CKM metrology at HL-LHC

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UTfit

* CKM metrology
* present status
* prospects in the hl-lhc era
* theoretical issues
* new opportunities

"Workshop on the physics of HL-LHC and perspective at HE-LHC"
CERN - 18 June 2018

CKM metrology

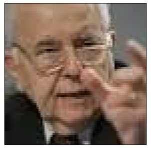
Flavour- and CP-violating quark couplings in the SM:

$$\mathcal{L}_Y^q = \bar{Q}_L Y_u u_R \tilde{\phi} + \bar{Q}_L Y_d d_R \phi + H.c.$$

10 physical parameters:

$$Y_{u,d} \xrightarrow[\text{EWSB}]{} 6\,\text{masses}\,m_q,\ 3\,\text{mixing angles}\,\theta_{ij},\ 1\,\text{CPV phase}\,\delta$$

quark masses + CKM matrix




$$V_{CKM} = \begin{pmatrix} \cos\theta_{12}\cos\theta_{13} & \sin\theta_{12}\cos\theta_{13} & \sin\theta_{13}\,e^{-i\delta} \\ -\sin\theta_{12}\cos\theta_{23} - \cos\theta_{12}\sin\theta_{13}\sin\theta_{23}\,e^{i\delta} & \cos\theta_{12}\cos\theta_{23} - \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\,e^{i\delta} & \cos\theta_{13}\sin\theta_{23} \\ \sin\theta_{12}\sin\theta_{23} - \cos\theta_{12}\sin\theta_{13}\cos\theta_{23}\,e^{i\delta} & -\cos\theta_{12}\sin\theta_{23} - \sin\theta_{12}\sin\theta_{13}\cos\theta_{23}\,e^{i\delta} & \cos\theta_{13}\cos\theta_{23} \end{pmatrix}$$

Relevant facts for CKM metrology:

- 3-generation unitarity → CPV from CPC measurements
- single CPV source → all CPV observables correlated

In principle, all one needs are 4 measurements:

1. $0^+ \to 0^+$ β decays (+ $K_{\ell 3}$) $\to |V_{ud}|$
2. semileptonic B decays with charm $\to |V_{cb}|$
3. charmless semileptonic B decays $\to |V_{ub}|$
4. $B^\pm \to D^{(*)}K^\pm$ $\to \gamma = \arg(-V_{ub}^* V_{ud} / V_{cb}^* V_{cd})$

$$\sin\theta_{13} = |V_{ub}|, \quad \cos\theta_{13} = \sqrt{1-\sin^2\theta_{13}},$$
$$\cos\theta_{12} = \frac{|V_{ud}|}{\cos\theta_{13}}, \quad \sin\theta_{12} = \sqrt{1-\cos^2\theta_{12}},$$
$$\sin\theta_{23} = \frac{|V_{cb}|}{\cos\theta_{13}}, \quad \cos\theta_{23} = \sqrt{1-\sin^2\theta_{23}},$$
$$\delta = 2\arctan\left(\frac{1 \mp \sqrt{1-(a^2-1)\tan^2\gamma}}{(a-1)\tan\gamma}\right), \quad a = \frac{\cos\theta_{12}\sin\theta_{13}\sin\theta_{23}}{\sin\theta_{12}\cos\theta_{23}}.$$

These are all tree-level constraints. Additional measurements of (loop-induced) CKM-dependent processes can:

→ improve the CKM metrology <<<<<<

(assuming that the SM is valid also at the loop level)

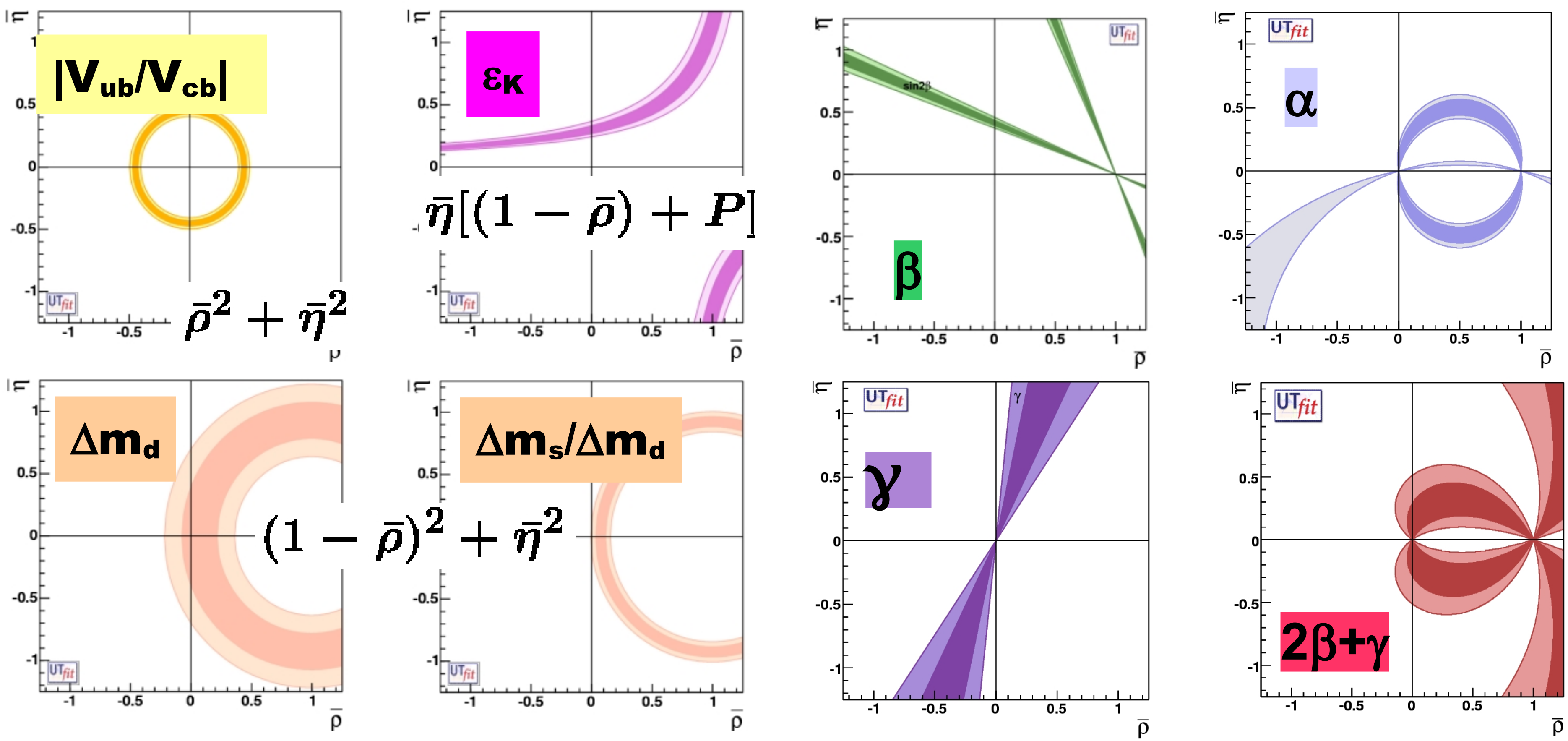
→ put upper bounds on NP contributions to loop processes

