CP violation in B decays

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Introduction:
motivating CPV measurements

CP violation in SM

In SM, the difference between mass and interaction basis induces rotation matrices, which are the ONLY origin of the CP Violation in SM!

$$\mathcal{L}_Y = \sum_{ij} Y^u_{ij} \overline{Q_{iL}} \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} u_{jR} + \sum_{ij} Y^d_{ij} \overline{Q_{iL}} \begin{pmatrix} -\phi^{-\dagger} \\ \phi^{0\dagger} \end{pmatrix} d_{jR} + h.c.$$

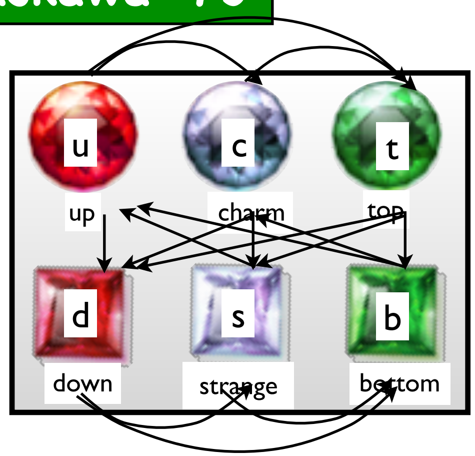
Yukawa coupling

$$(U^u_L)^\dagger U^d_L \equiv V_{\mathrm{CKM}}$$

Charged current: CKM matrix
Origin of CP Violation
(complex phase)!

Cabibbo '63
Kobayashi, Maskawa '73

GIM: FCNC suppressed



V_{CKM} matrix

- The existence of 3 generations allows a freedom of one complex phase, which provides the SINGLE source of the CP violation in quark sector in SM.

✓ **Test: V_{CKM} has to be a 3x3 unitary matrix which includes only one complex phase.**

Kobayashi-Maskawa mechanism at work!

- SM is a very concise model which incorporates:
  - ✓ Natural suppression of FCNC (i.e. GIM mechanism)
  - ✓ A source of CP violation in the V_{CKM} matrix (i.e. KM mechanism)

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

$+A\lambda^4(1/2-\rho-i\eta)$

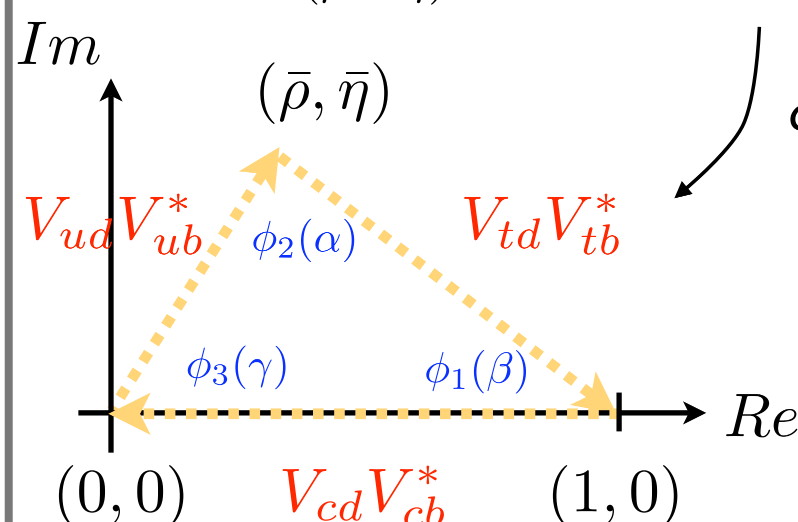
Unitarity Triangle

Test of Unitarity

Verify if the triangle closes at the apex by independently measuring the three sides and three angles!!

$$\underbrace{V_{ud}V_{ub}^*}_{A\lambda^3(\rho+i\eta)} + \underbrace{V_{cd}V_{cb}^*}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{A\lambda^3(1-\rho-i\eta)} = 0$$

divide by $A\lambda^3$

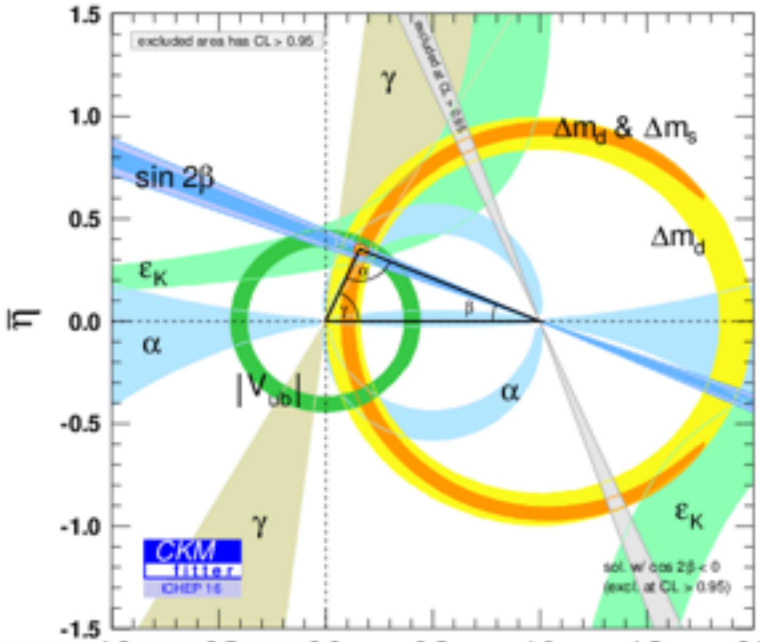


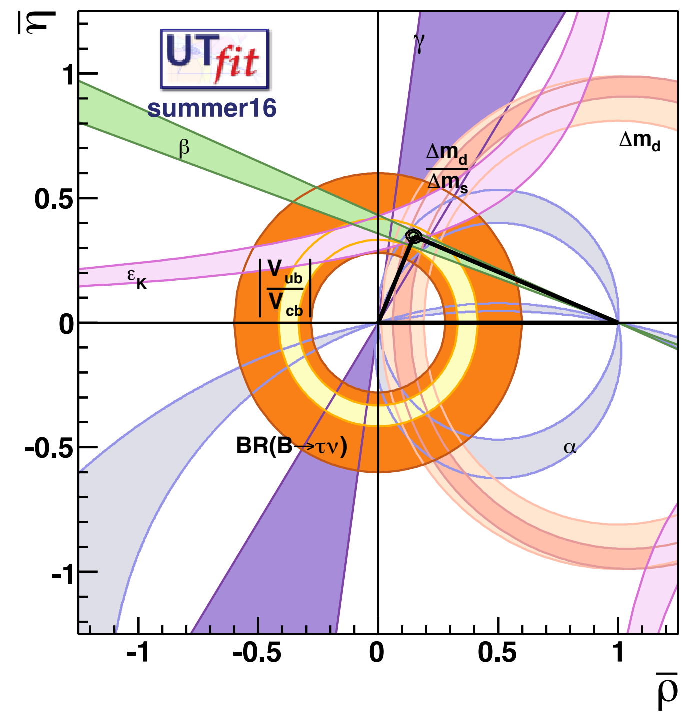
$$arg\left(\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cs}}\right) \equiv -\phi_1$$

$$arg\left(\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right) \equiv -\phi_2$$

$$arg\left(\frac{V_{cb}^* V_{cs}}{V_{ub}^* V_{ud}}\right) \equiv -\phi_3$$

The Unitarity triangle: test of Unitarity?

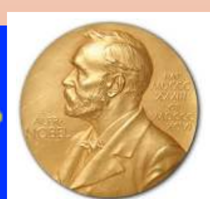




Nobel Prize to Kobayashi-Maskawa (2009)
Origin of CP violation in Standard Model

KEK (Japan) = Belle/KEKB

SLAC (US) = Babar/PEP-II



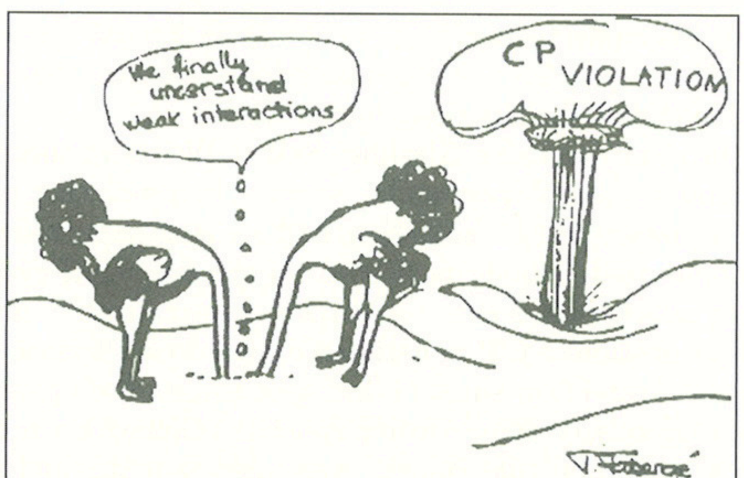
- Successful explanation of flavour physics up to now! Hundreds of observables (including dozens of CPV) are explained by this single matrix.

Flavour Physics beyond SM

The indirect search of new physics through quantum effect: very powerful tool to search for new physics signal!

- This very simple picture does not exist in most of the extensions of SM: suppression of the FCNC is NOT automatic and also CP violation parameters can appear.

  N.B.: SM also has an "unobserved" CP parameter (strong CP problem).



SUSY: Quark and Squark mass matrices can not be diagonalized at the same time ---> FCNC and CP violation

Mutli-Higgs model: Many Higgs appearing in this model ---> tree level FCNC and CP violation

Flavour Physics beyond SM

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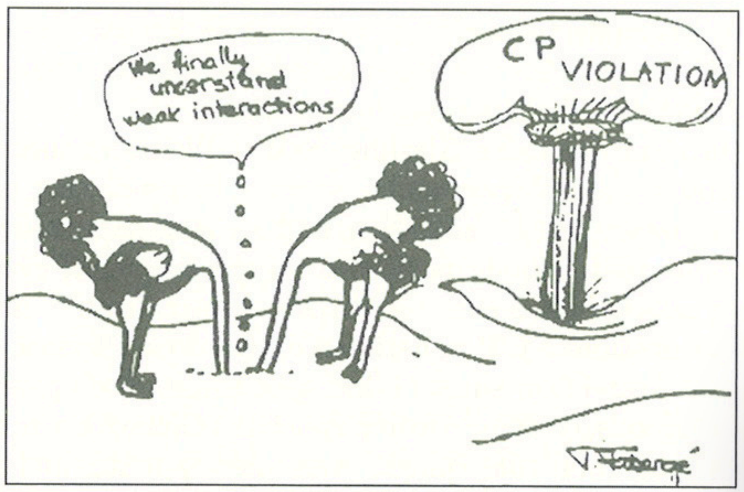


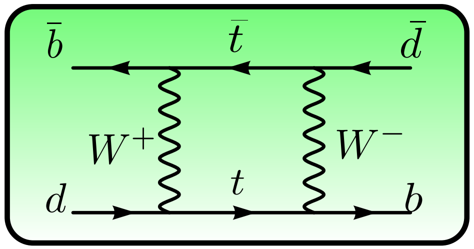
New particle introduces new source of flavour/CP violations. Then, if new physics exist, we should observe those phenomena at some point!

Searching New Physics via CPV measurement

CPV in oscillation measurements

Box digram induces oscillation. In B-Bbar oscillation contain CPV phase in SM.

B-Bbar oscillation



$$
\begin{aligned}
|B_1\rangle &= p|B\rangle + q|\overline{B}\rangle \\
|B_2\rangle &= p|B\rangle - q|\overline{B}\rangle
\end{aligned}
\quad \textit{with} \quad \frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}
$$

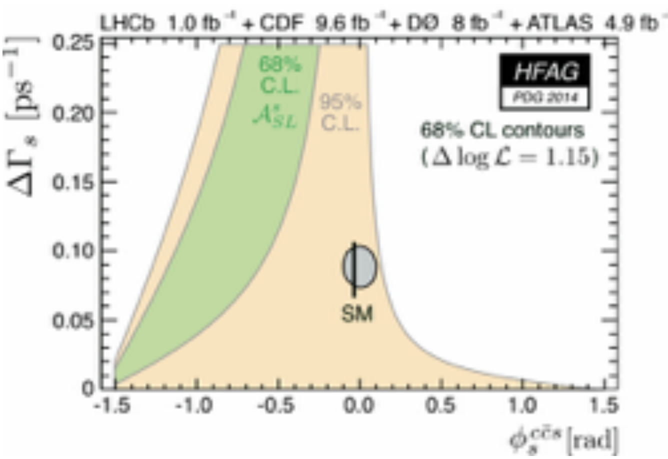
$\frac{q}{p} \neq 1$ is the condition to have CP violation.

