Measurement of φ_3 with $B \rightarrow D^{(*)0} K$ Dalitz analysis at Belle

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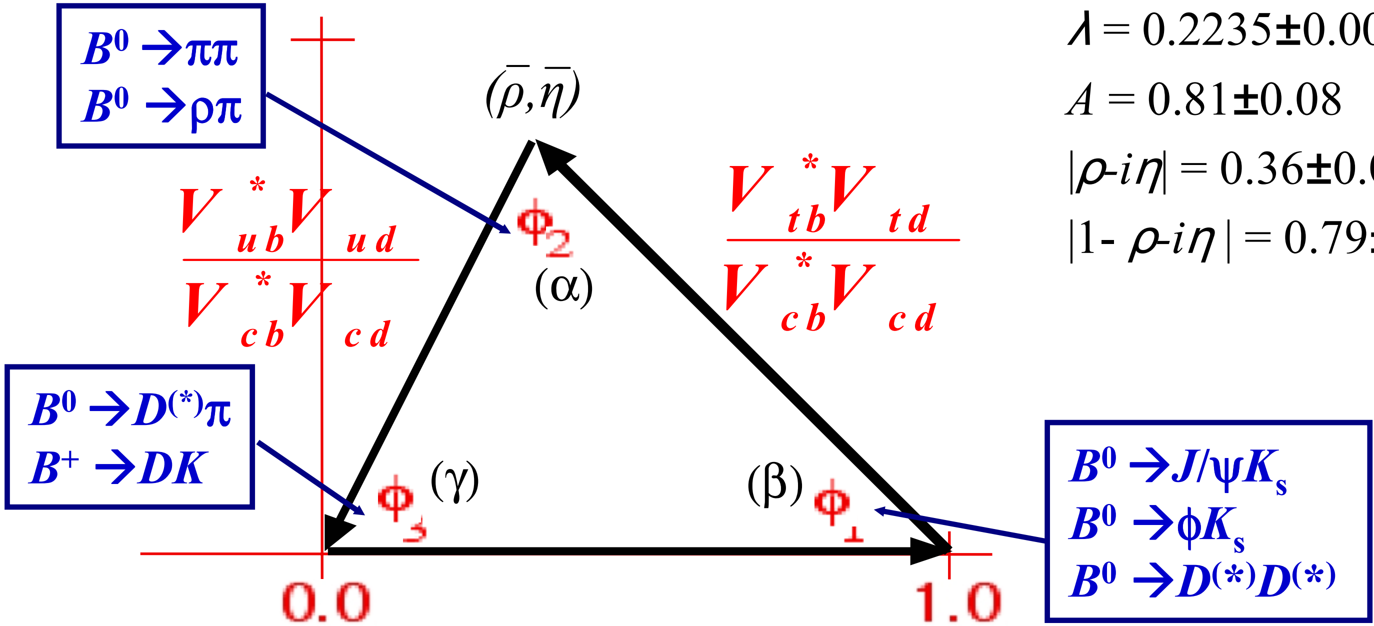
Outline:

- Introduction to the technique
- D^0 model determination
- Signal selection
- Estimation of statistical errors with toy MC
- Estimation of systematic errors
- Combined $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow D^{*0} K^+$ fit
- Conclusion

CKM matrix & unitarity triangle

$$V_{ij} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



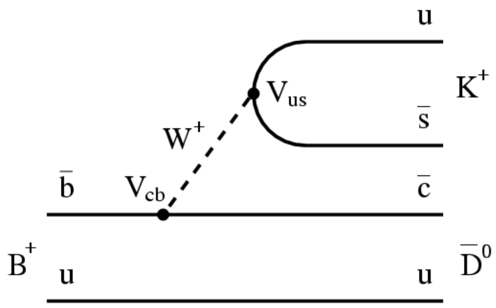
$\lambda = 0.2235 \pm 0.0033$

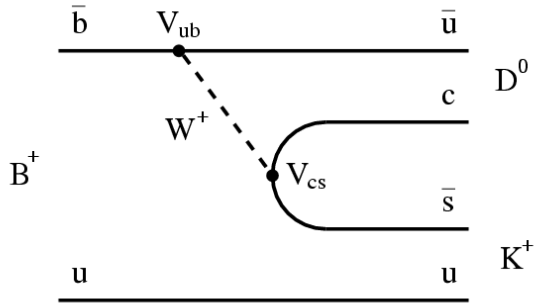
$A = 0.81 \pm 0.08$

$|\rho - i\eta| = 0.36 \pm 0.09$

$|1 - \rho - i\eta| = 0.79 \pm 0.19$

$B^+ \to D^0 K^+$ decay





$$M_1 \sim V_{cb}^* V_{us} \sim A\lambda^3 \qquad M_2 \sim V_{ub}^* V_{cs} \sim A\lambda^3(\rho + i\eta) \sim e^{i\phi_3}$$

If both D^0 and $\overline{D^0}$ decay into the same final state, $B^+ \to D^0 K^+$ and $B^+ \to \overline{D^0} K^+$ amplitudes interfere. Mixed state is produced: $|\tilde{D}^0\rangle = |\overline{D}^0\rangle + re^{i\theta}|D^0\rangle$

Phase θ is a sum of strong and weak phases: $\theta = \phi_3 + \delta$

Use 3-body final state, identical for D^0 and $\overline{D^0}$: $K_s\pi^+\pi^-$.

Dalitz plot density: $d\sigma(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) \propto |M|^2\, dm^2_{K_s\pi^+} dm^2_{K_s\pi^-}$

$$|M(m^2_{K_s\pi^+}, m^2_{K_s\pi^-})|^2 = |f(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) + re^{i\theta} f(m^2_{K_s\pi^-}, m^2_{K_s\pi^+})|^2$$

(assuming CP conservation in D^0 decay)

$B^+ \to D^0 K^+$ decay

$$\left|\tilde{D}^0\right\rangle = \left|\overline{D}^0\right\rangle + re^{i\theta}\left|D^0\right\rangle$$

If D^0 decay model is known, parameters r and θ can be obtained by Dalitz plot analysis.

For $B^- \to D^0 K^-$ weak phase of color-suppressed amplitude changes sign:

$$M_2 \propto V_{ub} V_{cs}^* \propto A\lambda^3(\rho - i\eta) \propto e^{-i\varphi_3}$$

Strong phase is not changed. Therefore, $\theta_- = \delta - \varphi_3$

(r, φ_3, δ) can be obtained with simultaneous fit of B^+ and B^- data.

Use unbinned likelihood technique to fit Dalitz plots.

$$r \approx \frac{\left|V_{ub}^* V_{cs}\right|}{\left|V_{cb}^* V_{us}\right|} \times \frac{|a_2|}{|fa_1 + a_2|} = 0.09/0.22 \times 0.35 \approx 1/8$$

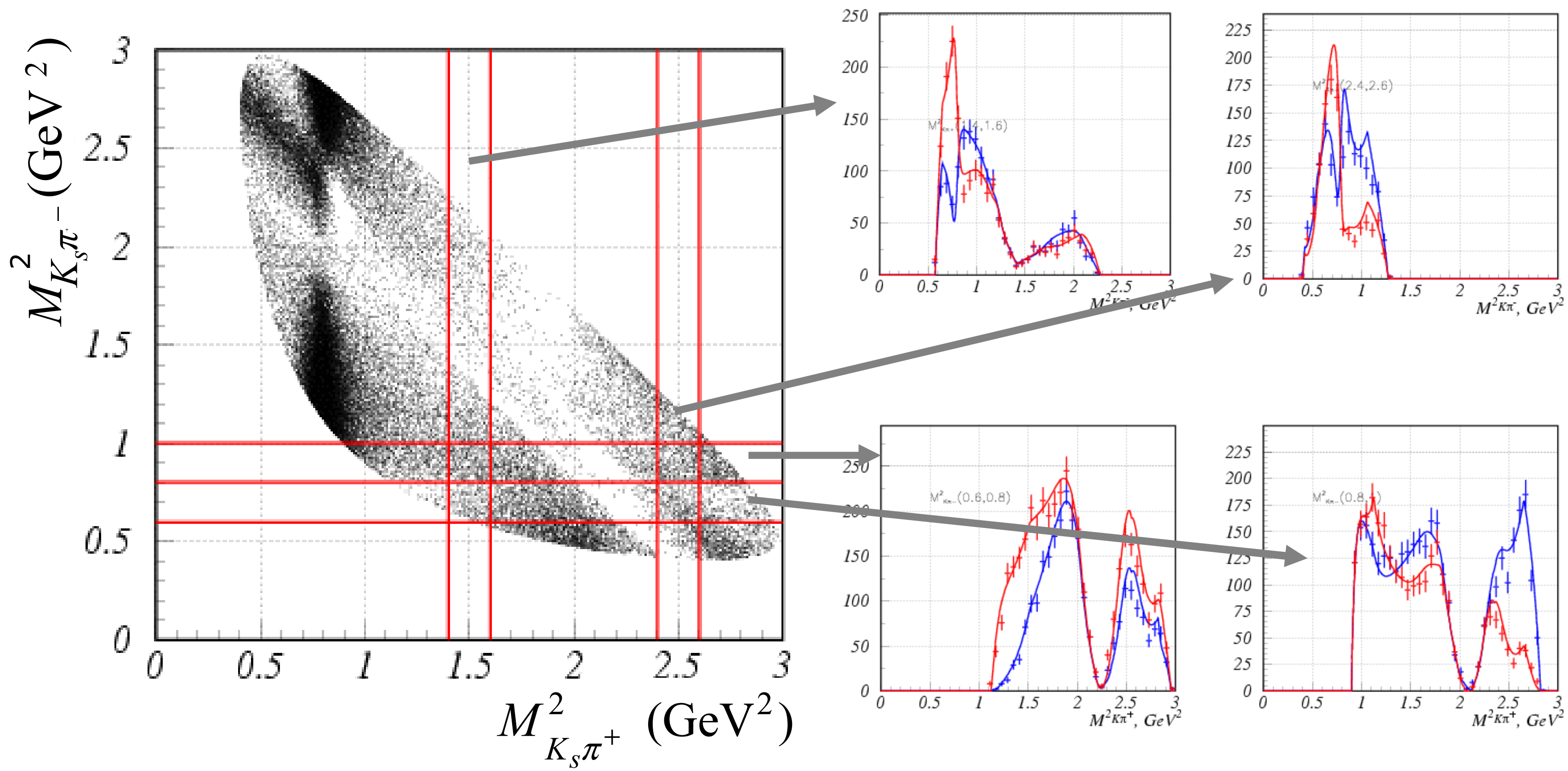
Factor $|a_2|/|fa_1+a_2|=0.35$ related to color suppression can be estimated from the ratio of $B^0 \to D^0 K^0$ and $B^+ \to D^0 K^+$ branching fractions (measured by Belle)

