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

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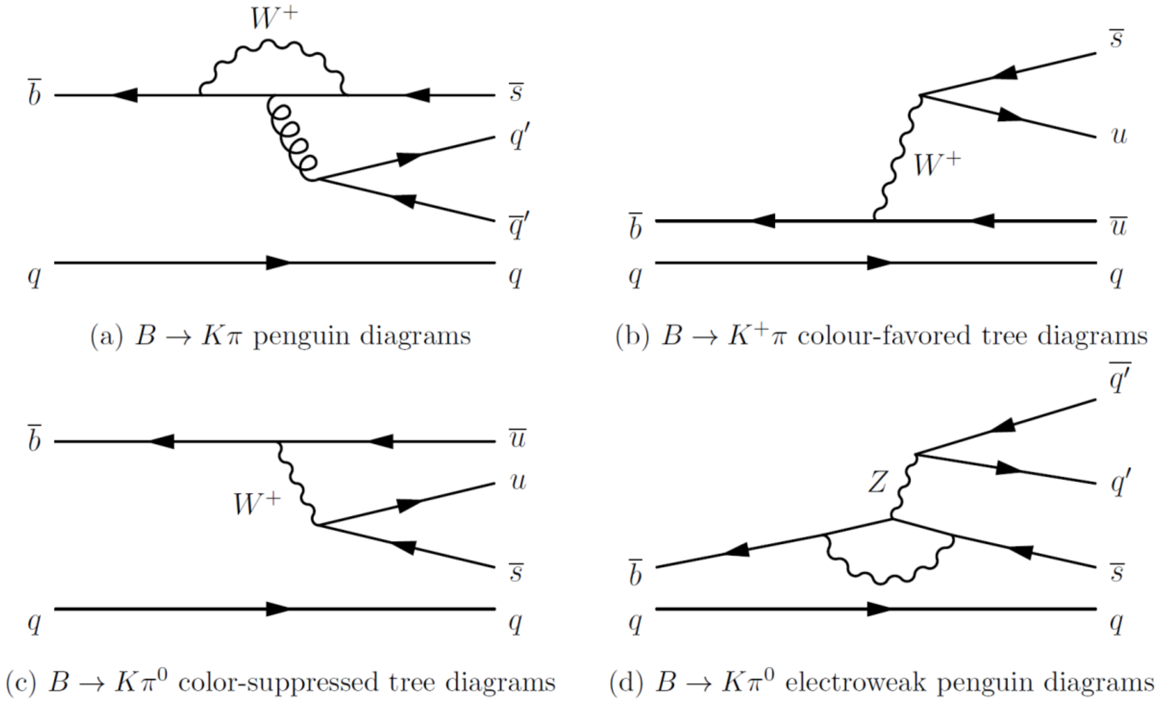
Motivation

- 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]	$-0.0824 \pm 0.0033 \pm 0.0033$ [7]
$B^+ \to K^+\pi^0$	$+0.030 \pm 0.039 \pm 0.010$ [8]	$+0.043 \pm 0.024 \pm 0.002$ [4]	

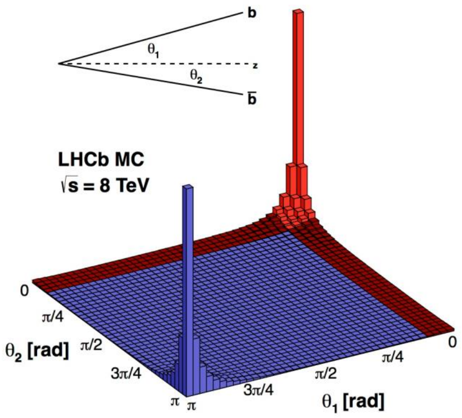
Sum rule prediction for $A_{CP}(K^0\pi^0)$: -0.150 +/- 0.032

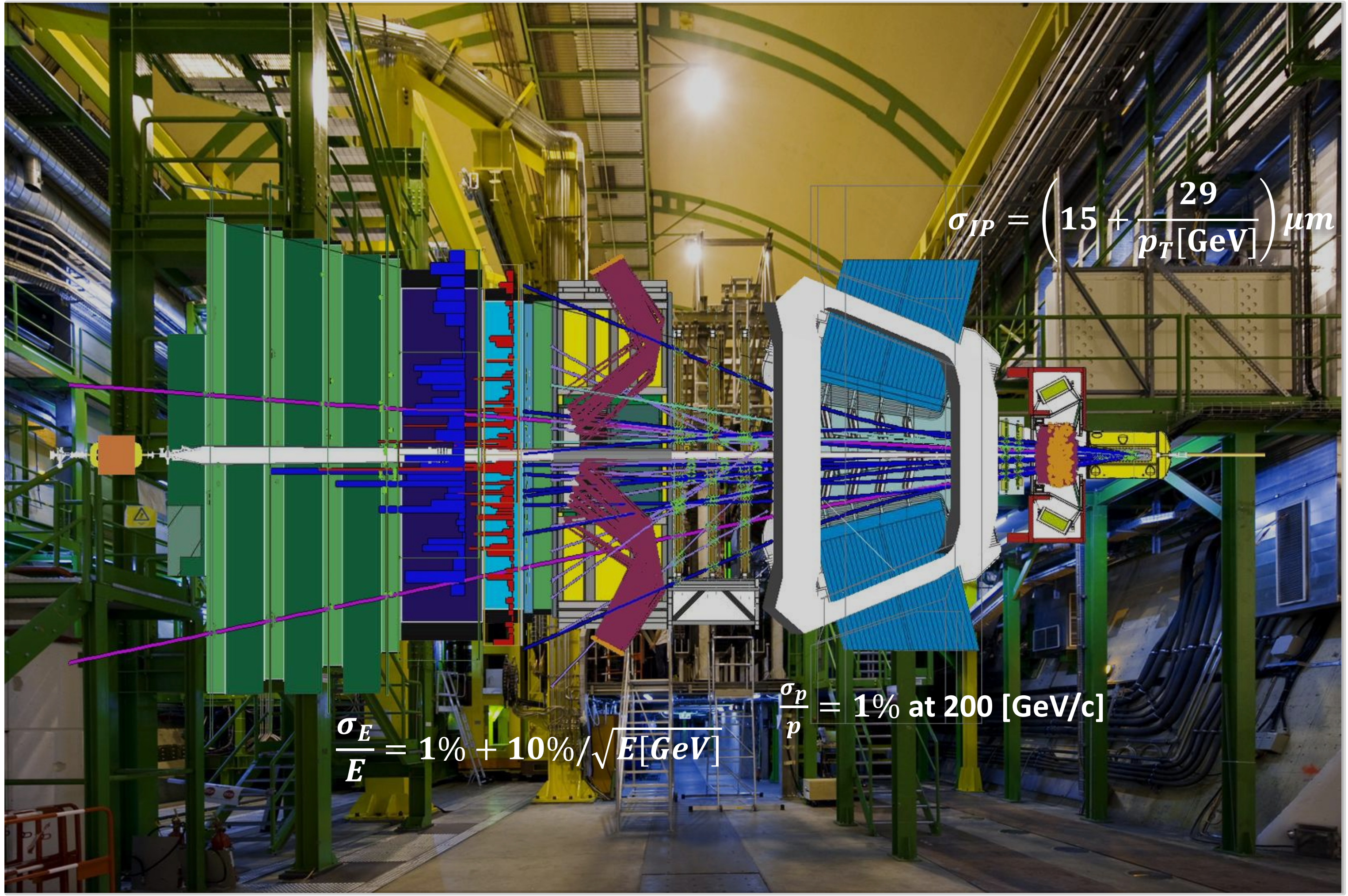
- **$B^+ \to K^+\pi^0$ is first analysis of a one-track B decay at a hadron collider**
  - Experimentally challenging – no secondary vertex
  - Secondary vertex a requirement for all Run I software triggers, dedicated trigger line developed for Run II
- Proof of concept for other modes of similar topology 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]:JHEP 03(2021)075 [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