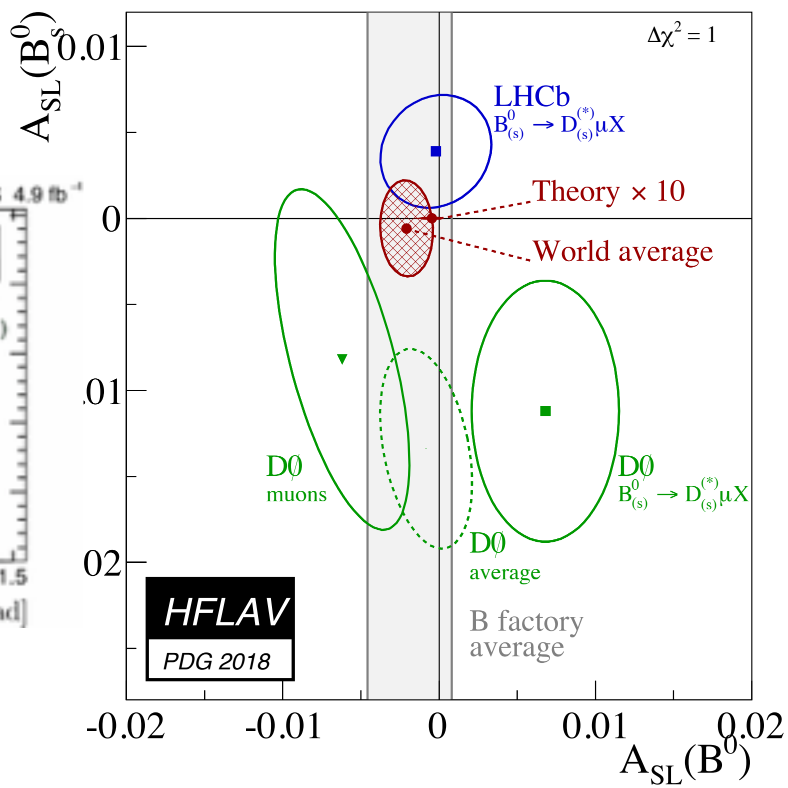
- Wrong sign semi-leptonic decays measurement:

B and Bbar produce same-sign lepton after oscillation.

$$
\mathcal{A} = \frac{\Gamma(\overline{B}^0 B^0 \to X l^+ l^+) - \Gamma(\overline{B}^0 B^0 \to X l^- l^-)}{\Gamma(\overline{B}^0 B^0 \to X l^+ l^+) + \Gamma(\overline{B}^0 B^0 \to X l^- l^-)} = \frac{|p/q|^4 - 1}{|p/q|^4 + 1}
$$

Wrong sign semi-leptonic decays measurement





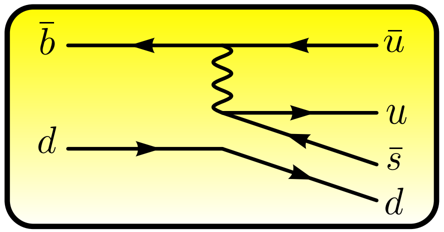
Theory prediction:
M. Artuso, G. Borissov and A. Lenz,
arXiv:1511.09466 [hep-ph]]

- Unfortunately, the D0 anomaly is not confirmed by LHCb.
- The standard Model prediction is re-evaluated: the uncertainty is VERY small.
- Since it enters with power of 4, even a small deviation can be enhanced!

CPV in decay measurement

Interference of Tree and Penguin diagrams induce CPV observable.

B decay



$$|A(B \to f)| \neq |A(\overline{B} \to \overline{f})|$$

is the condition to have CP violation.

We can measure $\not{CP}$ *only* through an interference of two amplitudes with different CP conserving and CP violating phases.

$$\begin{aligned} A(\overline{B}^0 \to \overline{f}) &= A_1 e^{+i\theta_1} e^{+i\delta_1} + A_2 e^{+i\theta_2} e^{+i\delta_2} \\ A(B^0 \to f) &= A_1 e^{-i\theta_1} e^{+i\delta_1} + A_2 e^{-i\theta_2} e^{+i\delta_2} \end{aligned}$$

$\theta_{1,2}$: CP the violating phase, $\delta_{1,2}$: the CP conserving phase.

$$\frac{\Gamma(\overline{B}^0 \to \overline{f}) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to \overline{f}) + \Gamma(B^0 \to f)} = \frac{2(A_2/A_1)\sin(\theta_1 - \theta_2)\sin(\delta_1 - \delta_2)}{1 + 2(A_2/A_1)\cos(\theta_1 - \theta_2)\cos(\delta_1 - \delta_2)}$$

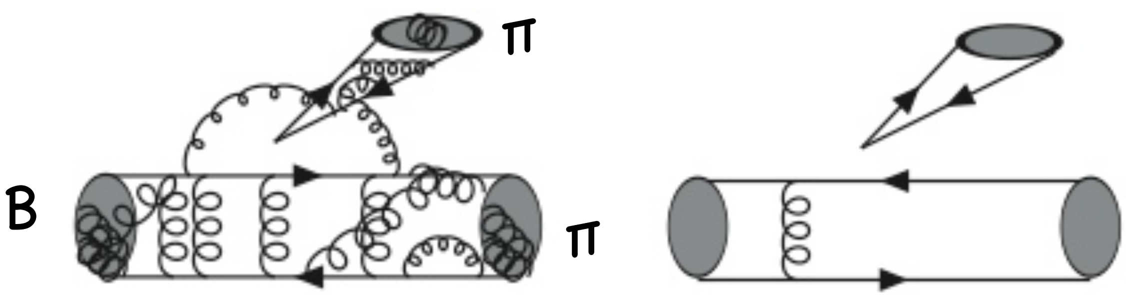
Overlaps with two diagrams with different CPV phase with different CPV phase needed.

- Tree/Penguin contributions provide two sources of weak phases.
- Big challenge is to theoretically/experimentally obtain the strong phase difference.

CPV in decay measurement

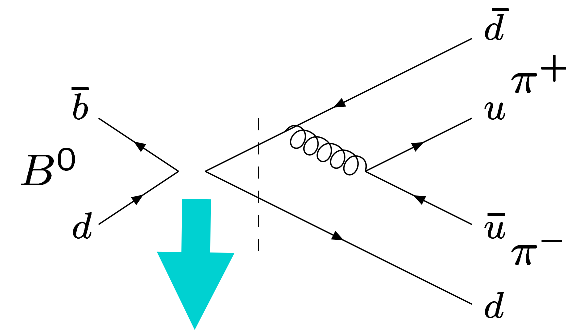
Challenge of extracting the strong poses

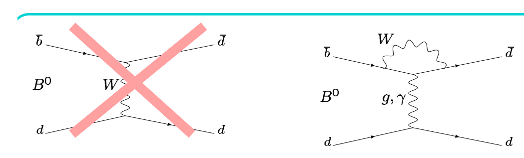
Two body decays



Perturbative QCD computation

Source of strong phase from penguin annihilation diagrams



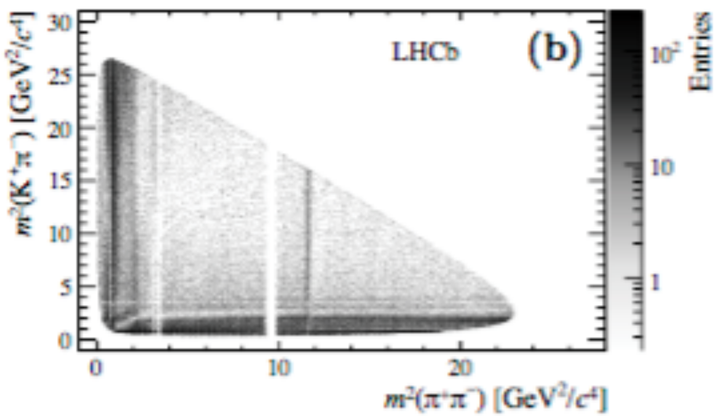


- Theoretical development in QCD higher order corrections, Lattice QCD etc allow to reduce the theoretical uncertainties.
- Improved measurements of "theoretical control channels" are very important to reduce the theoretical errors.

CPV in decay measurement

Challenge of extracting the strong poses

Three body decays



Dalitz plot contains full of source of strong phases: "Breit-Wigner" phase, ππ/Kπ/KK scattering phase.

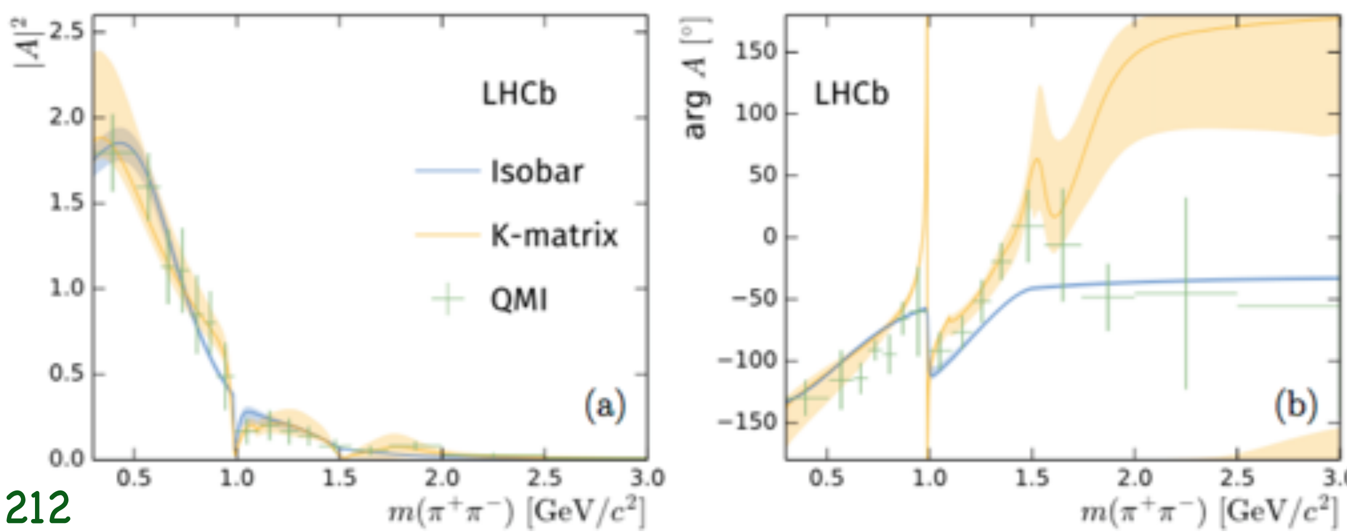
CPV is VERY large locally...

and smallish after integrating the whole region

arXiv:1408.5373

$$
\begin{aligned}
A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) &= +0.025 \pm 0.004 \pm 0.004 \pm 0.007\,,\\
A_{CP}(B^\pm \to K^\pm K^+K^-) &= -0.036 \pm 0.004 \pm 0.002 \pm 0.007\,,\\
A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) &= +0.058 \pm 0.008 \pm 0.009 \pm 0.007\,,\\
A_{CP}(B^\pm \to \pi^\pm K^+K^-) &= -0.123 \pm 0.017 \pm 0.012 \pm 0.007\,,
\end{aligned}
$$

- Strong phase can be obtained by the Amplitude Analysis (cf $\phi_3(\gamma)$ measurement).

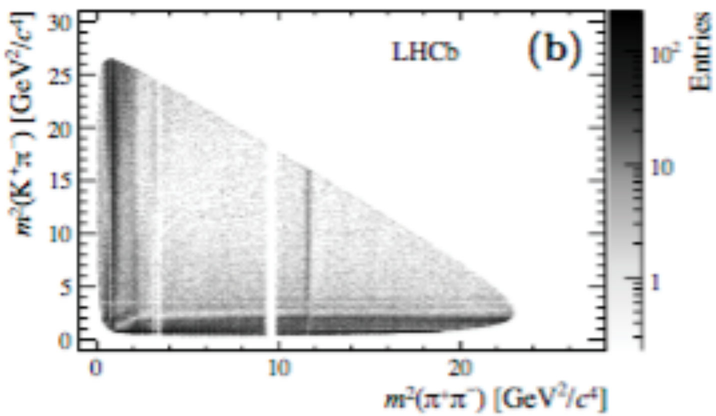


arXiv:1909.05212

CPV in decay measurement

Challenge of extracting the strong poses

Three body decays



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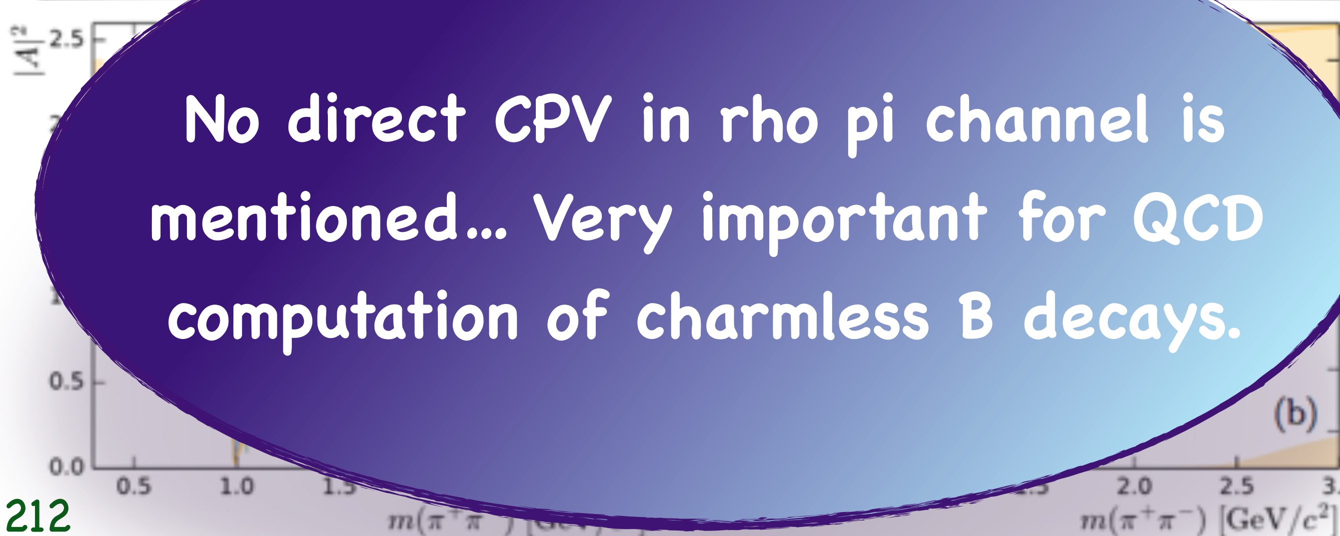
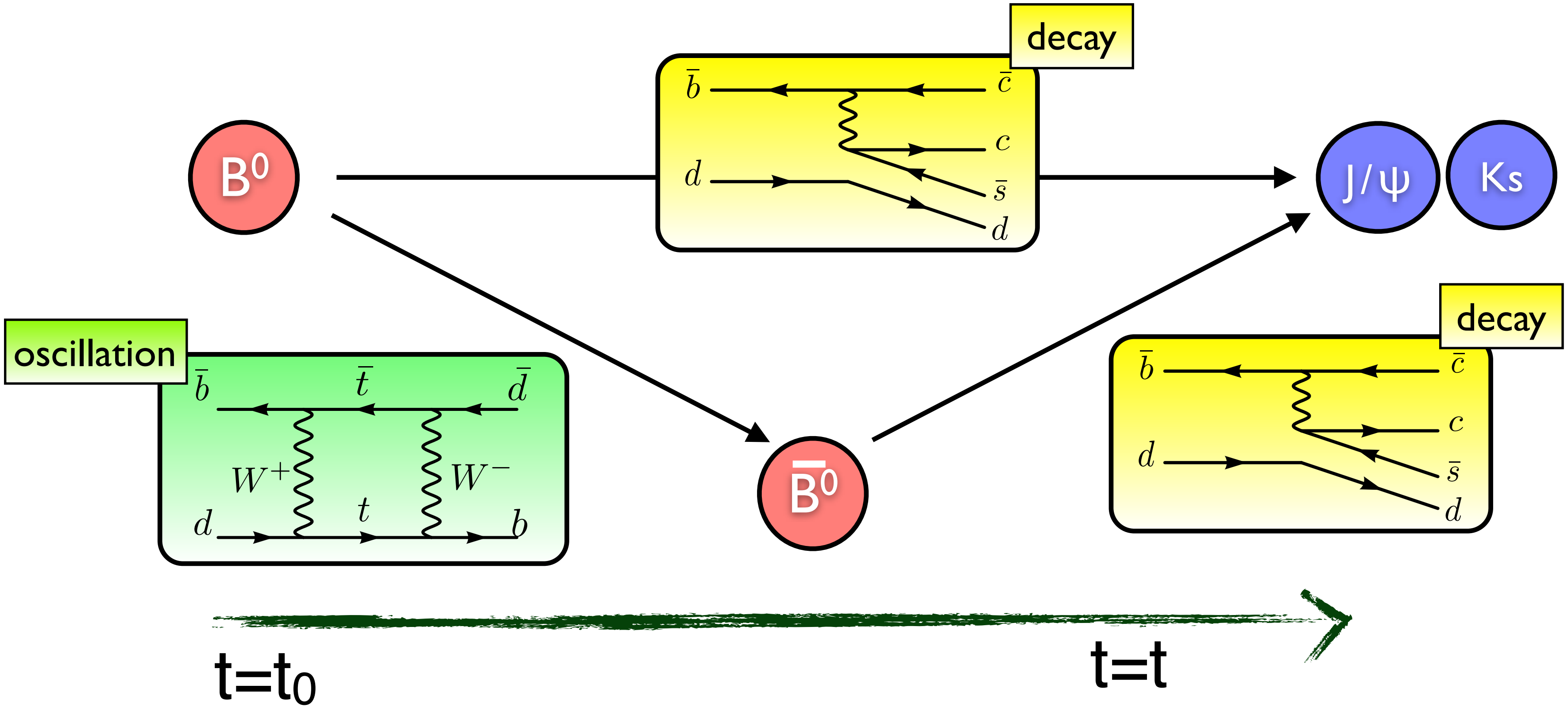
- Strong phase can be obtained by the Amplitude A ... rement).



