Study of Hadronic B and Bs Decays at Belle

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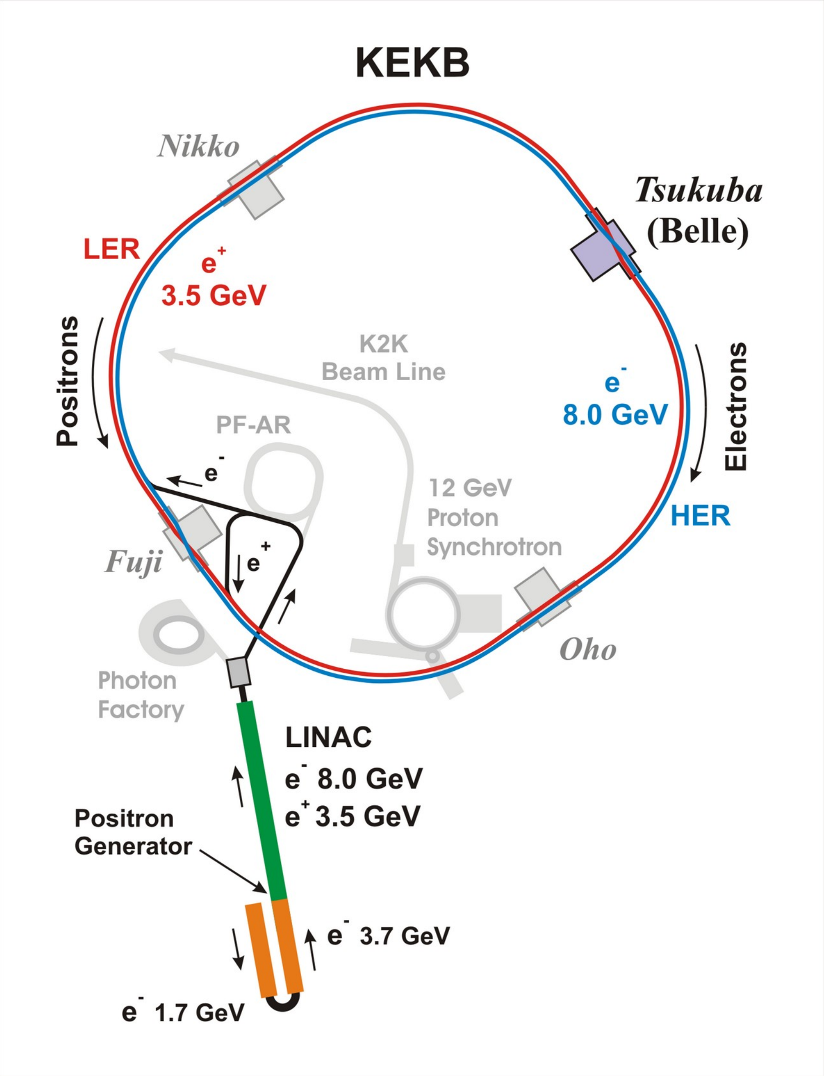
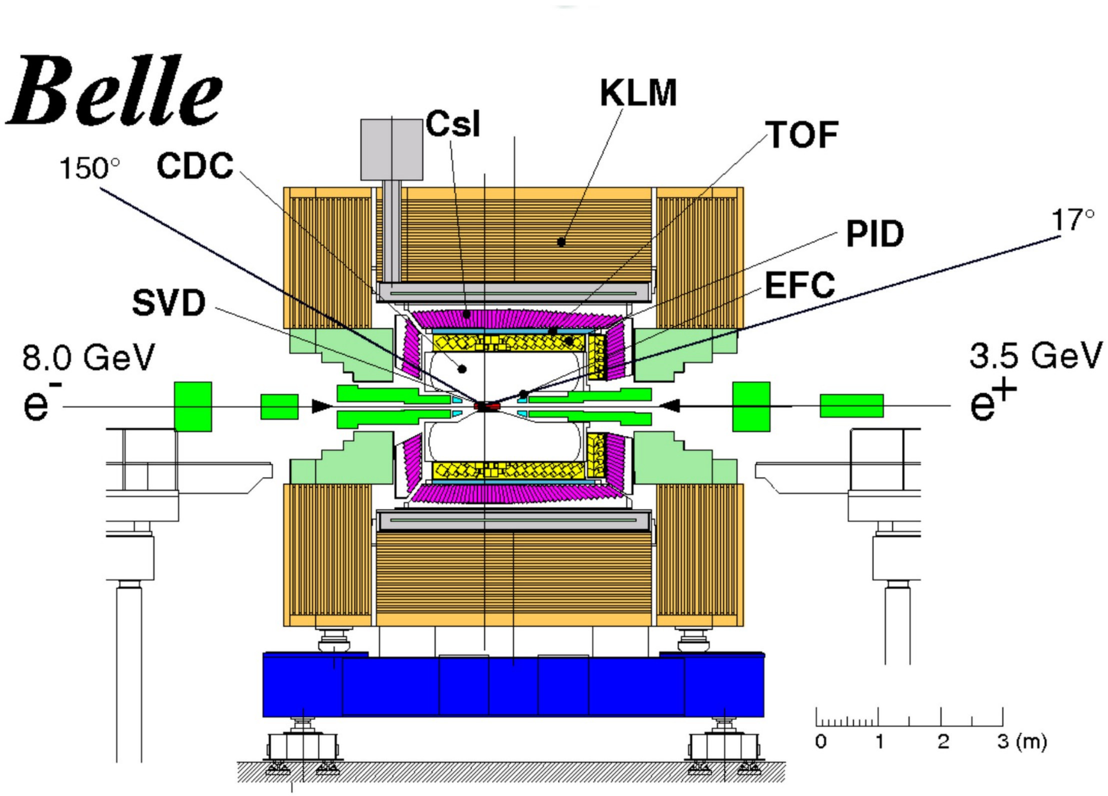
Outline

1) **Motivation**
2) $B_s^0 \to \eta'(\to \eta\pi^+\pi^-)X_{s\bar{s}}$
3) $B_s^0 \to \eta\eta'(\to \eta\pi^+\pi^-)$
4) $B_s^0 \to D_s X$
5) $B^+ \to K^+K^-\pi^-$
6) **Summary and Conclusion**

