BABAR status and prospects for *CP* asymmetry measurements: $\sin(2\beta + \gamma)$

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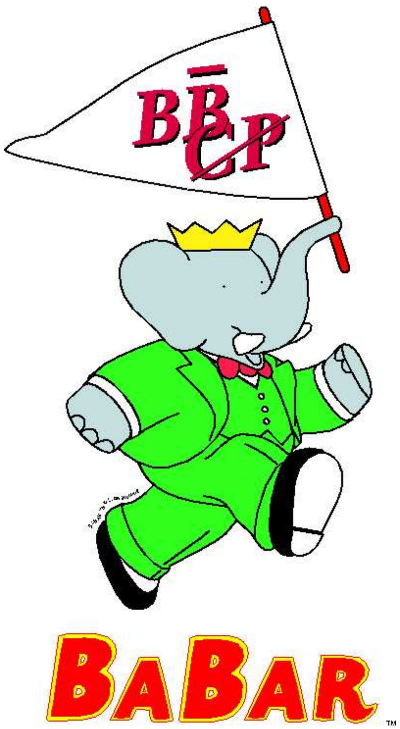

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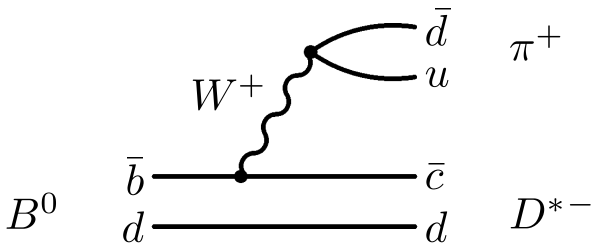
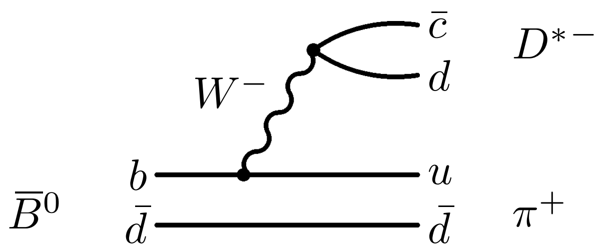
- The B decays relevant to the $\sin(2\beta+\gamma)$ have either small branching fraction ($B \to D^{(*)}K^{(*)}$) or a small asymmetry ($B \to D^{(*)}\pi/\rho/a_1$)



Cabibbo favoured

$A_{b\to c} \sim V^*_{ud}V_{cb} \sim (1-\lambda^2)A\lambda^2$



doubly Cabibbo suppressed

$A_{b\to u} \sim V^*_{cd}V_{ub}e^{i\delta} \sim -A\lambda^4 e^{i\gamma}e^{i\delta}$

strong phase δ,
weak phase $2\beta+\gamma$
(-2β from mixing)

$\lambda = \sin\theta_{cab}$

- Contribution from only pure tree decays (no penguin)

- Time evolution:

$$P(B^0 \to D^{*\mp}\pi^{\pm}, \Delta t) \propto 1 \pm C\cos(\Delta m_d \Delta t) + S^{\mp}\sin(\Delta m_d \Delta t)$$
$$P(\overline{B}^0 \to D^{*\mp}\pi^{\pm}, \Delta t) \propto 1 \mp C\cos(\Delta m_d \Delta t) - S^{\pm}\sin(\Delta m_d \Delta t)$$

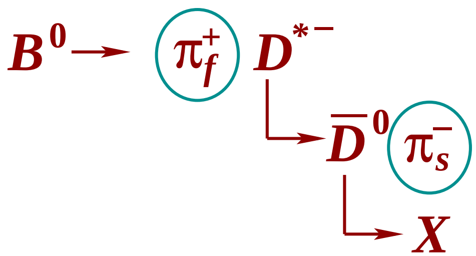
$$\boldsymbol{S^{\pm} = \frac{2r}{1+r^2}\sin(2\beta+\gamma\pm\delta)} \qquad \boldsymbol{C = \frac{1-r^2}{1+r^2} \approx 1}$$

$$r = \frac{A(\overline{B}^0 \to D^{*-}\pi^+)}{A(B^0 \to D^{*-}\pi^+)} \approx 0.02$$

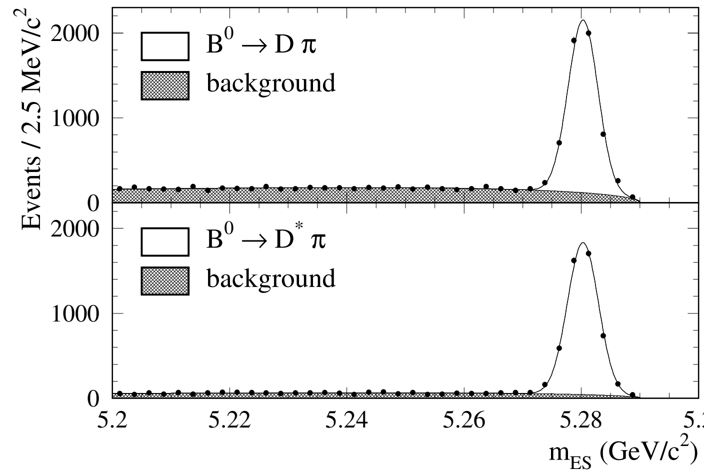
- small CP violating asymmetries

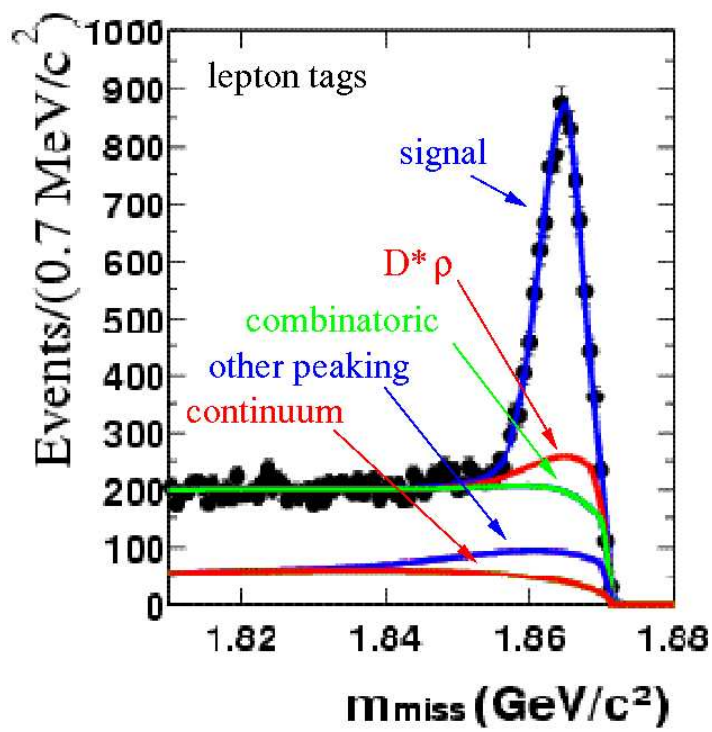
- r can not be extracted fitting C $(1 - C \sim 10^{-4})$

