Flavor Physics Highlights

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

Brookhaven Forum

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

1980's- 2000's -B factories

CKM verification → Search for NP & new sources of CPV

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,

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda_i^2} + \cdots$$

Isidori ,Nir, Perez

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

Some of the Recent advances

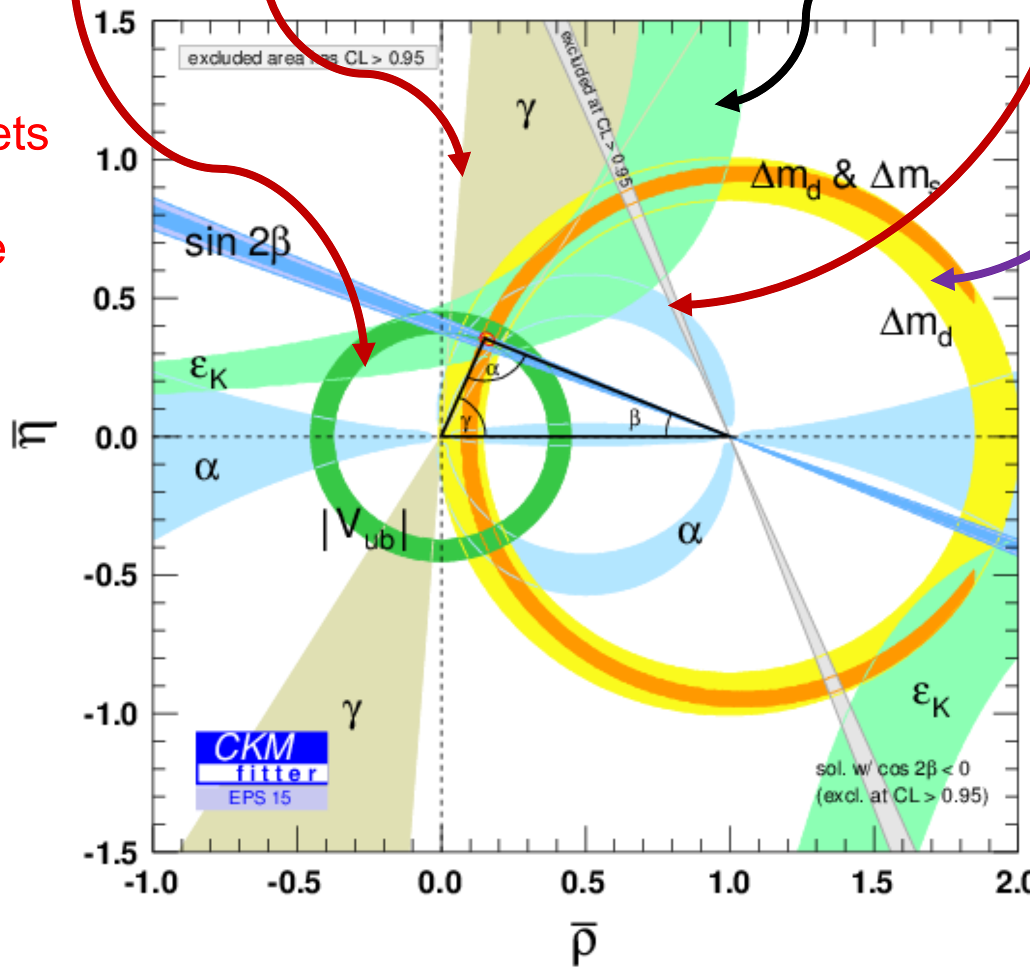
- The CKM picture continues to be sharpened:
  - Improved precision of Unitarity angle γ
  - Improved measurements of time-dependent CPV in B_s^0: ϕ_s
- B-Anomalies: a few measurements are in tension with SM
  - Tests of Lepton Flavor Universality in B decays involving charged and neutral currents
- 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^{-1}) being installed:2019-2020
  - LHCb upgrade II (300 fb^{-1}) in conception/design (→2030)

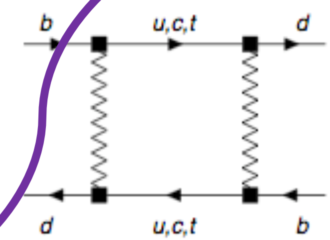
Sharpening the CKM picture

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

tree level processes: V_{ub} & γ
Free of New Physics effects

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

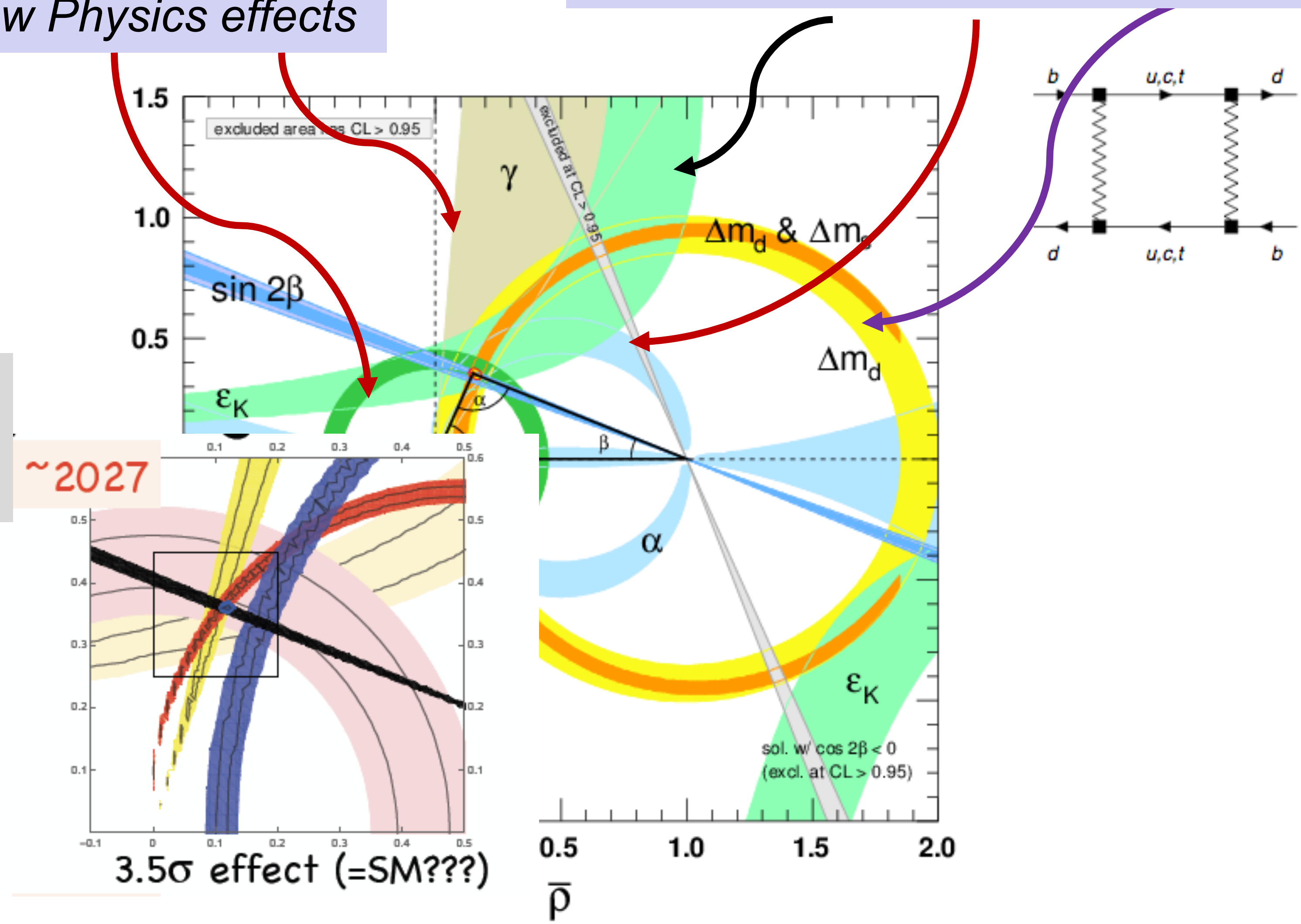




Sharpening the CKM picture

tree level processes: V_{ub} & γ
Free of New Physics effects

Observables involving loop diagrams (K⁰ and B⁰ oscillations) are *sensitive to New Physics*



Adapted from Emi Kou FPCP 2019)

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

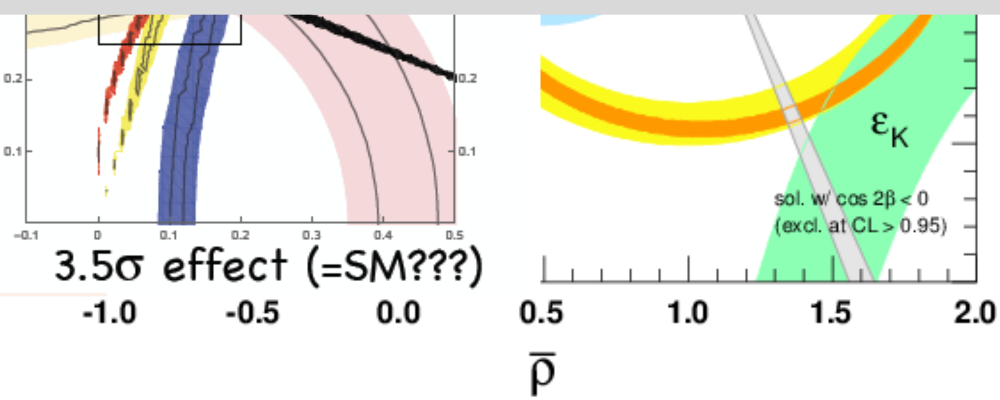
Sharpening the CKM picture

Recent progress :

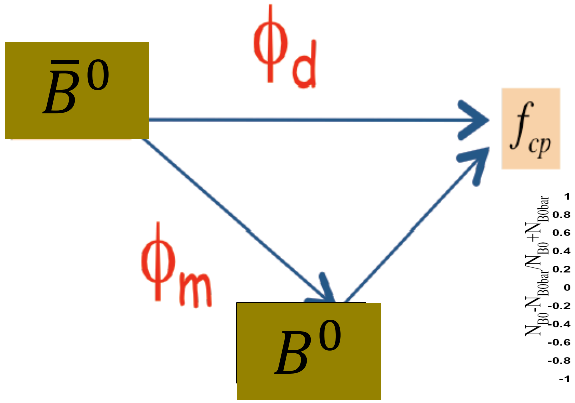
- Improved measurements of γ at LHCb
- Improved measurements of φ_s at ATLAS and LHCb
- Improved $|V_{cb}|$ and $|V_{ub}|$ measurements. Persistent tension between measurements using exclusive and inclusive decays. New measurements of $|V_{cb}|$ at Belle and BaBar. $|V_{ub}|$ measurement at LHCb using Λ_b decays

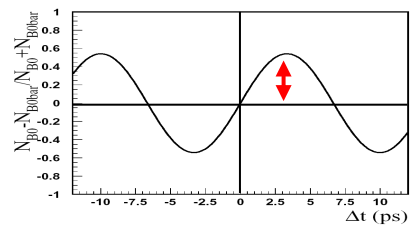
exactly the same (though unlikely)...

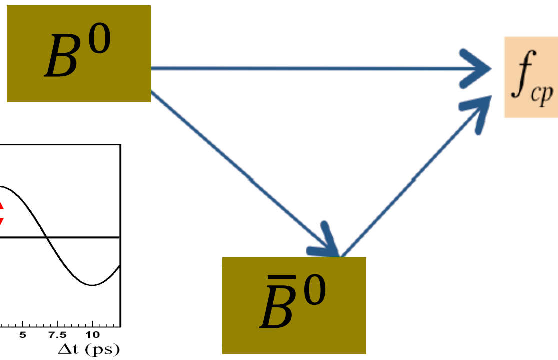
Emi Kou- FPCP 2019)



Reminder: How we access the CKM phase

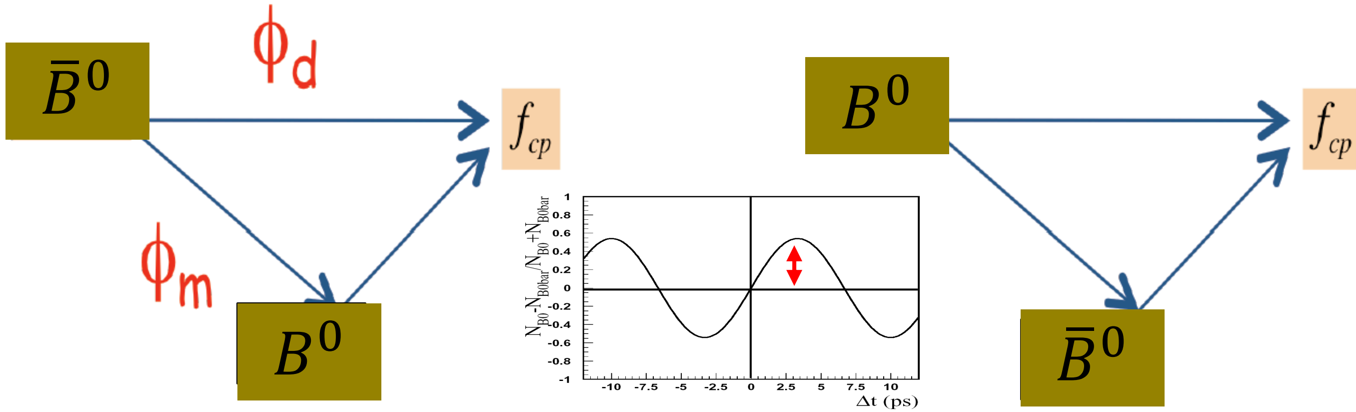






$$A_{cp(t)} = \frac{\Gamma(B^0(t)\rightarrow f_{cp}) - \Gamma(\,(\bar{B}^0(t)\rightarrow f_{cp})}{\Gamma(B^0(t)\rightarrow f_{cp}) + \Gamma(\,(\bar{B}^0(t)\rightarrow f_{cp})} = sin2(\varphi_m\text{-}\ \varphi_d) sin\Delta mt$$

