Experimental status of $|V_{ub}/V_{cb}|$ and $\gamma(\phi_3)$

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Outline

- Importance of $|V_{ub}/V_{cb}|$ and γ
  - Why they are related
- Introduction to the experiments
  - BABAR, Belle, CLEO-c, LHCb, Belle II
- Measurements of $|V_{ub}/V_{cb}|$
  - Different methods
- Measurements of γ
  - Different methods

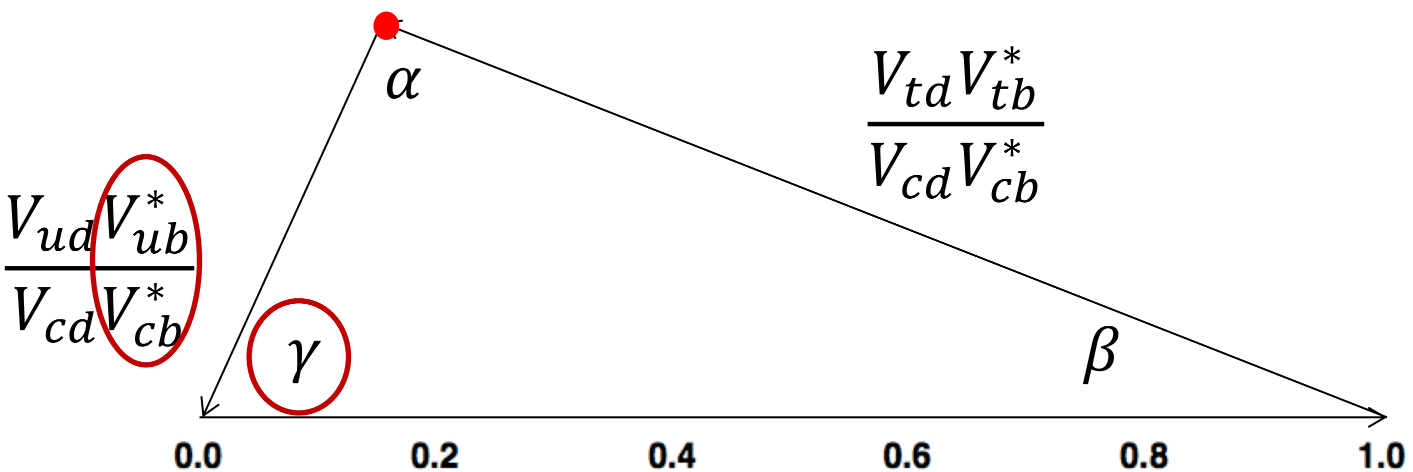
I will give only a selection of results and averages from [PDG](PDG) based mostly on HFLAV and CKMFitter

Importance of $|V_{ub}/V_{cb}|$ and γ

- The Cabibbo-Kobayashi-Maskawa (CKM) matrix contains 4 fundamental parameters of the SM.
- 2 of the 4 parameters can be parameterized as $|V_{ub}/V_{cb}|$ and γ
- They originate from some high-scale new physics
- Their precision measurement is critical to the definition of the SM
- It also provides a stress-test of the SM and probe of NP

CKM unitarity triangle

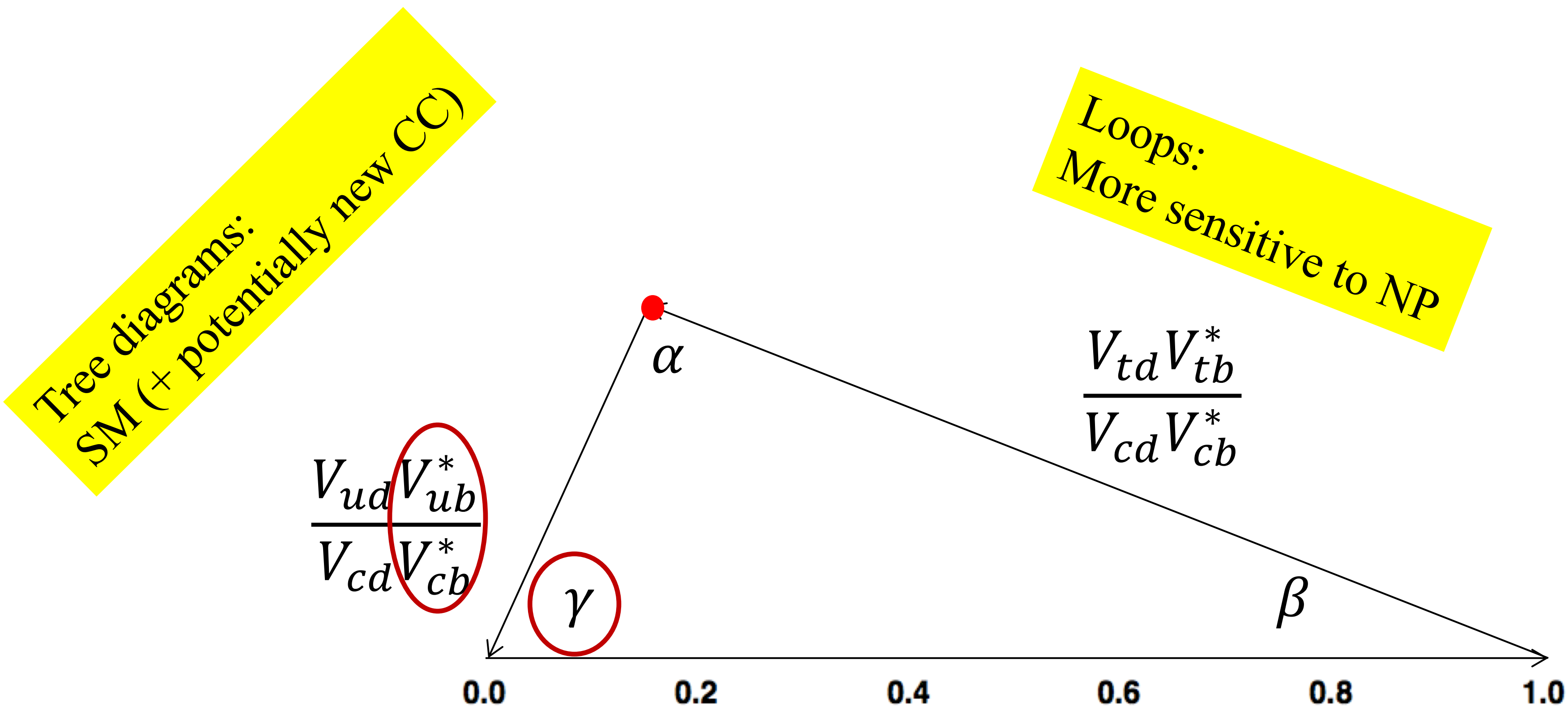
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Testing the consistency of this SM picture probes NP

Probing new physics (NP)

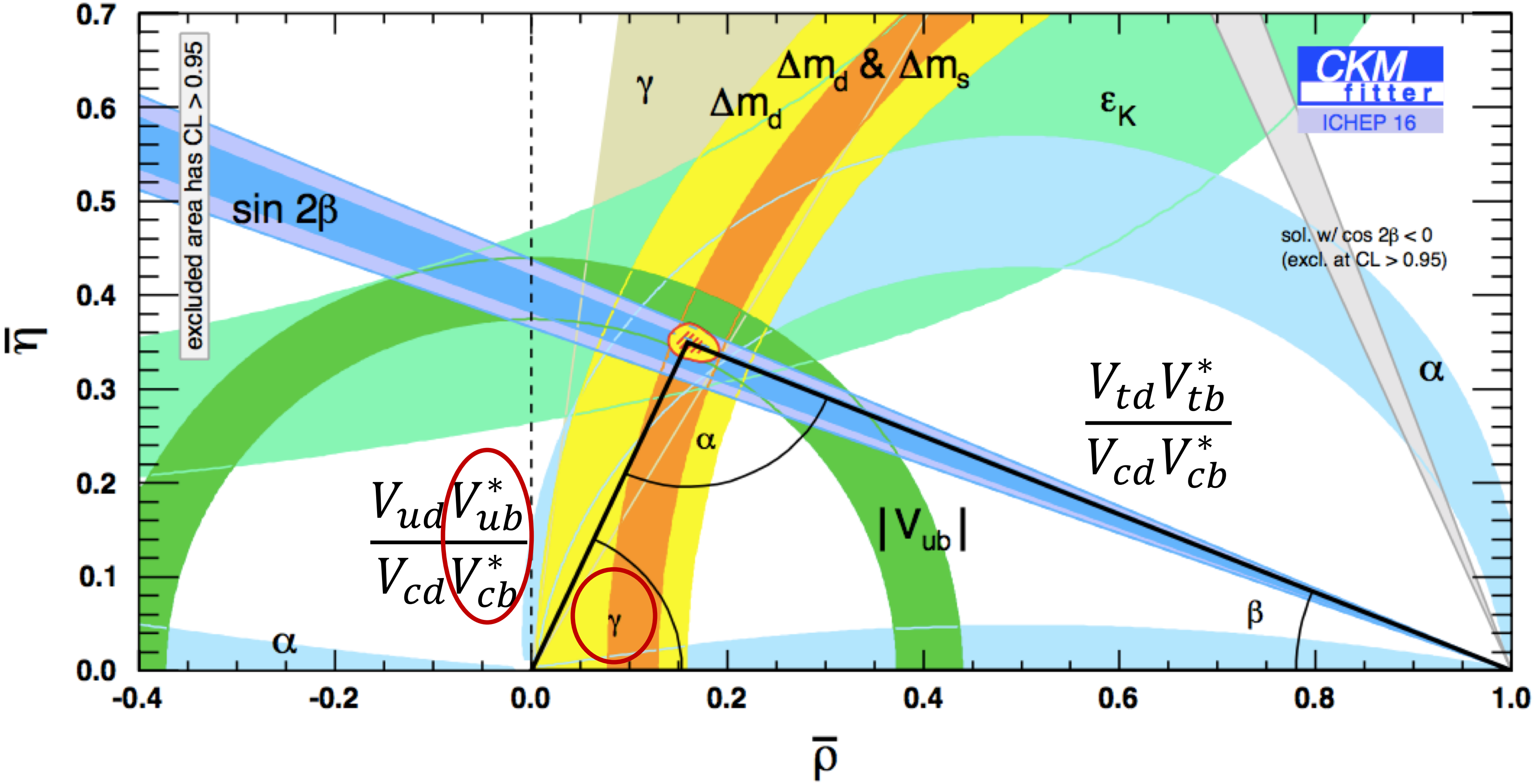
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Testing the consistency of this SM picture probes NP

