# Prospects for the determination of the CKM angle γ from Dalitz plot analysis of $B^\pm \to DK^\pm\pi^0$ decays

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# Importance of γ from B→DK(π)

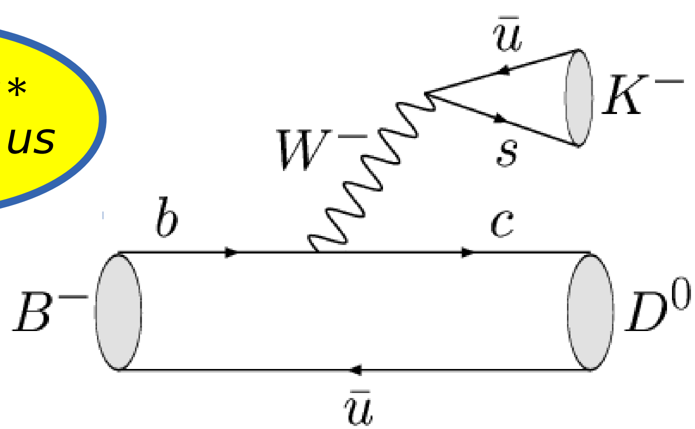
- γ plays a unique role in flavour physics

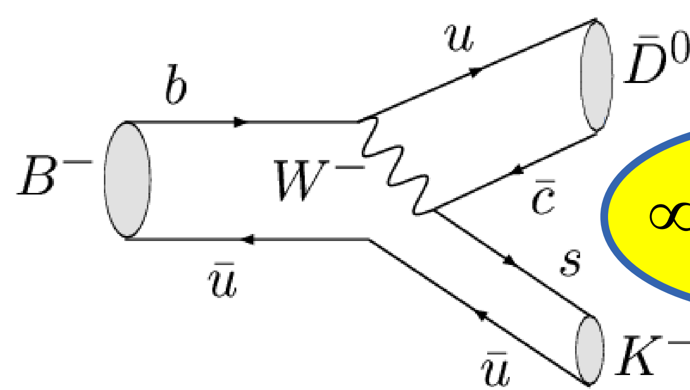
the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

$\propto V_{cb} V_{us}^{*}$



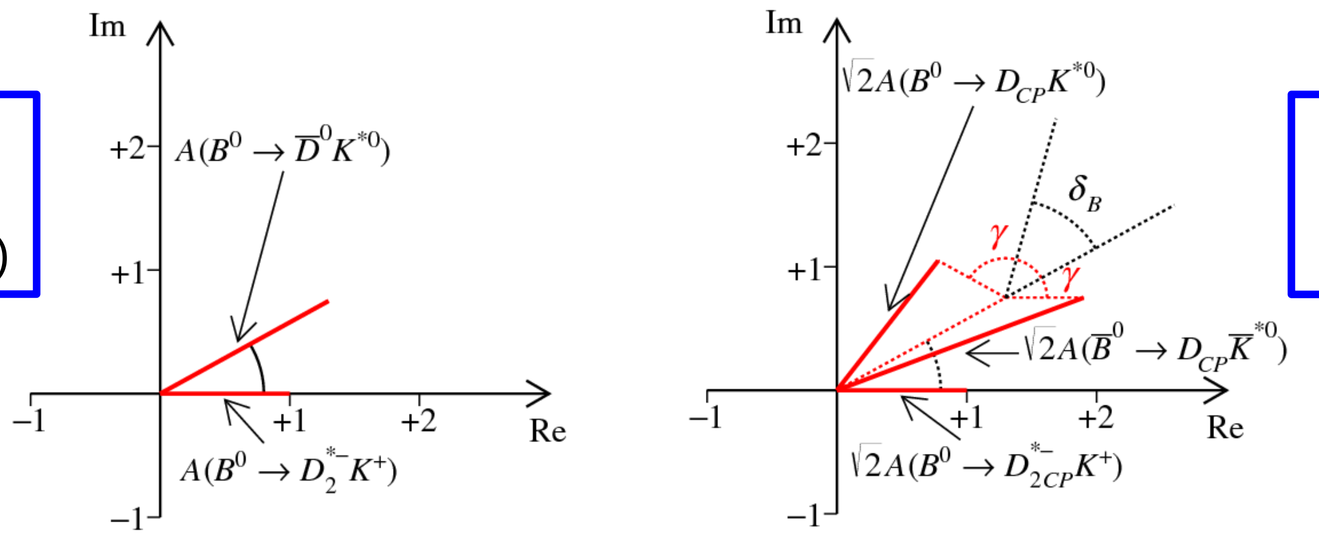

$\propto V_{ub} V_{cs}^{*}$

Variants use different B or D decays
require a final state common to both $D^0$ and $\overline{D}^0$

