Measurement of direct CP violation in the decay $B^+ \to K^+\pi^0$

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on behalf of the LHCb collaboration

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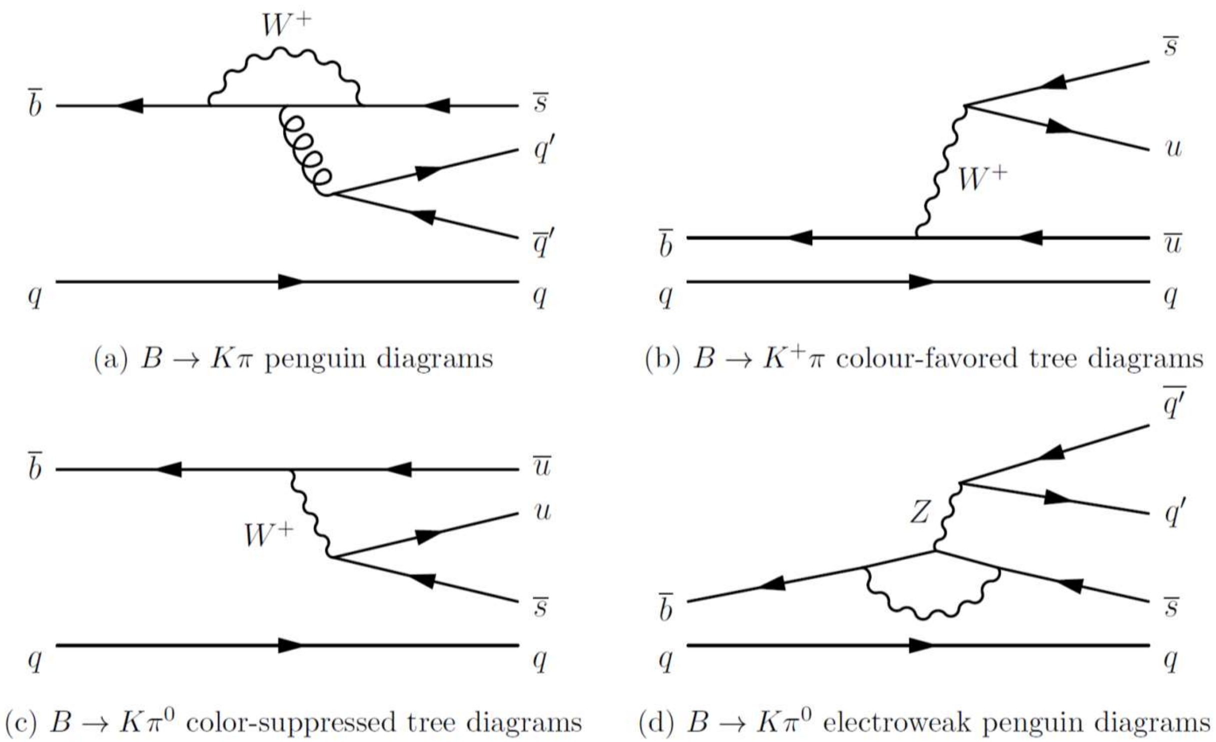
Motivation

- Family of $B \to K\pi$ decays dominated by hadronic loop amplitudes, but diagrams contribute differently to decays
- Amplitudes expected to obey isospin relations, but measurements of CP asymmetries find $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.122 \pm 0.022$ (HFLAV 2018)
- More precise to incorporate all four CP asymmetries and branching fractions (Phys.Lett.B 627 (2005) 82)
- Tension in fit to $K\pi$ measurements can be resolved by enhancement of color-suppressed trees or NP in penguins (JHEP 01 (2018) 074, Phys.Lett.B 785 (2018) 525)



(a) $B \to K\pi$ penguin diagrams

(b) $B \to K^+\pi$ colour-favored tree diagrams

(c) $B \to K\pi^0$ color-suppressed tree diagrams

(d) $B \to K\pi^0$ electroweak penguin diagrams

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathrm{B}(K^0\pi^+)}{\mathrm{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathrm{B}(K^+\pi^0)}{\mathrm{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathrm{B}(K^0\pi^0)}{\mathrm{B}(K^+\pi^-)}$$

$K\pi$ sum rule

Experimental Status

$\mathcal{A}^{CP}$ measurements for the $B \to K\pi$ decay modes

	BaBar	Belle	LHCb
$B^0 \to K^0\pi^0$	$+0.13 \pm 0.13 \pm 0.03$ [1]	$+0.14 \pm 0.13 \pm 0.06$ [2]	
$B^+ \to K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$ [3]	$-0.011 \pm 0.021 \pm 0.006$ [4]	$-0.022 \pm 0.025 \pm 0.010$ [5]
$B^0 \to K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$ [6]	$-0.069 \pm 0.014 \pm 0.007$ [4]	$-0.084 \pm 0.004 \pm 0.003$ [7]
$B^+ \to K^+\pi^0$	$+0.030 \pm 0.039 \pm 0.010$ [8]	$+0.043 \pm 0.024 \pm 0.002$ [4]	

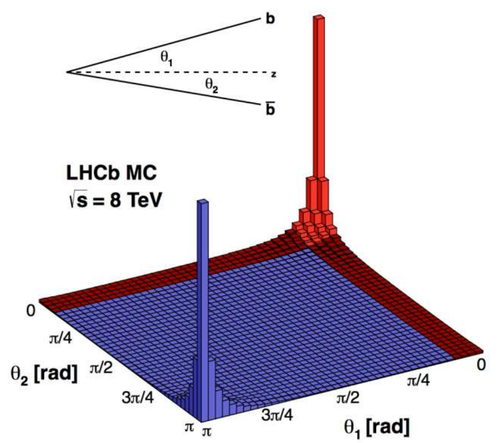
Sum rule prediction for $A_{CP}(K^0\pi^0)$: -0.150 +/- 0.032

