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

Zishuo Yang

University of Maryland

on behalf of LHCb Collaboration

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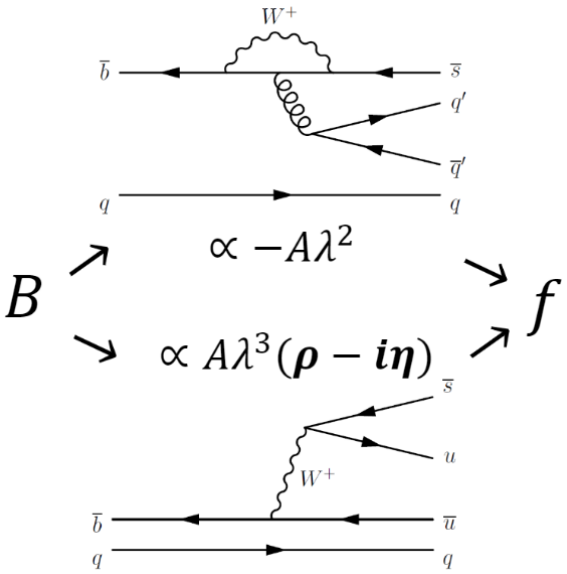
CP Violation in B System

- The breaking of charge-parity symmetry arises from the interference between two contributing amplitudes with *different strong and weak phases*

- Direct CP violation: interference in decay amplitudes

$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)} .$$



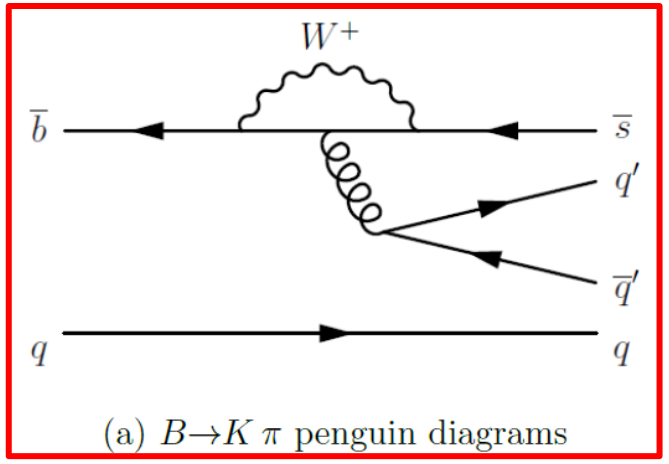
- CP violation in mixing: interference in mixing amplitudes

- Indirect CP violation: interference between mixing and decay amplitudes

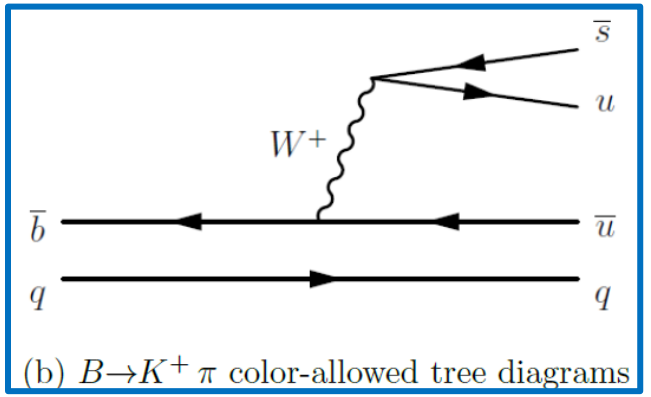
- Because CKM matrix is the only CPV source in SM, any deviation could indicate new physics

The $B \to K\,\pi$ System

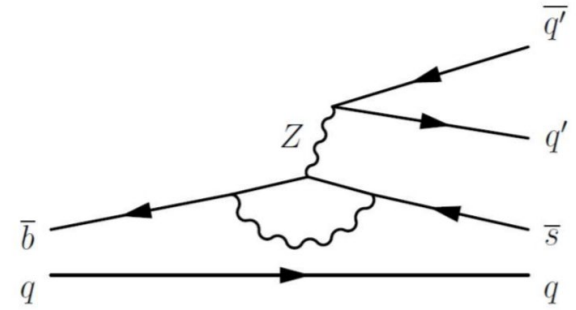
- There are four $B \to K\,\pi$ decays: $B^0 \to K^+\,\pi^-$, $B^+ \to K^+\,\pi^0$, $B^0 \to K^0\,\pi^0$, $B^+ \to K^0\,\pi^+$
- Particularly interesting because:
  - Tree amplitudes are suppressed by the CKM matrix element $V_{ub} = A\lambda^3(\rho - i\eta)$.
  - Leading contribution is from QCD penguin amplitudes



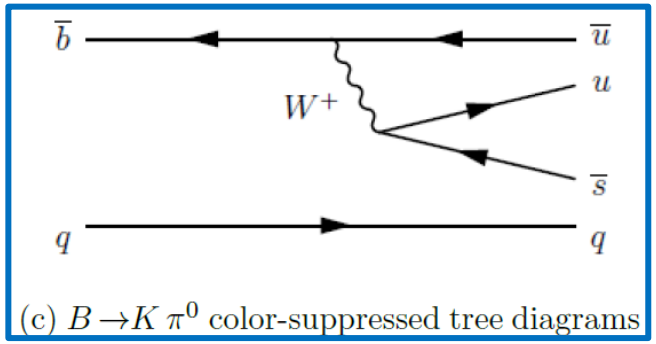
(a) $B \to K\,\pi$ penguin diagrams



(b) $B \to K^+\,\pi$ color-allowed tree diagrams



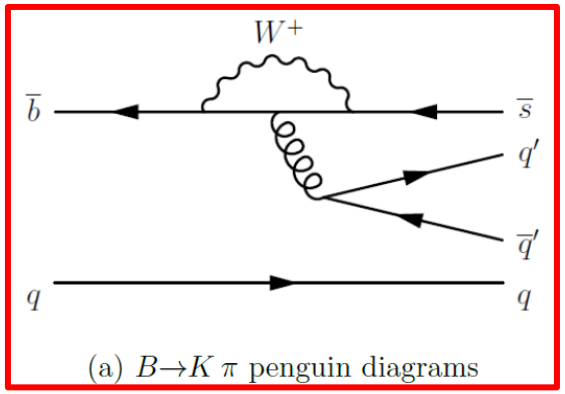
(d) $B \to K\pi^0$ electroweak penguin diagrams



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

The $B \to K\,\pi$ System

- $B^0 \to K^0\pi^0$ and $B^+ \to K^0\pi^+$
  - dominated by QCD penguin amplitude
- $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$
  - leading contribution is QCD penguin, non-negligible tree amplitudes



