Latest developments on $|V_{ub}|$ and $|V_{cb}|$

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

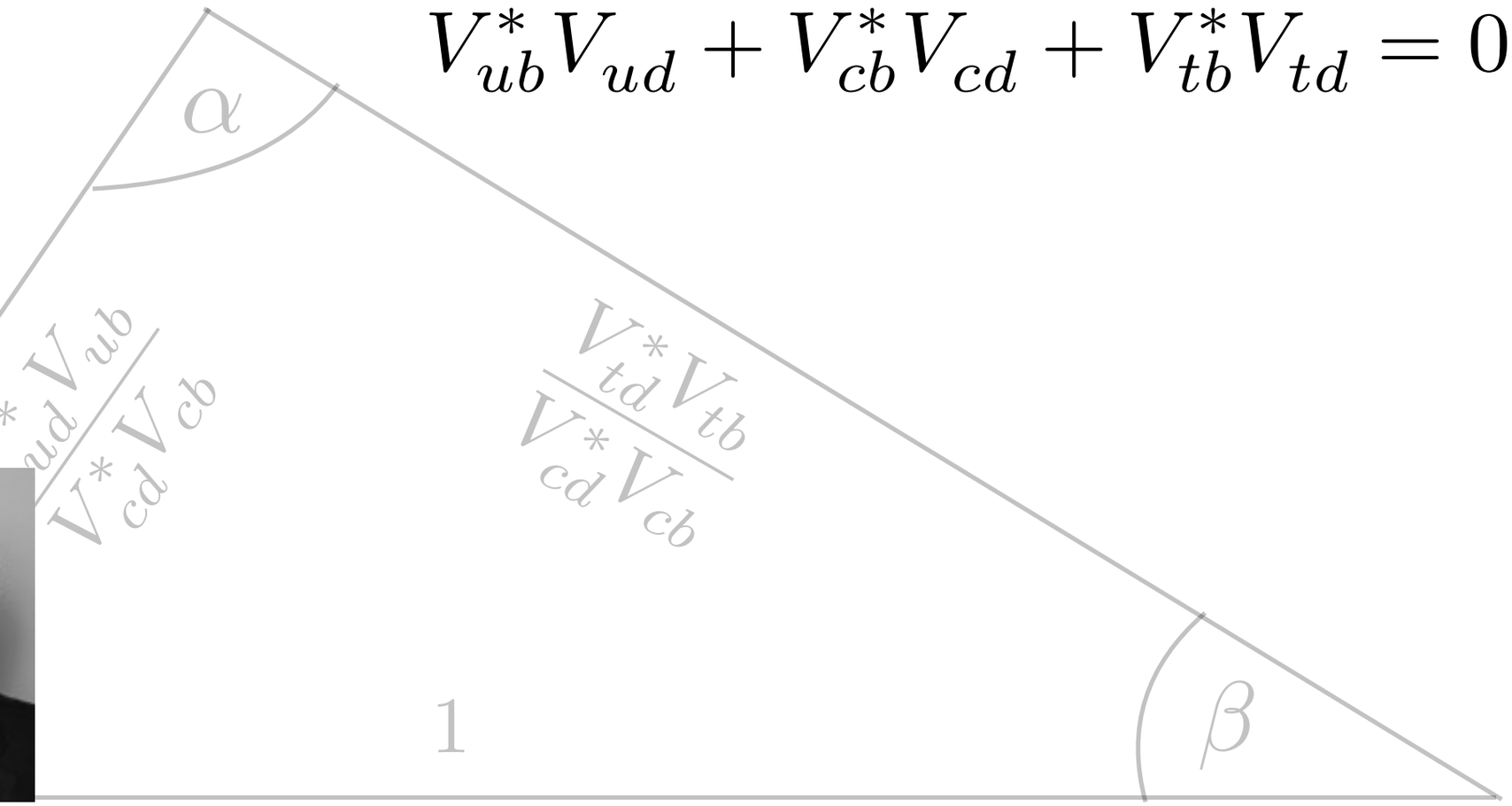
Why is it important to measure $|V_{ub}|$ & $|V_{cb}|$?

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

Unitarity
$CC^\dagger = 1$

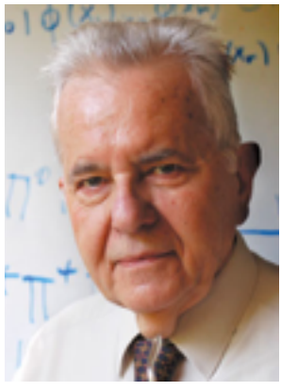
Overconstrain Unitarity condition
→ Potent test of Standard Model

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



CKM Matrix

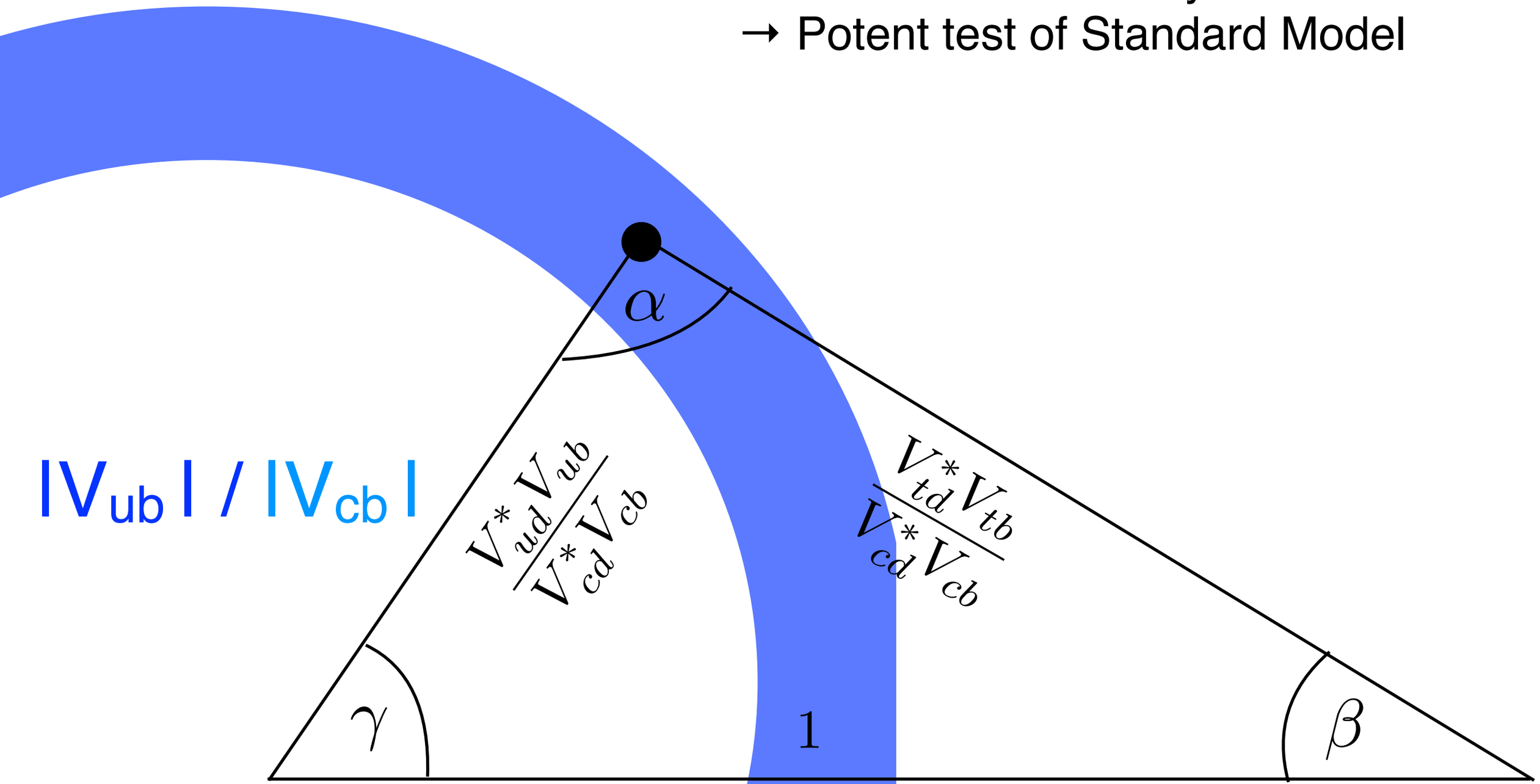
SM: Unitary 3x3 Matrix



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

Overconstrain Unitarity condition
→ Potent test of Standard Model

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

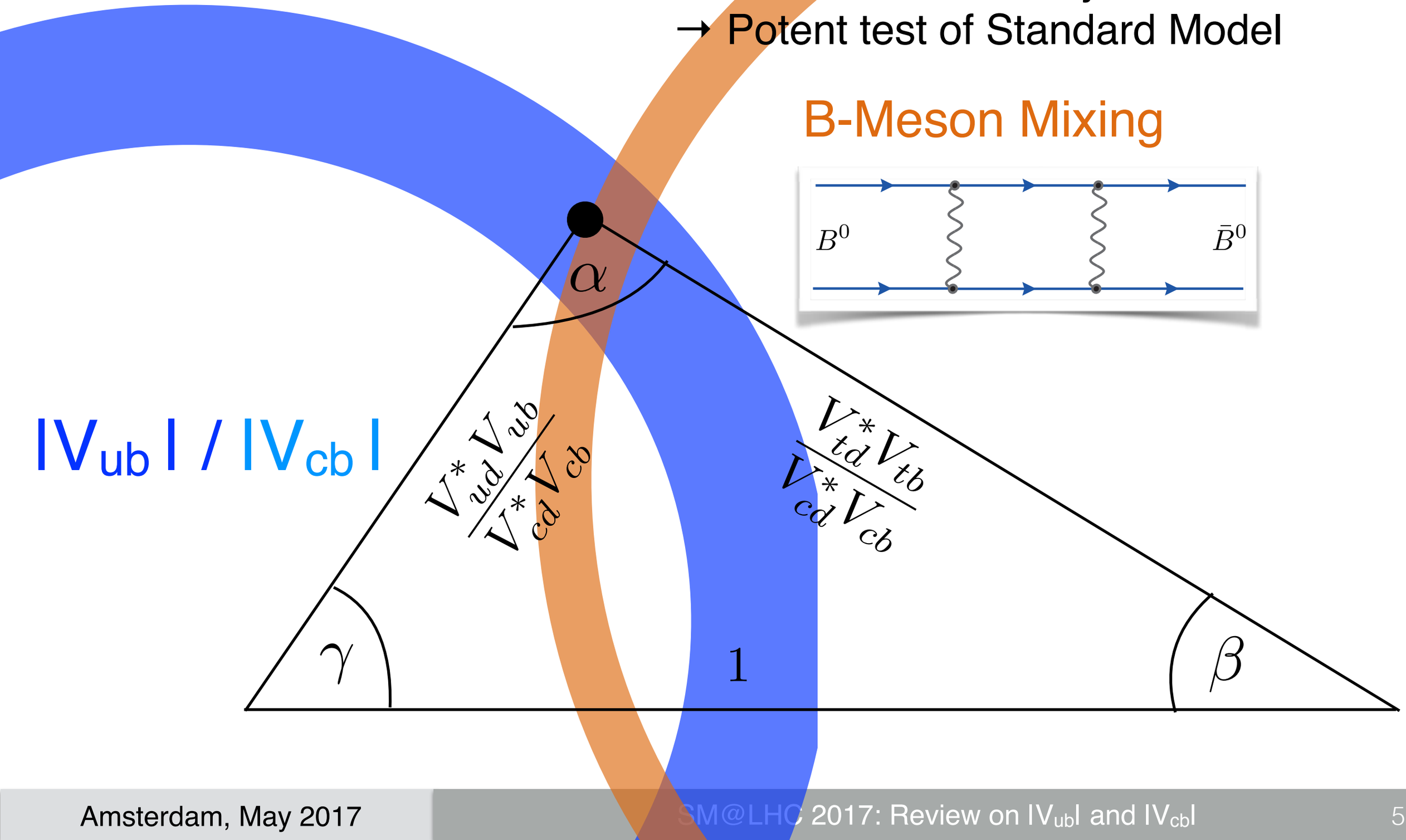


Why is it important to measure $|V_{ub}|$ & $|V_{cb}|$?

Overconstrain Unitarity condition
→ Potent test of Standard Model

B-Meson Mixing

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



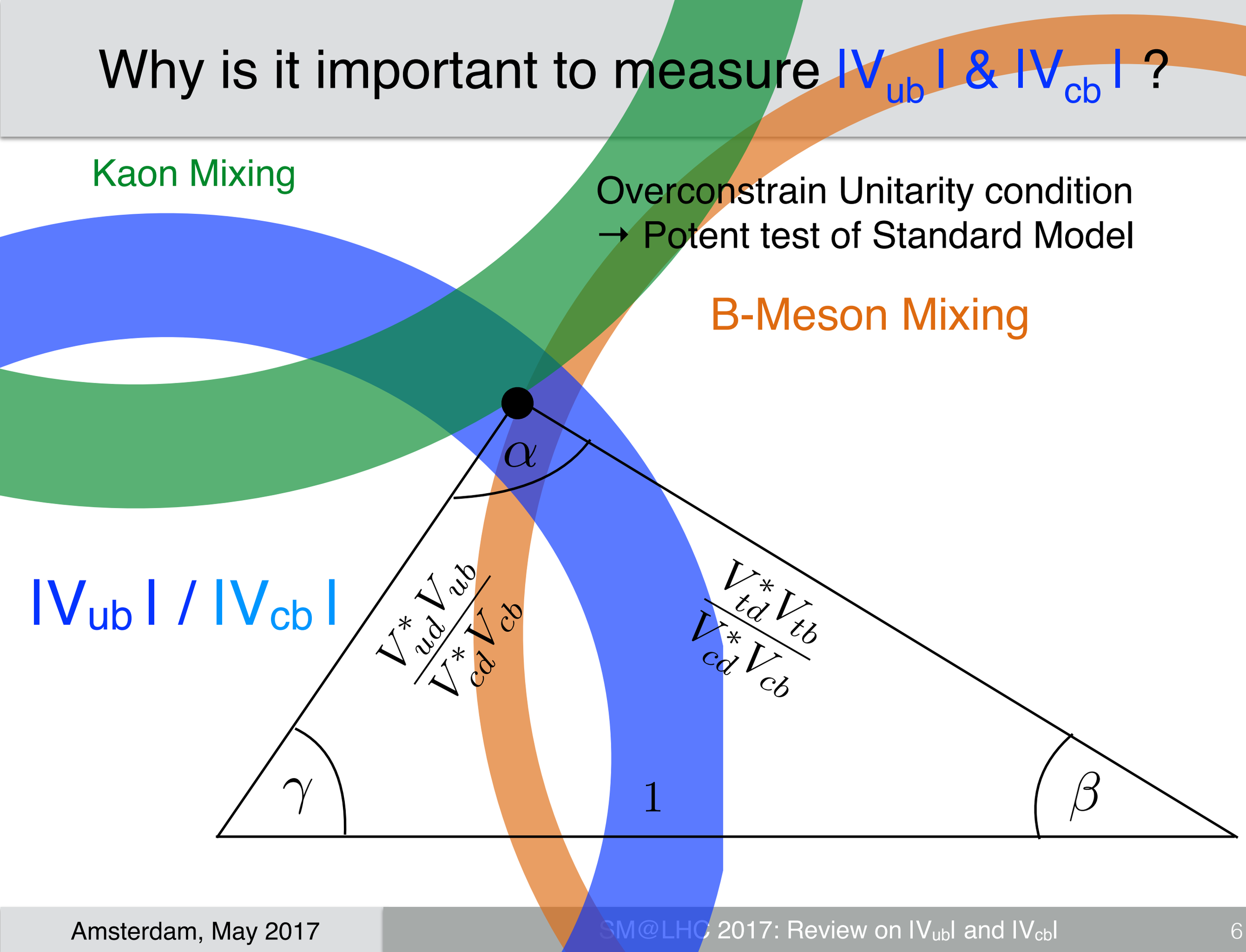
Why is it important to measure $|V_{ub}|$ & $|V_{cb}|$?