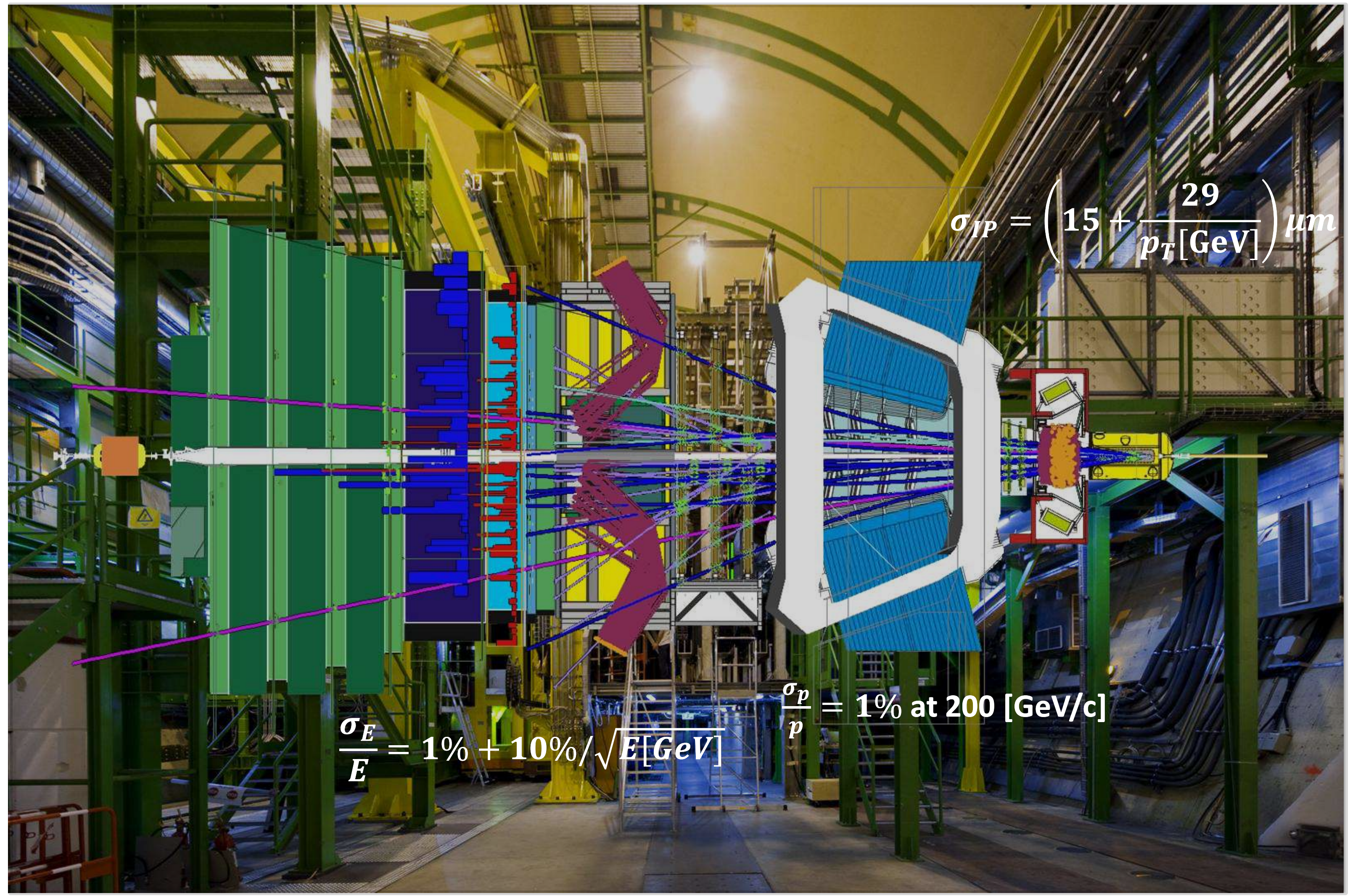
- All four $B \to K\pi$ modes measured at B factories
- Charged pion modes measured by LHCb
- **$B^+ \to K^+\pi^0$ is first analysis of a one-track B decay at a hadron collider**
  - Experimentally challenging – no secondary vertex
  - Secondary vertex a requirement for all Run I software triggers, dedicated trigger line developed for Run II
- Proof of concept for other modes of similar topology such as $B^0 \to K^0\pi^0$

[1]:Phys.Rev.D 79, 052003 [2]:Phys.Rev.D 81, 011101(R) [3]:Phys.Rev.Lett. 97, 171805 [4]:Phys.Rev.D 87, 031103(R)
[5]:Phys.Lett.B 726 (2013) 646 [6]:Phys.Rev.D 87, 052009 [7]:Phys.Rev.D 98, 032004 [8]:Phys.Rev.D 76, 091102(R)

The LHCb Detector

- Forward spectrometer covering $10 < \theta < 300$ mrad
- $b\bar{b}$ production peaked forward/backward
  - 25% in ~4% solid angle

