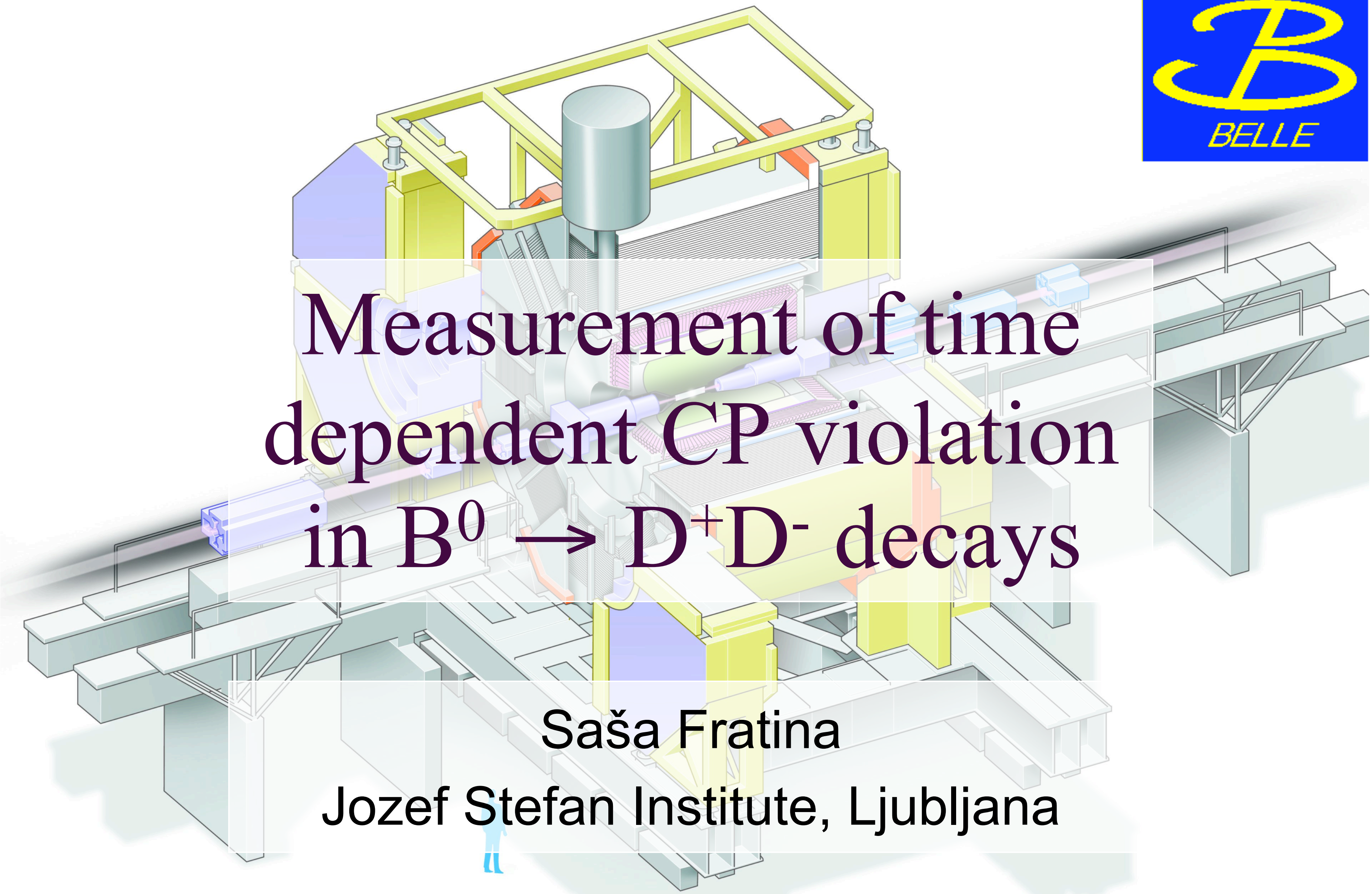


Measurement of time dependent CP violation in $B^0 \rightarrow D^+D^-$ decays

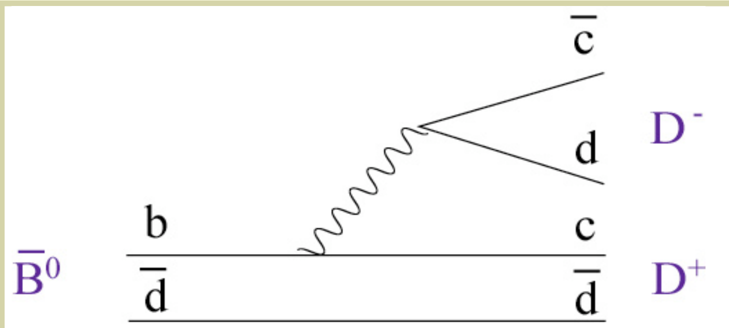
Saša Fratina
Jozef Stefan Institute, Ljubljana

Physics motivation

Measure CP violation parameters in $B^0 \to D^+ D^-$ decay.

$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau}}{4\tau}(1 + q(S\sin(\Delta m \Delta t) + A\cos(\Delta m \Delta t)))$$

time-dependent CP violation



+ penguin

Δt: time between the decay of two B mesons, $\Delta z = \beta\gamma\, c\, \Delta t$

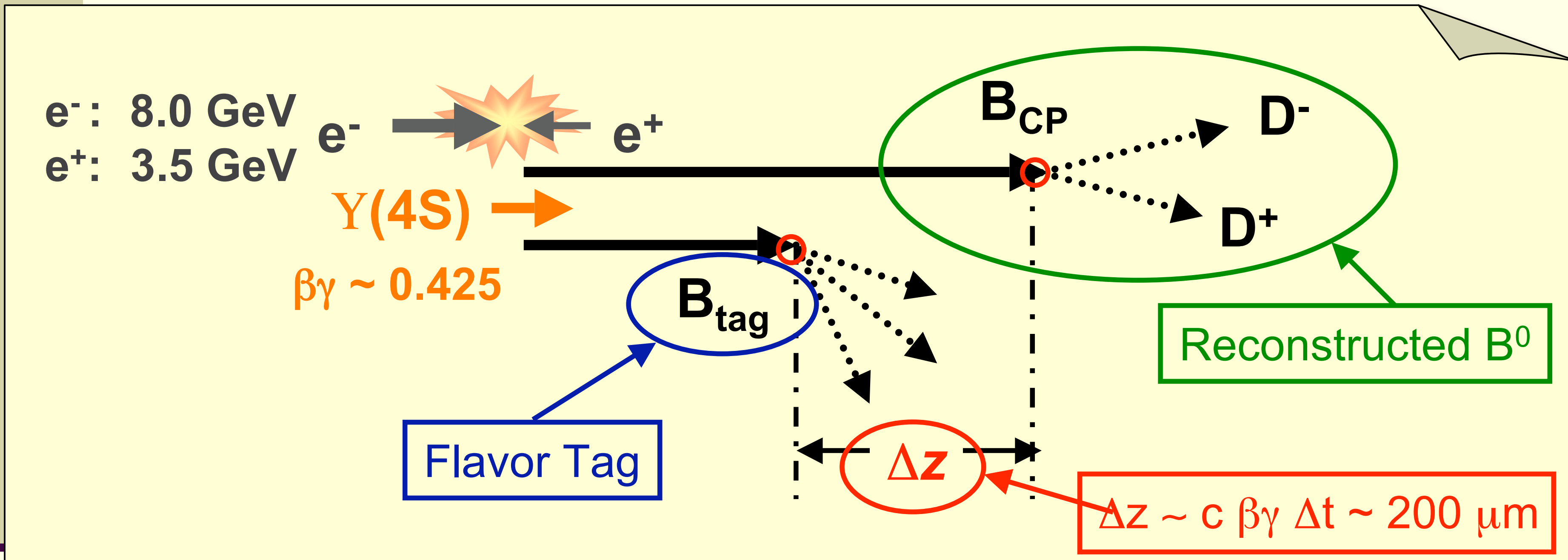
q: flavor of B meson decaying to a CP eigenstate

Δm: B mass difference $m(B_1)-m(B_2)$

S, A: CP violation parameters

SM expectations: $S \approx -\sin 2\phi_1$, $A \approx 3\%$ [Z.Z.Xing, PRD61, 014010 (2000)]

