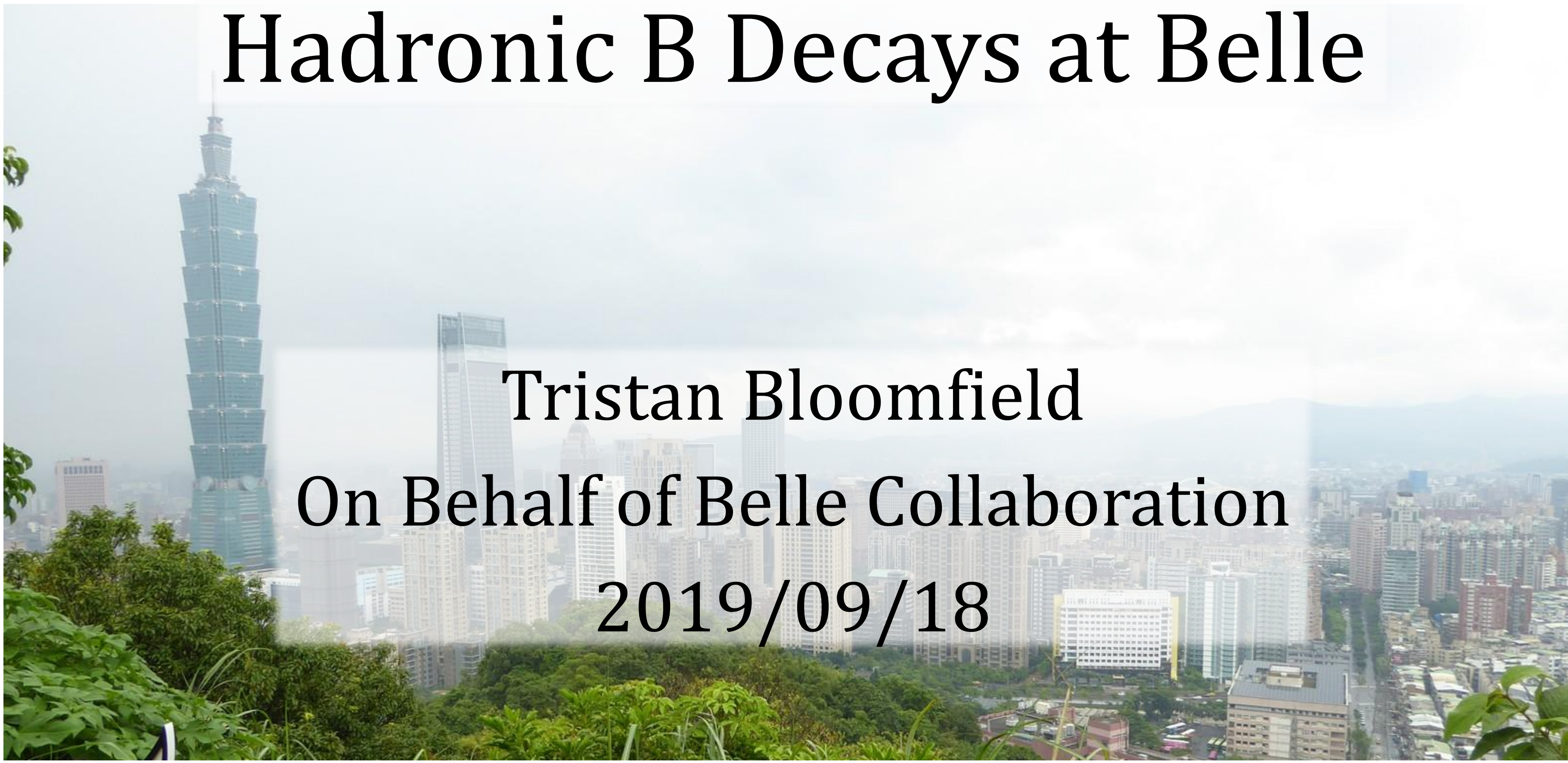
Hadronic B Decays at Belle



Tristan Bloomfield

On Behalf of Belle Collaboration

2019/09/18

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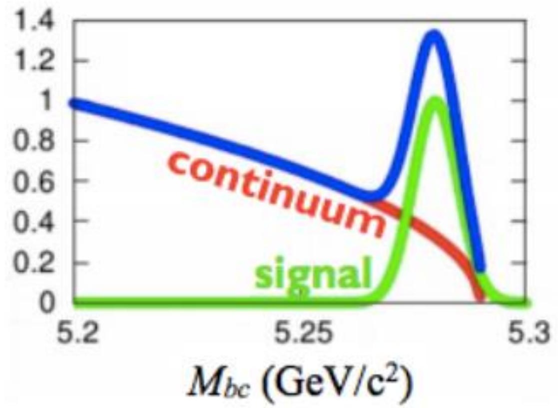
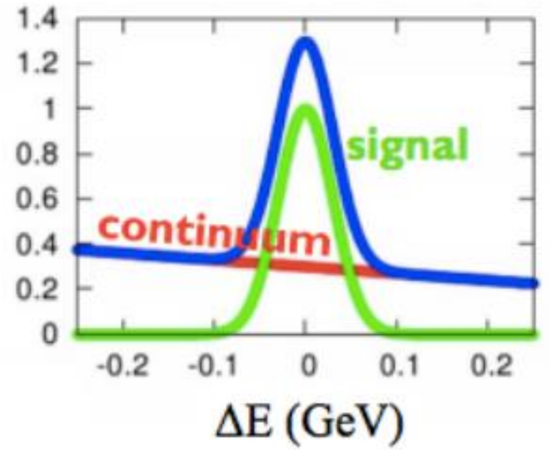
- Recent results
  - Measurement of the B and CP asymmetry in $B^0 \to \overline{D^0}\pi^0$ and $B^+ \to \overline{D^0}\pi^+$decays.
    NEW
  - Measurement of branching fraction and final-state asymmetry for the $B^0 \to K^-\pi^+K_s$ decay.
    Phys. Rev. D 100, 011101 (2019)
  - Evidence of the decay $B^0 \to p\bar{p}\pi^0$.
    Phys. Rev. D 99, 091104 (2019)
  - Study of $B \to p\bar{p}\pi\pi$
    NEW
- Summary

Signal Reconstruction

- Charged particles from hadron ID and tracking.
- Neutral particles from decays:
  - $\pi^0 \rightarrow \gamma\gamma$, pairs in ECL.
  - $K_s \rightarrow \pi^+\pi^-$
- Kinematic variables for fitting:

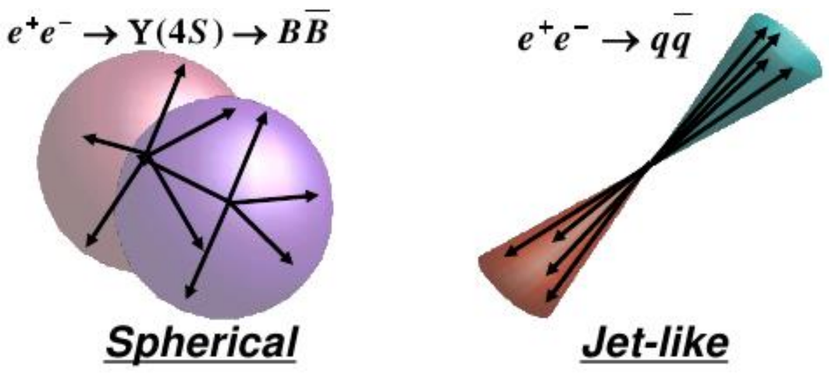
$$M_{bc} = \sqrt{E_{Beam}^2 - p_B^2}, \qquad \Delta E = E_B - E_{Beam}$$





Continuum Suppression

- $e^+e^- \to q\overline{q}\,(q \in u, d, s, c)$ dominant background. $\sim$3 times $e^+e^- \to \Upsilon(4S)$ cross-section.
- Discriminate using event topology.