Kaon Mixing

Overconstrain Unitarity condition
→ Potent test of Standard Model

B-Meson Mixing

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



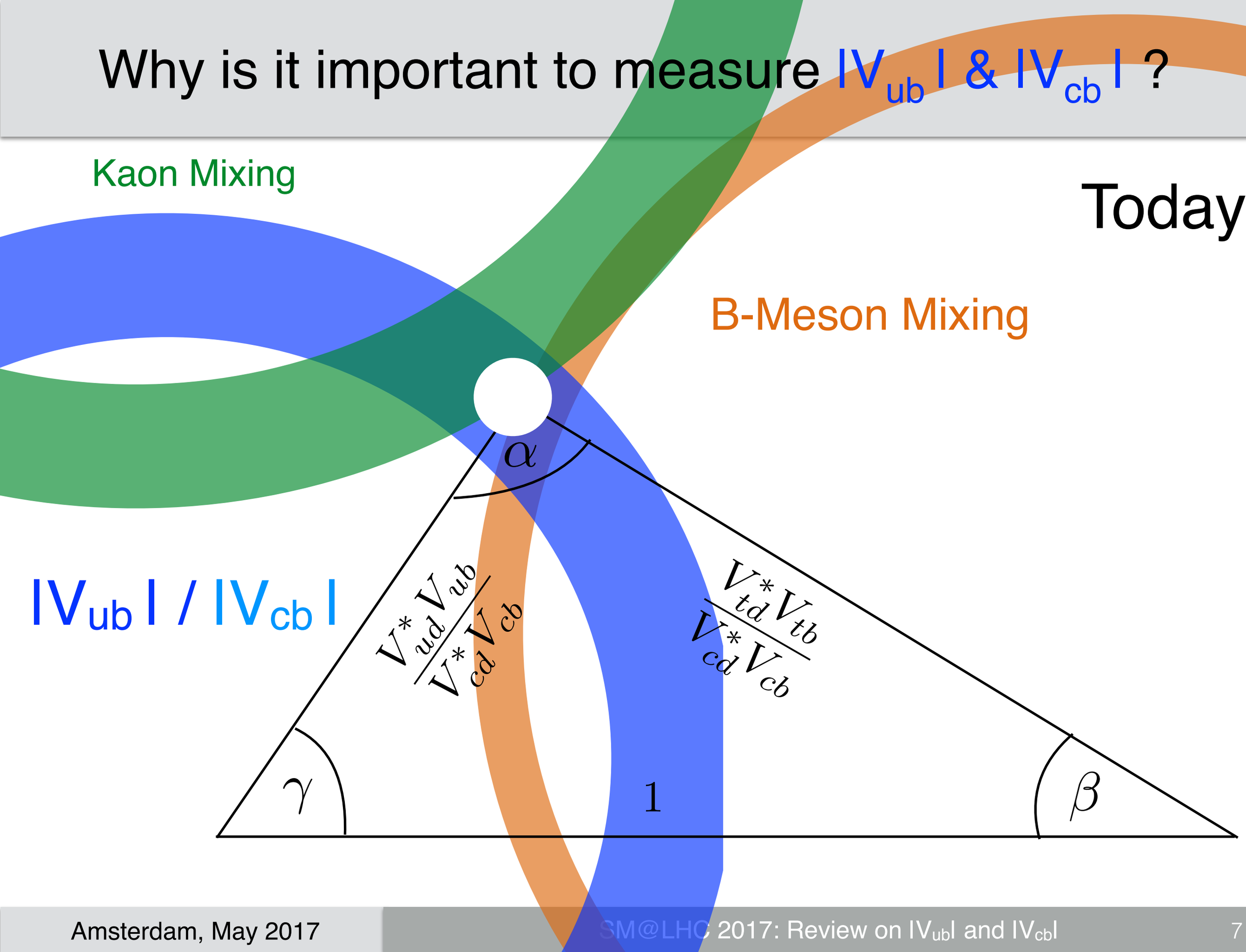
Why is it important to measure $|V_{ub}|$ & $|V_{cb}|$?

Kaon Mixing

Today

B-Meson Mixing

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

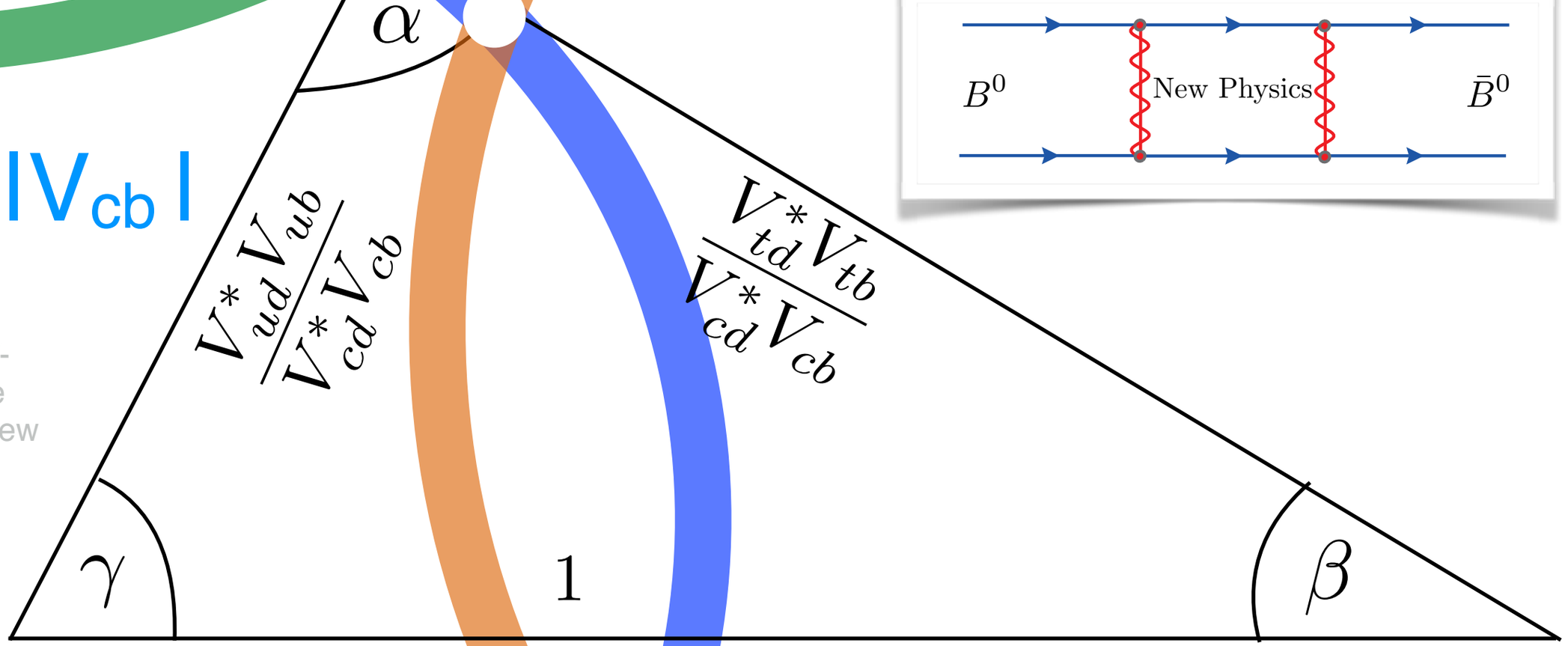


Why is it important to measure $|V_{ub}|$ & $|V_{cb}|$?

Kaon Mixing

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

Dominated by W-Boson exchange a-priori free from new physics

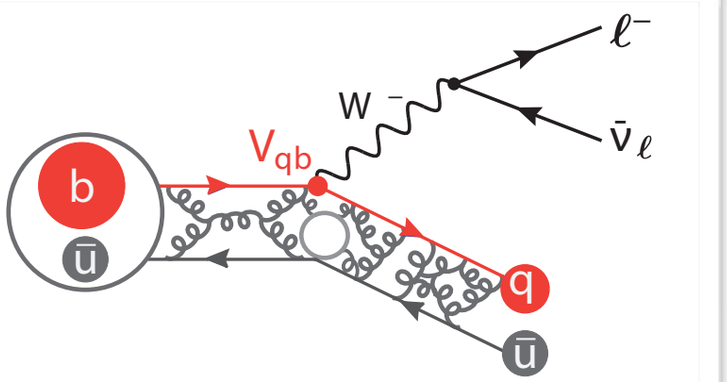


The future with New Physics?

B-Meson Mixing

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

How does one measure $|V_{ub}|$ & $|V_{cb}|$?



Inclusive $|V_{ub}|$

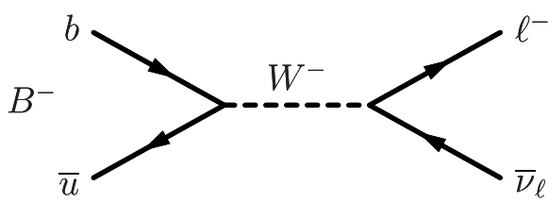
$$\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell$$

Inclusive $|V_{cb}|$

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

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

‘Leptonic’ $|V_{ub}|$



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

B-Meson decay constant

Exclusive $|V_{ub}|$

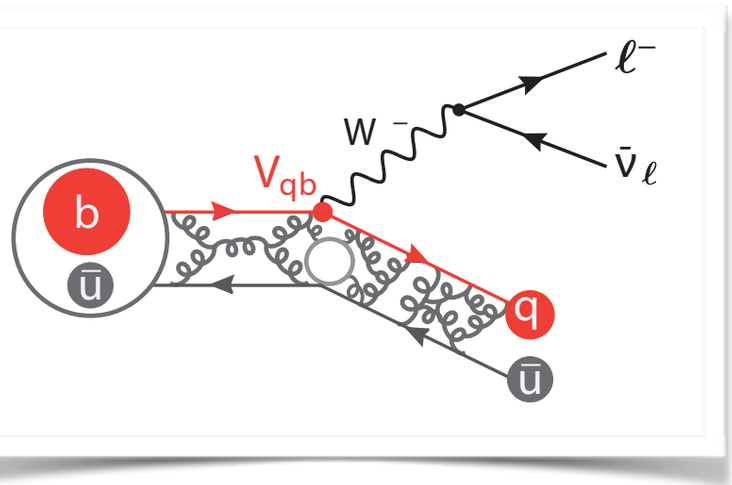
$$\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell, \Lambda_b \to p \, \mu \, \bar{\nu}_\mu$$

Exclusive $|V_{cb}|$

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

$$\mathcal{B} \propto |V_{cb}|^2 \, f^2$$ ← Form Factors

How does one measure $|V_{ub}|$ & $|V_{cb}|$?



Inclusive $|V_{ub}|$

Inclusive $|V_{cb}|$

Measured
Branching Fraction

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

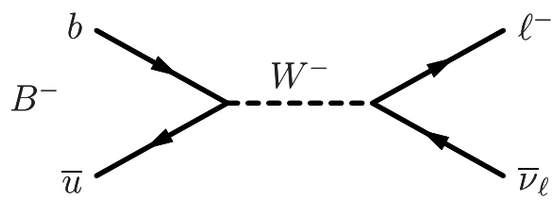
Prediction from
Theory but often also constrained
from **measured differential distributions**

Theory from non-perturbative Methods:

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

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

‘Leptonic’ $|V_{ub}|$

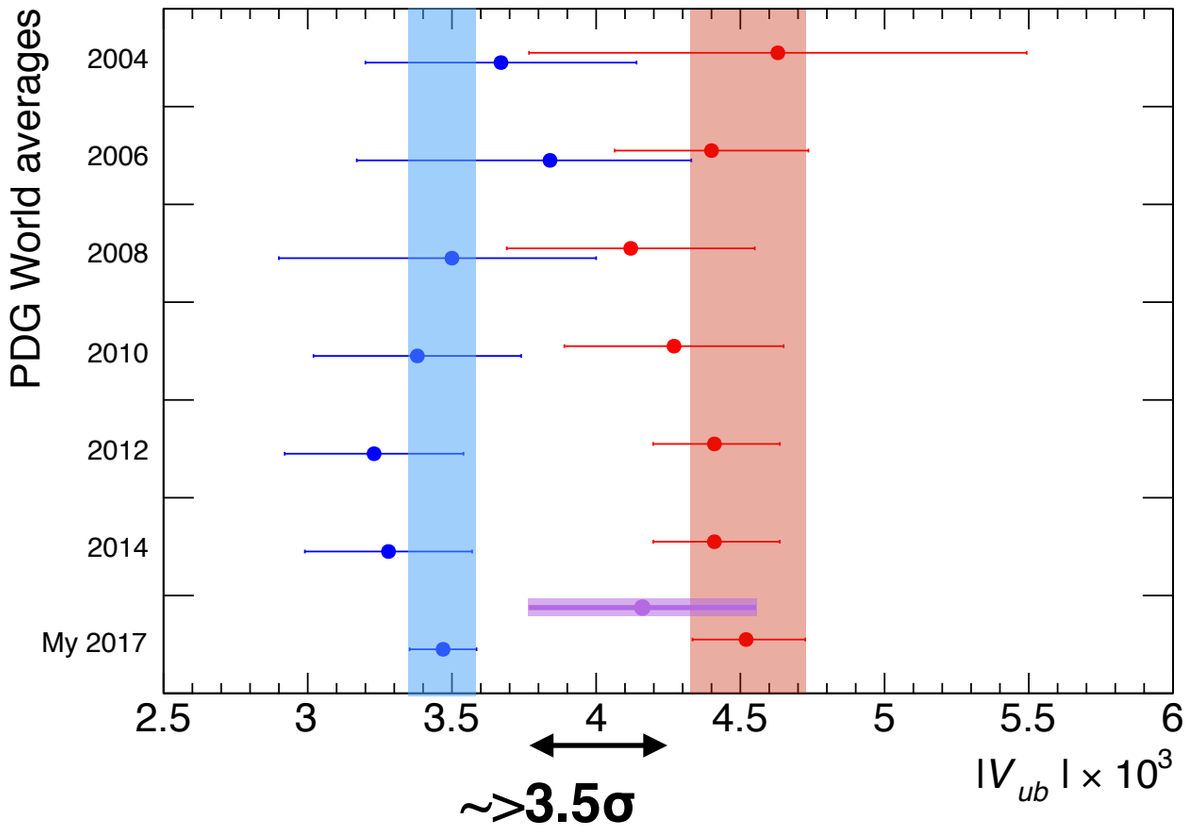


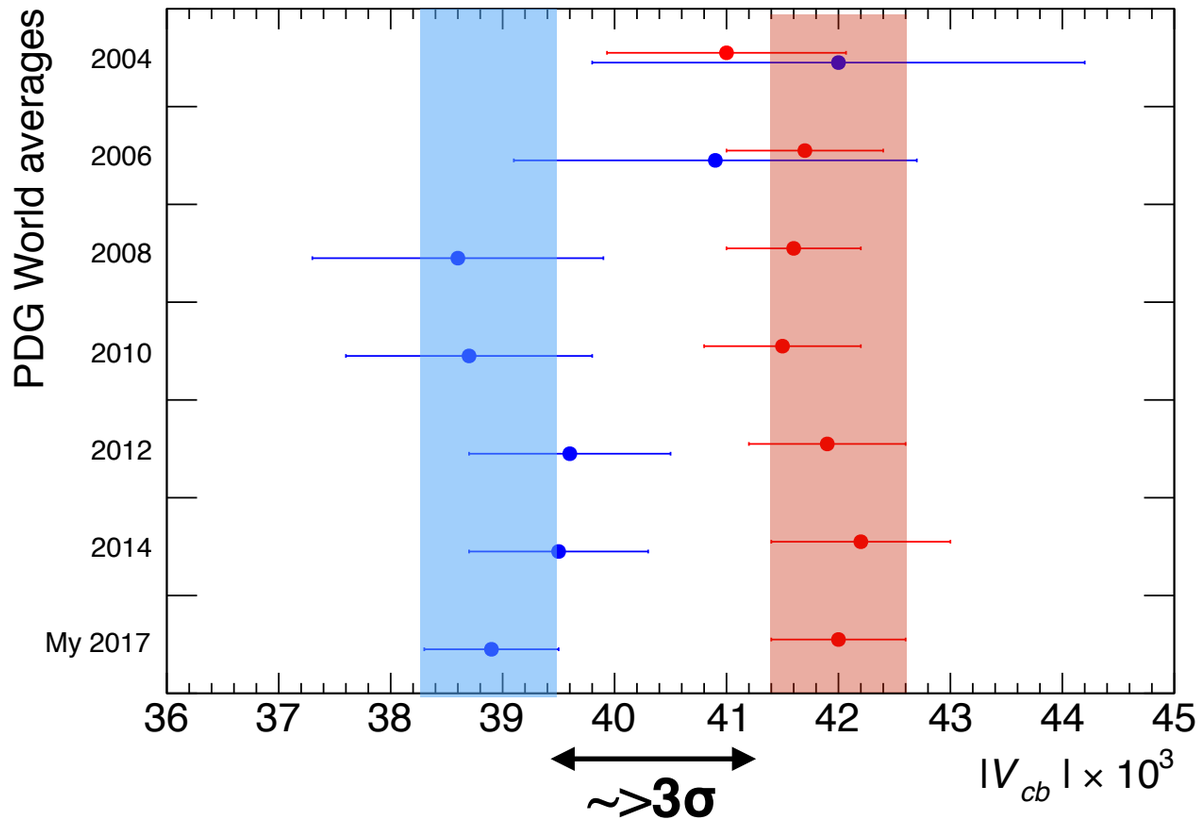
$$\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2$$

B-Meson decay constant

Current status and latest developments

Overall status of $|V_{ub}|$ & $|V_{cb}|$ Measurements





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

Exclusive Approach

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

Inclusive Approach

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

Leptonic Decays

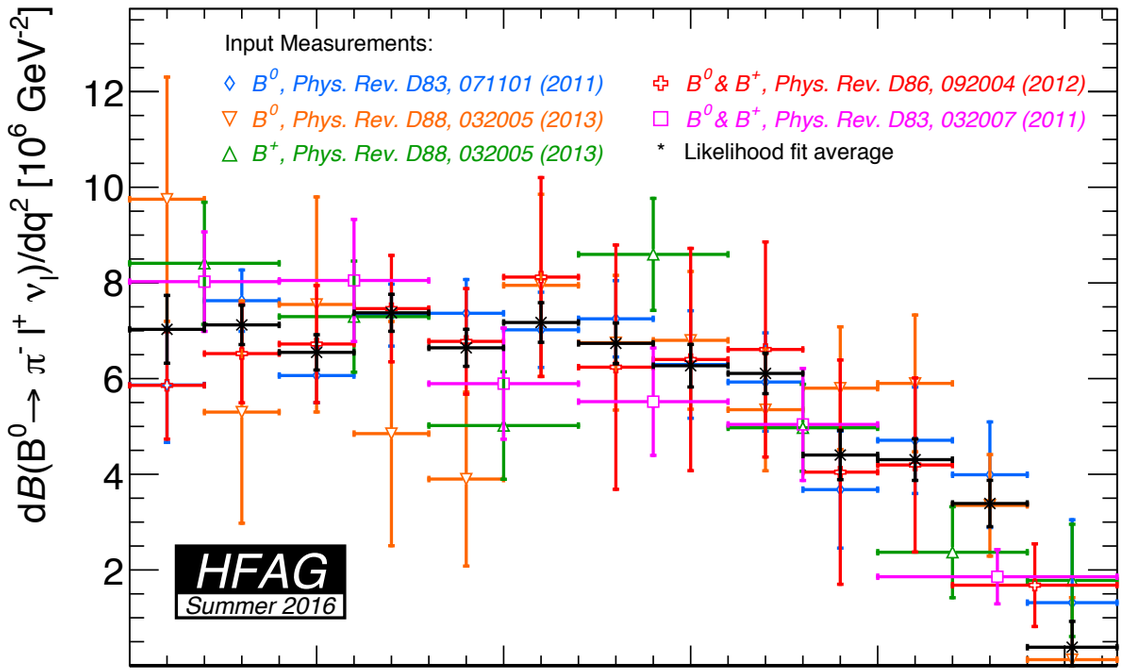
Recent developments: Excl. $|V_{ub}|$

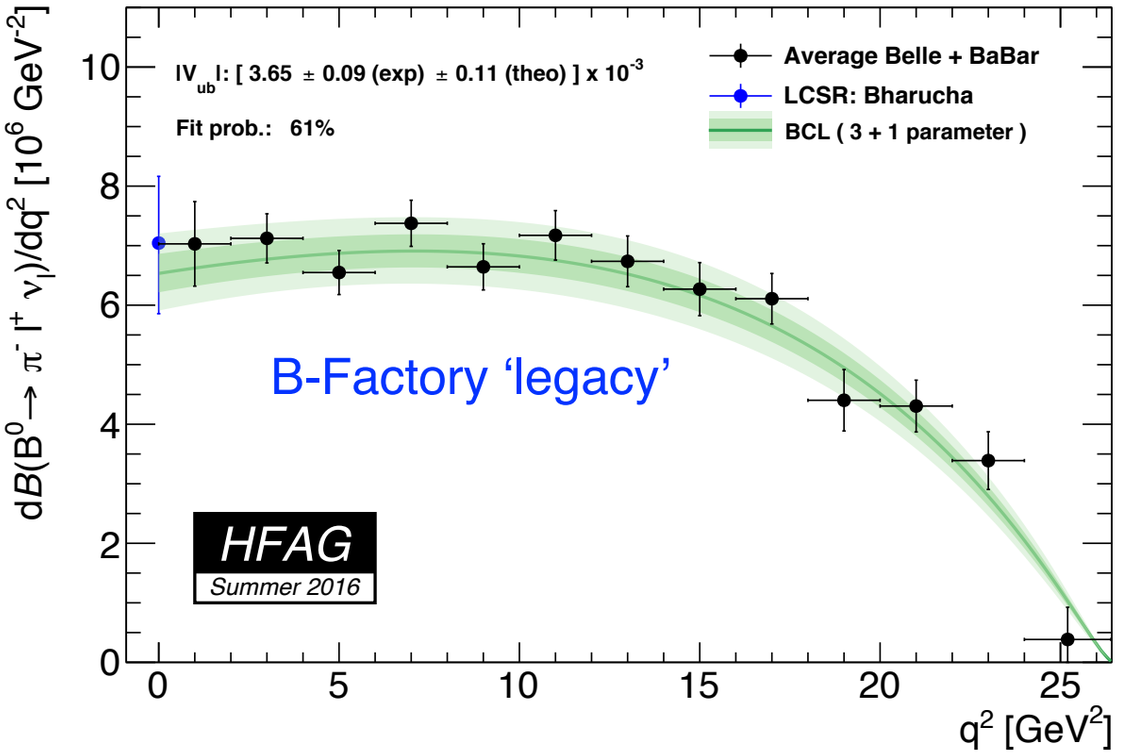
$$q^2 = (p_B - p_\pi)^2$$

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**

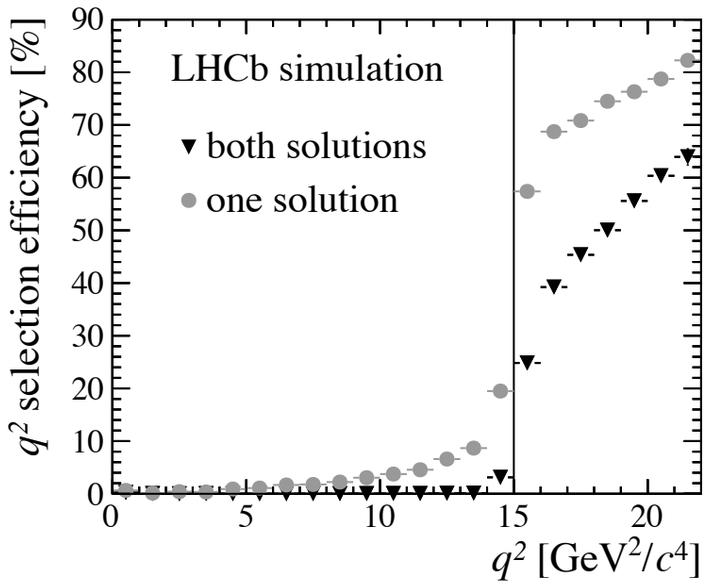
BGL: Phys. Rev. Lett. 74, 4603 (1995)

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

Nature Physics 10 (2015) 1038

First measurement at a Hadron Collider

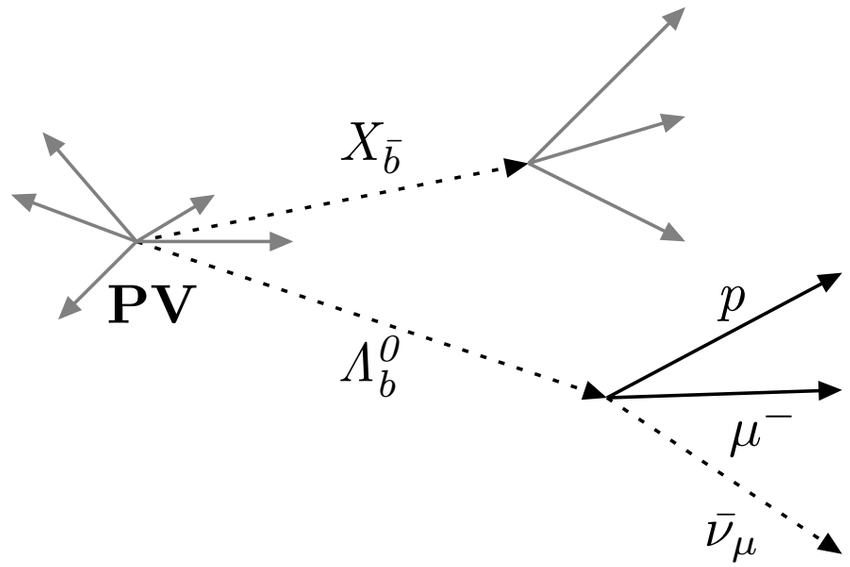
- Uses $\Lambda_b \to p\,\mu\,\bar{\nu}_\mu$ & $\Lambda_b \to \Lambda_c\,\mu\,\bar{\nu}_\mu$
- q^2 reconstructed up to two-fold ambiguity

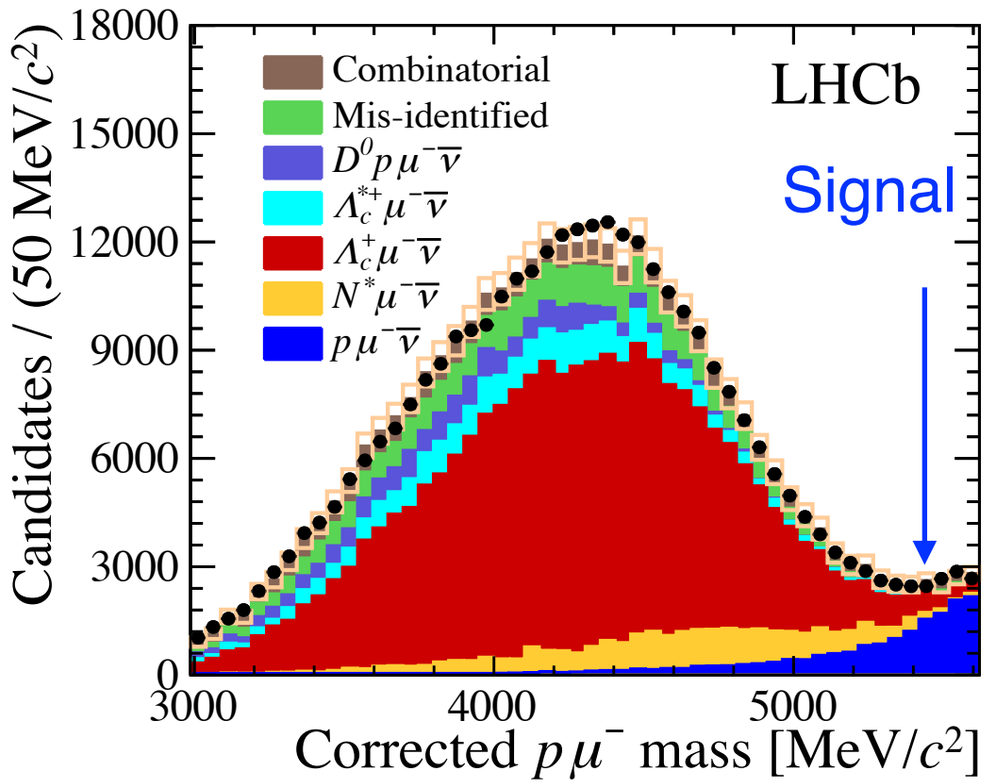


Measure $\dfrac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}}$ using

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

pμ- or Λ_cμ-pair mass pμ- or Λ_cμ-pair p_T





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

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Nature Physics 10 (2015) 1038