Measuring the CP parameters S and A



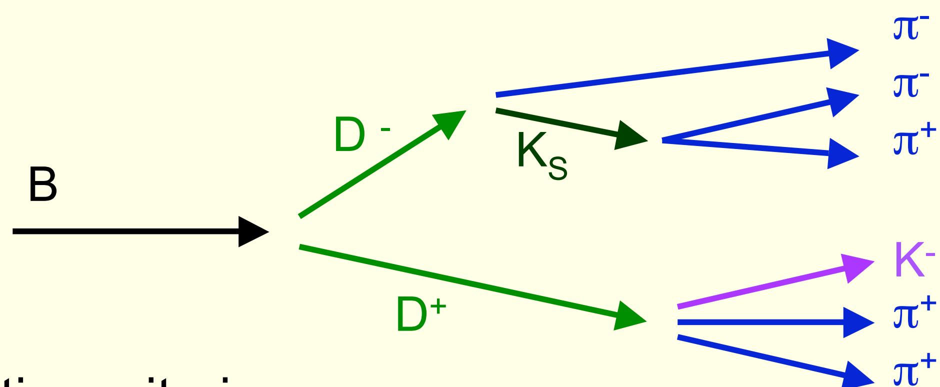
$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau}}{4\tau}(1 + q(S\sin(\Delta m\Delta t) + A\cos(\Delta m\Delta t)))$$

Outline of the talk

- Event reconstruction and selection
  - Branching fraction measurement
- CP analysis
  - PDF description, cross-checks
  - Result for the 535 M BB-events data sample
- Summary

Event reconstruction & selection

- $B^0 \rightarrow D^+ D^-$, $D \rightarrow K\pi\pi$ or $D \rightarrow K_s\pi$ reconstruction channels
- Vertex reconstruction: first D^+ and D^-, then B0 from D^+D^- and the IP

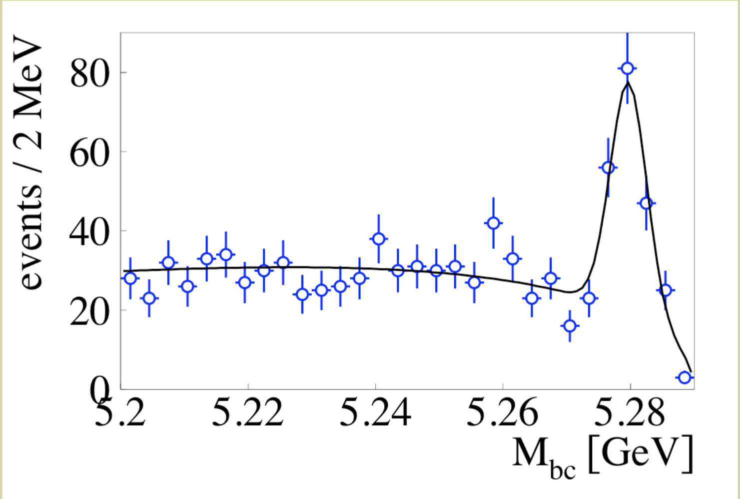


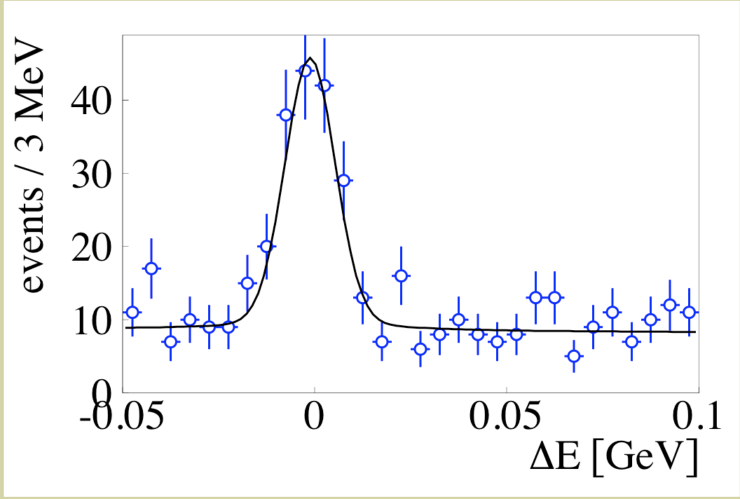
- Event selection criteria:
  - continuum supression: use spherical moments to seperate jet-like and spherical events
  - D mass cut, D mass is also used for a best candidate selection
  - pion and kaon PID, electron veto
  - distance from the interaction point $|\Delta r|$ and $|\Delta z|$
- 12% event reconstruction efficiency

Peaking background study

- Non-resonant B decays peaking in the M_{bc}, ΔE
  - $B^0 \rightarrow D^- \pi^+ K^0$ ($K^0 \rightarrow K_S$) $\rightarrow$ peaking in $K_S\pi$
  - $B^0 \rightarrow D^- \pi^+ K^{*0}(892)$ ($K^{*0}(892) \rightarrow K^- \pi^+$) $\rightarrow$ in $K\pi\pi$
- Determine the amount from D mass sidebands in data sample (cross-check with MC)
  - One D meson from the D mass signal region, the other from the sideband
- No significant peaking observed,
  - $K\pi\pi$: 2.0 ± 1.8 events expected in the sig. region
  - $K_S\pi$: 1.4 ± 1.0 events
- Taken into account for the CP-fit

Signal yield for the 535 10^6 $B\bar{B}$ events





$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$ (in the CMS system) $$\Delta E = E_B - E_{beam}$$

	N_{sig}	N_{nr}	N_{bcg}
$K\pi\pi$	123±19	2.0±1.8	109±1
$K_S\pi$	24±8	1.4±1.0	15±1

about 130 signal events with S/(S+B) ~ 0.6 available for the time-dependent analysis

Branching fraction measurement

- Previous measurements:
  - $(1.91 \pm 0.51 \pm 0.30)\ 10^{-4}$ [Belle, PRL95, 040813 (2005)]
  - $(2.8 \pm 0.4 \pm 0.5)\ 10^{-4}$ [Babar, PRL95, 131802 (2005)]
- An update with higher statistics;
  - sum the number of reconstructed events in the $K\pi\pi$ and $K_S\pi$ rec. ch. and average the efficiency
  - $Br\ (B^0 \rightarrow D^+D^-) = (\ 1.98 \pm 0.23 \pm 0.22\ )\ 10^{-4}$ Preliminary
    (stat) (syst)
  - Systematic errors: D meson branching fractions (6%), track reconstruction efficiency (6%), PID eff. (6%), other smaller than 2%

CP analysis

Δt: time between the decay of two B mesons, $\Delta z = \beta\gamma\, c\, \Delta t$

q: flavor of B meson decaying to a CP eigenstate

Δm: B mass difference $m(B_1)$-$m(B_2)$

S, A: CP violation parameters

- Signal:

$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau}}{4\tau}(1 + q(S\sin(\Delta m \Delta t) + A\cos(\Delta m \Delta t))) \otimes \text{det. resol.}$$

Imperfect tagging: q → q (1-2w);

w is a wrong tag fraction

kinematic smearing

detector resolution

non-primary tracks

- Background:

$$\frac{dP_{bcg}}{dt}(\Delta t) = \left[(1-f)\frac{e^{-|\Delta t|/\tau}}{2\tau} + f\delta(\Delta t)\right] \otimes \frac{e^{-\Delta t^2/2\sigma^2}}{\sqrt{2\pi}\sigma}$$

- **Event PDF**: → **unbinned ML fit**

$$\frac{dP}{dt}(\Delta t, q) = f_{sig}\frac{dP_{sig}}{dt}(\Delta t) + f_{nr}\frac{dP_{nr}}{dt}(\Delta t) + f_{bcg}\frac{dP_{bcg}}{dt}(\Delta t)$$