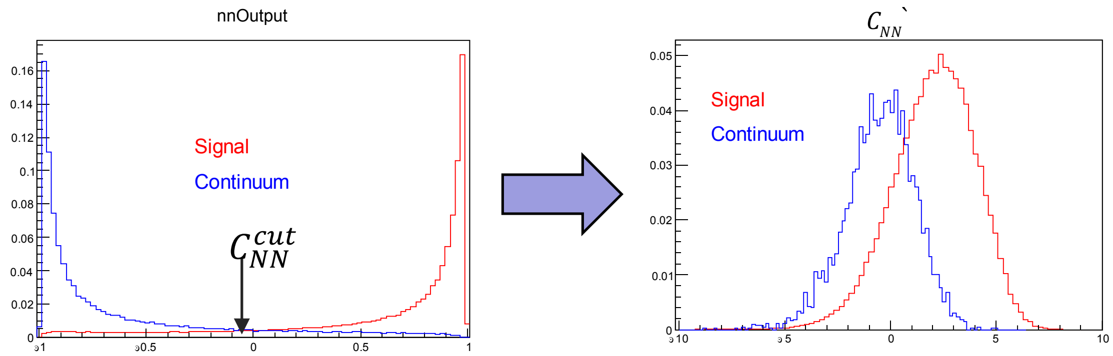


- Modified Fox-Wolfram moments

$$R_2 = \frac{\sum_{i,j} |p_i||p_j| P_2(\cos\theta_{i,j})}{\sum_{i,j} |p_i||p_j|}$$

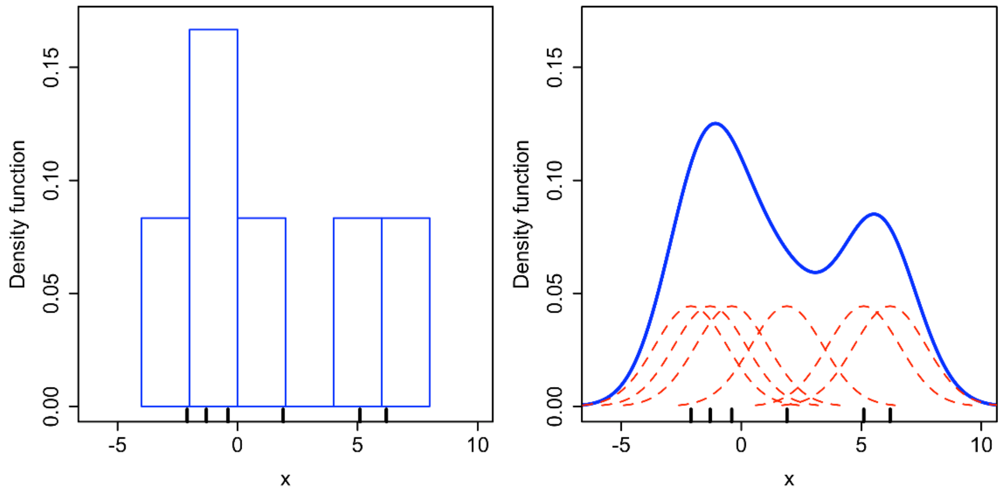
- Combine with other variables in artificial neural network.
- Transform to fit:

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



KEST PDF for 2D MC based models

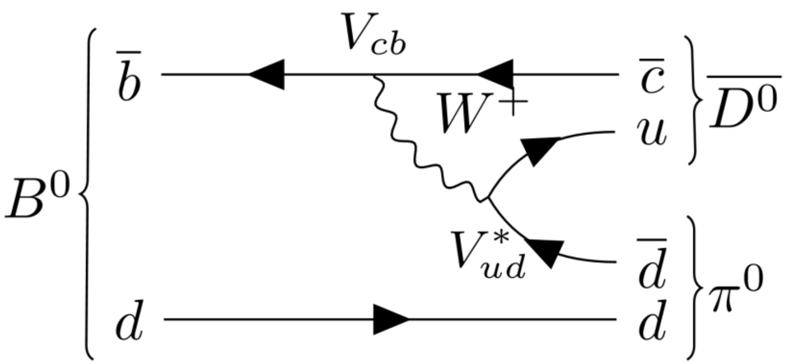
- Kernel density estimation models dataset by superposition of kernel function (Gaussian) for each datapoint.
- Use adaptive bandwidth to adjust Gaussian width based on local event density.
- Retains information in high density areas while smoothing low density.



$B^0 \to \overline{D^0}\pi^0$ and $B^+ \to \overline{D^0}\pi^+$

Preliminary

- $b \to c\bar{u}d$ decay.
- No penguin as final state quark different flavour $\Rightarrow$ expect no A_{CP}.



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

Colour suppressed

Previous results:

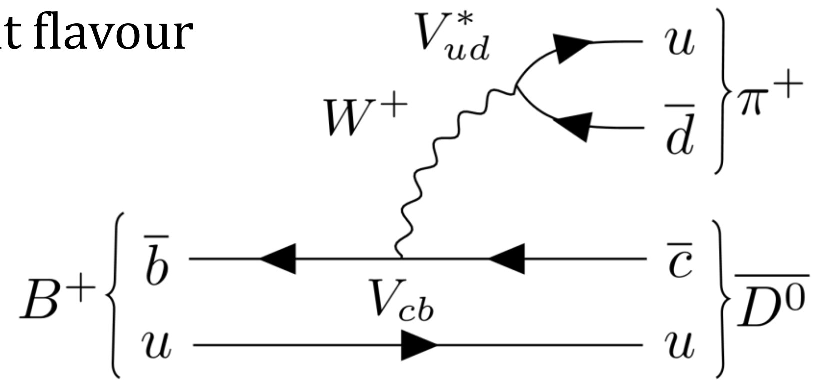
Belle: $\mathfrak{B} = (2.25 \pm 0.14 \pm 0.35) \times 10^{-4}$

PRD 74, 092002 (2006)

Babar: $\mathfrak{B} = (2.69 \pm 0.09 \pm 0.13) \times 10^{-4}$

PRD 84(3), 112007 (2011)

A_{CP} is unmeasured.



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

Colour favour, $\mathfrak{B}$ is $\mathcal{O}(10)$ higher.

Previous results:

Belle: $\mathfrak{B} = (4.34 \pm 0.10 \pm 0.23) \times 10^{-3}$

PRD 97(1), 012005 (2018)

Babar: $\mathfrak{B} = (4.90 \pm 0.07 \pm 0.22) \times 10^{-3}$

PRD 75, 031101 (2007)

Belle: $A_{CP} = (-0.8 \pm 0.8)\%$

PRD 73, 051106 (2006)

LHCb: $A_{CP} = (-0.6 \pm 0.5 \pm 1.0)\%$

PLB 723, 4453 (2013)

