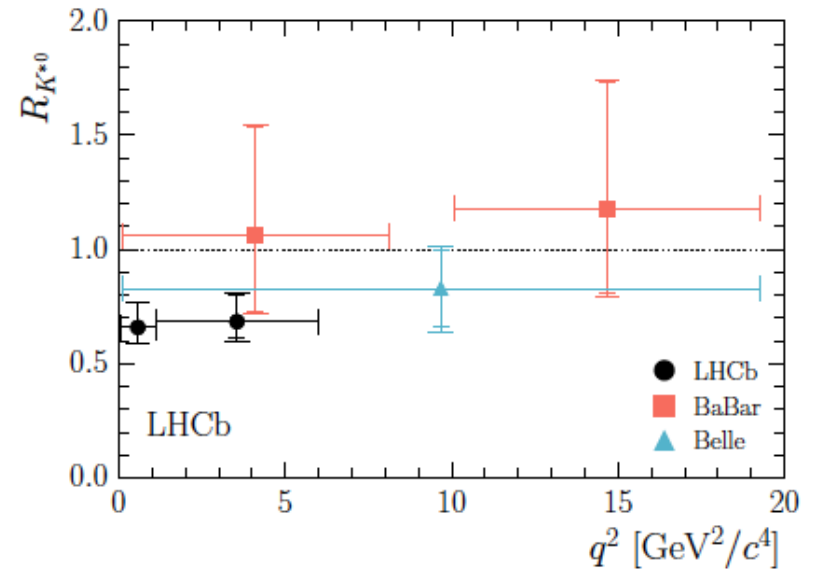
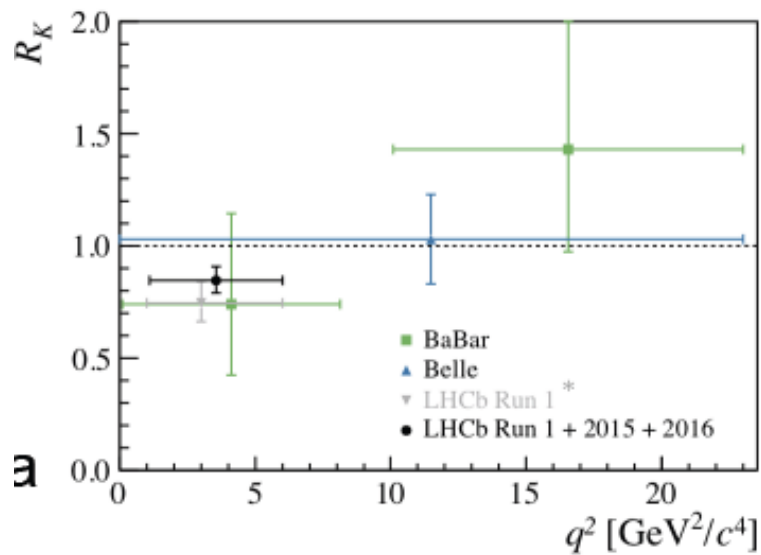
$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+)} \bigg/ \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow e^+ e^-) K^+)}.$$

- Check that  $r_{J/\psi} = \mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+) / \mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow e^+ e^-) K^+) = 1$
- $R_K^{\psi(2S)} = \frac{\mathcal{B}(B^+ \rightarrow \psi(2S) (\rightarrow \mu^+ \mu^-) K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+)} \bigg/ \frac{\mathcal{B}(B^+ \rightarrow \psi(2S) (\rightarrow e^+ e^-) K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow e^+ e^-) K^+)} = 1$

# Tests of Lepton Flavor Universality: $B \rightarrow K^{(*)} \ell^+ \ell^-$

$$R_H = \frac{\int \frac{d\Gamma(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H e^+ e^-)}{dq^2} dq^2}$$

Within SM:  $R_{K^{(*)}} = 1$

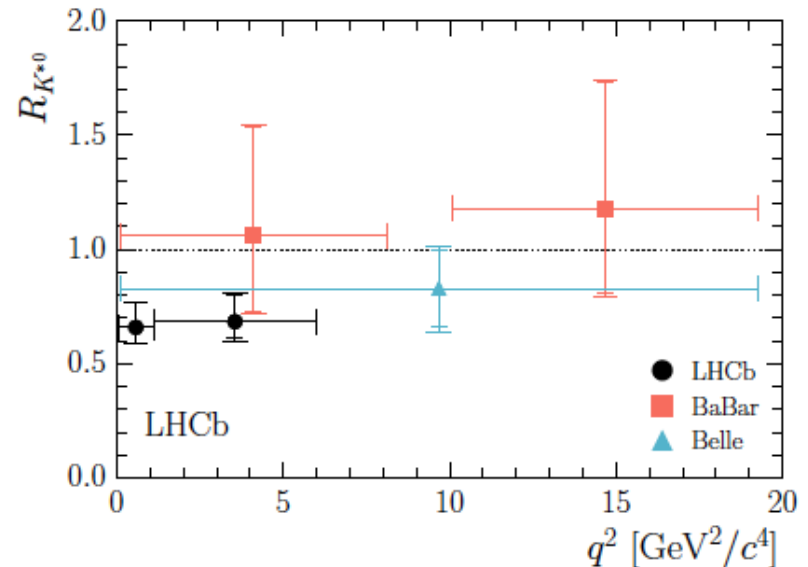
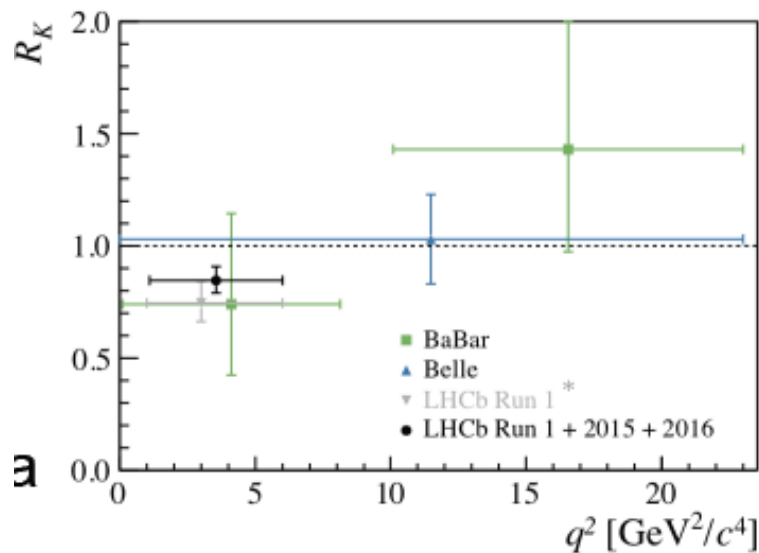




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Within SM:  $R_{K^{(*)}} = 1$



## Hints of departure from LFU in LHCb data

25#

[LHCb-PAPER-2019-009]

LHCb: Run1+2015 & 2016

$$R_K = 0.846^{+0.060}_{-0.054} \text{ (stat)} \quad {}^{+0.014}_{-0.016} \text{ (syst)}$$

Within  $2.5 \sigma$  of SM

$$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024 \text{ low-} q^2$$

$$R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047 \text{ high-} q^2$$

Within  $2.1\text{-}2.3 \sigma$  &  $2.4\text{-}2.5 \sigma$  of SM

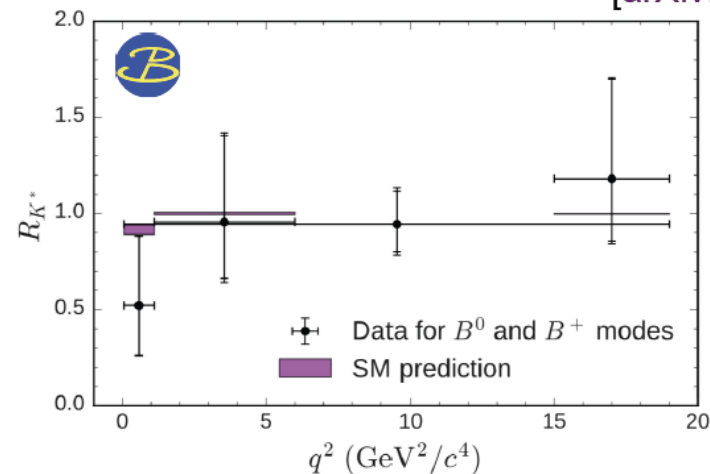
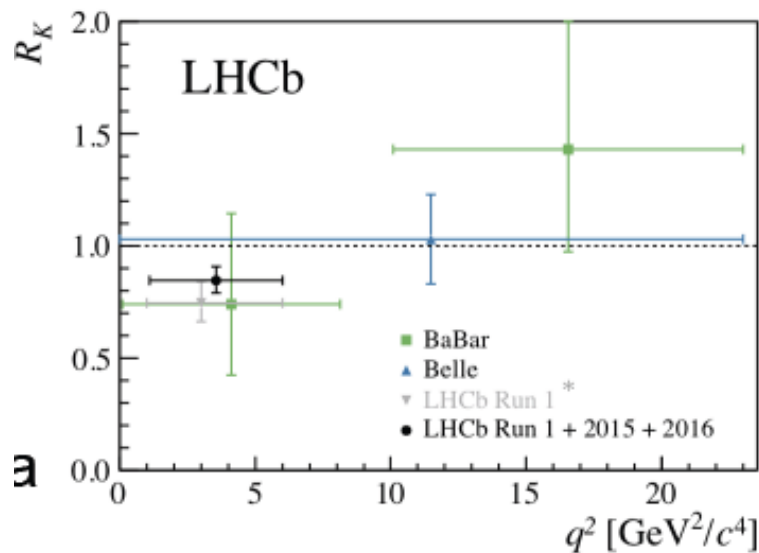
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Within SM:  $R_{K^{(*)}} = 1$

