Direct CP Violation in $B^+ \to K^+\pi^0$ and the Upstream Tracker at LHCb

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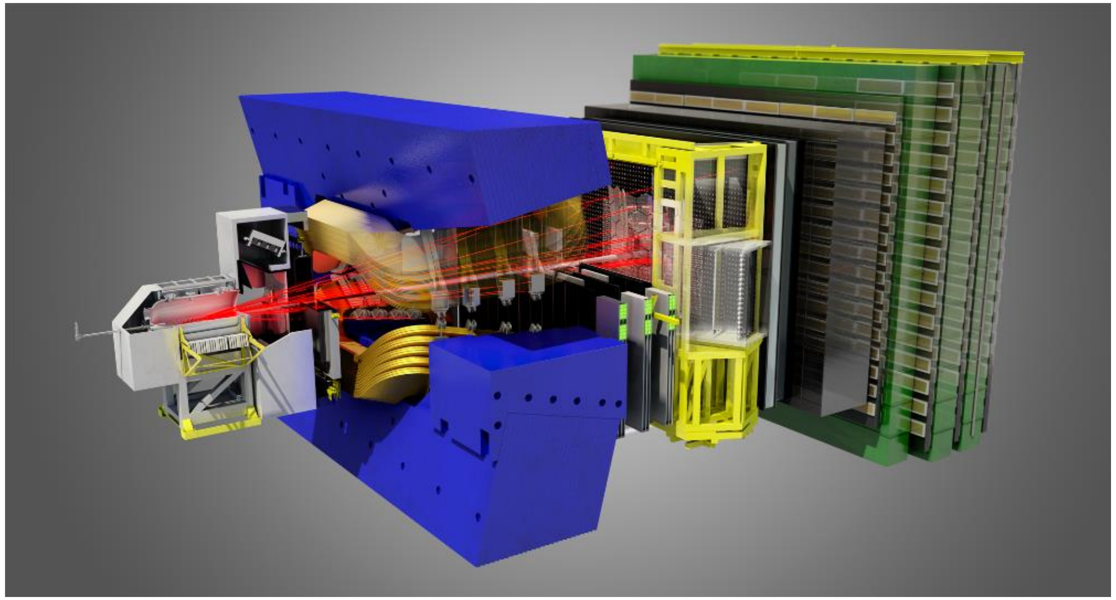
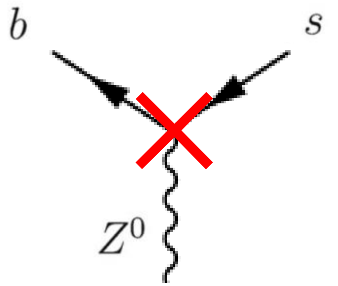
Overview

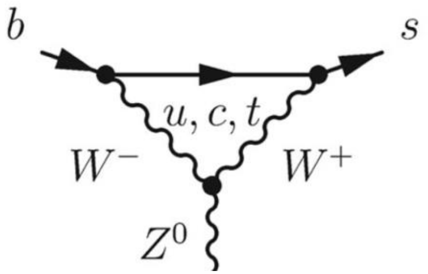
- Introduction to B physics and the $K\pi$ puzzle
- LHCb and neutral particles
- New measurement of $A_{CP}(B^+ \rightarrow K^+\pi^0)$
- Ongoing upgrade of LHCb and prospects for $A_{CP}(B^+ \rightarrow K^+\pi^0)$



The CKM Matrix

- CKM matrix describes the interaction of quarks with the weak force
- Inter-generation transitions suppressed
  - Interesting b quark properties: long lifetime $\gamma c \tau_B \sim 7\mathrm{mm}$, particular sensitivity to NP
- Flavor Changing Neutral Currents forbidden to first order

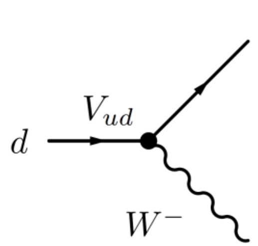


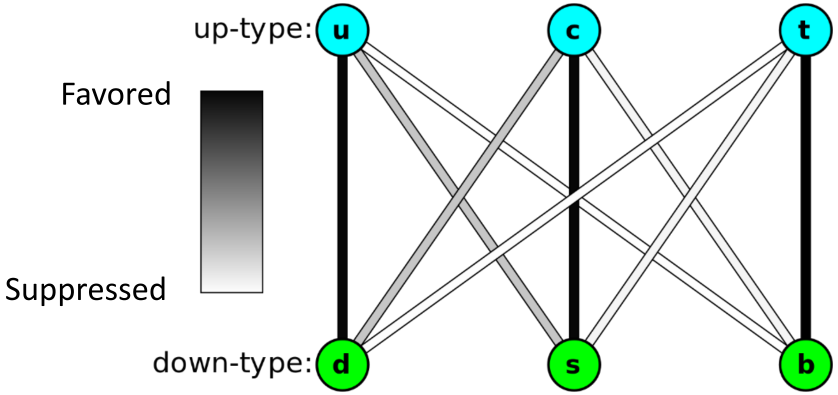


- Single complex phase source of CP asymmetry
  - CP violation requires at least three generations

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\boldsymbol{\rho} - \boldsymbol{i\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\boldsymbol{\rho}-\boldsymbol{i\eta}) & -A\lambda^2 & 1 \end{bmatrix}$$

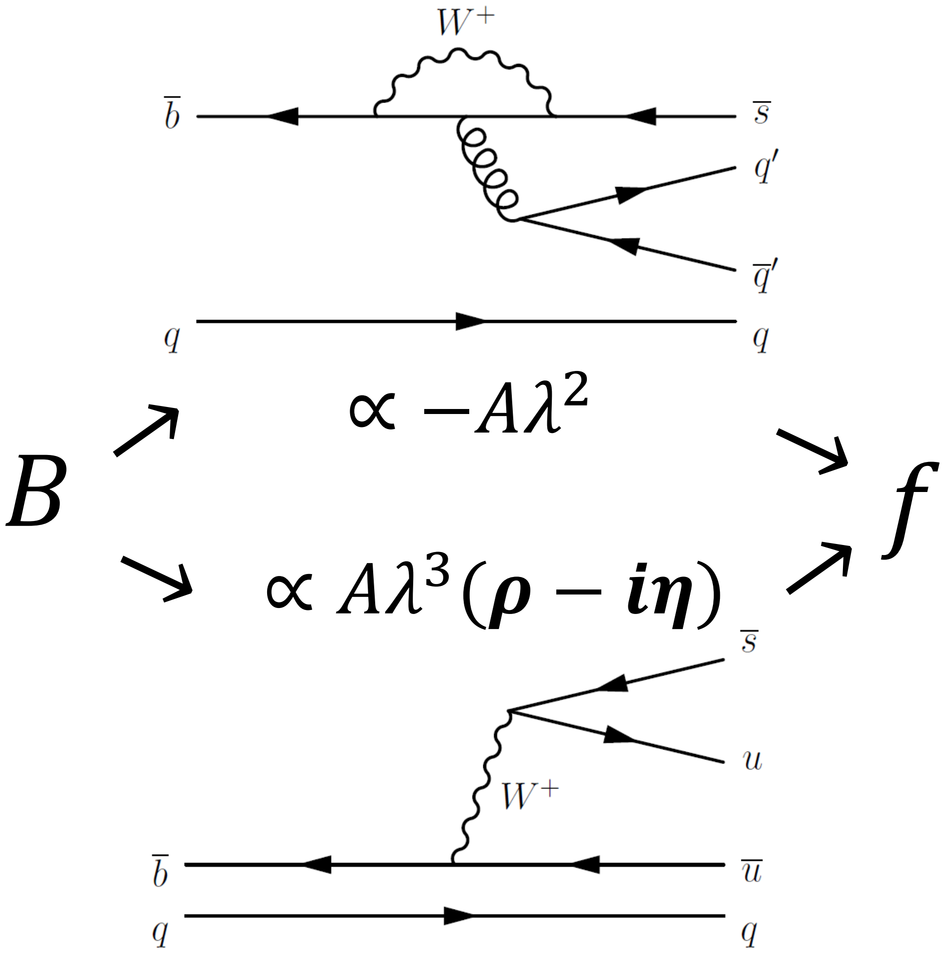
$\boldsymbol{V_{ud}} \propto$





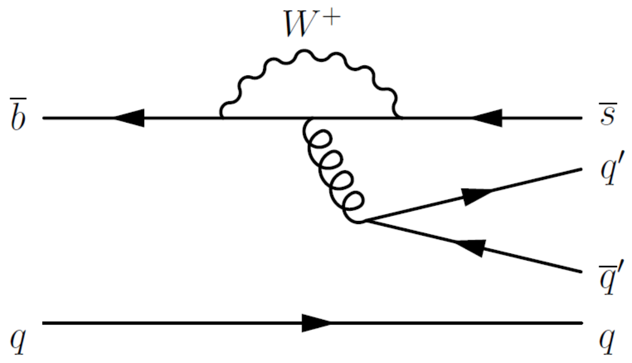
CP Violation

- Physical laws not invariant under charge conjugation + parity inversion (mirror flip)
- Consequence of interference when a physical process can proceed in different ways
- CP violation in mixing: $B^0 \to \overline{B^0} \neq \overline{B^0} \to B^0$
- Indirect CP violation: asymmetry due to interference between mixing and decay amplitudes
- **Direct CP violation:** $B \to f \neq \bar{B} \to \bar{f}$ due to interference in decay amplitudes
  - Requires non-zero relative weak and strong phase between amplitudes

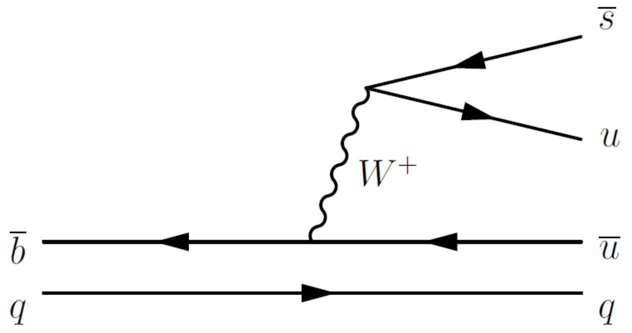


The $B \to K\pi$ System

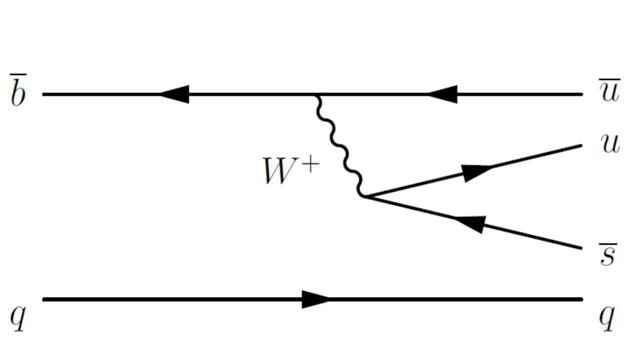
- $B^0 \to K^+\pi^-$, $B^0 \to K^0\pi^0$, $B^+ \to K^+\pi^0$, $B^+ \to K^0\pi^+$
- Dominated by QCD penguin diagrams
  - Suppressed by loop
  - Tree suppressed by V_{ub}
- Different $K\pi$ decays have contributions from different diagrams
- Potentially sensitive to new physics through massive virtual particles in loops



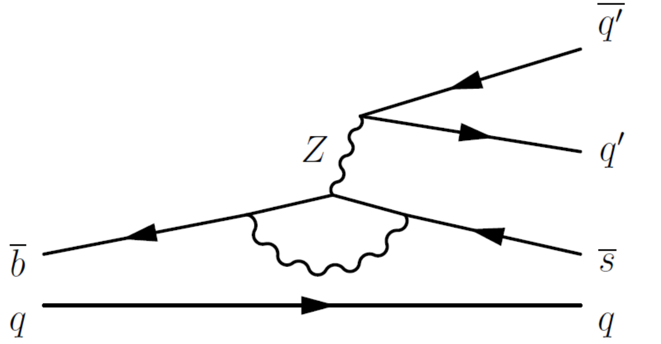
(a) $B \to K\pi$ penguin diagrams



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



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



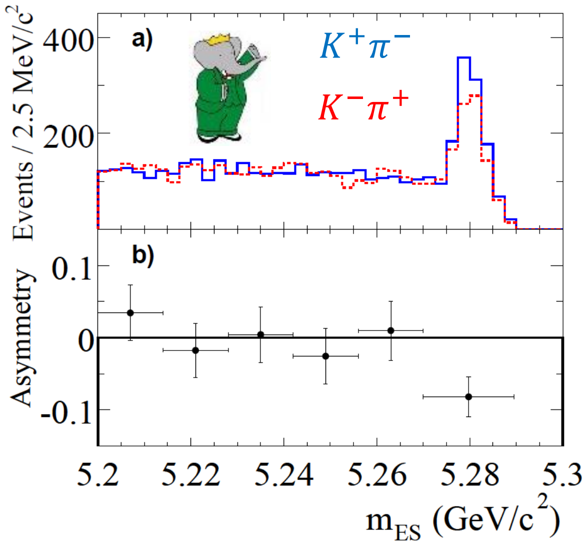
(d) $B \to K\pi^0$ electroweak penguin diagrams

Observation of Direct CPV in B mesons

A_{CP} and branching fraction world averages for the $B \to K\pi$ decay modes.

