$\phi_3(\gamma)$ measurement by $B^0 \to [K_S^0\pi^+\pi^-]_D K^{*0}$ at Belle

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BELLE

Introduction

- CKM (Cabibbo-Kobayashi-Maskawa) matrix
  - The quark mixing matrix, which is unitary.

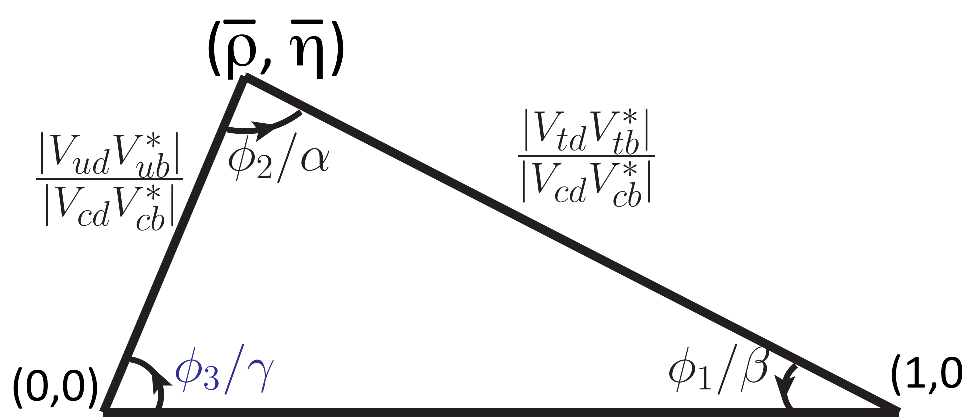
Complex phase

$$V_{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Unitary triangle $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$\phi_3/\gamma \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right)$$

$$\sim -\arg(V_{ub})$$



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- Unitary triangle

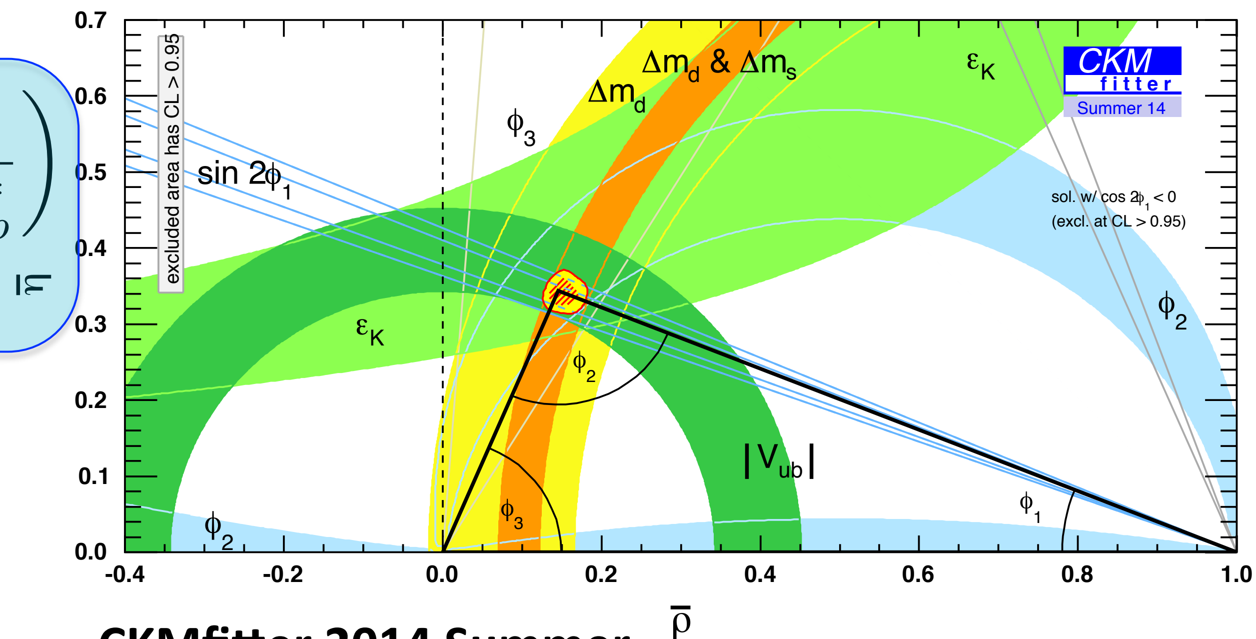
$$\phi_3/\gamma \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right)$$

$$\sim -\arg(V_{ub})$$

$$\phi_1 = (21.50^{+0.75}_{-0.74})^\circ$$

$$\phi_2 = (85.4^{+4.0}_{-3.9})^\circ$$

$$\phi_3 = (70.0^{+7.7}_{-9.0})^\circ$$

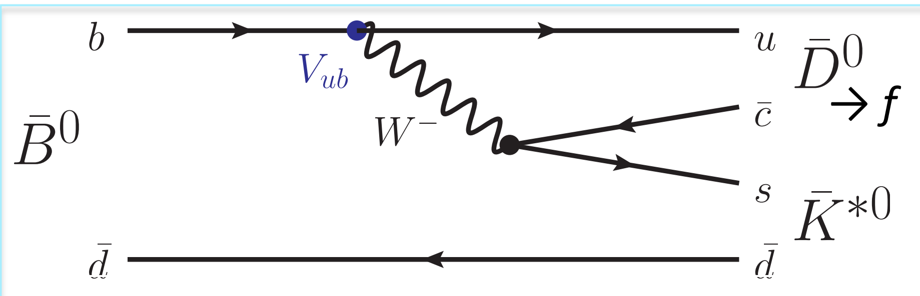


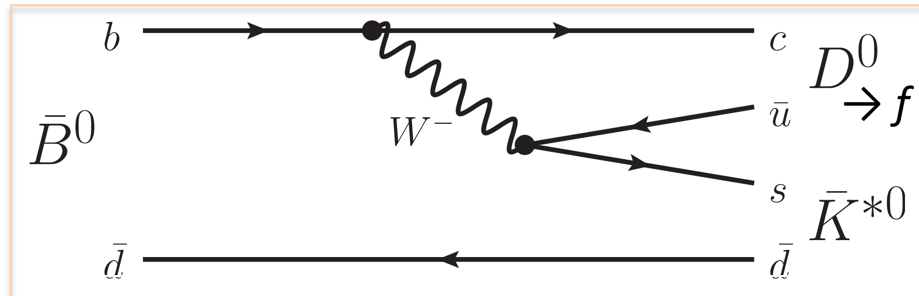
CKMfitter 2014 Summer

ϕ_3 Measurement

$\bar{B}^0 \to [f]_D \bar{K}^{*0}$

(No penguin)





$$V_{ub}V_{cs}^* \sim A\lambda^3(\rho + i\eta)$$

$$V_{cb}V_{us}^* \sim A\lambda^3$$

- B flavor can be decided by the charge of K from K^{*0}.

Br($K^{*0} \to K^+\pi^-$) = 2/3

– Access ϕ_3 with interference $\bar{D}^0\bar{K}^{*0}$ and $D^0\bar{K}^{*0}$ decays.

	Weak Int. phase	Strong Int. phase	Amp.
Difference between D^0K^{*0} and $\bar{D}^0K^{*0}$	ϕ_3	δ_S	$r_S \equiv \left\| \frac{A(\bar{B}^0 \to \bar{D}^0 \bar{K}^{*0})}{A(\bar{B}^0 \to D^0 \bar{K}^{*0})} \right\|$

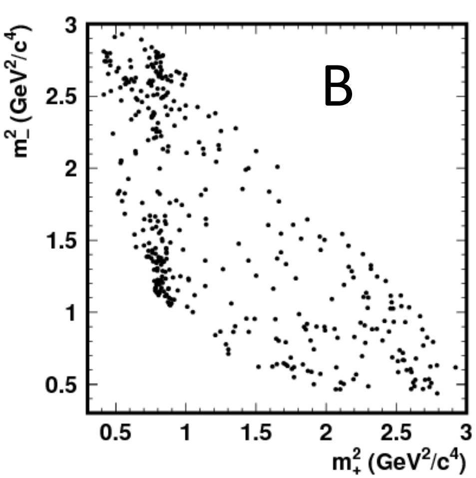
r_S is crucial parameter in ϕ_3 measurement.
(Expected to be ~0.3.)