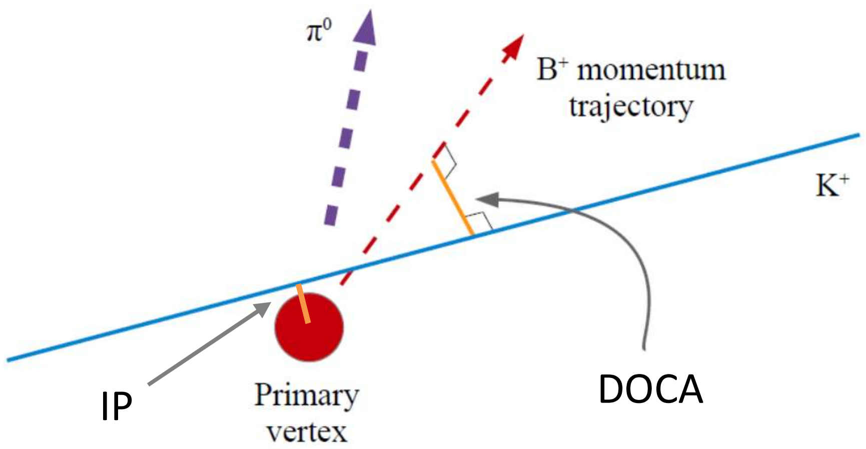


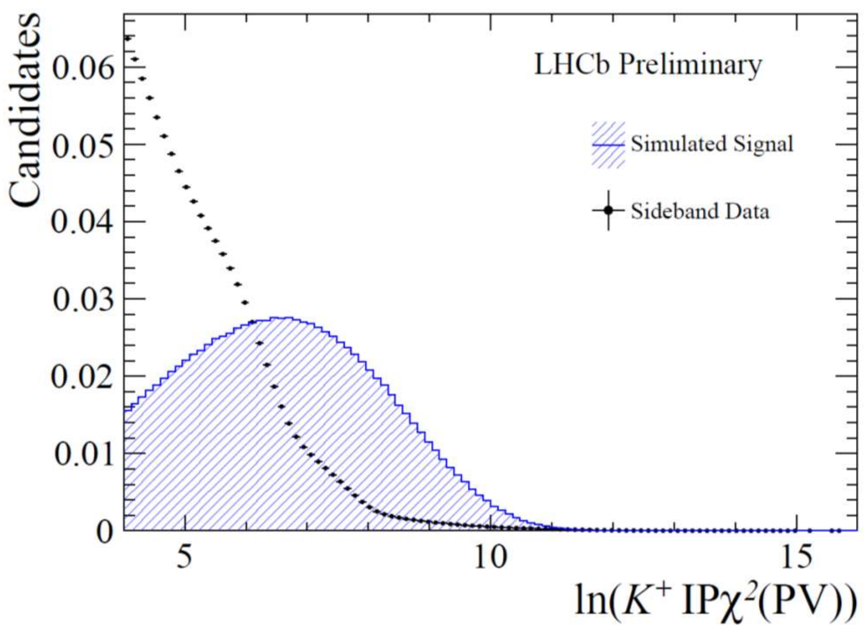


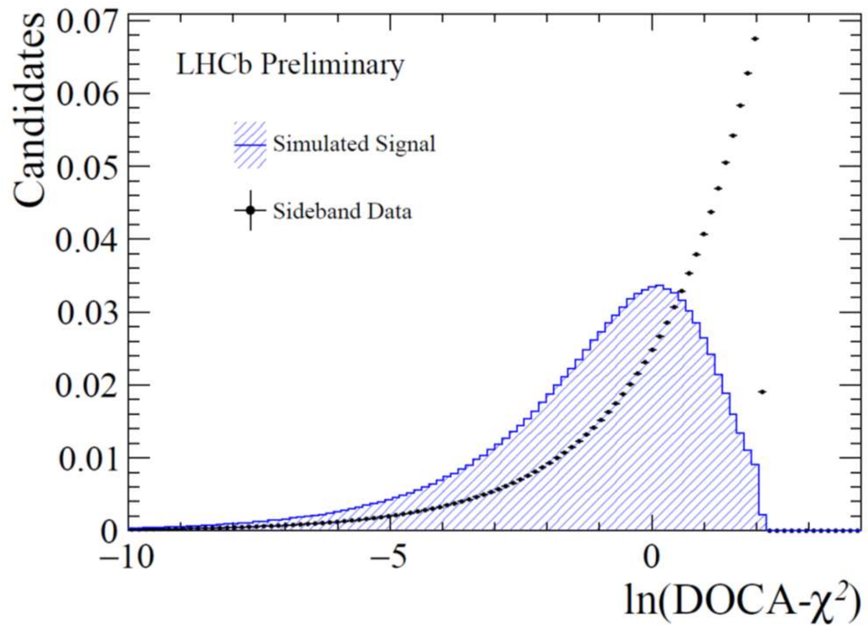
JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

Trigger

- Major challenge to suppress background in absence of displaced secondary vertex
- Dedicated trigger
  - Tight kinematic cuts
  - π^0 from photons merged into single calorimeter cluster
    - Higher energy, lower combinatorial background
  - K^+ impact parameter inconsistent with PV
  - K^+ distance of closest approach consistent with B^+ trajectory