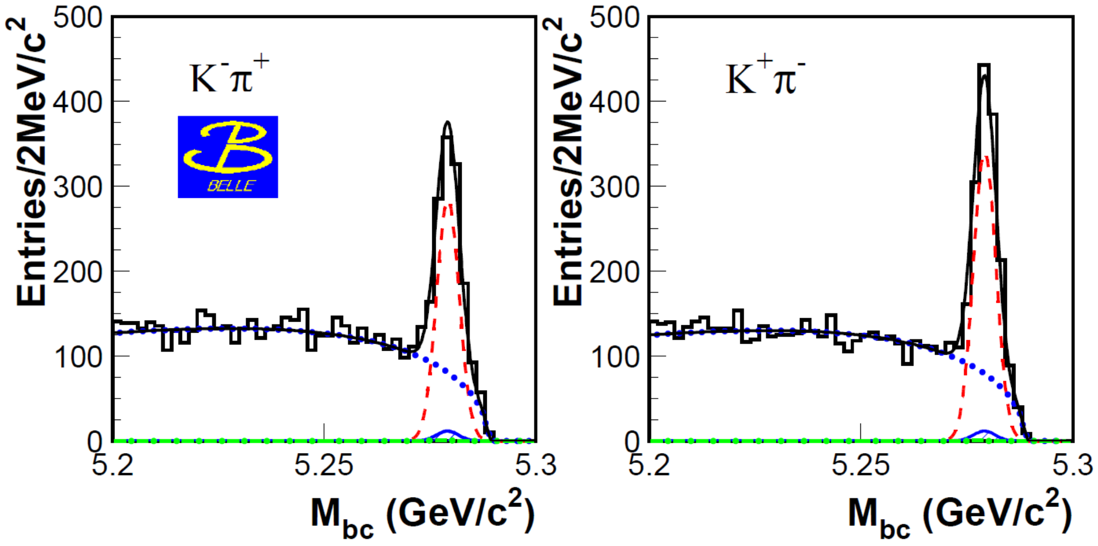
	BF$\times 10^{-6}$	Direct A_{CP}	$\sin(2\beta^{eff})$
$B^0 \to K^0\pi^0$	9.9 ± 0.5	0.01 ± 0.10	0.57 ± 0.17
$B^+ \to K^0\pi^+$	23.8 ± 0.8	-0.017 ± 0.016	
$B^0 \to K^+\pi^-$	19.6 ± 0.5	-0.084 ± 0.004	
$B^+ \to K^+\pi^0$	12.9 ± 0.5	0.040 ± 0.021	

HFLAV 2018



Phys. Rev. Lett. 93 (2004) 131801

- BaBar and Belle: experiments at e^+e^- colliders devoted to studying B mesons
- First observed direct CP violation in B mesons in $B^0 \to K^+\pi^-$ decays
- Measured branching fractions and CP asymmetries for all $K\pi$ modes

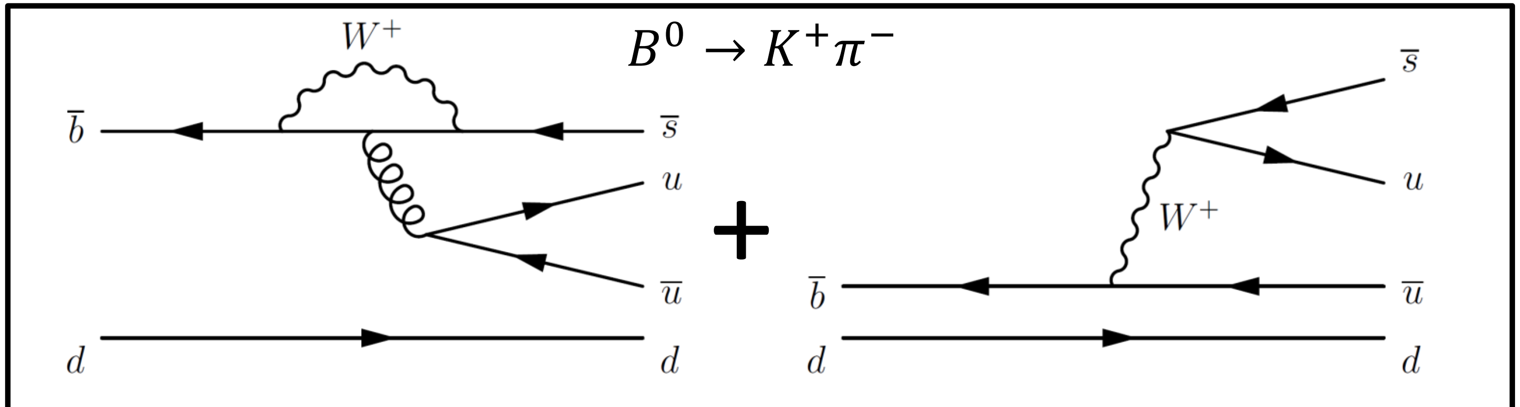


Phys. Rev. Lett. 93 (2004) 191802

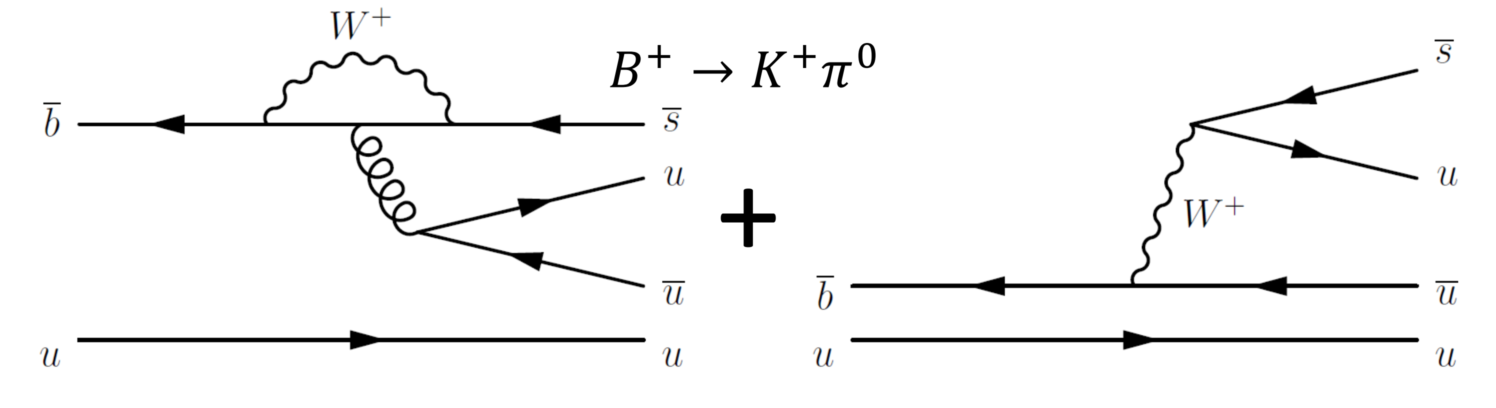
The $K\pi$ Puzzle

- CP asymmetry in $B^0 \to K^+\pi^-$ and $\mathrm{B}^+ \to K^+\pi^0$ from interference between tree and penguin diagrams
- Expected to be equal from isospin arguments
- Differs by more than 5σ according to current measurements

$$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.124 \pm 0.021$$



(a) $B \to K^+\pi^-$ penguin diagram (b) $B \to K^+\pi^-$ colour-favored tree diagram



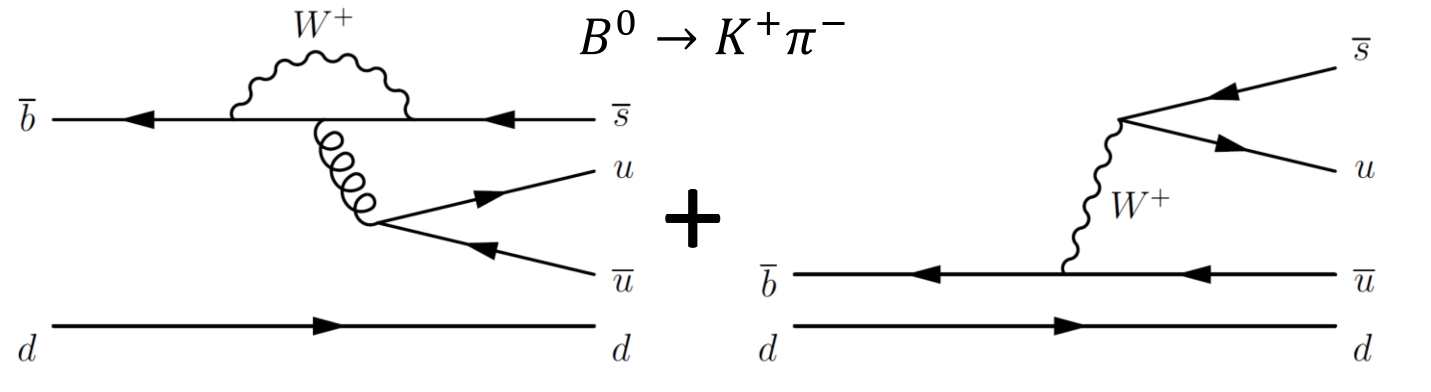
(a) $B \to K^+\pi^0$ penguin diagram (b) $B \to K^+\pi^0$ colour-favored tree diagram

The $K\pi$ Puzzle

$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-)$
$= 0.124 \pm 0.021$

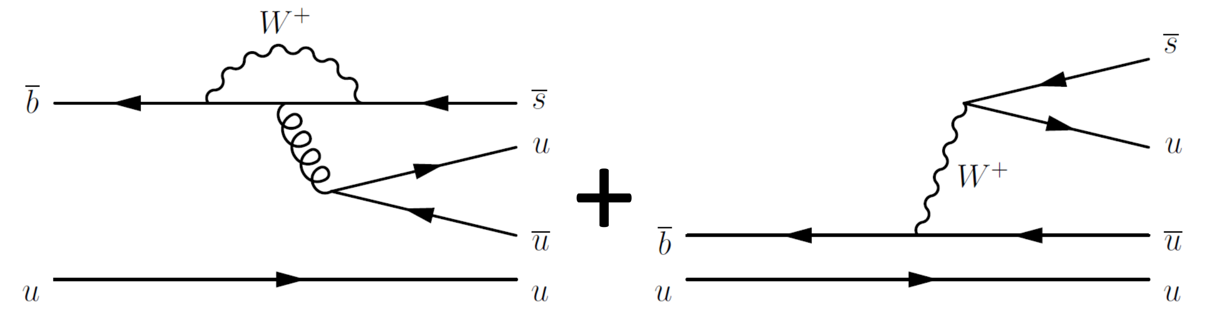
- Color-suppressed tree and electroweak penguin diagrams contribute to $K^+\pi^0$ but not $K^+\pi^-$

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



(a) $B \to K^+\pi^-$ penguin diagram (b) $B \to K^+\pi^-$ colour-favored tree diagram

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



(a) $B \to K^+\pi^0$ penguin diagram (b) $B \to K^+\pi^0$ colour-favored tree diagram

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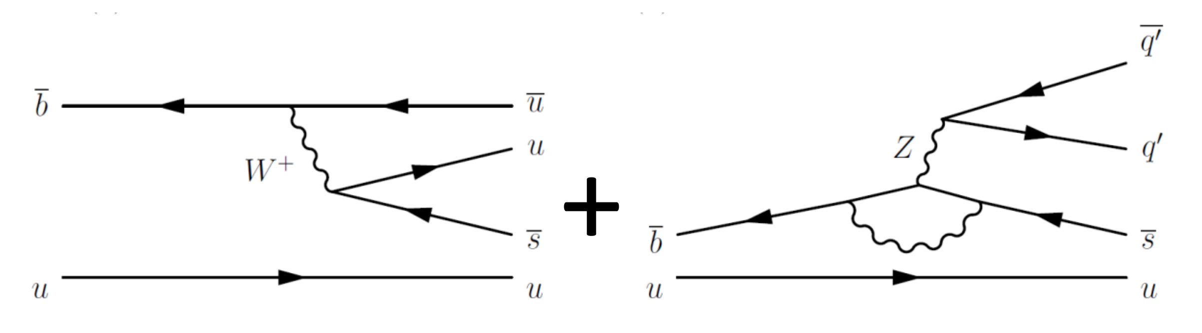
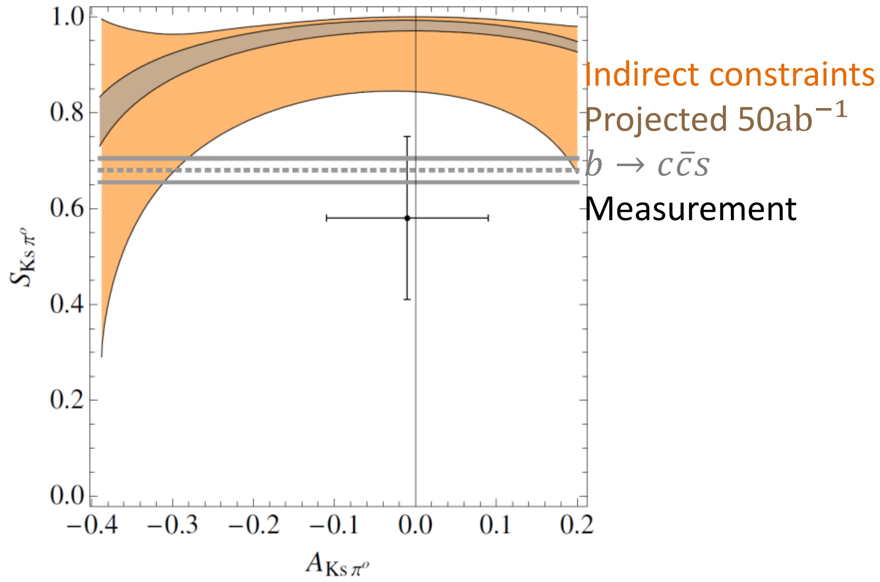


(c) $B \to K^+\pi^0$ color-suppressed tree diagrams (d) $B \to K^+\pi^0$ electroweak penguin diagrams

The $K\pi$ Puzzle Continued

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

- All $K\pi$ CP asymmetries and branching fractions can be incorporated in more precise equivalence derived from isospin relations between widths
- Current measurements (HFLAV 2018) predict $A_{CP}(K^0\pi^0) = -0.150 \pm 0.032$, value measured by B factories: 0.01 ± 0.10
- Fits to $K\pi$ observables show some tension
- Can be resolved by enhancement of color-suppressed trees or NP in penguins
- $B^0 \to K_S^0\pi^0$ is a key component of Belle II physics program



Phys. Rev. D 78, 111501(R)

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S. Baek et al., Phys. Rev. D 71 (2005) 057502, Phys. Lett. B 653 (2007) 249, Phys. Lett. B 675 (2009) 59;
M. Gronau, Phys. Lett.B 627 (2005) 82; N. B. Beaudry et al., JHEP01(2018) 074; R. Fleischer et al., Phys. Lett. B 785 (2018) 525

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]	

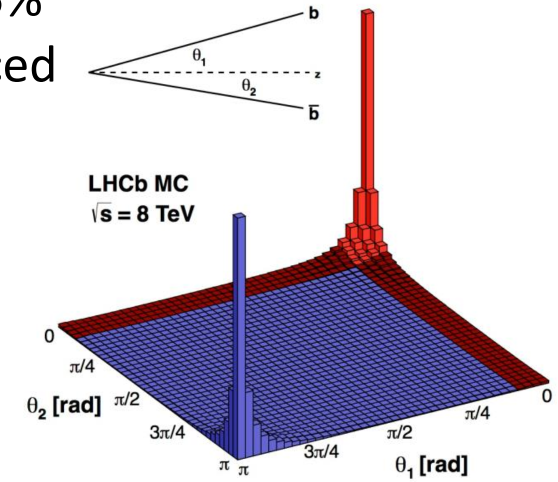
- LHCb has measured charged pion modes, modes with π^0 only measured at B factories
- **$B^+ \to K^+\pi^0$ is first analysis of a one-track B decay at a hadron collider**
- Experimentally challenging
  - No secondary vertex to identify B decay
  - Relatively low π^0 efficiency
  - High combinatorial background
- Proof of concept for other modes of similar topology such as $B^0 \to K^0\pi^0$