# Power of Dalitz plot analyses

- Interference between resonances in a Dalitz plot provides additional sensitivity to relative phases
  - avoid Q2B assumption that introduces new hadronic parameters
- Example: $B^0 \to DK^+\pi^-$ (PR D79 (2009) 051301, D80 (2009) 092002)

$D \to K\pi$
($b \to c$ amplitude only)




$D \to KK, \pi\pi$
($b \to c$ and $b \to u$ amplitudes)

Key point is that $D_2^{*-}K^+$ amplitude is flavour-tagged and therefore identical in all final states

# γ from $B^0 \to DK^+\pi^-$

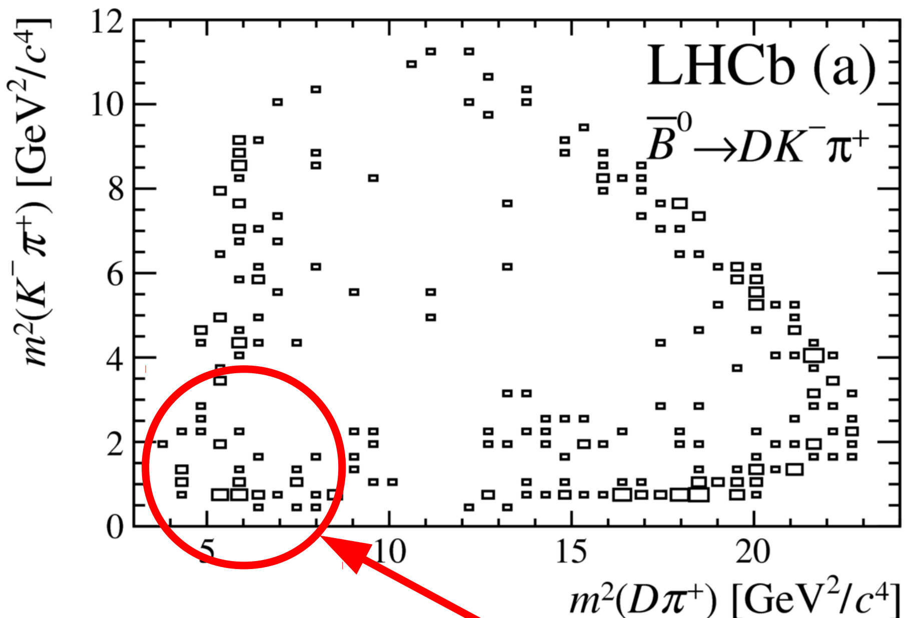
PR D92 (2015) 012012, PR D93 (2016) 112018

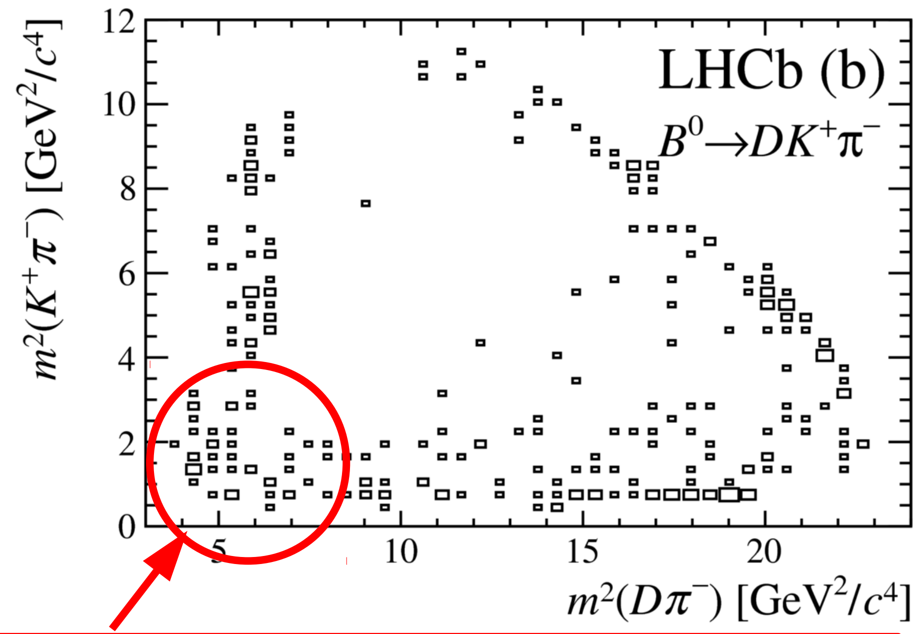
This method recently implemented by LHCb

[technical detail: simultaneous fit using Laura++ (arXiv:1603.00752) with *jFit* method (arXiv:1409.5080)]