No direct CPV in rho pi channel is mentioned... Very important for QCD computation of charmless B decays.

CPV in time-dependent measurement

Gold-plated



$$|B(t)\rangle = f_+(t)|B\rangle + \frac{q}{p} f_-(t)|\overline{B}\rangle$$

where

$$f_\pm = \frac{1}{2} e^{-iM_1 t} e^{-\frac{1}{2}\Gamma_1 t}\left[1 \pm e^{-i\Delta M t} e^{\frac{1}{2}\Delta\Gamma t}\right]$$

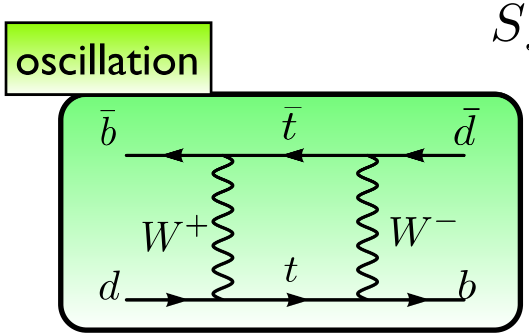
The time-evolution gives the CP conserving phase and the B-B mixing gives the CP violating phase.

In SM $\quad |\frac{q}{p}| = 1, \quad \frac{q}{p} \neq 1$

Gold-plated

sin2Φ$_1$(β) measurement with tree decay

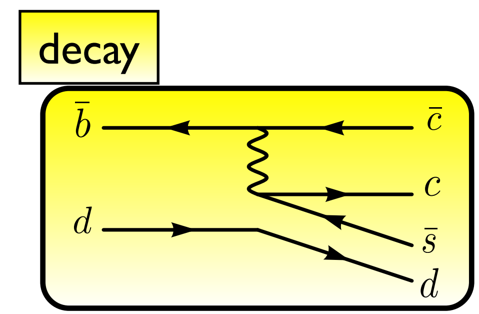
$$A_{J/\psi K_S}(t) = \frac{\Gamma(\overline{B}^0(t)\to J/\psi K_S)-\Gamma(B^0(t)\to J/\psi K_S)}{\Gamma(\overline{B}^0(t)\to J/\psi K_S)+\Gamma(B^0(t)\to J/\psi K_S)} = S_{J/\psi K_s}\sin\Delta M_B\, t$$



$$S_{J/\psi K_S} = \mathrm{Im}\left[\underbrace{\frac{q}{p}}_{\text{oscillation}}\ \underbrace{\frac{\mathcal{A}(\overline{B}\to J/\psi K_S)}{\mathcal{A}(B\to J/\psi K_S)}}_{decay}\right]$$

$$= \mathrm{Im}\left[-\underbrace{\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}}_{\simeq e^{-2i\beta}}\ \underbrace{\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}}_{\simeq 1}\right]$$

$$= \sin 2\beta$$



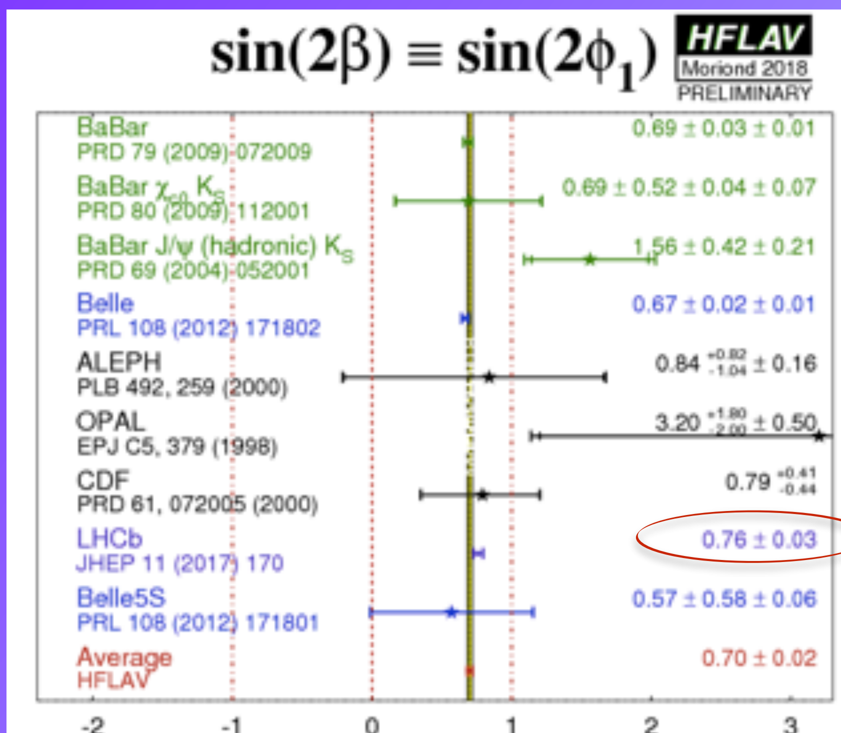
New physics particle might be in the loop!

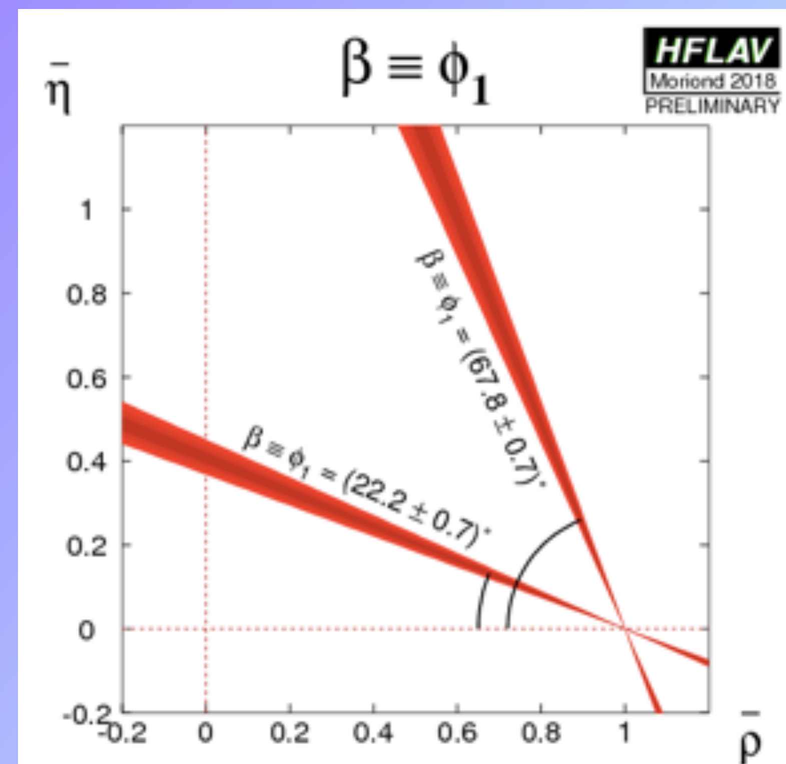
Gold-plated

sin2Φ_1(β) measurement with tree decay

$$A_{J/\psi K_S}(t) = \frac{\Gamma(\overline{B}^0(t)\to J/\psi K_S)-\Gamma(B^0(t)\to J/\psi K_S)}{\Gamma(\overline{B}^0(t)\to J/\psi K_S)+\Gamma(B^0(t)\to J/\psi K_S)} = S_{J/\psi K_s}\sin\Delta M_B\, t$$

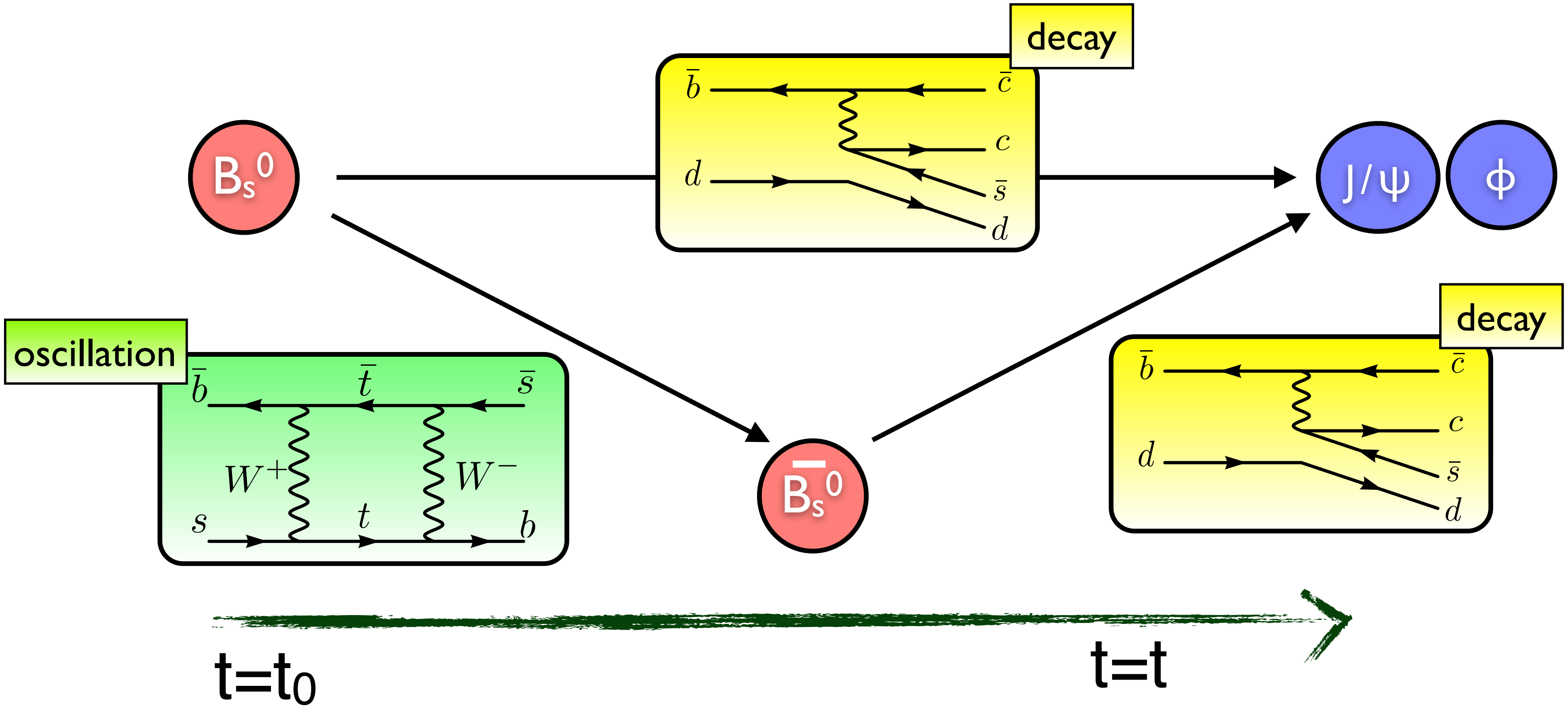
osci





We'll come back to the interpretation later...