Motivation

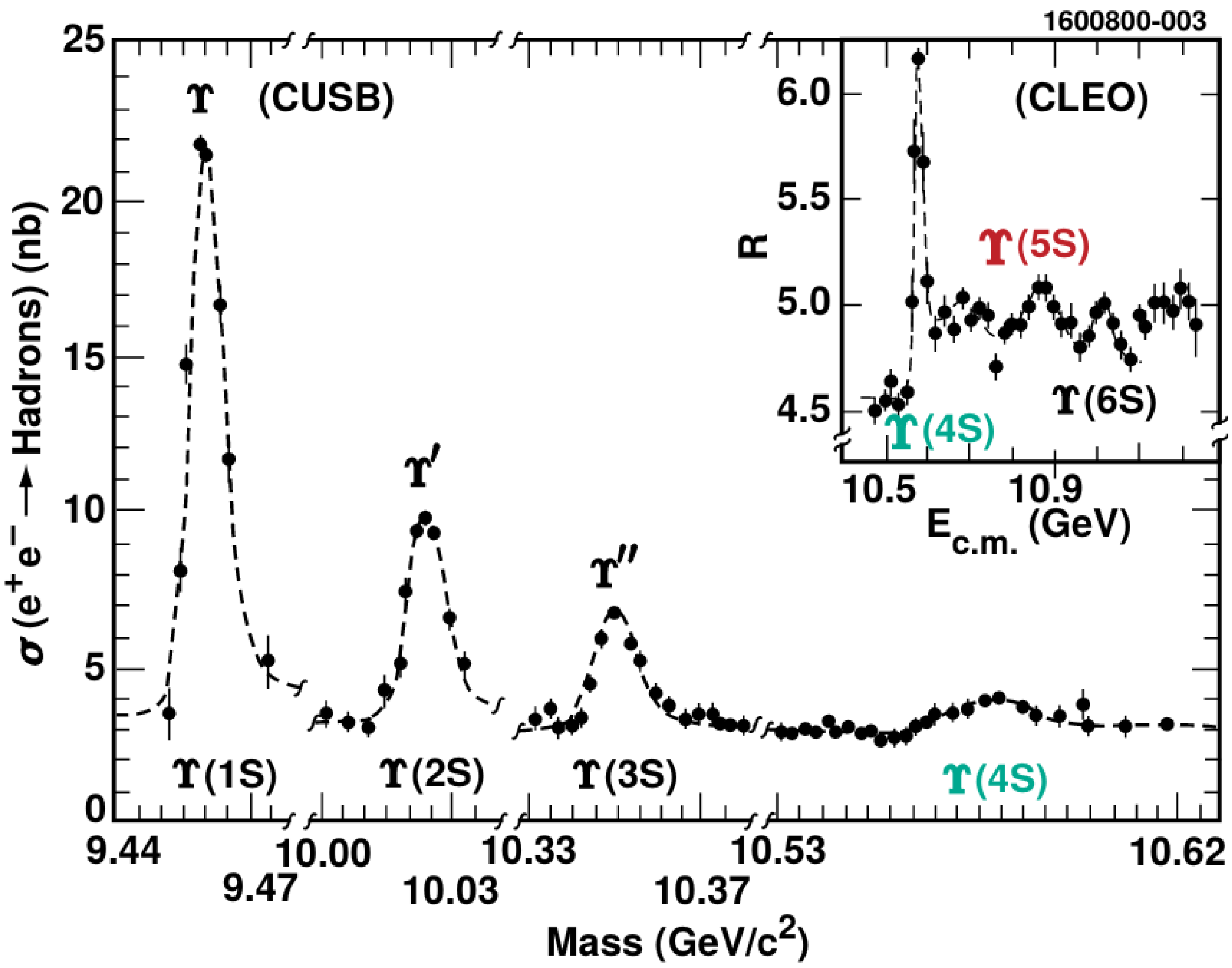


KEKB
Nikko
Tsukuba
(Belle)
LER
e+
3.5 GeV
Positrons
K2K
Beam Line
e-
8.0 GeV
Electrons
PF-AR
e-
12 GeV
Proton
Synchrotron
HER
Fuji
e+
Oho
Photon
Factory
LINAC
e- 8.0 GeV
e+ 3.5 GeV
Positron
Generator
e- 3.7 GeV
e- 1.7 GeV



Belle
CsI
KLM
TOF
150°
CDC
PID
17°
EFC
SVD
8.0 GeV
e-
3.5 GeV
e+
0
1
2
3 (m)

Motivation



Annu. Rev. Nucl. Part. Sci. 1993.43:333-78

Motivation

- **Suppressed in the Standard Model**
- **Can be probes of new physics beyond the Standard Model**
  - e.g. differences between branching fraction and CP measurements and theoretical predictions
- **Belle provides large Upsilon(4S) (711/fb) and Upsilon(5S) (121.4/fb) data samples from e+e- collisions**

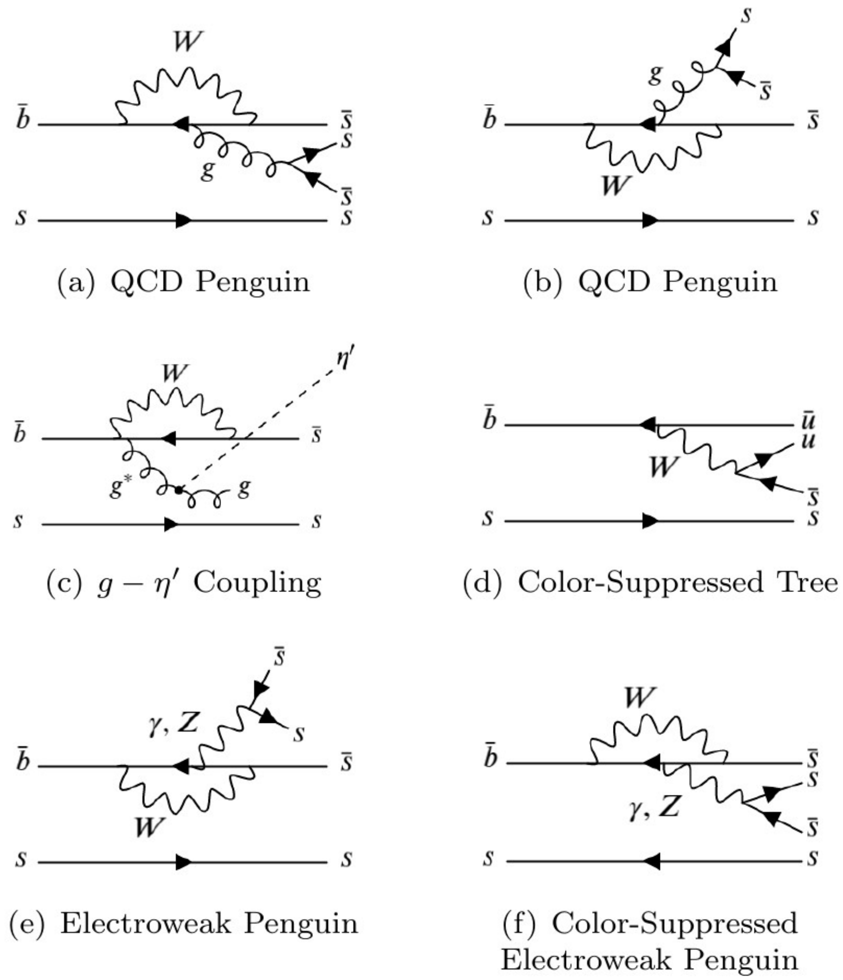
Modes

$$B_s^0 \to \eta' X_{s\bar{s}}$$

$B_s^0 \to \eta' X_{s\bar{s}}$

- World's first measurement.
- No inclusive B_s^0 mode with η' has been measured.
- May help provide an understanding of the eta' mass through e.g. an anomalous $\eta' - g$ coupling

$B_s^0 \to \eta' X_{s\bar{s}}$



$B_s^0 \to \eta' X_{s\bar{s}}$

$$\eta' \to \eta\pi^+\pi^-$$

$B_s^0 \to \eta' K^+ K^-$
$B_s^0 \to \eta' K^+ K^- \pi^0$
$B_s^0 \to \eta' K^+ K^- \pi^+ \pi^-$
$B_s^0 \to \eta' K^+ K^- \pi^+ \pi^- \pi^0$
$B_s^0 \to \eta' K^+ K^- \pi^+ \pi^- \pi^+ \pi^-$
$B_s^0 \to \eta' K_S^0 K^+ \pi^-$
$B_s^0 \to \eta' K_S^0 K^+ \pi^- \pi^0$
$B_s^0 \to \eta' K_S^0 K^+ \pi^- \pi^+ \pi^-$
$B_s^0 \to \eta' K_S^0 K^+ \pi^- \pi^+ \pi^- \pi^0$

"sum-of-exclusive technique"

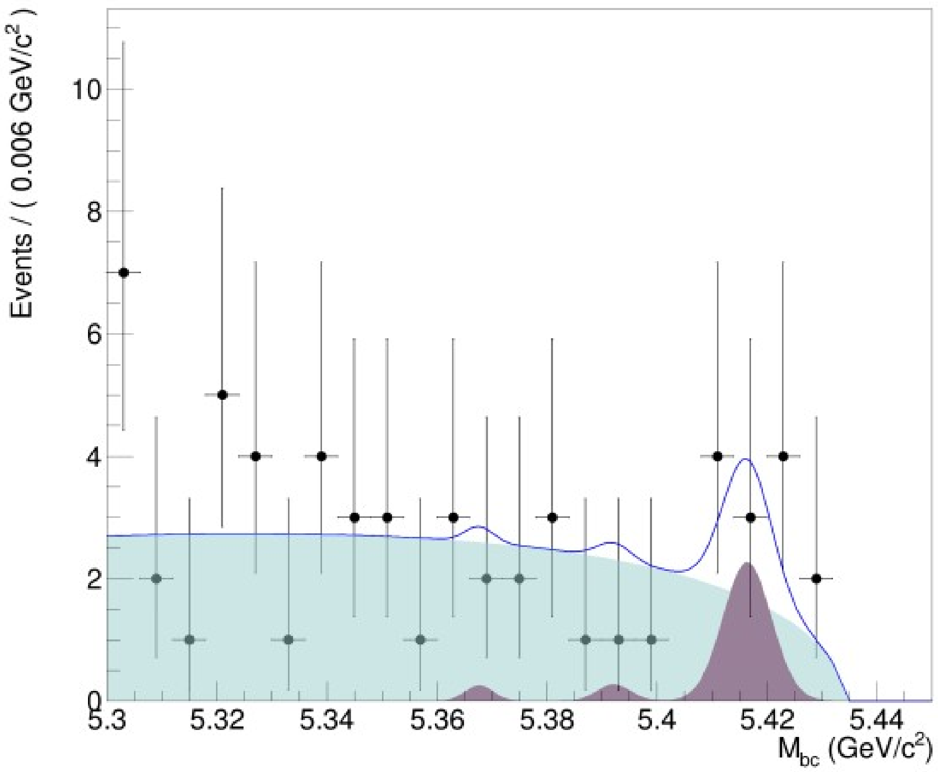
$B_s^0 \to \eta' X_{s\bar{s}}$

Signal extraction strategy: 1D ML fits to beam-energy-constrained mass M_{bc} in bins of $M(X_{s\bar{s}})$ to extract the signal yield.

