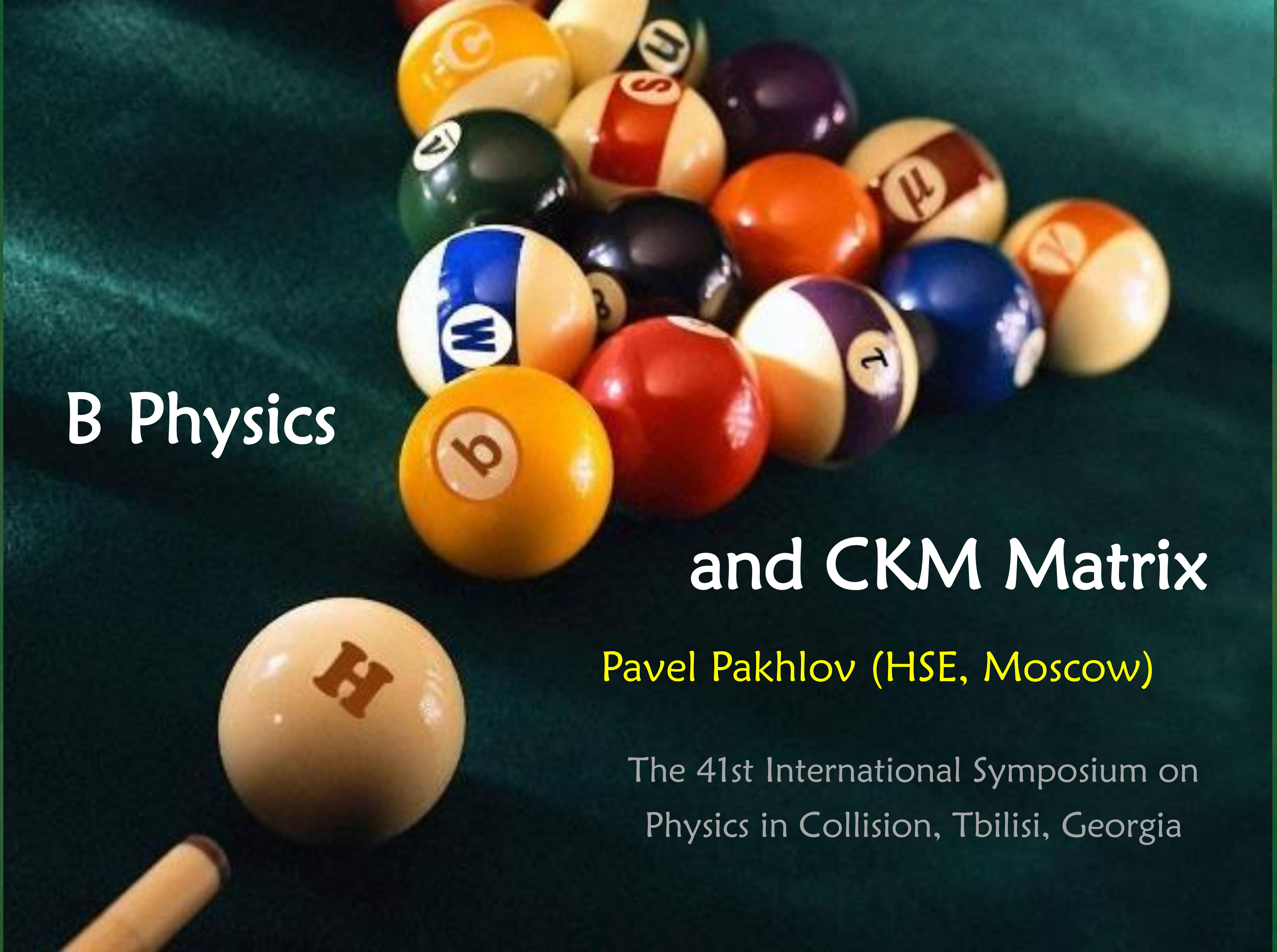
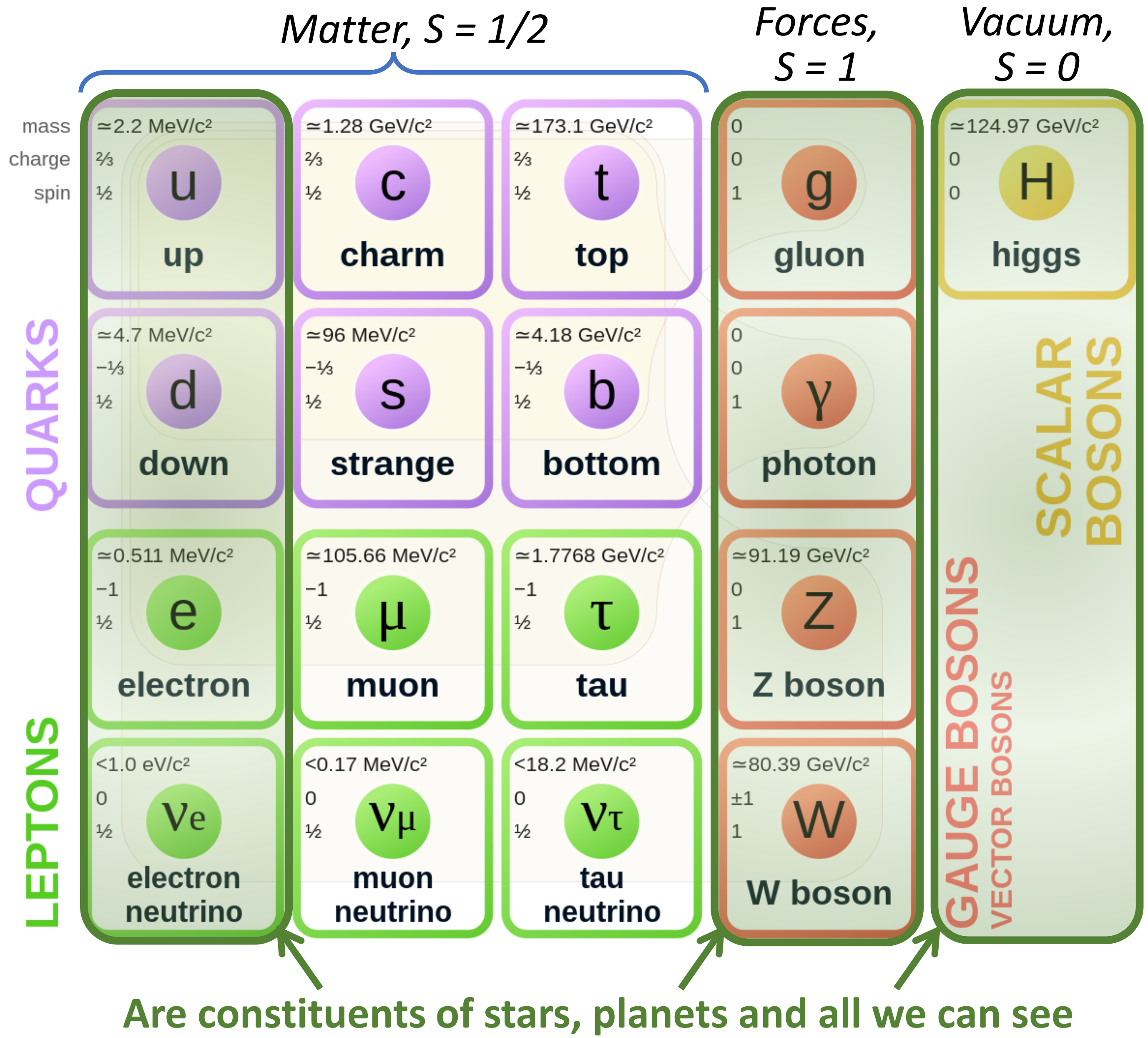


B Physics and CKM Matrix

Pavel Pakhlov (HSE, Moscow)

The 41st International Symposium on Physics in Collision, Tbilisi, Georgia

Standard Model



Three sectors: fermions (spin $= {}^{1}/_{2}$), gauge bosons ($S = 1$) and scalar fields ($S = 0$);

P. Maupertuis:
God is not a craftsman (mechanic) and governs the world not with equations, but with principles

SM: Lorentz and gauge invariance allows to derive almost all Lagrangian terms… ALMOST ALL, but no ALL!

Some extra important principle

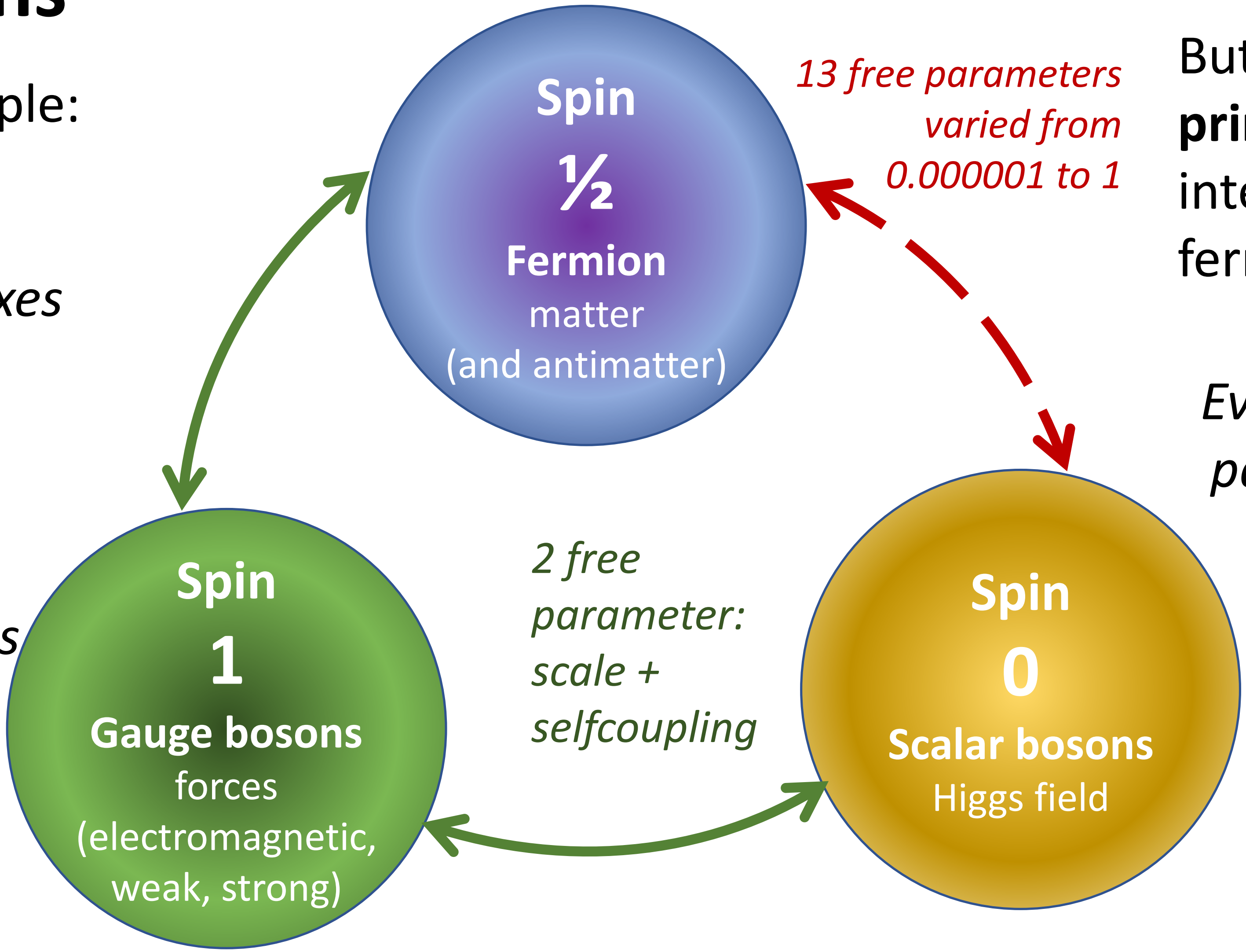
related to CKM

still successfully avoided our understanding.

SM interactions

Important SM principle:
gauge invariance

Gauge invariance fixes all interaction of gauge bosons: selfinteraction and interaction with fermions and scalars



3 free coupling constants ~ 1

But there is **no known principle** on interaction between fermions and scalar

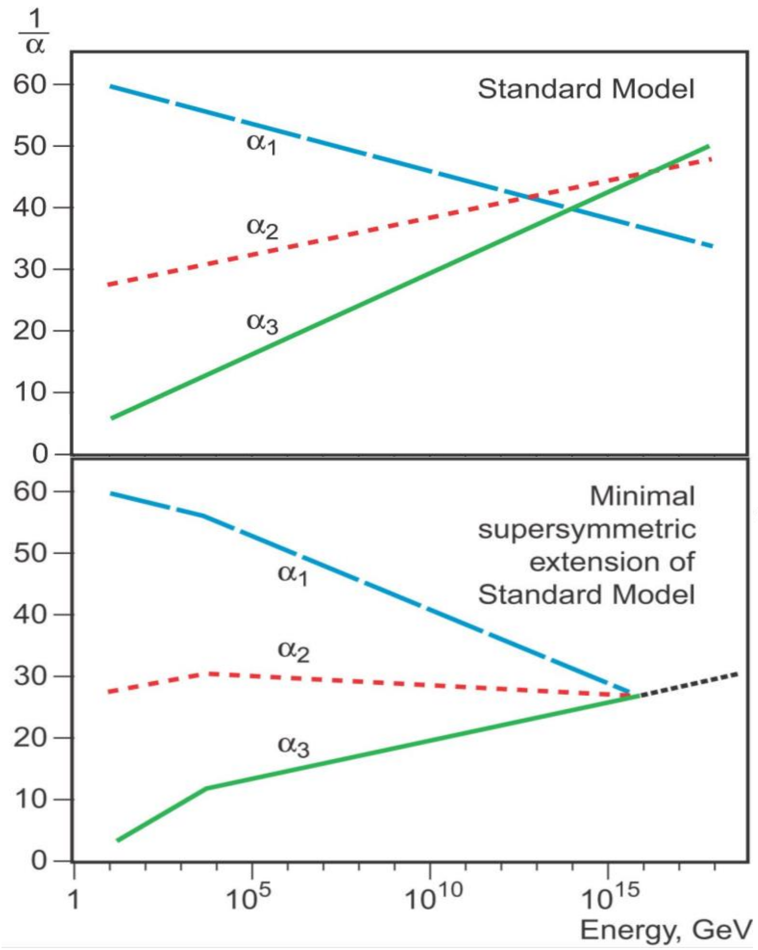
Even knowing all the parameters of these interactions with high accuracy, we cannot guess the principle.

SM is really built on few keystone principles, but we haven't grasped some principles yet. This is not the SM problem – this is likely a problem of lack of our creativity…

Parameters of the Standard Model

- 3 gauge couplings (of the same order ~1, moreover, they are running and seem to be trending to the same value)
- 2 Higgs parameters (one is scaling parameter – we can't avoid this, another is selfcoupling ~1)
- 6 quark masses
- CKM: 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

= 18 (+7)



after 50 years of thinking, we still have no ideas.

() = with Dirac neutrino masses

Fermion interactions

$$\mathcal{L} = \cdots - \underbrace{\sum_{i,j=1}^{3}\left[Y_U^{ij}\overline{U'}_R^i\phi^\dagger\begin{pmatrix}U'^j_L\\D'^j_L\end{pmatrix} + Y_D^{ij}\overline{D'}_R^i\phi^T i\sigma_2\begin{pmatrix}U'^j_L\\D'^j_L\end{pmatrix}\right]}_{\text{with Higgs field}} + \underbrace{\frac{g}{\sqrt{2}}\sum_{i=1}^{3}\left(\overline{U'}_L^i\,\overline{D'}_L^i\right)\gamma^\mu\begin{pmatrix}0 & W_\mu^+\\W_\mu^- & 0\end{pmatrix}\begin{pmatrix}U'^i_L\\D'^i_L\end{pmatrix}}_{\text{with W-bosons}} + \cdots$$

Two 3×3 arbitrary complex matrices!

$9\cdot 2\cdot 2 = 36$ free parameters?

Fortunately, many parameters are unphysical!

