QCD factorization tests with $\bar{B}^0 \to D^+ h^-(K/\pi)$ and $B \to \bar{D}^0 \pi$ decays at Belle

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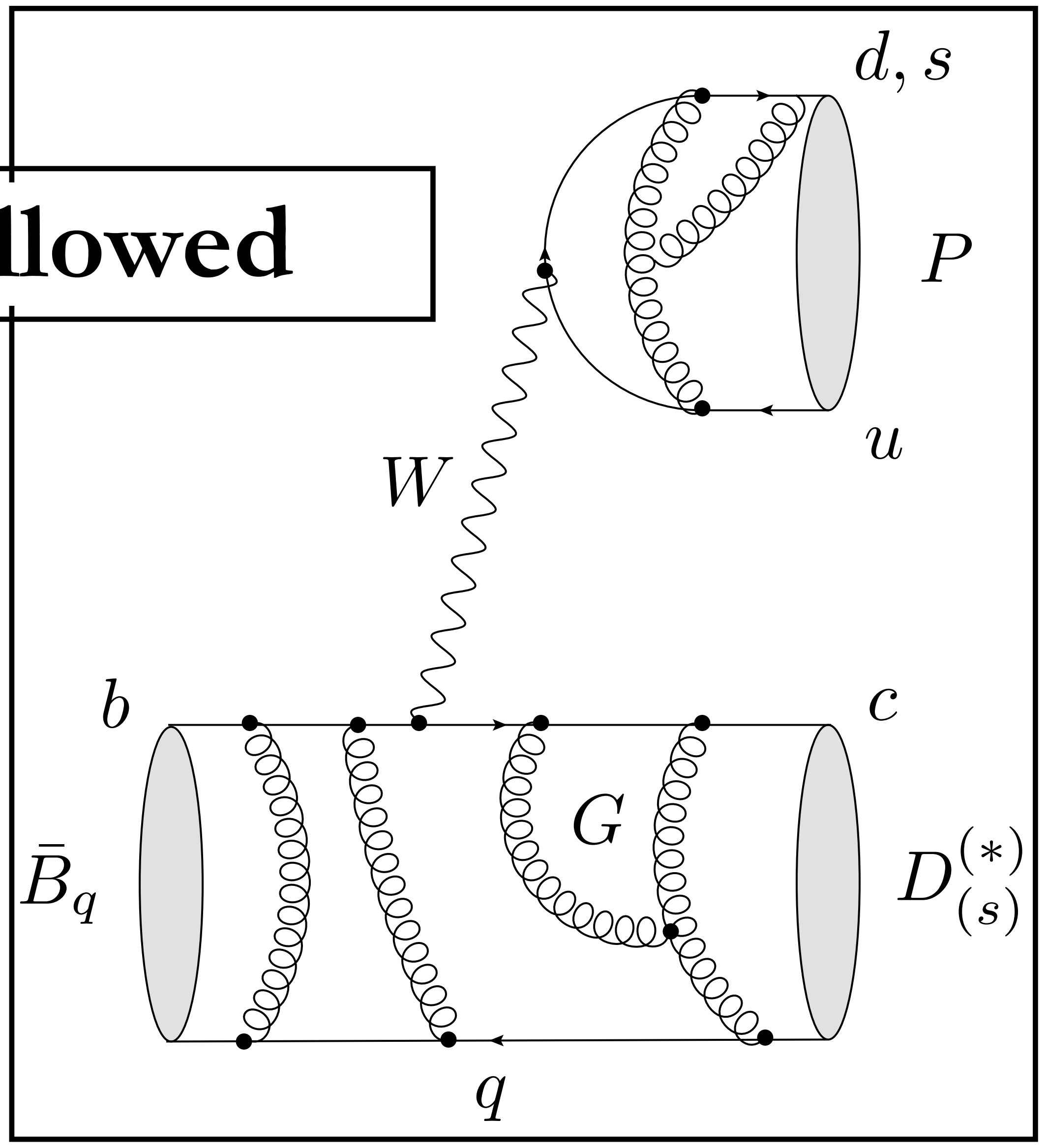
KEK High Energy Accelerator Research Organization

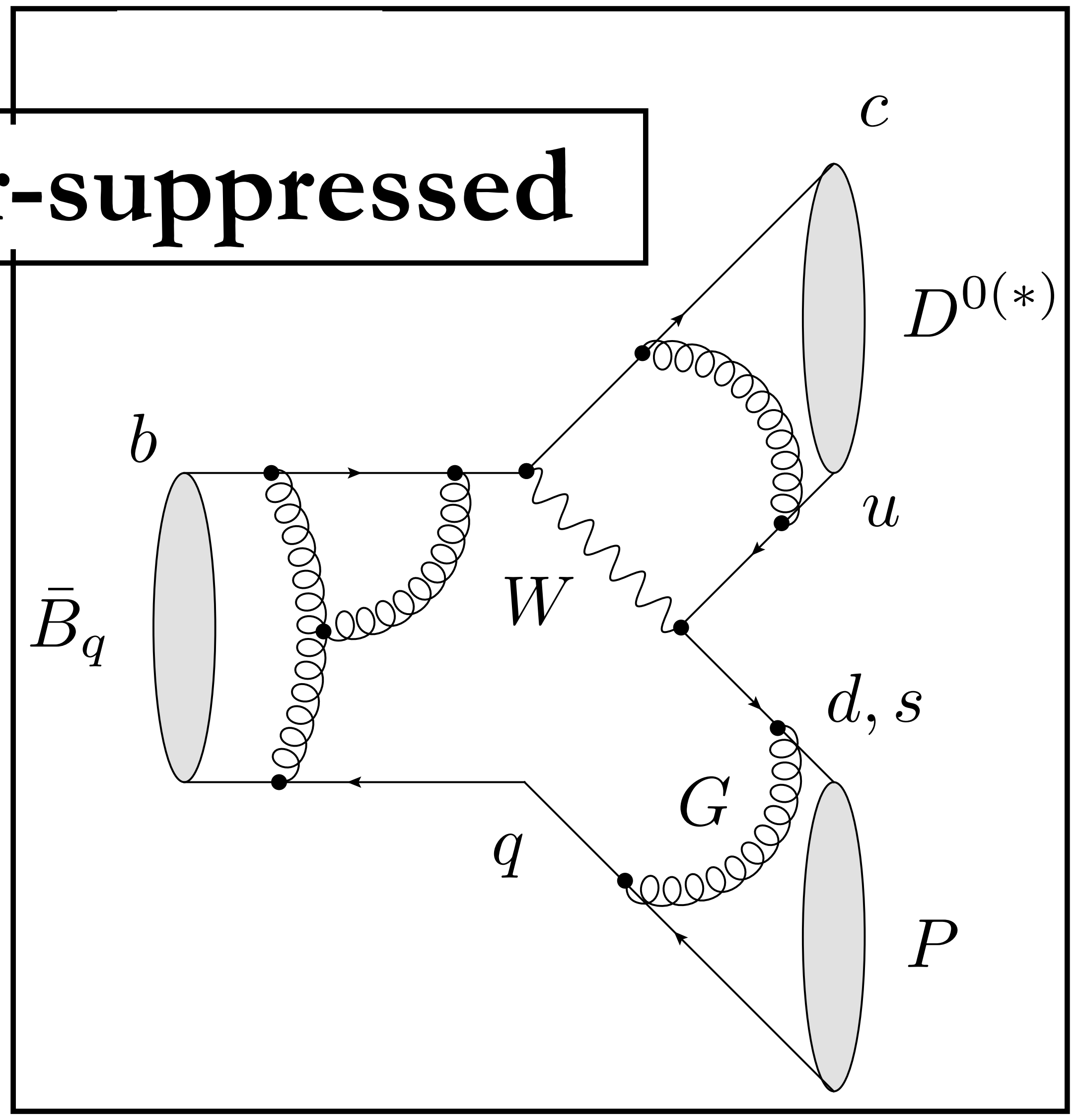
Test of Factorization in B decays

- Non-leptonic weak decays of B mesons play an excellent role to explore **flavor physics** and **strong interactions**.
- Factorization → estimate matrix element of four-quark operators through the product of the matrix elements of corresponding quark currents.
- Factorization works well in $\bar{B}^0 \to D^{(*)+}K^-$ decays Phys.Rev.D83:014017,2011
  - Contributions from color-allowed (tree level) topologies as $\bar{B}^0 \to D^{(*)+}\pi^-$.
- $\bar{B}^0 \to D^{(*)+}\pi^-$ amplitude can be probed in three ways
  - Comparing the hadronic branching fractions to the semi-leptonic decay rates→ calculating $|a_1|$ **(Results from Belle coming soon)**
  - Ratios of branching fractions governed by the color-allowed and color-suppressed amplitudes → calculating $\text{Ratio} = \dfrac{\mathcal{B}(B^0 \to D^{(*)-}K^+)}{\mathcal{B}(B^0 \to D^{(*)-}\pi^+)}$
  - probing decays amplitude directly through the branching fractions of decays.

Color-allowed



Color-suppressed



Study of $\bar{B}^0 \to D^+h^-(h = K/\pi)$

- Both modes are important → signal or control channels for measurements related ϕ_3 angle.
- $B^0 \to D^-\pi^+$ provide very good opportunities to test the theories of hadronic B-meson decays → clean and dominant hadronic decay channel.
- Improved measurements of the color-favored hadronic two-body decay of the B meson → better understanding of QCD effects.
- Branching fraction for Cabibbo suppressed $B^0 \to D^-K^+$ is related to $B^0 \to D^-\pi^+$ by

$$\boxed{R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+K^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} \simeq \tan^2\theta_C \left(\frac{f_K}{f_\pi}\right)^2 = 0.077 \pm 0.002}$$

θ_c is Cabibbo angle, and f_K and f_π are meson decay constants.

10.1007/JHEP09(2016)112

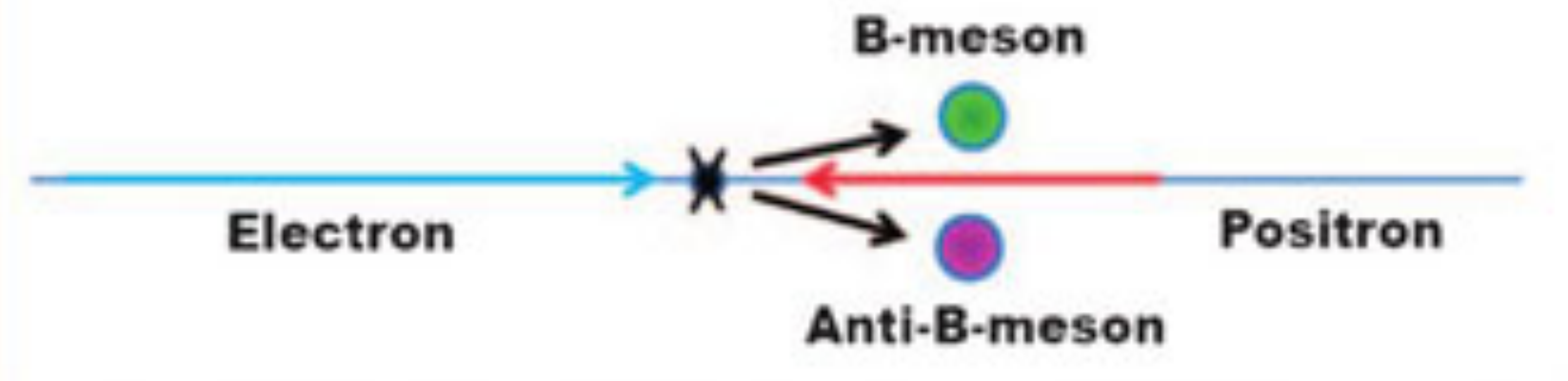
  - Ratio of branching fraction measured systematic cancel out → important for the decays which are systematic limited.
- Both decays have not been measured with full Belle data set.