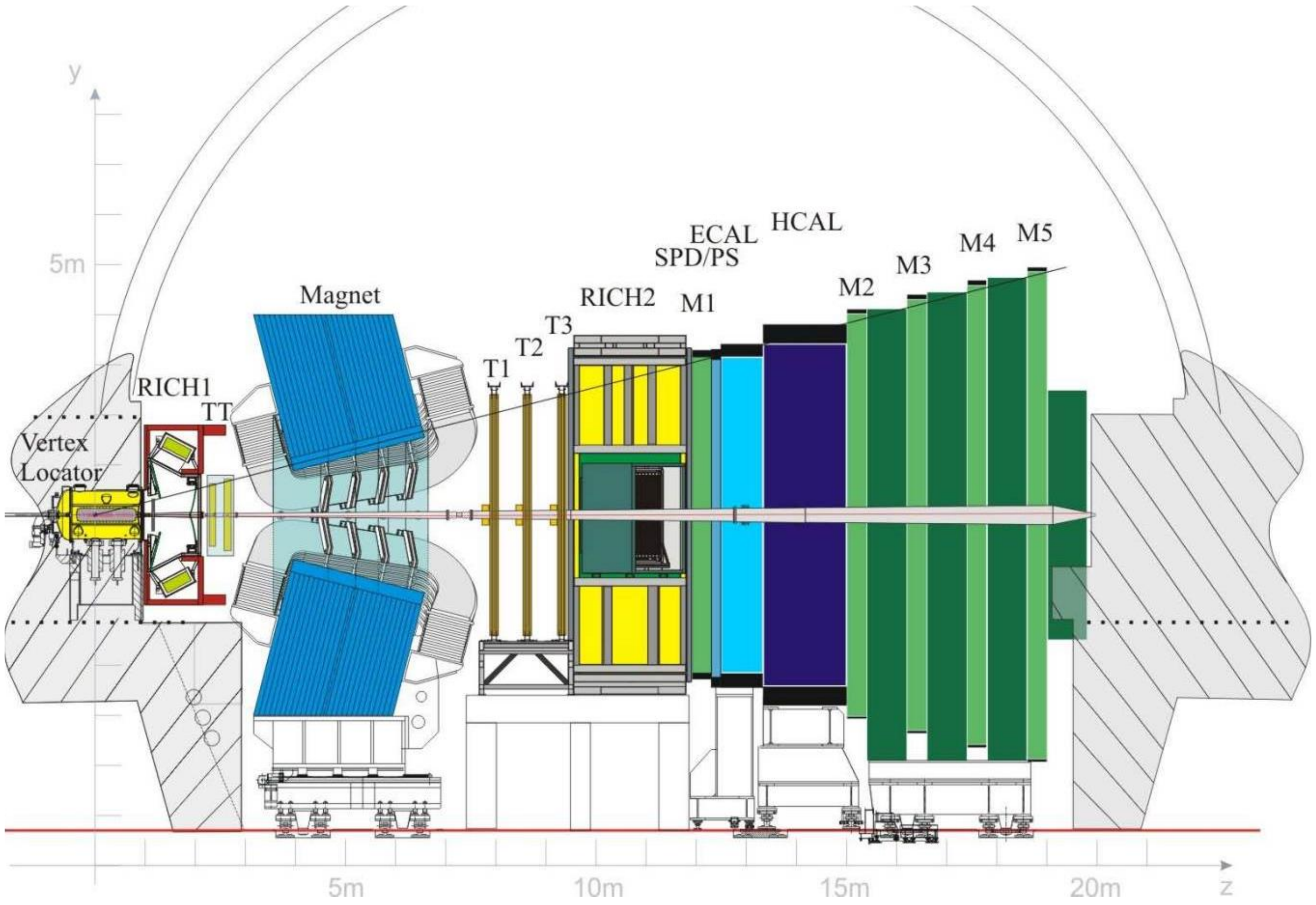
[1]:Phys.Rev.D 79, 052003 [2]:Phys.Rev.D 81, 011101(R) [3]:Phys.Rev.Lett. 97, 171805 [4]:Phys.Rev.D 87, 031103(R)
[5]:Phys.Lett.B 726 (2013) 646 [6]:Phys.Rev.D 87, 052009 [7]:JHEP 03(2021)075 [8]:Phys.Rev.D 76, 091102(R)

The LHCb Detector

The LHCb Detector

- High cross sections for b and c production at the LHC
  - $\sigma_{b\bar{b}}$~$500\ \mu b$ at 14 TeV
  - Produced predominantly at high η
- Central detector instrumenting $|\eta| < 2.5$ would instrument 98% solid angle and capture 45% of $b\bar{b}$ pairs
- Instrumenting $2 < \eta < 5$ (~4% solid angle) captures 25% of $b\bar{b}$ pairs produced

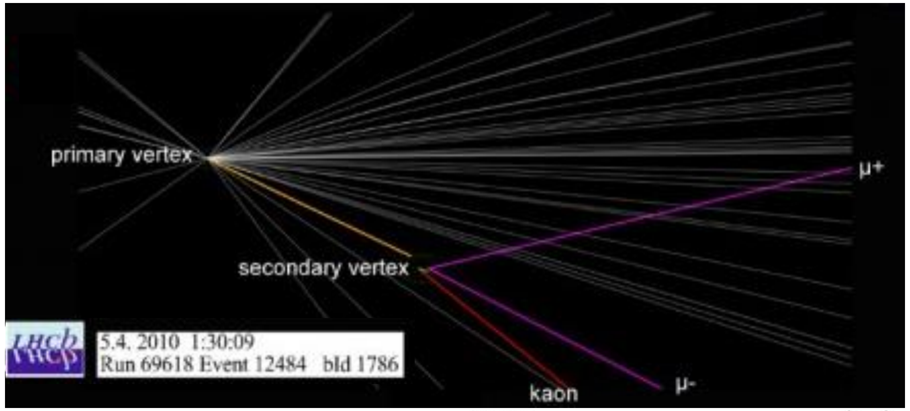


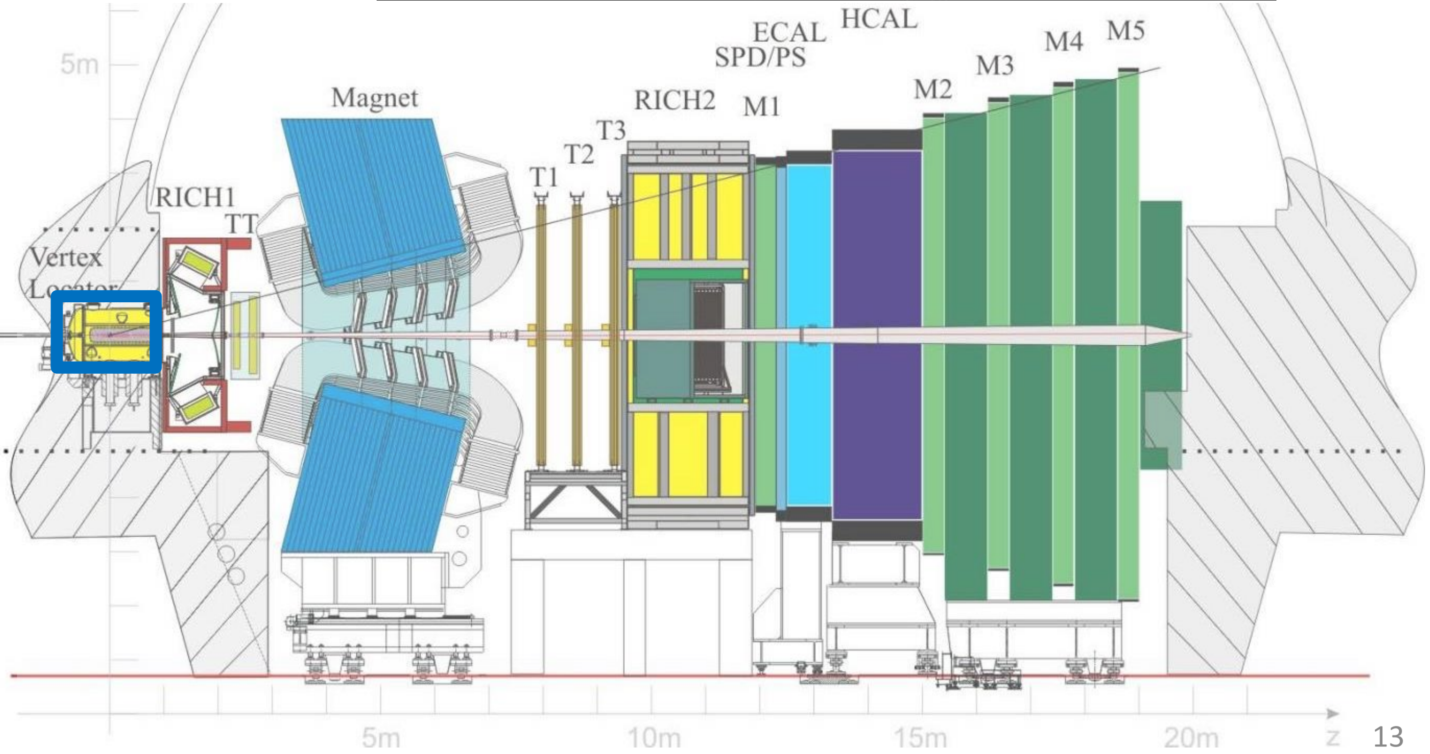


JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

Vertex Locator

- Silicon strip detector located inside the beam pipe, 8mm from beam
- Provides precision information on charged track position
- $\sigma_{IP} = \left(15 + \frac{29}{p_T[\text{GeV}]}\right) \mu m$





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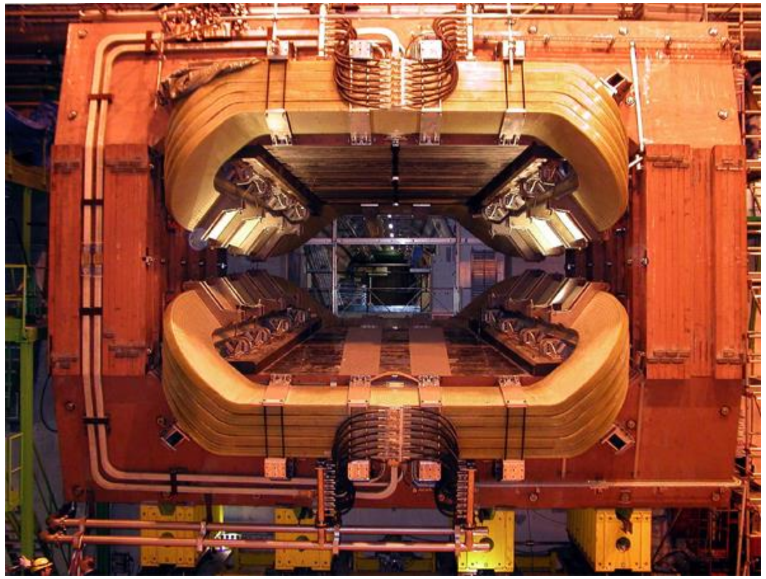
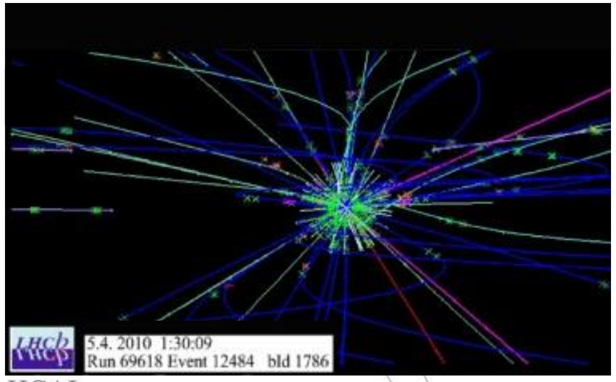
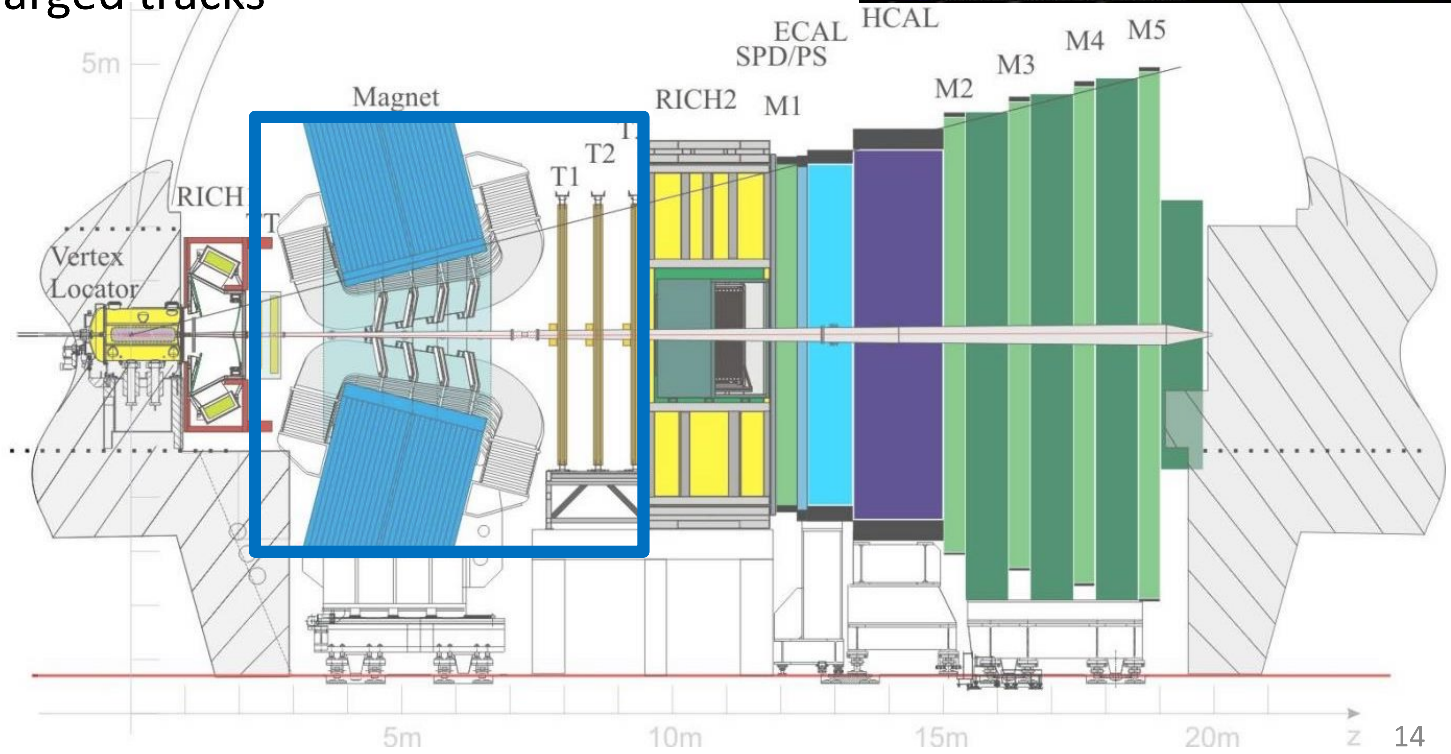
Tracking System

- 4 Tm dipole magnet
- Silicon strip sensors before magnet and in high-occupancy region around beampipe
- Straw tubes for coverage of lower occupancy region
- Provides momentum information for charged tracks
- $\frac{\sigma_p}{p} = 1\%$ at 200 [GeV/c]