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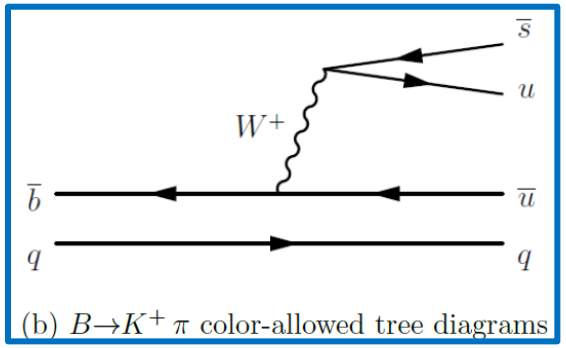

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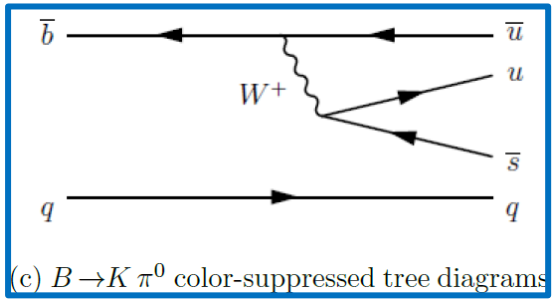

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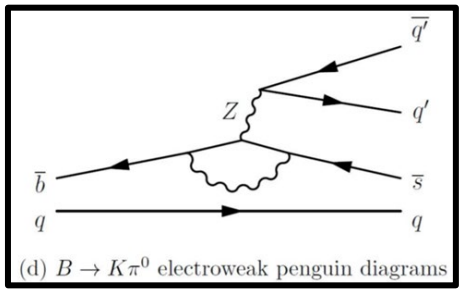

(d) $B \to K\pi^0$ electroweak penguin diagrams

- interesting to see if the pattern of decays follow SM predictions -- extensive studies done at B factories and now LHCb

Origin of the $B \to K\pi$ Puzzle

- The current status of A_{CP} measurements:

decay	*BaBar*	*Belle*	*LHCb*
$B^0 \to K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
$B^+ \to K^+\pi^0$	$+0.030 \pm 0.039 \pm 0.010$	$+0.043 \pm 0.024 \pm 0.002$	n/a
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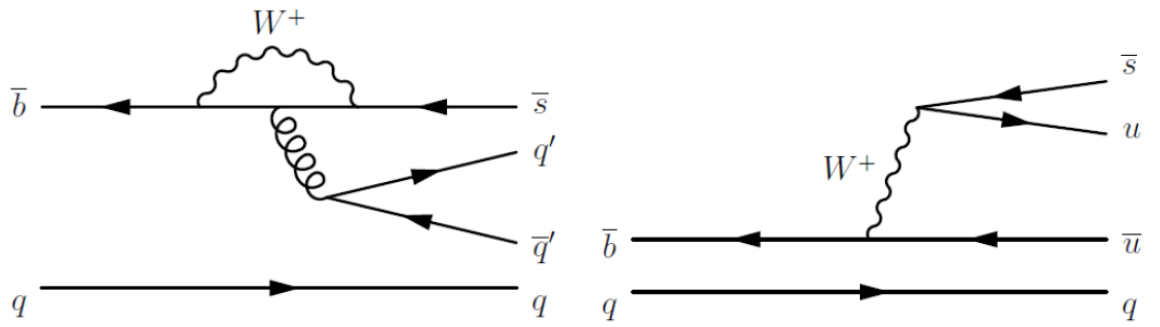
$B^+ \to K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$	$+0.043 \pm 0.024 \pm 0.002$	$-0.022 \pm 0.025 \pm 0.010$

- $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$
  - Both penguin and tree diagrams differ only in the spectator quark (u or d)

➡ $A_{CP}^{K^+\pi^-} \sim A_{CP}^{K^+\pi^0}$



(a) $B \to K\pi$ penguin diagrams (b) $B \to K^+\pi$ color-allowed tree diagrams

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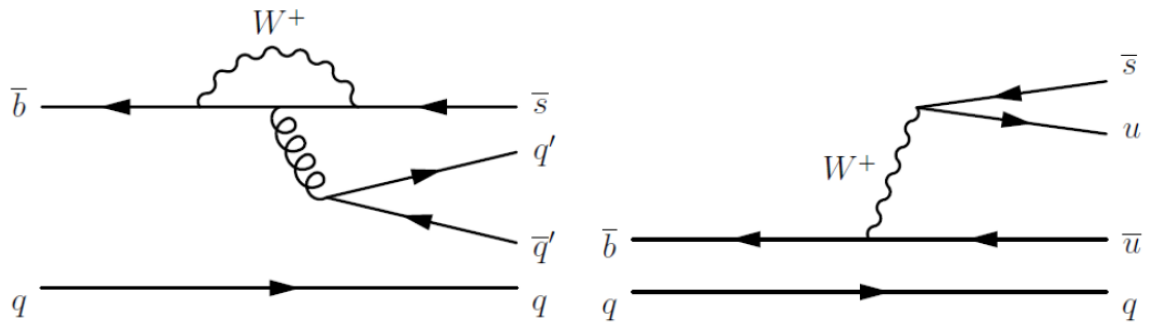
➡ $A_{CP}^{K^+\pi^-} \sim A_{CP}^{K^+\pi^0}$

Not as expected
(disagreement above 5σ)



(a) $B \to K\pi$ penguin diagrams (b) $B \to K^+\pi$ color-allowed tree diagrams

Broader Picture of the $B \to K\pi$ Puzzle

- Guided by isospin symmetry, a sum rule was derived:

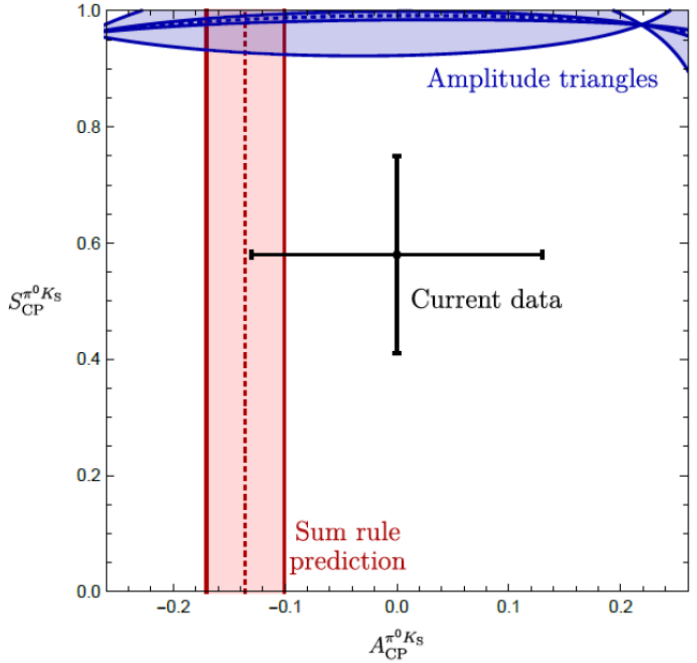
$$\left[A_{CP}^{K^0\pi^+}\frac{\mathcal{B}^{K^0\pi^+}}{\mathcal{B}^{K^+\pi^-}} - A_{CP}^{K^+\pi^0}\frac{2\mathcal{B}^{K^+\pi^0}}{\mathcal{B}^{K^+\pi^-}}\right]\frac{\tau_{B^0}}{\tau_{B^\pm}} + \left[A_{CP}^{K^+\pi^-} - A_{CP}^{K^0\pi^0}\frac{2\mathcal{B}^{K^0\pi^0}}{\mathcal{B}^{K^+\pi^-}}\right] = 0$$

arXiv:0508.047
arXiv:0608.040
arXiv:1712.02323

- $B^0 \to K^0\pi^0$ is least precisely measured among all decay modes:
  - Sum rule predicts $A_{CP}\left(K_S^0\pi^0\right) = -0.150 \pm 0.032$
  - Measured $A_{CP}\left(K_S^0\pi^0\right) = 0.01 \pm 0.10$

- Global study of $B \to K\pi$ system indicates need for significant enhancement of color-suppressed tree or EW penguin arXiv:1812.02672

- $B \to K\pi$ system need to be measured more precisely (room to probe for new physics)



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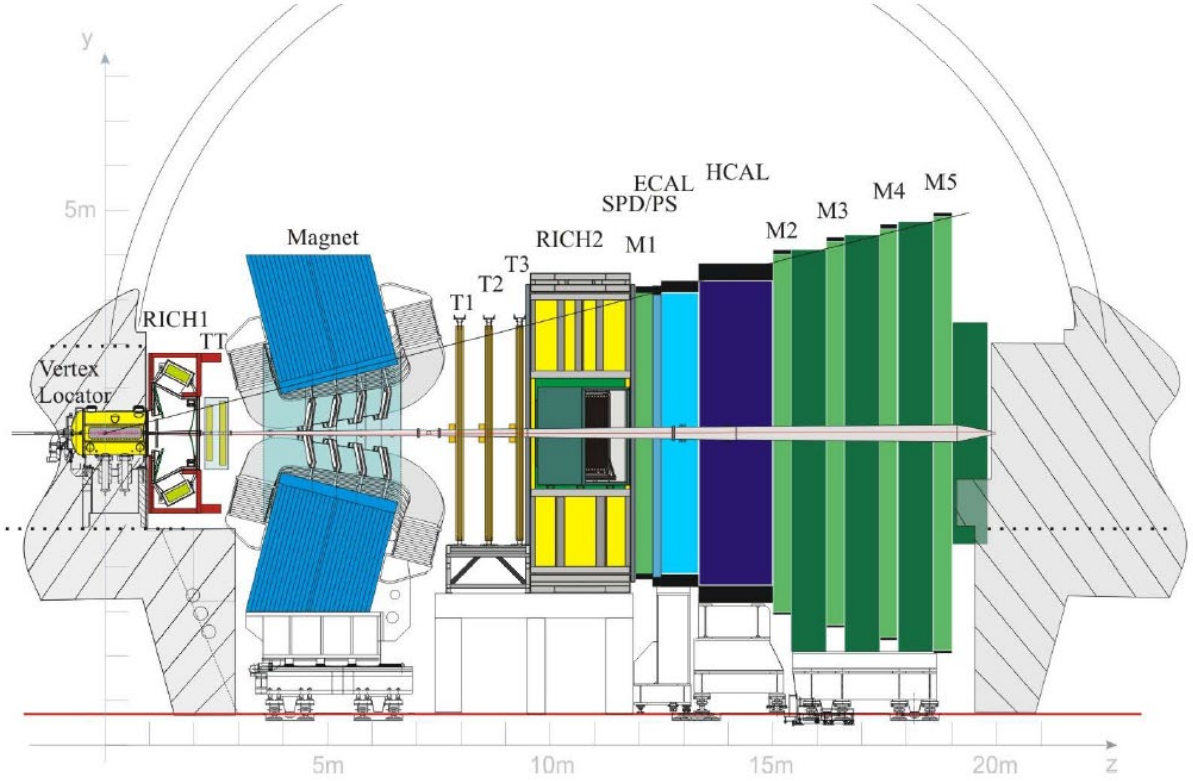
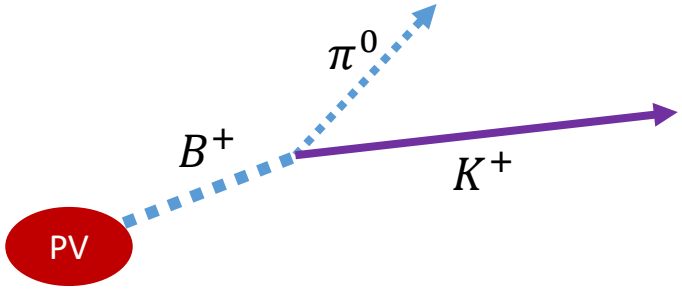
$B^+ \to K^+\pi^0$ at LHCb

- LHCb is designed to study CP violation and search for new physics in the heavy flavor sector
- Challenging mode with no secondary vertex (1 track + 1 calorimeter cluster)
  - Run1 software triggers relied on secondary vertex
  - Dedicated trigger developed for Run2