→ EFT → put lower bounds on the NP scale

Unitarity Triangle analysis

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

Constraints are graphically represented in the complex plane, where the SM predicts them to meet in one point: the apex of the (rescaled) unitarity triangle



UTA results tree-level constraints

Summer 2018 - preliminary

valid if tree-level processes are SM-like

$$R_u\, e^{i\gamma} + R_t\, e^{-i\beta} = 1$$

$R_u = 0.399 \pm 0.028$

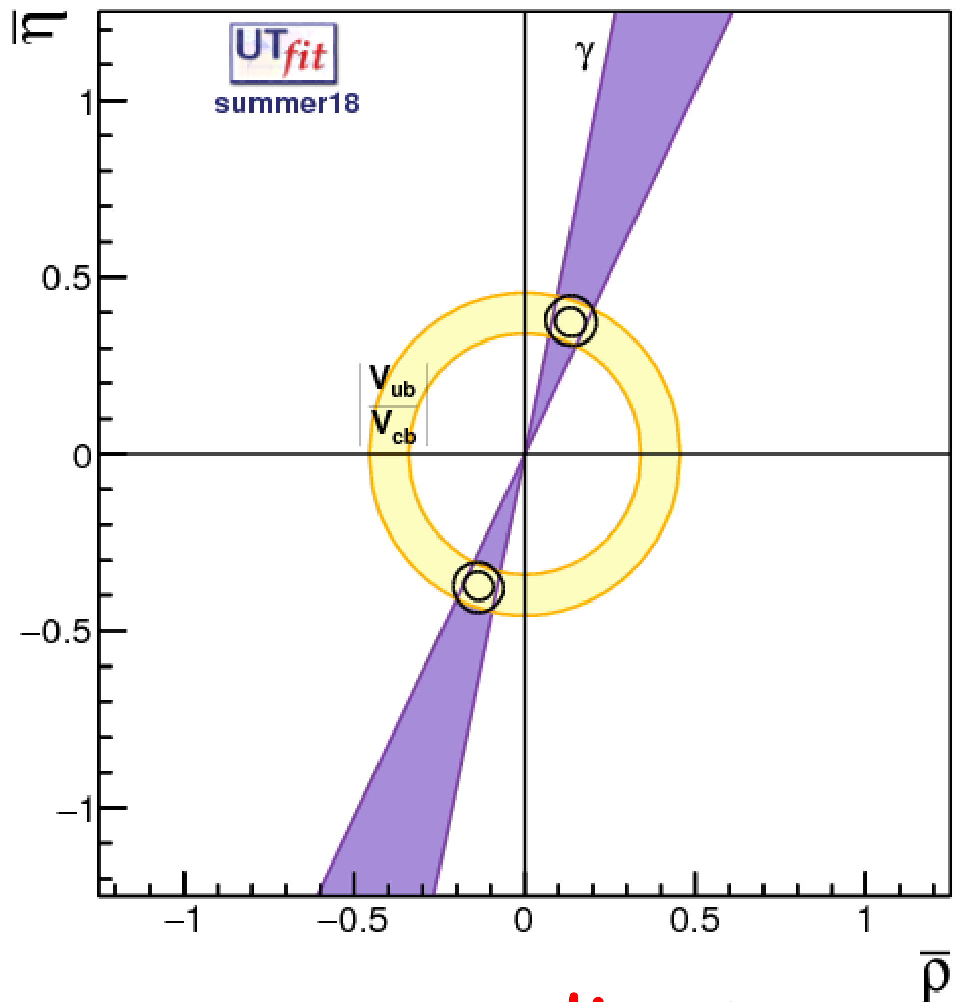
$R_t = 0.943 \pm 0.029$

$\gamma = (70.2 \pm 4.2)°$

$\beta = (23.4 \pm 1.7)°$

$\alpha = (86.5 \pm 4.5)°$

negative region excluded model independently by a_{SL}^{d} Laplace et al., hep-ph/0202010