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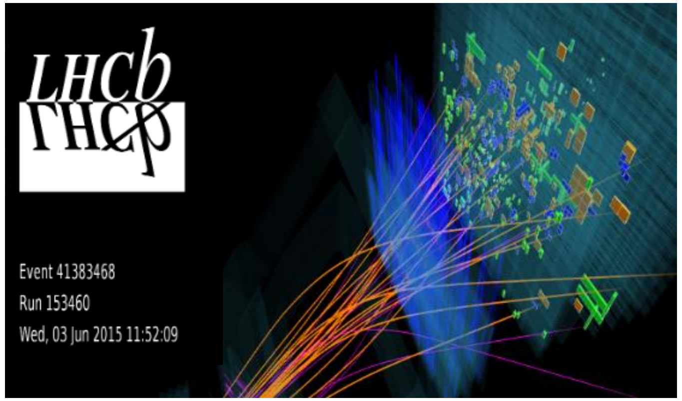
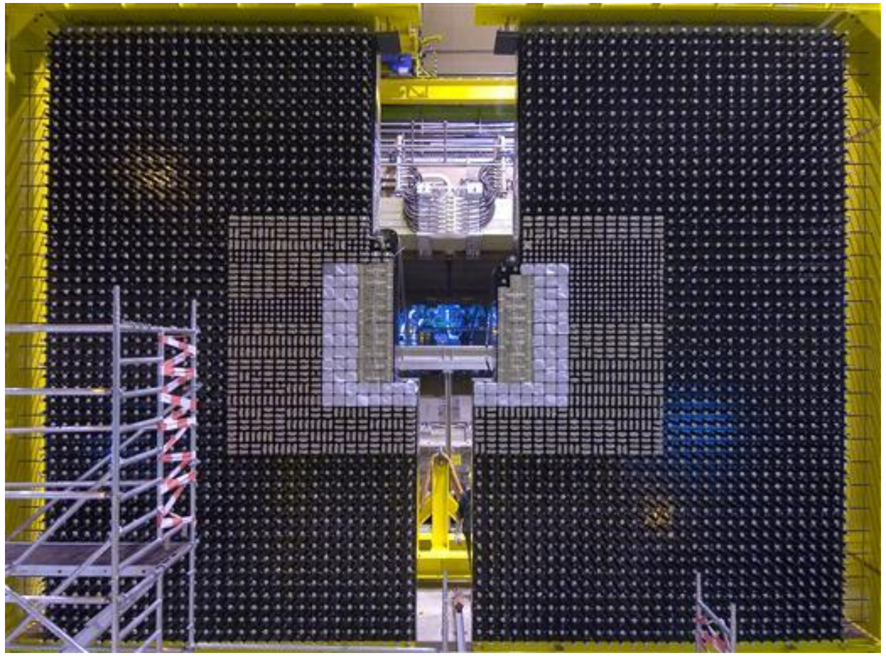
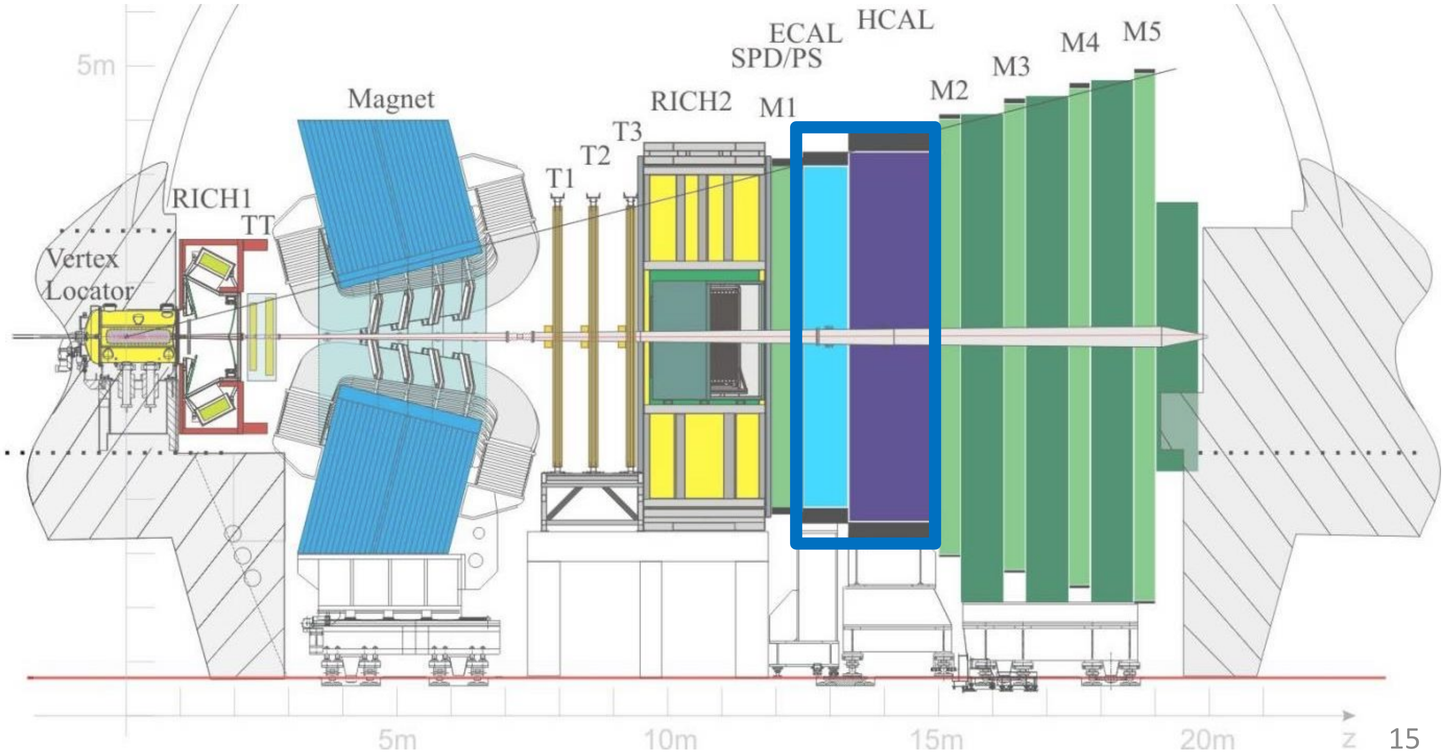
Calorimeter

- Sampling calorimeter with SPD/PS for $e/h/\gamma$ identification
- Measures and triggers on energy deposited by charged and neutral particles
- **Only information about neutral particles**
- $\frac{\sigma_E}{E} = 1\% + 10\%/\sqrt{E[\text{GeV}]}$







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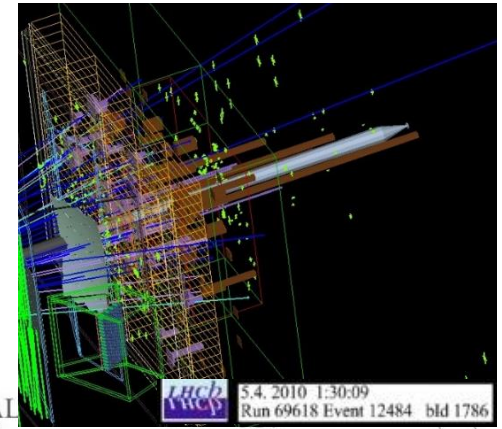
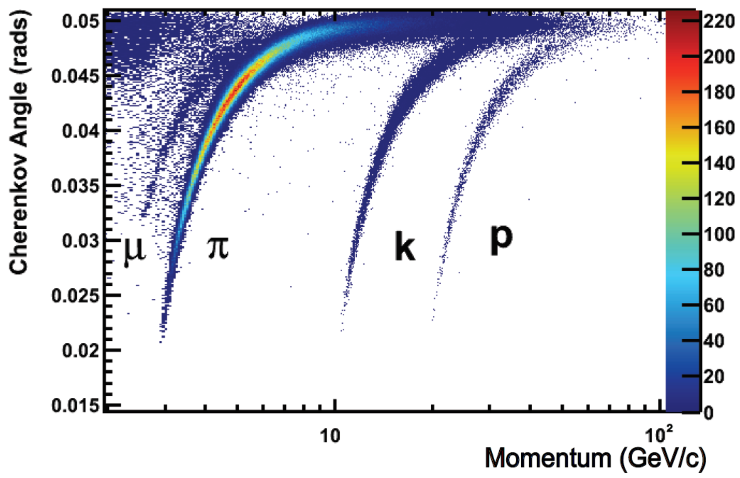
Particle Identification

- Ring Imaging Cherenkov Detector measures particle velocity for identification
- Muon MWPC identifies and triggers on muons
- e ~ 90% at ~ 5% $e \rightarrow h$ mis-id
- K ~ 95% at ~ 5% $\pi \rightarrow K$ mis-id
- μ ~ 97% at ~ 1-3% $\pi \rightarrow \mu$ mis-id





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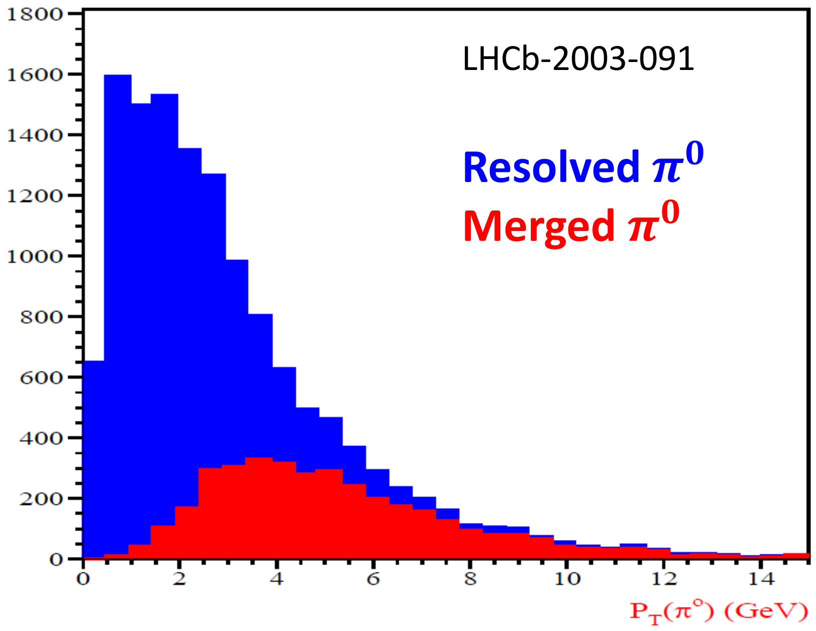
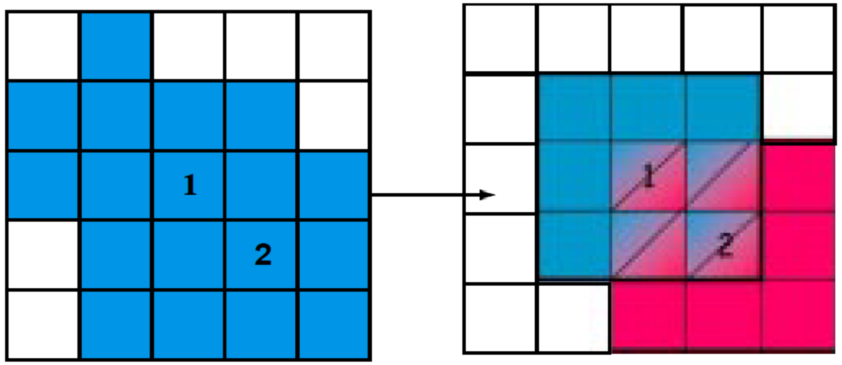
π^0 Reconstruction

- 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 $B^0 \to \pi^+\pi^-\pi^0$





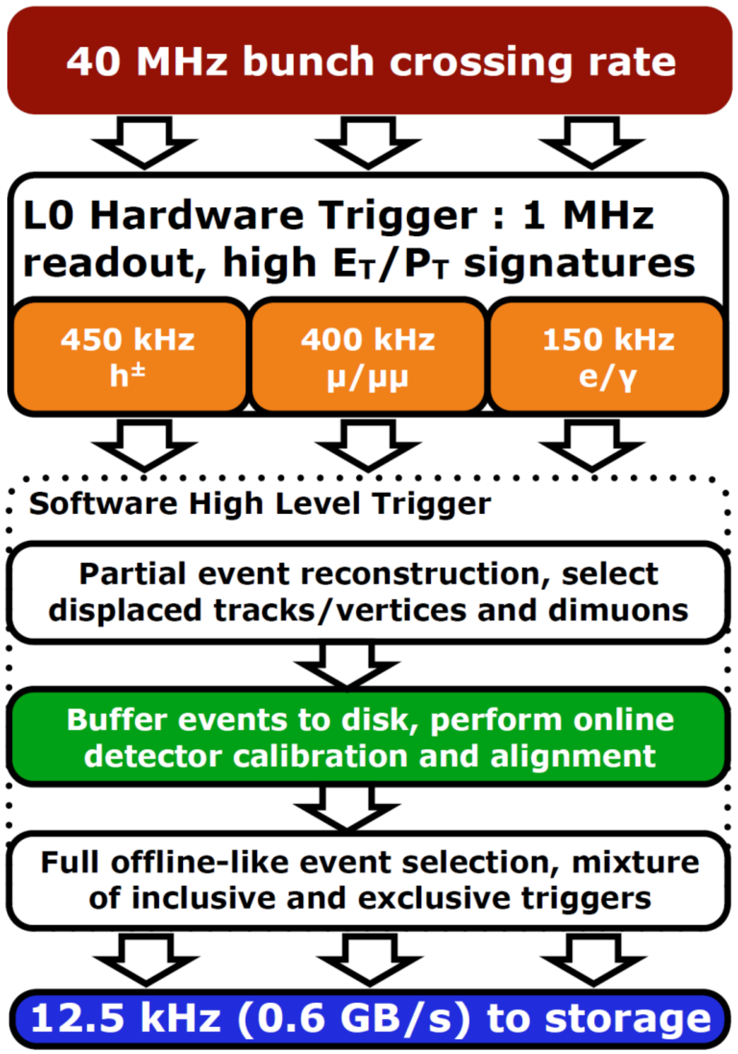
Single cluster

2 interleaved subclusters

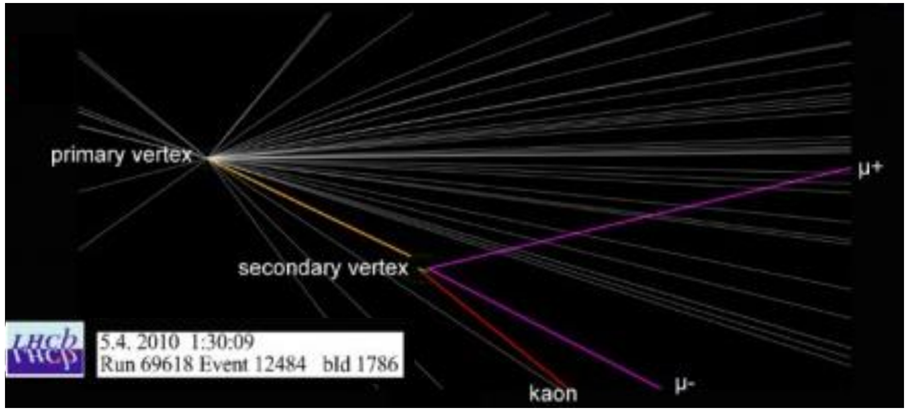
Trigger Strategy

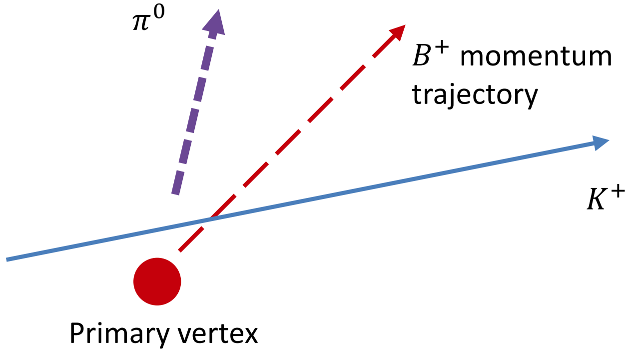
- Flavor physics results are largely limited by data recorded, rather than beam energy
- Trigger has to cope with high forward occupancy while preserving relatively low-energy b and c physics
- Low-level hardware trigger relies on high E_T/p_T signature from calorimeter or muon detector
- Two step high-level trigger buffers events to disk to perform full reconstruction