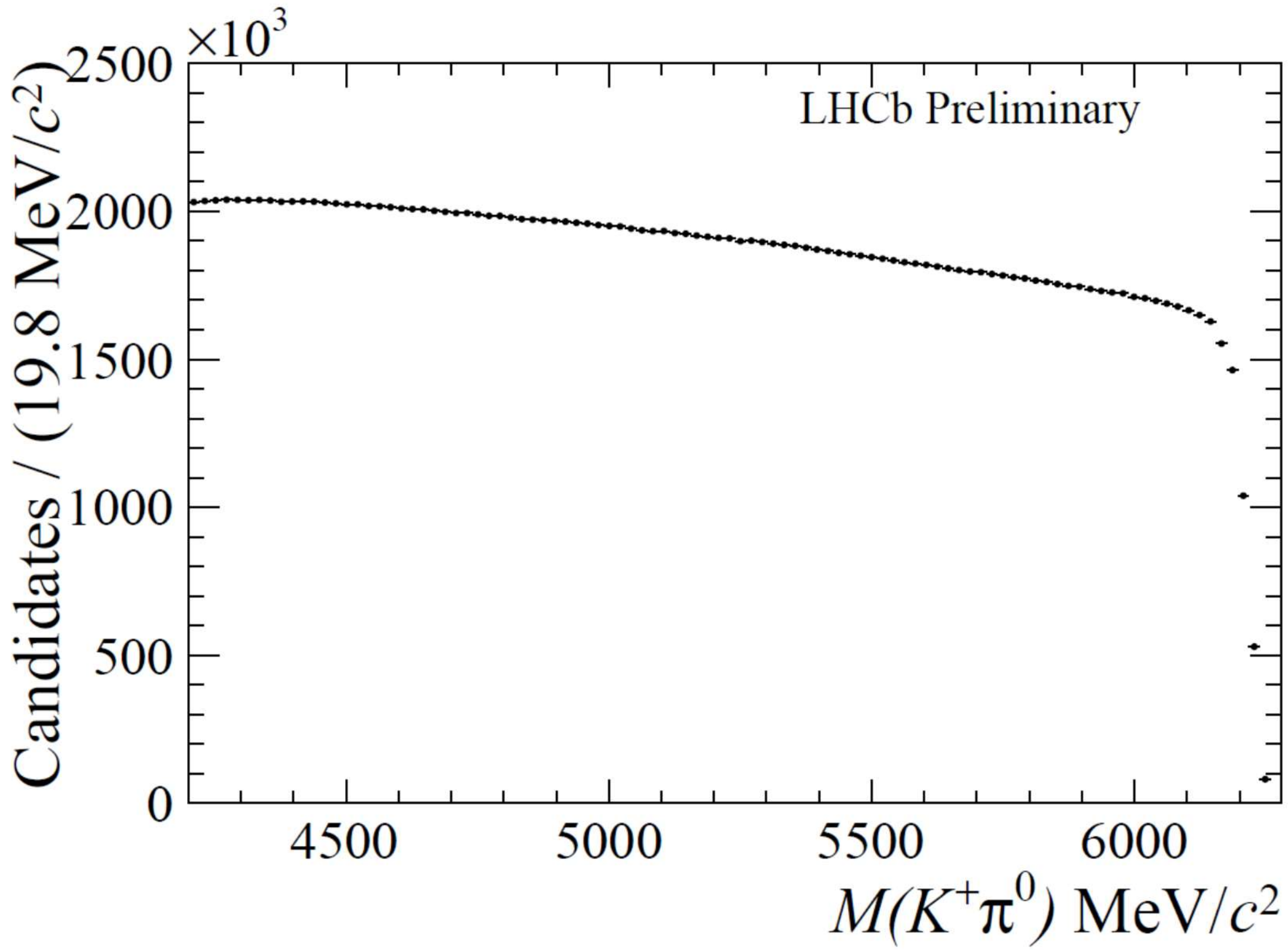






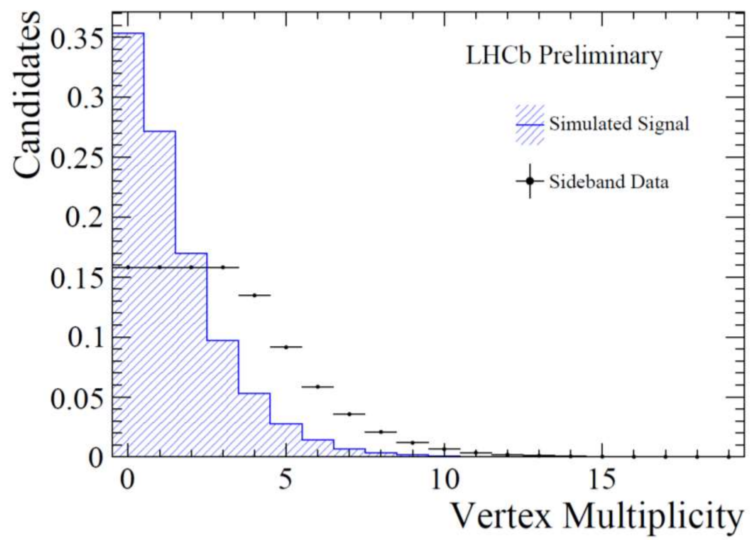
Offline Selection

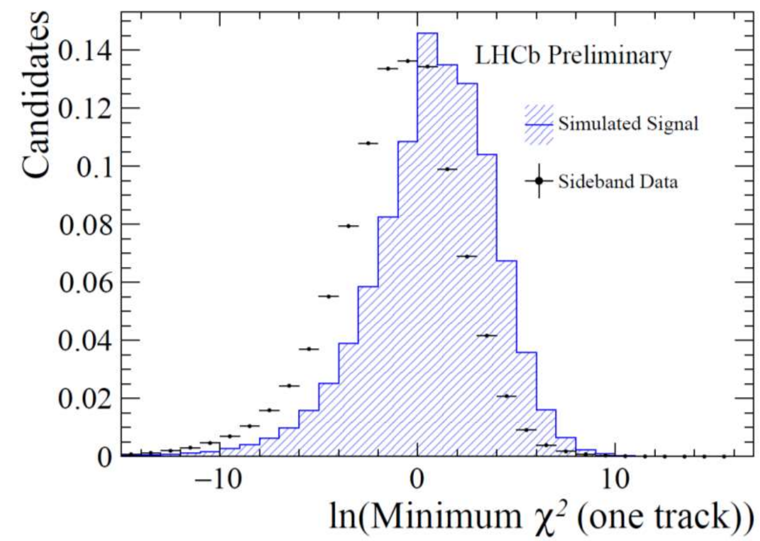
- Use boosted decision trees to overcome S/B of $\sim 3.3 \times 10^{-4}$
- Trained on high-mass and low-mass sidebands and simulated signal events
- Split and cross-validated to take advantage of full dataset and avoid overtraining
- Rely on kinematics, IPχ^2(PV) and DOCA-χ^2, and isolation (next slide)

