Time-dependent γ measurements at *BABAR*

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BABAR Collaboration

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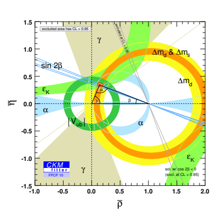
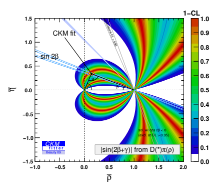
Over-constraining the UT angle γ



$\rho - \eta$ **from global CKM fit**



$\rho - \eta$ **from sin$(2\beta + \gamma)$**

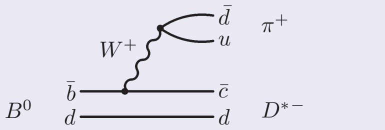
- **Test the SM, look for new physics, check for consistency with indirect, high statistics measurements**
  - Most precise measurement of γ from CKM fit $(67.2 \pm 3.9)^\circ$(CKMfitter), $(67.3 \pm 4.8)^\circ$(UTfit) Error $\approx$ 6 – 7%
  - Direct measurements: $(71^{+21}_{-25})^\circ$, Error $\approx$ 35%
- **Extract γ from sin$(2\beta + \gamma)$ with TD analyses of $B^0\overline{B}^0$**
  - Interference between V_{ub}, V_{cb} from relative weak phase $e^{i\gamma}$
  - 2β from $B^0\overline{B}^0$ mixing
- Why?
  - Theoretically clean compared to time integrated methods
  - Tree level only - no penguin contributions.
  - Purity of the $D^{(*)}\pi$ modes
  - Possibility of large asymmetries in $B^0 \to D^{0(*)}K^0_S$ modes
- **But γ is the most difficult angle to measure directly**
  - Smaller branching ratios & reconstruction efficiencies
  - CP violating effect in each mode depends on the (small) ratio of magnitudes of V_{ub} : V_{cb}

Summary of *BaBar* results of γ measurement via TD methods

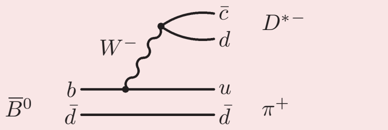
- ***Measurement of Time-Dependent CP-Violating Asymmetries and Constraints on*** $\sin(2\beta+\gamma)$ ***with Partial Reconstruction of*** $B \to D^{*\mp}\pi^{\pm}$ ***Decays***
  Phys.Rev.D **71**, 112003 (2005)
  232×10^6 $B\overline{B}$ pairs
- ***Measurement of time-dependent CP asymmetries in*** $B^0 \to D^{(*)\pm}\pi^{\mp}$ ***and*** $B^0 \to D^{\pm}\rho^{\mp}$ ***decays***
  Phys.Rev.D **73**, 111101 (2006)
  232×10^6 $B\overline{B}$ pairs
- ***Time-dependent Dalitz plot analysis of*** $B^0 \to D^{\mp}K^0\pi^{\pm}$ ***decays.***
  Phys.Rev.D **77**, 071102 (2008)
  347×10^6 $B\overline{B}$ pairs
- **Measurement of** $\overline{B}^0 \to D^{(*)0}\overline{K}^{(*)0}$ **Branching Fraction**
  Phys.Rev.D **74**, 031101 (2006)
  226×10^6 $B\overline{B}$ pairs