LHCb Run II Trigger



$B^+ \to K^+\pi^0$ in Run I





- Long lifetime $c\tau_B \sim 400\mu m$ characteristic b signature
- All run I software triggers rely on secondary vertex
- Cannot be reconstructed for $B^+ \to K^+\pi^0$ with only one charged track
- Trigger on the presence of an unrelated secondary vertex in the event **(8-11% efficiency)**
- Extremely high combinatorial background: $S/B \sim 10^{-7}$
- 72 ± 26 signal events observed in Run I
- Motivated the development of a dedicated trigger for Run II

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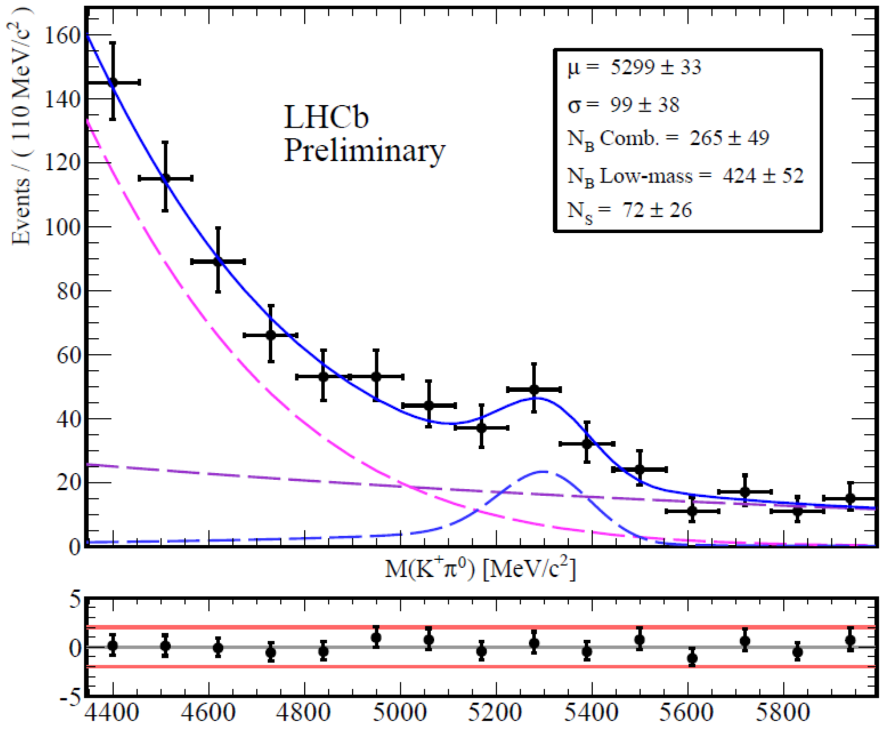
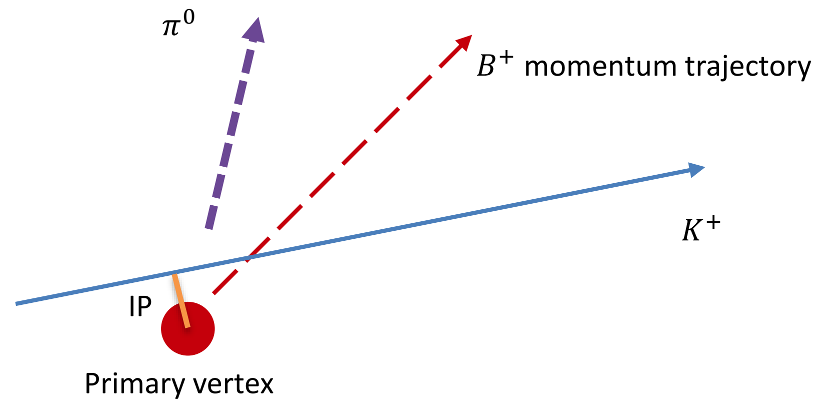


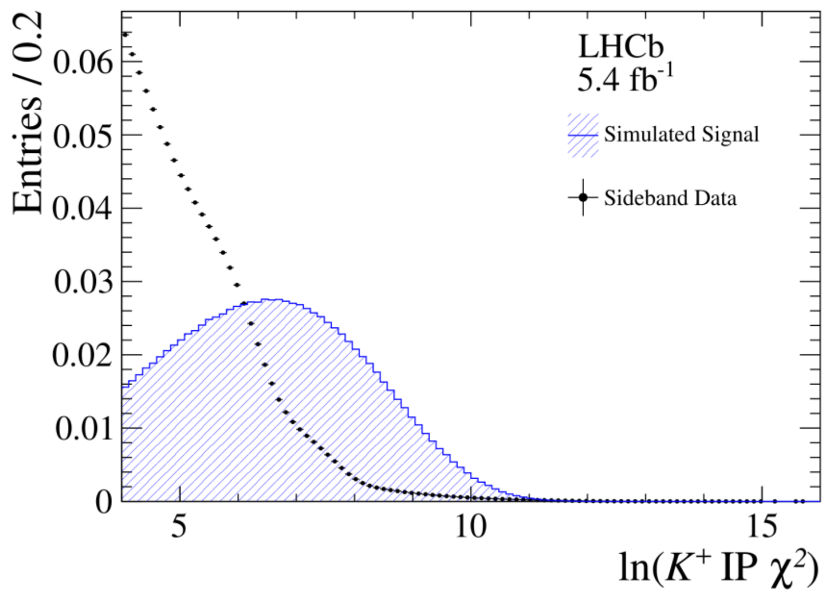
Run II Measurement

- Dedicated trigger and event selection
- Fit to determine CP asymmetry
- Corrections and systematics
- Results

Dedicated Trigger: K^+ IP

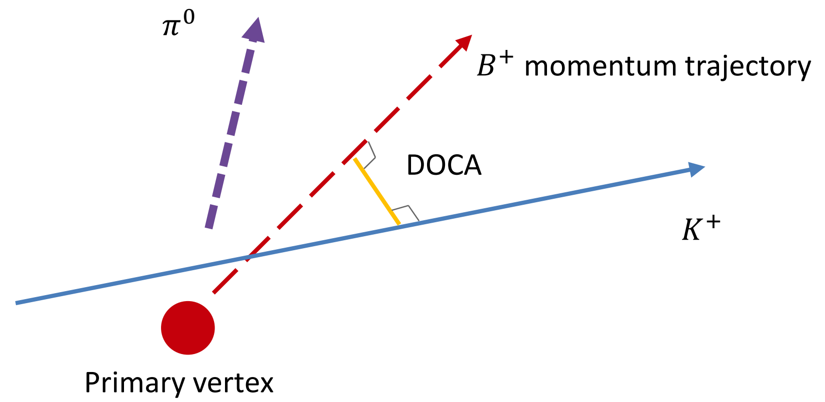
- **No secondary vertex, but still take advantage of LHCb's precision tracking**
- K^+ should be inconsistent with originating from any primary vertex
- Cut on $\mathrm{IP}\chi^2(\mathrm{PV})$, $\Delta\chi^2$ when K^+ is included in the primary vertex fit
- Suppresses background from promptly produced K^+ (unlikely to be B^+ decay product)

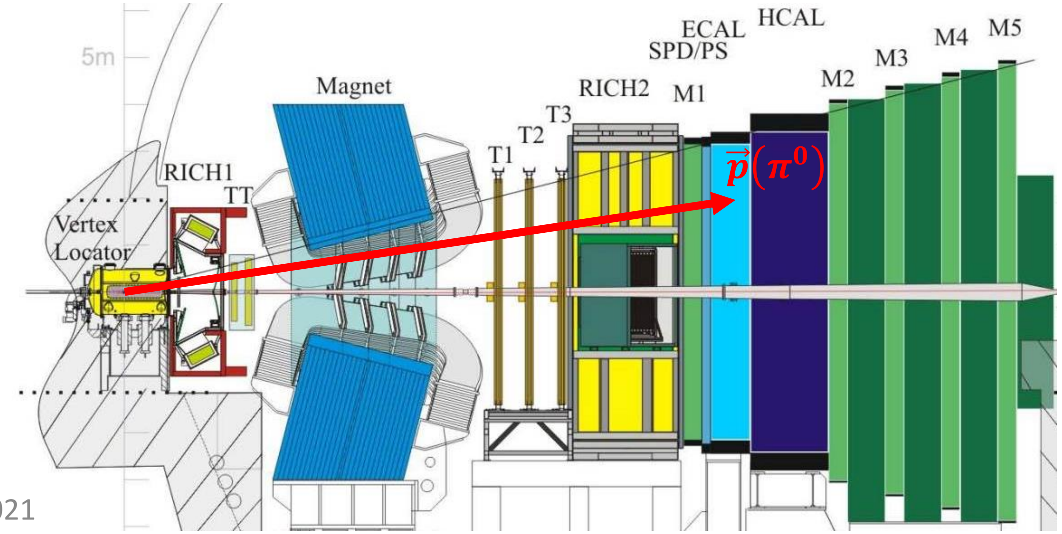


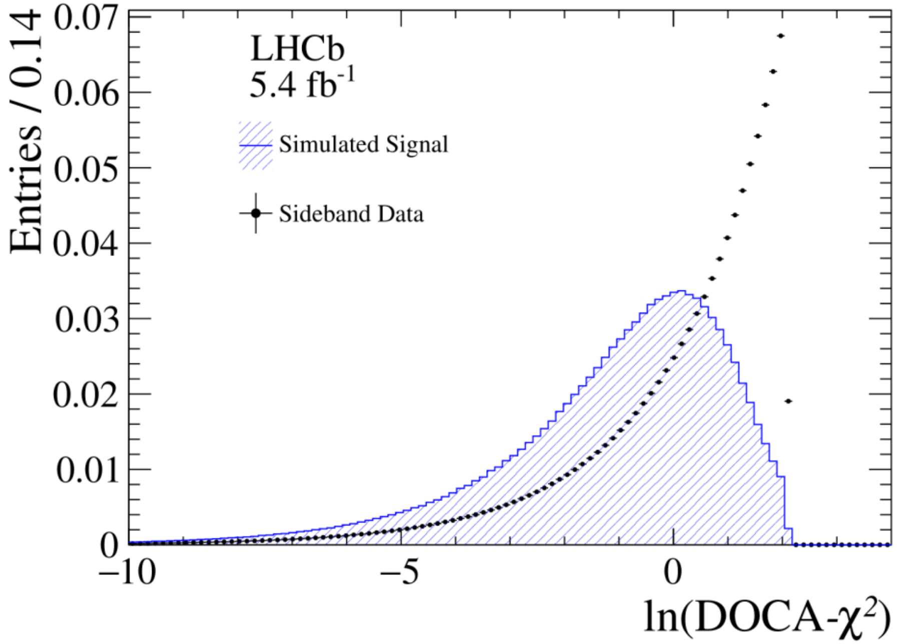


K^+ DOCA: The Key Variable

- K^+ should be consistent with originating from the trajectory of the B^+
- Add K^+ and π^0 momenta to form B^+ trajectory
  - Define π^0 momentum as pointing from interaction point to calorimeter energy deposit
- Cut on significance of distance of closest approach (DOCA) of K^+ and B^+
- Suppresses background from combinatorial K^+ and π^0

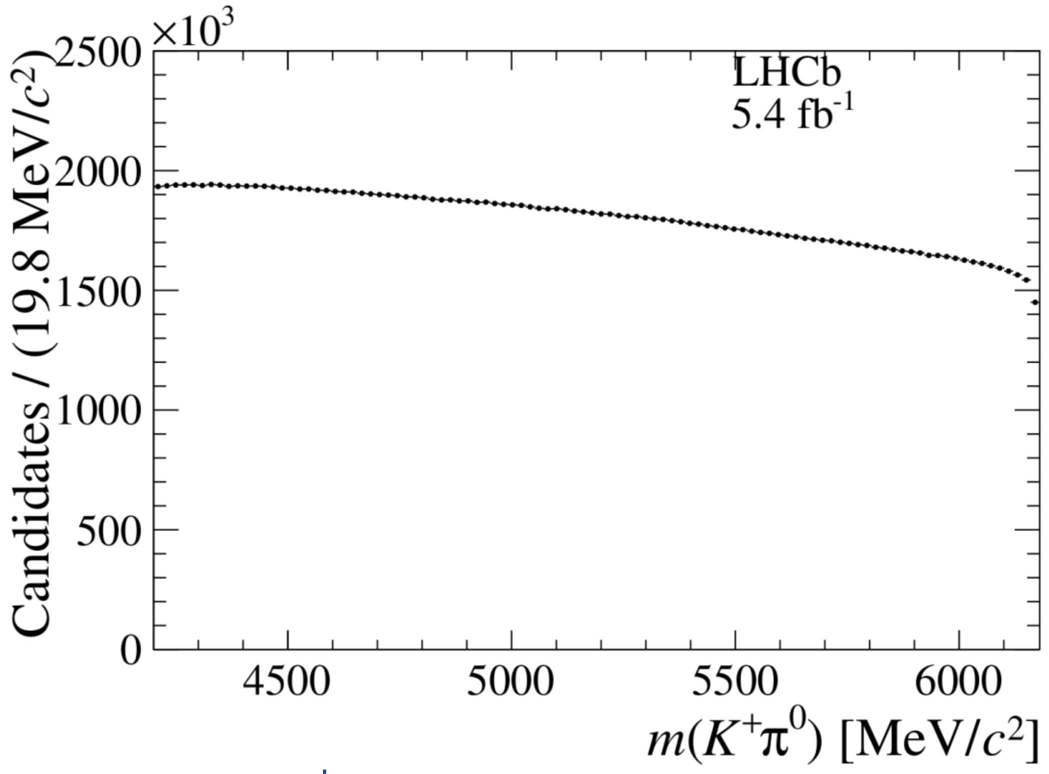


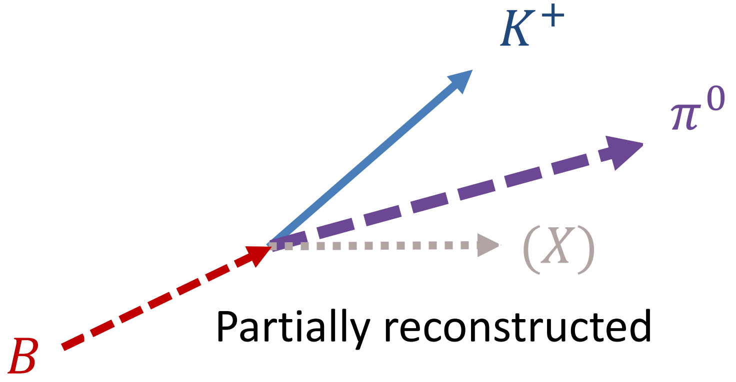




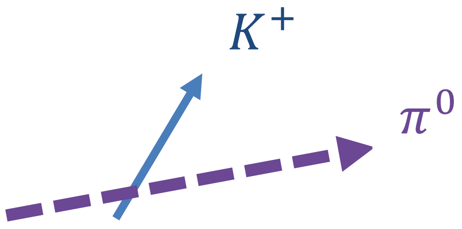
Trigger Output

- Dedicated software trigger takes advantage of $IP\chi^2(PV)$ and DOCA-χ^2 variables, B^+ invariant mass window and kinematic cuts of final selection
- S/B after trigger still $\sim 3.3 \times 10^{-4}$
- Dominant background comes from random combinations of K^+ and π^0
- Below the B mass $B \to K^+\pi^0 X$ is also a significant background
  - Similar event topology to signal