B_s^0–$\overline{B_s}^0$ mixing and Φ_s measurement



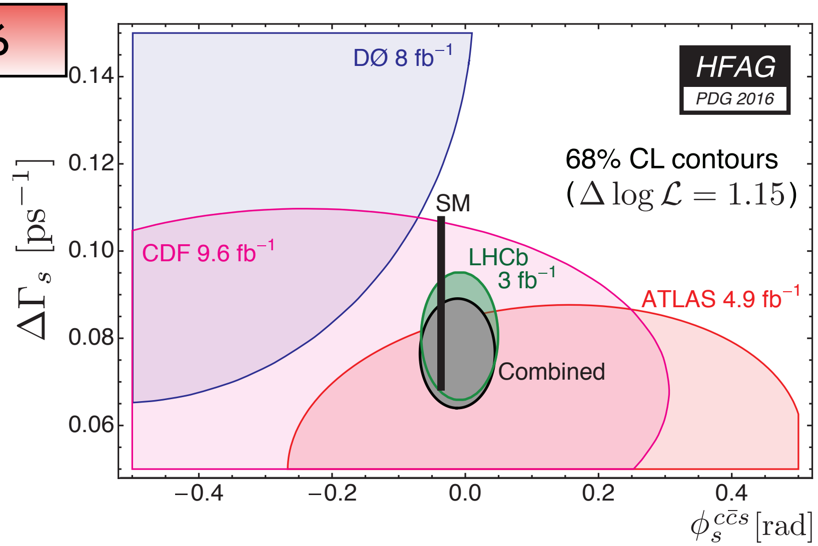
For Bs mixing, the analysis becomes much more involved since:

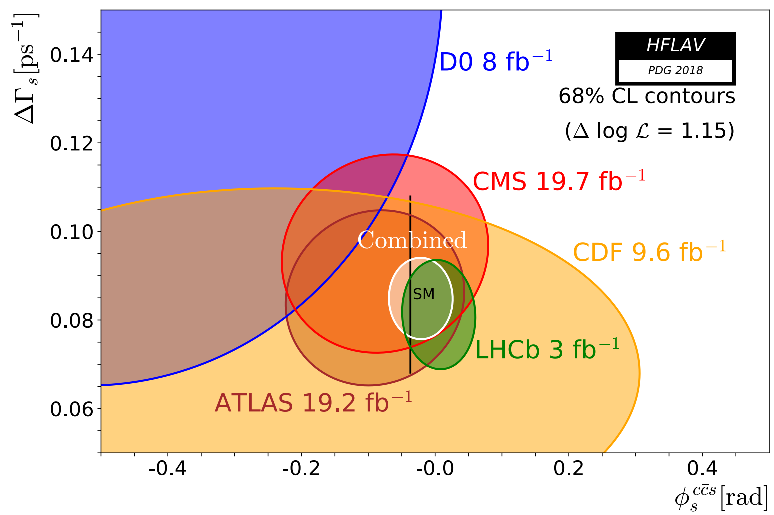
- the width deference, ΔΓ for Bs. It has to be simultaneously measured.
- the final state J/ψϕ is not only S-wave, the angular momentum has to be decomposed.

https://arxiv.org/pdf/1909.11087.pdf

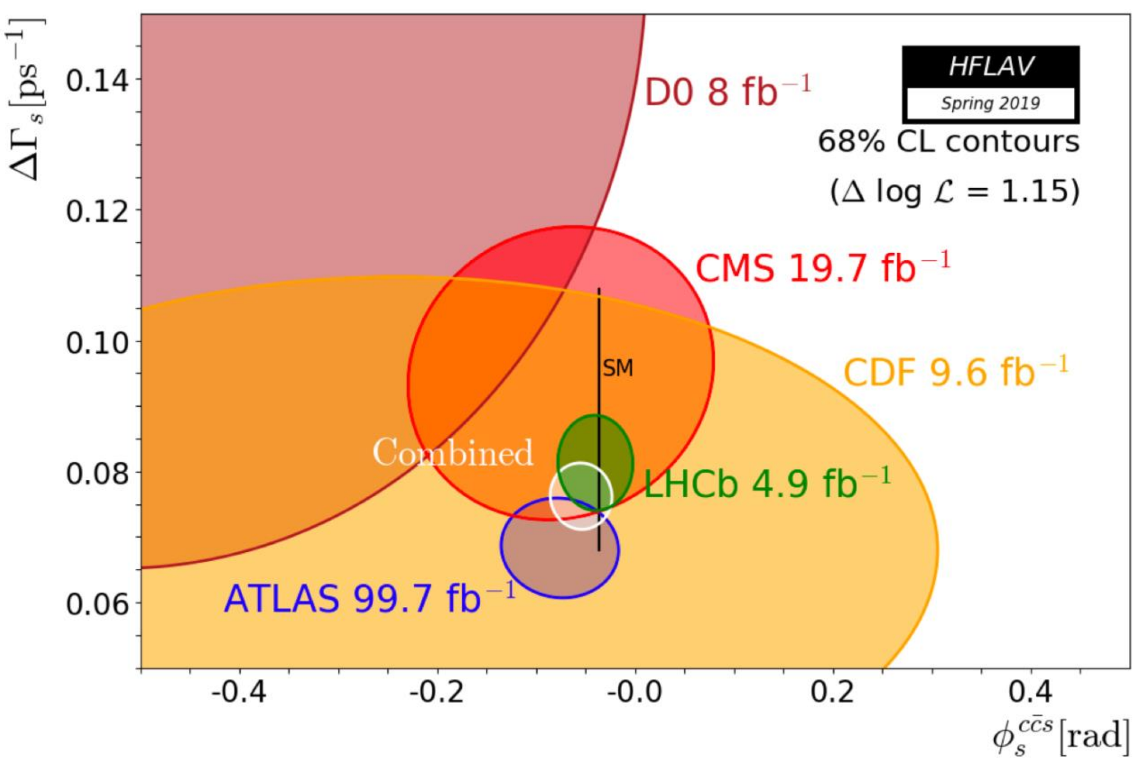
B_s^0–$\overline{B_s}^0$ mixing and Φ_s measurement

2016





2018



2019

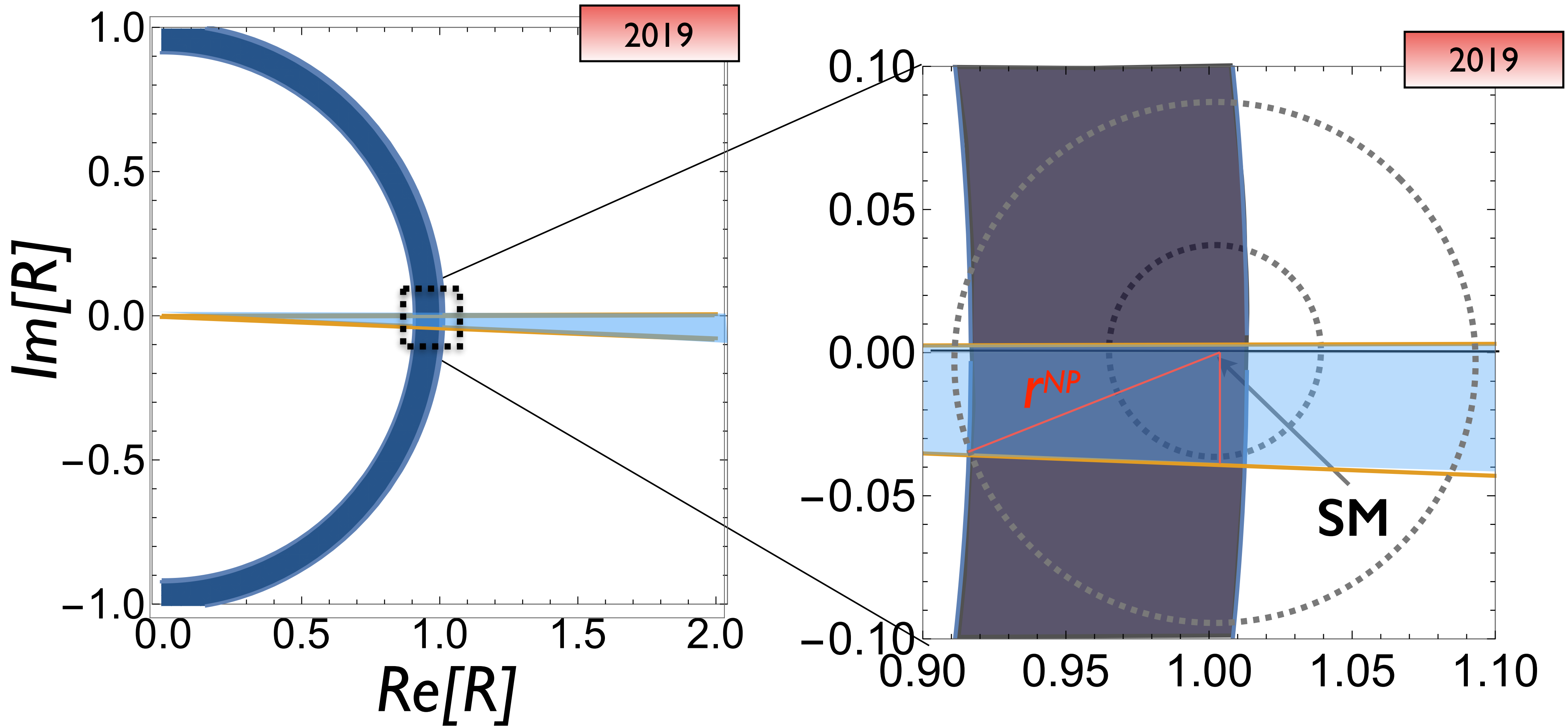
ϕ_s=-0.055±0.021

comparing to

ϕ_s^{SM}=-0.0368±0.0009

B_s^0–$\overline{B}_s^0$ mixing and Φ_s measurement

$$R \equiv \frac{\langle B_s^0 | \mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP} | \overline{B}_s^0 \rangle}{\langle B_s^0 | \mathcal{H}_{\rm eff}^{\rm SM} | \overline{B}_s^0 \rangle} = 1 + r^{\rm NP} e^{i\phi^{\rm NP}}$$



New physics scenarios with 5-10% with large CPV phases are possible!

$\mathrm{Sin}2\Phi_1(\beta)$ measurement with penguin decays

Time dependent CP asymmetry in the B_d system

With tree process

$$S_{J/\psi K_s} = Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to J/\psi K_S)}{A(B\to J/\psi K_S)}}_{decay}\right]$$

$$= Im\left[\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}}_{decay}\right]$$

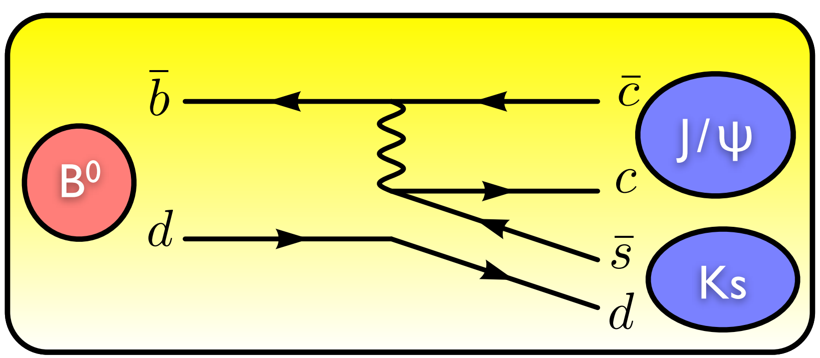
$$= \sin 2\beta(2\phi_1)$$

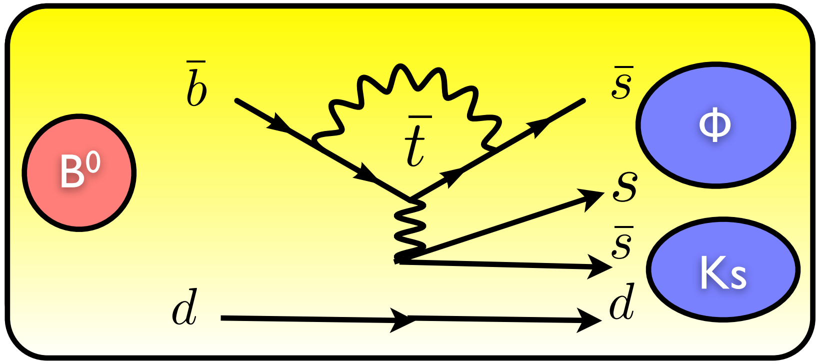
With penguin process

$$S_{\phi K_s} = Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to \phi K_S)}{A(B\to \phi K_S)}}_{decay}\right]$$

$$= Im\left[\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}_{decay}\right]$$

$$= \sin 2\beta(2\phi_1)$$





No phase in SM!

Sin2Φ1(β) measurement with penguin decays

Time dependent CP asymmetry in the B_d system

With tree process

$$S_{J/\psi K_s} = Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to J/\psi K_S)}{A(B\to J/\psi K_S)}}_{decay}\right]$$

$$= Im$$

$$= \sin 2\beta(2\phi_1)$$

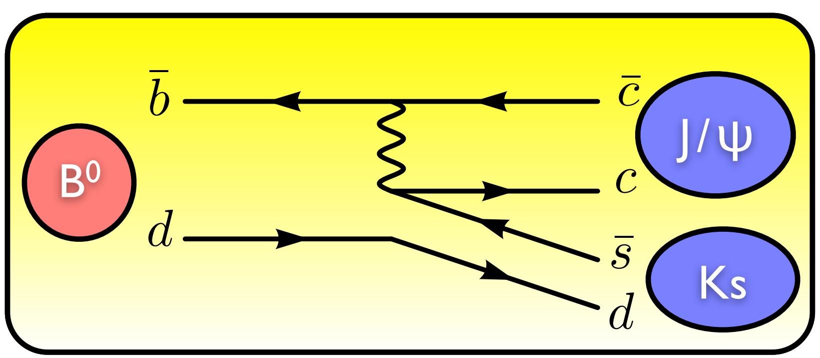
With penguin process

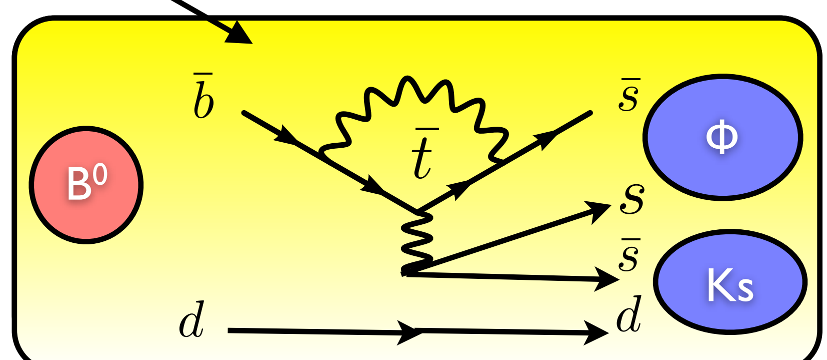
$$S_{\phi K_s} = Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to \phi K_S)}{A(B\to \phi K_S)}}_{decay}\right]$$