Dalitz Analysis Method

- Measure $\bar{B}^0/B^0$ asymmetry across Dalitz plot.
  - D is required to decay in to three body like $K_S^0\pi^+\pi^-$.

$$\bar{B}^0 \to [K_S^0\pi^+\pi^-]_D \bar{K}^{*0}$$

$$A_{\bar{B}^0(B^0)} = f(m_+^2, m_-^2) + r_S e^{i(\delta_S \pm \phi_3)} f(m_-^2, m_+^2)$$



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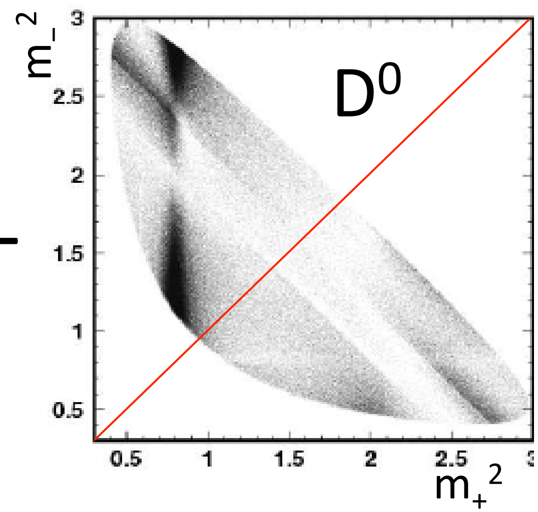
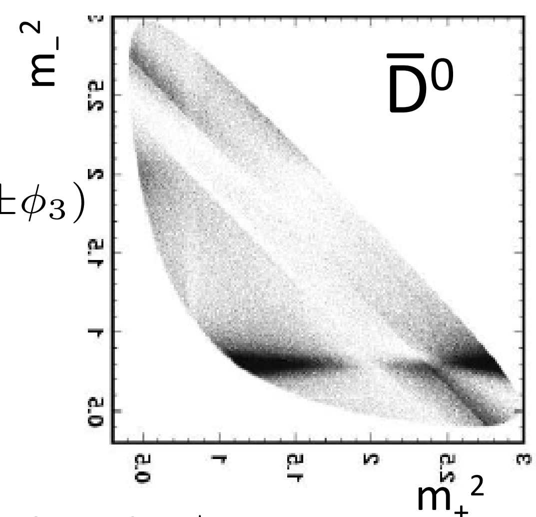


$$+ r_S e^{i(\delta_S \pm \phi_3)}$$

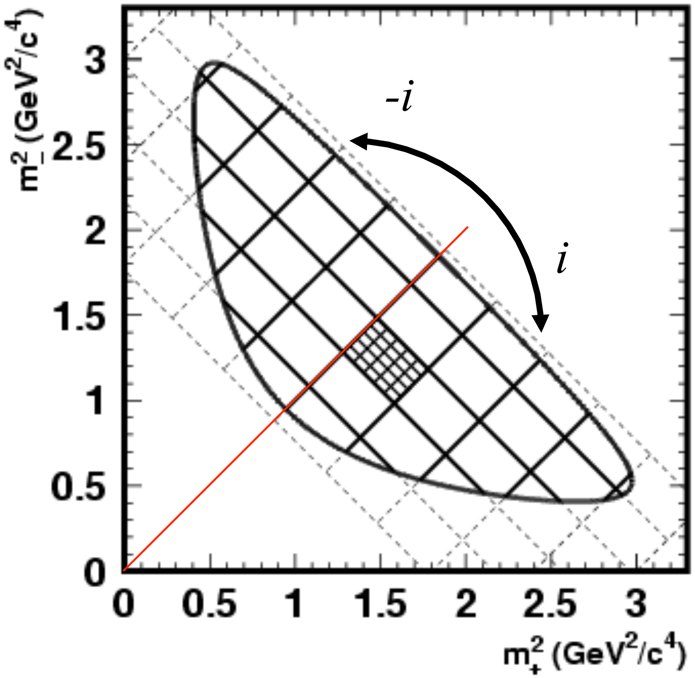


$$m_\pm^2 \equiv m^2(K_S^0\pi^\pm)$$

- Sensitivity to ϕ_3 in interference term.
  - $|f(m^2_+, m^2_-)|$ from flavor-tagged $D^{*+} \to D^0\pi^+$ events.
  - Phase difference(δ_D) between $D^0/\bar{D}^0$ from Charm-Factory.

Model-Independent Dalitz

[A. Giri, Y. Grossman, A. Soffer, J. Zupan, PRD 68, 054018 (2003)]



Number of events in **D⁰**-plot : K_i

Number of events in **B**-plot :

$$N_i = h_B[K_i + (x^2+y^2)K_{-i} + 2k\sqrt{K_iK_{-i}}(xc_i + ys_i)]$$

$$C(m_+^2, m_-^2) = \cos(\delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2))$$

$$S(m_+^2, m_-^2) = \sin(\delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2))$$

From Charm-Factory

$D_{CP} \to K_S^0\pi^+\pi^-$

$$P_{CP\pm}(m_+^2, m_-^2) = \mid f_D \pm \bar{f}_D \mid^2 = P_D + \bar{P}_D \pm 2\sqrt{P_D\bar{P}_D}C$$

$\Psi(3770) \to [K_S^0\pi^+\pi^-]_D[K_S^0\pi^+\pi^-]_D$

$$P_{Corr.}(m_+^2, m_-^2, m_+'^2, m_-'^2) = \mid f_D\bar{f}_D' - \bar{f}_D f_D' \mid^2$$

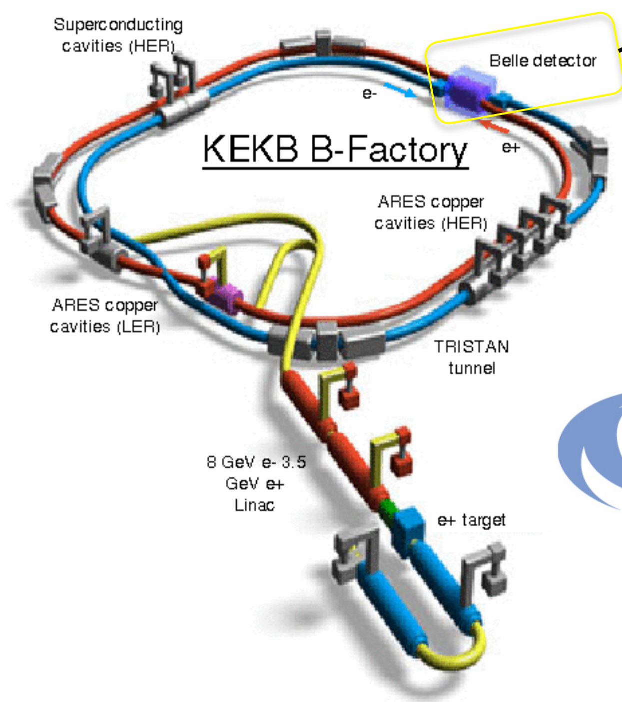
$$= P_D\bar{P}_D' + \bar{P}_D P_D' - 2\sqrt{P_D\bar{P}_D P_D'\bar{P}_D'}(CC' + SS')$$

where
$$\left.\begin{aligned} x_\pm &= r_S\cos(\delta_S \pm \phi_3) \\ y_\pm &= r_S\sin(\delta_S \pm \phi_3) \end{aligned}\right\}$$
observables

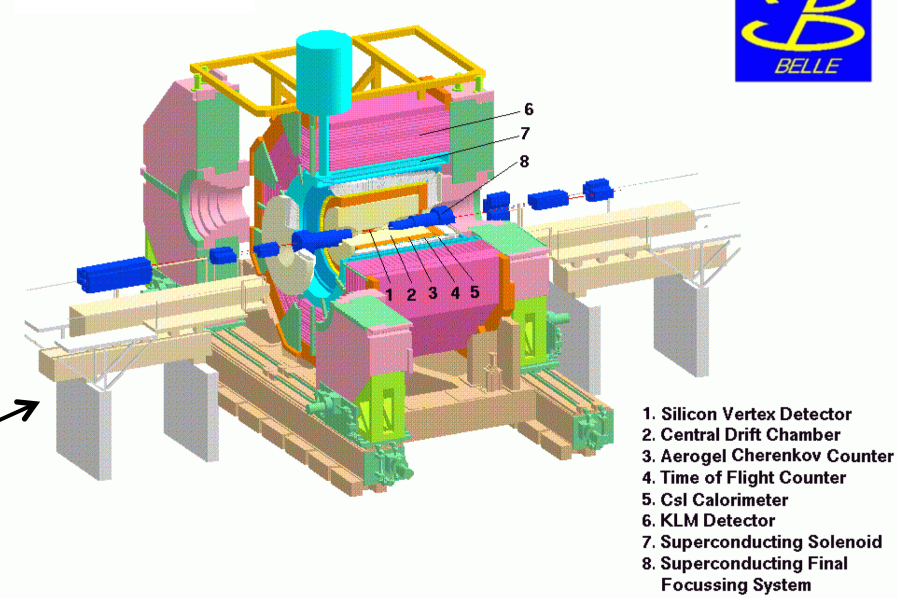
Belle Experiments

KEKB accelerator

- Asymmetric energy collision
  - (8.0 v.s. 3.5 GeV)
- 10.58 GeV center of mass energy at $\Upsilon(4S)$ resonance; It is suitable for BB production.
- 772×10^6 BB pair