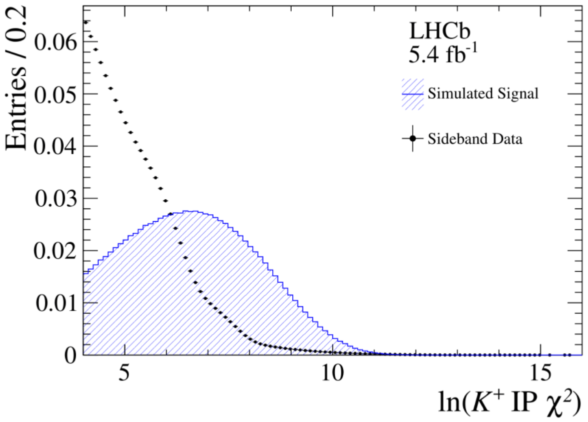
Partially reconstructed

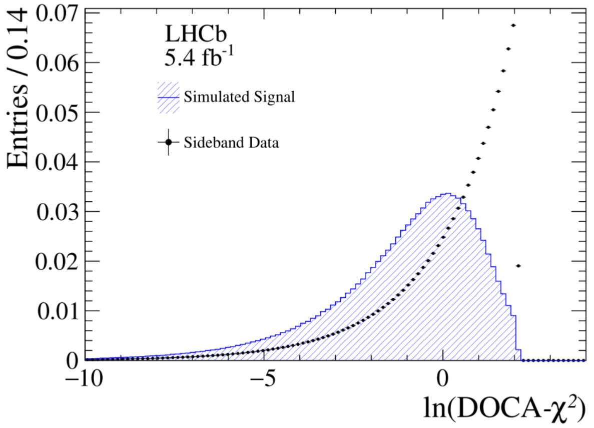


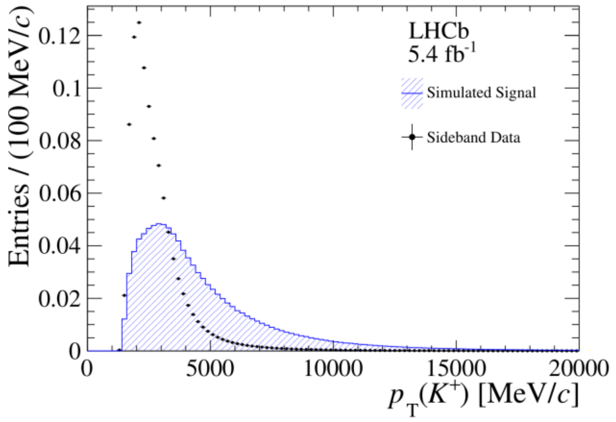
Combinatorial

Multivariate Analysis

- Train Boosted Decision Trees to reject background efficiently
- Two BDTs trained against different backgrounds:
  - Upper mass sideband $M(K^+\pi^0) > 5700\ \mathrm{MeV}/c^2$ (combinatorial)
  - Lower mass sideband $M(K^+\pi^0) < 4860\ \mathrm{MeV}/c^2$ (partially reconstructed)
  - Both trained on simulated signal
- Split and cross-validated for best statistics without overtraining
- Same set of inputs for both BDTs:
  - IPχ^2(PV) and DOCA-χ^2
  - Kinematics (restricted to prevent reconstructing B^+ mass)
  - Isolation variables (next slides)

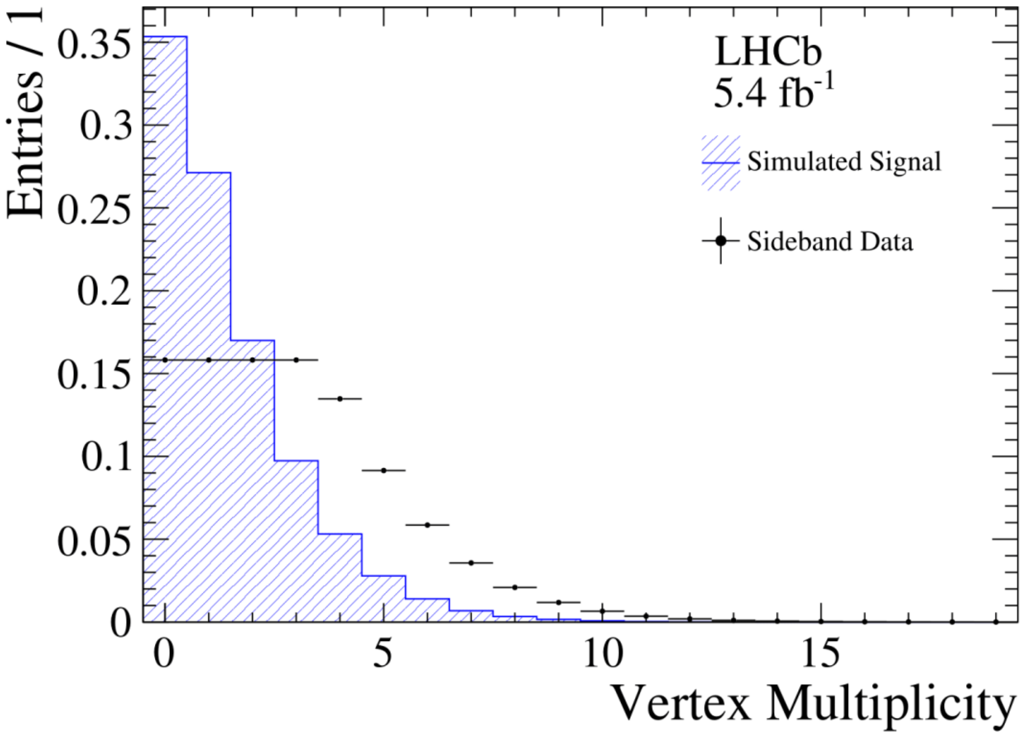


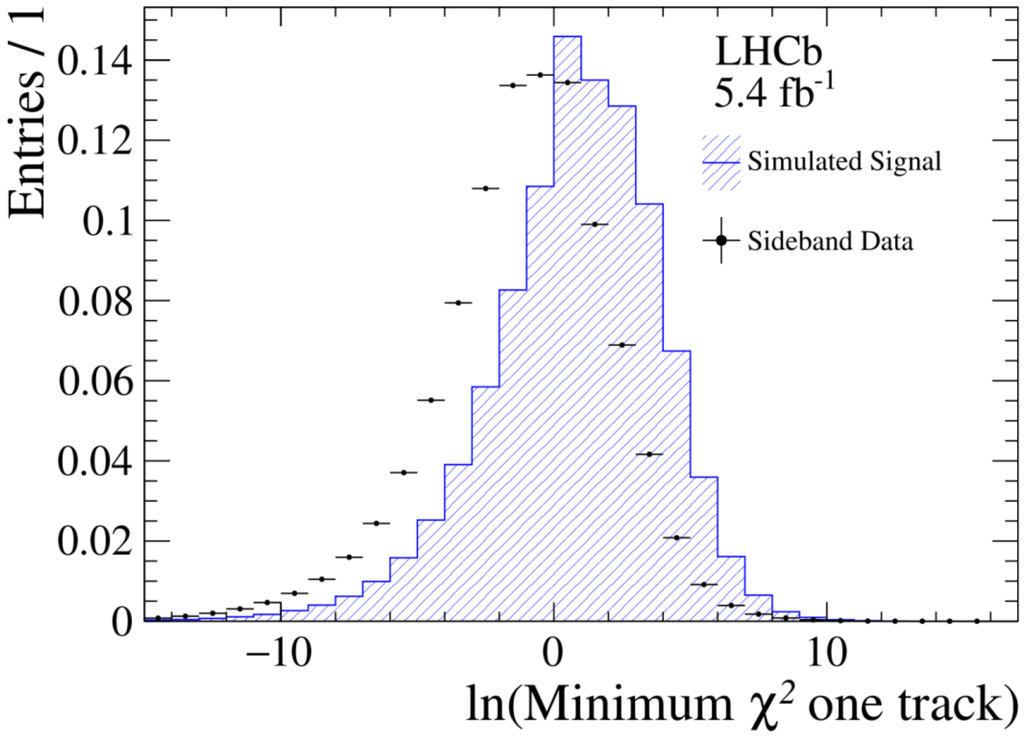




Isolation Variables: Vertex

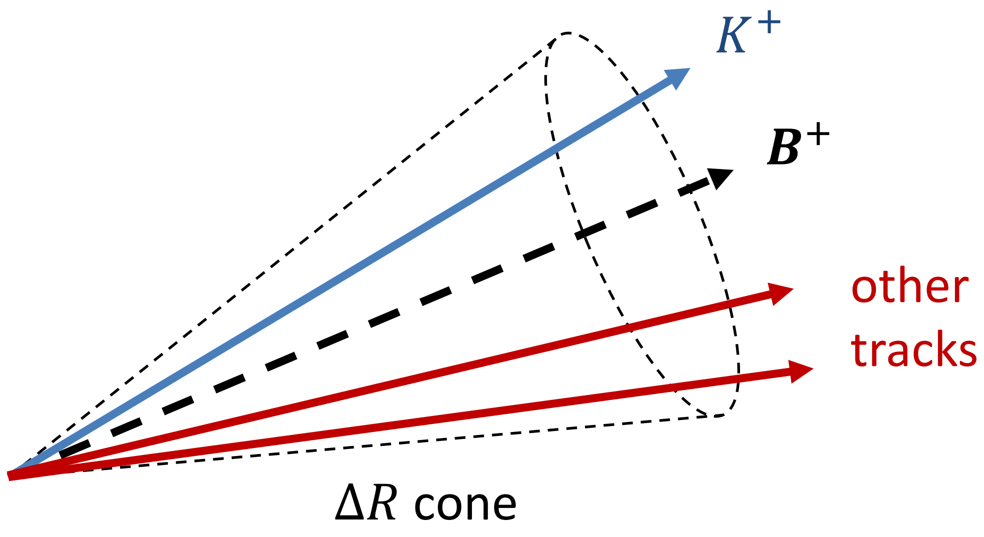
- Events with other tracks pointing back to B candidate are unlikely to be $B^+ \to K^+\pi^0$ decays
- Combine each track in the event individually with K^+ to form vertices

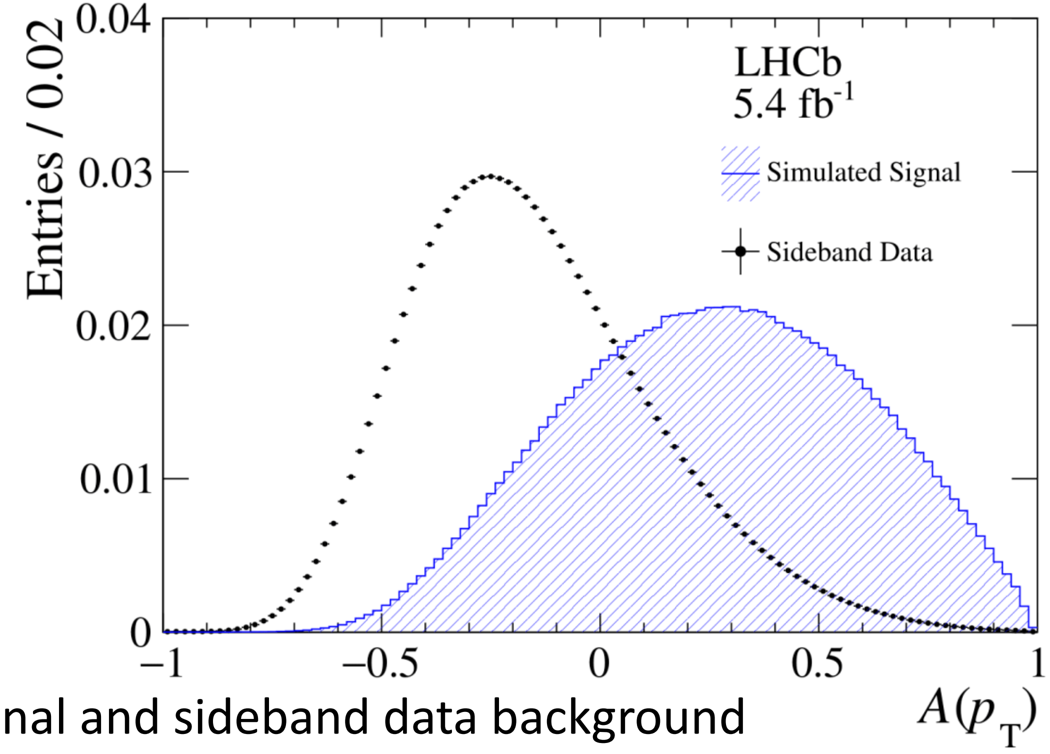




Isolation Variables: Cone

- Consider tracks in cone of $\Delta R = 1.7$ around B^+
- Define cone p_T asymmetry $A(p_T) \equiv \frac{p_T(B) - p_T(\text{cone})}{p_T(B) + p_T(\text{cone})}$

