CKM Parameters: Present and Future

with a focus on $|V_{ub}|$ and $|V_{cb}|$

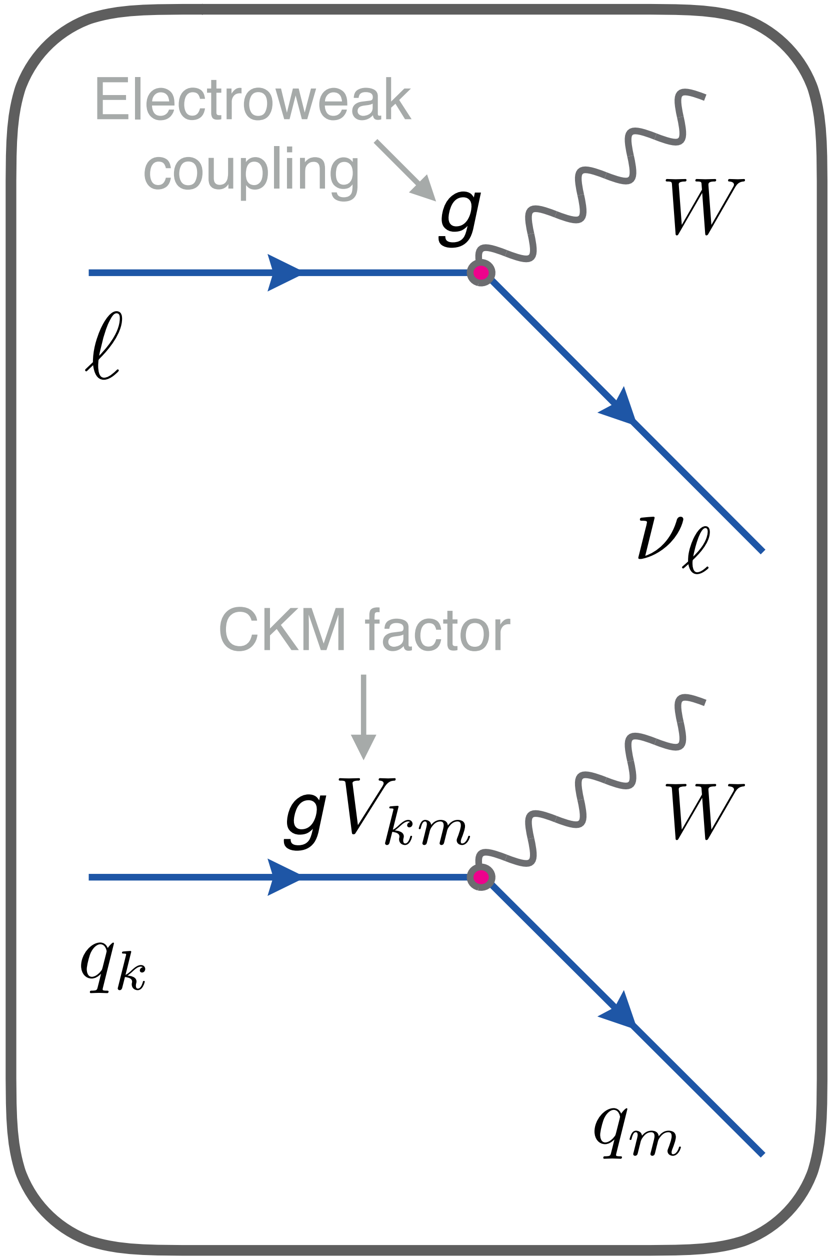
11th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"

Florian Bernlochner | florian.bernlchner@kit.edu

The Weak interaction and the CKM Mechanism

- Weak interaction in the SM is special!
  - Only interaction that allows changing flavour, violates Parity and CP symmetries.
  - Experimentally observe universal coupling for leptons and apparent non-universality for quarks
  - Mediated by massive force carriers

Lead initially to the Cabibbo matrix for 2 quark families with Cabibbo angle $\sin\theta_C \simeq 0.22$



The Weak interaction and the CKM Mechanism

- Weak interaction in the SM is special!
  - Only interaction that allows changing flavour, violates Parity and CP symmetries.
  - Experimentally observe universal coupling for leptons and apparent non-universality for quarks
  - Mediated by massive force carriers

Intimate link to Higgs sector of SM

Yukawa coupling of Higgs boson to quark fields:

$$\mathcal{L}_M^q = -(M_d)_{ij}\overline{D'_{Li}}D'_{Rj} - (M_u)_{ij}\overline{U'_{Li}}U'_{Rj},$$

Family indices

Chirality

Quark fields:

$$U' = (u', c', t')$$
$$D' = (d', s', b')$$

Couplings ~ Matrices related to Yukawa coupling matrices $M_q = vY^q/\sqrt{2}$

The Weak interaction and the CKM Mechanism

- Weak interaction in the SM is special!
  - Only interaction that allows changing flavour, violates Parity and CP symmetries.
  - Experimentally observe universal coupling for leptons and apparent non-universality for quarks
  - Mediated by massive force carriers

Intimate link to Higgs sector of SM

Yukawa coupling of Higgs boson to quark fields:

$$\mathcal{L}_M^q = -(M_d)_{ij}\overline{D'_{Li}}D'_{Rj} - (M_u)_{ij}\overline{U'_{Li}}U'_{Rj},$$

Family indices

Chirality

Quark fields:

$$U' = (u', c', t')$$
$$D' = (d', s', b')$$

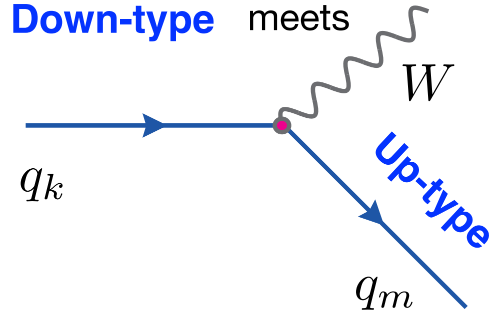
Couplings ~ Matrices related to Yukawa coupling matrices $M_q = vY^q/\sqrt{2}$.

$$A_u^\dagger \; M_u \; B_u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \quad A_d^\dagger \; M_d \; B_d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

Need two independent transformations to diagonalise

Always shows up when

Down-type meets



The Weak interaction and the CKM Mechanism

Only charged current interactions between
Quarks and W-Bosons affected:

Rotation matrices from previous slide

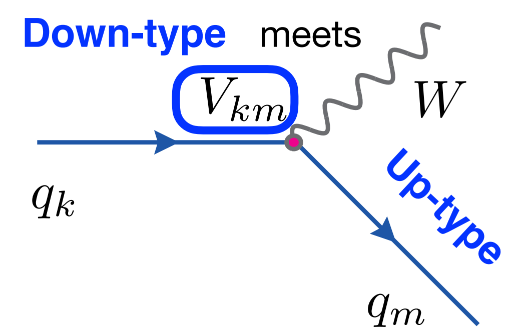
Up-type mass eigenstates

$$\mathcal{L}_{W^{\pm}} = -\frac{g}{\sqrt{2}}\overline{U}_i\gamma^{\mu}\frac{1-\gamma^5}{2}\boxed{\overset{B_u^{\dagger}B_d\,\cdot}{\overset{\shortparallel}{(V_{\mathrm{CKM}})}}}_{ij}\,D_j W_{\mu}^{+} + \mathrm{h.c.},$$

Down-type mass eigenstates

V-A Current that violates P, but preserves
CP if V_{ckm} has no complex phase

Always shows up when



- And this is what gives you the famous CKM Matrix V_{ckm}

The Weak interaction and the CKM Mechanism

Only charged current interactions between Quarks and W-Bosons affected:

Rotation matrices from previous slide

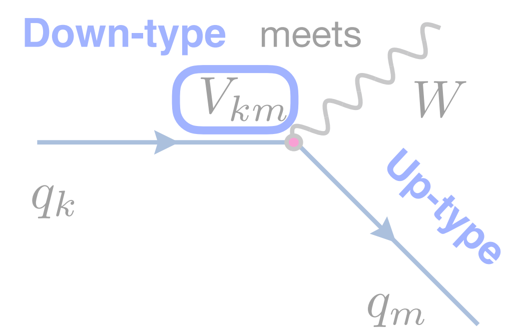
Up-type mass eigenstates

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} \overline{U}_i \gamma^\mu \frac{1-\gamma^5}{2} \underbrace{\boxed{(V_{\mathrm{CKM}})}}_{\overset{\|}{B_u^\dagger B_d}}{}_{ij} D_j W_\mu^+ + \mathrm{h.c.},$$

Down-type mass eigenstates

V-A Current that violates P, but preserves CP if V_{ckm} has no complex phase

Always shows up when



- And this is what gives you the famous CKM Matrix V_{ckm}

- But there is more:
  - V_{ckm} is unitary in the SM
    - For 3 quark families can be parametrised via **4 Parameters**
  - If V_{ckm} has complex Phase ↔ CPV

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

do we /
should we /
can we

Why measure $|V_{ub}|$ & $|V_{cb}|$?

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

Why is it important to measure $|V_{ub}|$ and $|V_{cb}|$?

$$
\begin{array}{c|ccc}
 & d & s & b \\
\hline
u & & & \\
c & & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} & \\
t & & &
\end{array}
$$

CKM Matrix

SM: Unitary 3x3 Matrix

Overconstrain Unitarity condition

→ Potent test of Standard Model

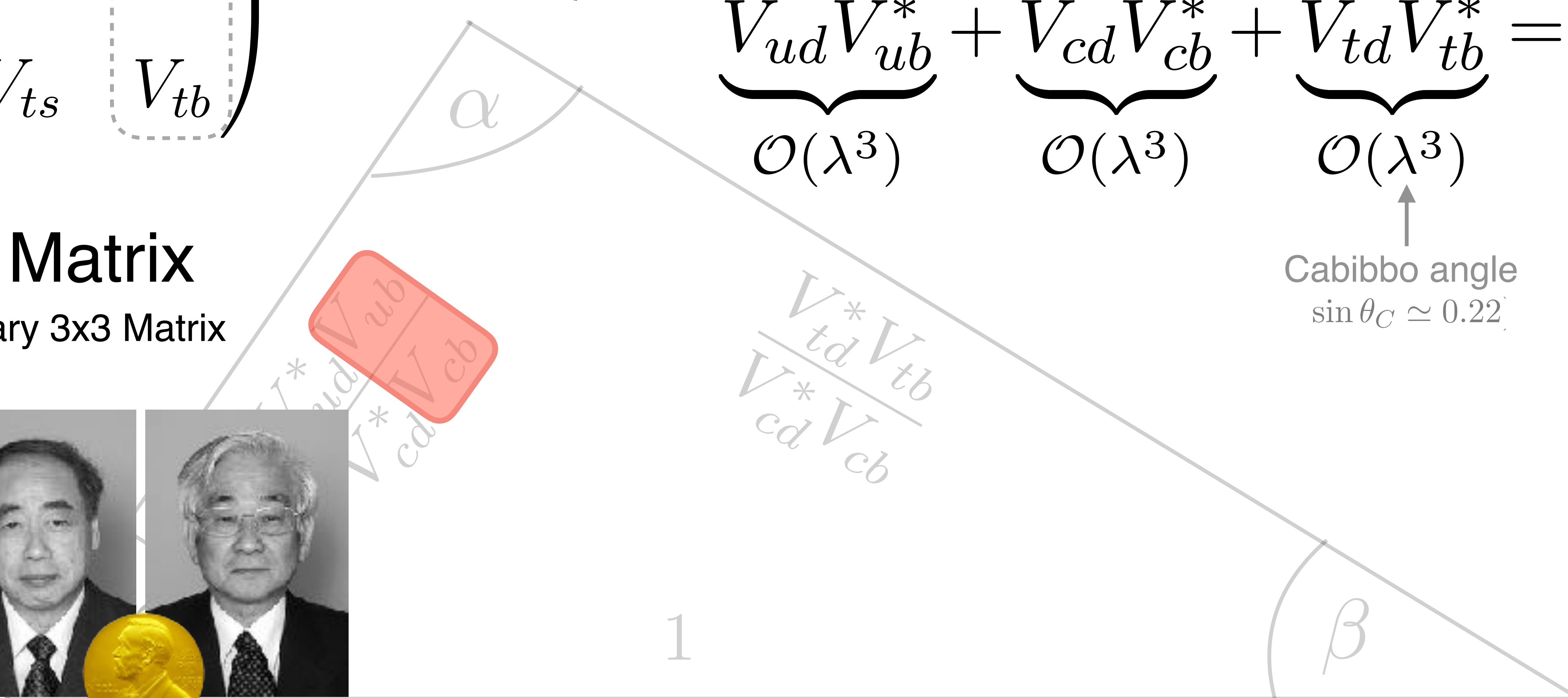
Unitarity

$CC^\dagger = 1$

$$\underbrace{V_{ud}V_{ub}^*}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{cd}V_{cb}^*}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{td}V_{tb}^*}_{\mathcal{O}(\lambda^3)} = 0$$

Cabibbo angle

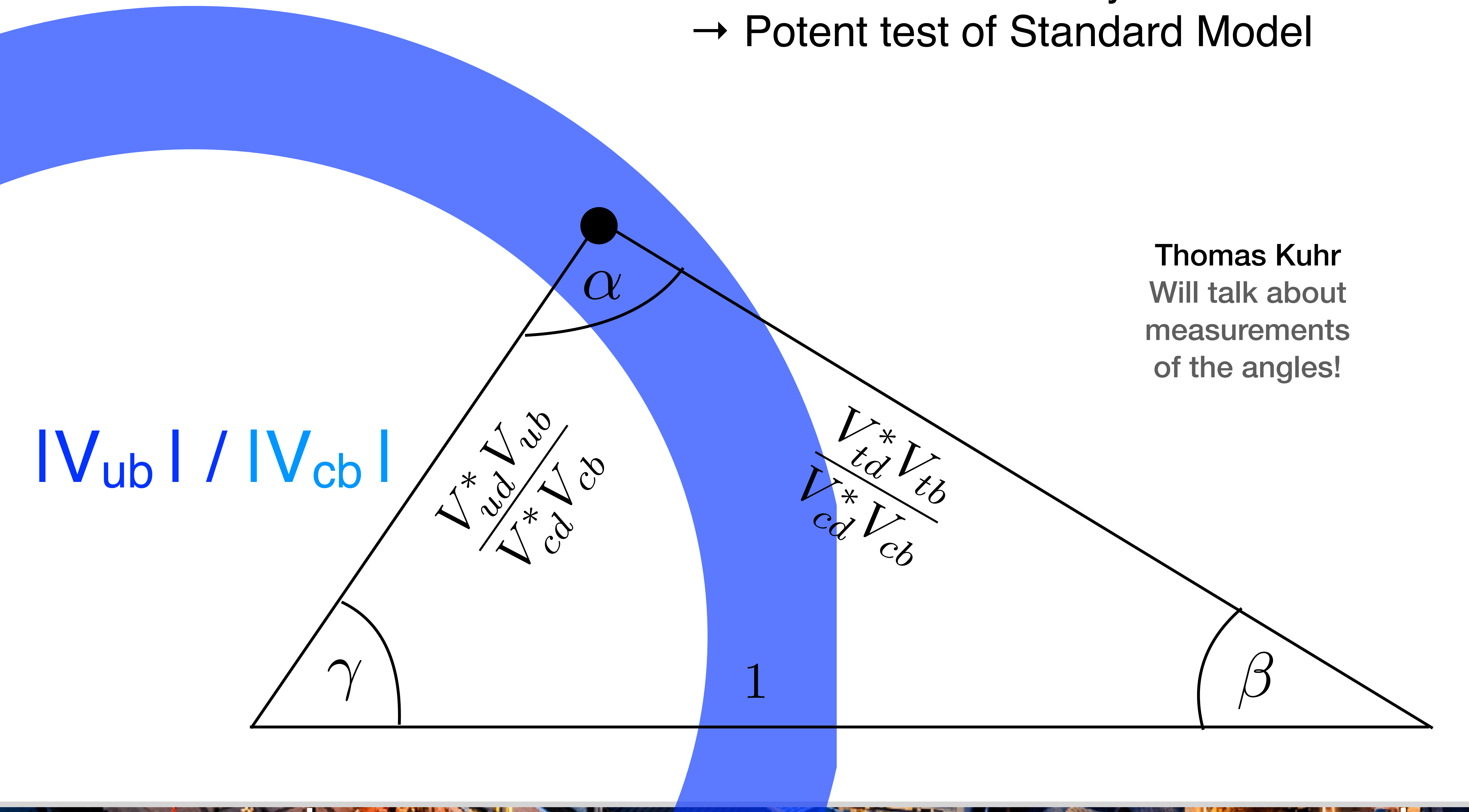
$\sin\theta_C \simeq 0.22$



Nobel prize 2008!

Why is it important to measure $|V_{ub}|$ and $|V_{cb}|$?

Overconstrain Unitarity condition
→ Potent test of Standard Model



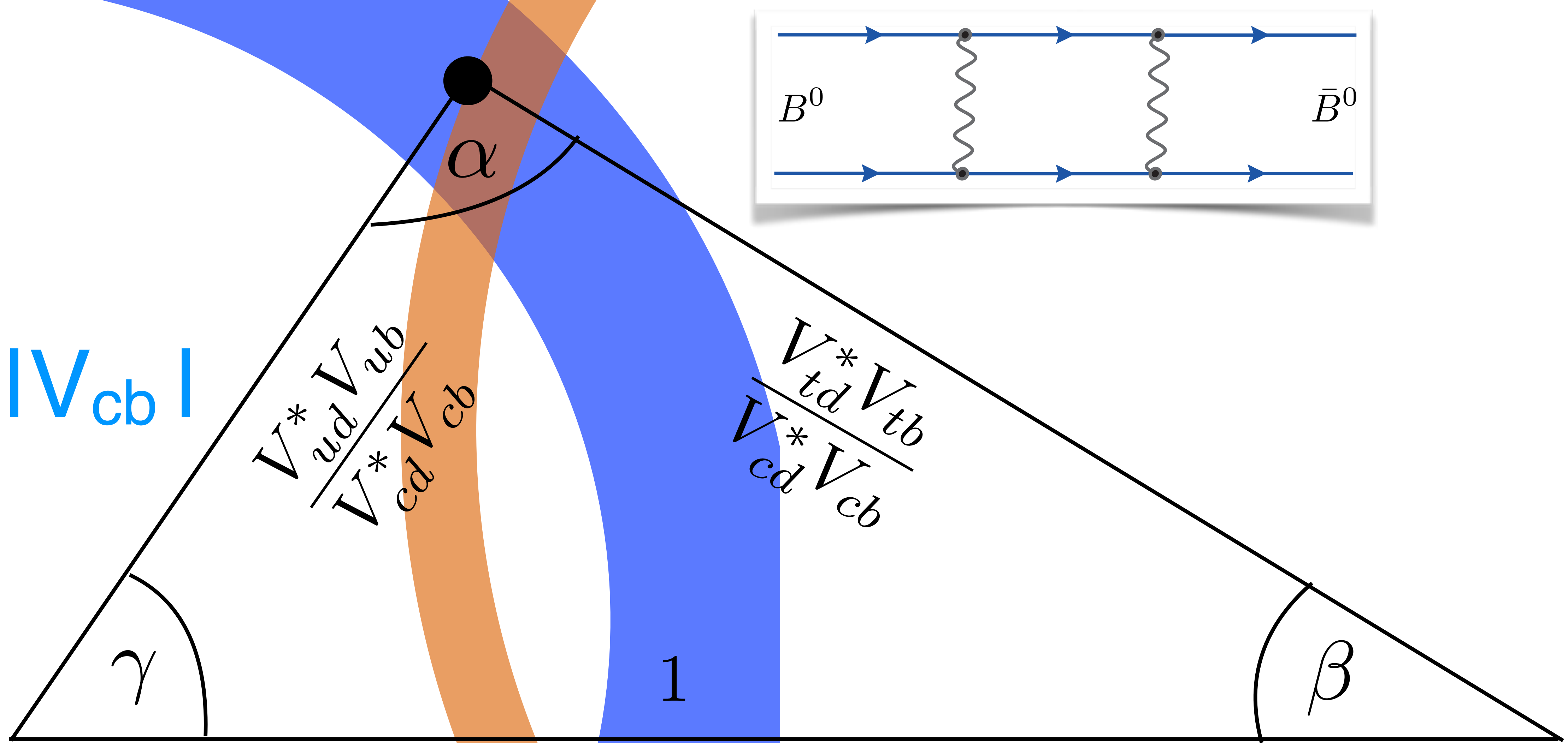
Thomas Kuhr
Will talk about measurements of the angles!