Good sensitivity to CP violation parameters in $B^0 \to DK^{*0}$

Complementary to results with $B^0 \to DK^{*0}$, $D \to K_S\pi\pi$




$D \to KK, \pi\pi$

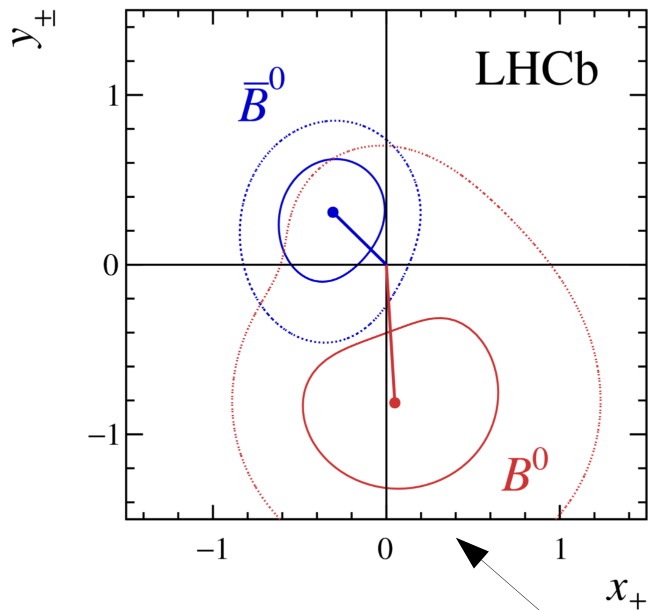
Interference effects in the $D_2^{*-}$–$K^{*0}$ overlap region enhance sensitivity to γ

# γ from $B^0 \to DK^{*0}$

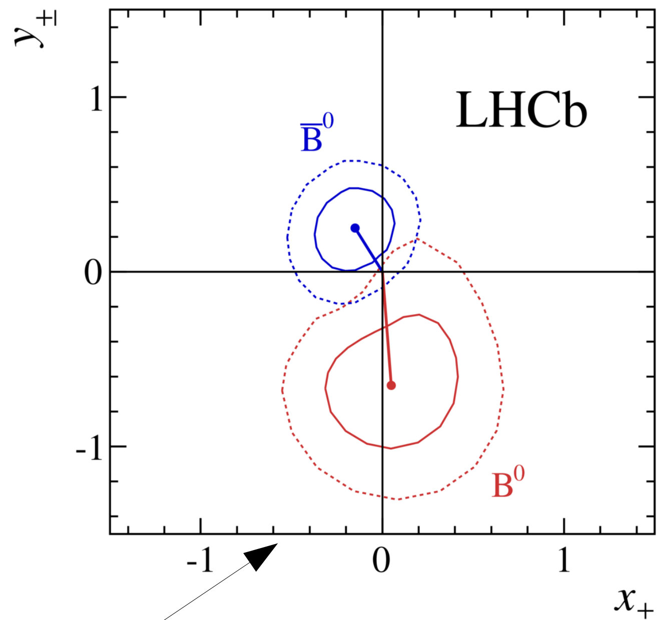
JHEP 06 (2016) 131

arXiv:1605.01082

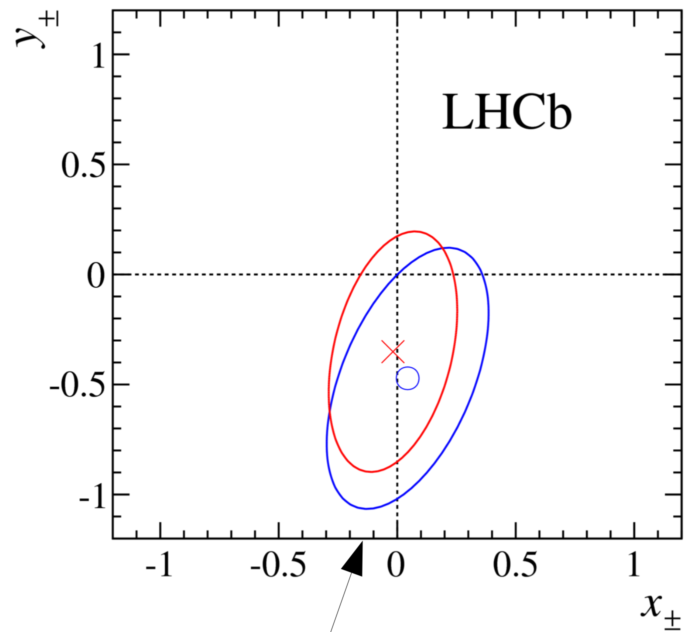
PR D93 (2016) 112018




model-independent




model-dependent




$B^0 \to DK^{*0}$ Q2B
$D \to K_S\pi\pi$

$B^0 \to DK\pi$ DP analysis
$D \to KK,\pi\pi$

Comparison of results in terms of $x_\pm = r_B\cos(\delta_B \pm \gamma)$, $y_\pm = r_B\sin(\delta_B \pm \gamma)$