apex coordinates

$\bar{\rho} = 0.135 \pm 0.030$

$\bar{\eta} = 0.373 \pm 0.034$

UTA results
all constraints

Summer 2018 - preliminary

<u>SM</u> determination of the Unitarity Triangle

$R_u\, e^{i\gamma} + R_t\, e^{-i\beta} = 1$

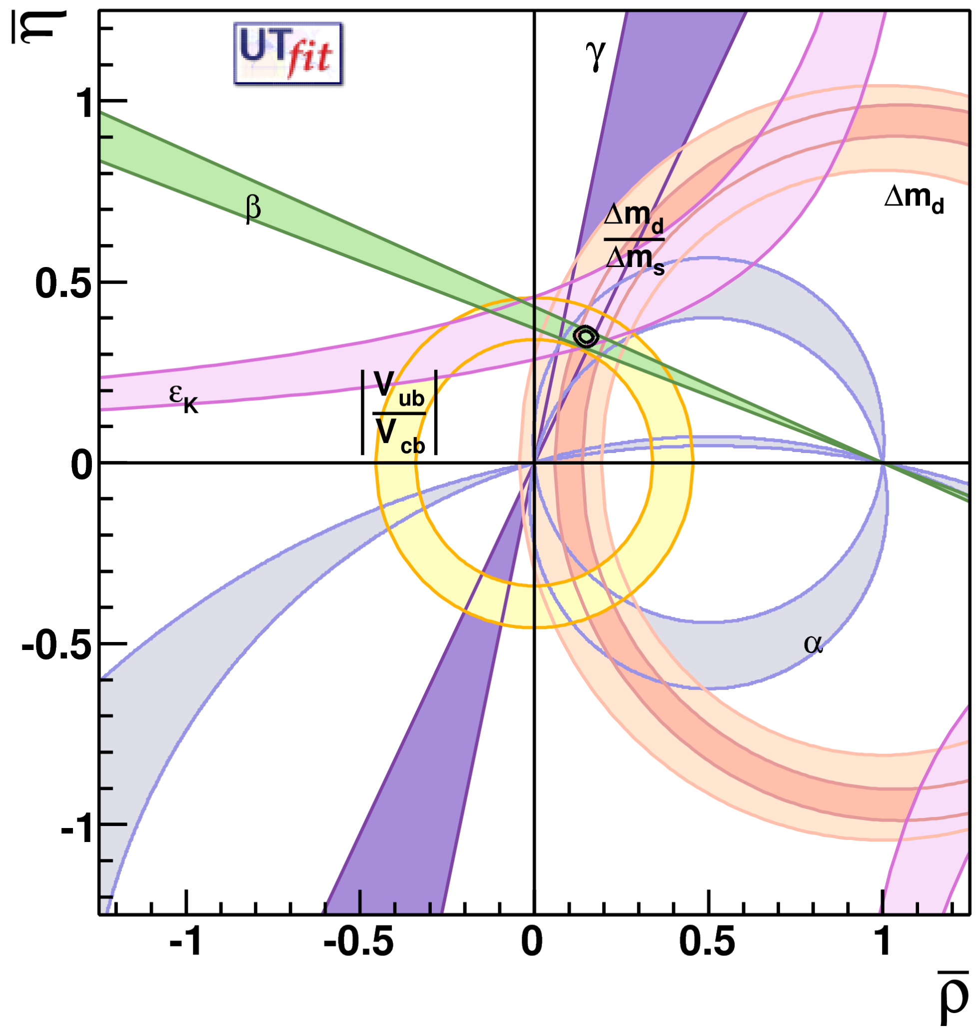
$R_u = 0.380 \pm 0.011$

$R_t = 0.920 \pm 0.013$

$\gamma = (66.8 \pm 2.0)^\circ$

$\beta = (22.25 \pm 0.65)^\circ$

$\alpha = (90.9 \pm 2.0)^\circ$



apex coordinates

$\bar{\rho} = 0.148 \pm 0.013$

$\bar{\eta} = 0.348 \pm 0.010$

The CKM matrix in the SM

$$\begin{pmatrix} 0.9743(1) & 0.2251(6) & 3.7(1)\cdot 10^{-3} e^{-i67(2)^\circ} \\ -0.2250(5)e^{i0.035(1)^\circ} & 0.9734(1)e^{-i0.00188(5)^\circ} & 4.24(7)\cdot 10^{-2} \\ 8.7(1)\cdot 10^{-3} e^{-i22.2(6)^\circ} & -4.12(6)\cdot 10^{-2} e^{i1.06(3)^\circ} & 0.99911(2) \end{pmatrix}$$

Standard parametrization (PDG)

$\sin\Theta_{12} = 0.2250 \pm 0.001$ $\sin\Theta_{23} = (4.20 \pm 0.06)\cdot 10^{-2}$

$\sin\Theta_{13} = (3.68 \pm 0.10)\cdot 10^{-3}$ $\delta = (66.9 \pm 2.0)^\circ$

Wolfenstein parametrization

$\lambda = 0.2254 \pm 0.0007$ $A = 0.826 \pm 0.012$

$\rho = 0.152 \pm 0.014$ $\eta = 0.357 \pm 0.010$

SM predictions

	Measurement	%	Prediction	Pull(σ)
$\sin 2\beta$	0.689 ± 0.023	3.3	0.738 ± 0.033	+1.2
γ	$(70.8\pm7.8)^\circ$	11	$(65.8\pm2.2)^\circ$	< 1
α	$(90.9\pm8.0)^\circ$	8.8	$(91.1\pm2.2)^\circ$	< 1
β_s	$(0.60\pm0.88)^\circ$	150	$(1.06\pm0.03)^\circ$	< 1
$\lvert V_{cb}\rvert\cdot10^3$	40.5 ± 1.1	2.7	42.4 ± 0.7	+1.5
$\lvert V_{ub}\rvert\cdot10^3$	3.72 ± 0.23	6.2	3.66 ± 0.11	< 1
$\lvert\varepsilon_K\rvert\cdot10^3$	2.228 ± 0.011	0.5	1.88 ± 0.20	-1.5
$\Delta m_s[ps^{-1}]$	17.757 ± 0.021	0.1	17.25 ± 0.85	< 1