Reminder: How we access the CKM phase

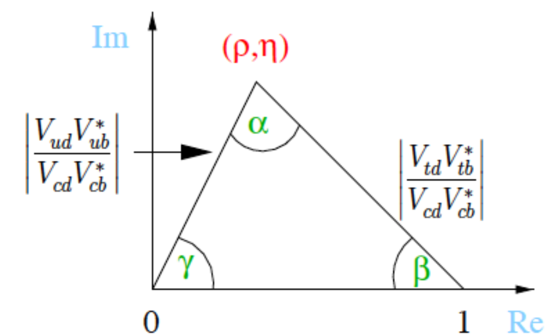


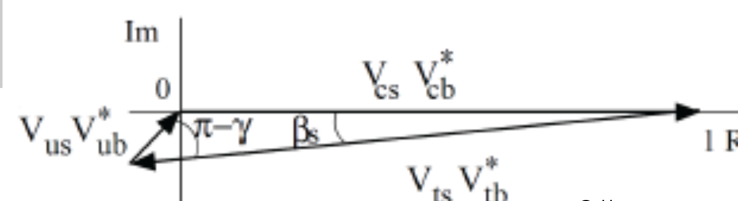
$$A_{cp(t)} = \frac{\Gamma(B^0(t)\to f_{cp}) - \Gamma((\bar{B}^0(t)\to f_{cp})}{\Gamma(B^0(t)\to f_{cp}) + \Gamma((\bar{B}^0(t)\to f_{cp})} = sin2(\varphi_m - \varphi_d) sin\Delta mt$$

With careful set up of the initial and final states:

$B_d \rightarrow J/\psi\ K^0_s$ :: $\boldsymbol{\beta \propto \arg(V^*_{td}) \sim 24^o}$

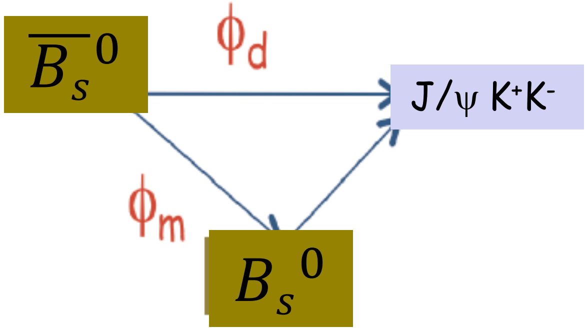
$B_s \rightarrow J/\psi\ K^+K^-$ :: $\boldsymbol{\varphi_s\ (= -2\beta_s) \propto \arg(V^*_{ts}) \sim 1^o}$





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

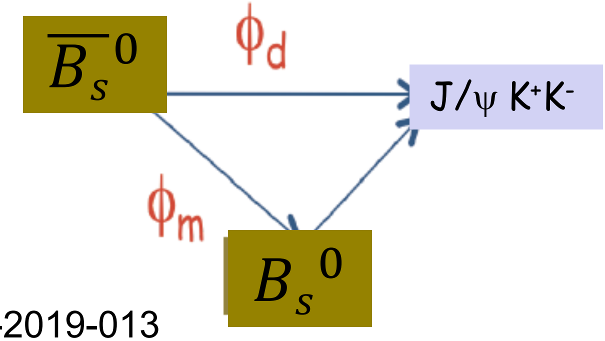
- From Time-dependent CPV in:
- $B_s^0 \to J/\psi\ K^+K^-$ [$\phi \to$ K+K-, s-wave (K+K-)]
- $B_s^0 \to J/\psi\ K^+K^-$ -high-mass region
- $B_s^0 \to J/\psi\ \pi^+\pi^-$
- $B_s^0 \to \psi(2s)\ K^+K^-$



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

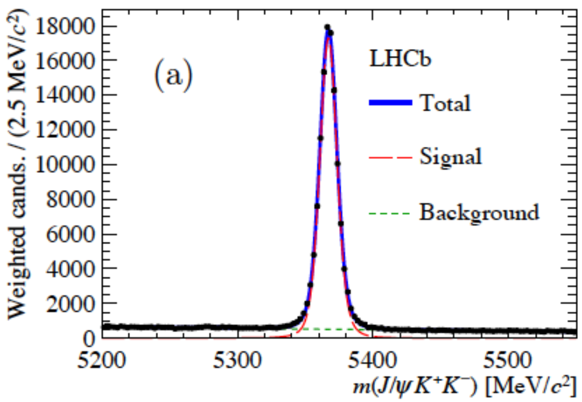
From CKM fit

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

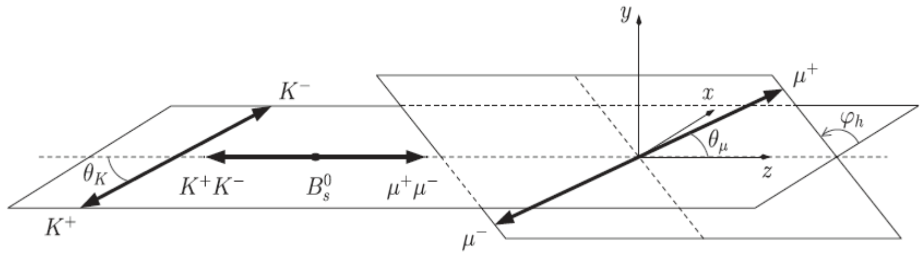


- From Time-dependent CPV in:
- $B_s^0 \to J/\psi\, K^+K^-$ [$\phi \to K^+K^-$, s-wave (K^+K^-)]
- $B_s^0 \to J/\psi\, K^+K^-$ -high-mass region
- $B_s^0 \to J/\psi\, \pi^+\pi^-$
- $B_s^0 \to \psi(2s)\, K^+K$

LHCb-paper-2019-013



- Mixture of CP odd & CP even states- Angular analysis required to extract CPV info.

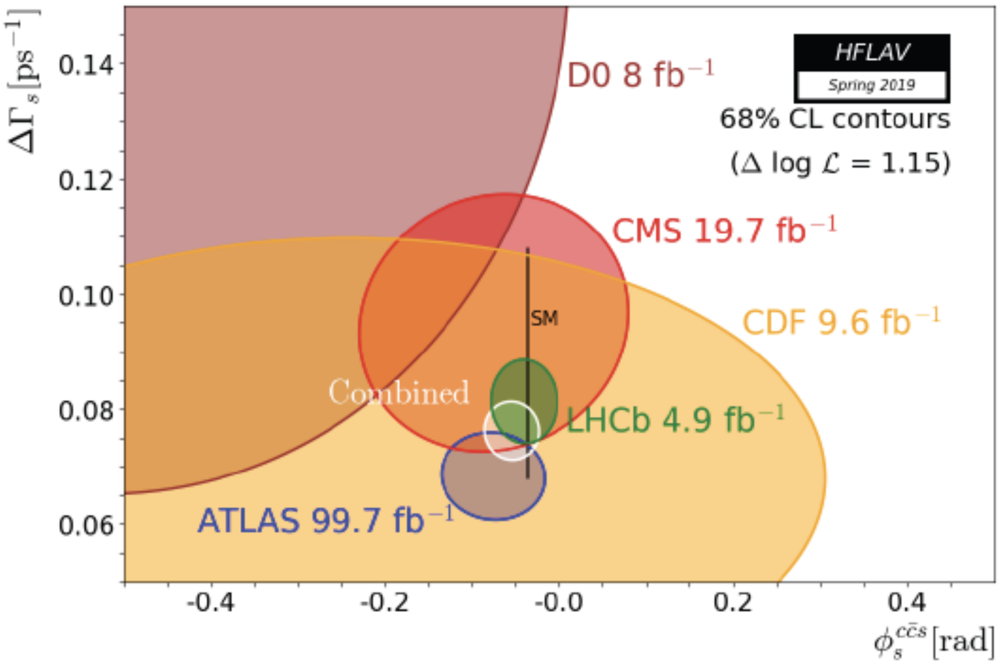


The decay is described in terms of four helicity amplitudes

➢Observables: ϕ_s
$\Delta\Gamma = \Gamma_H - \Gamma_L$,
$\Delta m = m_H - m_L$

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

Recent major improvements from ATLAS and LHCb



ATLAS
ϕ_s=-76$\pm$39 mrad
$\Delta\Gamma_s$=0.068$\pm$0.005 ps^{-1}

LHCb
ϕ_s=-41$\pm$25 mrad
$\Delta\Gamma_s$=0.0816$\pm$0.0048 ps^{-1}

HFLAV average

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

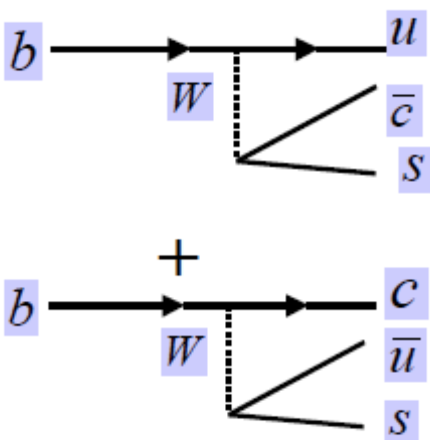
$$\Delta\Gamma_s = 0.0764 \pm 0.0024 \text{ ps}^{-1}$$

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->c & b->u amplitudes



$\propto A\lambda^3(\rho + i\eta)$

$B^- -> \bar{D}^0 K^-$

phase
$-\gamma+\delta_u$

f - common to D^0 & $\bar{D}^0$

$B^- -> D^0 K^-$

$\propto A\lambda^3$

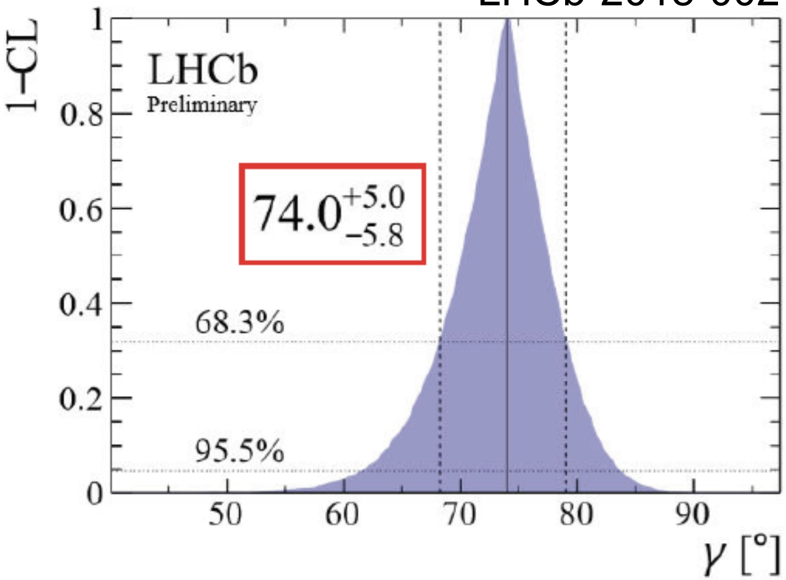
phase
δ_c

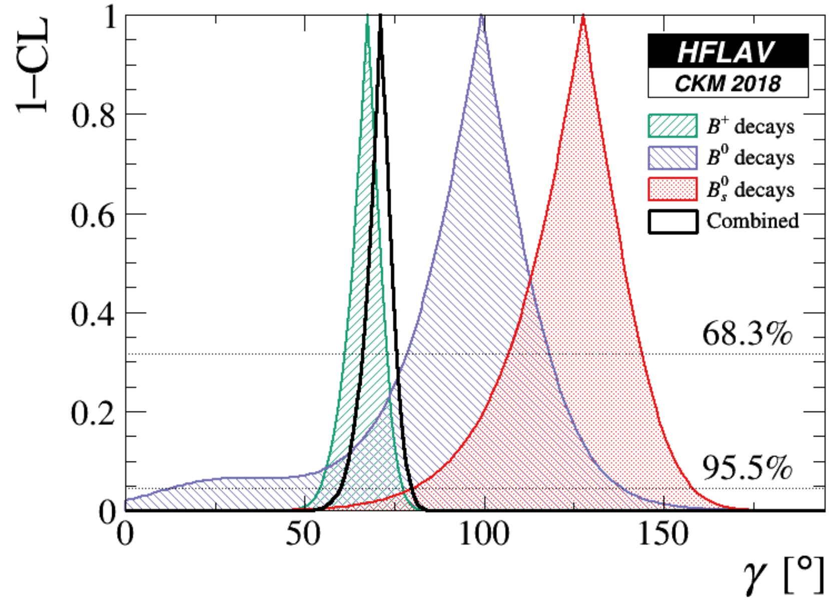
$$\boxed{A[B^- \to (D \to f)K^-] = A_c A_f e^{i(\delta_c + \delta_f)} + A_u A_{\bar{f}} e^{i(\delta_u + \delta_{\bar{f}} - \gamma)}}$$