References:

- A. Giri, Yu. Grossman, A. Soffer, J. Zupan, hep-ph/0303187
- Belle collaboration, hep-ex/0308043 (Contributed to LP2003)

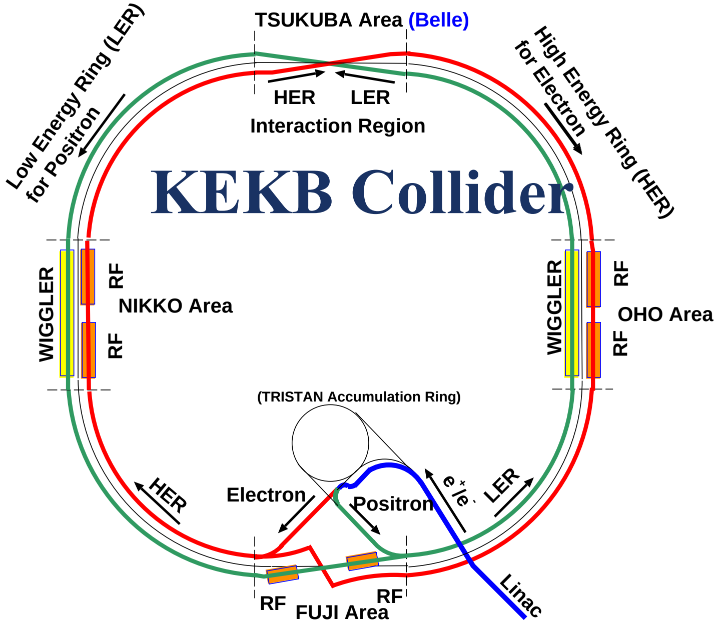
Effect of CPV and φ_3 (MC)

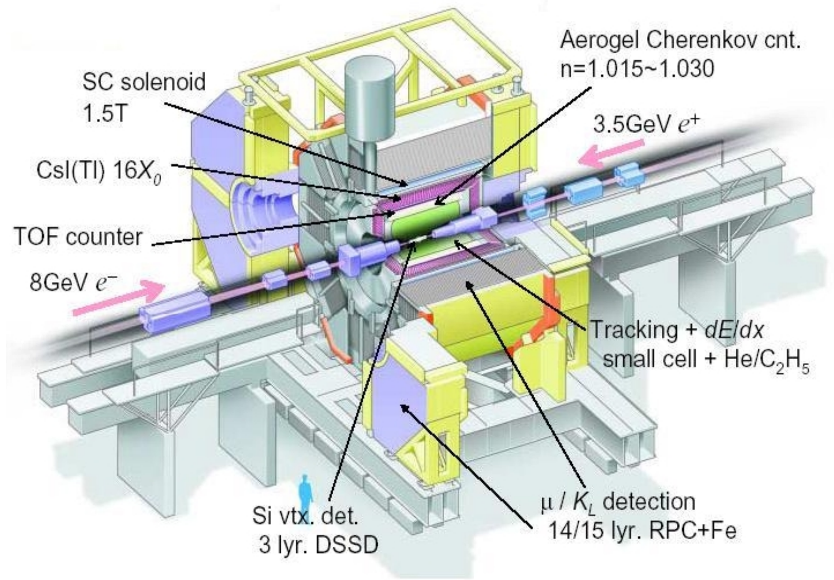
MC generated statistics (50000 $B \to D^0 K$ decays)



Most sensitive regions of the Dalitz plot ($r = 0.125$, δ=0, φ_3=70°)

Belle detector





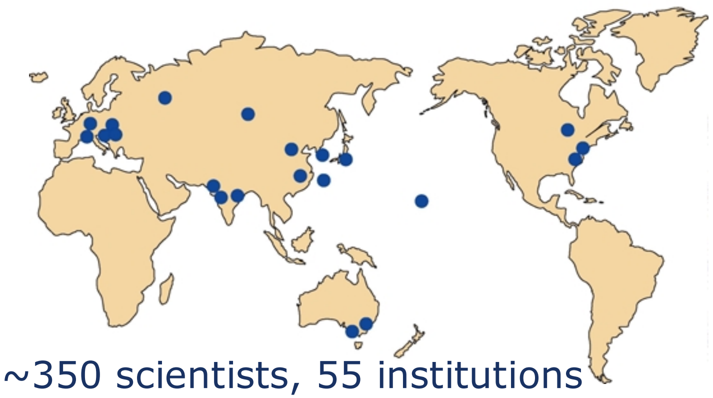
3.5 GeV e^+ & 8 GeV e^- asymmetric Collider

3 km circumference, 11 mrad crossing angle

L= 1.2 x 10^{34} $cm^{-2}s^{-1}$ (world record)

$\int L\,dt$ = 219 fb^{-1} @ $\Upsilon(4S)$+off(~10%)

(140 fb^{-1}: 1.52 x 10^8 $B\bar{B}$ pairs)

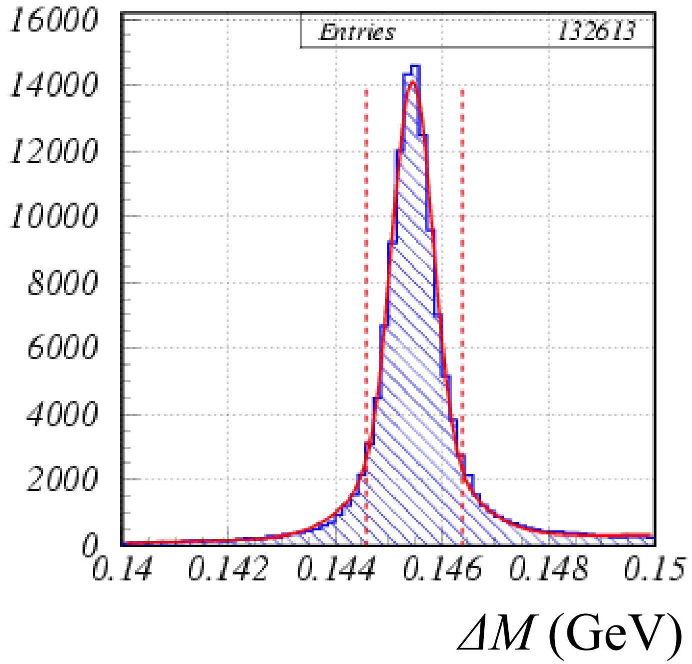


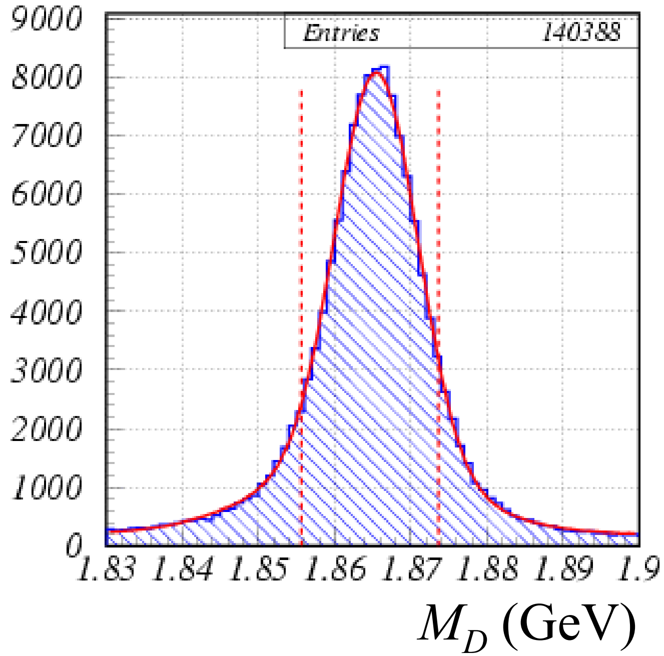
~350 scientists, 55 institutions

Analysis overview

- Determination of $D^0 \to K_s\pi^+\pi^-$ decay model
  - Use flavor tagged sample of D^0's from $D^{*-} \to D^0\pi^-$, $D^0 \to K_s\pi^+\pi^-$ produced in continuum
- Selection of $B^+ \to D^0K^+$ events
- Selection of $B^+ \to D^{*0}K^+$, $D^{*0} \to D^0\pi^0$ events
- Unbinned maximum likelihood fit of the D^0 Dalitz plots with free parameters (r, φ_3, δ)
- Fits to control samples without opposite flavor contributions: $B^+ \to D^0\pi^+$, $B^+ \to D^{*0}\pi^+$, $B^0 \to D^{*+}\pi^-$
- Evaluation of statistical errors using large number of toy MC pseudo-experiments
- Evaluation of systematic and model errors
- Combined φ_3 measurement

$D^{*-} \to D^0\pi^-$, $D^0 \to K_s\pi^+\pi^-$ selection





140 fb^{-1} statistics
101800 events
3.1% background
(shape from ΔM sidebands)