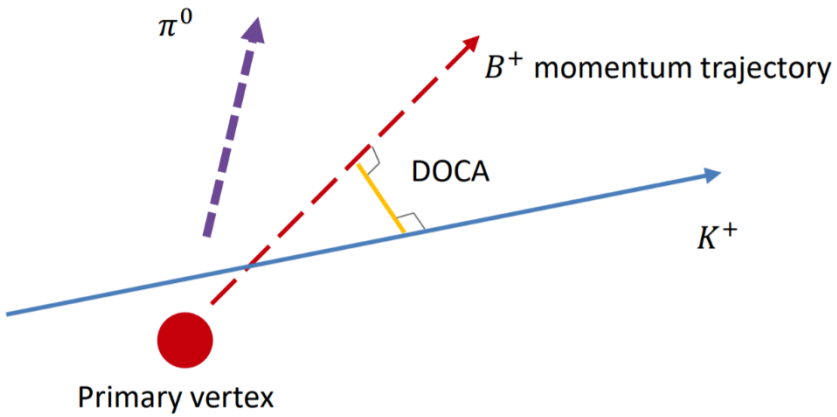
Key Variables

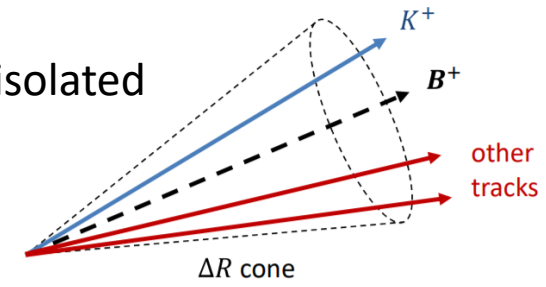
- No secondary vertex, but still take advantage of LHCb's precision tracking
  - initial $S/B \sim 10^{-7}$

- K^+ should be originating from the trajectory of B
  - Cut on distance of closest approach

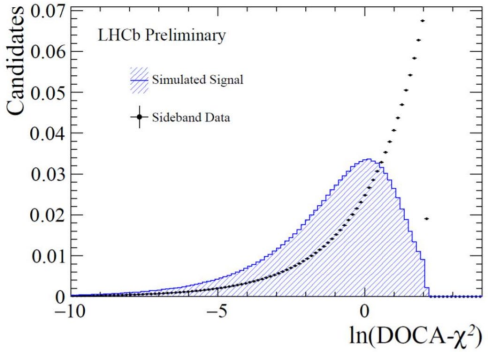
- K^+ should be inconsistent with originating from any primary vertex
  - Cut on impact parameter w.r.t. PV, when K^+ is included in primary vertex fit

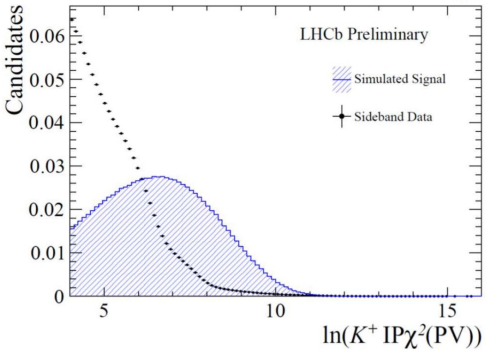
- B candidate should be more isolated from other high-pT tracks:

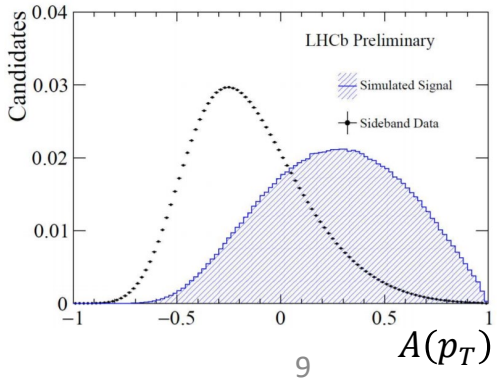




$$A(p_T) \equiv \frac{p_T(B) - p_T(cone)}{p_T(B) + p_T(cone)}$$



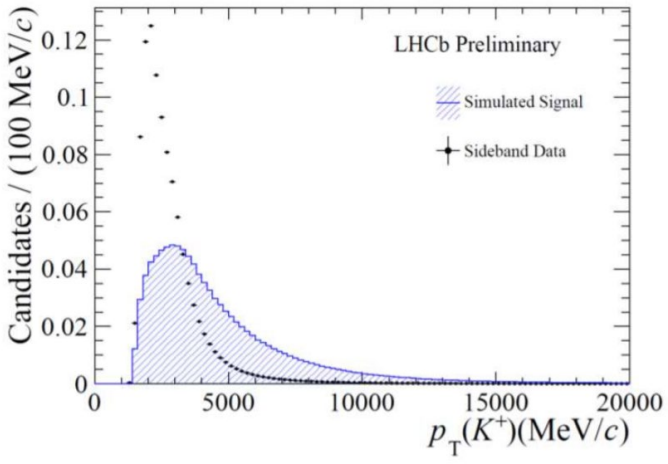


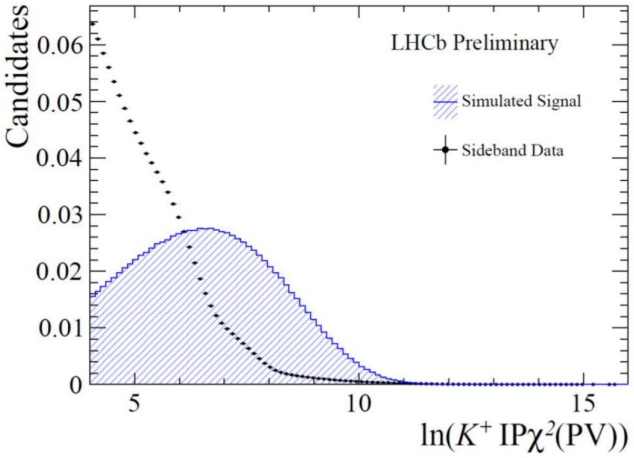


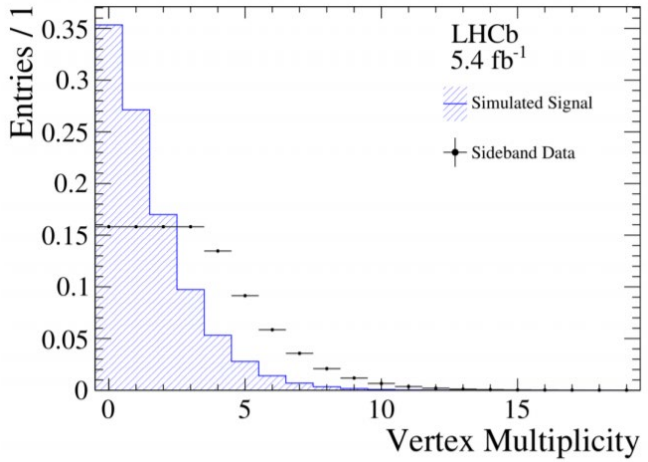
Multivariate Analysis

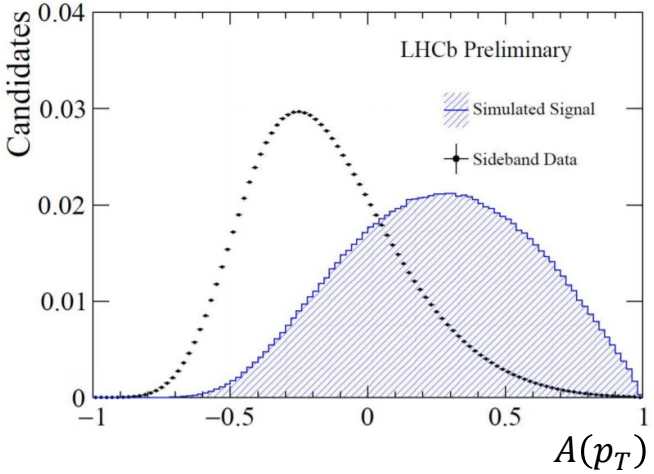
- Using discriminant variables including
  - impact parameters
  - kinematics
  - isolation variables

- Train Boosted Decision Trees to optimize $\frac{\in_{MC}}{\sqrt{S+B}}$







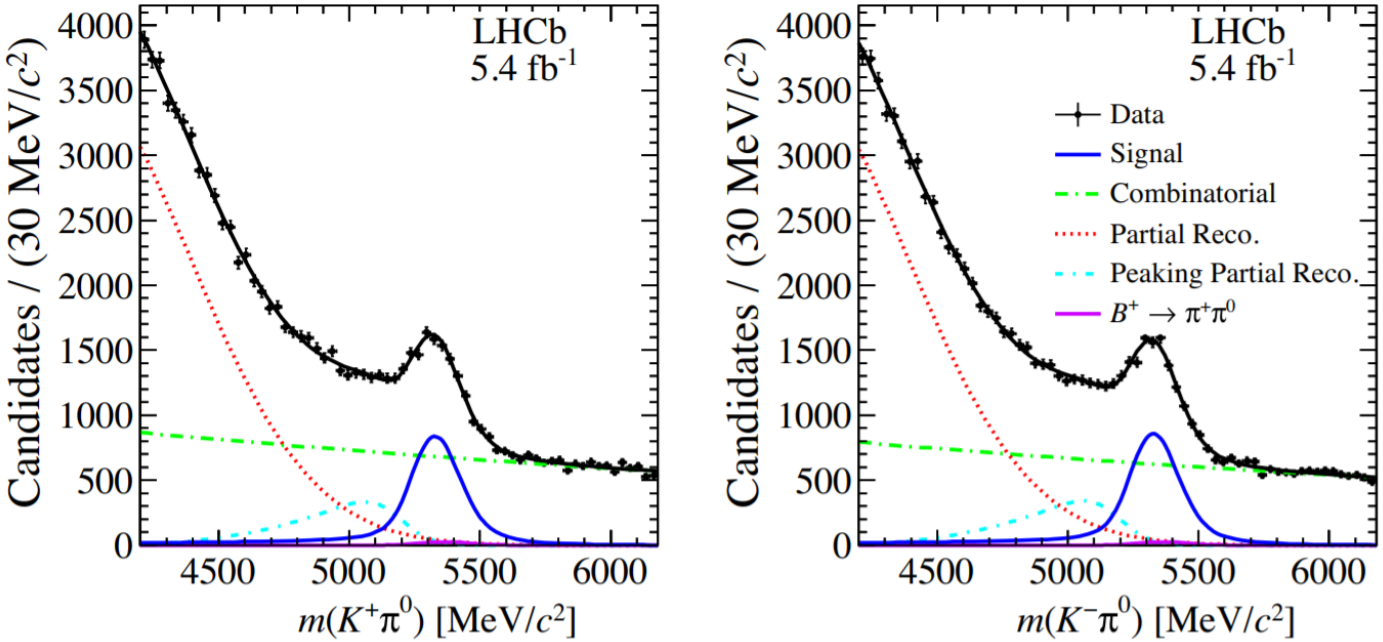


Invariant Mass Fit

- Two more background categories:
  - $B^+ \to \pi^+\pi^0$ where $\pi^+$is misidentified as K
  - Peaking partial reconstructed, e.g.
    - $B^{+/0} \to (K^{*+/0} \to K^+ \pi^{0/-})\pi^0$

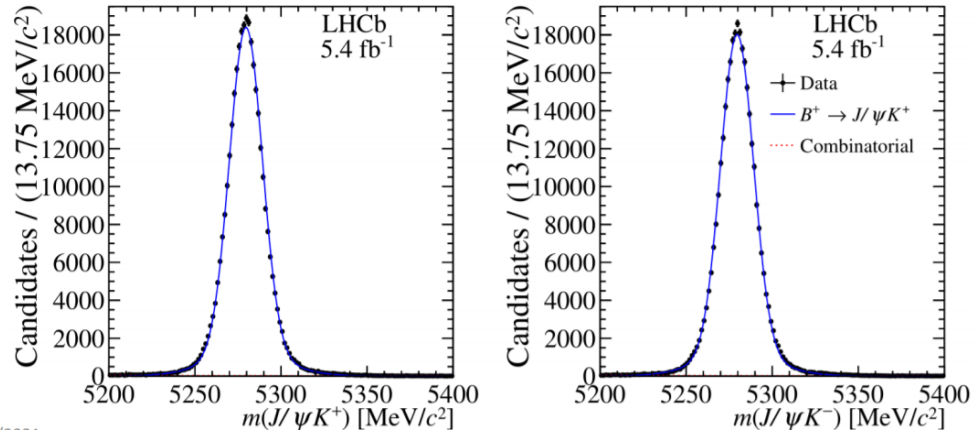
- Total N$(B^\pm \to K^\pm\pi^0) \approx 16500$

- Raw $A_{cp}(B^+ \to K^+\pi^0) = 0.005 \pm 0.022$ (Magnet Up),
  0.019 ± 0.021 (Magnet Down)



- Apply corrections due to B production asymmetry and K detection asymmetry
  - directly measured using $B^\pm \to J/\psi\, K^\pm$ data

- Raw $A_{cp}(B^+ \to J/\psi\, K^+) = -0.009 \pm 0.002$ (Magnet Up),
  -0.012 ± 0.002 (Magnet Down)