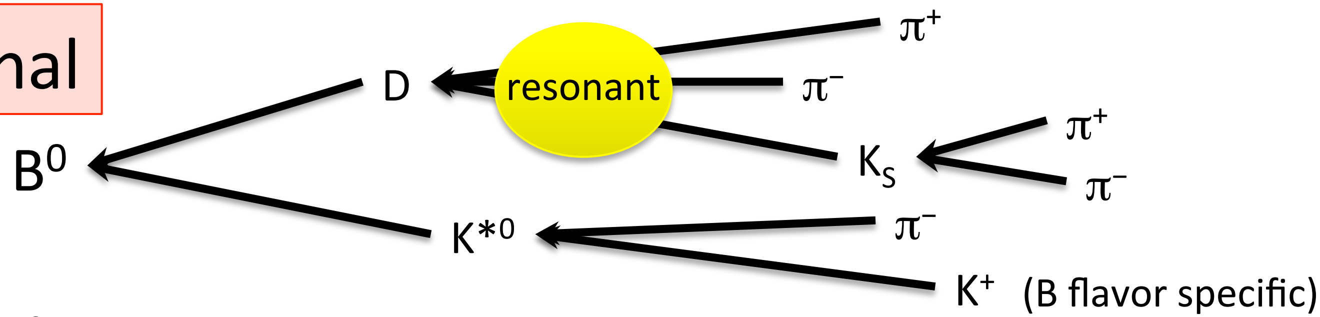
Belle detector



- Charged particle momentum ($\sigma_{pt}/p_t(\%) = 0.19p_t \oplus 0.30\beta$)
- Good particle identification ((K/π) Eff. ~90%, Fake ~10%)
- Good vertex resolution (~50 μm)

Signal and Backgrounds

Signal



Peaking BG

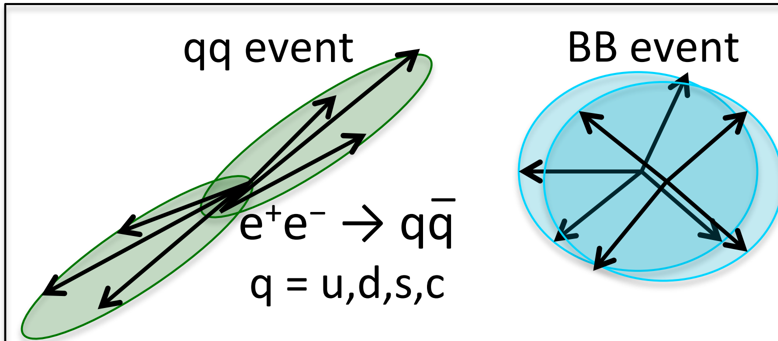
- 1 mis-PID π as K
  - $D^0\rho^0$
- 1mis-PID and 1 lost π
  - $D^0a_1^+$

BB BG

- Other B decay modes.
- Difficult to distinguish from signal.
  - D true BB BG
  - D fake BB BG

qq BG

- Light quark jets (u,d,s,c).
- Random mis-reconstruction makes fake signal candidate.



Rejection

Use decay shape difference.

Signal : spherical decay

qq BG : 2 jet-like decay

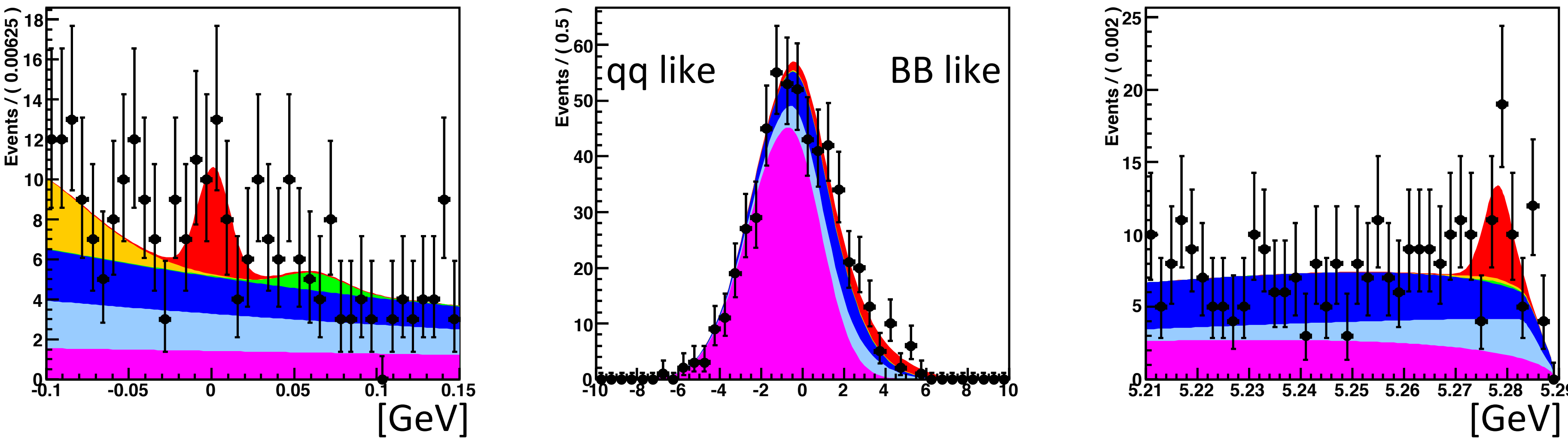
Neural network is used for multi variable analysis.

3D Fit for Signal Extraction

After reconstruction and BG rejection, 3-D fit (ΔE, C'_{NB}, M_{bc}) is done without Dalitz information.

Each component yield is free. Shapes are fixed.

Red : Signal Yellow : $D^0\rho^0$ Green : $D^0 a_1^+$ Blue : D fake BB Light blue : D true BB Magenta : qq



$$\Delta E \equiv E_B - E_{\mathrm{Beam}}$$

Energy difference btw. beam energy and B candidate.

C'_{NB}

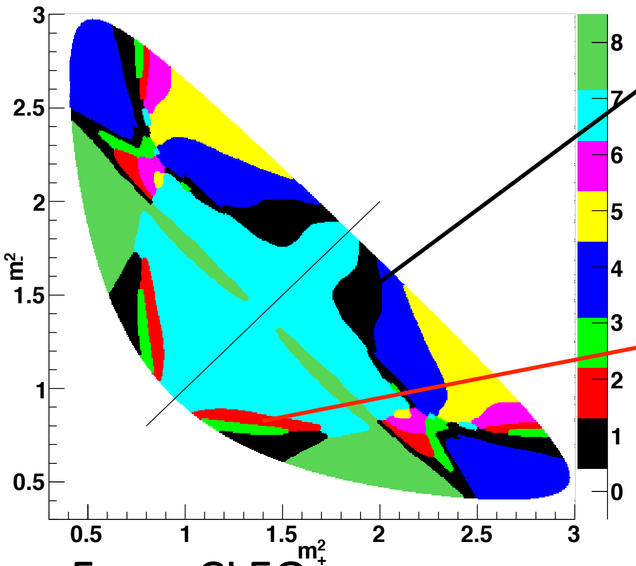
Modified distribution of Neural network output used qq suppression.

$$M_{\mathrm{bc}} \equiv \sqrt{E_{\mathrm{Beam}}^2 - p_B^2}$$

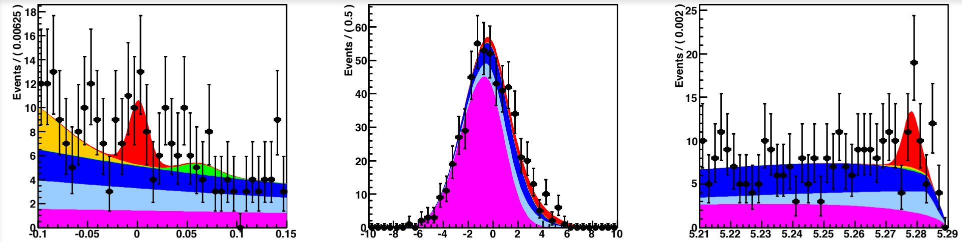
Mass of B candidate from beam energy and B's momentum.