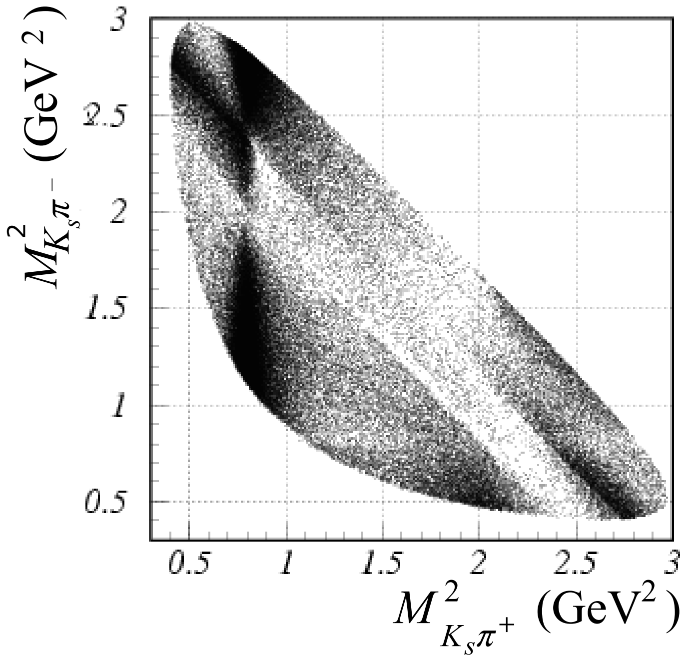
- $144.6 < M_{D*} - M_D < 146.4$ MeV
- $1.856 < M_D < 1.874$ GeV
- $P_{D*} > 2.7$ GeV

$D^0 \to K_s \pi^+ \pi^-$ decay model

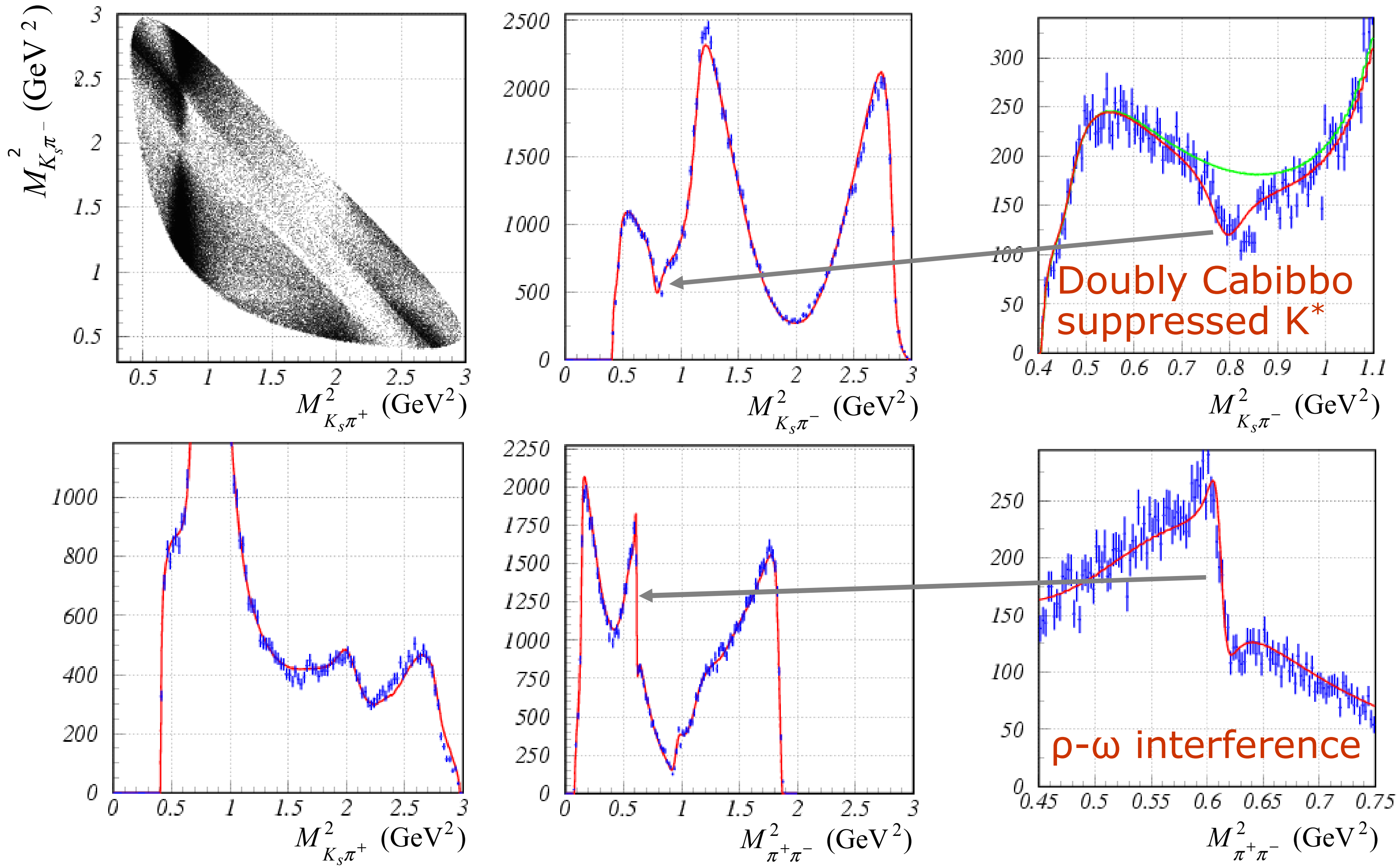
Resonance	Our fit		
	Amplitude	Phase, °	Fit fraction
$\sigma_1 K_s$	1.66±0.11	218.0±3.8	11%
$\rho(770) K_S$	1	0	21%
ωK_s	(3.30±1.13)·10^-2	114.3±2.3	0.4%
$f_0(980) K_s$	0.405±0.008	212.9±2.3	4.8%
$\sigma_2 K_s$	0.31±0.05	236±11	0.9%
$f_2(1270) K_s$	1.36±0.06	352±3	1.5%
$f_0(1370) K_s$	0.82±0.10	308±8	0.9%
$K^*(892)^-\pi^+$	1.656±0.012	137.6±0.6	60%
$K^*(892)^+\pi^-$	0.149±0.007	325.2±2.2	0.5%
$K^*_0(1430)^-\pi^+$	1.96±0.04	357.3±1.5	5.8%
$K^*_0(1430)^+\pi^-$	0.30±0.05	128±8	0.1%
$K^*_2(1430)^-\pi^+$	1.32±0.03	313.5±1.8	2.8%
$K^*_2(1430)^+\pi^-$	0.21±0.03	281.5±9	0.07%
$K^*(1680)^+\pi^-$	2.56±0.22	70±6	0.4%
$K^*(1680)^-\pi^+$	1.02±0.22	102±11	0.07%
Non resonant	6.1±0.3	146±3	24%

Sum of two-body amplitudes:

$$f = a_{K^*} e^{i\varphi_{K^*}} [F_D F_{K^*} M^J BW(m^2_{K_s\pi^-})] + a_\rho e^{i\varphi_\rho} [F_D F_\rho M^J BW(m^2_{\pi^+\pi^-})] + \ldots$$



$D^{*-} \to D^0\pi^-$, $D^0 \to K_s\pi^+\pi^-$ Dalitz plot



B candidate selection

Pairs of B mesons are produced in $Y(4S)$ decays (near $B\bar{B}$ mass threshold)

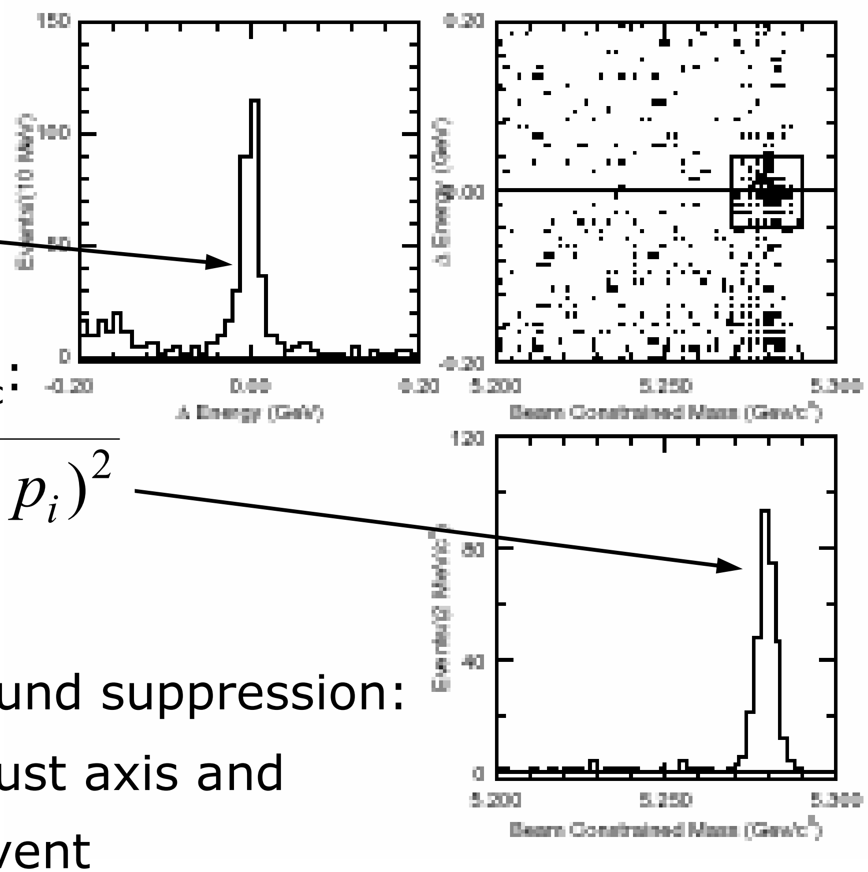
$\Rightarrow E_B = E_{cm}/2$, low p in CM frame

CM energy difference:

$$\Delta E = \sum E_i - (E_{cm}/2)$$

B meson beam-constrained mass M_{bc}:

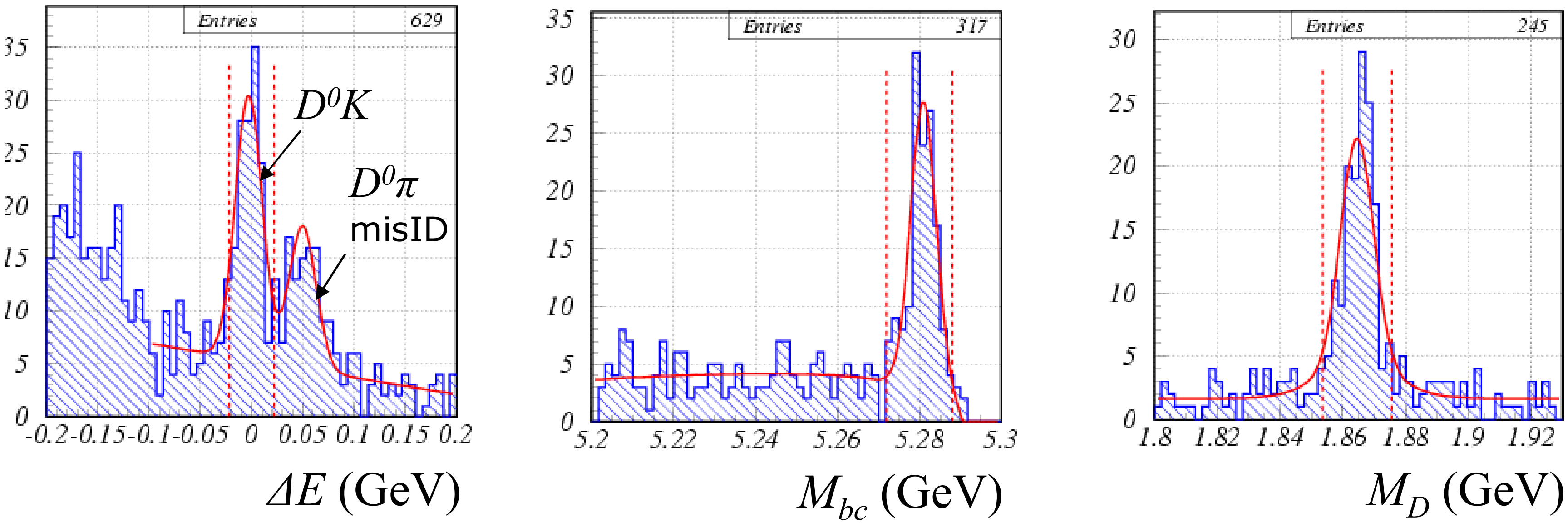
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - (\sum p_i)^2}$$



Continuum ($e^+e^- \to uu,dd,ss$) background suppression:

- Angle between B candidate thrust axis and thrust axis of the rest of the event
- Fisher discriminant based on "virtual calorimeter"

$B^+ \to D^0 K^+$ signal with 140 fb ^{1}



12% reconstruction efficiency

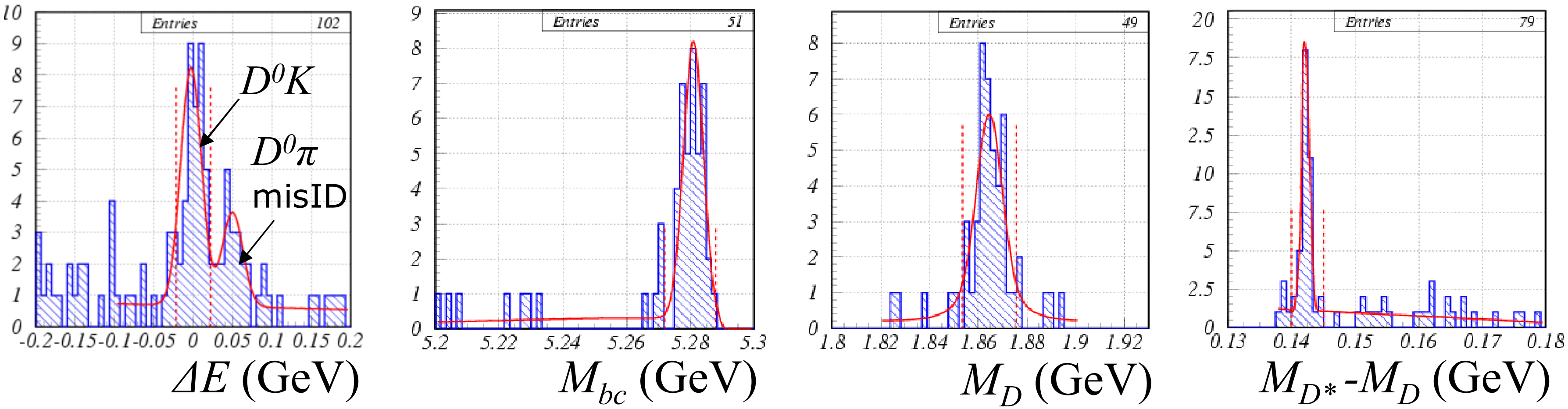
146 events

112±12 signal

36±3 background (25%)

- $|\Delta E|$<22 MeV
- 5.272<M_{bc}<5.288 GeV
- $|M_D$-1.86 GeV$|$<11 MeV
- $|\cos\Theta_{thr}|$<0.8
- Fisher discriminant $\mathcal{F}$>-0.7
- PID(K/π)>0.7

$B^+ \to D^{*0} K^+$ signal with 140 fb^{-1}



6.2% reconstruction efficiency

39 events

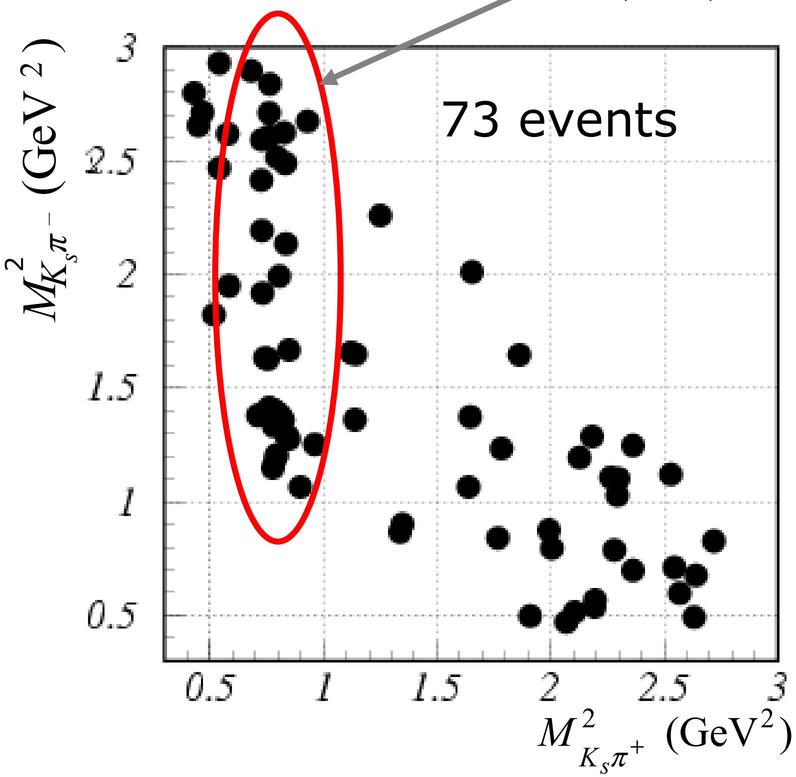
33.6±6.2 signal

4.6±1.1 background (12%)

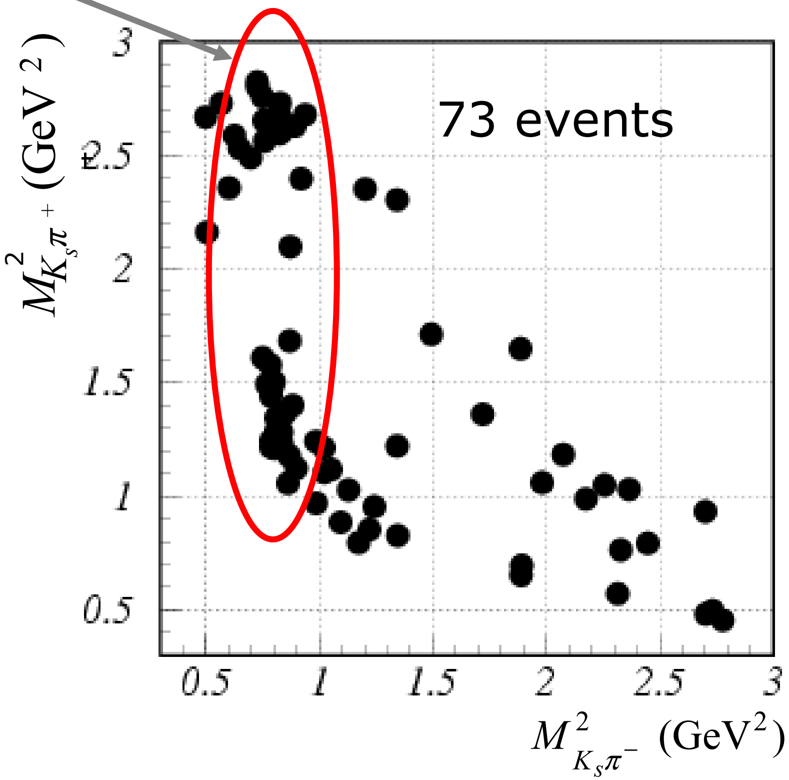
- $|\Delta E|$<22 MeV
- 5.272<M_{bc}<5.288 GeV
- $|M_D$-1.86 GeV$|$<11 MeV
- 140<M_{D*}-M_D<145 MeV
- $|\cos\Theta_{thr}|$<0.8
- Fisher discriminant $\mathcal{F}$>-0.7
- PID(K/π)>0.7