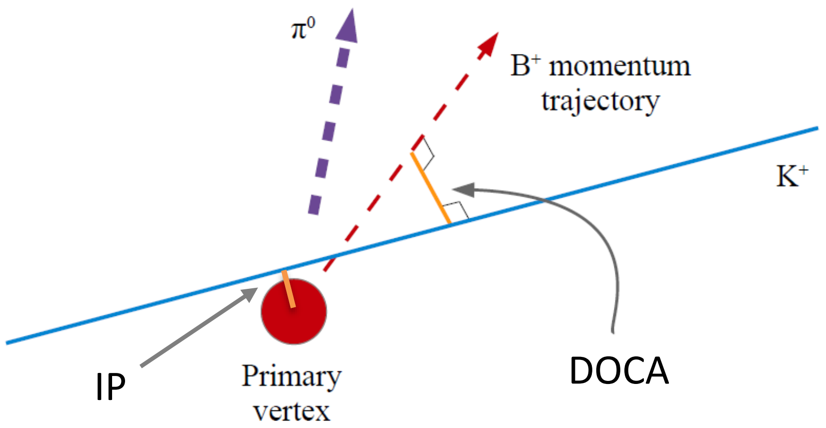


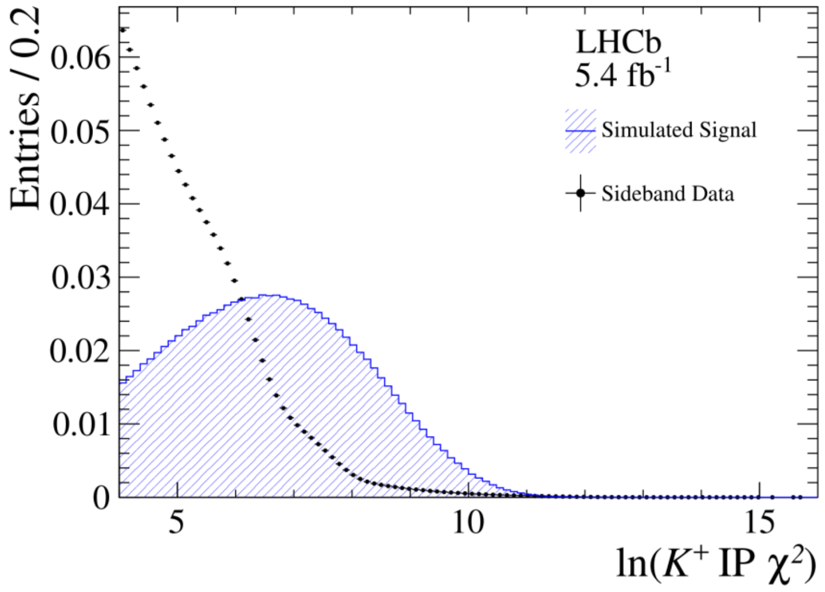


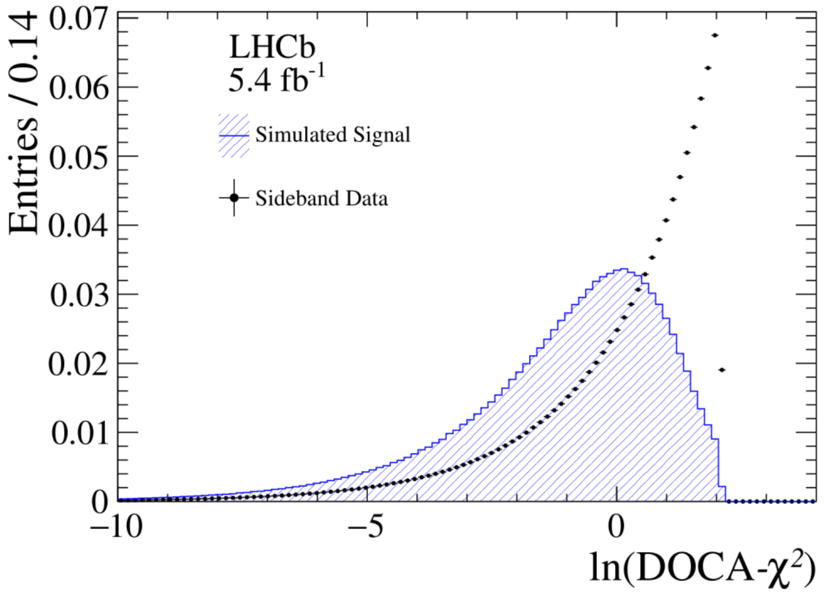
JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

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 and distance of closest approach







