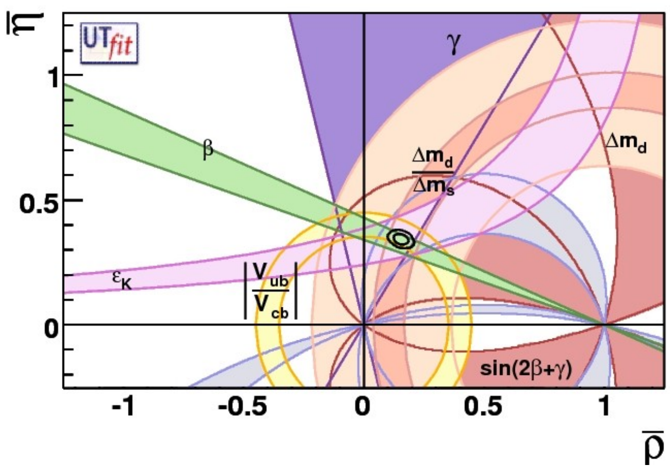
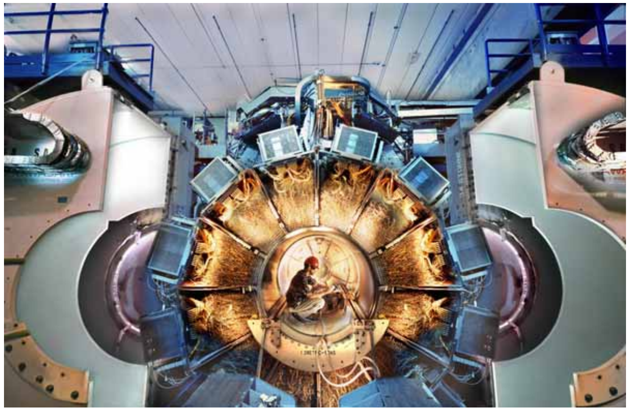
CP violation lectures



Marcella Bona

Queen Mary
University of London



Post-FPCP 2018 Summer School

IIT Hyderabad, India

Lecture 4

Outline

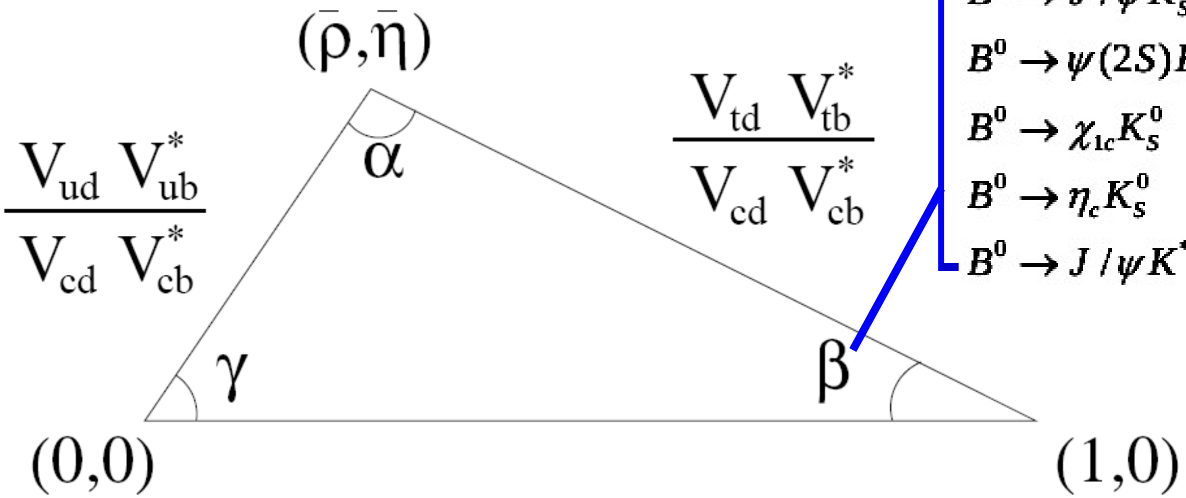
- quick recap on angles
- wrap-up on $\gamma/\phi3$ measurement
- direct CP violation and charmless two-body B decays
- sides of the Unitarity Triangle
- extraction of the CKM parameters

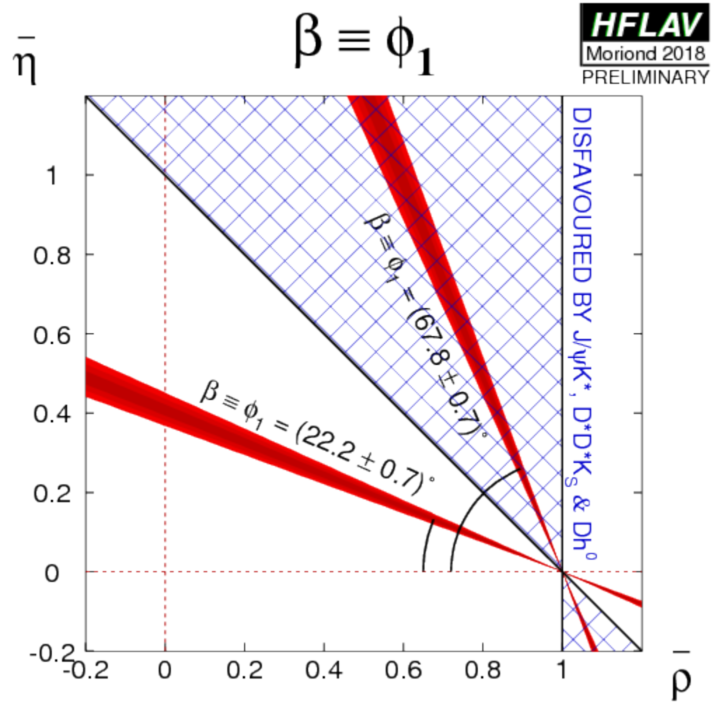
β/ϕ_1 angle [recap]

Theoretically cleaner (SM uncertainties ~10^{-2} to 10^{-3})
→ tree dominated decays to Charmonium + K^0 final states.

$$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$

$b \rightarrow c\bar{c}s$
- $B^0 \rightarrow J/\psi K_L^0$
- $B^0 \rightarrow J/\psi K_S^0$
- $B^0 \rightarrow \psi(2S) K_S^0$
- $B^0 \rightarrow \chi_{1c} K_S^0$
- $B^0 \rightarrow \eta_c K_S^0$
- $B^0 \rightarrow J/\psi K^{*0}$





$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) - \Gamma(B^0(t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) + \Gamma(B^0(t) \rightarrow f_{CP})}$$

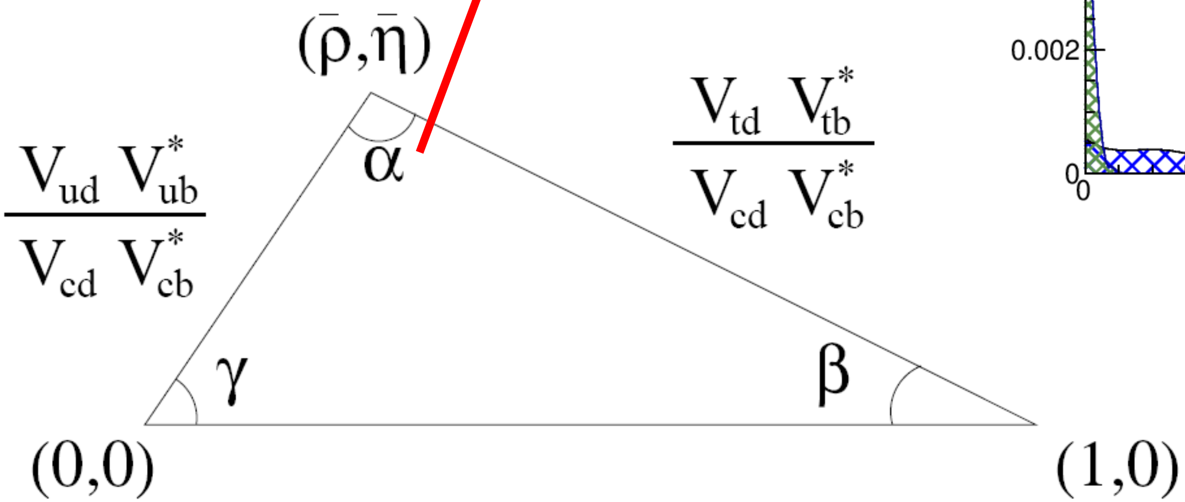
α/ϕ_2 angle [recap]

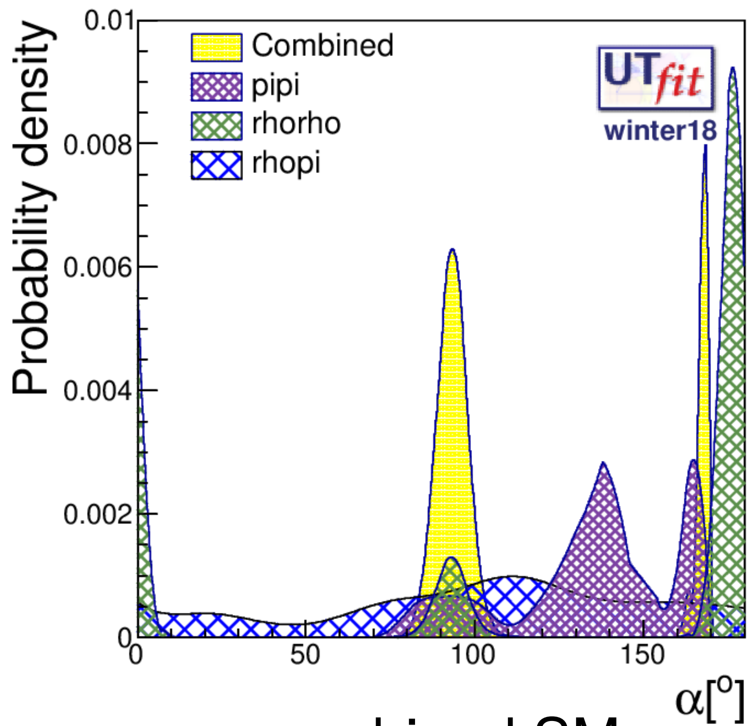
$$\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$

$b \to u\bar{u}d$ transitions with possible loop contributions. Extract α using

- SU(2) Isospin relations.
- SU(3) flavour related processes.

$b \to u\bar{u}d$
$B \to \pi\pi$
$B \to \rho\pi$
$B \to \rho\rho$





combined SM:

$\alpha = (93.3 \pm 5.6)°$

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

γ/ϕ_3 angle

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$

$b \to c$ interfering with $b \to u$

$B \to D^{(*)}K^{(*)}$

$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)}\pi$

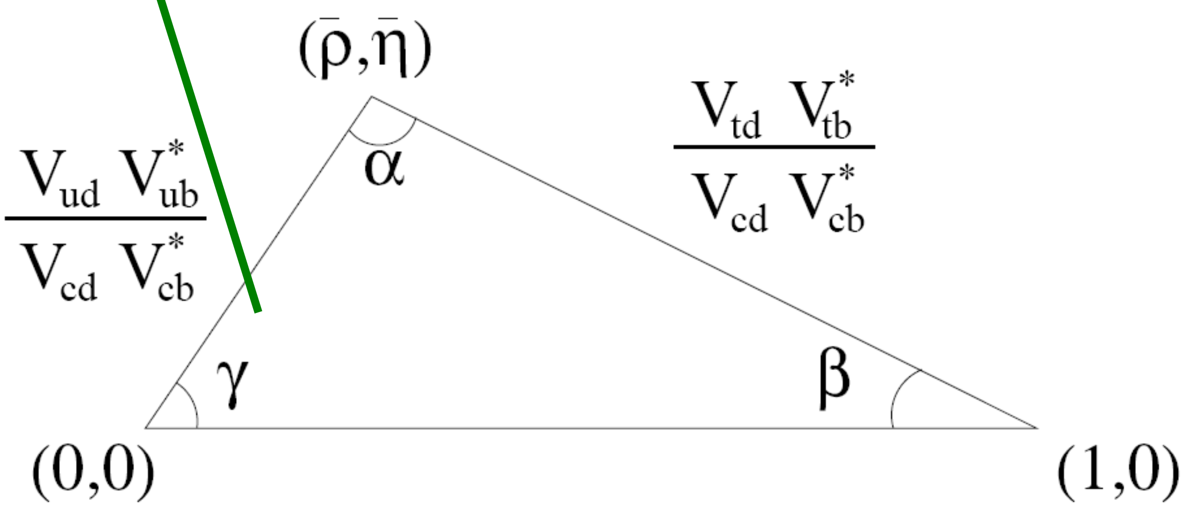
$B^0 \to D^{(*)}\rho$

$+$ *charmless*

Extract γ using $B \to D^{(*)}K^{(*)}$ final states using:

- GLW: Use CP eigenstates of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D \to K_s h^+ h^-$ decays.

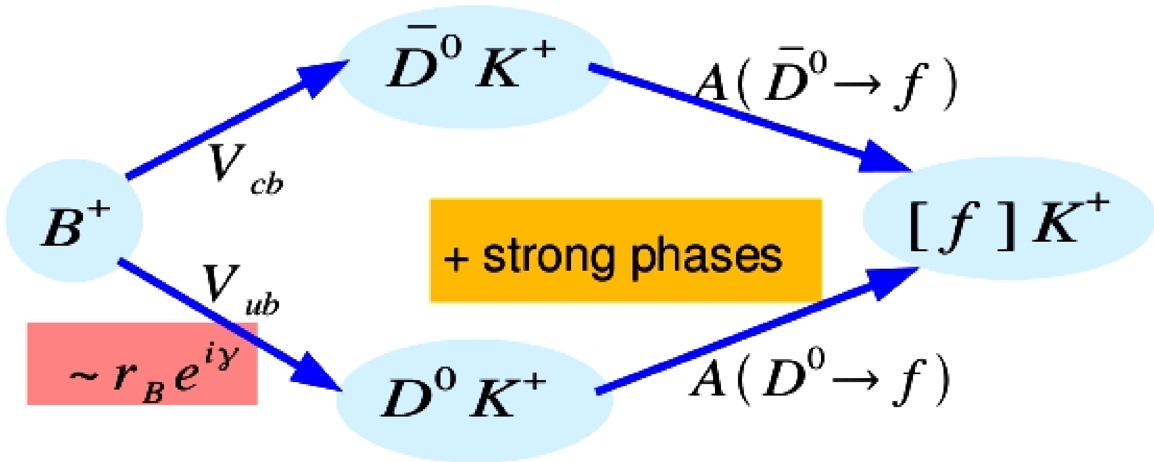
Measurements using neutral D mesons ignore D mixing.



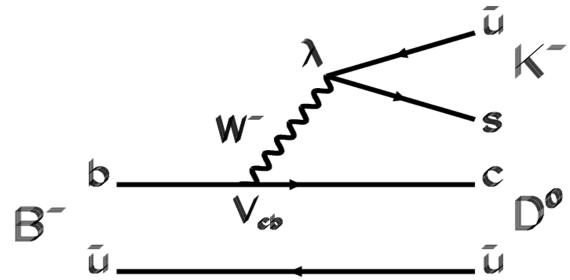
$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$

γ and DK trees

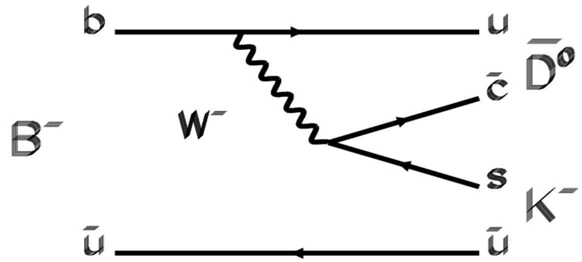
- $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates
- the phase γ is measured exploiting interferences: two amplitudes leading to the same final states
- some rates can be really small: ~ 10^{-7}



Theoretically clean (no penguins *neglecting the D^0 mixing*)

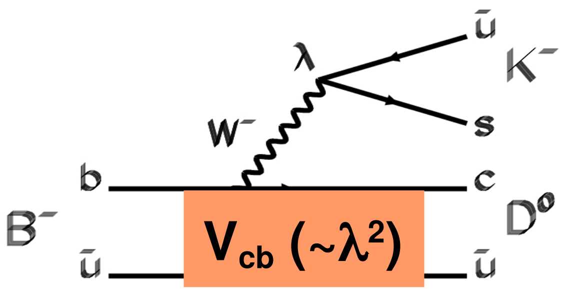


V_{cb} $(\sim\lambda^2)$

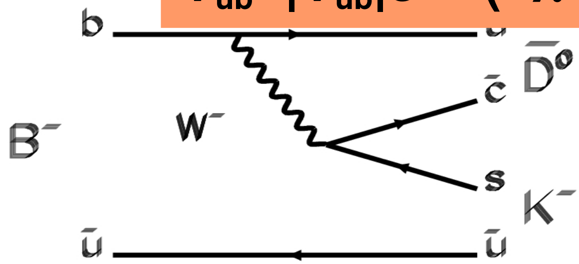


$V_{ub}=|V_{ub}|e^{-i\gamma}$ $(\sim\lambda^3)$

Sensitivity to γ: the ratio r_B



V_{cb} ($\sim\lambda^2$)



$V_{ub}=|V_{ub}|e^{-i\gamma}$ ($\sim\lambda^3$)

δ_B = strong phase diff.

$$A(B^- \to D^0K^-) = A_B \qquad A(B^- \to \bar{D}^0K^-) = A_B r_B e^{i(\delta_B-\gamma)}$$

$$A(B^+ \to \bar{D}^0K^+) = A_B \qquad A(B^+ \to D^0K^+) = A_B r_B e^{i(\delta_B+\gamma)}$$

r_B = amplitude ratio

$$r_B = \left|\frac{B^- \to \bar{D}^0K^-}{B^- \to D^0K^-}\right| = \sqrt{\bar{\eta}^2+\bar{\rho}^2} \times F_{CS}$$

$\sqrt{\bar{\eta}^2+\bar{\rho}^2}$ ↙ **~0.36**

F_{CS} ↙ hadronic contribution channel-dependent

- in $B^+ \to D^{(*)0}K^+$: r_B is ~0.1
- to be measured: $r_B(DK)$, $r^*_B(D^*K)$ and $r^s_B(DK^*)$

Three ways to make DK interfere

GLW(*Gronau, London, Wyler*) method:

more sensitive to r_B

uses the CP eigenstates $D^{(*)0}_{CP}$ with final states:

K^+K^-, $\pi^+\pi^-$ (CP-even), $K_s\pi^0$ (ω,ϕ) (CP-odd)

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B \qquad A_{CP\pm} = \frac{\pm 2r_B \sin\gamma \sin\delta_B}{1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B}$$

ADS(*Atwood, Dunietz, Soni*) method: B^0 and $\bar{B}^0$ in the same final state with $D^0 \to K^+\pi^-$ (suppr.) and $\bar{D}^0 \to K^+\pi^-$ (fav.)

$$R_{ADS} = r_B^2 + r_{DCS}^2 + 2r_B r_{DCS} \cos\gamma \cos(\delta_B + \delta_D)$$

the most sensitive way to γ

D^0 Dalitz plot with the decays $B^- \to D^{(*)0}[K_S\pi^+\pi^-]\,K^-$

three free parameters to extract: γ , r_B and δ_B

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

γ: GLW Method

- GLW Method: Study $B^+ \to D_{CP}^0 X^+$ and $B^+ \to \bar{D} X^+$ + cc ($\bar{D}^0 \to K^+\pi^-$)
- X^+ is a strangeness one meson e.g. a K^+ or K^{*+}.
- D_{CP}^0 is a CP eigenstate (use these to extract γ):

$$D^0_{CP=+1} = K^+K^-, \pi^-\pi^+$$
$$D^0_{CP=-1} = K^0_S\pi^0, K^0_S\omega, K^0_S\phi$$

- 4 observables
- 3 unknowns: r_B, γ and δ

$$R_{CP\pm} = \frac{BF(B^- \to D^0_\pm K^-) + BF(B^+ \to D^0_\pm K^+)}{BF(B^- \to D^0 K^-) + BF(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2r_B\cos\delta\cos\gamma$$
$$A_{CP\pm} = \frac{BF(B^- \to D^0_\pm K^-) - BF(B^+ \to D^0_\pm K^+)}{BF(B^- \to D^0_\pm K^-) + BF(B^+ \to D^0_\pm K^+)} = \pm 2r_B\sin\delta\sin\gamma / R_{CP\pm}$$

- The precision on γ is strongly dependent on the value of r_B.
  - r_B~0.1 as this is a ratio of Cabibbo suppressed to Cabibbo allowed decays and also includes a colour suppression factor for $B^+ \to D^{(*)}K^{(*)}$ b→u decays.
- Measurement has an 8-fold ambiguity on γ.