Why is it important to measure $|V_{ub}|$ and $|V_{cb}|$?

Overconstrain Unitarity condition
→ Potent test of Standard Model

B-Meson Mixing

$|V_{ub}| \,/\, |V_{cb}|$



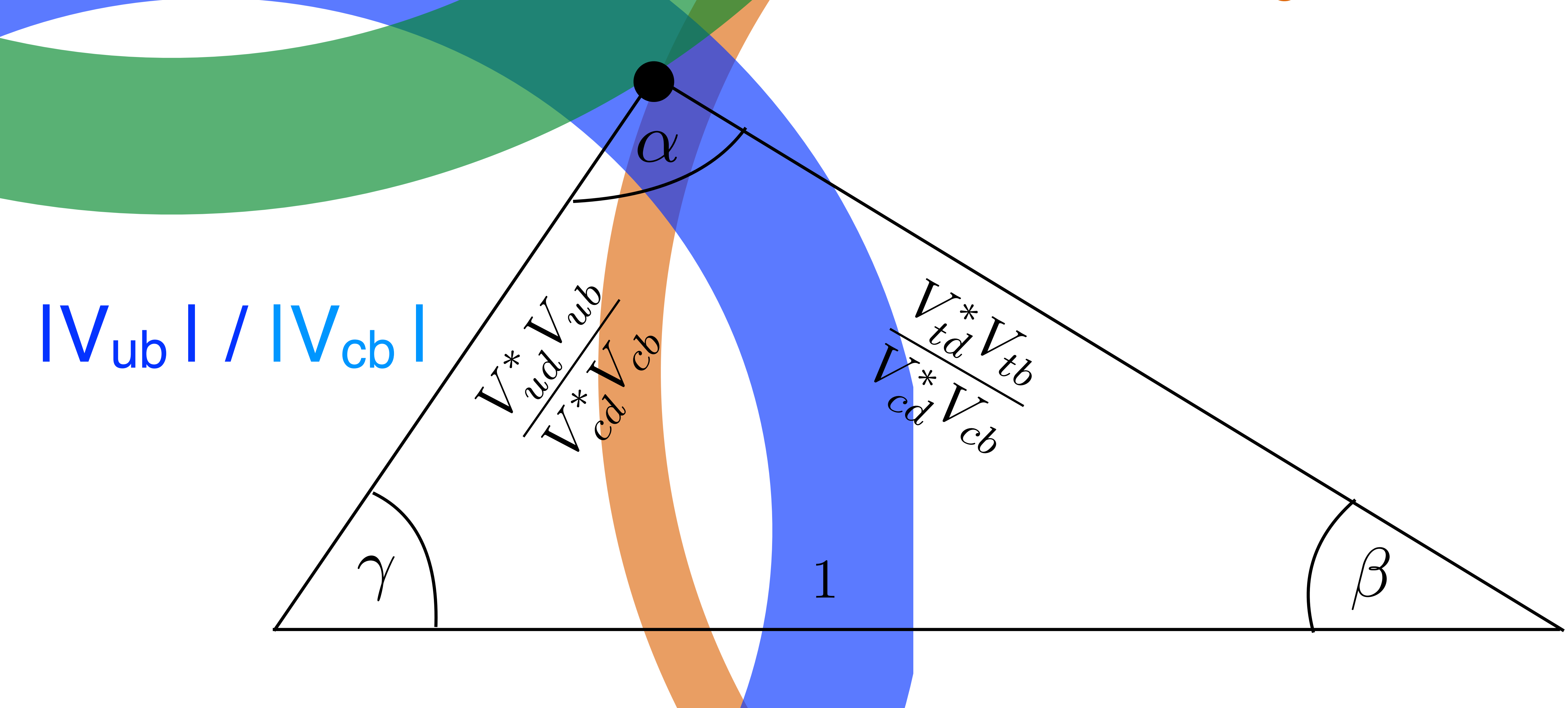
Why is it important to measure $|V_{ub}|$ and $|V_{cb}|$?

CPV Kaon Mixing

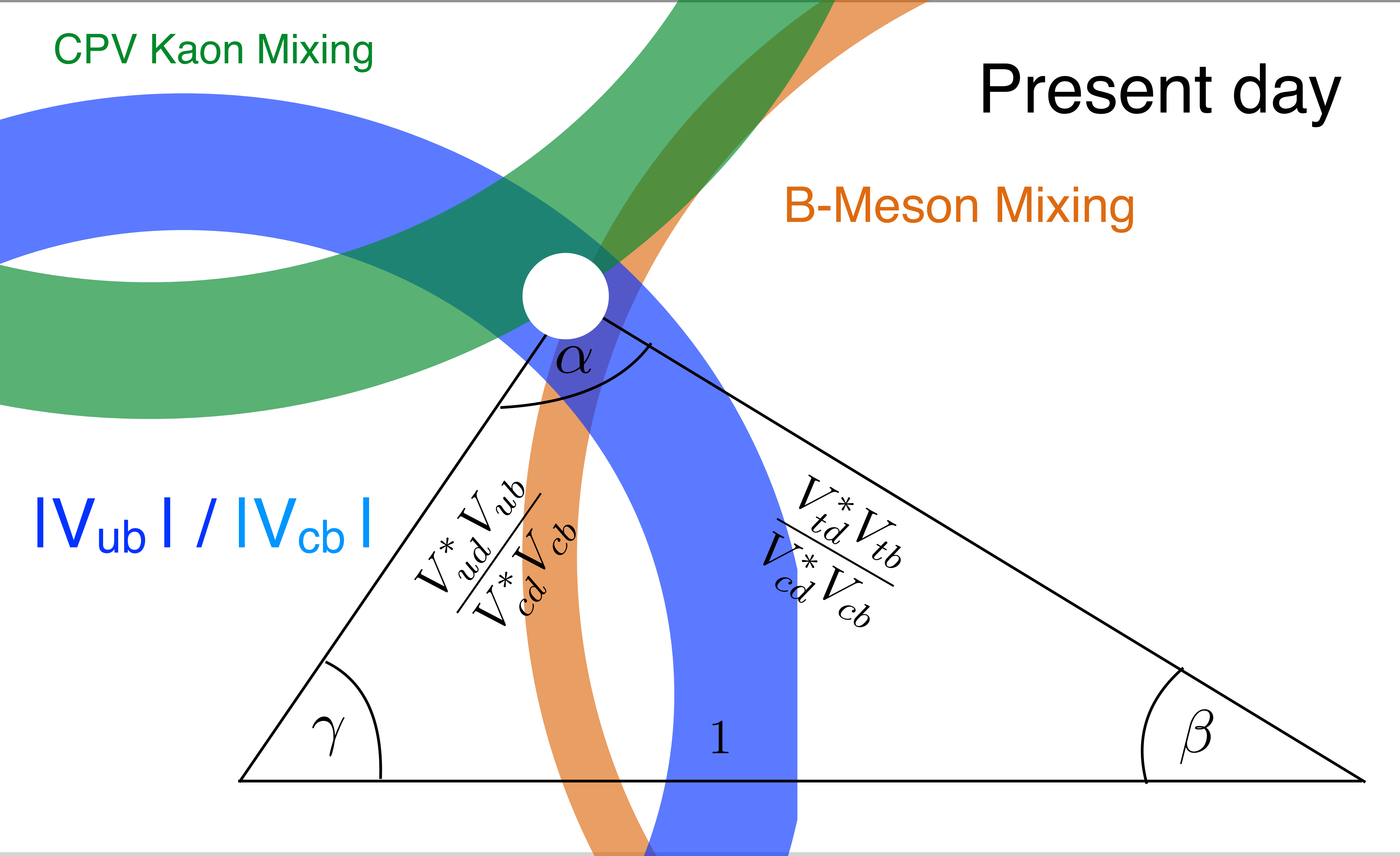
Overconstrain Unitarity condition
→ Potent test of Standard Model

B-Meson Mixing

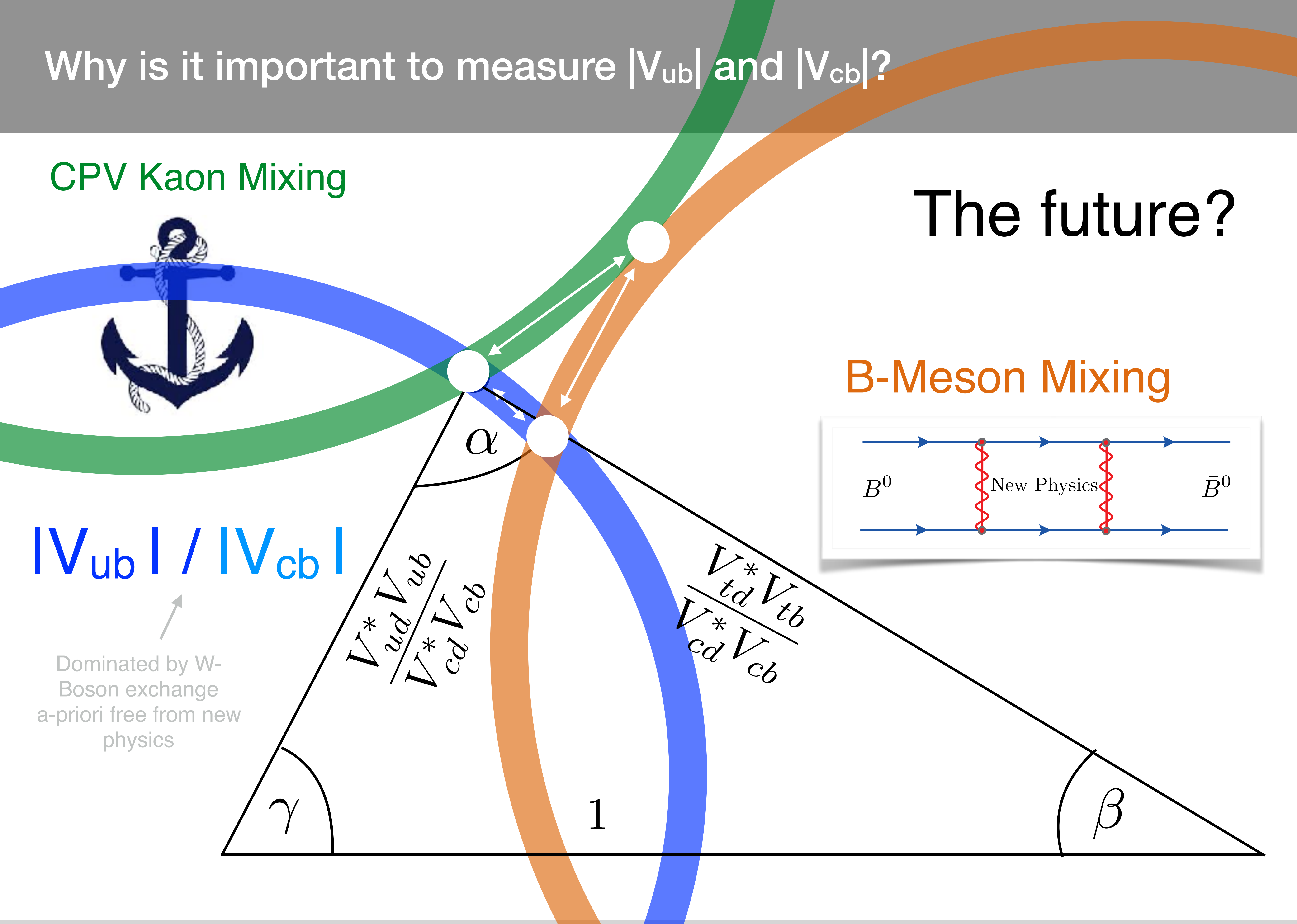
$|V_{ub}| \,/\, |V_{cb}|$



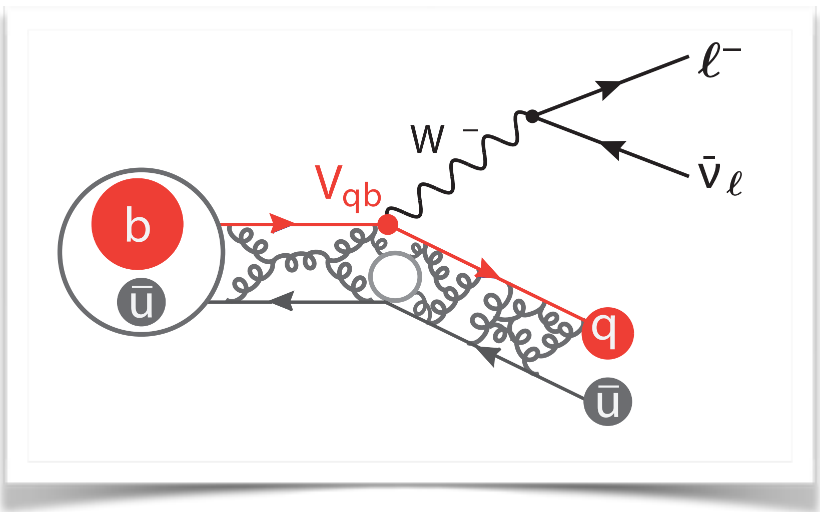
Why is it important to measure $|V_{ub}|$ and $|V_{cb}|$?



Why is it important to measure $|V_{ub}|$ and $|V_{cb}|$?



How do we measure $|V_{ub}|$ and $|V_{cb}|$?



Inclusive $|V_{ub}|$

$$\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell$$

+ Fermi Motion / Shape Function

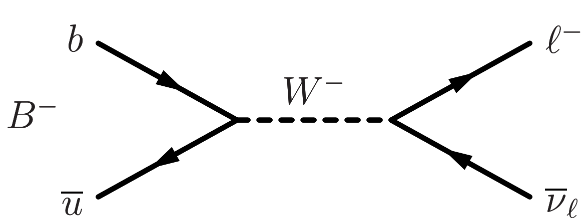
Inclusive $|V_{cb}|$

$$\bar{B} \to X_c \, \ell \, \bar{\nu}_\ell$$

Operator Product Expansion

$$\boxed{\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q \, \ell \, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]}$$

'Leptonic' $|V_{ub}|$



$$\boxed{\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2}$$

B-Meson decay constant

Exclusive $|V_{ub}|$

$$\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell, \Lambda_b \to p \, \mu \, \bar{\nu}_\mu$$

Exclusive $|V_{cb}|$

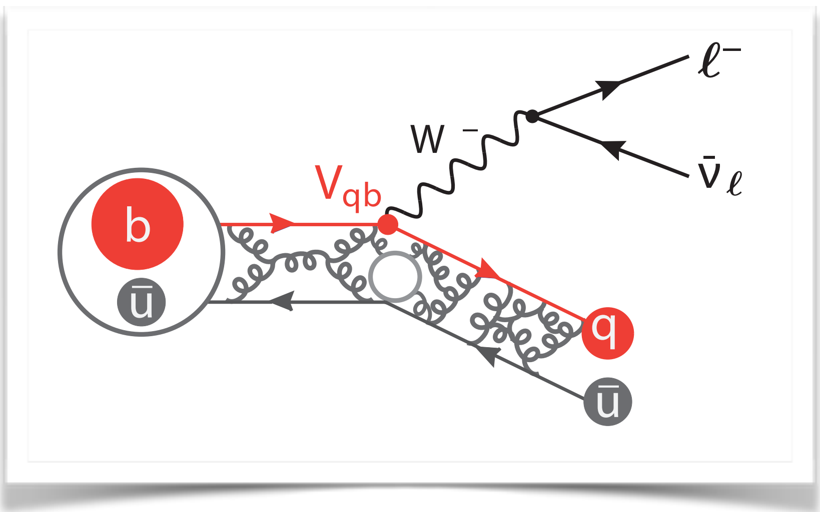
$$\bar{B} \to D \, \ell \, \bar{\nu}_\ell, \bar{B} \to D^* \, \ell \, \bar{\nu}_\ell$$

$$\boxed{\mathcal{B} \propto |V_{cb}|^2 \, f^2}$$

Form Factors

$$\langle B | H_\mu | P \rangle = (p + p')_\mu \, f_+$$

How do we measure $|V_{ub}|$ and $|V_{cb}|$?