Unitarity triangle constraints

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



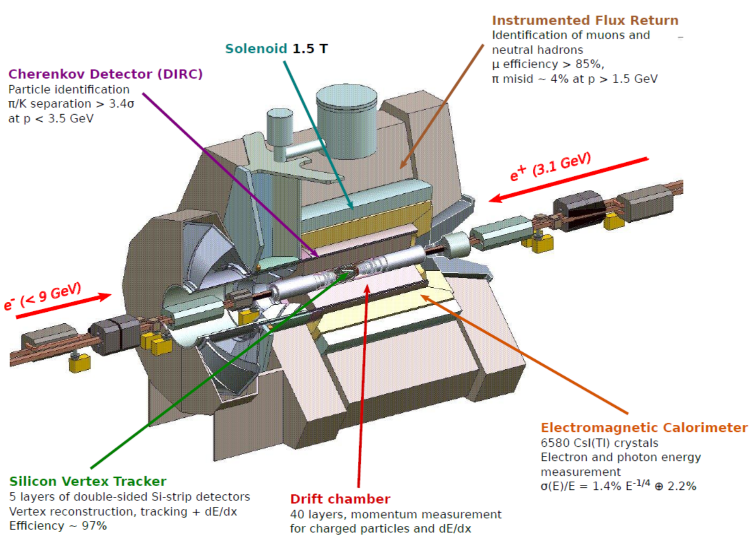
Testing the consistency of this SM picture probes NP

The experiments

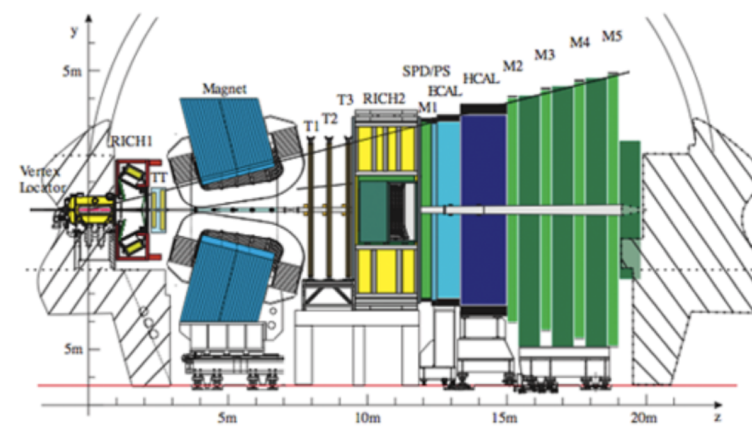
- BABAR: 1999-2008, ~470M $e^+e^- \to B\bar{B}$
- Belle 1999-2010, ~770M $e^+e^- \to B\bar{B}$
- LHCb 2010- , $pp \to b\bar{b}X$
- CLEO-c 2003-2006?, ~3M $e^+e^- \to D\bar{D}$
- Belle II 2019-2026?, ~50,000M $e^+e^- \to B\bar{B}$

- Silicon tracker
- Gas-based tracker
- Cherenkov hadron-ID
- EM calorimeter
- Muon system

BABAR



LHCb



V_{ub}/V_{cb}

See Matic Lubej's talk this afternoon

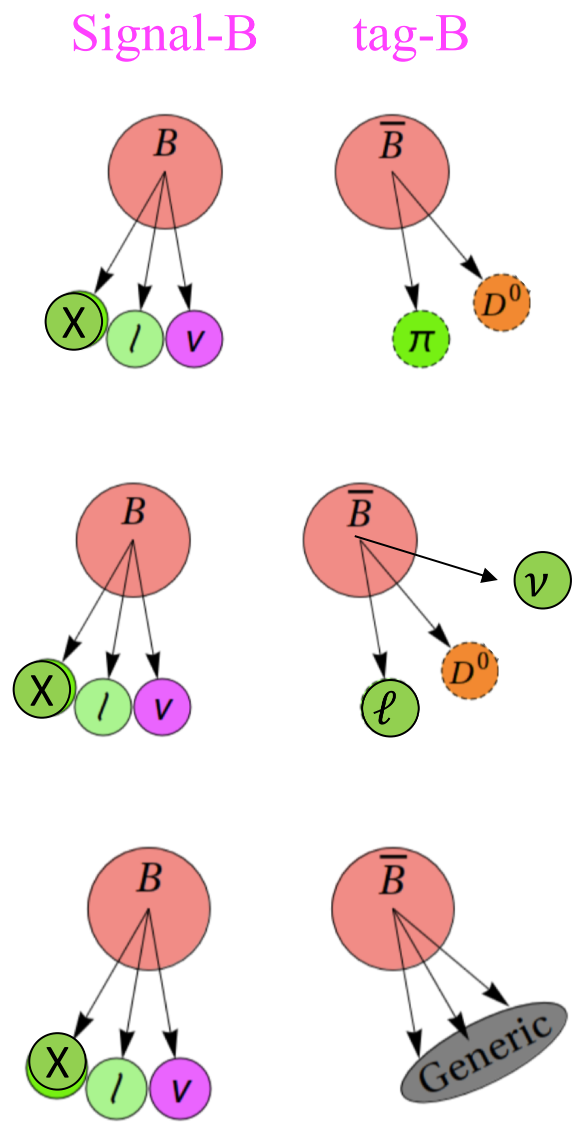
- Measured via $b \to u\ell\bar{\nu}$ and $b \to c\ell\bar{\nu}$ (where $\ell = e, \mu$)
  - Measurements with τ also possible in principle, but…
    - they are experimentally less precise
    - not yet clear what the ~ 4σ SM discrepancy in $\bar{B} \to D^{(*)}\tau\bar{\nu}$ is telling us
- Measured via both exclusive and inclusive final states.

exclusive	inclusive
$\bar{B} \to \pi\ell\bar{\nu}$	$\bar{B} \to X_u\ell\bar{\nu}$
$\bar{B} \to D^{(*)}\ell\bar{\nu}$	$\bar{B} \to X_c\ell\bar{\nu}$

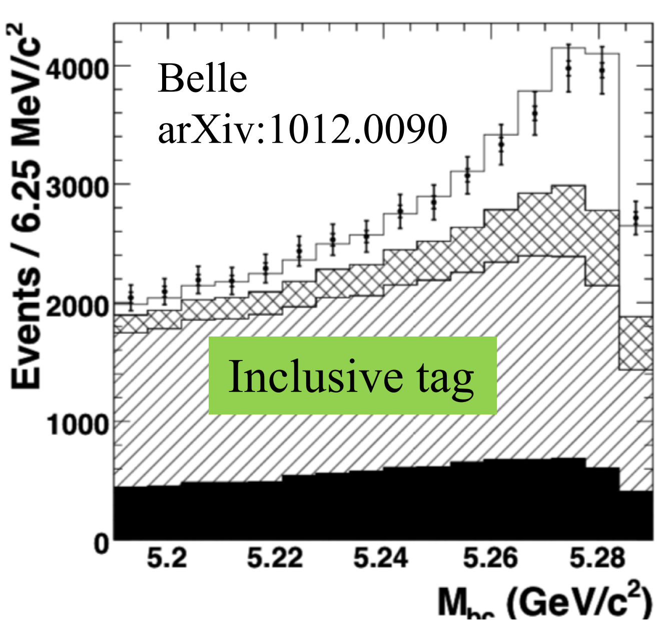
- Significant model dependence → different values of $|V_{ub}|$ & $|V_{ub}|$
- Close interaction between theoretical and experimental inputs

Other-B tagging at a e^+e^- B factory

- Hadronic
  - Fully reconstruct in >1000 hadronic decay chains
  - Reduces combinatorial background
  - $\vec{p}_\nu$ well determined
  - Efficiency ~0.5%
- Semileptonic
  - Reconstruct as $B \to \overline{D}^{(*)}\ell^+\nu$
  - Reduces combinatorial background
  - Efficiency ~0.5%
- Inclusive
  - Use all tracks and clusters to try and reconstruct neutrino 4-momentum
  - Efficiency ~10s%
  - Higher background
  - $\vec{p}_\nu$ not well determined: finite B momentum, missing/fake particles

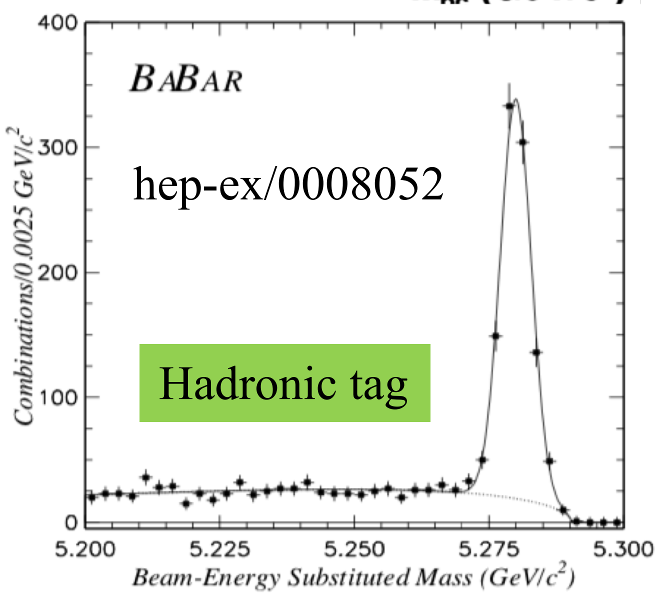


A comparison of other-B tagging methods

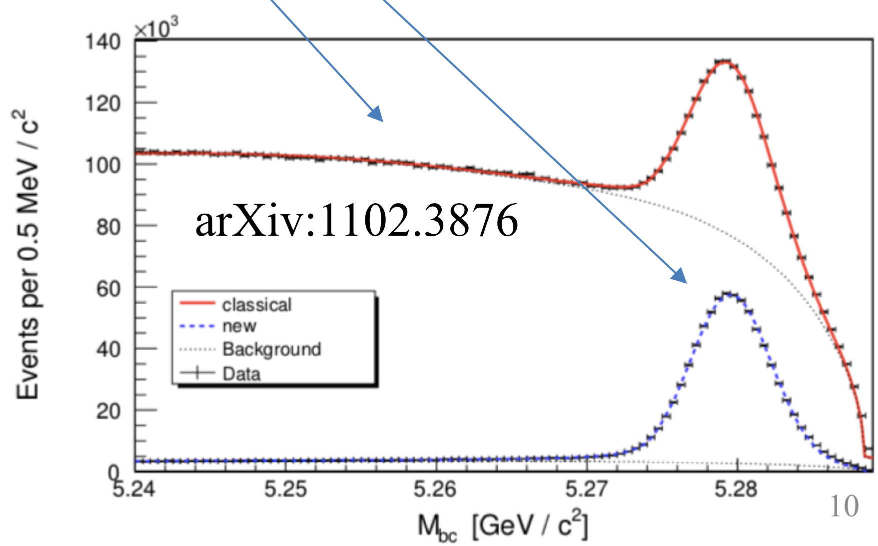


“Beam-constrained mass”