$B \to \overline{D^0}\pi$ Motivations

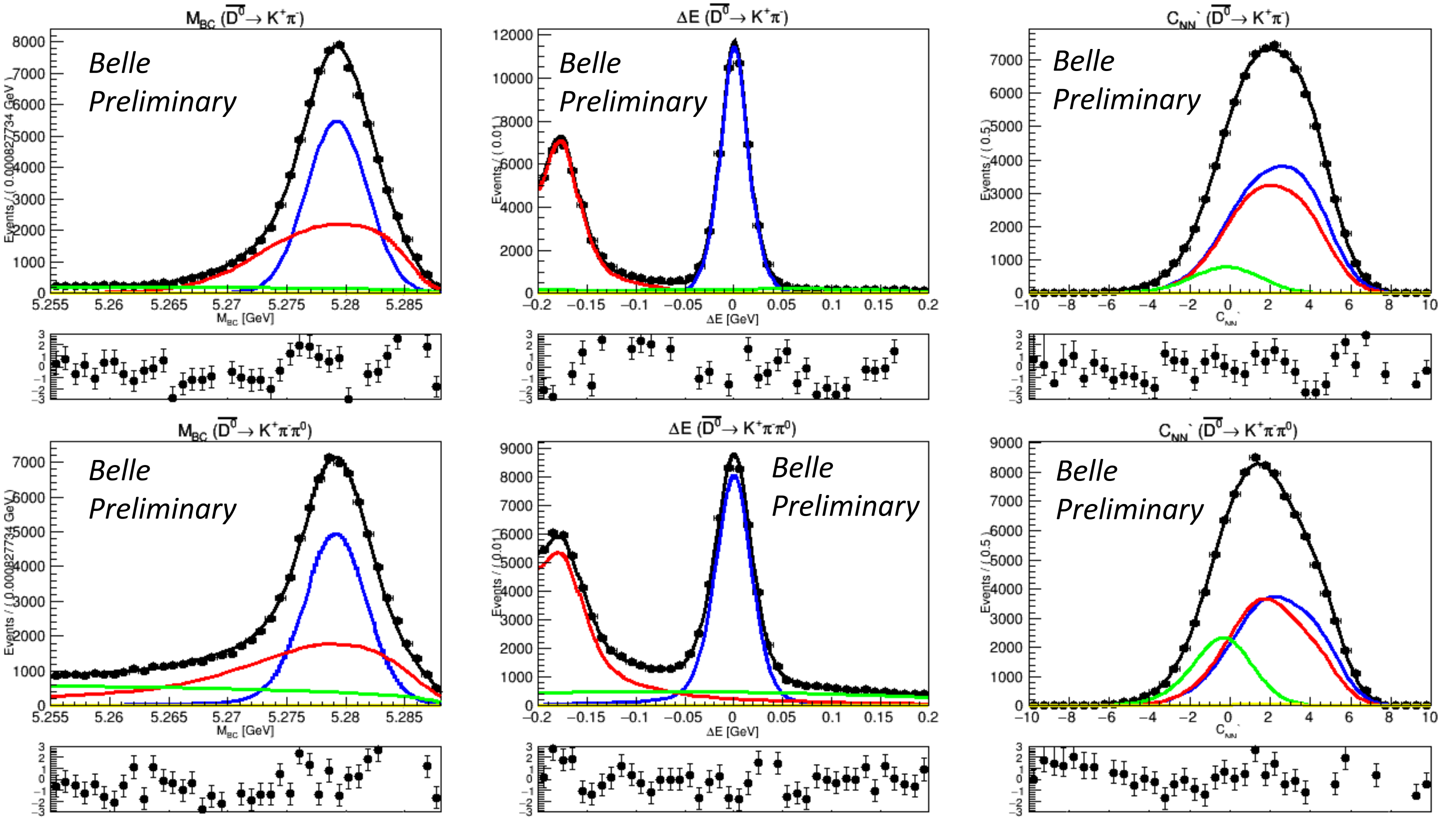
Preliminary

- Both commonly used control mode in other analysis, allow for high-precision validations of techniques.
  - Important for Belle II precision frontier.

- $\mathrm{B}^0 \to \overline{\mathrm{D}^0}\pi^0$ notably large non-factorisable components.
  - $\mathfrak{B} \gg$ 'naïve' factorisation predictions.
  - Constraints for models of final state interactions
  - SCET, pQCD

$B^+ \to \overline{D^0}\pi^+$ Result

Preliminary



Unbinned maximum likelihood fit in M_{BC}, ΔE and C_{NN}'

Simultaneous fit over 4 datasets divided by D^0 decay and Kaon charge.

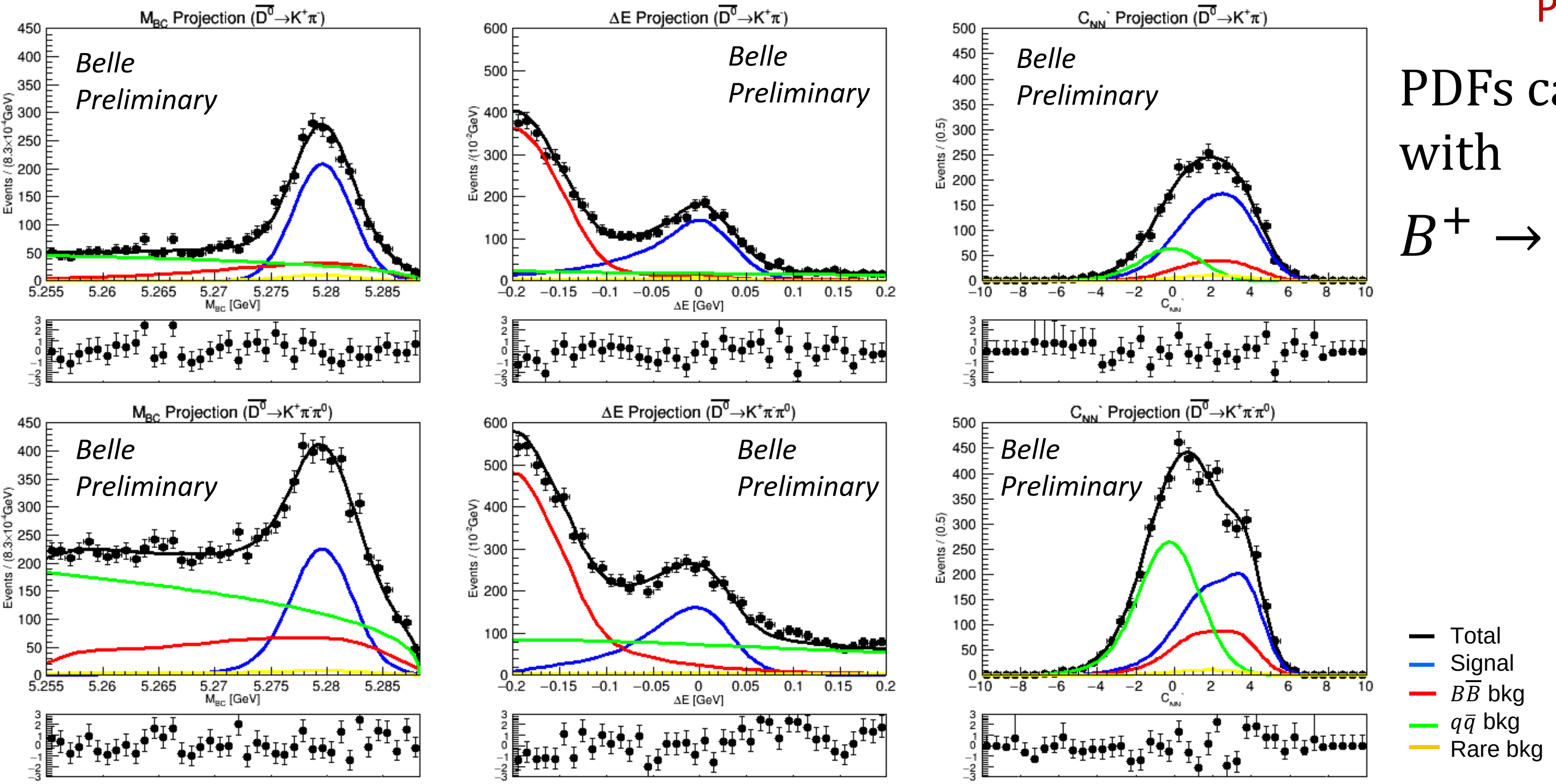
$$\mathfrak{B} = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$

$$A_{CP} = (0.19 \pm 0.36 \pm 0.57)\%$$

~1.7x improvement in precision

$B^0 \to \overline{D^0}\pi^0$ Result

Preliminary



PDFs calibrated with $B^+ \to \overline{D^0}\pi^+$ fit.

$$\mathfrak{B} = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}$$

Most precise measurement in this channel

$$A_{CP} = (0.10 \pm 2.05 \pm 1.22)\%$$

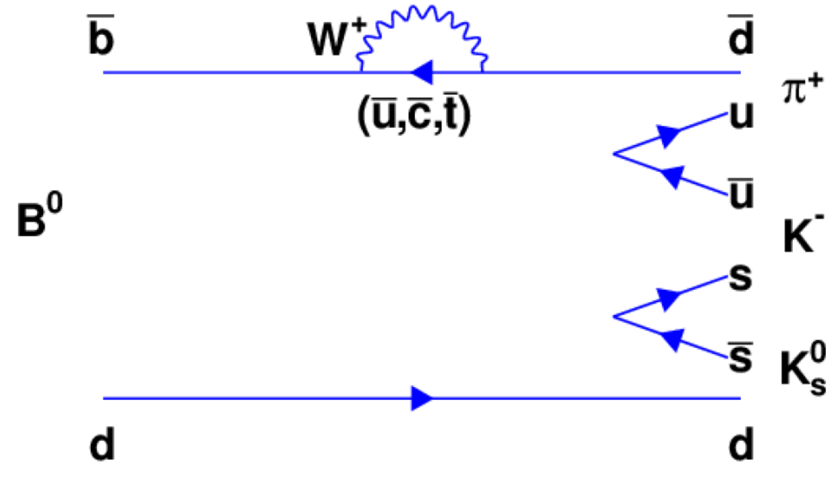
First measurement in this channel

$B^0 \to K^-\pi^+K_s$ Motivation

Y.-T. Lai et al. Phys. Rev. D 100, 011101 (2019)

- Decays with even number of kaons suppressed in SM.
  - Sensitive to CP violation localized in the phase space
- $b \to d$ penguins sensitive to NP
- Related $B^+ \to K^+K^-\pi^+$ shows evidence of large CPV localised in low M_{KK} region.
- BaBar study hints at excess in low $M_{K^-\pi^+}$ and $M_{K^-K_S}$ region
  - large asymmetric helicity angle distribution.