Gronau, London, Wyler, PLB253 p483 (1991).

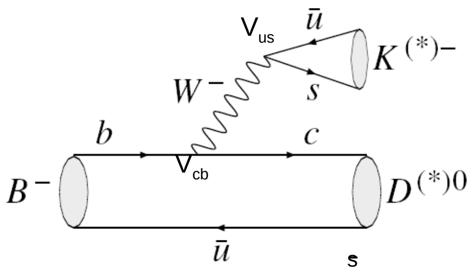
γ: ADS Method

Attwood, Dunietz, Soni, PRL **78** 3257 (1997)

- ADS Method: Study $B^{\pm,0} \to D^{(*)0}\, K^{(*)\pm}$
- Reconstruct doubly suppressed decays with common final states and extract γ through interference between these amplitudes:

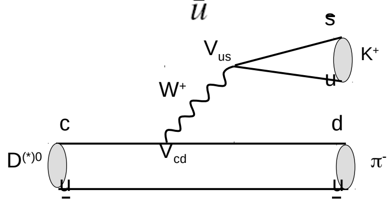
$B^{-} \to D^{(*)0}\, K^{(*)-}$

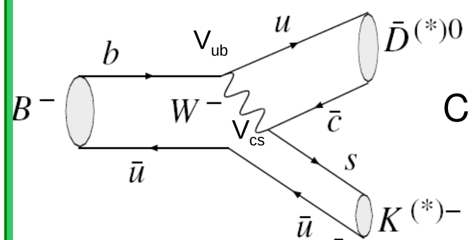
CKM Favoured



$D^{(*)0} \to K^{+}\pi^{-}$

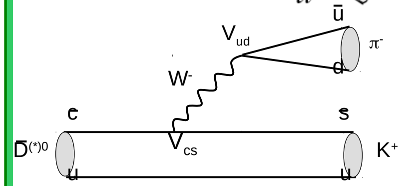
Doubly CKM Suppressed





$B^{-} \to \overline{D}^{(*)0}\, K^{(*)-}$

CKM and Color Suppressed



$\overline{D}^{(*)0} \to K^{+}\pi^{-}$

CKM Favoured

- γ extracted using ratios of rates:

$$r_B^{(*)} = \left|\frac{A(B^- \to \overline{D}^{(*)0}K^-)}{A(B^- \to D^{(*)0}K^-)}\right|$$

$$r_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right|$$

- $\delta^{(*)} = \delta^{(*)}{}_B + \delta_D$
- $\delta^{(*)}$ is the sum of strong phase differences between the two B and D decay amplitudes.
- r_D and r_B are measured in B and charm factories.
- δ_D is measured by CLEO-c

γ: GGSZ Method

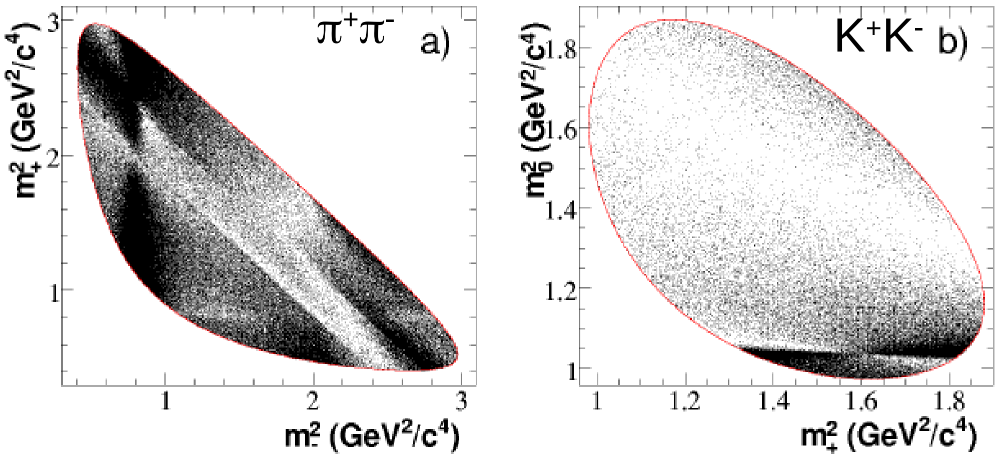
- GGSZ ("Dalitz") Method: Study $D^{(*)0}K^{(*)}$ using the $D^{(*)0} \to K_s h^+ h^-$ Dalitz structure to constrain γ. (h = π, K)
  - Self tagging: use charge for $B^{\pm}$ decays or $K^{(*)}$ flavour for B^0 mesons.

$$A(B^{\pm} \to (K_S^0 h^+ h^-)_D K^{\pm}) \propto f(m_+^2, m_-^2) + f(m_-^2, m_+^2) r_B e^{i(\delta_B \pm \gamma)}$$

where $m_{\pm} = m_{K_S^0 h^{\pm}}$

  - Need detailed model of the amplitudes in the D meson Dalitz plot.
    - Use a control sample (CLEO-c data or $D^{*+} \to D^0\pi^+$) to measure the Dalitz plot.

$$D^{*+} \to D^0 \pi^-$$
$$\hookrightarrow D^0 \to K_S^0 h^+ h^-$$



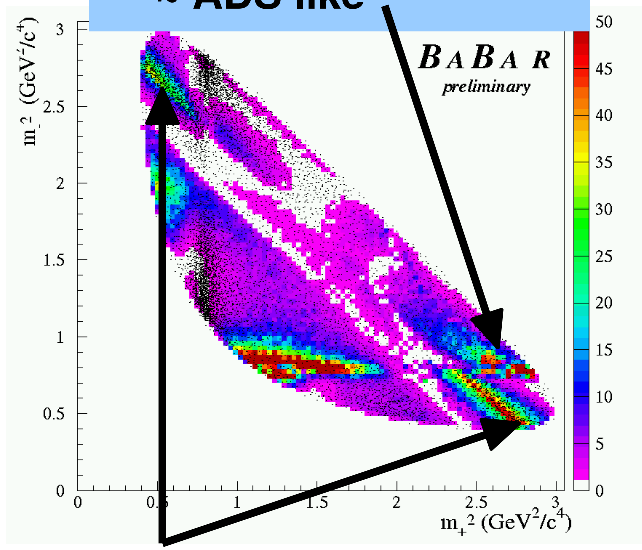
Control sample plots from BaBar GGSZ paper

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

γ: GGSZ Method

- neutral D mesons reconstructed in three-body CP-eigenstate final states (typically $D^0 \to K_S\pi^-\pi^+$)
- the complete structure (amplitude and strong phases) of the D^0 decay in the phase space is obtained on independent data sets and used as input to the analysis
- use of the cartesian coordinate:
  - $x_\pm = r_B \cos(\delta \pm \gamma)$
  - $y_\pm = r_B \sin(\delta \pm \gamma)$
- γ , r_B and δ_B are obtained from a simultaneous fit of the $K_S\pi^+\pi^-$ Dalitz plot density for B^+ and B^-
- need a model for the Dalitz amplitudes
- 2-fold ambiguity on γ

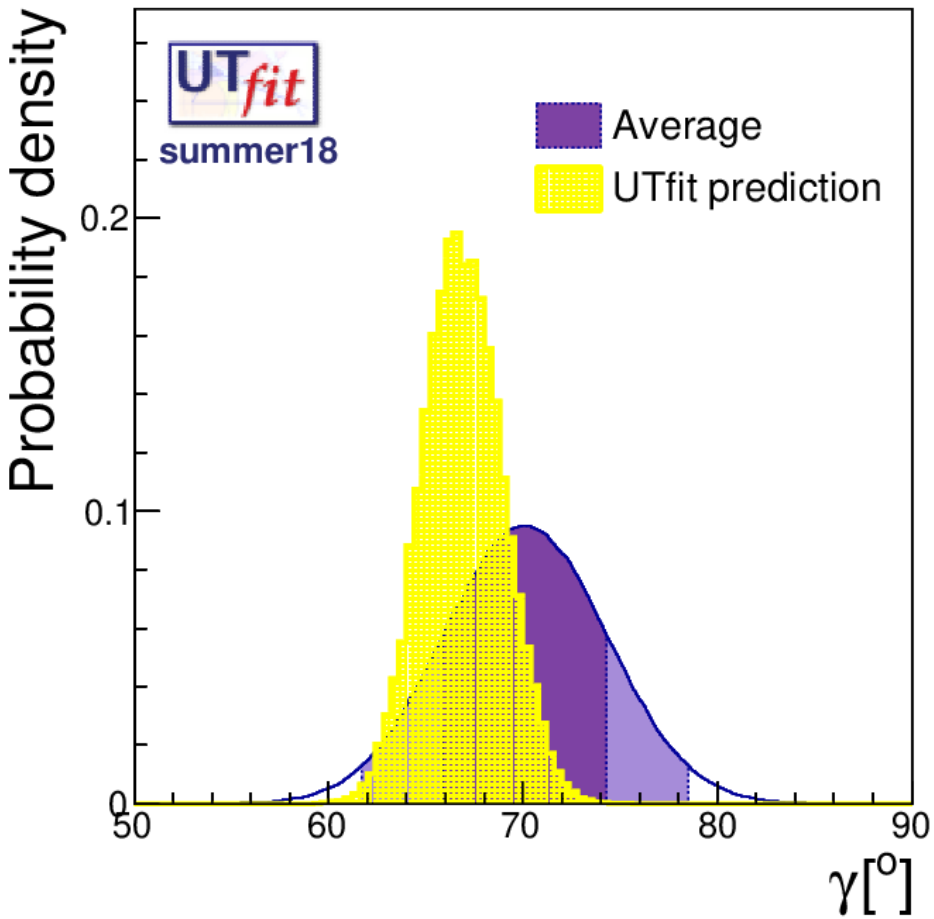
Interference of
$B^- \to D^0K^-$, $D^0 \to K^{*+}\pi^-$
(suppressed) with
$B^- \to \overline{D}{}^0K^-$, $\overline{D}{}^0 \to K^{*+}\pi^-$
~ ADS like



Interference of
$B^- \to D^0K^-$, $D^0 \to K^0_S\rho^0$
with
$B^- \to \overline{D}{}^0K^-$, $\overline{D}{}^0 \to K^0_S\rho^0$
~ GLW like

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$

CP violation: γ



γ from B into DK decays:

combined: (73.4 ± 4.4)°

UTfit prediction: (65.8 ± 2.2)°

direct CP violation

Time-integrated direct CP asymmetries

- can be measured in decays of both neutral and charged mesons
- measure a direct CP asymmetry by comparing amplitudes of decay:

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

- Event counting exercise: when studying neutral B mesons we can select a self-tagging final state.
- need an interference between (*at least*) two amplitudes contributing to the same final state

$$A_1 = a_1 e^{i(\phi_1+\delta_1)}$$
$$A_2 = a_2 e^{i(\phi_2+\delta_2)}$$

δ_i: strong phases CP even

ϕ_i: weak phases CP odd

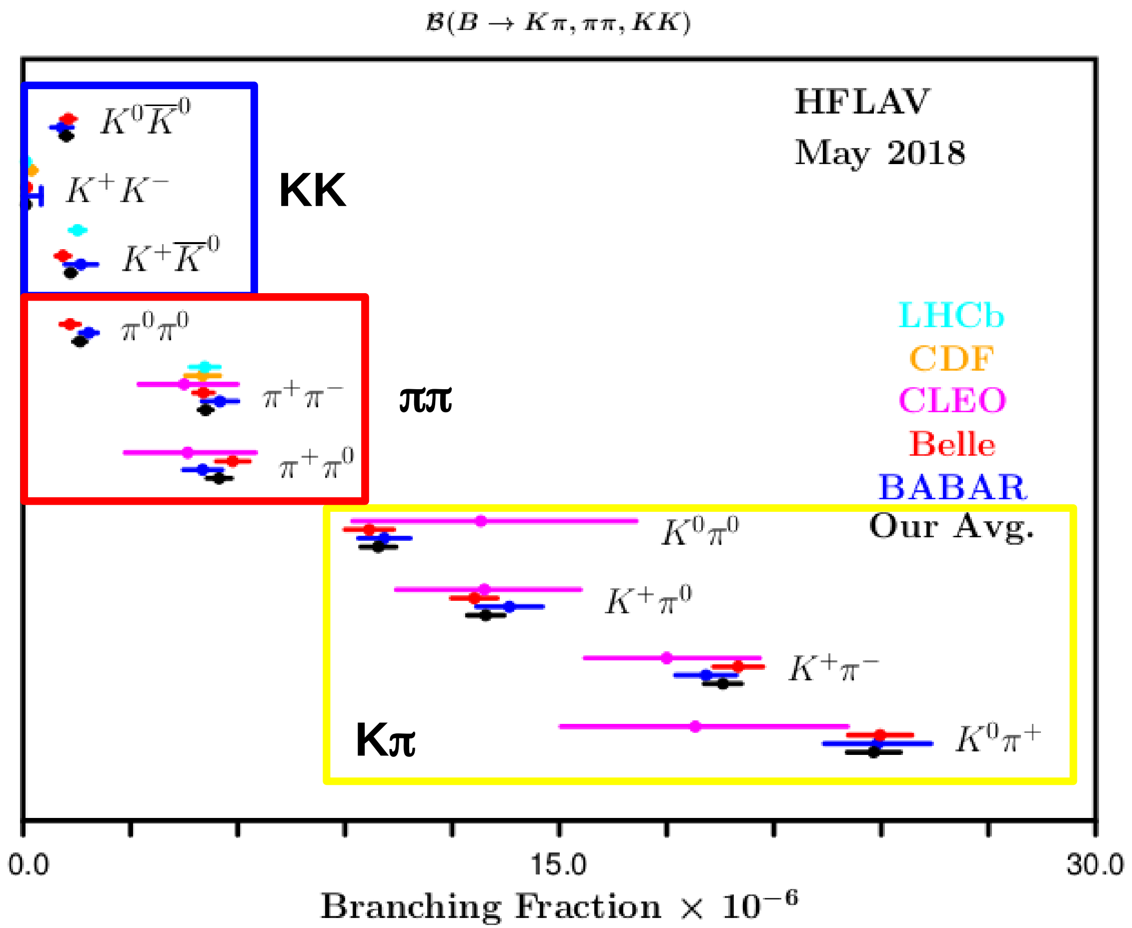
$$A_f = a_1 \exp[i(\delta_1 + \phi_1)] + a_2 \exp[i(\delta_2 + \phi_2)]$$
$$\bar{A}_{\bar{f}} = a_1 \exp[i(\delta_1 - \phi_1)] + a_2 \exp[i(\delta_2 - \phi_2)]$$

- the measured asymmetry becomes:

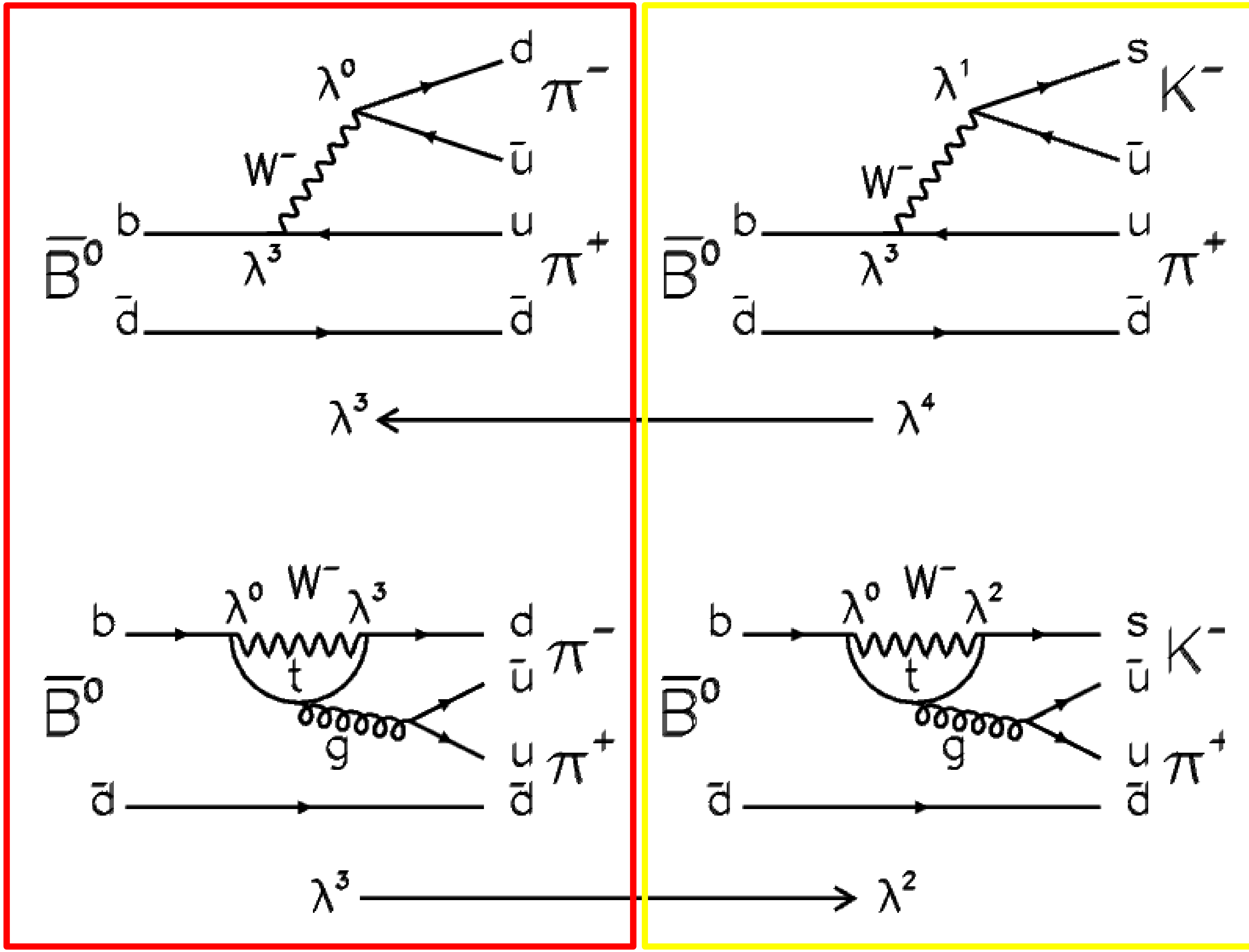
$$A_{CP} \equiv \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \sim \sum_{i,j} a_i a_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j)$$

- limited by our knowledge of weak and strong phase differences.
  - ▻ But there are many possible measurements that we can compare!