New **Belle** Measurement over full  $q^2$   
compatible with SM & LHCb- still precise  
than LHCb

[arXiv:1904.02440]



## Hints of departure from LFU in LHCb data

[LHCb-PAPER-2019-009]

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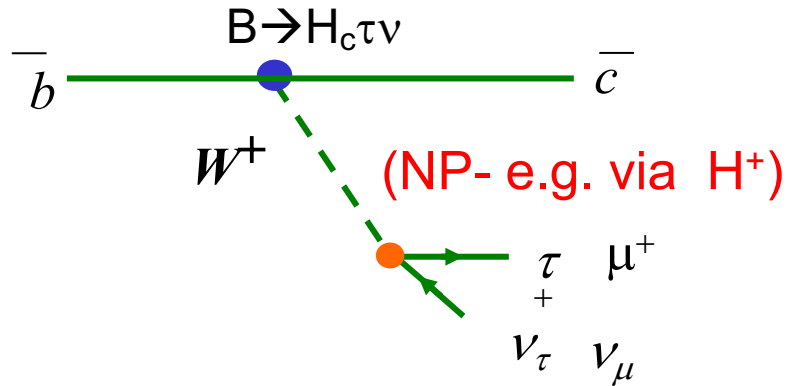
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Within 2.1-2.3  $\sigma$  & 2.4-2.5  $\sigma$  of SM

Tests of Lepton Flavor Universality  
in Semileptonic decays:  $B \rightarrow H_c \ell \nu$

$$\underline{\tau \text{ vs } \mu/e}$$

# Tests of Lepton Flavor Universality: $\tau$ vs $\mu$



In SM, decays to  $\mu$  &  $\tau$  differ only due to the lepton mass differences

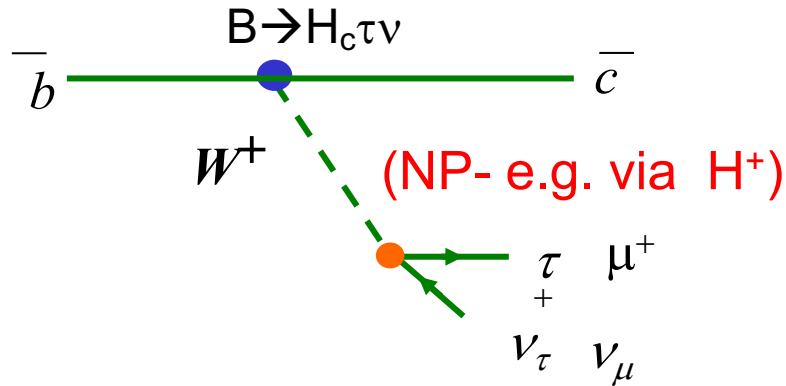
• Ratio of Branching ratios are theoretically and experimentally very "clean" probes of LFU

- Most hadronic uncertainties & CKM dependences cancel
- Many experimental uncertainties also cancel

$$R(D^{(*)}) = \frac{B(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu})}{B(\bar{B} \rightarrow D^{(*)} \mu \bar{\nu})}$$

$$R(J/\psi) = \frac{B(B_c^+ \rightarrow J/\psi \tau^+ \bar{\nu})}{B(B_c^+ \rightarrow J/\psi \mu^+ \bar{\nu})}$$

# Tests of Lepton Flavor Universality: $\tau$ vs $\mu$



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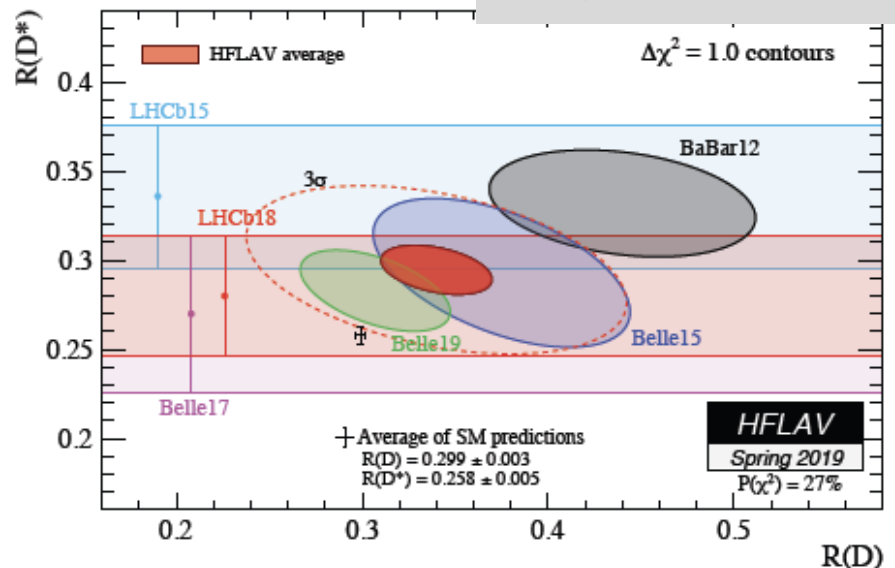
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- Most hadronic uncertainties & CKM dependences cancel
- Many experimental uncertainties also cancel

Current Status  
 $3.1\sigma$  from LFU

$$R(D^{(*)}) = \frac{B(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu})}{B(\bar{B} \rightarrow D^{(*)} \mu \bar{\nu})}$$

$$R(J/\psi) = \frac{B(B_c^+ \rightarrow J/\psi \tau^+ \bar{\nu})}{B(B_c^+ \rightarrow J/\psi \mu^+ \bar{\nu})}$$



# How well do we know the SM predictions?

Adopted from Dean Robinson (DPF2019)

Coll.	Approach	$R(D)$	$R(D^*)$	corr.
1607.00299 [FLAG]	Lattice	$0.300 \pm 0.008$	—	—
1606.08030 [Bigi, Gambino]	Lattice + Belle/BaBar	$0.299 \pm 0.003$	—	—
1203.2654 [Fajfer, Kamenik, Nisandzic]	Cont.+ Belle	—	$0.252 \pm 0.003$	—
1703.05330 [Bernlochner, Ligeti, Papucci, & DR]	Lattice + Belle + HQET NLO	$0.299 \pm 0.003$	$0.257 \pm 0.003$	0.44
1707.09509 [Bigi, Gambino, Schacht]	BGL + BLPR + $1/m_c^2$ error estimate	—	$0.260 \pm 0.008$	—
1707.09977 [Jaiswal, Nandi, Patra]	BGL/HQET + $1/m_c^2$ parameter	$0.299 \pm 0.004$	$0.257 \pm 0.005$	$\sim 0.1$
<b>HFLAV</b>	Arithmetic average	<b><math>0.299 \pm 0.003</math></b>	<b><math>0.258 \pm 0.005</math></b>	<b>—</b>