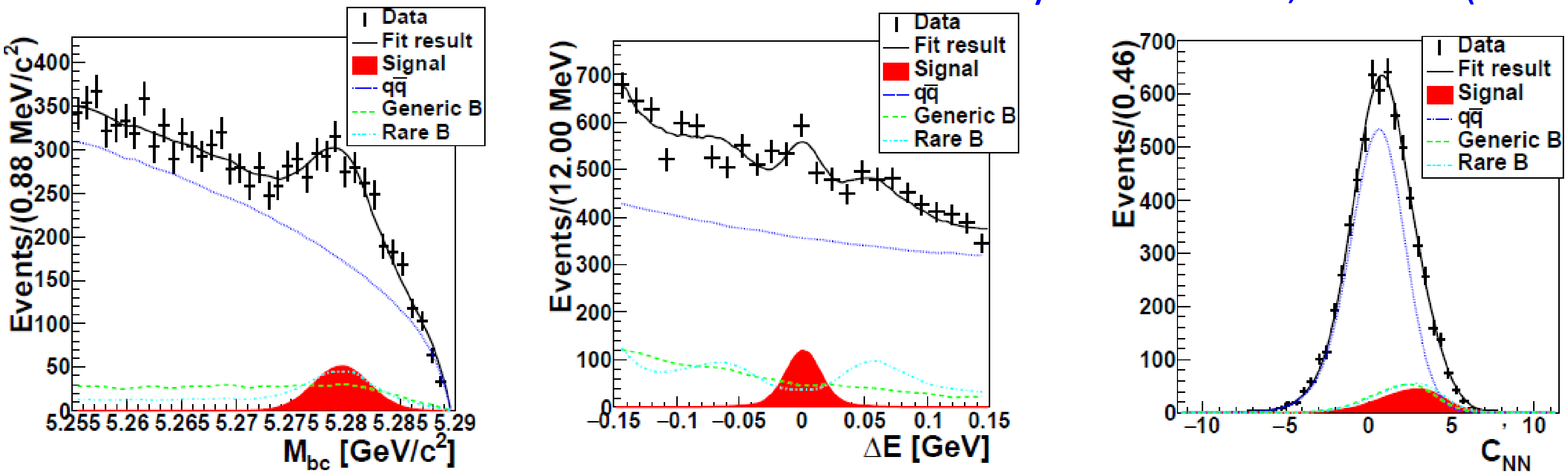
- Previous result by BaBar:
  - $\mathfrak{B} = (3.2 \pm 0.5 \pm 0.3) \times 10^{-6}$ (PRD.82.031101)



b → d penguin

$B^0 \to K^-\pi^+K_s$ Results

Y.-T. Lai et al. Phys. Rev. D 100, 011101 (2019)



- $b \to c$ background rejected with charm veto.
- Model peaking from particle misID ($K^-K^+K_s, \pi^-\pi^+K_s$)
- 3D Unbinned maximum likelihood fit for yield and A_{CP}.

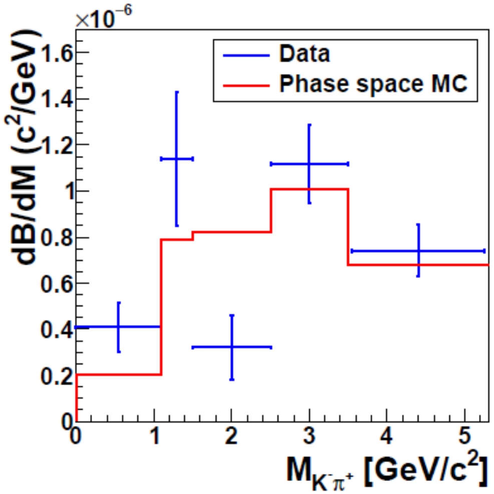
$$Yield = 489.98^{+45.8}_{-45.1}$$

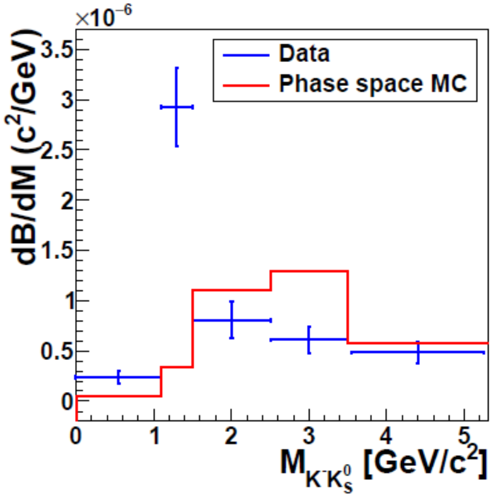
$$\mathfrak{B} = (3.60 \pm 0.33 \pm 0.15) \times 10^{-6}$$

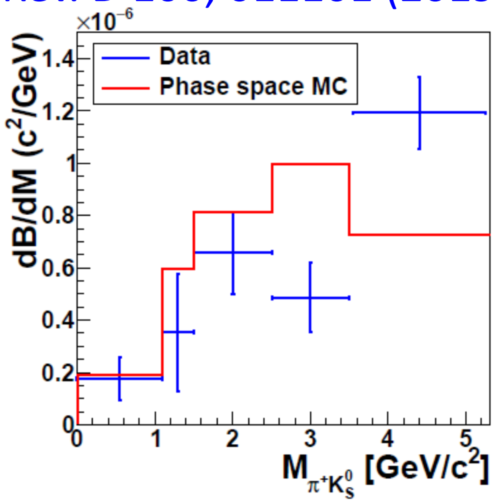
$$A_{CP} = (-8.5 \pm 8.9 \pm 0.2)\%$$

$B^0 \to K^-\pi^+K_s$ Results

Y.-T. Lai et al. Phys. Rev. D 100, 011101 (2019)



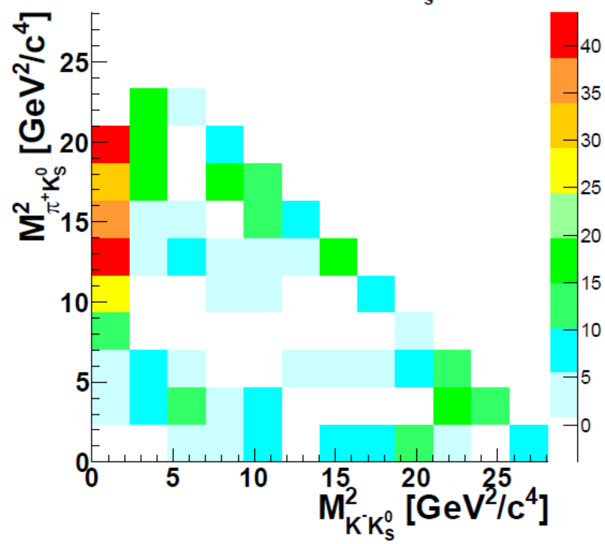




Dalitz variables are recovered using ${}_s\mathcal{P}lot$.

Some hints of peaking structure is observed at $M_{K^-K_S} < 1.5\ GeV/c^2$.