Prospects for the HL-LHC era

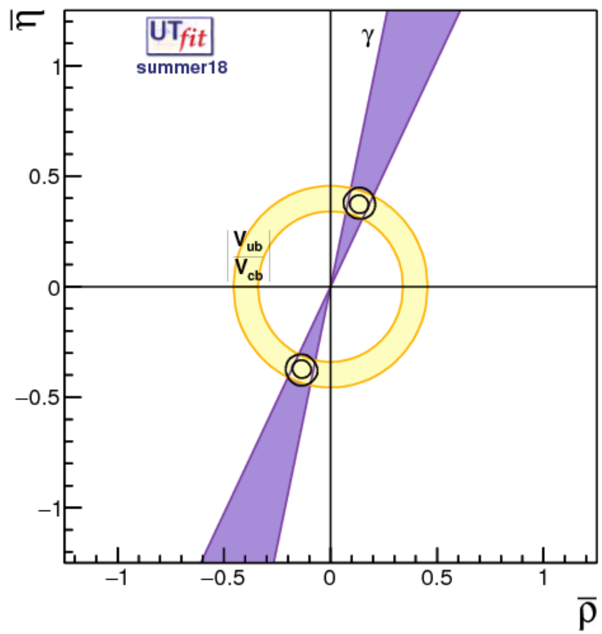
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]

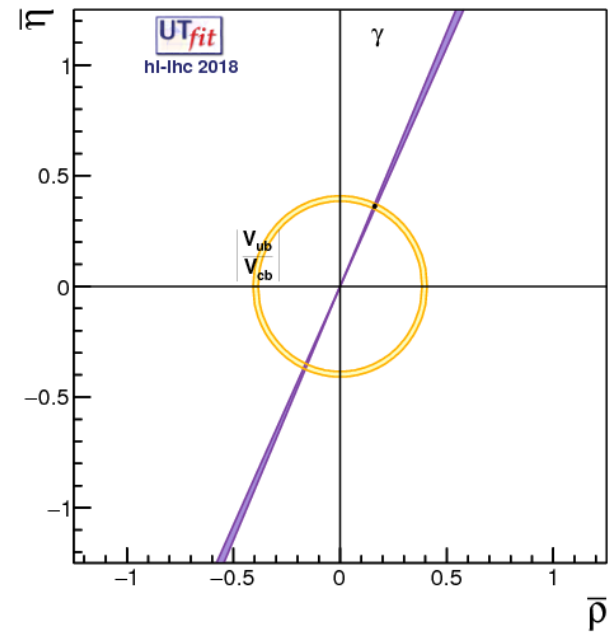
Tarantino, What next - CSN1

Parameter	Error				
	Now	50/fb	300/fb	1000/fb	3000/fb
ΔM_d [ps^{-1}]	0.002	0.0005	0.0002	0.0001	0.00006
ΔM_s [ps^{-1}]	0.021	0.005	0.002	0.001	0.0006
α [°]	5.5	1	Belle II		
V_{cb}	2.7%	1%	Belle II		
V_{ub}	10%	1%	Belle II		
$\alpha_s(M_Z)$	0.0005	0.0002			
m_t	760 MeV	250 MeV	theory limited		
m_b	50 MeV	10 MeV			

Hadronic Parameter	What Next Era (2025)
$f_+^{K\pi}(0)$	0.1%
B_K	0.1 – 0.5%
f_{B_s}	0.5%
f_{B_s}/f_B	0.5%
B_{B_s}	0.5 – 1%
B_{B_s}/B_B	0.5 – 1%
$F_{D^*}(1)$	0.5%
$B \to \pi$	$\geq 1\%$