Inclusive $|V_{ub}|$

Inclusive $|V_{cb}|$

Measured
Branching Fraction

$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(\bar{B} \to X_q \, \ell \, \bar{\nu}_\ell)}{\tau \, \Gamma(\bar{B} \to X_q \, \ell \, \bar{\nu}_\ell)}}$$

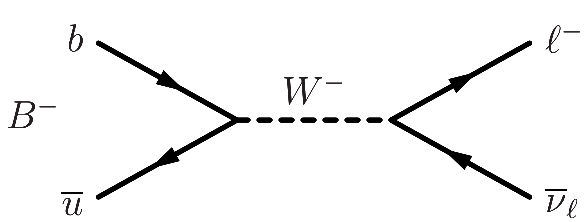
Prediction from
Theory but often also constrained from **measured differential distributions**

Theory from non-perturbative Methods:

- Lattice QCD (high q^2)
- QCD Sum rules (low q^2)

$$q^2 = (p - p')^2$$

'Leptonic' $|V_{ub}|$



$$\boxed{\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2}$$

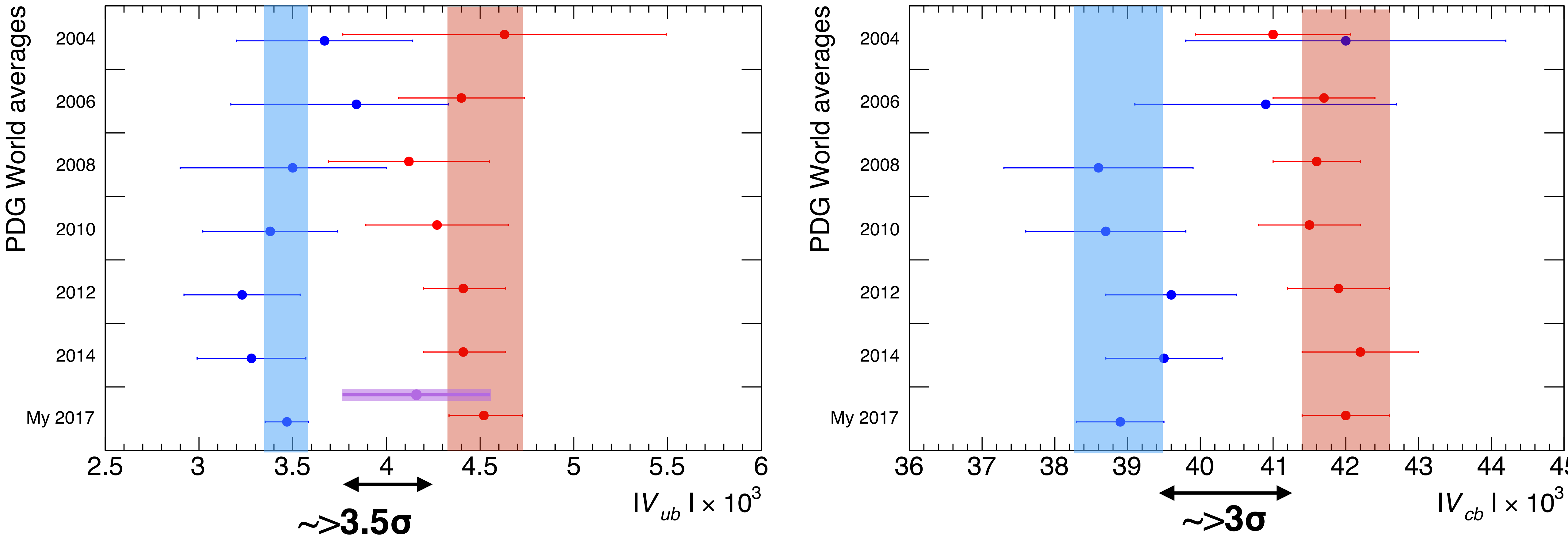
B-Meson decay constant

inclusive, exclusive, leptonic

inclusive, exclusive

Current status of $|V_{ub}|$ and $|V_{cb}|$

Overview: 2004 - 2017



$$\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell, \bar{B} \to D^{(*)} \, \ell \, \bar{\nu}_\ell$$
$$\Lambda_b \to p \, \mu \, \bar{\nu}_\mu$$

$$\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell, \bar{B} \to X_c \, \ell \, \bar{\nu}_\ell$$

$$\bar{B} \to \tau \, \bar{\nu}_\tau$$

Exclusive Approach

Inclusive Approach

Leptonic Decays

Recent developments: Excl. $|V_{ub}|$

$$q^2 = (p_B - p_\pi)^2$$

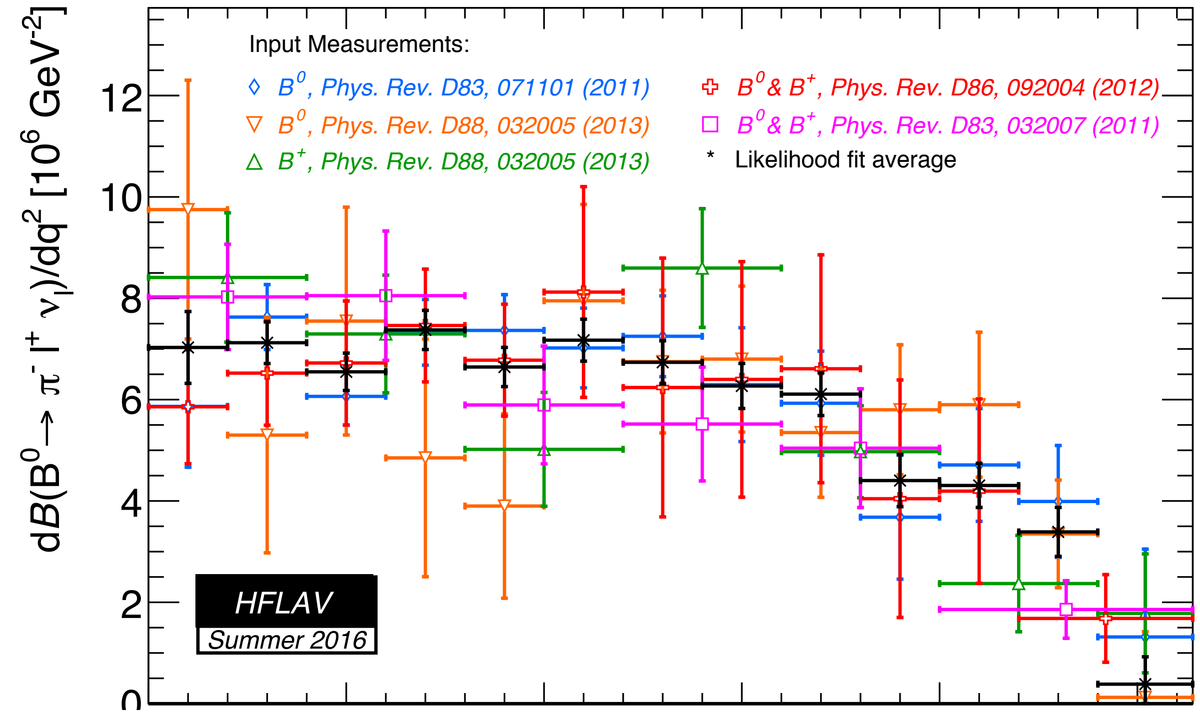
arXiv:1612.07233

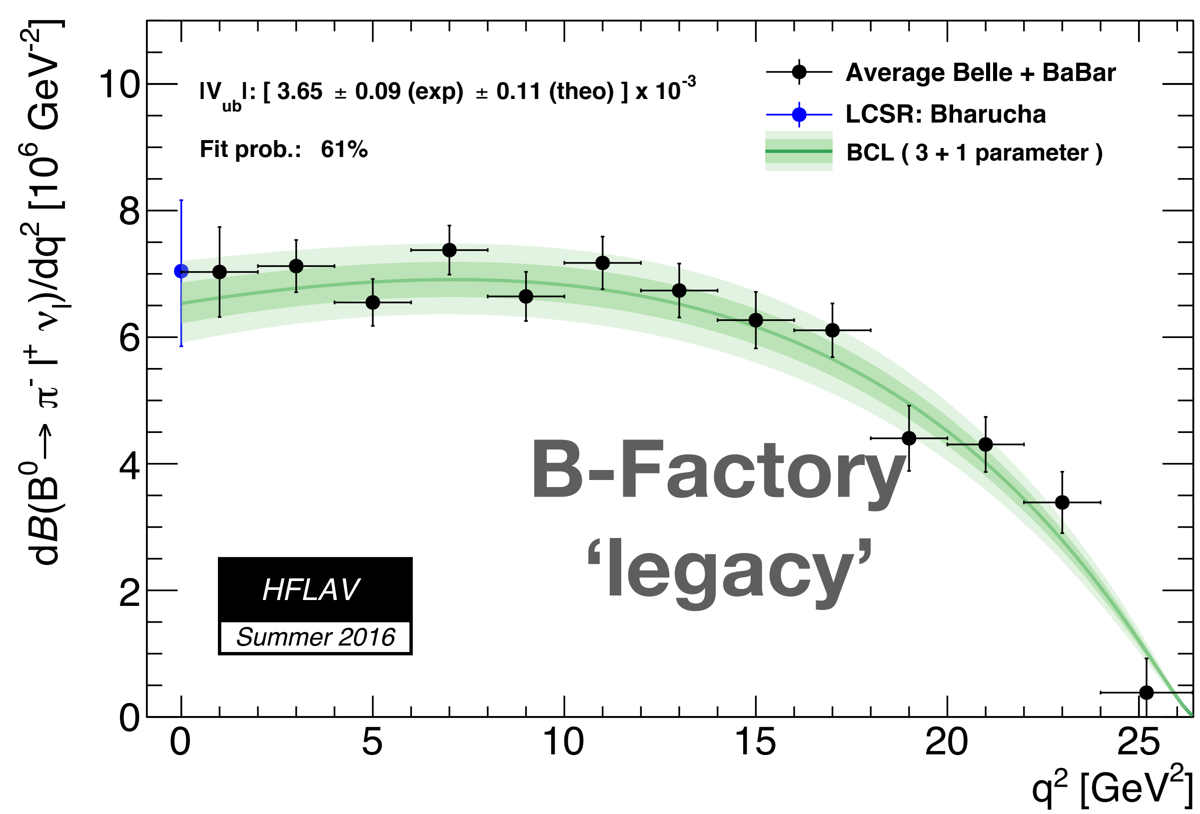
New HFAG Average of $\bar{B} \to \pi \ell \bar{\nu}_\ell$

- Combines measured q^2 bins into global Likelihood
  - **Systematics** described with **Nuisance parameters**, allowing for correlated 'pulls'
- **Second fit** to combined spectrum, lattice information and sum-rule predictions
  - Simultaneously determine form factors and $|V_{ub}|$

BGL	*Data+Lattice*	*Data+ Lattice+LCSR*
$|V_{ub}| \times 10^3$	**3.68 ± 0.16**	**3.65 ± 0.14**

BGL: Phys. Rev. Lett. 74, 4603 (1995)

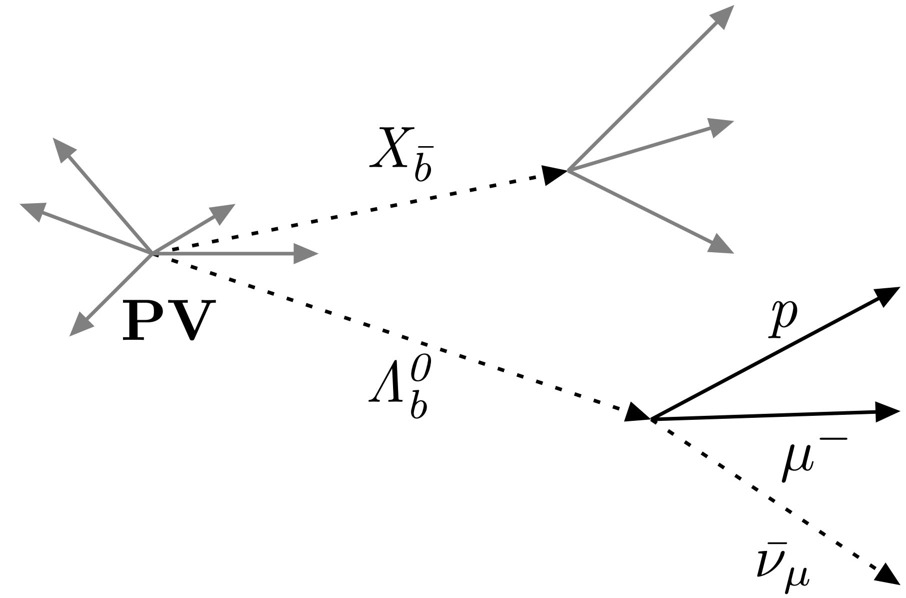


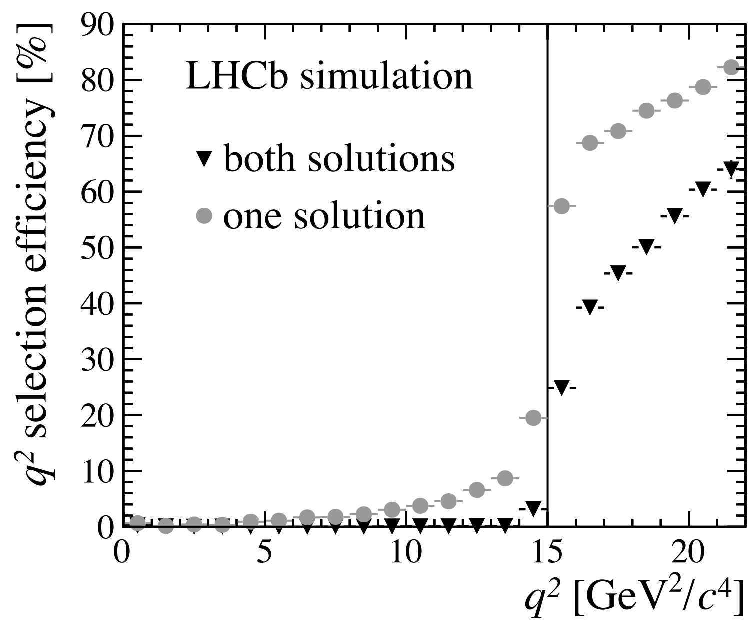


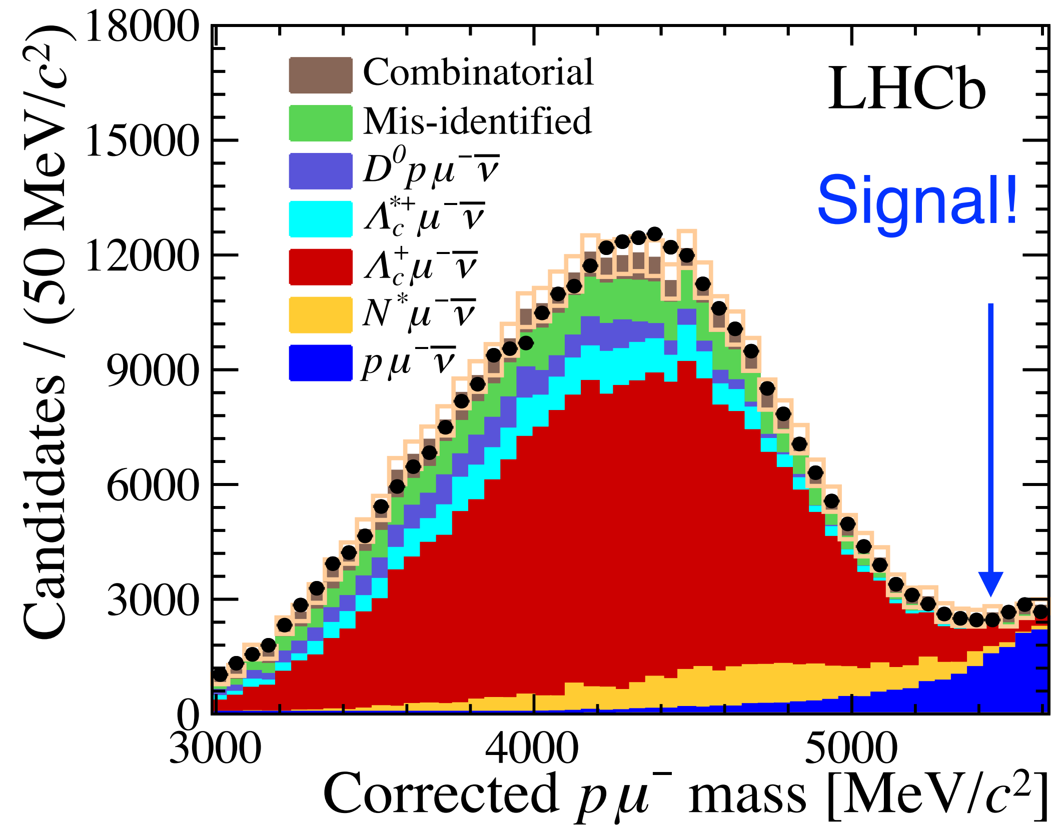
$$q^2 = (p_{\Lambda_b} - p_p)^2$$

First measurement at a Hadron Collider

- Uses $\Lambda_b \to p\,\mu\,\bar{\nu}_\mu$ & $\Lambda_b \to \Lambda_c\,\mu\,\bar{\nu}_\mu$
- q^2 reconstructed up to two-fold ambiguity







Measure $\dfrac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}}$ using

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp,$$

$p\mu$- or $\Lambda_c\mu$-pair mass $p\mu$- or $\Lambda_c\mu$-pair p_T

Recent developments: Excl. $|V_{ub}|$

$$q^2 = (p_{\Lambda_b} - p_p)^2$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (0.95 \pm 0.04 \pm 0.07) \times 10^{-2}$$

Includes updated $\Lambda_c \to pK\pi$ BF from HFAG/BES III

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$ ← **± 3.7**
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

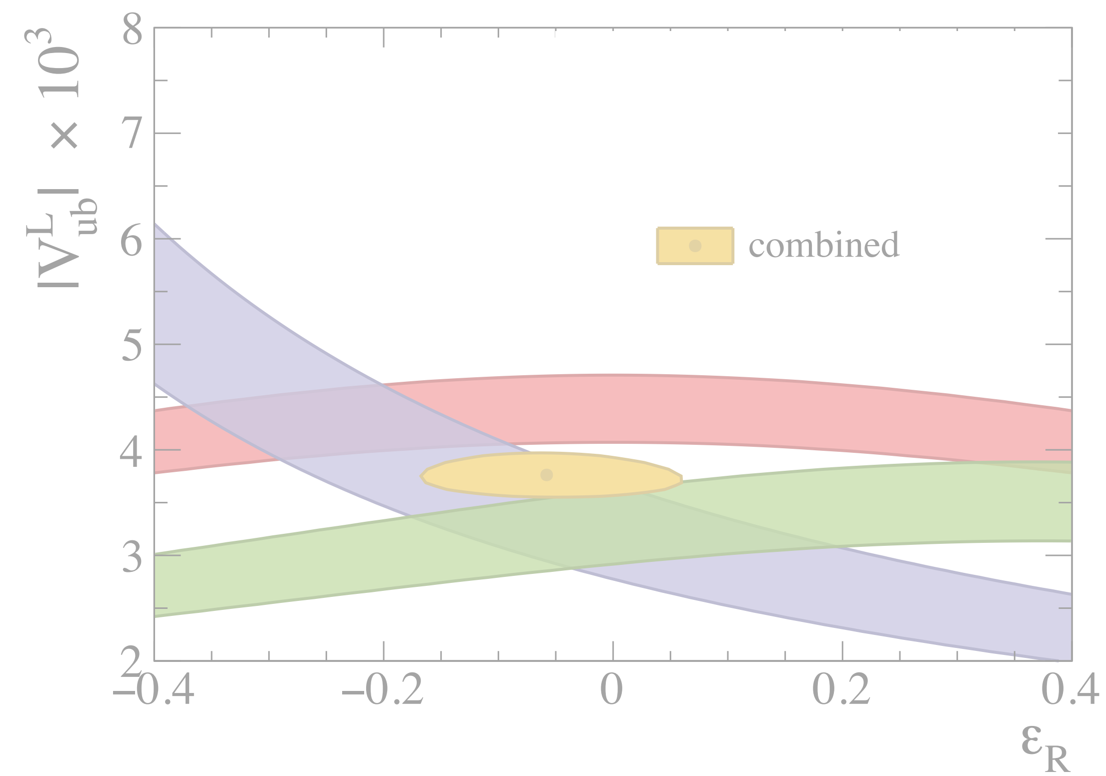
Using Lattice results from Phys. Rev. D 92, 034503 (2015) can convert this into $|V_{ub}|/|V_{cb}|$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.080 \pm 0.004_{Exp.} \pm 0.004_{F.F.}$$