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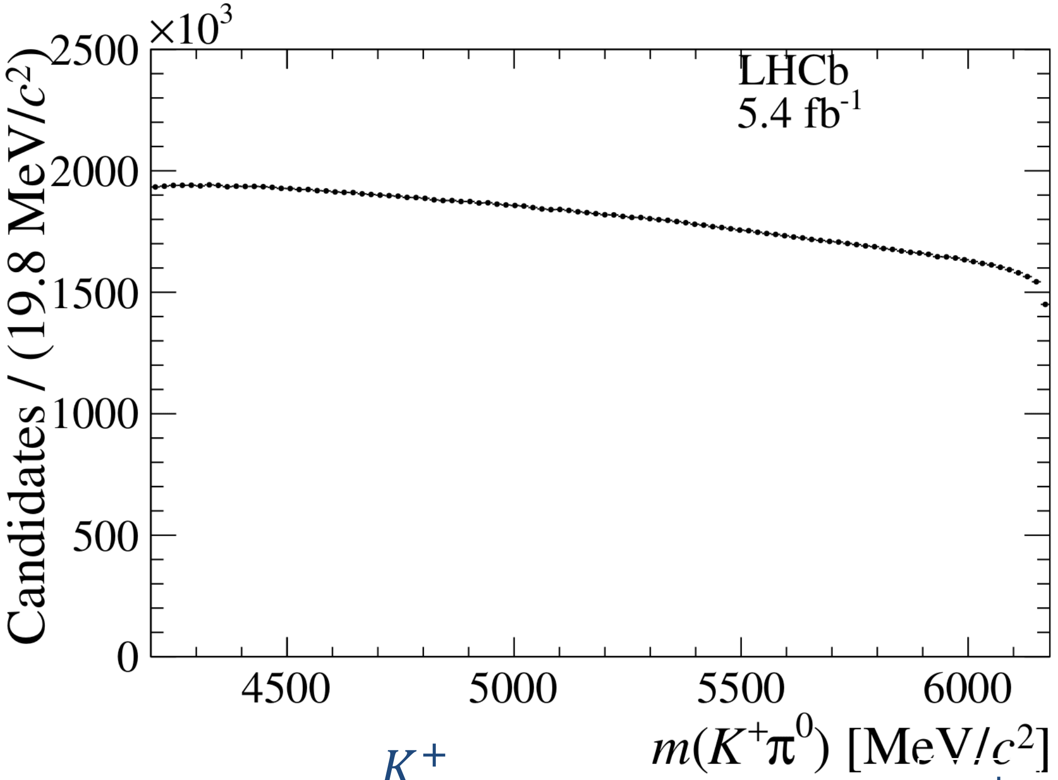
Offline Selection

- $S/B \sim 3.3 \times 10^{-4}$
- Train Boosted Decision Trees (BDTs) to reject background efficiently
- **Signal Sample:** Simulated events
- **Background Sample:** Train separately on upper and lower data sidebands



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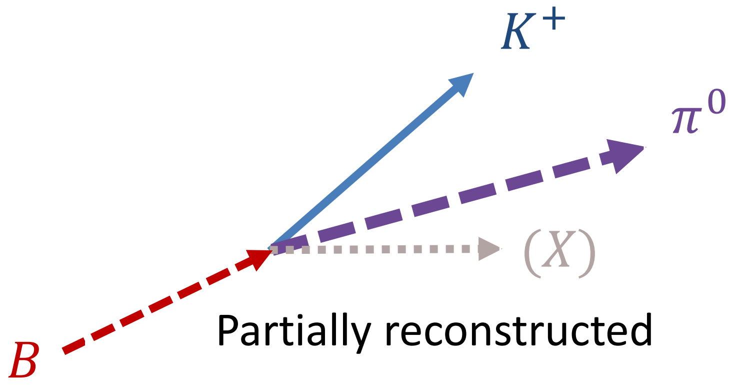
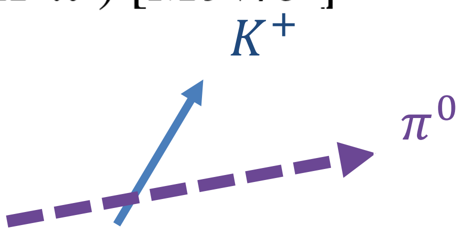
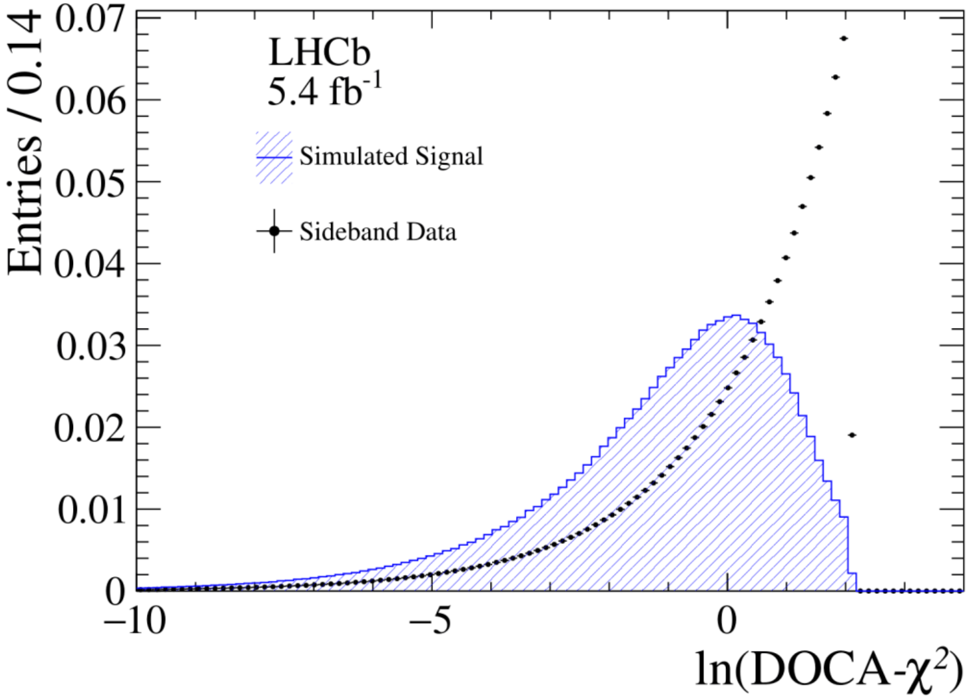