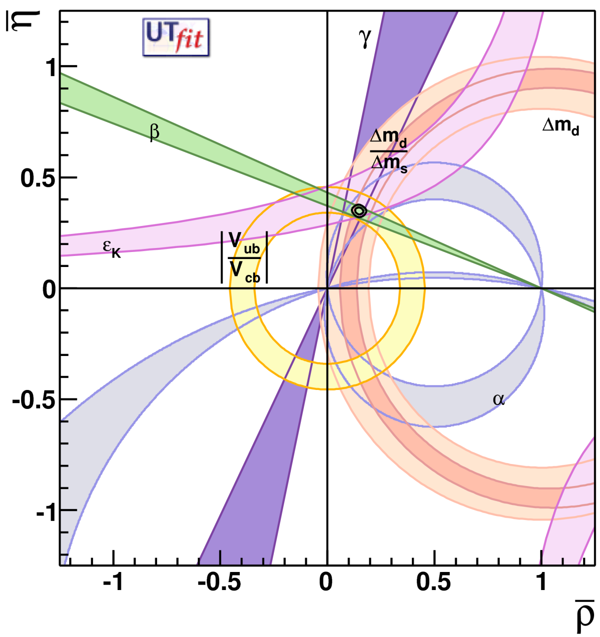
Tree-level constraints

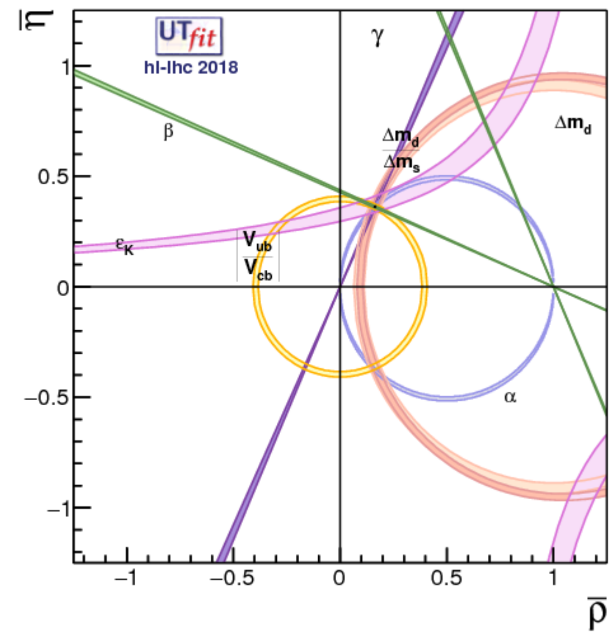




$\delta\bar{\rho}/\bar{\rho} = 22\%$	$\delta\bar{\rho}/\bar{\rho} = 2\%$
$\delta\bar{\eta}/\bar{\eta} = 9\%$	$\delta\bar{\eta}/\bar{\eta} = 0.8\%$
$\delta\alpha/\alpha = 5\%$	$\delta\alpha/\alpha = 0.4\%$
$\delta\beta/\beta = 7\%$	$\delta\beta/\beta = 0.8\%$
$\delta\gamma/\gamma = 6\%$	$\delta\gamma/\gamma = 0.5\%$

SM UTA





$\delta\bar{\rho}/\bar{\rho}$ = 9% | $\delta\bar{\rho}/\bar{\rho}$ = 0.8%

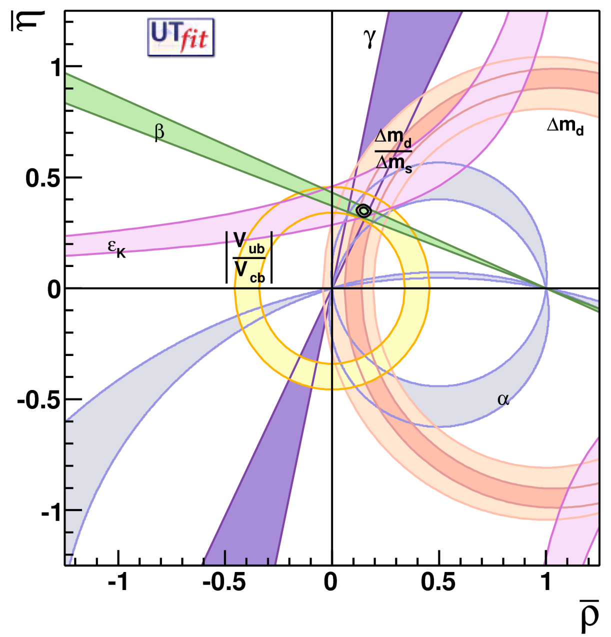
$\delta\bar{\eta}/\bar{\eta}$ = 3% | $\delta\bar{\eta}/\bar{\eta}$ = 0.3%

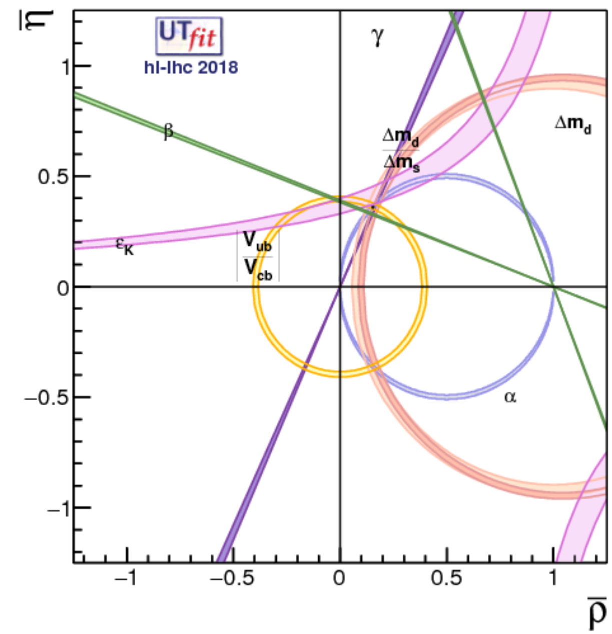
$\delta\alpha/\alpha$ = 2% | $\delta\alpha/\alpha$ = 0.1%