RED: $(x_+,y_+)$, BLUE $(x_-,y_-)$

# Apply similar ideas to $B^+ \rightarrow DK^+\pi^0$

- Challenge:
  - ($D\pi$) resonances now not flavour tagged → require more complicated formalism compared to $B^0 \rightarrow DK^+\pi^-$
- Possible benefit:
  - More interference between $b\rightarrow u$ & $b\rightarrow c$ amplitudes → more sensitivity to γ
- Extra information:
  - Relative magnitude ($r_B$) of $b\rightarrow u$ & $b\rightarrow c$ amplitudes in ($D\pi$) resonances can be known from $B^+\rightarrow D^+K^+\pi^-$ and $B^+\rightarrow D^-K^+\pi^+$ decays (N. Sinha PR D70 (2004) 097501)
- Previous work:
  - Same channel investigated by Aleksan, Petersen & Soffer (PR D67 (2003) 096002), but with assumptions that are now known to be too simplistic

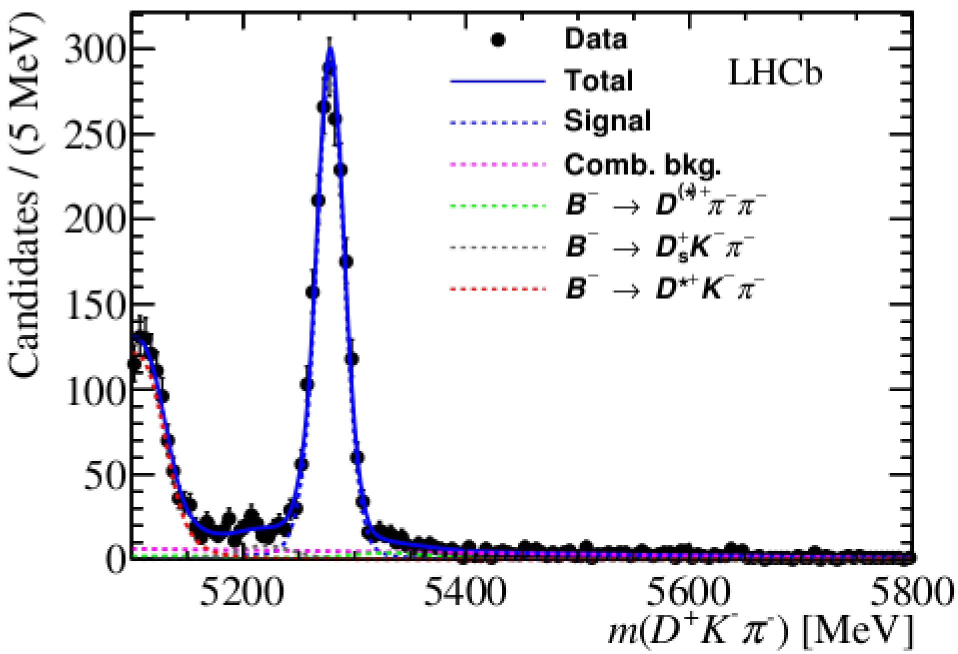
Requires a careful study

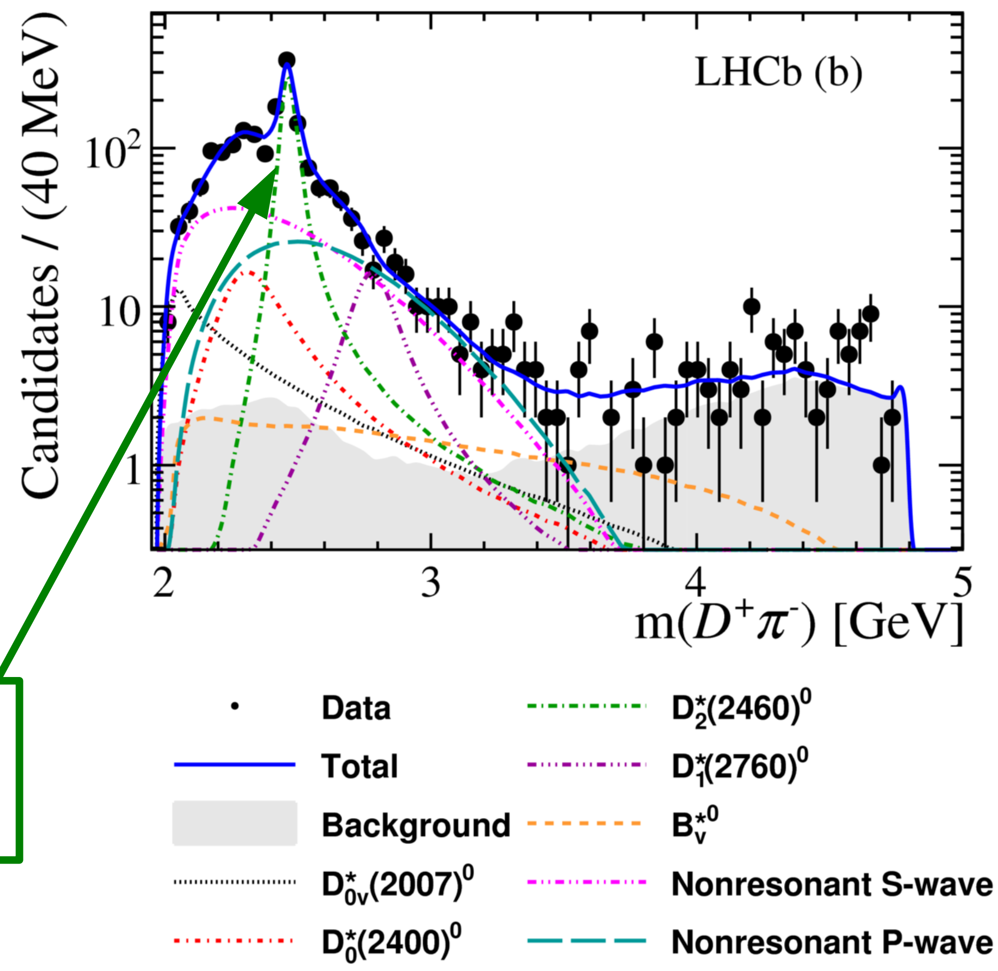
- Will also be experimentally challenging, but leave such issues aside for now

# $B^+ \to D^+K^+\pi^-$ and $B^+ \to D^-K^+\pi^+$ decays

PR D91 (2015) 092002, PR D93 (2016) 051101

- Recent first observations of both modes by LHCb




Large $D_2^*(2460)^0$ component in favoured mode

Tim Gershon
γ from $B^\pm \to DK^\pm\pi^0$

# $B^+ \to D^+K^+\pi^-$ and $B^+ \to D^-K^+\pi^+$ decays

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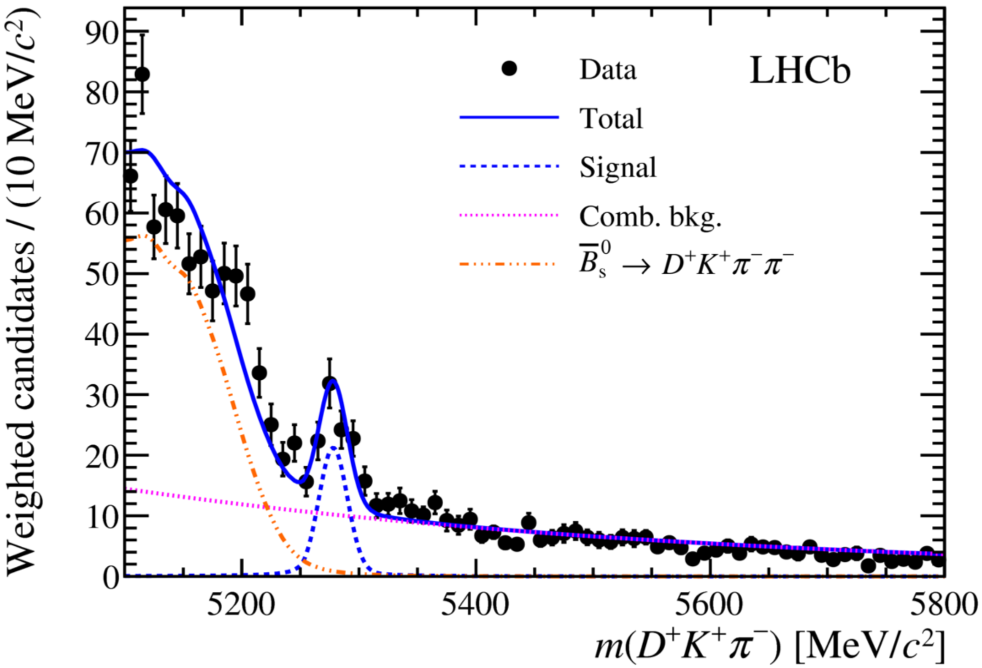