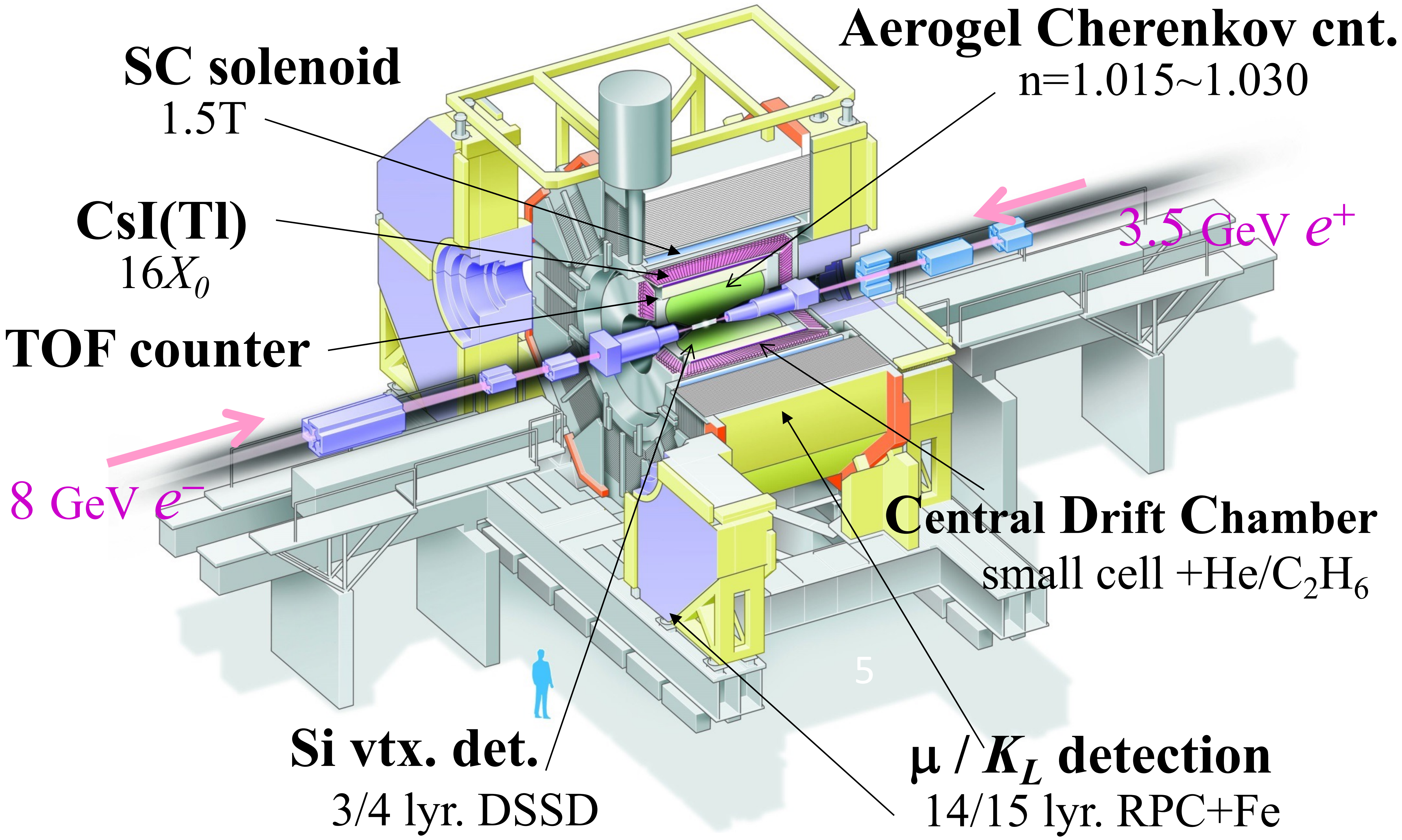
The Belle Experiment

- 3.5 GeV positrons on 8 GeV electrons
- E_{cm} = 10.58 GeV,

The Belle Detector

- K/π identification is carried out by the information from independent measurement from
  - dE/dx measurement by CDC
  - TOF measurement
  - Measurement of number of photo electrons in ACC





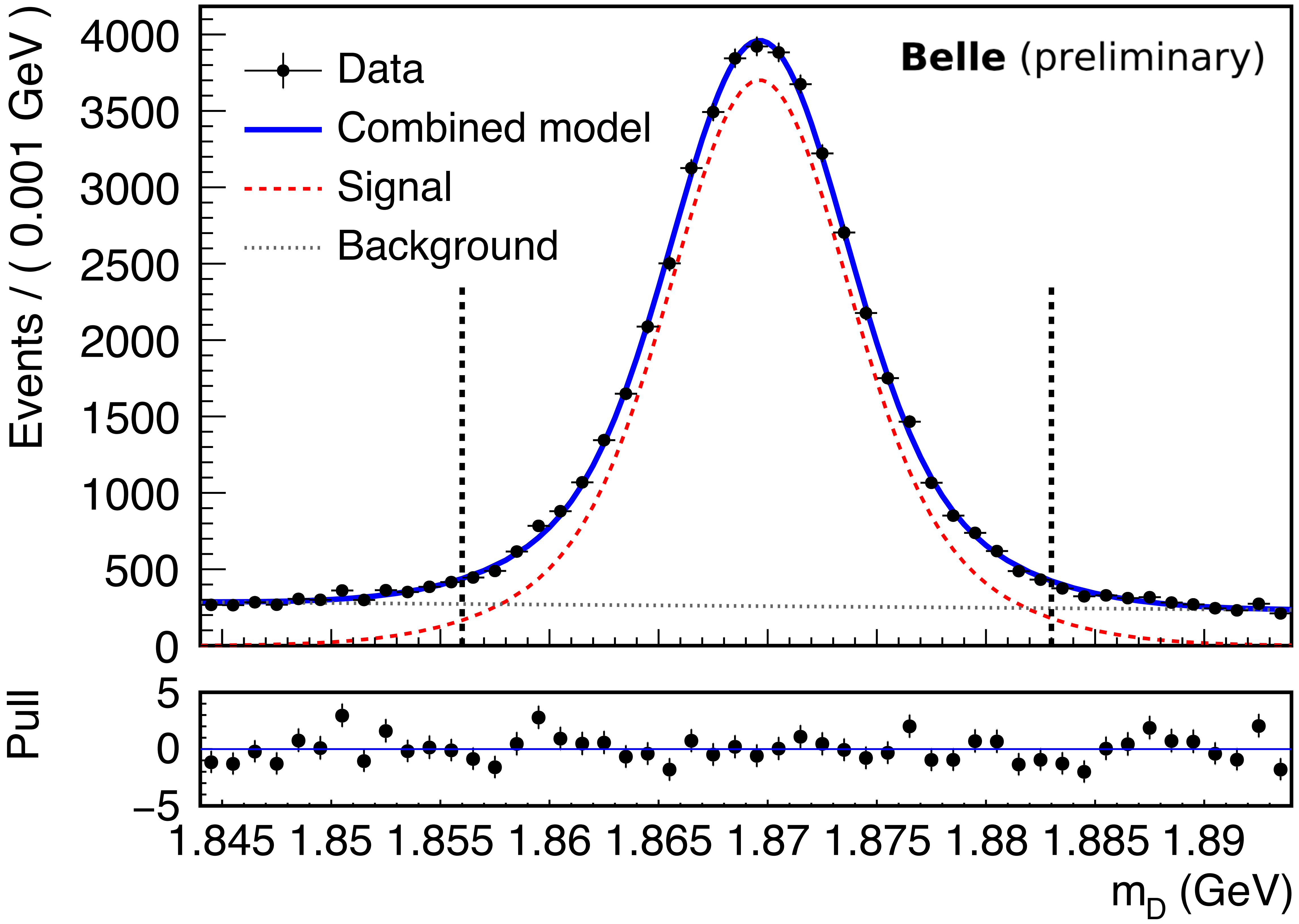
Analysis Strategy of $B^0 \to D^- h^+ (h = K/\pi)$

- Analysis with full Belle data set of 711fb^{-1}
- Decay Chain: $B^0 \to D^-(\to K^+\pi^-\pi^-)K^+$ and $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$
- Both modes are topologically very similar therefore same event selection criteria is applied $\longrightarrow$ minimize efficiency differences between the modes.
- High momentum particle identification capability of the Belle detector enables us to extract signals for $B^0 \to D^- K^+$ that are well separated from the more abundant, Cabibbo favored $B^0 \to D^- \pi^+$ processes.

Variable	Cut
Prompt K^+	$\mathcal{L}(K/\pi) > 0.6$
Prompt π^+	$\mathcal{L}(K/\pi) < 0.6$
$D^-(\to K^+\pi^-\pi^-)$ mass	$M_{\rm PDG} - 2.5\sigma_M < M < M_{\rm PDG} + 2.5\sigma_M$
$M_{\rm bc} = \sqrt{E^2_{beam} - p^*_B}$	$M_{\rm bc}$>5.27 GeV
$\Delta E = E^*_B - E_{beam}$	-0.13 GeV $<\Delta E<$0.13 GeV
p^*_D	2.06 GeV $<p^*_D$ <2.55 GeV
Fox–Wolfram Moment R_2	R_2<0.3

Reconstruction of D meson

- Mass constrained fit is applied to the D^- candidate $D^- \to K^+\pi^-\pi^-$ to ensure consistency with the D meson decay topology.
- D^- meson candidates are required to have a mass within 2.5σ of the true mass.