$B_s^0 \to \eta' X_{s\bar{s}}$

Example

$$M_{\rm bc} = \sqrt{E_{\rm beam}^2/c^4 - p_{B_s}^2/c^2}$$
$$E_{\rm beam} = \sqrt{s}/2$$



$$1.6 \le M(X_{s\bar{s}}) \le 1.8 \text{ GeV}/c^2$$

$B_s^0 \to \eta' X_{s\bar{s}}$

$$M_{\rm bc} = \sqrt{E_{\rm beam}^2/c^4 - p_{B_s}^2/c^2}$$

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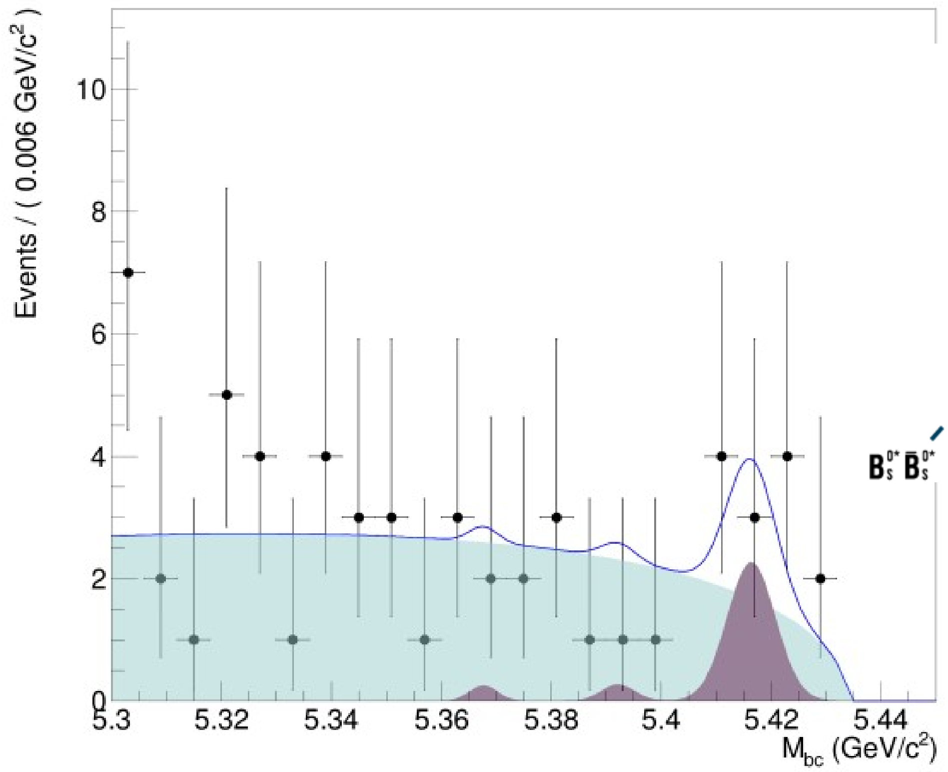

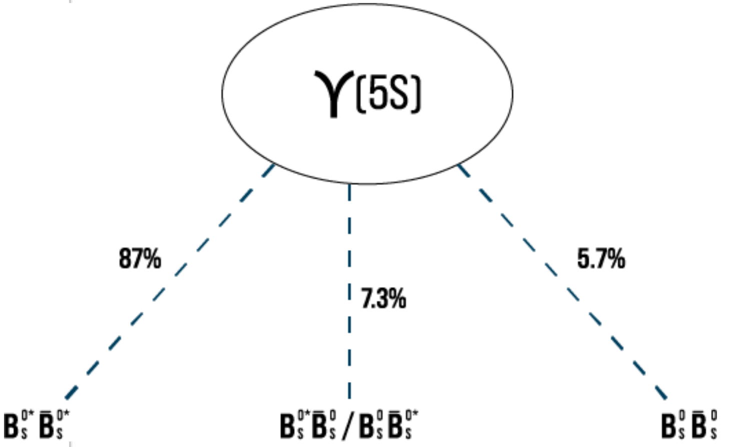

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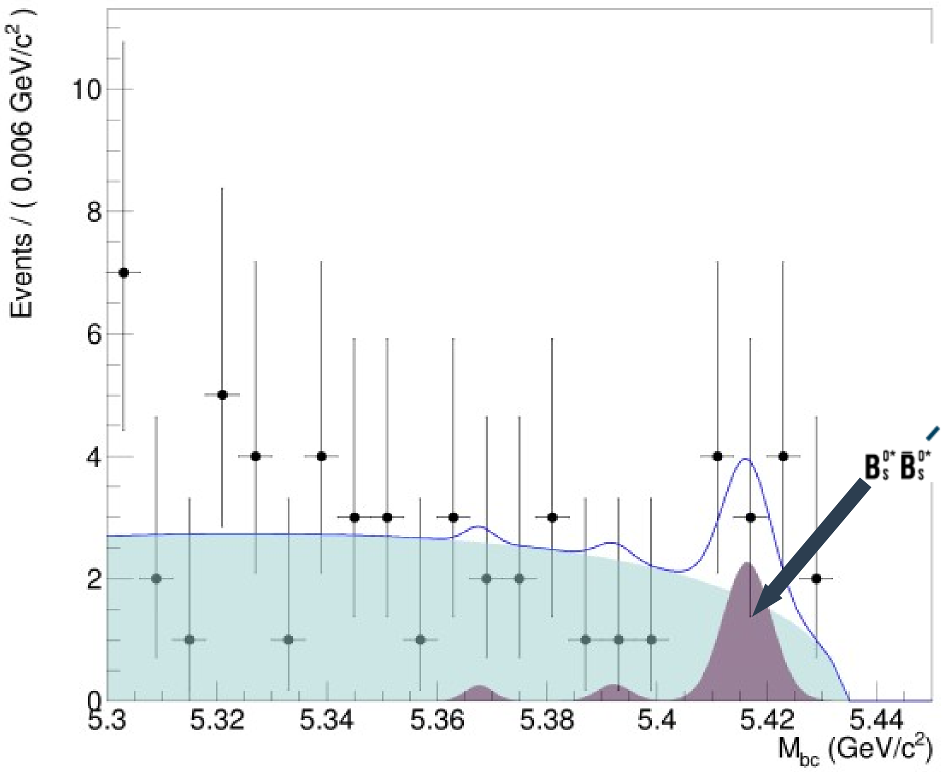
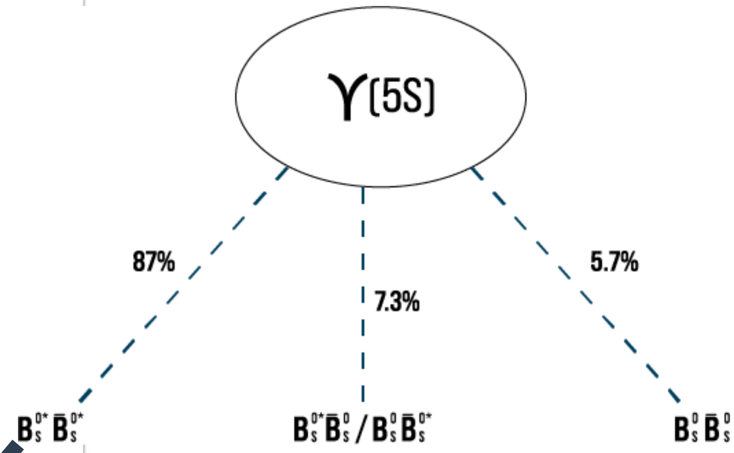