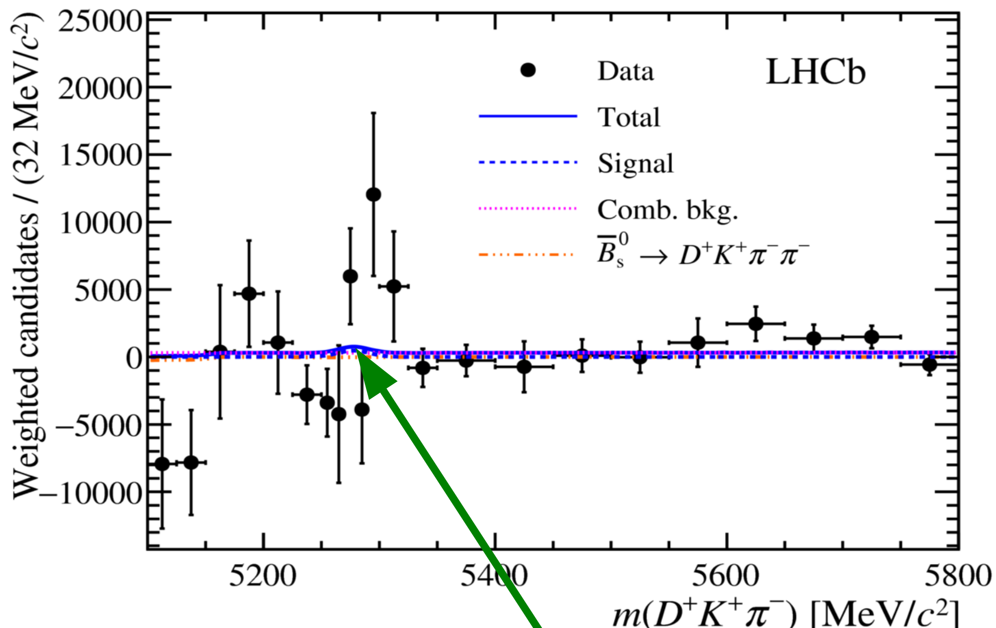


$r_B(D_2^*(2460)^0K^+)^2 = 0.04 \pm 0.18$ (stat) $\pm 0.06$ (syst)
$< 0.027$ (0.033) @ 90 (95) % CL

Angular-moment-weighted data show no $D_2^*(2460)^0$ component in suppressed mode

# Toy model for $B^+ \to DK^+\pi^0$

Resonances possible in all three two-body combinations
Consider $K^*(892)^+$, $D_2^*(2460)^0$ & $D_{s1}^*(2700)^+$ as examples