$$\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}_{decay}\Bigg]$$

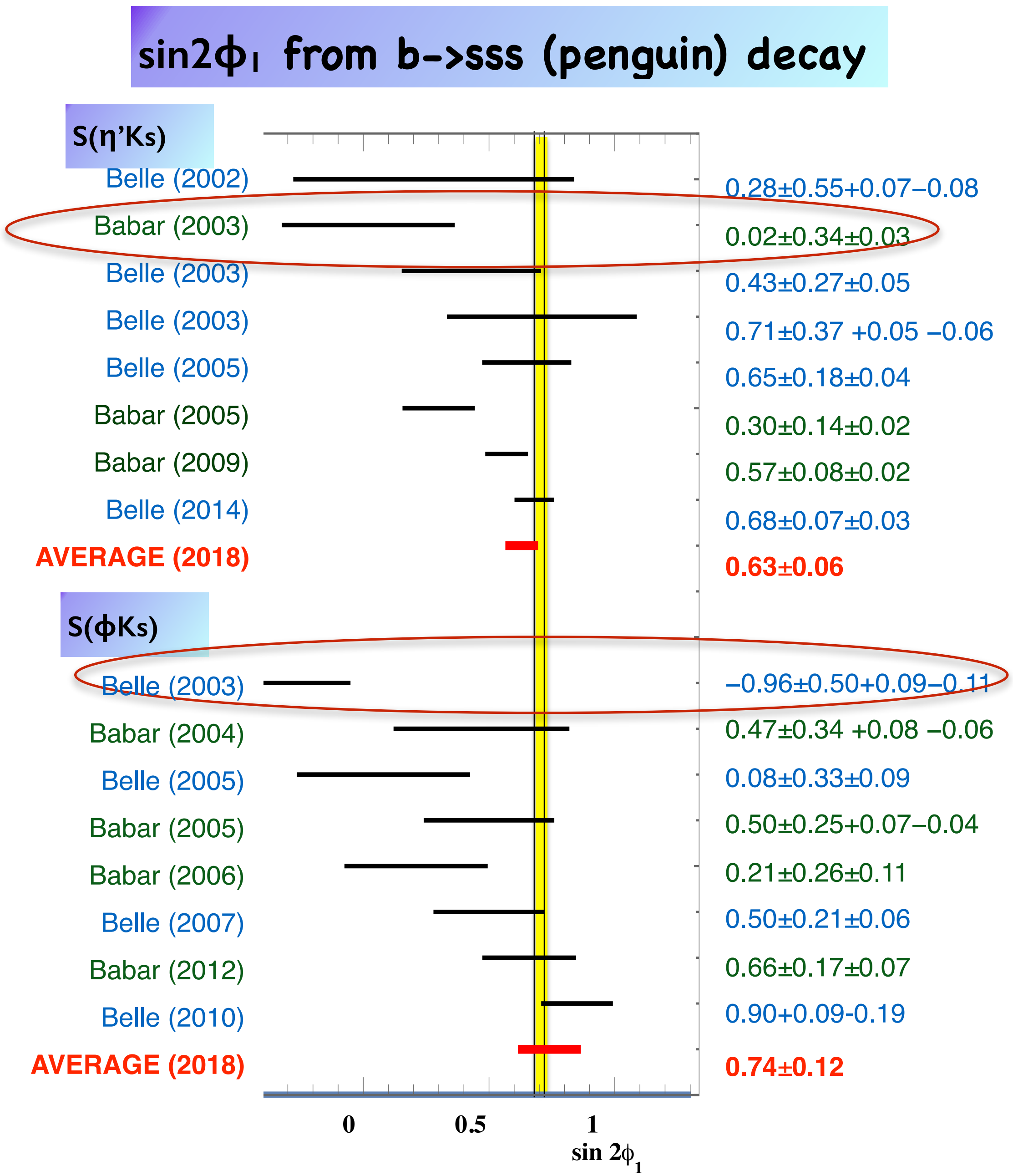
$$\sin 2\beta(2\phi_1)$$

Difference in the measured β(Φ1) value is the indication of the new physics in the penguin loop!





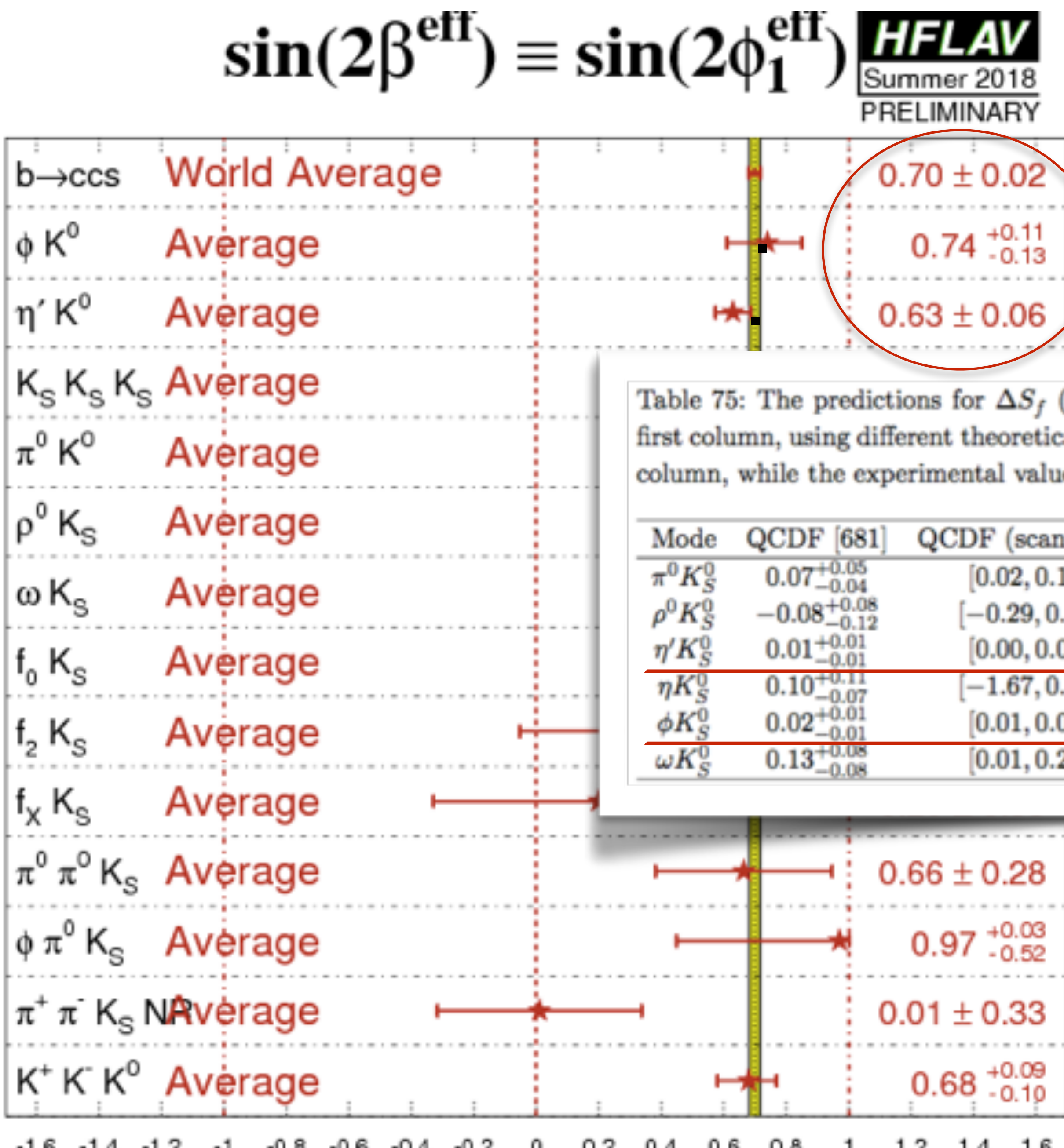
$\mathrm{Sin}2\Phi_1(\beta)$ measurement with penguin modes



$\sin 2\phi_1 = 0.70 \pm 0.02$ as of today

- Summer 2002, Babar/ Belle announced 2.7 sigma deviation!
- Unfortunately, the deviation is diminished as time goes…

Sin2Φ$_1$(β) measurement with penguin modes



Various channels are measured but some contains tree contributions at leading order, which induces SM $\sin 2\phi_1^{\rm eff} \neq \sin 2\phi_1^{\rm tree}$. arXiv:1808.10567

Table 75: The predictions for ΔS_f (315), for charmless two-body final states listed in the first column, using different theoretical approaches, are listed in the second, third, and fourth column, while the experimental values ([230]) are given in the last column.

Mode	QCDF [681]	QCDF (scan) [681]	$SU(3)$	Data
$\pi^0 K^0_S$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [683]	$-0.11^{+0.17}_{-0.17}$
$\rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$		$-0.14^{+0.18}_{-0.21}$
$\eta' K^0_S$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_1)\sin\gamma$ [684]	-0.05 ± 0.06
ηK^0_S	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$		—
ϕK^0_S	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_1)\sin\gamma$ [684]	$0.06^{+0.11}_{-0.13}$
ωK^0_S	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$		$0.03^{+0.21}_{-0.21}$

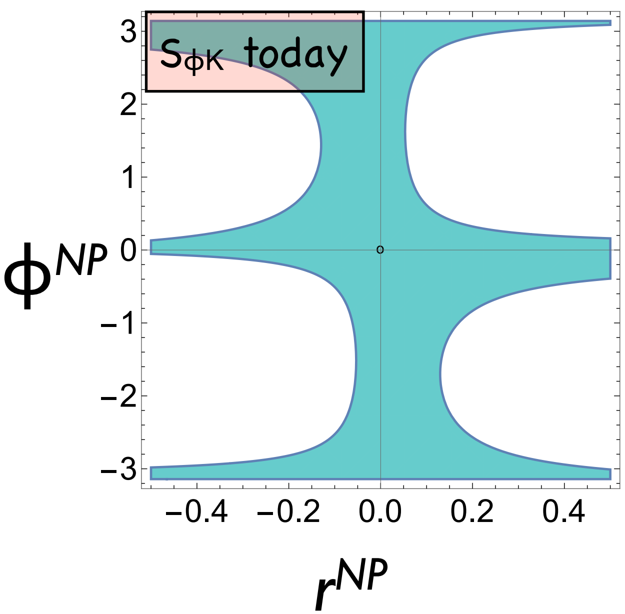
- Theoretical computations show that φK and η'K modes are very clear (penguin-dominant).

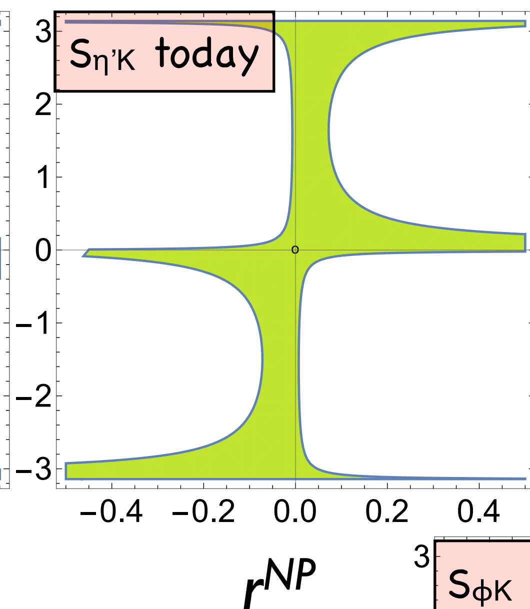
$\sin 2\Phi_1(\beta)$ measurement with penguin modes

$$S_{\phi K_S} = \frac{\sin 2\phi_1 + 2r^{\rm NP}\sin(2\phi_1 - \phi^{\rm NP}) + (r^{\rm NP})^2 \sin(2\phi_1 - 2\phi^{\rm NP})}{1 + 2r^{\rm NP}\cos\phi^{\rm NP} + (r^{\rm NP})^2}$$

with

$$\frac{A^{\rm NP}}{A^{\rm SM}} = r^{\rm NP} e^{i\phi^{\rm NP}}$$



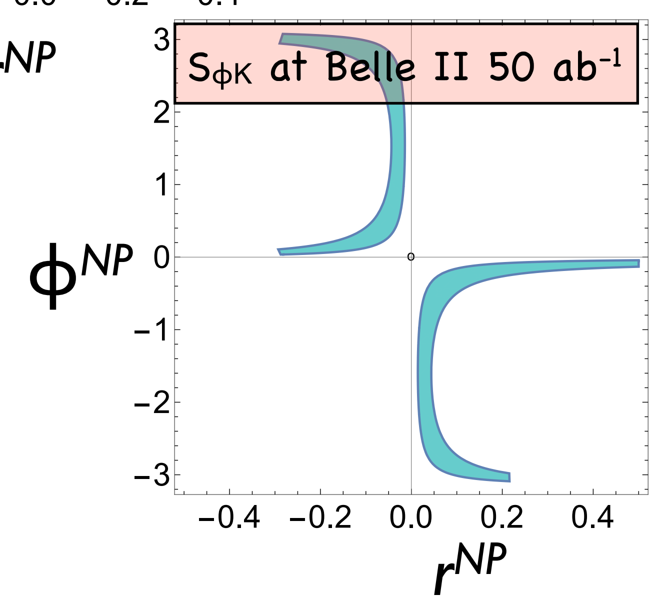


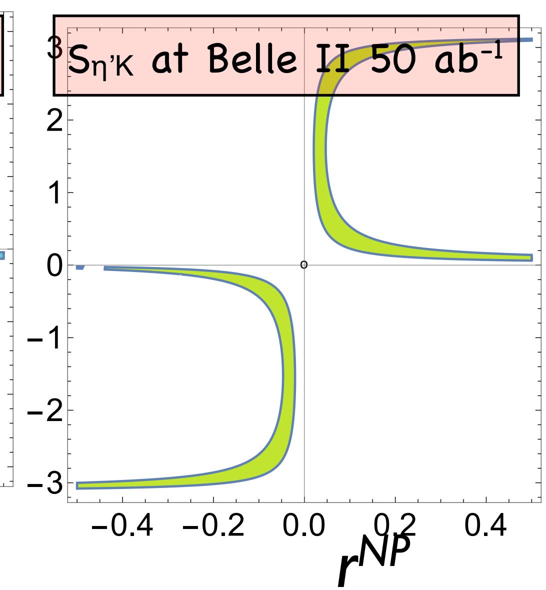
$S_{\phi K}=0.74\pm0.12$

$S_{\eta' K}=0.63\pm0.06$

comparing to $S_{J/\psi K}=0.70\pm0.02$

With the same central value with ±0.02

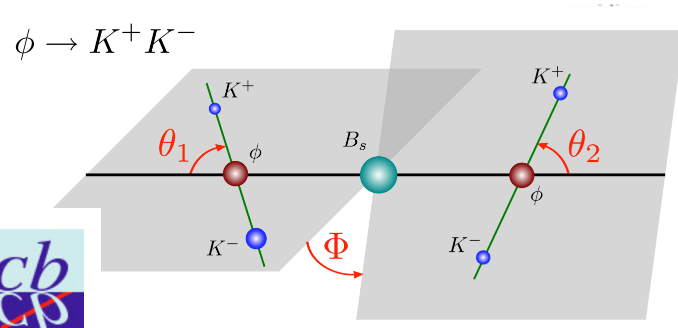




The experimental errors will go down to 2% level at Belle II. An appearance of a few to a few 10% of new physics effects (r^{NP}) are possible.