- CP asymmetry is small $\Rightarrow$ statistics is crucial
- Two methods of the reconstruction:
- exclusive: low background
- partial reconstruction: increases efficiency about x10



Sample	Yields	Purity
Fully Reconstructed	(232 M $B\overline{B}$)	
$D^{\pm}\pi^{\mp}$ (all tag)	15038 ± 132	87%
$D^{*\pm}\pi^{\mp}$ (all tag)	14002 ± 123	93%
$D^{\pm}\rho^{\mp}$ (all tag)	8736 ± 101	82%
Partially Reconstructed (232 M $B\overline{B}$)		
$D^{*\pm}\pi^{\mp}$ (ℓ)	18705 ± 273	54%
$D^{*\pm}\pi^{\mp}$ (K)	70584 ± 661	31%



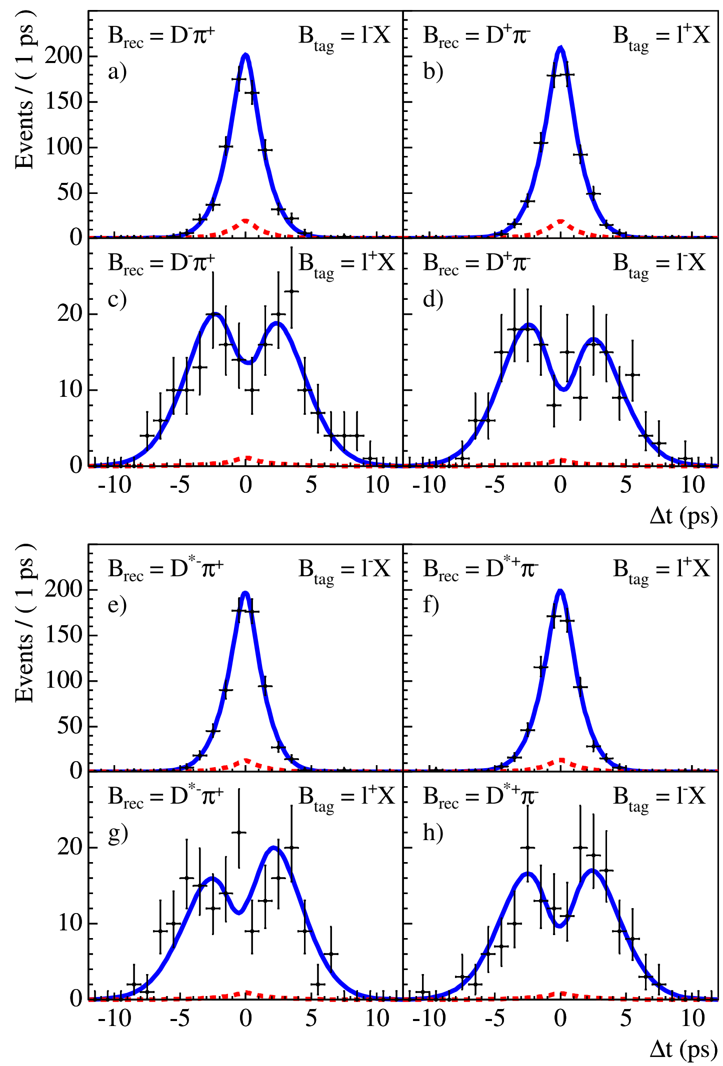


- exclusive reconstruction [Phys.Rev.D **73**, 111101 (2006)]
- presence of the DCS decays on tag-side introduces extra CP-violation [Phys.Rev.D **68**, 034010 (2003)]
  - ➠ use abc-parameterization

$$a = 2r\sin(2\beta+\gamma)\cos\delta$$
$$b = 2r'\sin(2\beta+\gamma)\cos\delta'$$
$$c = 2\cos(2\beta+\gamma)(r\sin\delta - r'\sin\delta')$$

- PDF includes combinatorial and peaking backgrounc
- fit all decay samples and tagging categories simultaneously (assume $r'=0$ for lepton tag)

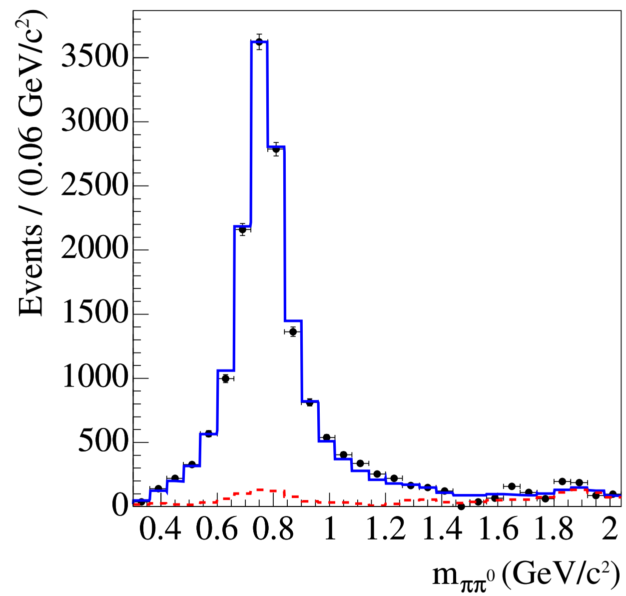
$$a^{D\pi} = -0.010 \pm 0.023 \pm 0.007$$
$$c_{\rm lep}^{D\pi} = -0.033 \pm 0.042 \pm 0.012$$
$$a^{D^*\pi} = -0.040 \pm 0.023 \pm 0.010$$
$$c_{\rm lep}^{D^*\pi} = 0.049 \pm 0.042 \pm 0.015$$
$$a^{D\rho} = -0.024 \pm 0.031 \pm 0.009$$
$$c_{\rm lep}^{D\rho} = -0.098 \pm 0.055 \pm 0.018$$



- 3-Gaussian resolution function

- Dominant systematic error $\Rightarrow$ vertexing
  - SVT misalignment, resolution function;
  - beam spot position and z-scale uncertainty.