$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$$



Old and new algorithms, same efficiency



V_{cb} from exclusive $\bar{B} \to D^* \ell \bar{\nu}$

- Experiments measure differential decay rate, given by:

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3} |V_{cb}|^2 (w^2 - 1)^{1/2} P(w) (\eta_{\rm ew} \mathcal{F}(w))^2$$

$w \equiv v_B \cdot v_{D^*}$

Phase-space

~1, EW correction

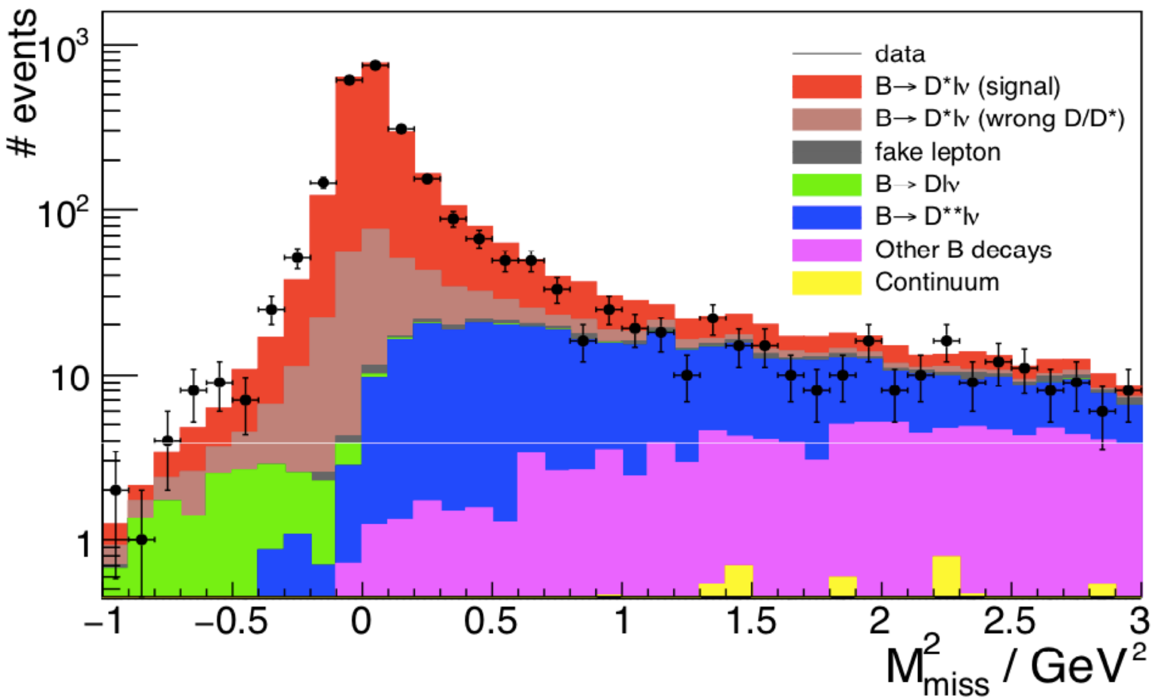
Form factor (lattice or lightcone sum rules)

- Measurements performed by Belle, BABAR, CLEO, LEP.
- Most use a form-factor polynomial expansion (CLN) around $w = 1$, considered by PDG to be too constraining given current high precision
- PDG prefers the more flexible BGL form-factor parameterization (Boyd, Grinstein, Lebed, PRL 74, 4603)
- ~10% differences seen b/w CLN and BGL parameterizations
- Only one analysis (Belle, arXiv:1702.01521) uses BGL…

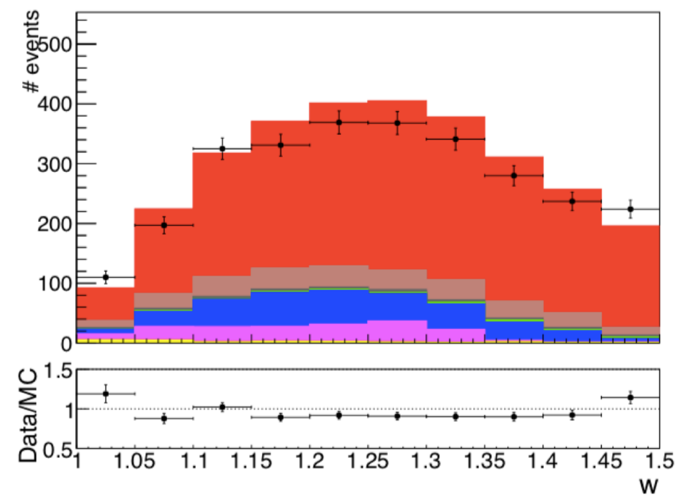
Recent Belle had-tag $\bar{B} \to D^* \ell \bar{\nu}$ analysis

arXiv:1702.01521

$$p_{\text{miss}} = p_\nu = p_{e^+e^-} - p_{\text{tag}} - p_{D^*} - p_\ell$$



One of the distributions:



From these inputs, PDG quotes $|V_{cb}| = (41.9\,^{+2.0}_{-1.9}) \times 10^{-3}$

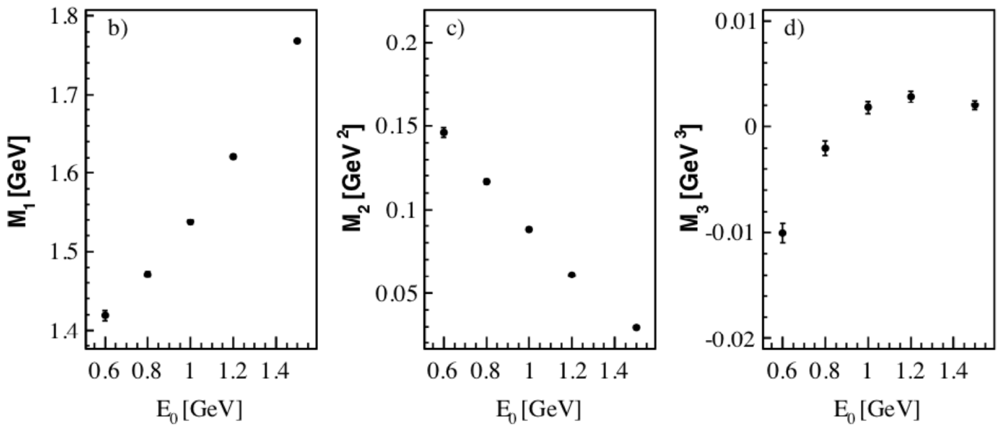
V_{cb} from inclusive $\bar{B} \to X_c \ell \bar{\nu}$

- Differential decay rate is given as a heavy-quark expansion (HQE) in terms of lepton-energy moments,

$$\langle E_e^n \rangle_{E_e > E_{\rm cut}} = \int_{E_{\rm cut}}^{E_{\rm max}} \frac{d\Gamma}{dE_e} E_e^n \, dE_e \Big/ \int_{E_{\rm cut}}^{E_{\rm max}} \frac{d\Gamma}{dE_e} dE_e$$

  for different value of the minimal lepton energy $E_{\rm cut}$,
  and similarly for the hadronic invariant mass and hadronic energy.

- E.g., Lepton-energy moments from BABAR arXiv:0908.0415: →



- Global Fits to these moments are used to obtain V_{cb} in various b-mass schemes

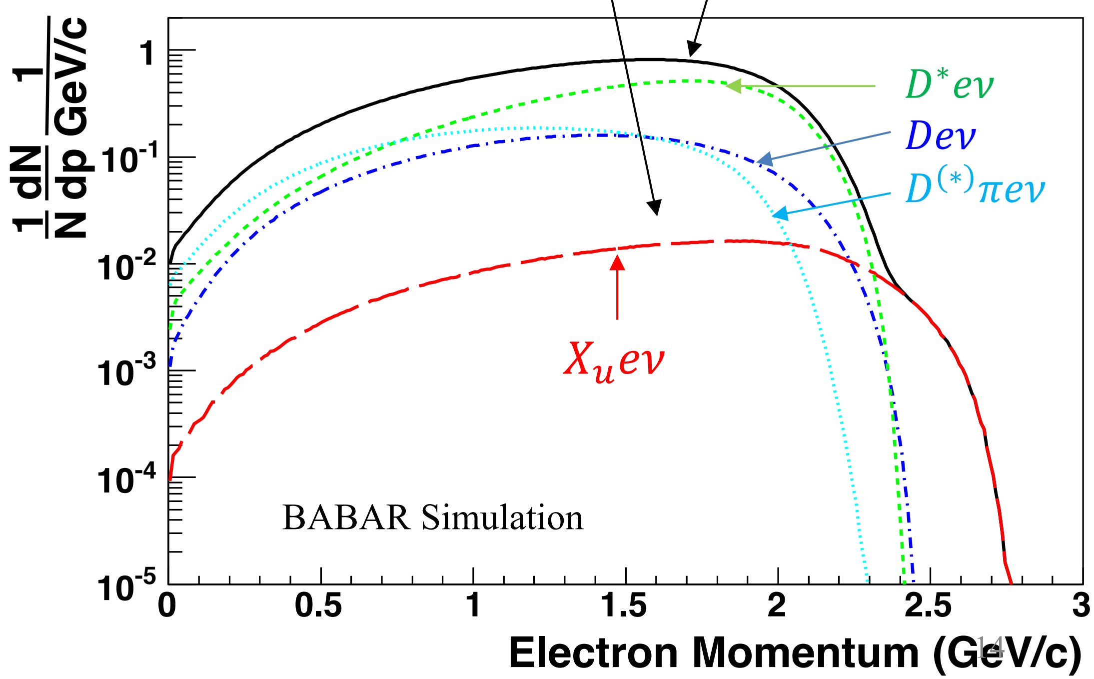
- PDG choose the kinetic scheme result $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$

V_{ub} from inclusive $\bar{B} \to X_u \ell \bar{\nu}$

- The total $B \to X_u \ell \nu$ decay rate is calculated based on the operator product expansion (OPE) in α_s and $\Lambda_{\mathrm{QCD}}/m_b$, with a ~5% uncertainty
  - But the total rate is hard to measure, due to large $B \to X_c \ell \nu$ background
  - V_{ub} measurement requires model for distributions of $B \to X_u \ell \nu$ and $B \to X_c \ell \nu$

- The high-E_ℓ region favored experimentally
  - Projecting to full spectrum incurs large corrections from a nonperturbative ”shape function” (SF) that accounts for the Fermi motion of the b inside the B.