$$f_i = f_i(M_{bc}, \Delta E)$$

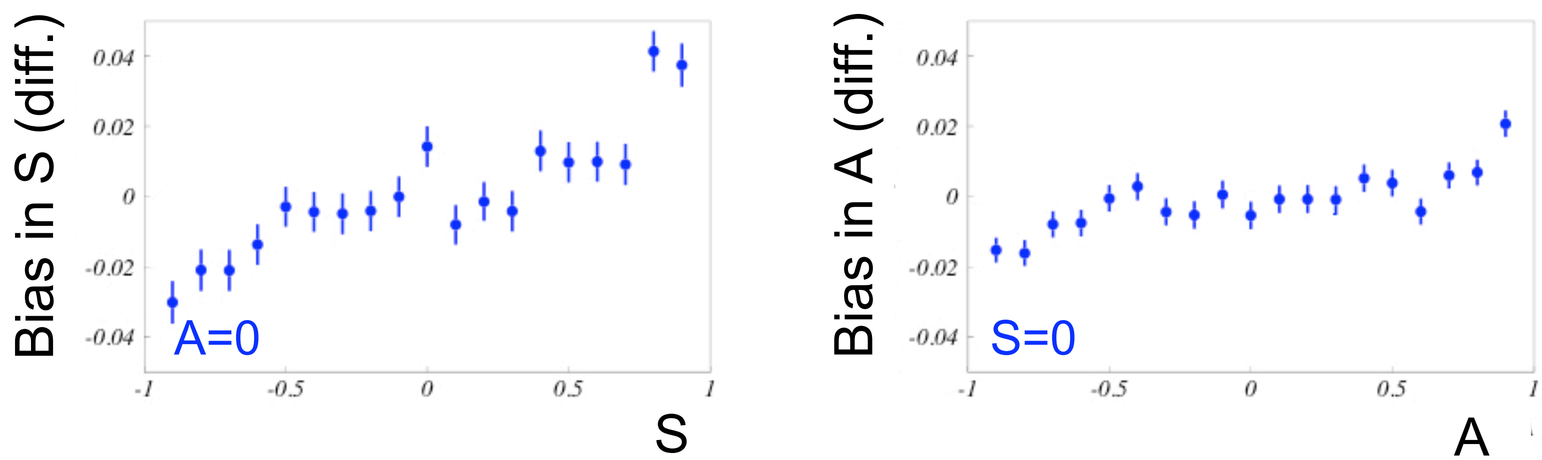
CP analysis, cont.

- Use kinematically similar $B^0 \to D_s^+ D^-$ decays as a control sample
  - $B^0 \to D_s^+ D^-$ reconstruction [hep-ex/0508040, LP2005]
  - approx. 2000 reconstructed events (larger data sample)
  - Also used to determine the B_{CP} vertex resolution parameters for the data sample

Test for CP-fit bias

- Use signal MC and toy MC to check if there is any fit bias due to the small sample statistics

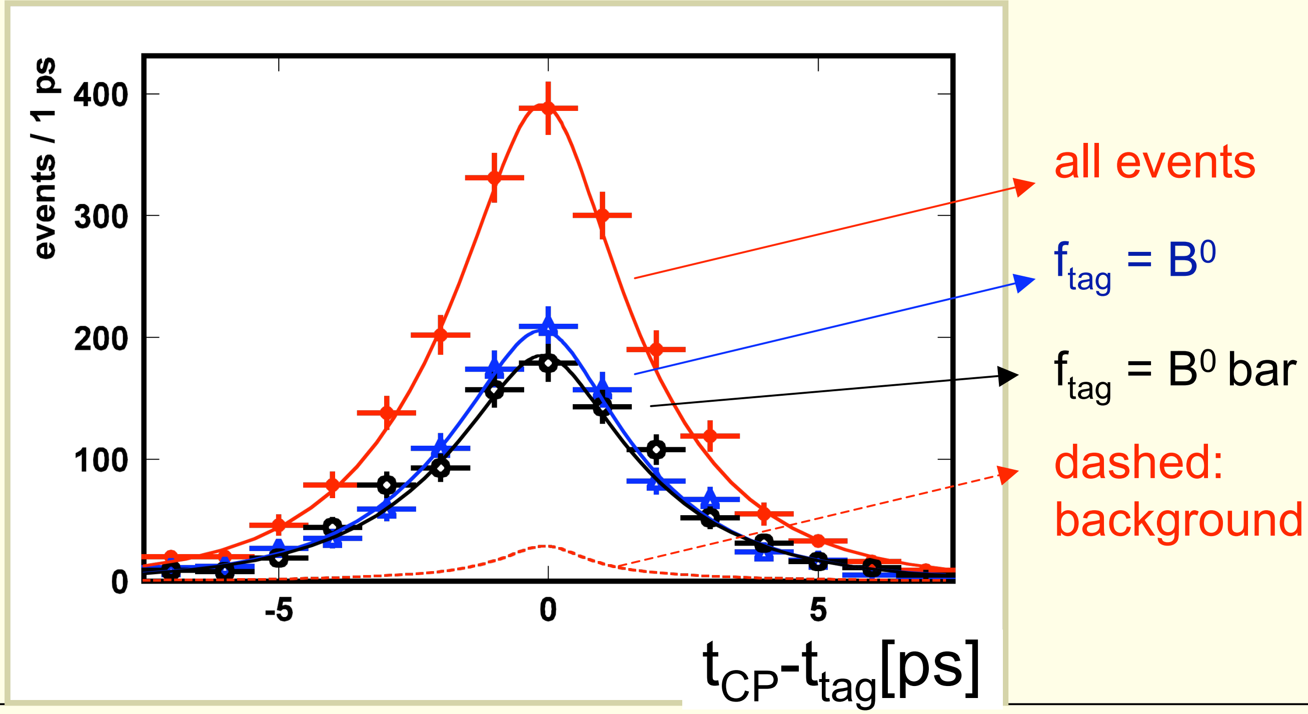
Toy MC, signal only



- Fit the bias dependence on S and A (sig+bcg toy MC):
  - $\mu_S \approx [\,0.99 + 0.07\,(S^2+A^2)\,]\,S$
  - $\mu_A \approx [\,0.99 + 0.03\,(S^2+A^2)\,]\,A$

CP-fit to the control sample data

- Control sample of $B^0 \to D_s^+ D^-$ decays
- S = -0.064 ± 0.094 (stat) ± 0.012 (syst)
- A = 0.091 ± 0.060 (stat) ± 0.010 (syst)

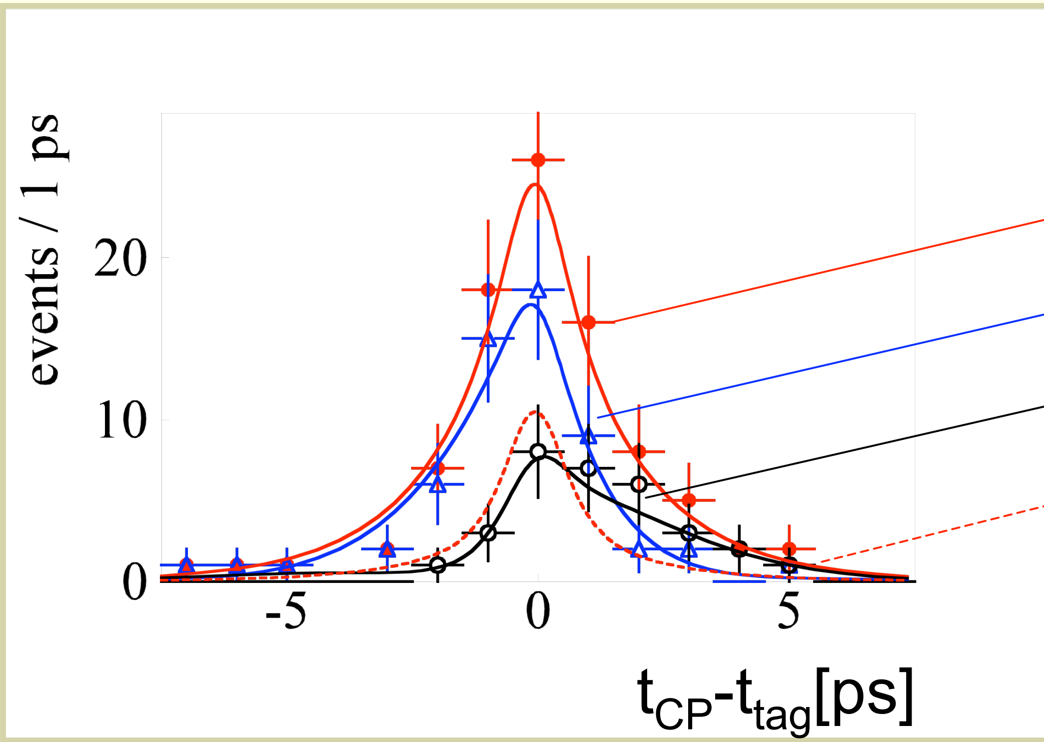


$B^0 \rightarrow D^+D^-$ CP violation parameters

$S = -1.12 \pm 0.37\,(stat) \pm 0.09\,(syst)$

$A = 0.92 \pm 0.23\,(stat) \pm 0.05\,(syst)$

Preliminary



all events

$f_{tag} = B^0$

$f_{tag} = B^0$ bar

dashed: background

Systematic errors

	σ_S	σ_A
CP-fit bias	0.06	0.02
signal fraction	0.035	0.015
non-resonant background	0.01	0.02
vertex resolution function params.	0.04	0.03
background distribution	0.02	0.01
vertex quality cuts	0.01	0.01
wrong tag fraction	0.017	0.014
values of τ and Δm	0.023	0.007
sum in squares	0.09	0.05

For all contributions, vary relevant parameters by $\pm\sigma$ or do the same in the toy MC study (explained in the back-up slides).