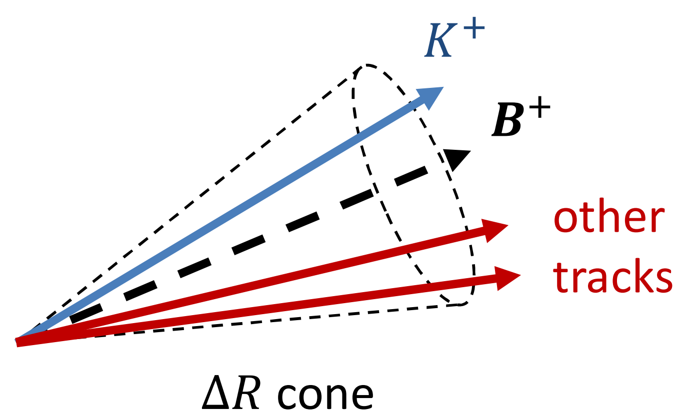


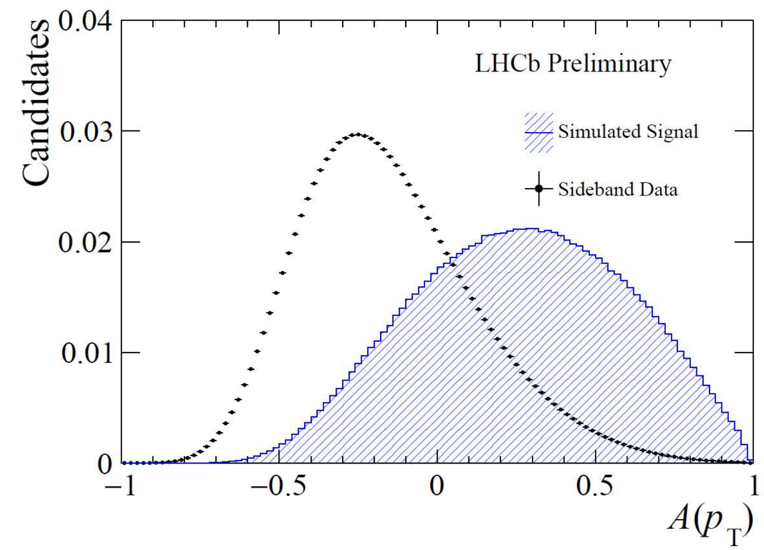
Isolation Variables

- Events with other tracks pointing back to B candidate are unlikely to be $B^+ \to K^+\pi^0$ decays
- Combine each track individually with K^+: multiplicity of good vertices, χ^2 of vertices formed
- Consider tracks in ΔR cone around B^+: $A_{p_T} \equiv \frac{p_T(B)-p_T(\text{cone})}{p_T(B)+p_T(\text{cone})}$
- Isolation depends on track multiplicity
  - Corrected by comparing $B^0 \to K^+\pi^-$ data and simulation