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

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)

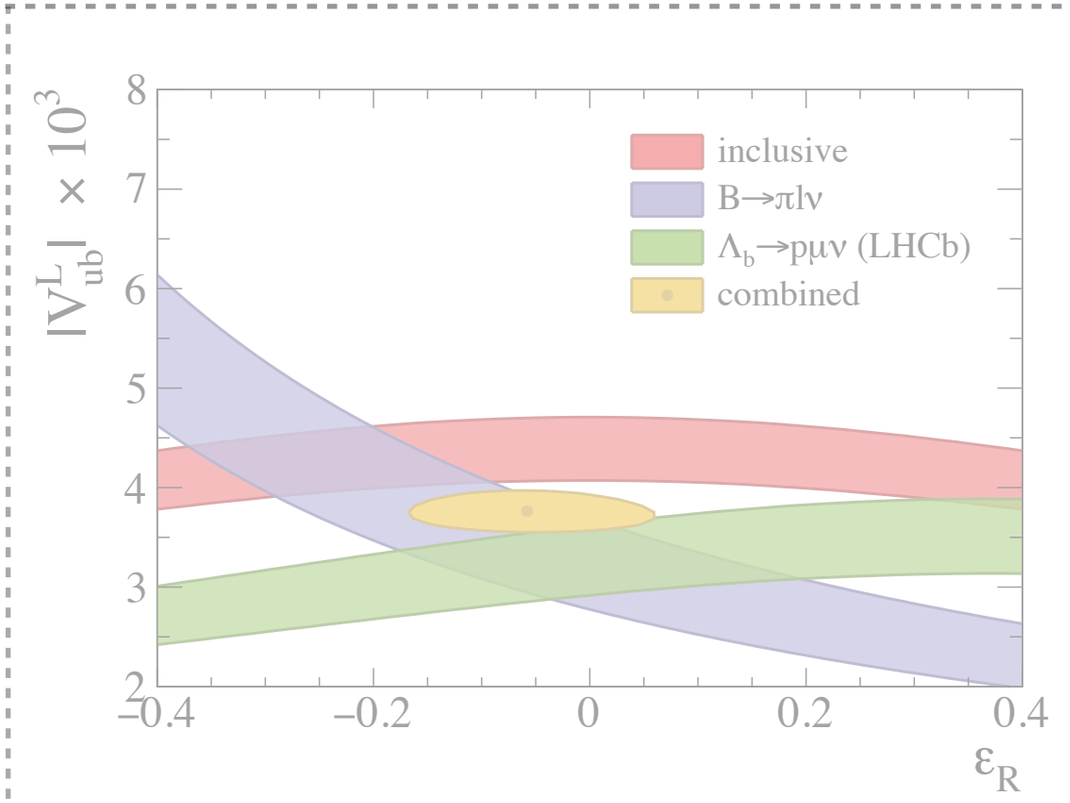
can convert this into $|V_{ub}|/|V_{cb}|$

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

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



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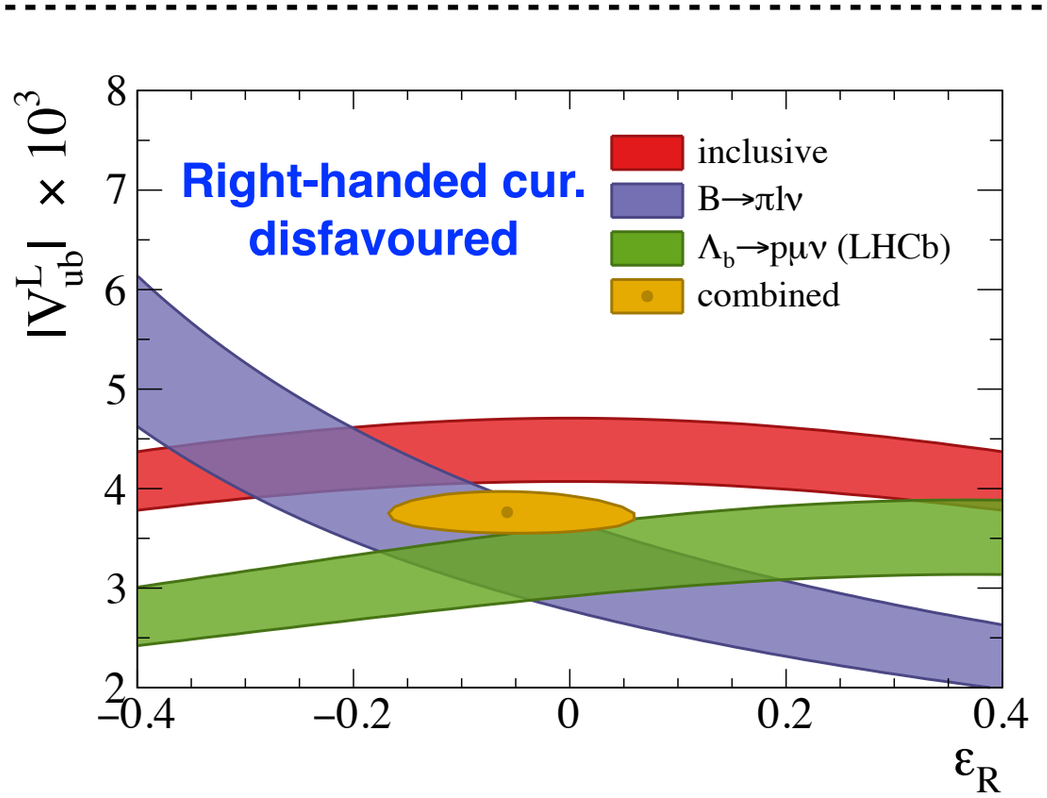

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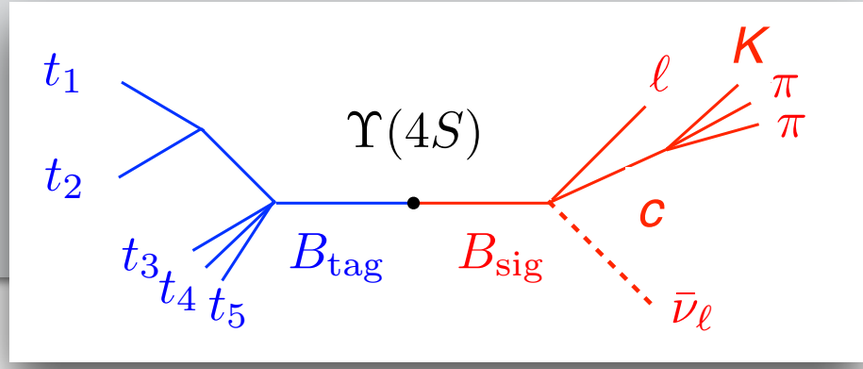


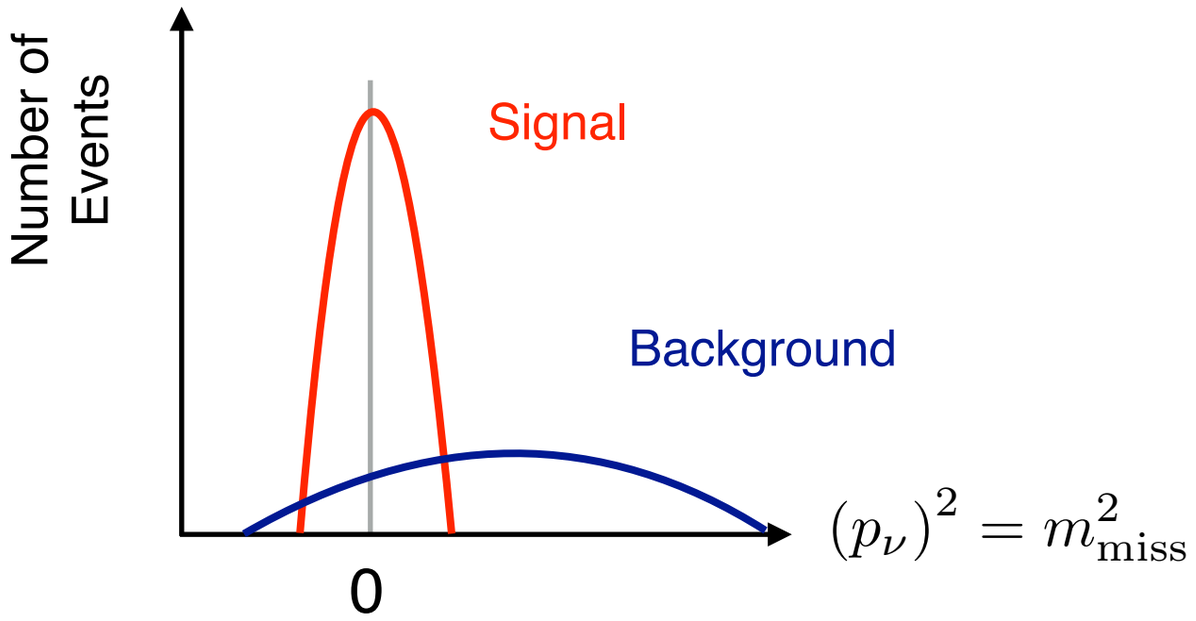
Belle-Conf 1612, 1702.01521
Phys. Rev. D 93, 032006 (2016)

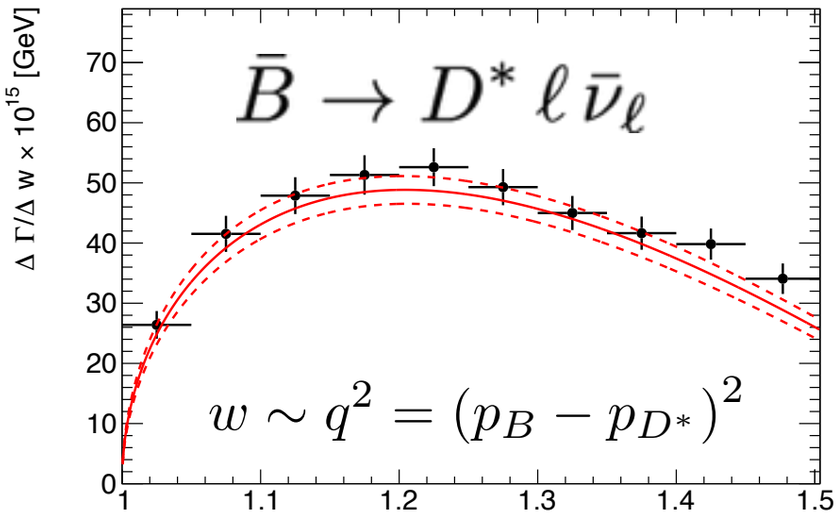
Two new measurements from Belle

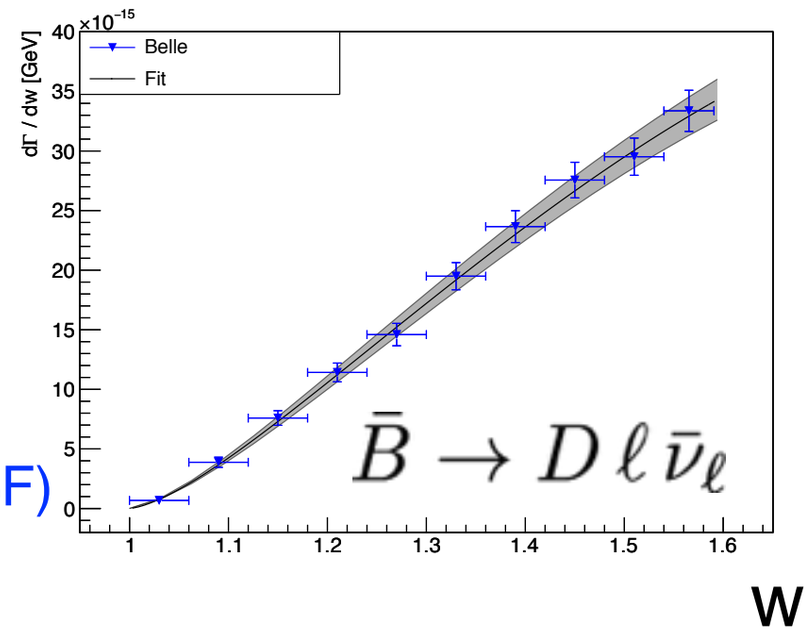
- Measure $\bar{B} \to D^* \ell \bar{\nu}_\ell$ & $\bar{B} \to D \ell \bar{\nu}_\ell$
- **Hadronic tagged,** allows for neutrino reconstruction

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

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

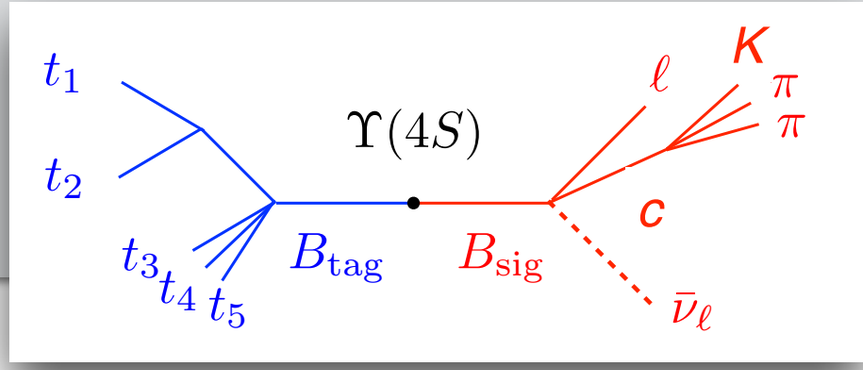






- Reconstruct w ~ q^2 and projections of *D** decay angles
  - **Largest Systematic**: hadronic tagging calibration (~3-4% on BF)
  - Full correlations of *D** decay angles and w