Statistical errors and significance

- Use Feldman-Cousins method to determine the statistical significance (similar as for the Belle $B^0 \to \pi^+\pi^-$ analysis)
- First: confirm that the RMS of the S and A distributions (from toy MC) simulate the expected errors in data

	Data, CP-blind fit	Toy MC S = -0.725, A = 0	Toy MC S = -0.725, A = 0.6
σ_S	0.37	0.36	0.37
σ_A	0.22	0.24	0.23

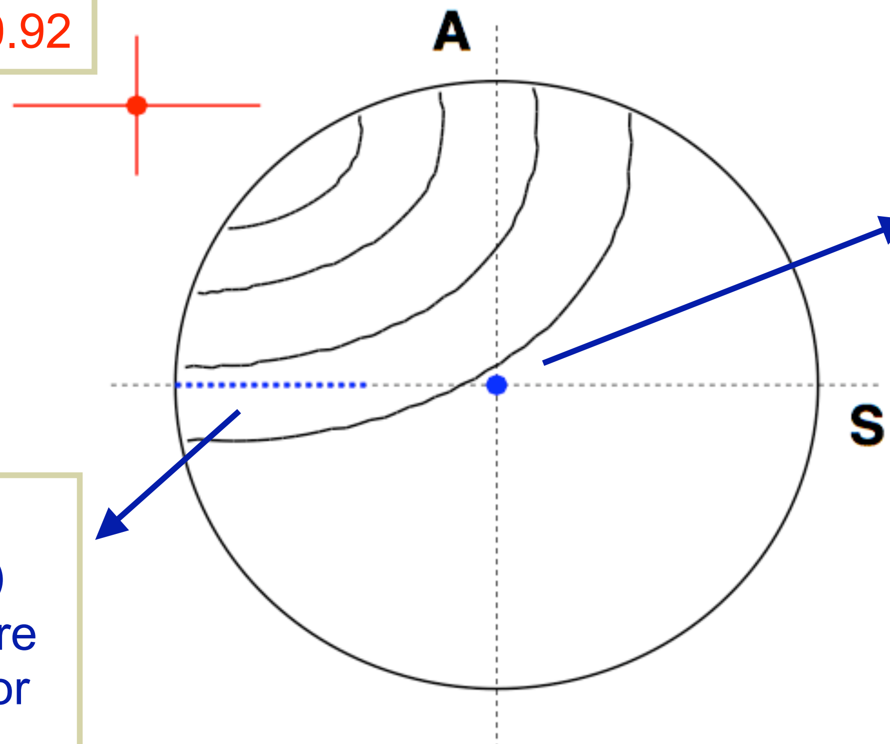
5-10% difference, its impact on the significance is evaluated by rescaling the toy MC widths with the corresponding factors (+8% change in CL)

Systematic errors are included in the simulation.

Result of the Feldman-Cousins significance study

Preliminary

data point:
S = -1.12, A = 0.92



Zero CP violation (S = A = 0) excluded at a 4.1 σ CL

Zero direct CP violation (A = 0) excluded at more than 3.2 σ CL for any value of S

Time-integrated fit

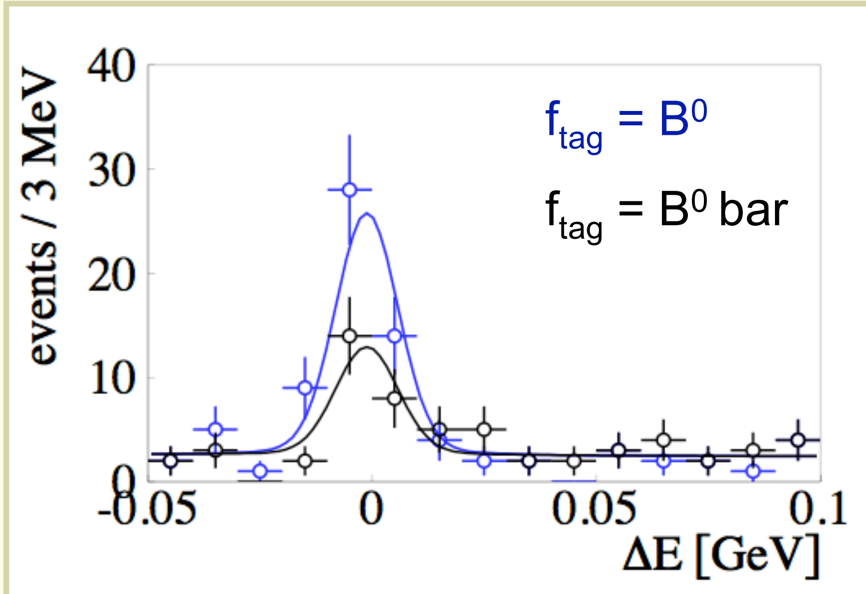
- $A \neq 0 \Rightarrow$ Raw asymmetry = $\dfrac{N_{tag=B0} - N_{tag=B0bar}}{N_{tag=B0} + N_{tag=B0bar}} \neq 0$
- Can check the consistency of the result if one does not use any time information
- Time-integrated cross-check:

  $A = 0.86 \pm 0.32$ ($2.7\ \sigma$);

  consistent with

  time-dependent fit

r > 0.5



Check for flavor asymmetry in the background events

- Perform the CP-fit for the background events in the $M_{bc} < 5.27$ GeV / c^2 sideband region
  - larger number of events (6000)
  - assign the same signal fraction to all events (0.63)
  - $S = 0.03 \pm 0.10$; $A = -0.01 \pm 0.06$; consistent with zero

Preliminary

Summary

- New measurement in $B^0 \to D^+D^-$ decays based on the data sample of 535 10^6 B meson pairs recorded by the Belle detector
- Updated branching fraction:

  $Br = (1.98 \pm 0.23\ (stat) \pm 0.22\ (syst)\ )\ 10^{-4}$
- We measure the CP parameters to be:

  $S = -1.12 \pm 0.37 \pm 0.09$; $A = 0.92 \pm 0.23 \pm 0.05$
  - SM expectations: $S = -0.72$; $A \approx 3\%$;
  - BaBar, 232M BB pairs [PRL95, 131802 (2005)]: $S = -0.29 \pm 0.63 \pm 0.06$; $A = -0.11 \pm 0.35 \pm 0.06$ difference at a 2.2 σ level.

Preliminary

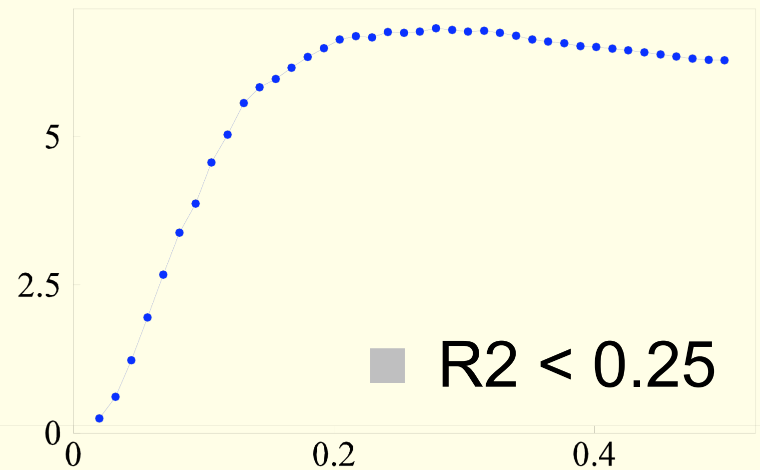
Summary

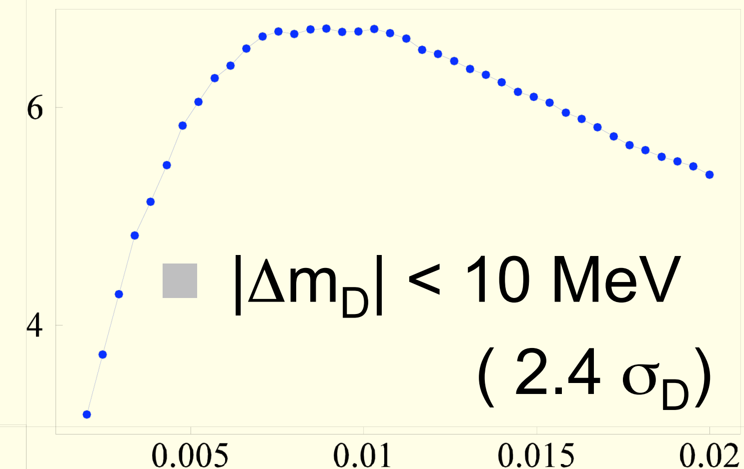
- First evidence of CP violation in $B^0 \to D^+D^-$ decays at a 4.1σ CL.
- Evidence of direct CPV at a 3.2 σ CL.
  - Such a large direct CPV not expected by the SM.
  - Not indicated by the previous measurement.
- Need more data to settle the issue, study isospin-conjugated $B^- \to D^0D^-$ decays