Mass resolution is ~5 MeV

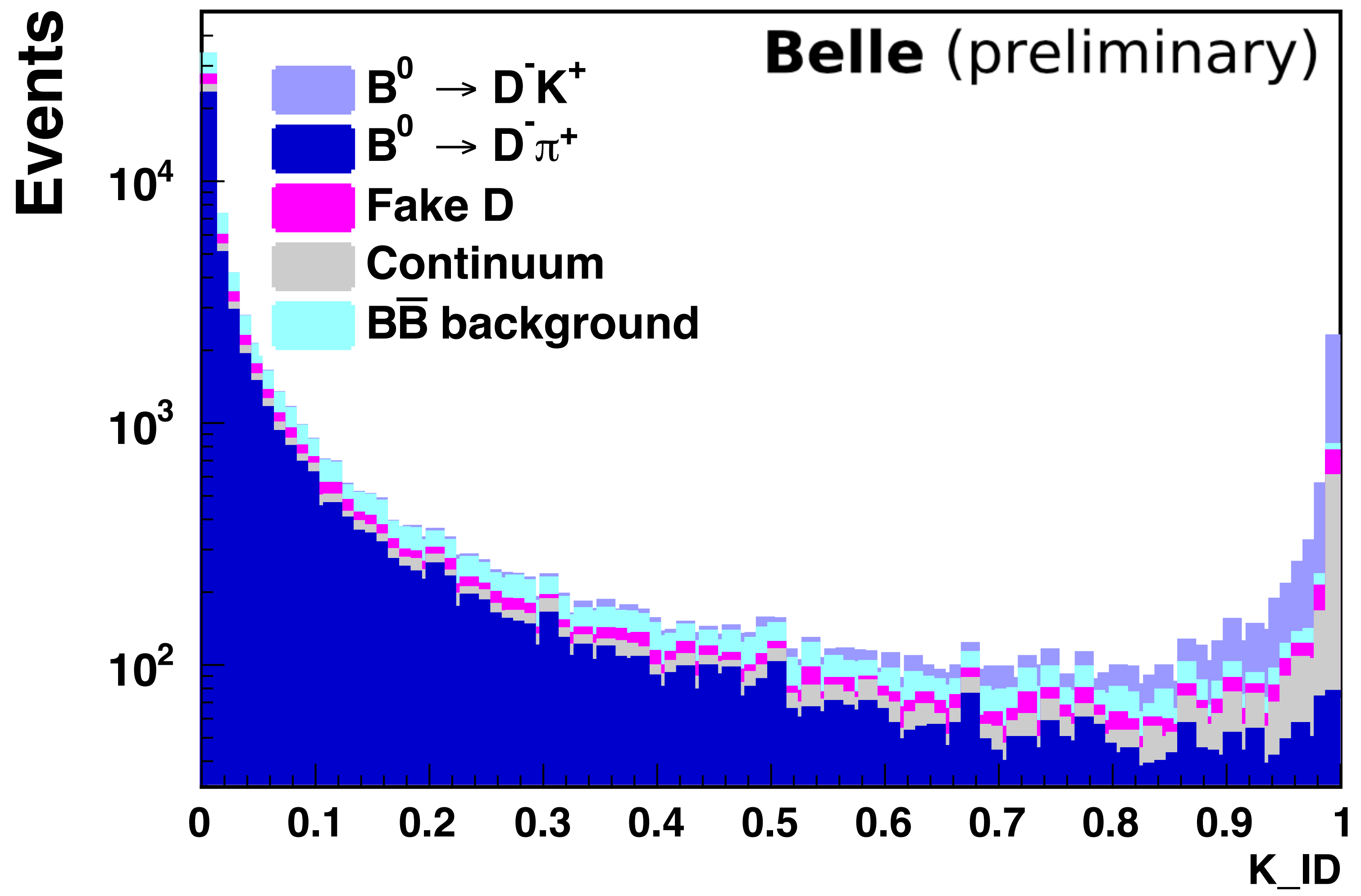
Particle Identification at Belle

- Particle identification system at Belle is used to determine a K/π likelihood ratio $\mathscr{L}(K/\pi)$ for the charged tracks.
- The likelihood ranges from 0 to 1.
  - 0 means likely to be a π and 1 means likely to be K.
- To ensure high efficiency and purity of kaons and pions we require,

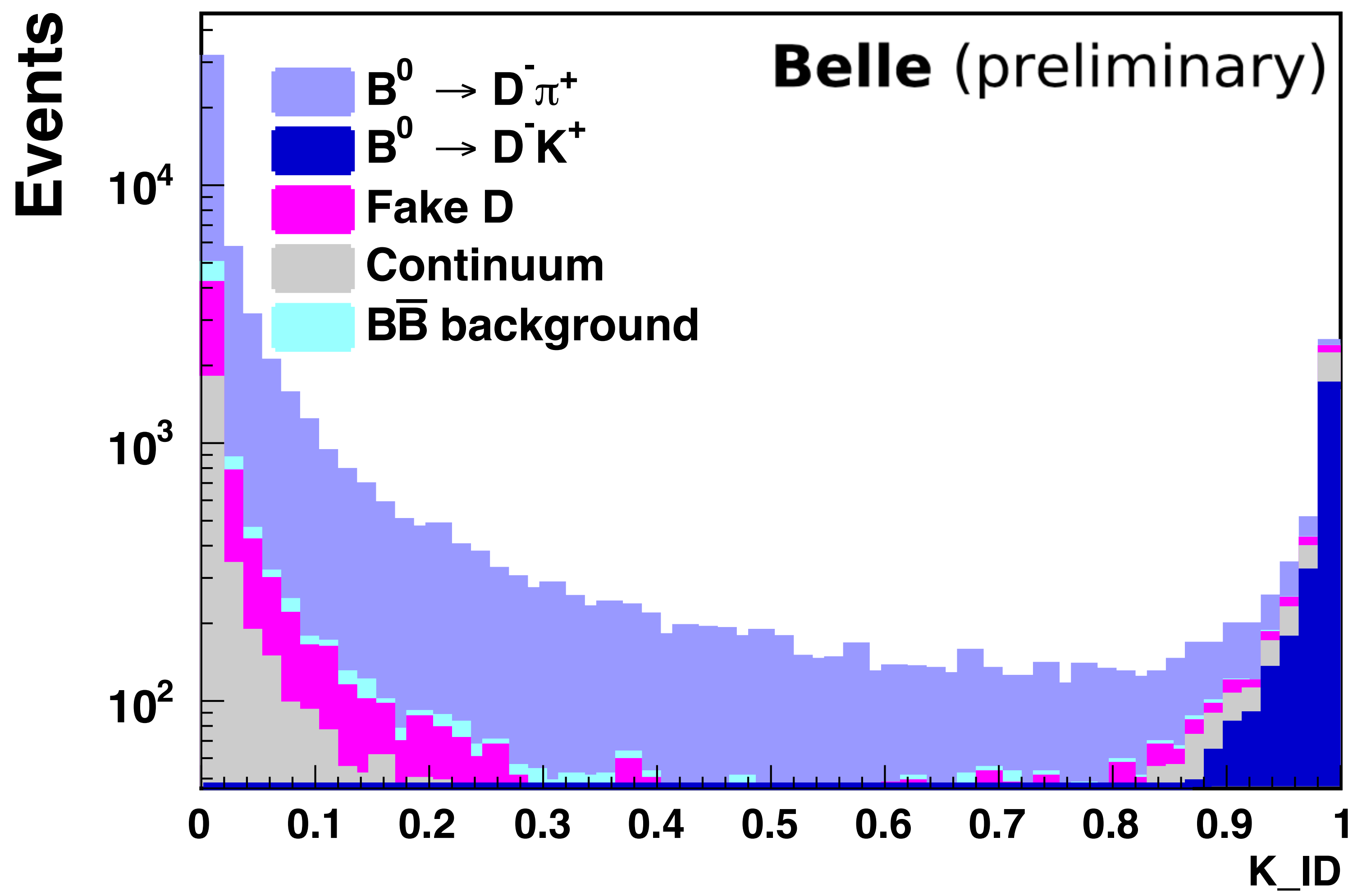
$$\boxed{\mathcal{L}(K/\pi) = \frac{\mathcal{L}_K}{\mathcal{L}_K+\mathcal{L}_\pi} > 0.6 \text{ for kaons}}$$

$$\boxed{\mathcal{L}(K/\pi) = \frac{\mathcal{L}_K}{\mathcal{L}_K+\mathcal{L}_\pi} < 0.6 \text{ for pions}}$$

$B^0 \to D^- h^+ (h = K)$



$B^0 \to D^- h^+ (h = \pi)$



Fit Strategy to Extract Ratio $\equiv R^D = \dfrac{\bar{B}^0 \to D^+K^-}{\bar{B}^0 \to D^+\pi^-}$

- Significant background from $\bar{B}^0 \to D^+\pi^-$ decays in $\bar{B}^0 \to D^+K^-$ due to the misidentification of pion as a kaon.
- A **simultaneous fit** is performed to samples enhanced in prompt tracks that are either **pions** [$\mathscr{L}(K/\pi) < 0.6$] or **kaons** [$\mathscr{L}(K/\pi) > 0.6$]
- Cross-feed from both decay modes is also determined from the simultaneous fit.
- Due to the low yield of $\bar{B}^0 \to D^+K^-$ cross feed to the pion-enhanced sample, the kaon identification efficiency ϵ_K is fixed.
- Un-binned maximum likelihood fit is performed to extract the signal yield by fitting the $\Delta E = E_B^* - E_{beam}$ distribution simultaneously in $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^-$ samples.

$$
\begin{aligned}
N^{D^+\pi^-}_{\text{pion enhanced}} &= (1-\kappa)\, N^{D^+\pi^-}_{\text{total}} \\
N^{D^+K^-}_{\text{pion enhanced}} &= (1-\epsilon_K)\, R^D\, N^{D^+\pi^-}_{\text{total}} \\
N^{D^+K^-}_{\text{kaon enhanced}} &= \epsilon_K\, R^D\, N^{D^+\pi^-}_{\text{total}} \\
N^{D^+\pi^-}_{\text{kaon enhanced}} &= \kappa\, N^{D^+\pi^-}_{\text{total}}
\end{aligned}
$$

Fix in fit

Floating in fit

- ✦ $N^{D^+\pi^-}_{\text{total}}$ is the total yield in both decays.
- ✦ ϵ_K is kaon identification efficiency
- ✦ κ is pion misidentification rate/pion fake rate
- ✦ R^D is the ratio

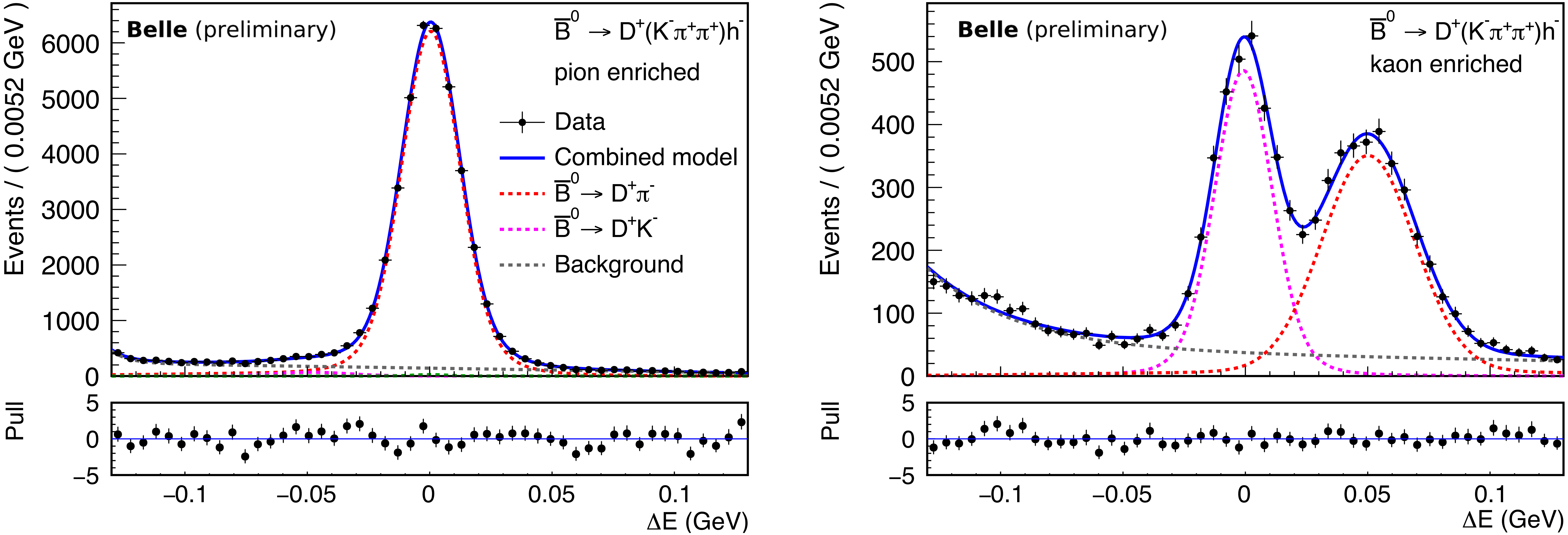
From Belle official PID system →

$\epsilon_K = (84.46 \pm 0.12)\,\%$
$\kappa = (7.64 \pm 0.96)\,\%$

Simultaneous Fit to Extract Ratio $\equiv R^D = \frac{\bar{B}^0 \to D^+K^-}{\bar{B}^0 \to D^+\pi^-}$