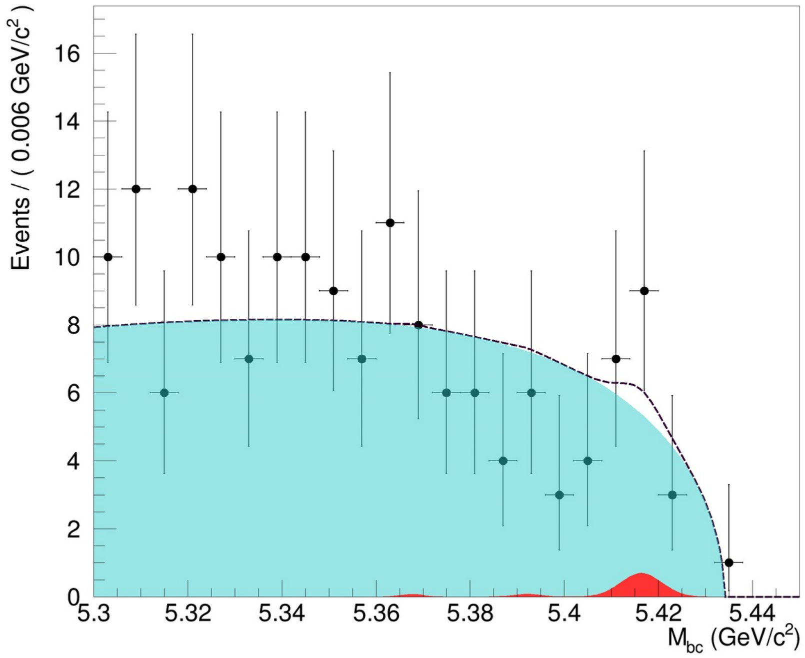


$$1.6 \le M(X_{s\bar{s}}) \le 1.8\ \mathrm{GeV}/c^2$$

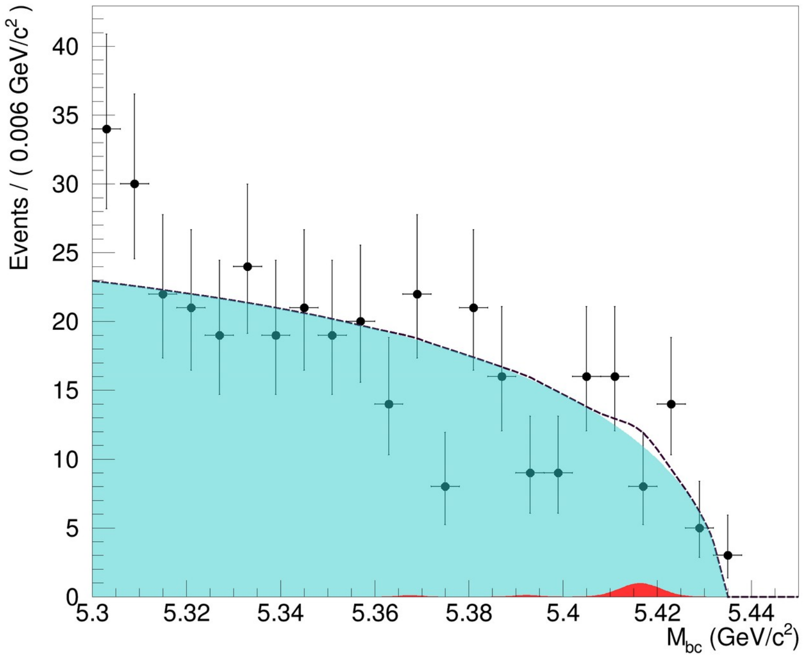
$B_s^0 \to \eta' X_{s\bar{s}}$

Results

$B_s^0 \to \eta' K^+ K^- + n\pi$



$B_s^0 \to \eta' K^\pm K_S^0 + n\pi$



Sum of the 1D fits in $M_{\rm bc}$, overlaid on the data

$B_s^0 \to \eta' X_{s\bar{s}}$

Results

$$\mathcal{B}(\mathrm{B}_s^0 \to \eta' X_{s\bar{s}}) = [-0.7 \pm 8.1\ (\mathrm{stat.}) \pm 0.7\ (\mathrm{syst.})\ ^{+3.0}_{-6.0}\ (\mathrm{FM}) \pm 0.1\ (\mathrm{N}_{B_s^{0(*)}\bar{B}_s^{0(*)}})] \times 10^{-4}\ \mathrm{for}\ M(X_{s\bar{s}}) \leq 2.4\ \mathrm{GeV}/c^2$$

$$\mathcal{R}(\eta') = \mathcal{B}(B_s^0 \to \eta' X_{s\bar{s}})/\mathcal{B}(B \to \eta' X_s) = -0.2 \pm 2.1(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})^{+0.8}_{-1.5}(\mathrm{FM}) \pm 0.03(N_{B_s^{0(*)}\bar{B}_s^{0(*)}})$$

<u>90% Confidence Level Upper Limits</u>

$$\mathcal{B}(B_s^0 \to \eta' X_{s\bar{s}}) < 1.4 \times 10^{-3}$$

$$\mathcal{R}(\eta') < 3.5$$

Phys. Rev. D 104, 012007 (2021)

arXiv:2102.10266

$B_s^0 \to \eta' X_{s\bar{s}}$

Results

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<u>90% Confidence Level Upper Limits</u>

$$\mathcal{B}(B_s^0 \to \eta' X_{s\bar{s}}) < 1.4 \times 10^{-3}$$

$$\mathcal{R}(\eta') < 3.5$$

~ 1 *assuming naive* $SU(3)$ *symmetry*

Phys. Rev. D 104, 012007 (2021)

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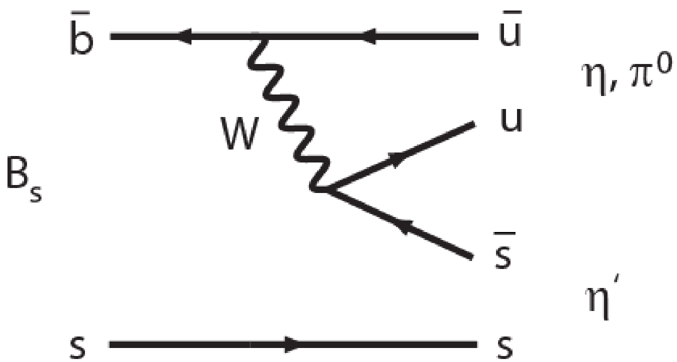
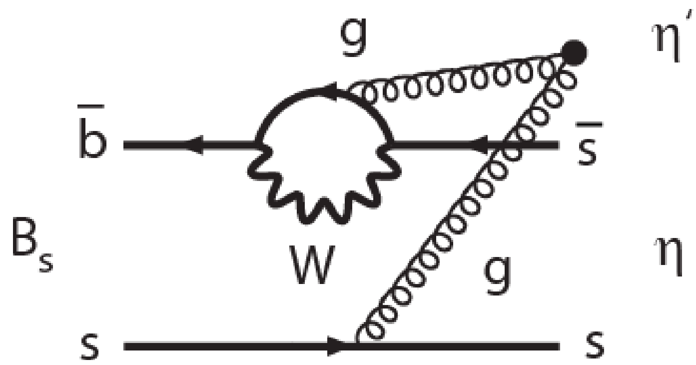
$$B_s^0 \to \eta\eta'$$

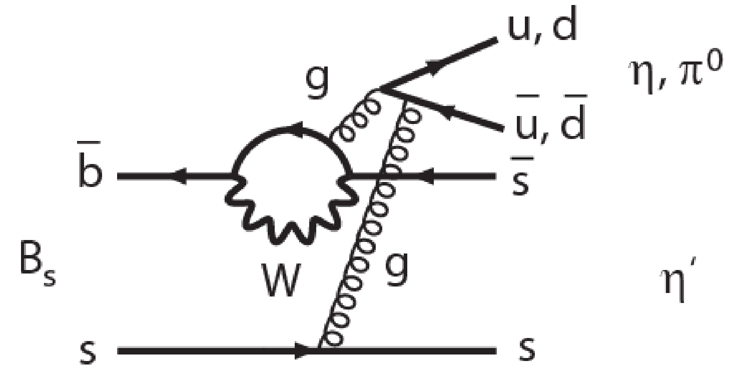
$B_s^0 \to \eta\eta'$

- World's first measurement.
- Suppressed in the SM and sensitive to NP.
  - e.g. 4^{th} gen. fermions, two-Higggs doublet w/ FCNC, etc.

$B_s^0 \to \eta\eta'$

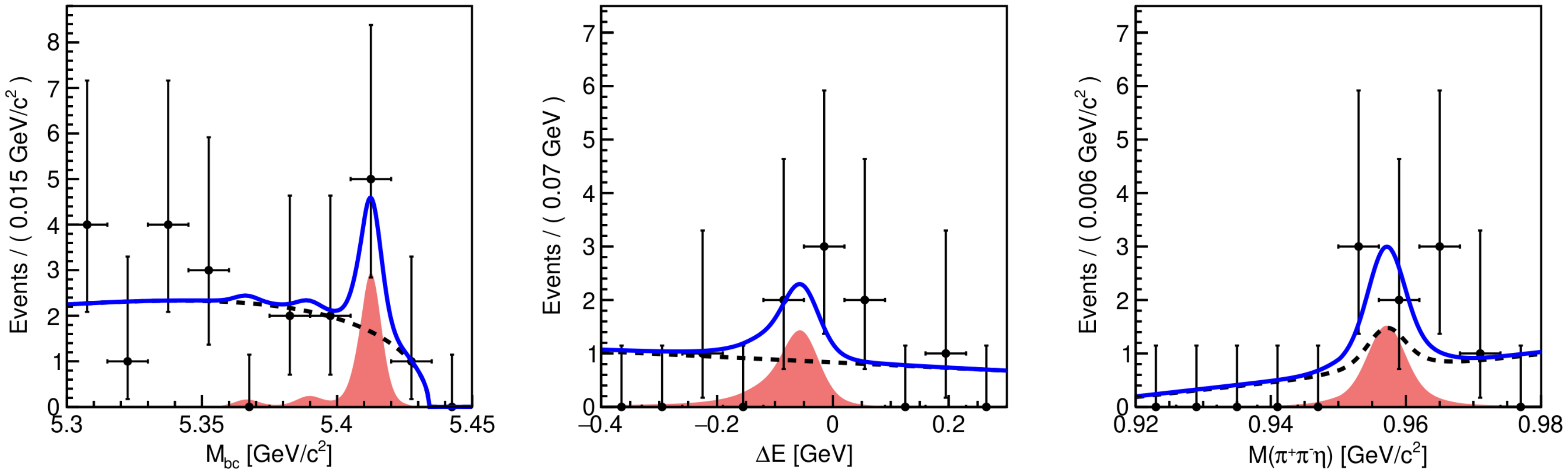






$B_s^0 \to \eta\eta'$

Signal extraction strategy:
3D ML fit to $M_{\rm bc} - \Delta E - M(\eta\pi^+\pi^-)$



Fit projections of 3D fit in the signal region.