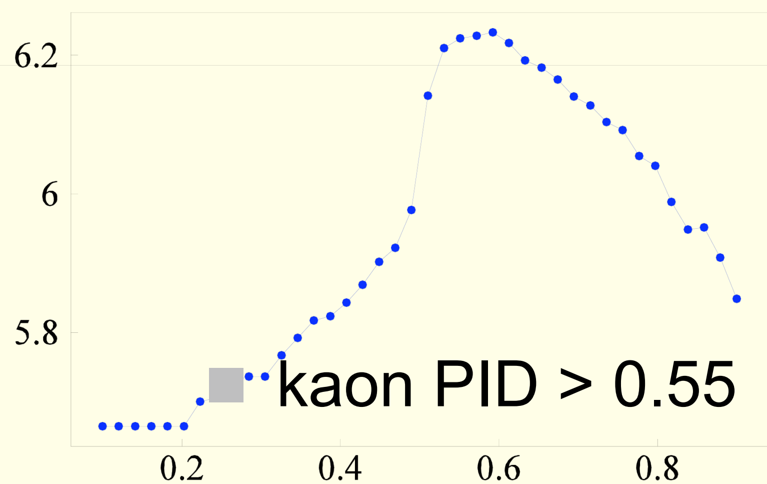
Back-up slides

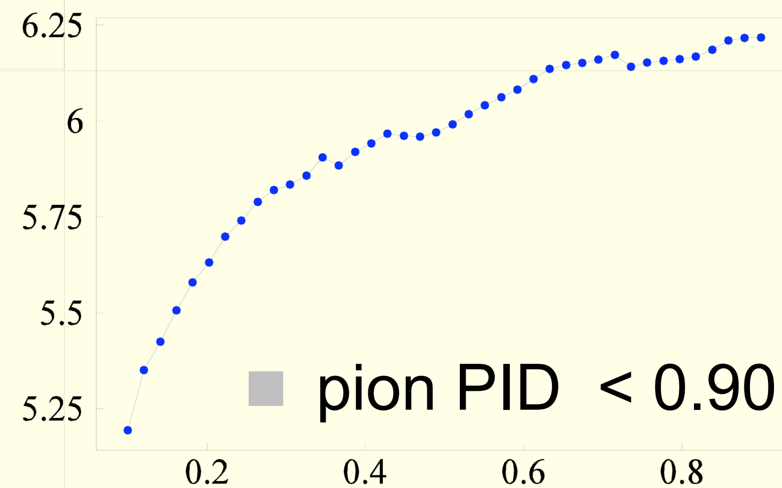
Event selection criteria

plot $\frac{S}{\sqrt{S+B}}$ rescaled to 417fb^{-1}, after all other cuts









The Feldman – Cousins method

- Simulate toy MC according to the corresponding distributions in data:
  - Signal and background Δt distributions
  - Signal fraction, kinematic variables
  - CP- and tag-side vertex errors and vertex quality, vertex residuals
  - wrong tag fractions
- Fit S and A for each toy MC sample: $P(S, A \mid S^{hyp}, A^{hyp})$
- Use the Feldman - Cousins ordering principle:
  - F-C: $P(S, A \mid S^{hyp}, A^{hyp}) / P(S, A \mid S^{best}, A^{best})$, where (S^{best}, A^{best}) are the values inside the physical region for which $P(S, A \mid S^{best}, A^{best})$ is maximal (definition)
- $CL = \int_{\Omega} P(S, A \mid S^{hyp}, A^{hyp})\, dS\, dA$

  where the int. area Ω is determined by the above criteria

Treatment of the systematic error

- Procedure:
  a) Generate a toy MC sample with the default parameters.
  b) Smear the CP-side resolution parameters used for the fit and repeat the fit on the same toy MC sample
  c) Repeat the same for the parameters describing the signal fraction
- The difference (a-b) and (a-c) is the corresponding systematic error

Toy MC: $P(S, A \mid S^{hyp}, A^{hyp})$

- $P(S, A \mid S^{hyp}, A^{hyp}) = G(S \mid \mu_S, \sigma_S^p, \sigma_S^n)\, G(A \mid \mu_A, \sigma_A^p, \sigma_A^n)$
  - $\mu_S = \mu_S (S^{hyp}, A^{hyp})$
  - $\sigma_S^p = \sigma_S^p (S^{hyp}, A^{hyp})$
  - ...
- Simulate toy MC for different input values S^{hyp}, A^{hyp}
- Fit the parameters μ_S, σ_S^p,... for all S^{hyp}, A^{hyp}
- Fit the dependency $\mu_S (S^{hyp}, A^{hyp})$,... with an up to 4th order polynomial function

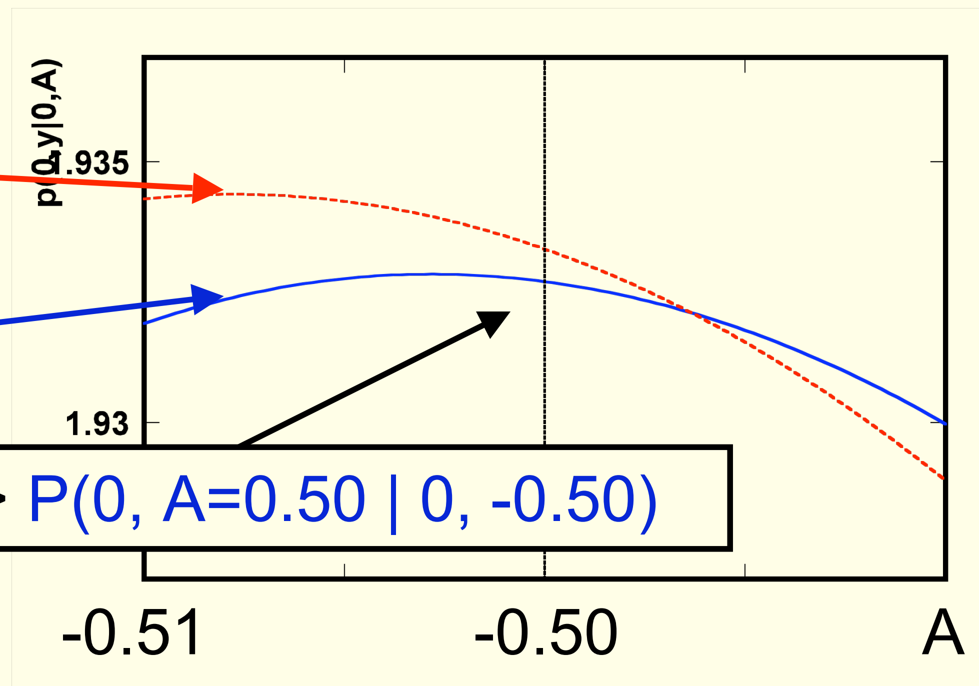
- The possibility of wider-than Gaussian tails is taken into account

S^{best}, A^{best}

- For a given measured point (S, A), the values (S^{best}, A^{best}) are the values inside the physical region for which P(S, A | S^{best}, A^{best}) is maximal
- (S^{best}, A^{best}) can be different from (S, A) even inside the physical region