The Φ_s measurement with penguin modes

3 angles and time dependent analysis.



$$\frac{d\Gamma}{dt\, d\cos\theta_1\, d\cos\theta_2\, d\Phi} \propto 4|\mathcal{A}(t,\theta_1,\theta_2,\Phi)|^2 = \sum_{i=1}^{15} K_i(t) f_i(\theta_1,\theta_2,\Phi)$$

Triple product measurement

$$A_U = -0.003 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst}),$$
$$A_V = -0.014 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst}),$$

Polarisation mesaurement

$$|A_0|^2 = 0.381 \pm 0.007\,(\text{stat}) \pm 0.012\,(\text{syst}),$$
$$|A_\perp|^2 = 0.290 \pm 0.008\,(\text{stat}) \pm 0.007\,(\text{syst}),$$
$$\delta_\perp = 2.818 \pm 0.178\,(\text{stat}) \pm 0.073\,(\text{syst})\ \text{rad},$$
$$\delta_\parallel = 2.559 \pm 0.045\,(\text{stat}) \pm 0.033\,(\text{syst})\ \text{rad}.$$

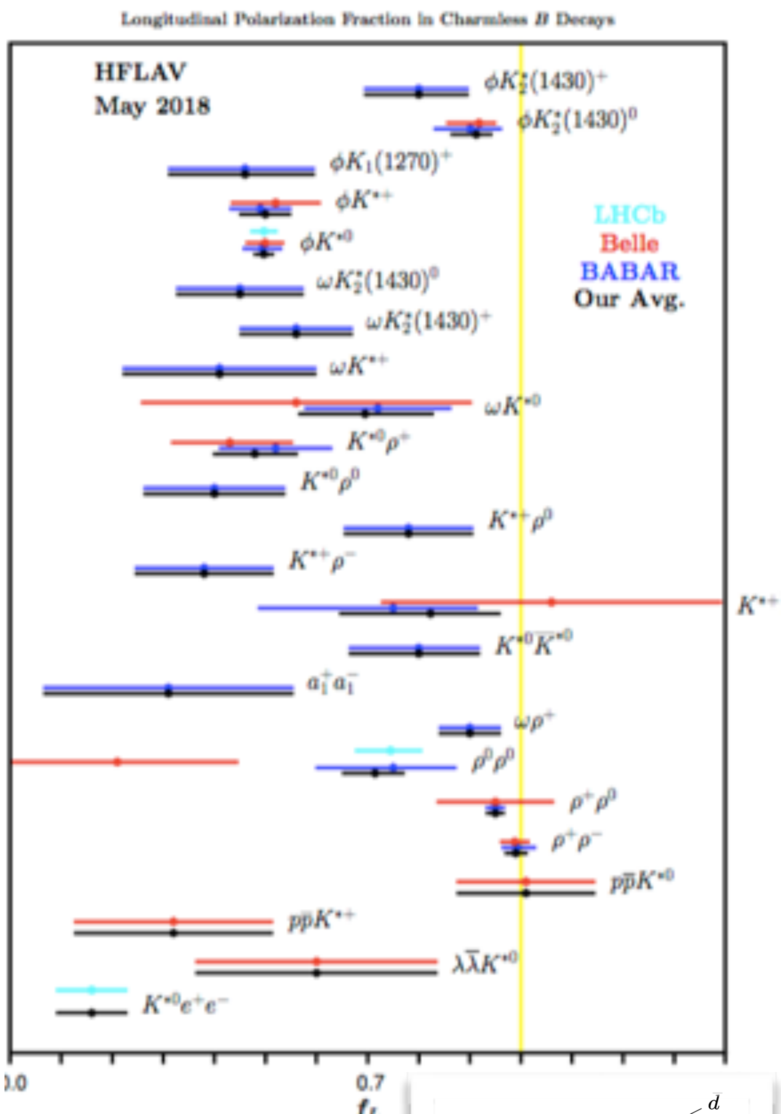
1907.10003.pdf

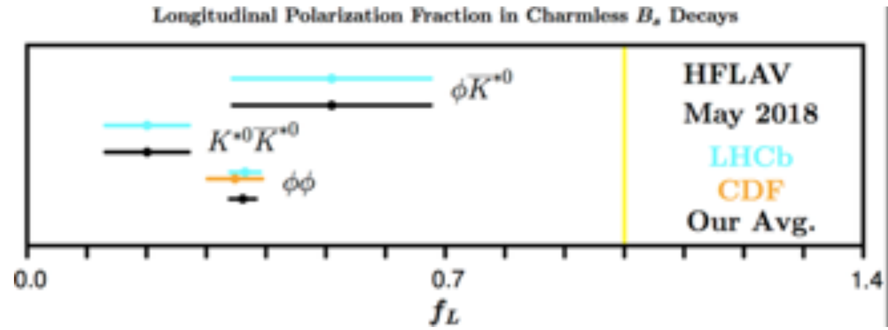
$$\phi_s^{s\bar{s}s} = -0.073 \pm 0.115\,(\text{stat}) \pm 0.027\,(\text{syst})\ \text{rad},$$
$$|\lambda| = 0.99 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

To be compared to ϕ_s=-0.055±0.021

- Theory predicts very small deviation from ϕ_s (2% level, penguin-dominant).
- Definitely a important case for upgrade of LHCb!
- Triple-product (yet another way to measure the CPV) is also studied.
- Study of polarisation is a very important input for QCD computation of hadronic charmless B decays.

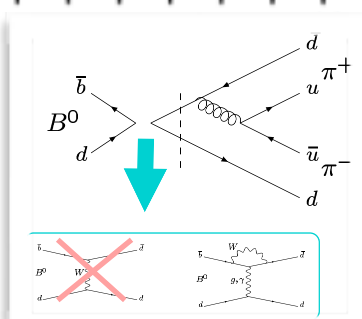
Polarisation measurement of B->VV modes





Longitudinal polarisation is dominant at LO QCD

$$A_0 : A_- : A_+ = 1 : \frac{\Lambda}{m_b} : \left(\frac{\Lambda}{m_b}\right)^2$$



- The breaking of f_L=1 is more significant in the penguin modes.
- Perturbative QCD computation explains the enhancement of the annihilation diagram (formally Λ/m_b) a part of the reason.
- Transverse polarisation is harder to compute in perturbative QCD.

arXiv:1808.10567

Perspective of CPV measurement with penguin decays

The 2002 "exercises":

- Is it possible to see order one new physics in b->s penguin process within the constraint coming from the Bs-Bs mixing (b->s box)? YES!
- Is it possible to see different new physics effects in $S_{\phi K}$ and $S_{\eta' K}$? YES!
- Is the SM uncertainty under control? YES!

The year 2019:

- LHC has changed completely the allowed parameter spaces for new physics.
- The new physics contributions are more like < a few 10%.
- What is the role of ϕ_s measurement of $B_s \to \phi\phi$ channel?

Perspective - Precision era just started! -:

- Experimental uncertainties will be reduced drastically in the near future.
- More theory works needed (effective theory approach?) to elucidate the possible new physics scenarios.
- Further verification of SM uncertainty is always welcome.

Perspective of CPV measurement with penguin decays

- Many statistical uncertainties become at a few per-cent level: increasing number of systematic uncertainties (of order of a few per-mill!) are to be taken into account.

e.g. systematic uncertainty for φs measurement with Bs->J/psi KK

LHCb upgrade LOI: CERN-LHCC-2011-001
see alo PoS(FPCP2016) 041

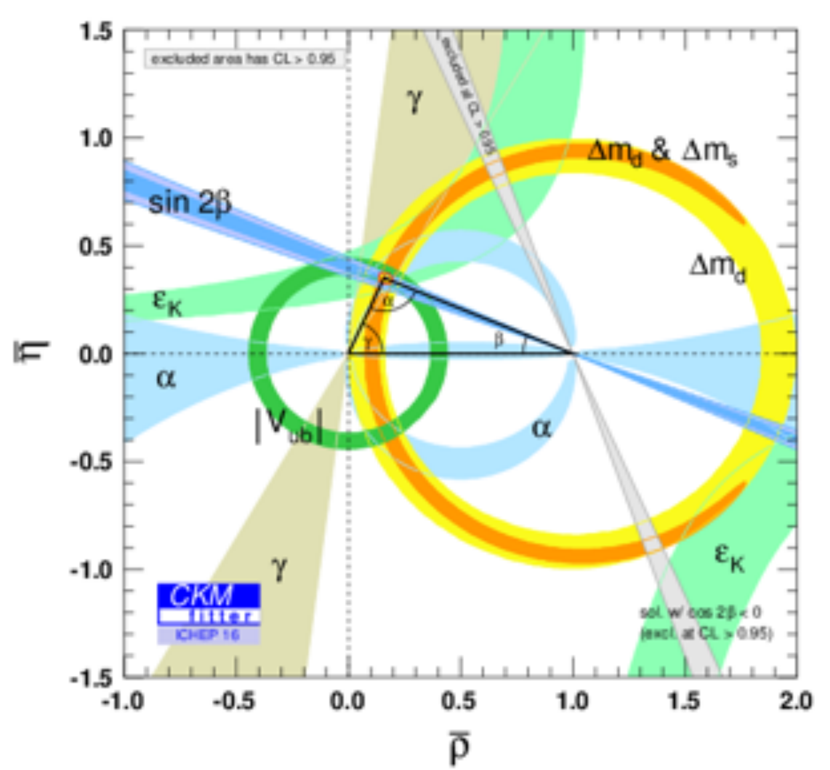
Observable	LHCb 2018	**Upgrade** (50 fb^{-1})
$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008
$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.045	0.014
a_{sl}^s	0.6×10^{-3}	0.2×10^{-3}
$2\beta_s^{eff}(B_s^0 \to \phi\phi)$	0.17	0.03
$2\beta_s^{eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	0.13	0.02
$2\beta^{eff}(B^0 \to \phi K_S^0)$	0.30	0.05
$2\beta_s^{eff}(B_s^0 \to \phi\gamma)$	0.09	0.02
$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5 %	1 %
$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.025	0.008
$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %
$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08	0.025
$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %

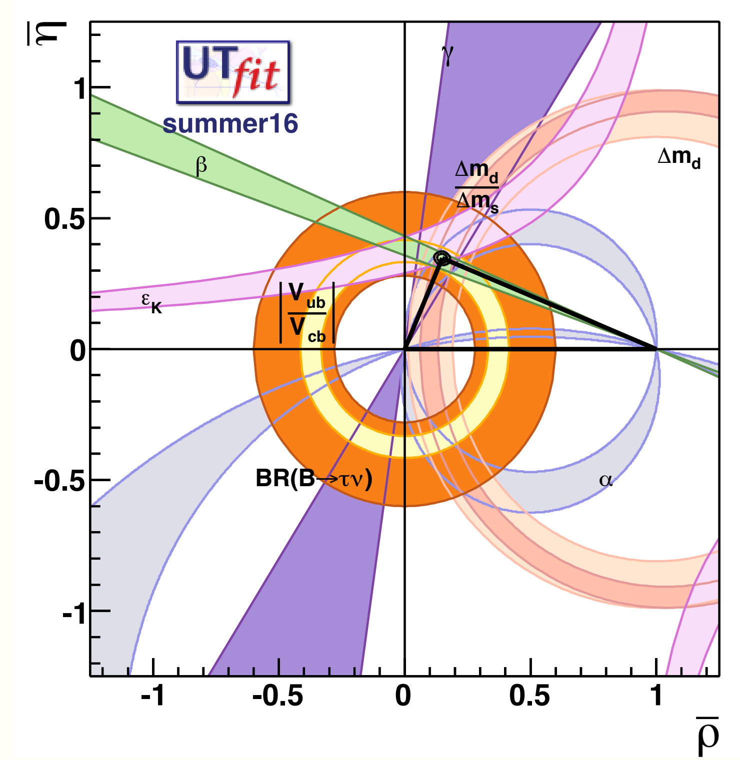
Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass width parametrisation	0.0006	0.0005	-	-	0.05	0.009	-	0.0002	0.001
Mass factorisation	0.0002	0.0004	0.004	0.0037	0.01	0.004	0.0007	0.0022	0.016
Multiple candidates	0.0006	0.0001	0.0011	0.0011	0.01	0.002	0.0003	0.0001	0.001
Fit bias	0.0001	0.0006	0.001	-	0.02	0.033	-	0.0003	0.001
C_{SP} factors	-	0.0001	0.001	0.0010	0.01	0.005	-	0.0001	0.002
Quadratic OS tagging	-	-	-	-	-	-	-	-	-
Time res.: statistical	-	-	-	-	-	-	-	-	-
Time res.: prompt	-	-	-	-	-	0.001	-	-	0.001
Time res.: mean offset	-	-	0.0032	0.0010	0.08	0.001	0.0002	0.0003	0.005
Time res.: Wrong PV	-	-	-	-	-	0.001	-	-	0.001
Ang. acc.: statistical	0.0003	0.0004	0.0011	0.0018	-	0.004	-	-	0.001
Ang. acc.: correction	0.0020	0.0011	0.0022	0.0043	0.01	0.008	0.0001	0.0002	0.001
Ang. acc.: low-quality tracks	0.0002	0.0001	0.0005	0.0014	-	0.002	0.0002	0.0001	-
Ang. acc.: t & σ_t dependence	0.0008	0.0012	0.0012	0.0007	0.03	0.006	0.0002	0.0010	0.003
Dec.-time eff.: statistical	0.0002	0.0003	-	-	-	-	0.0012	0.0008	-
Dec.-time eff.: $\Delta\Gamma_s = 0$ sim.	0.0001	0.0002	-	-	-	-	0.0003	0.0005	-
Dec.-time eff.: knot pos.	-	-	-	-	-	-	-	-	-
Dec.-time eff.: p.d.f. weighting	-	-	-	-	-	-	0.0001	0.0001	-
Dec.-time eff.: kin. weighting	-	-	-	-	-	-	0.0002	-	-
Length scale	-	-	-	-	-	-	-	-	0.004
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.10	0.037	0.0015	0.0026	0.018

What is the odds for discovery in CKM unitarity triangle

The Unitarity triangle: test of Unitarity?