Exclusive $|V_{cb}|$ Average

	$\Lambda_c \to p\mu\nu$	$B \to \pi\ell\nu$
$|V_{ub}| \times 10^3$	**3.11 ± 0.20**	**3.65 ± 0.14**

~>2σ



Recent developments: Excl. $|V_{ub}|$

$$q^2 = (p_{\Lambda_b} - p_p)^2$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (0.95 \pm 0.04 \pm 0.07) \times 10^{-2}$$

Includes updated $\Lambda_c \to pK\pi$ BF from HFAG/BES III

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$ ← ± 3.7
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

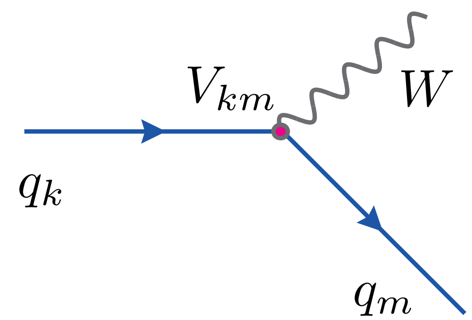
Using Lattice results from Phys. Rev. D 92, 034503 (2015)

can convert this into $|V_{ub}|/|V_{cb}|$

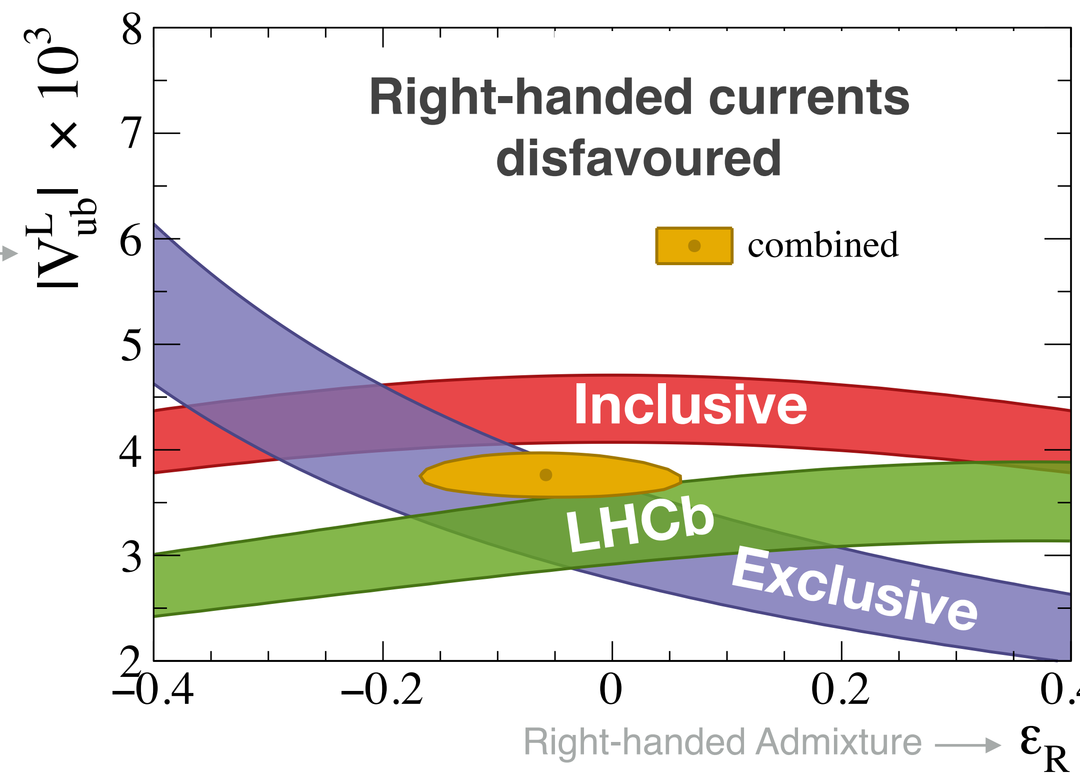
$$\frac{|V_{ub}|}{|V_{cb}|} =$$

$|V_{ub}| \times 10$

SM: V - A interaction



Corrected $|V_{ub}|$ →



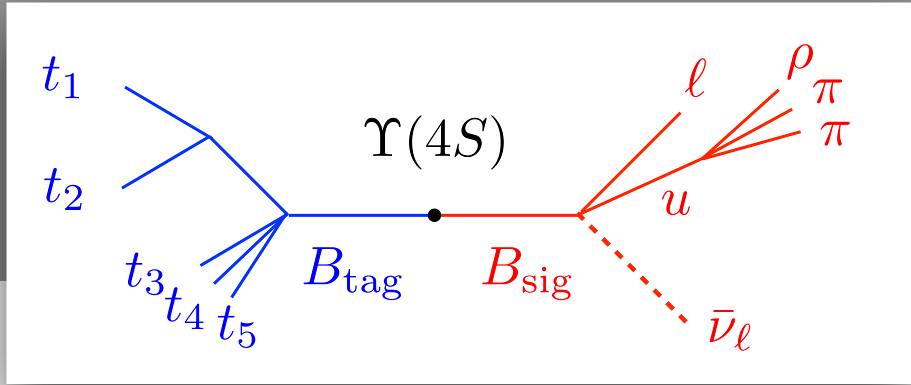
What if: **NP adds** V + A interaction?

ϵ_R

↑ Right-handed Admixture

Decay	$\lvert V_{ub}\rvert \times 10^3$	ϵ_R dependence
$B \to \pi\ell\bar{\nu}$	3.23 ± 0.30	$1 + \epsilon_R$
$B \to X_u\ell\bar{\nu}$	4.39 ± 0.21	$\sqrt{1+\epsilon_R^2}$
$B \to \tau\bar{\nu}_\tau$	4.32 ± 0.42	$1 - \epsilon_R$

Recent developments: Excl. $|V_{cb}|$



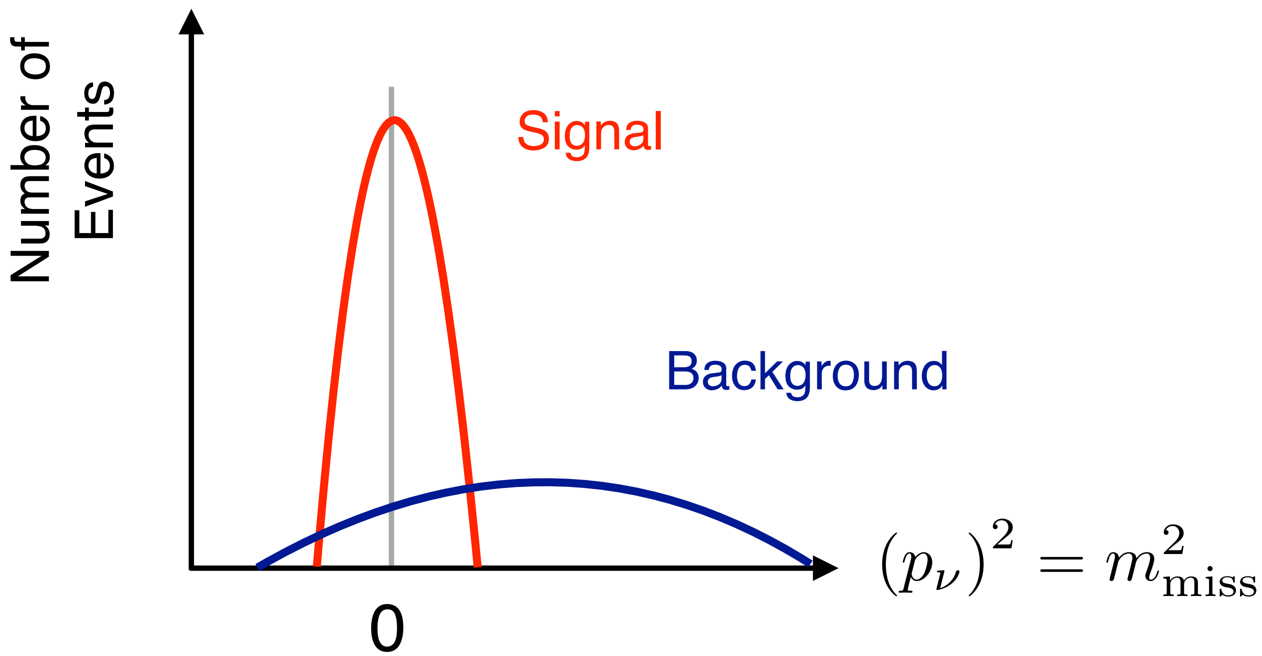
Belle-Conf 1612, 1702.01521
Phys. Rev. D 93, 032006 (2016)

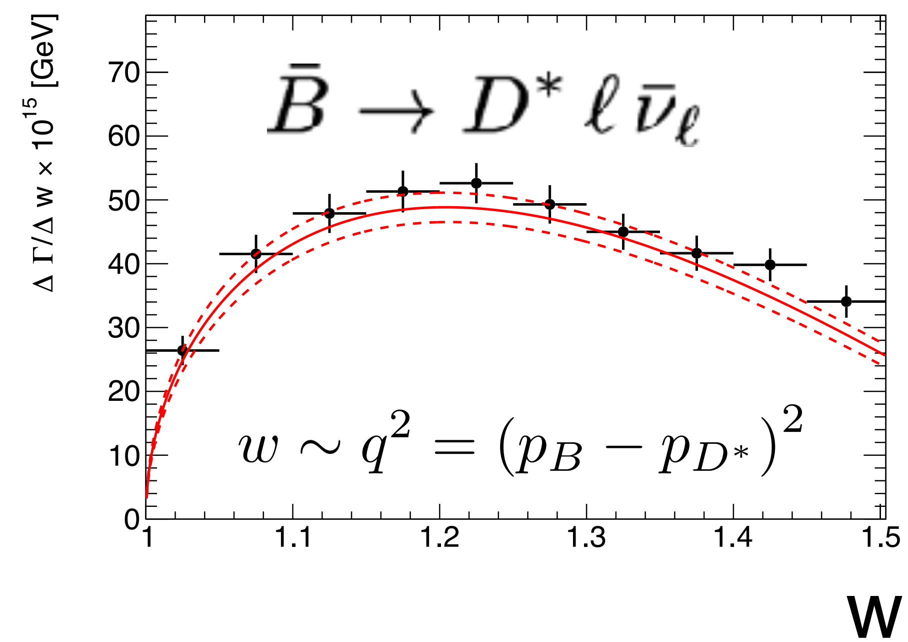
Two new measurements from Belle

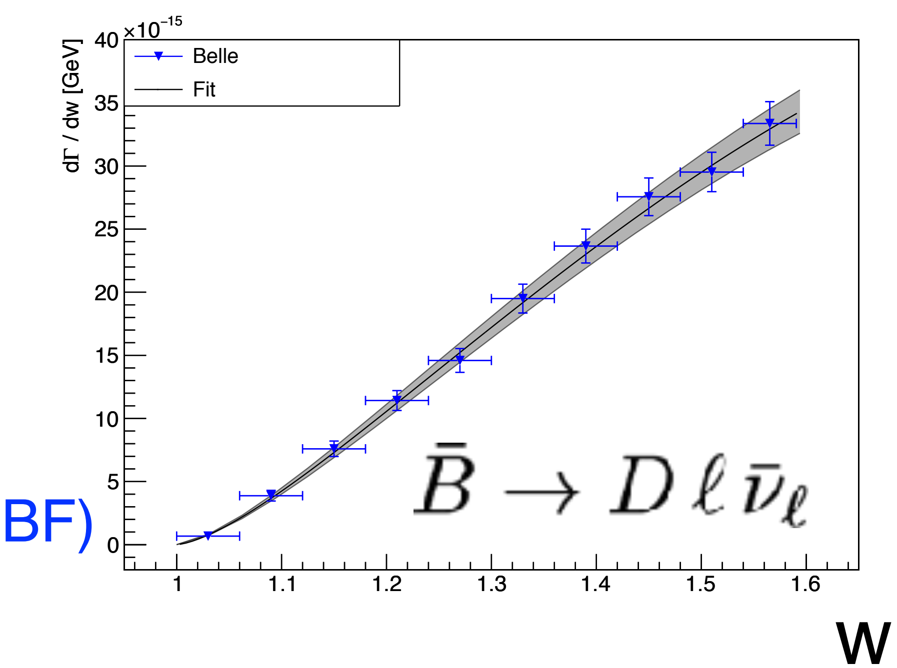
- Measure $\bar{B} \to D^* \, \ell \, \bar{\nu}_\ell$ & $\bar{B} \to D \, \ell \, \bar{\nu}_\ell$
- **Hadronic tagged,** allows for neutrino reconstruction

$$p_{\text{miss}} = \boxed{p_\nu} = \left(p_{e^+ \, e^-} - \boxed{p_{\text{tag}}} - \boxed{p_{X_q} - p_\ell} \right)$$

- Signal extracted via $(p_\nu)^2 = m^2_{\text{miss}}$

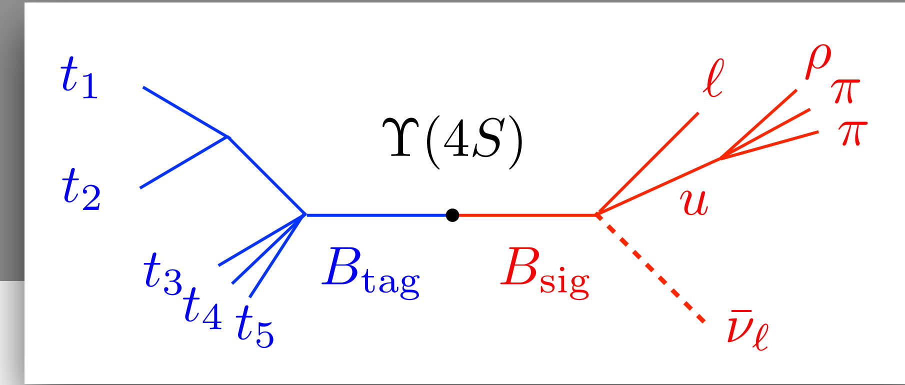






- Reconstruct w ~ q² and projections of *D** decay angles
  - **Largest Systematic**: hadronic tagging calibration (~3-4% on BF)
  - Full correlations of *D** decay angles and w

Recent developments: Excl. $|V_{cb}|$



Belle-Conf 1612, 1702.01521
Phys. Rev. D 93, 032006 (2016)

Two new measurements from Belle

- Measure $\bar{B} \to D^* \ell \bar{\nu}_\ell$ & $\bar{B} \to D \ell \bar{\nu}_\ell$
- **Hadronic tagged,** allows for neutrino reconstruction

$$p_{\rm miss} = \boxed{p_\nu} = \left(p_{e^+e^-} - \boxed{p_{\rm tag}} - \boxed{p_{X_q} - p_\ell}\right)$$

- Signal extracted via $(p_\nu)^2 = m^2_{\rm miss}$

CLN: Phys. Lett. B380, 376 (1996)

CLN	*D**	*D*	*Inclusive*
$\|V_{cb}\| \times 10^3$	37.4 ± 1.3	39.9 ± 1.3	42.0 ± 0.6

~1.4 σ

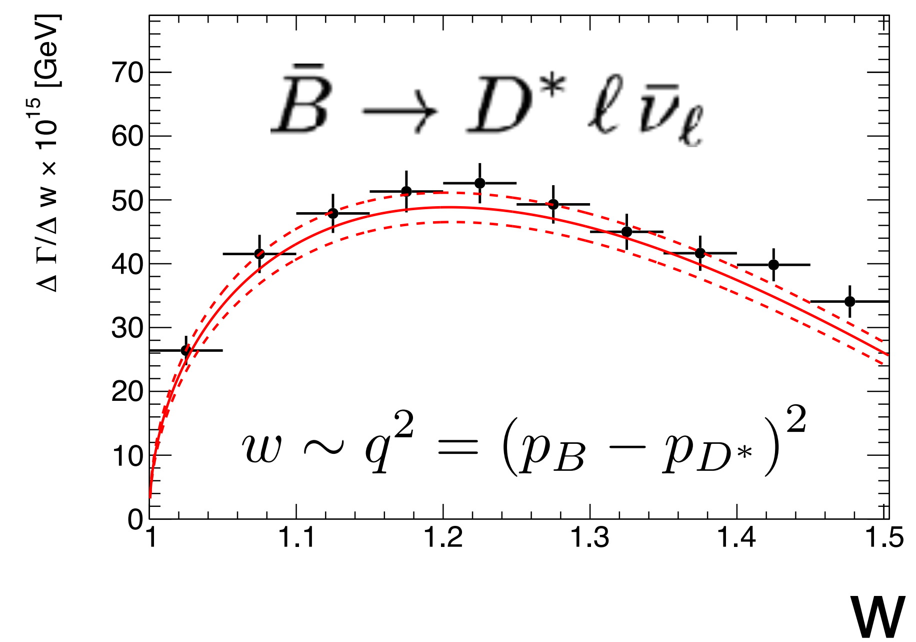
BGL: Phys. Rev. Lett. 74, 4603 (1995)

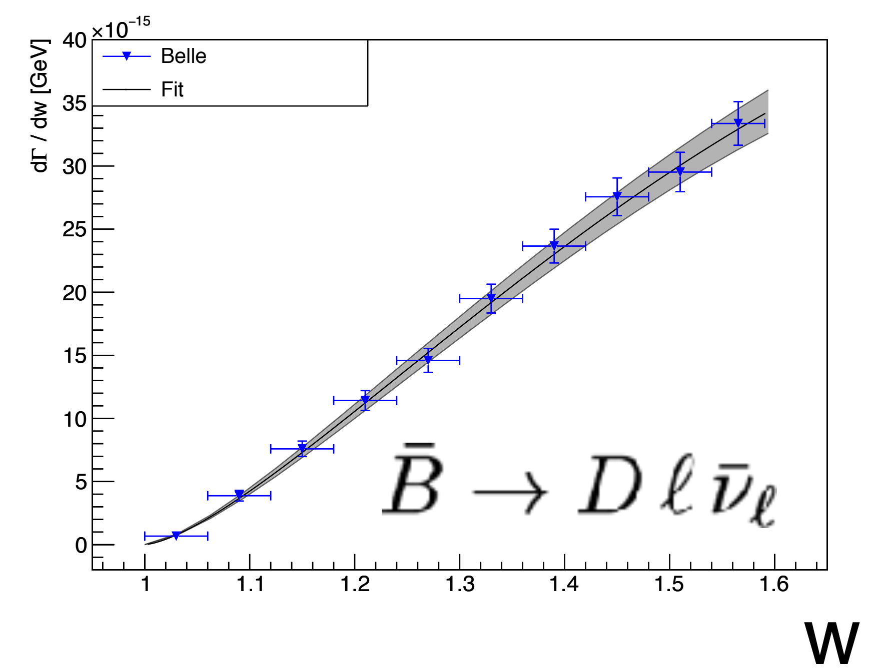
BGL	*D*
$\|V_{cb}\| \times 10^3$	40.8 ± 1.1

!