$B^+ \to D^0 K^+$, $D^0 \to K_s \pi^+ \pi^-$ Dalitz plot

$K^*(892)$ bands

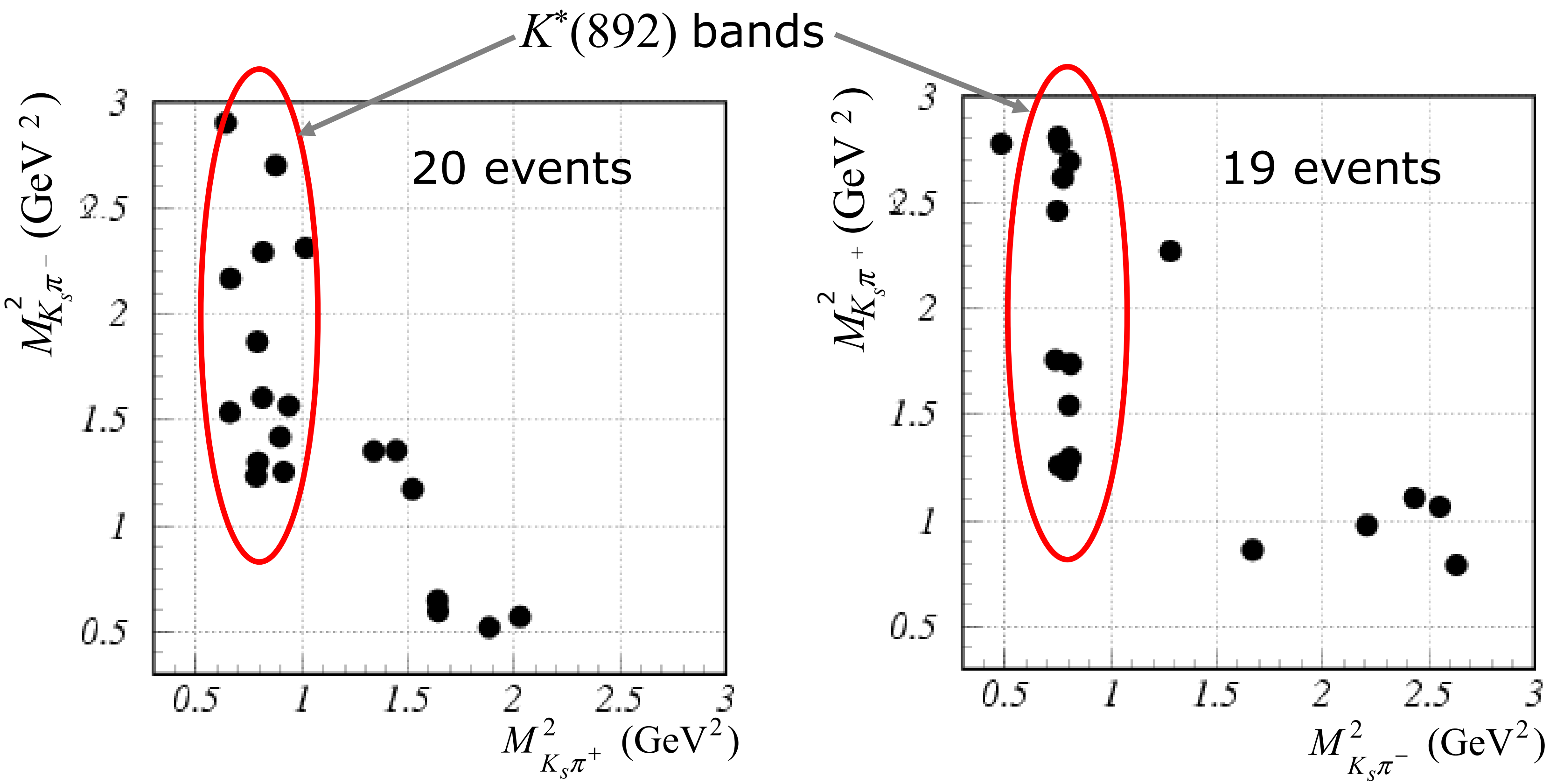


D^0 from $B^+ \to D^0 K^+$



D^0 from $B^- \to D^0 K^-$
(π^+ and π^- interchanged)

$B^+\to D^{*0}K^+$, $D^0\to K_s\pi^+\pi^-$ Dalitz plot



D^0 from $B^+\to D^{*0}K^+$

D^0 from $B^-\to D^{*0}K^-$
(π^+ and π^- interchanged)

Likelihood function

Minimizing logarithmic likelihood:

$$-2\log\mathcal{L} = -2\sum_{i=1}^{N}\log f(m_{+,i}^2, m_{-,i}^2) + 2\log\int f(m_+^2, m_-^2)\,\mathrm{d}m_+^2\,\mathrm{d}m_-^2$$

$m_{+,i}^2, m_{-,i}^2$ are Dalitz plot points

$$f(m_+^2, m_-^2) = |M(m_+^2, m_-^2)|^2 \times \varepsilon(m_+^2, m_-^2) \oplus \sigma_p(m_{\pi^+\pi^-}^2) + b(m_+^2, m_-^2)$$

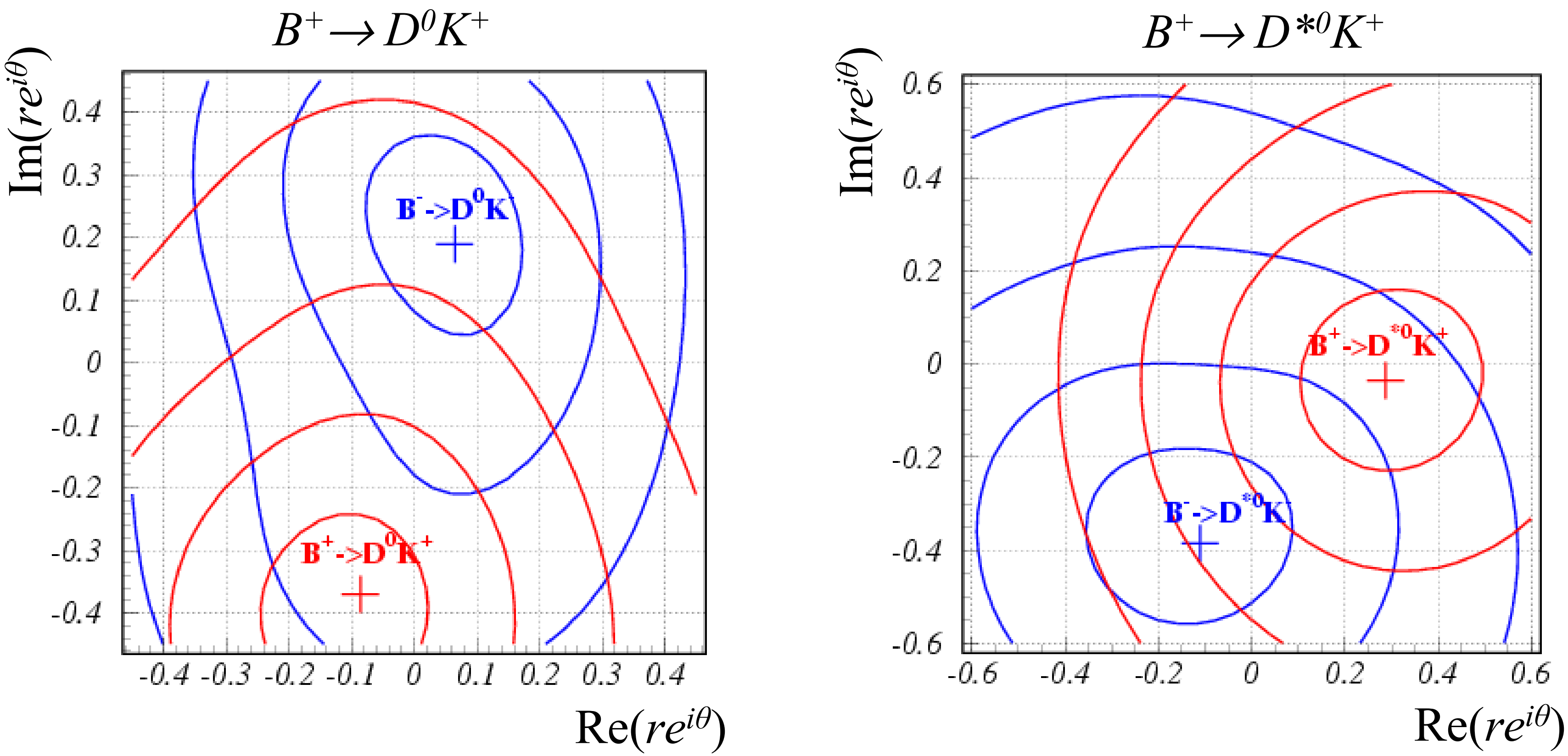
Matrix element $M(m_+^2, m_-^2) = f(m_+^2, m_-^2) + re^{i\theta} f(m_-^2, m_+^2)$

Efficiency shape $\varepsilon(m_+^2, m_-^2)$ - from phase-space MC

Momentum resolution $\sigma_p(m_{\pi^+\pi^-}^2)$ - from phase-space MC

Background $b(m_+^2, m_-^2)$

$B^+ \to D^{(*)0} K^+$ fit results

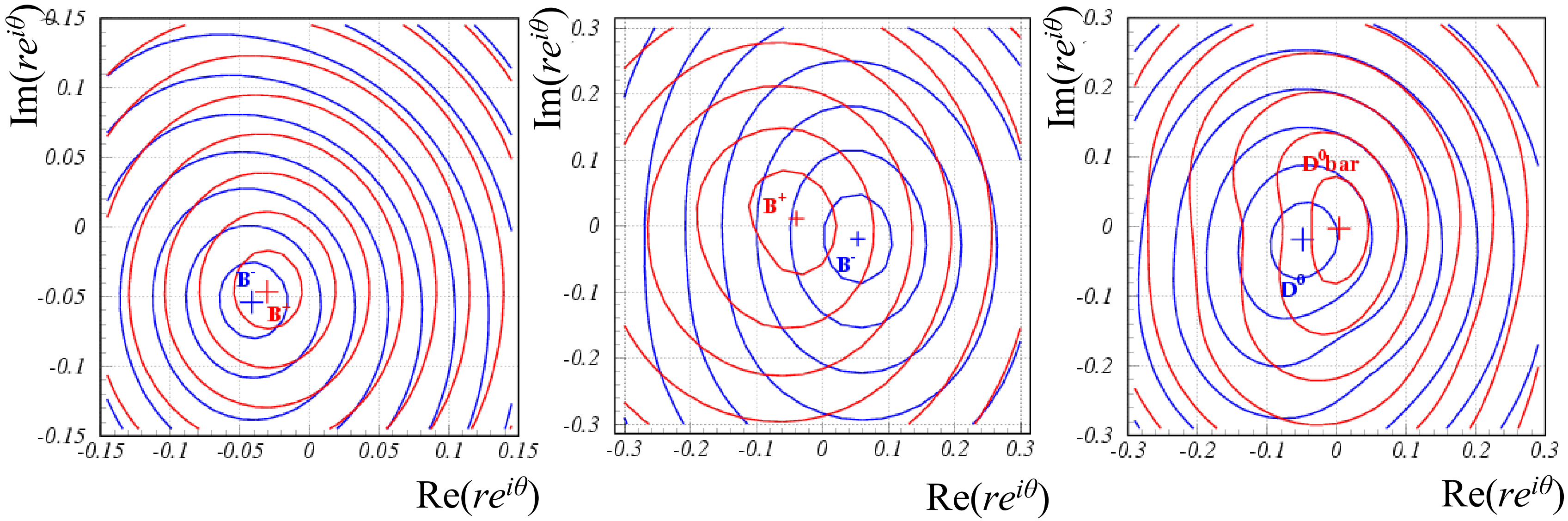


$r_+ = 0.40 \pm 0.15$, $\theta_+ = 256 \pm 19°$
$r_- = 0.21 \pm 0.15$, $\theta_- = 71 \pm 37°$