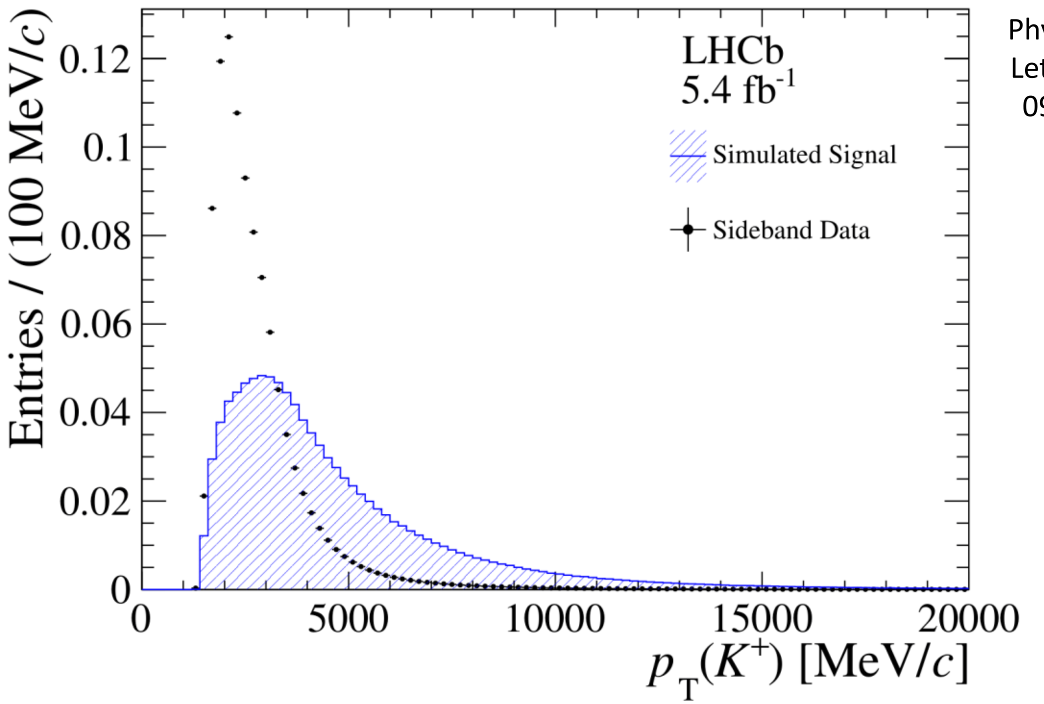
Partially reconstructed



Combinatorial

Signal Features





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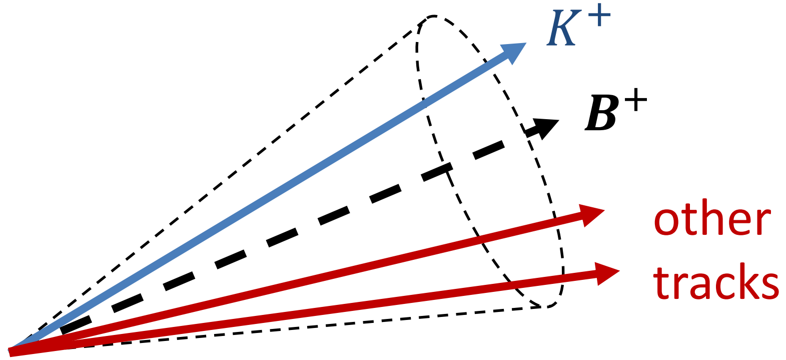
- Three categories of information
  - Track topology
  - Kinematics (restricted)
  - Track isolation (next slide)

Track Isolation

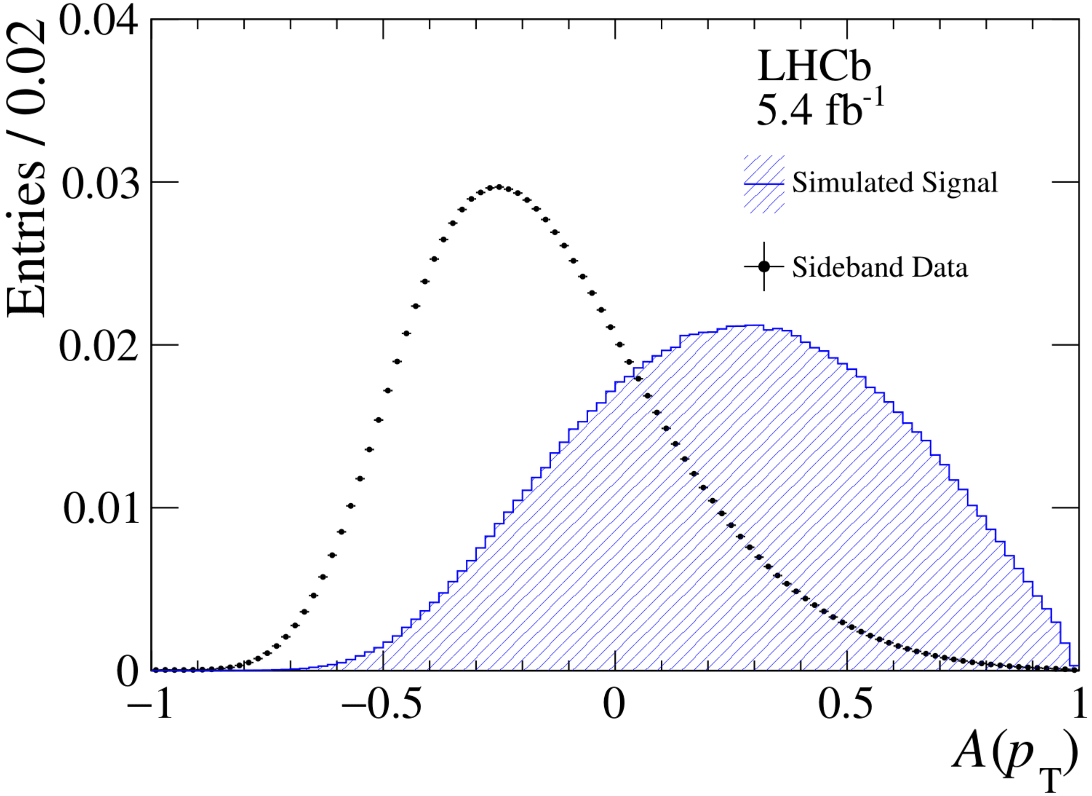
- Events with additional energetic tracks pointing back to B^+ likely to be partially reconstructed
- Consider cone of ΔR around B^+ trajectory