Yield is $N_{total} = 44.2^{+13.3}_{-12.1}$ (statistic significance 2.8 σ), which are used for the (x,y) fit.

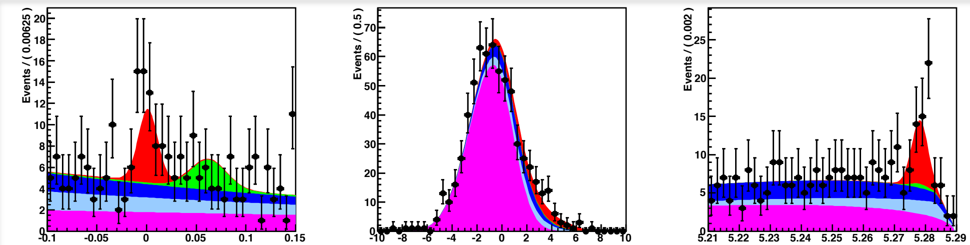
(x,y) Fit



From CLEO
PRD **82**, 112006 (2010)



Obtain the signal number, N_1.



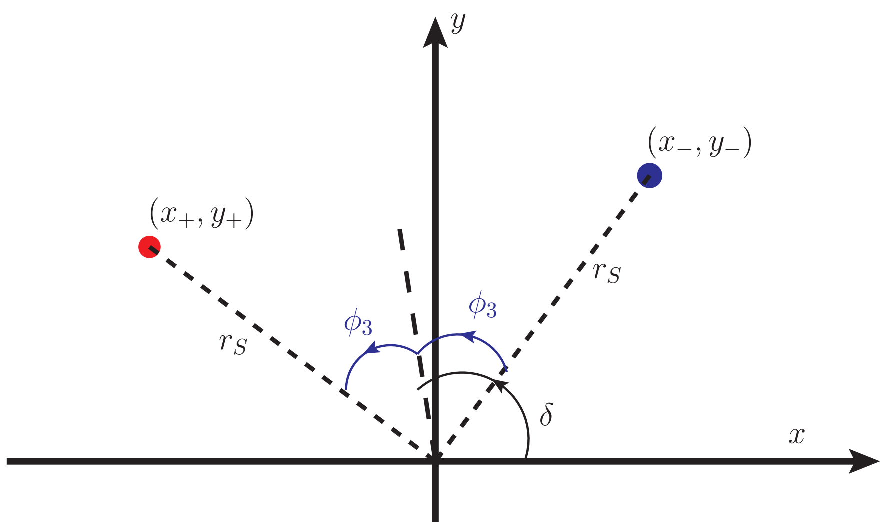
Obtain the signal number, N_2.

⋮

$$(B^0): N_i = h_B[K_i + (x_+^2 + y_+^2)K_{-i} + 2k\sqrt{K_iK_{-i}}(x_+c_i + y_+s_i)]$$

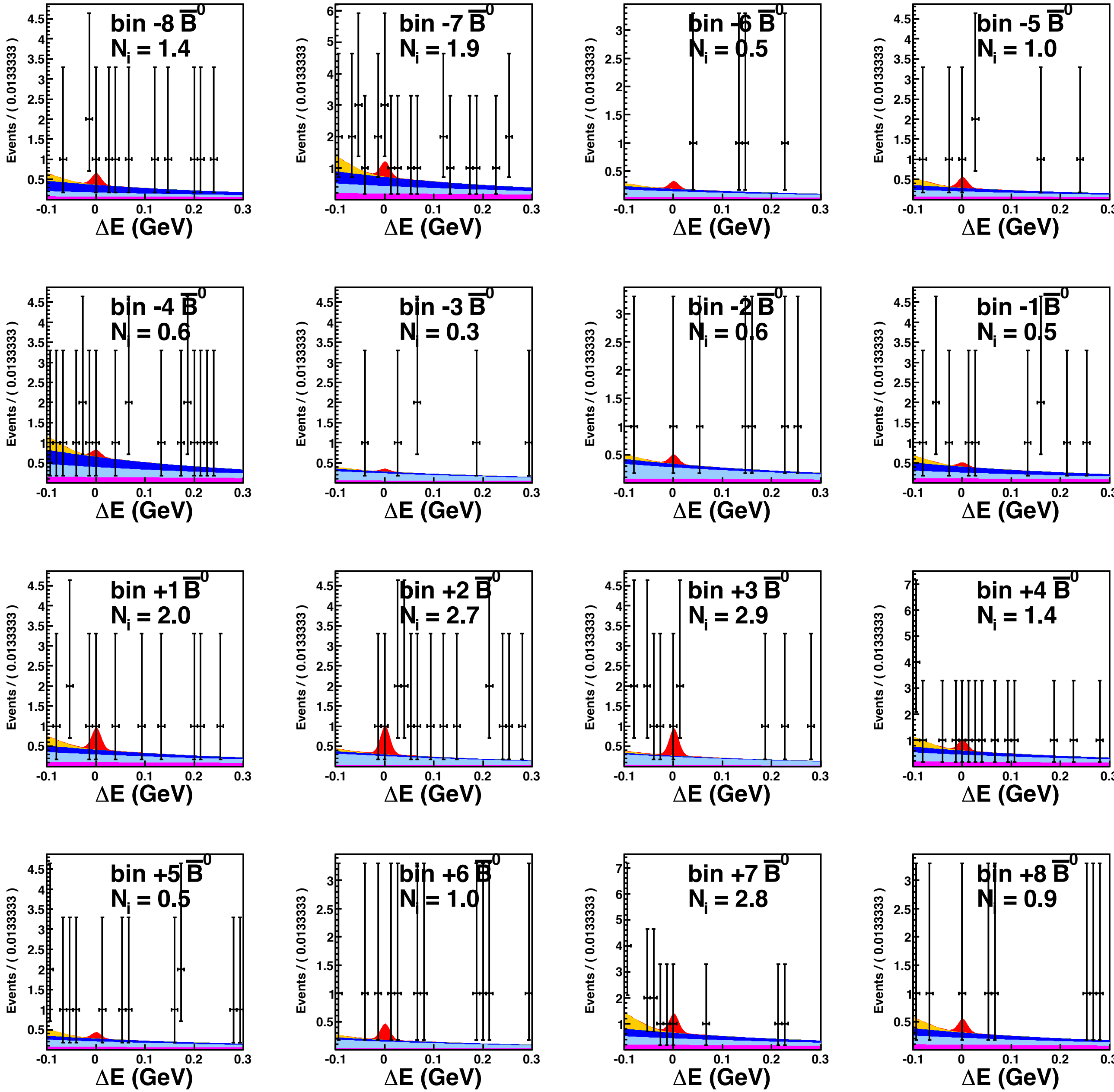
$$(\bar{B}^0): N_i = \bar{h}_B[K_i + (x_-^2 + y_-^2)K_{-i} + 2k\sqrt{K_iK_{-i}}(x_-c_i + y_-s_i)]$$

# Bin ($=i$)	c_i	s_i
1	-0.009	-0.438
2	$+0.900$	-0.490
3	$+0.292$	-1.243
4	-0.890	-0.119
5	-0.208	$+0.853$
6	$+0.258$	$+0.984$
7	$+0.869$	-0.041
8	$+0.798$	-0.107



K_i from $D^{*+} \to D^0\pi^+$, D^0 decay

(x, y) Result



BG fractions btw bins for each component are fixed from MC.