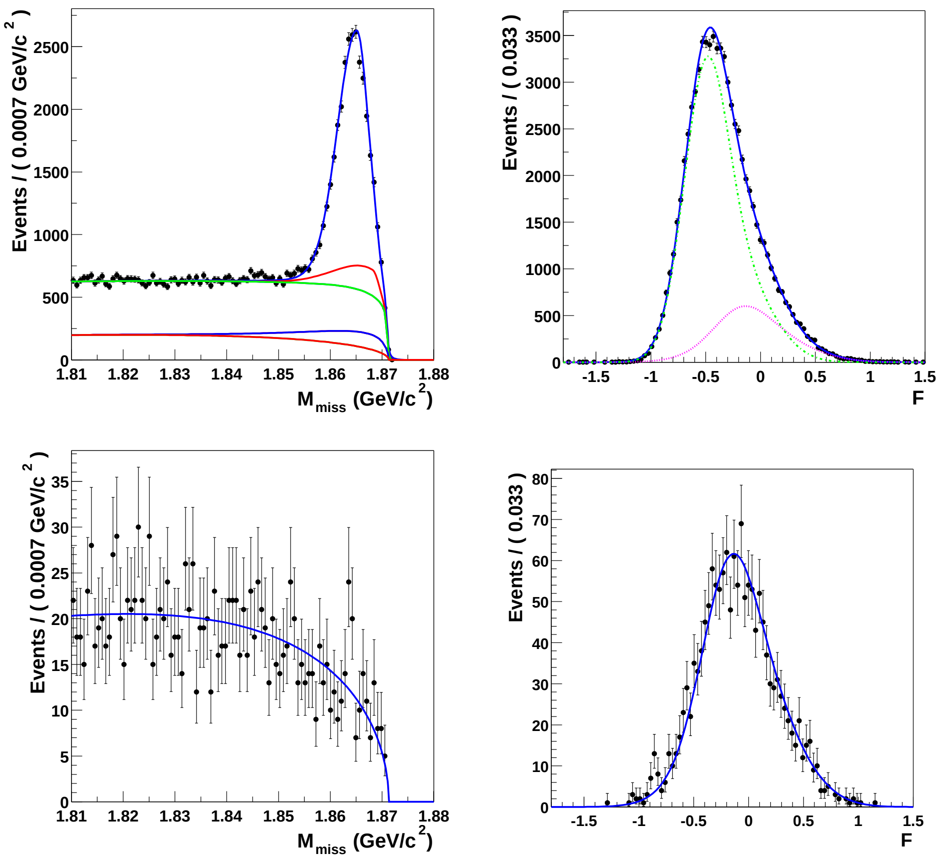
B^0 mode	$D^\pm\pi^\mp$		$D^{*\pm}\pi^\mp$		$D^\pm\rho^\mp$	
Source	σ_a	σ_c	σ_a	σ_c	σ_a	σ_c
Vertexing ($\sigma_{\Delta t}$)	0.37	0.64	0.80	1.14	0.47	1.15
Fit ($\sigma_{\rm fit}$)	0.51	0.95	0.52	0.99	0.75	1.34
Model ($\sigma_{\rm mod}$)	0.12	0.13	0.12	0.13	0.01	0.18
Tagging ($\sigma_{\rm tag}$)	0.07	0.16	0.11	0.14	0.06	0.12
Background ($\sigma_{\rm bkg}$)	0.13	0.10	0.10	0.09	0.28	0.29
$m_{\pi\pi^0}$ Dependence (σ_λ)	—	—	—	—	0.16	0.16
Total ($\sigma_{\rm tot}$)	0.66	1.17	0.97	1.53	0.94	1.81



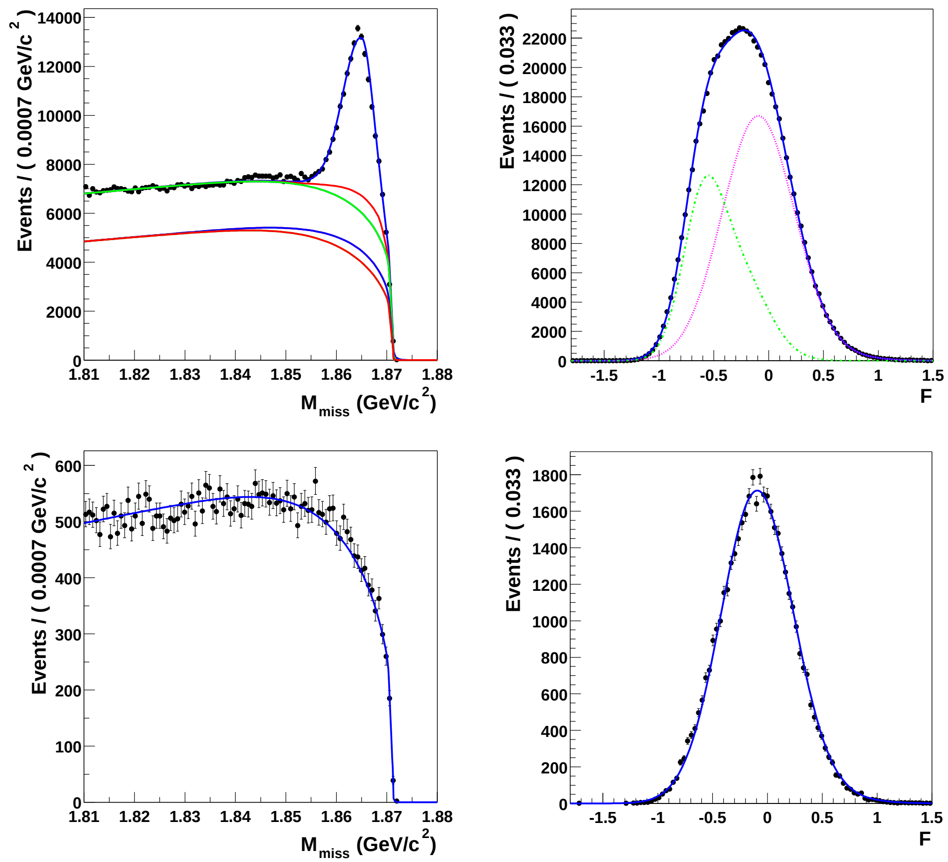
- In case of $B^0 \to D^\mp\rho^\pm$ two additional background components were considered: $B^0 \to D^\mp\rho^\pm(1450)$ and $B^0 \to D^\mp\pi^\pm\pi^0$ (non-resonant S-wave)
  - $\boldsymbol{f(D^\mp\rho^\pm(1450) + D^\mp\pi^\pm\pi^0) < 0.02}$ **at 90% CL**

Inclusive $B^0 \rightarrow D^{*\mp}\pi^{\pm}$ *(Kinematical Fit)*

Lepton tag



Kaon tag



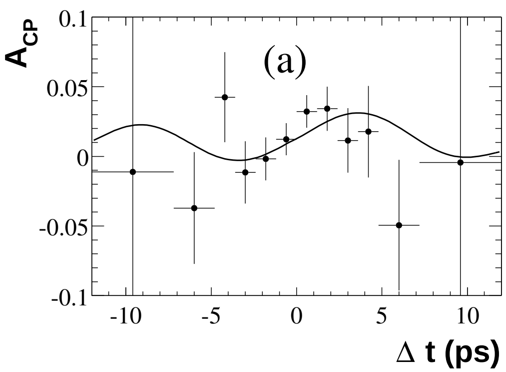
☞ 211.4 fb^{-1} (on-res.) (232 M $B\overline{B}$) and 21.7 fb^{-1} (off-res.)

☞ All PDF parameters are extracted from the data.