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

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

LHCb-2018-002



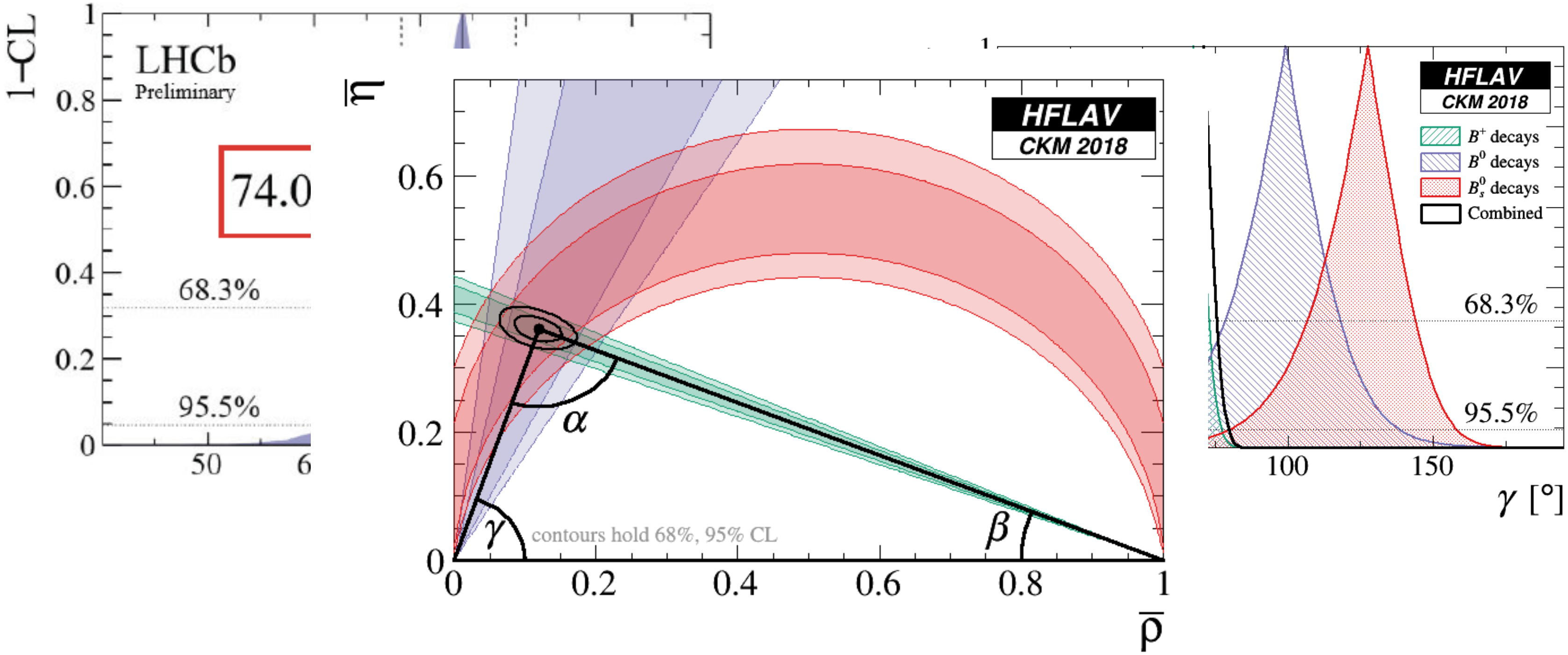


BaBar:	Belle:	LHCb:	combined:
$\gamma=(69^{+17}_{-16})^o$	$\gamma=(73^{+13}_{-15})^o$	$\gamma=(74.0^{+5.0}_{-5.8})^o$	$\gamma=(71.0^{+4.6}_{-5.3})^o$

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

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

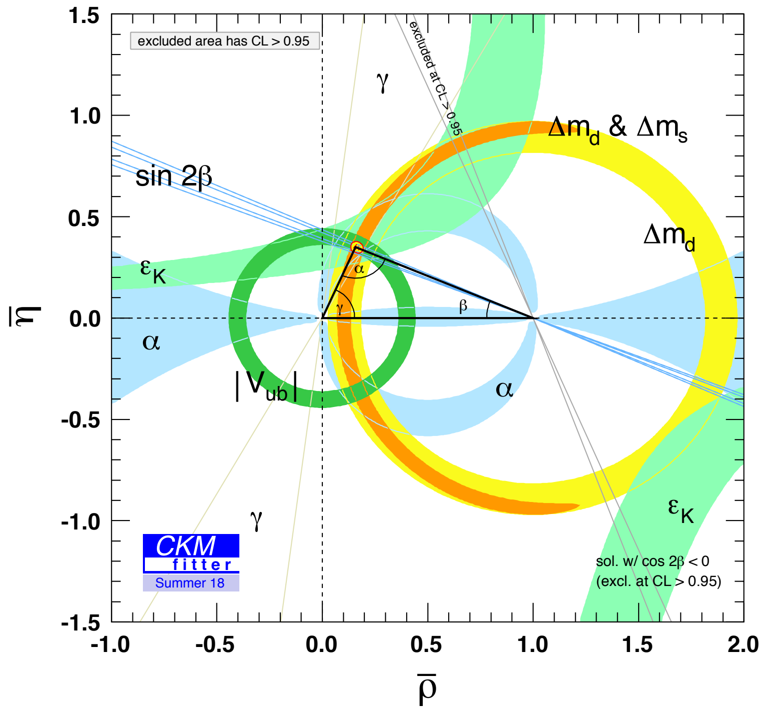
combined:
$\gamma = (71.0^{+4.6}_{-5.3})^o$



Still the less well measured angle of CKM unitarity triangle-
Super-flavor experiments aim for <1° accuracy

Status of CKM (2018)

The CKM picture in 2019:
Still no major inconsistency

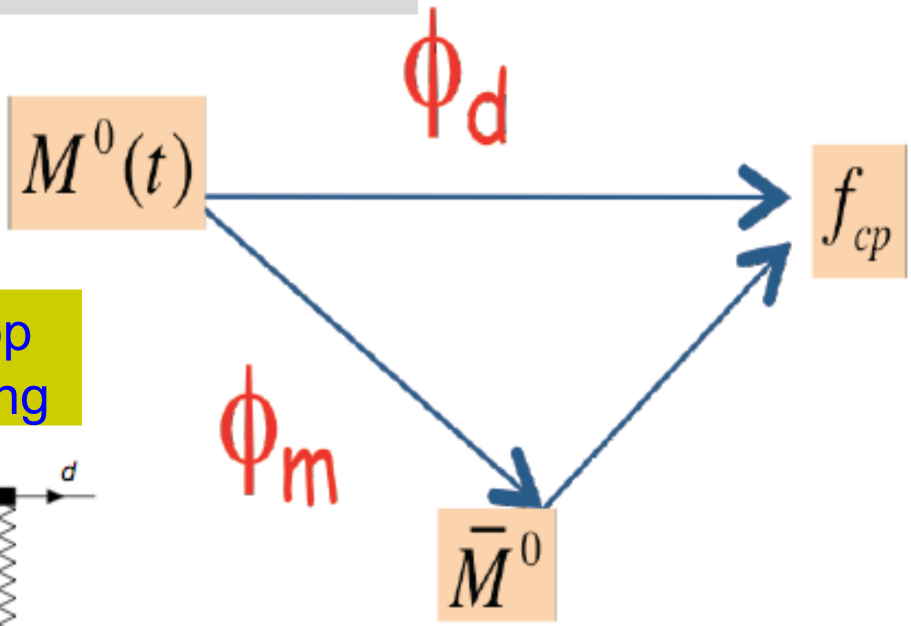


Direct (deg)	CKM fit (deg)
$\alpha = 86.4^{+4.5}_{-4.3}$	$91.9^{+3.0}_{-1.2}$
$\beta = 22.14^{+0.69}_{-0.67}$	$23.90^{+1.2}_{-1.2}$
$\gamma = 71^{+4.6}_{-5.3}$	$65.81^{+0.99}_{-1.66}$

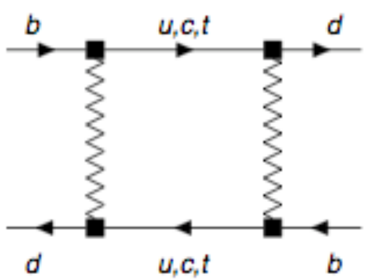
Implication for New Physics effects?

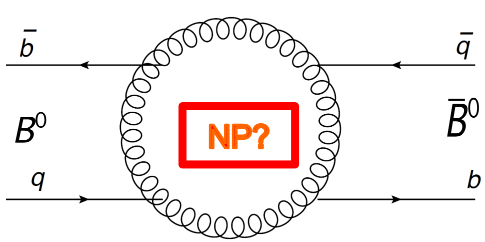
New Physics Through Mixing

New Physics may affect either leg of the interferometer



Through new loop diagrams in mixing



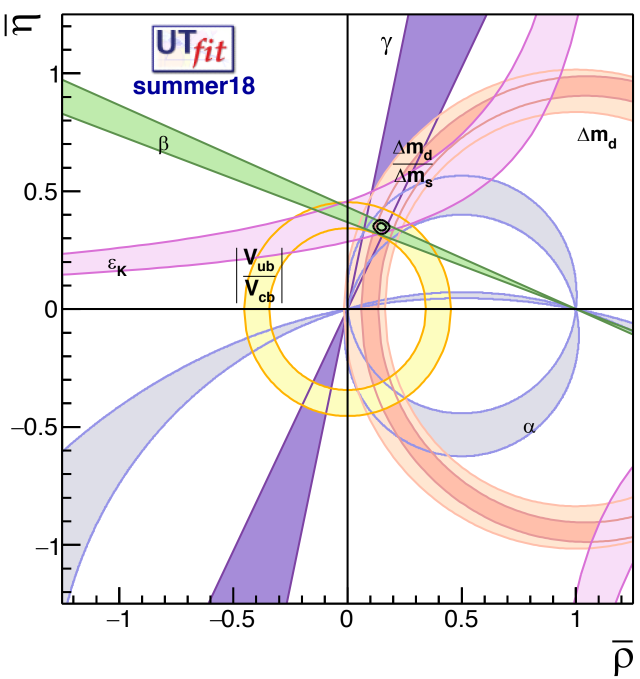


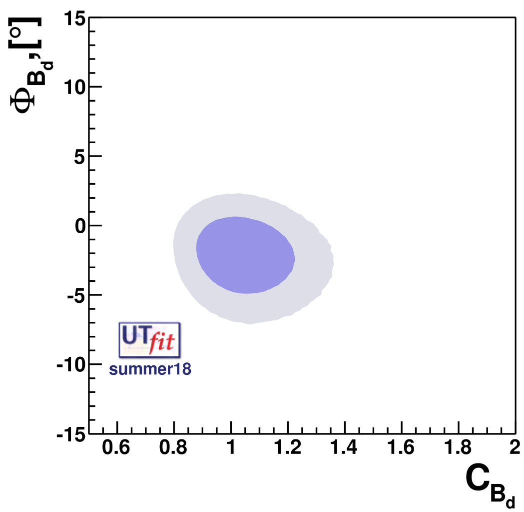
New Physics Through Mixing

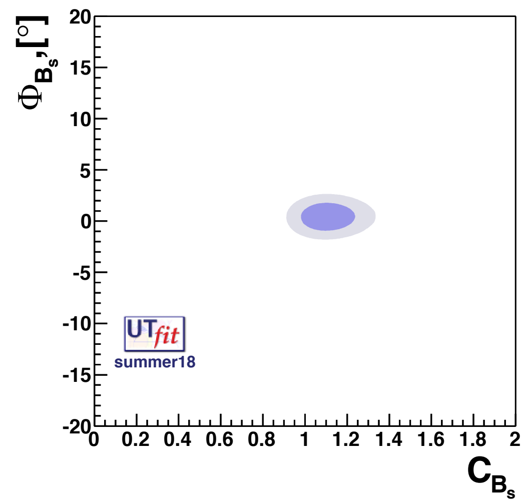
Fit the data allowing departure from SM in B^0 mixing amplitude

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

From the UT_{fit}







$C_{Bd} = 1.05 \pm 0.11$

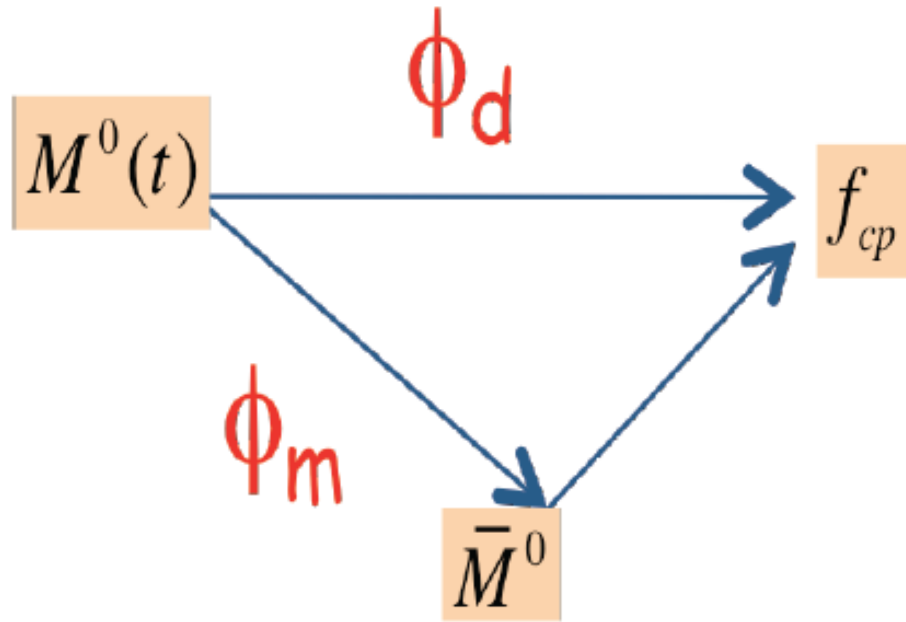
$\varphi_{Bd} = -2.0 \pm 1.8$

$C_{Bs} = 1.110 \pm 0.090$

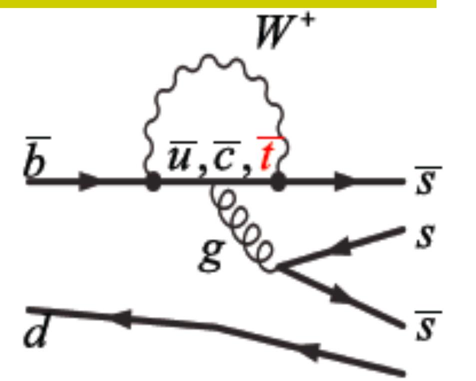
$\varphi_{Bs} = 0.42 \pm 0.89$

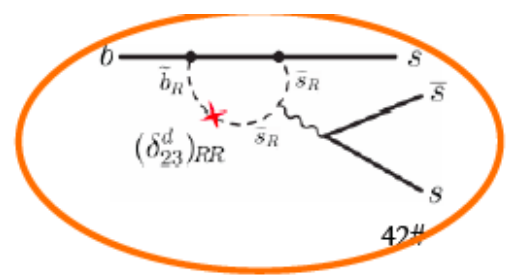
Consistent With SM

New Physics Through Decay



Through new loop diagrams in the decay amplitude:





New Physics loops can lead to deviation of CPV from sin2β

Penguin dominated B^0 decays:
Measurements of "sin2β", "ϕ_s"

New addition from B_s^0 to this program

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

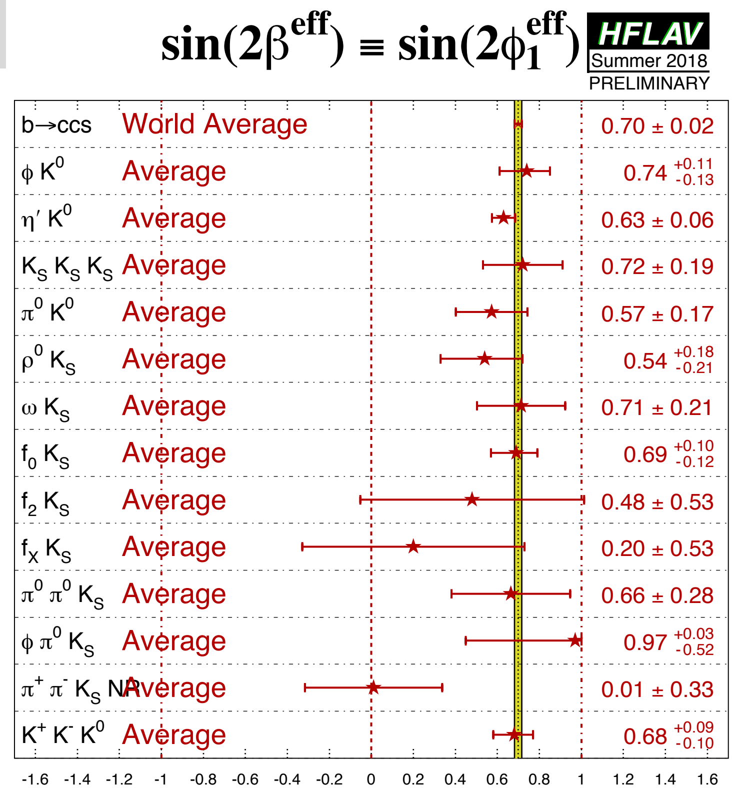
ϕ_s= -73 ± 115 ± 27 (mrad)
λ=0.99 ± 0.05 ± 0.01

Consistent with SM:

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

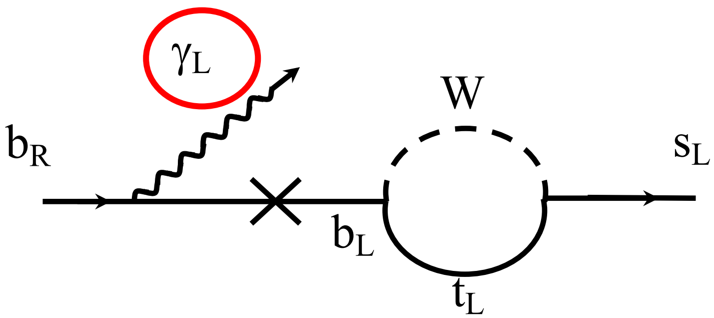
Naïve average of "sin2β"_pnguins: 0.648 ± 0.038

From (b→ccs): 0.70 ± 0.02

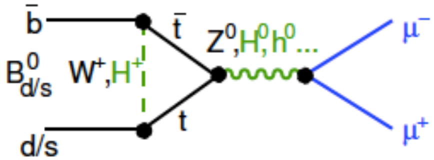


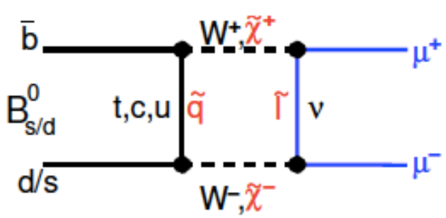
Current results are consistent with SM.
Caution: theoretical uncertainties are not well defined.

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

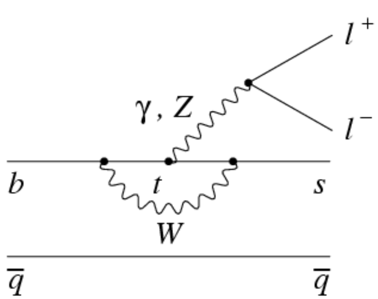


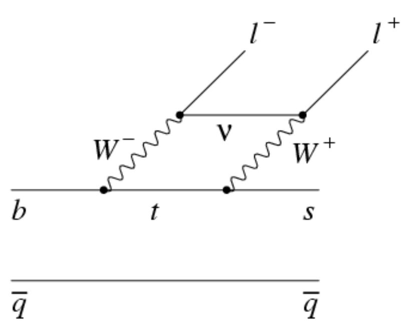


$$SM : Br(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

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

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

➢ Hints of non-LFU effects in the 3rd generation first emerged at BaBar

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

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

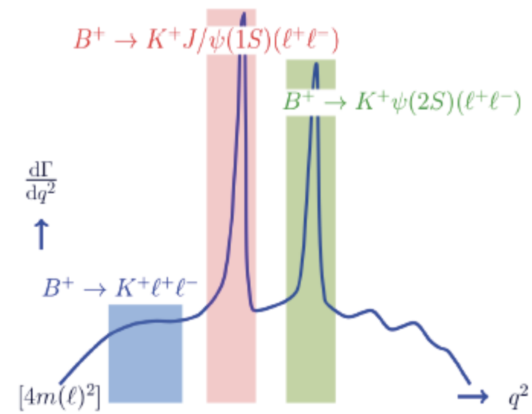
Tests of Lepton Flavor Universality: $B \to K^{(*)}\ell^+\ell^-$

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

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

- *Measurements performed in q^2 bins*
- *Region of q^2<6 GeV^2 avoids charmonium resonances & has clean theoretical predictions*

- *Resonance regions provide powerful checks on the analysis*



- *LHCb and recent Belle Measurements performed as*

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

- *Check that*

$$r_{J/\psi} = \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)/\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+) = 1$$

$$R_K^{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 1$$

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

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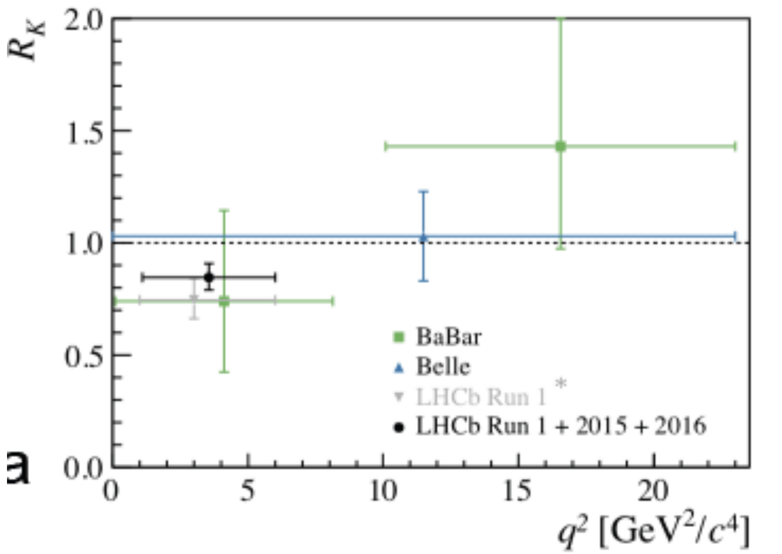
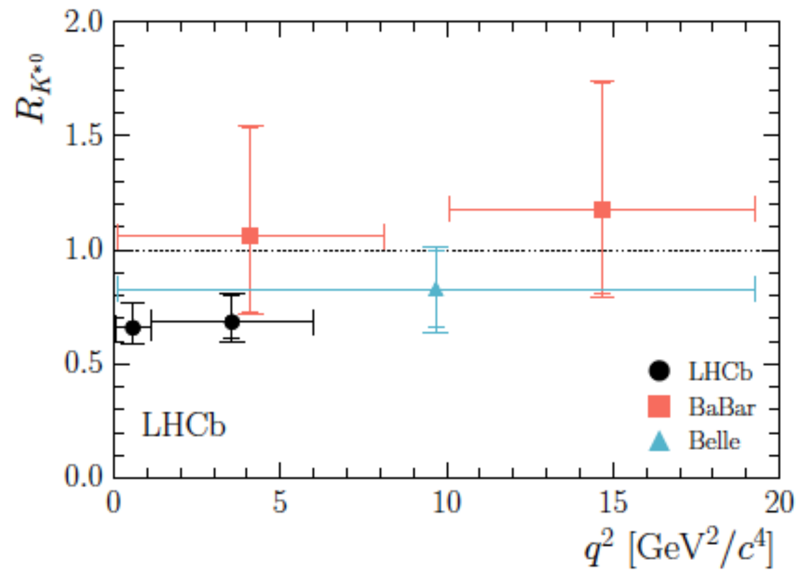
Within SM: $R_{K^{(*)}} = 1$





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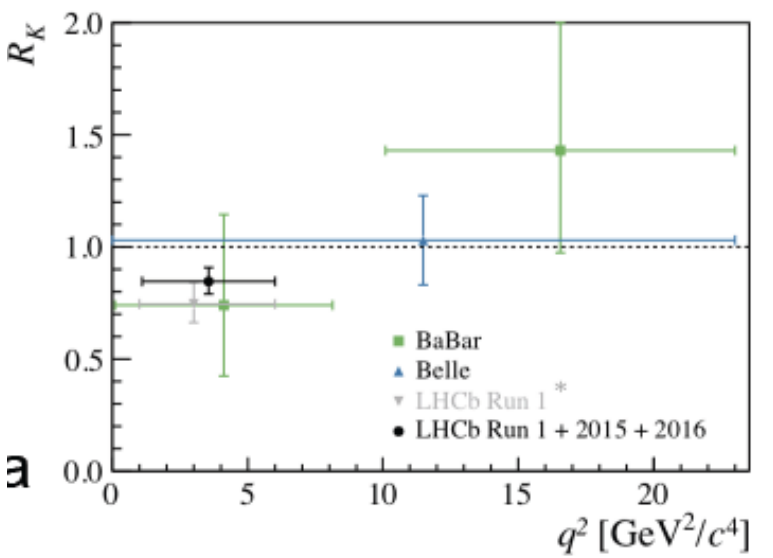

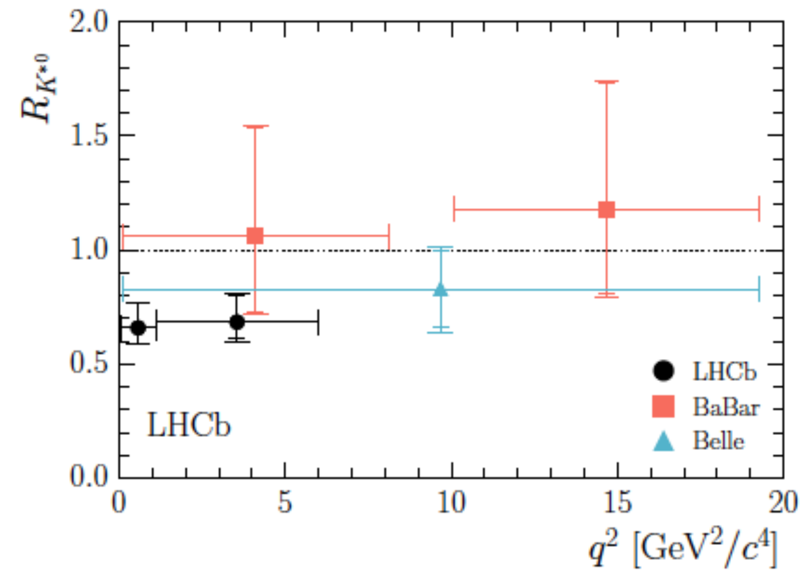

Hints of departure from LFU in LHCb data

[LHCb-PAPER-2019-009]