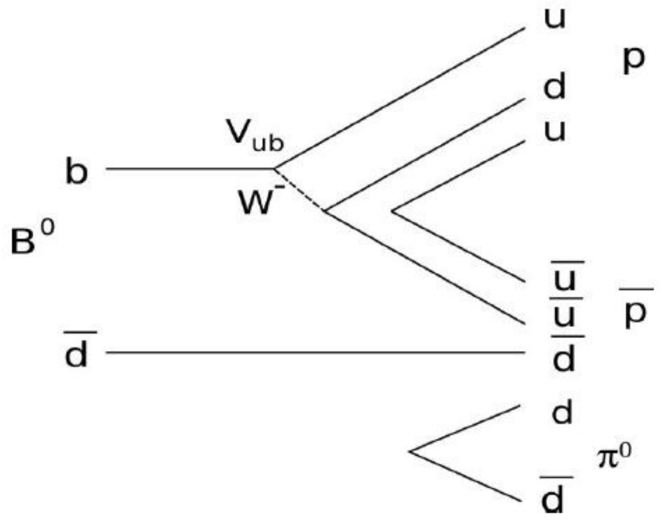
Consistent with Babar result.



$B^0 \to p\bar{p}\pi^0$ Motivation

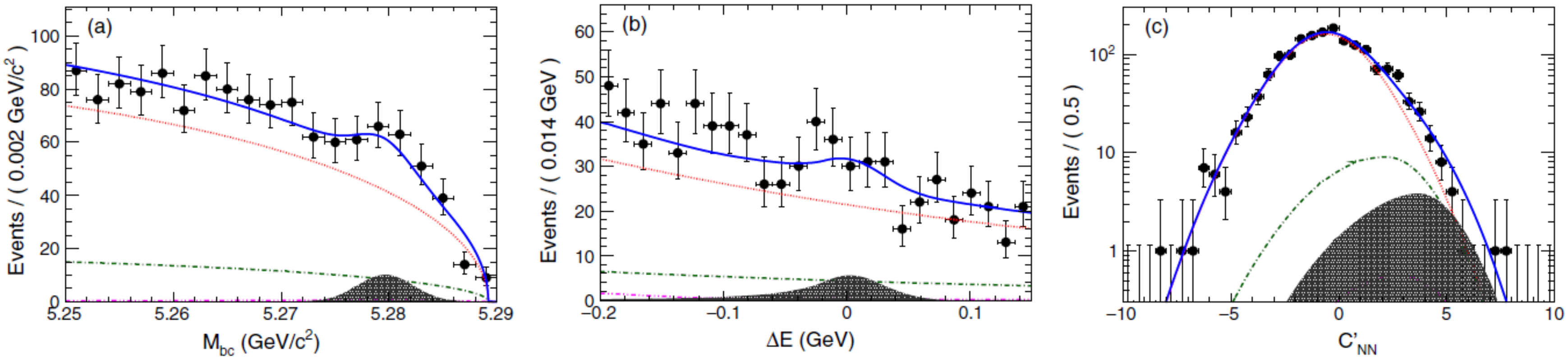
B. Pal et al. Phys. Rev. D 99, 091104 (2019)

- Charmless baryonic B-decays also proceed via V_{ub} and FCNC Penguin processes.
- Baryonic decays with neutral particles rarely studied.
- 2body < 3body < 4body
- Threshold effect: B meson decay prefer di-baryon pair + fast recoil meson
  - Why?



$B^0 \to p\bar{p}\pi^0$ Result

B. Pal et al. Phys. Rev. D 99, 091104 (2019)

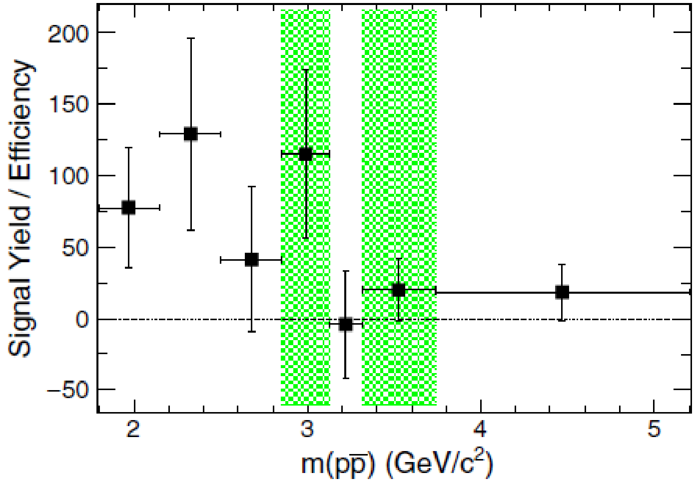


Yield $= 40.5 \pm 14.2$ events

$\mathfrak{B} = (5.0 \pm 1.8 \pm 0.6) \times 10^{-7}$

3.1σsignificance

First Evidence for this decay



${}_s\mathcal{P}lot$ NIM **A 555,** 356(2005) used to extract distributions as function of m_{pp}.

Threshold enhancement shown as expected.

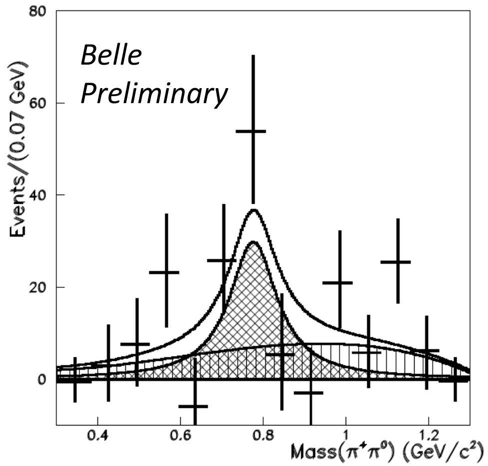
$B \to p\bar{p}\pi\pi$ Motivation

Preliminary

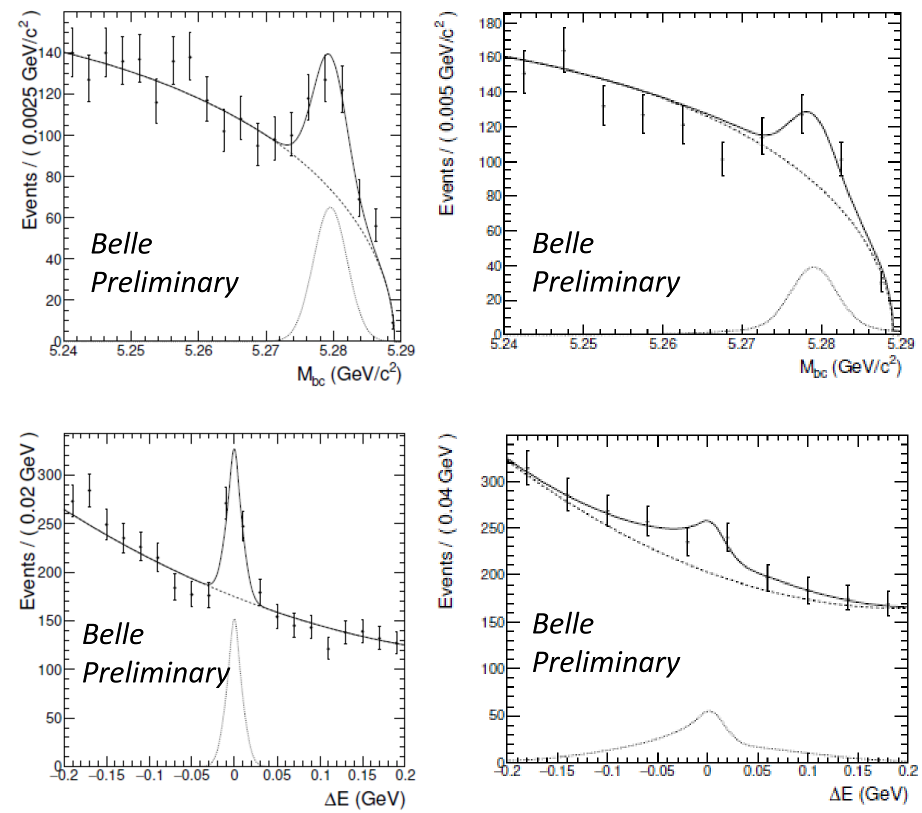
- $B^+ \to p\bar{p}K^+$ shows angular asymmetry between K and $\bar{p}$ in $p\bar{p}$ rest frame.
- Opposite asymmetry shown in $B^+ \to p\bar{p}\pi^+$.
- Most baryonic B decays studied are $b \to s$.
- Need more information on $b \to u$ for theory investigation.
- Inclusive $B^0 \to p\bar{p}\pi^+\pi^-$ by LHCb (PRL 113, 141801 (2014)) shows a hint of $p\bar{p}\rho$ structure.