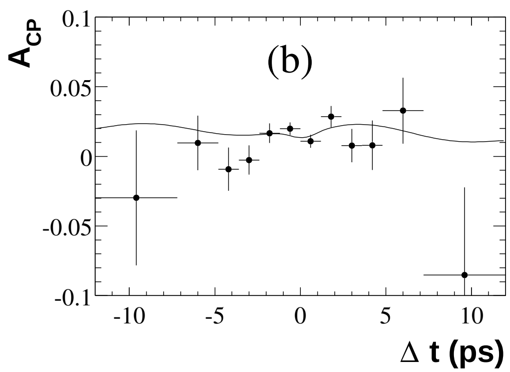
Inclusive $B^0 \to D^{*\mp}\pi^{\pm}$ *(Fit results)*

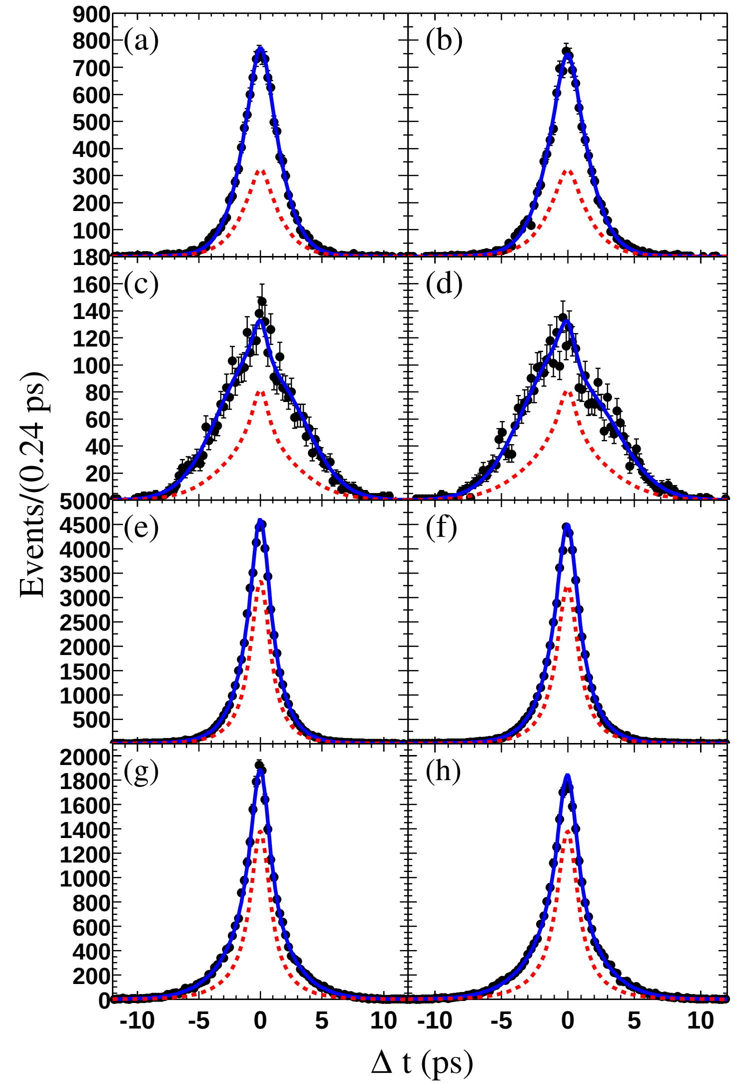
Lepton-tagged	
$2r\sin(2\beta+\gamma)\cos\delta^*$	**-0.042 ± 0.019 ±0.010**
$2r\cos(2\beta+\gamma)\sin\delta^*$	**-0.019 ± 0.022 ± 0.013**
Kaon-tagged	
$2r\sin(2\beta+\gamma)\cos\delta^*$	**-0.025 ± 0.020 ± 0.013**
$2r'\sin(2\beta+\gamma)\cos\delta'$	**-0.004 ± 0.010 ± 0.010**
$2\cos(2\beta+\gamma)(r\sin\delta^* - r'\sin\delta')$	**-0.002 ± 0.020 ± 0.015**

Lepton tag



Kaon tag





$$A_{CP} = \frac{N(B^0)-N(\bar{B}^0)}{N(B^0)+N(\bar{B}^0)}$$

☞ The most precise time-dependent CP asymmetry measurement [Phys.Rev.D **71**, 112003 (2005)]

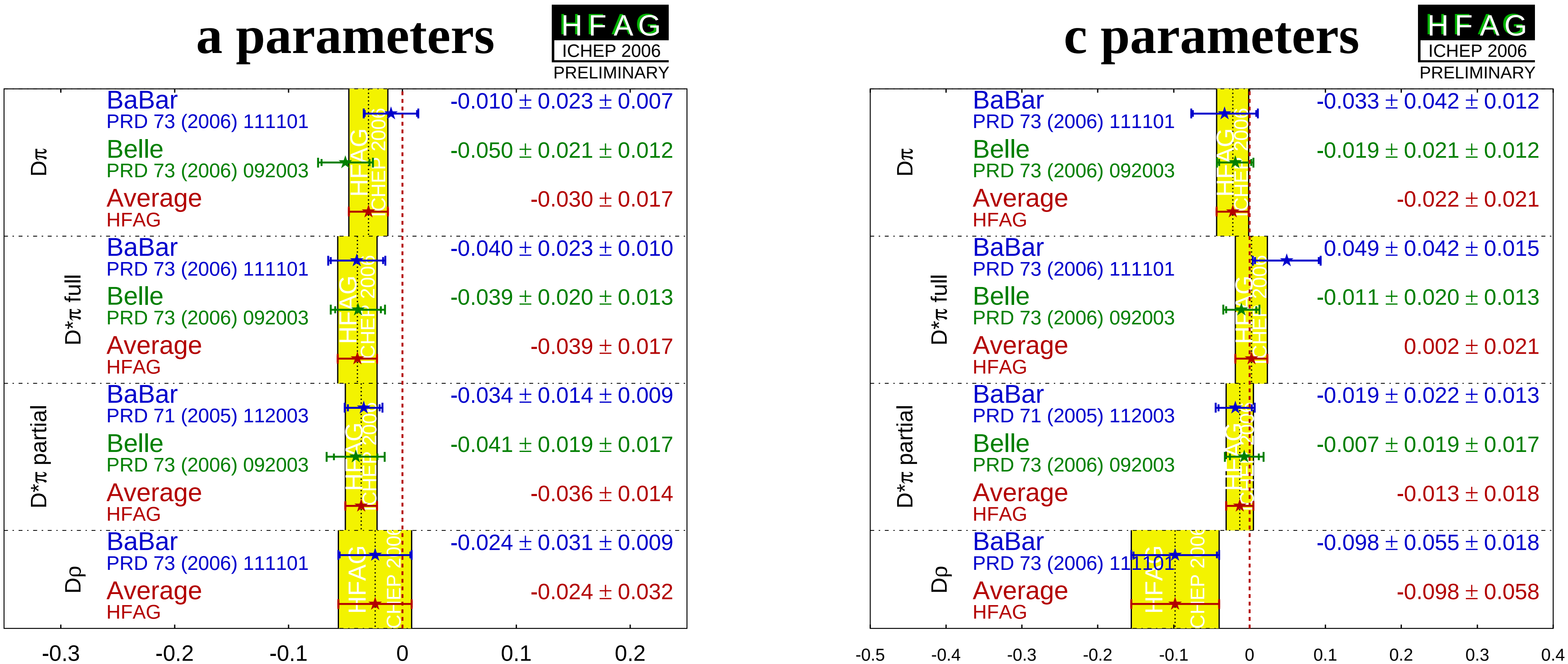
$$2r\sin(2\beta+\gamma)\cos\delta = -0.034 \pm 0.014 \pm 0.009$$