Can we expect a discovery of New Physics with the Unitarity Triangle ?!

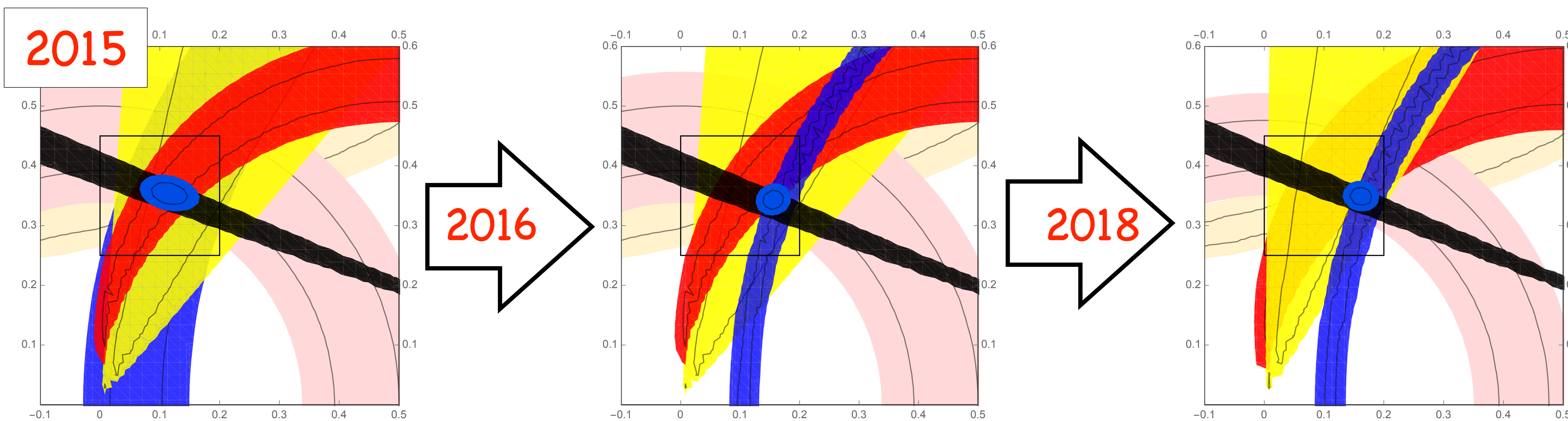




Future of the Unitarity Triangle

What do we expect to see in the future???

E.K. for B2TiP working group



Consistent with SM

New lattice result on $\Delta Ms/\Delta Md$ hadronic parameter: Consistent with SM

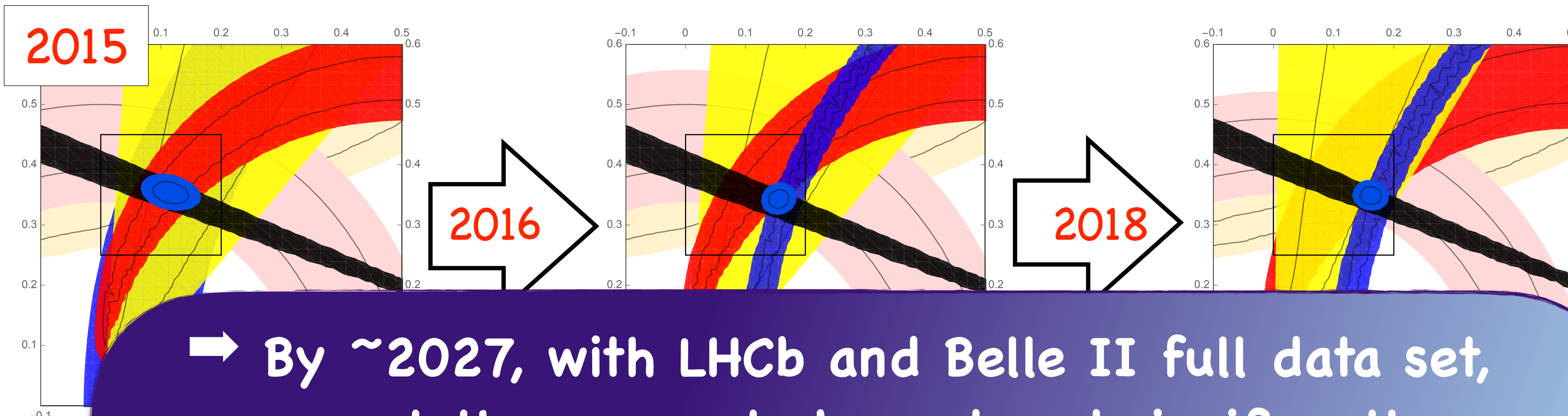
Latest average of the γ measurement of LHCb: Consistent with SM

Fermilab-MILK arXiv: 1602.03560
confirmed by RBC arXiv:1812.0879

Future of the Unitarity Triangle

What do we expect to see in the future???

E.K. for B2TiP working group



Con

➡ By ~2027, with LHCb and Belle II full data set, we expect the errors to be reduced significantly.

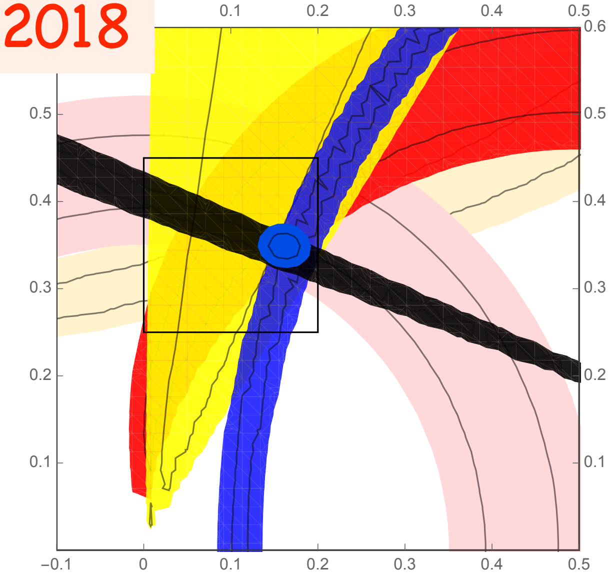
➡ Let's see what could happen when the error will go down to

$\delta\phi_1\ (\delta\beta)=0.4^\circ$, $\delta\phi_2\ (\delta\alpha)=1^\circ$, $\delta\phi_3\ (\delta\gamma)=1.5^\circ$,

$\delta V_{ub}^{today}/\delta V_{ub}=1/2$

Future of the Unitarity Triangle

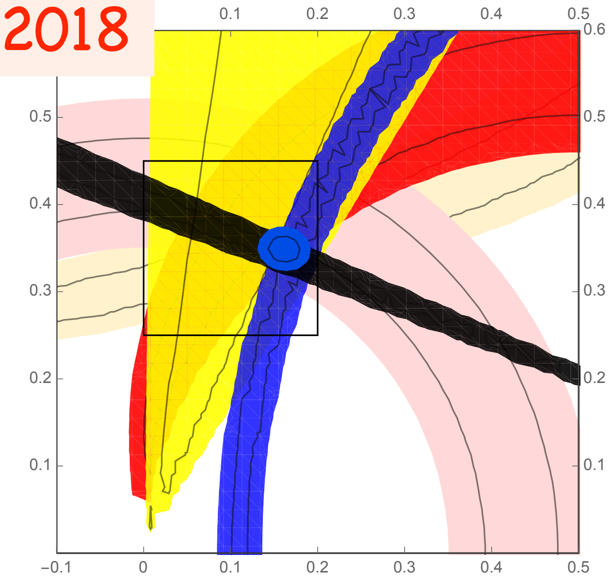
2018



Consistent with SM

Future of the Unitarity Triangle

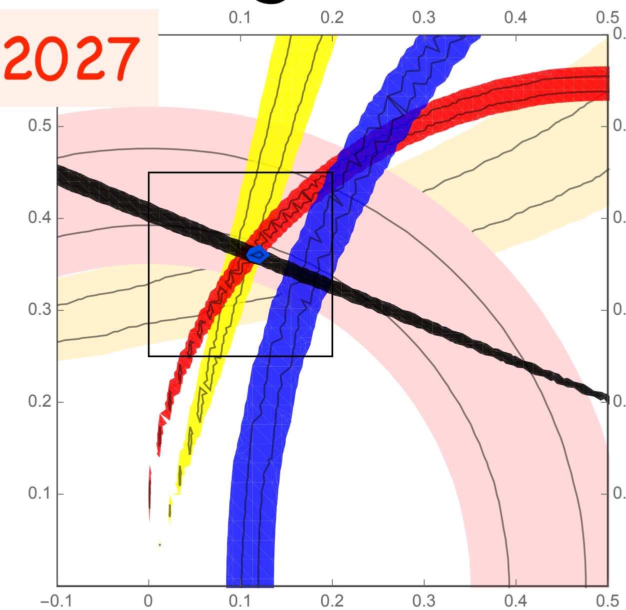
2018



Consistent with SM

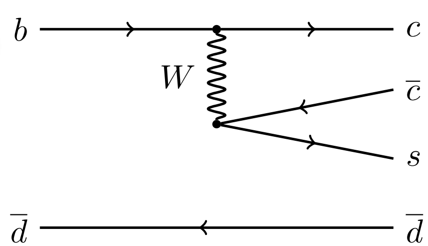
If the central value remains exactly the same (though unlikely)...

~2027



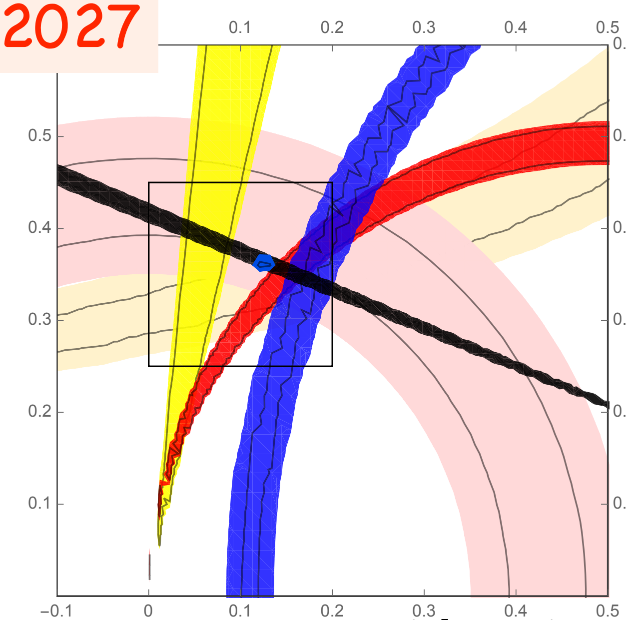
3.5σ effect (=SM???)

tree



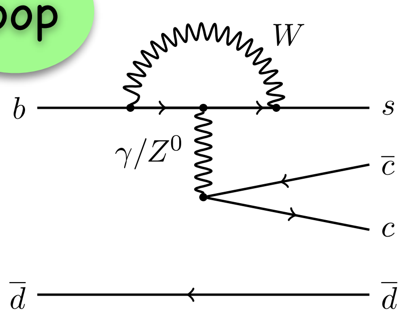
If 3 angles measurements move a little higher (within 1σ)...

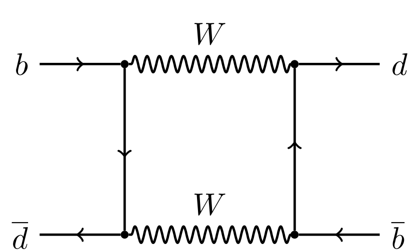
~2027



7σ effect (≠SM)!

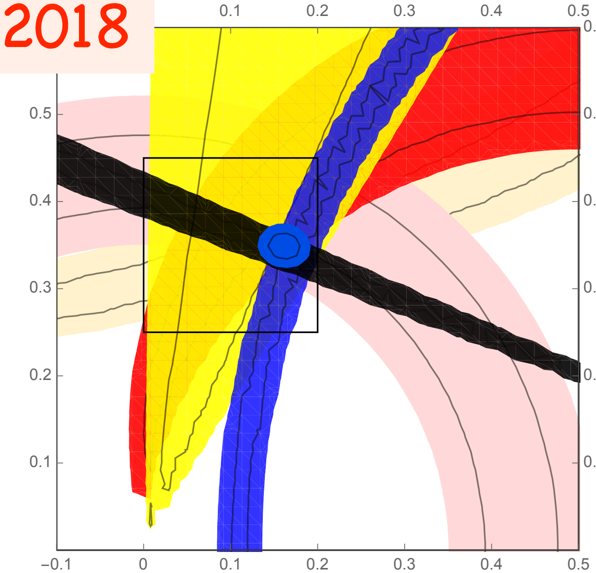
loop





Future of the Unitarity Triangle

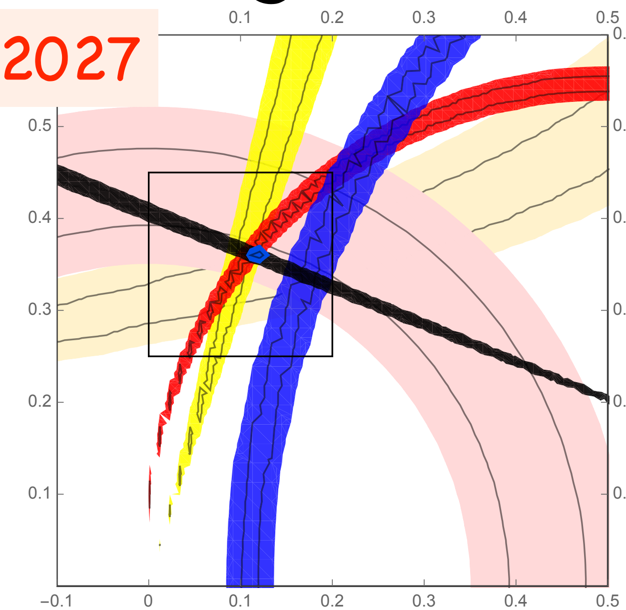
2018



Consistent with SM

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

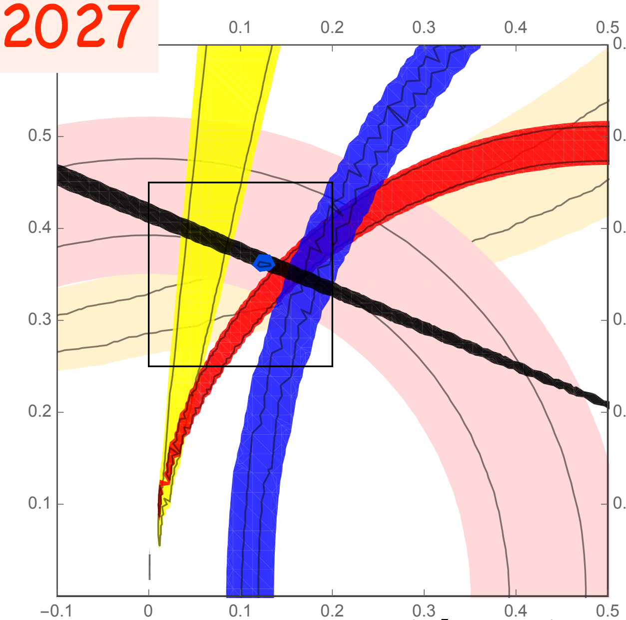
~2027



3.5σ effect (=SM???)