$r_+ = 0.29 \pm 0.19$, $\theta_+ = 353 \pm 38°$
$r_- = 0.38 \pm 0.19$, $\theta_- = 249 \pm 32°$

Test sample fits

$B^+ \to D^0\pi^+$ (1850 events) $B^+ \to D^{*0}\pi^+$ (351 events) $B^0 \to D^{*+}\pi^-$ (517 events)

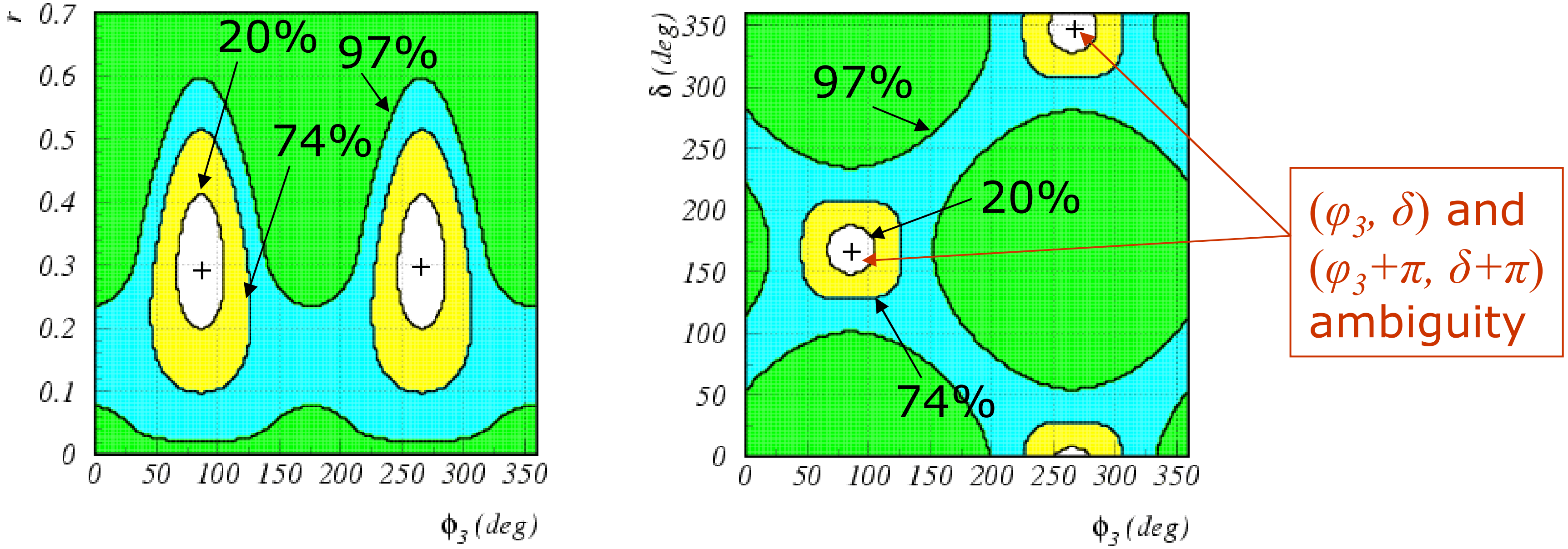


r_+=0.065±0.029, θ_+=232±24° r_+=0.041±0.069, θ_+=164±100° r_+=0.005±0.058, θ_+=324±686°

r_-=0.069±0.027, θ_-=228±23° r_-=0.057±0.054, θ_-= 340±65° r_-=0.052±0.053, θ_-= 201±57°

Bias in $B^+ \to D^0\pi^+$ sample (background, fluctuation?),
however, no CP violation observed

$B^+ \to D^0 K^+$ constraints



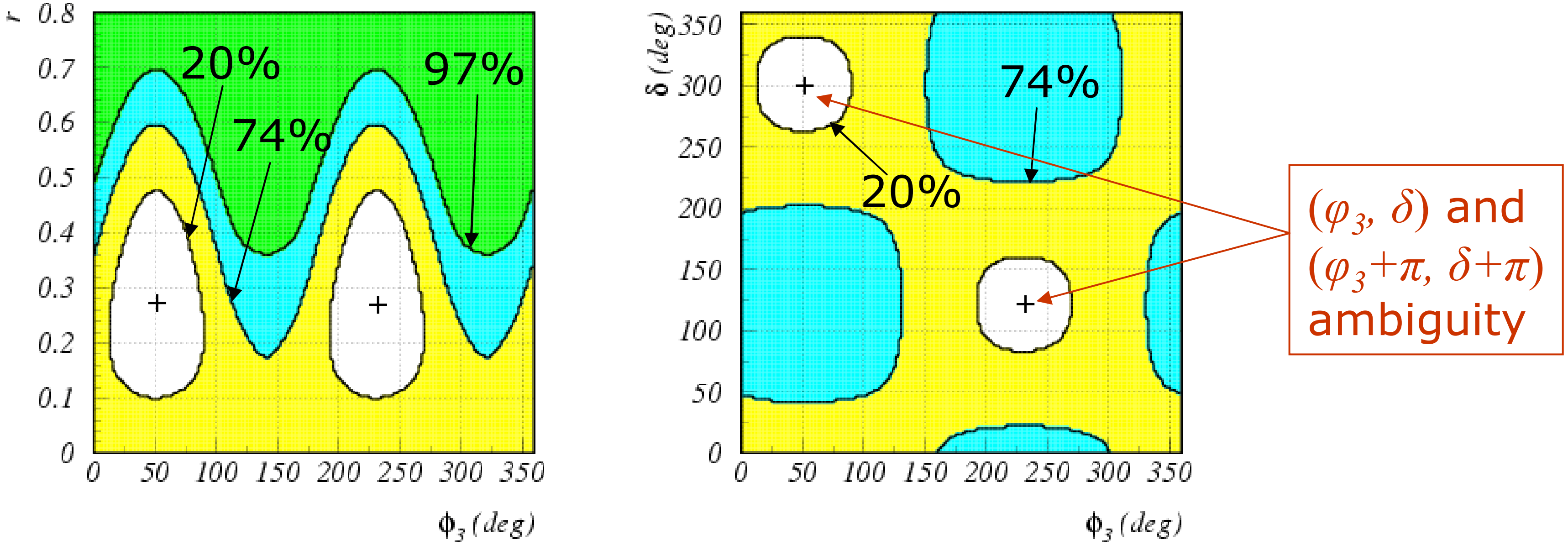
$r=0.28^{+0.09}_{-0.11}$, $\varphi_3=86\pm20°$, $\delta=168\pm20°$ — <68% CL interval from MC-based PDF

$0.07<r<0.45$, $37°<\varphi_3<135°$, $119°<\delta<217°$ — <95% CL interval.

CP violation significance: 94% ($\varphi_3\neq0$).

$r > 0$ with 97% CL.

$B^+ \to D^{*0} K^+$ constraints



$r<0.25$, $\varphi_3=51\pm47°$, $\delta=302\pm47°$ — <68% CL interval from MC-based PDF

$r<0.44$, $-31°<\varphi_3<133°$, $220°<\delta<384°$ — <95% CL interval.

CP violation significance: 38% ($\varphi_3\neq0$).

Estimation of systematic errors

	$B^+ \to D^0 K^+$	$B^+ \to D^{*0} K^+$
Background shape	4.6°	1.3°
Background fraction	0.1°	0.6°
Efficiency shape	3.5°	0.8°
Momentum resolution	2.5°	2.5°
$B^+ \to D^0 \pi^+$ test sample bias:	11°	11°
Total	13°	11°