Inclusive $B^0 \to D^{*\mp}\pi^{\pm}$ *(Systematics)*

Source	Error ($\times 10^{-2}$)				
	Lepton-tagged		Kaon-tagged		
	$a^{\ell}_{D^*\pi}$	$c^{\ell}_{D^*\pi}$	$a^{K}_{D^*\pi}$	$b^{K}_{D^*\pi}$	$c^{K}_{D^*\pi}$
1. Step 1 fit	0.04	0.04	0.10	0.04	0.04
2. Sideband statistics	0.08	0.08	0.40	0.12	0.44
3. $f^{\text{miss}}_{D^*\pi}$	0.02	0.02	0.02	negl.	negl.
4. $\rho_{D^*\pi}$	0.02	0.02	0.02	negl.	negl.
5. MC statistics	0.60	0.82	0.68	0.34	0.70
6. Beam spot size	0.10	0.10	0.07	0.13	0.06
7. Detector z scale	0.03	0.03	0.02	negl.	0.03
8. Detector alignment	0.25	0.55	0.25	0.13	0.41
9. Combinatoric background CP content	0.25	0.22	0.80	0.56	0.72
10. Peaking background CP content	0.36	0.38	0.29	0.17	0.27
11. $D^*\rho$ CP content	0.53	0.52	0.57	0.58	0.58
12. Peaking background	0.21	0.31	0.21	0.41	0.31
13. Signal region/sideband difference	0.0003	0.002	0.04	0.03	0.05
14. $\mathcal{B}(B \to D^{*\mp}\rho^{\pm})$	0.17	0.33	0.17	0.22	0.33
Total systematic error	1.0	1.3	1.4	1.0	1.5
Statistical uncertainty	1.9	2.2	2.0	1.0	2.0

☞ Measure CP-violation in $D^*\rho$ would minimize CP content systematics

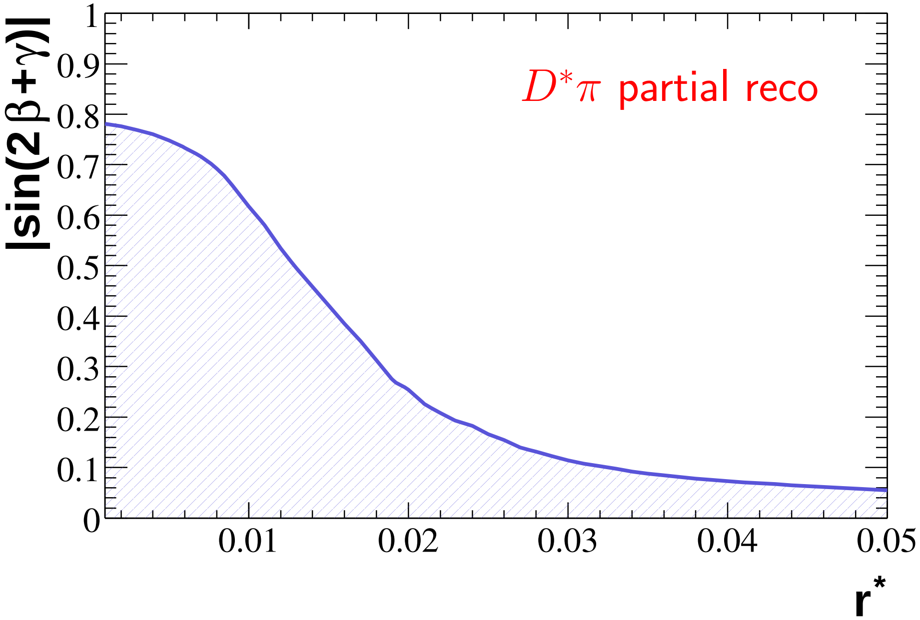
$B^0 \to D^{(*)\mp}\pi^\pm/\rho^\pm$ (Summary)



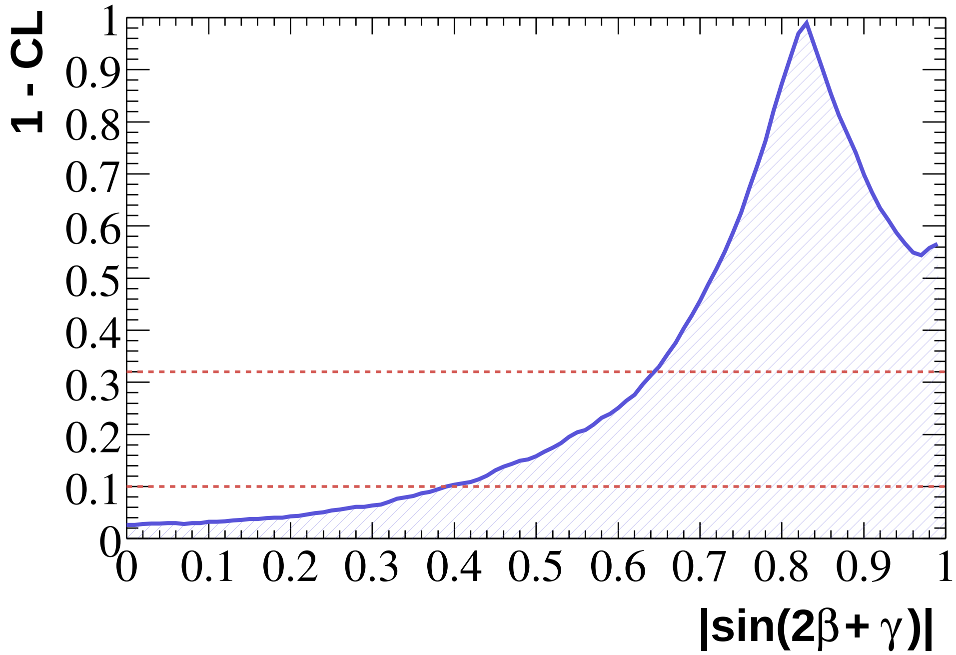
☞ Combined BABAR/BELLE result for $B^0 \to D^{*\mp}\pi^\pm$ decays

$$2r^{D^*\pi}\sin(2\beta+\gamma)\cos\delta = -0.037 \pm 0.011$$

- Use frequentistic approach
- Two methods of interpretation:
  - $|\sin(2\beta+\gamma)|$ limit $vs.$ $r^{D^*\pi}$;
  - use SU(3) symmetry to constraint r;