$B \to p\bar{p}\pi\pi$ Result

Preliminary



$B^0 \to p\bar{p}\pi^+\pi^-$ $\quad$ $B^+ \to p\bar{p}\pi^+\pi^0$



K_s resonances excluded from $\mathfrak{B}$.

$B^0 \to p\bar{p}\pi^+\pi^-$

$$\mathfrak{B} = (0.83^{+0.18}_{-0.17} \pm 0.17) \times 10^{-6}$$

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

$$\mathfrak{B} = (4.64^{+1.15}_{-1.10} \pm 0.68) \times 10^{-6}$$

$\mathfrak{B}(B^+ \to p\bar{p}\pi^+\pi^0)$ order of mag. smaller than theory predictions of $\mathfrak{B}(B^+ \to p\bar{p}\rho^+)$ (PRD 75, 094013 (2007))

Indication of ρ structure in $M_{\pi\pi}$.

Conclusion

First measurement of A_{CP}
Highest precision $\mathfrak{B}$.

Most precise measurement by almost 2x.

Excess observed in low $M_{K^-K_S}$ region.

First Observation of this decay

$\mathfrak{B}$ order of mag smaller than prediction

$\boldsymbol{B^0 \to \overline{D^0}\pi^0}$: **Preliminary**

$$\mathfrak{B} = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}$$
$$A_{CP} = (0.10 \pm 2.05 \pm 1.22)\%$$

$\boldsymbol{B^+ \to \overline{D^0}\pi^+}$: **Preliminary**

$$\mathfrak{B} = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$
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$\boldsymbol{B^0 \to K^-\pi^+K_s}$: Phys. Rev. D 100, 011101 (2019)

$$\mathfrak{B} = (3.60 \pm 0.33 \pm 15) \times 10^{-6}$$
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$\boldsymbol{B^0 \to p\bar{p}\pi^0}$: Phys. Rev. D 99, 091104 (2019)

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$\boldsymbol{B^0 \to p\bar{p}\pi^+\pi^-}$: **Preliminary**

$$\mathfrak{B} = (0.83^{+0.18}_{-0.17} \pm 0.17) \times 10^{-6}$$

$\boldsymbol{B^+ \to p\bar{p}\pi^+\pi^0}$: **Preliminary**

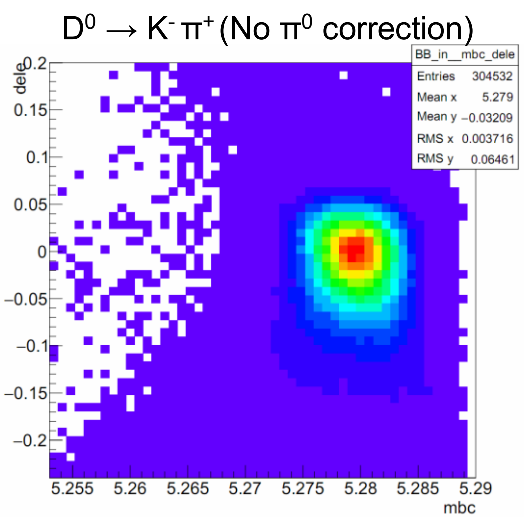
$$\mathfrak{B} = (4.64^{+1.15}_{-1.10} \pm 0.68) \times 10^{-6}$$

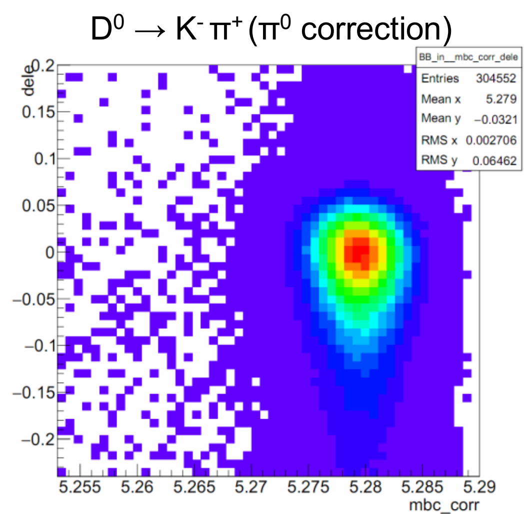
Thank You

Backup

π^0 Energy Correction

- Energy leakage in ECL means π^0 is measured low.
- Leads to high correlation in M_{BC} and ΔE.
- Calculate M_{BC} assuming $E_{\pi^0} = E_{beam} - E_{D^0}$
- $\overrightarrow{p_{\pi,corr}} = \dfrac{\sqrt{\left(E_{beam} - E_{D^0}\right)^2 - M_\pi^2}}{|p_\pi|} \times \overrightarrow{p_\pi}$