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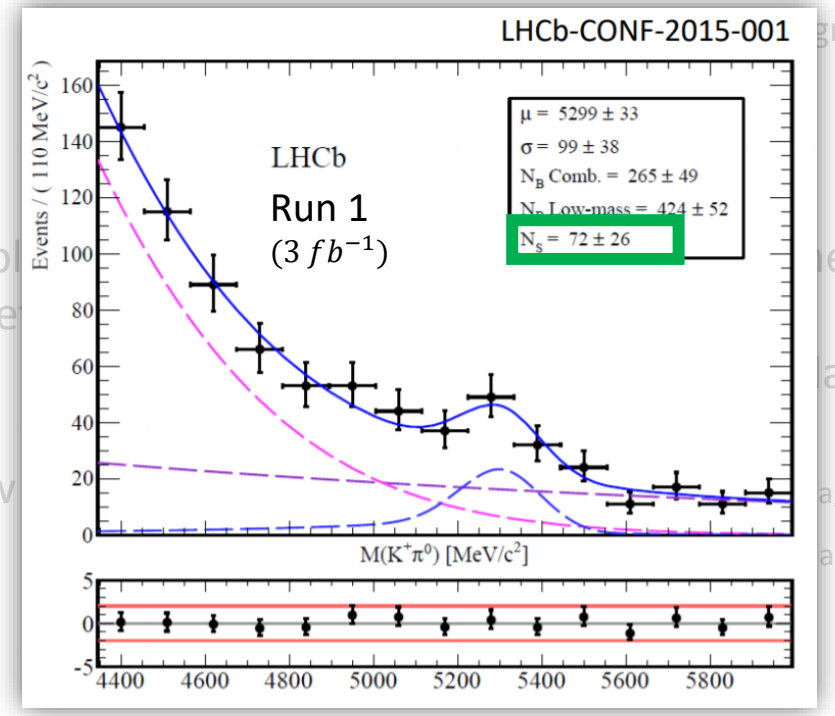

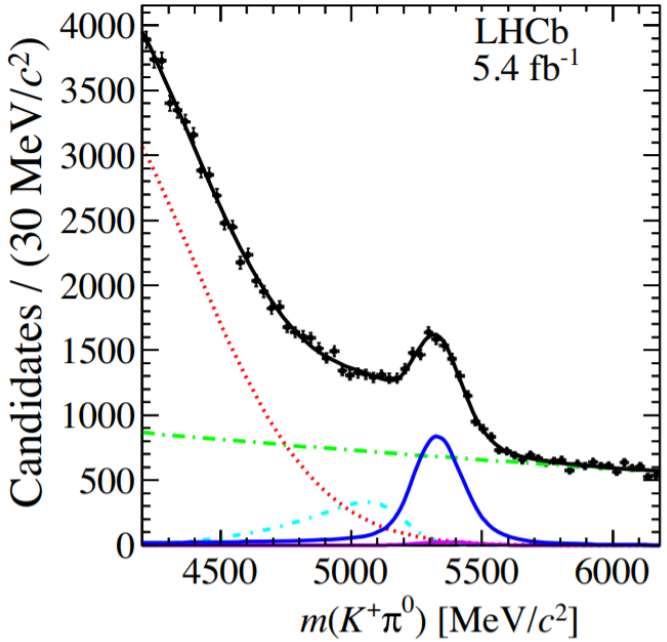

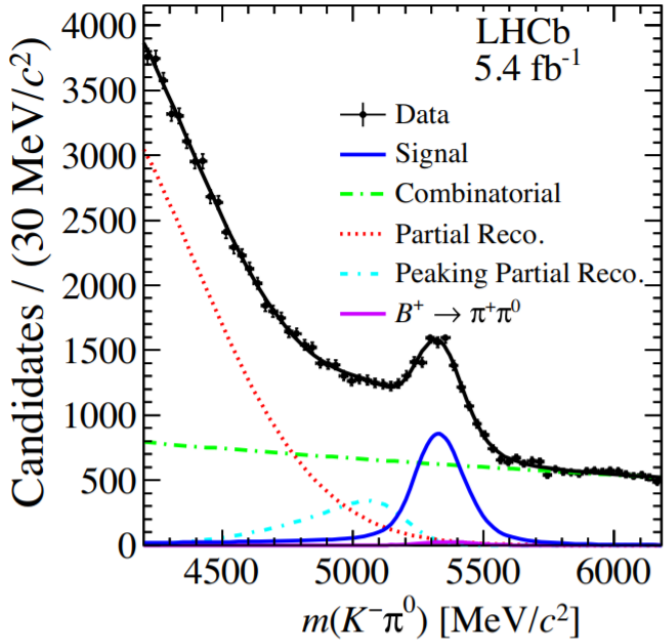

Results

- After corrections, the measurement result is

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

decay	*BaBar*	*Belle*	*LHCb*
$B^0 \to K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
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- Consistent with current world average, *the most precise to date*

- $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$, non-zero at 8.2$\sigma$
  - previously 0.124 ± 0.021, 5.9σ

- Updated sum rule prediction for $A_{CP}(K^0\pi^0) = -0.138 \pm 0.025$, non-zero at 5.5σ

Conclusion

- We have measured the direct CP violation in $B^+ \to K^+\pi^0$,

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

- Most precise measurement to date

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- Confirms and strengthens the *B*→*K* π puzzle
- PRL paper recently published: Phys. Rev. Lett. 126, 091802
- After Run3, LHCb would finish collecting $50\ fb^{-1}$: projected statistical uncertainty $\sim \pm 0.005$
- Highlights LHCb's potential in modes with neutral particles ($B^0 \to K^0\pi^0$ and beyond)

Backup slides

The CKM Mechanism

- In the Standard Model (SM), the Cabibbo-Kobayashi-Maskawa (CKM) mechanism describes the weak interactions between the three generations of quarks:
  - one universal weak coupling strength for quarks and leptons, but
  - the quarks' weak eigenstates differ from their mass eigenstates,
  - related by the 3x3 unitary CKM matrix V_{CKM},

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The CKM Mechanism

- In the Wolfenstein parametrization, the CKM matrix is written in terms of four real parameters, λ, A, ρ, and η:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

  - $\lambda = \sin\theta_C \approx 0.225$, where θ_C is the Cabibbo angle
  - η is associated with the *single irreducible phase* in the CKM matrix ➡ The *only* known source of CP violation in the SM

CP Violation

- Three possible CP-violating effects:
  - CP violation in decay (direct CPV)
  - CP violation in mixing
  - CP violation in the interference between mixing and decay