A lower 90% C.L. limit on $|\sin(2\beta+\gamma)|$

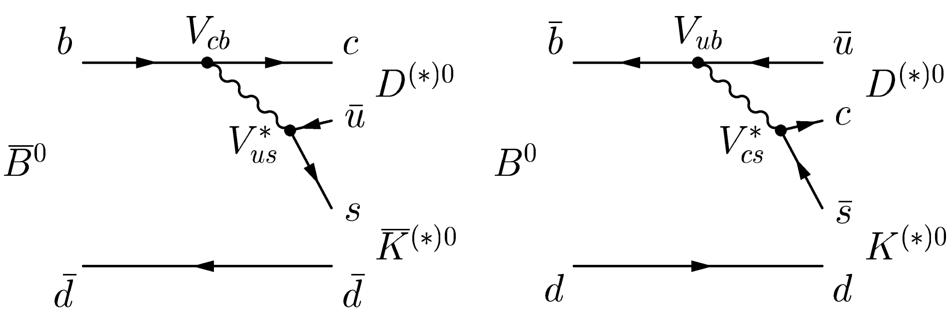


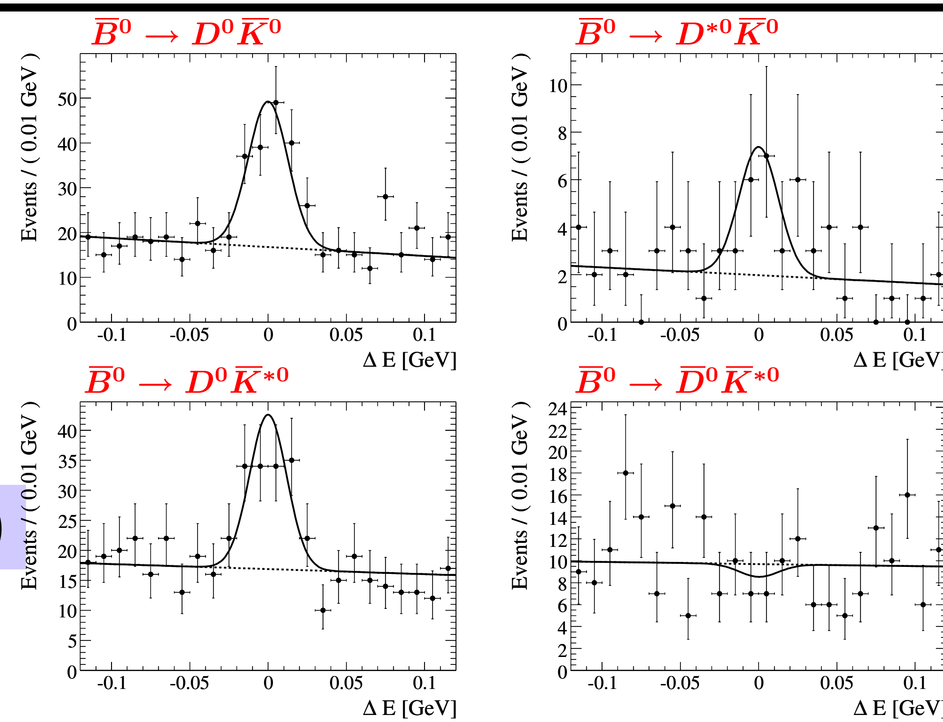
- Estimate r from $\mathcal{B}(B \to D_s^{(*)+}\pi^-)$ with additional 30% error due to SU(3) breaking

$$r^{D\pi} = 0.020 \pm 0.003$$
$$r^{D^*\pi} = 0.015^{+0.004}_{-0.006}$$
$$r^{D\rho} = 0.006 \pm 0.003$$

$$|\sin(2\beta+\gamma)| > 0.40,\ 90\%\text{CL}$$

Perspectives $(\overline{B}^0 \to D^{(*)0}\bar{K}^{(*)0})$





- ☞ Small $\mathcal{B} \sim \mathcal{O}(10^{-5})$, estimate from

$$\mathcal{B}(\overline{B}^0 \to D^{*0}\overline{K}^{*0}) \simeq \sin\theta_c\, \mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)$$

- ☞ Expect $\boldsymbol{r} \sim \mathbf{0.4} \Rightarrow$ enable to fit C
- ☞ Use 226 M $B\overline{B}$ [Phys.Rev.D **74**, 031101 (2006)]

$$\mathcal{B}(\overline{B}^0 \to D^0\overline{K}^0) = (5.3 \pm 0.7 \pm 0.3) \times 10^{-5}$$
$$\mathcal{B}(\overline{B}^0 \to D^{*0}\overline{K}^0) = (3.6 \pm 1.2 \pm 0.3) \times 10^{-5}$$
$$\mathcal{B}(\overline{B}^0 \to D^0\overline{K}^{*0}) = (4.0 \pm 0.7 \pm 0.3) \times 10^{-5}$$
$$\mathcal{B}(\overline{B}^0 \to \overline{D}^0\overline{K}^{*0}) < 1.1 \times 10^{-5} \text{ at } 90\% \text{ C.L.}$$

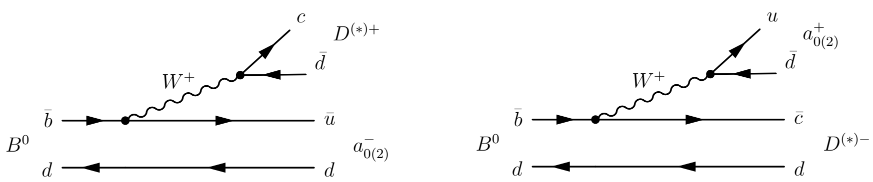
$$R = \frac{\Gamma([K^+\pi^-]_D\overline{K}^{*0})}{\Gamma([K^-\pi^+]_D\overline{K}^{*0})} = r_B^2 + r_D^2 + 2r_Br_D\cos(\gamma+\delta_i)$$

- ☞ Bayesian constraint from observables

  r_B<0.40 at 90% C.L.

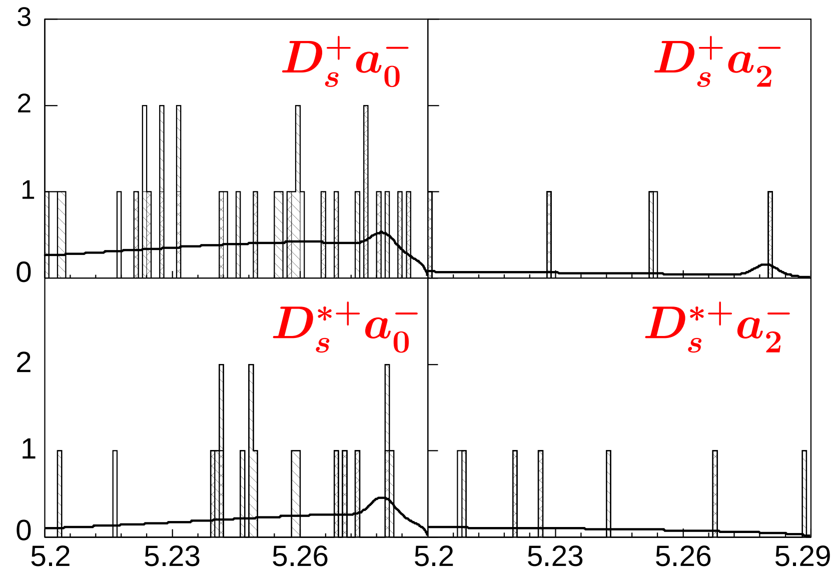
- ☞ Substentially larger data sample is required for $\sin(2\beta+\gamma)$ measurement