Introduction to $B \to D^{(*)\mp}\pi^{\pm}/\rho^{\pm}$ decays

Favored: $V_{cb} \approx 0.04$



Suppressed: $V_{ub} \approx 0.004$

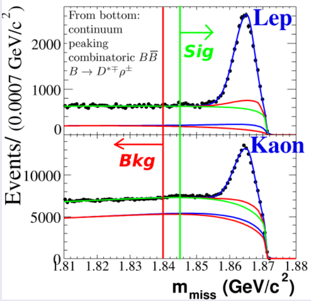


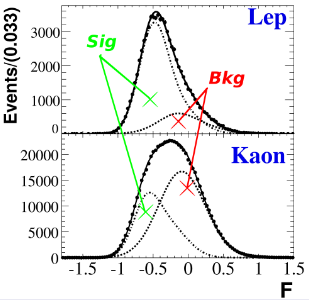
The TD decay rate

- $\frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 - B_{tag}(a + B_{tag}D_{tag}b + D_{tag}c)\sin(\Delta m \Delta t) + B_{tag}D_{tag}\cos(\Delta m \Delta t)]$
- $B_{tag} = +1(-1)$ for $B^{0}(\overline{B}^{0})$, $D_{tag} = +1(-1)$ for $D^{(*)+}(D^{(*)-})$
- **CP parameters**
  $a = 2r\sin(2\beta + \gamma)\cos\delta$
  $b = 2r'\sin(2\beta + \gamma)\cos\delta'$
  $c = 2\cos(2\beta + \gamma)(r\sin\delta - r'\sin\delta')$
  $'$ refers to CKM suppressed decays of the tagging B; $r'_{lepton} = 0,\ r'_{kaon} \approx r$
- All CP parameters $\propto r = |\frac{A_{suppressed}}{A_{favored}}| \to |\frac{V_{ub}V^{*}_{cd}}{V^{*}_{cb}V^{*}_{ud}}| \approx 0.02 \Rightarrow$ very small & difficult to measure

TD analysis of partially reconstructed $B \to D^{*\mp}\pi^{\pm}$

Phys.Rev.D **71**, 112003 (2005)





Partial reconstruction

- Why? Large single mode signal samples, but more bkg
- Only $B \to D^*\pi_h$, $D^* \to D^0\pi_s$ reconstructed
- Hard pion π_h from B, soft pion π_s from $D^{*\pm}$ used
- Missing mass: Ave.($\sqrt{|p_D(\cos(\phi))|^2}$) of min,max over ϕ
  - $\phi \to$ unknown dir. of B^0 (azimuthally about π_h)
  - Peaks @ D^0 mass
  - Resolution ≈ 3 MeV/c^2

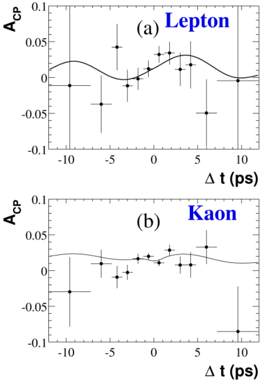
Procedure

- Extract sig, bkg fractions & PDF params from 2D MLL fit to $m_{miss} \times \mathcal{F}$ (Fisher Discriminant)
  - $\mathrm{N}^{sig}_{lep} = 18710 \pm 270$, $\mathrm{N}^{sig}_{kaon} = 70580 \pm 660$
  - Fix parameters for the next step
- Extract Δt bkg params from MLL fit to $m_{miss} \times \mathcal{F} \times \Delta t$ in the sideband $1.81 < m_{miss} < 1.84$ GeV/c^2 and fix
- Extract Δt sig params from MLL fit to $m_{miss} \times \mathcal{F} \times \Delta t$ in $m_{miss} > 1.845$ GeV/c^2

Results: partially reconstructed $B \to D^{*\mp}\pi^{\pm}$

Phys.Rev.D **71**, 112003 (2005)

Lepton tags		Kaon tags	
Parameter	Value	Parameter	Value
$a^{\ell}_{D^*\pi}$	$-0.042 \pm 0.019 \pm 0.010$	$a^{K}_{D^*\pi}$	$-0.025 \pm 0.020 \pm 0.013$
		$b^{K}_{D^*\pi}$	$-0.004 \pm 0.010 \pm 0.010$
$c^{\ell}_{D^*\pi}$	$-0.019 \pm 0.022 \pm 0.013$	$c^{K}_{D^*\pi}$	$-0.003 \pm 0.020 \pm 0.015$
$\Delta m_{D^*\pi}$	0.518 ± 0.010 ps^{-1}	$\Delta m_{D^*\pi}$	0.4911 ± 0.0076 ps^{-1}
$\tau_{D^*\pi}$	$(1.48 \pm 0.02 \pm 0.02)$ ps	$\tau_{D^*\pi}$	$(1.49 \pm 0.01 \pm 0.04)$ ps