Charmless two-body B decays



Charmless two-body B decays



Direct CP violation in charmless two-body B decays

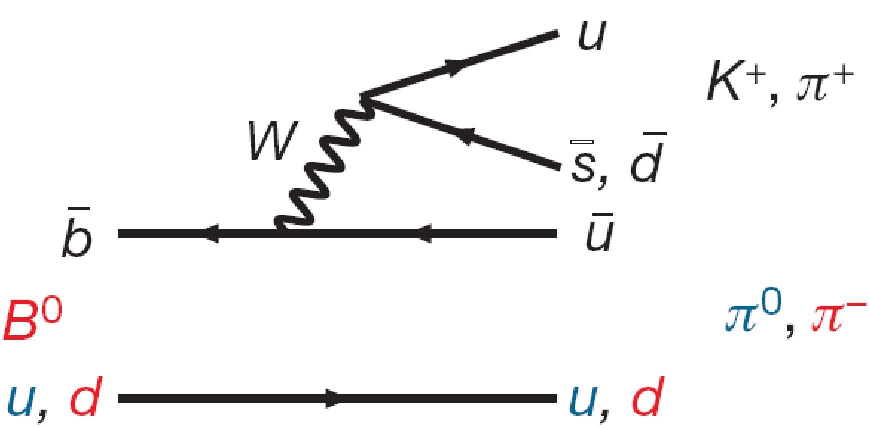
$$A_{CP} \equiv \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \sim \sum_{i,j} a_i\, a_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j)$$

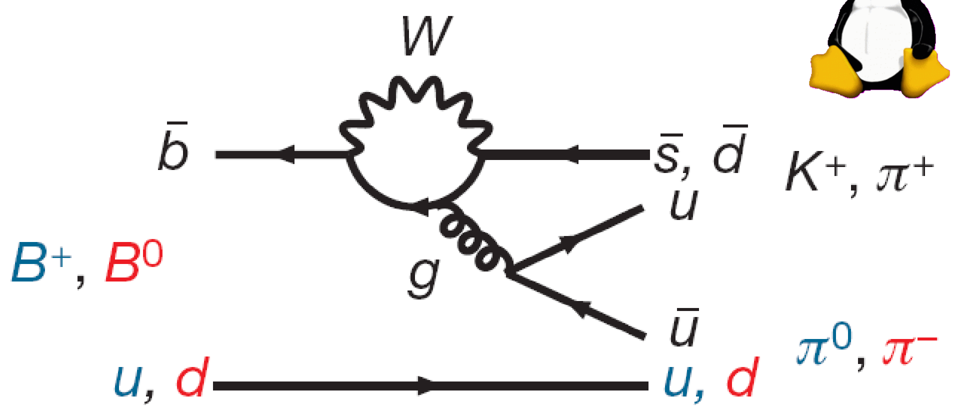
δ_i: strong phase
CP even

ϕ_i: weak phase
CP odd

interesting modes:

- $K^+\pi^-$: penguin+tree
- $K^+\pi^0$: penguin+tree
- $K^0\pi^+$: pure penguin





The kπ amplitudes

CKM enhanced | CKM suppressed

$$\mathcal{A}(B^0 \to K^+\pi^-) = V_{ts} V_{tb}^* \times P_1(c) - V_{us} V_{ub}^* \times \{E_1 - P_1^{GIM}(u-c)\}$$

$$\mathcal{A}(B^+ \to K^0\pi^+) = - V_{ts} V_{tb}^* \times P_1(c) + V_{us} V_{ub}^* \times \{A_1 - P_1^{GIM}(u-c)\}$$

$$\sqrt{2}\cdot \mathcal{A}(B^+ \to K^+\pi^0) = V_{ts} V_{tb}^* \times P_1(c) - V_{us} V_{ub}^* \times \{E_1 + E_2 + A_1 - P_1^{GIM}(u-c)\}$$

$$\sqrt{2}\cdot \mathcal{A}(B^0 \to K^0\pi^0) = - V_{ts} V_{tb}^* \times P_1(c) - V_{us} V_{ub}^* \times \{E_2 + P_1^{GIM}(u-c)\}$$

Charming Penguin $\sim \lambda^2$ | $V_{us} V_{ub}^* \sim \lambda^4$

The ingredients:

⇨ The elements of the CKM matrix (from the UT analysis)

⇨ Color Allowed (E_1) and Color suppressed (E_2) tree-level emissions

⇨ Charming (P_1) and GIM (P_1^{GIM}) penguins

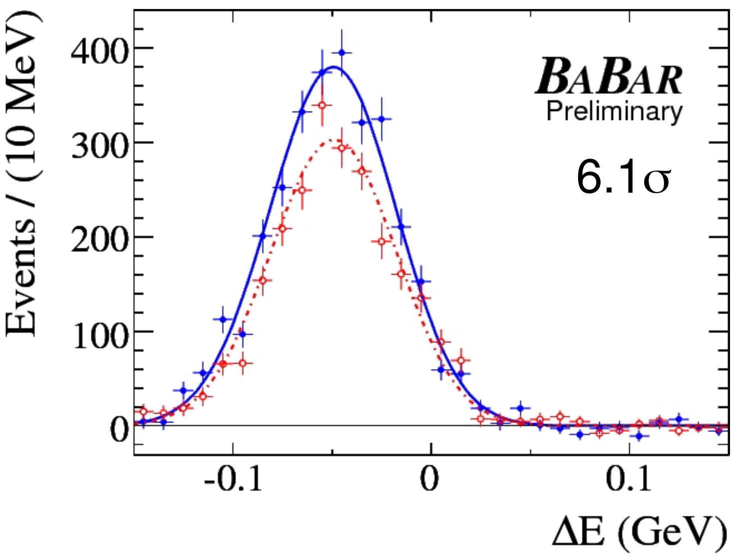
⇨ Annihilation (A_1)

Direct CP violation in charmless two-body B decays

- $B^0 \to K^{\pm}\pi^{\mp}$: tree and gluonic penguin contributions
- Compute time integrated asymmetry

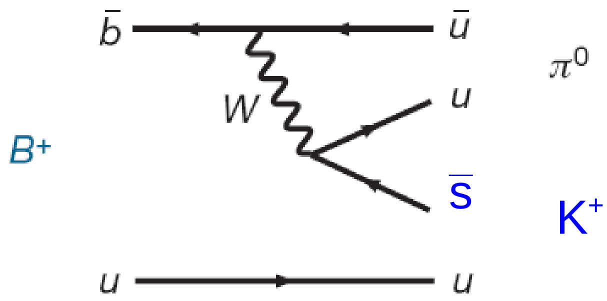
$$\mathcal{A}_{K^{\pm}\pi^{\mp}} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.084 \pm 0.004$$

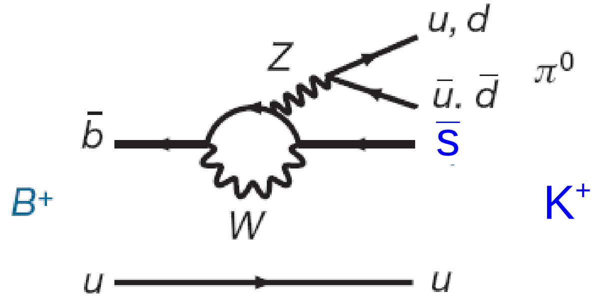
- Experimental results from Belle, BaBar, and now also LHCb have significant weight in the world average of this CP violation parameter.
- First measurement of direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we cannot use this to measure weak phases



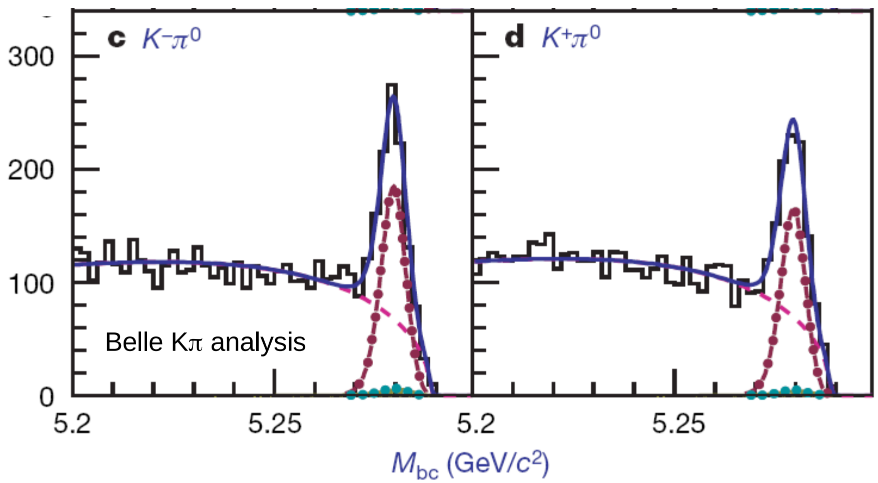
Direct CP violation in charmless two-body B decays

- $B^+ \to K^+\pi^0$: colour suppressed tree (in addition to the colour allowed one) and gluonic penguin contributions





- Experimentally measure: $A(K^+\pi^0) = 0.040 \pm 0.021$



- Difference between B^+ and B^0 asymmetries:

  $A(K^+\pi^-) = -0.084 \pm 0.004$

- Difference claimed to be an indication of new physics, however:
  - Theory calculations assume that only T+P contribute to $K^+\pi^-$, and C+P contribute to $K^+\pi^0$.
  - The C contribution is larger than originally expected in $K^+\pi^0$.

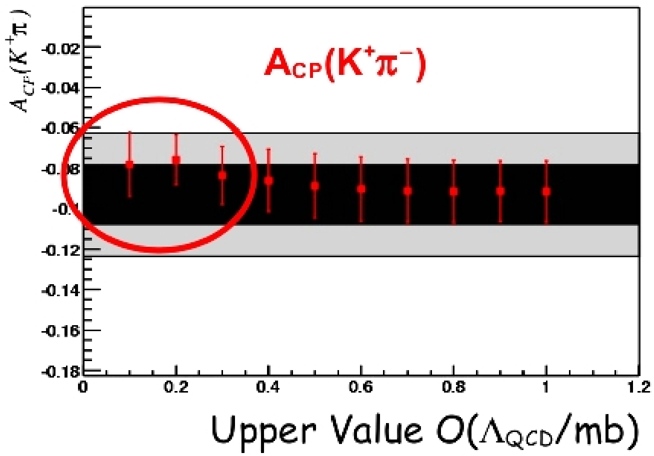
For example, see G. Hou arXiv:0808.1932 and references therein.

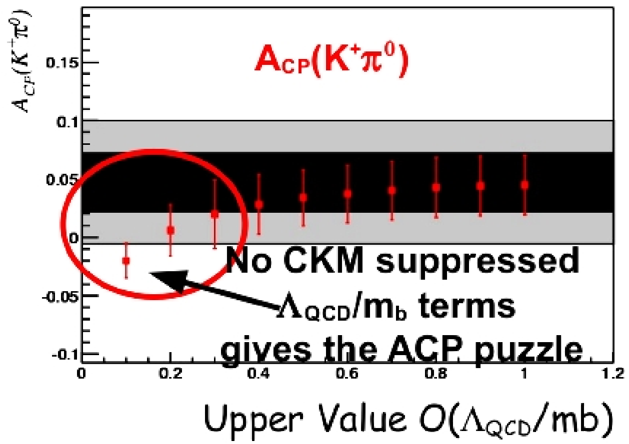
Is there a kπ puzzle?

caveat: quite old

Only SCET includes a non-factorizable $O(\Lambda_{QCD}/m_b)$ charming penguin.
All these approaches neglect the CKM-suppressed $O(\Lambda_{QCD}/m_b)$ corrections

	QCDF [50]	PQCD [54, 55]	SCET [58]	exp
$BR(\pi^-\bar{K}^0)$	$19.3^{+1.9+11.3+1.9+13.2}_{-1.9-7.8-2.1-5.6}$	$24.5^{+13.6}_{-8.1}$	$20.8\pm7.9\pm0.6\pm0.7$	23.1 ± 1.0
$A_{CP}(\pi^-\bar{K}^0)$	$0.9^{+0.2+0.3+0.1+0.6}_{-0.3-0.3-0.1-0.5}$	0 ± 0	<5	0.9 ± 2.5
$BR(\pi^0K^-)$	$11.1^{+1.8+5.8+0.9+6.9}_{-1.7-4.0-1.0-3.0}$	$13.9^{+10.0}_{-5.6}$	$11.3\pm4.1\pm1.0\pm0.3$	12.8 ± 0.6
$A_{CP}(\pi^0K^-)$	$7.1^{+1.7+2.0+0.8+9.0}_{-1.8-2.0-0.6-9.7}$	-1^{+3}_{-5}	$-11\pm9\pm11\pm2$	4.7 ± 2.6
$BR(\pi^+K^-)$	$16.3^{+2.6+9.6+1.4+11.4}_{-2.3-6.5-1.4-4.8}$	$20.9^{+15.6}_{-8.3}$	$20.1\pm7.4\pm1.3\pm0.6$	19.4 ± 0.6
$A_{CP}(\pi^+K^-)$	$4.5^{+1.1+2.2+0.5+8.7}_{-1.1-2.5-0.6-9.5}$	-9^{+6}_{-8}	$-6\pm5\pm6\pm2$	-9.5 ± 1.3
$BR(\pi^0\bar{K}^0)$	$7.0^{+0.7+4.7+0.7+5.4}_{-0.7-3.2-0.7-2.3}$	$9.1^{+5.6}_{-3.3}$	$9.4\pm3.6\pm0.2\pm0.3$	10.0 ± 0.6
$A_{CP}(\pi^0\bar{K}^0)$	$-3.3^{+1.0+1.3+0.5+3.4}_{-0.8-1.6-1.0-3.3}$	-7^{+3}_{-3}	$5\pm4\pm4\pm1$	-12 ± 11





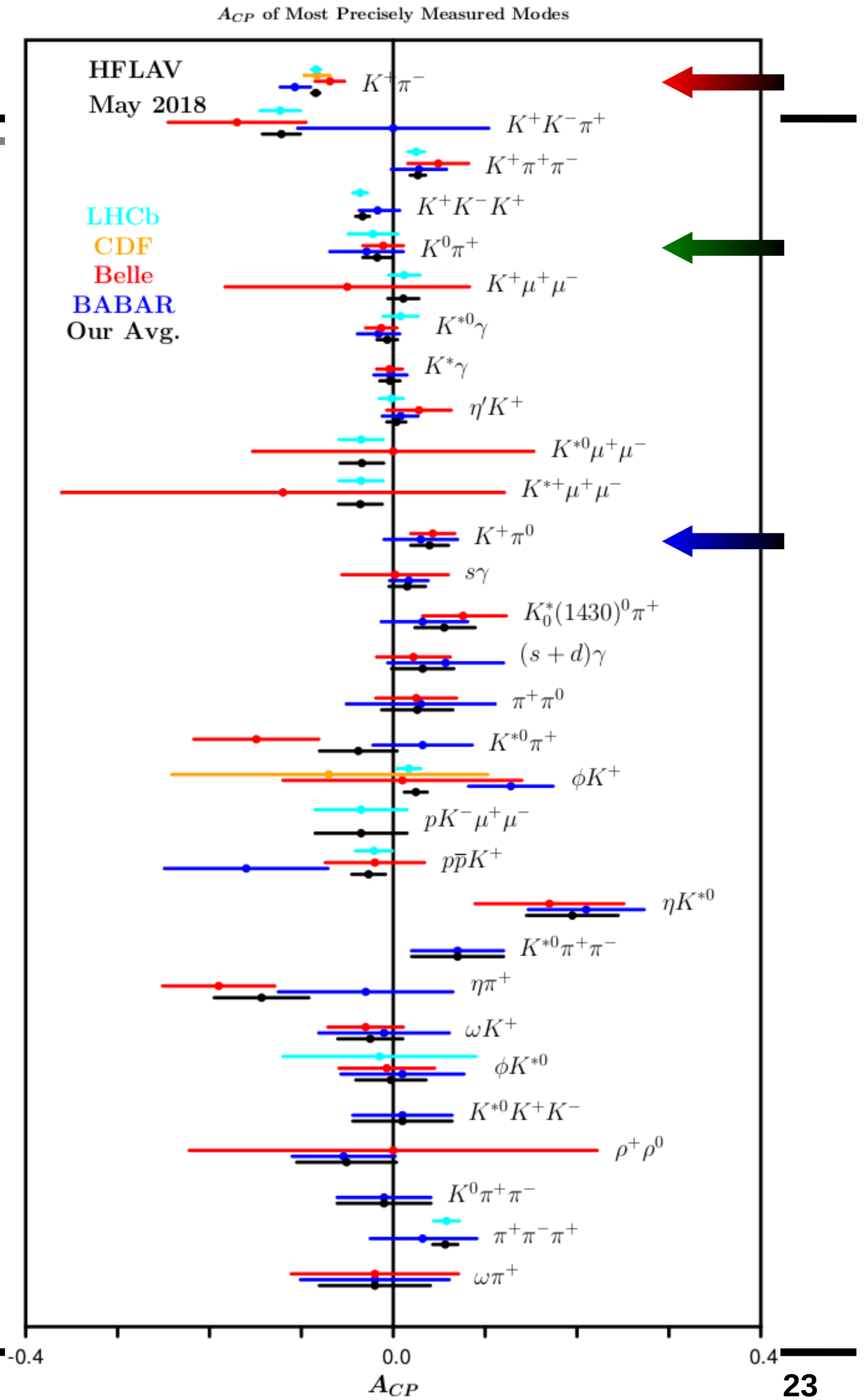
Direct CP violation searches

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

$A_{CP} = 0$

$= \text{no CP violation}$

- We have searched for direct CP violation now in a huge number of channels.
- This is a selection of the modes more precisely measured.



Sides of the Unitarity Triangle

Sides of the Unitarity Triangle

$b \to u l \nu$

$B \to \pi l \nu$

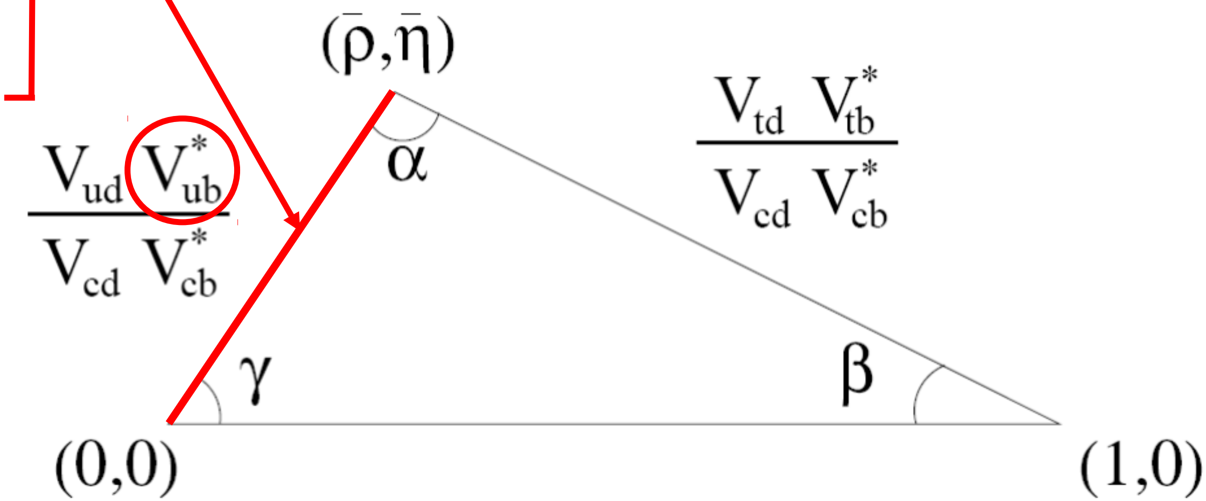
$B \to X_u l \nu$

$B \to \rho l \nu$

$B \to \omega l \nu$

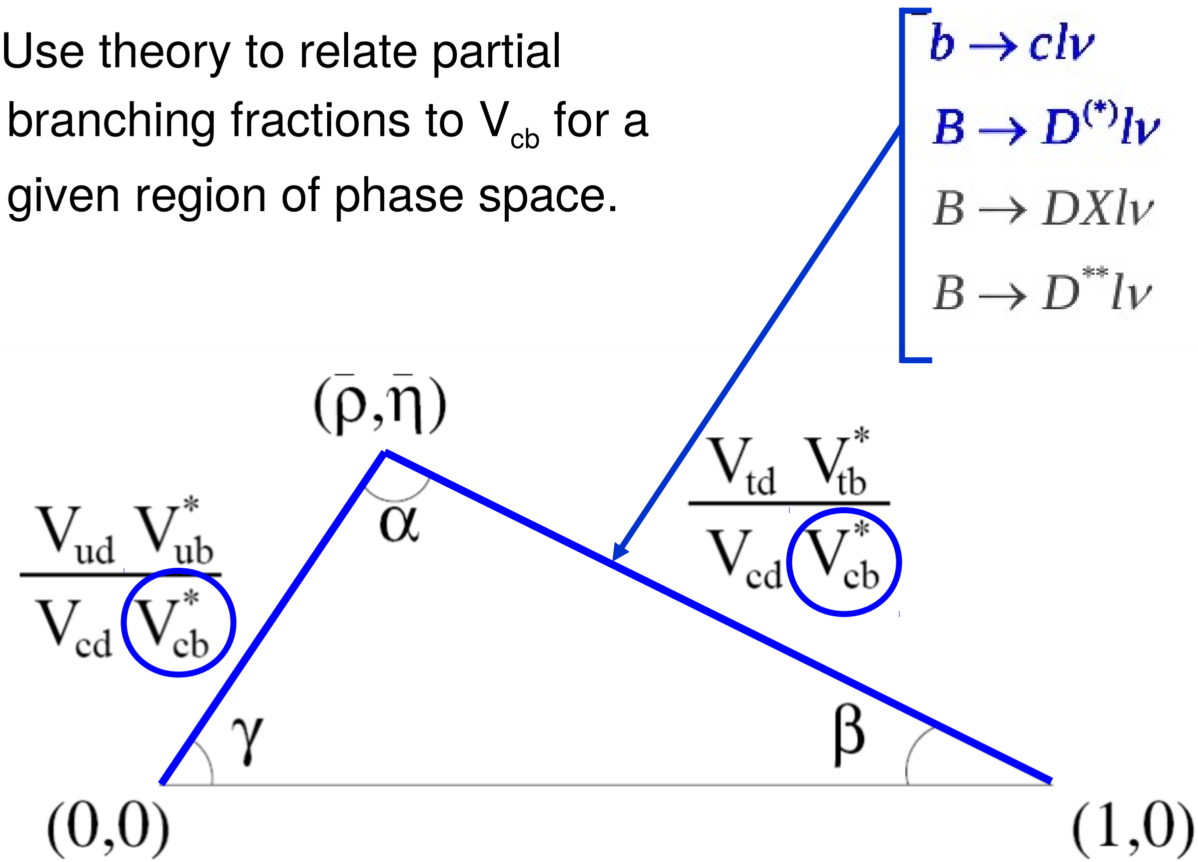
- Use theory to relate partial branching fractions to V_{ub} for a given region of phase space.