☞ Expect large CP asymmetry $(r \sim 1)$



Cabibbo suppressed isospin favoured

Cabibbo favoured isospin suppressed



☞ Search $B^0 \to D_s^{\mp} a^{\pm}_{0,2}$ (SU(3) conjugate) that have larger $\mathcal{B}$

☞ Naive factorization:

$$\mathcal{B}(B^0 \to D_s^{\mp} a_0^{\pm}) \simeq 8 \cdot 10^{-5}$$
$$\mathcal{B}(B^0 \to D_s^{\mp} a_2^{\pm}) \simeq 1.5 \cdot 10^{-5}$$

☞ Reconstruction modes:

➠ $D_s^+ \to \phi\pi^+,\ \overline{K}^{*0}K^+\ K^0_S K^+$

➠ $a^+_{0,2} \to \eta\pi^+$ ($\mathcal{B}$=100,15%)

☞ Use 230 M $B\overline{B}$ [Phys.Rev.D **73**, 071103 (2006)]

☞ Upper limits at 90% C.L.

$$\mathcal{B}(B^0 \to D_s^+ a_0^-) < 1.9 \cdot 10^{-5}$$
$$\mathcal{B}(B^0 \to D_s^+ a_2^-) < 1.9 \cdot 10^{-4}$$
$$\mathcal{B}(B^0 \to D_s^{*+} a_0^-) < 3.6 \cdot 10^{-5}$$
$$\mathcal{B}(B^0 \to D_s^{*+} a_2^-) < 2.0 \cdot 10^{-4}$$

☞ Rule out the naive factorization

☞ Decay modes relevant to $\mathbf{sin(2\beta+\gamma)}$ measurement:

- extraction of r (talk M.Baak): $B^0 \to D_s^{(*)+}\pi^-/\rho^-,\ B^+ \to D_{(s)}^+\pi^0$
- model independent $\sin(2\beta+\gamma)$ measurement with $\boldsymbol{B^0 \to D^{*\mp}\rho^\pm}$
  - time-dependent angular analysis with a fully reconstructed sample;
  - the interference term between different helicity amlitudes $\propto r$;
  - enhance statistics with a partally reconstructed sample;
- time-dependent Dalitz analysis (talk F.Polci): $B^0 \to D^+K^0\pi^-$

☞ Could be done

- $\boldsymbol{B^0 \to D^{*\mp}a_1^\pm}$ resolves two-fold ambiguity in CP angles
- $\boldsymbol{B^0 \to D^{**\mp}\pi^\pm}$ CLEO partial reconstruction proved the principle

- **BABAR has very broad program to measure $\sin(2\beta+\gamma)$**
- Available results with 232 M $B\overline{B}$:
  - $B^0 \to D^{(*)\mp}\pi^\pm$ and $B^0 \to D^\mp\rho^\pm$ with full reconstruction technique
  - $B^0 \to D^{*\mp}\pi^\pm$ with partial reconstruction technique
    - uses both “lepton” and “kaon” B flavor tagging;
    - provides the most precise measurement of time-dependent CP asymmetry:

$$\mathbf{2r\sin(2\beta+\gamma)\cos\delta = -0.034 \pm 0.014 \pm 0.009}$$

- The other analyses relevant to $\sin(2\beta+\gamma)$
  - $\overline{B}^0 \to D^{(*)0}\bar{K}^{(*)0}$ (BF)
  - $B^0 \to D^{(*)\mp}a^\pm_{0,2}$ (BF of SU(3) partners)
  - $B^0 \to D^{*\mp}\rho^\pm$ (BF, lifetime, Δm, transversity)
- Other potential analyses could be done:
  - $B^0 \to D^{*\mp}a^\pm_1$
  - $B^0 \to D^{**\mp}\pi^\pm$

Backup slides

- Use a partial reconstruction technique for $B^0 \to D^{*\mp}\pi^{\pm}$
- PDFs
  - PDF for on-resonance data is a sum over the PDFs of the different event types:

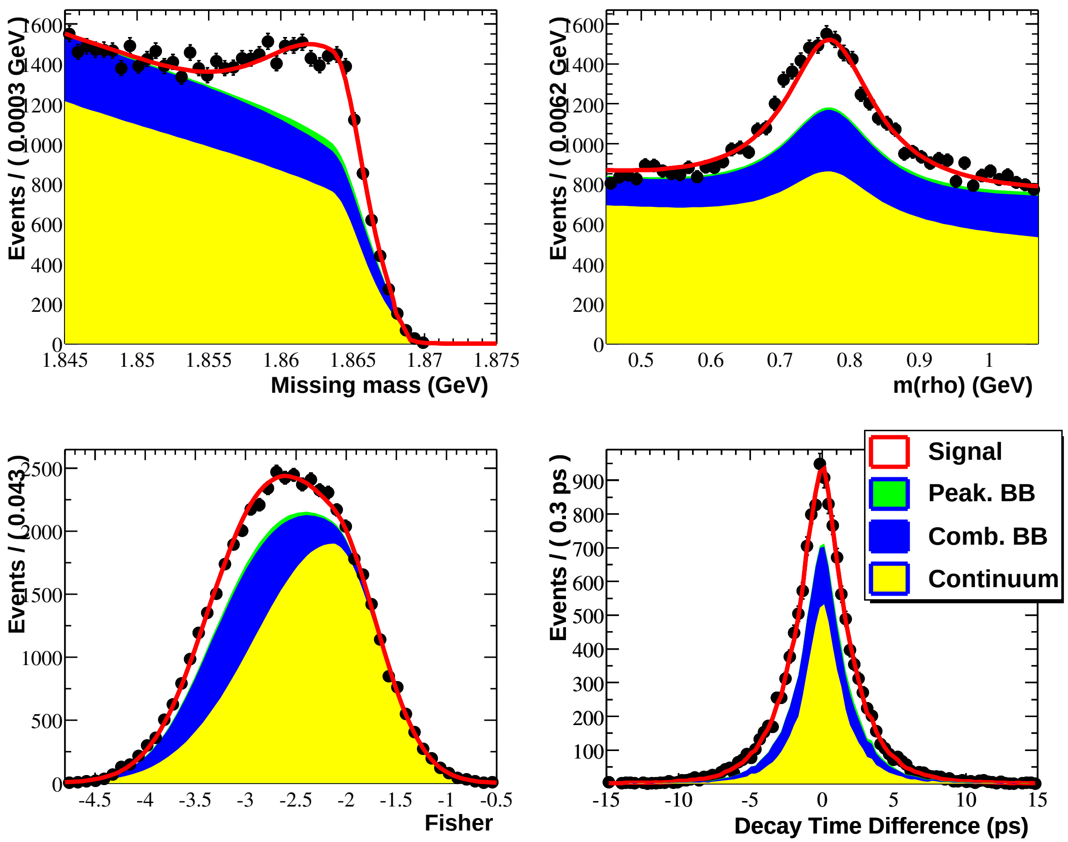
$$\mathcal{P} = \sum_i f_i \, \mathcal{P}_i,$$

where the index $i = \{D^*\pi, D^*\rho, \mathrm{peak}, \mathrm{comb}, q\overline{q}\}$

$$\mathcal{P}_i = \mathcal{M}_i(m_{\mathrm{miss}})\, \mathcal{F}_i(F)\, \mathcal{T}'_i(\Delta t, \sigma_{\Delta t}, s_{\mathrm{t}}, s_{\mathrm{m}}),$$