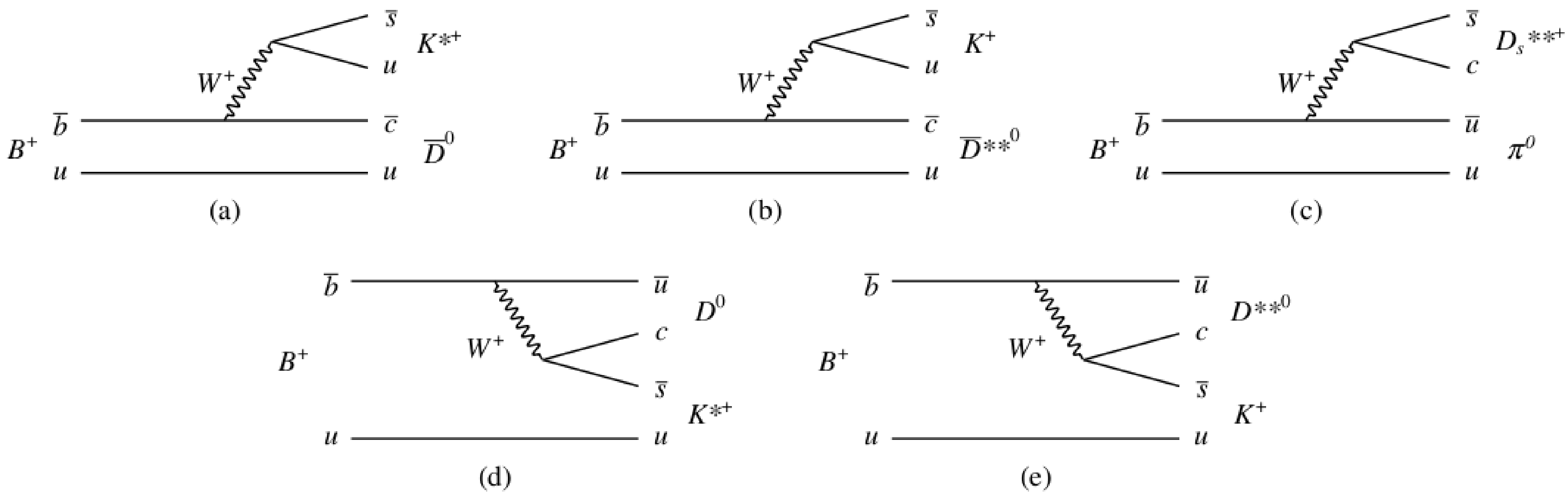


Figure 1: Diagrams for the contributions to $B^\pm \to DK^\pm\pi^0$ decays from (a,d) $K^\pm\pi^0$, (b,e) $D\pi^0$, and (c) $DK^\pm$ resonances. Note that (a,b) correspond to $b \to c$ transitions while (c,d,e) are $b \to u$ transitions, and that (a,b,c) are colour-allowed while (d,e) are colour-suppressed.

# Full expressions

Table 1: Relative amplitudes for $D_2^*(2460)$, $K^*(892)$ and $D_{s1}^*(2700)$ components in (top) $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ and (bottom) $B^\pm \to DK^\pm\pi^0$ Dalitz plots, expressed in terms of $\gamma$ and hadronic parameters. The + and − signs correspond to $B$ (*i.e.* $B^+$ and $B^0$) and $\overline{B}$ ($B^-$ and $\overline{B}^0$) decays respectively. Normalisation factors that are common to all expressions on each row have been dropped.

| | $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ | | |
|---|---|---|---|
| | $D_2^*(2460)^\mp$ | $\overset{(-)}{K}{}^*(892)^0$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific ($b \to c$) | 1 | $c^{K^*}$ | 0 |
| Flavour specific ($b \to u$) | 0 | $c^{K^*} r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | 1 | $c^{K^*}\left(1 + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | 1 | $c^{K^*}\left(1 - r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | 1 | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| | $B^\pm \to DK^\pm\pi^0$ | | |
| | $D_2^*(2460)$ | $K^*(892)^\pm$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific ($b \to c$) | 1 | $c^{K^*}$ | 0 |
| Flavour specific ($b \to u$) | $r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*} r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | $1 + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | $1 - r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(1 - r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | $1 + r_B^{D^{**}} r_D \exp\left[i(\delta_B^{D^{**}} - \delta_D \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right] + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

# Full expressions

Table 1: Relative amplitudes for $D_2^*(2460)$, $K^*(892)$ and $D_{s1}^*(2700)$ components in (top) $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ and (bottom) $B^\pm \to DK^\pm\pi^0$ Dalitz plots, expressed in terms of $\gamma$ and hadronic parameters. The + and − signs correspond to $B$ (*i.e.* $B^+$ and $B^0$) and $\overline{B}$ ($B^-$ and $\overline{B}^0$) decays respectively. Normalisation factors that are common to all expressions on each row have been dropped.

| $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ | | | |
|---|---|---|---|
| | $D_2^*(2460)^\mp$ | $\overset{(-)}{K}{}^*(892)^0$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific ($b \to c$) | 1 | $c^{K^*}$ | 0 |
| Flavour specific ($b \to u$) | 0 | $c^{K^*} r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | 1 | $c^{K^*}\left(1 + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | 1 | $c^{K^*}\left(1 - r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | 1 | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

For $B^0 \to DK^+\pi^-$ sufficient to determine $K^{*0}$ amplitude relative to $D_2^*(2460)$ in flavour-specific and CP ($B$ & $\overline{B}$) modes only

6 observables & 5 unknowns

# Full expressions

Table 1: Relative amplitudes for $D_2^*(2460)$, $K^*(892)$ and $D_{s1}^*(2700)$ components in (top) $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ and (bottom) $B^\pm \to DK^\pm\pi^0$ Dalitz plots, expressed in terms of $\gamma$ and hadronic parameters. The $+$ and $-$ signs correspond to $B$ (*i.e.* $B^+$ and $B^0$) and $\overline{B}$ ($B^-$ and $\overline{B}^0$) decays respectively. Normalisation factors that are common to all expressions on each row have been dropped.

For $B^+ \to DK^+\pi^0$ same 6 observables depend on 7 unknowns

$\to$ at minimum must allow for CP violation in $B^+ \to D_{2\,CP}^*K^+$

can also impose constraint on $r_B(D_2^*(2460)^0K^+)^2$

| | $D_2^*(2460)$ | $K^*(892)^\pm$ | $D_{s1}^*(2700)^\pm$ |
|---|---|---|---|
| Flavour specific ($b \to c$) | $1$ | $c^{K^*}$ | $0$ |
| Flavour specific ($b \to u$) | $r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*} r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | $1 + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | $1 - r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(1 - r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | $1 + r_B^{D^{**}} r_D \exp\left[i(\delta_B^{D^{**}} - \delta_D \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right] + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