- Several theoretical schemes available.



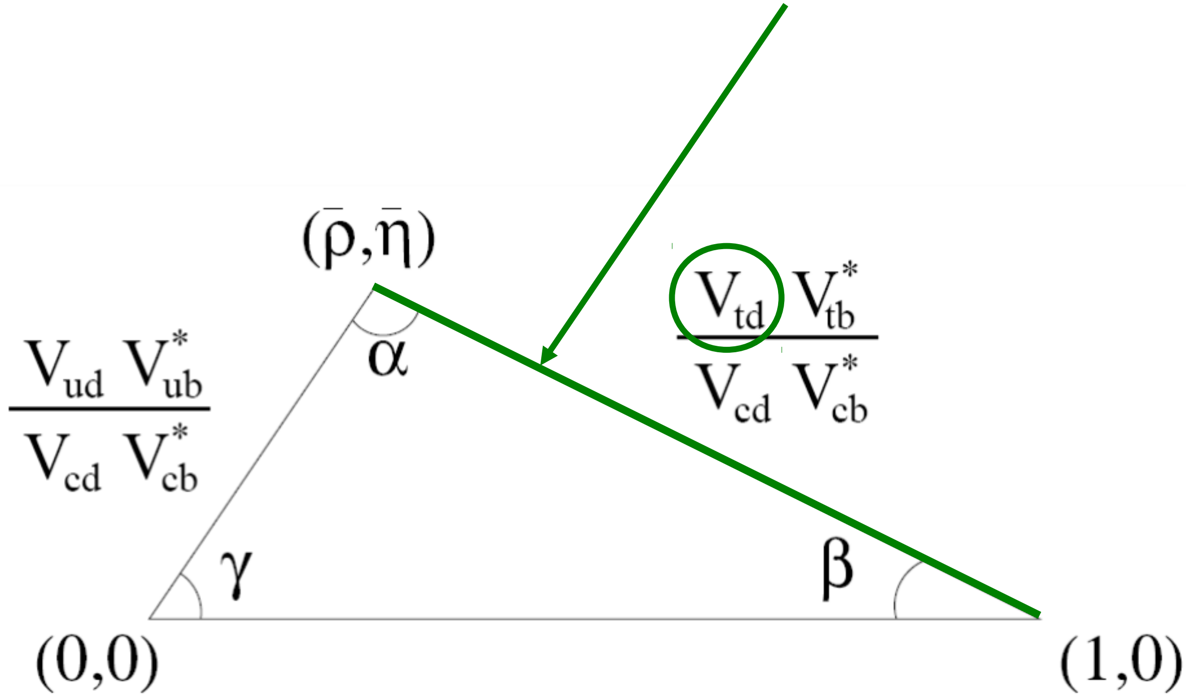
Sides of the Unitarity Triangle

- Use theory to relate partial branching fractions to V_{cb} for a given region of phase space.



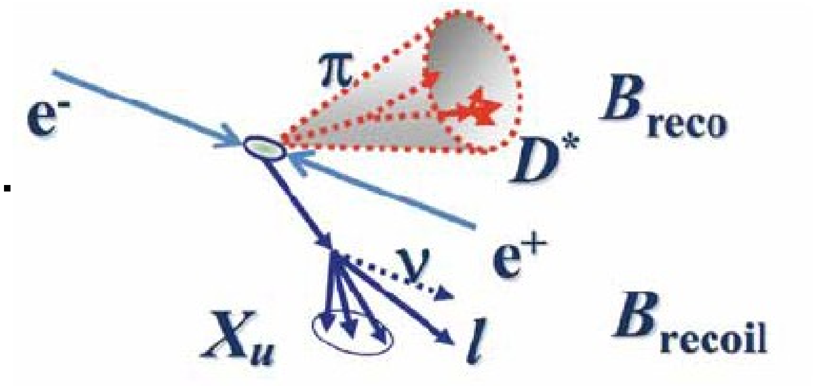
Sides of the Unitarity Triangle

V_{td} is linked to the B^0 mixing (box) diagram so to the B^0 oscillation parameter Δm_d



Side measurement: V_{ub}

- $|V_{ub}| \propto BR(B \to X_u l\nu)$ in a limited region of phase space.



- Reconstruct both B mesons in an event.
  - Study the B_{recoil} to measure V_{ub}.
  - Measure BR as a function of

    $$q^2_{l\nu},\ m_X,\ m_{MISS}\ \text{or}\ E_l$$

    and use theory to convert these results into $|V_{ub}|$.
- Can study modes exclusively or inclusively.
- Several models available to estimate $|V_{ub}|$
  - The resulting values have a significant model uncertainty.

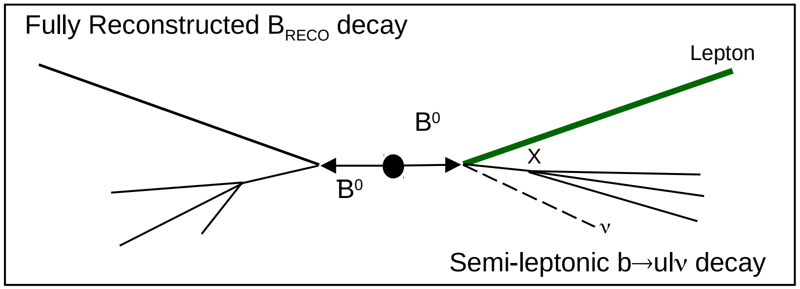
Exclusively reconstructed $b \to ul\nu$

- If we fully reconstruct one B meson in an event, then …
- … with a single ν in the event, we can infer P^ν and 'reconstruct' the ν
- Clean signals
- but low efficiency

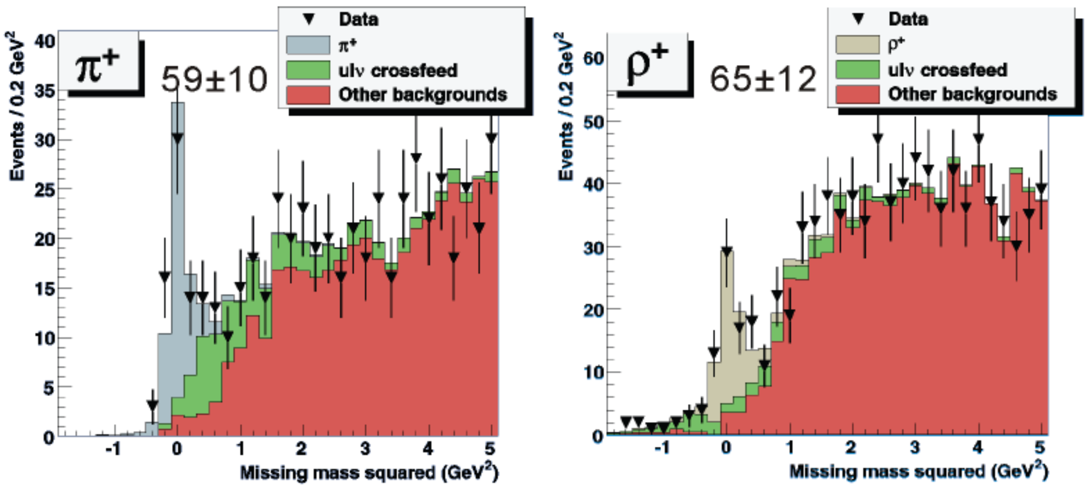
- Study B decays to:

$$B^0 \to \pi^- l^+ \nu$$
$$B^0 \to \rho^- l^+ \nu$$
$$B^+ \to \pi^0 l^+ \nu$$
$$B^+ \to \rho^0 l^+ \nu$$
$$B^+ \to \omega l^+ \nu$$

- Fully reconstruct B_{RECO}
- tagged or untagged for the second B
- Extract yields from m^2_{MISS} in q2 bins to reduce form factor dependence
- Then compute $|V_{ub}|$.

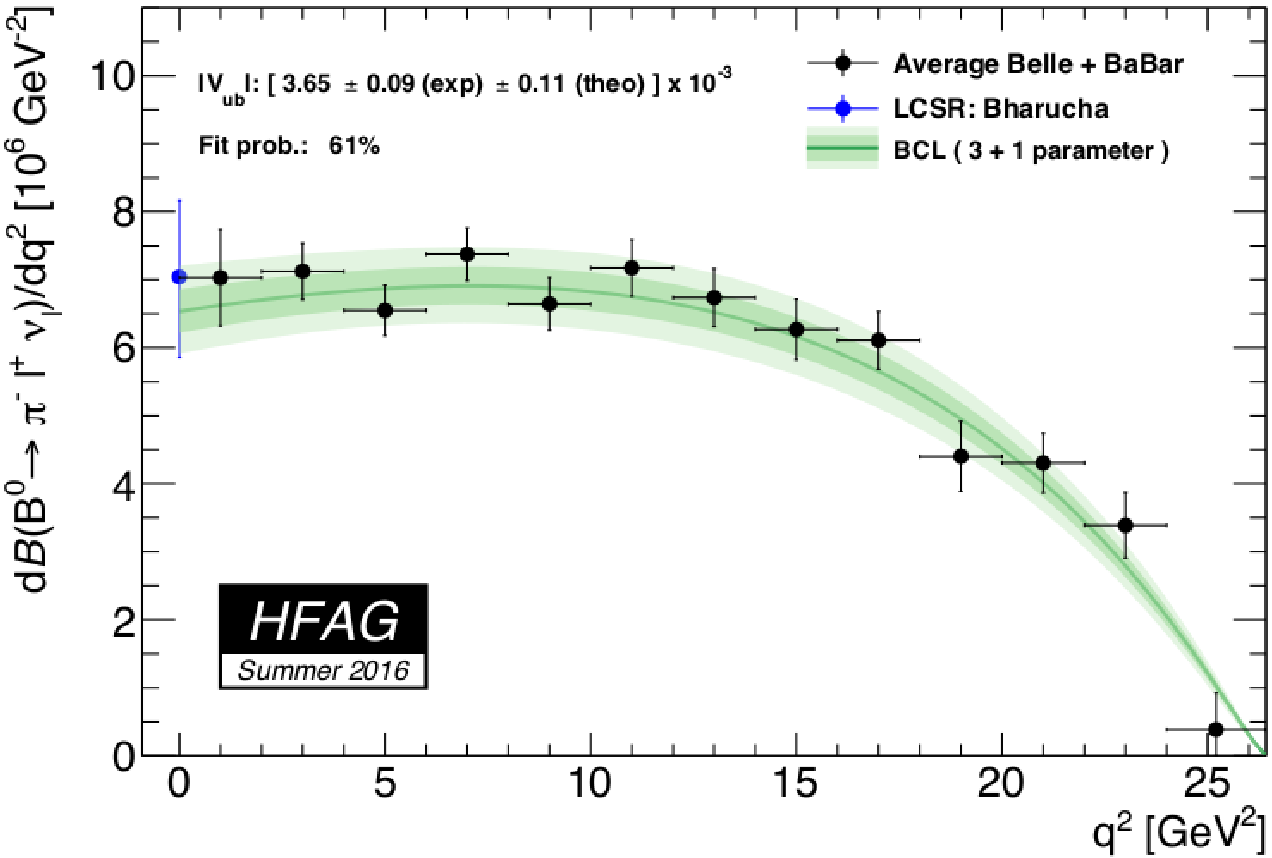


Use the beam energy to constrain P^ν to effectively 'reconstruct' the ν from the missing energy-momentum: $m_{MISS} = m_\nu = 0$.



V_{ub}: Using q^2 distribution

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 \; p_\pi^3 \; |f(q^2)|^2$$



$|V_{ub}|$ is determined from a combined fit of a B → π form factor parameterization to theory predictions and the average q^2 spectrum in data.

Form factor input:

◆ Low q^2 region (< 6-7 GeV^2): Light cone sum rules, unperturbative, at $q^2 = 0$

◆ Intermediate to high q^2 region (>14 GeV^2): LQCD, unquenched.

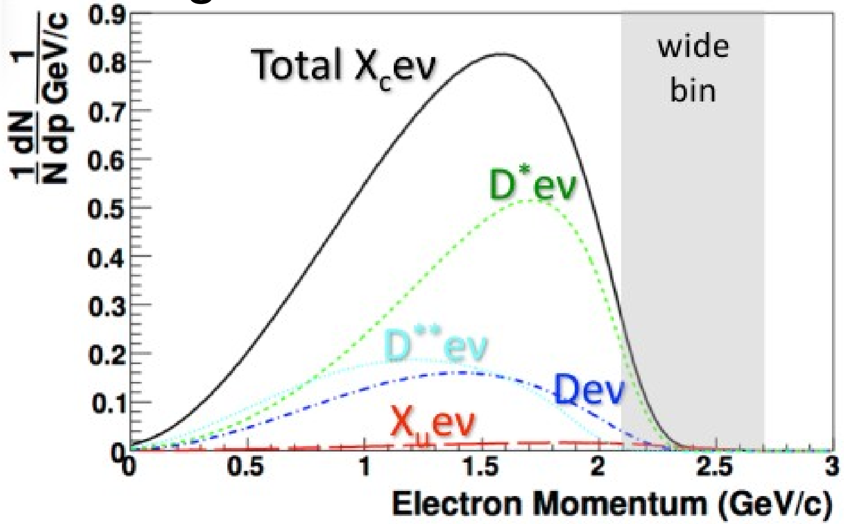
From the fit (in 10^{-3}):

$|V_{ub}| = (3.65 \pm 0.09 \pm 0.11)$

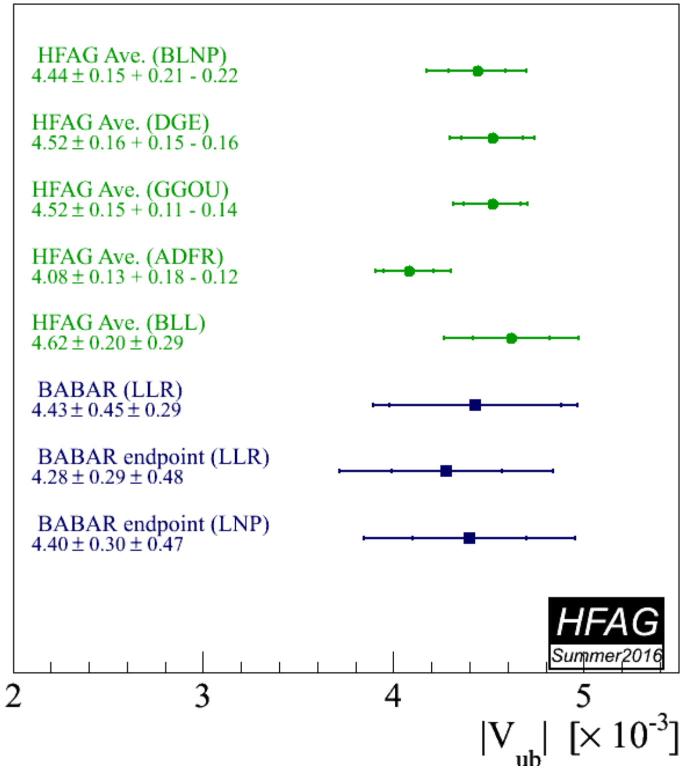
uncertainty 14%

V_{ub}: inclusive analysis

- Treat B meson decay like a free b quark (+corrections)
- High background from clν decays.
  - Kinematic cuts are used to suppress background.
- Use Operator Product Expansions to translate measured branching fractions to V_{ub}.
- Measure branching fraction in different kinematic regions.



The following theoretical calculations are used to extract |Vub|:
BLNP [arXiv:hep-ph/0504071v3]
DGE [arXiv:hep-ph/0509360v2].
Recent update: [arXiv:0806.4524]
GGOU [arXiv:0707.2493].
ADFR [arXiv:0711.0860]
BLL [arXiv:hep-ph/0107074v1]
No averaged value for |Vub| from the different theoretical models



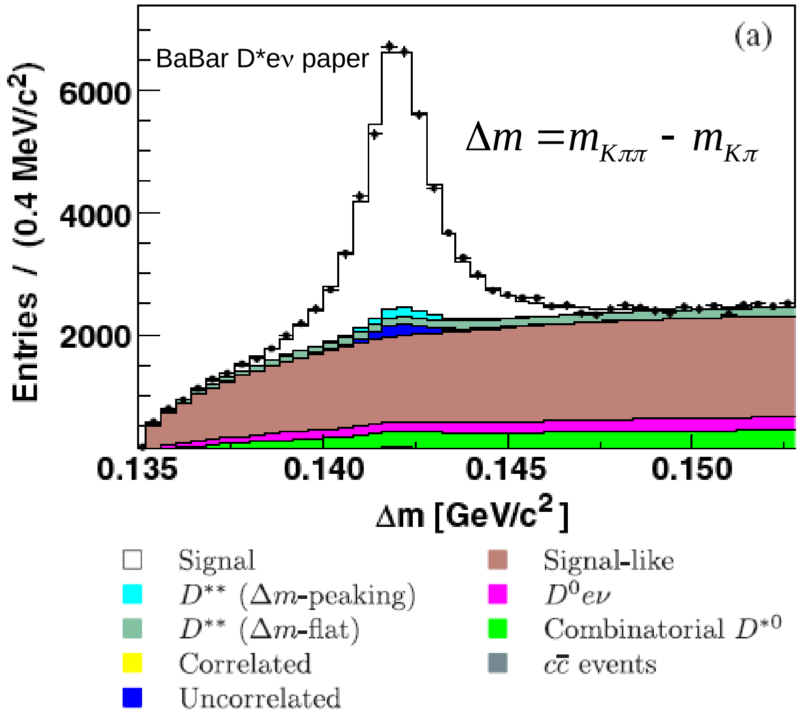
Side measurements: V_{cb}

◎ Use the differential decay rates of $B \to D^* l\nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \to D^* l^- \bar{\nu})}{d\omega d\cos\theta_l d\cos\theta_V d\chi} \propto F^2(\omega, \theta_l, \theta_V, \chi) |V_{cb}|^2$$

- F is a form factor.
- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

- Reconstruct $B^- \to D^{*0} e^- \bar{\nu}_e$, $D^{*0} \to D\pi$, $D \to K^+\pi^-$



- Measurement is not statistically limited, so use clean signal mode for $D \to K\pi$ decay only.