stat. syst. c_i, s_i

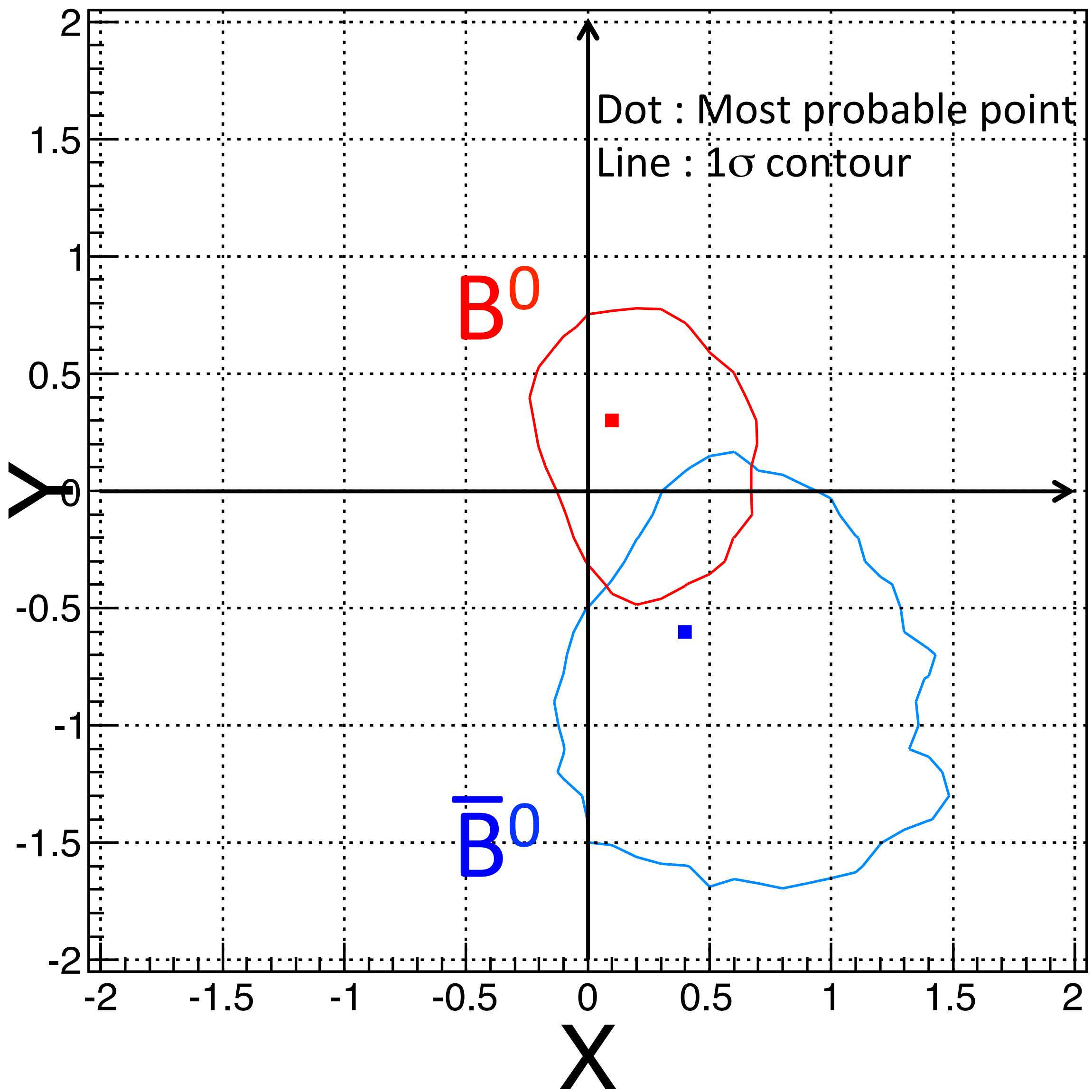
$$x_- = +0.4^{+1.0}_{-0.6}\,{}^{+0.0}_{-0.1} \pm 0.0$$

$$y_- = -0.6^{+0.8}_{-1.0}\,{}^{+0.1}_{-0.0} \pm 0.1$$

$$x_+ = +0.1^{+0.7}_{-0.4}\,{}^{+0.0}_{-0.1} \pm 0.1$$

$$y_+ = +0.3^{+0.5}_{-0.8}\,{}^{+0.0}_{-0.1} \pm 0.1$$

(x, y) Result



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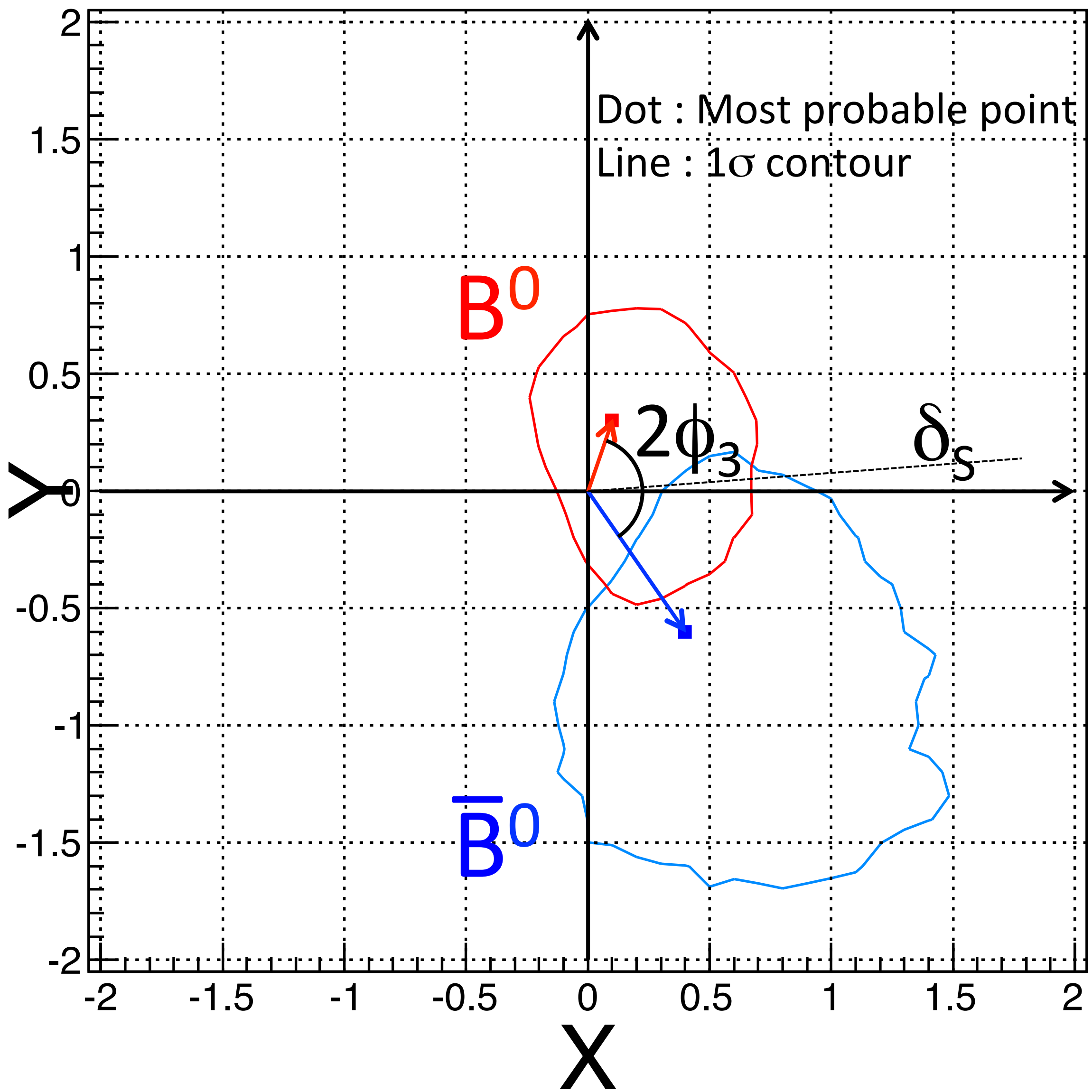
(x, y) Result



(x_+, y_+) (B^0) is 0 consistent.