Model uncertainty

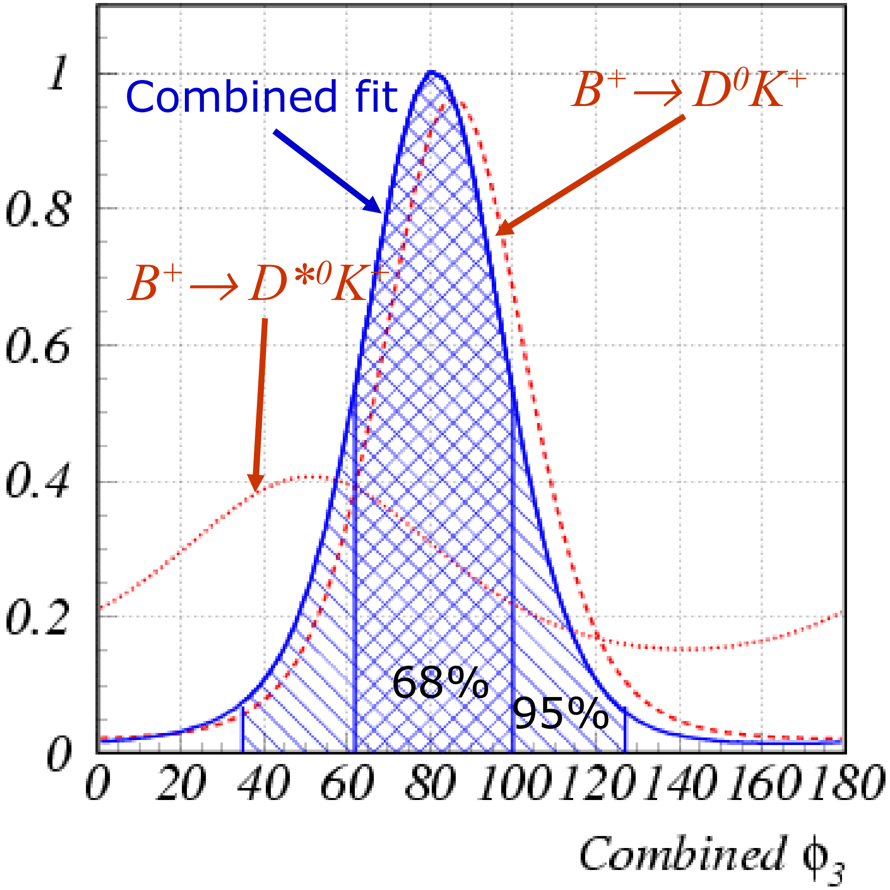
D^0 decay amplitude $f = |f(m_+^2, m_-^2)|\, e^{i\phi(m_+^2, m_-^2)}$

$|f(m_+^2, m_-^2)|^2$ directly measured

$\phi(m_+^2, m_-^2)$ model-dependent

Fit model	$(\Delta\varphi_3)_{max}$,°
K^*, ρ, ω, f_0 + non-resonant	9.9
Meson formfactors $F_r = F_D = 1$	3.1
Constant BW width $\Gamma(q^2) = Const$	4.7
Non-resonant amplitude $a_{NR} = 0$	0.4
No $\sigma(500)$	0.7
Total	11

$B^+ \to D^0 K^+$ and $B^+ \to D^{*0} K^+$ combined



Multiply φ_3 PDF's for $B^+ \to D^0 K^+$ and $B^+ \to D^{*0} K^+$ samples
(r and δ left independent)

Stat. confidence intervals:

$\varphi_3 = 81 \pm 19°$ (68% CL)

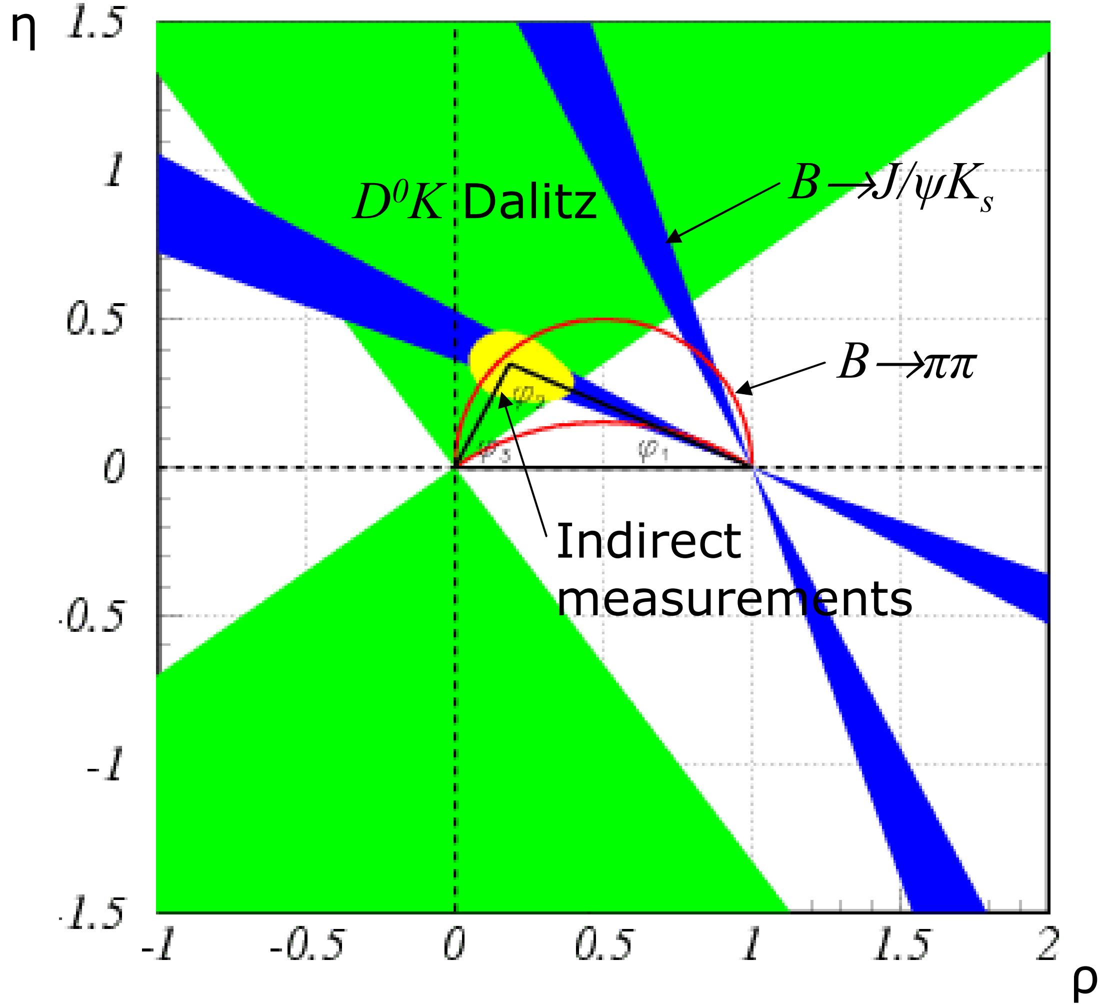
$\varphi_3 = 81 \pm 46°$ (95% CL)

Combined result:

$\varphi_3 = 81 \pm 19° \pm 13°(\text{syst}) \pm 11°(\text{model})$

Constraints on unitarity triangle

<95% CL regions



Conclusion

- $B^+\to D^0K^+$ and $B^+\to D^{*0}K^+$, $D^0\to K_s\pi^+\pi^-$ samples analyzed with 140 fb^{-1}

  φ_3=81°±19°±13°(syst)±11°(model) for combined fit

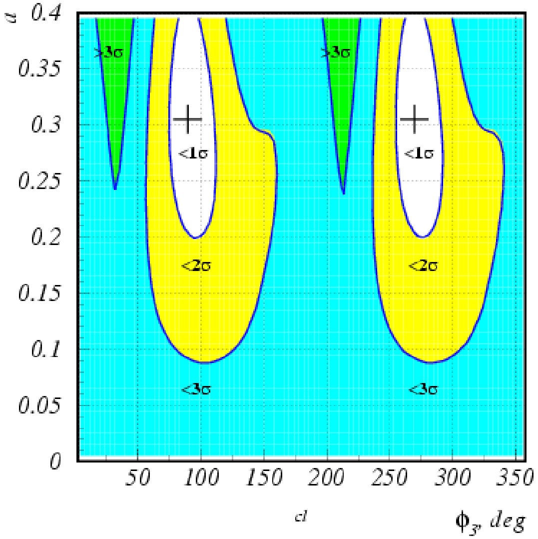
  95% CL interval from combined fit: $35° < \varphi_3 < 127°$
- Direct CP violation effect significance is 94%.
- A new promising method to measure φ_3 using Dalitz plot analysis of D^0 from $B\to D^{(*)0}K$ decay is applied to the data collected by Belle.
- Advantages:
  - Higher statistical power than methods based on branching fractions
  - No absolute branching fractions involved ⇒ lower detector systematics
  - Model-independent approach exists based on the cτ-factory data.
- The precision can be increased by adding other suitable modes (neutral B decays, other three- and four-body D^0 decays)

$D^0 \to K_s \pi^+ \pi^-$ fit result (discussion)

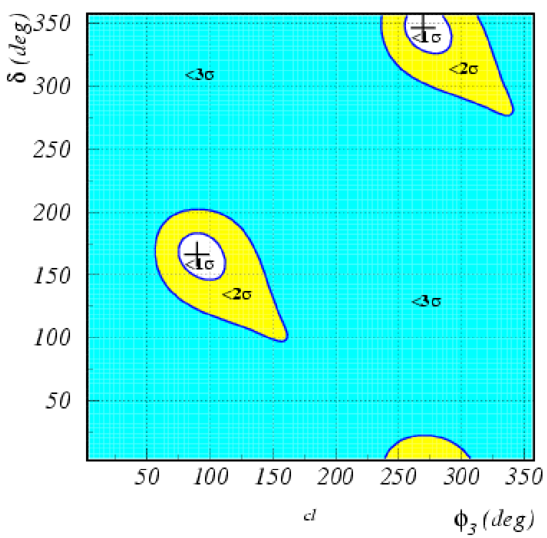
- Needed to introduce two scalars in $\pi^+\pi^-$ channel:
  - σ_1 with mass M=538±9 MeV, BW width Γ=452±15 MeV
  - σ_2 with mass M=1048±8 MeV, BW width Γ=109±11 MeV
- Large non-resonant amplitude observed.
  - Correlated with σ_1 amplitude:
    - a_{NR}=4.66±0.15 for a_σ =0 (compared to 6.1±0.3)
    - a_σ =0.78±0.05 for a_{NR}=0 (compared to 1.65±0.10)
  - Probably indicates poor description of σ_1. Consider as a systematic effect.
- Use symmetric set of resonances, i.e. take doubly Cabibbo suppressed partners for all flavor-specific modes ($K^*(892)^+\pi^-$, $K^*_0(1430)^+\pi^-$, $K^*_0(1430)^+\pi^-$, $K^*(1680)^+\pi^-$). Otherwise systematic bias of opposite flavor admixture r.