- So measure V_{ub} with different
  - kinematic regions
  - analysis methods
  - calculation schemes



Some inclusive V_{ub} results (10^{-5}), RPP 2016/7

	Ref.	cut (GeV)	BLNP	GGOU	DGE
CLEO	[108]	$E_e > 2.1$	$428 \pm 50 \, {}^{+31}_{-36}$	$421 \pm 49 \, {}^{+23}_{-33}$	$390 \pm 45 \, {}^{+26}_{-28}$
BABAR	[111]	$E_e - q^2$	$453 \pm 22 \, {}^{+33}_{-38}$	not available	$417 \pm 20 \, {}^{+28}_{-29}$
BABAR	[110]	$E_e > 2.0$	$454 \pm 26 \, {}^{+27}_{-33}$	$450 \pm 26 \, {}^{+18}_{-25}$	$434 \pm 25 \, {}^{+23}_{-25}$
Belle	[109]	$E_e > 1.9$	$493 \pm 46 \, {}^{+27}_{-29}$	$493 \pm 46 \, {}^{+17}_{-22}$	$485 \pm 45 \, {}^{+21}_{-25}$
BABAR	[113]	$q^2{>}8$, $m_X{<}1.7$	$430 \pm 23 \, {}^{+26}_{-28}$	$432 \pm 23 \, {}^{+27}_{-30}$	$427 \pm 22 \, {}^{+20}_{-20}$
	[113]	$P_+ < 0.66$	$415 \pm 25 \, {}^{+28}_{-27}$	$424 \pm 26 \, {}^{+32}_{-32}$	$424 \pm 26 \, {}^{+37}_{-32}$
	[113]	$m_X < 1.55$	$430 \pm 20 \, {}^{+28}_{-27}$	$429 \pm 20 \, {}^{+21}_{-22}$	$453 \pm 21 \, {}^{+24}_{-22}$
	[113]	$E_\ell > 1$	$432 \pm 24 \, {}^{+19}_{-21}$	$442 \pm 24 \, {}^{+9}_{-11}$	$446 \pm 24 \, {}^{+13}_{-13}$
Belle	[115]	$E_\ell > 1$	$449 \pm 27 \, {}^{+20}_{-22}$	$460 \pm 27 \, {}^{+10}_{-11}$	$463 \pm 28 \, {}^{+13}_{-13}$
BABAR	[121]	$E_\ell > 0.8$	$456 \pm 13^{+28}_{-26}$	$396 \pm 10 \pm 17$	supersedes [110]

Inclusive tagging

p_ℓ

Some V_{ub} values are recalculations by HFLAV

Hadronic tagging

p_ℓ

- Note that results with different cuts are correlated
- PDG averages over methods with additional error:

$$|V_{ub}| = (4.49 \pm 0.15_{\rm exp} \, {}^{+0.16}_{-0.17}{}_{\rm theo} \pm 0.17_{\Delta {\rm BF}}) \times 10^{-3}$$

BLNP: B.O. Lange, M. Neubert, and G. Paz, Phys. Rev. **D72**, 073006 (2005).
GGOU: P. Gambino *et al.*, JHEP **0710**, 058 (2007).
DGE: J.R. Andersen and E. Gardi, JHEP **0601**, 097 (2006).

108. A. Bornheim *et al.* (CLEO Collab.), Phys. Rev. Lett. **88**, 231803 (2002).
109. A. Limosani *et al.* (Belle Collab.), Phys. Lett. **B621**, 28 (2005).
110. B. Aubert *et al.* (BABAR Collab.), Phys. Rev. **D73**, 012006 (2006).
111. B. Aubert *et al.* (BABAR Collab.), Phys. Rev. Lett. **95**, 111801 (2005), Erratum: Phys. Rev. Lett. **97**, 019903 (2006).
112. R. Kowalewski and S. Menke, Phys. Lett. **B541**, 29 (2002).
113. J.P. Lees *et al.* (BABAR Collab.), arXiv:1112.0702.
114. I. Bizjak *et al.* (Belle Collab.), Phys. Rev. Lett. **95**, 241801 (2005).
115. P. Urquijo *et al.* (Belle Collab.), Phys. Rev. Lett. **104**, 021801 (2010).
121. J. P. Lees *et al.* (BABAR Collab.) Phys. Rev. **D95**, 072001 (2017)

V_{ub} from exclusive $\bar{B} \to \pi \ell \bar{\nu}$ (PDG17)

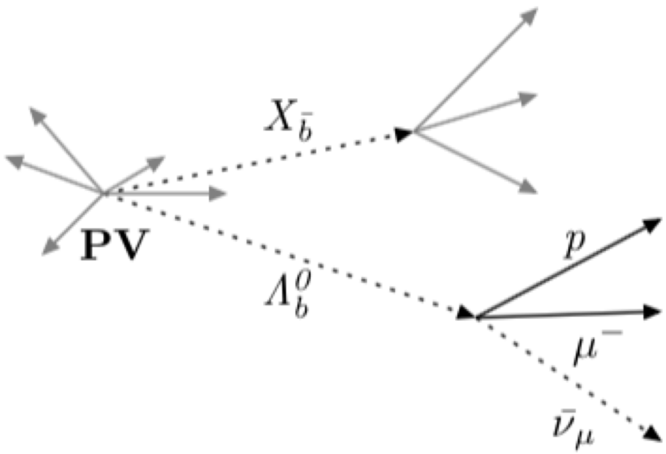
- As with exclusive V_{cb}, relate partial Br to V_{ub} using lattice or sum rules

	$\mathcal{B} \times 10^4$	$\mathcal{B}(q^2 > 16) \times 10^4\ \mathrm{GeV}^2$
CLEO π^+, π^0 [129]	$1.38 \pm 0.15 \pm 0.11$	$0.41 \pm 0.08 \pm 0.04$
BABAR π^+, π^0 [130]	$1.41 \pm 0.05 \pm 0.08$	$0.32 \pm 0.02 \pm 0.03$
BABAR π^+ [131]	$1.44 \pm 0.04 \pm 0.06$	$0.37 \pm 0.02 \pm 0.02$
Belle π^+, π^0 [143]	$1.48 \pm 0.04 \pm 0.07$	$0.40 \pm 0.02 \pm 0.02$
Belle SL π^+ [144]	$1.41 \pm 0.19 \pm 0.15$	$0.37 \pm 0.10 \pm 0.04$
Belle SL π^0 [144]	$1.41 \pm 0.26 \pm 0.15$	$0.37 \pm 0.15 \pm 0.04$
Belle Had π^+ [124]	$1.49 \pm 0.09 \pm 0.07$	$0.45 \pm 0.05 \pm 0.02$
Belle Had π^0 [124]	$1.48 \pm 0.15 \pm 0.08$	$0.36 \pm 0.07 \pm 0.02$
BABAR SL π^+ [145]	$1.38 \pm 0.21 \pm 0.08$	$0.46 \pm 0.13 \pm 0.03$
BABAR SL π^0 [145]	$1.78 \pm 0.28 \pm 0.15$	$0.44 \pm 0.17 \pm 0.06$
BABAR Had π^+ [146]	$1.07 \pm 0.27 \pm 0.19$	$0.65 \pm 0.20 \pm 0.13$
BABAR Had π^0 [146]	$1.52 \pm 0.41 \pm 0.30$	$0.48 \pm 0.22 \pm 0.12$
Average [147]	$1.45 \pm 0.02 \pm 0.04$	$0.38 \pm 0.01 \pm 0.01$

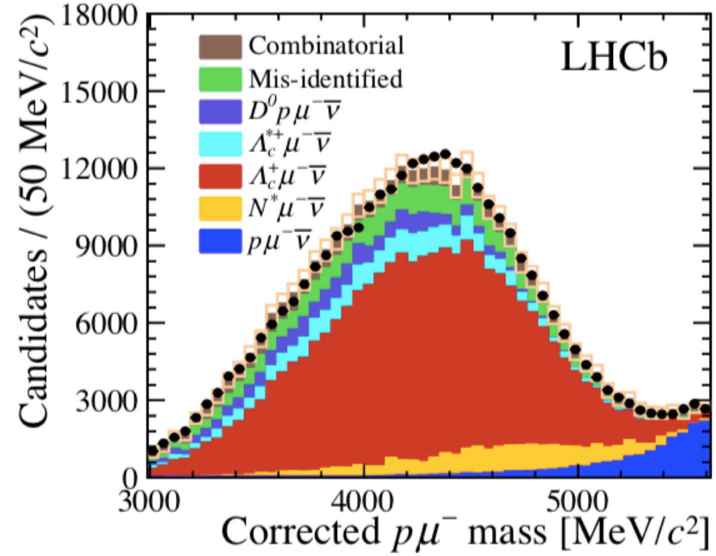
$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12\,) \times 10^{-3}$$