$B_s^0 \to \eta\eta'$

Results

2.7 ± 2.5 signal events

57.3 ± 7.8 background events

$$\mathcal{B}(B_s^0 \to \eta'\eta) = (2.5 \pm 2.2 \pm 0.6) \times 10^{-5}$$

<u>90% Confidence Level Upper Limit</u>

$$\mathcal{B}(B_s^0 \to \eta'\eta) < 6.5 \times 10^{-5}$$

Accepted in Phys. Rev. D

arXiv:2106.09695

$$B_s^0 \to D_s X$$

$B_s^0 \to D_s X$

- Inclusive mode that provides information on the B_s^0 production rate f_s at the $\Upsilon(5S)$ resonance – the fraction of $\Upsilon(5S)$ events with B_s^0 pairs.
- B_s^0 properties can provide important information on CKM matrix parameters.

$B_s^0 \to D_s X$

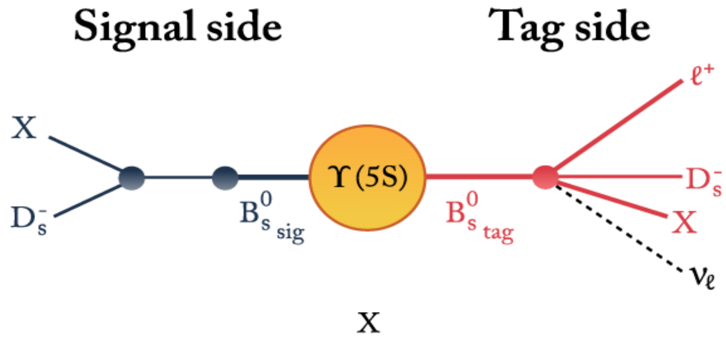
Mode is used to determine the production of B_s^0 in $\Upsilon(5S)$ decays

Study uses a semileptonic tagging method; partial reconstruction of

$$B_s^0 \to D_s X \ell \nu, \ell = e, \mu$$

Signal-side D_s is reconstructed from tracks remaining in the event

Tag Channel	Signal Channel
$\phi\pi$	$\phi\{K^+K^-\}\pi$
	$K_S^0\{\pi^+\pi^-\}K$
	$K^{*0}\{K^\pm\pi^\mp\}K$
$K_S^0 K$	$\phi\{K^+K^-\}\pi$
	$K_S^0\{\pi^+\pi^-\}K$
	$K^{*0}\{K^\pm\pi^\mp\}K$



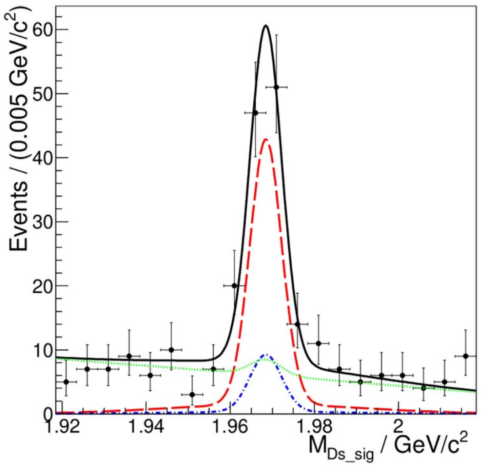
$B_s^0 \to D_s X$

Number of B_s^0 tags for each D_s channel is found by fitting M^2_{miss} and M(D_s) distributions to:

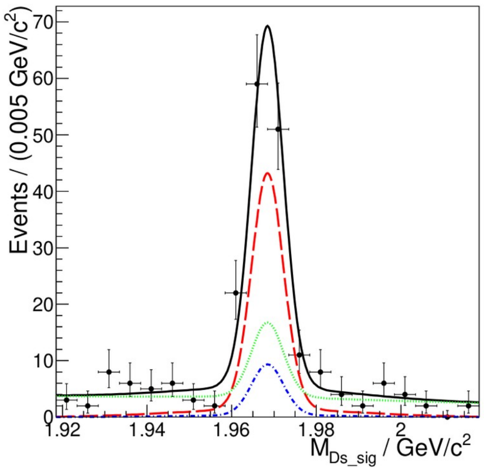
1) Correct tags
2) Incorrect tags where tag-lepton is paired with signal-side D_s
3) Other incorrect tags

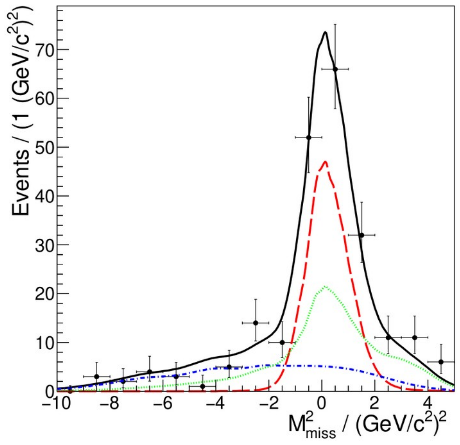
Number of signal-side D_s is found by a 3D fit to M^2_{miss} and inv. mass dist. of tag and signal-side D_s

$B_s^0 \to D_s X$



1D Projections of results from 3D fits, all D_s modes combined, for M_{Ds}^{sig} (top), M_{Ds}^{tag} (center) and M_{miss}^2 (bottom): data (points with error bars), signal (red, dashed), cross-feed (blue, dash-dotted), background (green, dotted), and total (black, solid). For each projected variable, signal band requirements are made in the other two: $M_{Ds}^{\mathrm{sig}}, M_{Ds}^{\mathrm{tag}} \in m_{Ds}^{\mathrm{PDG}} \pm 0.02\mathrm{GeV}/c^2$, $M_{\mathrm{miss}}^2 \in [-2, 2](\mathrm{GeV}/c^2)^2$.





$B_s^0 \to D_s X$

Our Current Results:

$$\mathcal{B}(B_s^0 \to D_s X) = [61.6 \pm 5.3(\text{syst.}) \pm 2.1(\text{syst.})]\%$$

$$f_s = 0.278 \pm 0.028(\text{stat.}) \pm 0.035(\text{syst.})$$

Previous Belle Results:

$$\mathcal{B}(B_s^0 \to D_s X) = [91 \pm 18(\text{stat.}) \pm 41(\text{syst.})]\%$$

$$f_s = 0.181 \pm 0.036(\text{stat.}) \pm 0.075(\text{syst.})$$

Current result uses full 121.4/fb data set
Previous result uses 1.86/fb

$B_s^0 \to D_s X$

Our BF result is smaller than the world average by approximately 1.2 σ .

It is also smaller than the theoretical prediction of 86^{+8}_{-13} %.

The lower measured rate my be explained by a higher than expected rate of $c\bar{s} \to D \text{ vs } D_s$