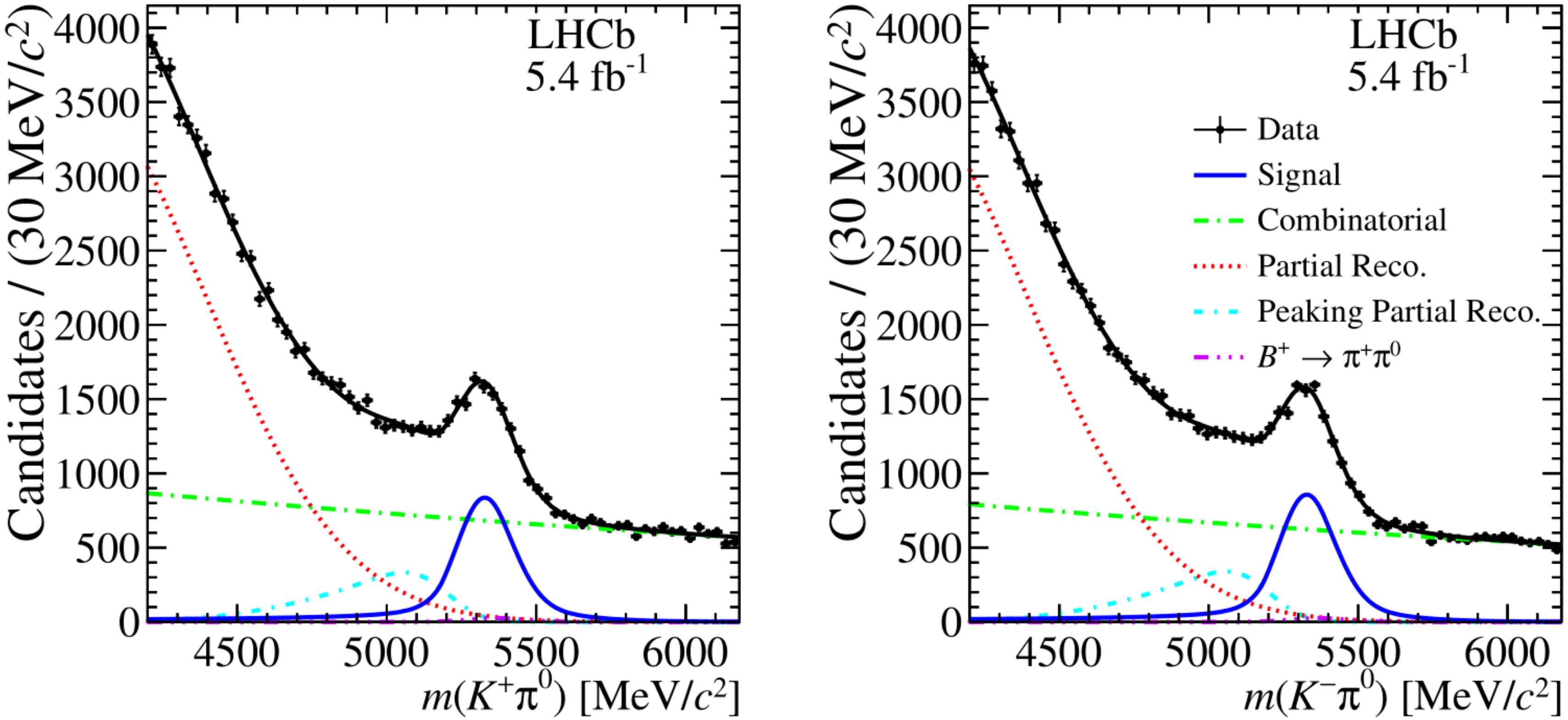




- BDTs trained on simulated signal and sideband data background
- Isolation variables depend on track multiplicity
- Corrected by comparing $B^0 \to K^+\pi^-$ data and simulation
  - Good signal efficiency and purity

Final Event Selection

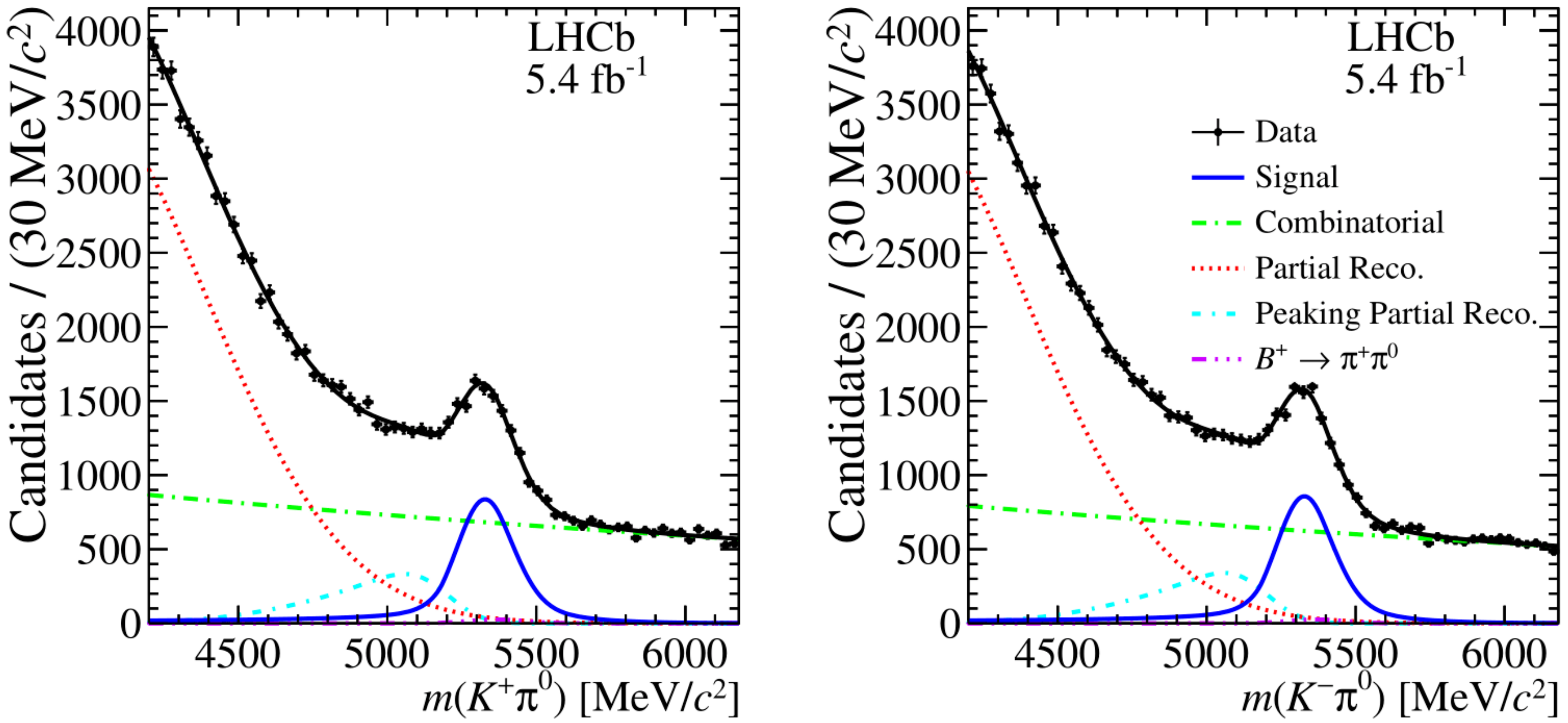
- Find 2D cut on BDT outputs that maximizes $\epsilon_{MC}/\sqrt{S+B}$
- S/B improved by factor of ~300
- Two more background categories:
- $B^+ \to \pi^+\pi^0$ where π^+ is misidentified as K^+
- Peaking partial reco. e.g. $B^{+/0} \to \left(K^{*+/0} \to \boldsymbol{K}^+\pi^{0/-}\right)\boldsymbol{\pi^0}$,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



B rest frame

Invariant Mass Fit

- Fit to mass distribution separated by $B^{\pm}$
- Further separate by magnet polarity (not shown) to correct for detector effects
- Shape parameters fixed between sub-samples, signal and background yields float independently
- $A_{raw} = \frac{N(B^{-}\to K^{-}\pi^{0}) - N(B^{+}\to K^{+}\pi^{0})}{N(B^{-}\to K^{-}\pi^{0}) + N(B^{+}\to K^{+}\pi^{0})}$



- $A_{raw} = 0.005 \pm 0.022$ (Magnet Up),
  0.019 ± 0.021 (Magnet Down)
- ~16,500 signal events (200x Run I)

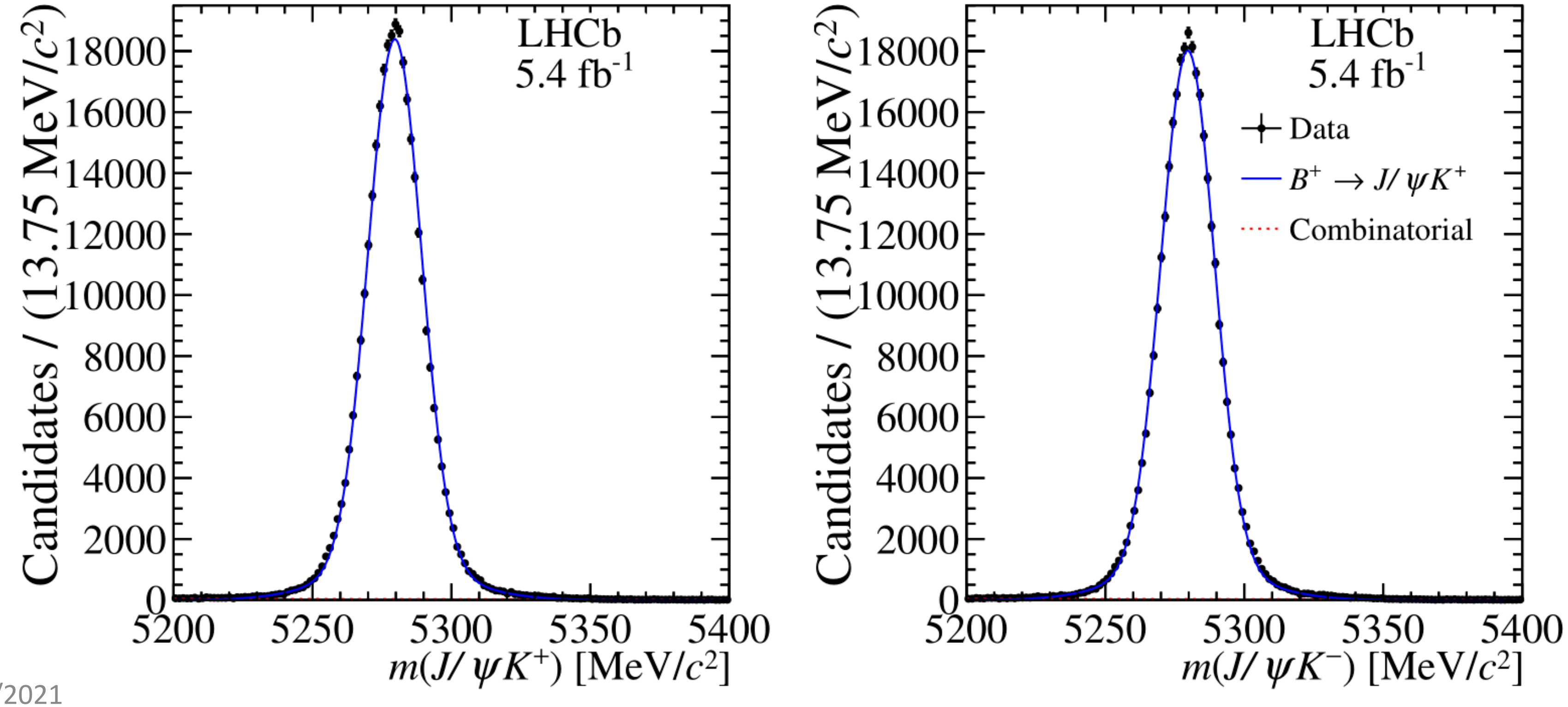
Production and Detection Asymmetry

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

- LHC is a proton-proton collider → $B^\pm$ production asymmetry
- LHCb is made of matter → $K^\pm$ 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, kinematics, particle identification
  - 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



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

Systematic Uncertainties

- Assess systematics on fit variations
  - Signal and background shapes
  - Parameters fixed to simulation/physical values
- Dominant uncertainty: modeling of signal tails in the fit
- 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**

A_{CP} Determination

- Correcting and averaging Magnet Up and Magnet Down results and adding systematic uncertainties in quadrature we find

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

- Result is consistent between years, magnet polarity, and bins of kaon momentum
- **Most precise measurement of $\boldsymbol{A_{CP}\left(B^+ \rightarrow K^+ \pi^0\right)}$**
- Combining with world average $A_{CP}(B^+ \rightarrow K^+ \pi^0) = 0.031 \pm 0.013$

Status of the B → $K\pi$ System

Table 15: $\mathcal{A}^{CP}$ 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]	$+0.024 \pm 0.015 \pm 0.006 \pm 0.003$

Phys. Rev. Lett. **126**, 091802

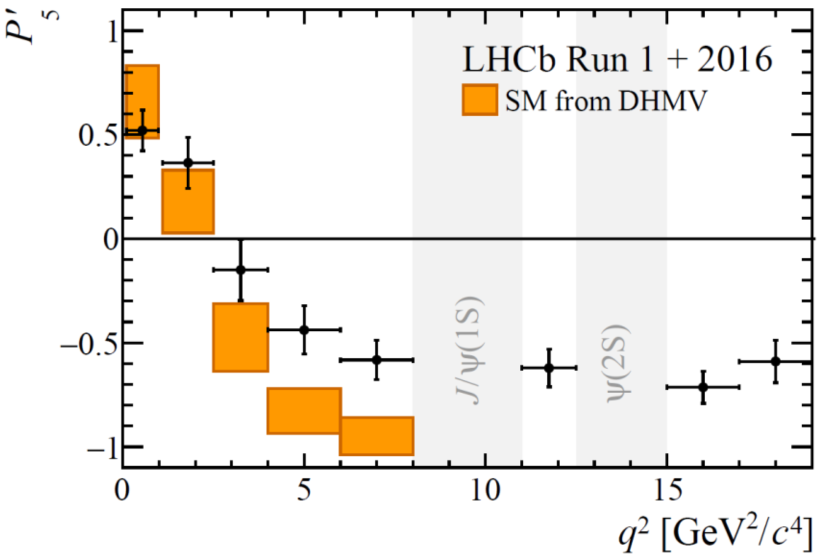
- $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$, non-zero at 8.2σ (previously 0.124 ± 0.021, 5.9σ)
  - LHCb results: $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.106 \pm 0.017$
- Updated sum rule prediction for $A_{CP}(K^0\pi^0)$: -0.138 ± 0.025, non-zero at 5.5σ (previously -0.150 ± 0.032, 4.7σ)

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

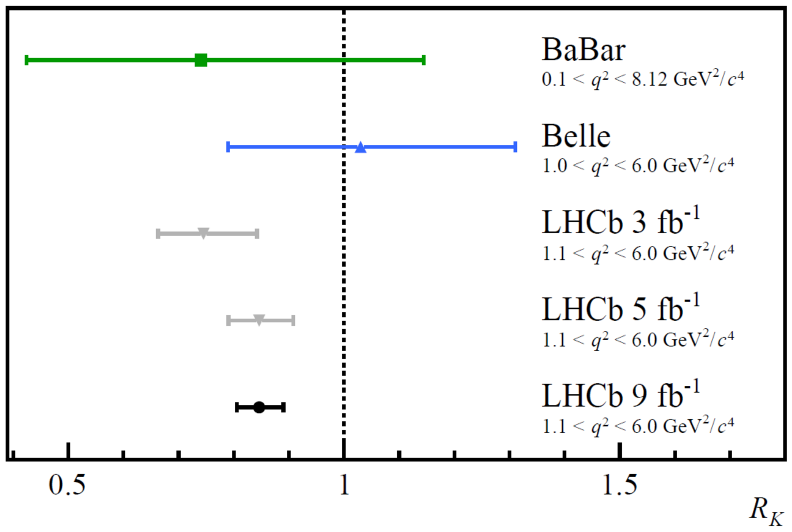
[1]:Phys.Rev.D 79, 052003 [2]:Phys.Rev.D 81, 011101(R) [3]:Phys.Rev.Lett. 97, 171805 [4]:Phys.Rev.D 87, 031103(R)
[5]:Phys.Lett.B 726 (2013) 646 [6]:Phys.Rev.D 87, 052009 [7]:JHEP 03(2021)075 [8]:Phys.Rev.D 76, 091102(R)