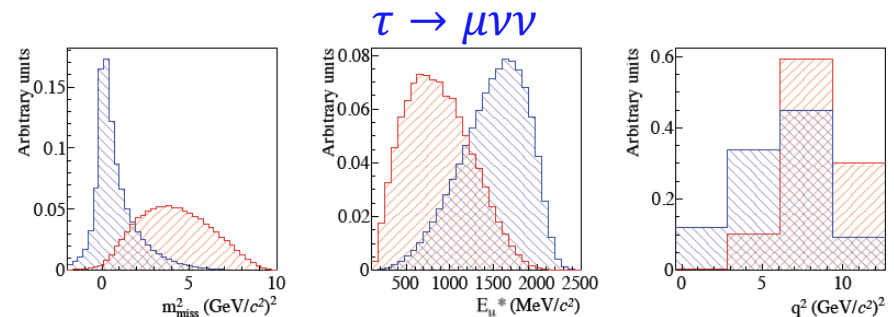
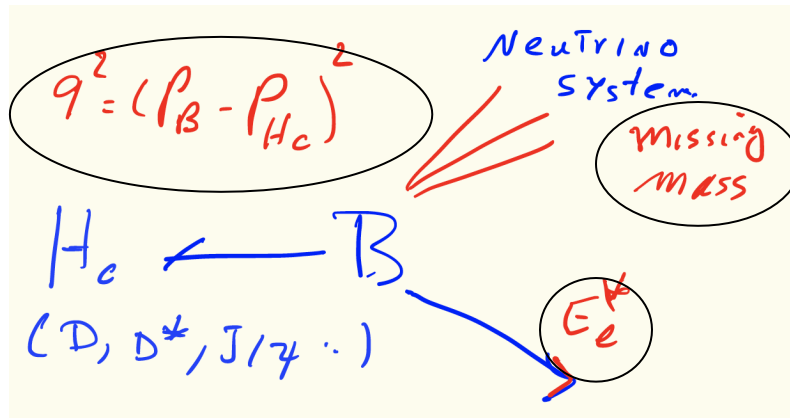
$R(J/\psi)$ :  $0.290 \pm 0.007$   
Preliminary Lattice result

Uncertainties dominated by the scalar Form-Factor - significant only for the tau channel & unconstrained by data

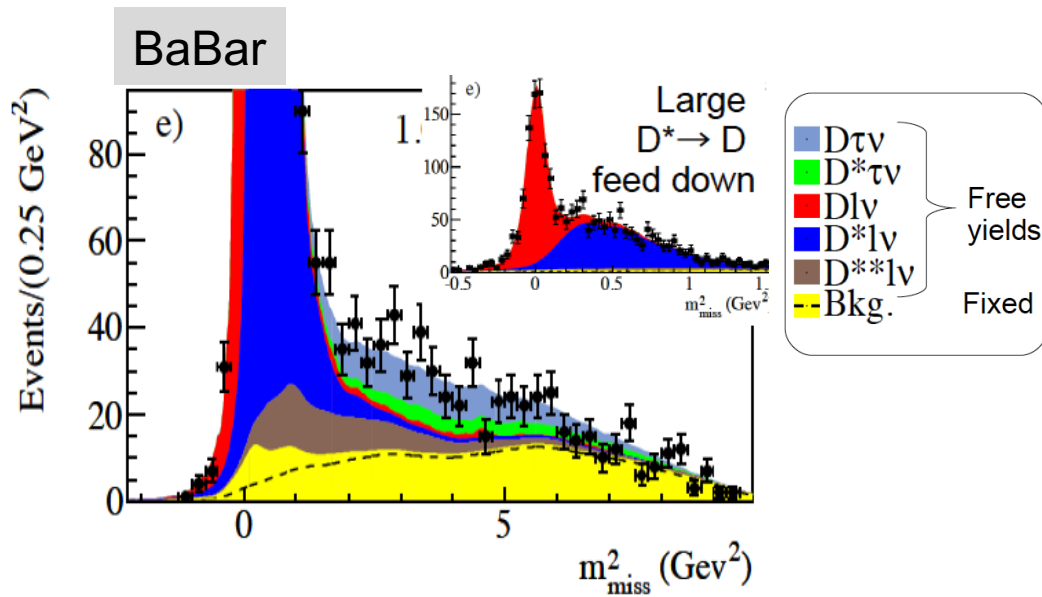
# Experimental measurements

Semileptonic decays are usually analyzed in the B rest frame kinematic variables:

$$B \rightarrow H_c \ell \nu, [\ell = e, \mu, \tau \text{ (with } \tau \rightarrow \mu \nu \nu, \tau \rightarrow 3 \pi \nu, \dots)]$$



Equivalent/alternative kinematic variables for  $\tau \rightarrow 3 \pi \nu$

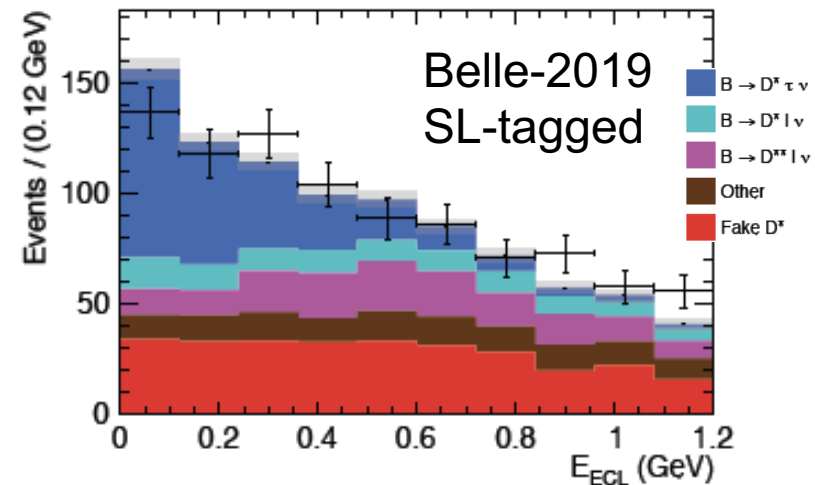
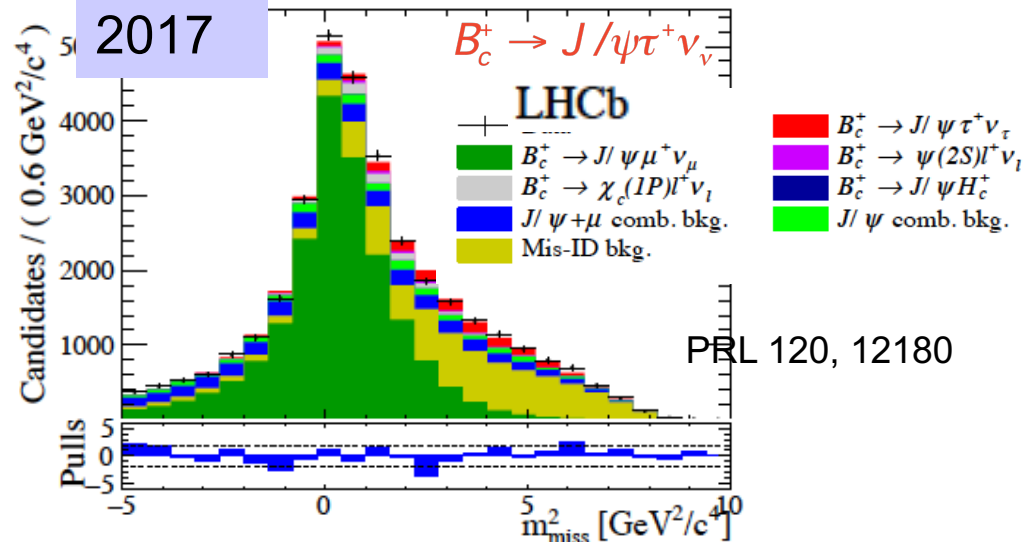
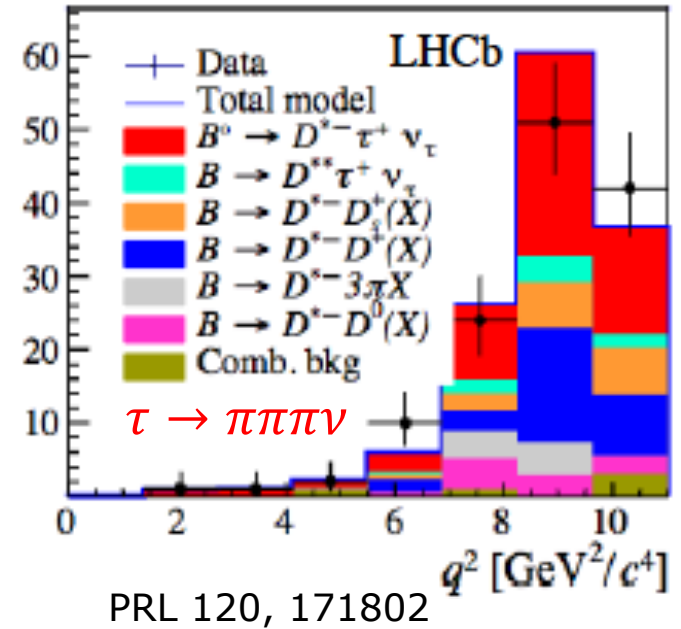
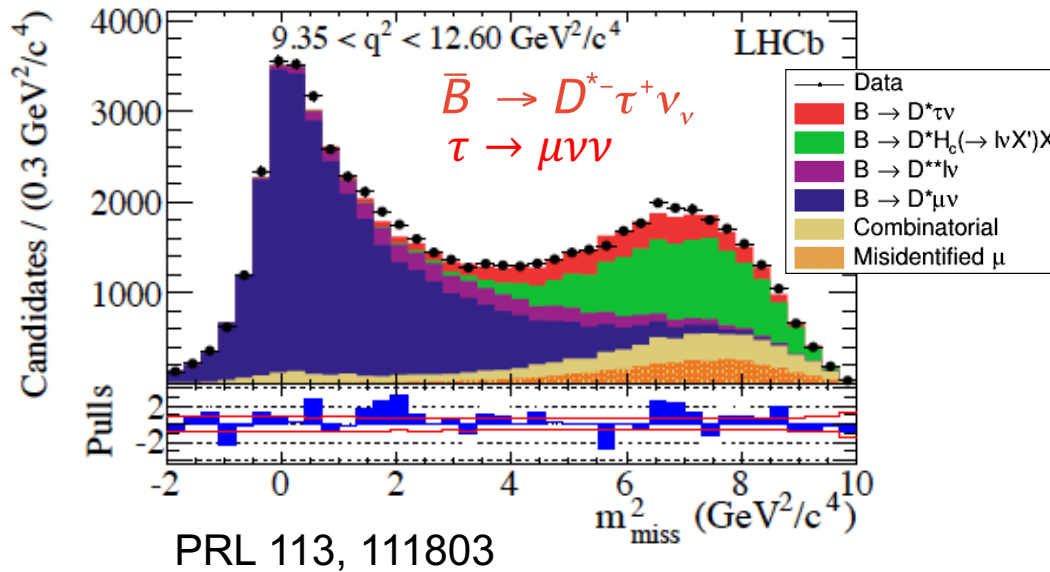