- Define cone p_T asymmetry

$$A(p_T) \equiv \frac{p_T(B) - p_T(\text{cone})}{p_T(B) + p_T(\text{cone})}$$

- Track multiplicity corrected by comparing $B^0 \to K^+\pi^-$ data and simulation



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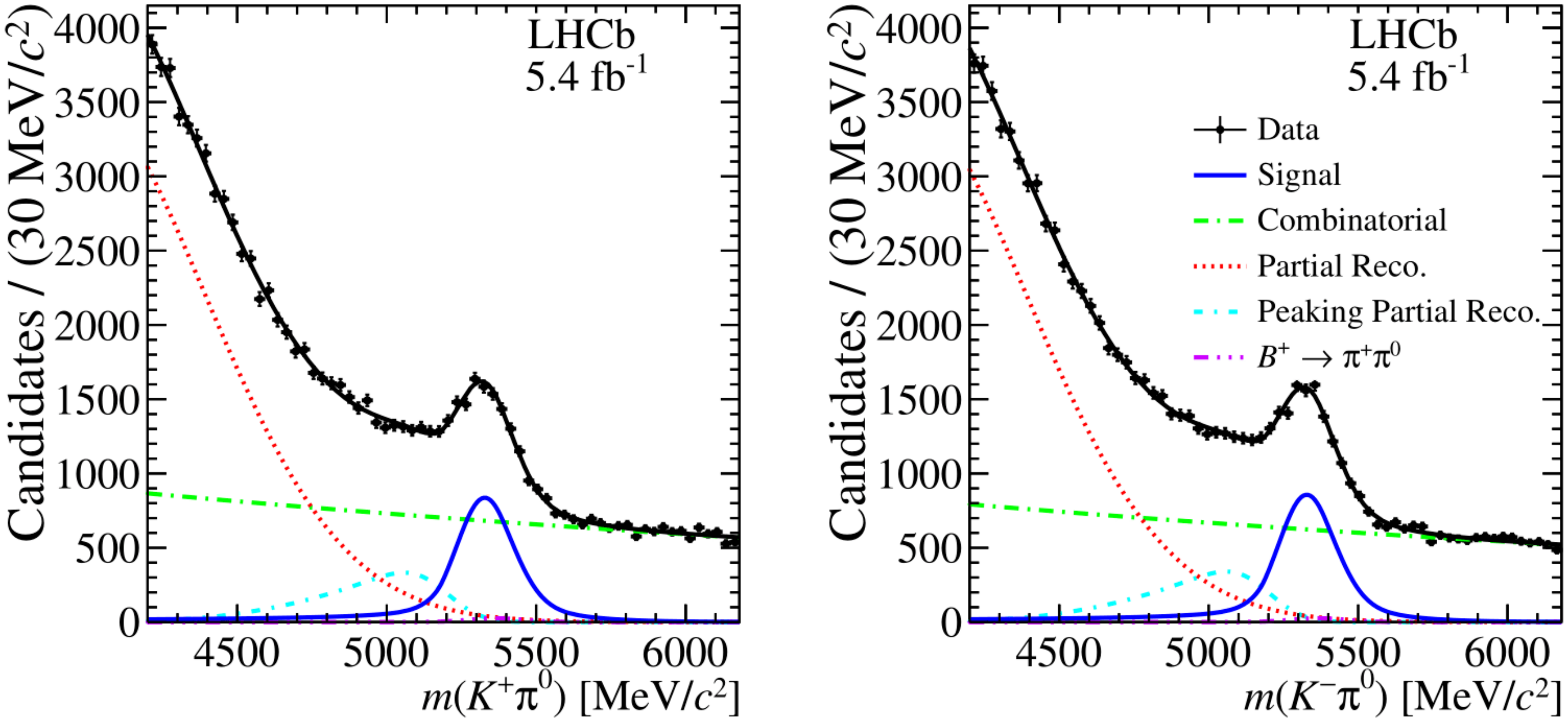
Raw Asymmetry Measurement

- Cut on BDT output to maximize sensitivity
- Fix some shape parameters to simulated/physical values
- Separate matter and anti-matter decays and fit yields to determine asymmetry
- Note: also split data by magnet polarity to correct for detector effects



$$A_{\mathbf{raw}} = \mathbf{0.005 \pm 0.022\ (MU),\ 0.019 \pm 0.021\ (MD)}$$

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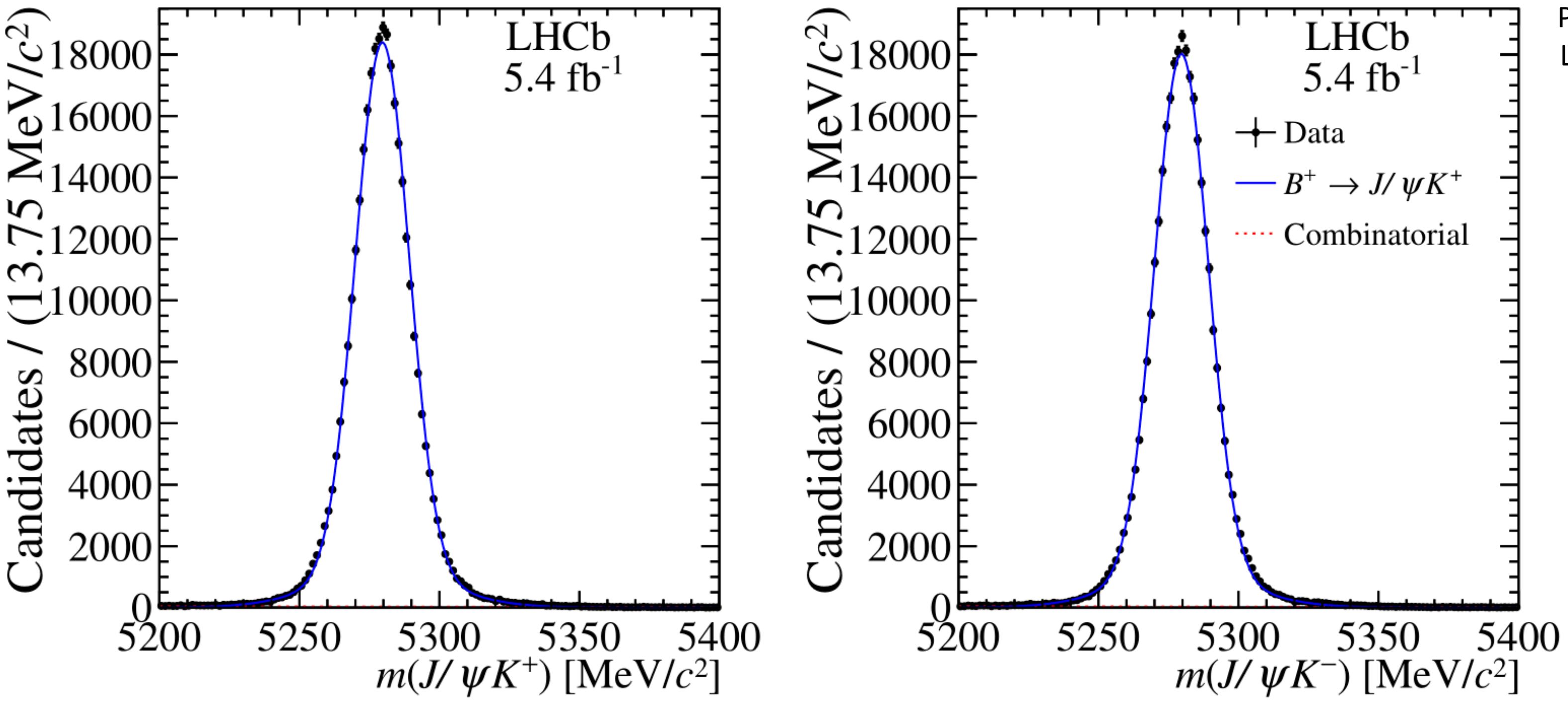
Production and Detection Asymmetry