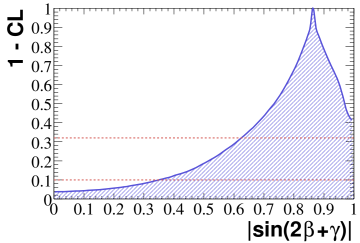
- Raw, TD asymmetry

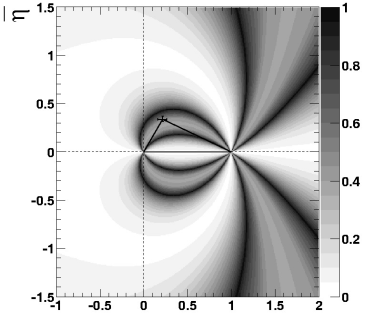
$$A(\Delta t) = \frac{N_{B_{tag}=1}(\Delta t) - N_{B_{tag}=-1}(\Delta t)}{N_{B_{tag}=1}(\Delta t) + N_{B_{tag}=-1}(\Delta t)}$$

- In the limit of no bkg + high statistics $\Rightarrow$ $A(\Delta t)$ is sinusoidal if $a_{D^*\pi} \neq 0$
- Δm & τ in good agreement with PDG

Interpretation of results in terms of $\sin(2\beta+\gamma)$

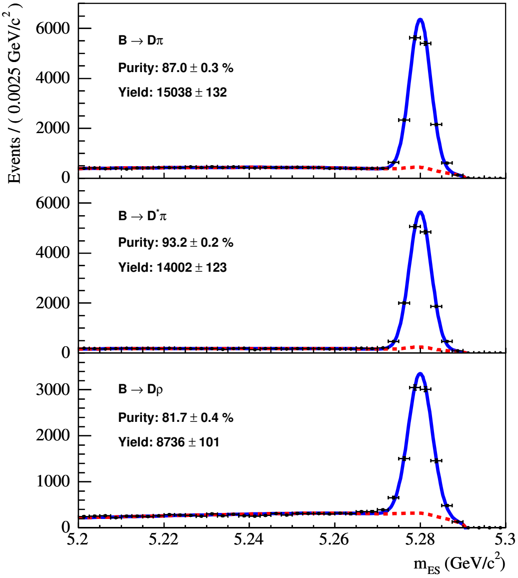
- Must estimate r due to low statistics $r = \sqrt{\frac{\mathcal{B}(B^0 \to D_s^{*+}\pi^-)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)}} \frac{f_{D^*}}{f_{D_s^*}} \tan(\theta_C) \Rightarrow 0.015^{+0.004}_{-0.006} + 30\%$ theoretical uncertainty
  to account for:
  - Small but unknown contribution of exchange diagram amplitudes ($< 10\%$)
  - Ratio of decay constants $\frac{f_{D^*}}{f_{D_s^*}}$ to take into account SU(3) breaking & factorization
- $|\sin(2\beta+\gamma)| > 0.62(0.35)$ @ 68%(90%) CL





TD analysis of fully reconstructed $B \to D^{*\mp}\pi^{\pm}/\rho^{\pm}$

Phys.Rev.D **73**, 111101 (2006)



Peaking bkg $\approx$ 1 – 2%

Why?

- High purity and signal yields

Reconstructed modes

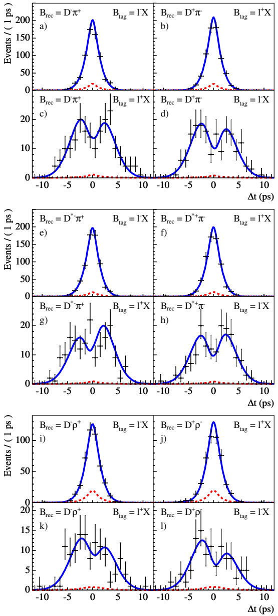
- $D^{*+} \to D^0\pi^+$
- $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^0_S\pi^+\pi^-$
- $\rho^+ \to \pi^+\pi^0$

Procedure

- Extract signal & background fractions & $m_{\rm ES}$ PDF params from MLL fit to $m_{\rm ES}$ and then fix
- Extract CP params from 2D MLL fit to $m_{\rm ES} \times \Delta t$

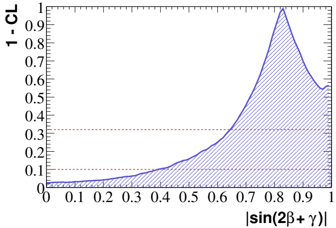
Results of fully reconstructed $B \to D^{*\mp}\pi^{\pm}/\rho^{\pm}$