- can be measured in the decay rate difference between a process and its charge conjugate

$$\text{e.g.} \left|A(\bar{B}^0 \to \bar{f})\right| \neq |A(B^0 \to f)|.$$

$$M = |M_1| e^{i\theta_1} e^{i\phi_1} + |M_2| e^{i\theta_2} e^{i\phi_2}$$
$$\bar{M} = |M_1| e^{i\theta_1} e^{-i\phi_1} + |M_2| e^{i\theta_2} e^{-i\phi_2}$$
$$|M|^2 - |\bar{M}|^2 = -4|M_1||M_2| \sin(\theta_1 - \theta_2) \sin(\phi_1 - \phi_2)$$

CP Violation

- Three possible CP-violating effect:
  - CP violation in decay
  - CP violation in mixing
  - CP violation in the interference between mixing and decay

- seen in the transition rate difference between a neutral meson ***to*** and ***from*** its antiparticle,

$$\text{e.g. } \left|A(B^0 \to \bar{B}^0)\right| \neq \left|A(\bar{B}^0 \to B^0)\right|.$$

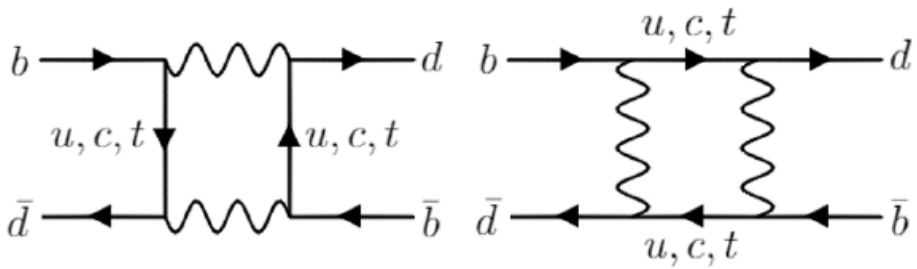


Figure 1: One-loop box diagrams for B^0-$\bar{B}^0$ mixing

CP Violation

- Three possible CP-violating effect:
  - CP violation in decay
  - CP violation in mixing
  - CP violation in the interference between mixing and decay

- arises from the interference between decays ***with*** and ***without*** *mixing.*

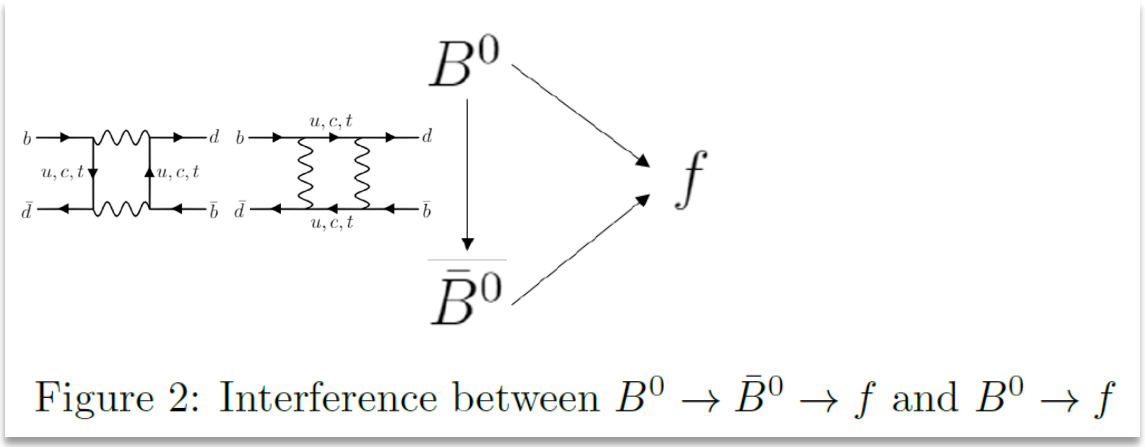


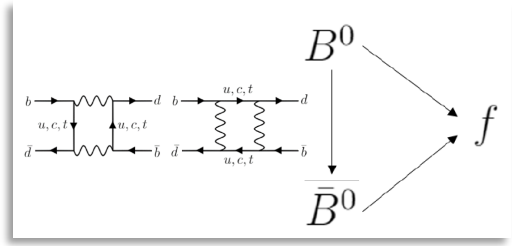
Figure 2: Interference between $B^0 \to \bar{B}^0 \to f$ and $B^0 \to f$

The Broader Picture of the $B \to K\pi$ Puzzle

- Uniquely, $B^0 \to K^0\pi^0$ allows CP violation in the interference between mixing and decay.
- The observable $S_{CP}^{K_S^0\pi^0}$ can be measured in the time-dependent decay rate asymmetry,

$$\frac{\Gamma(\bar{B}^0(t) \to K_S^0\pi^0) - \Gamma(B^0(t) \to K_S^0\pi^0)}{\Gamma(\bar{B}^0(t) \to K_S^0\pi^0) + \Gamma(B^0(t) \to K_S^0\pi^0)} = A_{CP}^{K_S^0\pi^0} \cos(\Delta m\, t) + S_{CP}^{K_S^0\pi^0} \sin(\Delta m\, t)$$

- Because a single penguin amplitude is expected to dominate,
  - $S_{CP}^{K_S^0\pi^0}$ should arise mostly from the phase 2β of B^0-$\bar{B}^0$ mixing ($\beta \equiv arg(V_{td}^*)$)
  - sin(2β) has been precisely measured
  - new physics at loop level will deviate $S_{CP}^{K_S^0\pi^0}$ from sin(2β)



- Precise measurement of $S_{CP}^{K_S^0\pi^0}$ can probe for new physics at loop level

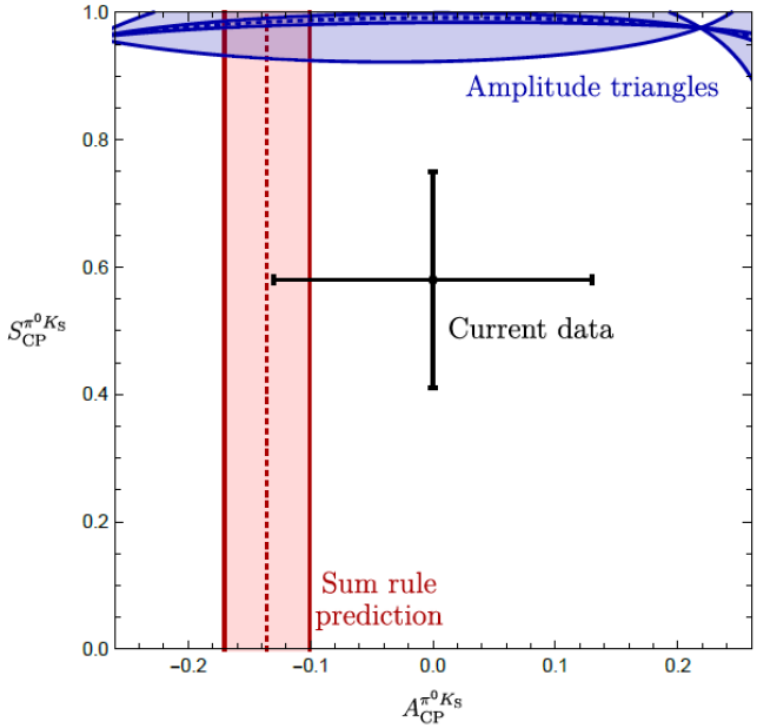
The Broader Picture of the $B \to K\pi$ Puzzle