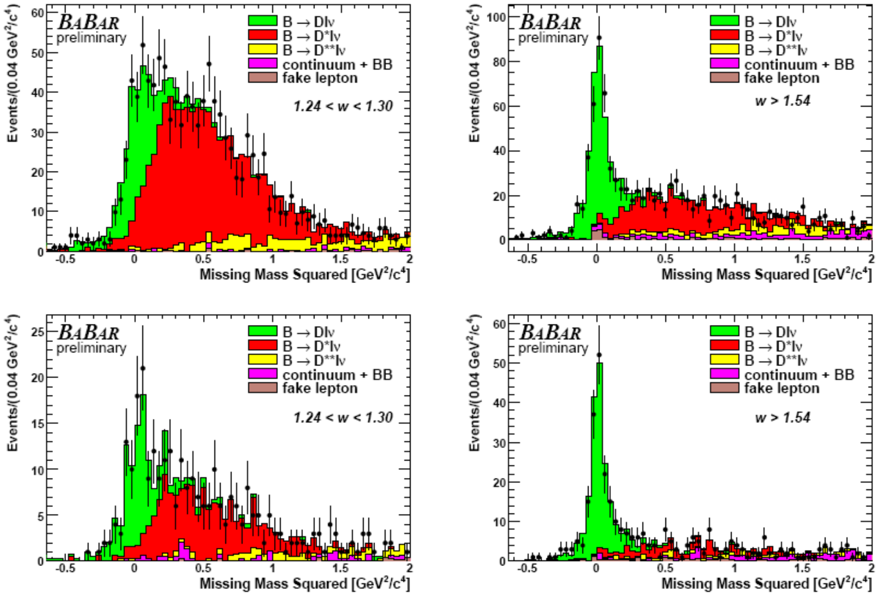
- Extract signal yield, $F(1)|V_{cb}|$ and ρ from 3D binned fit to data.

Side measurements: V_{cb}

◎ Use the differential decay rates of B → Dlν to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \to D l^- \bar{\nu})}{d\omega d\cos\theta_l d\cos\theta_V d\chi} \propto G^2(\omega) |V_{cb}|^2$$

- Use a sample of fully reconstructed tag B mesons, then look for the signal.
- Improves background rejection, at the cost of signal efficiency.

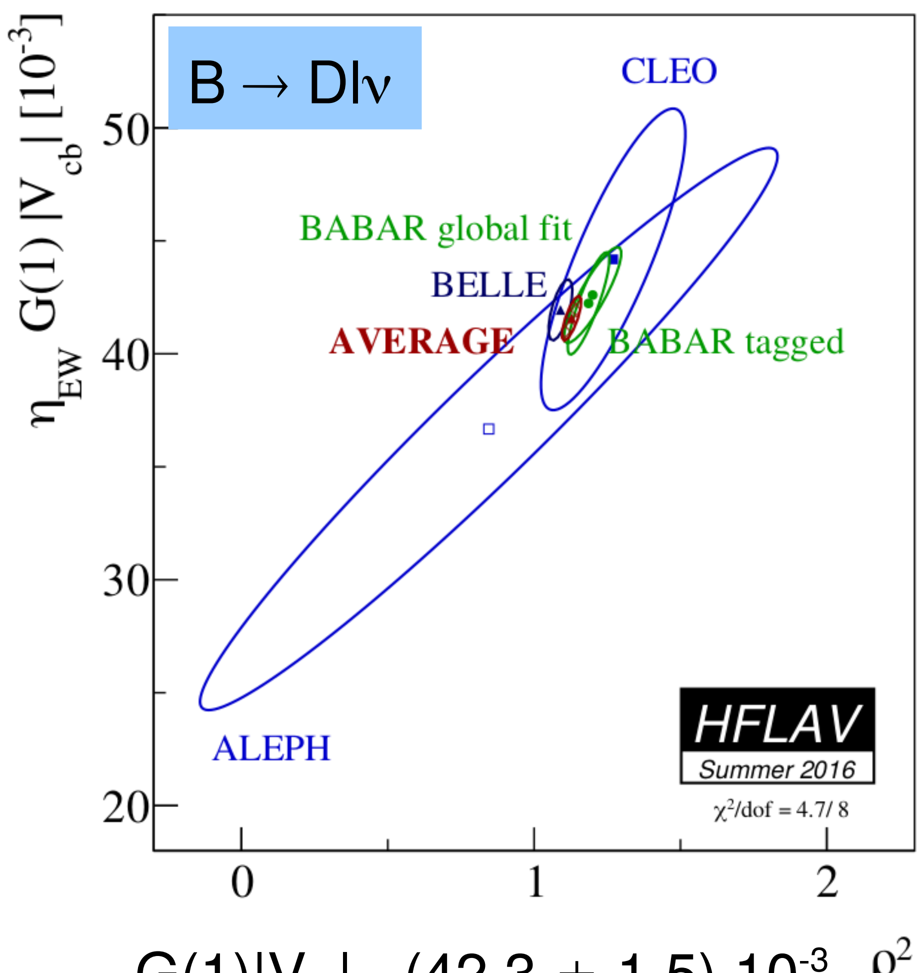


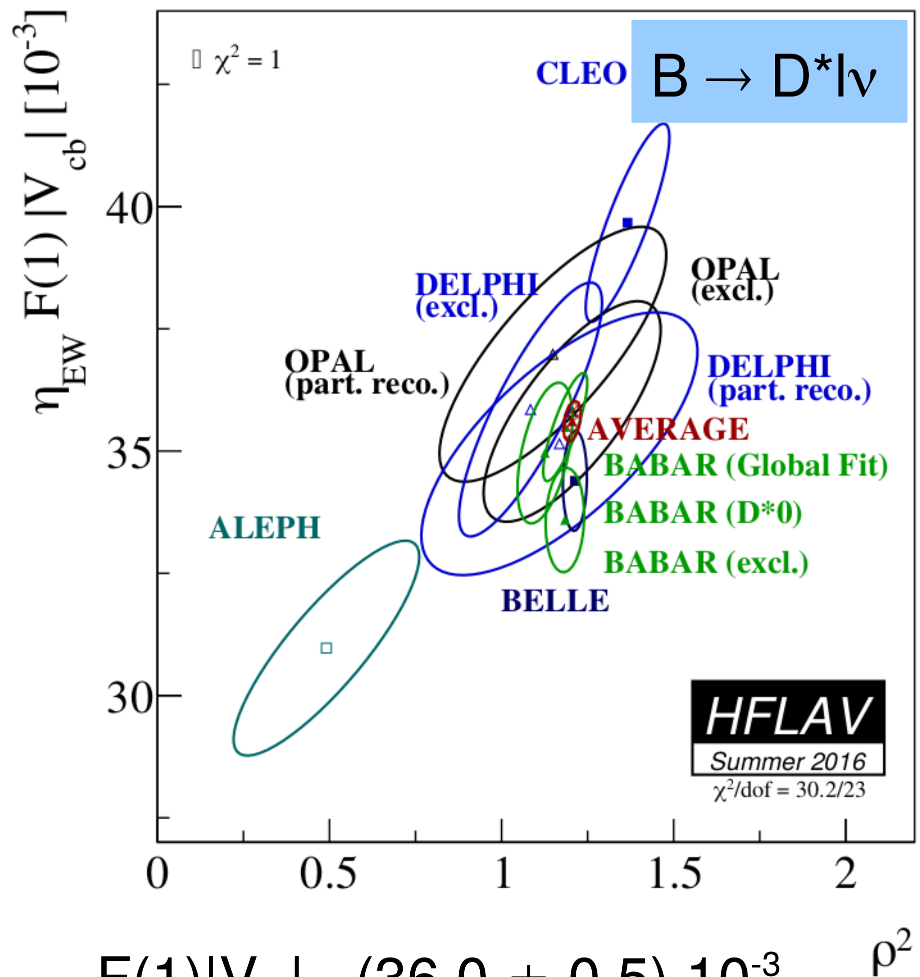
ω is related to q^2 of the B meson to the D

- G is a form factor.
- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.
- Reconstruct the following D decay channels:

$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$
$K^-\pi^+\pi^-\pi^+$	$K^0_S\pi^+$
$K^0_S\pi^+\pi^-$	$K^0_S\pi^+\pi^0$
$K^0_S\pi^+\pi^-\pi^0$	$K^+K^-\pi^+$
$K^0_S\pi^0$	$K^0_S K^+$
K^+K^-	$K^0_S\pi^+\pi^+\pi^-$
$\pi^+\pi^-$	
$K^0_S K^0_S$	

Exclusive $|V_{cb}|$





$G(1)|V_{cb}| = (42.3 \pm 1.5)\ 10^{-3}$

$|V_{cb}| = (39.4 \pm 1.7)\ 10^{-3}$

$F(1)|V_{cb}| = (36.0 \pm 0.5)\ 10^{-3}$

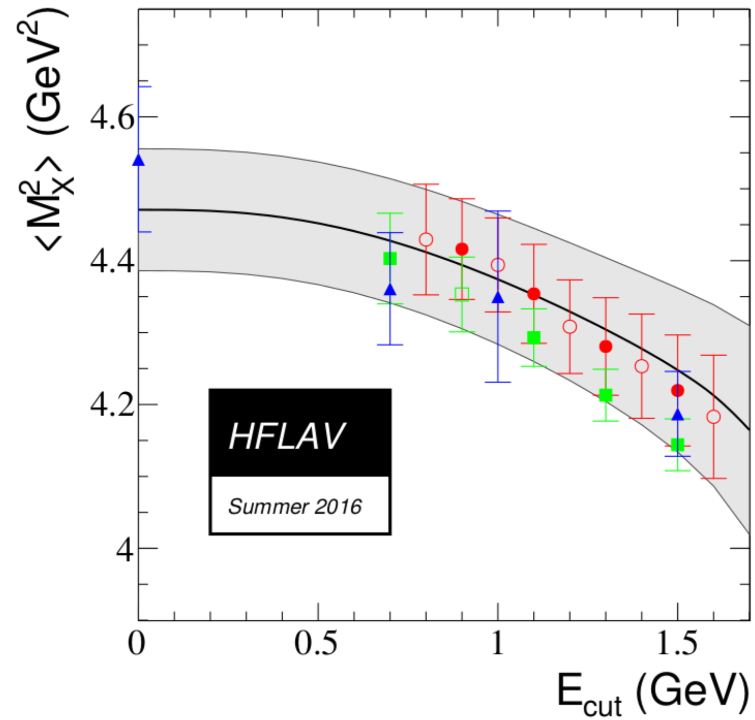
$|V_{cb}| = (39.0 \pm 1.1)\ 10^{-3}$

Inclusive $|V_{cb}|$

At parton level, the decay rate for $b \to c l \nu$ can be calculated accurately and is proportional to $|V_{cb}|^2$
To relate measurements of semileptonic B-meson decays to $|V_{cb}|^2$ the parton-level expressions have to be corrected for the effects of non-perturbative effects.
Heavy-Quark-Expansions (HQE) successful tool to incorporate perturbative and nonperturbative QCD corrections.

$$\Gamma_{sl} = \Gamma_0 \Big[1 + a^{(1)}\frac{\alpha_s(m_b)}{\pi} + a^{(2,\beta_0)}\beta_0\left(\frac{\alpha_s}{\pi}\right)^2 + a^{(2)}\left(\frac{\alpha_s}{\pi}\right)^2 + \left(-\frac{1}{2}+p^{(1)}\frac{\alpha_s}{\pi}\right)\frac{\mu_\pi^2}{m_b^2} + \left(g^{(0)}+g^{(1)}\frac{\alpha_s}{\pi}\right)\frac{\mu_G^2(m_b)}{m_b^2} + d^{(0)}\frac{\rho_D^3}{m_b^3} - g^{(0)}\frac{\rho_{LS}^3}{m_b^3} + \text{higher orders}\Big]$$

E.g. total decay rate expanded in the kinetic scheme
Determine the five parameters + $|V_{cb}|$
from a simultaneous fit to moments



From the fit (in 10^{-3}):

$|V_{cb}| = (42.19 \pm 0.78)$

uncertainty 2%

$|V_{cb}|$ and $|V_{ub}|$ in 2018

$|V_{cb}|$ *(excl)* = $(38.9 \pm 0.6)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.19 \pm 0.78)\ 10^{-3}$

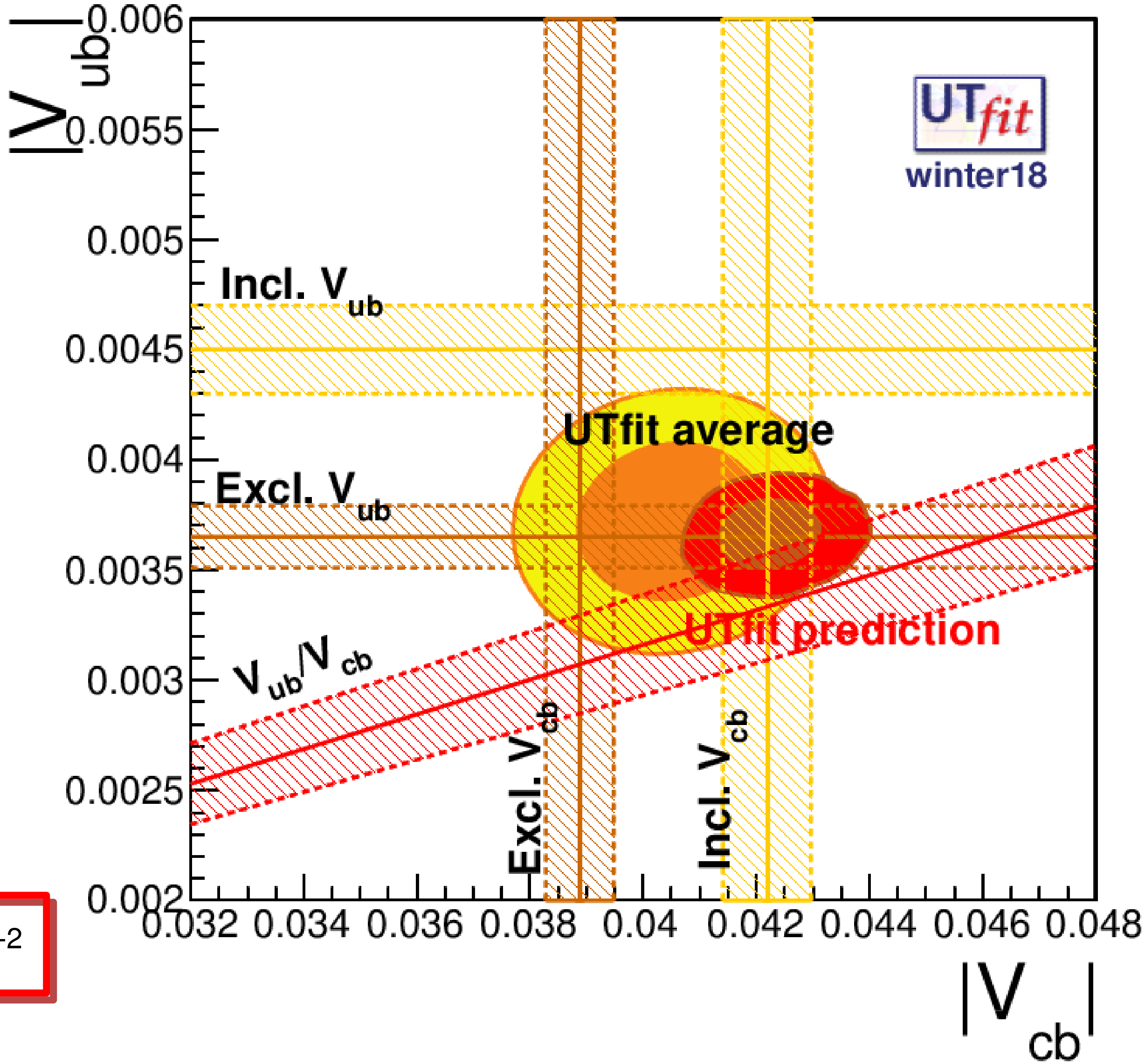
~3.3σ discrepancy

$|V_{ub}|$ *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

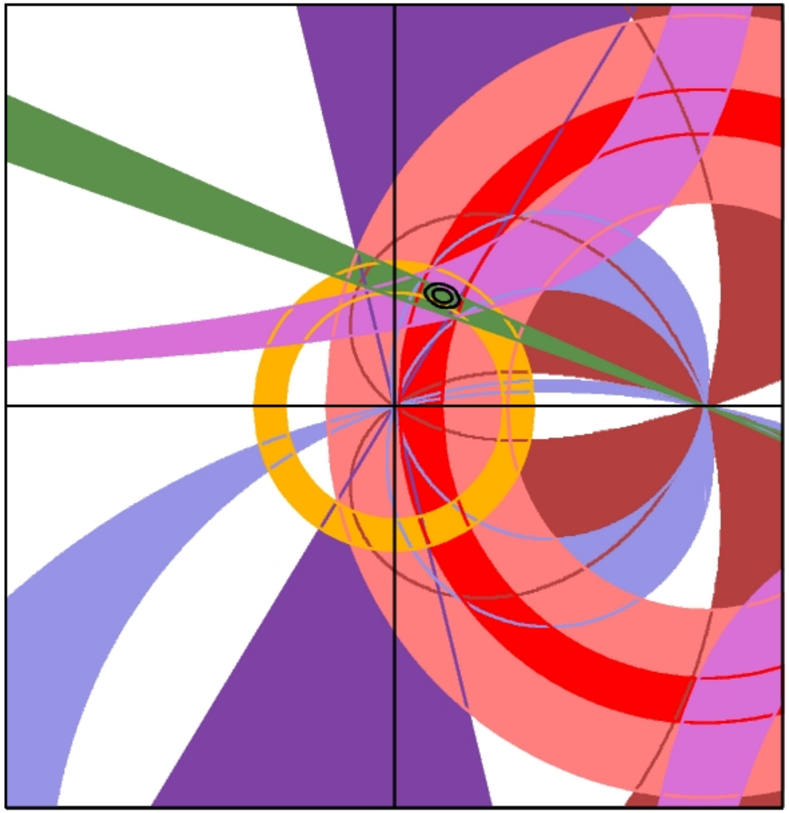
$|V_{ub}|$ *(incl)* = $(4.50 \pm 0.20)\ 10^{-3}$

~3.4σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(7.9 \pm 0.6)\ 10^{-2}$



Unitarity Triangle analysis



Unitarity Triangle analysis in the SM

- SM UT analysis:
  - provide the best determination of CKM parameters
  - test the consistency of the SM (“direct” vs “indirect” determinations)
  - provide predictions for future experiments (ex. sin2β, Δm_s, ...)

analysis from UTfit

M. Bona *et al*. (UTfit)
JHEP0507:028, 2005

www.utfit.org

the method and the inputs

$$f(\bar{\rho},\bar{\eta},X|c_1,\ldots,c_m) \sim \prod_{j=1,m} f_j(\mathcal{C}|\bar{\rho},\bar{\eta},X) * \prod_{i=1,N} f_i(x_i) f_0(\bar{\rho},\bar{\eta})$$

Bayes Theorem

$$X \equiv x_1,\ldots,x_n = m_t, B_K, F_B, \ldots$$

$$\mathcal{C} \equiv c_1,\ldots,c_m = \epsilon, \Delta m_d/\Delta m_s, A_{CP}(J/\psi K_S), \ldots$$