If 3 angles ...asurements ... a little ... within ...σ)...

~2027

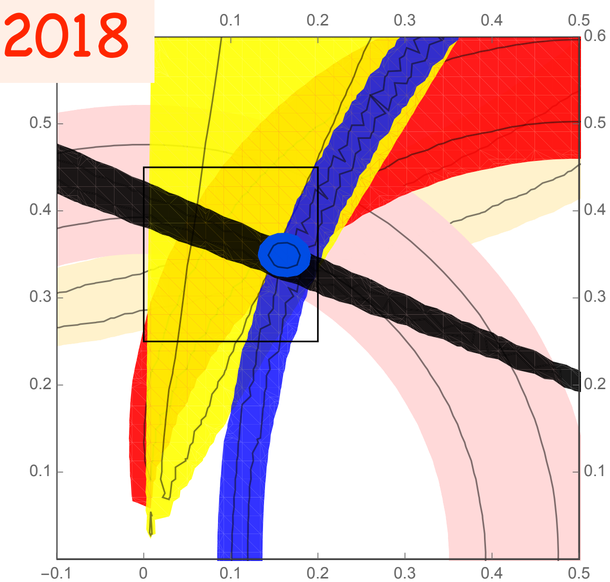


7σ effect (≠SM)!

Is this 7σ an "odd case" ???
(the answer is NO!)

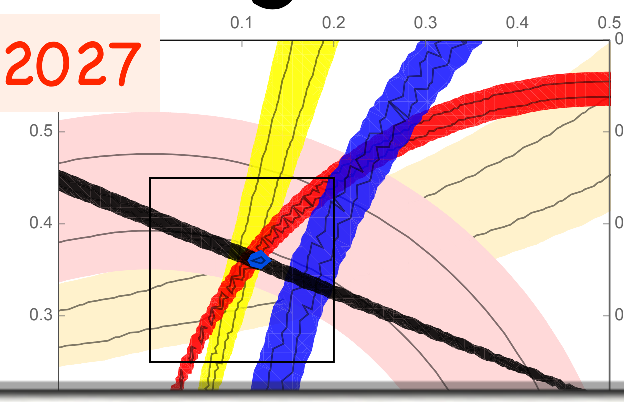
Future of the Unitarity Triangle

2018



Consistent with SM

~2027



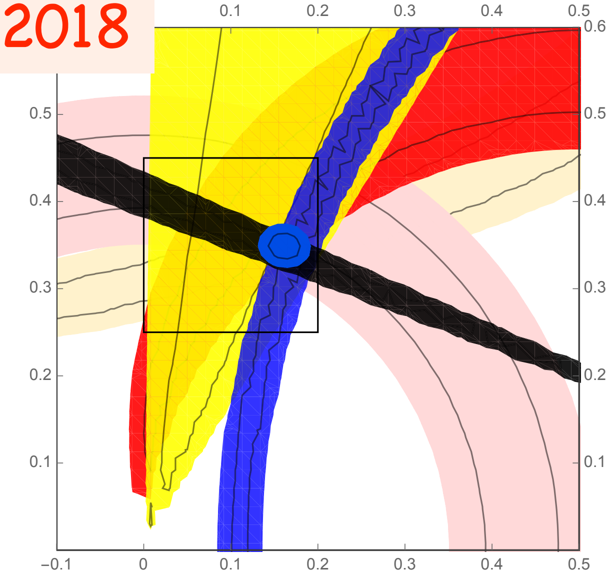
If the central value remains exactly the

- To understand this “7σ” effect better, we have run a Monte Carlo simulation.
- We randomly sample the central values (1000 trials) assuming Gaussian measurements and compute the significance.
- The result shows that **the chance to observe deviation more than 7σ significance is currently 20% !**

Is this 7σ an “odd case” ? (the answer is N

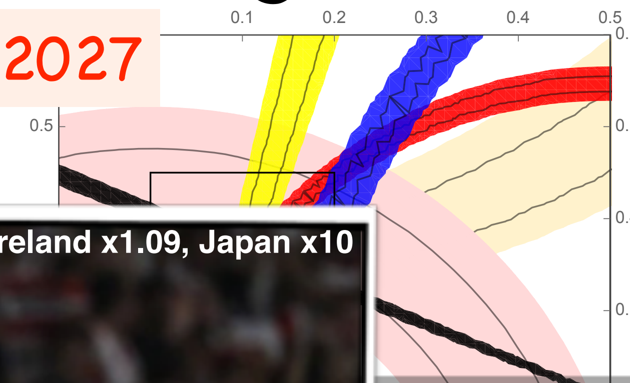
Future of the Unitarity Triangle

2018



Consistent with SM

~2027



If the central

better,

ulation.

al values

e

significance.

- The result shows that **the chance to observe deviation more than 7σ significance is currently 20% !**

Is this 7σ

an “odd case” ?

(the answer is N

Conclusions

- The coming years are very exciting for flavour physics: the startup of Belle II and the upgrades of LHCb will improve the sensitivity to new physics drastically.
- Searching new physics through CPV is legitimate: introducing a new particle induces an extra freedom for CP violating phase.
- The direct CPV in 3 body charmless B decay result is very intriguing. The amplitude analysis push forward that a deep understanding of the strong phase.
- Advancing mixing CPV measurements narrows the allowed range of new physics contributions: we are entering "precision measurement era". Global study of various observables would be useful to elucidate new physics scenarios.

Backup

Strategy II: reducing theoretical uncertainties

arXiv:1808.10567 (PTEP 2019)
Belle II Physics Book

e.g. Vub measurement from exclusive B->πlν decay
(agreement inclusive/exclusive crucial!)

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\lvert V_{ub}\rvert$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3

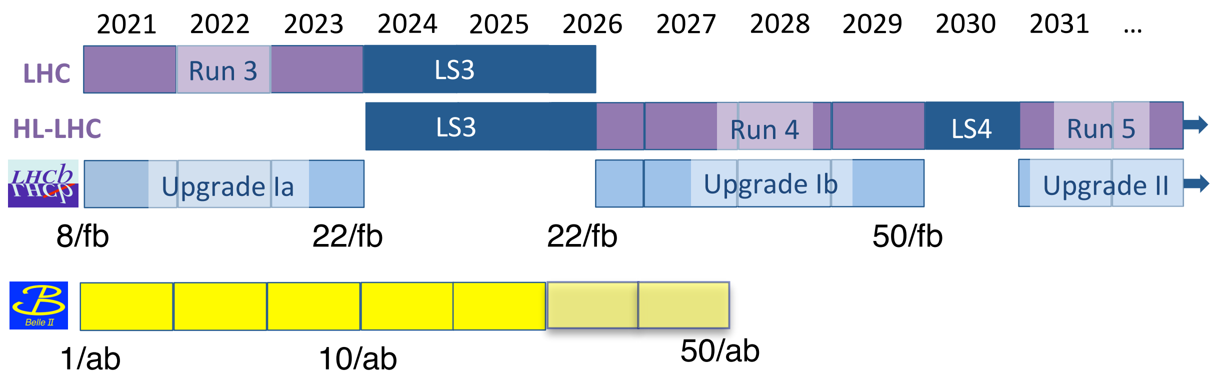
Lattice forecast

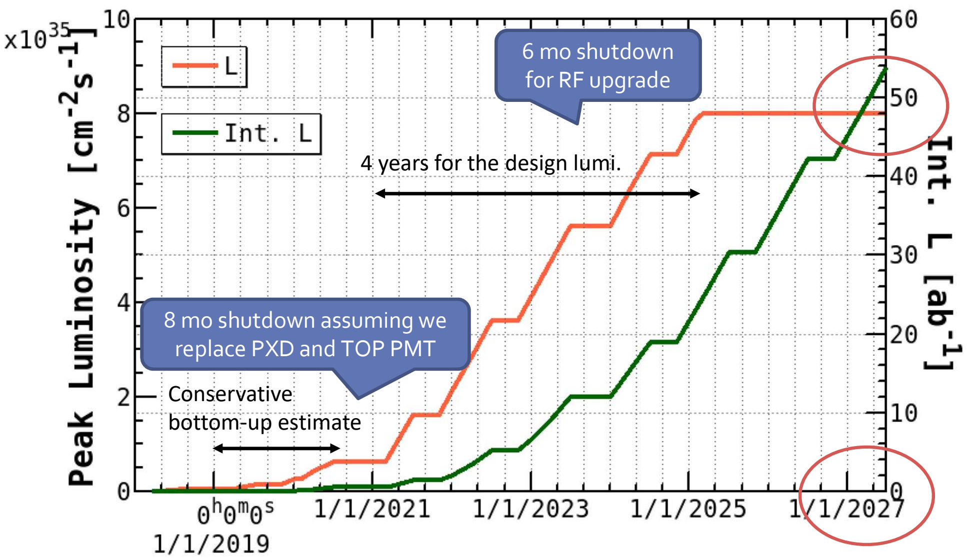
	$\mathcal{L}$ [ab^{-1}]	$\sigma_{\mathcal{B}}$ (stat, sys)	$\sigma_{\mathrm{QCD}}^{\mathrm{forecast}}$	$\sigma_{V_{ub}}$(EM)	$\sigma_{V_{ub}}$(no EM)
1	T	3.6, 4.4	current	6.2	-
	UT	1.3, 3.6		3.6	3.6
5	T	1.6, 2.7	in 5 yrs	3.2	3.0
	UT	0.6, 2.2		2.1	1.9
10	T	1.2, 2.4	in 5 yrs	2.7	2.6
	UT	0.4, 1.9		1.9	1.7
50	T	0.5, 2.1	in 10 yrs	1.7	1.4
	UT	0.2, 1.7		1.3	1.0

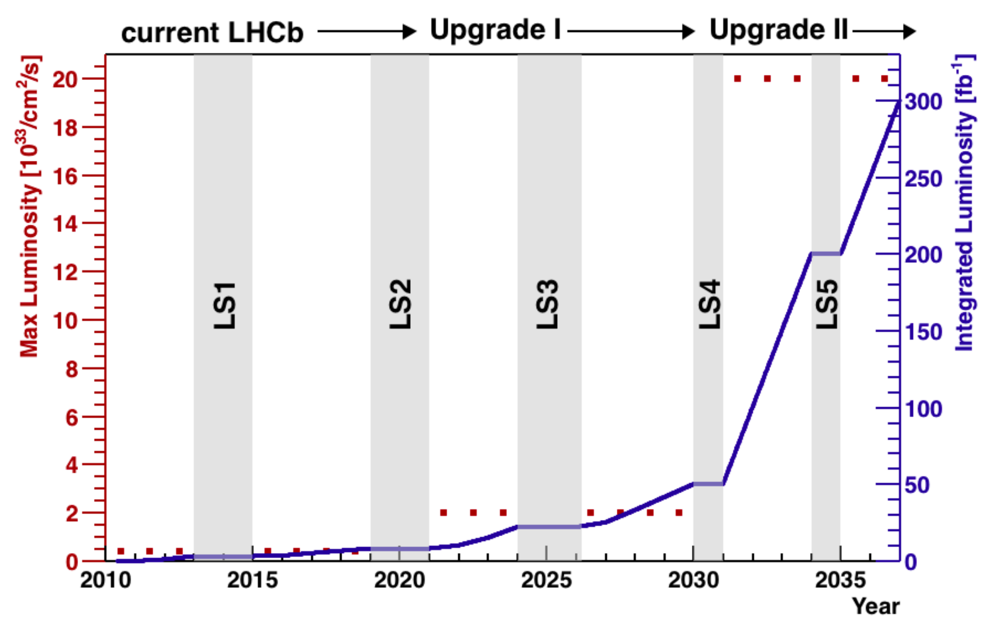
e.g. sin 2Φ_1 from b->sss penguin modes

Theory predictions depend on models. Different theoretical methods must be applied to cross check.

Mode	QCDF [662]	QCDF (scan) [662]	$SU(3)$
$\pi^0 K_S^0$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [664]
$\rho^0 K_S^0$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$	
$\eta' K_S^0$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_1)\sin\gamma$ [665]
ηK_S^0	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$	
ϕK_S^0	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_1)\sin\gamma$ [665]
ωK_S^0	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$	


2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 ...
LHC
Run 3
LS3
HL-LHC
LS3
Run 4
LS4
Run 5
Upgrade Ia
Upgrade Ib
Upgrade II
8/fb
22/fb
22/fb
50/fb
1/ab
10/ab
50/ab


x10^35
Peak Luminosity [cm^-2s^-1]
Int. L [ab^-1]
L
Int. L
6 mo shutdown for RF upgrade
4 years for the design lumi.
8 mo shutdown assuming we replace PXD and TOP PMT
Conservative bottom-up estimate
1/1/2019
1/1/2021
1/1/2023
1/1/2025
1/1/2027


current LHCb
Upgrade I
Upgrade II
Max Luminosity [10^33/cm^2/s]
Integrated Luminosity [fb^-1]
LS1
LS2
LS3
LS4
LS5
2010 2015 2020 2025 2030 2035
Year