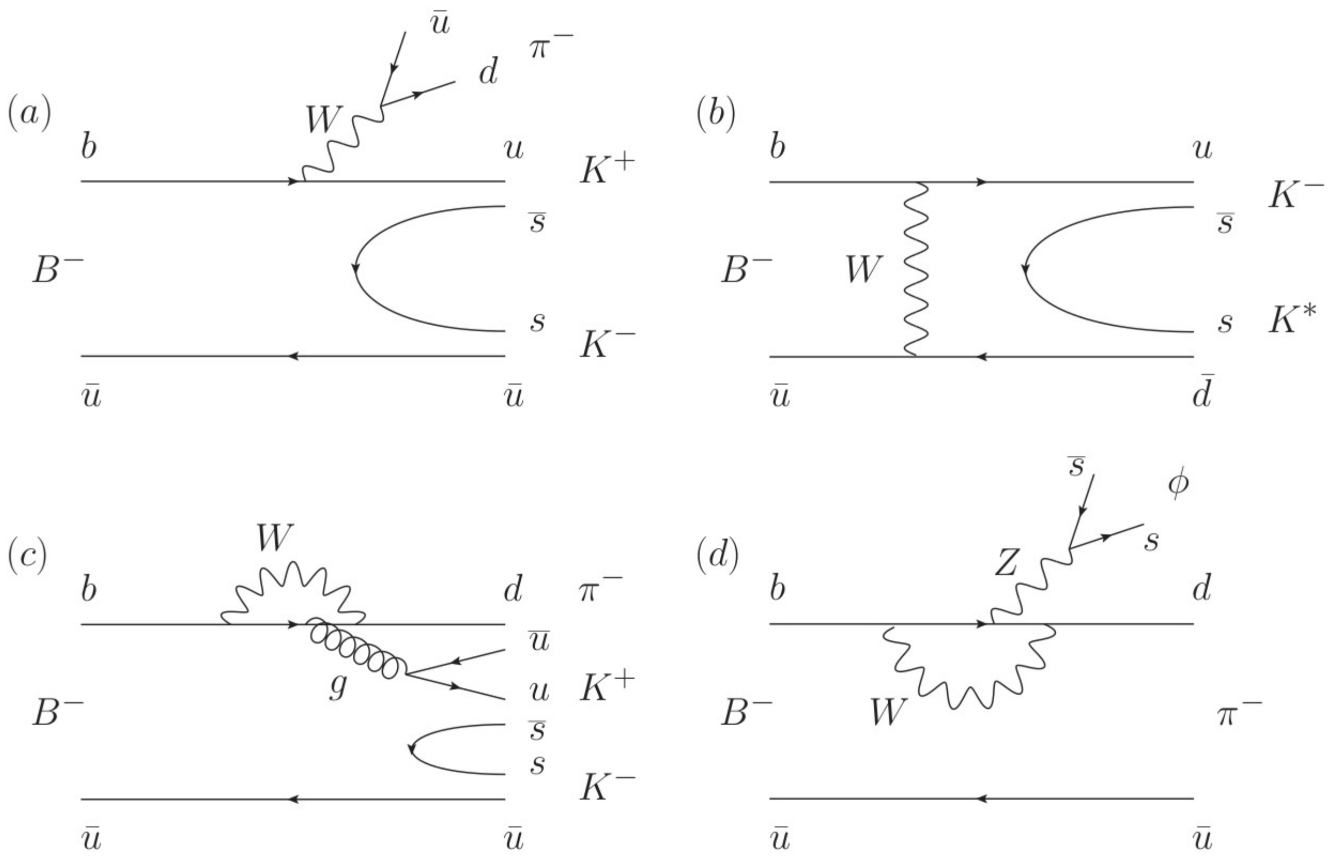
$$B^+ \to K^+ K^- \pi^-$$

$B^+ \to K^+ K^- \pi^-$

- Highly suppressed in the SM.
- Sensitive to NP, e.g. through BF enhancements.
- NP can occur in the loop diagrams
  - e.g. BSM particles
- LHCb: $\mathcal{A}_{CP} = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$

$$\mathcal{A}_{CP} = -0.328 \pm 0.028 \pm 0.029 \pm 0.007,\ 1.0 < M(K^+K^-) < 1.5\ \mathrm{GeV}/c^2$$

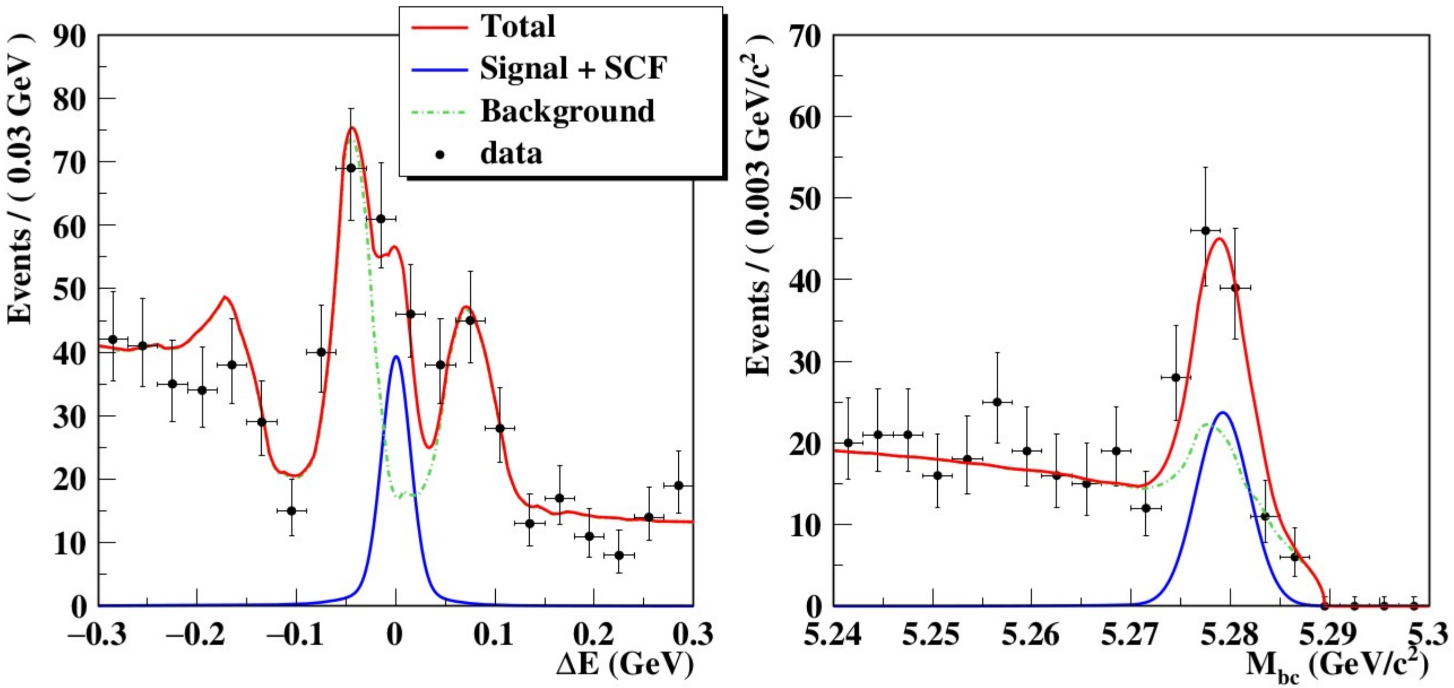
$B^+ \to K^+ K^- \pi^-$


(a)
ū
π⁻
d
W
b
u
K⁺
s̄
B⁻
s
K⁻
ū
ū
(b)
b
u
K⁻
s̄
B⁻
W
s
K*
ū
d̄
(c)
W
b
d
π⁻
ū
g
u
K⁺
B⁻
s̄
s
K⁻
ū
ū
(d)
s̄
ϕ
s
Z
b
d
B⁻
W
π⁻
ū
ū

$B^+ \to K^+K^-\pi^-$

Results

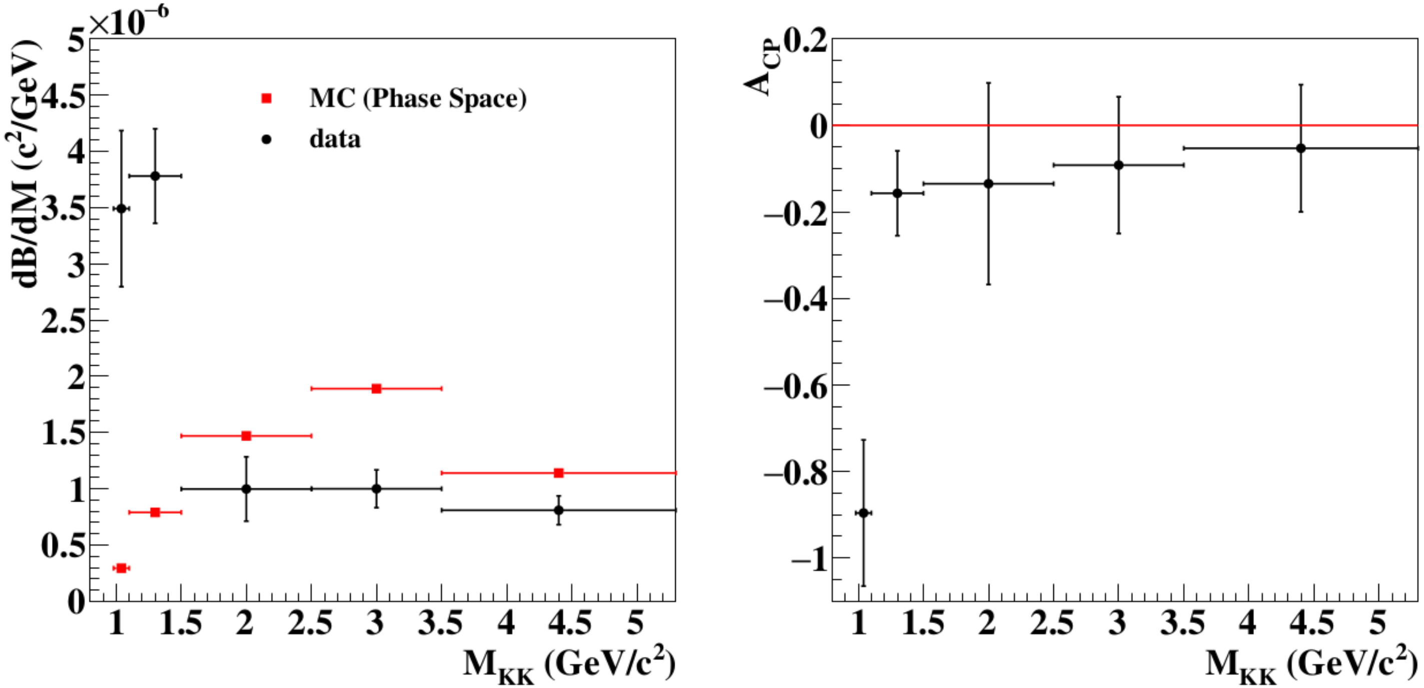
Signal extraction strategy: extract signal from 2D ML fits in bins of $M(K^+K^-)$ and $M(K^+\pi^-)$.