Belle EPS Preliminary

$$\Delta E = E_B^* - E_{beam}$$



Results from the fit:

$R^D = (8.20 \pm 0.20) \times 10^{-2}$

$\kappa = (8.10 \pm 0.21) \times 10^{-2}$ (agree with official Belle PID value within $\sim 2\sigma$)

From Belle PID
$\kappa = (7.64 \pm 0.96)\,\%$

Calculation of Systematics Uncertainties

Belle EPS Preliminary

- Kinematics of $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^-$ processes are quite similar, most of the systematic effects cancel in the ratio of the branching fractions.
- The main source of systematic error that do not cancel is the uncertainty in K/π identification efficiency.
- All the sources of systematic uncertainty are assumed to be independent.
- Total systematic uncertainty is the sum in quadrature of the contributions from individual sources.

Source	R^D	$\mathcal{B}(\overline{B}^0 \to D^+\pi^-)$	$\mathcal{B}(\overline{B}^0 \to D^+K^-)$
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	–	1.71%	1.71%
Multiplicative uncertainties			
Tracking	–	1.40%	1.40%
MC statistics	–	0.04%	0.04%
$\Delta N_{B\bar{B}}$	–	1.37%	1.37%
f_{00}	–	1.23%	1.23%
PID efficiency of K/π (stat.)	0.01%	0.00%	0.31%
PID efficiency of K/π (syst.)	0.01%	0.04%	0.64%
Total multiplicative	0.01%	2.31%	2.42 %
Additive uncertainties			
PDF parameterisation	0.199×10^{-2}	0.040×10^{-3}	0.028×10^{-4}
D^+ mass selection window	0.002×10^{-2}	0.058×10^{-3}	0.047×10^{-4}
J/ψ veto selection	0.003×10^{-2}	0.001×10^{-3}	0.000×10^{-4}
Fit bias	–	0.030×10^{-3}	0.020×10^{-4}
Total additive	0.199×10^{-2}	0.077×10^{-3}	0.058×10^{-4}

Results

- The ratio of $B^0 \to D^- K^+$ and $B^0 \to D^- \pi^+$ branching fraction

$$R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+ K^-)}{\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)} = (8.20 \pm 0.20(\mathrm{stat}) \pm 0.20(\mathrm{syst})) \times 10^{-2}$$

LHCb: J. High Energ. Phys. 2013, 1 (2013)

Ratio $= 8.22 \pm 0.11(\mathrm{stat}) \pm 0.25(\mathrm{syst})$

- Measurement of branching fraction for $B^0 \to D^- \pi^+$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = \frac{N_{D\pi}^{\mathrm{total}}}{2 \times f_{00} \times N_{B\bar{B}} \times \epsilon_{D\pi} \times \mathcal{B}(D^- \to K^+\pi^-\pi^-)}$$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = [2.50 \pm 0.01_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}} \pm 0.04_{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-3}$$

BaBar: Phys.Rev.D 75 (2007) 031101

$\mathcal{B}[B^0 \to D^-\pi^+] = [2.55 \pm 0.05_{\mathrm{stat}} \pm 0.16_{\mathrm{syst}}] \times 10^{-3}$

CLEO2: Phys.Rev.D 66 (2002) 031101

$\mathcal{B}[B^0 \to D^-\pi^+] = [2.68 \pm 0.12_{\mathrm{stat}} \pm 0.24_{\mathrm{syst}}] \times 10^{-3}$

- Measurement of branching fraction for $B^0 \to D^- K^+$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = \mathcal{B}(B^0 \to D^-\pi^+) \times R^D$$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = [2.05 \pm 0.05_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}} \pm 0.04_{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-4}$$

LHCb: Phys.Rev.Lett. 107 (2011) 211801

$\mathcal{B}[B^0 \to D^-K^+] = [1.89 \pm 0.19_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}] \times 10^{-4}$

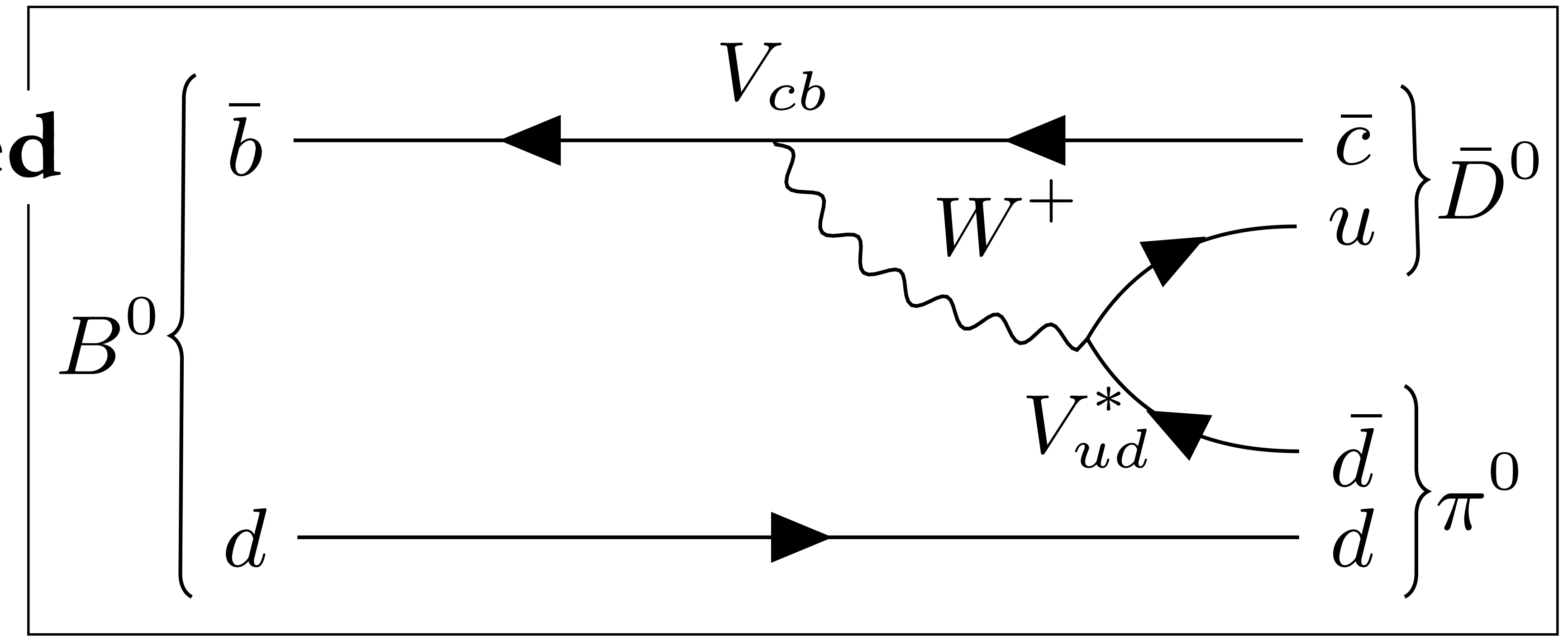
Belle: Phys.Rev.Lett. 87 (2001) 111801

$\mathcal{B}[B^0 \to D^-K^+] = [1.7 \pm 0.4_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}}] \times 10^{-4}$

Study of $B \to \bar{D}^0\pi$

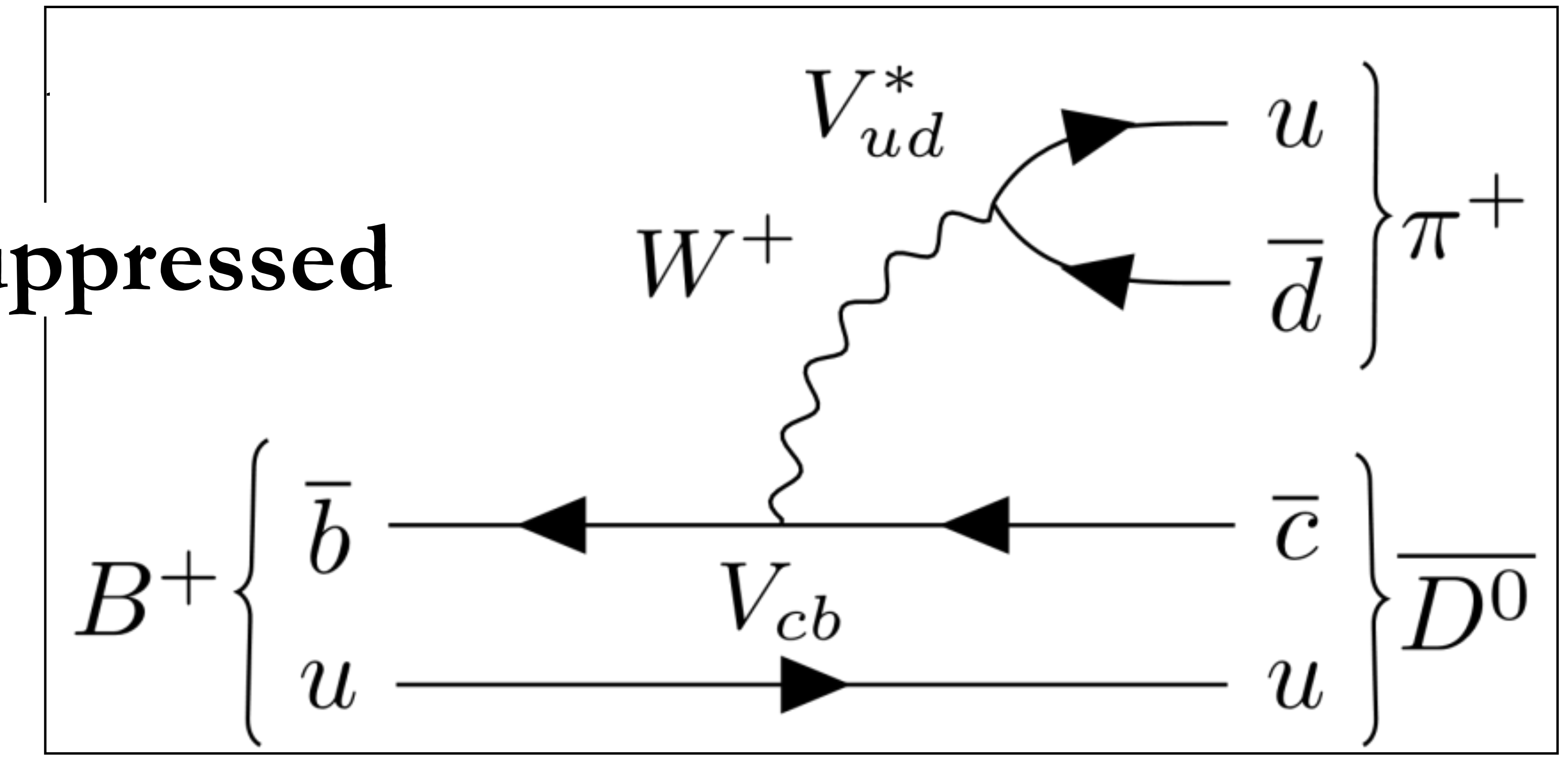
- $b \to c\bar{u}d$ transition does not have simple penguin amplitude.
- No penguin diagram possible as final state quark different flavour
- Branching fraction of color suppressed $B^0 \to \bar{D}^0\pi^0$ has been measured using "naive" factorization model. Nucl.Phys.B591:313-418,2000
- Both are commonly used control mode in many analysis $\to$ allow for high-precision validations of techniques.
  - Important for Belle II precision frontier.