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

- Raw asymmetry includes $B^\pm$ production and $K^\pm$ detection asymmetry
- Same order of magnitude as physical CP asymmetry
- Can measure the same combination of effects in decay $B^+ \to (J/\psi \to \mu^+\mu^-)K^+$
  - π^0 and J/ψ own antiparticles – no asymmetry
  - Match K^+ selection to signal – trigger, particle identification, kinematic cuts
  - Weight $p/p_T(B^+/K^+)$ distributions to signal kinematics

Prod./Det. Asymmetry Correction

- Charged tracks and reconstructible J/ψ mass make selection clean (99%)
- Follow same procedure as signal to extract raw asymmetry
- CP asymmetry in $B^+ \to J/\psi K^+$ known precisely (0.002 ± 0.003, PDG)
- Remainder attributed to same combination of B production and K detection as in $B^+ \to K^+\pi^0$ measurement



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$$A_{raw}(B^+ \to J/\psi K^+) = -0.009 \pm 0.002\ (\mathrm{MU}), -0.012 \pm 0.002\ (\mathrm{MD})$$

Systematic Uncertainties

- Assess systematics on fit variations
  - Signal and background shapes
  - Parameters fixed to simulation/physical values
- Small statistical uncertainty in determining production/detection asymmetry
- Effect of weighting used to estimate any residual kinematic differences in $B^+ \to K^+\pi^0$ and $B^+ \to J/\psi K^+$ asymmetries

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

Fit Component	Systematic	Value
Combinatorial bkg.	Shape	0.0013
Partial Reco. bkg.	Shape	0.0013
Peaking Partial Reco. 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
Statistical uncertainty		**0.015**

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Results

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

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

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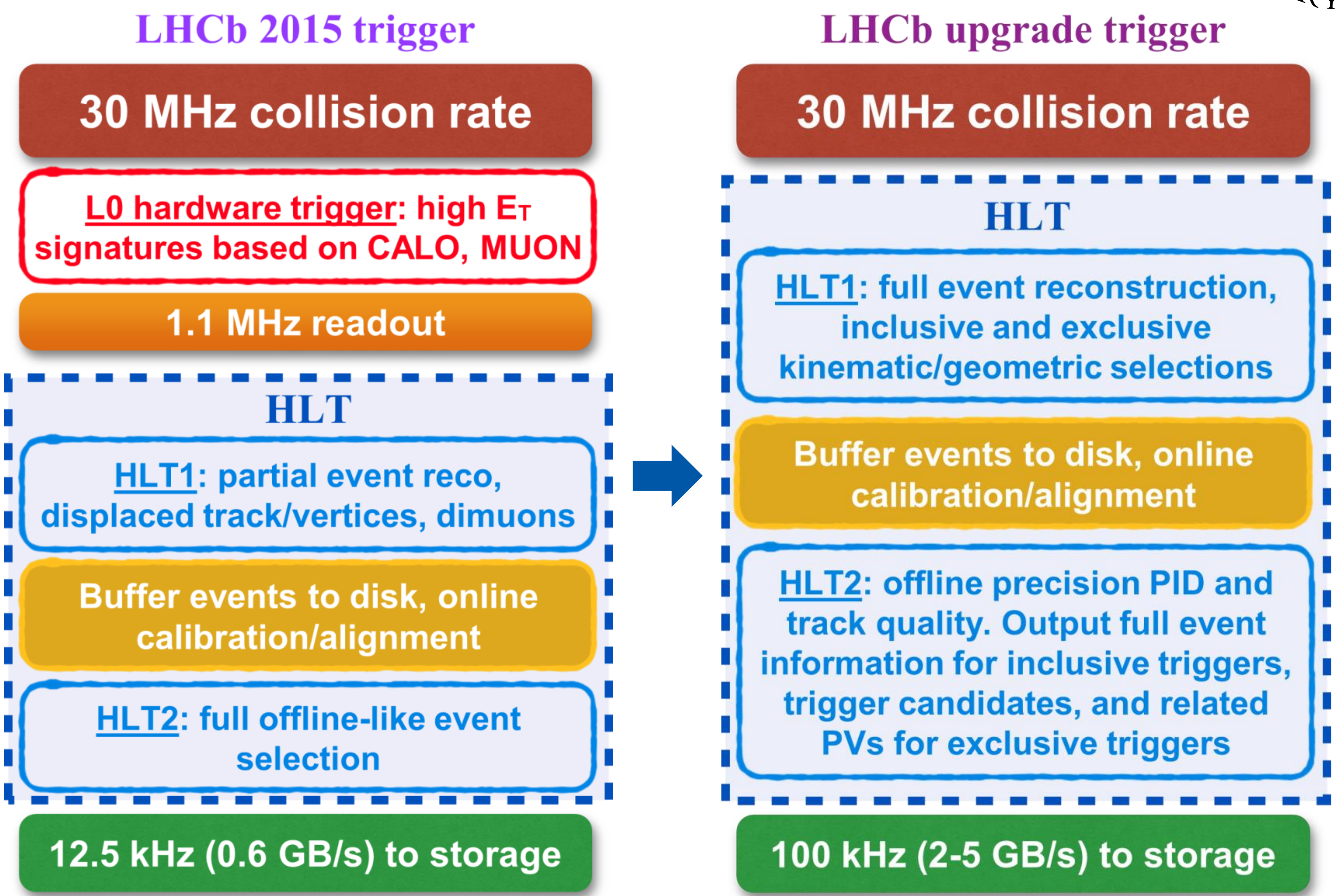
- $\mathbf{A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015(stat.) \pm 0.006(syst.) \pm 0.003(ext.}$
- $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$,
  non-zero at 8.2σ (previously 0.124 ± 0.021, 5.9σ)
- Updated sum rule prediction for $A_{CP}(K^0\pi^0)$: -0.138 ± 0.025,
  non-zero at 5.5σ (previously -0.150 ± 0.032, 4.7σ)