Mass basis

$$U'^i_L \to U^i_L = (L_U U'_L)^i,\quad U'^i_R \to U^i_R = (R_U U'_R)^i$$

$$\left(L_U Y_U R_U^\dagger\right)^{ij}\langle\phi^0\rangle = \hat{Y}_U^{ii}\delta^{ij}\langle\phi^0\rangle$$

diagonal

$3+3$ free parameters: masses

$$\frac{g}{\sqrt{2}}\sum_{i,j=1}^{3}\left(\overline{U}_L^i\,\overline{D}_L^i\right)\gamma^\mu V_{CKM}^{ij}\begin{pmatrix}0 & W_\mu^+\\W_\mu^- & 0\end{pmatrix}\begin{pmatrix}U^i_L\\D^i_L\end{pmatrix}$$

$$V_{CKM}^{ij} = \left(L_U L_D^\dagger\right)^{ij}$$

4 free parameters: CKM mixing

$3+3+4=10$ is much better than 36 but worse than 0 (expected for ToE)

Flavour physics

***Aristotle: Nature Does Nothing In Vain* (NDNIV)**

We used almost the entire contents of the SM particle table to build the World, but two fermion generations (and all antifermions) remain unused…

As for the macroscopic role of the particles of the second and the third generations, it seems at first glance trifling. These particles resemble the rough sketches, which the Creator has thrown out as unsuccessful, and which we with our sophisticated equipment dug in his wastebasket. Now we are starting to understand that these particles play an important role in the first moments of the Big Bang…

Lev Okun

CP violation

CP violation is necessary for evolution of matter dominated universe, from symmetric initial state (A. Sakharov, 1967).

Nature chosen an expensive way to remove (life-threatening) antimatter (Why even create it then?) using two extra quark's generation. CP violation through the complex quark mixing (M. Kobayashi & T. Maskawa, 1972).

$$|V_{CKM}| = \begin{pmatrix} 0.9740 & 0.2265 & 0.0036 \\ 0.2264 & 0.9732 & 0.0405 \\ 0.0085 & 0.0398 & 0.9992 \end{pmatrix} \pm \begin{pmatrix} 0.0001 & 0.0005 & 0.0001 \\ 0.0005 & 0.0001 & 0.0008 \\ 0.0002 & 0.0008 & 0.0000 \end{pmatrix}$$

Almost identity

Almost diagonal

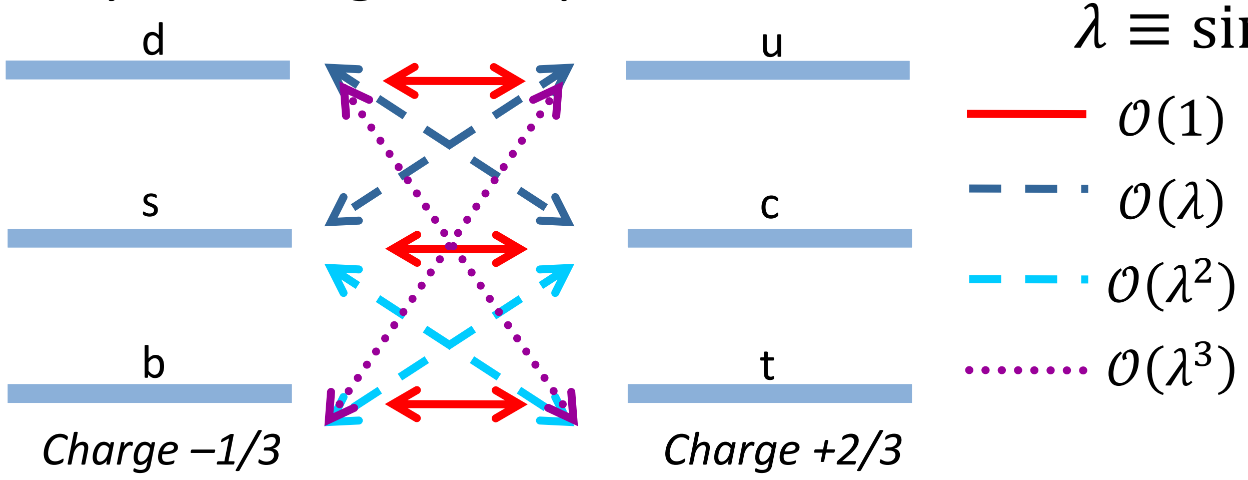
Almost symmetric

$$J_{CP} = \left|\mathrm{Im}\left(V_{i\alpha} V_{j\beta} V^*_{i\beta} V^*_{j\alpha}\right)\right| = (2.96^{+0.20}_{-016}) \times 10^{-5}$$

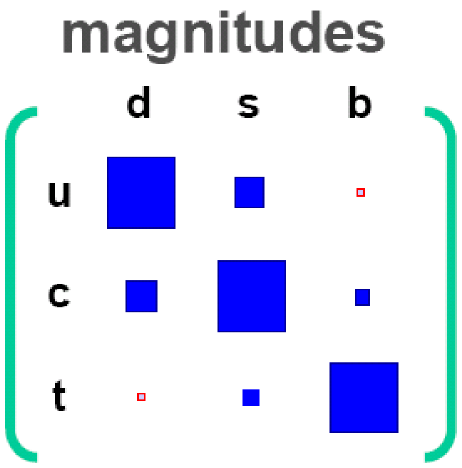
CPV is tiny in CKM; it is not enough to produce BAU

Wolfenstein parameterization

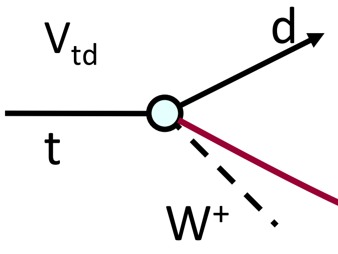
Hierarchy of strengths of quark transitions



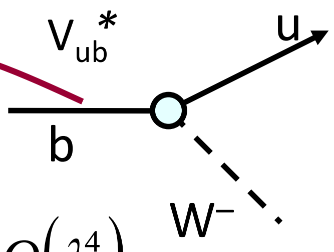
$$\lambda \equiv \sin\theta_C = \sin\theta_{12} \approx 0.23$$



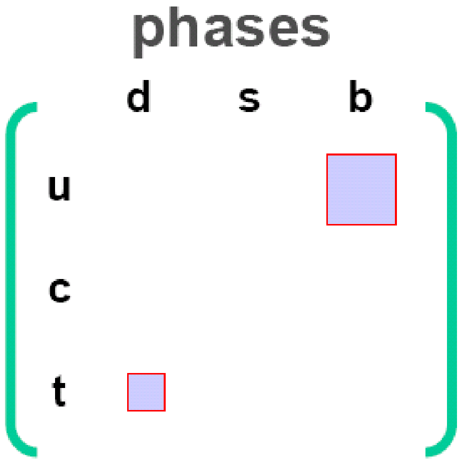
Expansion on a small parameter λ:



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



CPV phases are in the corners



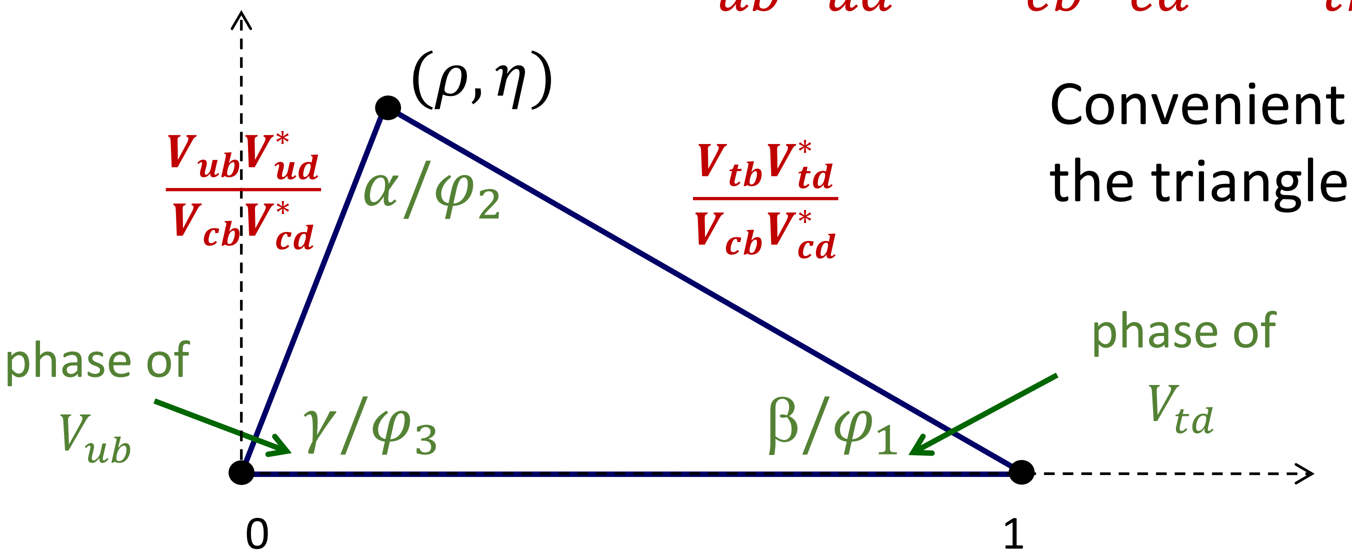
$$A = \frac{\sin\theta_{23}}{\sin^2\theta_{12}} \approx 0.8 \qquad (\rho,\eta) = \frac{\sin\theta_{13}}{\sin\theta_{12}\sin\theta_{23}}(\cos\delta, \sin\delta)$$

Unitarity Triangle

Unitarity condition of CKM matrix $V^{\dagger}_{CKM}V_{CKM} = 1$ gives 9 constrains $V_{ij}V^{*}_{ik} = \delta_{jk}$:

- 3 ($j = k$) says that the probability for each quark to couple to W^{-} is summed up to 1;
- 6 ($j \neq k$) can be represented by triangles in the complex plane.
- 4 triangles are degenerate; 2 has comparable sides ($\propto \lambda^3$).
- One is a Very Important Triangle:

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



Convenient to normalize all sides to the base of the triangle ($V_{cd}V^{*}_{cb} = A\lambda^3$).

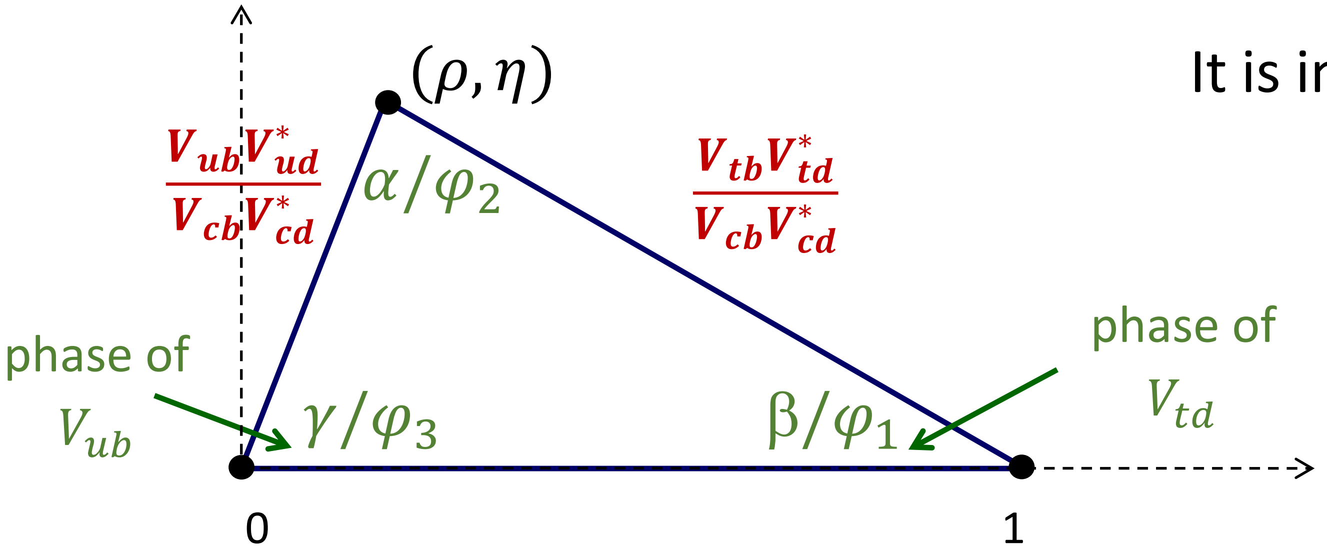
Then the coordinates of the upper apex are expressed through Wolfenstein parameters (ρ,η).

Very Important UT

This UT is about almost all CKM elements (not only their absolute values, but phases as well).

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

$$\boldsymbol{V_{CKM}} = \begin{pmatrix} \boldsymbol{V_{ud}} & \boldsymbol{V_{us}} & \boldsymbol{V_{ub}} \\ \boldsymbol{V_{cd}} & \boldsymbol{V_{cs}} & \boldsymbol{V_{cb}} \\ \boldsymbol{V_{td}} & \boldsymbol{V_{ts}} & \boldsymbol{V_{tb}} \end{pmatrix}$$

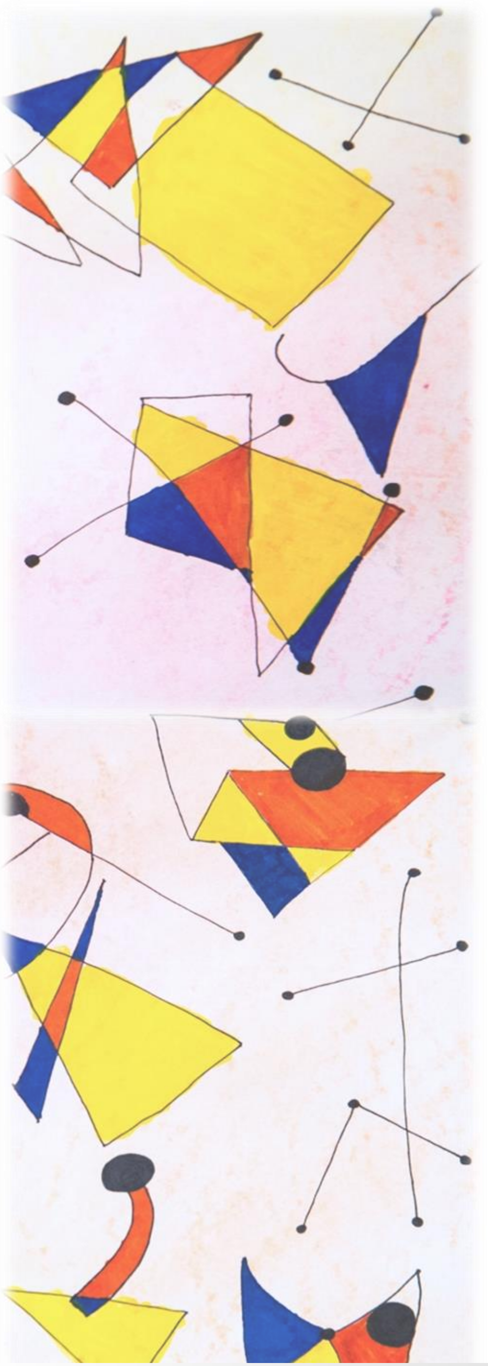


It is important to test CM-ansatz consistency (to check that 4, rather than 5 or more parameters fix whole CKM)

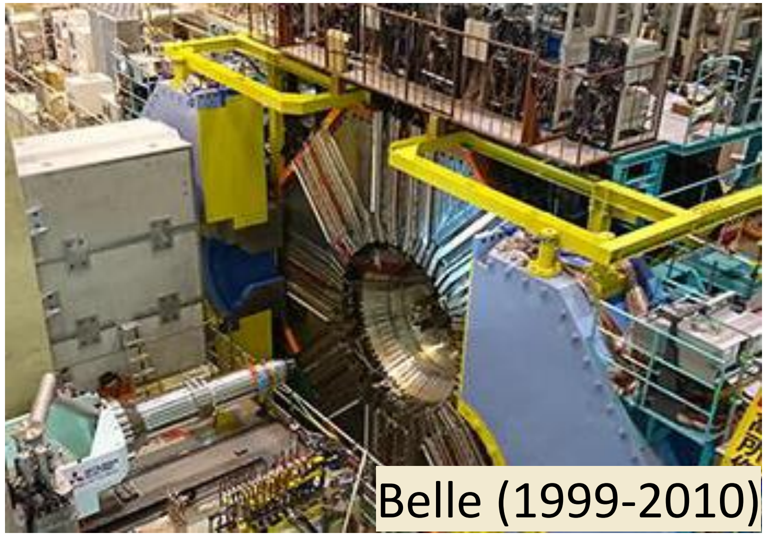
Almost all information on UT sides and angles comes from B-physics.