Phys.Rev.D **73**, 111101 (2006)



CP parameters

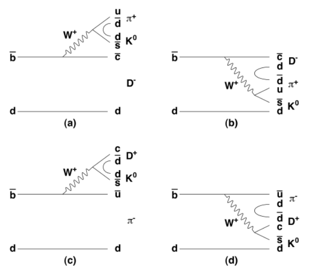
$$a_{D\pi} = -0.010 \pm 0.023 \pm 0.007$$
$$c^{\ell}_{D\pi} = -0.033 \pm 0.042 \pm 0.012$$
$$a_{D^*\pi} = -0.040 \pm 0.023 \pm 0.010$$
$$c^{\ell}_{D^*\pi} = 0.049 \pm 0.042 \pm 0.015$$
$$a_{D\rho} = -0.024 \pm 0.031 \pm 0.009$$
$$c^{\ell}_{D\rho} = -0.098 \pm 0.055 \pm 0.018$$



Interpretation of results in terms of $\sin(2\beta + \gamma)$

- Combined CP results from partially reconstructed $B \to D^{*\mp}\pi^{\pm}$ study
- Used same r with 30% theoretical uncertainty
- $|\sin(2\beta + \gamma)| > 0.64(0.40)$ @ 68%(90%) CL

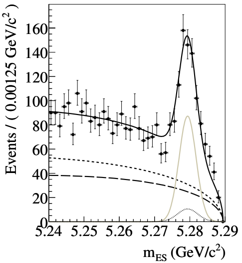
TD Dalitz plot analysis of $B^0 \to D^{\mp} K^0 \pi^{\pm}$



- Why?
  - Avoids limitation of small $r(b \to u : b \to c) \approx 0.02$
  - For this three-body B-decay r has been estimated to be as large as 0.3 in some regions of the Dalitz plot
  - Ultimately, $sin(2\beta + \gamma)$ from this measurement has very little dependence on the value of r
- **Final state reached through the following intermediate states**
  - $B^0 \to D^{**0} K_S^0$ *(right column, color-suppressed)* with $D^{**0} = \{D_0^{**}(2400),\ D_2^{**}(2460)\}$
  - $B^0 \to D^- K^{*+}$ *(left column, tree-level)* with $K^* = \{K^*(892),\ K_0^*(1430),\ K_2^*(1430),\ K^*(1680)\}$
  - $D^+ \to K^- \pi^+ \pi^-$
  - Small contribution from $B^0 \to D_s^{*+}(2573)\pi^-$ expected
- **CP sensitivity of $B^0 \to D^{\mp} K^0 \pi^{\pm}$ comes from interference between**
  - $b \to c$ *(b)* & $b \to u$ *(d)* transitions of $D^{**0} K_S^0$
  - $D^{**0} K_S^0$ $b \to u$ *(d)* & $D^- K^{*+}$ $b \to c$ *(a)* decays

Overview of $B^0 \to D^{\mp} K^0 \pi^{\pm}$ analysis procedure

Phys.Rev.D **77**, 071102 (2008)



- Extract fit parameters & yields from 3D MLL fit to $m_{\mathrm{ES}} \times \Delta E \times \mathcal{F}$
  $N_{sig} = 558 \pm 34$
- Fix parameters for next step
- Fit TD Dalitz plot

TD Dalitz plot PDF

$$\frac{A_c^2 + A_u^2}{2} \times \frac{e^{-\frac{|\Delta t|}{\tau_B}}}{4\tau_B} \times \{1 - D_{tag} B_{tag} C \cos(\Delta m_d \Delta t) + B_{tag} S_{D_{tag}} \sin(\Delta m_d \Delta t)\}$$

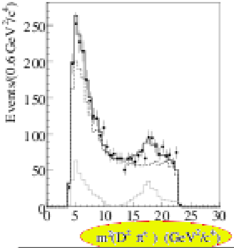
with:

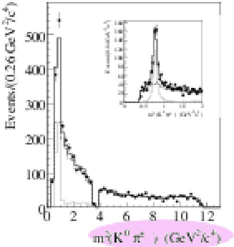
- $S_{D_{tag}} = \frac{2\mathrm{Im}(A_c A_u e^{i(2\beta+\gamma)+D_{tag} i(\phi_c - \phi_u)})}{A_c^2 + A_u^2}$
- $C = \frac{A_c^2 - A_u^2}{A_c^2 + A_u^2}$
- $A_c, \phi_c \Rightarrow$ Amplitude, strong phase at each point of the Dalitz plot for $b \to c$
- $A_u, \phi_u \Rightarrow$ Amplitude, strong phase at each point of the Dalitz plot for $b \to u$
- Unable to determine A_u $\Rightarrow$ fix the ratio of $A_u / A_c = 0.3$

Results of TD Dalitz plot analysis of $B^0 \to D^{\mp} K^0 \pi^{\pm}$

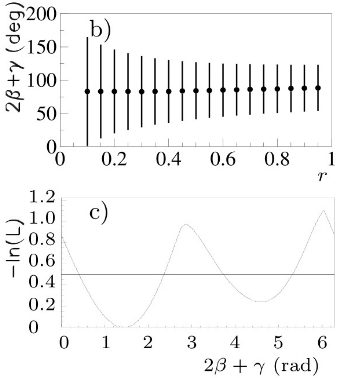
Phys.Rev.D **77**, 071102 (2008)

Dalitz plot PDF projections on data:



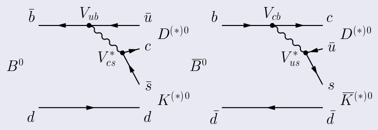


Resonance	V_{cb} magnitude	Phase (°)
$K^*(892)$	1.	0.
$D_0^*(2400)$	$0.290 \pm 0.048 \pm 0.067$	$267 \pm 22 \pm 35$
$D_2^*(2460)$	$0.042 \pm 0.050 \pm 0.048$	$325 \pm 46 \pm 20$
$K_0^*(1430)$	$0.135 \pm 0.058 \pm 0.099$	$284 \pm 30 \pm 11$
$K_2^*(1430)$	$0.108 \pm 0.056 \pm 0.051$	$221 \pm 30 \pm 14$
$K^*(1680)$	$0.404 \pm 0.047 \pm 0.046$	$128 \pm 22 \pm 24$
$2\beta+\gamma$	$(83 \pm 53 \pm 20)^\circ$ and $(263 \pm 53 \pm 20)^\circ$	

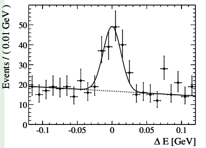


- Central value has weak dependence on $r = \frac{A(b\to u)}{A(b\to c)}$ *(b)*
- Errors decrease as $r \to 1$ as expected
- Ambiguity at $(83 + 180)^\circ$ *(c)*

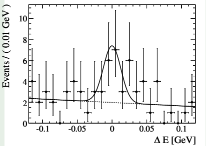
BABAR



$B^0 \to D^0 K_S^0$



$B^0 \to D^{0*} K_S^0$



- **TD Decay rate**

  $$\propto e^{-\Delta t/\tau} \times [1 - B_{tag} D_{rec} \left(\frac{1-r_b^2}{1+r_b^2}\right) \cos(\Delta m_d \Delta t) +$$
  $$B_{tag} \left(\frac{r_b}{1+r_b^2}\right) \sin(2\beta + \gamma + D_{rec}\delta) \sin(\Delta m_d \Delta t)]$$

- **Small theoretical uncertainty**
- $\mathcal{A}(B^0 \to D^0 K^0) \propto V_{ub} V_{cs}^*$ &
  $\mathcal{A}(\overline{B}^0 \to D^0 \overline{K}^0) \propto V_{cb}^* V_{us} \Rightarrow \mathcal{O}(\lambda^3)$,
  $\lambda = \sin(\theta_{Cabibbo}) = 0.22$
- **Expect large asymmetries**
- **Previous analyses measured $\mathcal{B}$ only**
- **At $2\times$ the previous data set expect more than 200 $B^0 \to D^0 K_S^0$ events**
- **Final state reconstructed via the following**
  - $D^{*0} \to D^0 \pi^0$
  - $D^0 \to K^- \pi^+, K^- \pi^+ \pi^0, K^- \pi^+ \pi^- \pi^+$
  - $\overline{K}^{*0} \to K^- \pi^+$
- **$\mathcal{B}$ result from 2D MLL fit to $m_{ES} \times \Delta E$:**