**Note:** many contributors to the distribution- some can be constrained/determined along with signal, others need theoretical input on Form Factors and rates.

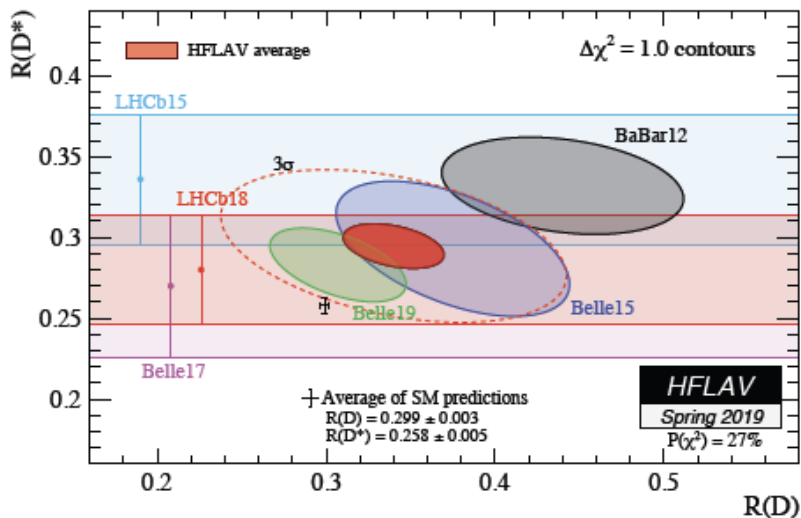
2015

LHCb and Belle measurements

2017

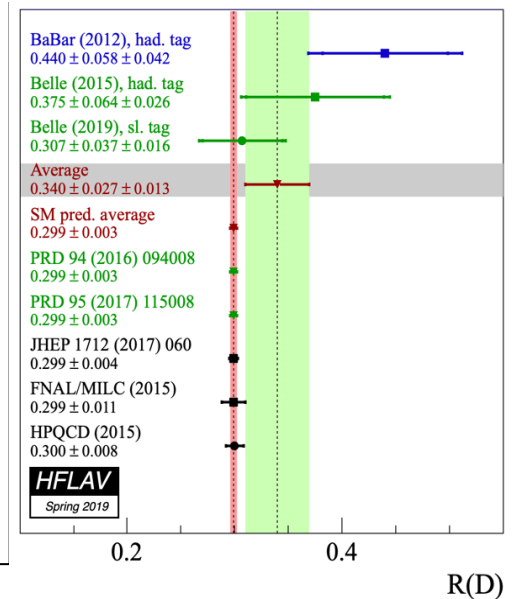
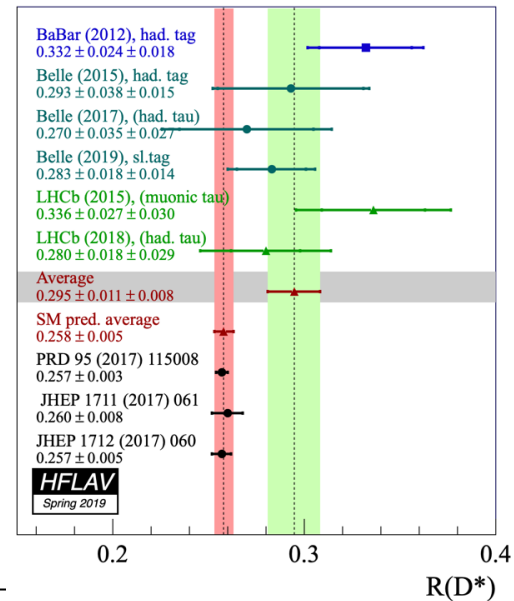






Overall:  
3.1  $\sigma$  tension  
with LFU/SM

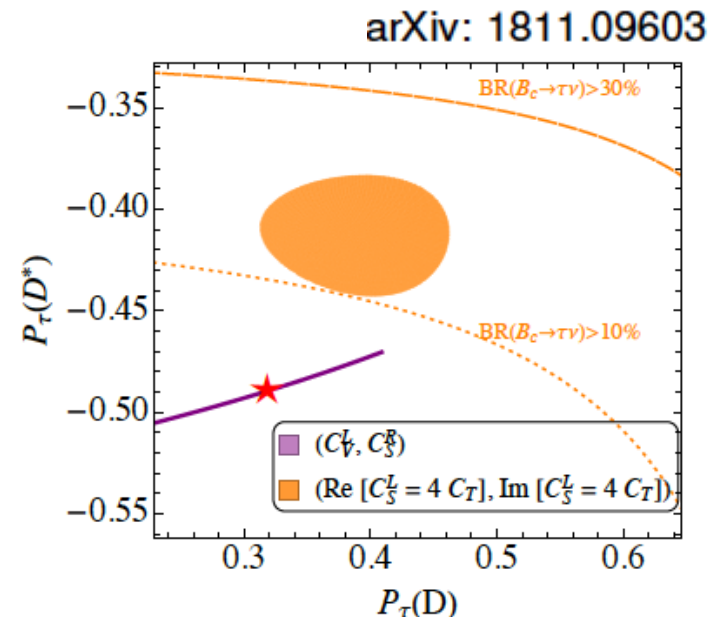
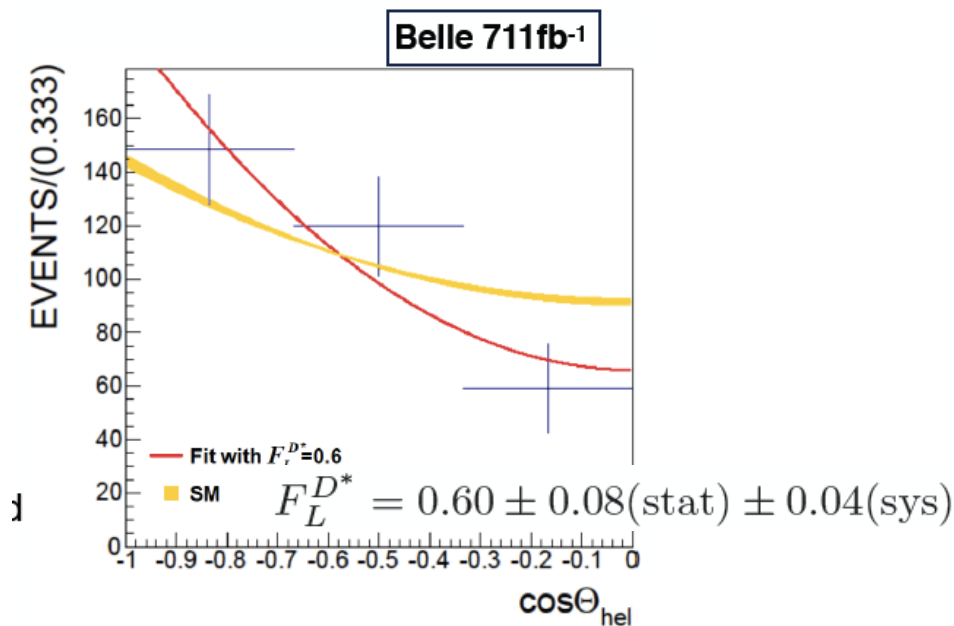
- All results exceed SM predictions
  - Latest Belle results consistent with SM & others
- No single measurement is yet at or beyond 3 sigma from SM
- Extensive literature on theoretical interpretations:
  - New Spin-1 states,  $W'$ ,  $Z'$ , or leptoquarks are favored.
  - New scalars (incl. charged Higgs) disfavored by constraints on  $B_c \rightarrow \tau \nu$