See also
Phys. Rev. D 94, 094008 (2016)

- Both measurements provide **unfolded** decay distributions





Recent developments: Excl. $|V_{cb}|$

*D** **unfolded** distributions analysed by three groups

Includes additional measurement & beyond zero recoil lattice constraints

arXiv:1703.06124,1703.08170

ρ = ?

$\bar{B} \to D^* \ell \bar{\nu}_\ell$

CLN	*D**
$|V_{cb}| \times 10^3$	38.2 ± 1.5

CLN: Phys. Lett. B380, 376 (1996)

From unfolded data, slightly higher than 'folded' result of previous slide

BGL	*D**
$|V_{cb}| \times 10^3$	41.9 ± 1.9

BGL: Phys. Rev. Lett. 74, 4603 (1995)

arXiv:1703.05330

BLPR	*D + D**
$|V_{cb}| \times 10^3$	39.3 ± 1.0

Both $|V_{cb}|$ values are correlated, so how significant is this shift?

Recent developments: Excl. $|V_{cb}|$

*D** **unfolded** distributions analysed by three groups

Includes additional measurement & beyond zero recoil lattice constraints

$\bar{B} \to D^* \ell \bar{\nu}_\ell$

CLN	*D**
$|V_{cb}| \times 10^3$	38.2 ± 1.5

CLN: Phys. Lett. B380, 376 (1996)

From unfolded data, slightly higher than 'folded' result of previous slide

~ 3 σ

arXiv:1703.06124,1703.08170

BGL	*D**
$|V_{cb}| \times 10^3$	41.9 ± 1.9

BGL: Phys. Rev. Lett. 74, 4603 (1995)

arXiv:1703.05330

BLPR	*D + D**
$|V_{cb}| \times 10^3$	39.3

arXiv:1708.07134

	$|V_{cb}|_{\text{CLN}}$	$|V_{cb}|_{\text{CLNnoR}}$	$|V_{cb}|_{\text{noHQS}}$	$|V_{cb}|_{\text{BGL}}$
$|V_{cb}|_{\text{CLN}}$	1.	0.75	0.69	0.76
$|V_{cb}|_{\text{CLNnoR}}$		1.	0.95	0.97
$|V_{cb}|_{\text{noHQS}}$			1.	0.97
$|V_{cb}|_{\text{BGL}}$				1.

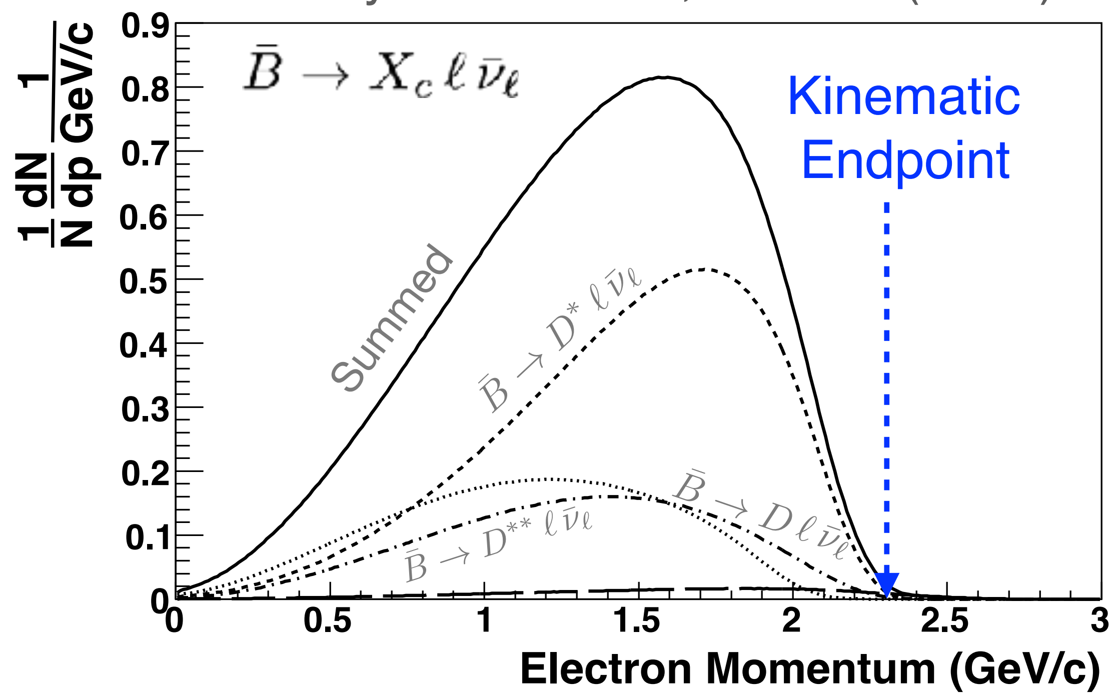
But some indications of HQS effects in Belle prel. measurements, thus…

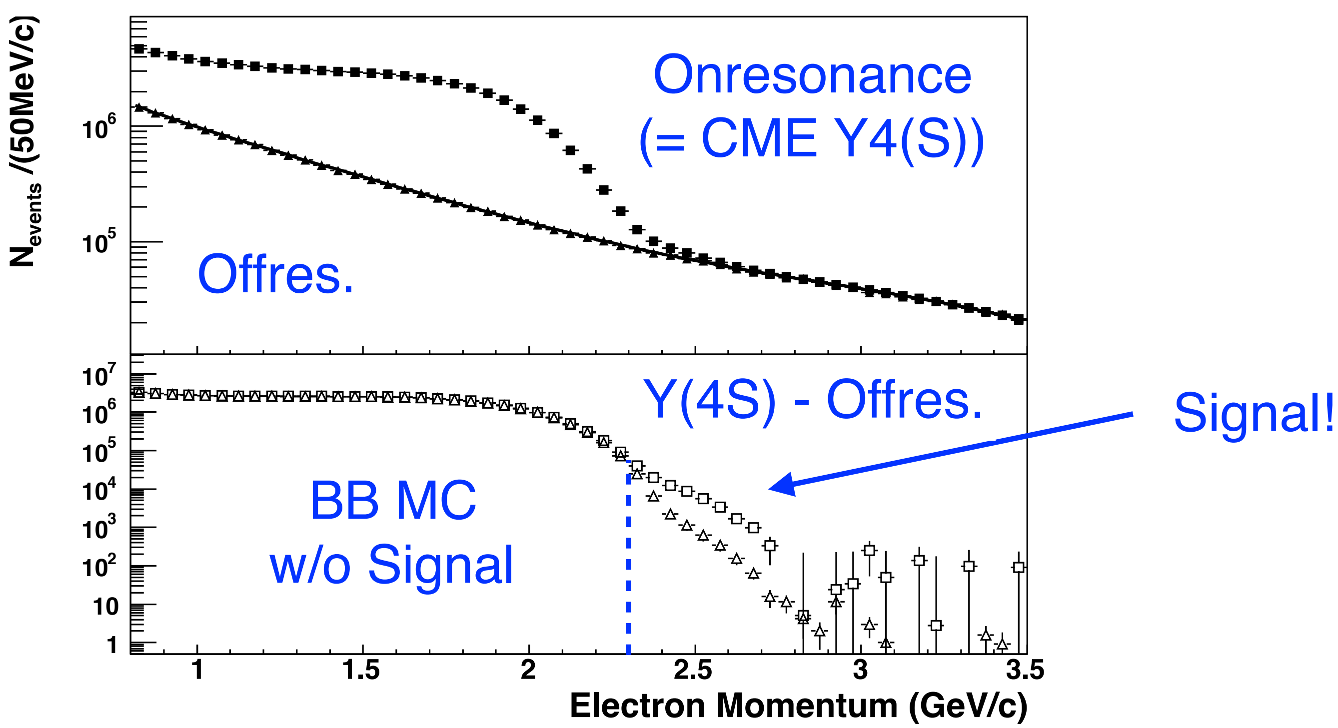
Recent developments: Incl. $|V_{ub}|$

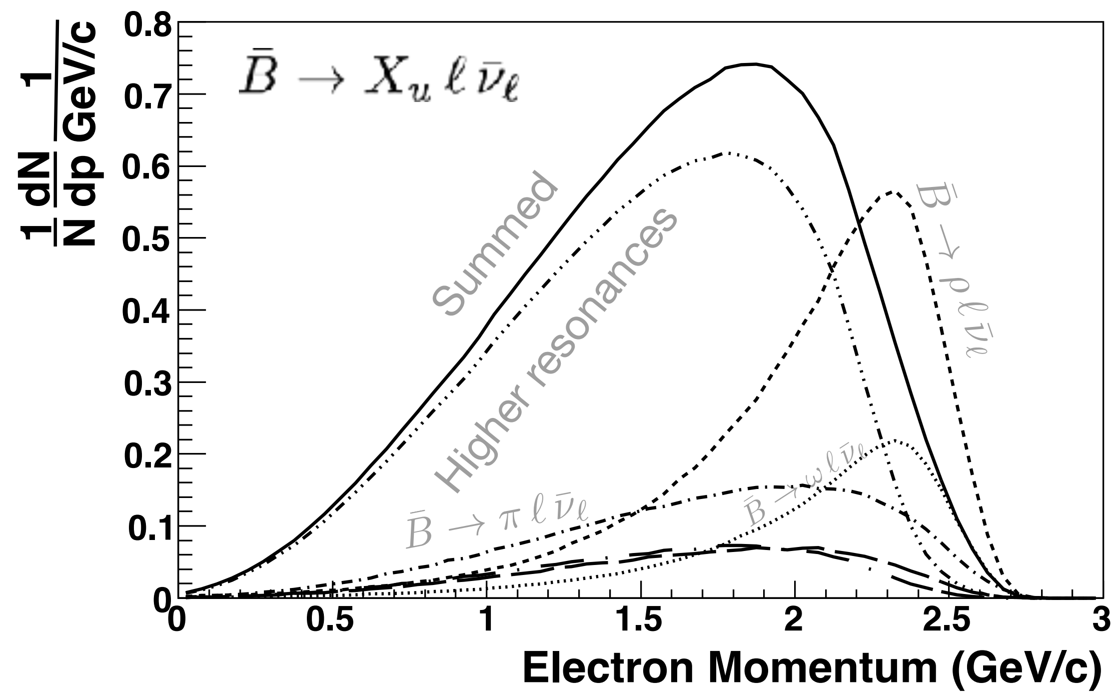
Phys. Rev. D 95, 072001 (2017)

One new measurements from BaBar

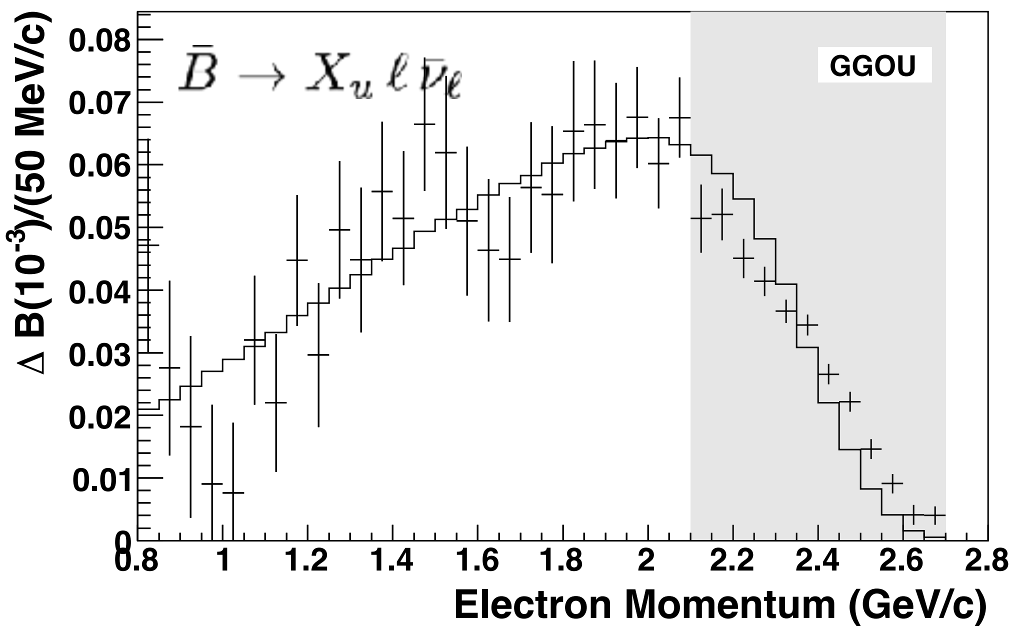
- **Untagged** analysis of the lepton momentum spectrum
- Signal extracted using a binned fit of the lepton spectrum
  - 4 different calculations used for $b \to u \ell \nu$
    - BLNP, GGOU, DN, DGE

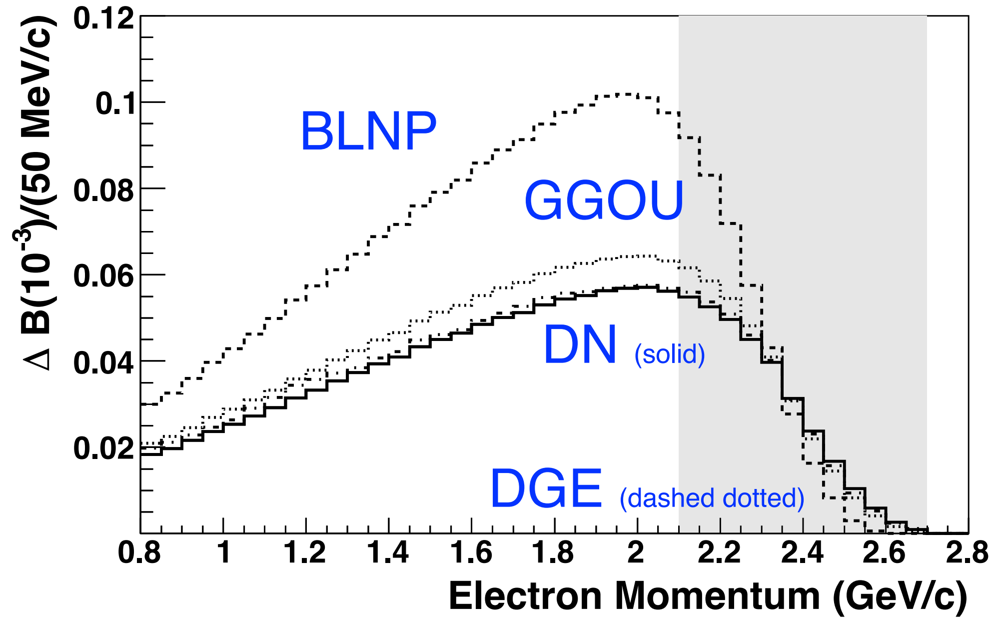






Phys. Rev. D 95, 072001 (2017)

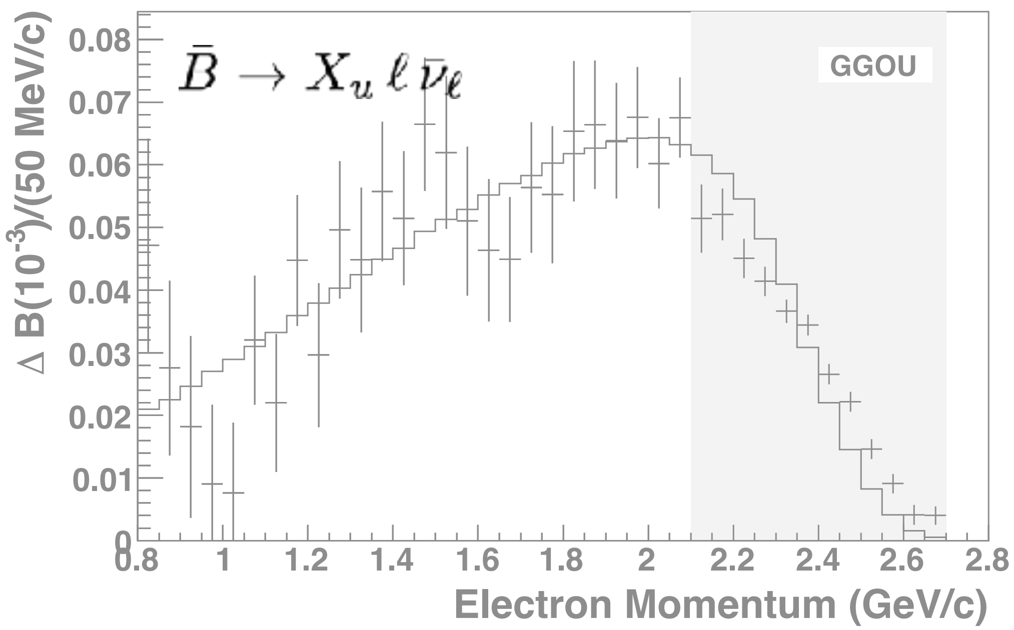


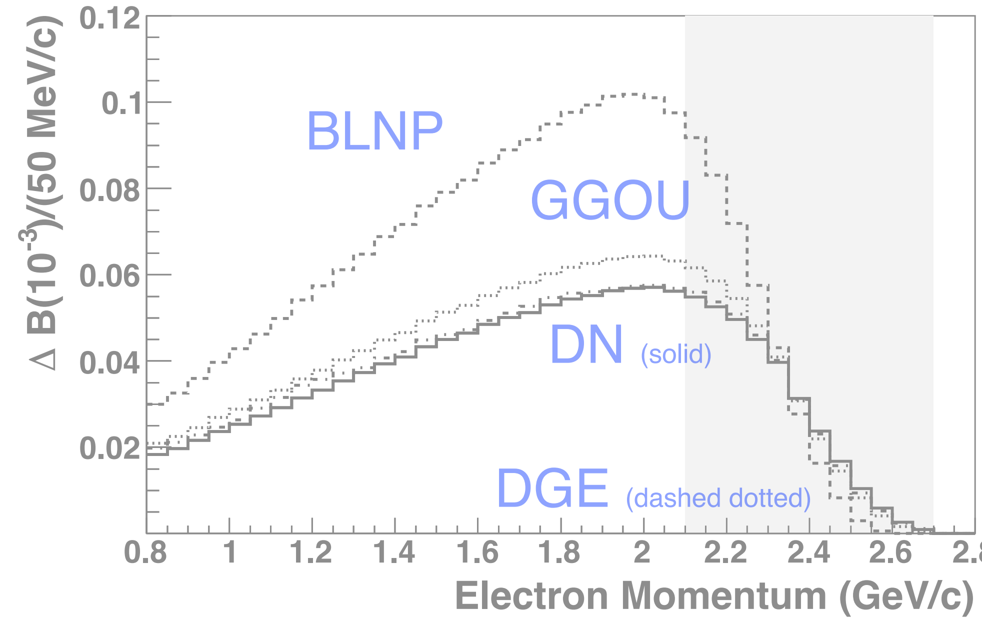


	BLNP	***GGOU***	***DN***	***DGE***
$\|V_{ub}\| \times 10^3$	**4.6 ± 0.3**	**4.0 ± 0.3**	**3.8 ± 0.3**	**3.8 ± 0.1**

Depending on Input *($b \to c \ell \nu$ or $b \to s\gamma$) can span a range from 4.3 - 4.6 x 10^{-3}*

Phys. Rev. D 95, 072001 (2017)





	BLNP	GGOU	DN	DGE
$\lvert V_{ub}\rvert \times 10^3$	4.6 ± 0.3	4.0 ± 0.3	3.8 ± 0.3	3.8 ± 0.1

Some tensions..