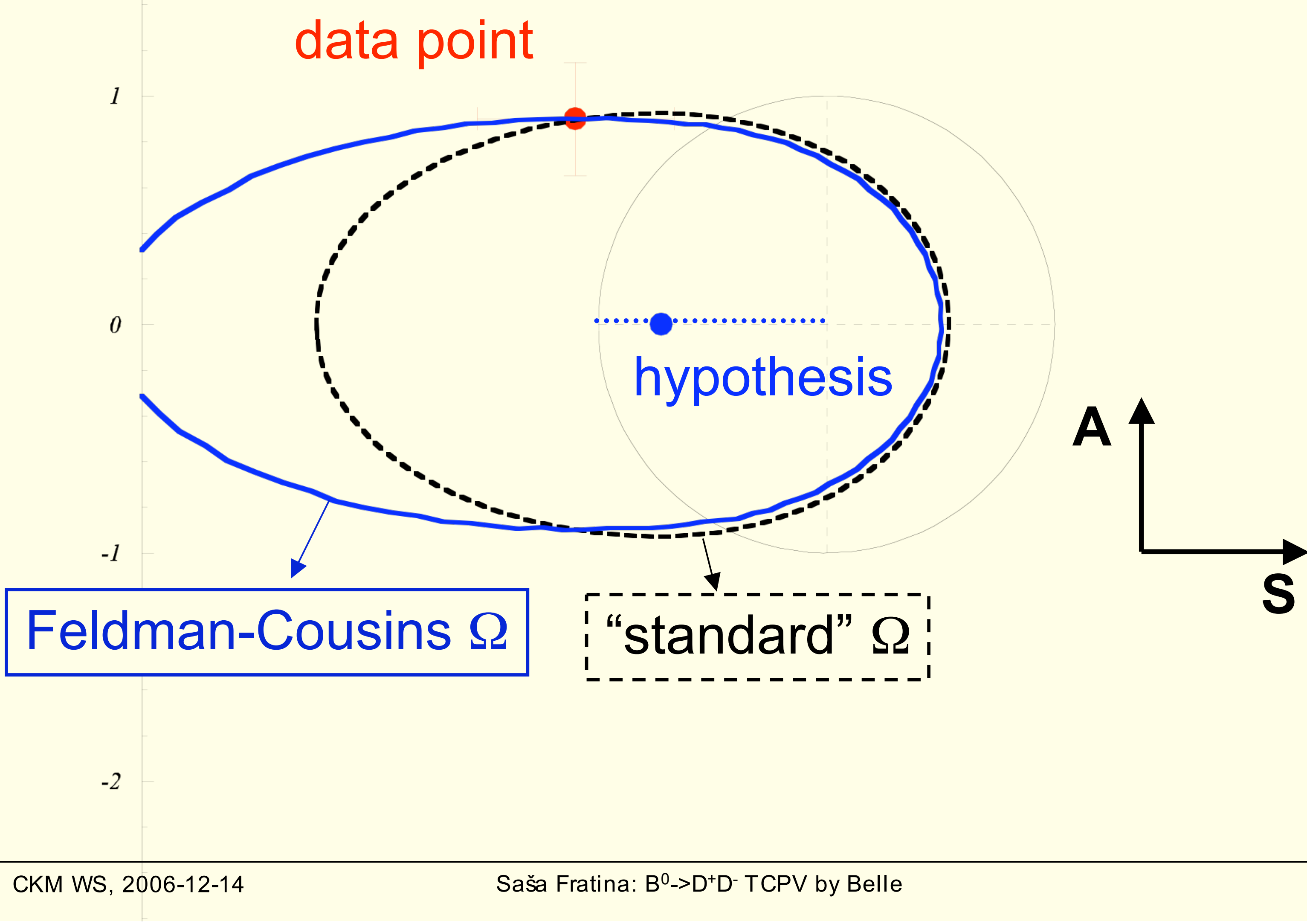
P(0, A | 0, -0.51)

P(0, A | 0, -0.50)



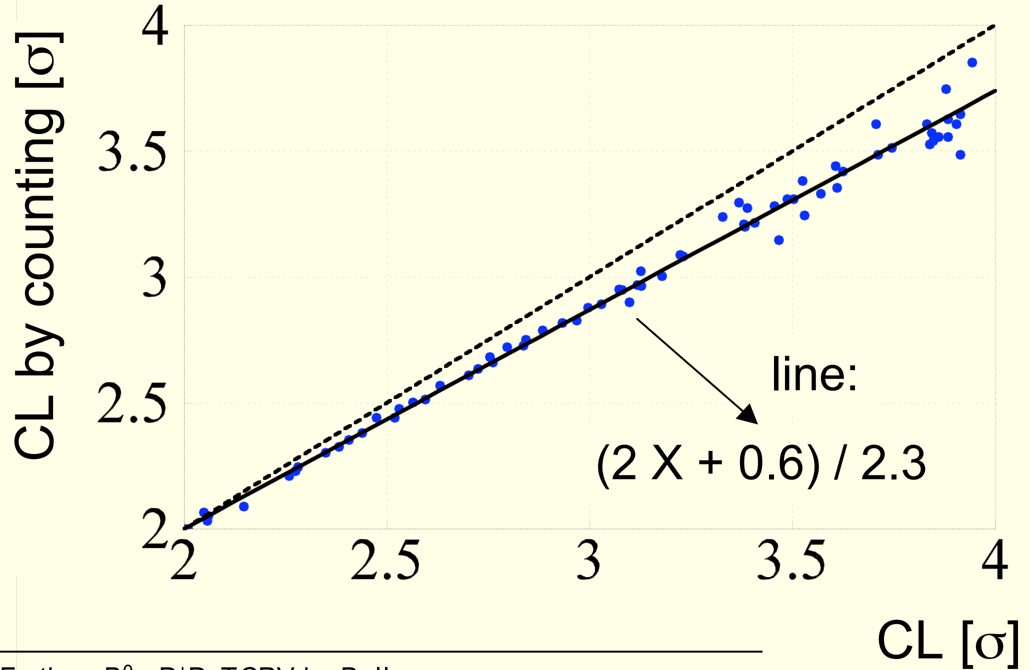
P(0, A=0.50 | 0, -0.51) > P(0, A=0.50 | 0, -0.50)

Integration area

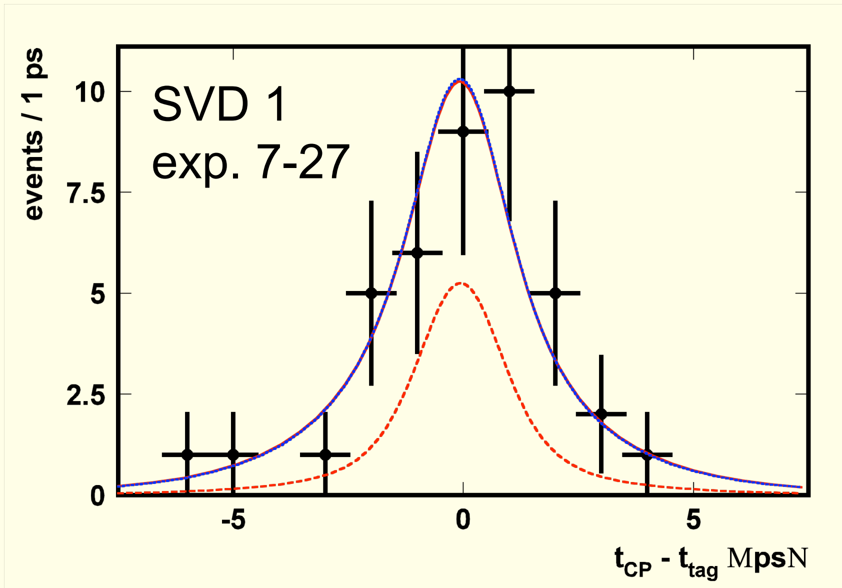


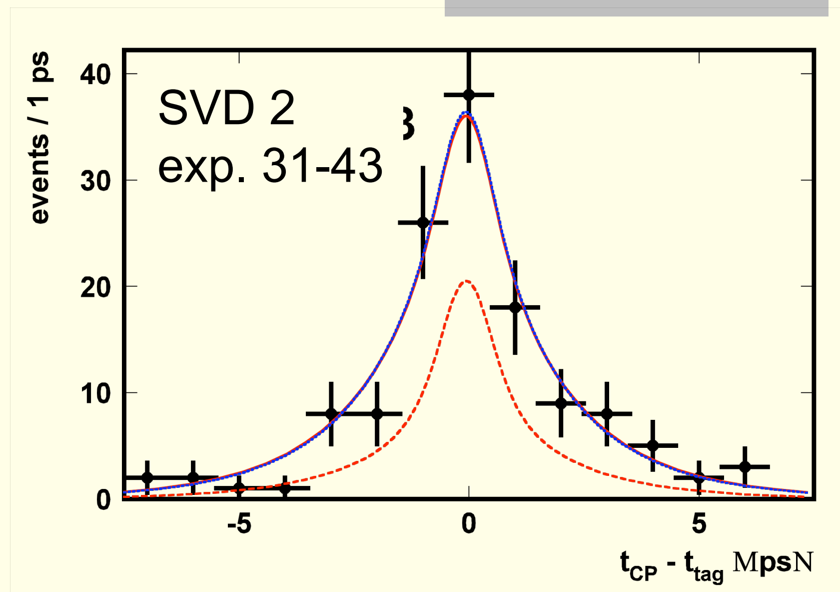
Counting method

- $P(S, A \mid S^{hyp}, A^{hyp})$ is described by the Gaussian f.
- If the tails in the distributions are wider than is the case of the Gaussian distr., this would lead to an over-estimation of the significance
- One can obtain the CL also by counting the fraction of toy MC samples satisfying the F-C ordering principle ($N(\Omega)/N(\text{all})$ instead of $\int_\Omega$; larger fluctuations)