$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

## Near Future:

- Improved precision of measurements with Belle-II and LHCb data:
  - Simultaneous R(D) and R(D\*) from LHCb
  - R(D\*) (with hadronic tau decay), R(Ds), R( $\Lambda_c$ ), R(J/psi)
- Much Later: Additional observables that may help distinguish new physics sources of LFU:
  - D\* polarization FL(D\*)
  - Tau polarization:  $P_\tau(D^*) = \frac{\Gamma(\tau^{\lambda=+1/2}) - \Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2}) + \Gamma(\tau^{\lambda=-1/2})}$   $P_\tau(D) = \frac{\Gamma(\tau^{\lambda=+1/2}) - \Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2}) + \Gamma(\tau^{\lambda=-1/2})}$
  - CPV in angular distributions of  $B \rightarrow D^*(\rightarrow D\pi)\tau\nu$



# Search for new Sources of CP Violation:

CPV in charm decays

# Within SM: CPV in charm decays is very small

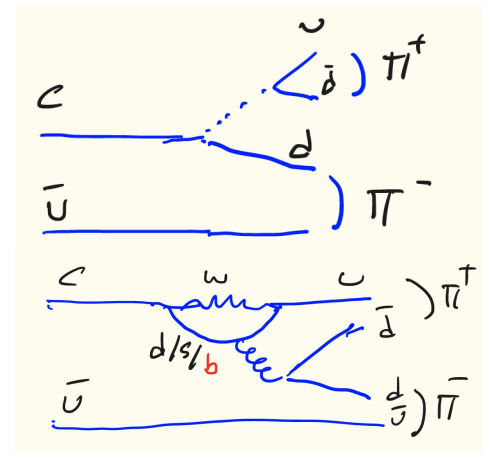
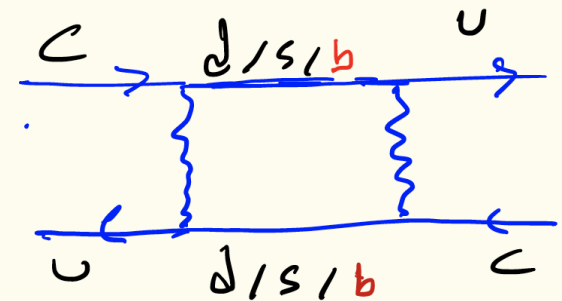
➤ CPV requires contribution from all three generations:

➤ CPV in  $D^0$  mixing:

Dominant contributions are from the 1<sup>st</sup> two generations → negligible CPV in  $D^0$  mixing

➤ Direct CPV from interference of Tree and penguin diagrams- also dominated by the 1<sup>st</sup> two generations; → negligible direct CPV

loops with some b-quark contributions can induce small CPV  $\sim O(|V_{ub}V_{cb}^*/V_{ud}V_{cd}^*|) \sim \lambda^4 \ll 10^{-3}$

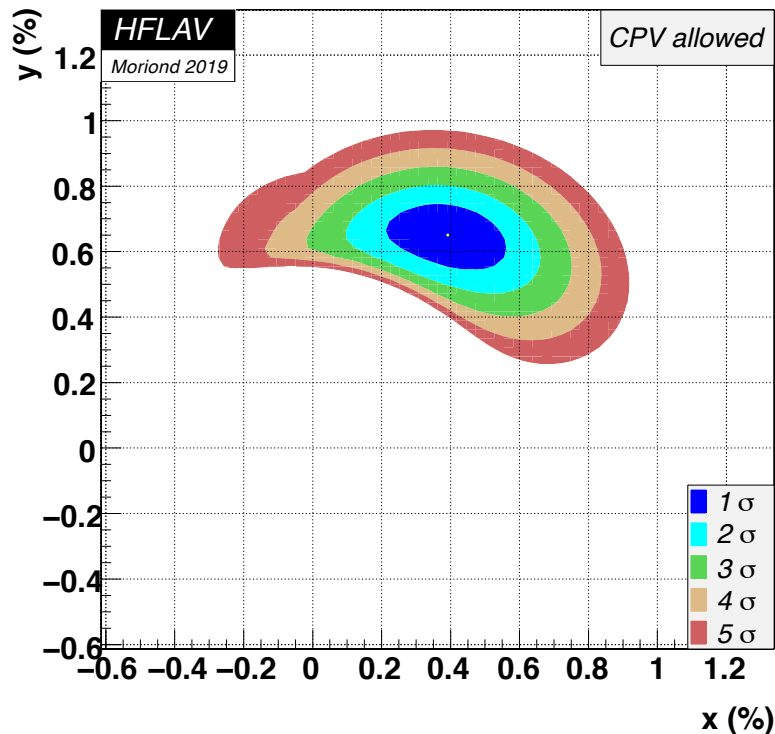


# CP Violation in $D^0$ mixing

Mixing is firmly established but no evidence for CPV in mixing

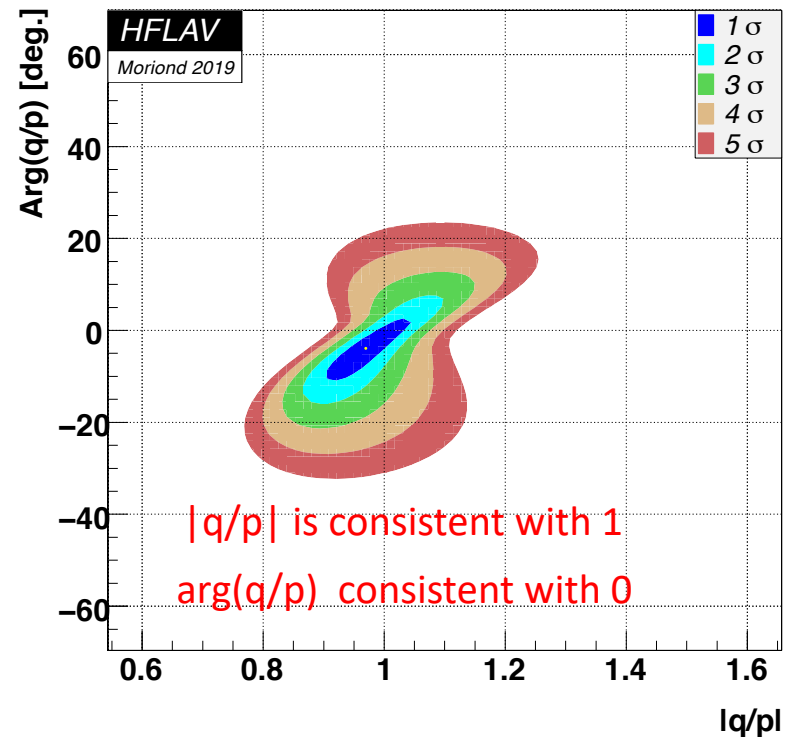
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$X = \frac{\Delta m}{\Gamma} \quad y = \frac{\Delta \Gamma}{\Gamma}$$



CPV if:

$$|q/p| \neq 1 \quad \arg(q/p) \neq 0$$



# Direct CPV in the charm system

$$A_{cp} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}$$

Searches performed in a large number of channels: No evidence for CPV  
Precision in some channels at  $\sim O(10^{-3})$  level already:

Channel  $A_{cp}$  (%) (From 2017 HFLAV averages)