stat. syst. c_i, s_i

$$x_- = +0.4^{+1.0}_{-0.6}\,^{+0.0}_{-0.1} \pm 0.0$$

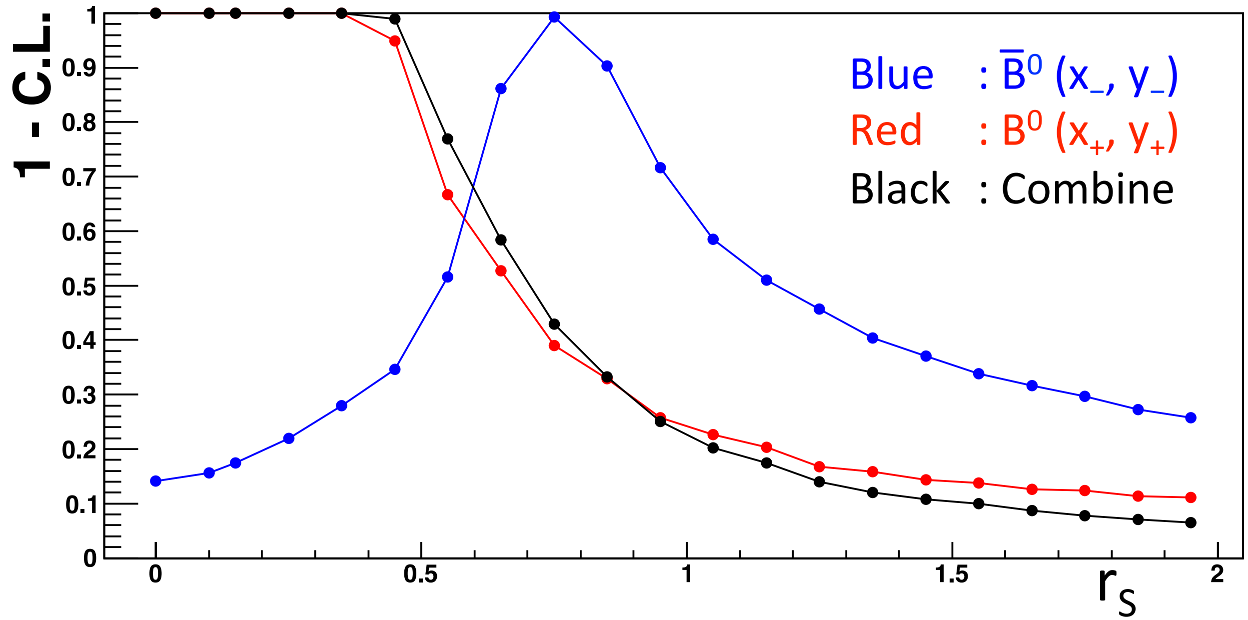
$$y_- = -0.6^{+0.8}_{-1.0}\,^{+0.1}_{-0.0} \pm 0.1$$

$$x_+ = +0.1^{+0.7}_{-0.4}\,^{+0.0}_{-0.1} \pm 0.1$$

$$y_+ = +0.3^{+0.5}_{-0.8}\,^{+0.0}_{-0.1} \pm 0.1$$

r_S Result

- r_S is crucial parameter in ϕ_3 measurement.
  - ϕ_3 uncertainty is scaled as $1/r$.



$B^0 \to [K\pi]_D K^{*0}$ *PRD* **86** , 011101 (2012)

$$R_{DK^{*0},ADS} \equiv \frac{Br(B^0 \to [K^-\pi^+]_D K^{*0})}{Br(B^0 \to [K^+\pi^-]_D K^{*0})}$$
$$= r_S^2 + r_D^2 + 2kr_S r_D \cos(\delta_S + \delta_D)\cos\phi_3$$
$$< 0.16 \quad \text{at } 95\% \text{ C.L.}$$

r_D is small. $r_D^2 = (3.79 \pm 0.18)10^{-3}$
$\to R_{DK^*} \sim r_S^2$
$r_S < 0.4$

$r_S < 0.87$ @ 68 % C.L.

Conclusion

- New result of $B^0 \to [K_S^0\pi^+\pi^-]_D K^{*0}$ Mod.-Ind. Dalitz analysis.

	stat.	syst.	c_i, s_i
$x_- = +0.4$	$^{+1.0}_{-0.6}$	$^{+0.0}_{-0.1}$	± 0.0
$y_- = -0.6$	$^{+0.8}_{-1.0}$	$^{+0.1}_{-0.0}$	± 0.1
$x_+ = +0.1$	$^{+0.7}_{-0.4}$	$^{+0.0}_{-0.1}$	± 0.1
$y_+ = +0.3$	$^{+0.5}_{-0.8}$	$^{+0.0}_{-0.1}$	± 0.1

$r_S < 0.87$ at 68 % C.L.

ϕ_3 measurement with neutral B is promising for Belle II!!

BACK UP

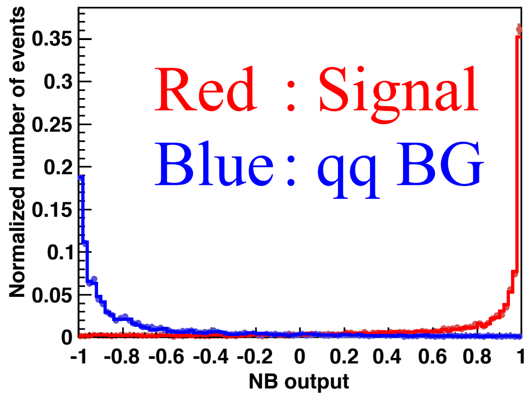
Event Selection

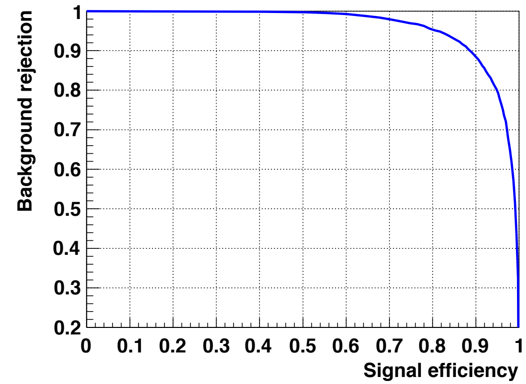
- Primary track
  - IP $|\Delta r| < 5$ mm, $|\Delta z| < 5$ cm
- K_S reconstruction
  - NIS K_S Finder
- D^0 reconstruction
  - K_S and opposite charge 2 π(LR(K/π) < 0.6)
  - $|M_{Ks\pi\pi} - m_{D0}| < 0.015$ GeV
- K^{*0} reconstruction
  - Opposite charge K(LR(K/π) > 0.7) and π(LR(K/π) < 0.6)
  - $|M_{K\pi} - m_{K^*0}| < 0.050$ GeV
- B^0 reconstruction
  - Best candidate is selected by D^0 mass and B^0 vertex
  - $\Delta m > 0.15$ GeV for real D^0 BG from $D^{*\pm}$
  - $|M_{K^{*0}\pi^-} - m_{D0}| > 0.04$ GeV for $[K^+\pi^-\pi^-]_{D^-}[K_S\pi^+]_{K^{*+}}$

qq suppression

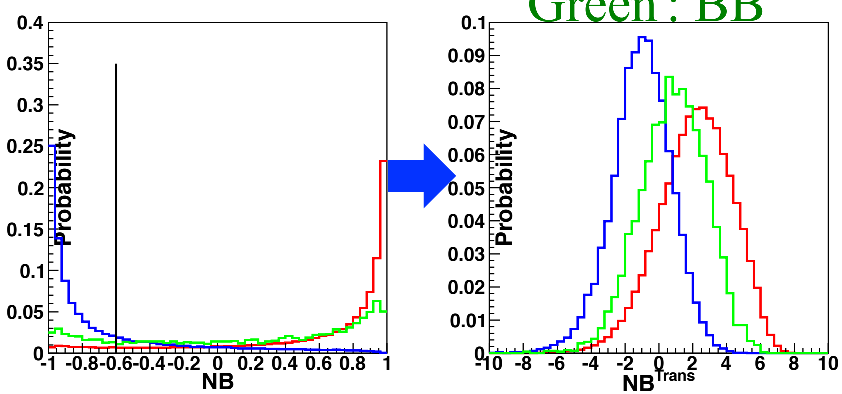
- qq events are suppressed by using following 12 parameters as NeuroBayes inputs.