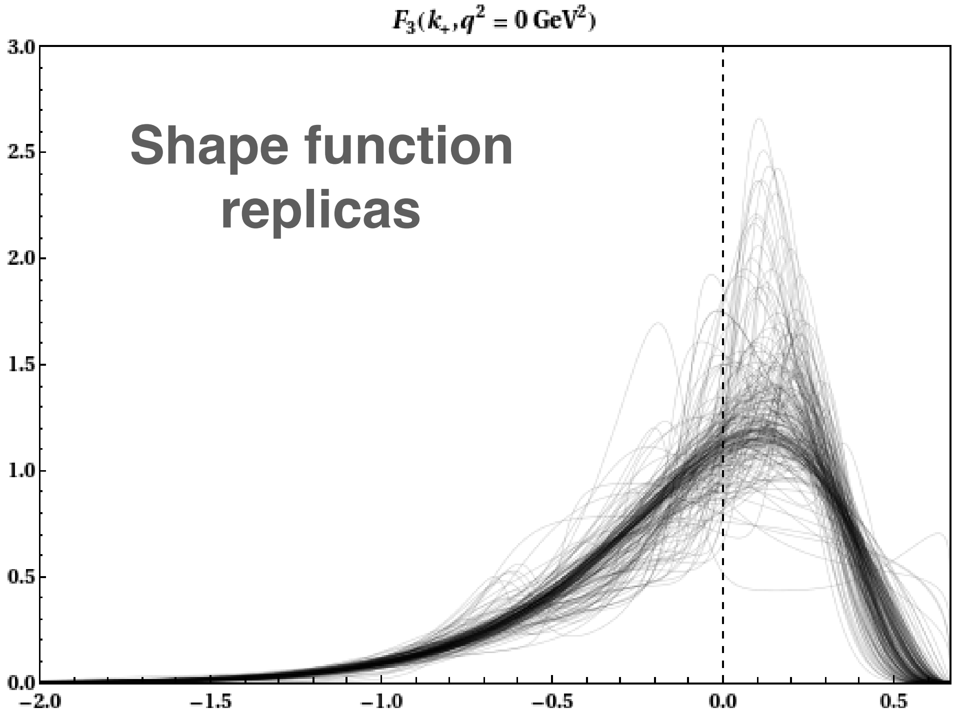
World Averages	BLNP	GGOU	DN	DGE
$\lvert V_{ub}\rvert \times 10^3$	4.4 ± 0.3	4.5 ± 0.2	-	4.5 ± 0.3

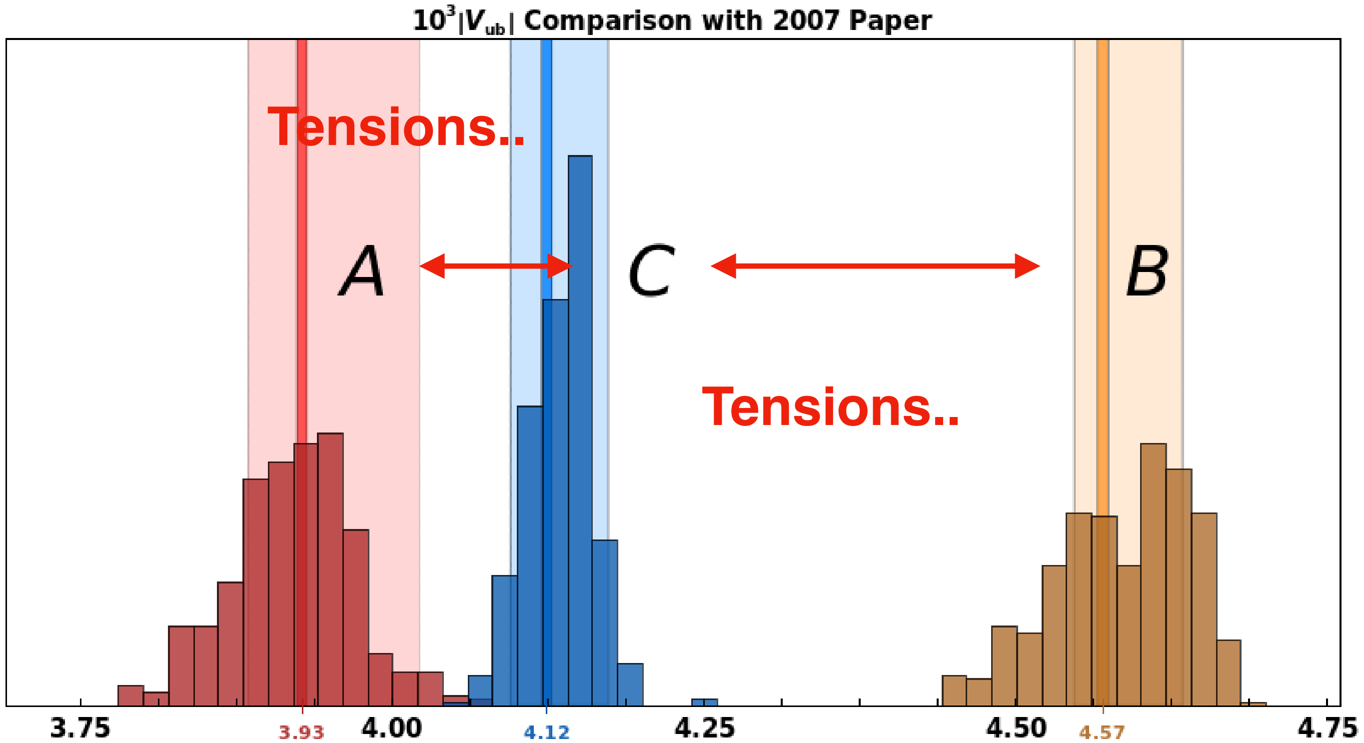
Recent developments: Incl. $|V_{ub}|$

Largest unknown: shape function ⟷ Moments constraint by $b \to c\ell\nu$ or $b \to s\gamma$, but functional form **not known**

~ B-Meson 'PDF'

NNVub: Phys. Rev. D 94, 014031 (2016)





A M_X cut: $M_X < 1.7$, $\boxed{E_\ell > 1.0\ \text{GeV},}$ Belle [40];

B Combined M_X and q^2 cuts: $M_X \leq 1.7\text{GeV}$, $q^2 > 8\text{GeV}^2$, $\boxed{E_\ell > 1.0\ \text{GeV},}$ Babar & Belle [40, 42];

C Lepton endpoint: $\boxed{E_\ell > 2.0\ \text{GeV},}$ Babar [41],

But not possible to propagate errors to acceptance

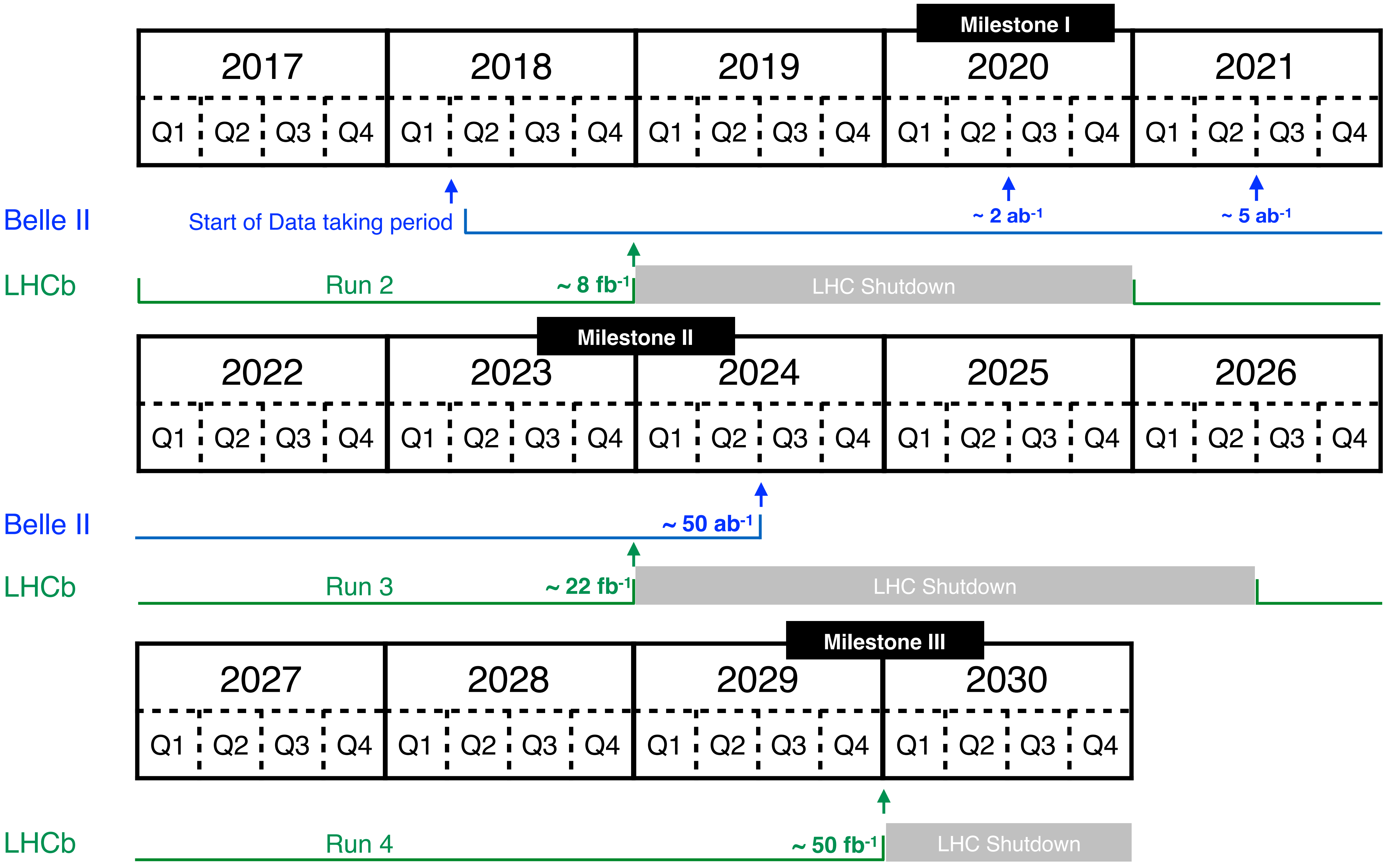
Interesting future direction: global fits to everything, see e.g. also **SIMBA** 1303.0958

$$\frac{\text{BaBar data set}}{\text{CLEO data set}} \sim \frac{\text{Belle II data set}}{\text{Belle data set}} \sim 50 \sim \frac{\text{LHCb Upgrade}}{\text{LHCb 1/fb}}$$

$|V_{ub}|$ and $|V_{cb}|$ in the Belle II and LHCb era

The future of flavour

B-Factory data sets: ~1.2 ab^{-1}
LHCb data set: ~ 5 fb^{-1}



The future of $|V_{ub}|$ and $|V_{cb}|$

Excl. $|V_{ub}|$ Today: ~ 3%

Belle II	*5/ab*	*50/ab*
rel. Error	1,9 %	1,0 %

Based on Belle II MC study, assuming improvements in lattice

Today: ~ 6%

LHCb	*10/fb*	*22/fb*	*50/fb*
rel. Error	4 %	3 %	2 %

Stat. scaling,
improvements in syst. such that
3% (exp) (+)
lattice error down to 2% and 1%

Excl. $|V_{cb}|$ Today: ~ 2%

Belle II	*5/ab*	*50/ab*
rel. Error	1,6 %	1,1 %

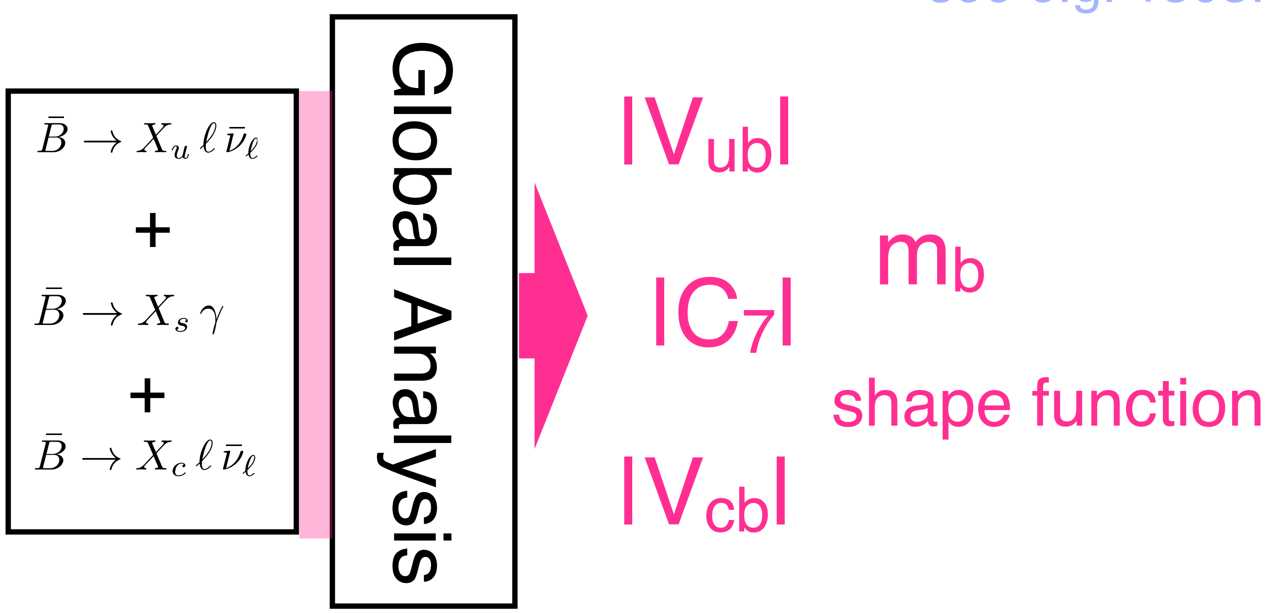
Based on stat. scaling of current untagged measurements

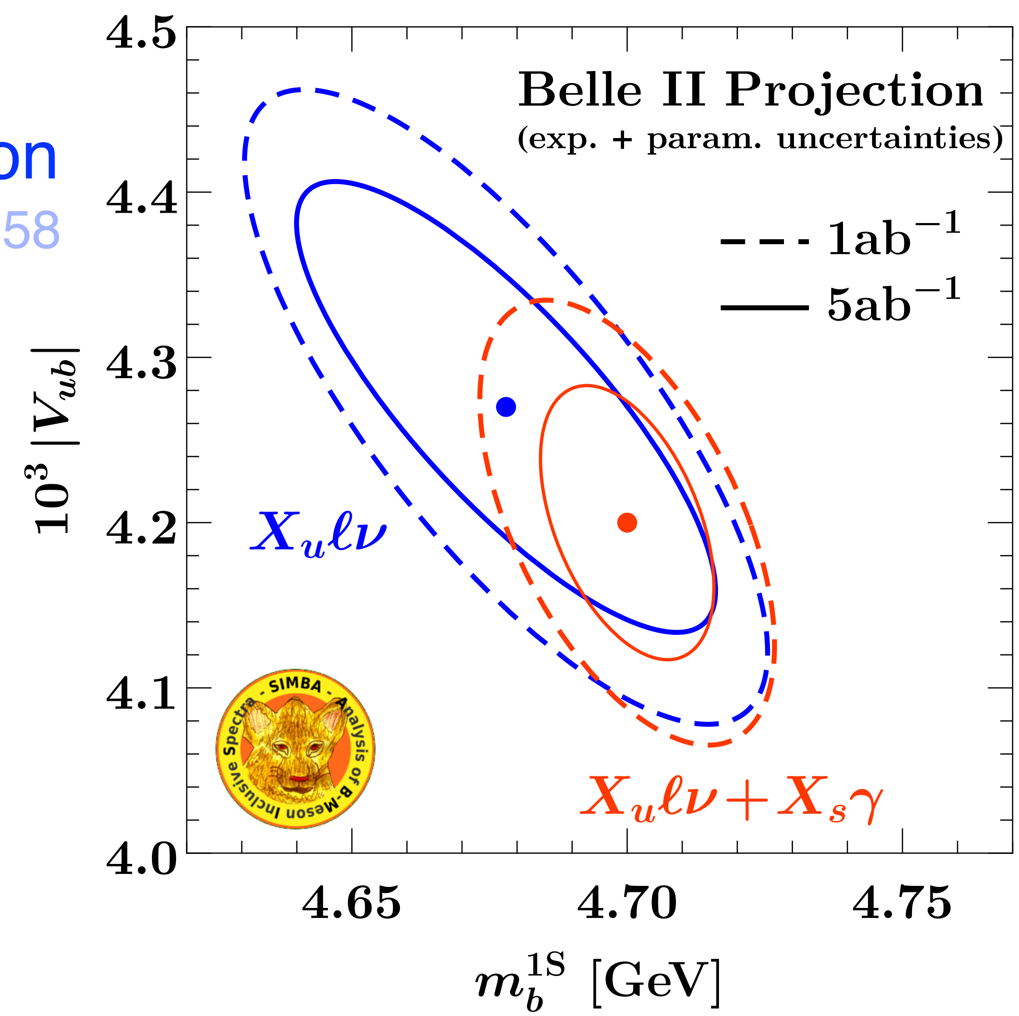
The future of $|V_{ub}|$ and $|V_{cb}|$

Incl. $|V_{ub}|$ Today: ~ 5%

* Global model independent fits for shape function

see e.g. 1303.0958





Belle II	*1/ab*	*5/ab*
rel. Error	3 %	2 %

No theory Errors included

Incl. $|V_{cb}|$ →

Hard to improve
(today 1.4% to 1.2% at 50/ab)

The future of $|V_{ub}|$ and $|V_{cb}|$

$$\frac{\text{Belle II data set}}{\text{Belle data set}} \sim 50 \sim \frac{\text{LHCb Upgrade}}{\text{LHCb 1/fb}}$$

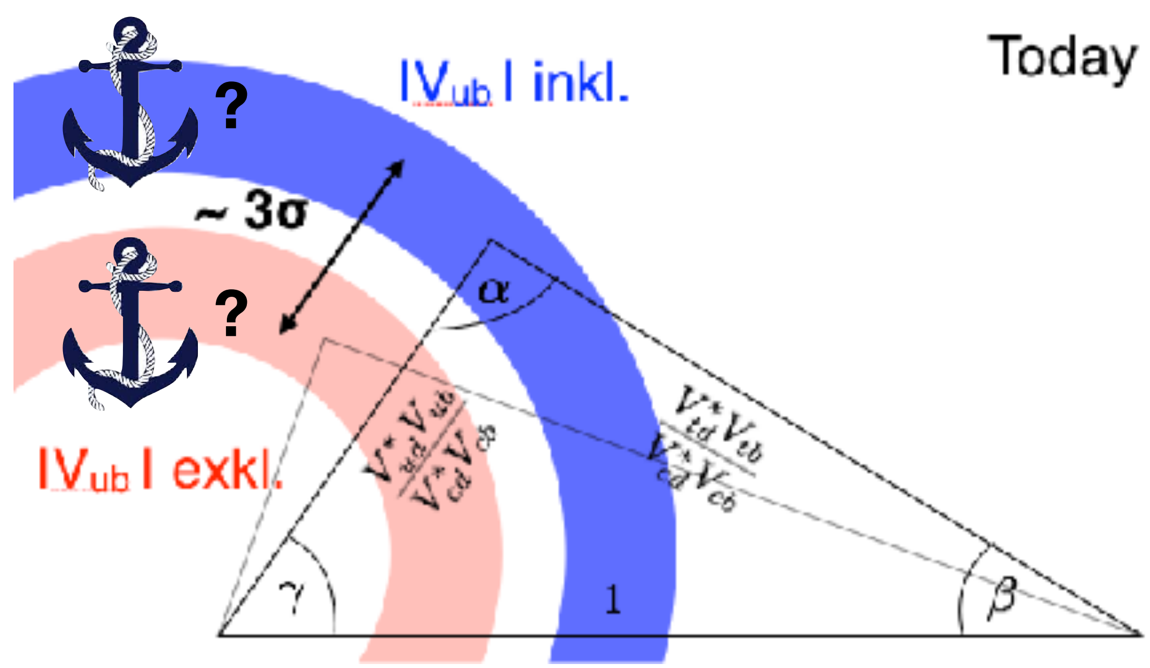
- There will be more channels: $B_s \to K^{(*)}\,\ell\,\bar{\nu}_\ell$

- But more data also will mean, more ideas
  - Already mentioned: Global Fits
  - Combined incl. and excl. determinations $B \to X_u\,\ell\,\bar{\nu}_\ell + B \to \pi\,\ell\,\bar{\nu}_\ell$
  - Combined analyses across channels $B \to D\,\ell\,\bar{\nu}_\ell + B \to D^*\,\ell\,\bar{\nu}_\ell$

    Phys. Rev. D 95, 115008 (2017), arXiv:1703.05330

- Important to sort out excl. versus incl. tension as it limits our capability to challenge the SM

  Currently global CKM fits average over the difference and inflate uncertainties.