LHCb: Run1+2015 &2016

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

Within 2.5 σ of SM

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

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

Within 2.1-2.3 σ & 2.4-2.5 σ of SM

JHEP 08(2017)055

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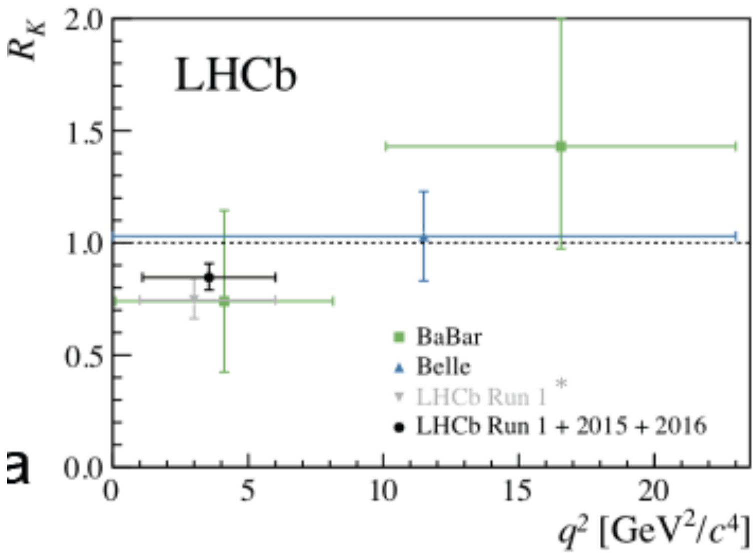
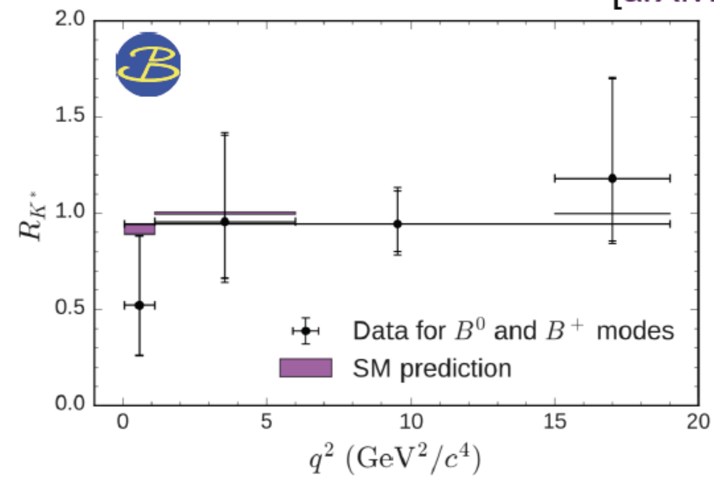


New **Belle** Measurement over full q^2 compatible with SM & LHCb- still precise than LHCb

[arXiv:1904.02440]



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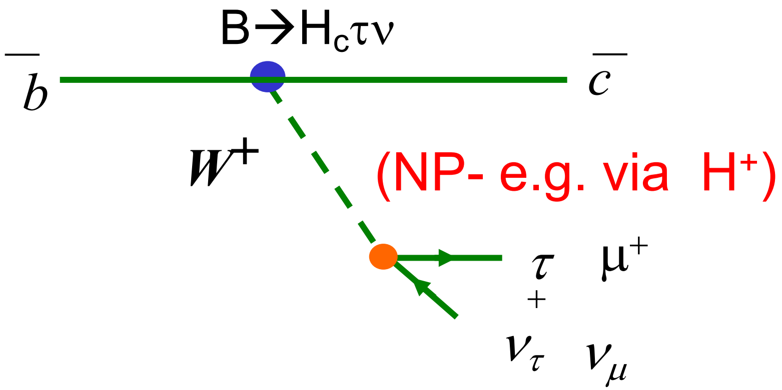
JHEP 08(2017)055

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

τ vs μ/e

Tests of Lepton Flavor Universality: τ vs μ



In SM, decays to μ & τ differ only due to the lepton mass differences

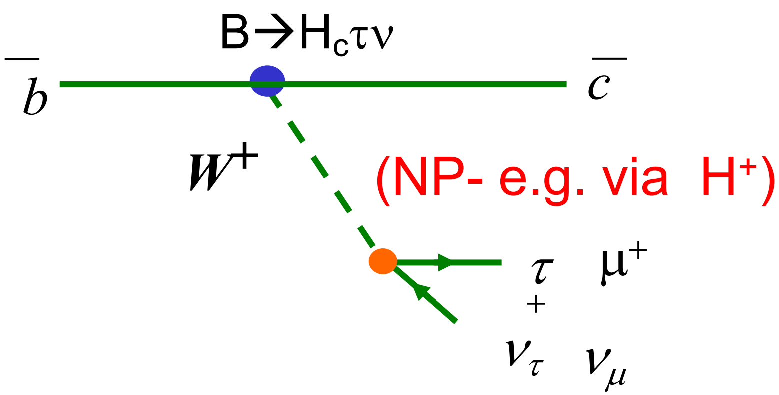
•Ratio of Branching ratios are theoretically and experimentally very "clean" probes of LFU

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

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

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

Tests of Lepton Flavor Universality: τ vs μ



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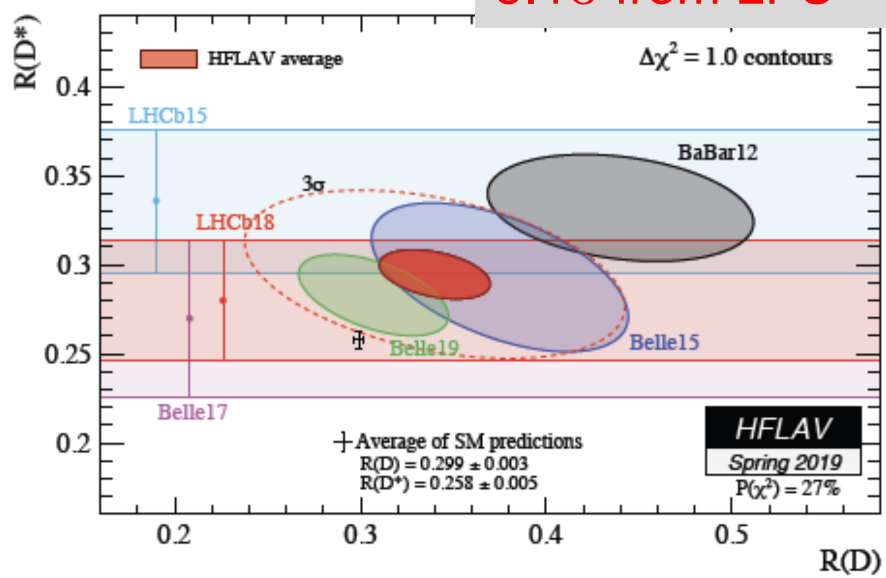
Current Status
3.1σ from LFU

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

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



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 ± 0.008	–	–
1606.08030 [Bigi, Gambino]	Lattice + Belle/BaBar	0.299 ± 0.003	—	—
1203.2654 [Fajfer, Kamenik, Nisandzic]	Cont.+ Belle	—	0.252 ± 0.003	—
1703.05330 [Bernlochner, Ligeti, Papucci, & DR]	Lattice + Belle + HQET NLO	0.299 ± 0.003	0.257 ± 0.003	0.44
1707.09509 [Bigi, Gambino, Schacht]	BGL + BLPR + $1/m_c^2$ error estimate	—	0.260 ± 0.008	—
1707.09977 [Jaiswal, Nandi, Patra]	BGL/HQET + $1/m_c^2$ parameter	0.299 ± 0.004	0.257 ± 0.005	~ 0.1
HFLAV	Arithmetic average	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.258 \pm 0.005}$	–

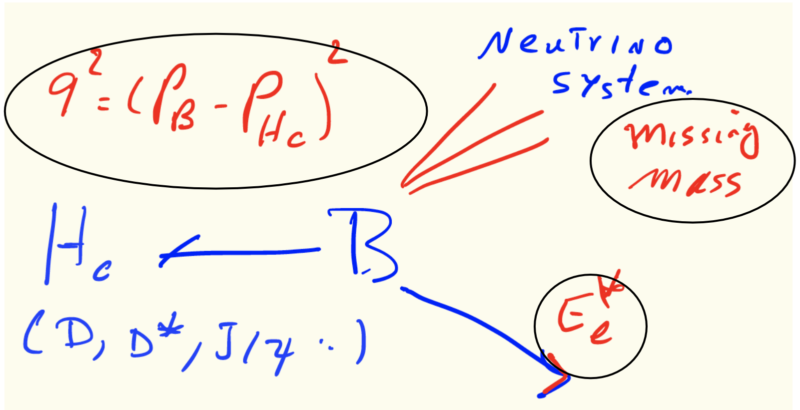
R(J/ψ): 0.290±0.007
Preliminary Lattice result

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

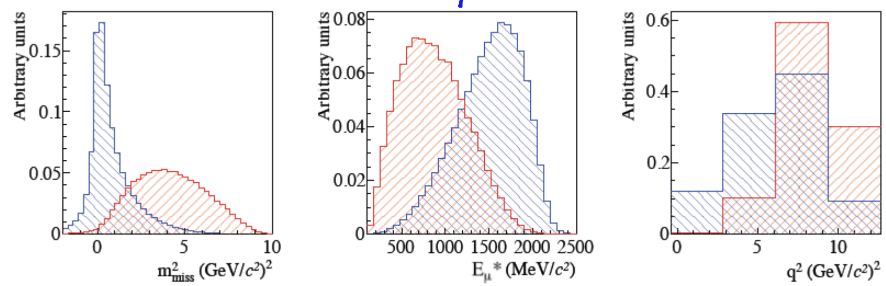
Experimental measurements

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

$B \to H_c \ell \nu$, $[\ell = e, \mu, \tau\ (\,with\ \tau \to \mu\nu\nu, \tau \to 3\pi\nu, \ldots)]$