1. LR(KSFW)
2. $\cos\theta_{thr}$
3. Δz
4. dist. DK*
5. $|qr|$
6. $|\cos\theta_B|$
7. $\cos\theta^D{}_B$
8. v1_z
9. v1_v1
10. v2_v2
11. v3_v3
12. thru oth





Red : Signal
Blue : qq
Green : BB



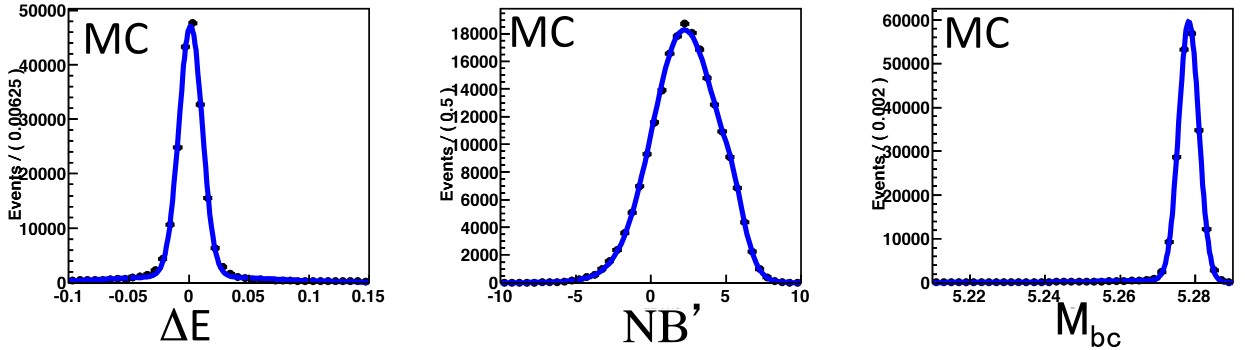
$$\mathcal{NB}^{\mathrm{TRANS}} = \ln\frac{\mathcal{NB} - NB_{\mathrm{low}}}{NB_{\mathrm{high}} - \mathcal{NB}}$$

$$NB_{\mathrm{low}} = -0.6$$

$$NB_{\mathrm{high}} = 0.9992$$

PDF

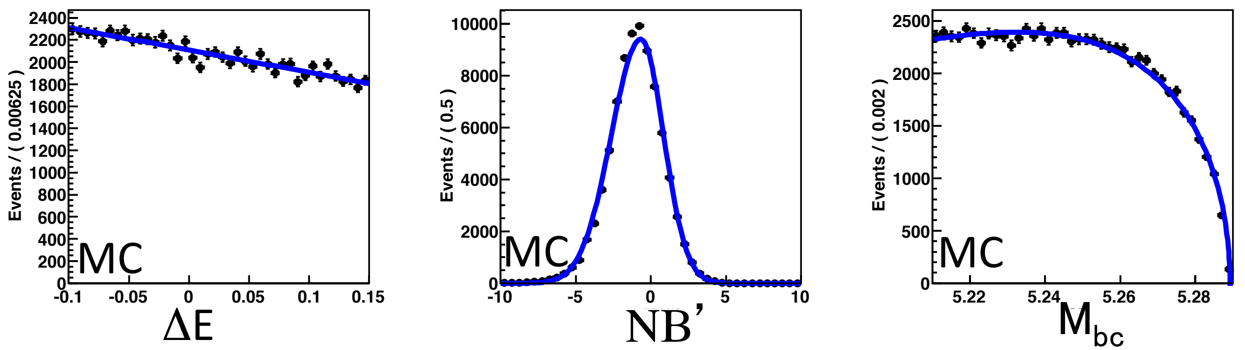
- シグナルは3次元(ΔE, NB', M_{bc})の分布をフィットして得る



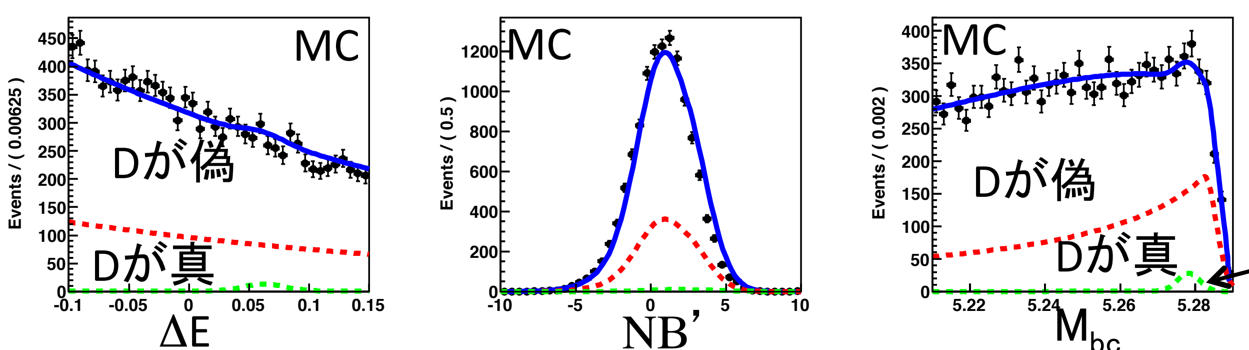
MCから
分布の形状を得る

- 同時に(コンティニュアム, $B\bar{B}$, ピーキング)背景事象もフィットする

コンティニュアム



$B\bar{B}$イベント+ピーキング



MCから
分布の形状を得る

ピーキング背景事象

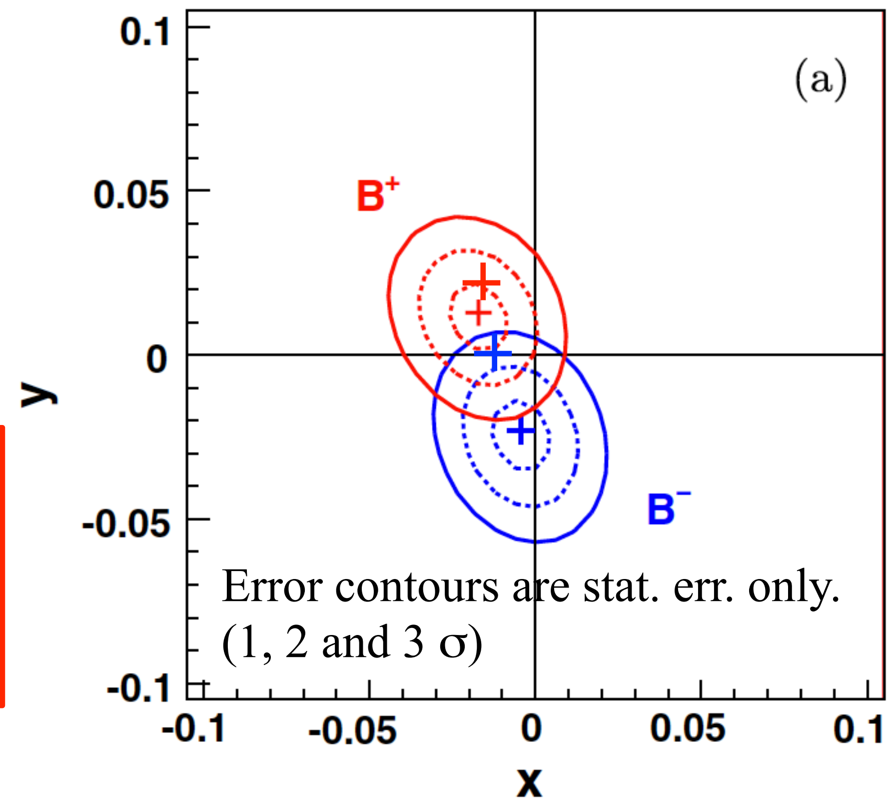
Dπ control sample analysis

- To check (x,y) fit, we use $B^+ \to D\pi^+$ as control sample.
- $B^+ \to D\pi^+$ is also analyzed as control sample of $B^+ \to DK^+$ (*PRD* **85**,112014(2012))

$x_- = -0.0130 \pm 0.0077$
$y_- = +0.0018 \pm 0.0076$
$x_+ = -0.0169 \pm 0.0083$
$y_+ = +0.0225 \pm 0.0076$

- Anton (Previous study, 605 fb^{-1})

$x_- = -0.0045 \pm 0.0087 \pm 0.0056$
$y_- = -0.0231 \pm 0.0107 \pm 0.0077$
$x_+ = -0.0172 \pm 0.0089 \pm 0.0065$
$y_+ = +0.0129 \pm 0.0103 \pm 0.0088$



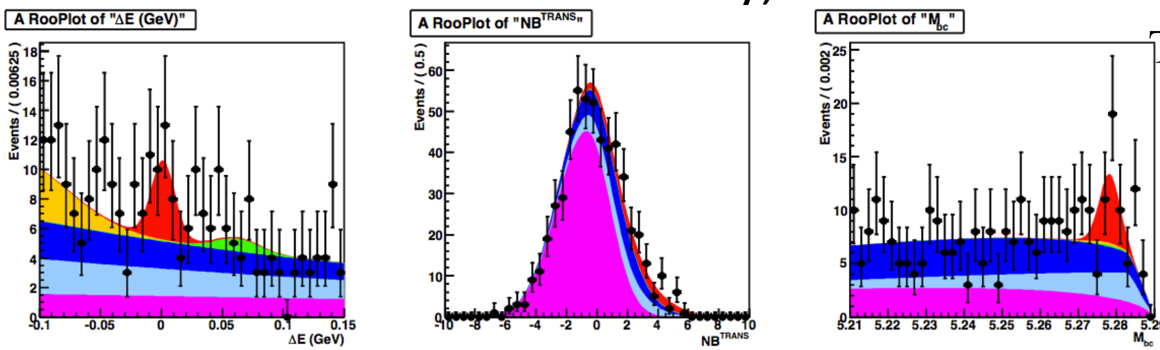
Difference of my and previous study

- **K_S selection**
- **qq suppression**
- ~~D^0 mass selection~~
- ~~BGs Dalitz distributions~~
- ~~Cross-feed between bins~~
- ~~Efficiency correction.~~

- We obtain Dπ (x,y) consistent with previous result.