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



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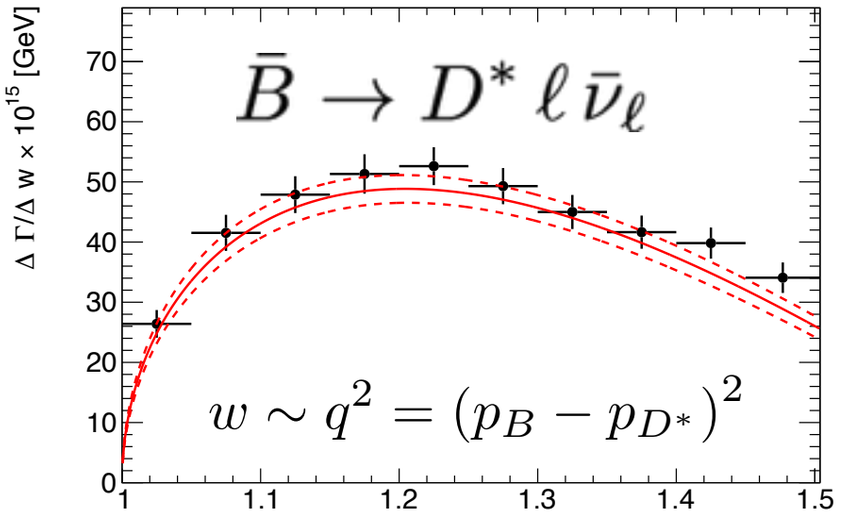


CLN: Phys. Lett. B380, 376 (1996)

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

~1.4 σ

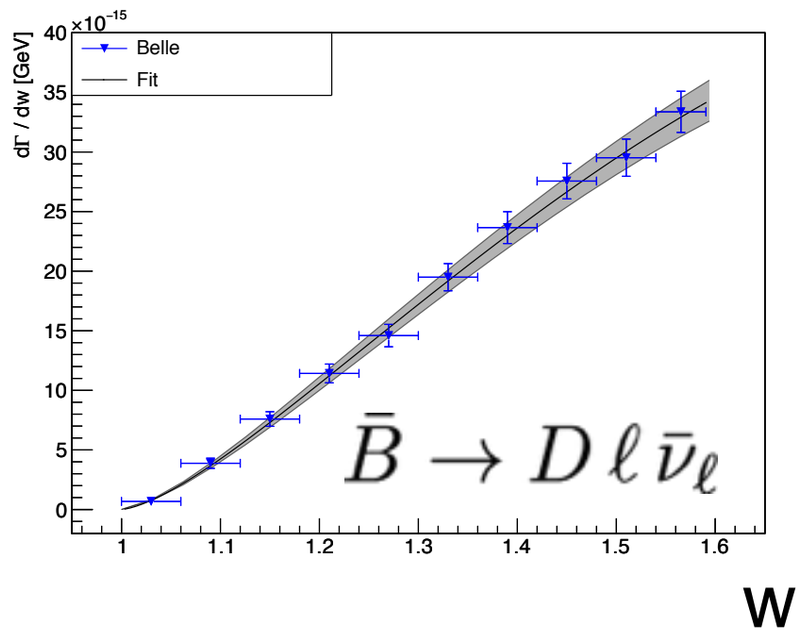
BGL: Phys. Rev. Lett. 74, 4603 (1995)

BGL	*D*
$\|V_{cb}\|$ x 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 analyzed by three groups

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

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

Includes additional measurement & beyond zero recoil lattice constraints

1703.06124, 1703.08170

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

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

1703.05330

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

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

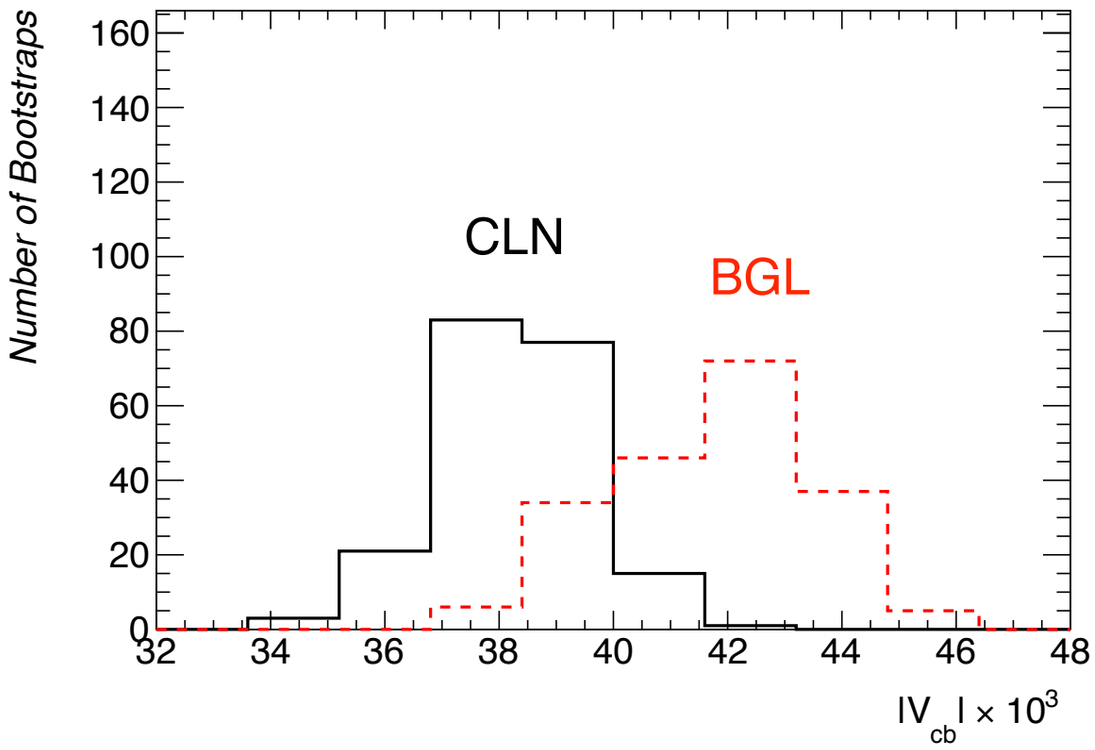
Recent developments: Excl. $|V_{cb}|$

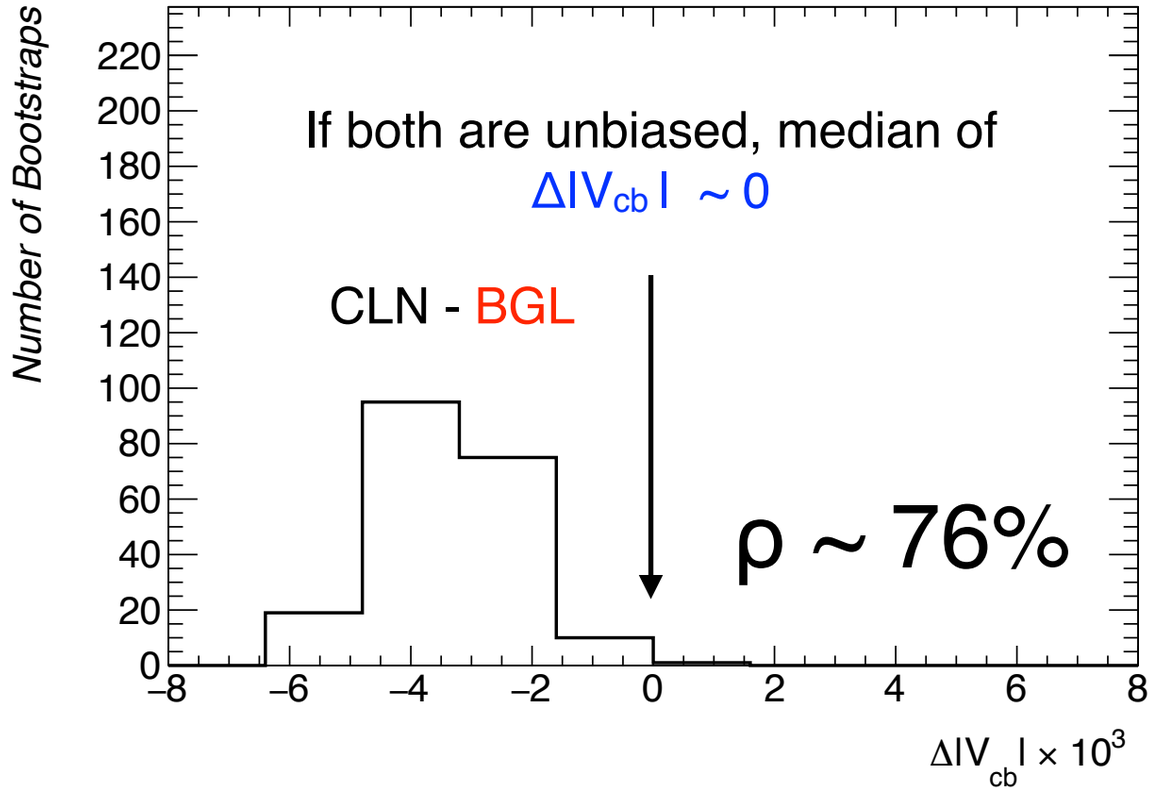
*D** **unfolded** distributions analyzed by three groups

Includes additional measurement & beyond zero recoil lattice constraints

FB

Correlation between CLN and BGL can be determined via bootstrapped ensembles





CLN ⟷ BGL

~3 σ

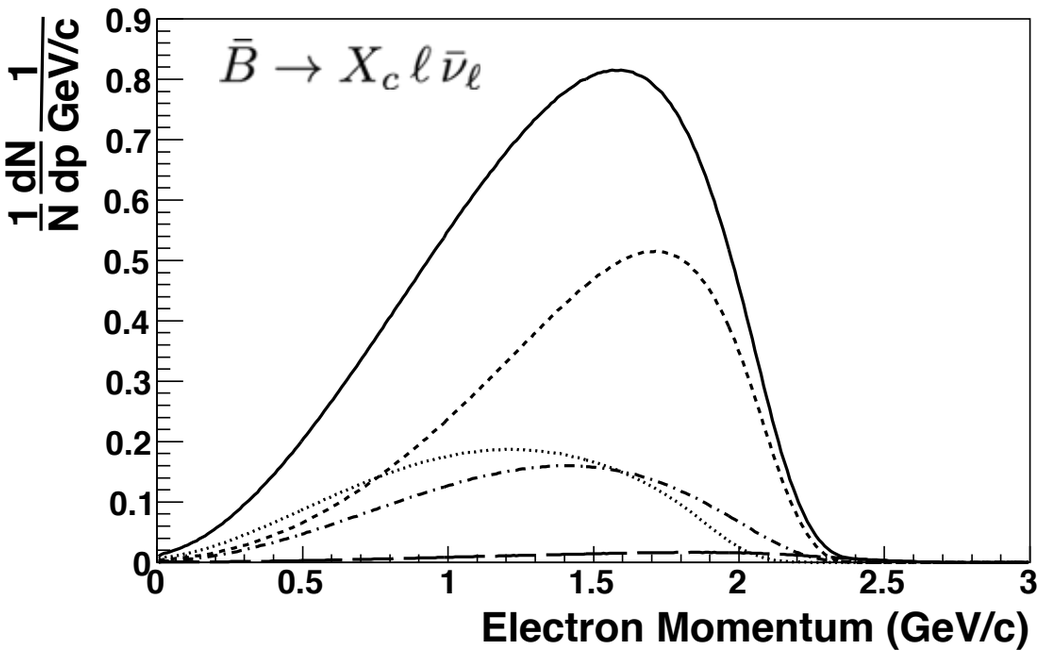
Naive estimate with ρ = 100% correlation gives a ~9σ tension

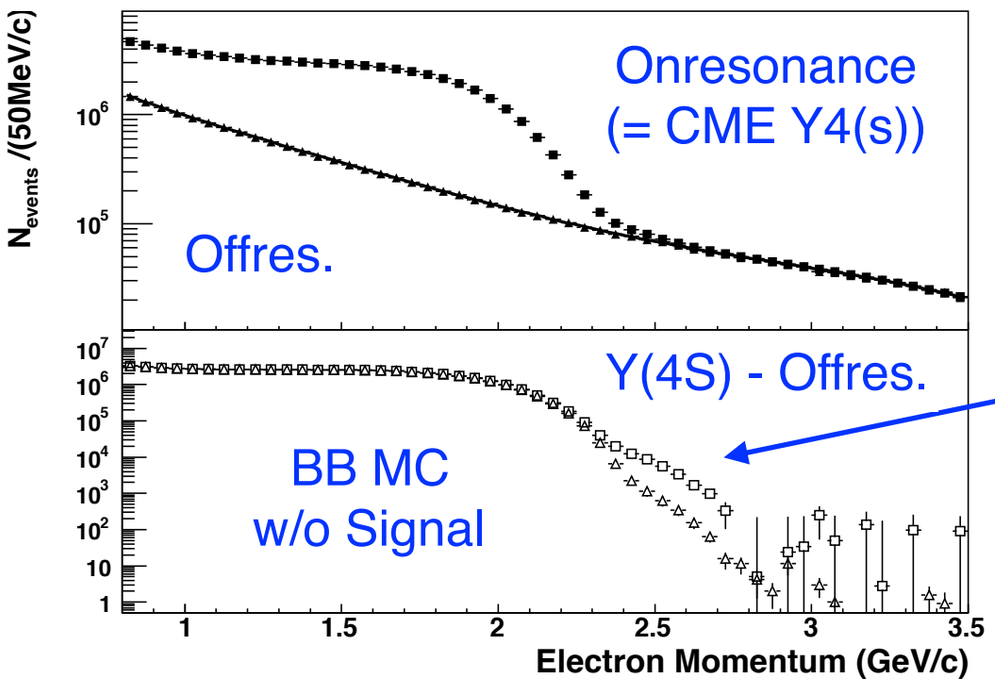
Recent developments: Incl. $|V_{ub}|$

Phys. Rev. D 95, 072001 (2017)