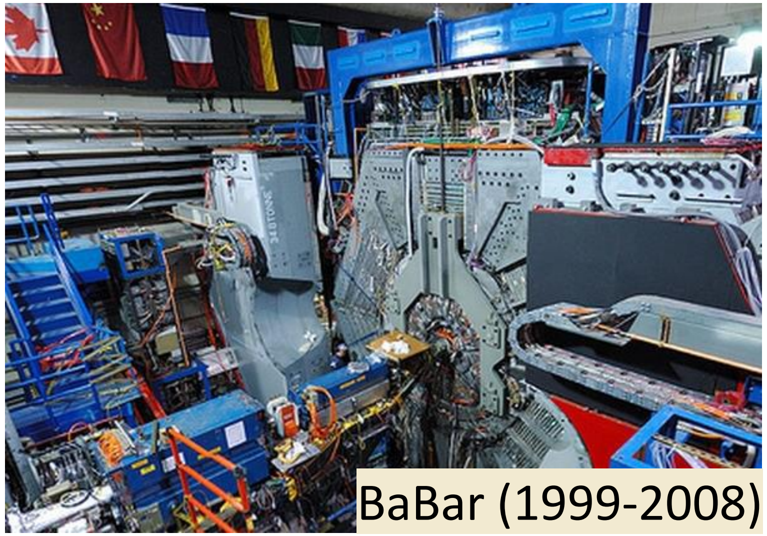
Where are we now

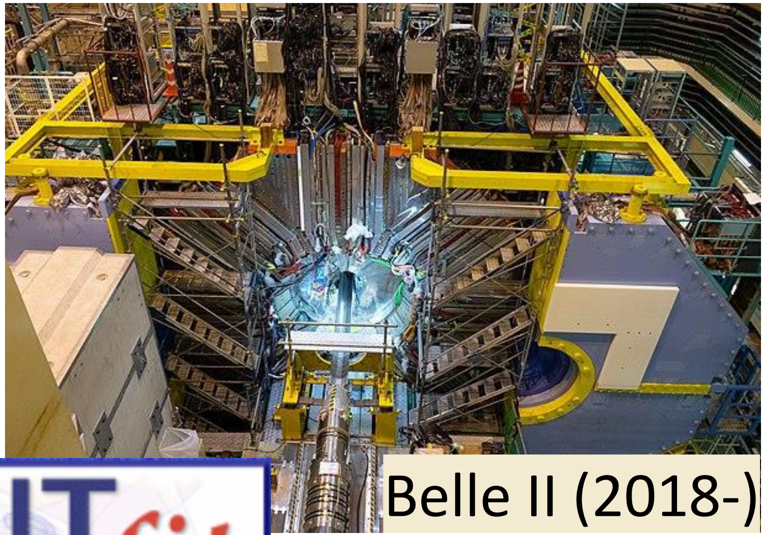
- Since early 90th evidence that CKM consists of complex phase by the first generation B-experiments (Argus and CLEO): observation of $B_d^0 - \bar{B}_d^0$ mixing and $b \to u$ transitions
- 2001 – first observation of CP violation in B-decays by B-factories (BaBar and Belle) confirms that CKM is really complex
- During the past 20 years success of the CKM picture: all CP-violation manifestations in lab experiments are amenable to a single complex CKM phase
- Now look for deviations from overall consistency of CM ansatz
- Updates mainly from B-factories full samples and new LHCb and Belle II results



B-physics & computer experiments

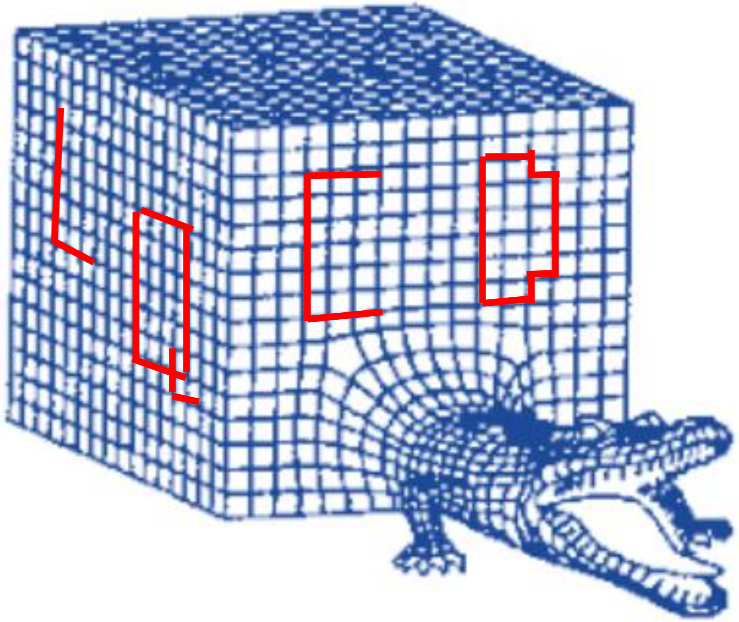

Belle (1999-2010)


BaBar (1999-2008)


Belle II (2018-)

LHCb runs 1,2(2010-2018)


LHCb run3(2023-)



UTfit

HFLAV

FLAG
Flavour Lattice Averaging Group

UT sides and absolute values of CKM elements

Absolute values...

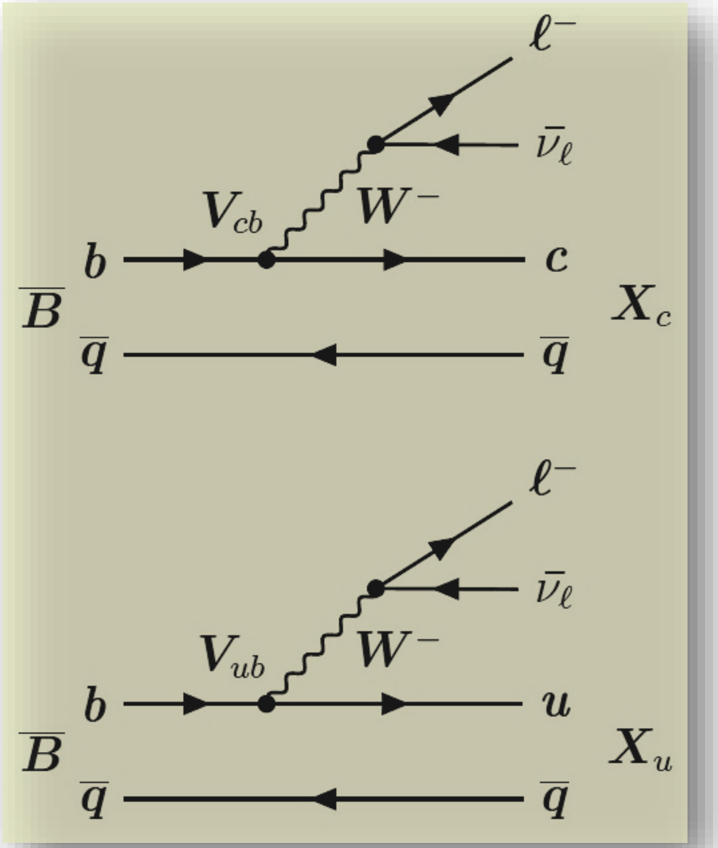
$$|V_{CKM}| =$$

V_{ud}: Nuclear beta-decays $\pi^+ \to \pi^0 \ell^+ \nu$ $\pi^+ \to \mu^+ \nu$	V_{us}: $K \to \pi \ell^+ \nu$ $K^+ \to \mu^+ \nu$ $\tau^+ \to K^+ \nu$	V_{ub}: $B \to \pi \ell^+ \nu$ $B_s^0 \to K \ell^+ \nu$ $\Lambda_b \to \Lambda \ell^+ \nu$ $B \to X_u \ell^+ \nu$
V_{cd}: $D \to \pi \ell^+ \nu$ $D \to \rho \ell^+ \nu$ $B_c \to B_d^0 \ell^+ \nu$ $D^+ \to \mu, \tau^+ \nu$	V_{cs}: $D \to K \ell^+ \nu$ $D \to K^* \ell^+ \nu$ $B_c \to B_s^0 \ell^+ \nu$ $D_s^+ \to \mu, \tau^+ \nu$	V_{cb}: $B \to D \ell^+ \nu$ $B \to D^* \ell^+ \nu$ $\Lambda_b \to \Lambda_c \ell^+ \nu$ $B \to X_c \ell^+ \nu$
V_{td}: Δm_d $B \to \rho \gamma$ $B \to X_d \gamma$	V_{ts}: Δm_s $B \to K^* \gamma$ $B \to X_s \gamma$ $B_s^0 \to \mu^+ \mu^-$	V_{tb}: Single top production $t \to bW$ $Z \to b\bar{b}$

$|V_{cb}|$& $|V_{ub}|$ determination

$|V_{cb}|$ normalizes the whole unitarity triangle;

measured using weak tree (no NP!) transition $b \to c(u)\ell\bar{\nu}_\ell$



Complementary experimental approaches:

Inclusive decays $\bar{B} \to X_{c(u)}\ell^-\bar{\nu}_\ell$; $X_{c(u)}$ is not reconstructed

- experiment: large backgrounds → only B factories
- theory: series in α_S and Λ_{QCD}/m_b relying on HQE

Exclusive decays such as $B \to D(\pi)\ell\bar{\nu}_\ell$ or $B \to D^*(\rho)\ell\bar{\nu}_\ell$

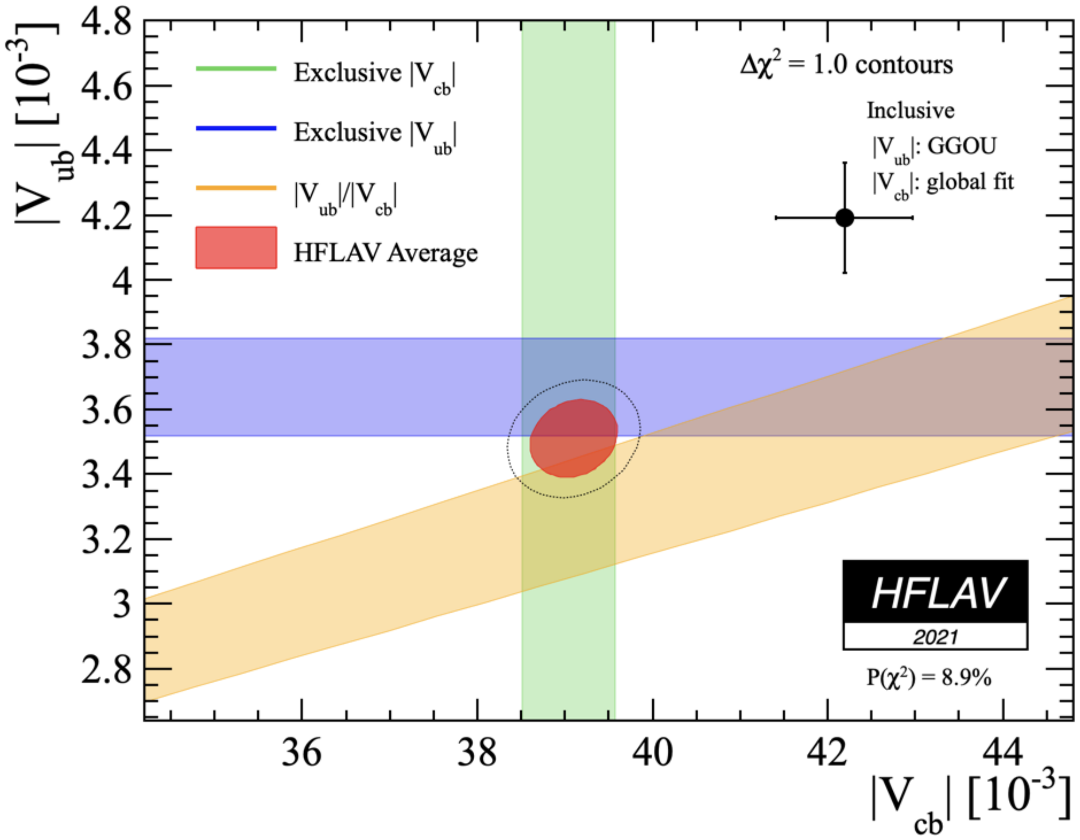
- experiment: controlled backgrounds → LHCb & B factories
- theory/lattice: Form Factors (FF)

Rely on different theoretical calculations;
Use different experimental techniques;
Have uncorrelated statistical and systematic uncertainties.

expected agreement would be a useful test of our understanding of both experiment and theory

Recent $|V_{cb}|$ & $|V_{ub}|$ studies

But, instead of agreement, long-standing tension (~3σ) between inclusive and exclusive measurements.



BELLE (full data set):

- q^2 moments in inclusive tagged $\bar{B} \to X_c \ell^- \bar{\nu}_\ell$
  PRD 104, 112011 (2021)

BELLE II:

- q^2 moments in inclusive tagged $\bar{B} \to X_c \ell^- \bar{\nu}_\ell$
  arXiv:2205.06372 (2022)
- exclusive tagged $\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ (preliminary (2022))
- exclusive tagged $B^0 \to D^{*-} \ell^+ \nu_\ell$ (preliminary (2022))
- inclusive tagged $\bar{B} \to X_u \ell^- \bar{\nu}_\ell$ (preliminary (2022))

LHCb:

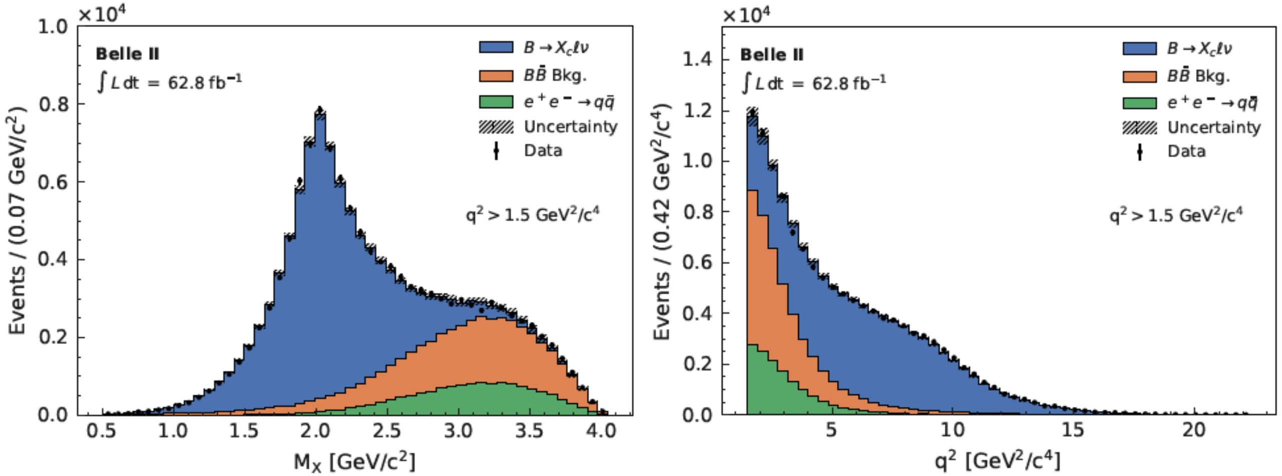
- exclusive $B_s^0 \to K^- \ell^+ \nu_\ell$
  PRL 126, 081804 (2021)
- exclusive $\Lambda_b^0 \to p \ell^- \bar{\nu}_\ell$
  Nature Physics 11, 743 (2015)

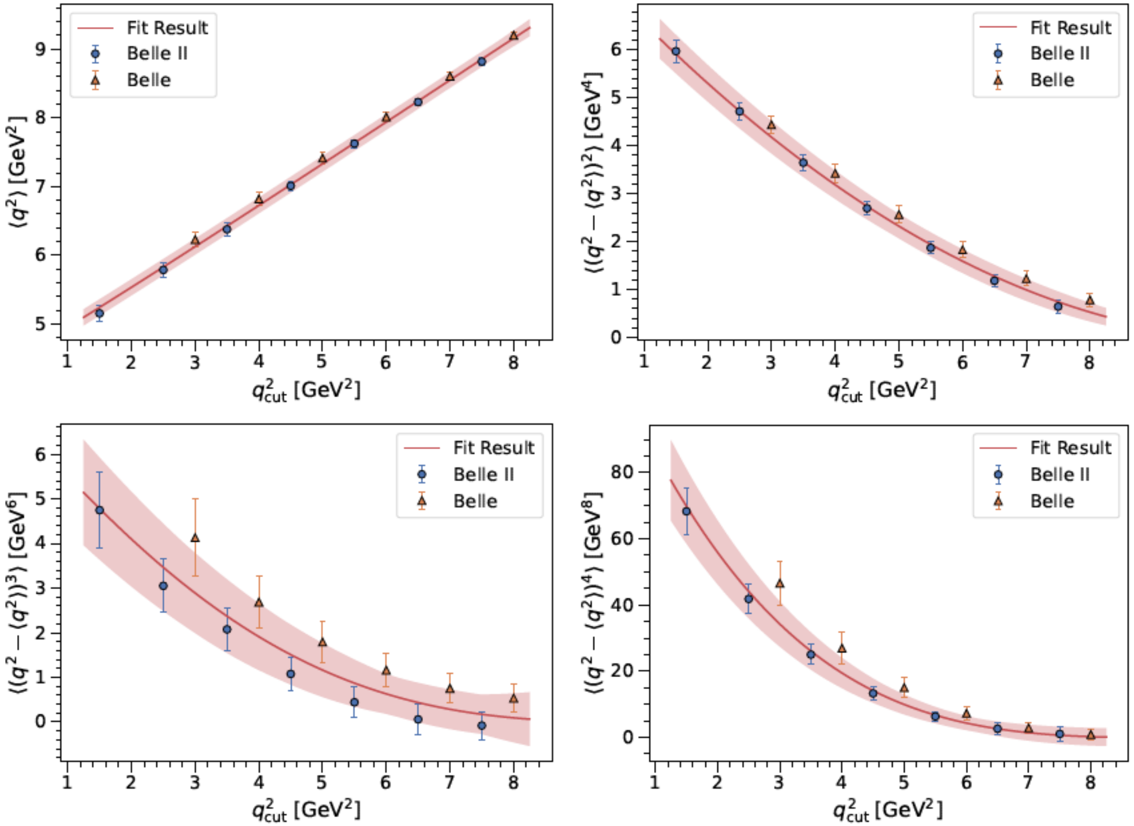
Inclusive $|V_{cb}|$ measurements

JHEP 02 (2019) 177 motivated a purely data-driven $|V_{cb}|$ analysis including higher order HQE corrections using $q^2 = (p_\ell + p_\nu)^2$ moments. Requires to "reconstruct" $\bar{\nu}_\ell$: only B-factories

arXiv:2205.06372 [hep-ex]

New Belle II (62.8/fb) measurement of q^2 moments in $\bar{B} \to X_c \ell^- \bar{\nu}_\ell$ using $B_{tag} \to hadrons$.
Good q^2 resolution with kinematic fit.