$|V_{ub}/V_{cb}|$ with Λ_b decays at LHCb

arXiv:1504.01568



Similar topology for $\Lambda_b \to \Lambda_c^+ \mu \bar{\nu}$
with $\Lambda_c^+ \to pK^-\pi^+$



$$m_{corr} = \sqrt{m_{p\mu}^2 + p_\perp^2} + p_\perp$$

$p_\perp = p\mu$ momentum $\perp$ Λ_b momentum

Measure $\hat{p}_{\Lambda_b}$ and $q^2 = (p_\mu + p_\nu)^2$ from vertex position with 1 (4) GeV^2 resolution for right (wrong) solution. Measure:

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

$|V_{ub}/V_{cb}|$ summary (PDG 2017)

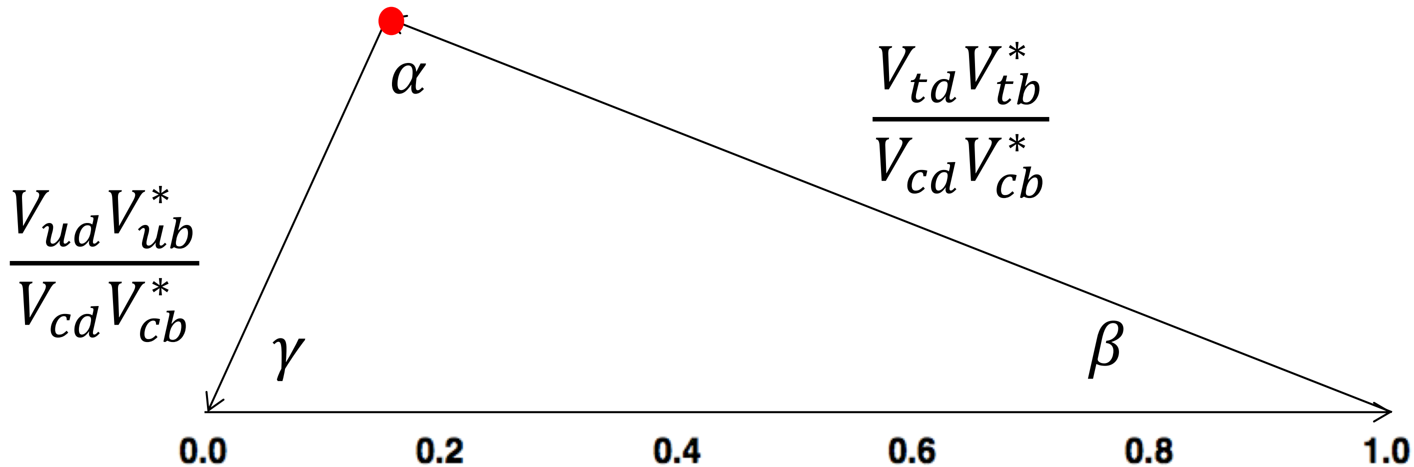
$$|V_{ub}|/|V_{cb}| = 0.107 \pm 0.007 \quad \text{(inclusive)}$$
$$|V_{ub}|/|V_{cb}| = 0.088 \pm 0.006 \quad \text{(exclusive)}$$

2σ difference (mostly due to 2.6σ difference in V_{ub} results)

$$|V_{ub}|/|V_{cb}| = 0.080 \pm 0.004 \pm 0.004 \quad \text{(LHCb)}$$

LHCb result is based on 1 precise lattice calculation.
Errors on B-factory results include differences b/w theory inputs, more crosschecks

Measuring γ



- To leading order in $\lambda = \sin\theta_C \approx 0.22$, can take

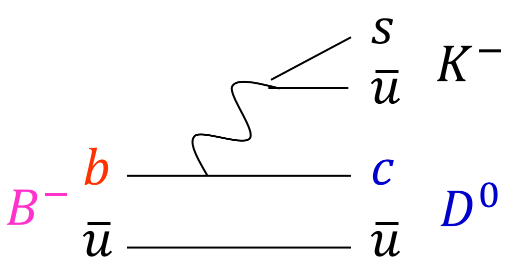
$$\gamma = \arg(-V_{ub}^*)$$

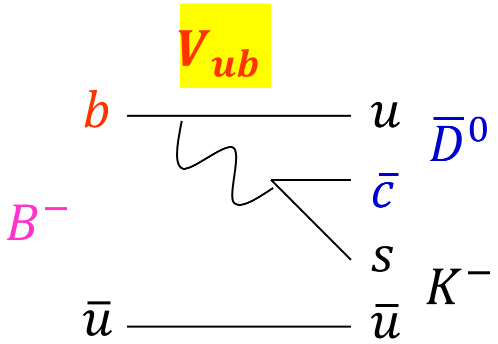
- γ is a CP-odd complex phase
- Its measurement requires
  1. Interference between two amplitudes, one with V_{ub}
  2. Comparison of between CP-conjugate processes

The GLW method

Gronau-London-Wyler (PLB 253, 483; PLB 265, 172)

- Consider the processes $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$





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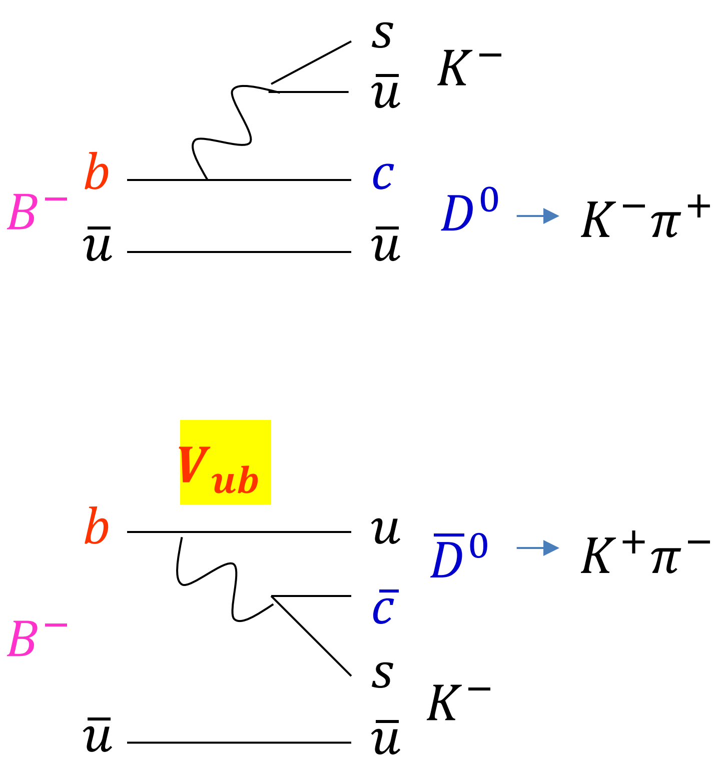
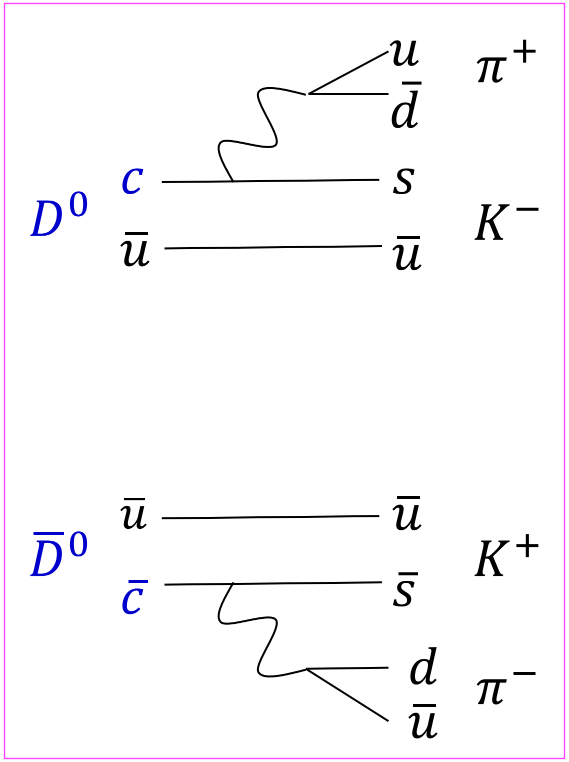
- Consider the processes $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$
- Their amplitudes are measured via Cabibbo-allowed charm decays





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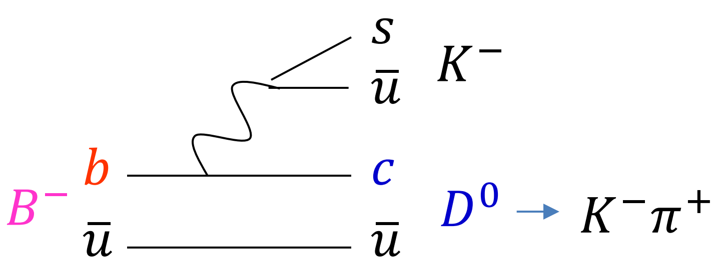
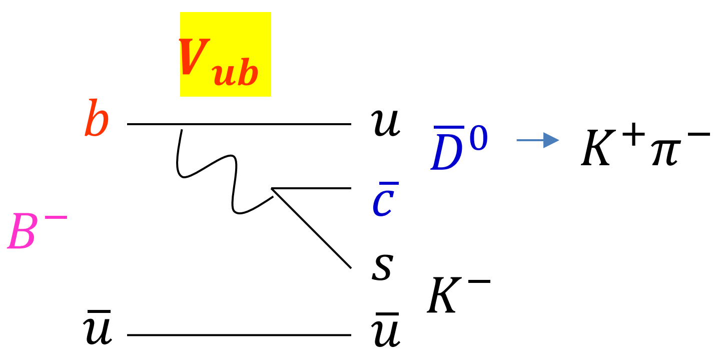