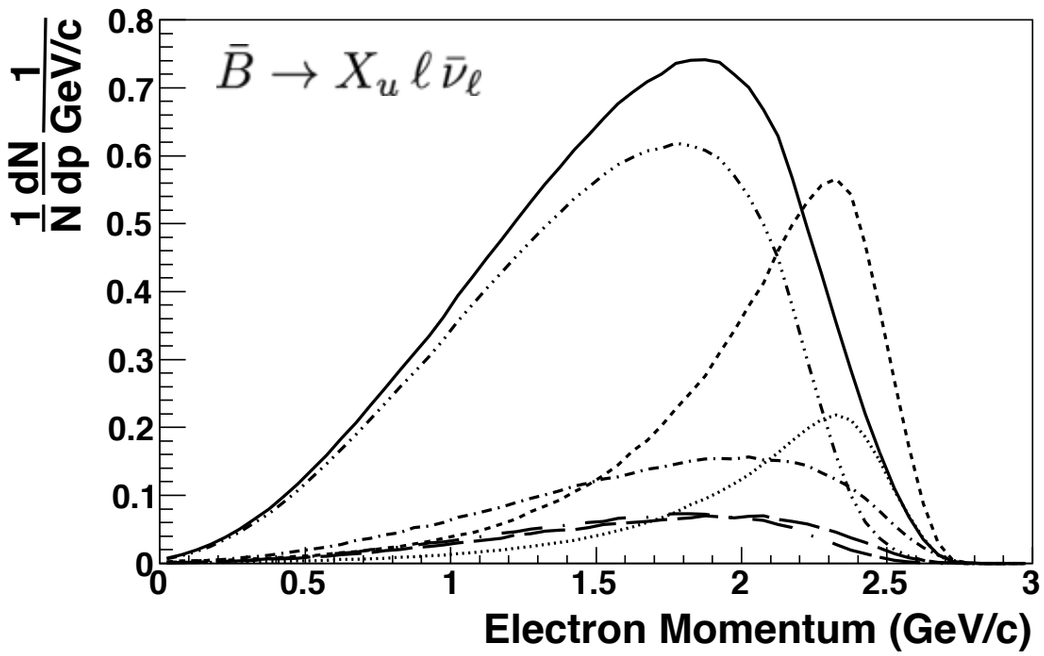
One new measurements from BaBar

- **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



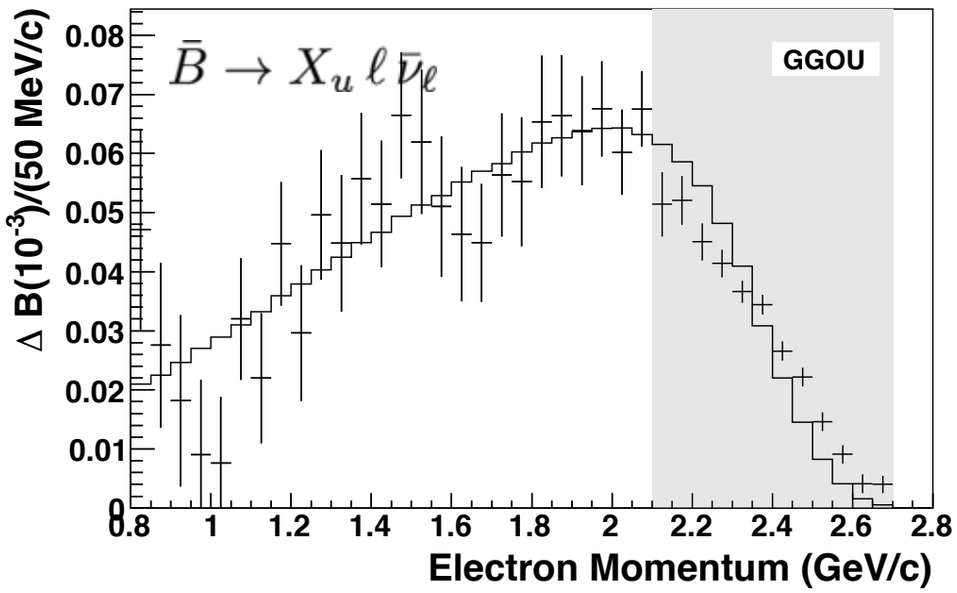


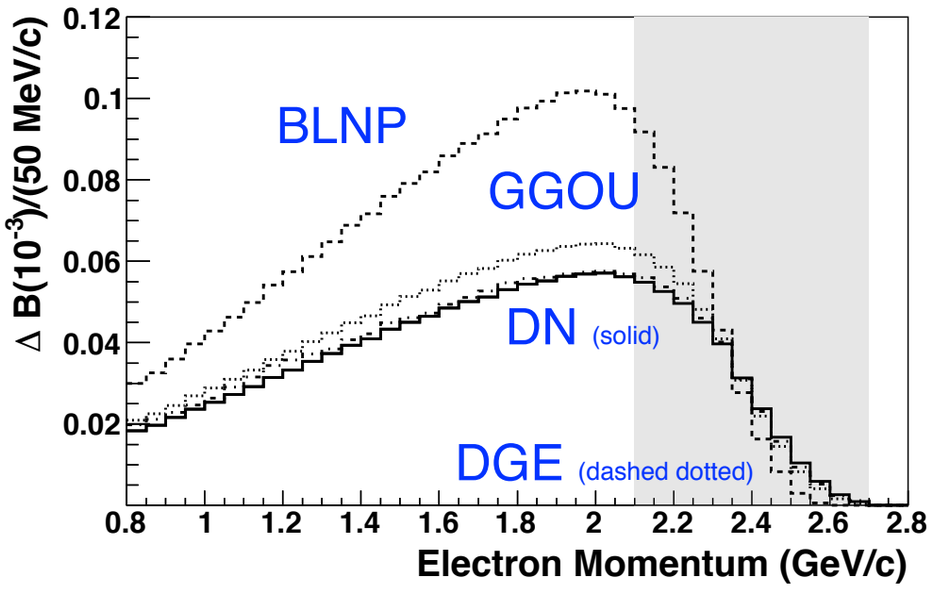
Signal!



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

Phys. Rev. D 95, 072001 (2017)



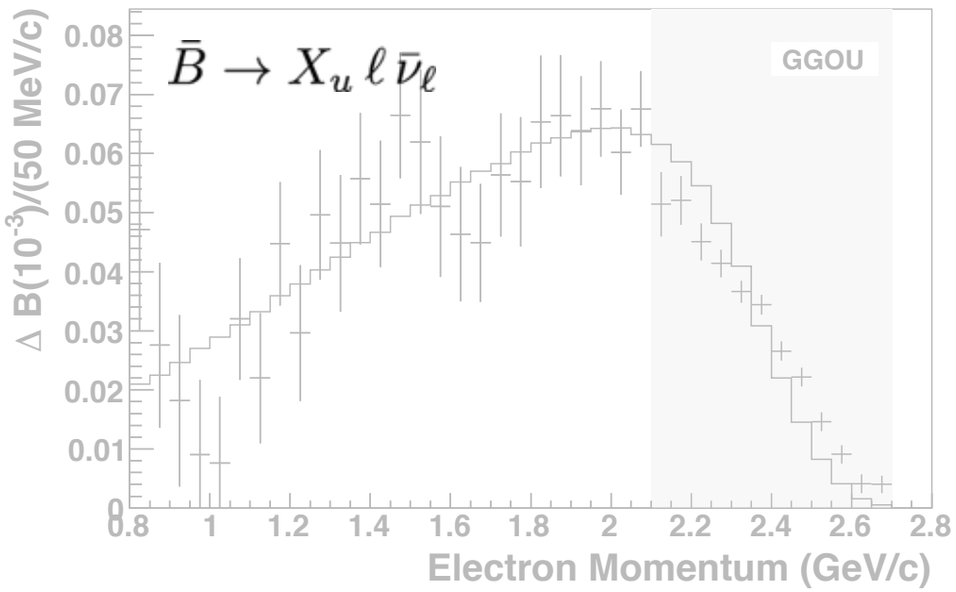


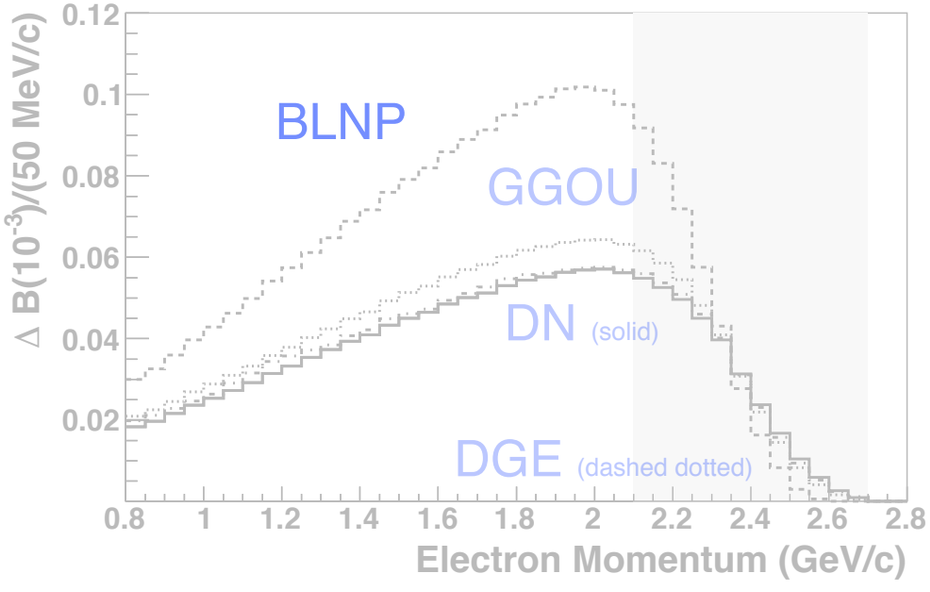
	BLNP	*GGOU*	*DN*	*DGE*
$\|V_{ub}\| \times 10^3$	**4.6 ± 0.3**	**4.0 ± 0.3**	**3.8 ± 0.3**	**3.8 ± 0.1**

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}

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

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**

Some tensions..

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

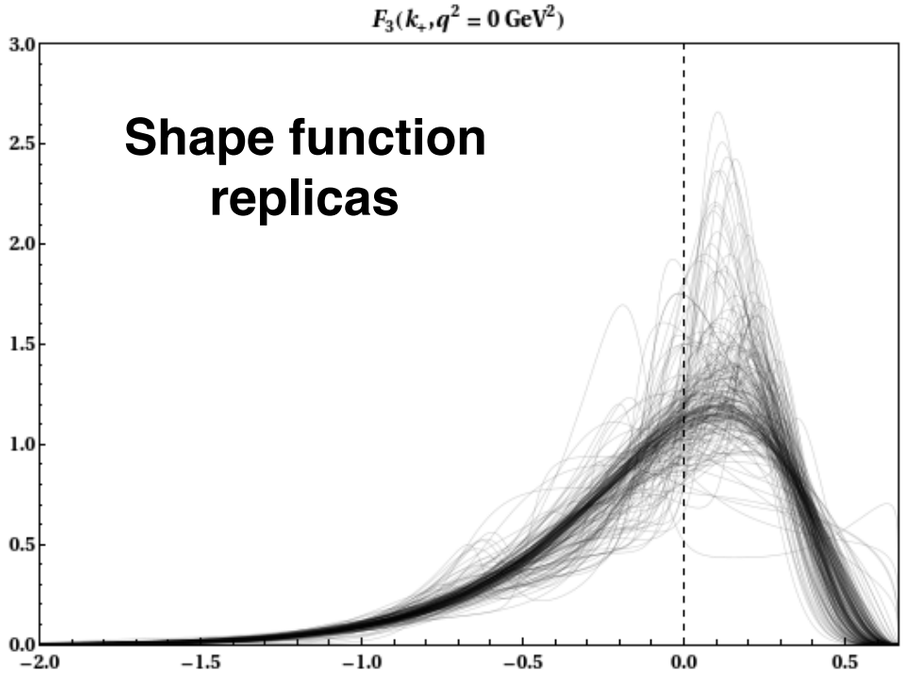
Recent developments: Incl. $|V_{ub}|$

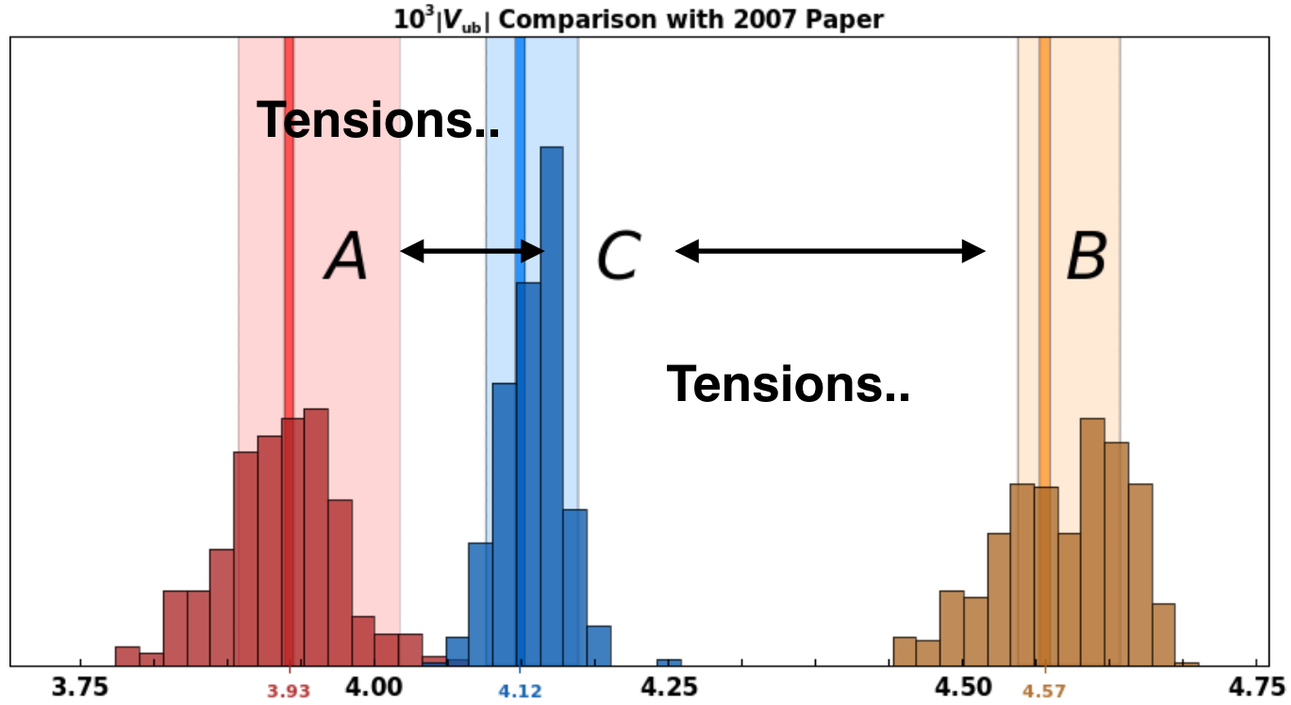
Largest unknown: shape function ⟷ Moments constraint by $b \to c\ell\nu$ or $b \to s\gamma$, but functional form **not known**