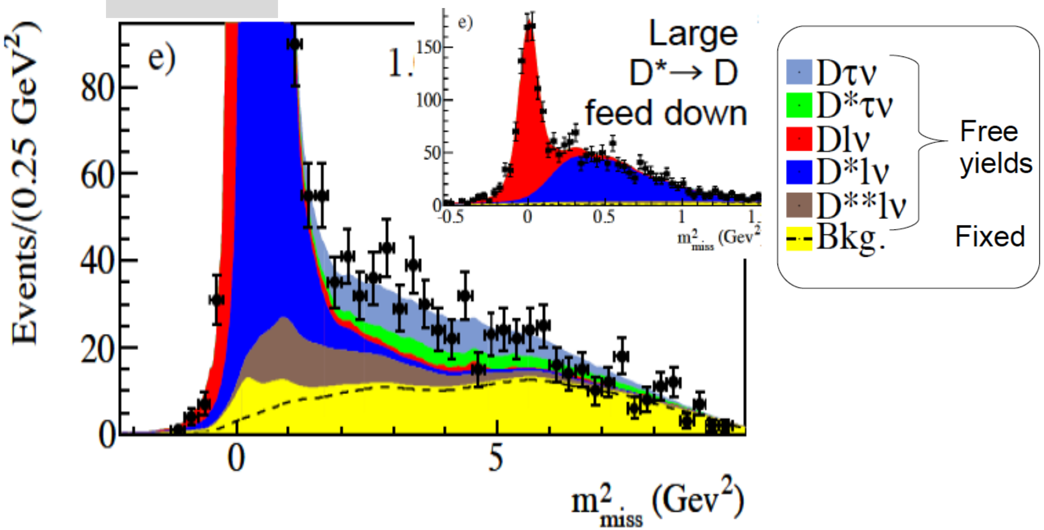


$\tau \to \mu\nu\nu$



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

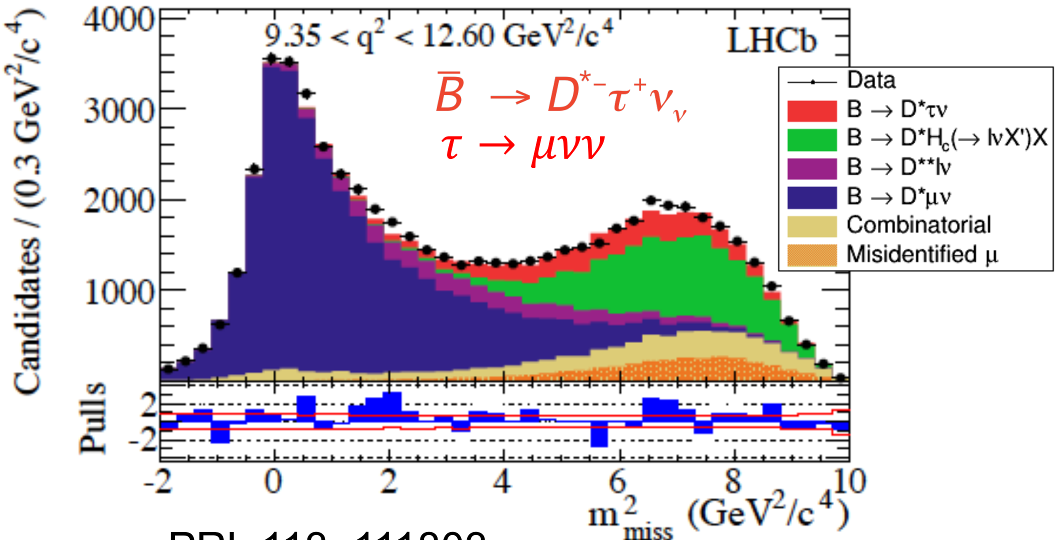
BaBar



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

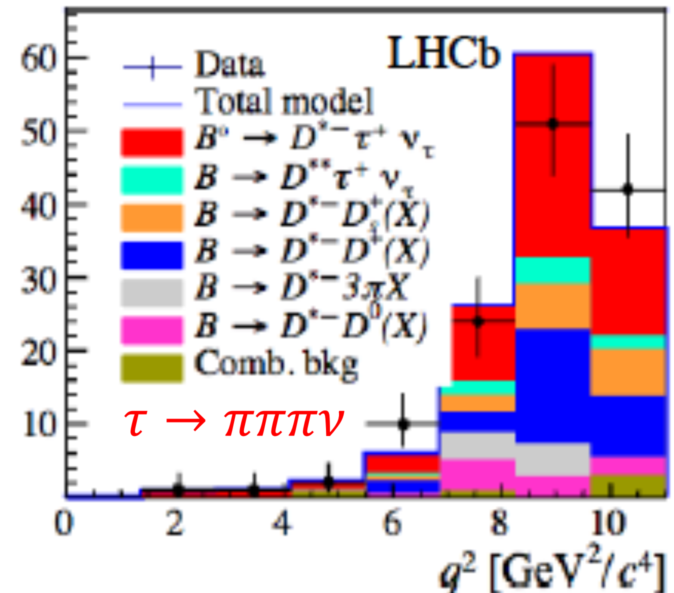
LHCb and Belle measurements

2015



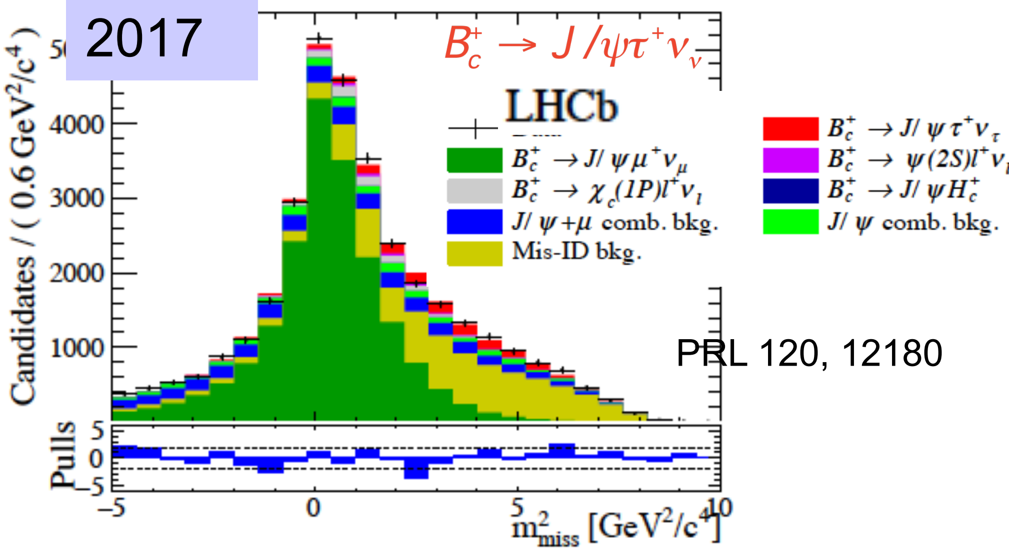
PRL 113, 111803

2017

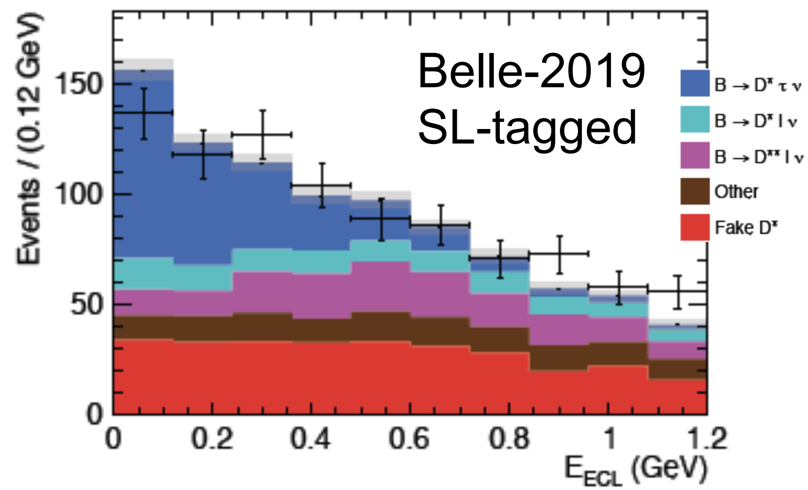


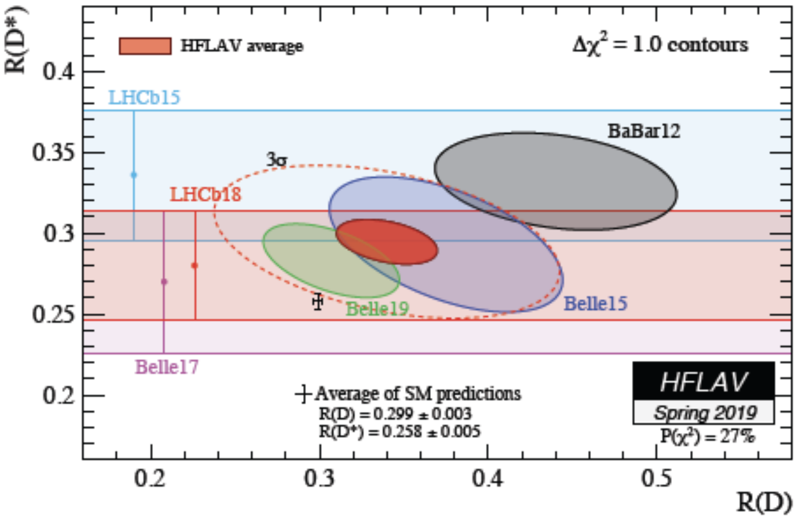
PRL 120, 171802

2017

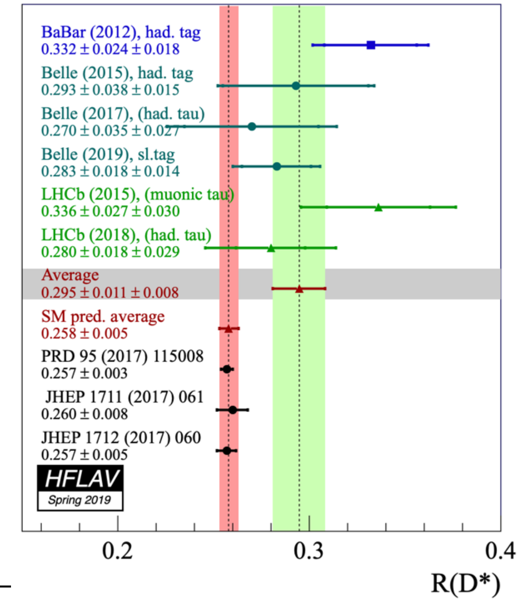


PRL 120, 12180



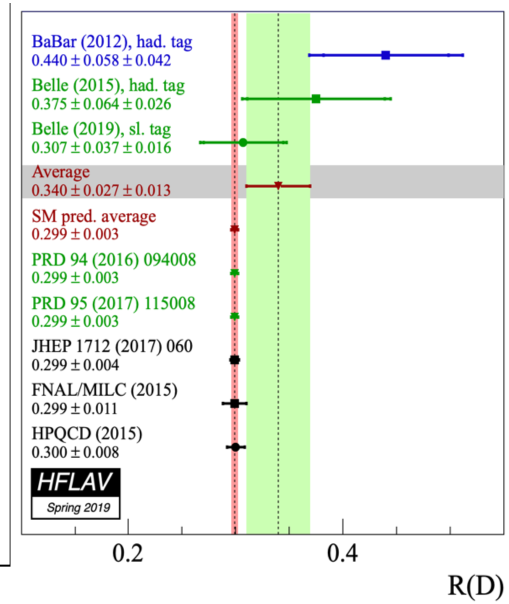


Overall:
3.1 σ tension
with LFU/SM



- 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 $B_c \rightarrow \tau\nu$

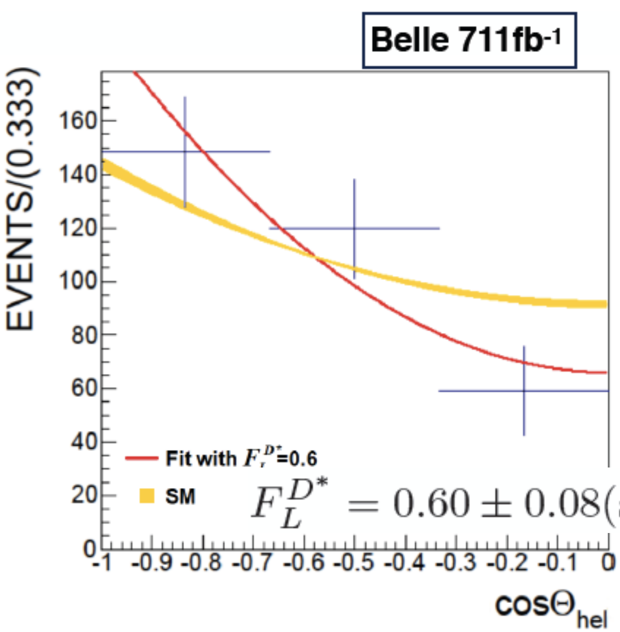


$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$

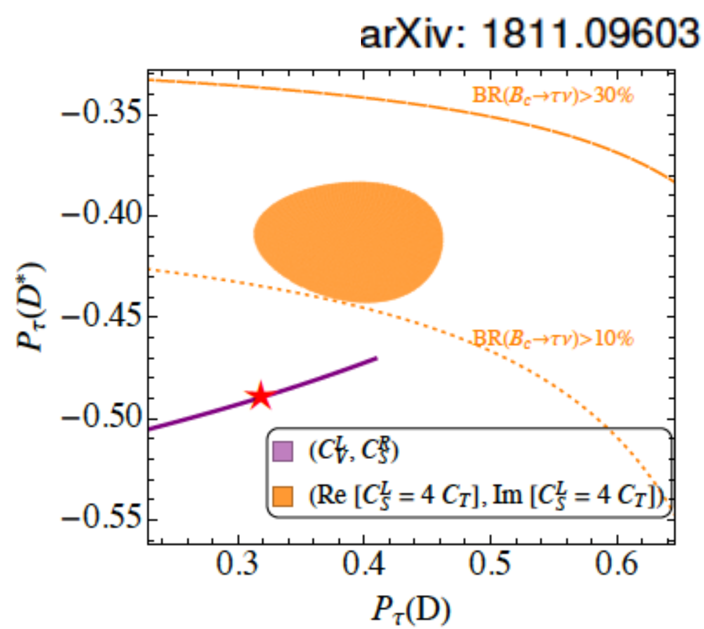
Near Future:

- 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(Λc), R(J/psi)

- Much Later: Additional observables that may help distinguish new physics sources of LFU:
  - D* polarization FL(D*)
  - Tau polarization: $P_\tau(D^*) = \frac{\Gamma(\tau^{\lambda=+1/2})-\Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2})+\Gamma(\tau^{\lambda=-1/2})}$ $\quad P_\tau(D) = \frac{\Gamma(\tau^{\lambda=+1/2})-\Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2})+\Gamma(\tau^{\lambda=-1/2})}$
  - CPV in angular distributions of B→D*(→Dπ)$\tau\nu$



$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{sys})$$



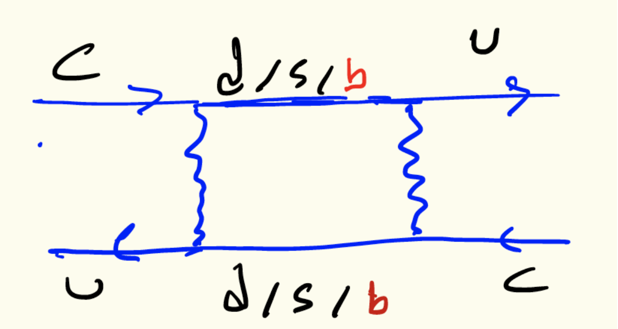
Search for new Sources of CP Violation:

CPV in charm decays

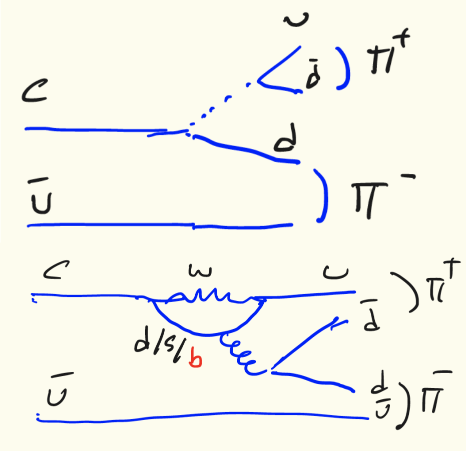
Within SM: CPV in charm decays is very small

- CPV requires contribution from all three generations:

  - CPV in D0 mixing:
    Dominant contributions are from the 1st two generations →negligible CPV in D0 mixing



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



loops with some b-quark contributions can induce small CPV ~$O(|V_{ub}V^*_{cb}/V_{ud}V^*_{cd}|)$ ~λ^4 <<10^{-3}