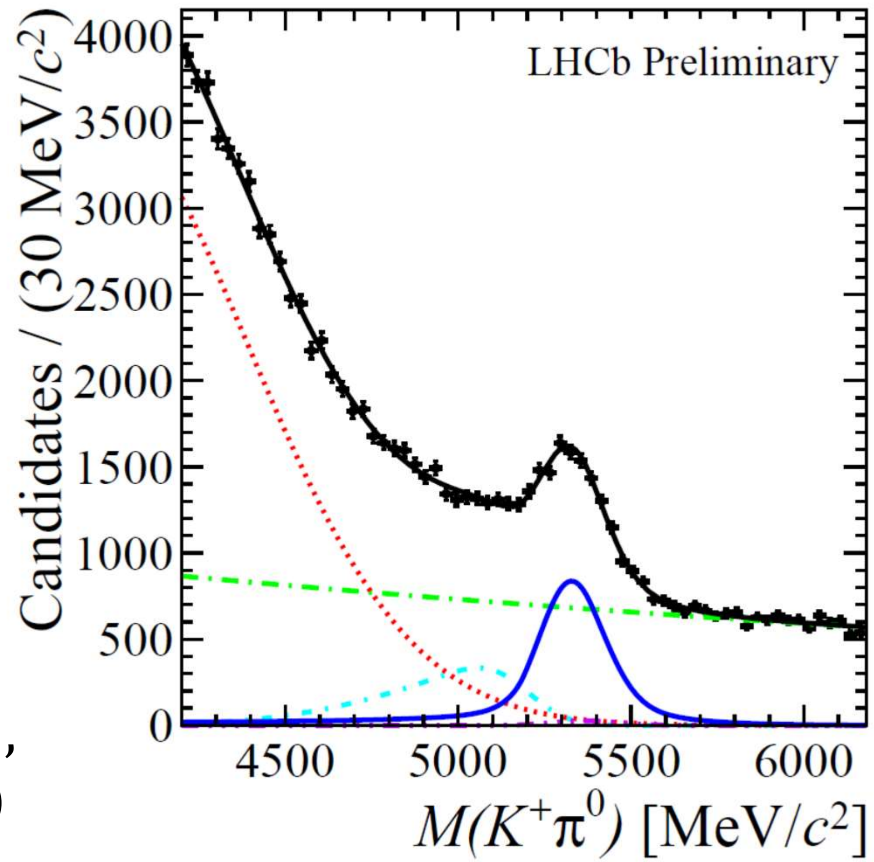


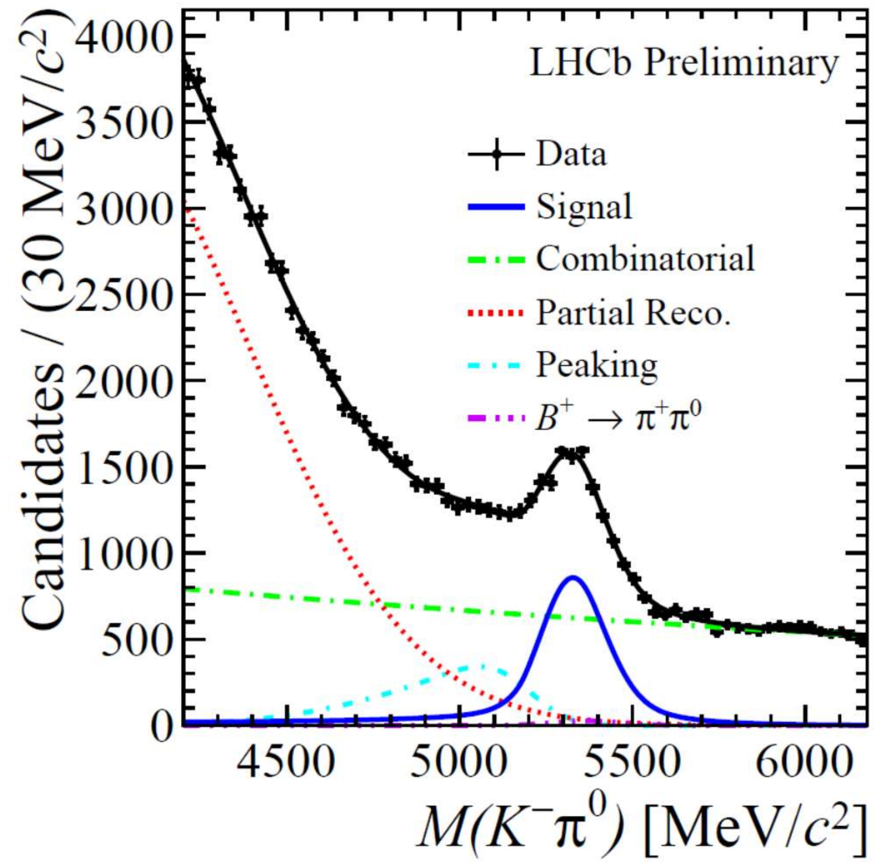




Raw Asymmetry Measurement

- Split data by B charge and magnet polarity
- Signal tails, some shape parameters of peaking and $B^+ \to \pi^+\pi^0$ from simulation
- Yields and asymmetries vary freely for all fit components (except $B^+ \to \pi^+\pi^0$)
- 8310 ± 255(MU), 8373 ± 253(MD) signal events
- $\boldsymbol{A_{\mathrm{raw}} = 0.005 \pm 0.022}$ **(MU)**, $\boldsymbol{0.019 \pm 0.021}$ **(MD)**