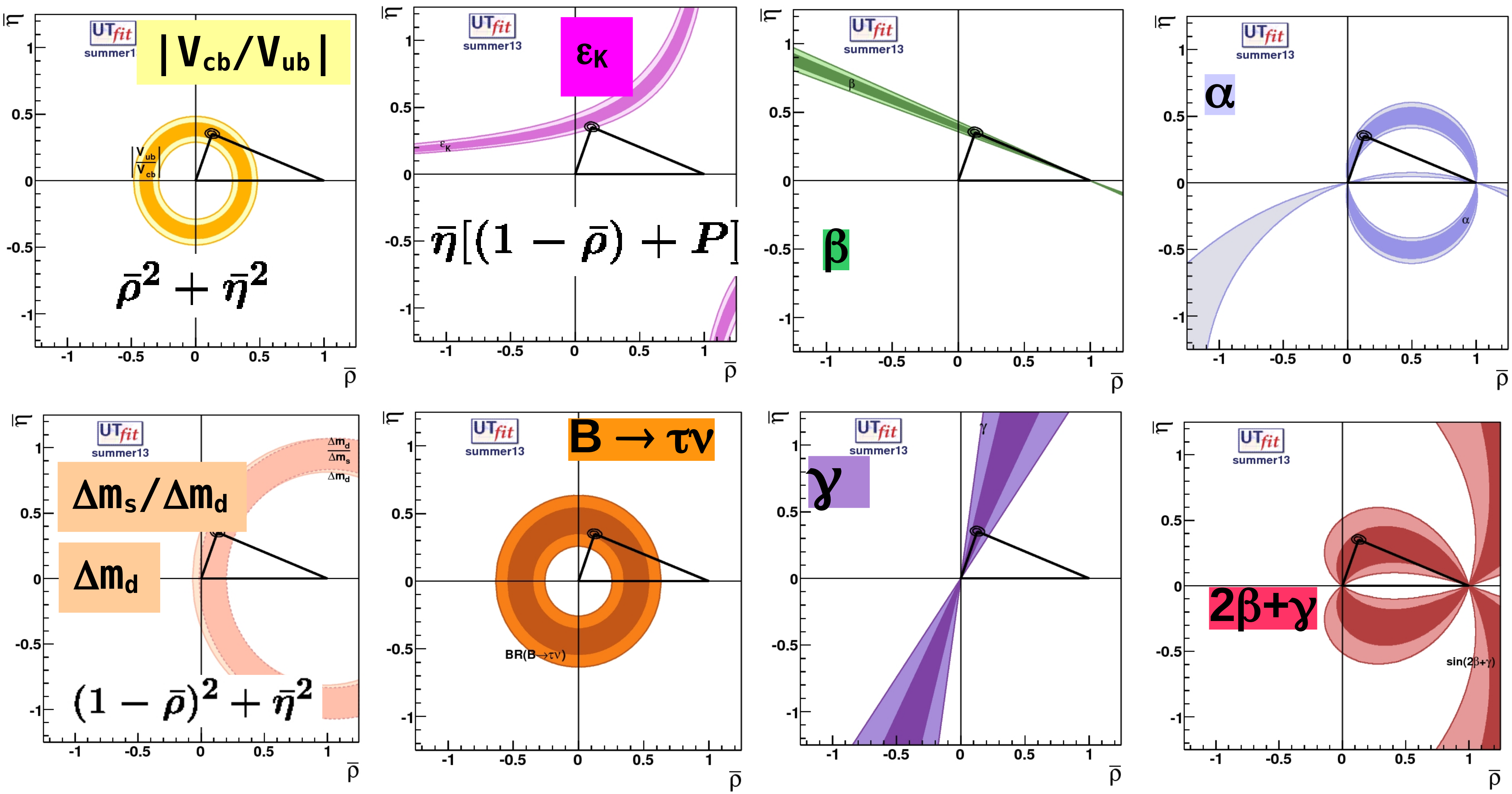
$(b \to u)/(b \to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$\bar{\Lambda}, \lambda_1, F(1), \ldots$
ϵ_K	$\bar{\eta}[(1-\bar{\rho}) + P]$	B_K
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f_B^2 B_B$
$\Delta m_d/\Delta m_s$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	

Standard Model +
OPE/HQET/
Lattice QCD
to go
from quarks
to hadrons

m_t

M. Bona *et al*. (UTfit Collaboration)
JHEP 0507:028,2005 hep-ph/0501199
M. Bona *et al*. (UTfit Collaboration)
JHEP 0603:080,2006 hep-ph/0509219

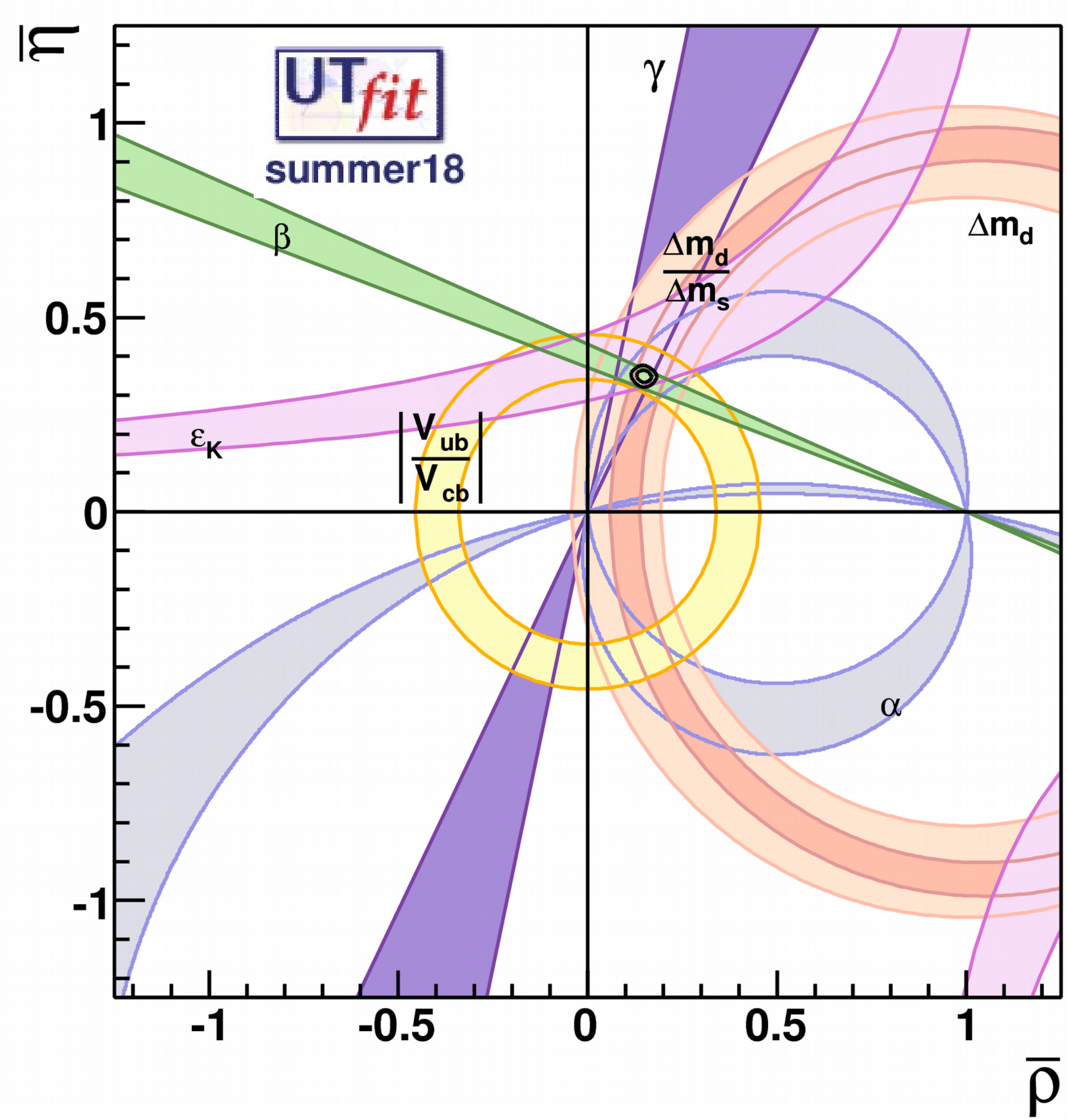
Unitarity Triangle analysis in the SM



Unitarity Triangle analysis in the SM

Observables	Accuracy
$\|V_{ub}/V_{cb}\|$	~ 7%
ε_K	~ 0.5%
Δm_d	~ 1%
$\|\Delta m_d/\Delta m_s\|$	~ 1%
$\sin 2\beta$	~ 3%
$\cos 2\beta$	~ 13%
α	~ 6%
γ	~ 6%
$BR(B \to \tau\nu)$	~ 22%

Unitarity Triangle analysis in the SM



levels @
95% Prob

~9%

$\bar{\rho} = 0.148 \pm 0.013$
$\bar{\eta} = 0.348 \pm 0.010$

~3%

M. Bona *et al.* (UTfit)
JHEP0507:028, 2005

analysis from UTfit
www.utfit.org

Unitarity Triangle analysis in the SM

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.689 ± 0.018	0.738 ± 0.033	~ 1.2
γ	73.4 ± 4.4	65.8 ± 2.2	< 1
α	93.3 ± 5.6	90.1 ± 2.2	< 1
$\|V_{ub}\| \cdot 10^3$	3.72 ± 0.23	3.66 ± 0.11	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.50 ± 0.20	-	~ 3.8
$\|V_{ub}\| \cdot 10^3$ (excl)	3.65 ± 0.14	-	< 1
$\|V_{cb}\| \cdot 10^3$	40.5 ± 1.1	42.4 ± 0.7	~ 1.4
$BR(B \rightarrow \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.81 ± 0.05	~ 1.2
$A_{SL}^d \cdot 10^3$	-2.1 ± 1.7	-0.292 ± 0.026	~ 1
$A_{SL}^s \cdot 10^3$	-0.6 ± 2.8	0.013 ± 0.001	< 1

Unitarity triangle fit beyond the SM

1. fit simultaneously for the CKM and the NP parameters (generalized UT fit)
   - add most general loop NP to all sectors
   - use all available experimental info
   - find out NP contributions to $\Delta F=2$ transitions

2. perform a $\Delta F=2$ EFT analysis to put bounds on the NP scale
   - consider different choices of the FV and CPV couplings

generic NP parameterization:

B_d and B_s mixing amplitudes
(2+2 real parameters):

$$C_{B_s} e^{-2i\phi_{B_s}} = \frac{\langle \overline{B}_s | H_{eff}^{SM} + H_{eff}^{NP} | B_s \rangle}{\langle \overline{B}_s | H_{eff}^{SM} | B_s \rangle} = 1 + \frac{A_{NP} e^{-2i\phi_{NP}}}{A_{SM} e^{-2i\beta_s}}$$

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})} \right) A_q^{SM} e^{2i\phi_q^{SM}}$$

Observables:

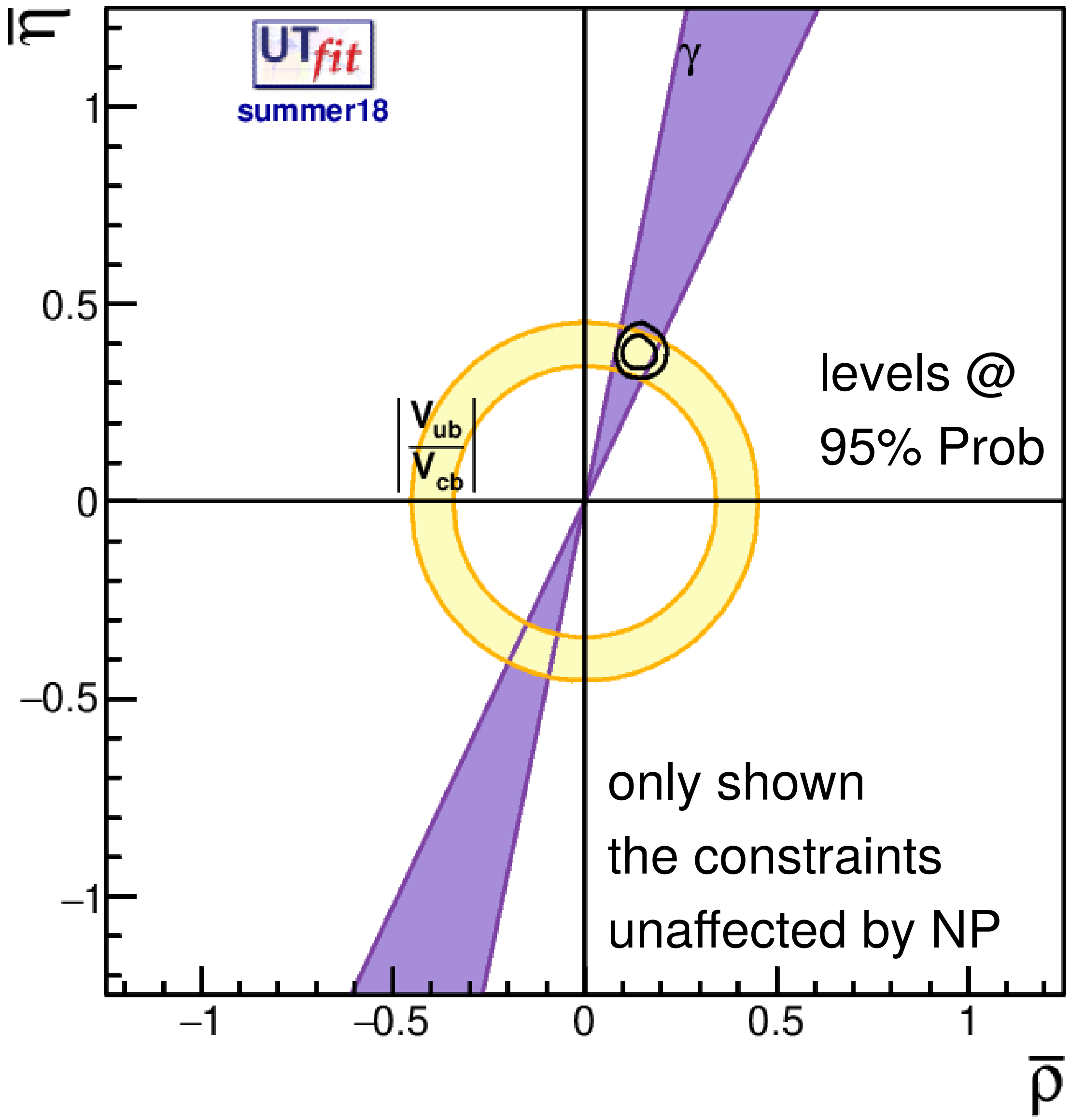
assume NP only in loop

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM} \qquad \varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d}) \qquad A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$A_{SL}^q = \mathrm{Im}(\Gamma_{12}^q / A_q) \qquad \Delta\Gamma^q / \Delta m_q = \mathrm{Re}(\Gamma_{12}^q / A_q)$$

NP analysis results



$\bar{\rho} = 0.144 \pm 0.028$

$\bar{\eta} = 0.378 \pm 0.027$

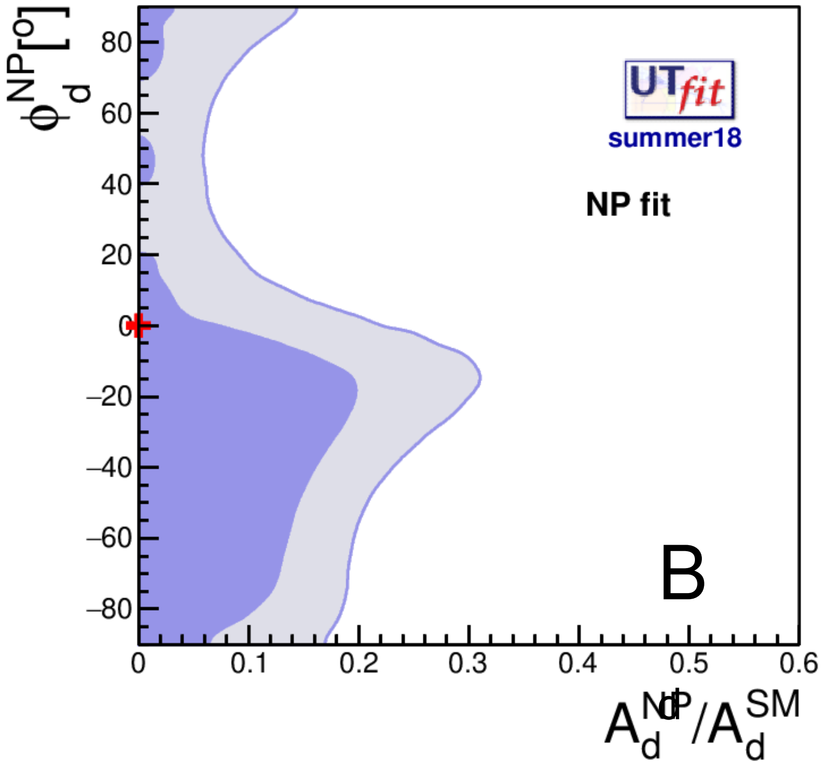
SM is

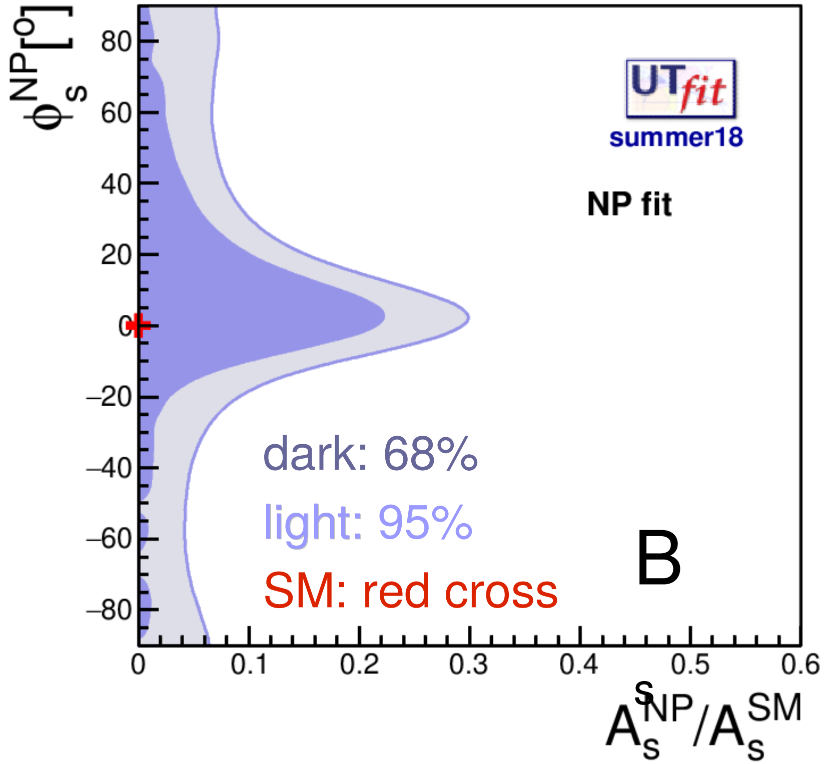
$\bar{\rho} = 0.148 \pm 0.013$

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

NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$





The ratio of NP/SM amplitudes is:

< 18% @68% prob. (30% @95%) in B_d mixing

< 20% @68% prob. (30% @95%) in B_s mixing

Testing the new-physics scale

M. Bona *et al.* (UTfit)
JHEP 0803:049,2008
arXiv:0707.0636

RGE

At the high scale

new physics enters according to its specific features

At the low scale

use OPE to write the most general effective Hamiltonian.
the operators have different chiralities than the SM
NP effects are in the Wilson Coefficients C

$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} \,, \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} \,, \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \,, \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} \,, \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} \,.
\end{aligned}$$

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

F_i: function of the NP flavour couplings
L_i: loop factor (in NP models with no tree-level FCNC)
Λ: NP scale (typical mass of new particles mediating $\Delta F=2$ processes)