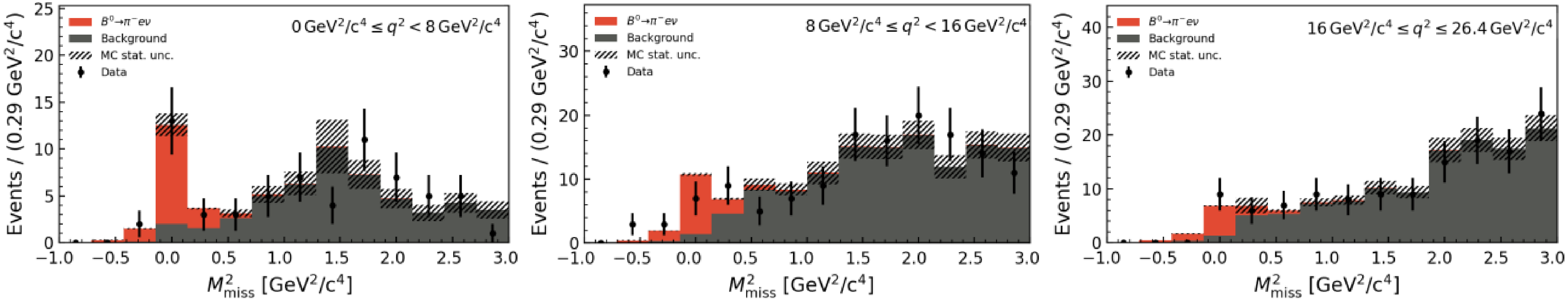


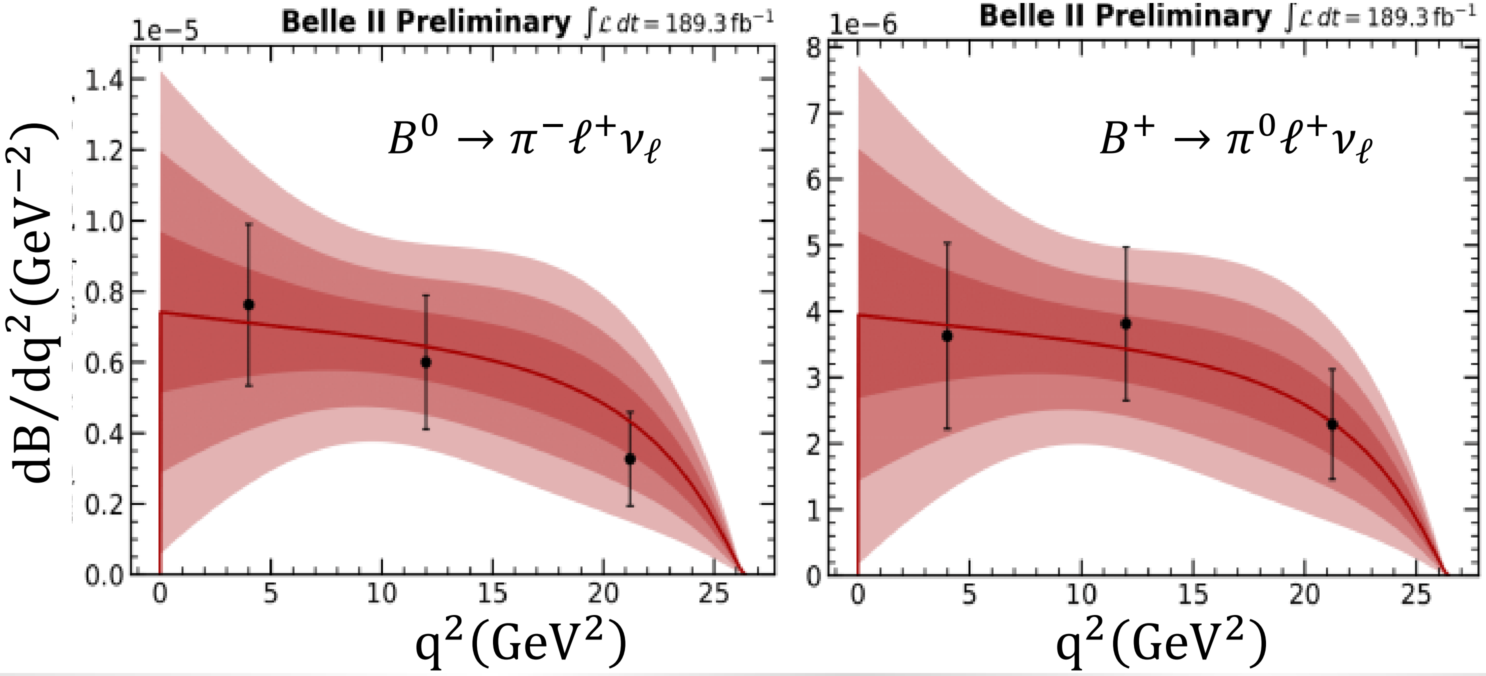
Belle II, Belle *PRD 104, 112011 (2021)* and fit by F. Bernlochner et al. *arXiv:2205.1027[hep-ph]*

$$|V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$$

$|V_{ub}|$ measurements

New Belle II (189.3/fb) measurement of $B^{0/+} \to \pi^{-/0}\ell^+\nu_\ell$ with hadronic tag. *Preliminary*





Fit M^2_{miss}

$$M^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_e - p_\pi\right)^2$$

in 3 bins of q^2

$$q^2 = \left(p_{e^+e^-} - p_{B_{tag}} - p_\pi\right)^2$$

$$\frac{d\Gamma(B \to \pi\ell^+\nu_\ell)}{dq^2} = \frac{G_F|V_{ub}|^2}{24\pi^3}|p_\pi|^3 f_+^2(q^2)$$

$$|V_{ub}| = (3.88 \pm 0.45)\cdot 10^{-3}$$

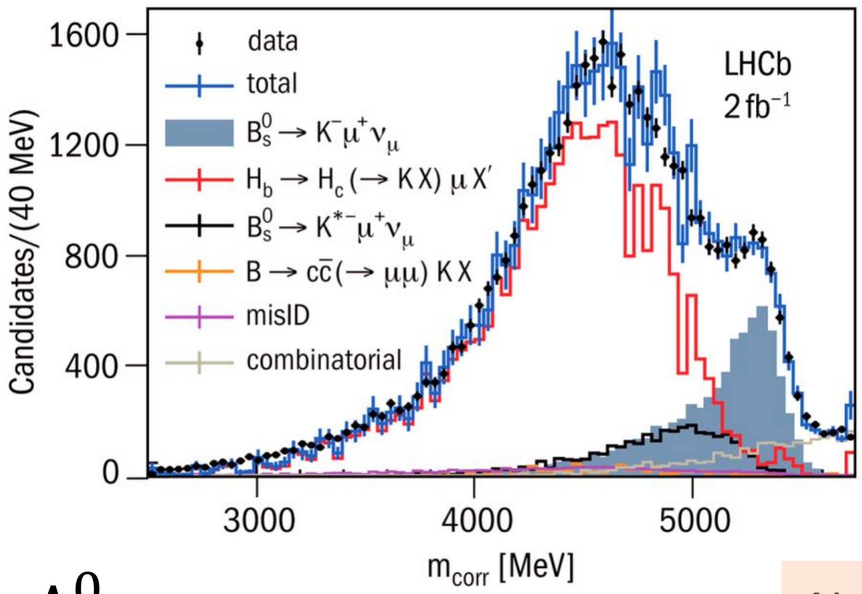
Exclusive Measurements of $|V_{ub}|/|V_{cb}|$ at LHCb

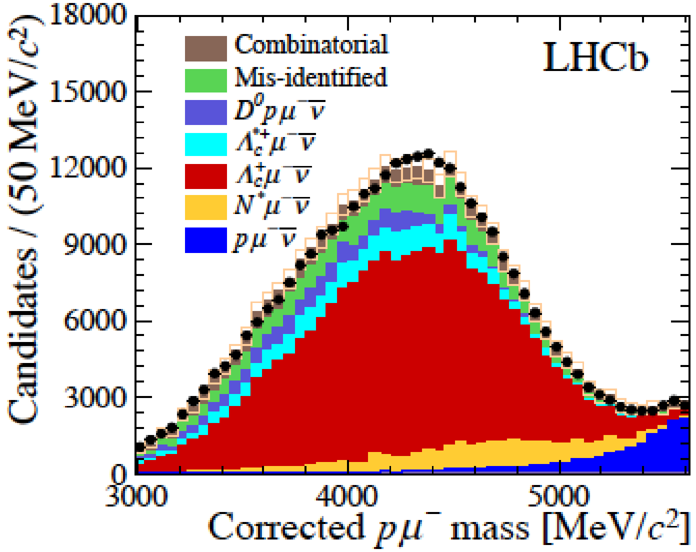
$B_s^0 \to K\mu\nu$

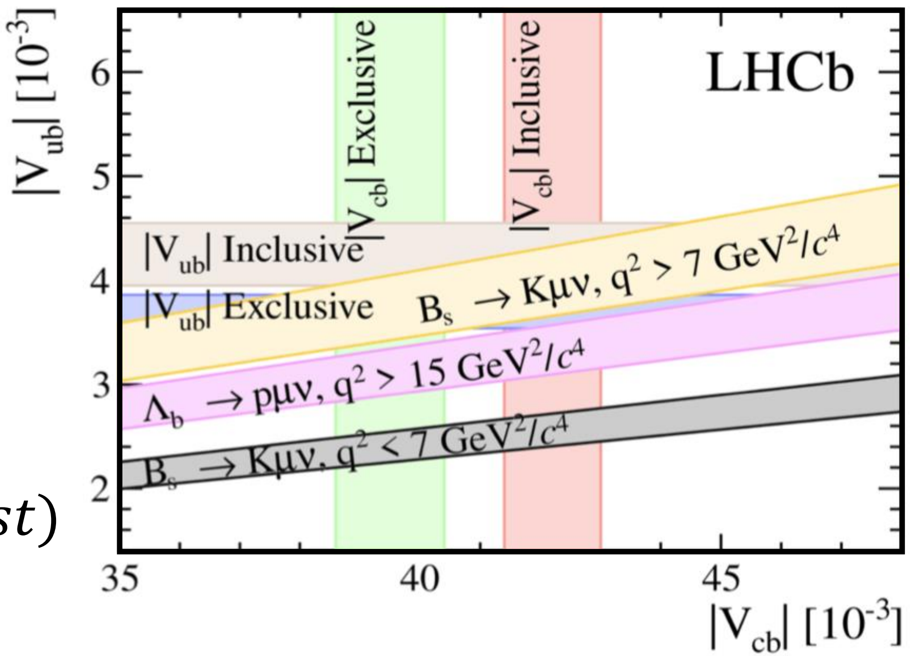
*PRL **126**, 081804 (2021)*

$$|V_{ub}|/|V_{cb}|_{\ low\ q^2} = 0.0607 \pm 0.0015(stat) \pm 0.0013(syst) \pm 0.0008(D_s) \pm 0.0030(FF)$$

$$|V_{ub}|/|V_{cb}|_{\ high\ q^2} = 0.0946 \pm 0.0030(stat)^{+0.0024}_{-0.0025}(syst) \pm 0.0013(D_s) \pm 0.0068(FF)$$







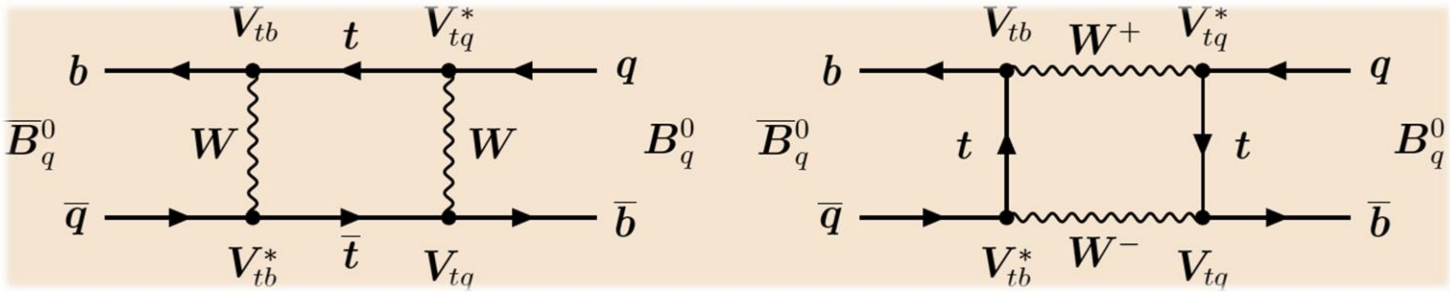
$\Lambda_b^0 \to p\mu\nu$

Nature 11, 743 (2015)

$$|V_{ub}|/|V_{cb}|_{\ q^2>15} = 0.083 \pm 0.004(stat) \pm 0.004(syst)$$

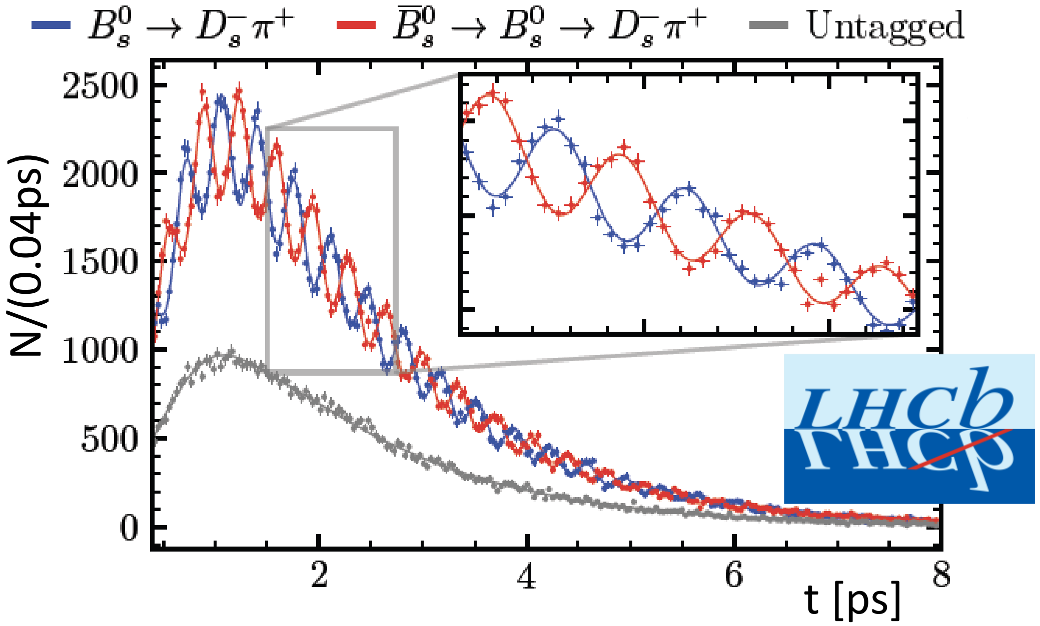
$|V_{td}|$& $|V_{ts}|$ determination

are not (yet) measurable in tree-level top quark decays;



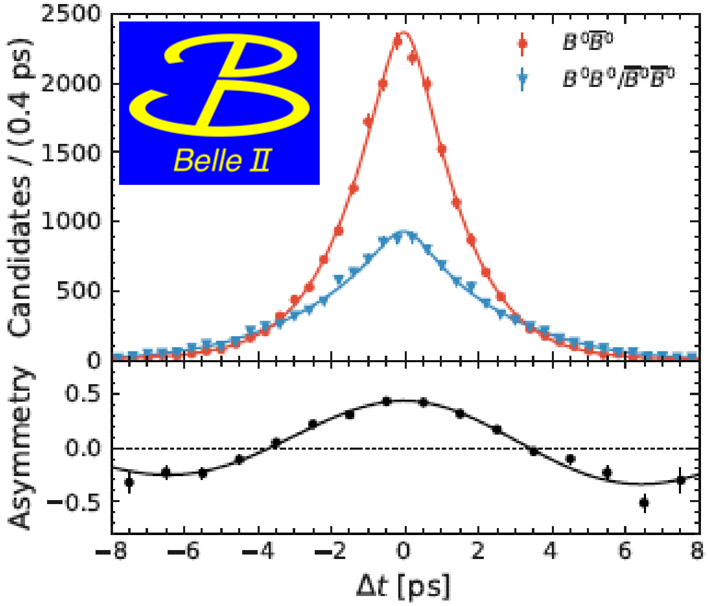
to be determined from B^0_q-$\bar{B}^0_q$ oscillations

New LHCb study 6/fb *Nature Phys. 18, 1 (2022)*



$\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032) ps^{-1}$

New Belle II study 190/fb *preliminary*



~40k $B^0 \to D^{(*)-}h^+$; $B^0 \to D^{(*)-}\ell^+\nu_\ell$ to be added soon.