$\delta\beta/\beta$ = 3% | $\delta\beta/\beta$ = 0.4%

$\delta\gamma/\gamma$ = 3% | $\delta\gamma/\gamma$ = 0.1%

SM UTA





$\delta\bar{\rho}/\bar{\rho}$ = 9%

$\delta\bar{\eta}/\bar{\eta}$ = 3%

$\delta\alpha/\alpha$ = 2%

$\delta\beta/\beta$ = 3%

$\delta\gamma/\gamma$ = 3%

NP dream scenario

CKM metrology back to tree-level constraints

Theoretical issues

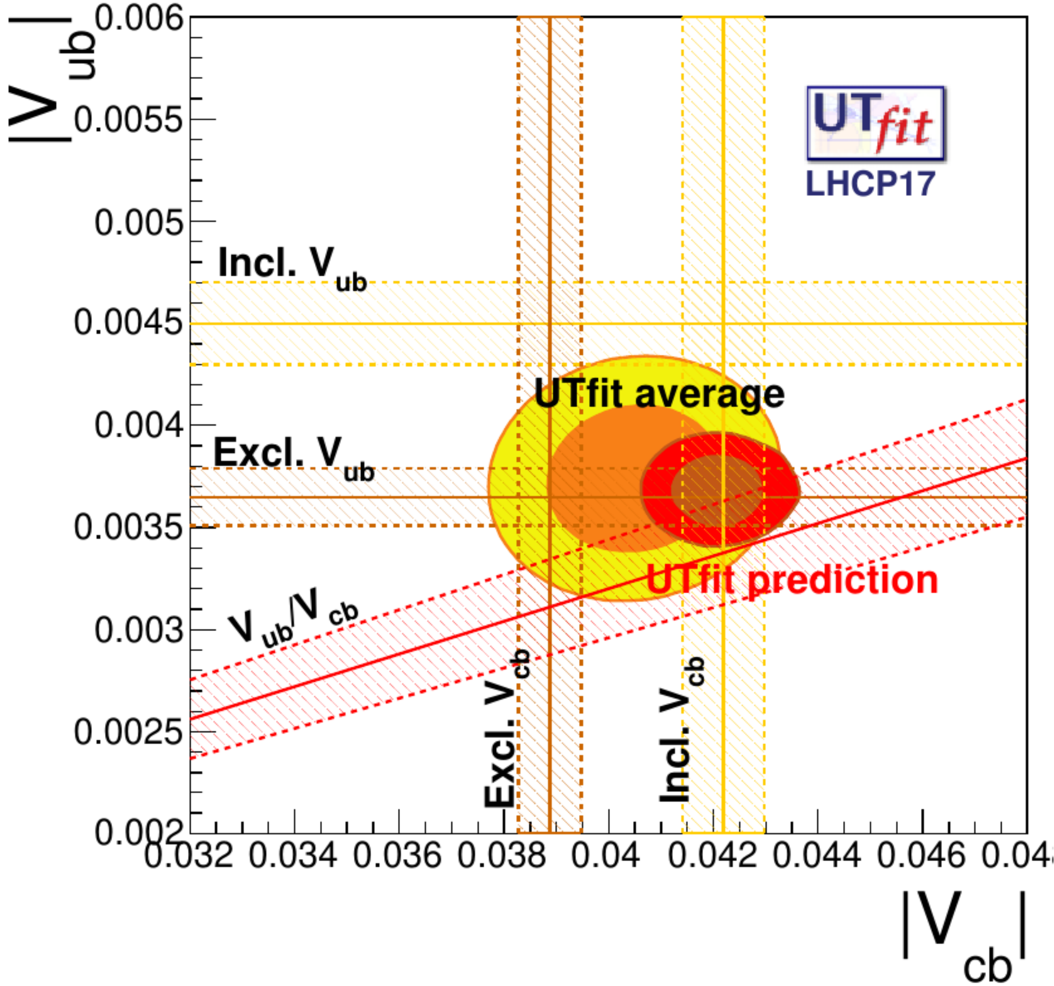
QUITE A FEW!

In the sub-percent era, many solid approximations used so far to compute hadronic amplitudes can't be relied on anymore (e.g. isospin symmetry, no QED corrections, no subleading amplitudes, no higher-dimensional operators, etc.)

Good news: the tree-level determination of γ from $B \to DK$ (GLW, ADS, GGSZ) safely extrapolates to the high precision. D mixing is manageble and EW corrections are still negligible

Brod, Zupan, arXiv:1308.5663

The other tree-level constraints from semileptonic B decays are in less good shape: the long-standing disagreement between incl. and excl. measurements is still there, but there are promising new developments



CLN parametrization of the $B \to D^*$ FF's uses HQ relations which may be responsible for the $|V_{cb}|$ discrepancy.
Still inconclusive, but…

Grinstein, Kobach, arXiv:1703.08170
Bigi, Gambino, Schacht, arXiv:1703.0612

New attempts at computing FF's on the lattice at small q^2

Martinelli et al., in progress

Loop-level constraints: th. prospects

→ Δm_d and Δm_s: decay constants and B parameters @1% call for QED corrections

→ ε_K: QED corrections, long-distance contributions, dimension-8 operators need to be controlled RBC-UKQCD MC et al., in progress

→ α: isospin breaking Gronau, Zupan, hep-ph/0502139 Charles et al., arXiv:1705.02981

→ β: subleading amplitude $A(B^0 \to J/\psi K) = V_{cb}^* V_{cs} T + \boxed{V_{ub}^* V_{us} P}$ bound using SU(3)-related b→d decays $B_s \to J/\psi K_S$ and $B \to J/\psi \pi^0$ where the 2nd term is not Cabibbo suppressed
th. error scales with the ones on control channels & matches the measurement accuracy Fleischer, hep-ph/9903455 MC et al., hep-ph/0507290, ... De Bruyn, Fleischer, arXiv:1412.6834

→ β_s: same as β, but trickier (larger effect, ϕ is not a pure octet, ...). Still likely controllable De Bruyn, Fleischer, arXiv:1412.6834

New opportunities

High statistics and high precision also provide new opportunities for CKM metrology

For example:

Parameters	$B_s^0 \to D_s^\mp K^\pm$ 23 fb^{-1}	$B_s^0 \to D_s^\mp K^\pm$ 300 fb^{-1}	$B^0 \to D^\mp \pi^\pm$ 23 fb^{-1}	$B^0 \to D^\mp \pi^\pm$ 300 fb^{-1}
S_f, $S_{\bar{f}}$	0.043	0.011	0.0041	0.0010
$A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$	0.065	0.016	–	–
C_f	0.030	0.007	–	–