$B^0 \rightarrow D^+D^-$ exp. 7-49 data sample lifetime and CP-blind fit





Lifetime fit

7-27	1.58 ± 0.40 ps
31-49	1.45 ± 0.23
7-49	1.48 ± 0.20

CP-blind fit

	S	A
μ	0.018	0.015
σ	0.40	0.25
< err >	0.38	0.24

Exp. 7-43 only for the CP-blind fit

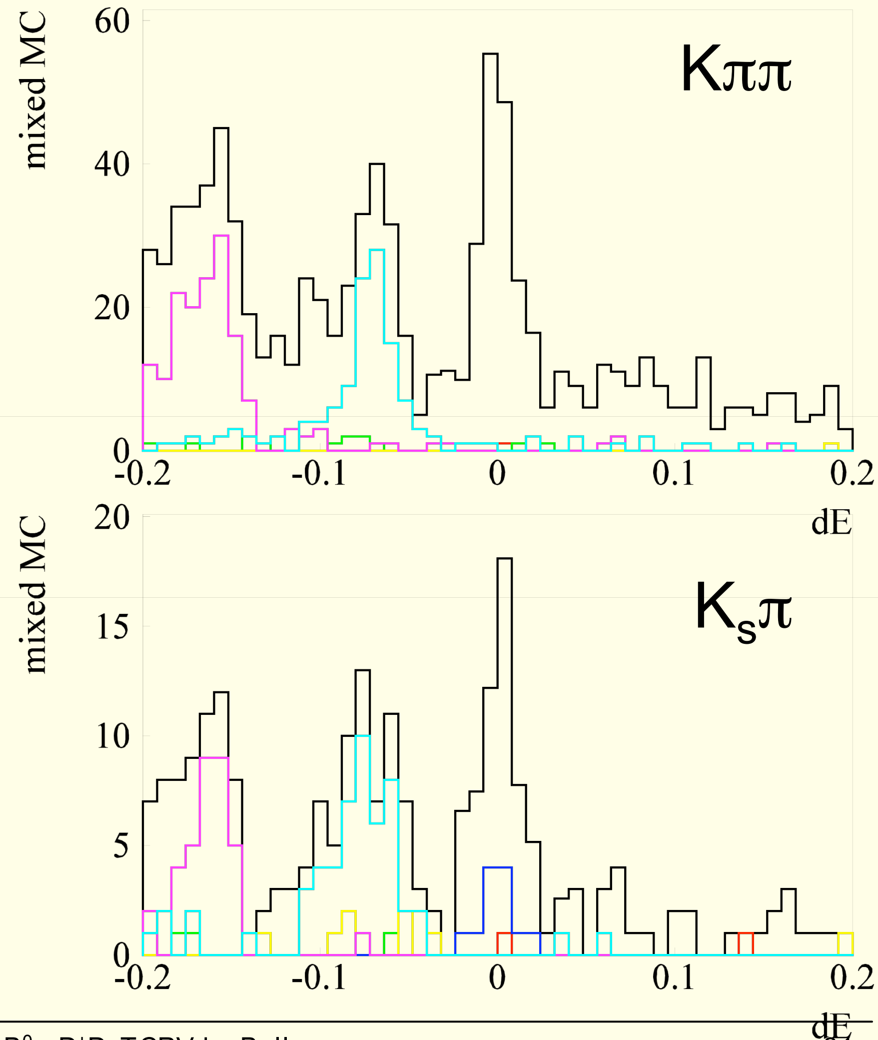
Time-integrated CP parameters (by unbinned ML fit for each r-bin)

- Expected $\mathcal{A}$ (from A=0.90) = (-Δw + (1 – 2 w) 0.626 A)
- Error on meas. $\mathcal{A}$ estimated as 1 / sqrt (N(B^0)+N(B^0bar))

r-bin	N(f_{tag}=B^0bar)	N(f_{tag}=B^0)	$\frac{N_{tag=B0} - N_{tag=B0bar}}{N_{tag=B0} + N_{tag=B0bar}}$	expect. $\mathcal{A}$
1	13	33	0.43 ± 0.15	0.03
2	7	7	0.03 ± 0.26	0.23
3	5	5	0.02 ± 0.31	0.29
4	5	13	0.47 ± 0.24	0.37
5	4	7	0.25 ± 0.30	0.47
6	6	19	0.54 ± 0.20	0.54

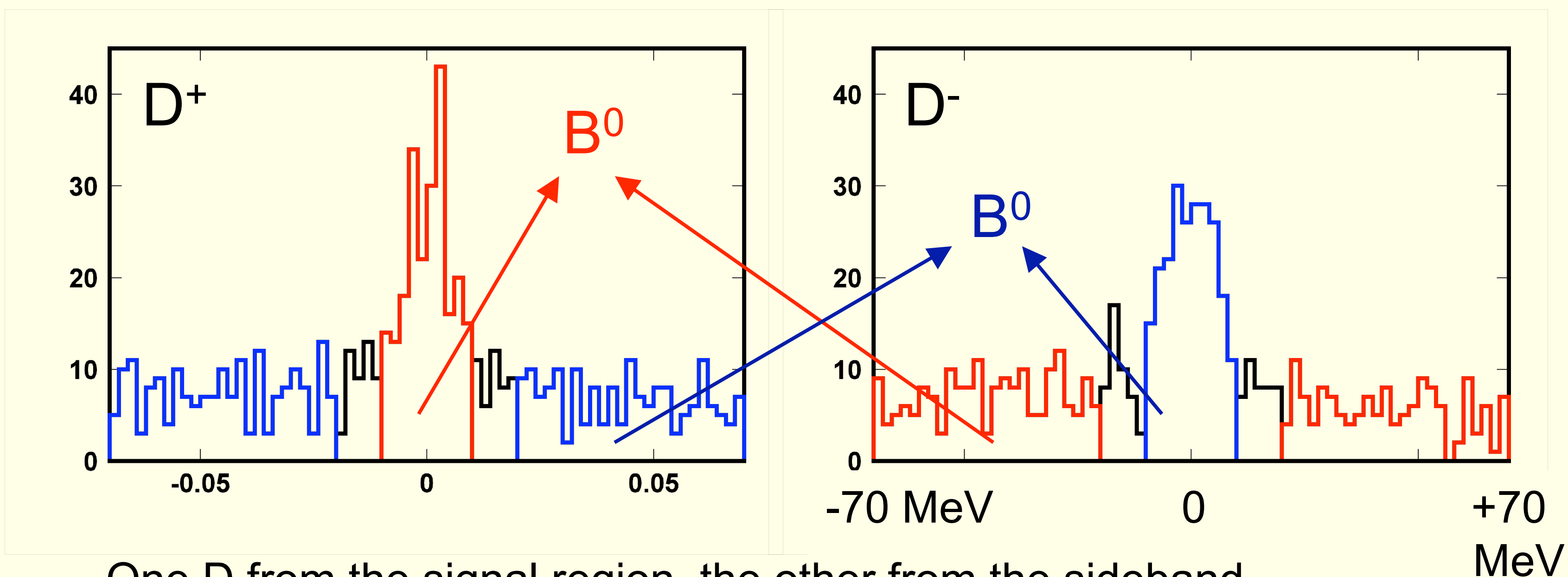
ΔE background study

- Contributions of different backgrounds in ΔE distribution for $K\pi\pi$ and $K_s\pi$ channel
  - $B^0 \rightarrow D^*D$
  - $B^0 \rightarrow D_s^+ D^-$
  - $B^0 \rightarrow D^- K^+ \overline{K^{*0}}(892)$
  - $B^0 \rightarrow D^- K^+ \overline{K^0}$
  - $B^0 \rightarrow D^- \pi^+ K^{*0}(892)$
  - $B^0 \rightarrow D^- \pi^+ K^0$