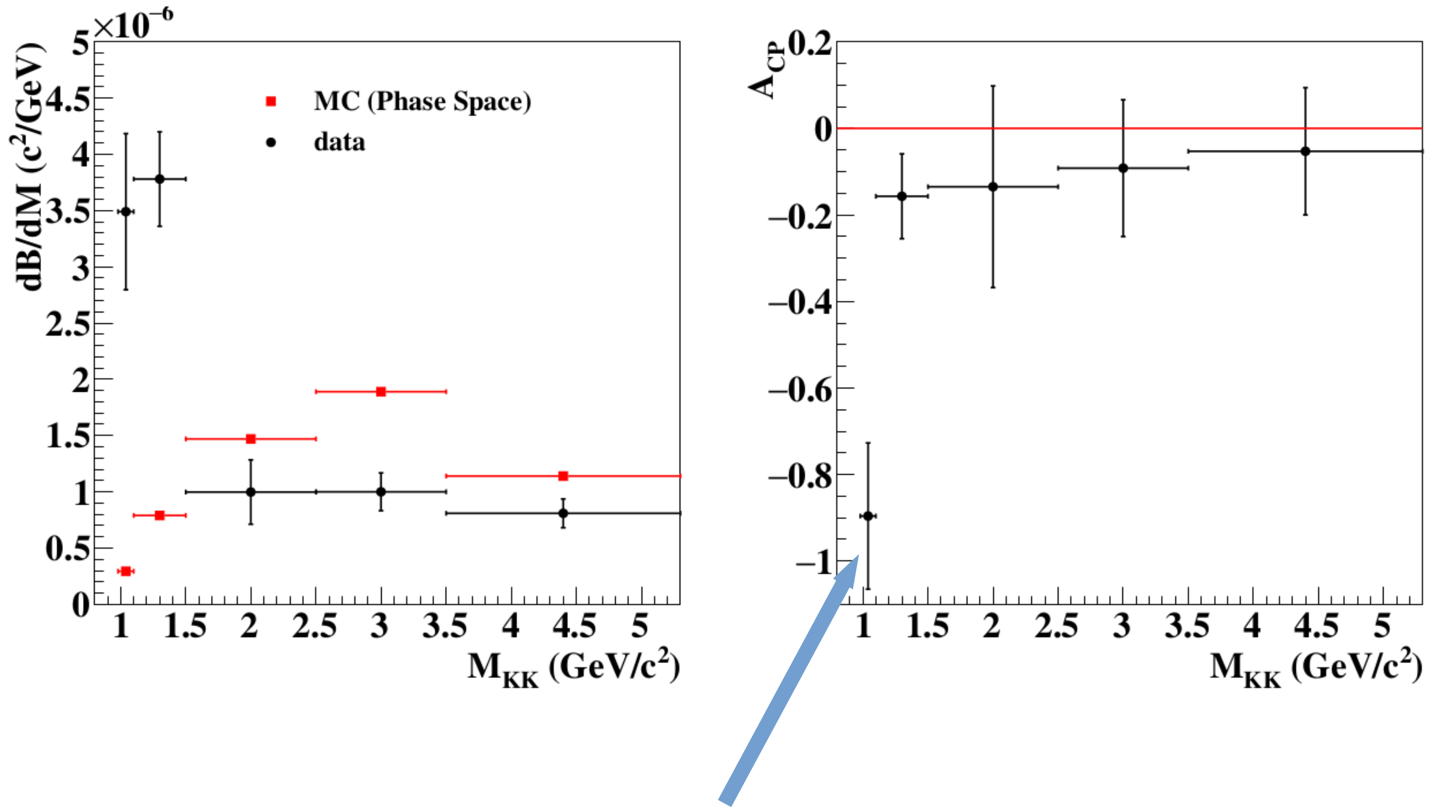
(a) $0.8 < M_{K^+K^-} < 1.1 \text{ GeV}/c^2$

Example of 2D fit projections in $M_{\rm bc} - \Delta E$

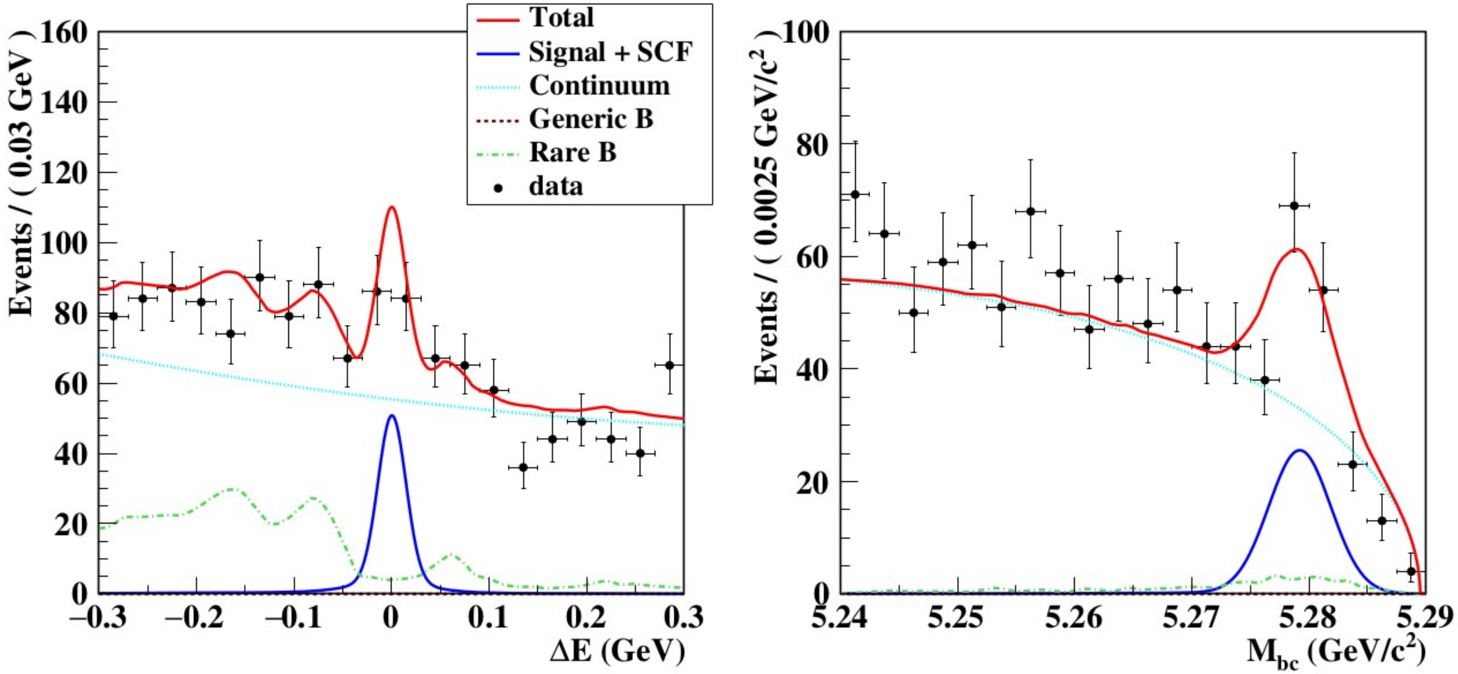
$B^+ \to K^+K^-\pi^-$



$B^+ \to K^+ K^- \pi^-$

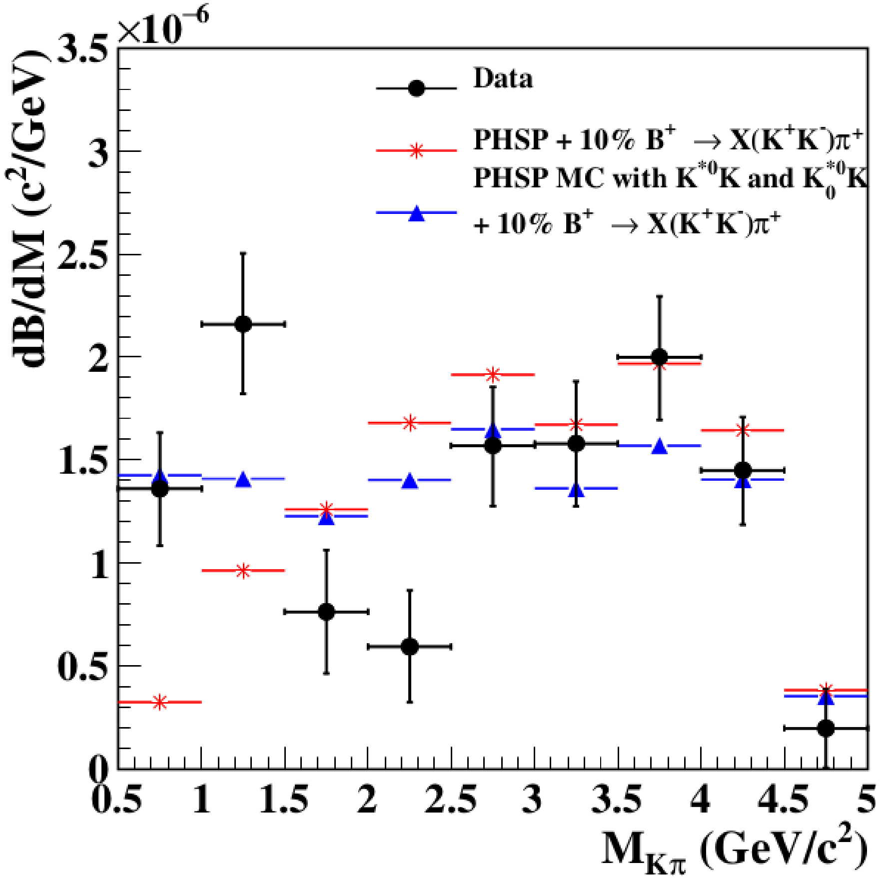


$B^+ \to K^+K^-\pi^-$



$$0.5 < M(K^+\pi^-) < 1.0 \text{ GeV}/c^2$$

$B^+ \to K^+K^-\pi^-$



×10⁻⁶
dB/dM (c²/GeV)
Data
PHSP + 10% B⁺ → X(K⁺K⁻)π⁺
PHSP MC with K*⁰K and K₀*⁰K
+ 10% B⁺ → X(K⁺K⁻)π⁺
M_Kπ (GeV/c²)
0 0.5 1 1.5 2 2.5 3 3.5
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