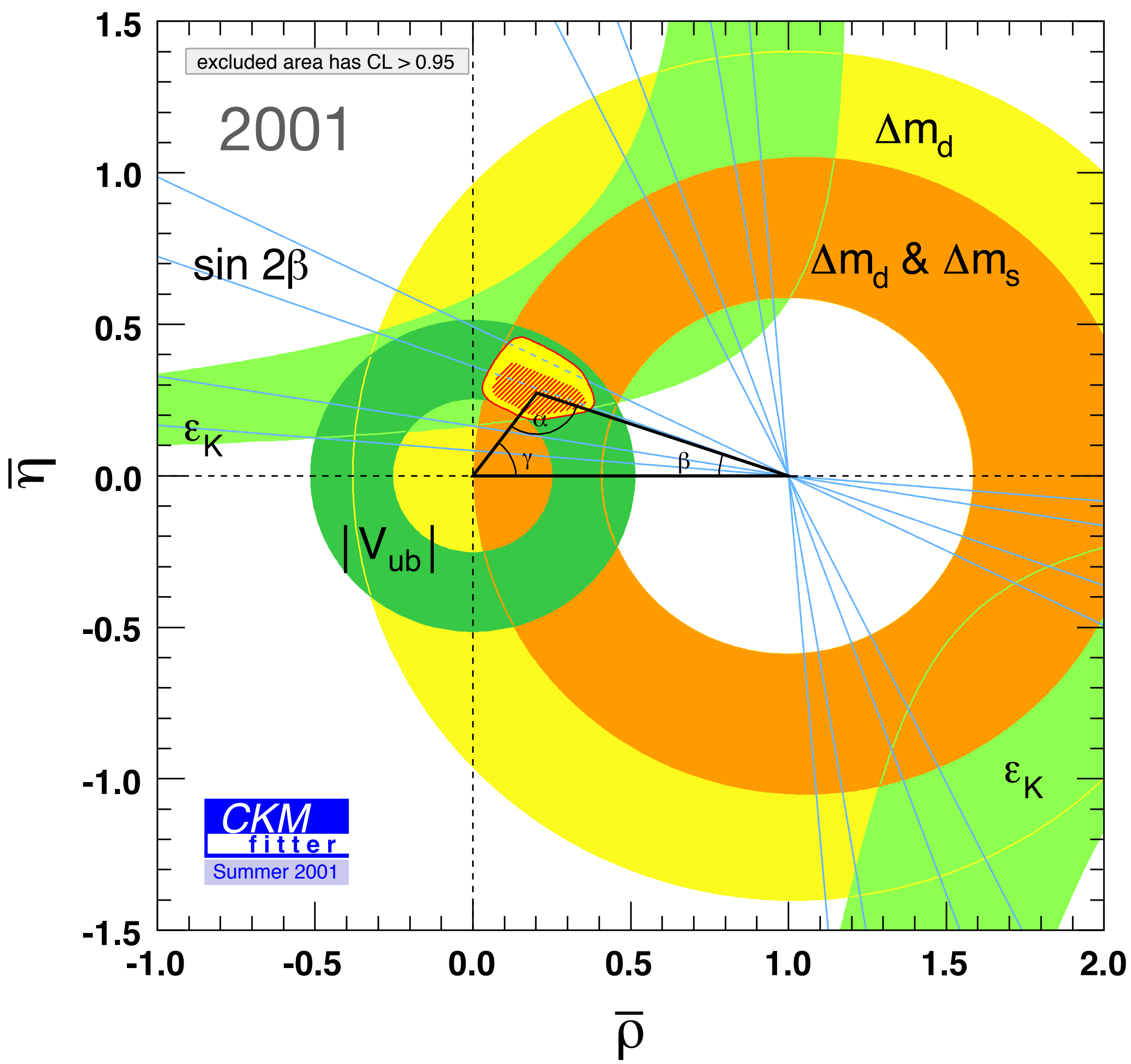
Beyond this point

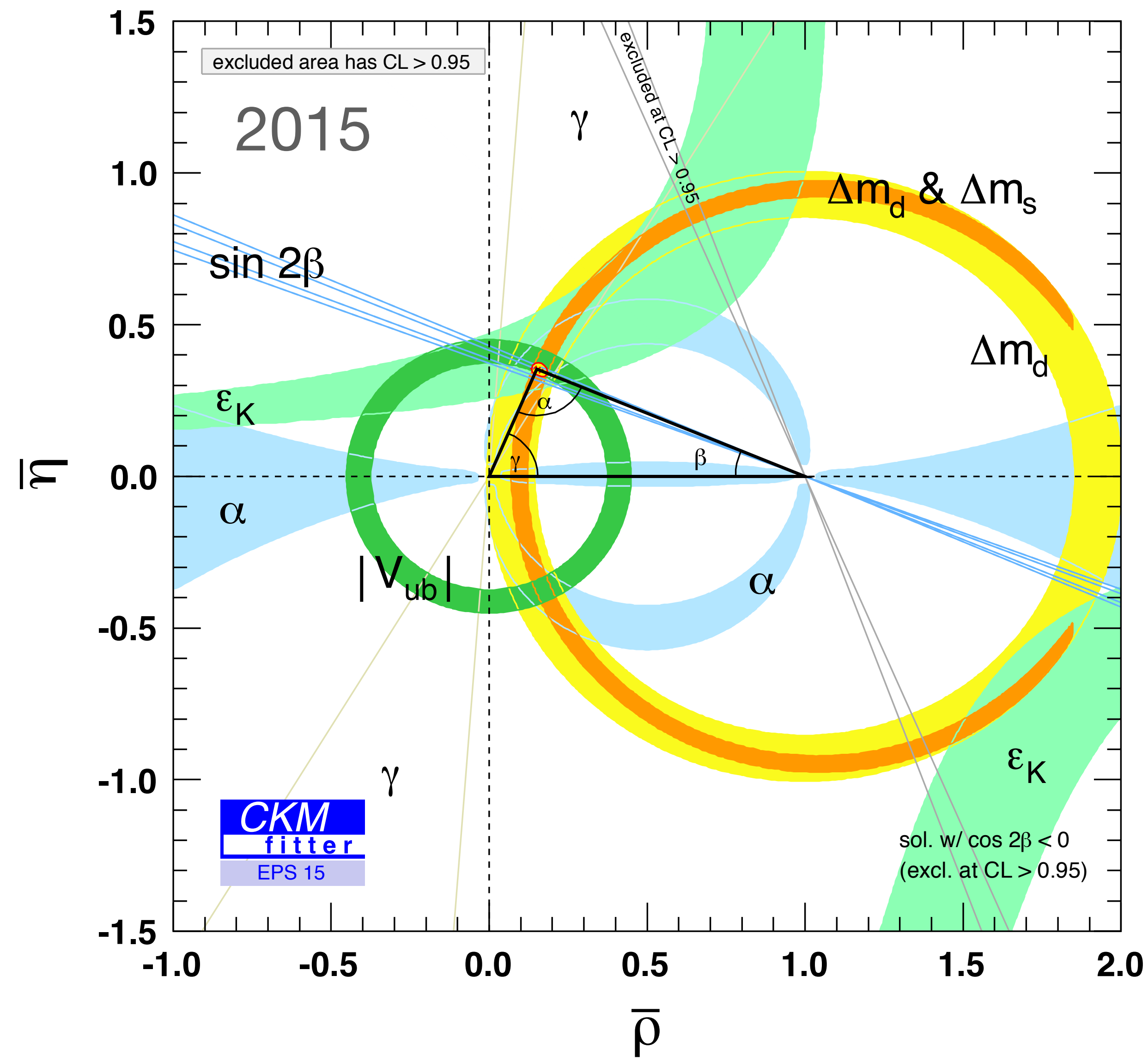
More Material

CKM Picture over the years: *from discovery to precision*

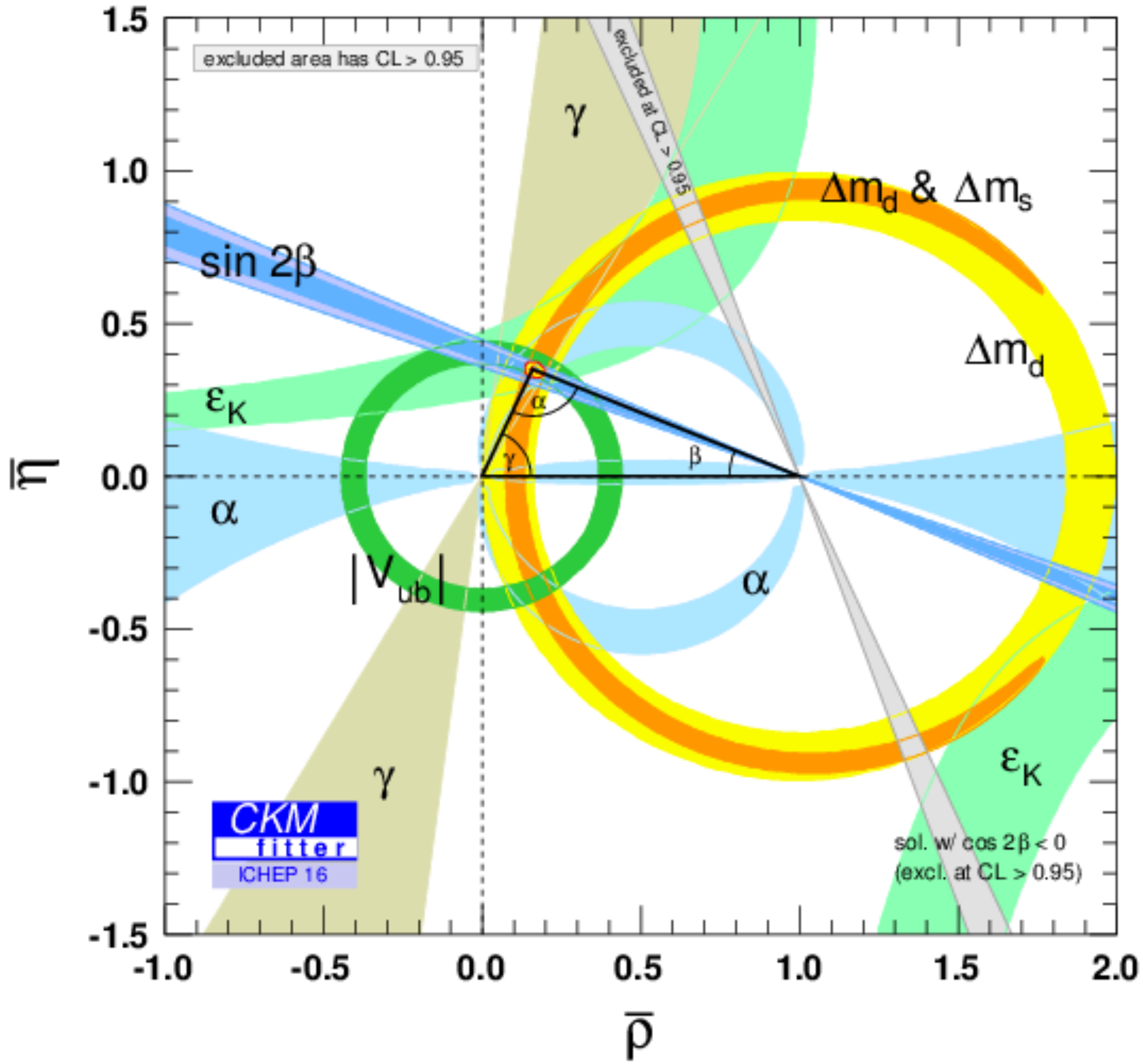
Existence of CPV phase established in 2001 by BaBar & Belle

- Picture still holds 15 years later, constrained with remarkable precision
- But: still leaves room for new physics contributions



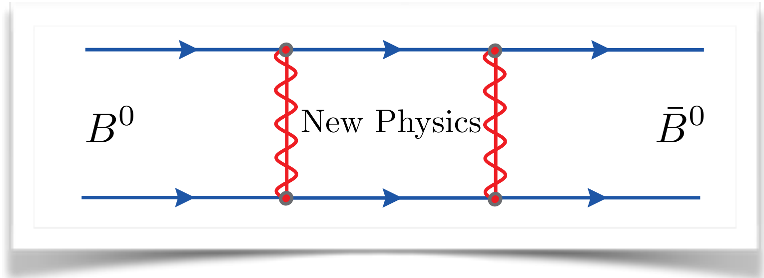


Latest CKM Fit from CKMfitter



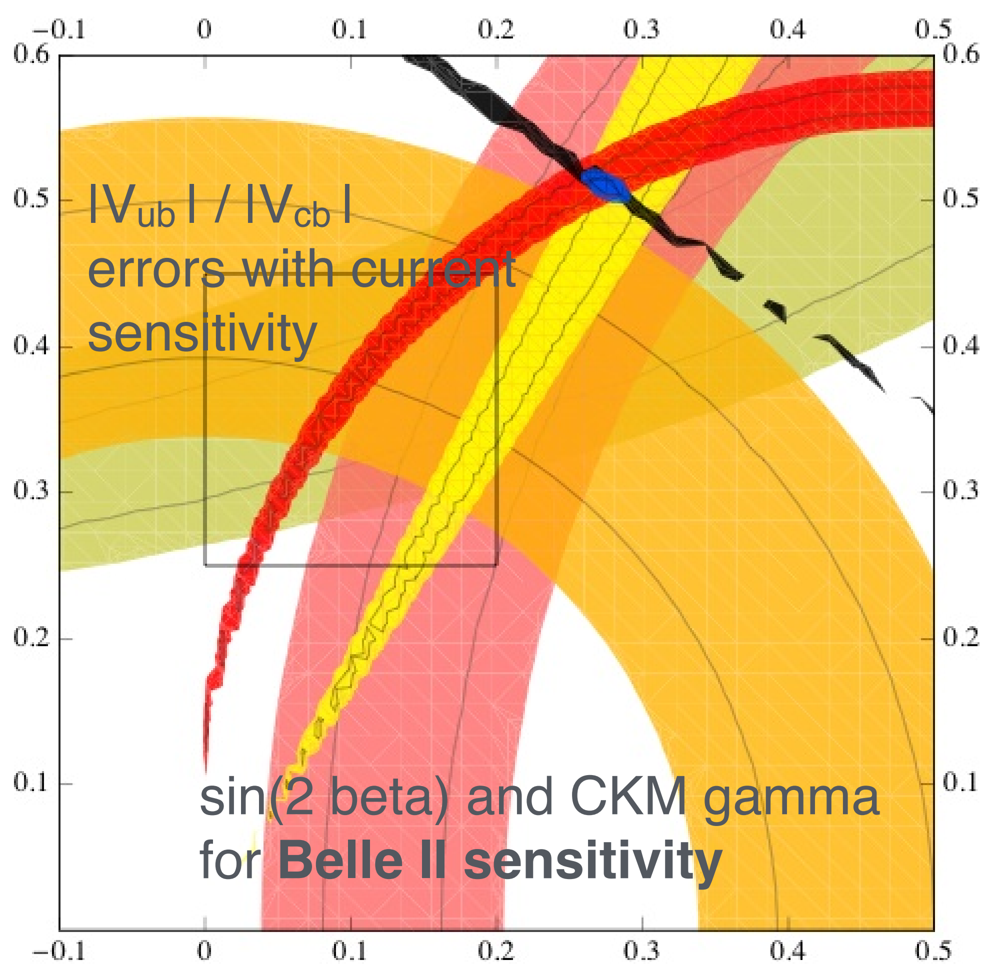
Example New Physics Scenario with $|V_{ub}|$ / $|V_{cb}|$ as an anchor