Effective BSM Hamiltonian for $\Delta F=2$ transitions

The dependence of C on Λ changes depending on the flavour structure.
We can consider different flavour scenarios:

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

- Generic: $C(\Lambda) = \alpha/\Lambda^2$ — $F_i \sim 1$, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_i \sim |F_{SM}|$, arbitrary phase
- MFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_1 \sim |F_{SM}|$, $F_{i\neq 1} \sim 0$, SM phase

α (L_i) is the coupling among NP and SM

- $\alpha \sim 1$ for strongly coupled NP
- $\alpha \sim \alpha_W$ (α_S) in case of loop coupling through weak (strong) interactions

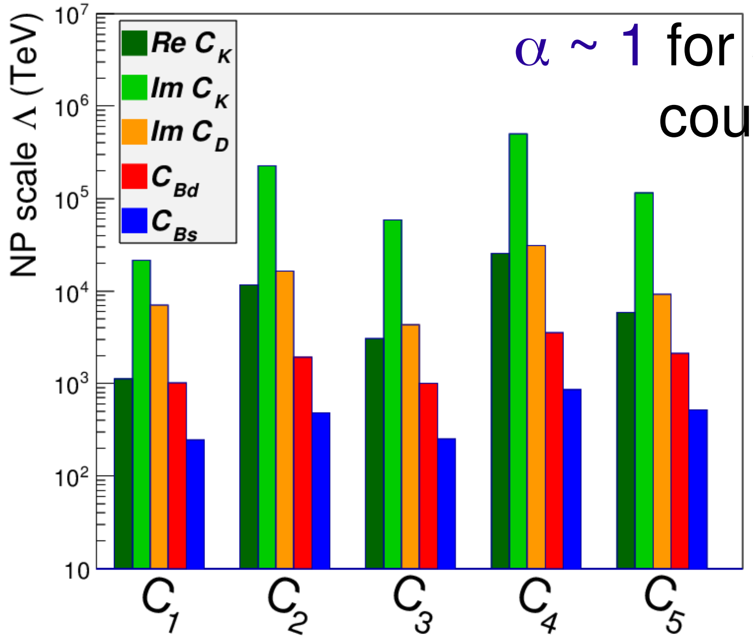
If no NP effect is seen lower bound on NP scale Λ

F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

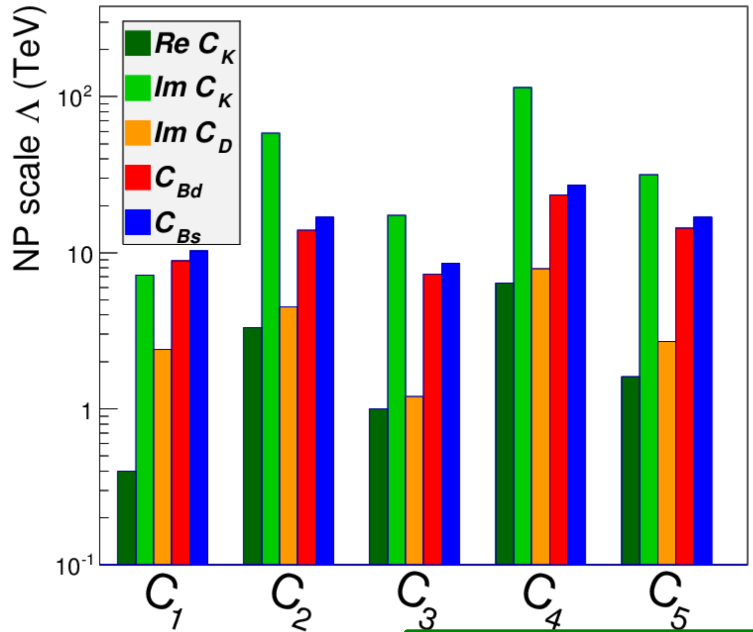
results from the Wilson coefficients

Generic: $C(\Lambda) = \alpha/\Lambda^2$, $F_i \sim 1$, arbitrary phase

NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$, $F_i \sim |F_{SM}|$, arbitrary phase



$\alpha \sim 1$ for strongly coupled NP



Lower bounds on NP scale

$\Lambda > 5.0\ 10^5$ TeV

$\Lambda > 114$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 1.5\ 10^4$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 3.4$ TeV

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

Summary

- Very partial, shallow and simplified vision of flavour physics
- Points to consider to measure a CP violating asymmetry.
  - Need more than one amplitude (more than one Feynman diagram) to have a non-zero CP violation signal.
    - Neutral mesons to measure the weak phase cleanly (usually).
    - Charged mesons to measure direct CP violation. Knowledge of strong phases limits how you can interpret these measurements in terms of the weak phases.
      - Need a model, and many measurements to say anything sensible.
      - Even then you will have a large theoretical uncertainty.
      - The right parameterisation for the experimental fit can be different from the theoretical framework. Keep an open mind.

Flavour physics has the fundamental role to carry on precise measurements and indirect searches that could be more powerful than the direct one in finding our way towards new physics

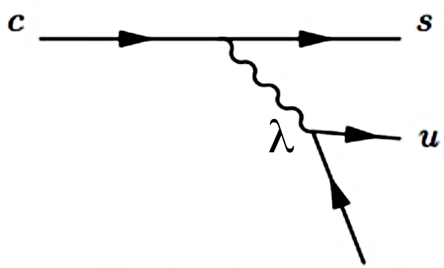
back-up

CP violation in the D system

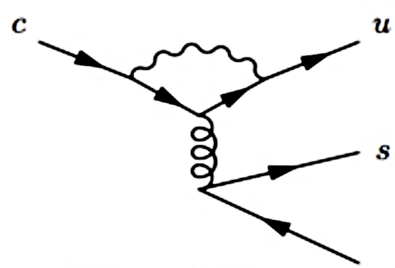
- B factories have measured the D mixing (2007)
- The time-integrated CP asymmetry have contributions from both direct CP violation (in the decays) and indirect CP violation (in the mixing or in interference)
- In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates:
  $\Rightarrow$ predictions of about $O(10^{-3})$ for CPV parameters
- Direct CP violation can be larger in SM:
  it depends on final state (on the specific amplitudes contributing)
  $\Rightarrow$ negligible in Cabibbo-favoured modes
  (SM tree dominates everything)
  $\Rightarrow$ In singly-Cabibbo-suppressed modes:
  up to $O(10^{-4} - 10^{-3})$ plausible
- Both can be enhanced by NP, in principle up to O(%)

Where to look for direct CP violation

- Remember: need (at least) two contributing amplitudes with different strong and weak phases to get CPV.
- **$D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays:**
  - Singly-Cabibbo-suppressed modes with gluonic penguin diagrams
  - Several classes of NP can contribute ... but also non-negligible SM contribution



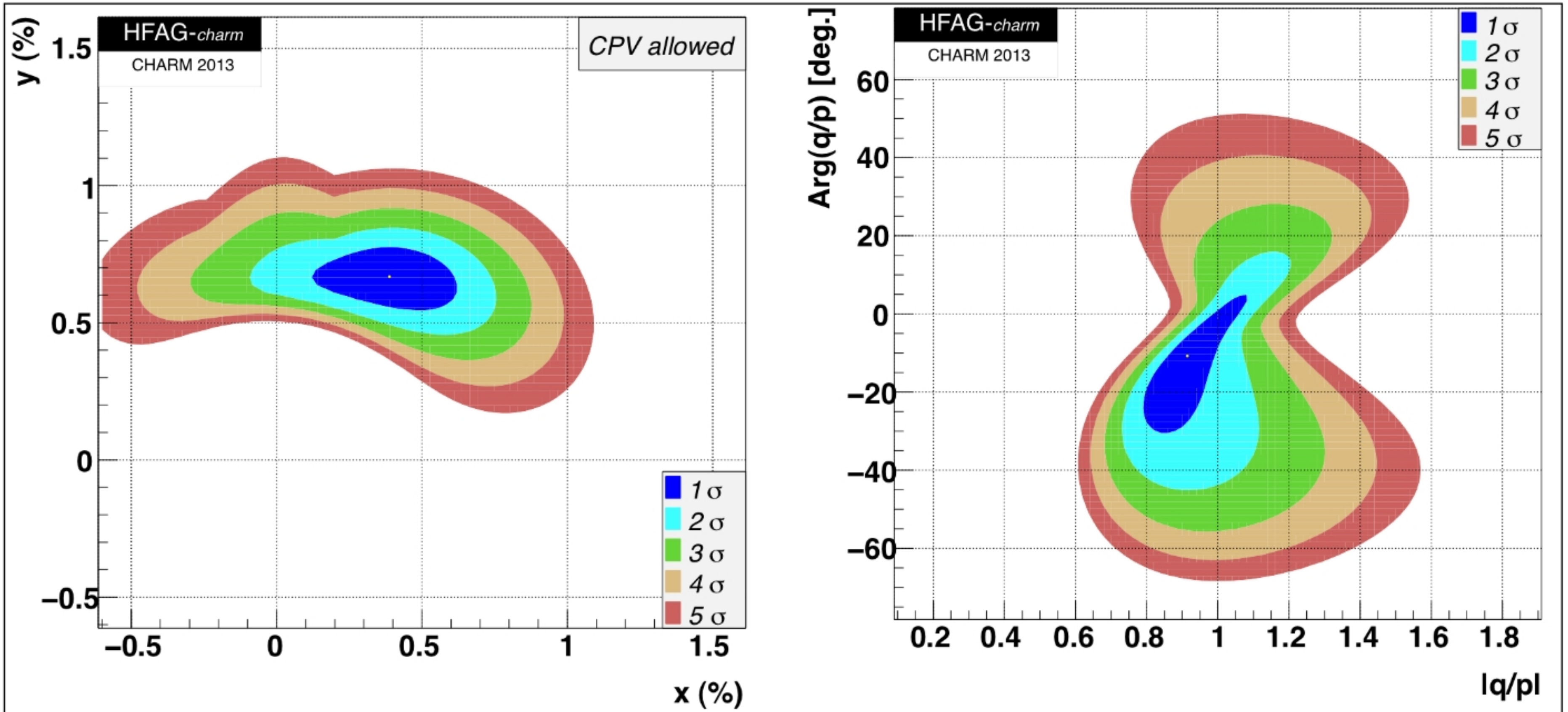
(a) Tree diagram.



(b) Penguin diagram.

No CP violation measured so far

$$\Gamma = \frac{\Gamma_2 + \Gamma_1}{2} \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$



CPV-allowed plot, no mixing (x,y) = (0,0) point: $\Delta\chi^2 > 300$
No CPV (|q/p|, φ) = (1,0) point: $\Delta\chi^2 = 1.479$, *CL = 0.48 , consistent with no CPV*

$\Delta\Gamma_s$ and ϕ_s measurement from $B_s \to J/\psi\phi$

- The time evolution of the meson B_S and $\bar{B}_S$ is described by the superposition of B_H and B_L states, with masses $m_S \pm \Delta m_S/2$ and lifetimes $\Gamma_S \pm \Delta\Gamma_S/2$.

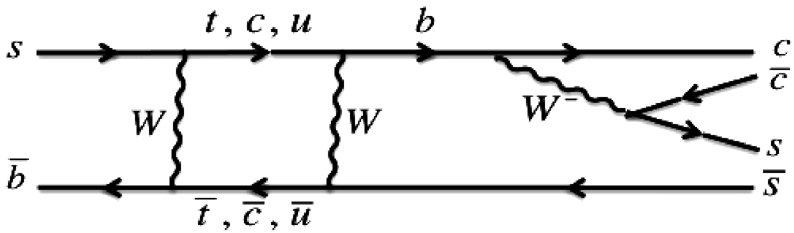
  These states deviate from defined values CP = ± 1, as described in the SM by the mixing phase ϕ_S ($\phi_S = -2\beta_S$),

  SM prediction (fit): $\phi_S = -0.0368 \pm 0.0018$ *rad*

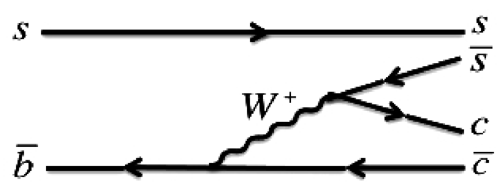
  $\Delta\Gamma_S = 0.082 \pm 0.021$ *ps*$^{-1}$

  New Physics can contribute to ϕ_S, and change the ratio $\Delta\Gamma_S/\Delta m_S$.

- In general, the decay to a final state that is coupled to B_S and/or $\bar{B}_S$, exhibits fast oscillations driven by Δm_S. Interference between amplitudes for both states generates CP violation, and conveys information on ϕ_S .



Decay amplitude with mixing (φ_s)

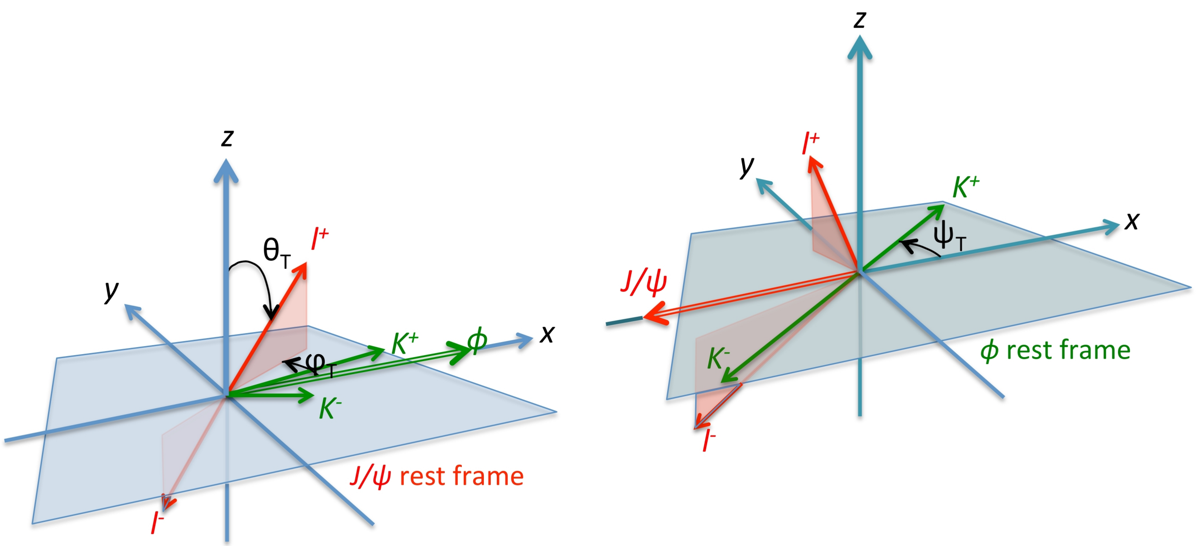


Amplitude with direct decay

If $\bar{B}$/B flavour at production is not determined (not tagged), the fast oscillations cannot be observed, but interference terms remain if the final state is described by a superposition of amplitudes of different CP values.

angular analysis in $B_s \to J/\psi\phi$

- In the decay $\bar{B}_S(B_S) \to J/\psi\phi \to l^+l^- K^+K^-$ different components in the angular-distributions amplitudes correspond to CP = +1 or −1
- The "transversity angles" are used to describe the angular distributions



angular analysis in $B_s \to J/\psi\phi$

- Angular analysis as a function of proper time and b-tagging
- Similar to B_d measurement in $B_d \to J/\psi K^*$
- Additional sensitivity from the $\Delta\Gamma_s$ terms (negligible for B_d)

$$\frac{d^4P(t,\vec{w})}{dtdw} \propto |A_0|^2 T_+ f_1(\vec{w}) + |A_{||}|^2 T_+ f_2(\vec{w}) + |A_\perp|^2 T_- f_3(w) + |A_{||}||A_\perp| U_+ f_4(w) + |A_0||A_{||}|\cos(\delta_{||}) T_+ f_5(w) + |A_0||A_\perp| V_+ f_6(w)$$

$$T_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \eta \sin(2\beta_s)\sin(\Delta m_s t)],\ \eta = +1(-1) \text{ for } P(\bar{P})$$

$$U_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_{||})\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_{||})\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

$$V_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

Dunietz et al.
Phys.Rev.D63:114015,2001

Ambiguities for

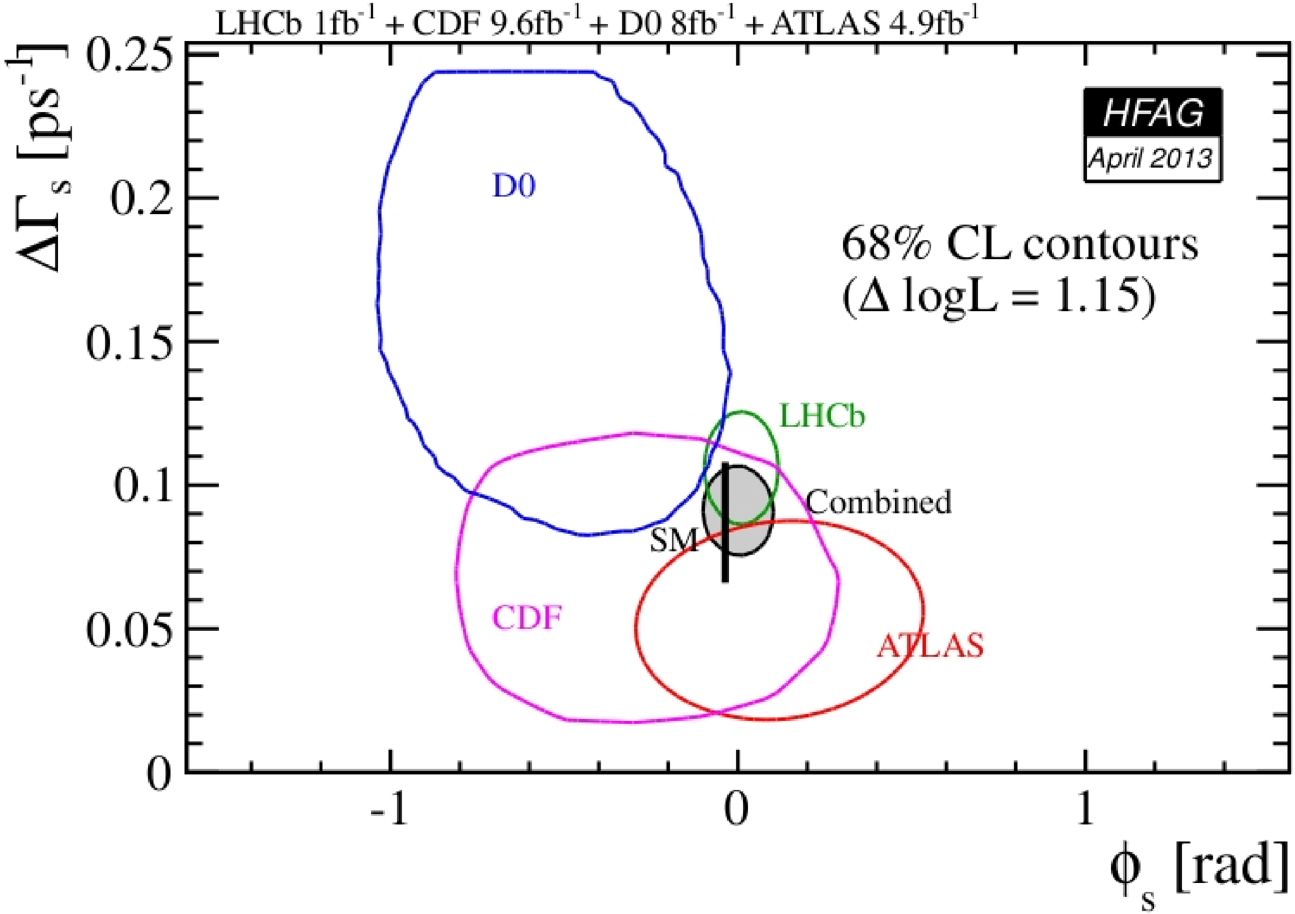
$\phi_s \to \pi - \phi_s$,

$\Delta\Gamma_s \to -\Delta\Gamma_s$,

$\cos(\delta_\perp - \delta_\parallel) \to -\cos(\delta_\perp - \delta_\parallel)$