Estimation of the peaking bcg. from the D-meson sidebands

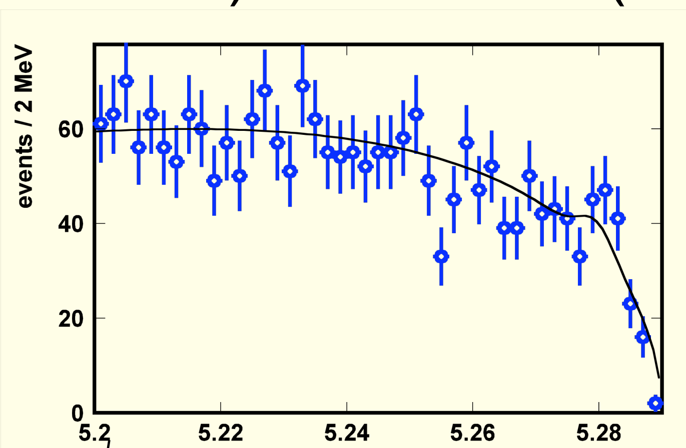
- Evtgen MC studies indicated m_{BC} ΔE peaking background in the $K_S\pi$ reconstruction channel coming from the non-resonant $B^0 \to D^- \pi^+ K^0$ decays
- Estimate its amount from the D-meson sideband study

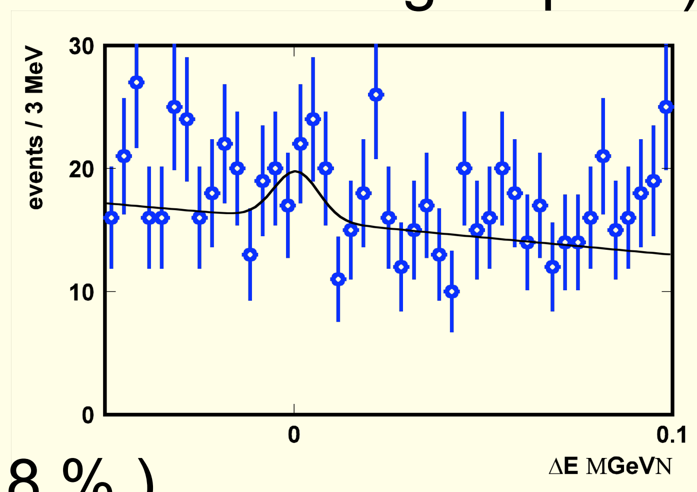


One D from the signal region, the other from the sideband.

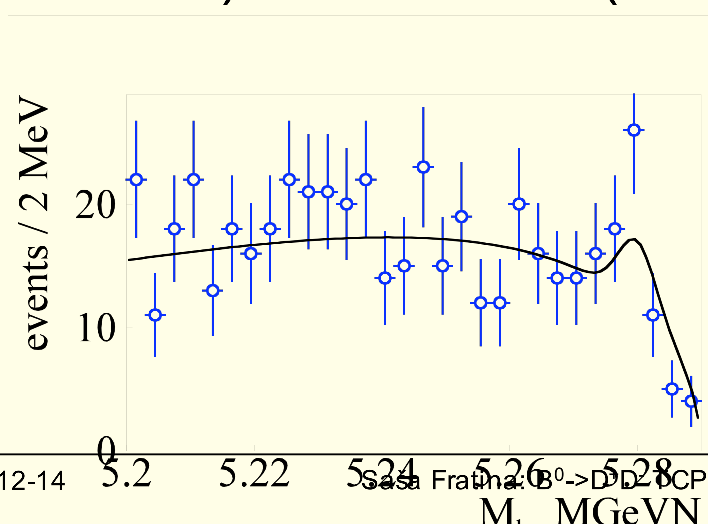
Unbinned 2D ML fit to the m_{BC} and ΔE distribution for the D-meson sidebands

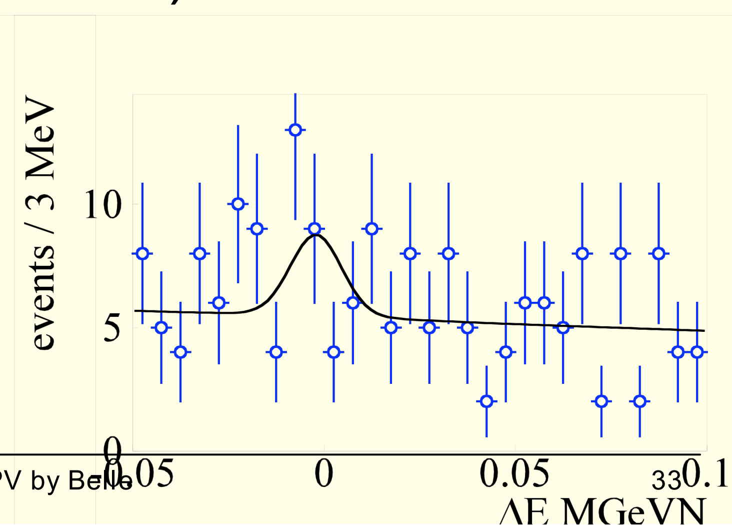
- $K\pi\pi$: (20 ± √315) / 10 = 2 ± 2 (2 ± 2 % of the signal peak)



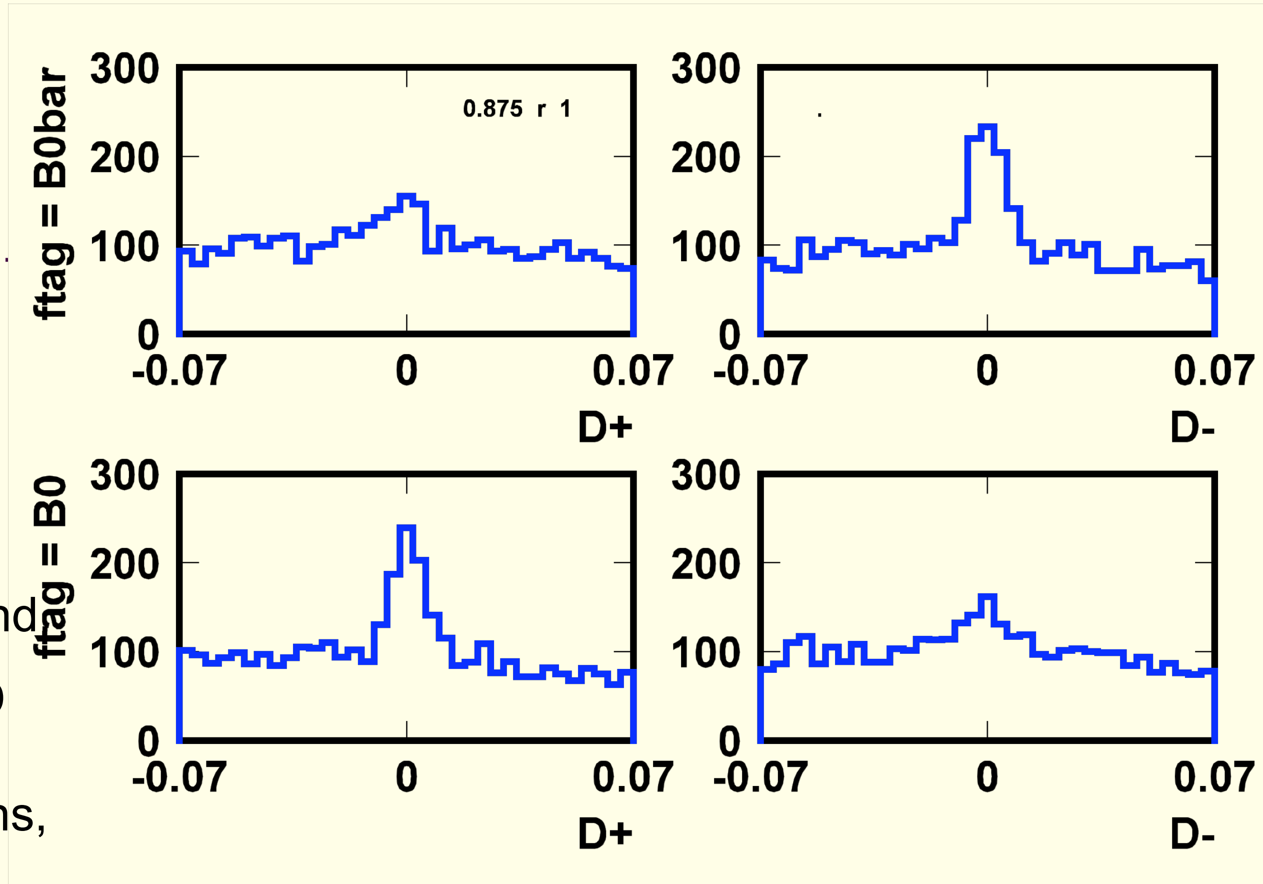


- $K_S\pi$: (12 ± √72) / 10 = 1 ± 1 (8 ± 8 %)





D mass sideband plots



Right: D mass (- D nominal mass), best r-bin, Mbc dE sidebands

Bottom: mBC plots, D mesons: signal / sideband combinations, different r-ranges