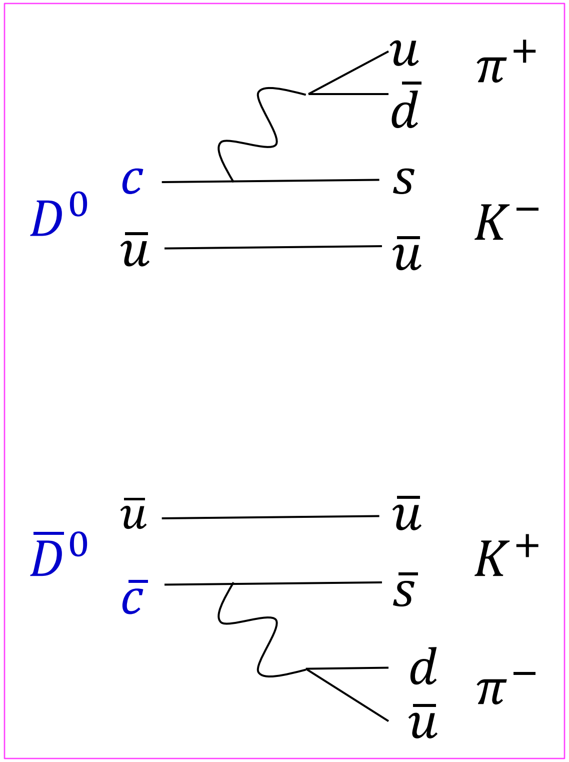
Amplitude

$|A|$



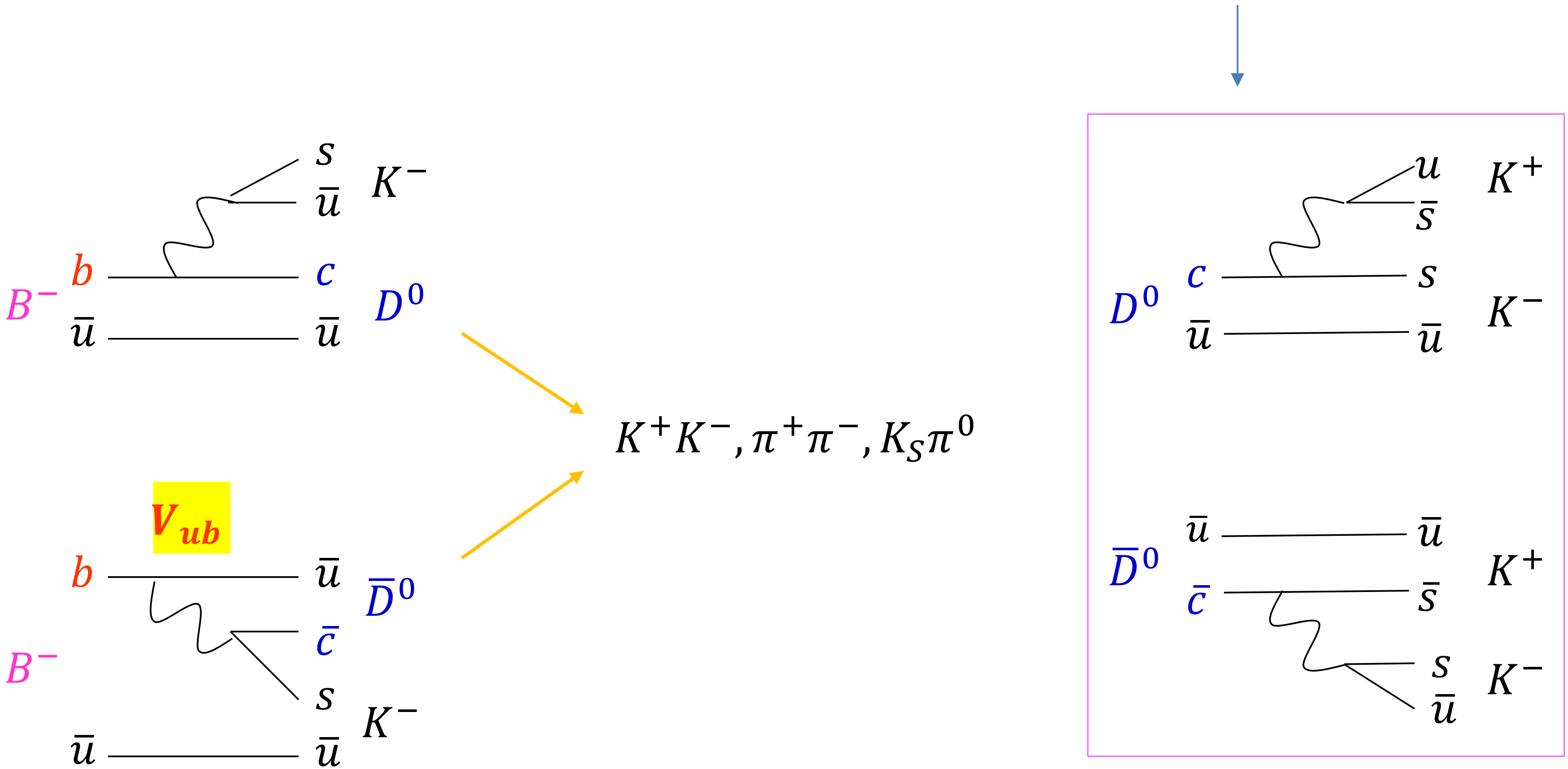
$|A| r_B e^{i(-\gamma+\delta_B)}$

Some CP-even phase due to strong interaction



The GLW method

- Interference when both D^0 and $\overline{D}^0$ decay to a common CP eigenstate



- Write the CP eigenstates as

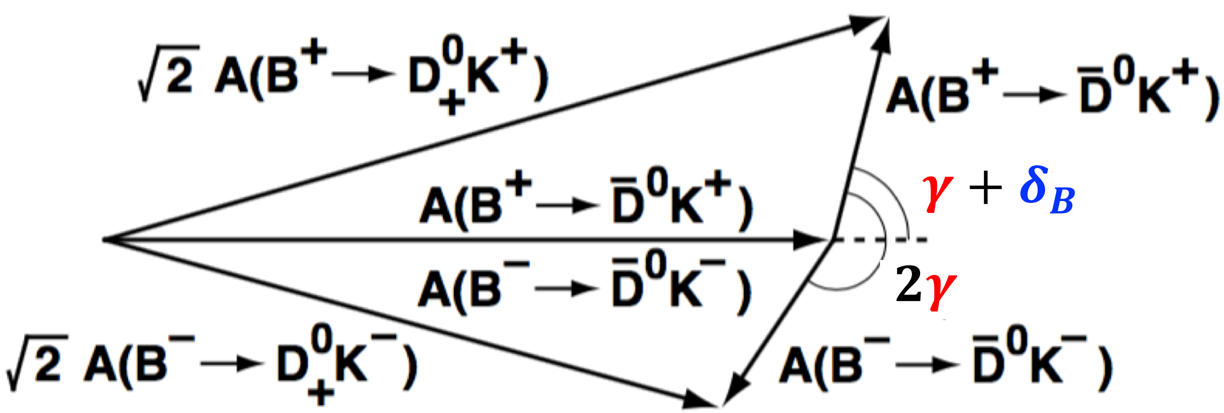
$$D^0_{\pm} = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$$

- Then the decay amplitudes satisfy

$$A\left(B^- \to D^0_{\pm}K^-\right) = \frac{1}{\sqrt{2}}\left(A(B^- \to D^0K^-) \pm A(B^- \to \bar{D}^0K^-)\right)$$

$$= \frac{1}{\sqrt{2}}|A|\left(1 \pm r_B e^{i(-\gamma+\delta_B)}\right)$$

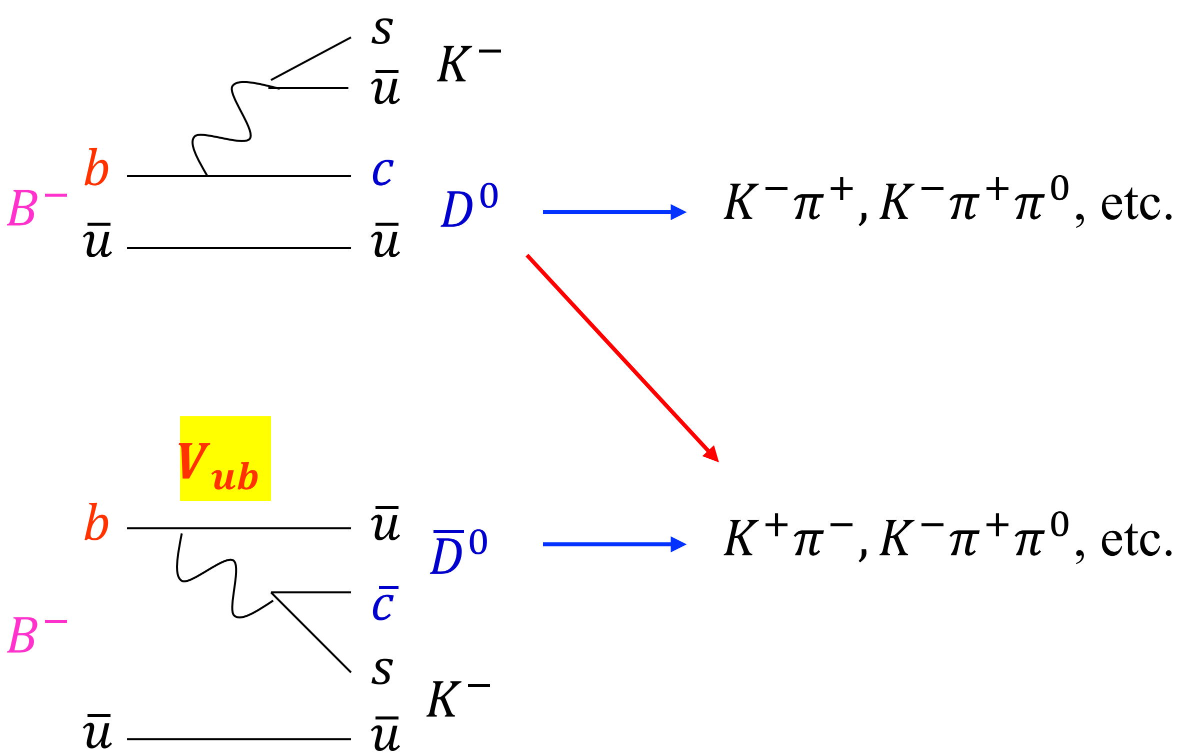
- With $-\gamma$ becoming $+\gamma$ for the B^+ decay
- This gives two triangles from which γ is extracted, with r_B and δ_B:

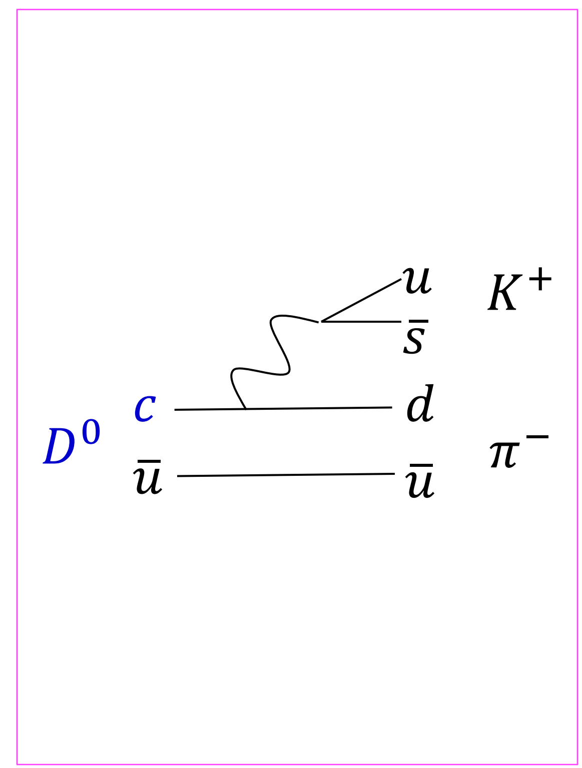


The ADS method

Atwood, Dunietz, Soni, PRL 78, 3257

- Ratio between interfering B decays is only $r_B \sim 0.1$: small interference
- Exploit doubly Cabbibo-suppressed decay $\overline{D}^0 \rightarrow K^- \, (n\pi)^+$:

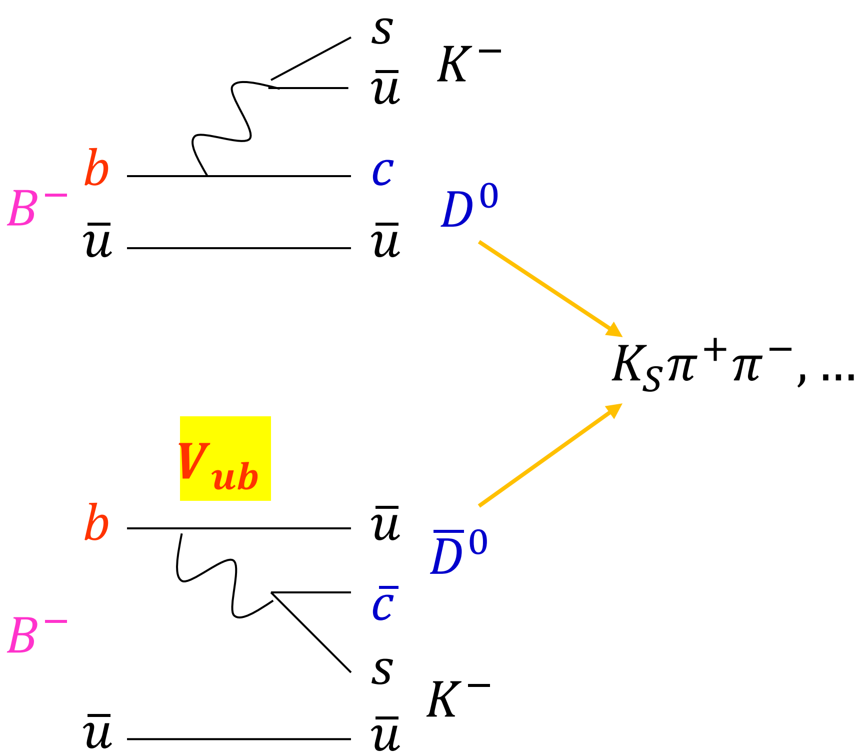




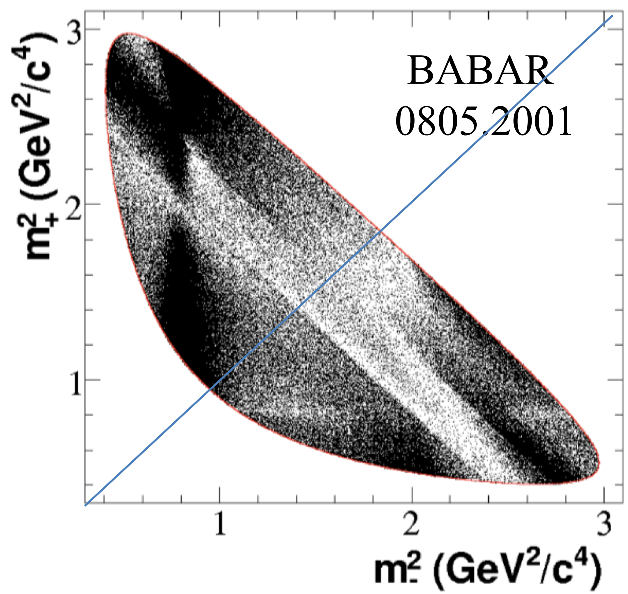
The GGSZ method

Giri, Grossman, Soffer, Zupan, PRD 68, 054018

- Exploit multibody D^0 decays
- Help resolve trig ambiguities in γ
- CP content depends on phase-space point
- Complex D^0 decay amplitude can be modeled (isobar+K-matrix, etc.) with a flavor-tagged D^0 sample:



$D^{*+} \to D^0\pi^+$



Or:

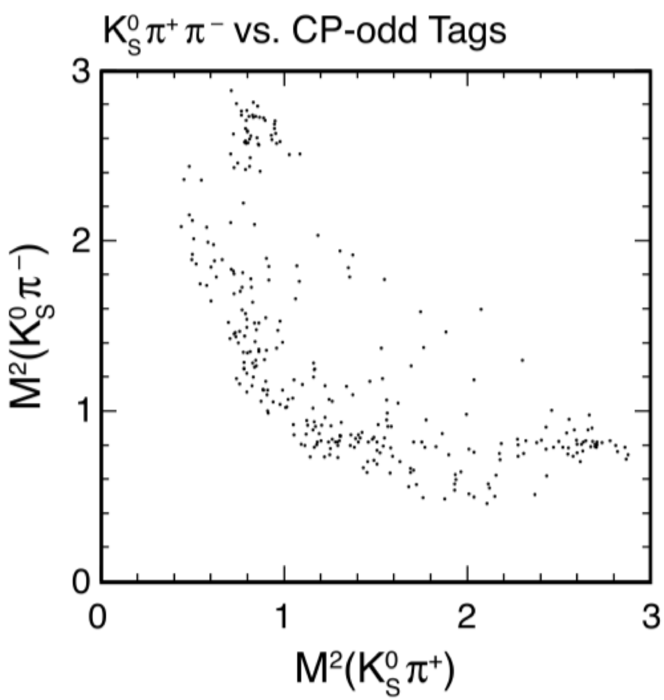
Complex D^0 decay amplitude can be obtained model-independently with a CP-tagged D sample:

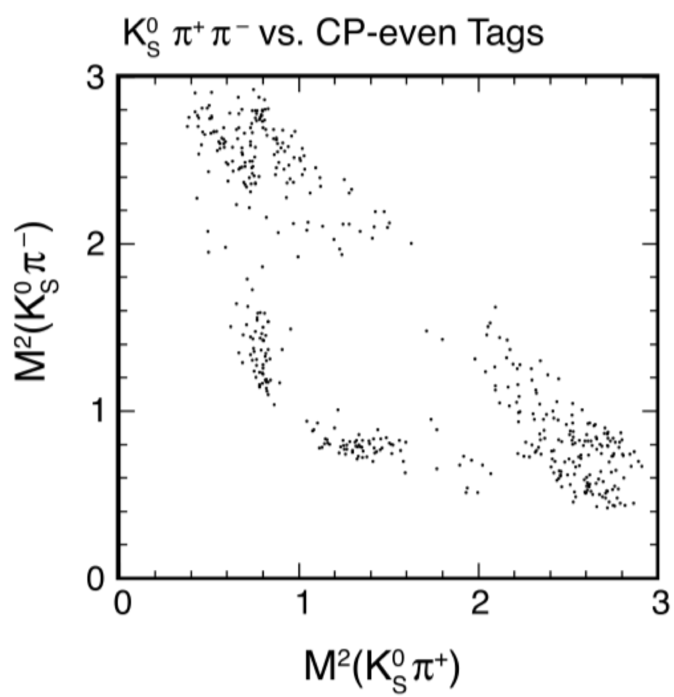
$$\psi(3770) \rightarrow D^0_+ D^0_-$$

$D^0_+ \rightarrow K^+K^-$, $D^0_- \rightarrow K_S\pi^+\pi^-$

- Belle (1509.01098) & LHCb (1408.2748) measured γ in this model-independent method
- Stat error > model-dependent case, but no assumptions re: strong phases

CLEO-c (0903.1681)