$D^0 \rightarrow \pi^+ \pi^-$   $+0.00 \pm 0.15$

$D^0 \rightarrow K^0_s \pi^0$   $-0.20 \pm 0.17$

$D^0 \rightarrow K^+ K^-$   $-0.16 \pm 0.12$

$D^+ \rightarrow K^0_s \pi^+$   $-0.41 \pm 0.09$

$D^+ \rightarrow K^0_s K^+$   $-0.11 \pm 0.25$

$D^+_s \rightarrow K^0_s K^+$   $+0.08 \pm 0.26$

$D^+_s \rightarrow K^0_s \pi^+$   $-0.38 \pm 0.48$

$>3\sigma$  Expect  $A_{cp} \sim -0.33\%$   
induced by indirect CPV in  $K^0$

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 induced by indirect CPV in  $K^0$

The LHCb data (Runs I & II) enables yet  
 another major step in precision  $\rightarrow O(10^{-4})$

# Observation of Direct CP violation in charm decays at LHCb

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

The idea is that:  $A_{raw}(D \rightarrow h^+h^-) = A_{CP}(h^+h^-) + \boxed{A(det) + A(prod)}$

Common to both channels

Flavor of  $D^0$  is tagged via:  $D^{*+} \rightarrow D^0 \pi^+$  or from  $B \rightarrow D \mu^+ \nu X$

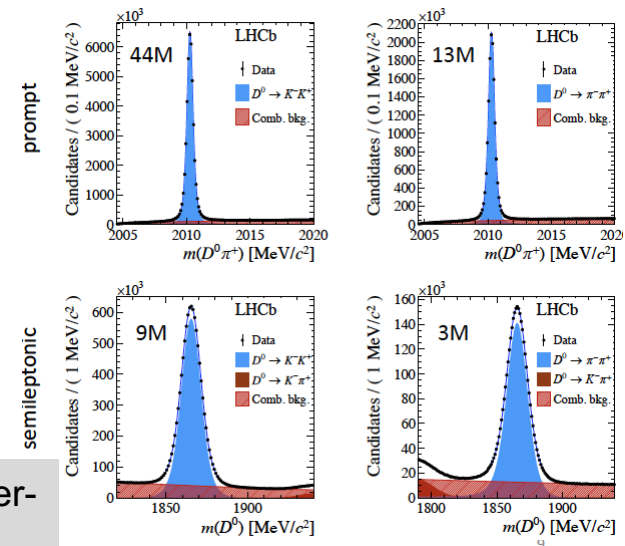
CP violation observed at 5.3 sigma

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

$$\Delta A_{CP} \simeq \Delta a_{CP}^{dir} \left( 1 + \frac{\langle \bar{t} \rangle}{\tau_{D^0}} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau_{D^0}} a_{CP}^{ind}$$

$$\boxed{\Delta a_{CP}^{dir} = (-15.6 \pm 2.9) \times 10^{-4}}$$

LHCb-paper-  
2019-006





# Observation of Direct CP violation in charm decays at LHCb

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

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Common to both channels

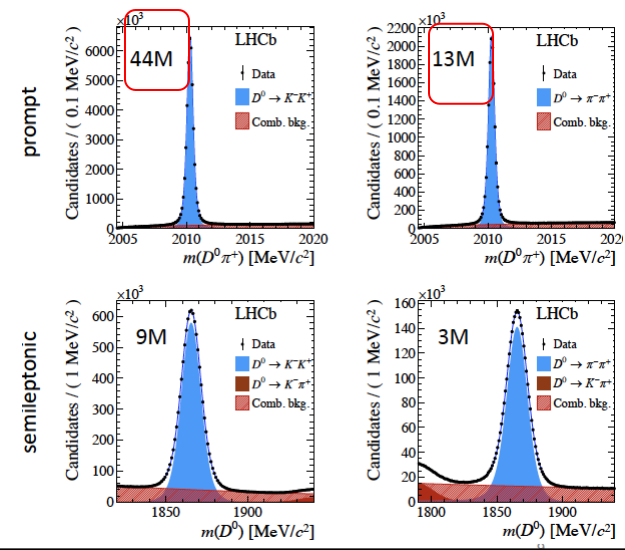
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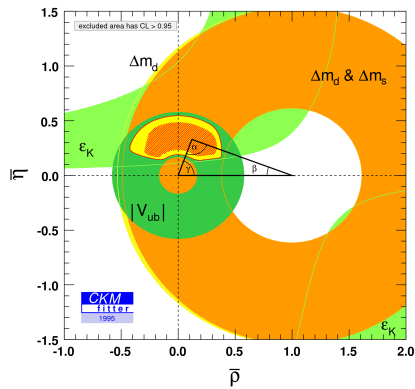


Not too far from SM ( $\sim 10^{-3}$ ). Specific mechanism yet to be determined: (Soni 2019), (Silvestrini et al 2019), Grossman & Schacht. Too soon to invoke BSM observation.

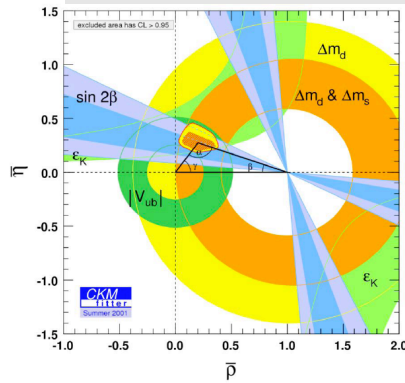
# Future

# Toward precision Flavor Physics-O(1%): CKM and Rare Decays & much more

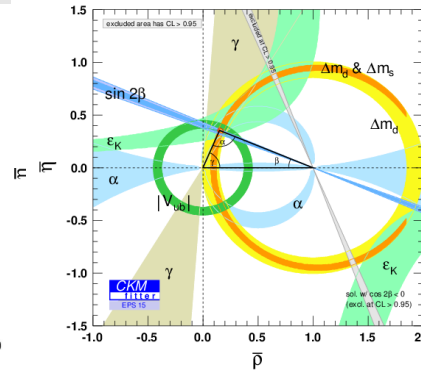
Last century



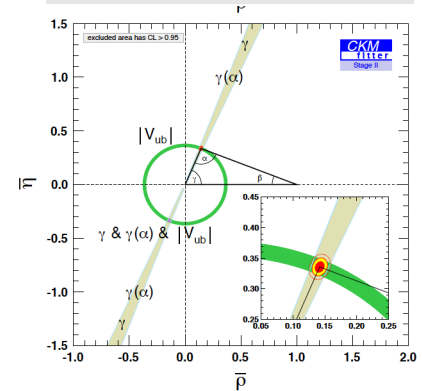
2001



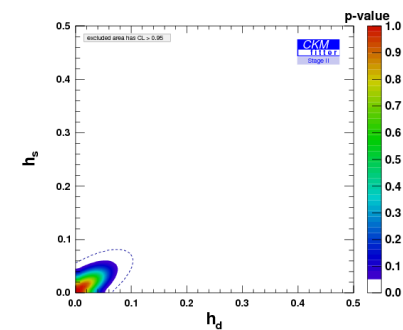
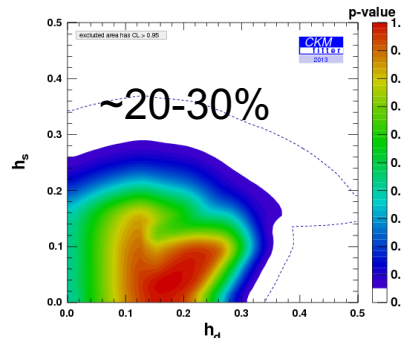
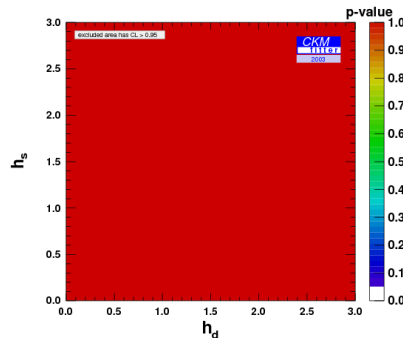
Today