Color-allowed



$B^0 \to \bar{D}^0\pi^0$

Color-suppressed



$B^+ \to \bar{D}^0\pi^+$

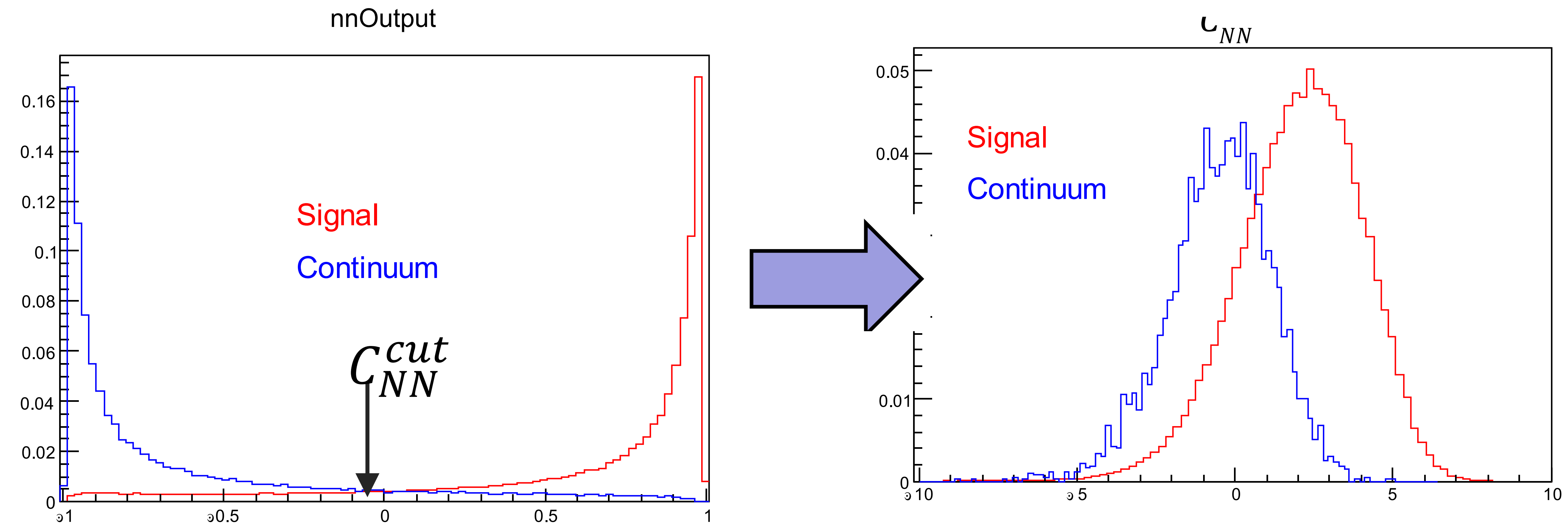
Analysis Strategy of $B \to \bar{D}^0\pi$

- Analysis performed with full Belle data set of $711\,\mathrm{fb}^{-1}$
- Decay Chain: $B \to \bar{D}^0(\to K^+\pi^-)\pi^0$ and $B \to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^0$; $\pi^0 \to \gamma\gamma$
- Signal reconstruction
  - Charged particles reconstructed from hadron ID and tracking
  - Neutral particles from $\pi^0 \to \gamma\gamma$ pairs in ECL
- Kinematic variables used for fitting $\Delta E = E_B^* - E_{beam}$ and

  $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - p_B^2}$
- Continuum Suppression using R_2 and variables in NN

  →transformation to fit as

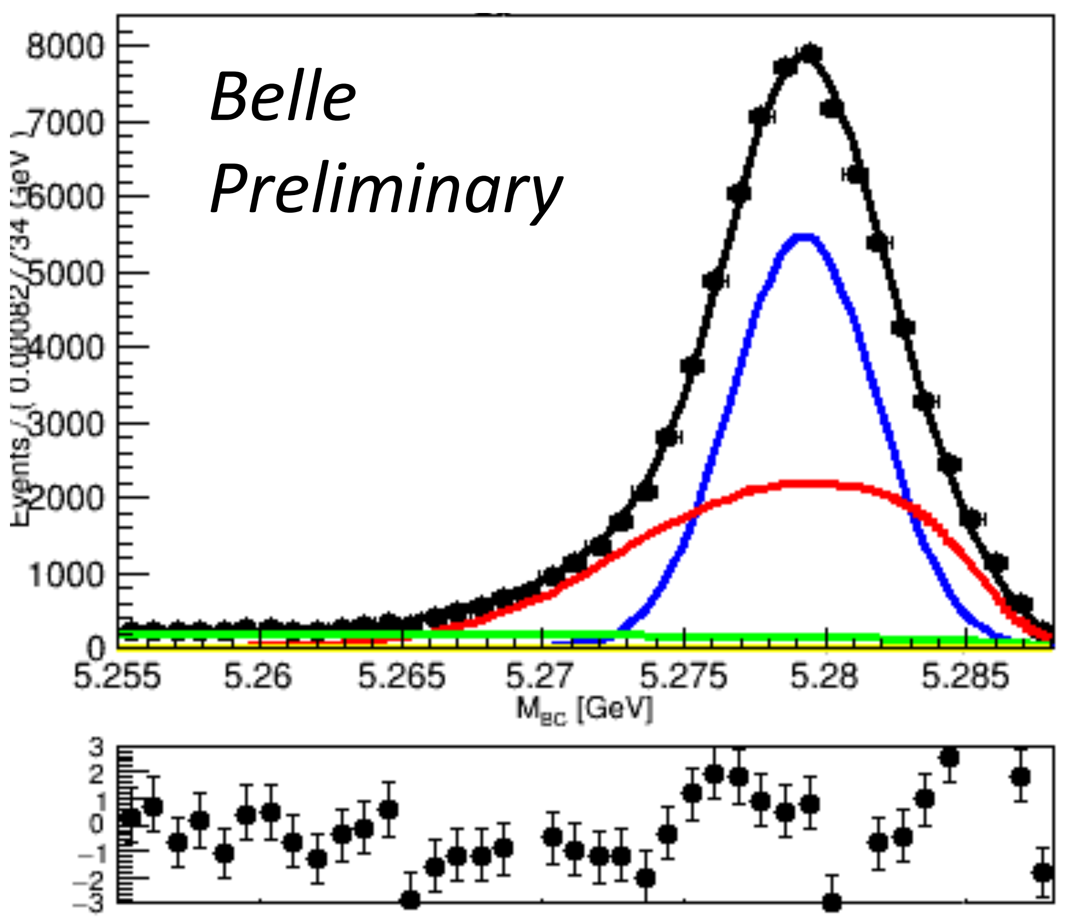
  - $C'_{NN} = log\left(\frac{C_{NN} - C_{NN}^{min}}{C_{NN}^{max} - C_{NN}}\right)$



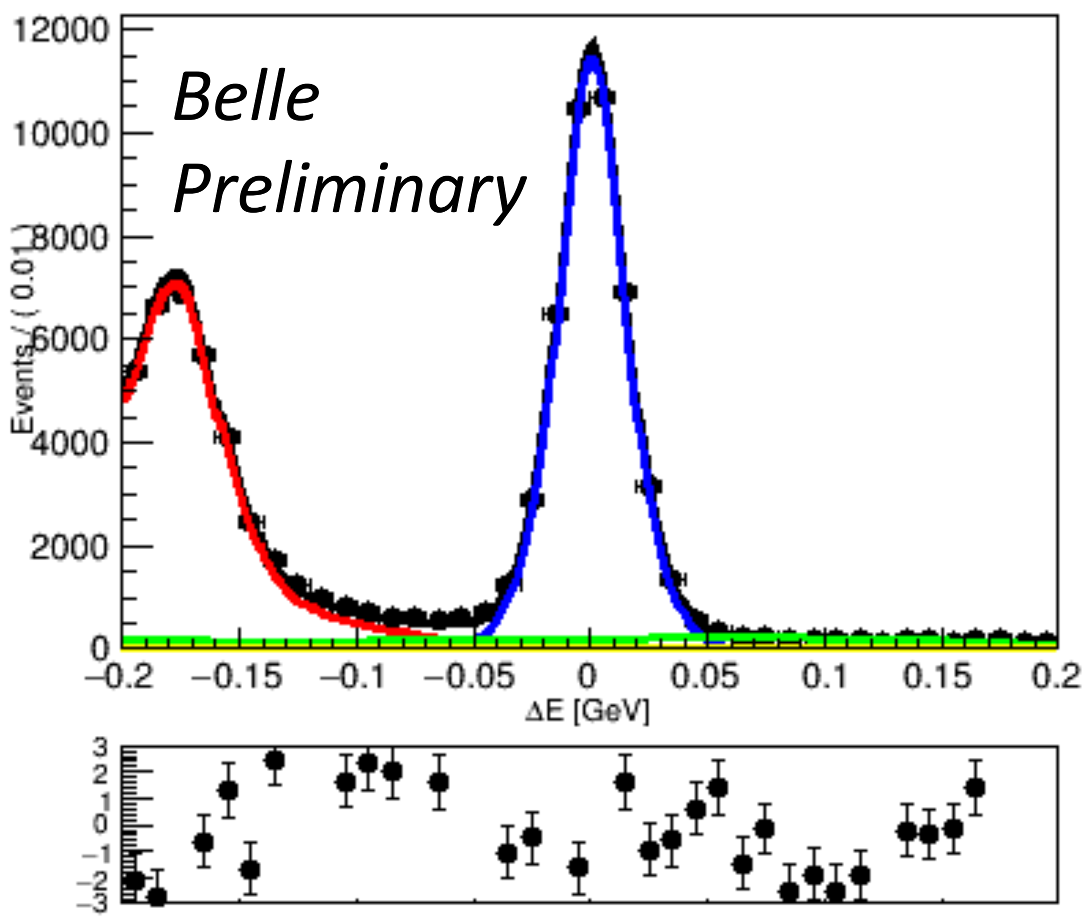
- Unbinned maximum likelihood fit in M_{bc} and ΔE and C'_{NN}
  - Simultaneous fit over four datasets divided by D^0 decay and kaon charge.