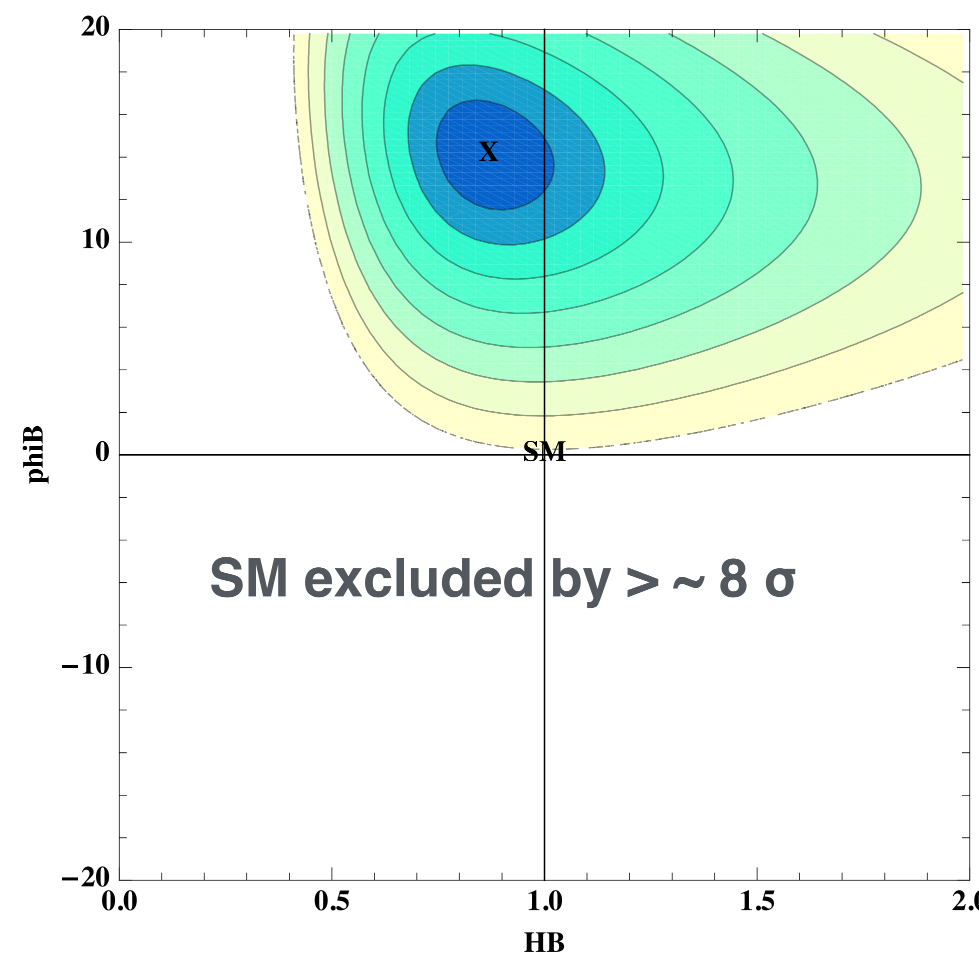
Example with New Physics in mixing:



$$H_{B_q}^{\rm NP} e^{2i\phi_{B_q}^{\rm NP}} \equiv \frac{\langle B_q^0|\mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP}|\overline{B}_q^0\rangle}{\langle B_q^0|\mathcal{H}_{\rm eff}^{\rm SM}|\overline{B}_q^0\rangle}$$

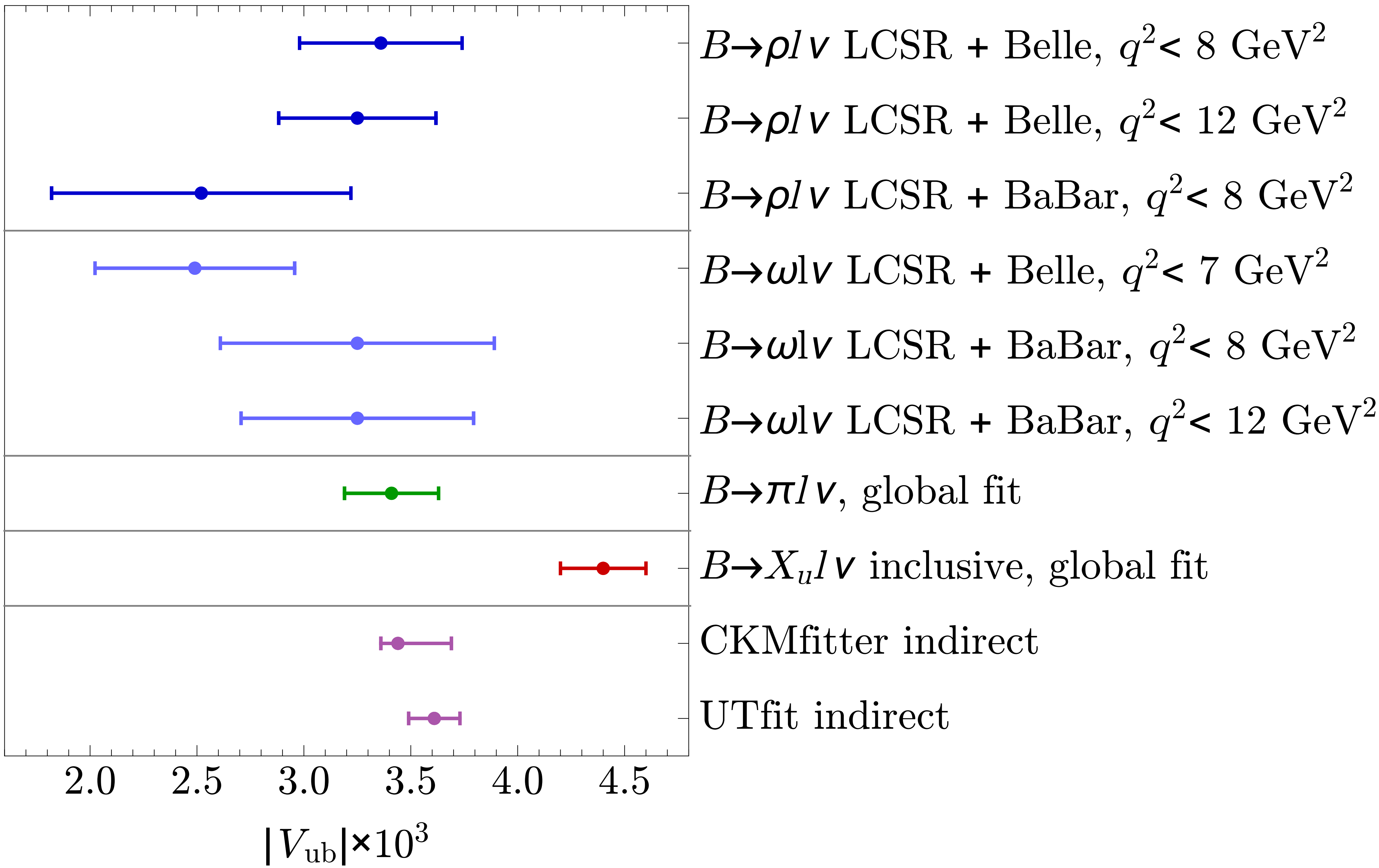
$$\sin 2\phi_1 = \sin 2(\phi_1^{\rm SM} + \phi_{B_d}^{\rm NP}), \quad \Delta M_q = H_{B_q} \Delta M_q^{\rm SM}$$



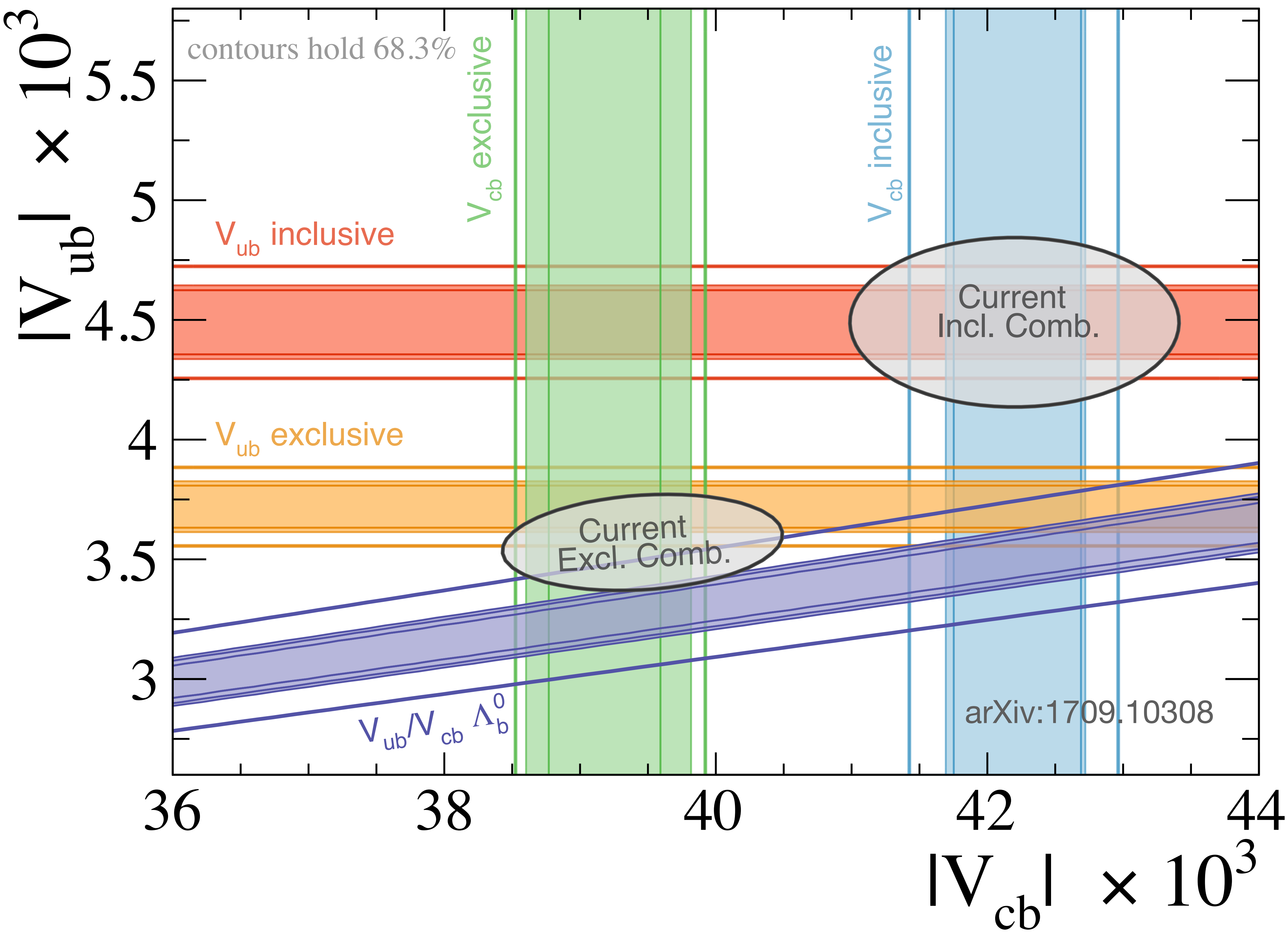


Compatibility of $|V_{ub}|$ from vector decays

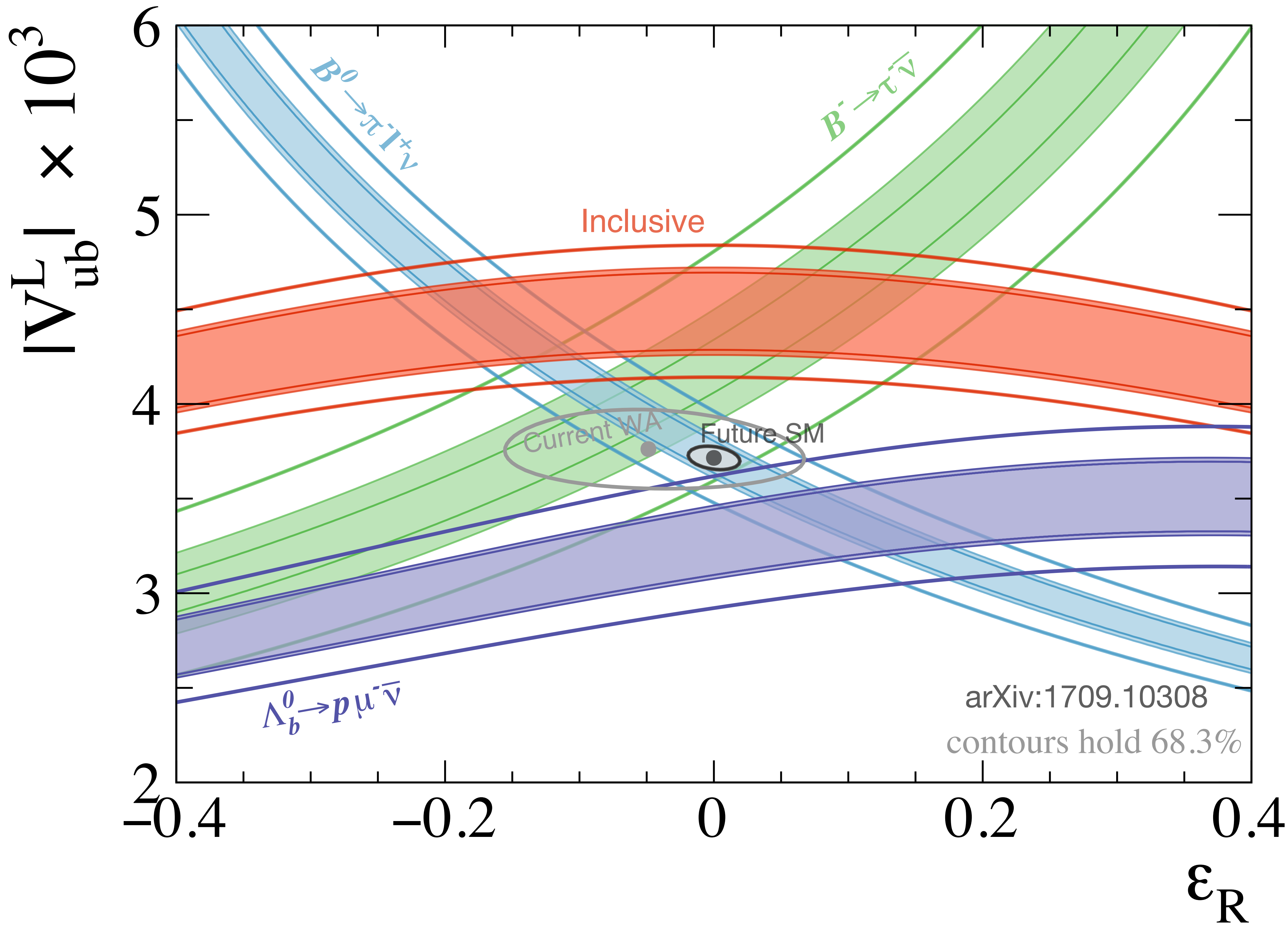
J. High Energ. Phys. (2016) 2016: 98



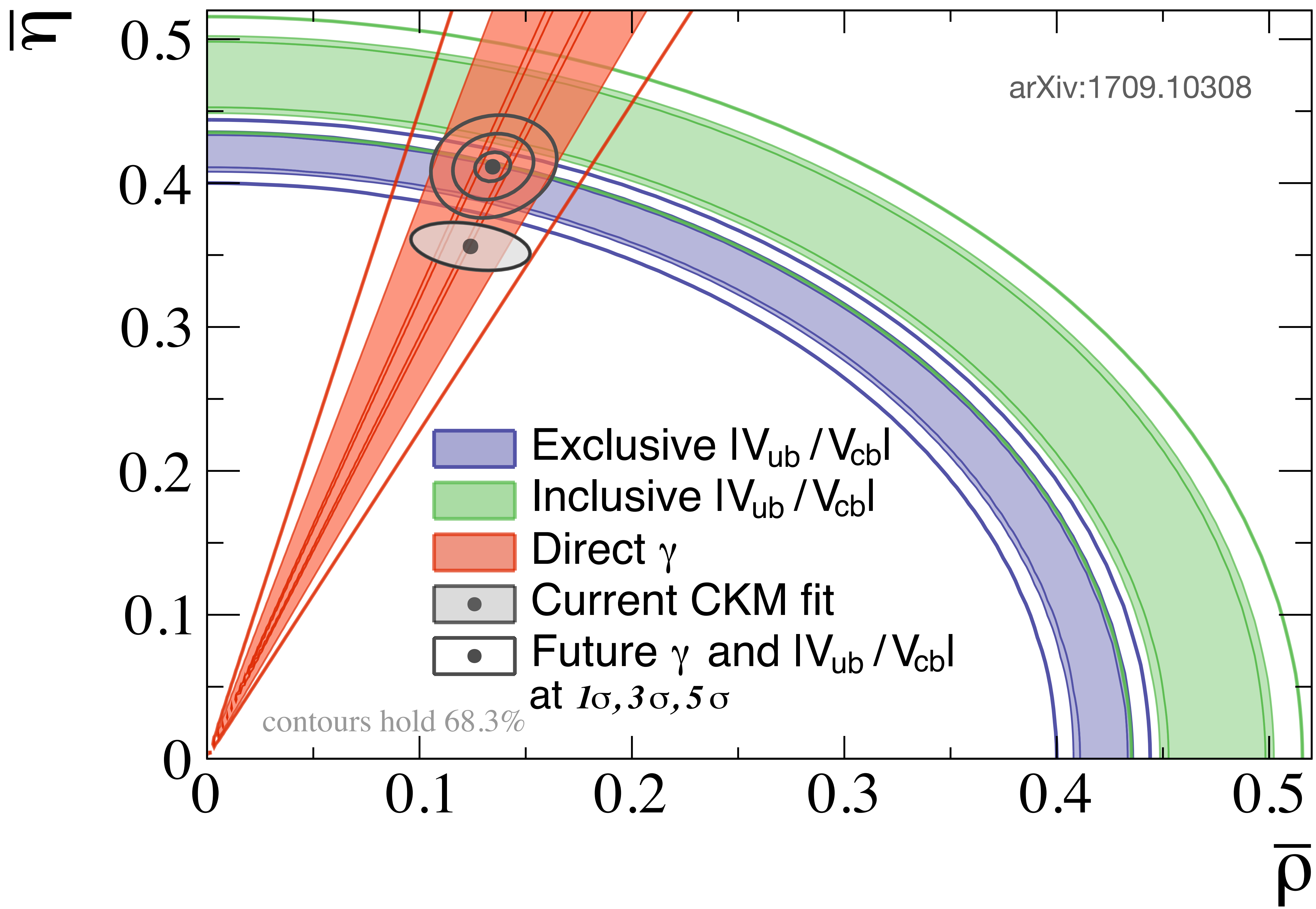
$|V_{ub}| / |V_{cb}|$


contours hold 68.3%
Vcb exclusive
Vcb inclusive
Vub inclusive
Vub exclusive
Current Incl. Comb.
Current Excl. Comb.
Vub/Vcb Λb0
arXiv:1709.10308
|Vub| × 10^3
|Vcb| × 10^3
5.5
5
4.5
4
3.5
3
36
38
40
42
44

Right-handed currents



Tree-level constraints only



Heavy Quark Symmetry tension in unfolded Belle Measurement

Belle-Conf 1612, 1702.01521

Ratio of these form factors $R_1(w) = \frac{h_V}{h_{A_1}}\,, \qquad R_2(w) = \frac{h_{A_3} + r_{D^*} h_{A_2}}{h_{A_1}}\,,$

do satisfy $R_{1,2}(w) = 1 + \mathcal{O}(\Lambda_{\rm QCD}/m_{c,b},\, \alpha_s)$ in heavy quark limit