$\Delta m_d = (0.516 \pm 0.008 \pm 0.005) ps^{-1}$

$|V_{td}|$& $|V_{ts}|$ determination

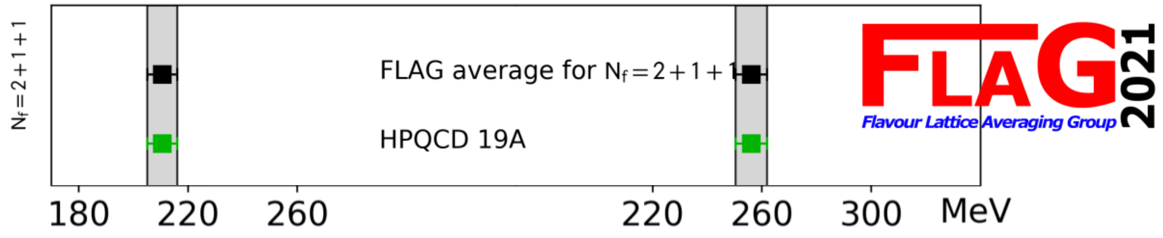
$$\Delta m_q \propto G_F^2 m_t^2 m_B \underbrace{f_{B_q}^2 B_{B_q}}_{\text{input from LQCD}} (V_{tq}^* V_{tb})^2$$

decay constant

bag parameter

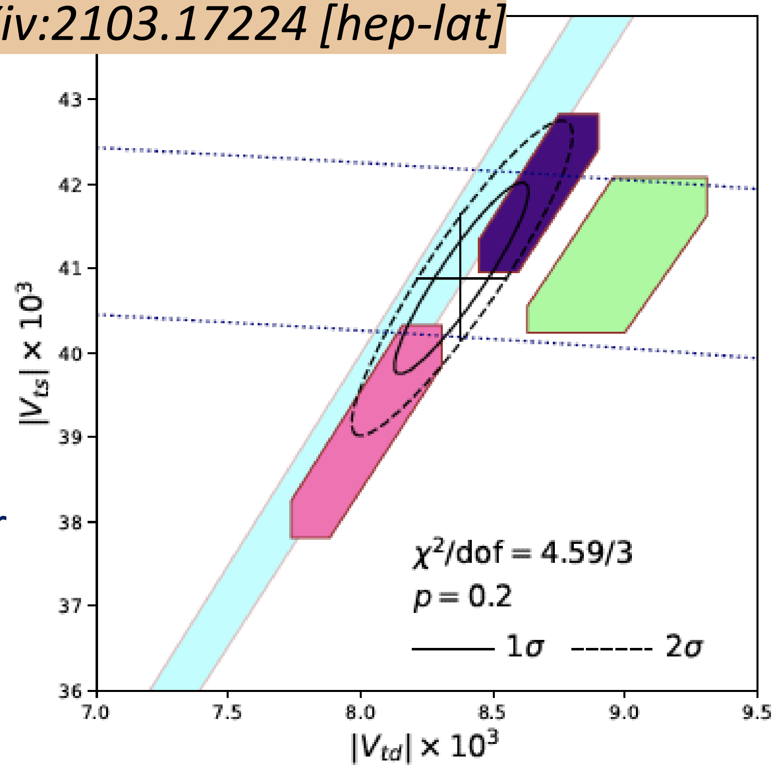
input from LQCD

$f_{B_d}\sqrt{B_{B_d}} = (210.6 \pm 5.5)\text{MeV}$ $f_{B_s}\sqrt{B_{B_s}} = (256.1 \pm 5.7)\text{MeV}$



$$|V_{td}| = (8.6 \pm 0.2) \times 10^{-3}$$
$$|V_{ts}| = (41.5 \pm 0.9) \times 10^{-3}$$

arXiv:2103.17224 [hep-lat]



$$\frac{|V_{td}|}{|V_{ts}|} = \sqrt{\frac{\Delta m_d \, m_{B_s}}{\Delta m_s m_{B_d}}}\,\xi = 0.2159 \pm 0.0004(exp) + 0.0107(LQCD)$$

$\xi = f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}} = 1.268 \pm 0.063$ $SU(3)$-flavour breaking factor

Other methods:

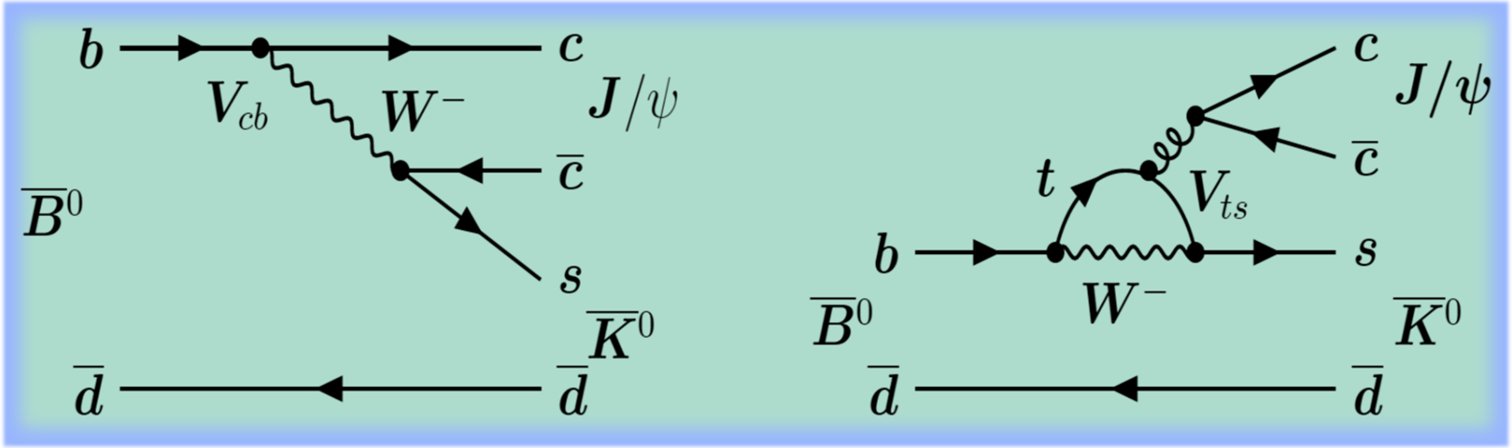
- $|V_{ts}|$ from $B_s^0 \to \mu^+\mu^-$
- $|V_{td}|/|V_{ts}|$ from ratio $\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma)$


UT angles
and
CKM phases

β/ϕ_1 measurements

the most theoretically clean.
Penguin contribution to the final states with charmonium

- are expected to be small;
- has the same SM weak phase.



	BaBar	Belle	LHCb
	Full dataset, 465 M$B\bar{B}$	Full dataset, 772 M$B\bar{B}$	3/fb
$sin2\beta =$	$0.687 \pm 0.028 \pm 0.012$	$0.667 \pm 0.023 \pm 0.012$	0.760 ± 0.034
$\mathcal{A} =$	$0.024 \pm 0.020 \pm 0.016$	$0.006 \pm 0.016 \pm 0.012$	-0.017 ± 0.029

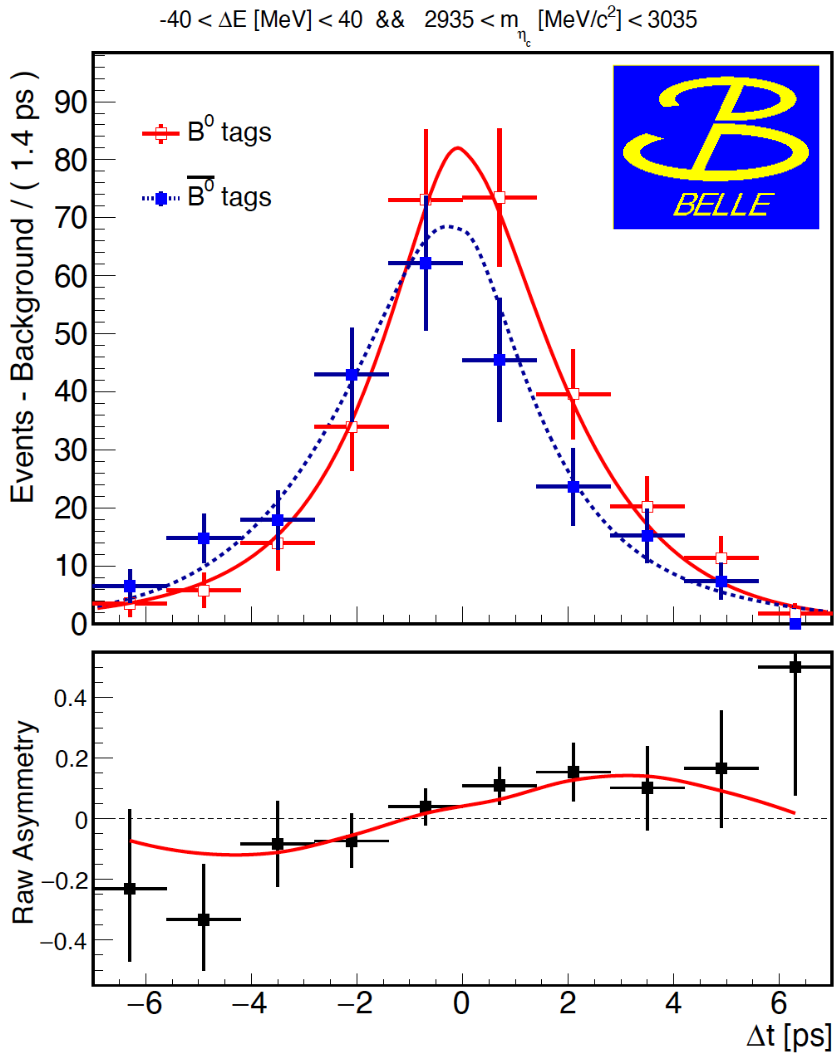
the most precise UT value: $\beta = (22.2 \pm 0.7)^{\circ}$, need at least two more measurements with comparable accuracy; but all others are not so precise yet…

Direct CP asymmetry is consistent with 0, confirming co-phasing of tree and penguin amplitudes

β/ϕ_1 measurements

Important to check consistency of all $B^0 \to \mathit{charmonium}\ K_S^0$:

- penguin contribution may be different for different charmonia (penguins can be underestimated or NP contribution to the loop)
- for broad states decaying into light hadrons also interesting to probe interference with non-resonant (penguin) contribution



New Belle (full data set, 772 M$B\bar{B}$) CPV study of $B^0 \to \eta_c K_S^0$. First shown at ICHEP22. *Preliminary*

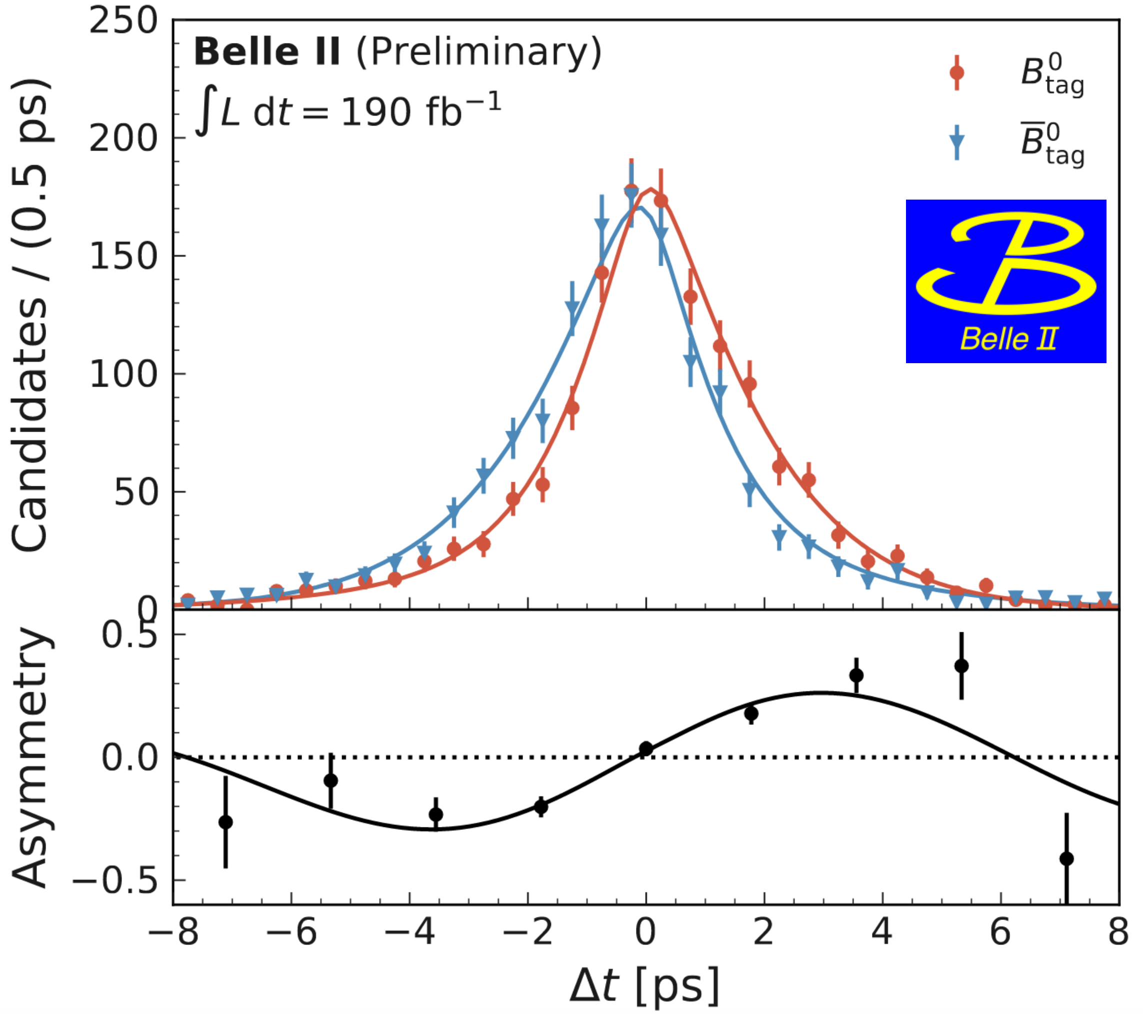
- Previous measurements of this channel BaBar – full data set; Belle – using 151 M$B\bar{B}$

$$\boldsymbol{S = 0.59 \pm 0.17 \pm 0.07} \qquad \boldsymbol{\mathcal{A} = 0.16 \pm 0.12 \pm 0.06}$$

β/ϕ_1 measurements

Belle II: first look at CPV in $B^0 \to J/\psi K_S^0$:

- $B_d^0 - \bar{B}_d^0$ oscillations study demonstrated that Δt resolution and flavor tagging working well.
- Use $B^+ \to J/\psi K^+$ for exercising: no CPV (neither indirect nor direct) is observed as expected.
- Systematics errors: the biggest contribution is from the statistical errors of the control samples.