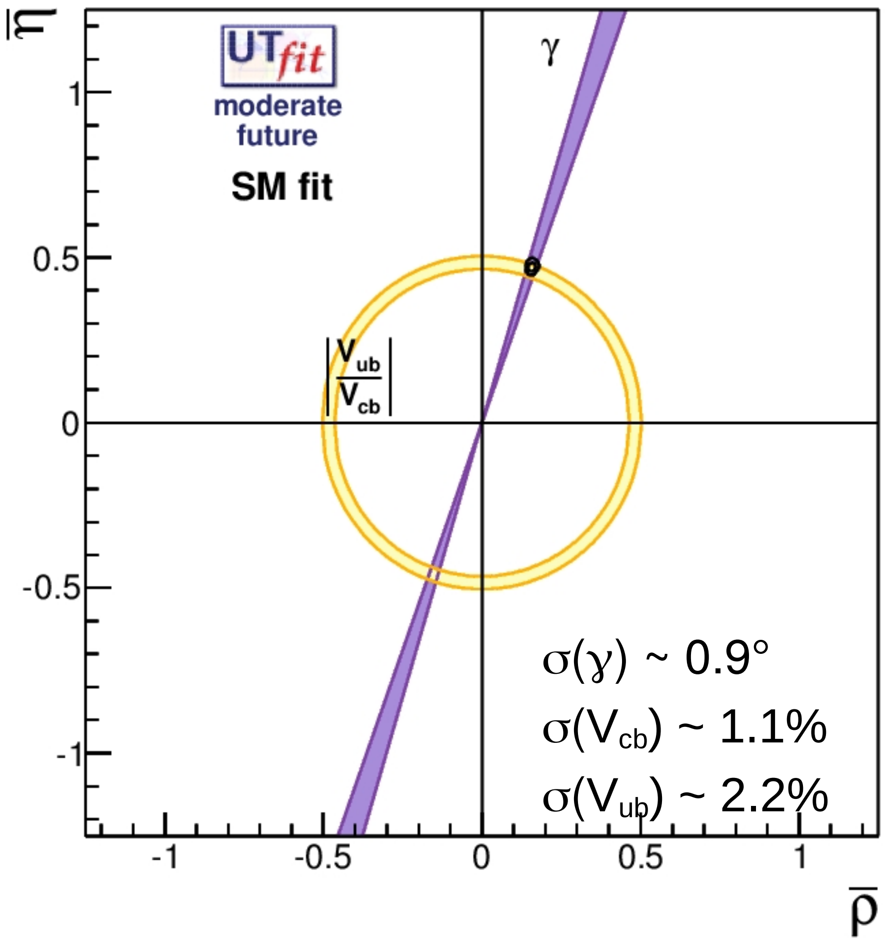
- transversity basis: $W(\theta, \varphi, \psi)$
- θ and φ: direction of the μ^+ from J/ψ decay
- ψ: between the decay planes of J/ψ and ϕ

angular analysis in $B_s \to J/\psi\phi$



Look at the future

errors predicted from
Belle II + LHCb upgrade



$\sigma(\gamma) \sim 0.9°$

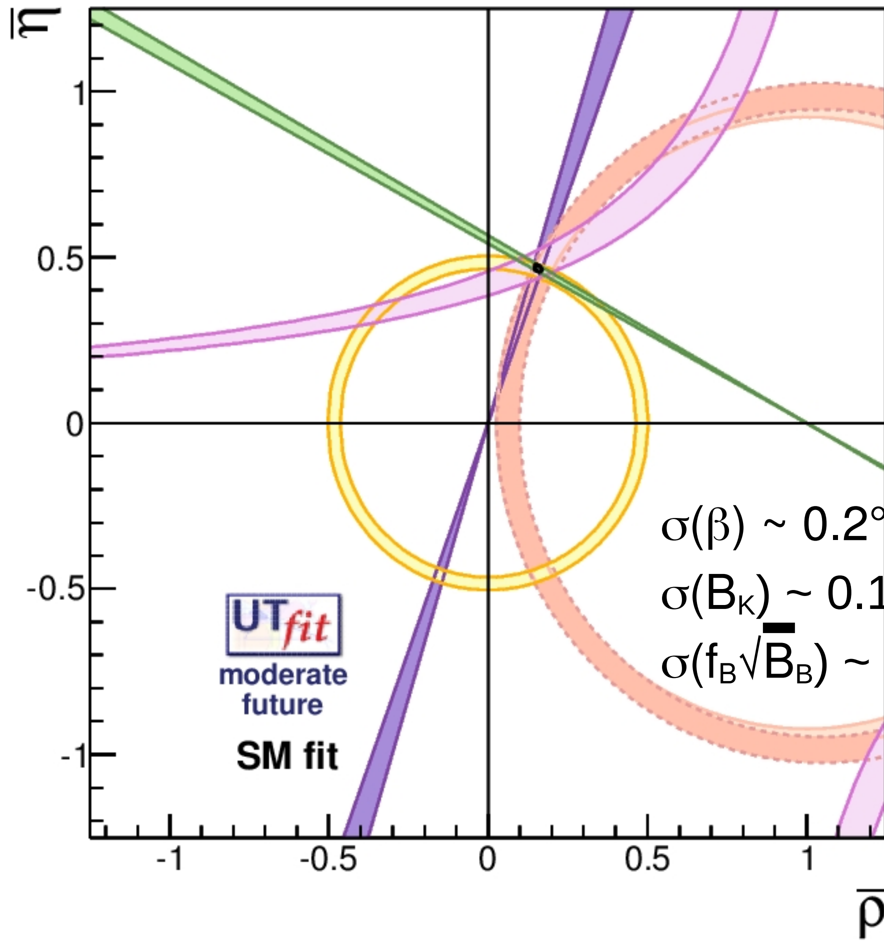
$\sigma(V_{cb}) \sim 1.1\%$

$\sigma(V_{ub}) \sim 2.2\%$

errors from tree-only fit on ρ and η:

σ(ρ) = 0.008 *[currently 0.051]*

σ(η) = 0.010 *[currently 0.050]*



$\sigma(\beta) \sim 0.2°$

$\sigma(B_K) \sim 0.1\%$

$\sigma(f_B\sqrt{B_B}) \sim 0.5\%$

errors from 5-constraint fit on ρ and η:

σ(ρ) = 0.005 *[currently 0.034]*

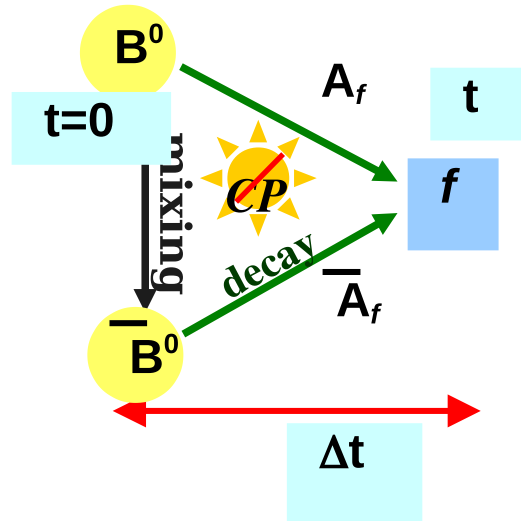
σ(η) = 0.004 *[currently 0.015]*

Summary

- Points to consider to measure a CP violating asymmetry.
  - Need more than one amplitude (more than one Feynman diagram) to have a non-zero CP violation signal.
    - Neutral mesons can be used to measure the weak phase cleanly (usually).
    - Charged mesons can be used to measure direct CP violation. Knowledge of strong phases limits how you can interpret these measurements in terms of the weak phases.
      - Need a model, and many measurements to say anything sensible.
      - Even then you will have a large theoretical uncertainty.
  - You can count the CKM vertex factors in the Feynman diagrams to tell you relative sizes of decays that you expect (This works for tree level processes. You need to consider colour / Zweig supression for more detailed guesses).

CP violation in interference between mixing and decay:

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$



- ◎ decays in final state *f* accessible to both a B or a $\bar{B}$ (*f* is not necessarily a CP eigenstate)
- ◎ if Im$\lambda \neq 0$ then → CP violation

$$\lambda = \frac{q}{p}\frac{A(\bar{B} \to f)}{A(B \to f)} = \frac{V_{td}^* V_{tb}}{V_{td} V_{tb}^*}\frac{\bar{A}}{A} \sim e^{-i2\beta}\frac{\bar{A}}{A}$$

β is the mixing phase

examples

	f	$\mathrm{Arg}(\frac{\bar{A}}{A})$	$\lvert\lambda\rvert$	parameter
mixing	$B^0 \to l\nu X, D^{(*)}\pi(\rho, a_1)$	0	~ 0	ΔM_{B^0}
"sin 2β"	$B^0 \to J/\psi K^0$, ...	0	1	$\sin 2\beta$
"sin 2α"	$B^0 \to \pi\pi, \rho\pi, \pi\pi\pi$	$\sim(-2\gamma)$	~ 1	$\sin 2\alpha$
"$\sin(2\beta+\gamma)$"	$B^0 \to D^{(*)}\pi$	$\sim(-\gamma)$	~ 0.02	$\sin(2\beta+\gamma)$

$B\bar{B}$ pair coherent production

◎ The B^0 and $\bar{B}^0$ mesons from the $\Upsilon(4S)$ are in a coherent L = 1 state:

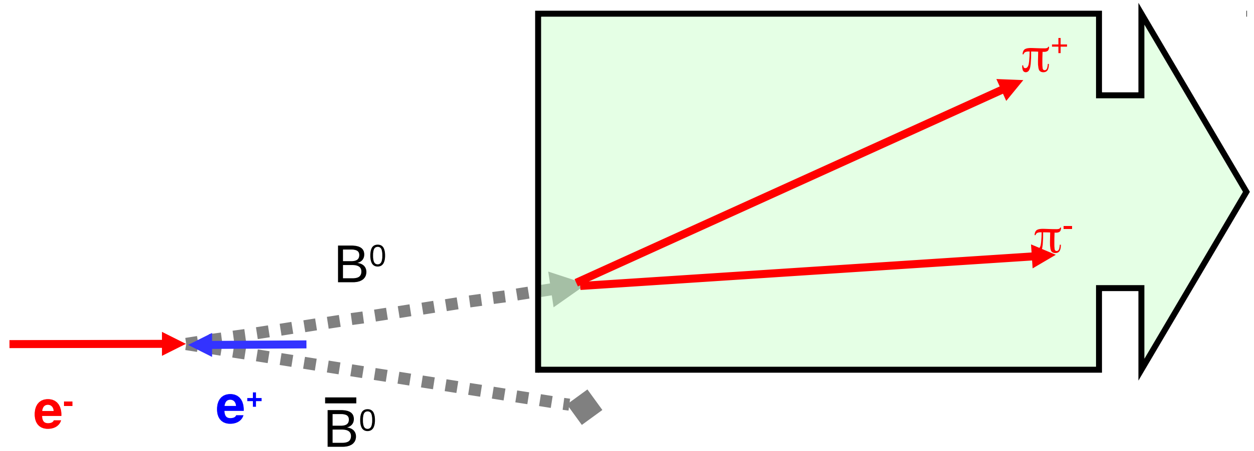
- ◉ The $\Upsilon(4S)$ is a $b\bar{b}$ state with **$J^{PC} = 1^{--}$**.
- ◉ B mesons are scalars (**$J^P = 0^-$**)
  - ⇨ total angular momentum conservation
  - ⇨ the $B\bar{B}$ pair has to be produced in a L = **1 state**.

◎ The $\Upsilon(4S)$ decays strongly so B mesons are produced in the two flavour eigenstates B^0 and $\bar{B}^{0:}$

- ◉ After production, each B evolves in time, but **in phase** so that at any time there is always exactly one B^0 and one $\bar{B}^0$ present, at least until one particle decays:
  - ⇨ If at a given time t one B could oscillate independently from the other, they could become a state made up of two identical mesons: but the L = 1 state is anti-symmetric, while a system of **two identical mesons (bosons!)** must be completely symmetric for the two particle exchange.

◎ Once one B decays the other continues to evolve, and so it is possible to have events with **two B or two $\bar{B}$ decays**.

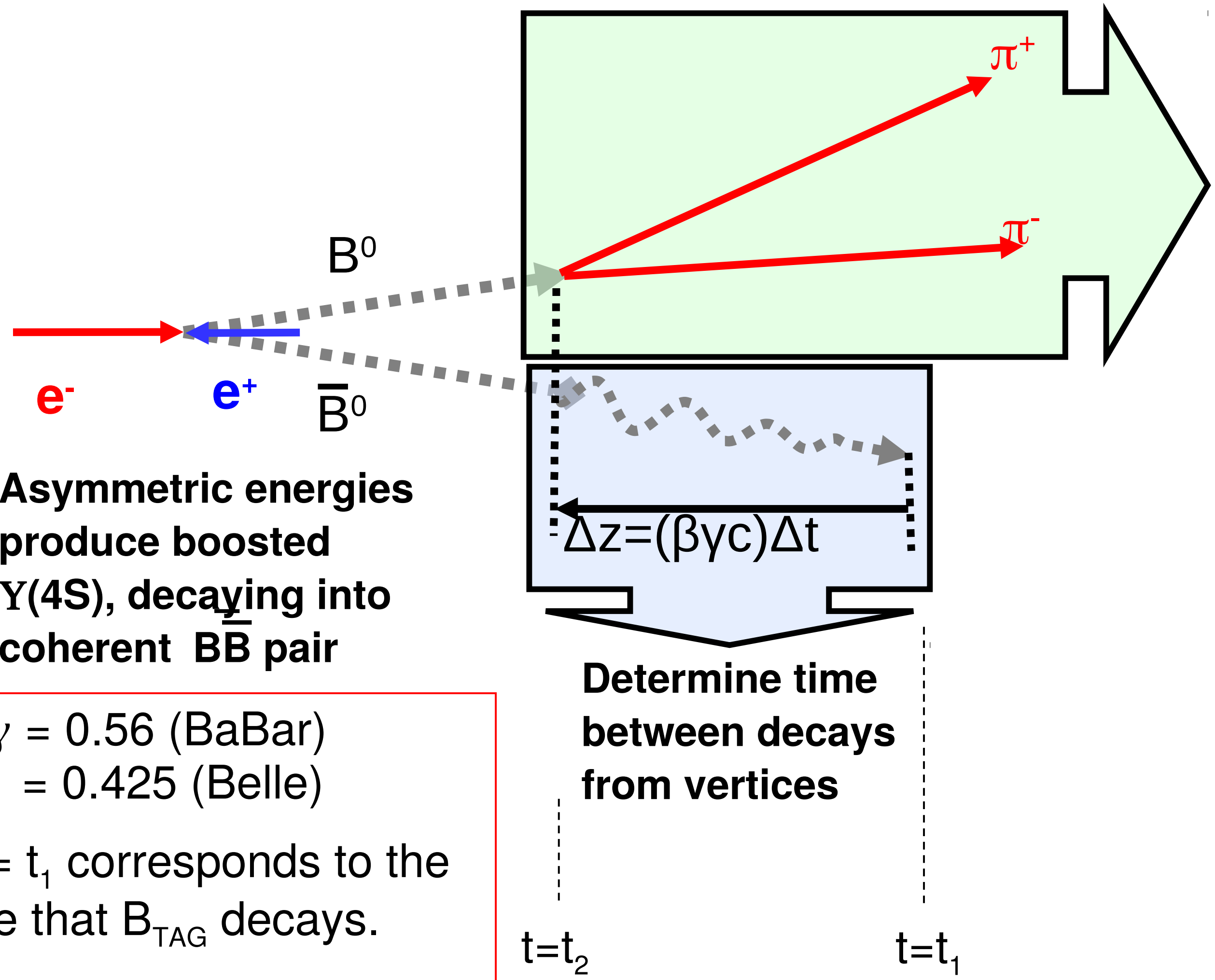
Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

Measuring Δt



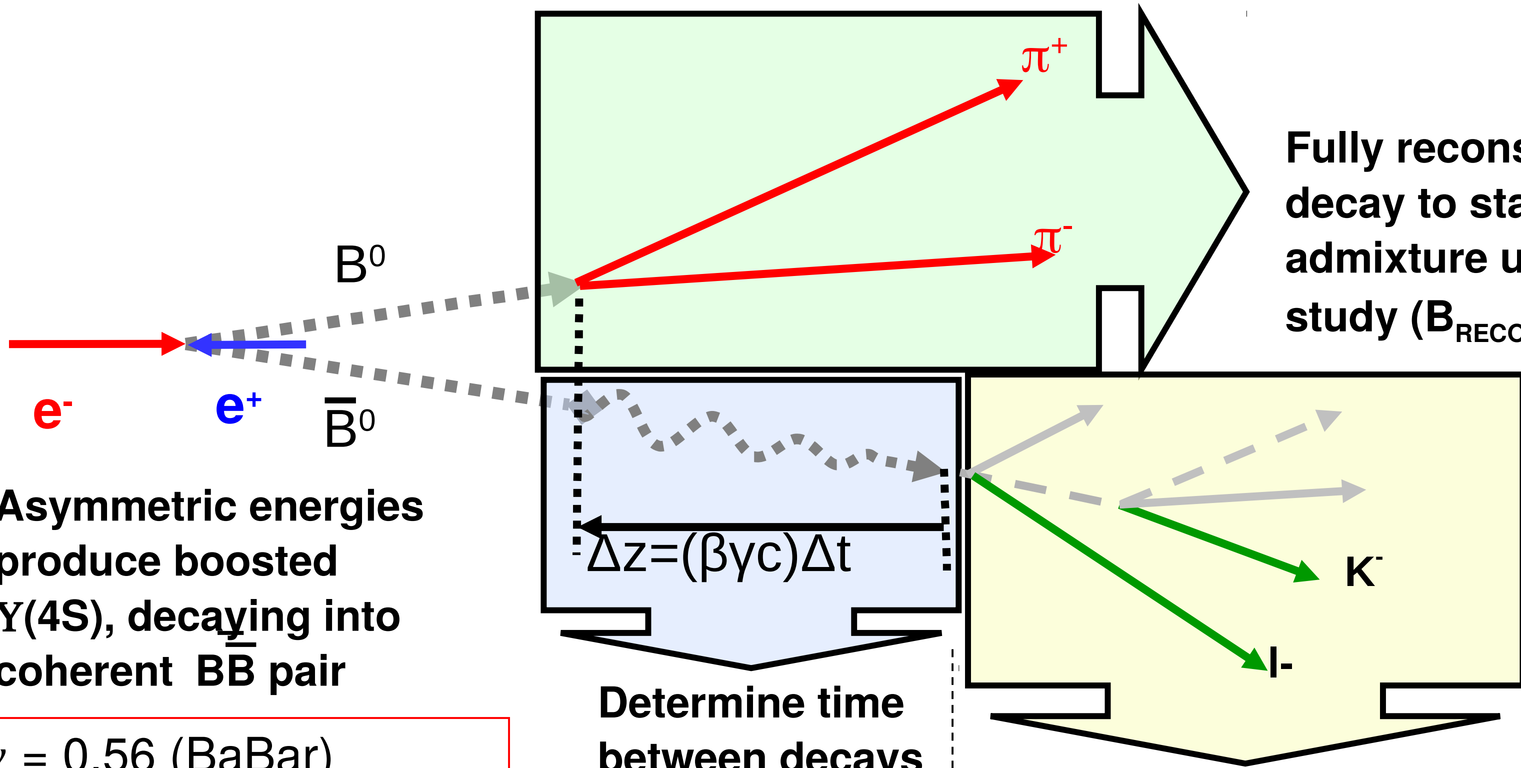
Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted ϒ(4S), decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted $\Upsilon(4S)$, decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

Determine flavour and vertex position of other B decay (B_{TAG})

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

$t=t_2$ $t=t_1$

⇨ Then fit the Δt distribution to obtain the amplitude of sine and cosine terms.