↑

~ B-Meson 'PDF'

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





But not possible to propagate errors to acceptance

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

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

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

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

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

50 : 1

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

50 : 1

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

Projections for excl. $|V_{ub}|$ & $|V_{cb}|$

Belle II Physics book,
to appear later this year

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*
rel. Error	**4%**	**3%**

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

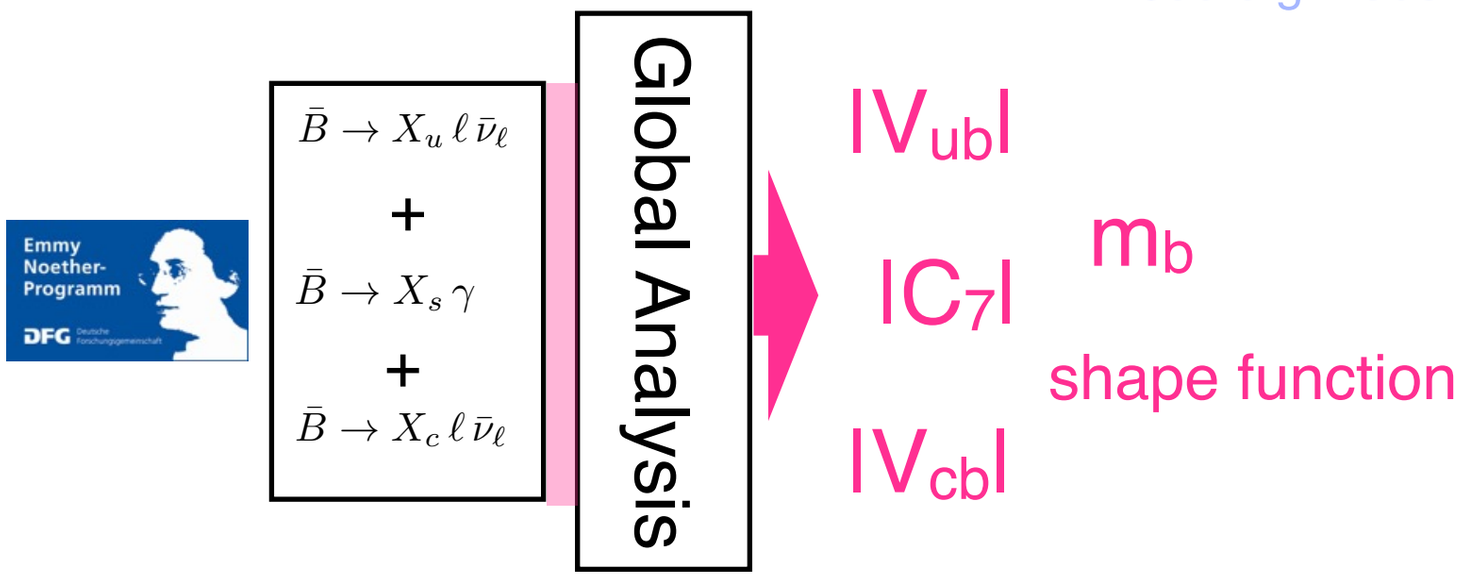
Projections for incl. $|V_{ub}|$

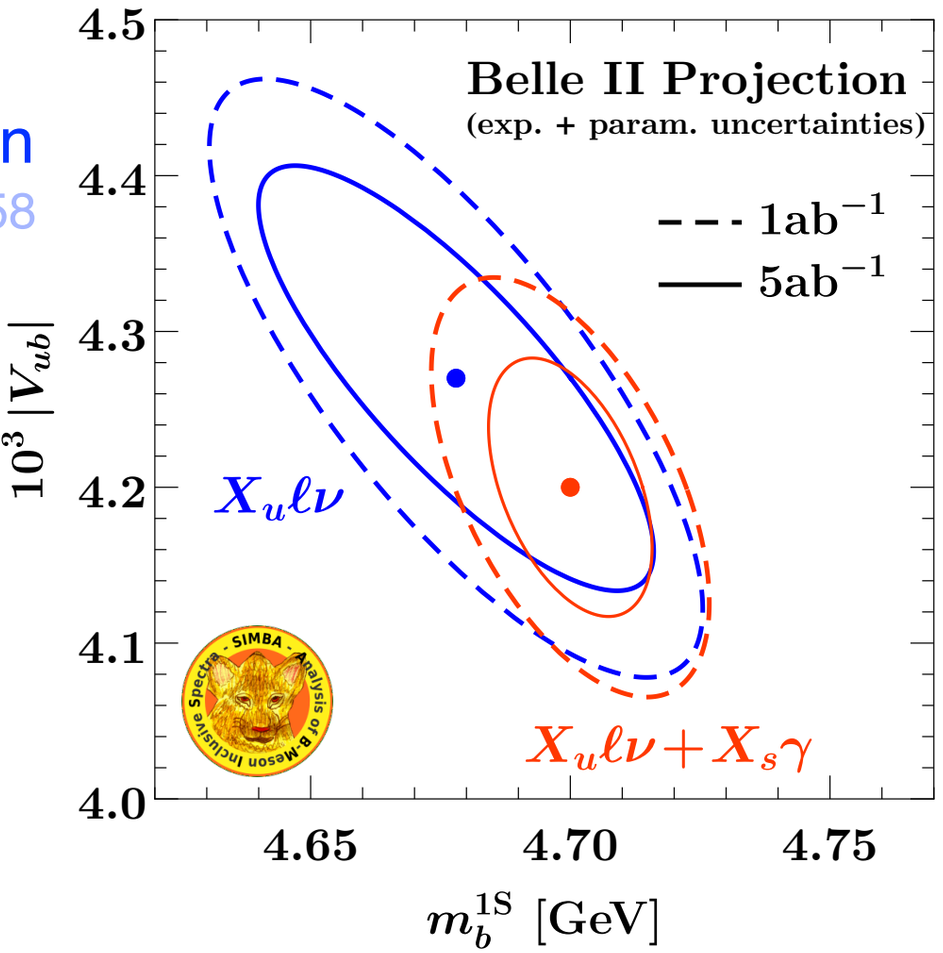
Belle II Physics book,
to appear later this year

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 :-/

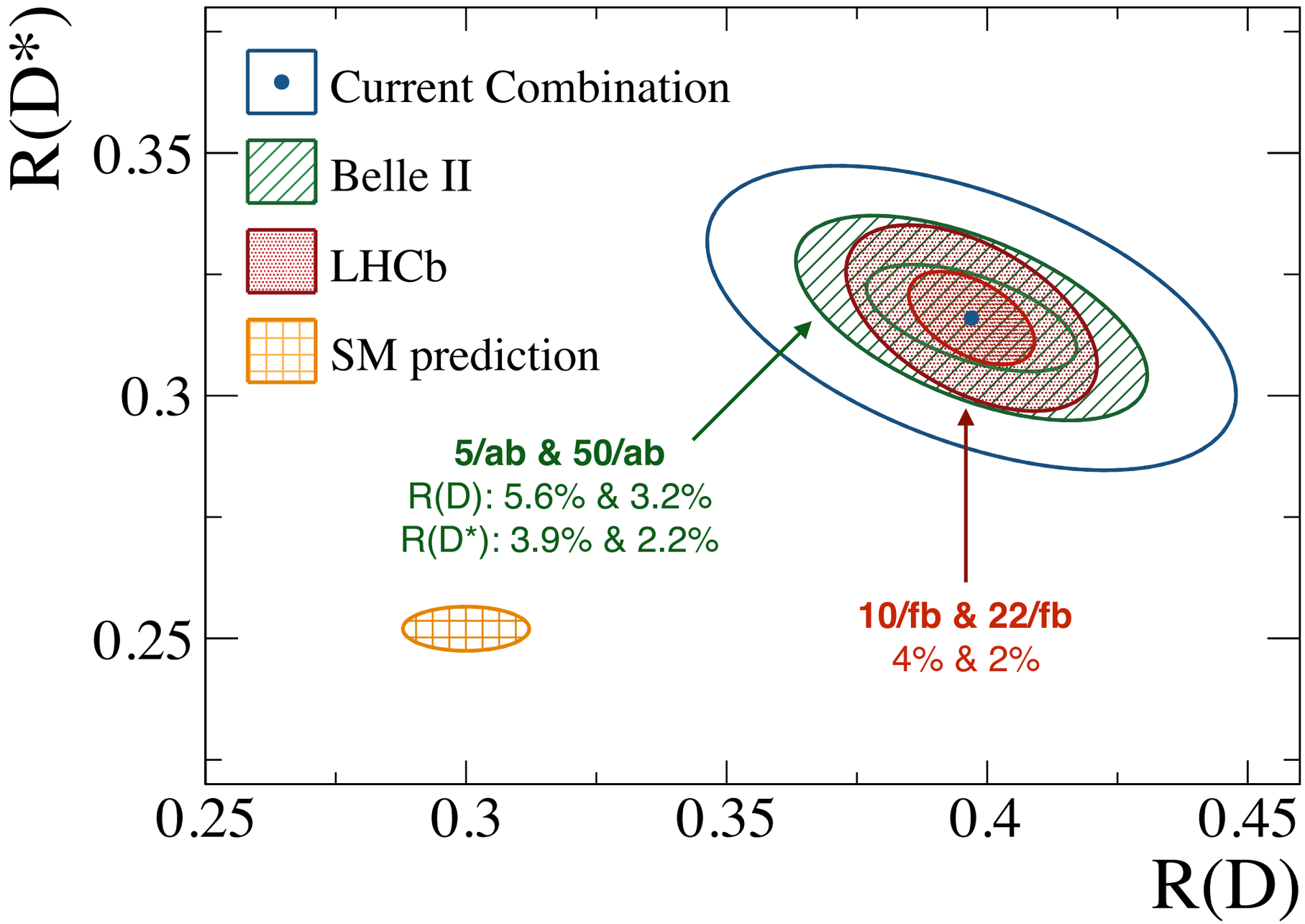
Incl. $|V_{cb}|$ → Hard to improve much (1.4% to 1.2% at 50/ab)

Projections for R(D) & R(D*) → See Backup

Backup

Projections for R(D) & R(D*)

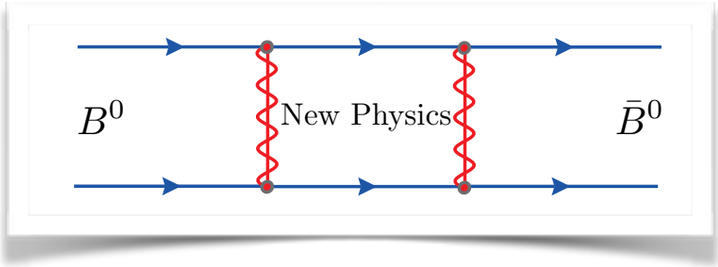
Today:
R(D): 11.6%
R(D*): 5.5%



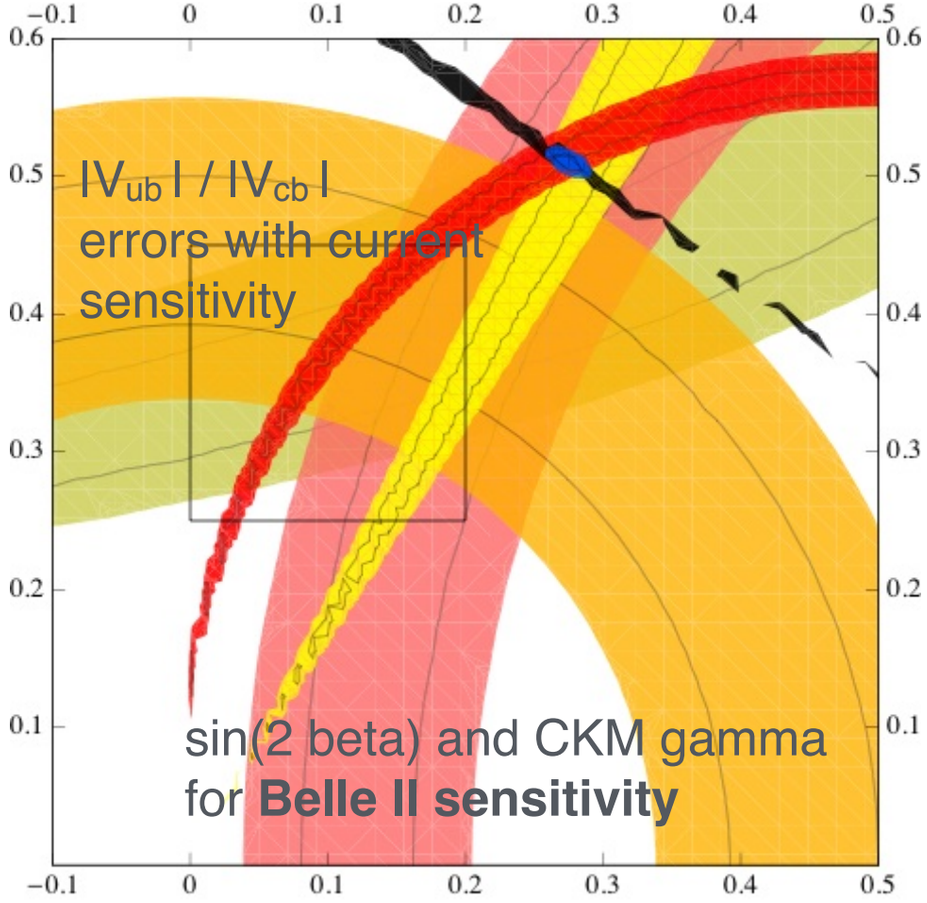
New Physics Scenarios with $|V_{ub}|$ / $|V_{cb}|$ as an anchor