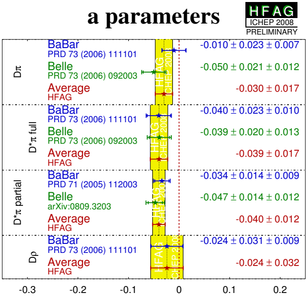
B Mode	N_S	$\mathcal{S}$	$\mathcal{B}$ $[10^{-5}]$
$\tilde{B}^0 \to D^0 \tilde{K}^0$	104 ± 14	9.2σ	$5.3 \pm 0.7 \pm 0.3$
$\tilde{B}^0 \to D^{*0} \tilde{K}^0$	17.1 ± 5.2	4.3σ	$3.6 \pm 1.2 \pm 0.3$

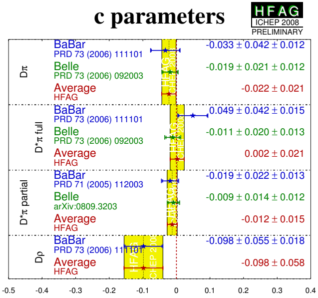
Conclusion

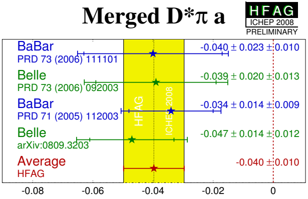
- All analyses need to be updated to the final data set
- We expect an improvement in the measurement of γ with $B \to D^{(*)\mp}\pi^{\pm}/\rho^{\pm}$ since r can be more precisely estimated
  - We can use the isospin relation $r = \sqrt{\frac{\tau_B^0}{\tau_B^+} \frac{2\mathcal{B}(B^+ \to D^{*+}\pi^0)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)}}$ as suggested by
  - ***Search for $B^+ \to D^{*+}\pi^0$ decay***
    BELLE, Phys. Rev. Lett. **101**, 041601 (2008)
  - And use the estimate $r < 0.051$ @ 90% CL
- The *BABAR* data sample is just large enough to possibly detect CP asymmetry in $B^0 \to D^0 K_S^0$
- Thus far, there is no experimental evidence of any sort of deviation from SM predictions for γ
- At present, the errors on direct measurements of γ are too large to detect variation from CKM fit: $(67.2^{+3.9}_{-3.9})^\circ$ vs. $(71^{+21}_{-25})^\circ$

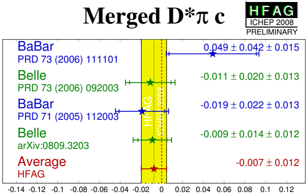
BABAR

Summary: HFAG CP param results, world averages for $B \to D^{*\mp}\pi^{\pm}/\rho^{\pm}$

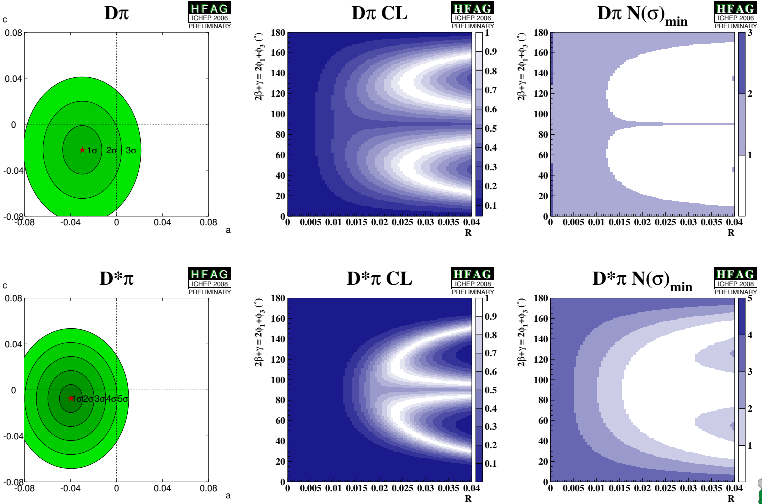








Summary: HFAG constraints on $2\beta + \gamma$ from $B \to D^{*\mp}\pi^{\pm}/\rho^{\pm}$



$\rho - \eta$ from UTfit