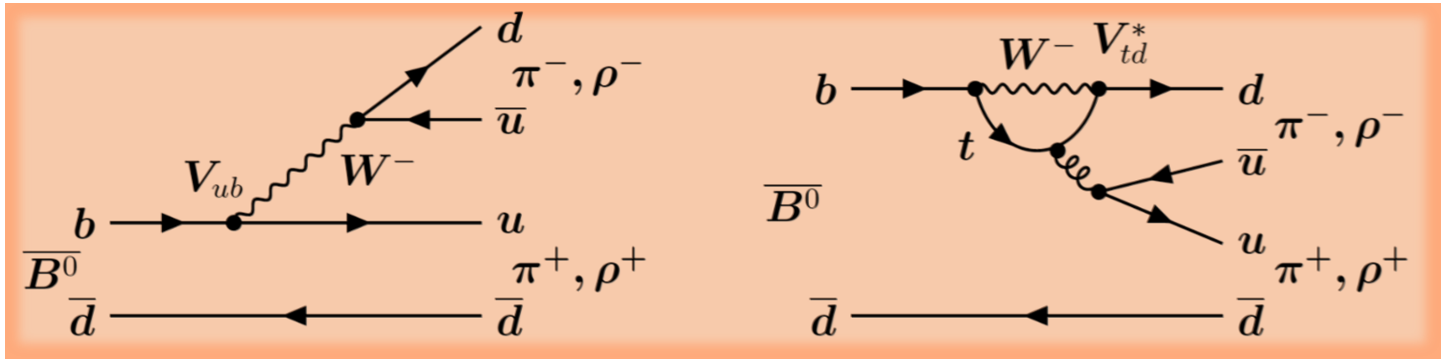


$$\boldsymbol{S = 0.720 \pm 0.062 \pm 0.016}$$

$$\boldsymbol{\mathcal{A} = 0.094 \pm 0.044^{+0.042}_{-0.017}}$$

The result is in good agreement with WA; statistical and systematics errors are as expected. Tools are ready for an impactful $\sin 2\phi_1$ measurement.

α/ϕ_2 measurements

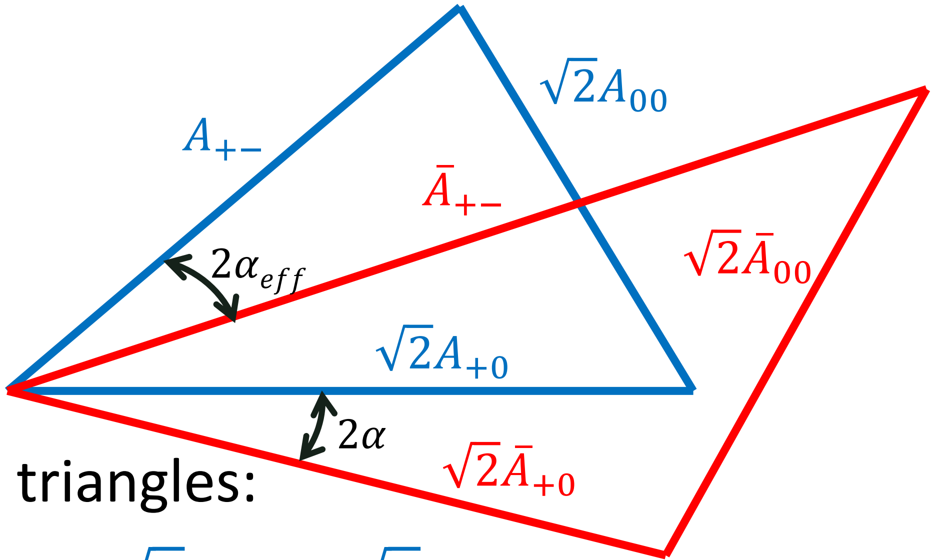


Penguin contribution:

- not expected to be small
- consists of different weak phase
- unknown strong phase

Isospin analysis PRL 65, 3381 (1990) based on relations:

$$A_{+-} \equiv \quad A(B^0 \to \pi^+\pi^-) \;= e^{-i\alpha}T^{+-} + P$$
$$\sqrt{2}A_{00} \equiv \sqrt{2}A(B^0 \to \pi^0\pi^0) \;= e^{-i\alpha}T^{00} + P$$
$$\sqrt{2}A_{+0} \equiv \sqrt{2}A(B^+ \to \pi^+\pi^0) = e^{-i\alpha}(T^{00} + T^{+-})$$



Need to measure :

- 6 BR's $B^0(\bar{B}^0)$ to $\pi^+\pi^-$; $\pi^0\pi^0$; and $B^\pm$ to $\pi^\pm\pi^0$
- indirect CPV in $B^0 \to \pi^+\pi^-$ ($\propto \sin 2\alpha_{eff}$)

	$\pi^+\pi^-$	$\pi^\pm\pi^0$	$\pi^0\pi^0$
B-factories			
LHCb			

Isospin triangles:

$$A_{+-} + \sqrt{2}A_{00} = \sqrt{2}A_{+0}$$
$$\bar{A}_{+-} + \sqrt{2}\bar{A}_{00} = \sqrt{2}\bar{A}_{+0}$$

Isospin breaking:

- *u*-*d* mass/charge difference
- π-η-η' (ρ-ω) mixing

α/ϕ_2 measurements

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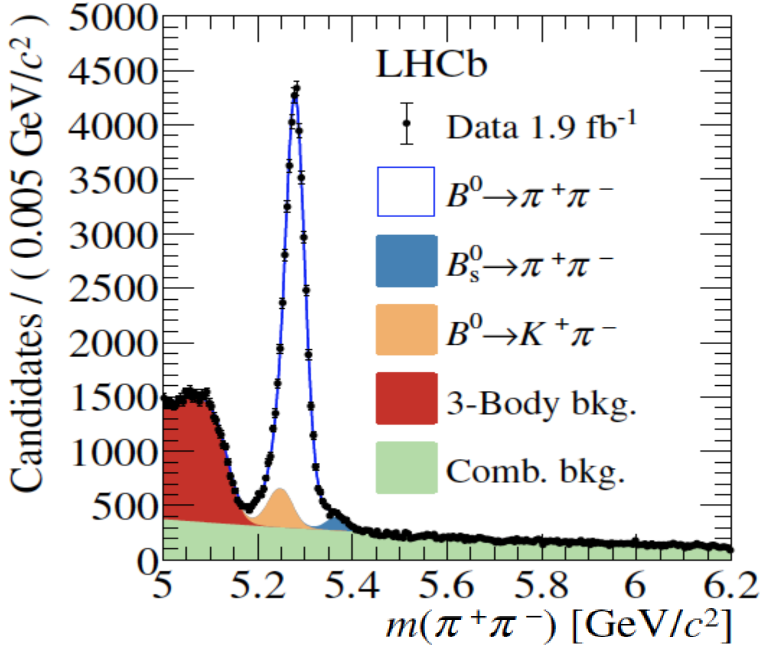


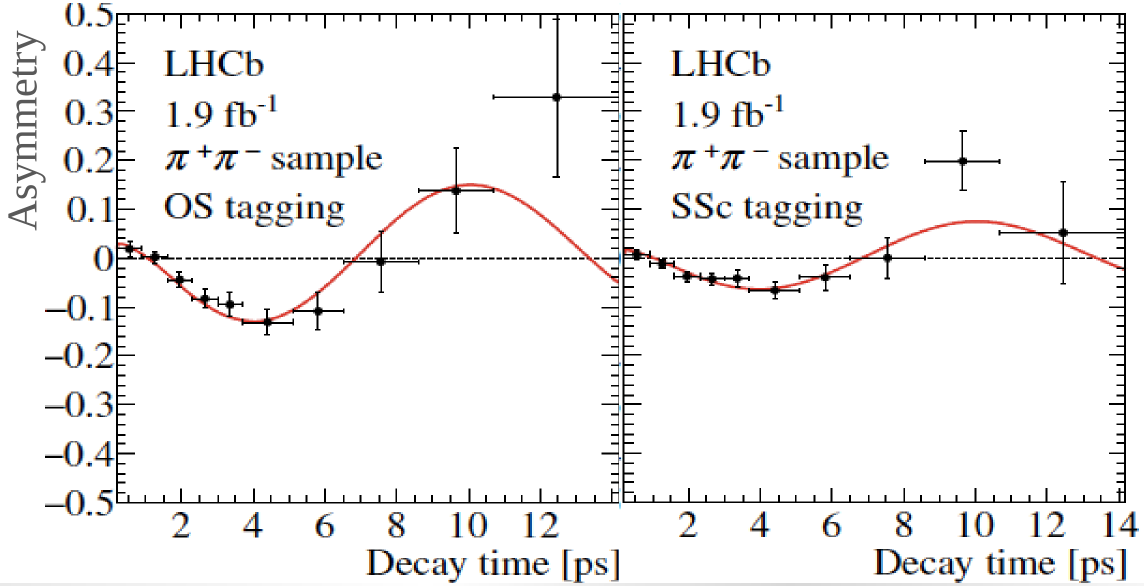
Recent LHCb (run 2 data set, 1.9/fb) CPV study of $B^0 \to \pi^+\pi^-$

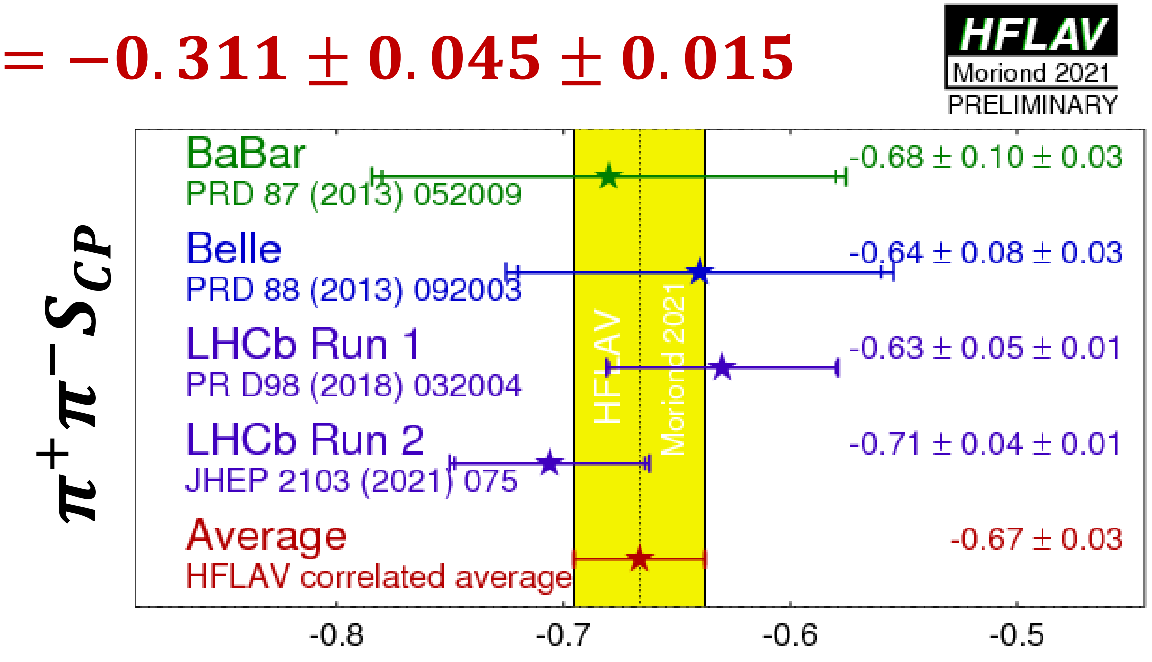
- Perfect hadron identification
- Vertex constraint
- Huge statistics
- Effective tagging (both same and opposite sides)

High signal purity & controlled bgs

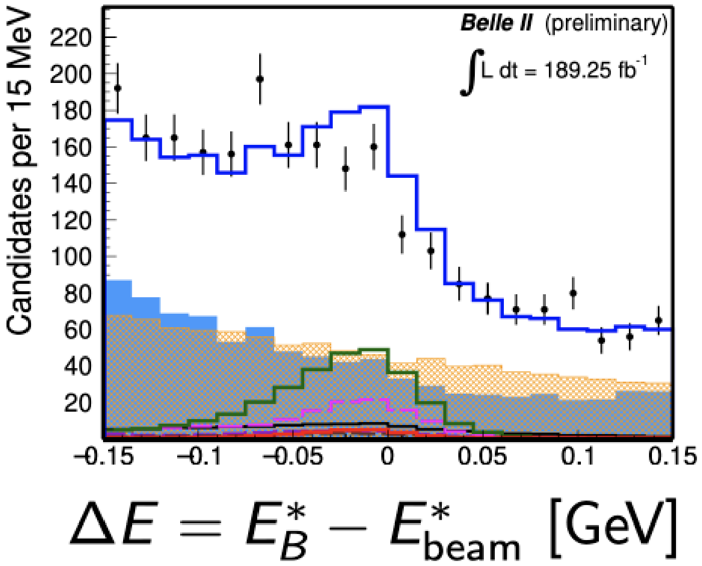
$$S = -0.706 \pm 0.042 \pm 0.013$$

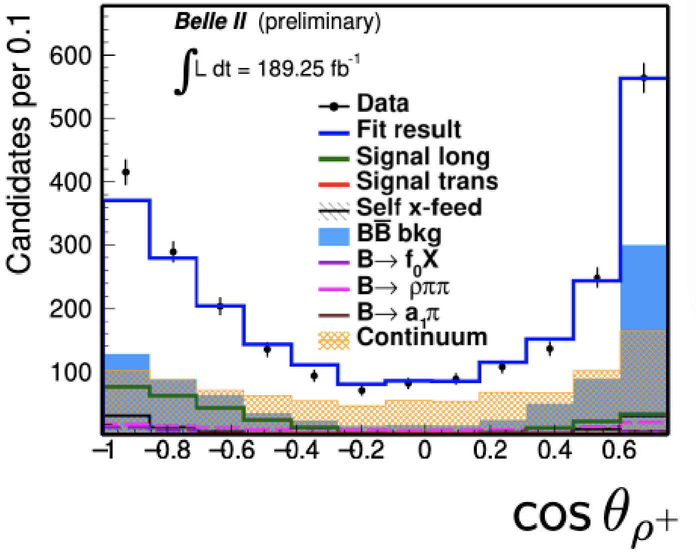
$$C = -0.311 \pm 0.045 \pm 0.015$$





α/ϕ_2 measurements



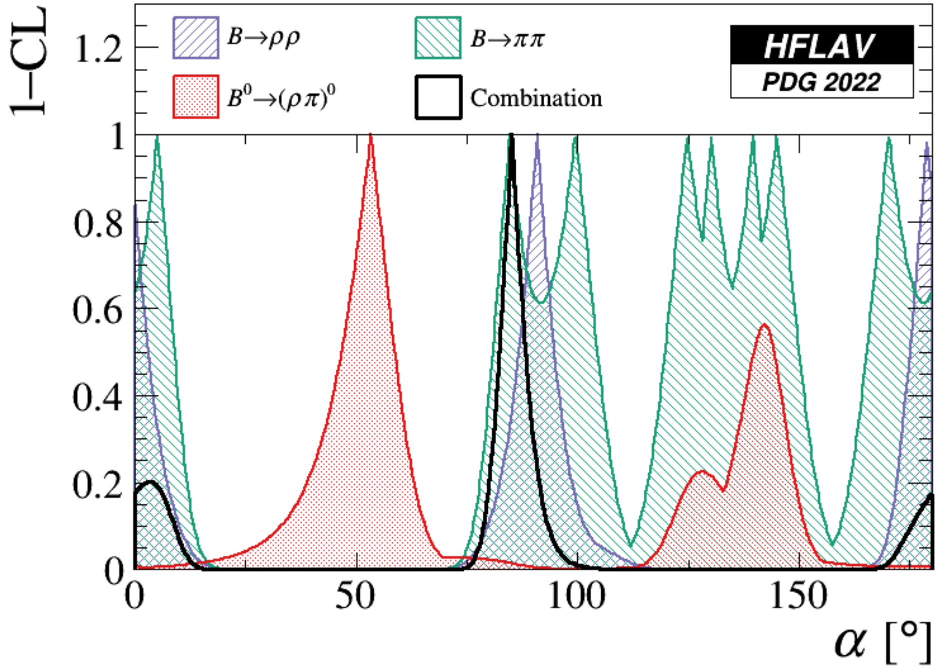


$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$A = -0069 \pm 0.068 \pm 0.060$$