$B^+ \to D^0 K^+$ fit result

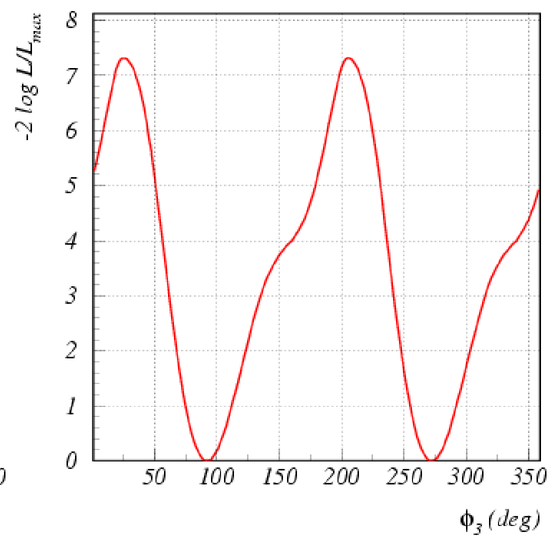
Error estimation from the fit likelihood



CL vs. (δ, φ_3)



CL vs. (r, φ_3)

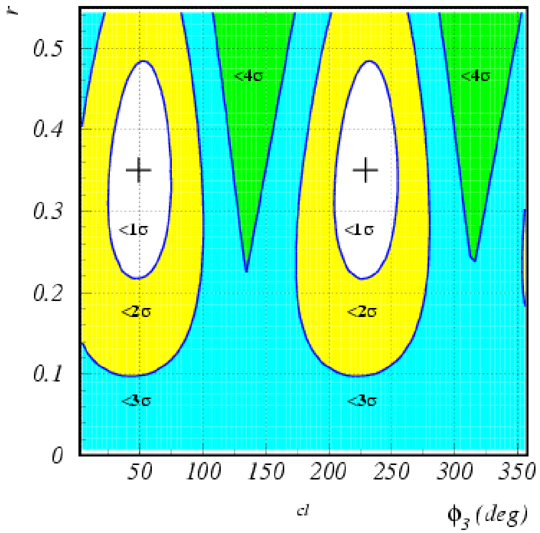


$-2 \log L$ vs. φ_3

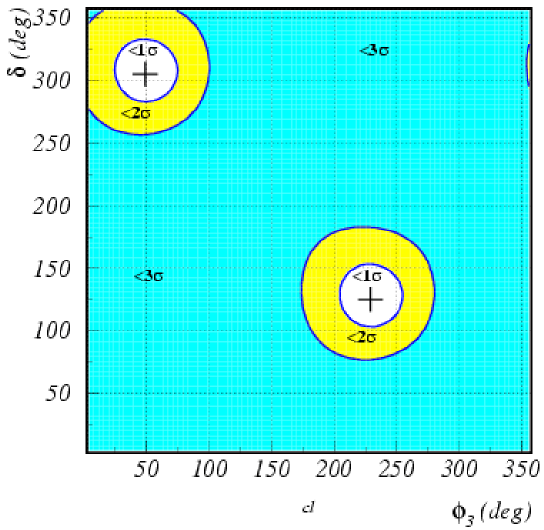
$r=0.31\pm0.11$, $\varphi_3=86\pm17°$, $\delta=168\pm17°$ or $(\varphi_3+\pi, \delta+\pi)$

$B^+ \to D^{*0} K^+$ fit result

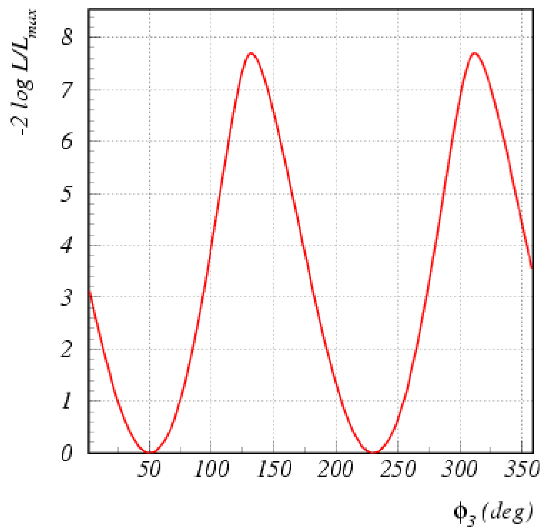
Error estimation from the fit likelihood



CL vs. (δ, φ_3)



CL vs. (r, φ_3)



-2 log L vs. φ_3

r=0.34±0.14, φ_3=51±25°, δ=302±25° or $(\varphi_3+\pi, \delta+\pi)$

Parameterization of fit PDF

PDF for the single Dalitz plot fit:

$$d^2P(r,\theta) \propto \exp[-\frac{(r\cos\theta - \bar{r}\cos\bar{\theta})^2 + (r\sin\theta - \bar{r}\sin\bar{\theta})^2}{2\sigma^2}]rdrd\theta$$

$\bar{r},\bar{\theta}$ - *true* values, r,θ - *reconstructed* values

PDF of *reconstructed* values r,φ_3,δ for a given set of *true* values $\bar{r},\bar{\varphi}_3,\bar{\delta}$ for combined fit of two Dalitz plots (B^+ and B^-):

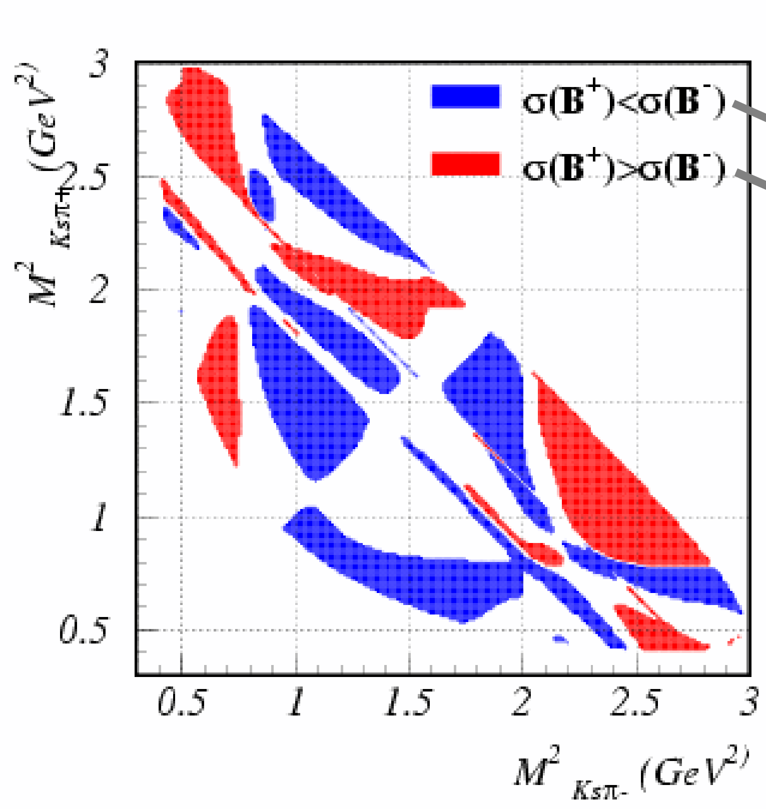
$$\frac{d^3P}{drd\varphi_3 d\delta}(r,\varphi_3,\delta) \propto \frac{d^2P}{drd\theta_+}(r,\delta+\varphi_3)\cdot\frac{d^2P}{drd\theta_-}(r,\delta-\varphi_3)$$

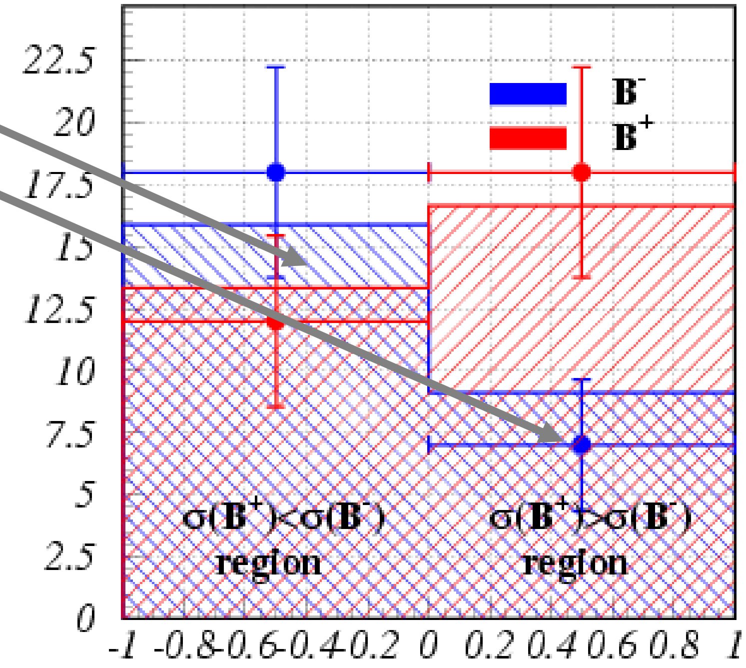
Can also obtain PDF of *true* values $\bar{r},\bar{\varphi}_3,\bar{\delta}$ for a given set of *reconstructed* values r,φ_3,δ with this parameterization. This PDF is used to obtain confidence intervals and significance.

Backgrounds

	$B \to D^0 K$	$B \to D^{*0} K$
• $q\bar{q}$ combinatorial (including real D^0) – Fraction: from ΔE distribution – Dalitz plot: from continuum data	22.1%	9.0%
• Other B decays – Fraction and Dalitz plot: from generic MC	2.2%	2.1%
• "Wrong" particles in D^0 decay – Fraction and Dalitz plot: from $B \to D^0 K$ MC	1.0%	0.6%
• $B \to D^0 \pi$ with K/π misID – Fraction: from ΔE distribution – Dalitz plot: D^0	0.4%	0.4%
• Flavor tagging K from combinatorics – Fraction from MC	<0.4%	<0.4%

Illustration of CP asymmetry





Select regions on Dalitz plot with $\sigma(B^+)>\sigma(B^-)$ or $\sigma(B^-)>\sigma(B^+)$ by >20%

Calculate the number of B^+ and B^- decays in each of the regions.

CP asymmetry ⇒ difference in number of B^+ and B^- events