$B^+ \to K^+ K^- \pi^-$

Results

$$\mathcal{B}(B^+ \to K^+ K^- \pi^+) = [5.38 \pm 0.40(\text{stat.}) \pm 0.35(\text{syst.})] \times 10^{-6}$$

$$\mathcal{A}_{CP} = -0.170 \pm 0.073(\text{stat.}) \pm 0.017(\text{syst.})$$

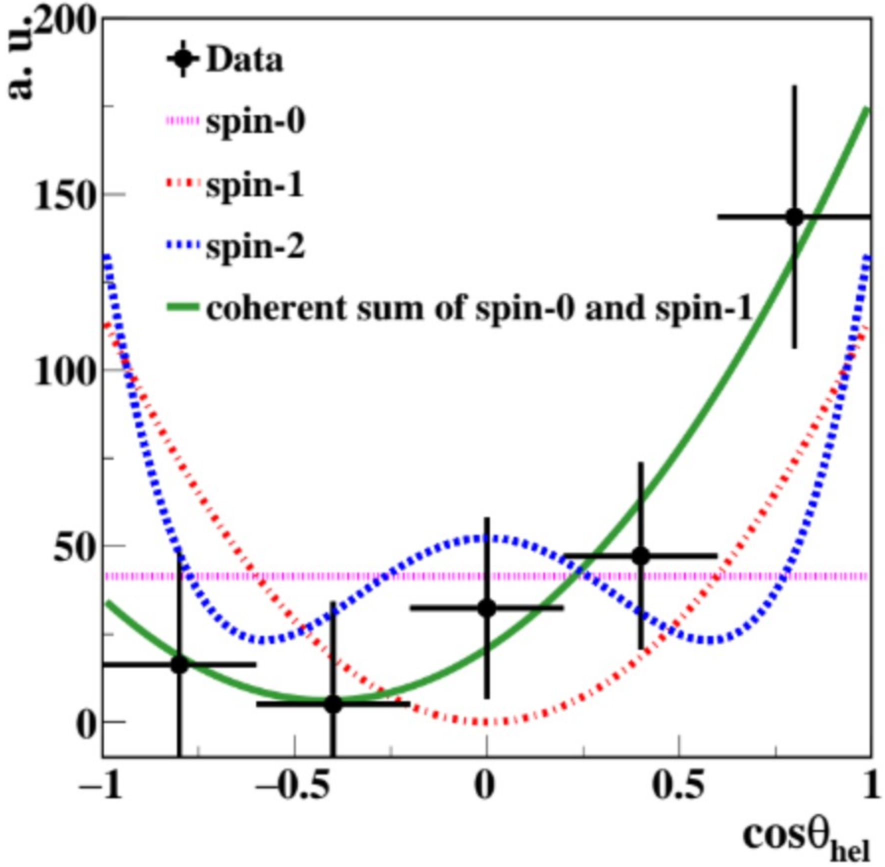
$$\mathcal{A}_{CP} = -0.90 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.}) \text{ for } M_{K^+K^-} < 1.1 \text{ GeV}/c^2$$

$$4.8\sigma \text{ significance}$$

Belle Preliminary

$B^+ \to K^+ K^- \pi^-$

Results



$$f(\cos\theta_{\rm hel}) = A_S^2 + 2A_S A_P \cos\theta_{SP} P_1(\cos\theta_{\rm hel}) + A_P^2 P_1(\cos\theta_{\rm hel}),$$

$$A_S = 4.6 \pm 2.1 \quad A_P = 9.2 \pm 2.8$$

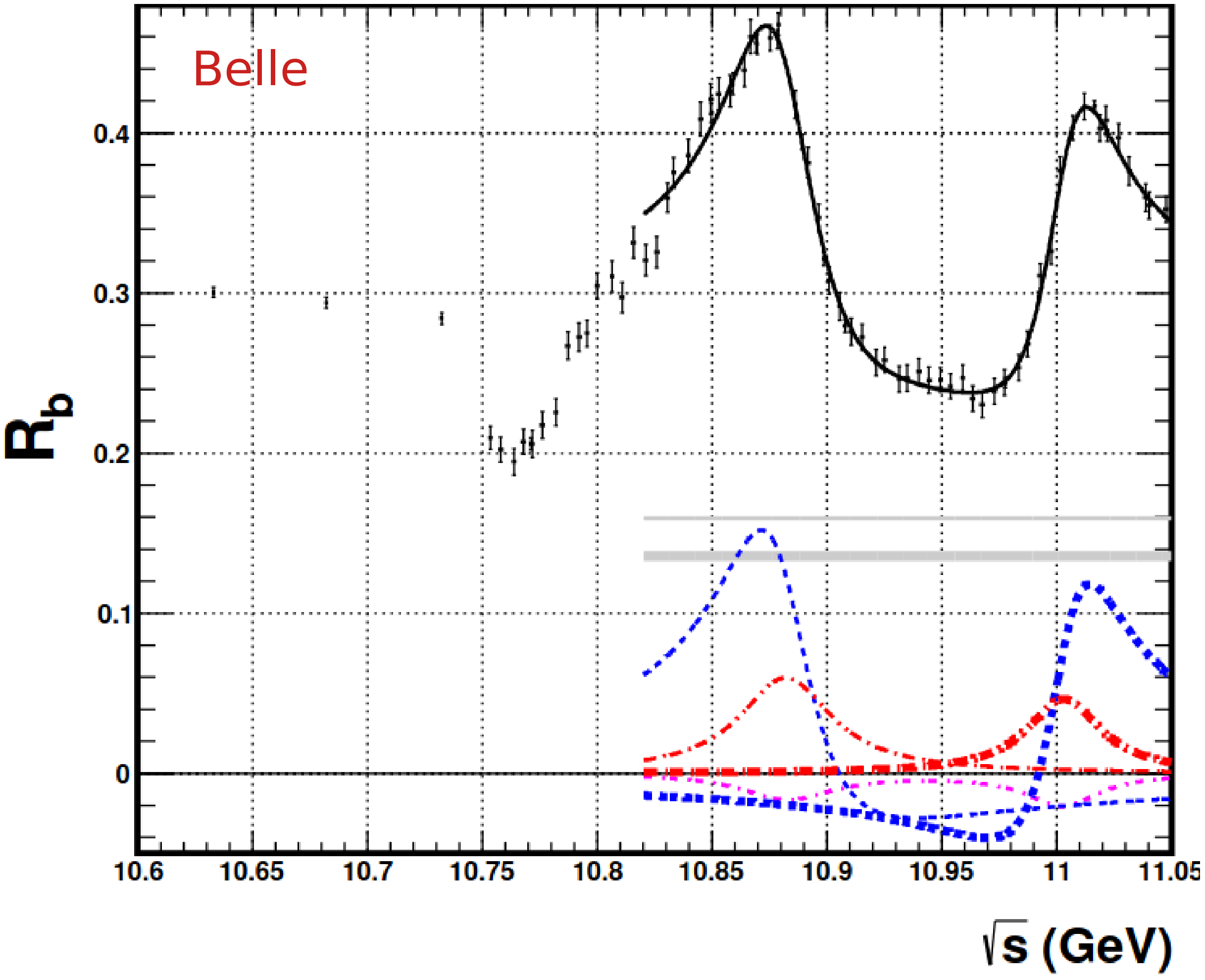
Belle Preliminary

Summary and Conclusion

Summary and Conclusion

- Four different hadronic B/B_s^0 decays have been presented.
- The two B_s^0 decays involving the η' are the world's first measurements. These are probes of new physics and may help us understand the η' mass.
- The $B_s^0 \to D_s X$ (re)measurement finds a lower BF than previous measurements.
- The $B^+ \to K^+ K^- \pi^+$ measurement confirms LHCb's finding of a large $\mathcal{A}_{cp}$ in the low $M(K^+K^-)$ region; we report a more complicated spin structure in the K^+K^- system, than a purely S- or P-wave structure.

Backup



Phys. Rev. D 93, 011101 (2016)