~ null direct CPV;
almost 100% one CP component

$$\alpha = \left(85.2^{+4.8}_{-4.3}\right)^\circ$$

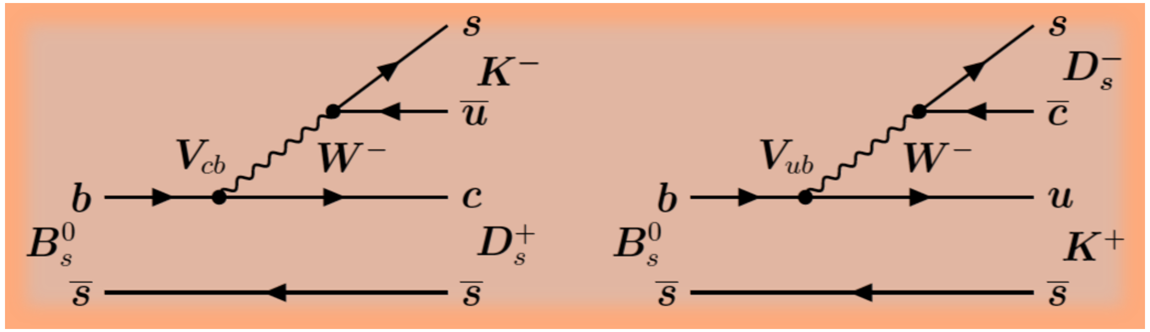


New Belle II (190/fb) study of direct CPV in $B^+ \to \rho^+\rho^0$

- Previous study showed small penguin contribution in this channel: more sensitivity to α from the isospin analysis.
- Only two-fold ambiguity (unlike 8-fold in $\pi\pi$)
- Vector-Vector final state: mixture of CP even and CP odd – to be disentangle by angular analysis

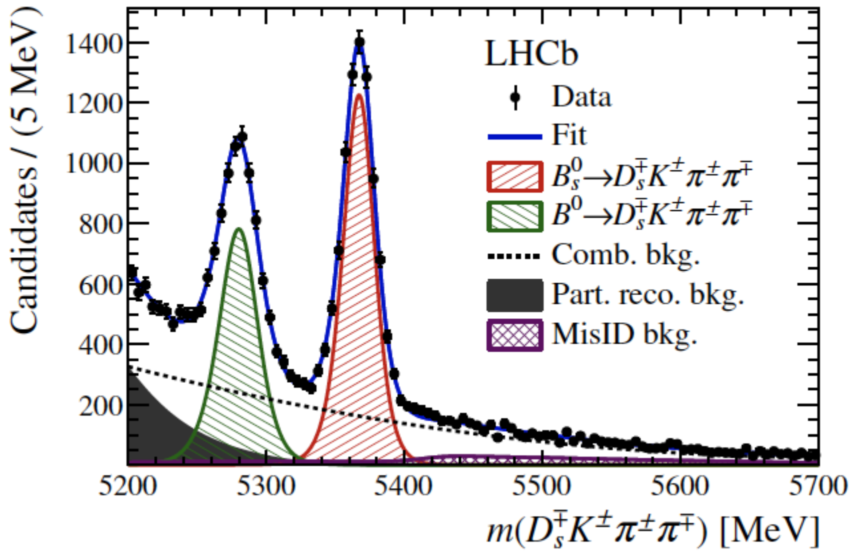
γ/ϕ_3 measurements

Angle between two amplitudes is γ, but the final states can interfere only via B_s^0-$\bar{B}_s^0$ mixing. Only LHCb can do such analysis.



Recent LHCb study (9/fb) JHEP03(2021)137 of indirect CPV in $B_s^0 \to D_s^- K^+\pi^+\pi^-$

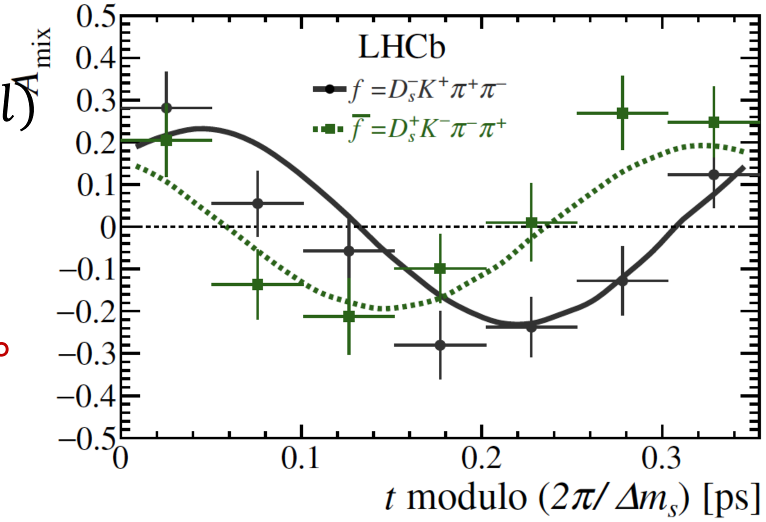
- Tagging and vertexing are tested and verified with $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$
- Many intermediate resonances (not obligatory with the same fraction in two diagrams): study of resonance decomposition (time-dependent amplitude analysis).



PS integrated coherence factor:

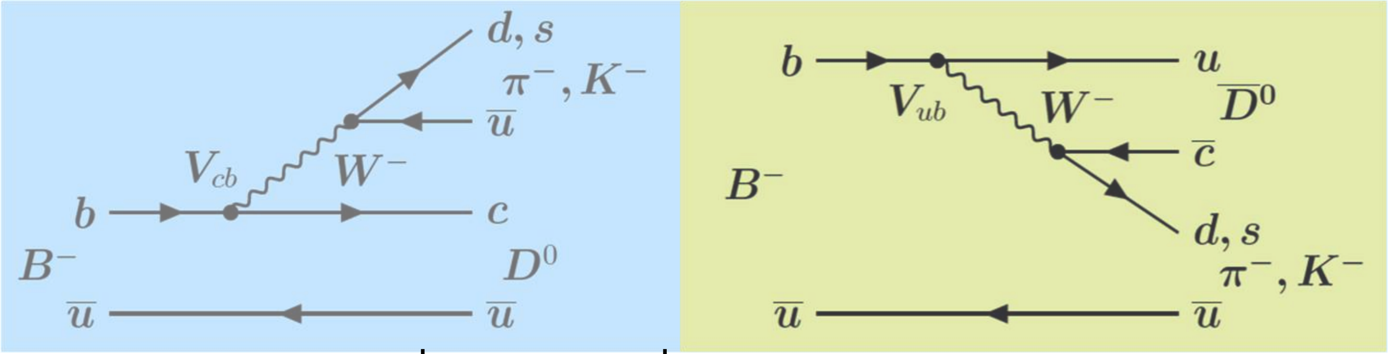
$\kappa = 0.72 \pm 0.04 \pm 0.06 \pm 0.04\ (model)$

$$\gamma - 2\beta_s \overset{\cong 0^\circ}{=} (42 \pm 10 \pm 4 \pm 5)^\circ$$



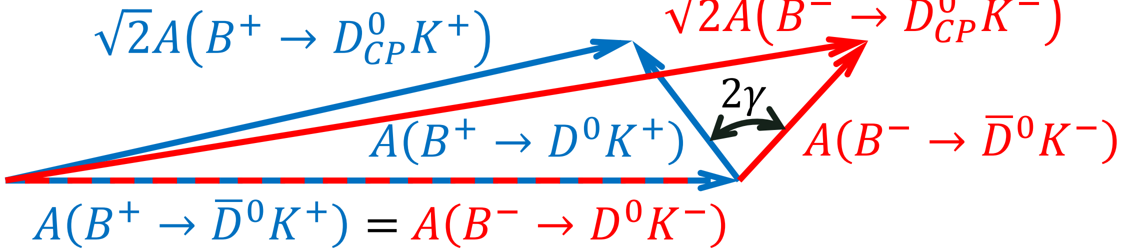
γ/ϕ_3 measurements

Angle between two amplitudes is γ, but the final states are different $D^0 \neq \overline{D}^0$. Special efforts are required to organize interference and CPV:



$A_{favoured} \propto \lambda$ $\quad r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \approx 0.1$ $\quad A_{suppressed} \propto \lambda^2 \times (1/3)_{color}$

- *GLW method* *PLB253, 483 (1991)*: D^0 decays into CP-eigenstate (Cabibbo suppressed modes, *e.g.* K^+K^-, $K_S^0\pi^0$)



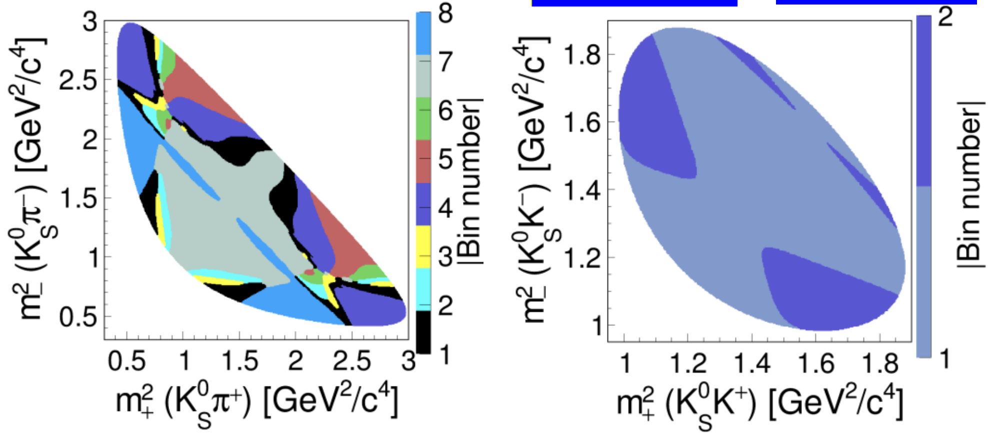
- *ADS method* *PRL78, 3357 (1997)*: D^0 decays into DCS mode in allowed final state: (very rarely, but improve r_B)
- *BPGGSZ method* *PRD68, 054018 (2003)*: D^0 decays into three body state (*e.g.* $K_S^0\pi^+\pi^-$): mixture of intermediate (interfering) resonances: non (CA and DCS) and opposite CP eigenstates ± 1. Resolve each contribution by Dalitz analysis. Improved by using binned Dalitz $D^0_{CP} \to K_S^0\pi^+\pi^-$ from CLEOc/BES data.

γ/ϕ_3 measurement

JHEP02(2022)063

New Belle (711/fb)+Belle II (128/fb) measurement of γ using BPGGSZ method $B^+ \to D^0 K^+(\pi^+), D^0 \to K_S^0\pi^+\pi^-, K_S^0 K^+ K^-$

- Use binned Dalitz $D_{CP}^0 \to K_S^0\pi^+\pi^-(K^+K^-)$ from CLEOc/BES data

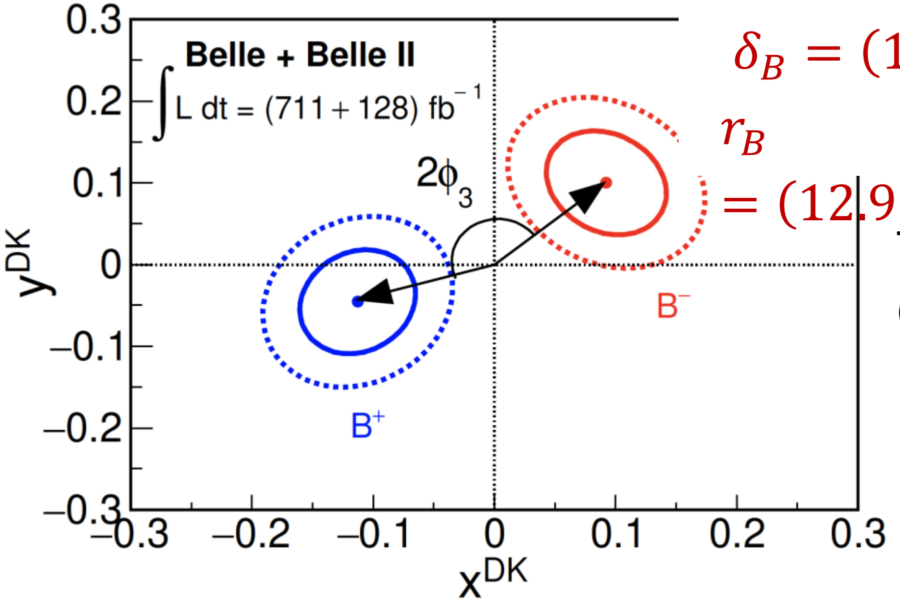


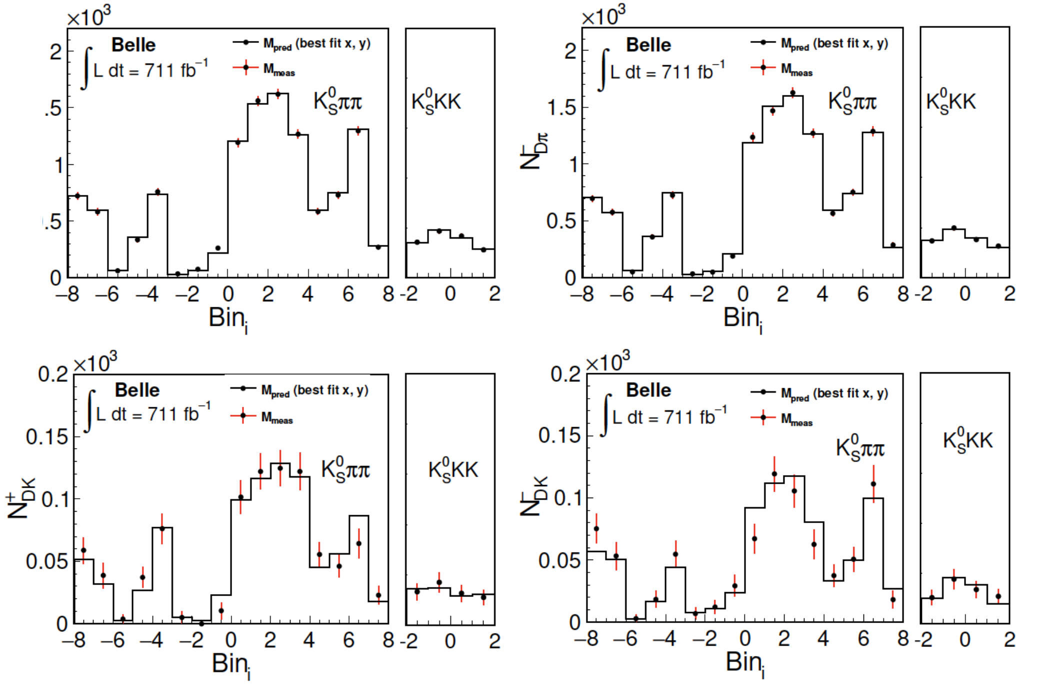
$$\gamma \equiv \varphi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$$

$$\delta_B = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ$$

$$r_B = (12.9 \pm 2.4 \pm 0.1 \pm 0.2) \times 10^{-2}$$

The third error is due to CLEOc/BES uncertainties in strong phase difference



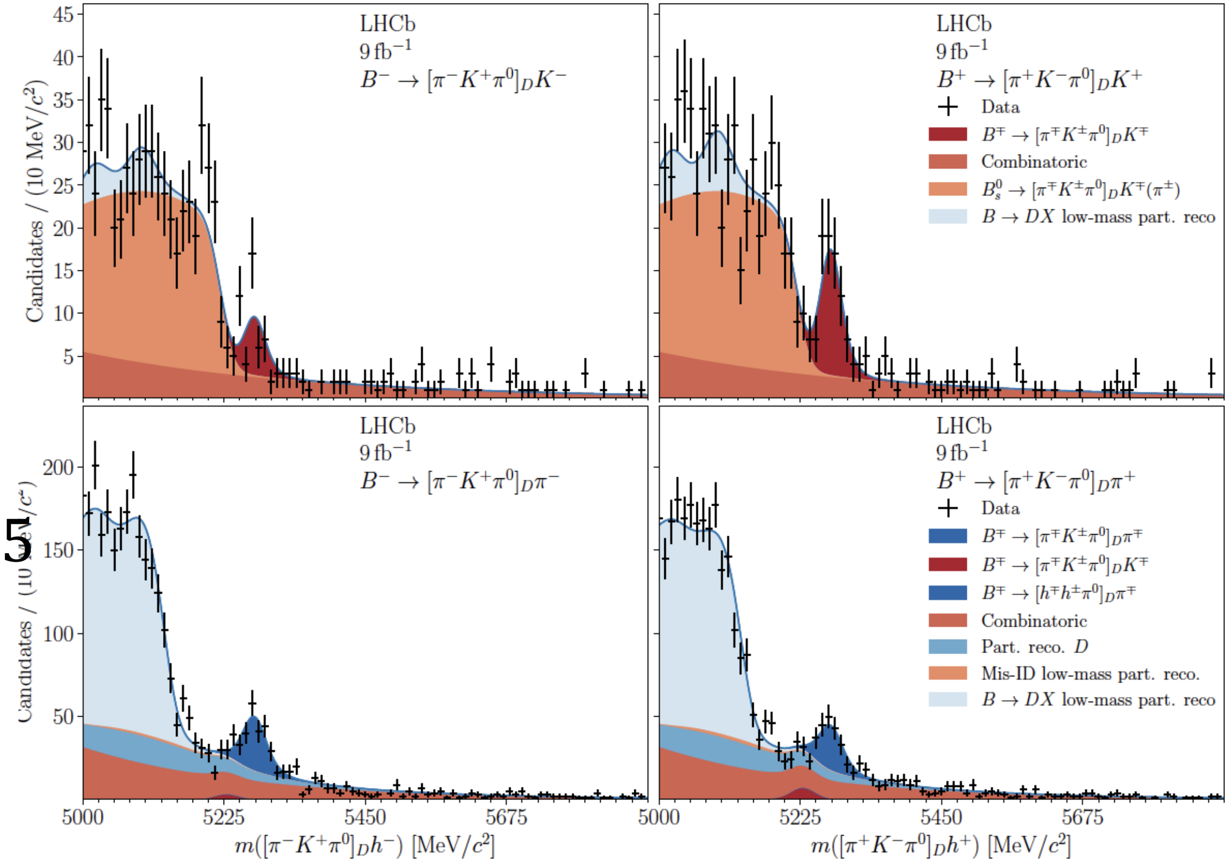


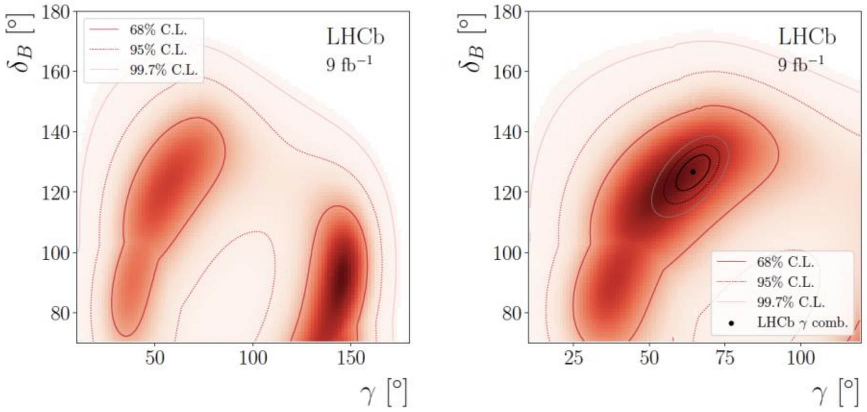
γ/ϕ_3 measurement

JHEP 07 (2022), 099

New LHCb (9/fb) measurement of γ in $B^+ \to D^0 K^+(\pi^+), D^0 \to K^+K^-\pi^0, \pi^+\pi^-\pi^0, K^\pm\pi^\mp\pi^0$