Results $B^+ \to \bar{D}^0\pi^+$

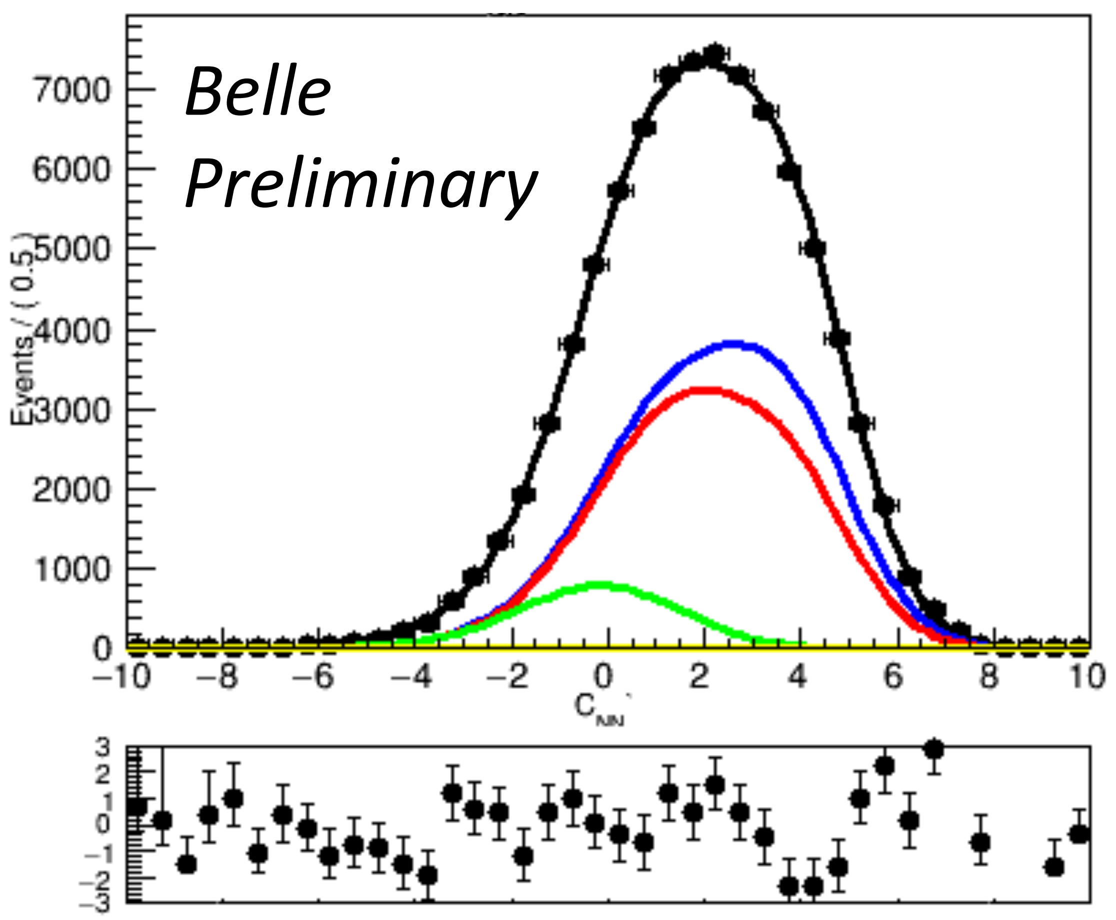
$M_{bc}(\bar{D}^0 \to K^+\pi^-)$



$\Delta E(\bar{D}^0 \to K^+\pi^-)$



$C'_{NN}(\bar{D}^0 \to K^+\pi^-)$

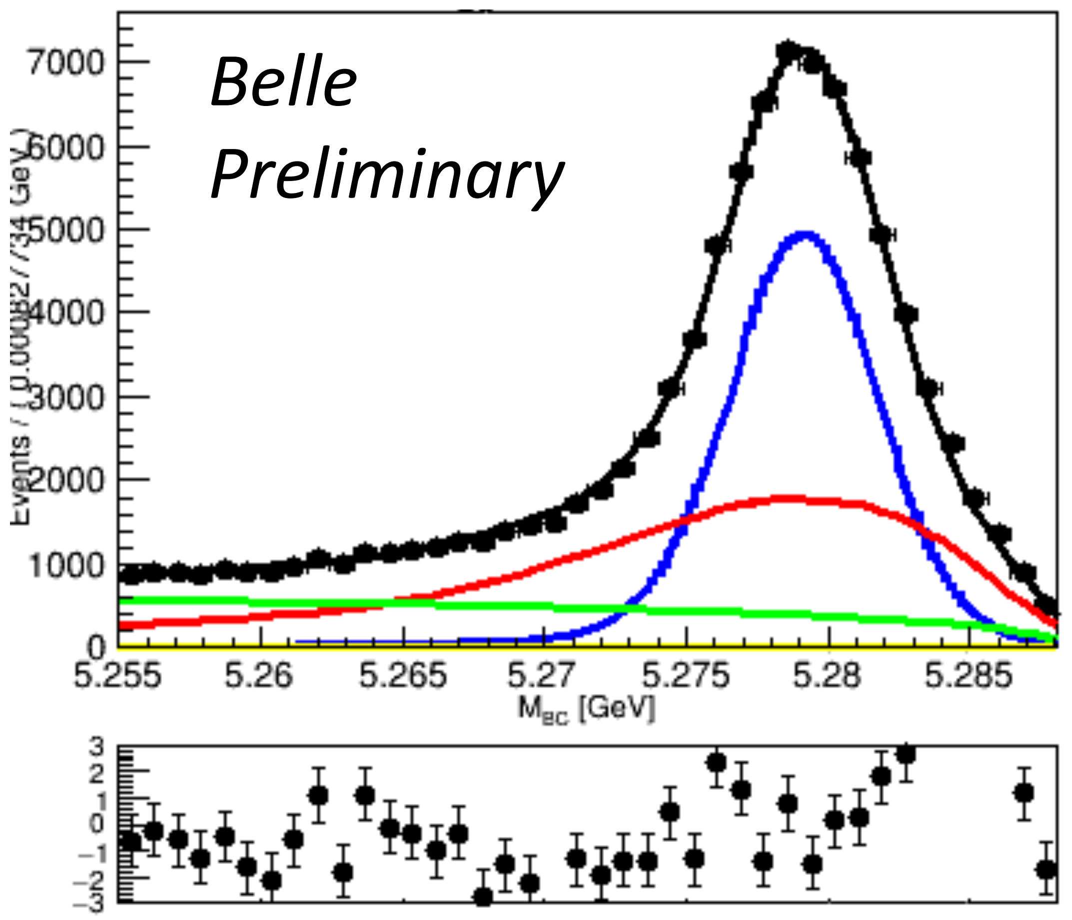


- Total
- Signal
- $B\bar{B}$ bkg
- $q\bar{q}$ bkg
- Rare bkg

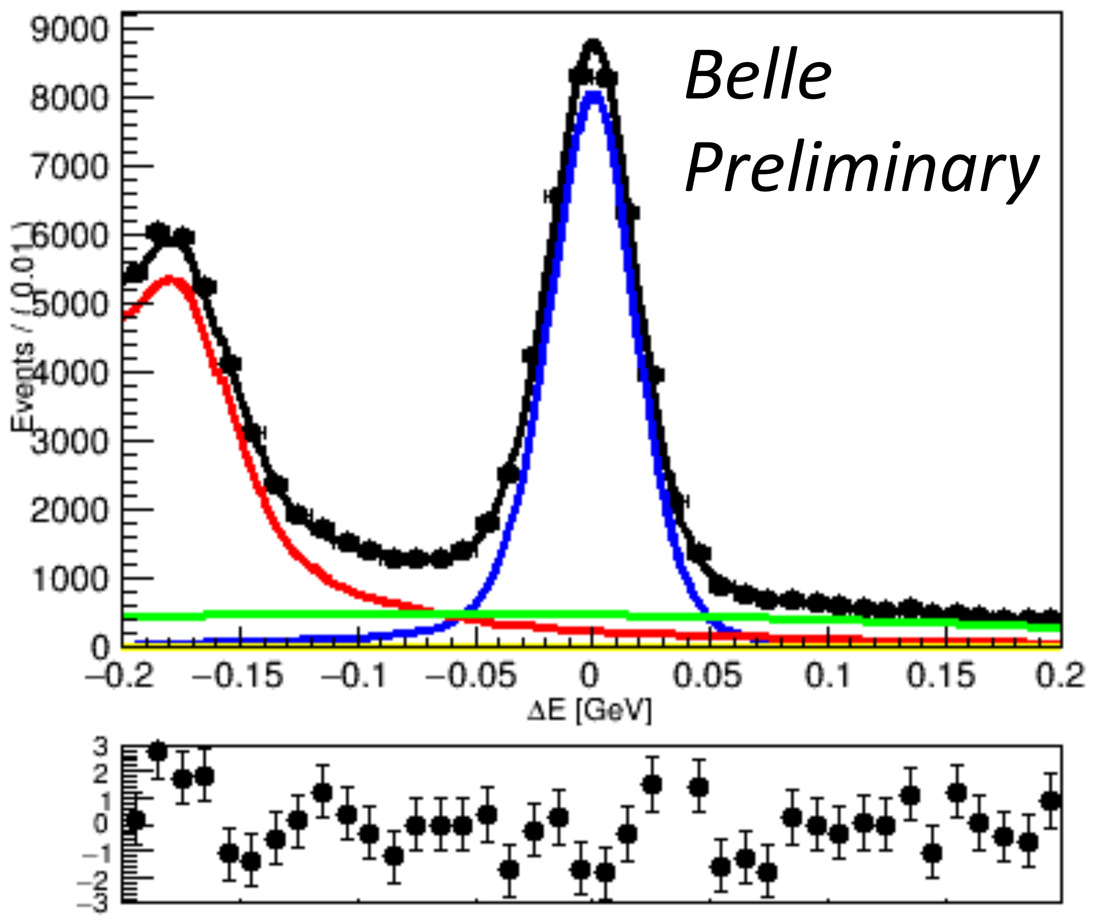
$$\mathscr{B}(B^+ \to \bar{D}^0\pi^+) = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$