[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]:JHEP 03(2021)075 [8]:Phys.Rev.D 76, 091102(R)

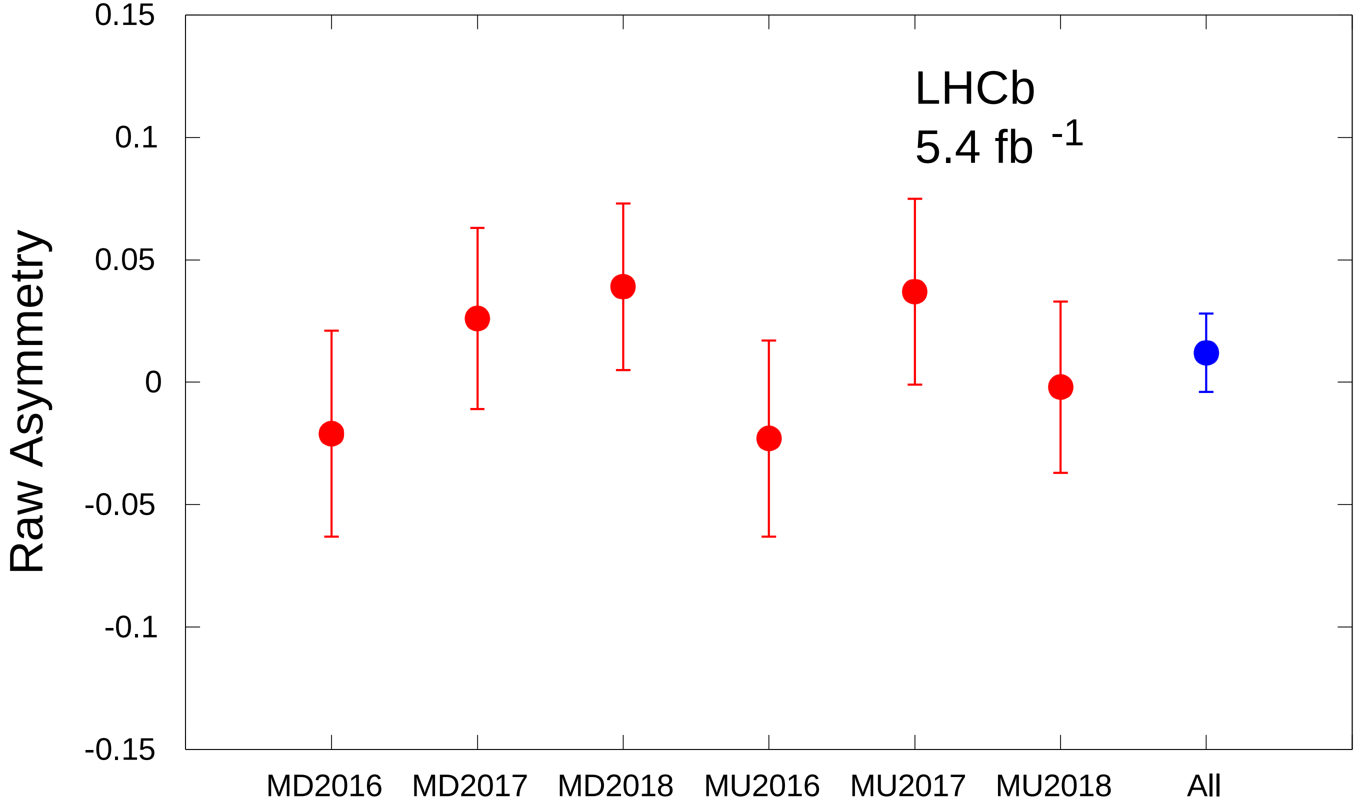
Prospects

- Upgrade underway to collect 50fb^{-1}
- Assume simple scaling with luminosity: $\pm\, 0.005(\text{stat.})$
- Dominant systematic uncertainties can be reduced with tighter event selection and additional control data
- Similar trigger in place for $B^0 \rightarrow K^0\pi^0$ events
- Stay tuned!