- Use GLW and ADS methods
- No Dalitz analysis but instead use information from CLEOc/BES on fraction of CP even component in $D^0 \to K^+K^-\pi^0, \pi^+\pi^-\pi^0$: $F_+^{\pi\pi\pi} = 0.973 \pm 0.017, F_+^{KK\pi} = 0.732 \pm 0.055$
- Significant signal in “ADS” mode observed
- Evidence for large CP violation in “ADS” mode





$$\gamma \equiv \varphi_3 = \left(56^{+24}_{-29}\right)^\circ$$

$$\delta_B = (122^{+19}_{-23})^\circ$$

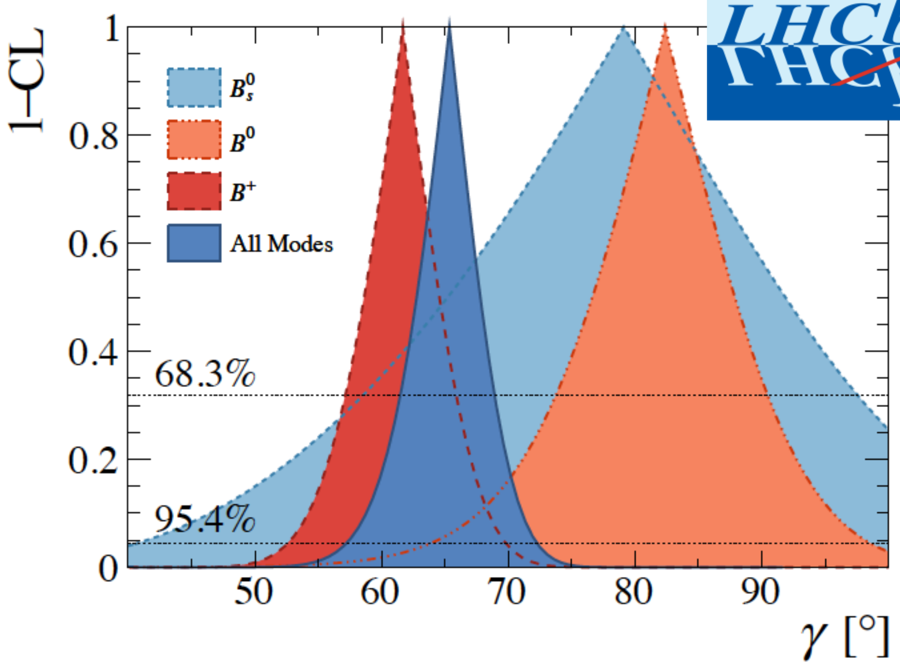
$$r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$$

γ/ϕ_3 measurement

JHEP 12 (2021), 141

Recent LHCb (run 1+2 data set) study $B_{(s)}^{0/+} \to D(1{,}2{,}3)h;\ D \to 2{,}3{,}4\ body$

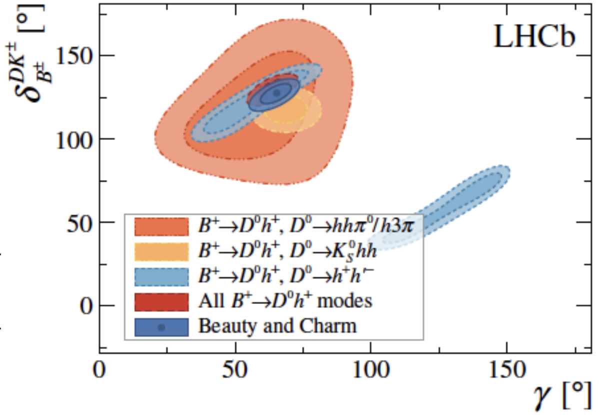
- Simultaneous fit to γ and charm mixing parameters
- Including several new and updated results

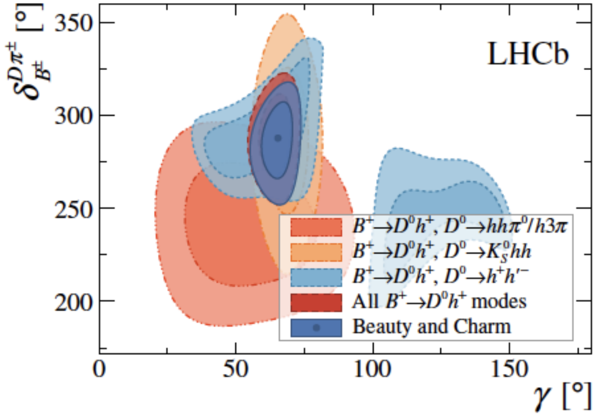


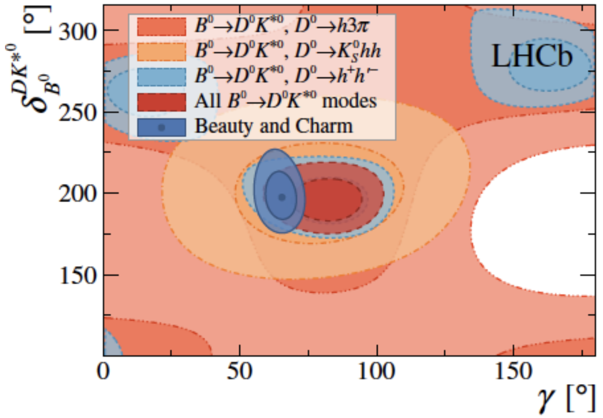
B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[20]	Run 1&2	Updated
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$	[19]	Run 1&2	Updated
$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$	[23]	Run 1&2	Updated
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[20]	Run 1&2	Updated
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	Updated
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	New
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[27]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[29]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[30]	Run 1&2	New

$$\gamma \equiv \varphi_3 = \left(65.4^{+3.8}_{-4.2}\right)^\circ$$

- Most precise by single experiment!
- ~2σ tension between charged and neutral B mesons.







γ/ϕ_3 measurement

Progress over the past two years mostly thanks to LHCb using full (9/fb run 1,2) data sets.

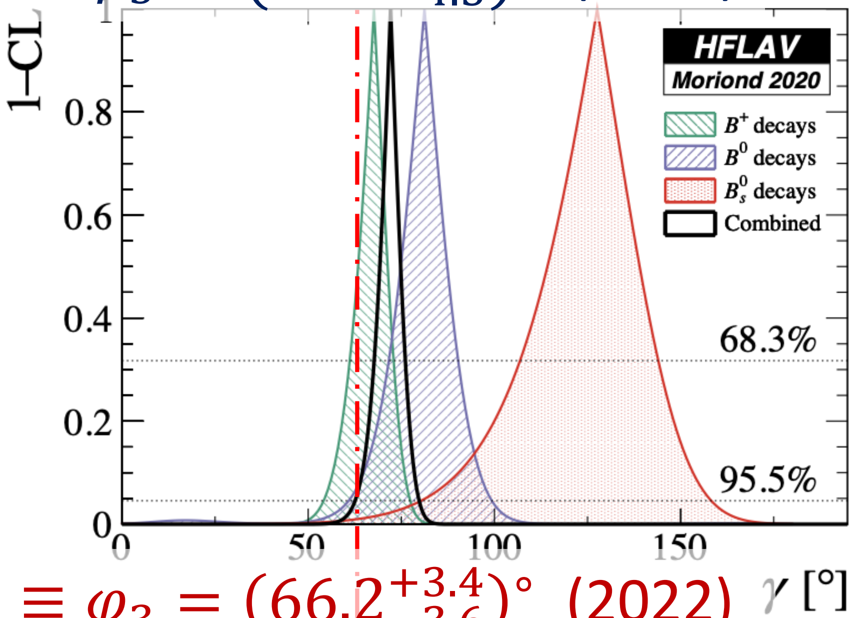
- New methods applied, old results updated
- The errors are improved by ~30%
- The central value moves by almost 2σ
- Now is in good agreement with global CKM fit

$$\gamma = (65.6^{+0.9}_{-2.7})^\circ$$

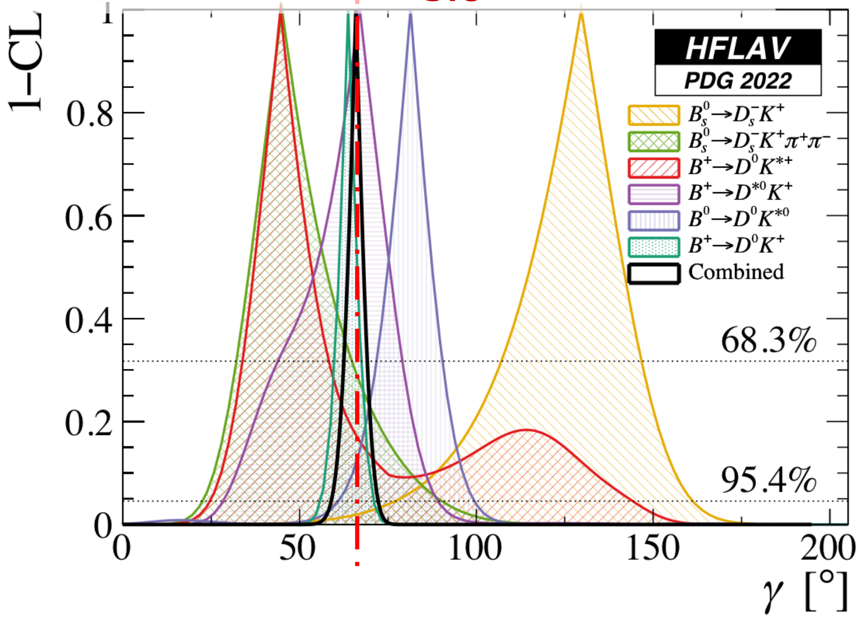
obtained from all other CKM parameters, except γ direct measurements.

- Still some tension between different methods/B's/channels

$$\gamma \equiv \varphi_3 = (72.1^{+4.1}_{-4.5})^\circ \;\; (2020)$$



$$\gamma \equiv \varphi_3 = (66.2^{+3.4}_{-3.6})^\circ \;\; (2022)$$



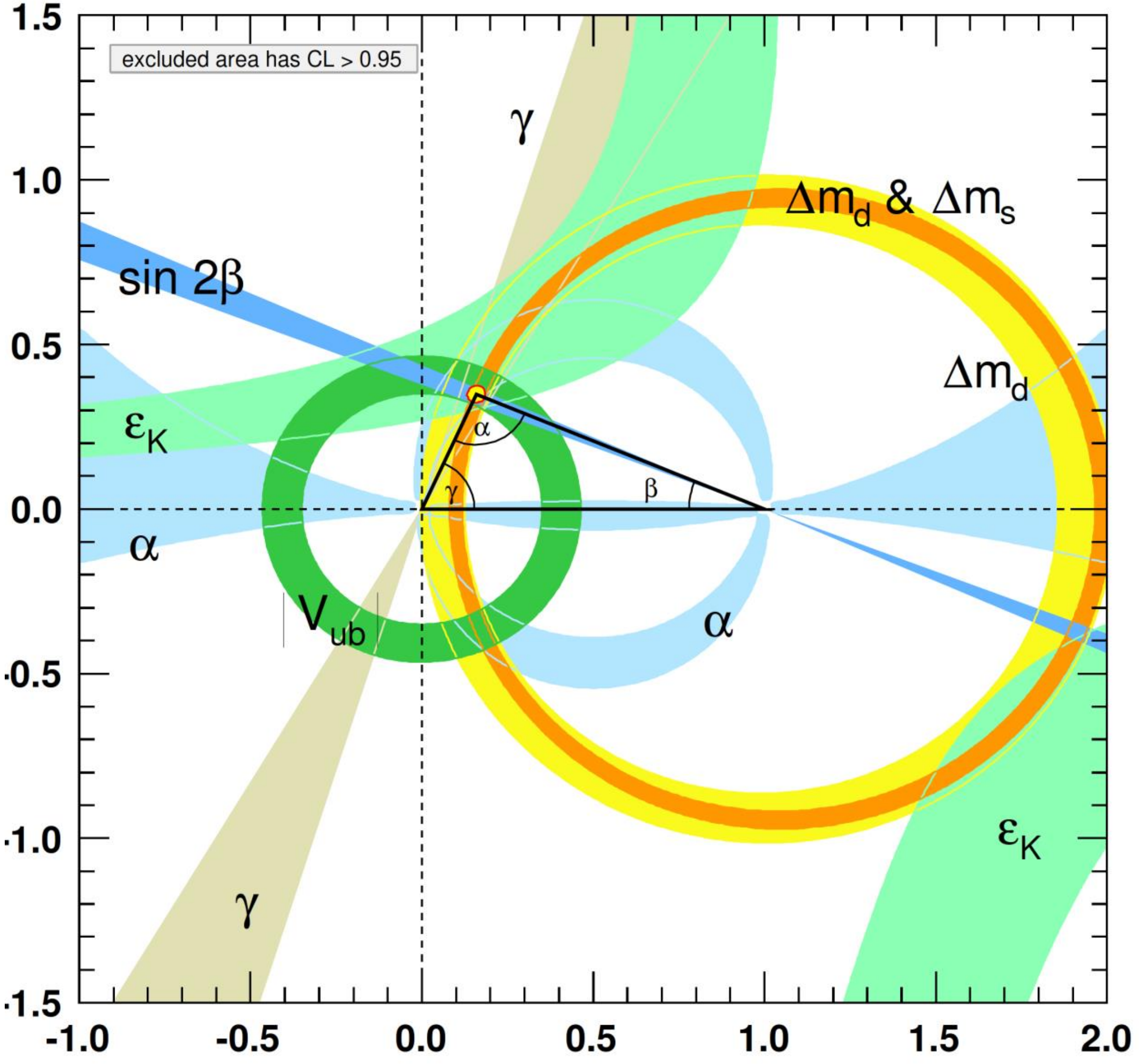
Summary

Progress over the past two years: modest but gradual and incremental.

- LHCb & Belle update many analysis using full data set
- Belle II first results: still smaller statistics than at Belle, but demonstrate readiness to go on

Good agreement in global CKM fit, though some tension between different methods for the same parameter: $|V_{cb}|$, $|V_{ub}|$, γ

Absolute values of CKM elements are dominated by theoretical/model/phenomenological uncertainties. Recent progress in LQCD + new inputs from charm sector to check and verify.



Summary

CKM future in 5-10 years

	B factories		LHCb	
	Belle+BaBar	Belle II	Run 1,2	Upgrade II
$\int \mathcal{L}\,dt$	(1+0.6)/ab	40/ab	9/fb	300/fb
α/ϕ_2	5°	1°		
β/ϕ_1	0.8°	0.2°	1°	0.1°
γ/ϕ_3	8°	1°	4°	0.3°