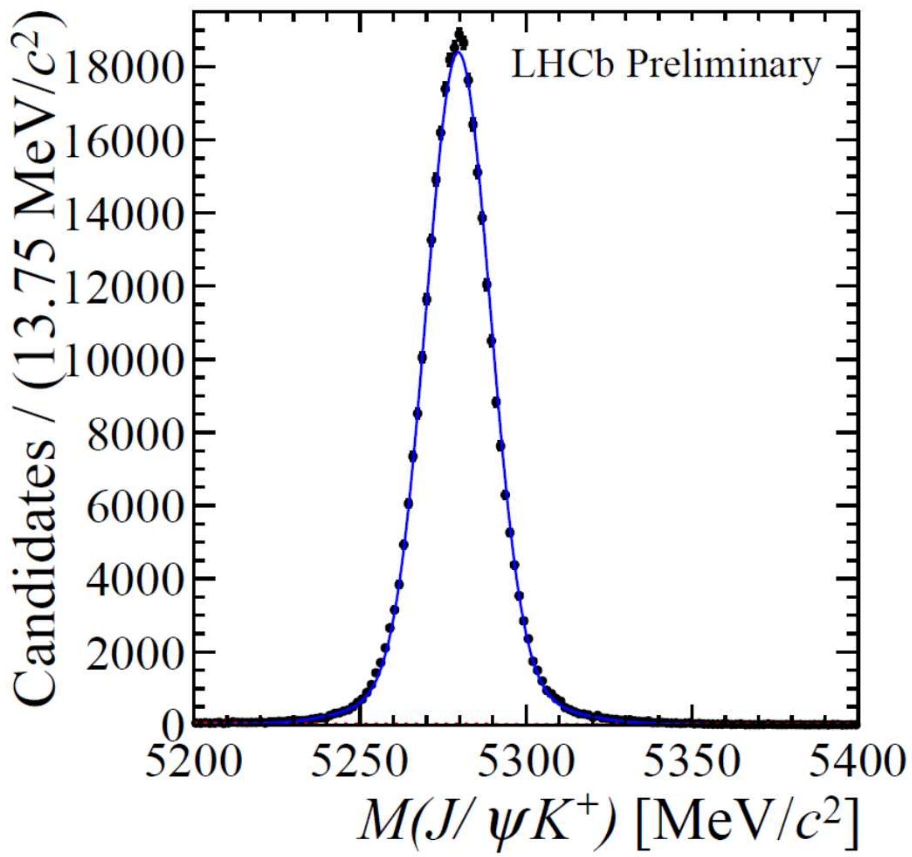
Production and Detection Asymmetry

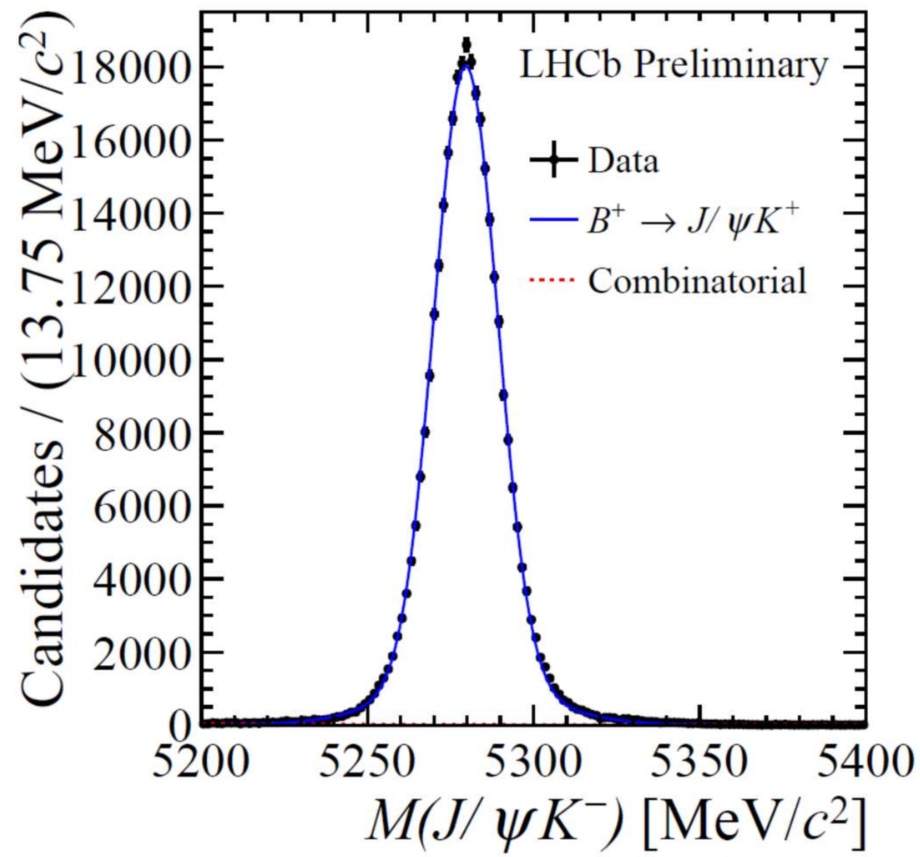
$$A_{CP}(B^+ \to K^+\pi^0) = A_{raw}(B^+ \to K^+\pi^0) - A^B_{prod.} - A^K_{det.} - A^K_{trig.} - A^K_{reco.}$$

- Raw asymmetry is a combination of physical CP asymmetry, $B^\pm$ production asymmetry and $K^\pm$ detection, reconstruction, and triggering
- Can measure the same combination of effects in $B^+ \to (J/\psi \to \mu^+\mu^-)K^+$ decays
  - π^0 neutral, $\mu^\pm$ symmetric
  - K^+ trigger, selection, reco. matches signal
  - Weight $p/p_T(B^+/K^+)$ distributions of $B^+ \to (J/\psi \to \mu^+\mu^-)K^+$ to match signal
- $A_{CP}(B^+ \to J/\psi K^+) = 0.002 \pm 0.003$ (PDG), introduces small external uncertainty to $A_{CP}(B^+ \to K^+\pi^0)$ measurement

Prod./Det. Asymmetry Correction

- Split data by B charge and magnet polarity
- ~99% signal purity
- $A_{raw}(B^+ \to J/\psi K^+) = -0.009 \pm 0.002$ (MU), -0.012 ± 0.002 (MD)





- $A_{CP}(B^+ \to K^+\pi^0) = A_{raw}(B^+ \to K^+\pi^0) - \left(A_{raw}(B \to J/\psi K^+) - A_{CP}(B \to J/\psi K^+)\right)$
$$= \mathbf{0.016 \pm 0.022\ (MU), 0.033 \pm 0.021\ (MD)}$$

Systematic Uncertainties

- Fit variation systematics determined from pseudoexperiments
- Dominant source of uncertainty modeling of signal tails
- Common value of 0.0013 from pseudoexperiment statistics
- Effect of $B^+ \to J/\psi K^+$ weighting used to estimate residual differences in asymmetries
- Averaging Magnet Up and Magnet Down results and adding systematic uncertainties in quadrature:

$$\mathbf{A_{CP}}\left(\boldsymbol{B^+ \to K^+ \pi^0}\right) \\ = \mathbf{0.025 \pm 0.015(stat.)} \\ \mathbf{\pm 0.006(syst.) \pm 0.003(ext.)}$$

Table 1: Systematic uncertainties on $A_{CP}(B^+ \to K^+\pi^0)$.