Thank You

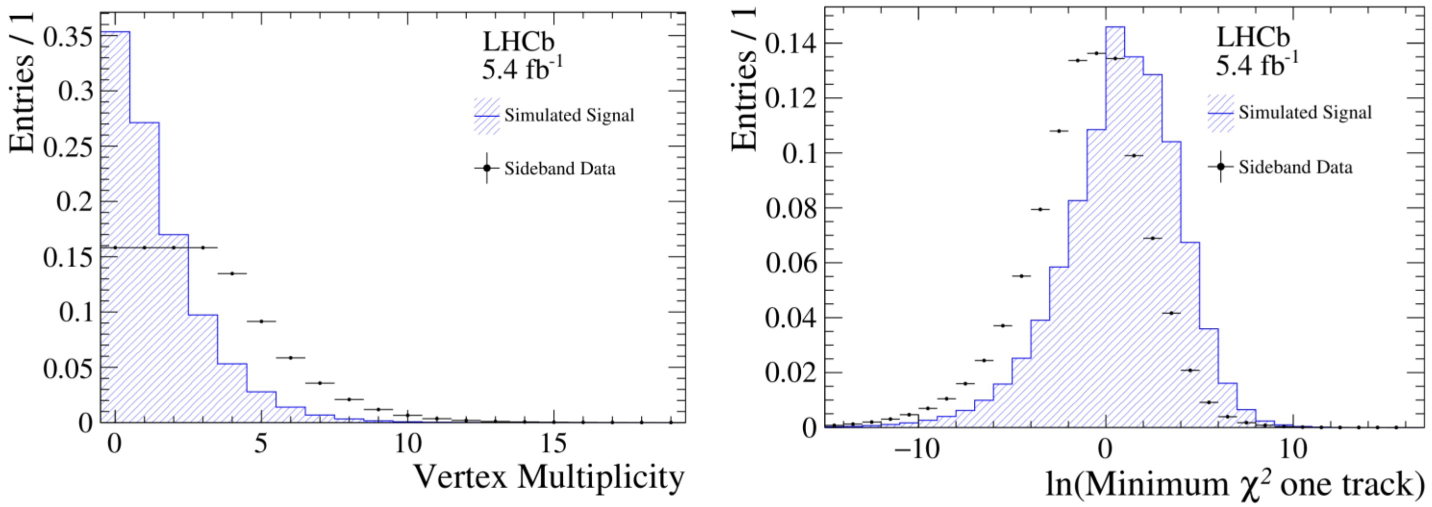
Consistency Checks



- 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

Vertex Isolation

- 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



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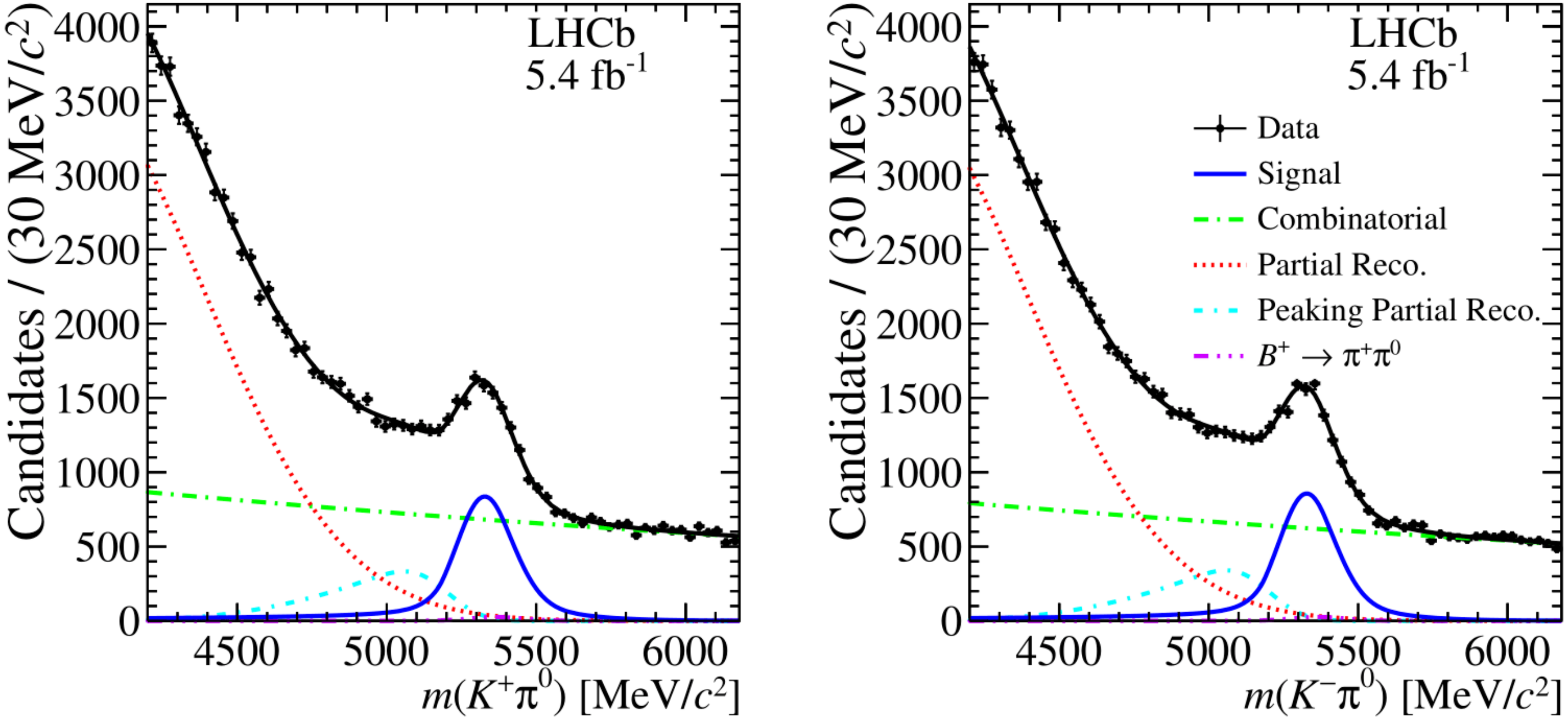
Final Event Selection

- Find 2D cut on BDT outputs that maximizes $\epsilon_{MC}/\sqrt{S+B}$
- S/B improved by factor of ~300
- Two more background categories:
- $B^+ \to \pi^+\pi^0$ where π^+ is misidentified as K^+
- Peaking partial reco. e.g. $B^{+/0} \to \left(K^{*+/0} \to \boldsymbol{K}^+\pi^{0/-}\right)\boldsymbol{\pi^0}$, $B \to \boldsymbol{K}^+(\rho^- \to \pi^-\boldsymbol{\pi^0})$
    - K^*/ρ polarization in B rest frame results in double-peaked mass structure



B rest frame

$B \to \mathrm{K}^*\boldsymbol{\pi^0}$ $\quad$ $\mathrm{K}^* \to \boldsymbol{K}\pi$

π^0 Reconstruction

- Neutral pions identified by decay to two photons
- Below $p_T = 3$ GeV photons can be resolved in two separate clusters, at higher energies clusters merge
- Cluster separated into two subclusters centered on highest energy deposits according to expected transverse profile
- Photon separation and invariant mass required to be consistent with π^0
- Merged π^0:
  + Higher p_T
  + Reduced combinatorial
  − Wider mass resolution
- For $B^+ \to K^+\pi^0$, keep only **merged π^0** to preserve trigger bandwidth

π^0 from $B^0 \to \pi^+\pi^-\pi^0$