Most precise measurement in this channel

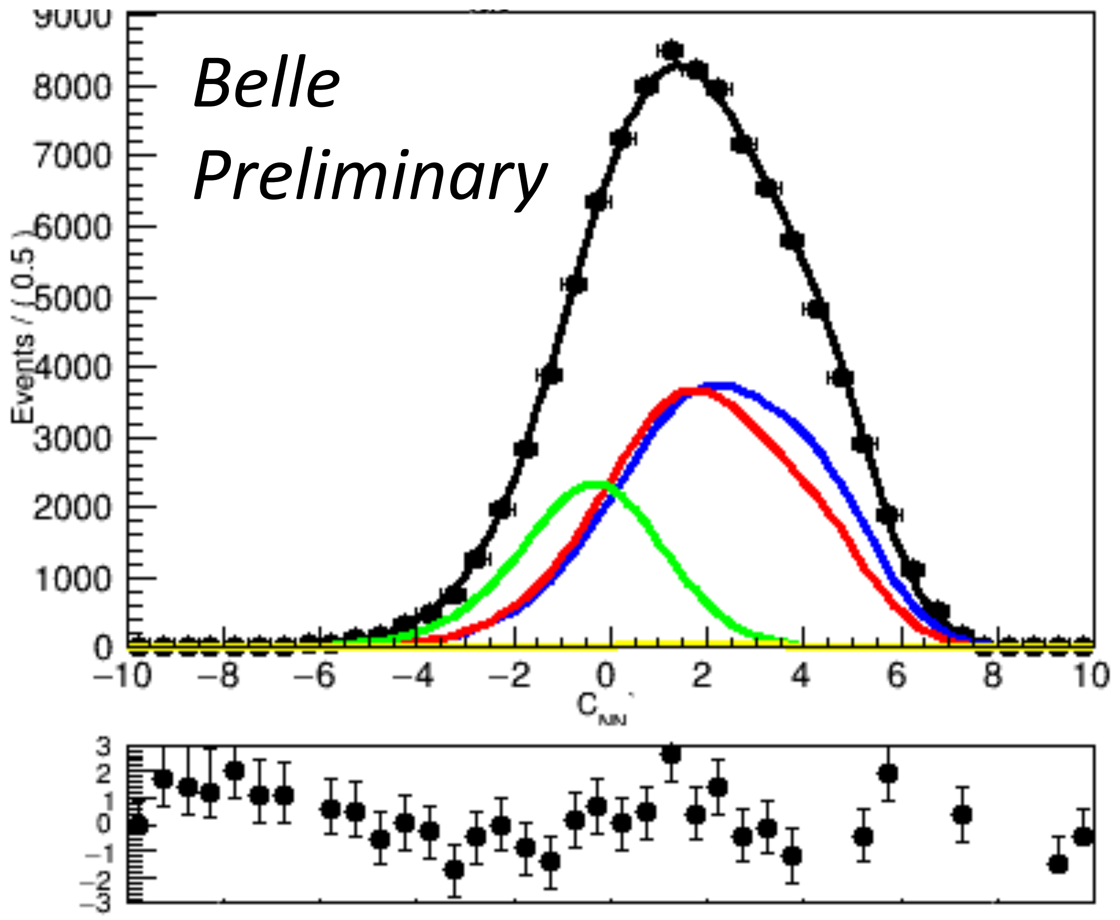
$M_{bc}(\bar{D}^0 \to K^+\pi^-\pi^0)$



$\Delta E(\bar{D}^0 \to K^+\pi^-\pi^0)$

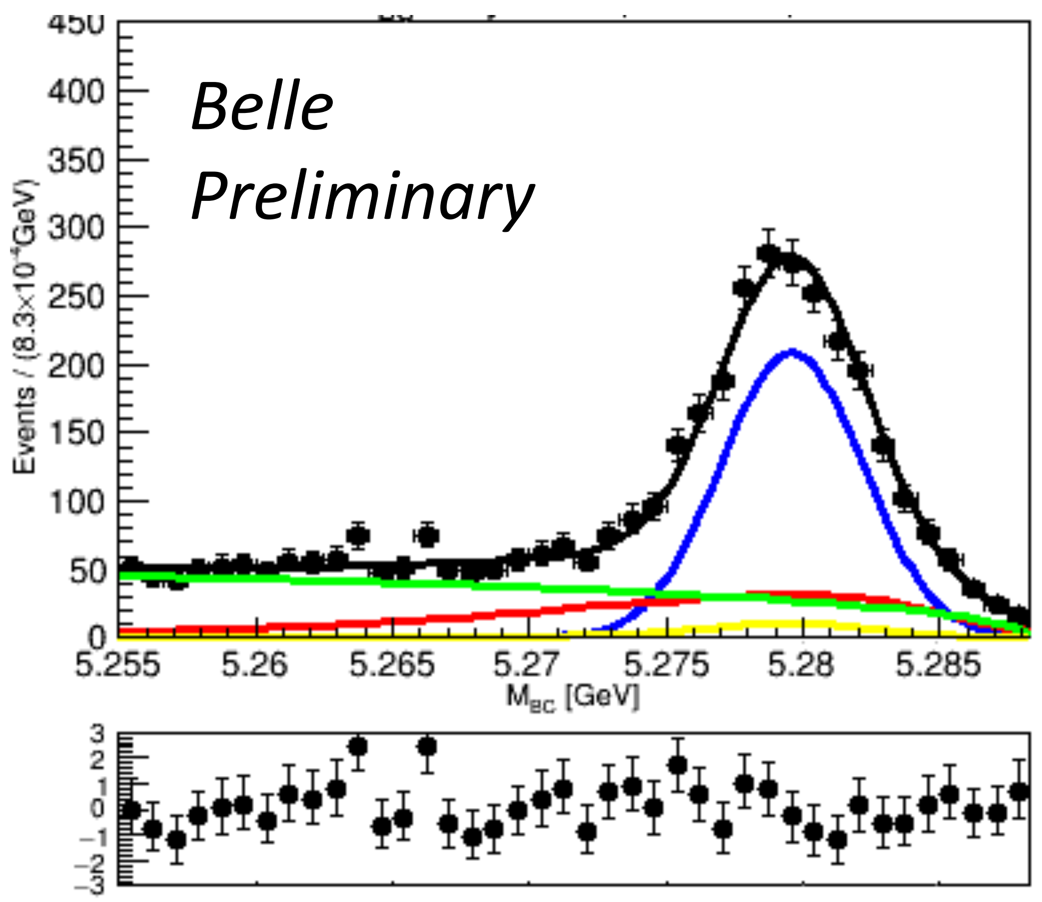


$C'_{NN}(\bar{D}^0 \to K^+\pi^-\pi^0)$

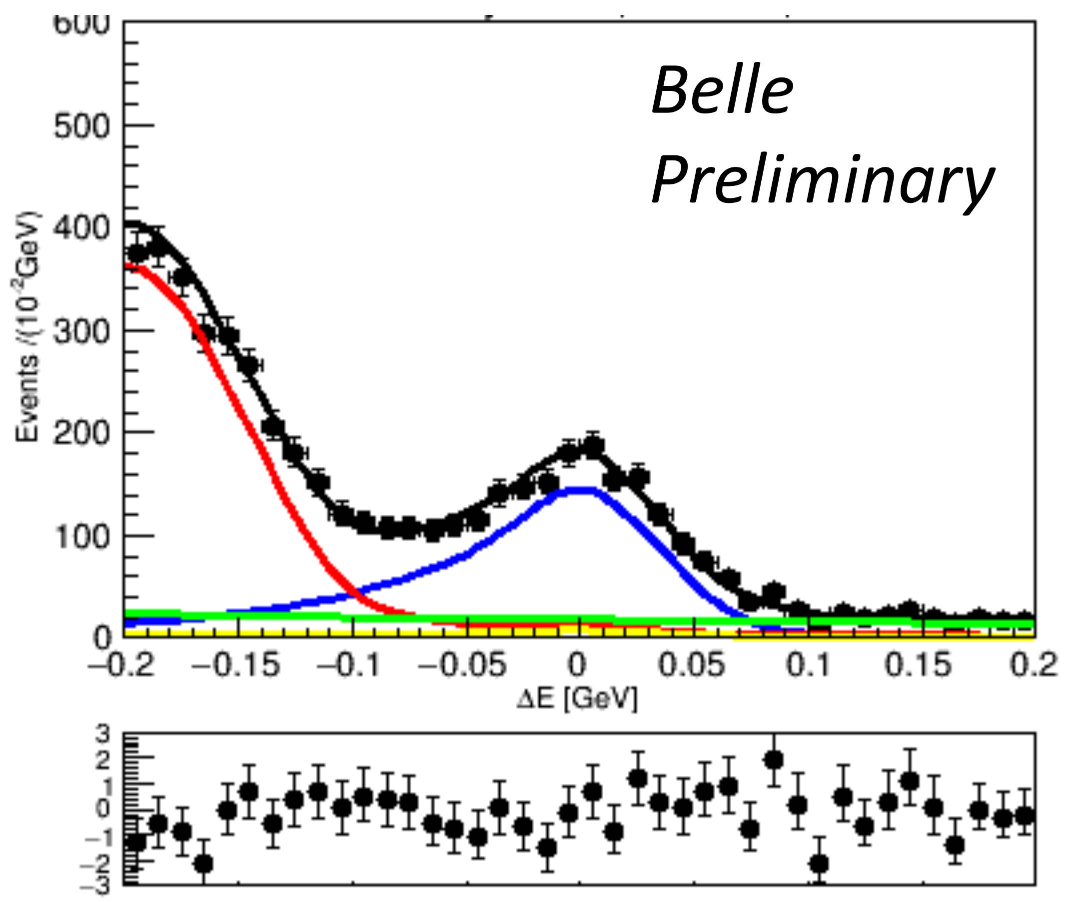


Results $B^0 \to \bar{D}^0\pi^0$

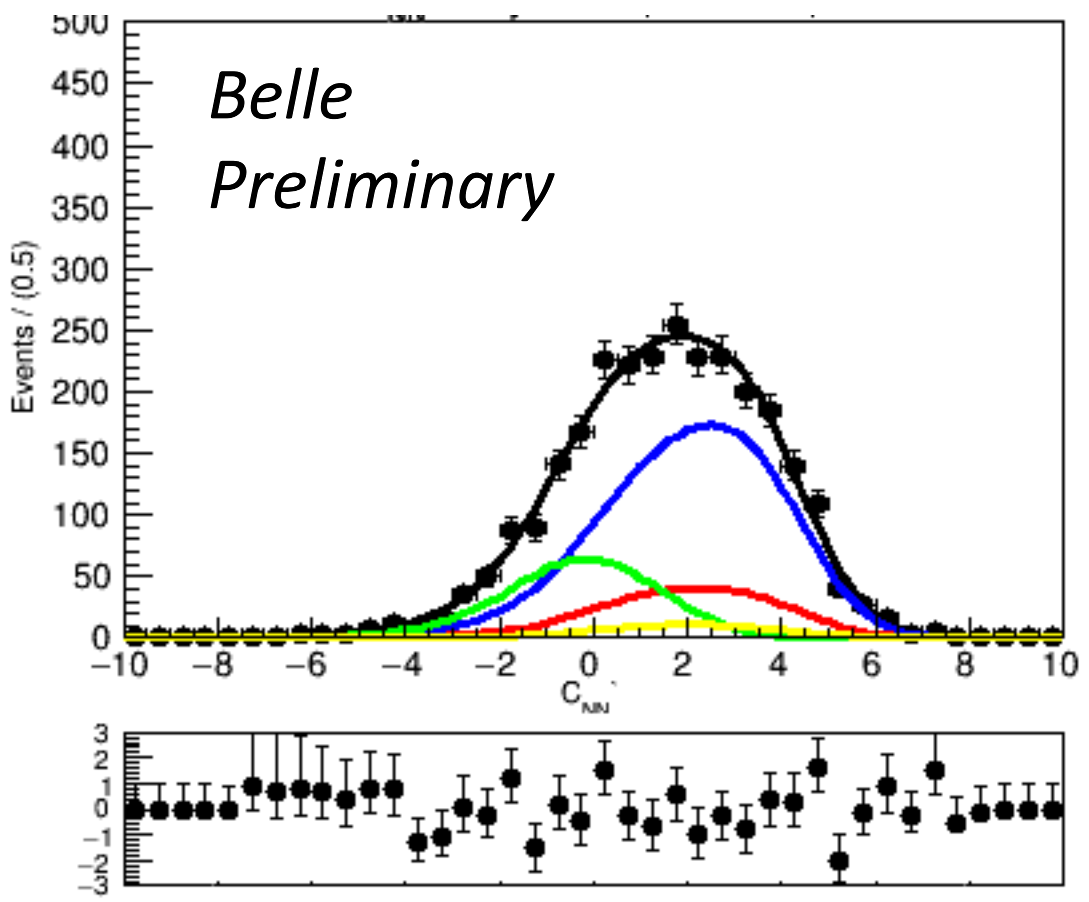
$M_{\rm bc}(\bar{D}^0 \to K^+\pi^-)$



$\Delta E(\bar{D}^0 \to K^+\pi^-)$

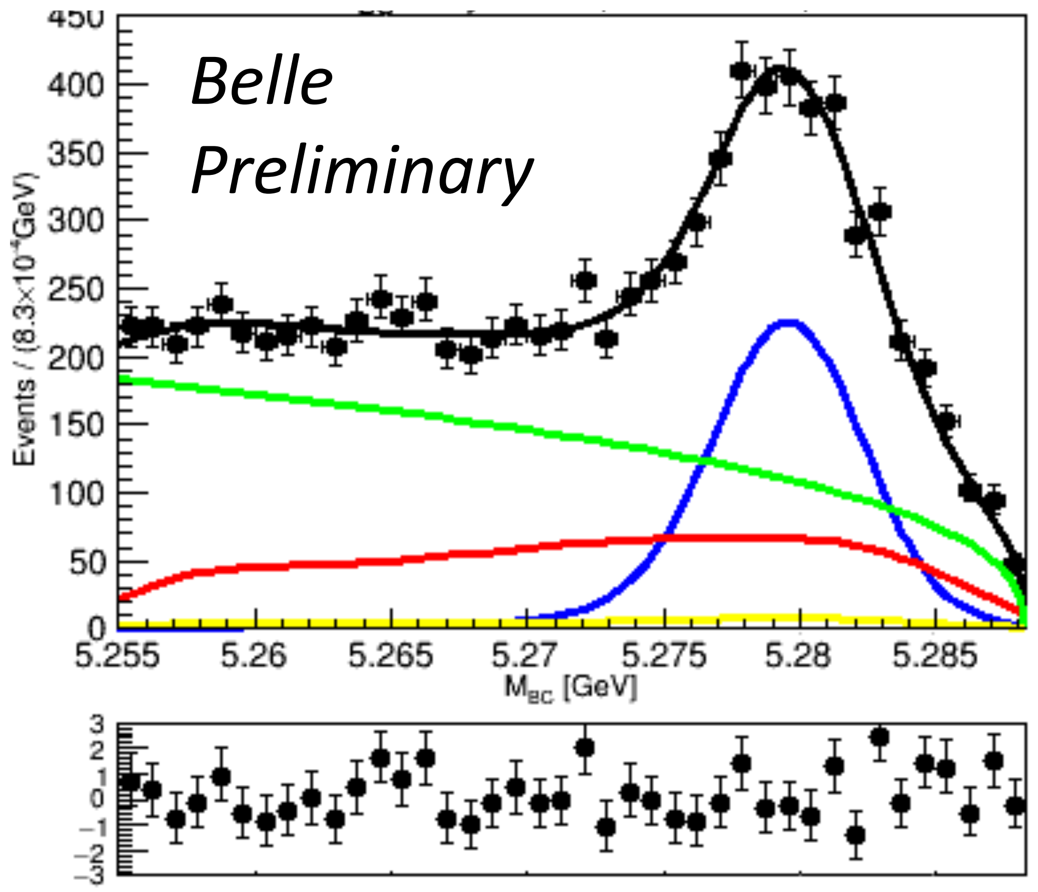


$C'_{NN}(\bar{D}^0 \to K^+\pi^-)$

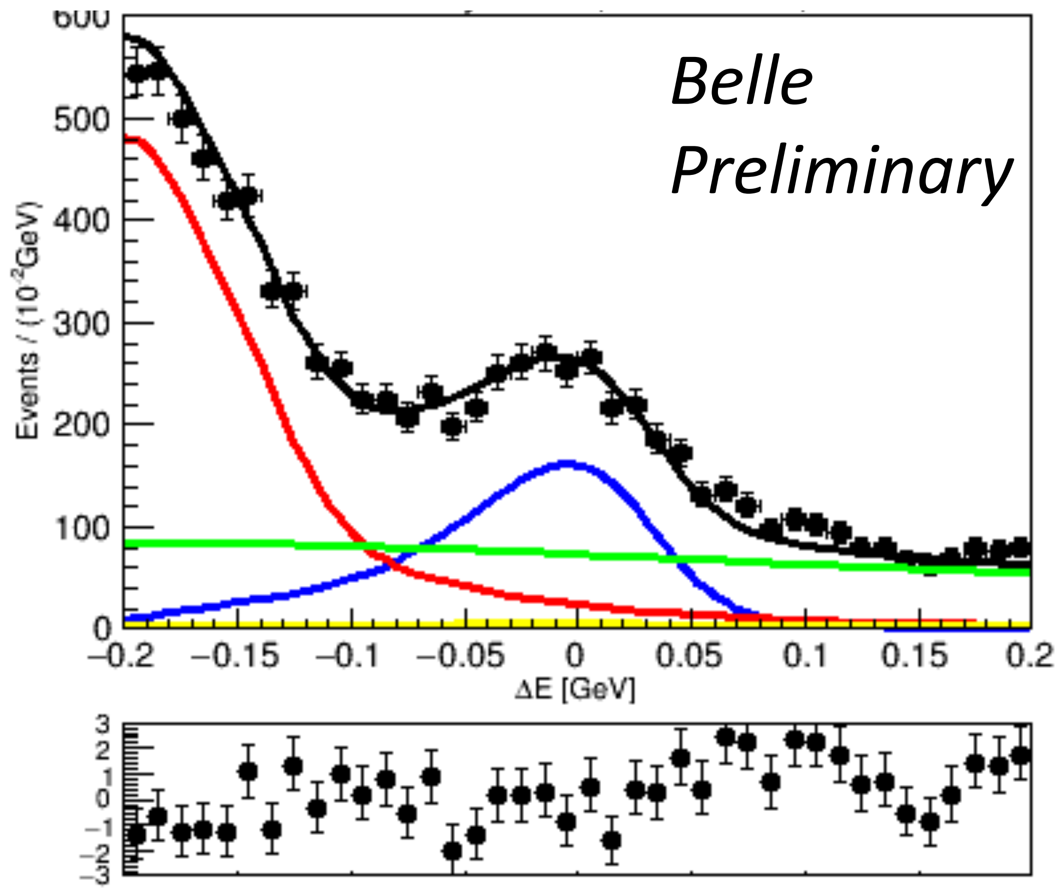


- Total
- Signal
- $B\bar{B}$ bkg
- $q\bar{q}$ bkg
- Rare bkg

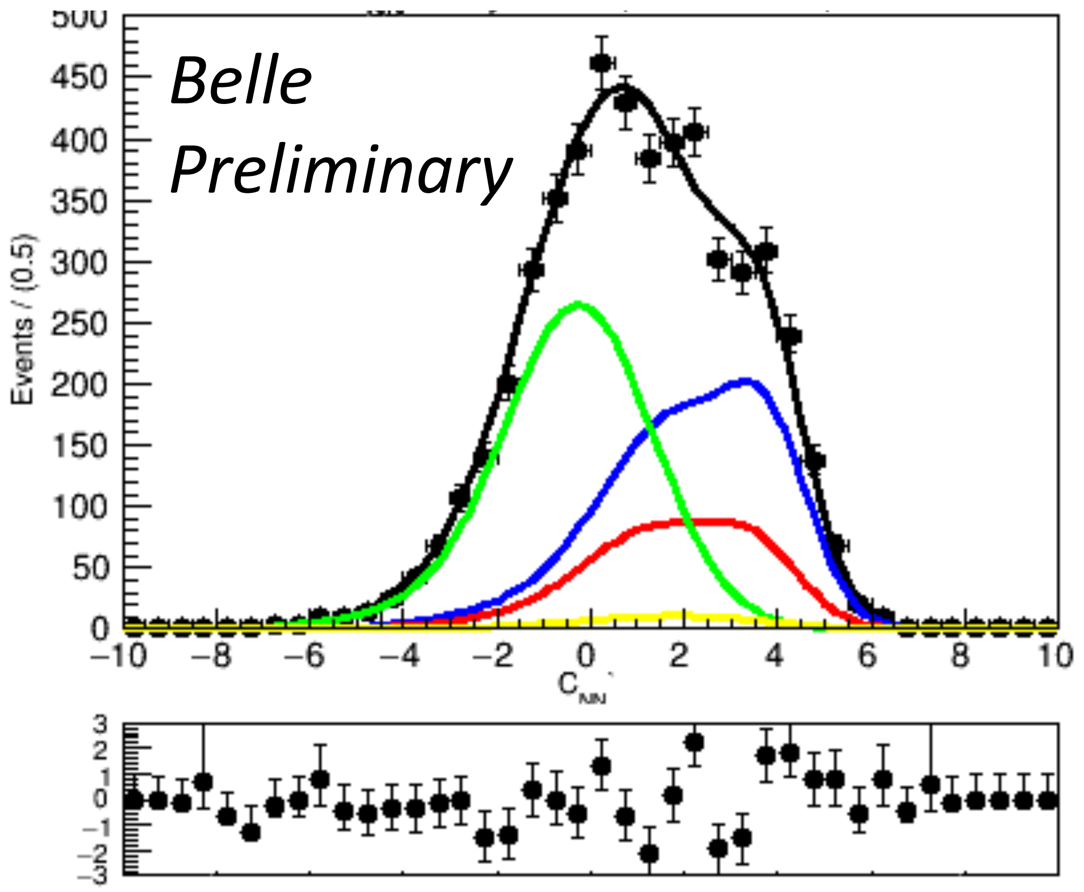
$M_{\rm bc}(\bar{D}^0 \to K^+\pi^-\pi^0)$



$\Delta E(\bar{D}^0 \to K^+\pi^-\pi^0)$



$C'_{NN}(\bar{D}^0 \to K^+\pi^-\pi^0)$



$$\boxed{\mathscr{B}(B^0 \to \bar{D}^0\pi^0) = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}}$$

Most precise measurement in this channel

Summary

- Measurements performed with full Belle data.
- Preliminary results for $\bar{B}^0 \to D^+ h^- (h = K/\pi)$ are

Belle EPS Preliminary

$$\boxed{\begin{aligned}&\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = [2.50 \pm 0.01_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.04_{\mathscr{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-3}\\ &\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = [2.05 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.04_{\mathscr{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-4}\end{aligned}}$$

$$\boxed{R^D = 0.082 \pm 0.002(\text{stat}) \pm 0.002(\text{syst})}$$

  - Most precise measurement till date and the values agrees with world averages.
  - $\bar{B}^0 \to D^{*+} h^- (h = K/\pi)$ results from Belle coming soon

- Preliminary results for $\bar{B} \to \bar{D}^0 \pi$ are

$$\mathscr{B}(B^+ \to \bar{D}^0\pi^+) = (4.53 \pm 0.02_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-3}$$

$$\mathscr{B}(B^0 \to D^0\pi^0) = (2.69 \pm 0.06_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}$$

  - Precision is improved in both decay channels.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Thank You