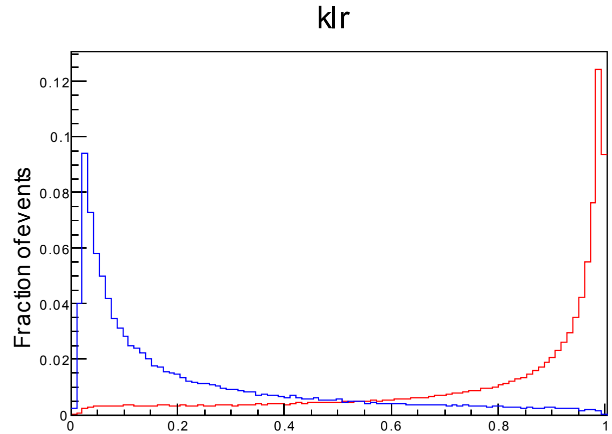


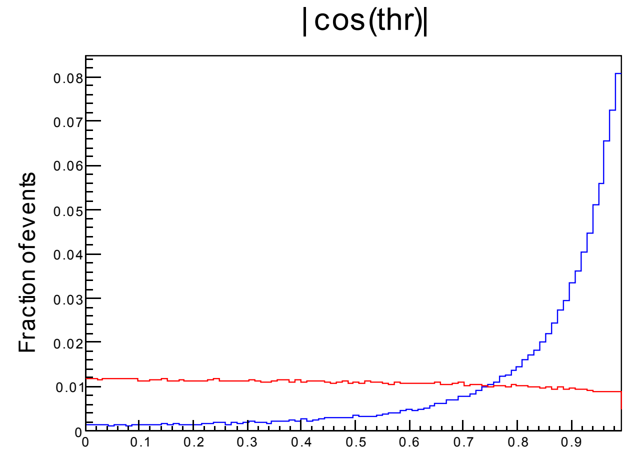


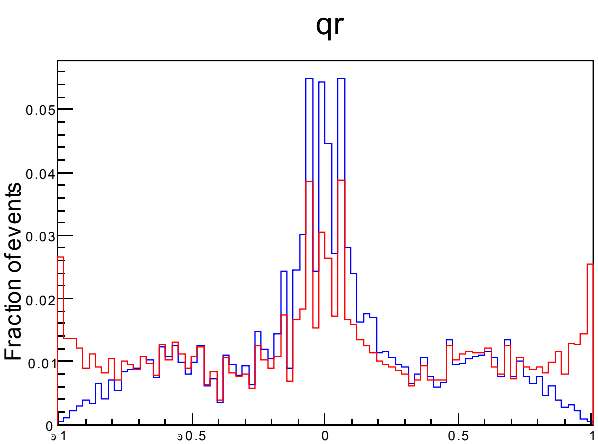
Continuum Suppression Variables

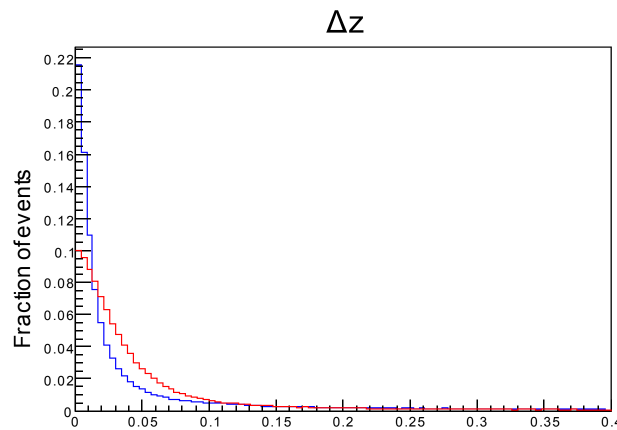
NeuroBayes input
2bd

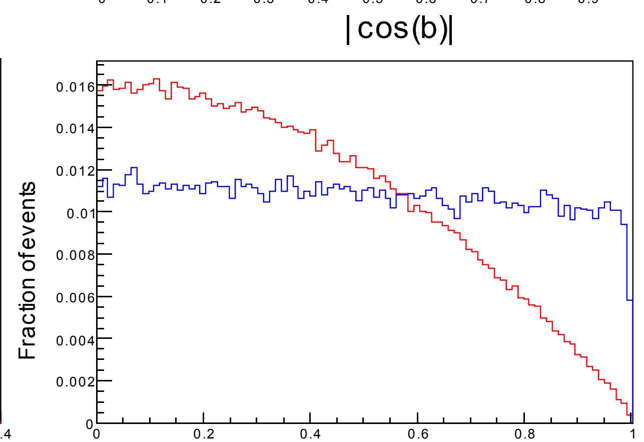
Signal
Continuum











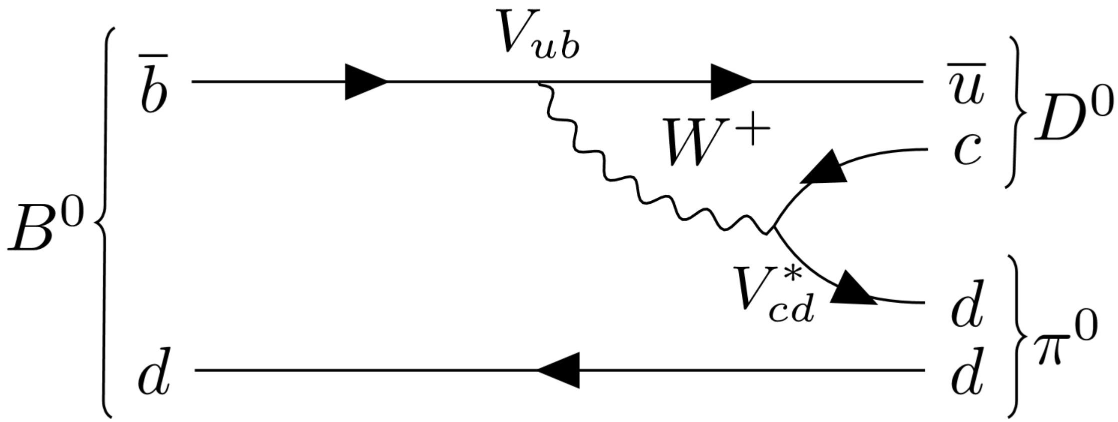
Wrong sign decays.

- What if $B^0 \to D^0\pi^0$ or $\overline{D^0} \to K^-\pi^+[\pi^0]$?
- $B^0 \to D^0\pi^0$ suppressed by λ^2.

$$R \equiv \frac{\mathfrak{B}_{WS}}{\mathfrak{B}_{RS}}$$

- $R(B^0 \to D^0\pi^0) \approx R(B^0 \to D^-\pi^+) = 2.92 \times 10^{-4}$
- $R\left(\overline{D^0}\right) = 2.85 \times 10^{-3}$

$$\Delta\mathfrak{B} = -0.3\% \qquad \Delta A_{CP} = +3 \times 10^{-5}$$



Fitter

- Unbinned maximum likelihood fit in M_{BC}, ΔE and $C_{NN}^{`}$ using RooFit for Yield and A_{CP} of each event type (signal, qq, $B\bar{B}$ bkg, Rare).
- 4 datasets divided by D^0 decay and Kaon charge.
- Constrained by $\overline{D^0} \to K^+\pi^-\pi^0$: $\overline{D^0} \to K^+\pi^-$ Yield ratio and A_{CP}.
  - $N_{K^+,2bd} = N \times (1 - A_{CP}) \times 0.5 \times (1 - R_{D^0 mode})$
  - $N_{K^-,2bd} = N \times (1 + A_{CP}) \times 0.5 \times (1 - R_{D^0 mode})$
  - $N_{K^+,3bd} = N \times (1 - A_{CP}) \times 0.5 \times (R_{D^0 mode})$
  - $N_{K^-,3bd} = N \times (1 + A_{CP}) \times 0.5 \times (R_{D^0 mode})$
- Background A_{CP} and signal $R_{D^0 mode}$ are fixed.
- PDF shapes from Monte Carlo.

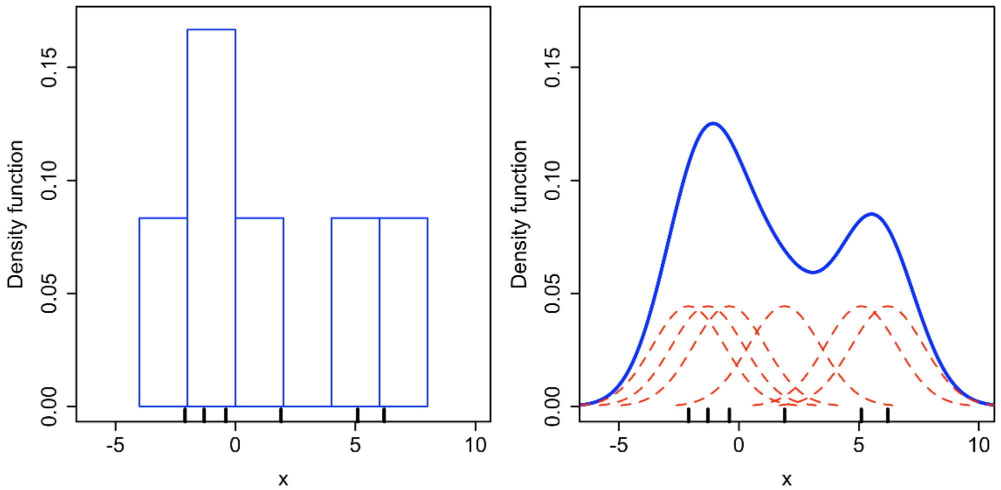
PDF Modelling

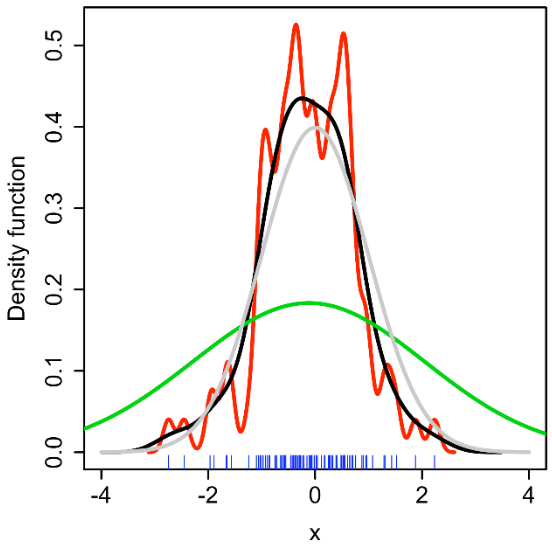
- Where possible
  - $\mathcal{P}(M_{BC}, \Delta E, C_{NN}^{`}) = \mathcal{P}(M_{BC}) \times \mathcal{P}(\Delta E) \times \mathcal{P}(C_{NN}^{`})$
- $B\overline{B}$ and Rare background and $K^+\pi^-\pi^0$ signal have high correlation in $M_{BC}, \Delta E$.
  - $\mathcal{P}(M_{BC}, \Delta E, C_{NN}^{`}) = \mathcal{P}(M_{BC}, \Delta E) \times \mathcal{P}(C_{NN}^{`})$