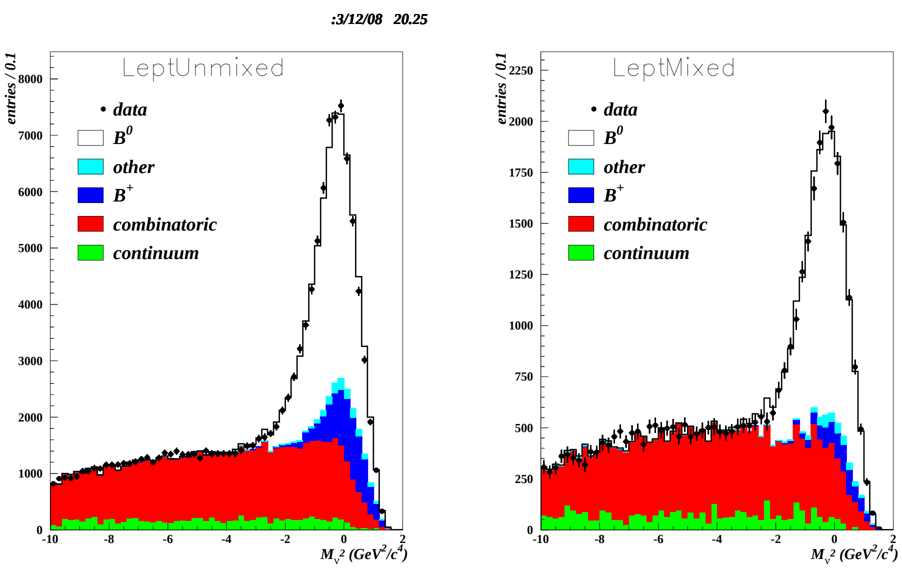
where $s_{\mathrm{t}} = 1(-1)$ for $B^0(\overline{B}^0)$, $s_{\mathrm{m}} = 1(-1)$ for "unmixed" ("mixed")

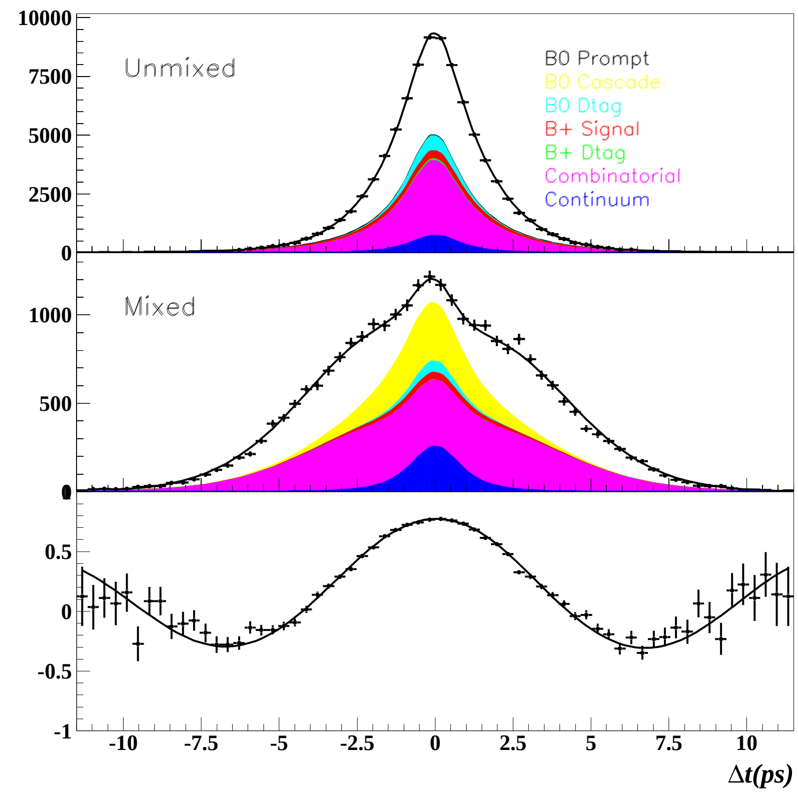
- Analysis steps:
  - Determine f_i, $\mathcal{F}_{q\overline{q}}$, and $\mathcal{F}_{B\overline{B}}$ from the kinematical (KIN) fit: $\mathcal{P}_i = \mathcal{M}_i(m_{\mathrm{miss}})\, \mathcal{F}_i(F)$
  - Determine $\mathcal{T}'_{\mathrm{comb}}$ and $\mathcal{T}'_{q\overline{q}}$ from fit of side-band (SB) region ($1.81 < m_{\mathrm{miss}} < 1.84\ \mathrm{GeV}/c^2$)
  - Determine $\mathcal{T}'_{D^*\pi}$ and $\mathcal{T}'_{q\overline{q}}$ from signal-region fit ($1.845 < m_{\mathrm{miss}} < 1.880\ \mathrm{GeV}/c^2$) using the results of the KIN and SB fits.
- All PDF parameters are extracted from the data.
- Use abc-parameterization to take into account tag-side CP-violation effect.



- ☞ 20.7 fb^{-1}- 5500 events
- ☞ In addition 690 peaked events from $B^0 \to D^{*\mp}a_1^{\pm}$
- ☞ $q\bar{q}$ continuum is a dominant background
- ☞ 200 fb^{-1}- about 55000 non-tagged signal events
- ☞ 200 fb^{-1}- 6000 (20000) events for lepton (kaon) tag

- Only one decay amplitude for $B^0 \rightarrow D^{*\mp} l^{\pm} \nu \Rightarrow$ no CP-violation
- Partial reconstruction provides large number of events (88 M $B\overline{B}$)
  - 117600 (561900)- lepton (kaon) tag
  - Expected statistical error $\boldsymbol{\sigma[2r' \sin(2\beta+\gamma)] \sim 0.008}$
- Use lepton tag as a validation check





- The most precise measurement of the lifetime and Δm [Phys.Rev.D **73**, 012004 (2006)]

$$\tau_{B_d} = 1.507 \pm 0.008 \pm 0.030\,\mathrm{ps}$$
$$\Delta m_{B_d} = 0.523 \pm 0.004 \pm 0.007\,\mathrm{ps}^{-1}$$