# Full expressions

Use of $(x_\pm + iy_\pm)$ as statistically well-behaved fit variables less straightforward

| $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ | | | |
|---|---|---|---|
| | $D_2^*(2460)^\mp$ | $\overset{(-)}{K}{}^*(892)^0$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific $(b \to c)$ | $1$ | $c^{K^*}$ | $0$ |
| Flavour specific $(b \to u)$ | $0$ | | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | $1$ | $c^{K^*}(1 + (x_\pm + iy_\pm))$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | $1$ | | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | $1$ | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

| $B^\pm \to DK^\pm\pi^0$ | | | |
|---|---|---|---|
| | $D_2^*(2460)$ | $K^*(892)^\pm$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific $(b \to c)$ | $1$ | $c^{K^*}$ | $0$ |
| Flavour specific $(b \to u)$ | | | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | $(1 + (x^{D^{**}}_\pm + iy^{D^{**}}_\pm))$ | $c^{K^*}(1 + (x^{K^*}_\pm + iy^{K^*}_\pm))$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | | | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | $1 + r_B^{D^{**}} r_D \exp\left[i(\delta_B^{D^{**}} - \delta_D \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right] + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

Relative K*/D** amplitude however has simple replacement to 1st order in $r_B^{D^{**}}$

$$x_\pm + iy_\pm \rightarrow (x^{K^*}_\pm - x^{D^{**}}_\pm) + i(y^{K^*}_\pm - y^{D^{**}}_\pm)$$

# Full expressions

Table 1: Relative amplitudes for $D_2^*(2460)$, $K^*(892)$ and $D_{s1}^*(2700)$ components in (top) $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ and (bottom) $B^\pm \to DK^\pm\pi^0$ Dalitz plots, expressed in terms of $\gamma$ and hadronic parameters. The + and − signs correspond to $B$ (*i.e.* $B^+$ and $B^0$) and $\overline{B}$ ($B^-$ and $\overline{B}^0$) decays respectively. Normalisation factors that are common to all expressions on each row have been dropped.

| $\overset{(-)}{B}{}^0 \to DK^\pm\pi^\mp$ | | | |
|---|---|---|---|
| | $D_2^*(2460)^\mp$ | $\overset{(-)}{K}{}^*(892)^0$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific ($b \to c$) | $1$ | $c^{K^*}$ | $0$ |
| Flavour specific ($b \to u$) | $0$ | $c^{K^*} r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | $1$ | $c^{K^*}\left(1 + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | $1$ | $c^{K^*}\left(1 - r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | $1$ | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

| $B^\pm \to DK^\pm\pi^0$ | | | |
|---|---|---|---|
| | $D_2^*(2460)$ | $K^*(892)^\pm$ | $D_{s1}^*(2700)^\pm$ |
| Flavour specific ($b \to c$) | $1$ | $c^{K^*}$ | $0$ |
| Flavour specific ($b \to u$) | $r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*} r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-even | $1 + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| $CP$-odd | $1 - r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(1 - r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $-c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |
| ADS-favoured | $1 + r_B^{D^{**}} r_D \exp\left[i(\delta_B^{D^{**}} - \delta_D \pm \gamma)\right]$ | $c^{K^*}\left(1 + r_B^{K^*} r_D \exp\left[i(\delta_B^{K^*} - \delta_D \pm \gamma)\right]\right)$ | $r_D\, c^{D_s^{**}} \exp\left[i(-\delta_D \pm \gamma)\right]$ |
| ADS-suppressed | $r_D \exp\left[-i\delta_D\right] + r_B^{D^{**}} \exp\left[i(\delta_B^{D^{**}} \pm \gamma)\right]$ | $c^{K^*}\left(r_D \exp\left[-i\delta_D\right] + r_B^{K^*} \exp\left[i(\delta_B^{K^*} \pm \gamma)\right]\right)$ | $c^{D_s^{**}} \exp\left[\pm i\gamma\right]$ |

In both cases can gain from including ADS-suppressed decays
($r_D$ and $\delta_D$ constrained from external measurements)

# Summary

- $B^+ \to DK^+\pi^0$ provides interesting possibilities to measure CKM angle $\gamma$
  - already used by B factories under $B^+ \to DK^*(892)^+$ Q2B approximation
  - future precise measurements will require correct handling of DP interference effects
- Hadronic parameters related to $b \to u$ contribution in $B^+ \to (D\pi^0)_{D^*}K^+$ decays complicate matters compared to $B^0 \to DK^+\pi^-$ DP analysis
  - not considered in detail in previous work on this mode
  - more observables needed, but enough are available
- Detailed sensitivity study in progress
  - different strategies for fit under evaluation