* β from $2\beta+\gamma$ and γ less precise than β from $B \to J/\psi\, K$, but free from subdominant penguin amplitudes and $\Delta F=1$ NP

* $|V_{ts}|/|V_{td}|$ from $BR(B_s \to \mu\mu)$ / $BR(B_d \to \mu\mu)$ less effective than $\Delta m_s / \Delta m_d$, but affected by different NP, $\Delta F=1$ instead of $\Delta F=2$

Conclusions

* CKM metrology still has a bright future ahead: tree-level constraints alone can provide a sub-percent determination of the CKM matrix, unleashing the full NP-constraining power of the loop observables

* Hadronic uncertainties seem controllable at the required level in many cases, but we need to revamp our toolbox and possibly develop some new tool: we are on the way, yet the devil is in the details…

A hard work, but hopefully rewarding, is ahead of both theorists and experimentalists

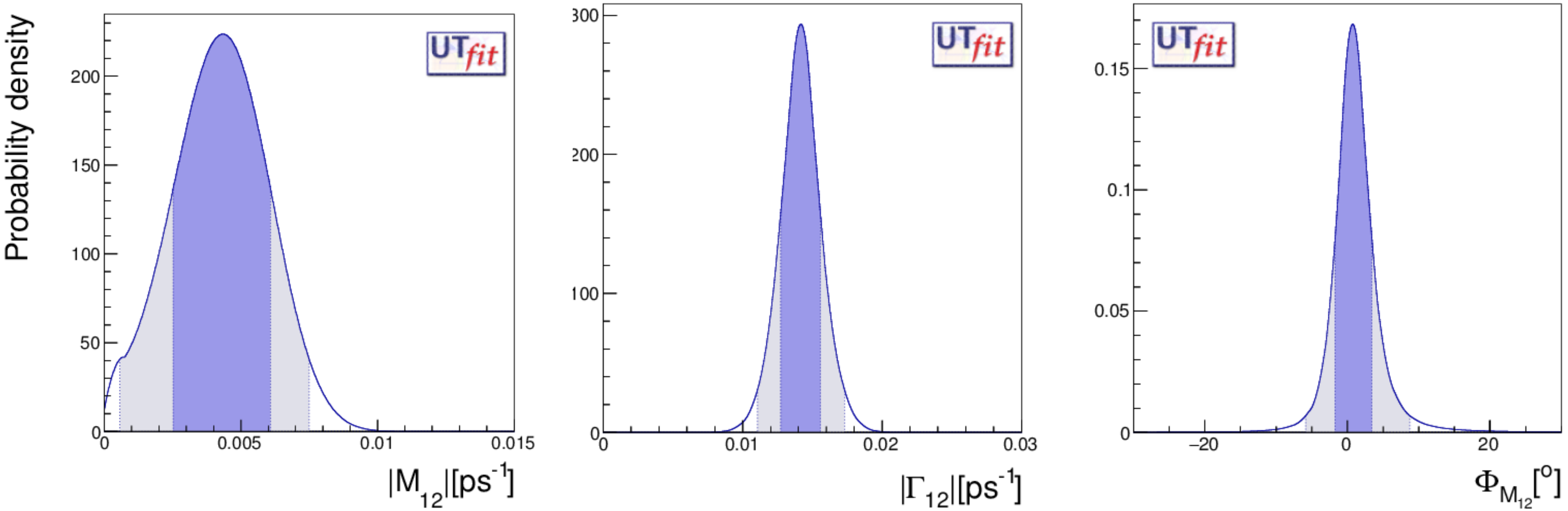
Backup

CPV in D mixing: today

- From a global analysis of D mixing data we extract the mixing parameters:

$$|M_{12}| = (4 \pm 2)/\text{fs},\ |\Gamma_{12}| = (14 \pm 1)/\text{fs}$$

$$\text{and } \Phi_{12} = (0 \pm 3)^\circ \ \ ([-6,9]^\circ \text{ @ } 95\% \text{ prob.})$$



CPV in D mixing: extrapolation

CPV contributions to Γ_{12} enhanced by $1/\varepsilon$:

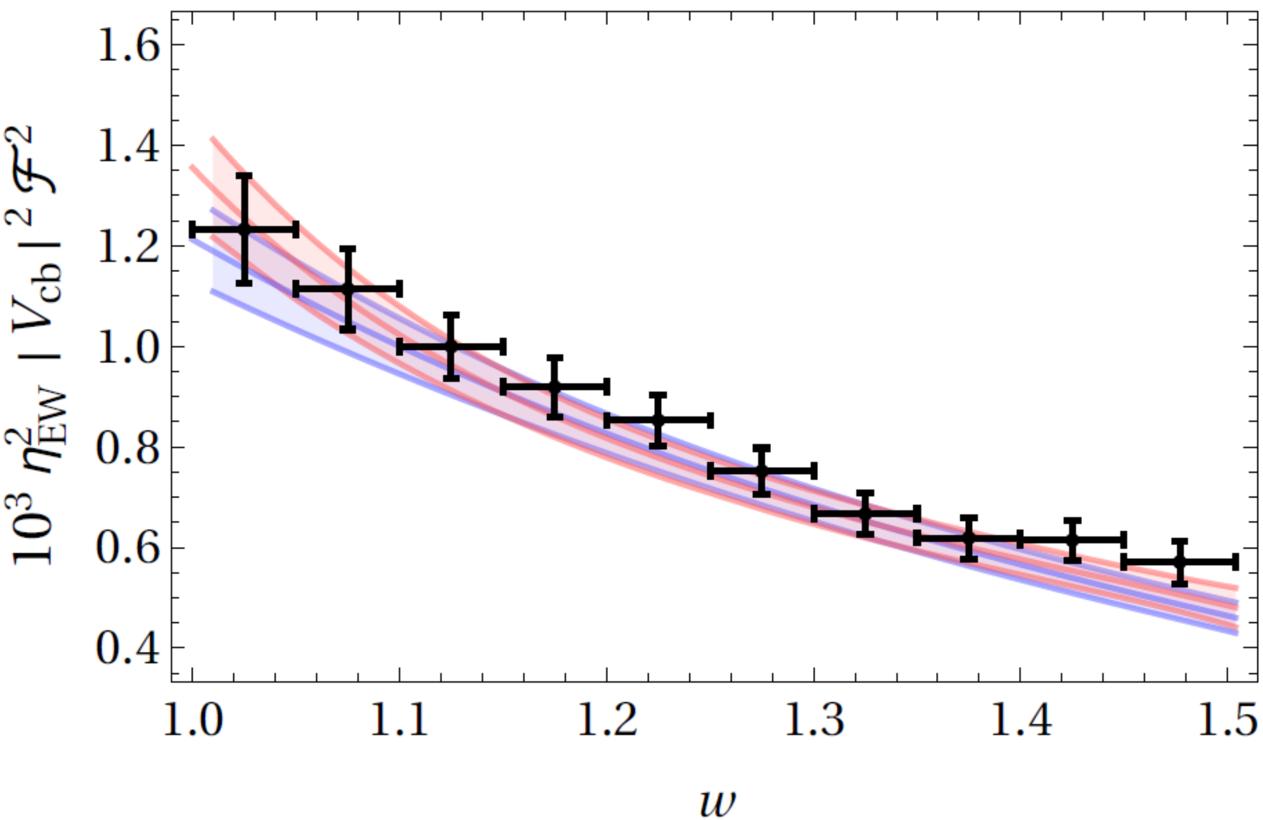
$\lambda_s^2\,\varepsilon^2 + \lambda_s\lambda_b\varepsilon$

can go beyond the "real SM" approximation by adding one universal phase $\phi_{\Gamma12}$ and fitting for ϕ_{M12} and $\phi_{\Gamma12}$

w. 300/fb expect $\delta x \sim 5\ 10^{-5}$, $\delta y \sim 3\ 10^{-5}$, $\delta|q/p| \sim 3\ 10^{-3}$, $\delta\phi \sim 1°$, $\delta A_\Gamma \sim 10^{-5}$

get $\delta\Phi_{M12} \sim 0.1°$ and $\delta\Phi_{\Gamma12} \sim 0.4°$

Bigi, Gambino, Schacht, arXiv:1703.0612



BGL Fit:	Data + lattice	Data + lattice + LCSR	Data + lattice	Data + lattice + LCSR
unitarity	weak	weak	strong	strong
χ^2/dof	28.2/33	32.0/36	29.6/33	33.1/36
$\lvert V_{cb}\rvert$	0.0424 (18)	0.0413 (14)	0.0415 (13)	$0.0406\,(^{+12}_{-13})$
$a_0^{A_1}$	0.01218(16)	0.01218(16)	0.01218(16)	0.01218(16)
$a_1^{A_1}$	$-0.053\,(^{+56}_{-44})$	$-0.052\,(^{+25}_{-14})$	$-0.046(^{+34}_{-18})$	$-0.029(^{+21}_{-13})$
$a_2^{A_1}$	$0.2\,(^{+8}_{-12})$	$0.99\,(^{+0}_{-46})$	$0.48(^{+2}_{-92})$	$0.5(^{+0}_{-3})$
$a_1^{A_5}$	$-0.0101\,(^{+59}_{-55})$	$-0.0072\,(^{+52}_{-50})$	$-0.0063(^{+36}_{-11})$	$-0.0051(^{+49}_{-13})$
$a_2^{A_5}$	0.12 (10)	$0.092\,(^{+92}_{-95})$	$0.062(^{+4}_{-64})$	$0.065\,(^{+9}_{-89})$
$a_0^{V_4}$	$0.011\,(^{+10}_{-8})$	$0.0286\,(^{+55}_{-36})$	$0.0209(^{+44}_{-0})$	$0.0299(^{+53}_{-35})$
$a_1^{V_4}$	$0.7\,(^{+3}_{-4})$	$0.08\,(^{+8}_{-22})$	$0.33(^{+4}_{-17})$	$0.04(^{+7}_{-20})$
$a_2^{V_4}$	$0.7\,(^{+2}_{-17})$	$-1.0\,(^{+20}_{-0})$	$0.6(^{+2}_{-13})$	$-0.9(^{+18}_{-0})$

EXTRAPOLATING LATTICE

Sector	$\varepsilon = 1\%$	$\varepsilon = 0.5\%$	$\varepsilon = 0.1\%$
π/K	0.5	15	$4 \cdot 10^4$
D	20	$7 \cdot 10^2$	$2 \cdot 10^6$
D_s	0.2	2	$5 \cdot 10^2$
B	10^3	-	-
B_s	20	$4 \cdot 10^2$	$3 \cdot 10^5$

Hadronic Parameter	What Next Era (2025)
$f_+^{K\pi}(0)$	0.1%
B_K	0.1 – 0.5%
f_{B_s}	0.5%
f_{B_s}/f_B	0.5%
B_{B_s}	0.5 – 1%
B_{B_s}/B_B	0.5 – 1%
$F_{D^*}(1)$	0.5%
$B \to \pi$	$\geq 1\%$

- Estimate the computational cost in Pflops*years of a given accuracy in LQCD
- Predict the accuracy in 2025 assuming that 100/500 Pflops*years will be available