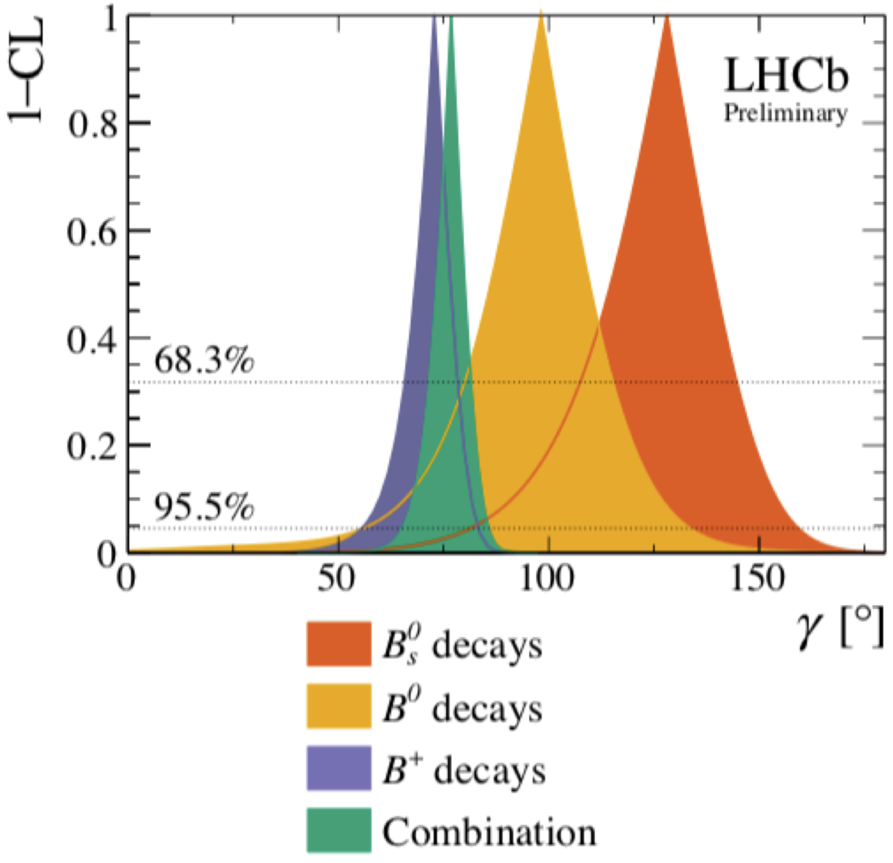
LHCb γ combination

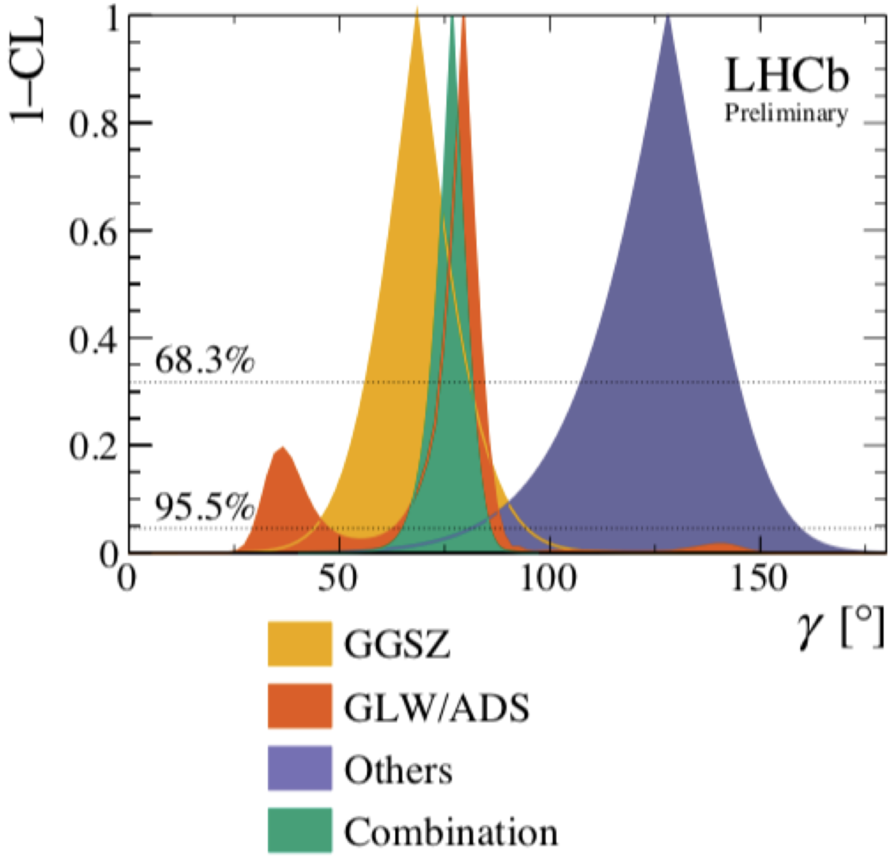
LHCb-CONF-2017-004.pdf

B decay	D decay	Method
$B^+ \to DK^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^+$	$D \to h^+h^-$	ADS
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K_S^0 K^+\pi^-$	GLS
$B^+ \to D^* K^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD

Underlined:
modifications of above methods

LHCb γ combination

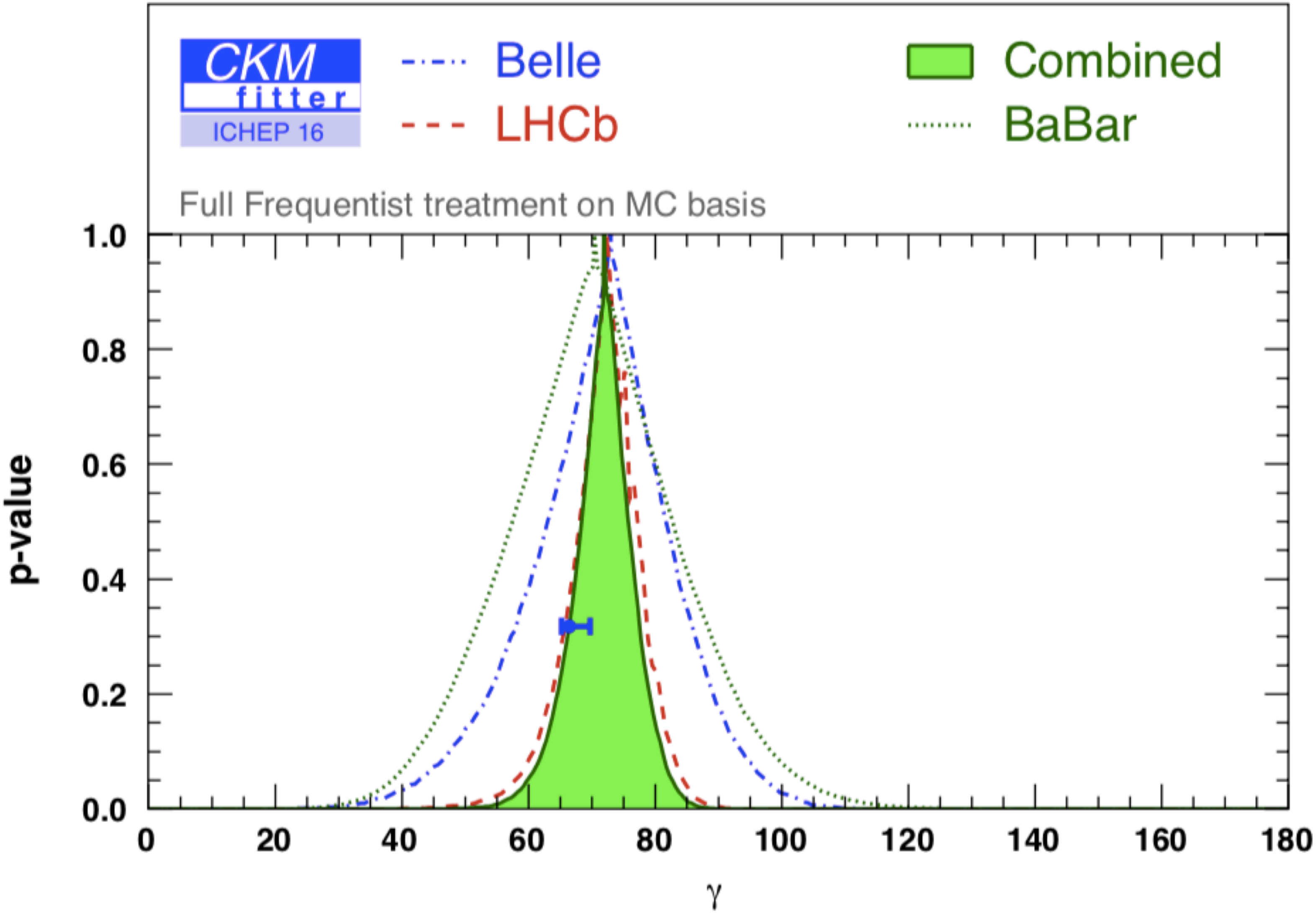




$\gamma = \left(76.8\,^{+5.1}_{-5.7}\right)^{\circ}$ (Up to a 180° ambiguity)

BABAR+Belle+LHCb combination

(Somewhat older LHCb results)



Summary & comments

- $|V_{ub}/V_{cb}|$ and $\gamma(\phi_3)$ are important SM parameters
- Crucial inputs to NP probing via unitarity triangle
- No significant inconsistency with the SM so far
- LHCb now competitive with BABAR+Belle in $|V_{ub}/V_{cb}|$
  - But relies on only one lattice calculation
- LHCb dominates measurement of γ
- Belle II will have ~35 times more data than BABAR+Belle
- See M. Lubej's talk for expected Belle II impact on $|V_{ub}/V_{cb}|$
  - Theory calculations will need to improve as well
- Belle II + LHCb should reach $\sigma_\gamma \sim 1°$ through combination of different methods

Backup slides

- CLN expansion of form factor:

$$F(w) = F(1) - \rho^2(w-1) + c(w-1)^2 + \cdots$$

- BGN expansion:

$$F(z) = \frac{1}{P_F(z)\phi_F(z)} \sum_{n=0}^{\infty} a_n z^n \qquad (94.6)$$

where the sum $\sum |a_n|^2$ is bounded. Furthermore, the function $P(z)$ takes into account the resonances in the $(\bar{c}b)$ system below the $\bar{D}B$ threshold, and the weighting functions $\phi_F(z)$ are derived from the unitarity constraint on the corresponding form factor. The values of z relevant to the decay are $0 \leq z \leq 0.06$, hence the series in z converges rapidly and only very few terms are needed. Eq. (94.6) will be referred to as the "BGL" expansion.

V_{ub} and V_{cb} summary (PDG 2017)

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad \text{(inclusive)}$$
$$|V_{cb}| = (41.9 \pm 2.0) \times 10^{-3} \quad \text{(exclusive)}$$

Comparable experiment & theory uncertainties
1% common systematic uncertainty.
Good agreement between the two results

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad \text{(average)}$$

$$|V_{ub}| = (4.49 \pm 0.15 \, {}^{+0.16}_{-0.17} \pm 0.17) \times 10^{-3} \quad \text{(inclusive)}$$
$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{(exclusive)}$$

Experiment Theory Extrapolation of model to full kinematic range