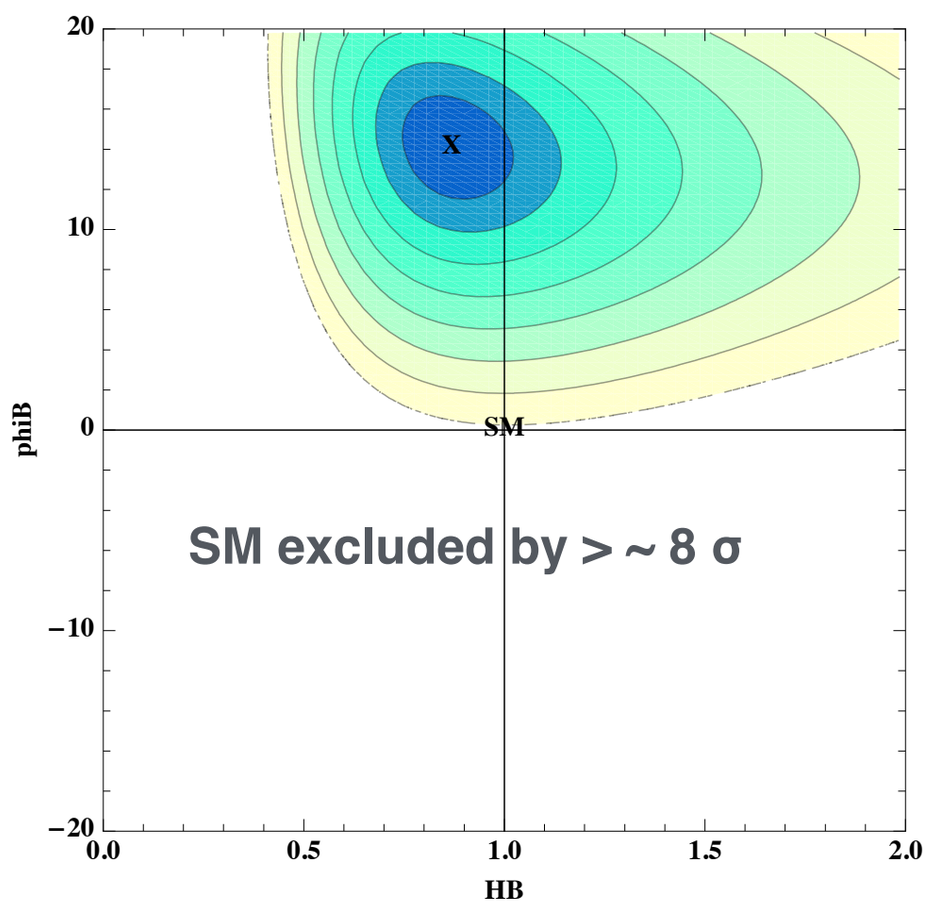
Emi Kou, in preparation

Example with New Physics in mixing:



$$H_{B_q}^{\rm NP} e^{2i\phi_{B_q}^{\rm NP}} \equiv \frac{\langle B_q^0|\mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP}|\overline{B}_q^0\rangle}{\langle B_q^0|\mathcal{H}_{\rm eff}^{\rm SM}|\overline{B}_q^0\rangle} \qquad \sin 2\phi_1 = \sin 2(\phi_1^{\rm SM} + \phi_{B_d}^{\rm NP}), \quad \Delta M_q = H_{B_q} \Delta M_q^{\rm SM}$$

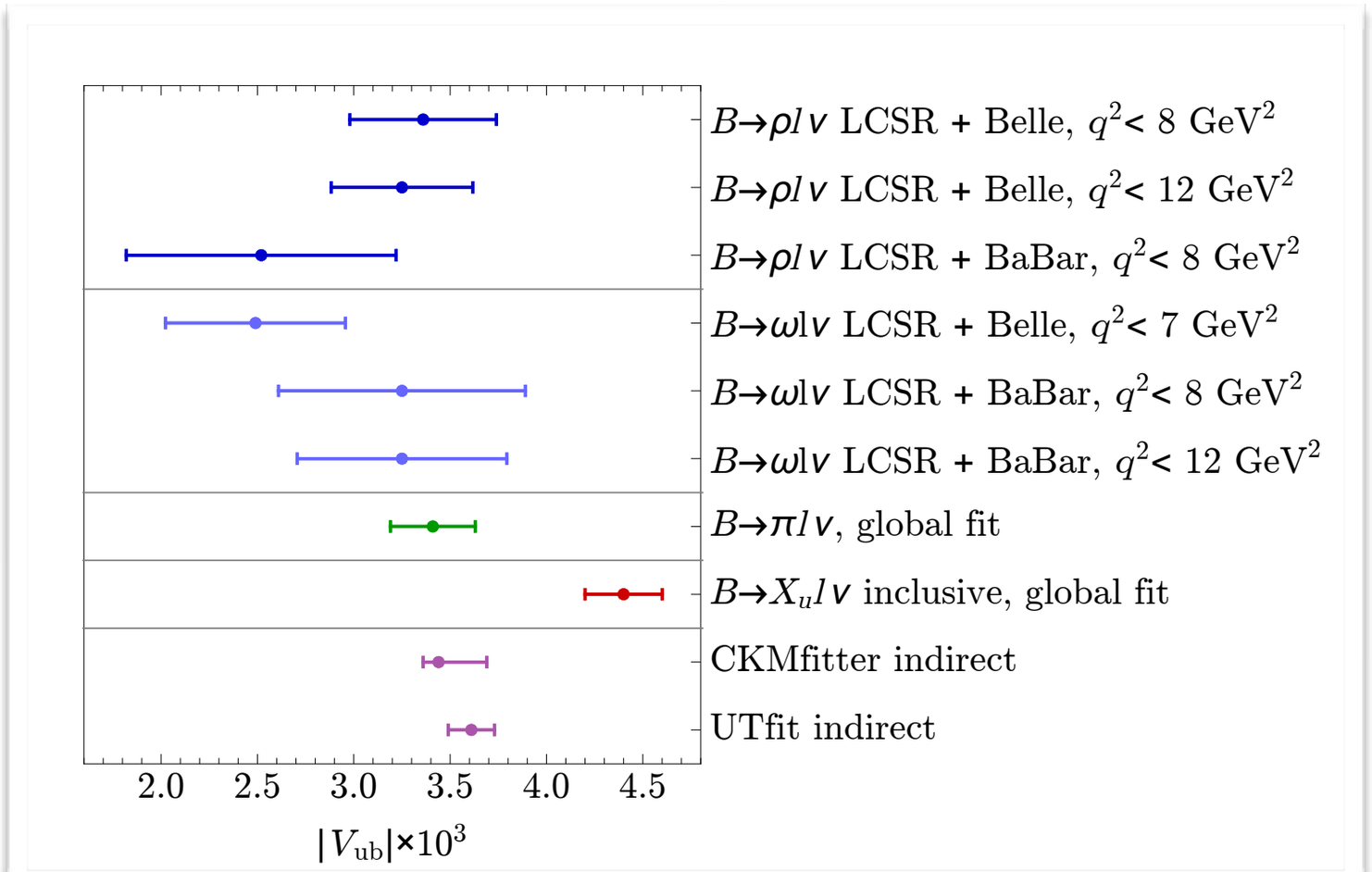


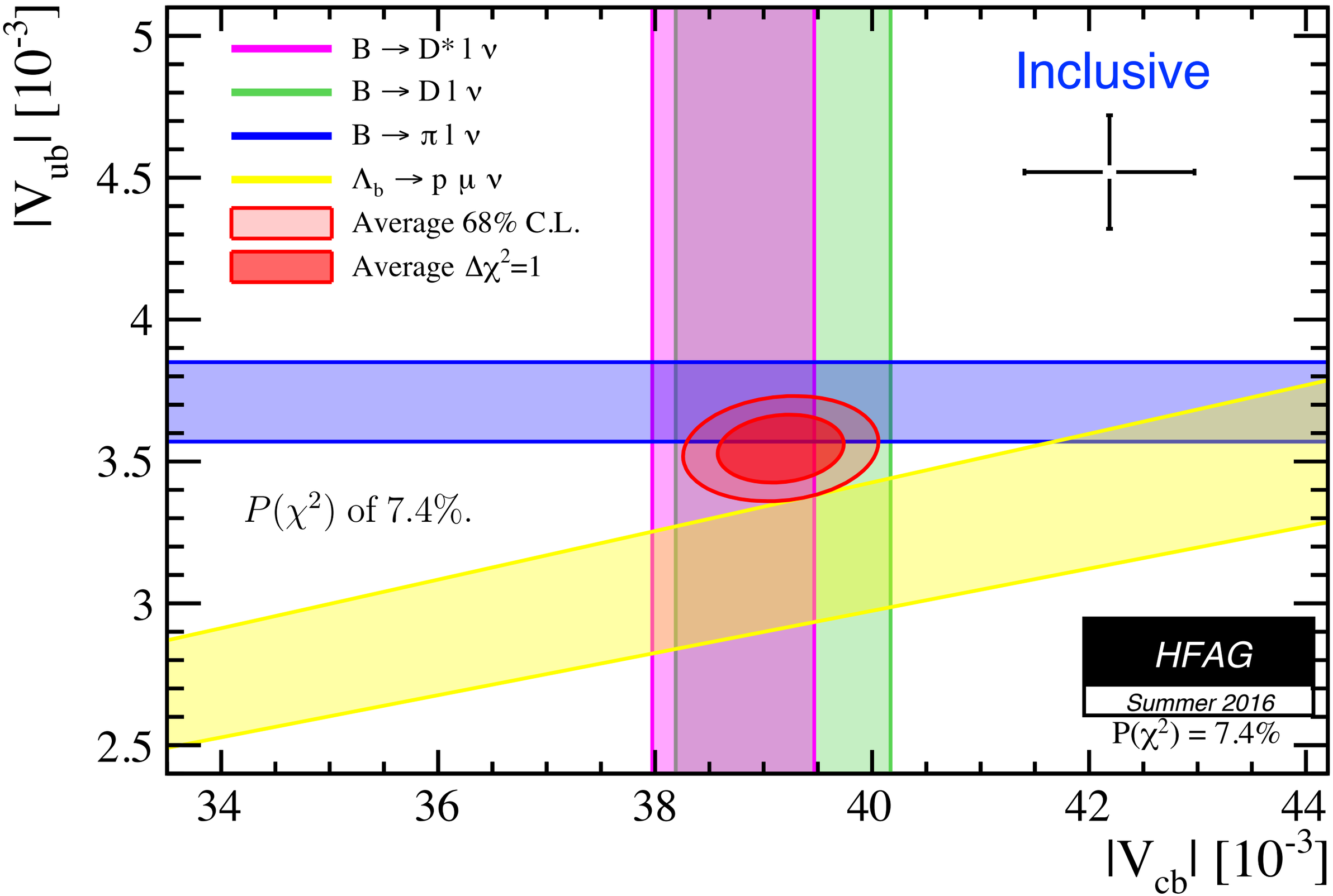


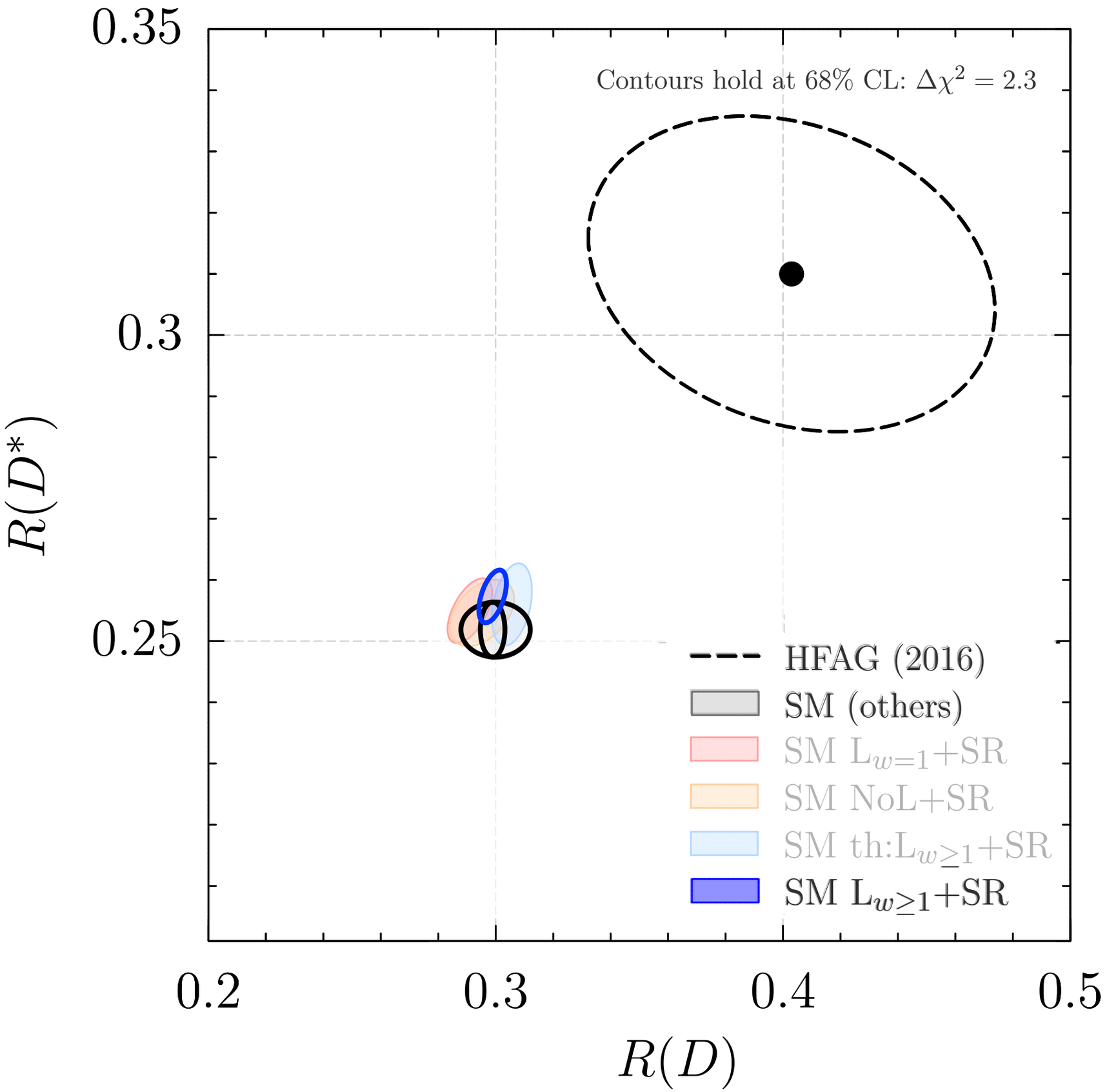
Recent developments: Excl. $|V_{ub}|$

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

Compatibility of $|V_{ub}|$ from vector decays (using LCSR)




$|V_{ub}|$ $[10^{-3}]$
5
4.5
4
3.5
3
2.5
B → D* l ν
B → D l ν
B → π l ν
Λ_b → p μ ν
Average 68% C.L.
Average $\Delta\chi^2$=1
Inclusive
$P(\chi^2)$ of 7.4%.
HFAG
Summer 2016
$P(\chi^2)$ = 7.4%
34
36
38
40
42
44
$|V_{cb}|$ $[10^{-3}]$


Contours hold at 68% CL: $\Delta\chi^2 = 2.3$
HFAG (2016)
SM (others)
SM $L_{w=1}$+SR
SM NoL+SR
SM th:$L_{w\geq 1}$+SR
SM $L_{w\geq 1}$+SR
$R(D^*)$
$R(D)$
0.35
0.3
0.25
0.2
0.3
0.4
0.5