Statistical uncertainty

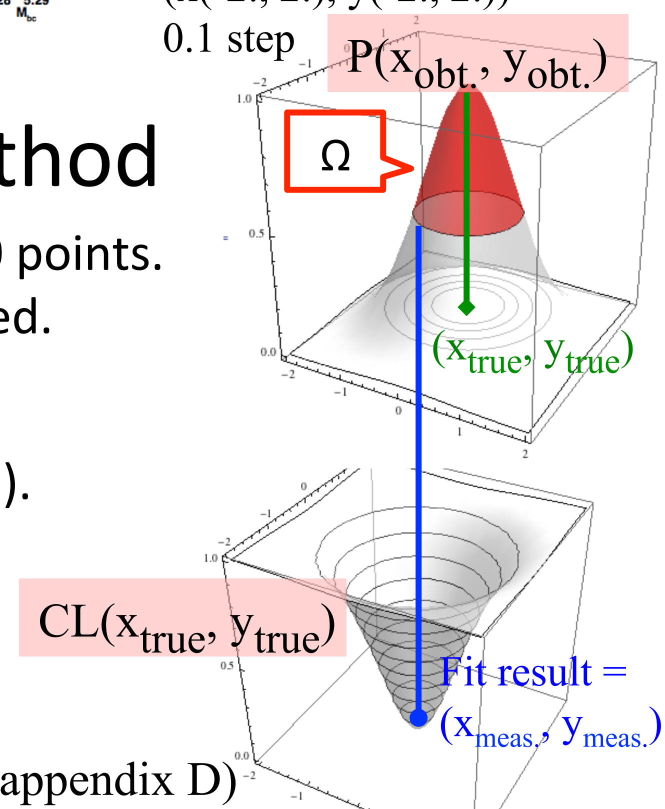
- We decide to not use normal error of likelihood distribution on (x,y) because of unreliable of (x,y) likelihood due to small statistics.
- To obtain statistic uncertainty, we use Feldman-Cousin method.



Total signal number = $44.2^{+13.3}_{-12.1}$

Statistic significance = 2.8 σ

(x(-2., 2.), y(-2., 2.))
0.1 step



Feldman-Cousin method

1. Generate >20,000 (x,y) fit result with toy MC at 1600 points.
2. Dist. of $(x,y)_{obt.}$ fit results at $(x,y)_{true}$ space are obtained. ($PDF(x_{obt.},y_{obt.}|x_{true},y_{true})$)
3. We define confidence level as integral of the PDF in a region Ω which satisfy PDF(x,y) > $PDF(x_{meas.},y_{meas.})$. (We call it "$CL(x_{true},y_{true})$".)
4. Draw contours of e.g.) α = 0.393 (1σ), 0.865 (2σ) and so on.

(BN#564 appendix D)

Systematic uncertainty

Source of uncertainty	Δx_-	Δy_-	Δx_+	Δy_+
1) Dalitz plots efficiency	± 0.00	$^{+0.01}_{-0.00}$	± 0.01	$^{+0.00}_{-0.01}$
2) Crossfeed between bins	± 0.00	$^{+0.01}_{-0.00}$	$^{+0.01}_{-0.00}$	± 0.00
3) PDF shape	$^{+0.01}_{-0.07}$	$^{+0.07}_{-0.01}$	$^{+0.01}_{-0.10}$	$^{+0.04}_{-0.06}$
Signal	± 0.00	± 0.00	± 0.00	± 0.00
$B\bar{B}$	$^{+0.01}_{-0.07}$	$^{+0.07}_{-0.01}$	$^{+0.01}_{-0.10}$	$^{+0.04}_{-0.06}$
Continuum	± 0.00	± 0.00	± 0.00	$^{+0.00}_{-0.01}$
$D^0\rho^0$	± 0.00	± 0.00	± 0.00	$^{+0.00}_{-0.01}$
$D^0 a_1^+$	± 0.00	$^{+0.00}_{-0.01}$	± 0.00	± 0.00
4) Flavor-tagged statistics	± 0.00	± 0.00	± 0.00	$^{+0.00}_{-0.01}$
5) c_i, s_i precision	± 0.03	$^{+0.09}_{-0.08}$	± 0.05	$^{+0.08}_{-0.10}$
6) k precision	± 0.00	± 0.01	± 0.00	± 0.00
Total without c_i, s_i precision	$^{+0.01}_{-0.07}$	$^{+0.07}_{-0.02}$	$^{+0.02}_{-0.10}$	$^{+0.04}_{-0.06}$
Total	$^{+0.03}_{-0.08}$	$^{+0.12}_{-0.08}$	$^{+0.05}_{-0.11}$	$^{+0.09}_{-0.12}$

w/o c_i,s_i c_i,s_i

- $\Delta x_- = {}^{+0.0}_{-0.1} \pm 0.0$
- $\Delta y_- = {}^{+0.1}_{-0.0} \pm 0.1$
- $\Delta x_+ = {}^{+0.0}_{-0.1} \pm 0.1$
- $\Delta y_+ = {}^{+0.0}_{-0.1} \pm 0.1$

We combine the uncertainty from stat. and syst. with assumption of (x,y) 2D Gauss. for syst. err.

Discussion

- r_S は0と無矛盾
  - $B^0 \to DK^{*0}$シグナル数が小さかった $44.2\ ^{+13.3}_{-12.1}$（統計誤差が支配的）
    崩壊分岐比で $Br(B^0 \to DK^{*0}) = (2.9 \pm 0.9) \times 10^{-5}$

	イベント数	$Br(B^0 \to DK^{*0})$	ずれ
本結果	44.2	$(2.9 \pm 0.9)\times10^{-5}$	
BaBar	78	$(5.2 \pm 1.2)\times10^{-5}$	-1.5σ
PDG	64	$(4.2 \pm 0.6)\times10^{-5}$	-1.2σ

ただし"ずれ"は大きくない

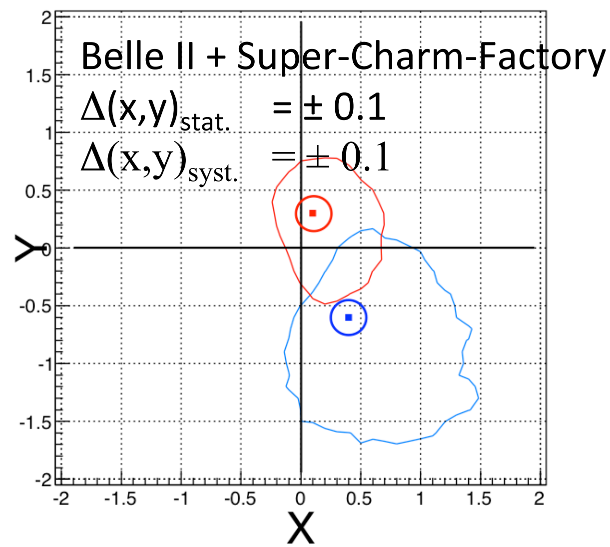
  - 統計的なふらつきによる
- Belle II 実験(予定)では

	統計	系統
$x_- = +0.4$	$^{+1.0}_{-0.6}$	$^{+0.0}_{-0.1}$
$y_- = -0.6$	$^{+0.8}_{-1.0}$	± 0.1
$x_+ = +0.1$	$^{+0.7}_{-0.4}$	± 0.1
$y_+ = +0.3$	$^{+0.5}_{-0.8}$	± 0.1

50倍$B\bar{B}$ →

- 統計誤差→ O(<0.1)
  現系統誤差と同等

1. K/π識別能力が上がる
   →$B\bar{B}$背景事象の抑制
2. Super-Charm-Factory
   →c_i, s_iの誤差が減る



$B^0 \to DK^{*0}$崩壊を用いϕ_3測定の可能性