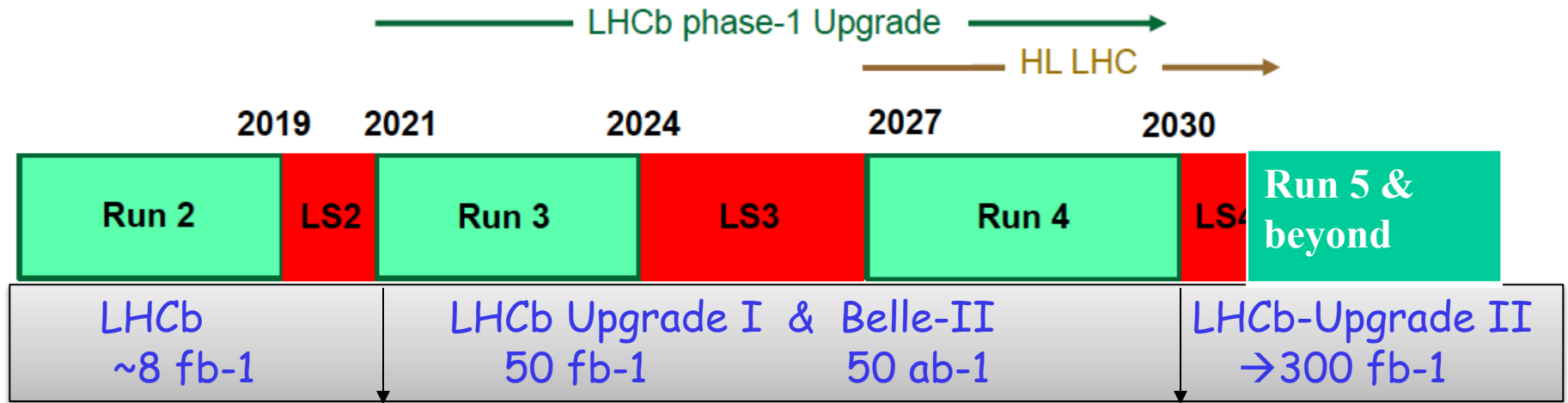
2025+



Constraint on  
NP/SM  
amplitude  
See (*arXiv:*  
*1309.2293*)



# Experimental Landscape



# Belle-II at SuperKEKB

## Tom Browder at Lepton – Photon 2019

SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron ( $e^+e^-$ ) rather than proton-proton (pp))

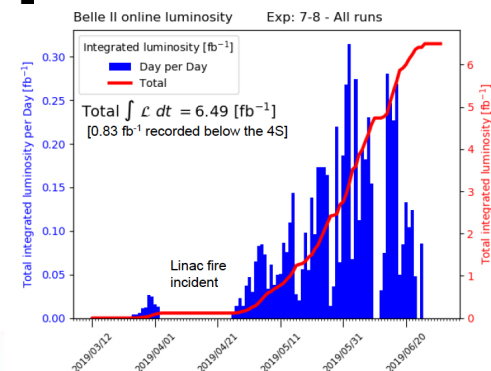
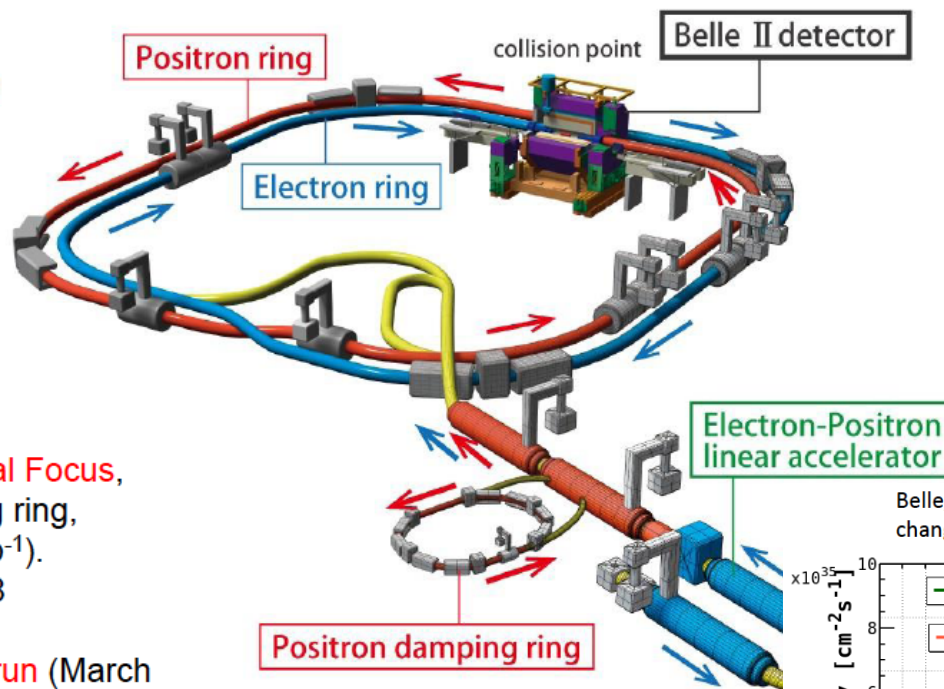


Phase 1:  
Background, Optics  
Commissioning  
Feb-June 2016.

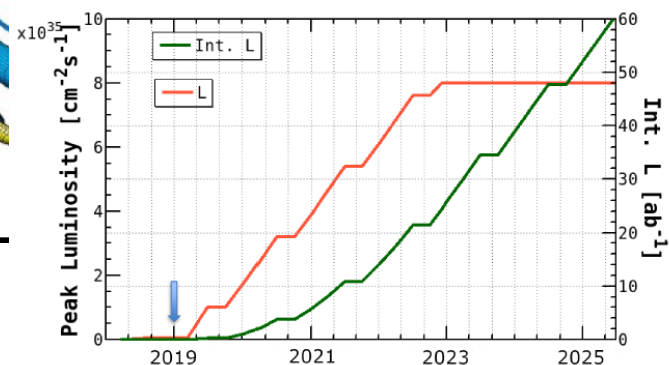
Brand new  
3 km positron ring.

Phase 2: Pilot run  
Superconducting Final Focus,  
add positron damping ring,  
First Collisions ( $0.5 \text{ fb}^{-1}$ ).  
April 27-July 17, 2018

Phase 3: → Physics run (March  
27-June 30<sup>th</sup>, 2019)



Belle/KEKB recorded  $\sim 1000 \text{ fb}^{-1}$ . Now have to change units on the y-axis to  $\text{ab}^{-1}$



# LHCb Upgrade-I in installation

High Luminosity running requires removal of hardware level trigger- detector readout at LHC beam crossing rate of 40 MHz

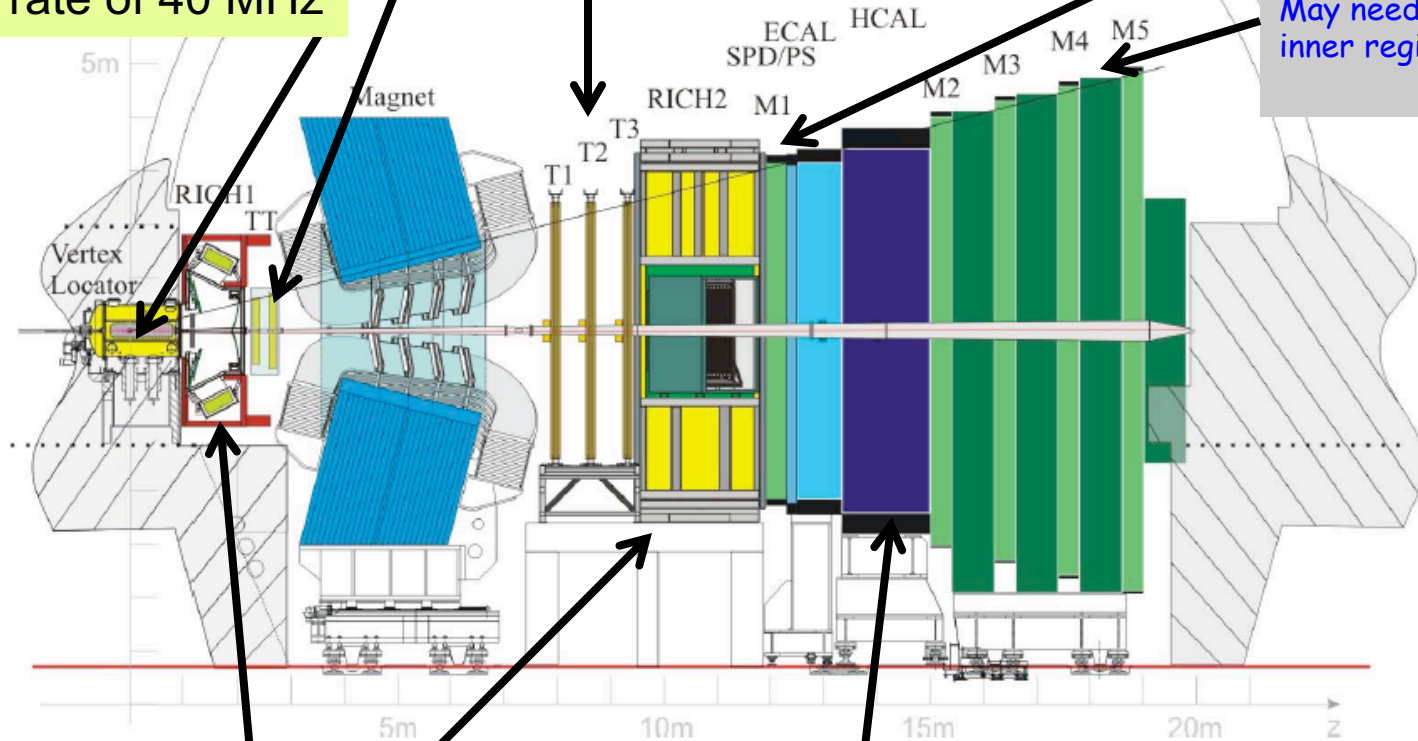
## Tracking system:

New VELO (Si strip  $\rightarrow$  Pixel)  
New upstream tracker (TT) (Si)  
New downstream tracker (Sci Fiber)

## Muon System:

Remove M1

M2-5 fine for  $1 \times 10^{33}$   
May need upgrade of inner region at  $2 \times 10^{33}$



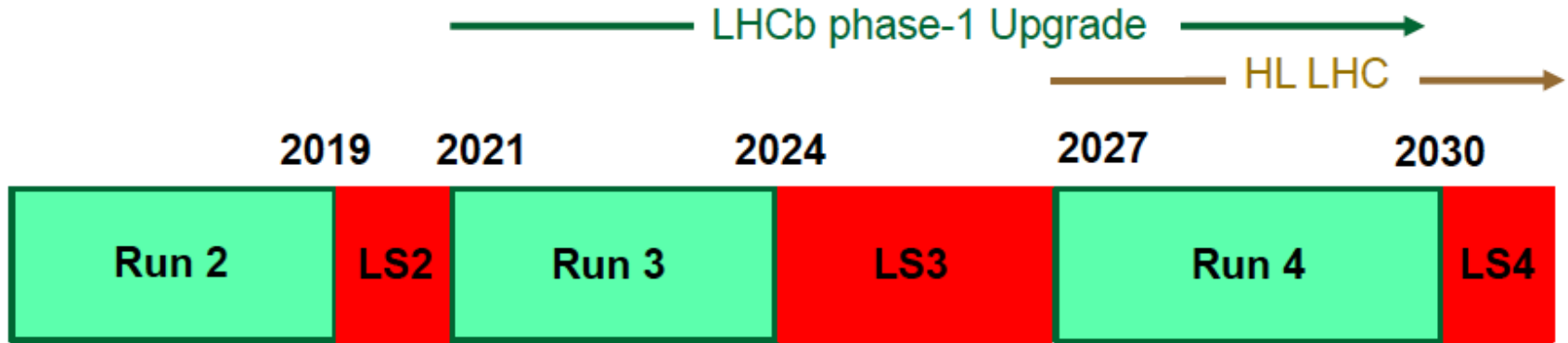
## RICH 1 & RICH 2

HPD  $\rightarrow$  MaPMT  
New 40 MHz R/O  
RICH1: new optics  
remove aerogel

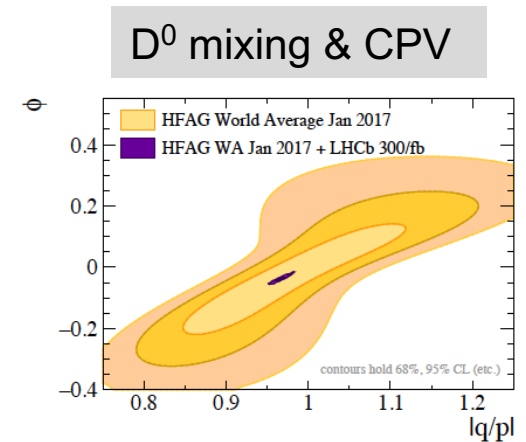
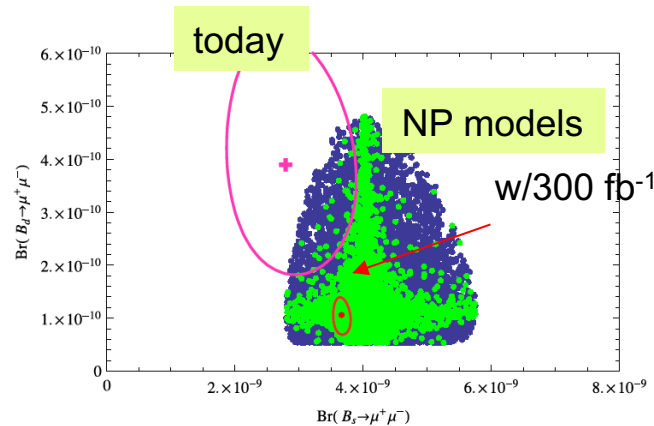
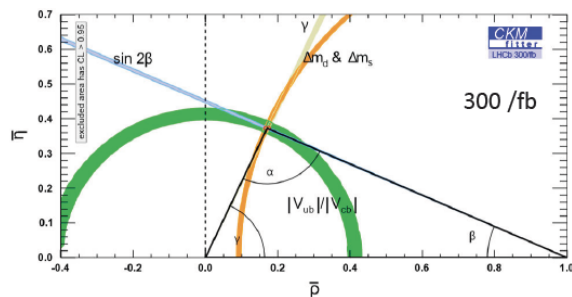
## Calorimeter:

New 40 MHz R/O  
Lower PMT gain to reduce anode current  
Remove SPD & PS

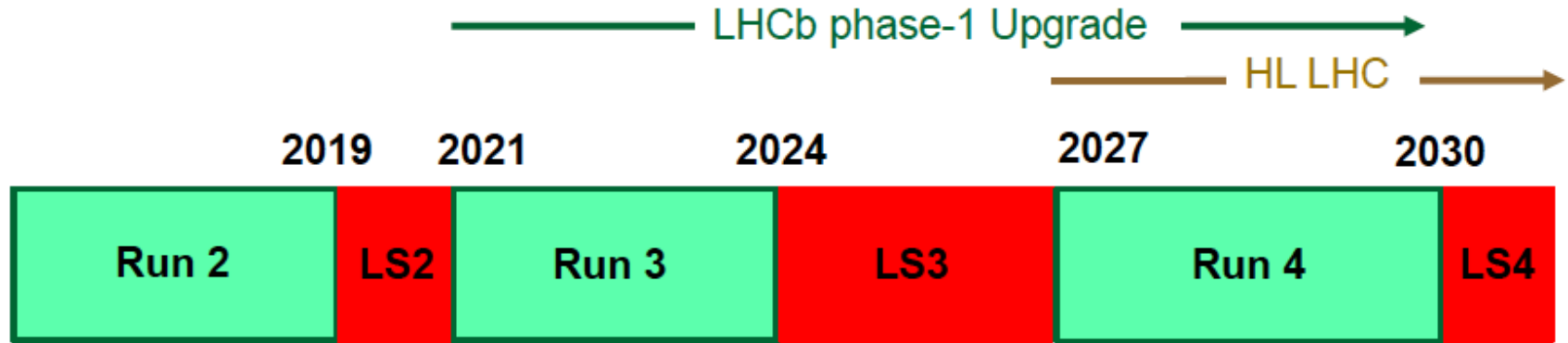
# LHCb Upgrade-II: Physics Goals



Expression-of-Interest & Physics Potential documents submitted for LHCb Upgrade-II



# Upgrade-II: Challenges



Major challenges for LHC & LHCb at peak Luminosity of  $2 \times 10^{34}$  /cm<sup>2</sup>/s:

- Current studies indicate  $2 \times 10^{34}$  is possible with changes to IP optics ( $\beta^*$  reduction) & shielding. Triplet lifetime may limit integ. Lum. to  $\sim 300 \text{ fb}^{-1}$
- At Int/crossing  $\sim 50$  (vs 1.1 now) & Track Multiplicity as high as 3500:
  - Will need a new tracking system & thinner pixels with finer granularity & time measurements in VELO
  - Improved PID & Calorimetry (with fine granularity- e.g. SiW)
  - Will need innovative solutions to enormous increase in data rate (  $\gg$  ATLAS & CMS)
- Next: narrow the space of solutions and develop TDR



# Summary comments

- Flavor physics remains one of the primary drivers of the search for the physics beyond SM, as most scenarios of New Physics are expected to leave a footprint in flavor processes.
  - The current data is consistent with the Standard Model, setting severe constraints on scenarios of New Physics, but many stones remain unturned.
    - There are some areas of tensions with SM, waiting for more precise measurements. Lepton Flavor Universality is under the microscope.
- The next phase of the flavor physics program with Belle-II and LHCb upgrades I & II will result in a much sharper picture of the physics of flavor- will resolve or solidify some of the current anomalies with potential to reveal solid evidence for new physics.