- More importantly, the correlation between $S_{CP}^{K_S^0\pi^0}$ and $A_{CP}^{K_S^0\pi^0}$ can be derived as:

$$S_{CP}^{K^0\pi^0} = \sin(\phi_d - \phi_{00})\sqrt{1-(A_{CP}^{K^0\pi^0})^2}$$

- ϕ_{00} is the angle between amplitude $A(B^0 \to K^0\pi^0)$ its charge conjugate
- $\phi_d = (43.2 \pm 1.8)^\circ$ is the B^0-$\bar{B}^0$ mixing phase

- The correlation, the sum rule prediction, and the current experimental values are shown on the $S_{CP}^{K_S^0\pi^0}$ - $A_{CP}^{K_S^0\pi^0}$ plane:



(2.5σ discrepancy)

R. Fleischer, R. Jaarsma, E. Malami, K. K. Vos, Probing New Physics in $B \to \pi K$ Decays, PoS LHCP2018 (2018) 176.

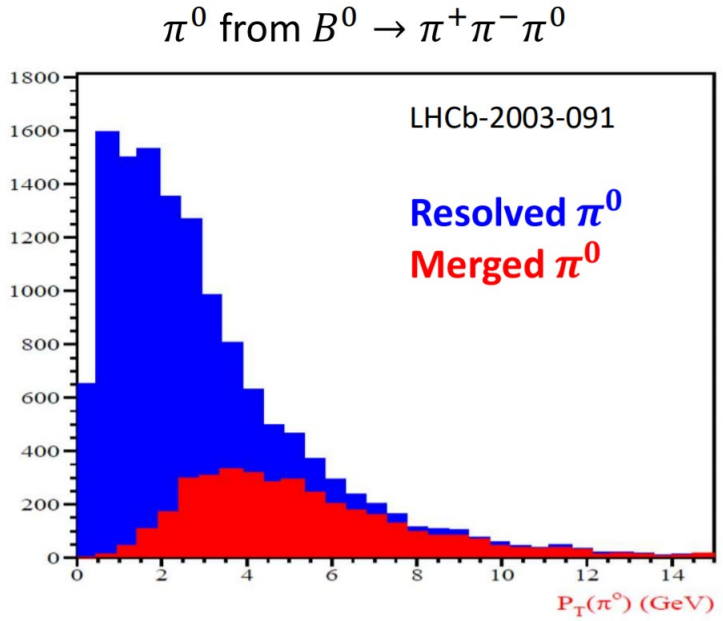
π^0 reconstruction

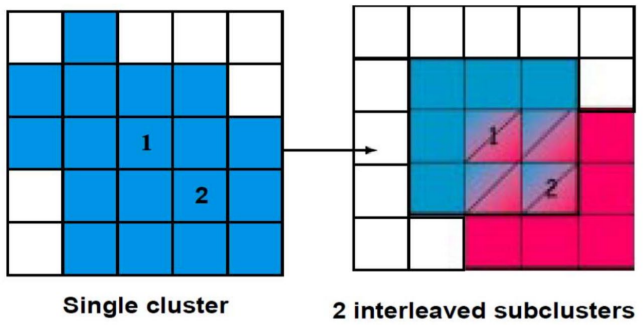
- π^0 identified by decay to two photons

- At higher pT, two photon showers merge into a single cluster

- Reconstructed as two subclusters centered on highest energy deposits according to expected transverse profile

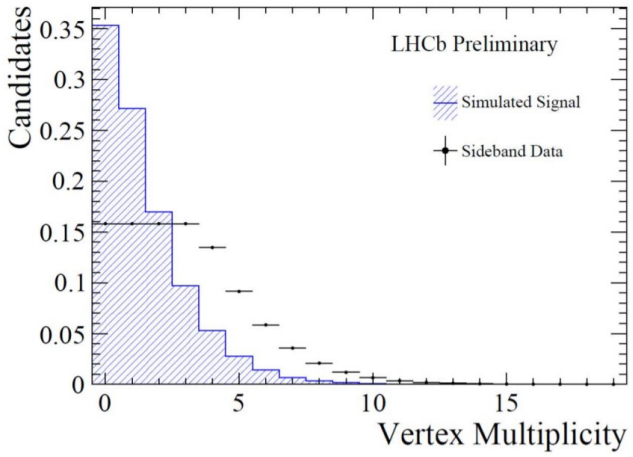
- Despite wider mass resolution, use only merged pi0 to reduce combinatorial background and preserve bandwidth

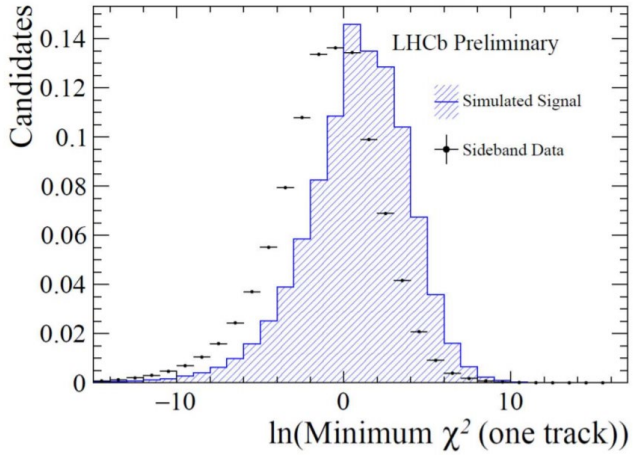




Isolation Variables

- Events with other tracks pointing back to B candidate are unlikely to be signal
- Combine each track in the event individually with K to form vertices





- Consider tracks within cone $\Delta R = 1.7$ around B momentum
- Define cone pT asymmetry $A(p_T) \equiv \frac{p_T(B) - p_T(cone)}{p_T(B) + p_T(cone)}$