CP Violation in D^0 mixing

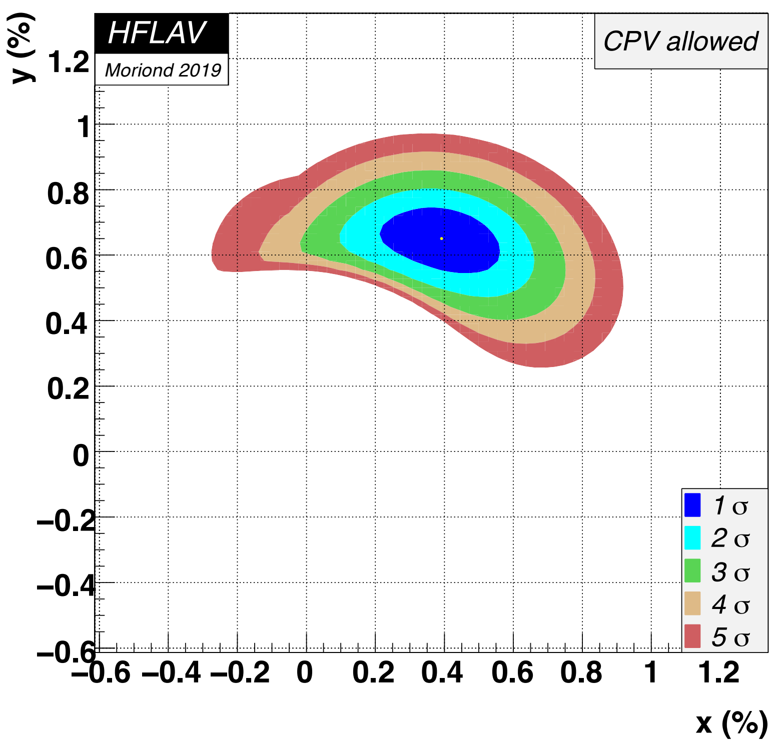
Mixing is firmly established but no evidence for CPV in mixing

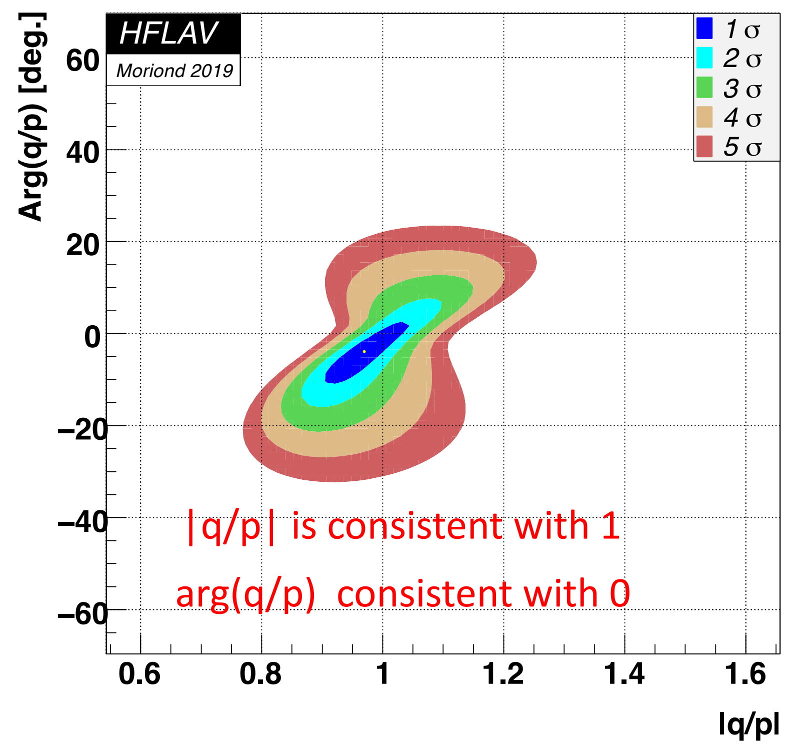
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

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

CPV if:

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





Direct CPV in the charm system

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

Searches performed in a large number of channels: No evidence for CPV

Precision in some channels at ~$O(10^{-3})$ level already:

Channel	A_{cp} (%) (From 2017 HFLAV averages)
$D^0 \to \pi^+\pi^-$	$+0.00 \pm 0.15$
$D^0 \to K^0_s\pi^0$	-0.20 ± 0.17
$D^0 \to K^+K^-$	-0.16 ± 0.12
$D^+ \to K^0_s\pi^+$	-0.41 ± 0.09
$D^+ \to K^0_sK^+$	-0.11 ± 0.25
$D^+_s \to K^0_sK^+$	$+0.08 \pm 0.26$
$D^+_s \to K^0_s\pi^+$	-0.38 ± 0.48

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

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The LHCb data (Runs I & II) enables yet another major step in precision → 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: $A_{raw}(D \to h+h-) = A_{cp}(h+h-) + \boxed{A(det) + A(prod)}$

Common to both channels

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

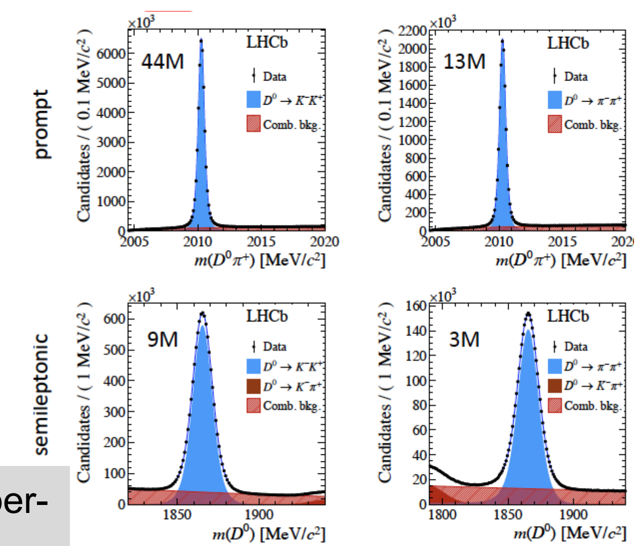
CP violation observed at 5.3 sigma

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

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

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

LHCb-paper-2019-006



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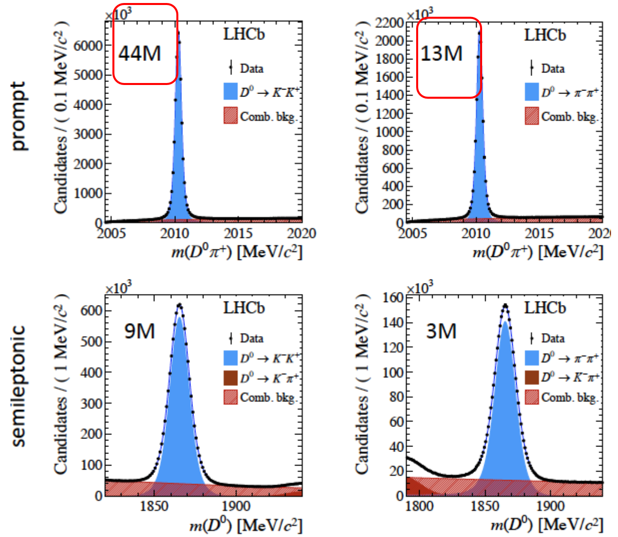
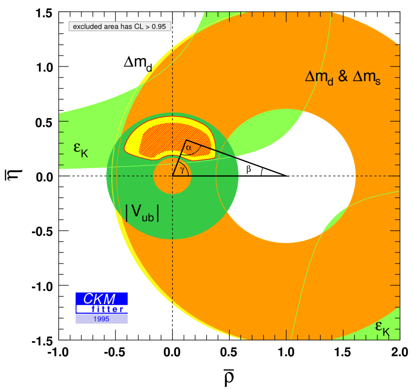


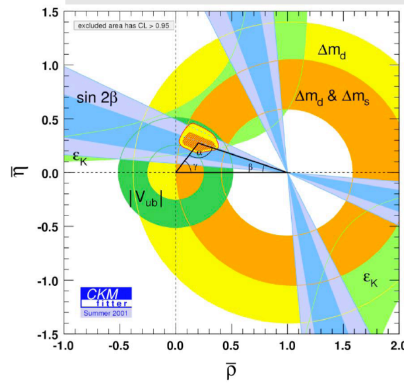
Not too far from SM (~10^{-3}) . Specific mechanism yet to be determined: (Soni 2019), (Silvestrini et al 2019), Grossman & Schacht. Too soon to invoke BSM observation.

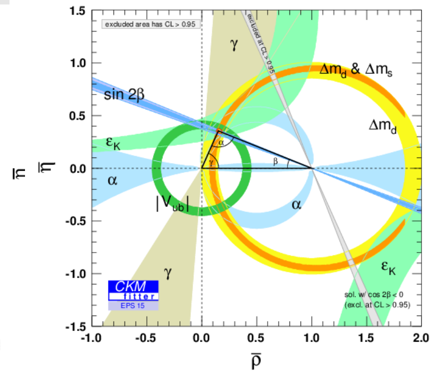
Future

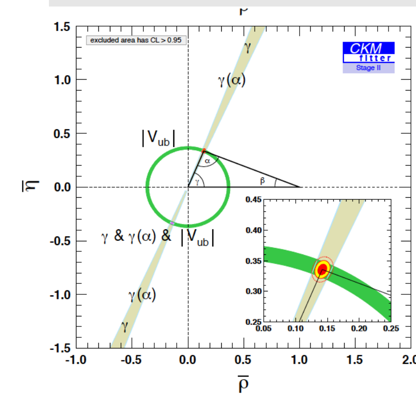
Toward precision Flavor Physics-O(1%): CKM and Rare Decays & much more

Last century	2001	Today	2025+

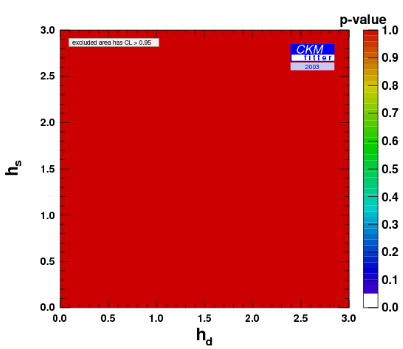


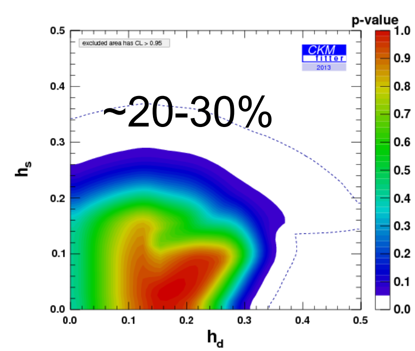


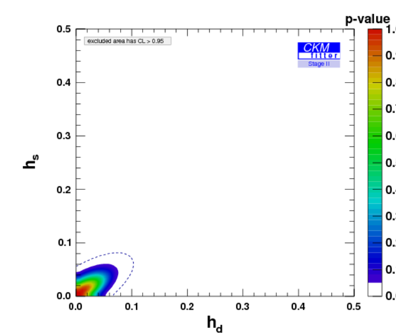




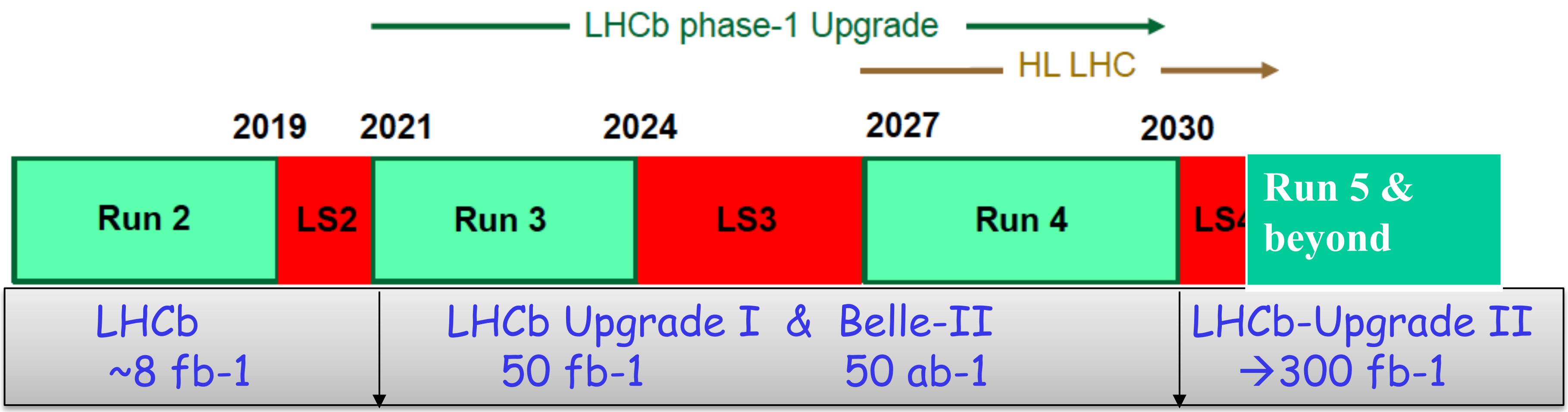
Constraint on NP/SM amplitude See *(arXiv: 1309.2293)*







Experimental Landscape



Belle-II at SuperKEKB

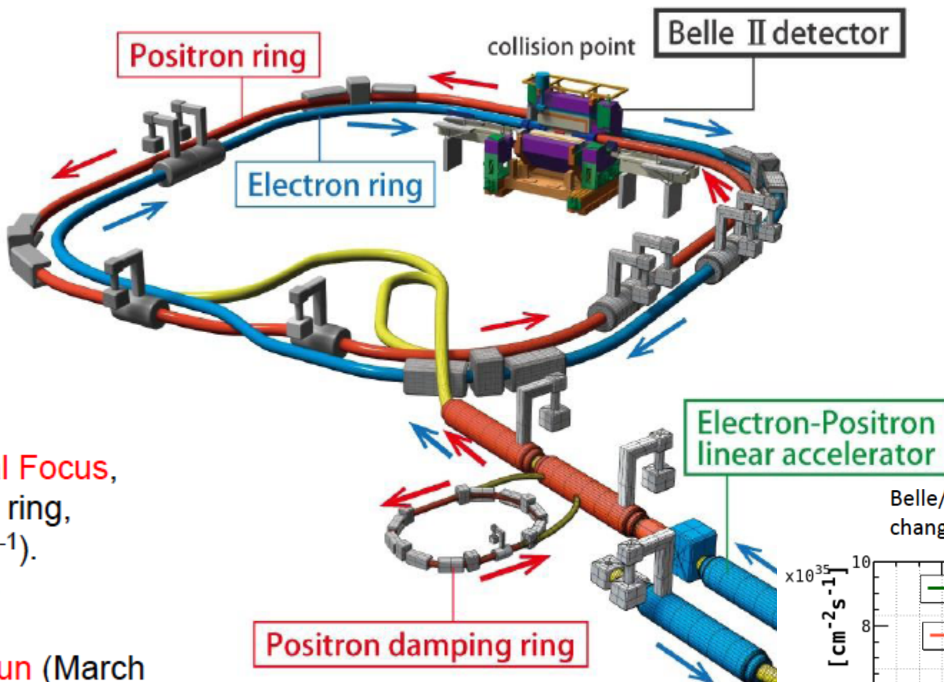
Tom Browder at Lepton – Photon 2019

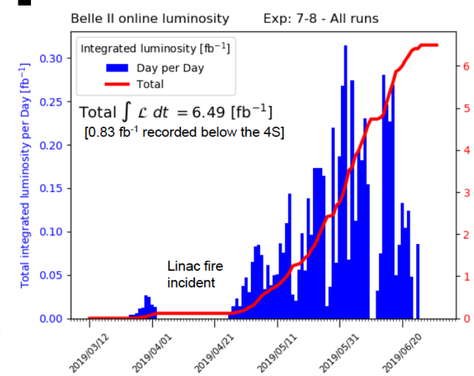
SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (pp))

Phase 1:
Background, Optics
Commissioning
Feb-June 2016.
Brand new
3 km positron ring.