	M_{BC}	ΔE	$C_{NN}^{`}$
Signal ($\overline{D^0} \to K^+\pi^-$)	Crystal Ball fn.	Crystal Ball fn. + Gaussian	3 Gaussians
Signal ($\overline{D^0} \to K^+\pi^-\pi^0$)	2D kernel estimation (KEST) histogram PDF		3 Gaussians
$B\overline{B}$ background	2D kernel estimation (KEST) histogram PDF		3 Gaussians
Continuum	ARGUS fn.	Chebyshev Polynomial	2 Gaussians
Rare B	2D kernel estimation (KEST) histogram PDF		3 Gaussians

KEST PDF for 2D MC based models

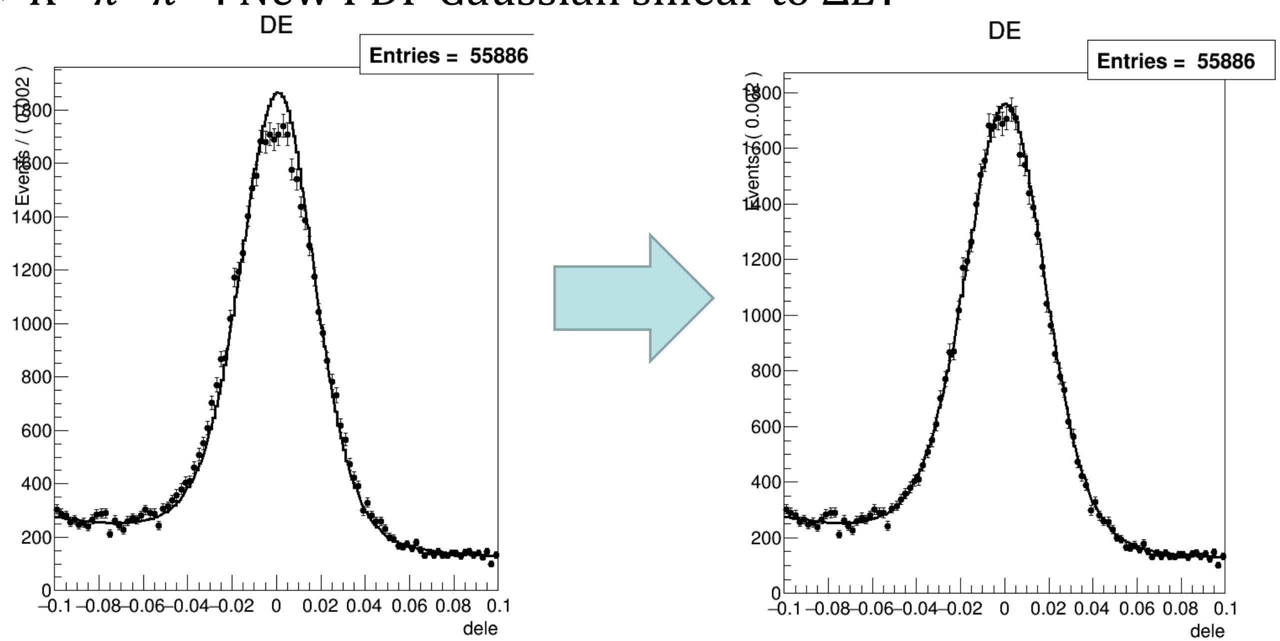
- Kernel density estimation models dataset by superposition of kernel function (Gaussian) for each datapoint.
- Roofit uses adaptive bandwidth to adjust Gaussian width based on local event density.
- Retains information in high density areas while smoothing low density.





Calibration Factors

- MC may not perfectly represent real data.
- Calibration mean shifts and width factors for $\grave{C}_{NN}$.
  - Applied to $\mathrm{B} \rightarrow \overline{\mathrm{D}^0}\pi^0$ for data fit.
- Signal ΔE has shaped changes.
  - $\overline{D^0} \rightarrow K^+\pi^-$: Mean shift and width factor floated in fit.
  - $\overline{D^0} \rightarrow K^+\pi^-\pi^0$: New PDF Gaussian smear to ΔE.



GWM Calculations

- $$\begin{aligned}\mathfrak{B} &= \mathrm{mean}\left(\mathfrak{B}_{\overline{\mathrm{D}^0}\to K^+\pi^-}, \mathfrak{B}_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}\right)\\ &= \mathrm{mean}\left(\frac{Y_{\overline{\mathrm{D}^0}\to K^+\pi^-}}{2\times N_{B^+B^-}\times\epsilon_{\overline{\mathrm{D}^0}\to K^+\pi^-}}, \frac{Y_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}}{2\times N_{B^+B^-}\times\epsilon_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}}\right)\\ &= \mathrm{mean}\left(\frac{f^S_{\overline{\mathrm{D}^0}\to K^+\pi^-}\times Y}{2\times N_{B^+B^-}\times\epsilon_{\overline{\mathrm{D}^0}\to K^+\pi^-}}, \frac{f^S_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}\times Y}{2\times N_{B^+B^-}\times\epsilon_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}}\right)\\ &= \frac{Y}{2\times N_{B^+B^-}}\times\mathrm{mean}\left(\frac{f^S_{\overline{\mathrm{D}^0}\to K^+\pi^-}}{\epsilon_{\overline{\mathrm{D}^0}\to K^+\pi^-}}, \frac{f^S_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}}{\epsilon_{\overline{\mathrm{D}^0}\to K^+\pi^-\pi^0}}\right),\end{aligned}$$
- $\bar{x} = \sigma^2_{\bar{x}}(J^T\Sigma^{-1}X)$
- $\sigma^2_{\bar{x}} = (J^T\Sigma^{-1}J)^{-1}$
- Uncorrelated: D decay $\mathfrak{B}$, recon eff.
- Correlated: Track eff., π^0 eff., PID eff.
- $\Sigma_{\mathrm{B^0\overline{D^0}\pi^0}} = \begin{bmatrix}1.48 & 2.40\\ 2.40 & 6.77\end{bmatrix}$, $\Sigma_{\mathrm{B^+\overline{D^0}\pi^+}} = \begin{bmatrix}1.17 & 1.05\\ 1.05 & 4.03\end{bmatrix}$
- 2.44% for $B^0 \to \overline{D^0}\pi^0$ and 2.54% for $B^+ \to \overline{D^0}\pi^+$

Systematic Uncertainties ($\mathfrak{B}$)

	$\boldsymbol{B^0 \to \overline{D^0}\pi^0}$	$\boldsymbol{B^+ \to \overline{D^0}\pi^+}$
No. $B\overline{B}$	1.37%	1.37%
$\mathfrak{B}(\Upsilon(4S))$	1.23%	1.17%
DCS mode correction	0.01%	0.02%
Fit bias	0.60%	0.20%
Mean efficiency	2.44%	2.54%
$\overline{D^0} \to K^+\pi^-\pi^0 : \overline{D^0} \to K^+\pi^-$ ratio	+0.31% −0.38%	+0.19% −0.08%
A_{CP} detector bias (backgrounds)	0.01%	0.05%
Calibration Factors (C'_{NN})	0.34%	0.06%
Modified KEST signal (M_{BC}, ΔE)	0.63%	0.24%
KEST PDFs	0.58%	0.05%
Fixed Charmless $B\overline{B}$ Yields	+0.26% −0.27%	$<$ 0.01%
Total	$\pm$**3.28**%	$\pm$**3.13**%

Systematic Uncertainties (A_{CP})

	$\boldsymbol{B^0 \to \overline{D^0}\pi^0}$ $(\times\, \mathbf{10^{-2}})$	$\boldsymbol{B^+ \to \overline{D^0}\pi^+}$ $(\times\, \mathbf{10^{-2}})$
Fit bias	0.03	0.02
$\overline{D^0}$ decay A_{CP}	0.35	0.35
A_{CP} detector bias (signal)*	0.66	0.42
A_{CP} detector bias (backgrounds)*	$^{+0.49}_{-0.49}$	$^{+0.03}_{-0.03}$
$\overline{D^0} \to K^+\pi^-\pi^0 : \overline{D^0} \to K^+\pi^-$ ratio	$^{+0.03}_{-0.02}$	< 0.01
Calibration Factors (C'_{NN})	0.06	< 0.01
Modified KEST signal (M_{BC}, ΔE)	0.06	< 0.01
KEST PDFs	0.15	< 0.01
Fixed Charmless $B\overline{B}$ Yields	< 0.01	< 0.01
Total	$\pm\mathbf{1.22}$	$\pm\mathbf{0.57}$