Fit Component	Systematic	Value
Combinatorial bkg.	Shape	0.0013
Low-mass bkg.	Shape	0.0013
Peaking bkg.	Shape	0.0012
	Offset	0.0013
	Resolution	0.0014
$B^+ \to \pi^+\pi^0$	Yield	0.0013
	CP Asymmetry	0.0015
Signal modeling	Shape	0.0043
Production/detection asymmetry	stat.	0.0021
	weights	0.0005
	Multiple candidates	0.0013
Sum in quadrature		0.0061

Conclusion

$\mathcal{A}^{CP}$ measurements for the $B \to K\pi$ decay modes

	BaBar	Belle	LHCb
$B^0 \to K^0\pi^0$	$+0.13 \pm 0.13 \pm 0.03$ [1]	$+0.14 \pm 0.13 \pm 0.06$ [2]	
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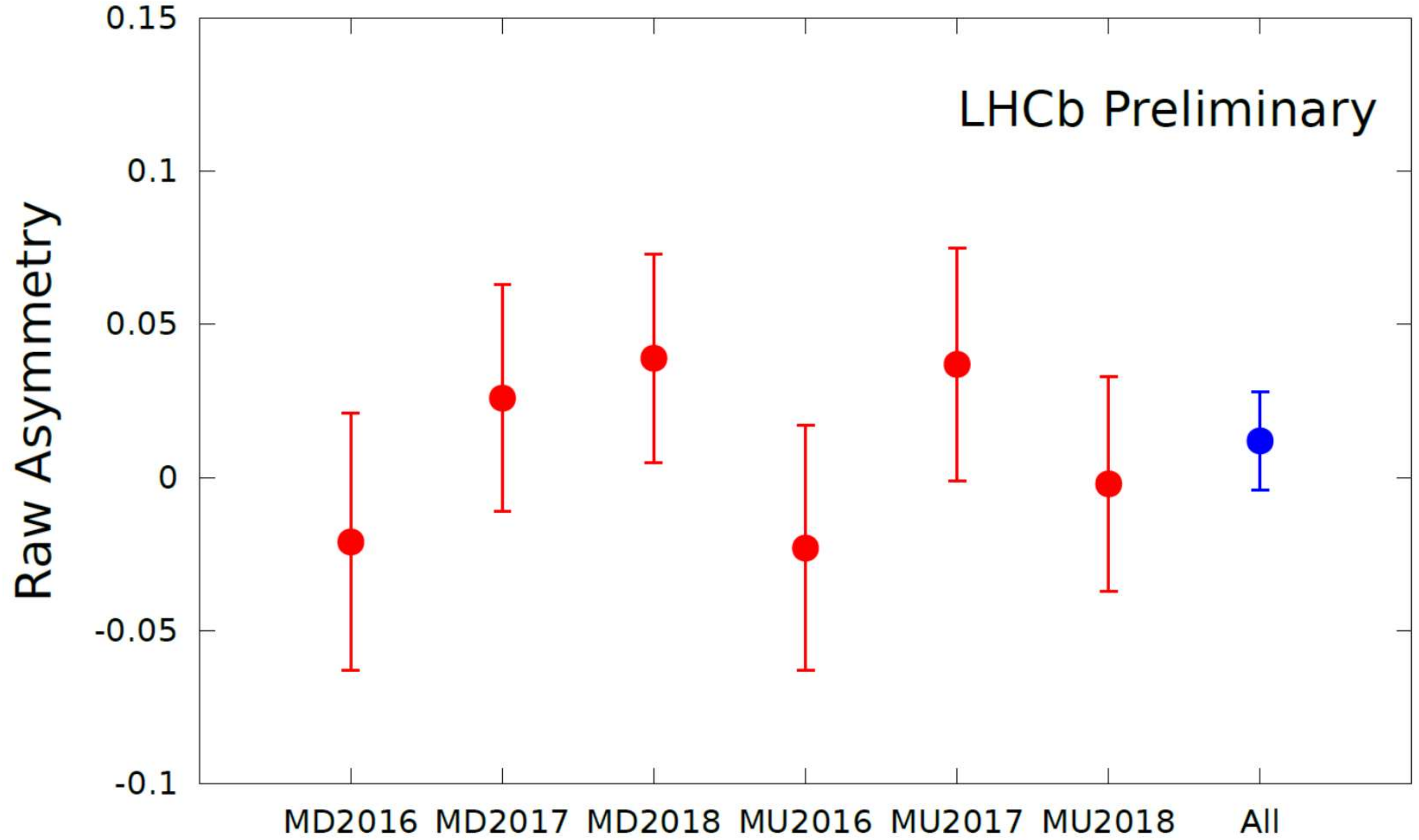
Previous sum rule prediction for $A_{CP}(K^0\pi^0)$: -0.150 +/- 0.032

- Most precise measurement of direct CP violation in $B^+ \to K^+\pi^0$ decays
- Consistent with world average, consistent with 0 at 1.5σ
- Combining with world average $A_{CP}(B^+ \to K^+\pi^0) = 0.031 \pm 0.013$ and $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$, non-zero at 8σ
- New sum rule prediction for $A_{CP}(K^0\pi^0)$: -0.138 +/- 0.025, non-zero at 5.5σ
- Similar trigger in place for $B^0 \to K^0\pi^0$
- Much more data coming with upgrade
  - Plan to migrate triggers to Run III Real Time Analysis

Backup

Consistency Checks



- Consistent between years and magnet polarities
- Additional checks: Binning by kaon p_T and magnet polarity, allowing shape parameters to vary between charges and magnet polarities
- Raw asymmetry consistent in all cases