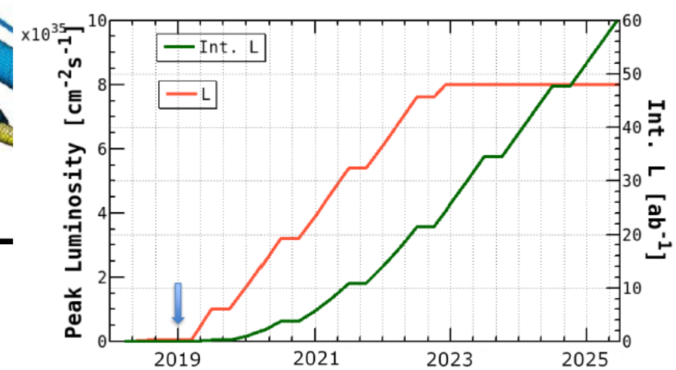
Phase 2: Pilot run
Superconducting Final Focus,
add positron damping ring,
First Collisions (0.5 fb^{-1}).
April 27-July 17, 2018

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





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



LHCb Upgrade-I in installation

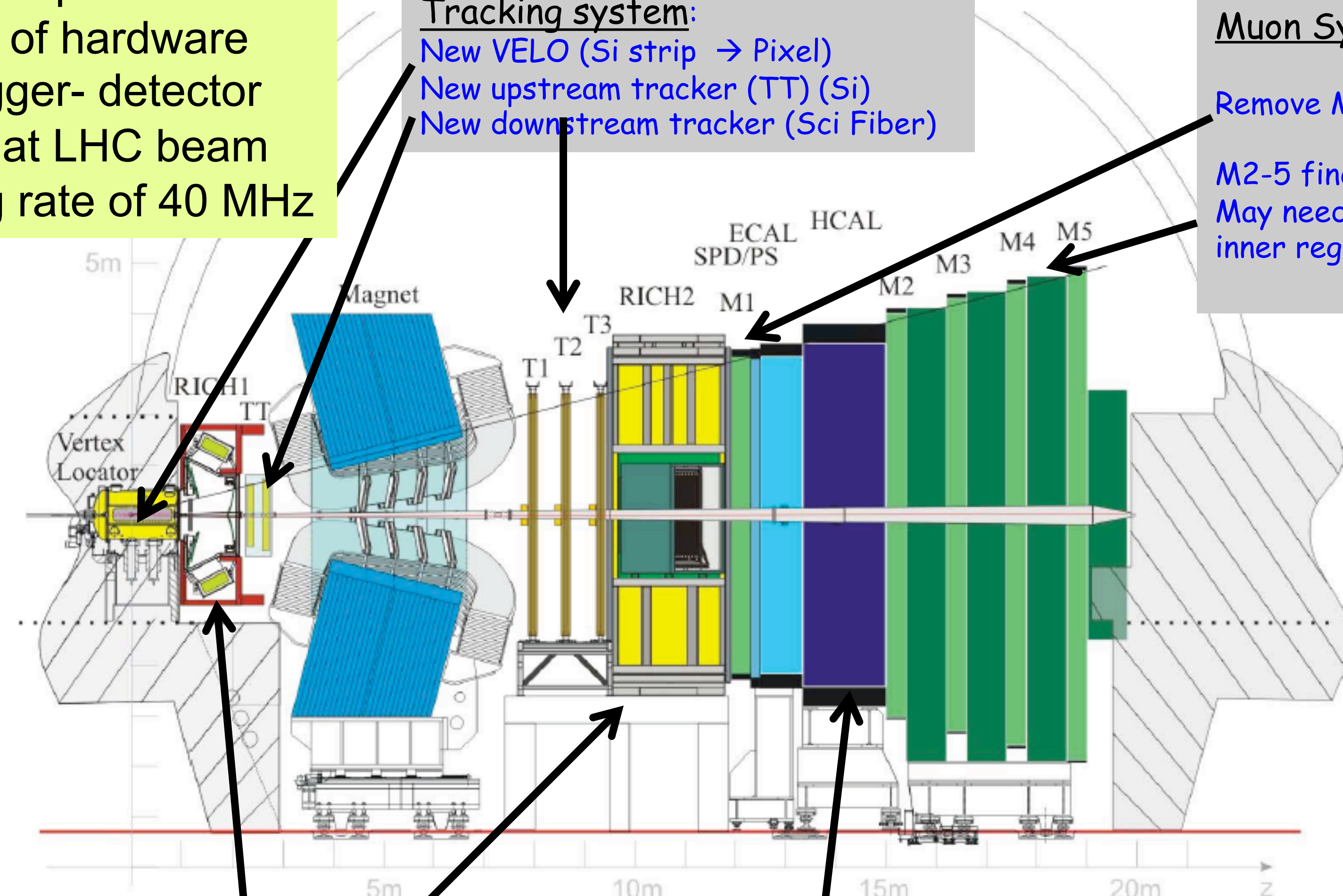
High Luminosity running requires removal of hardware level trigger- detector readout at LHC beam crossing rate of 40 MHz

<u>Tracking system</u>:
New VELO (Si strip → Pixel)
New upstream tracker (TT) (Si)
New downstream tracker (Sci Fiber)

<u>Muon System</u>:

Remove M1

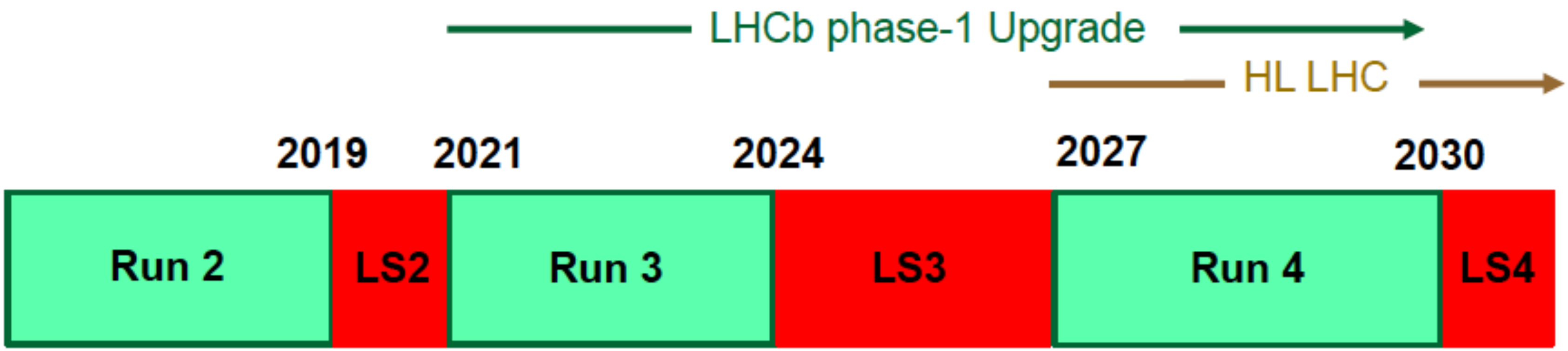
M2-5 fine for 1x10^{33}
May need upgrade of inner region at 2x10^{33}



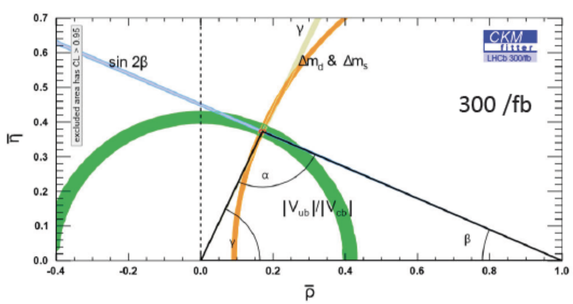
<u>RICH 1 & RICH 2</u>
HPD→ MaPMT
New 40 MHz R/O
RICH1: new optics
remove aerogel

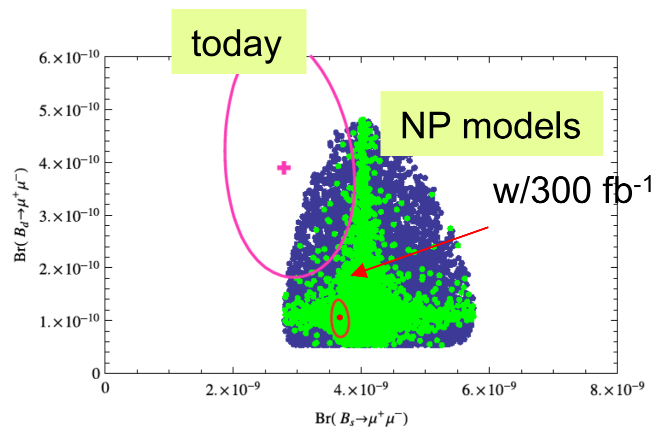
<u>Calorimeter</u>:
New 40 MHz R/O
Lower PMT gain to reduce anode current
Remove SPD & PS

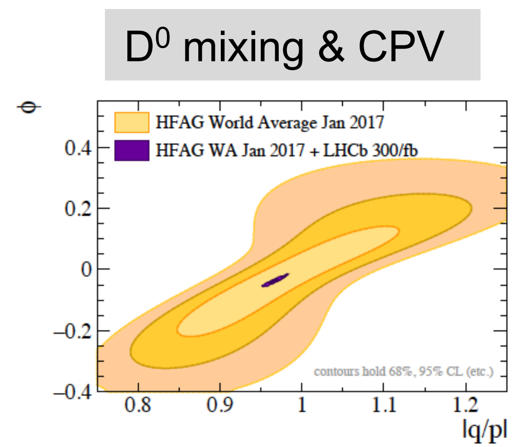
LHCb Upgrade-II: Physics Goals



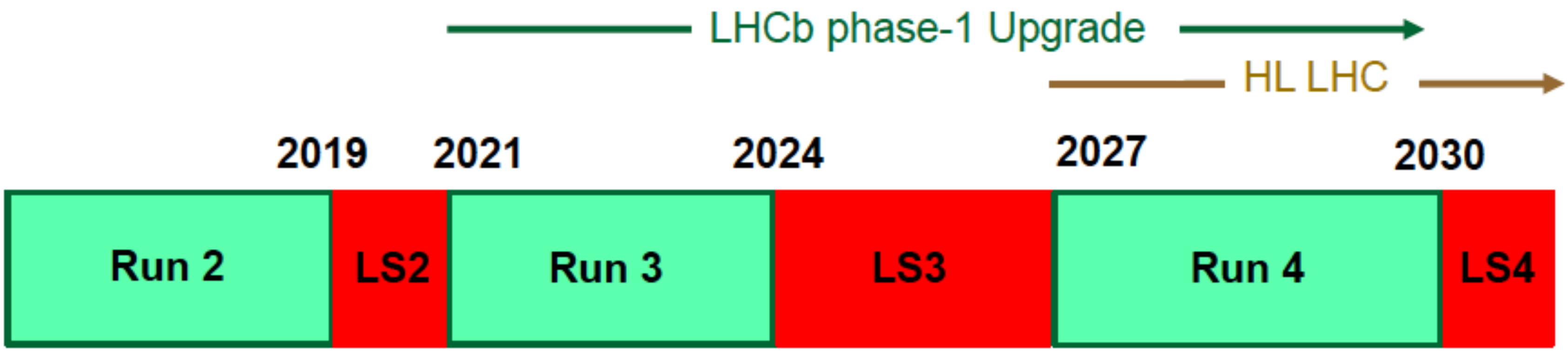
Expression-of-Interest & Physics Potential documents submitted for LHCb Upgrade-II







Upgrade-II: Challenges



Major challenges for LHC & LHCb at peak Luminosity of $2x10^{34}$ /cm^2/s:

➢ Current studies indicate $2x10^{34}$ is possible with changes to IP optics (β^* reduction) & shielding. Triplet lifetime may limit integ. Lum. to ~ 300 fb^{-1}

➢ At Int/crossing ~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 (>>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.