Flavor Physics Anomalies

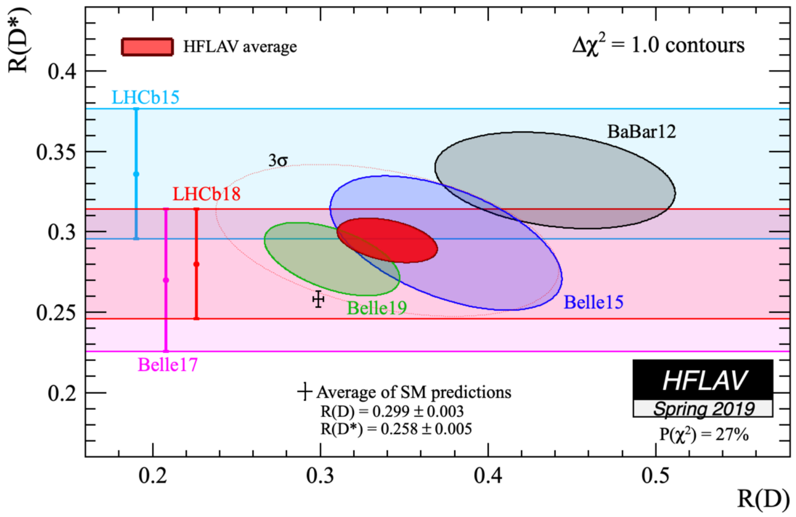
$B^0 \to K^{*0}\mu^+\mu^-$

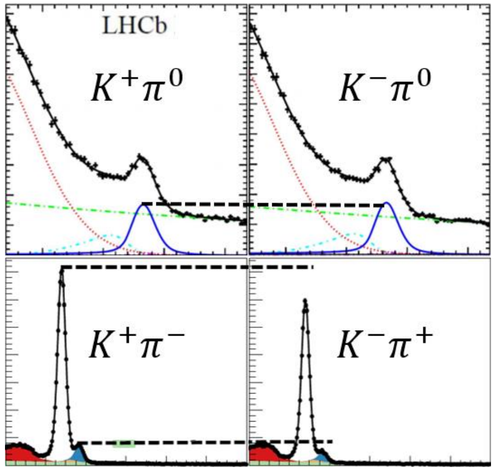


$B^+ \to K^+\mu\mu/K^+ee$



$B^0 \to D^{+(*)}\tau\nu/D^{+(*)}\mu\nu$



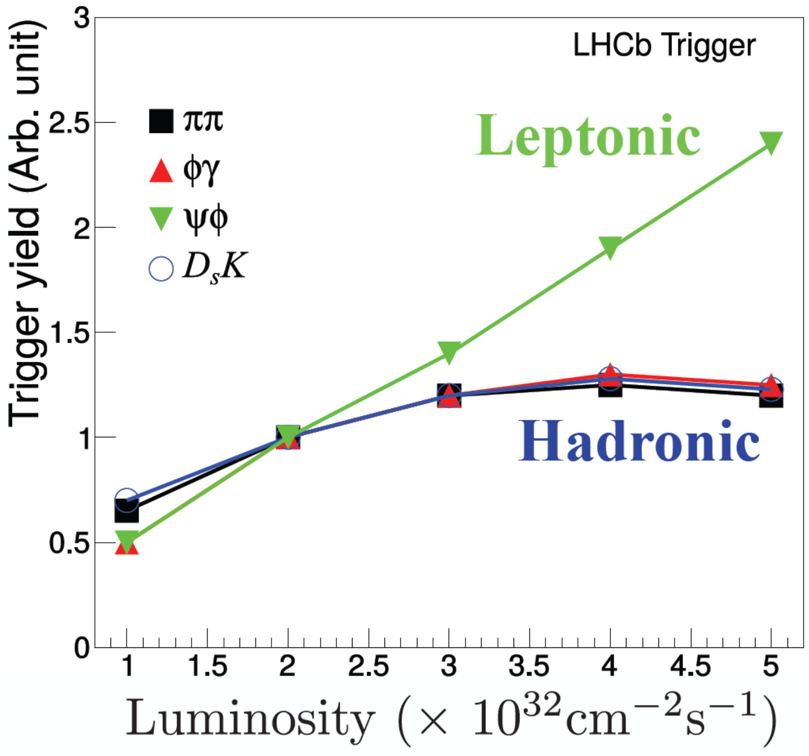


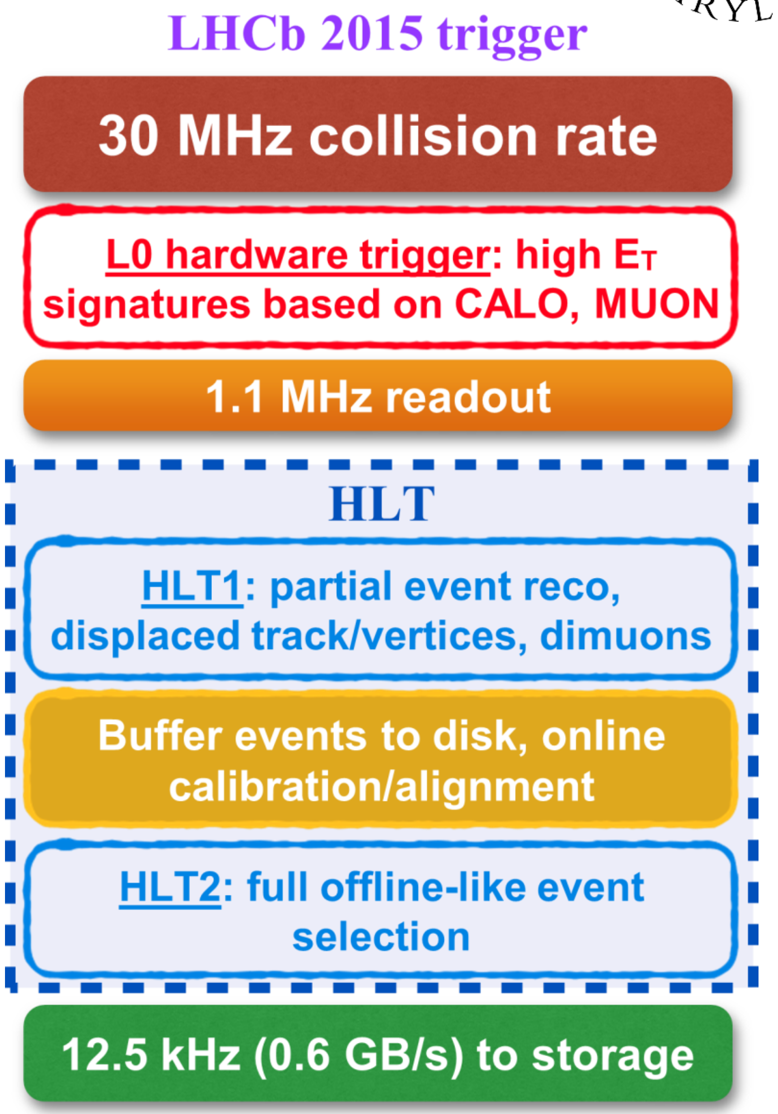
- $A_{CP}(B^+ \to K^+\pi^0)$ is just one of several anomalies observed in the decay of B mesons
- These results are primarily limited by statistics

The LHCb Phase I Upgrade

Current Trigger Limitations

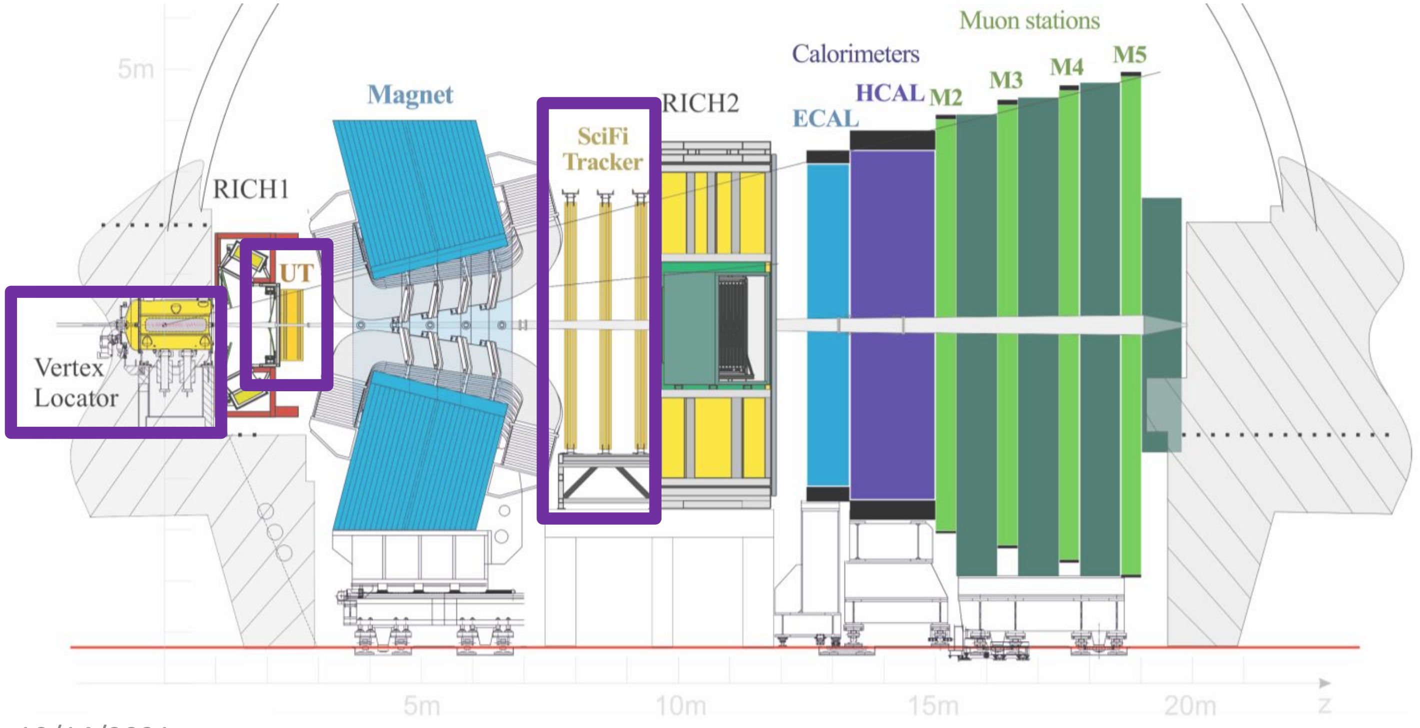
- Data collection currently limited by the trigger
- Increasing luminosity requires increasing energy thresholds
- Occupancy and radiation damage also an issue

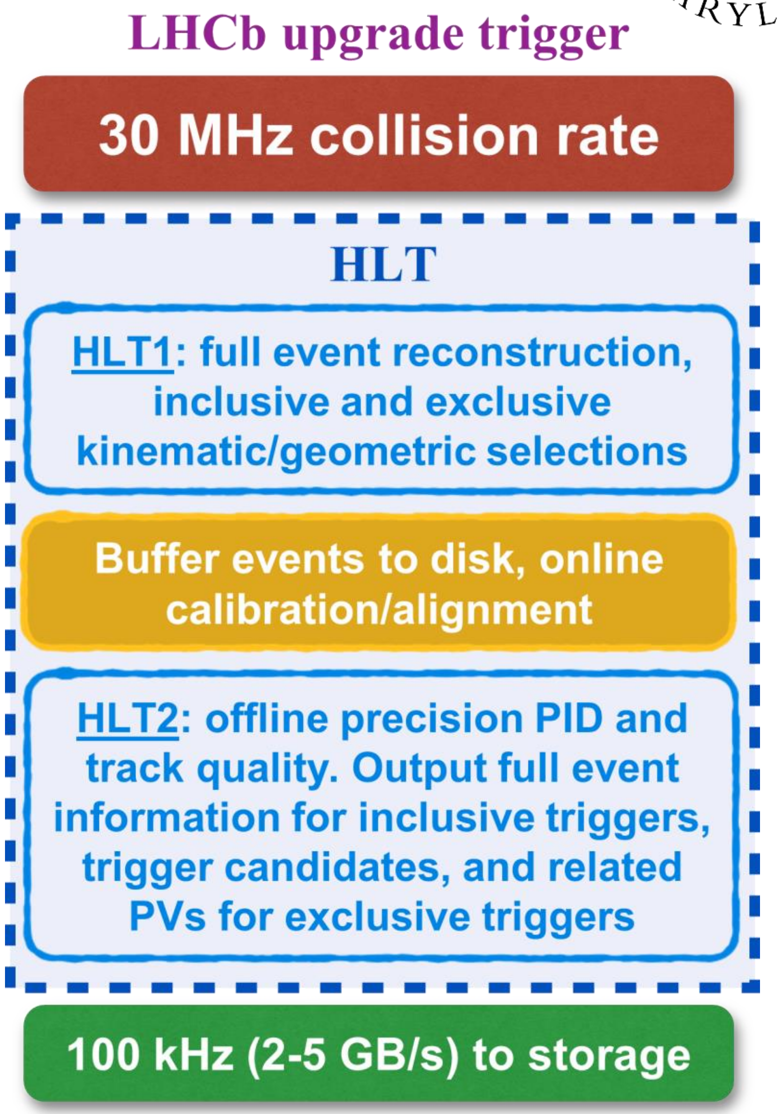




Upgrade Strategy

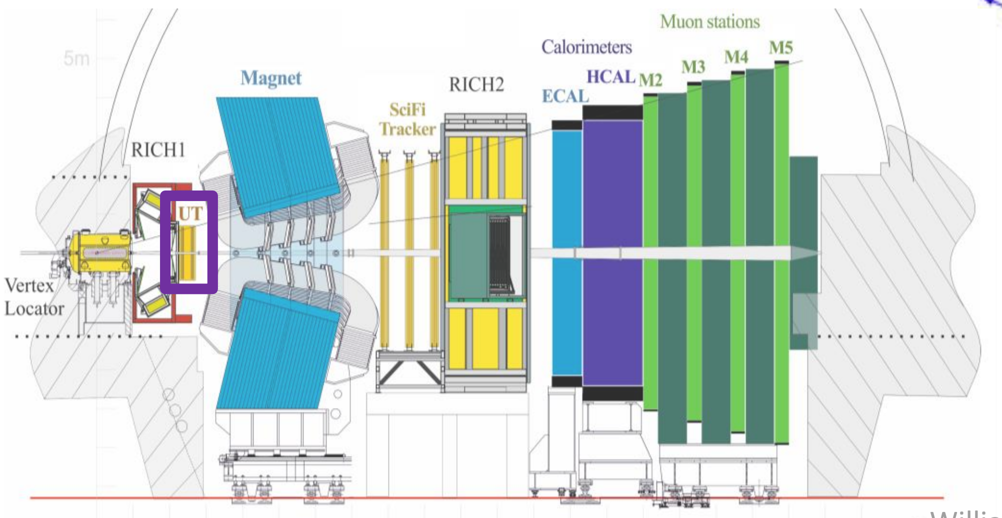
- Read out and reconstruct each event in software before decision
- **Collect 50fb^{-1} of data over the next decade (5x current dataset)**
- Three new detectors: VELOPix, UT, and SciFi
- Fast readout, higher occupancy, radiation tolerance

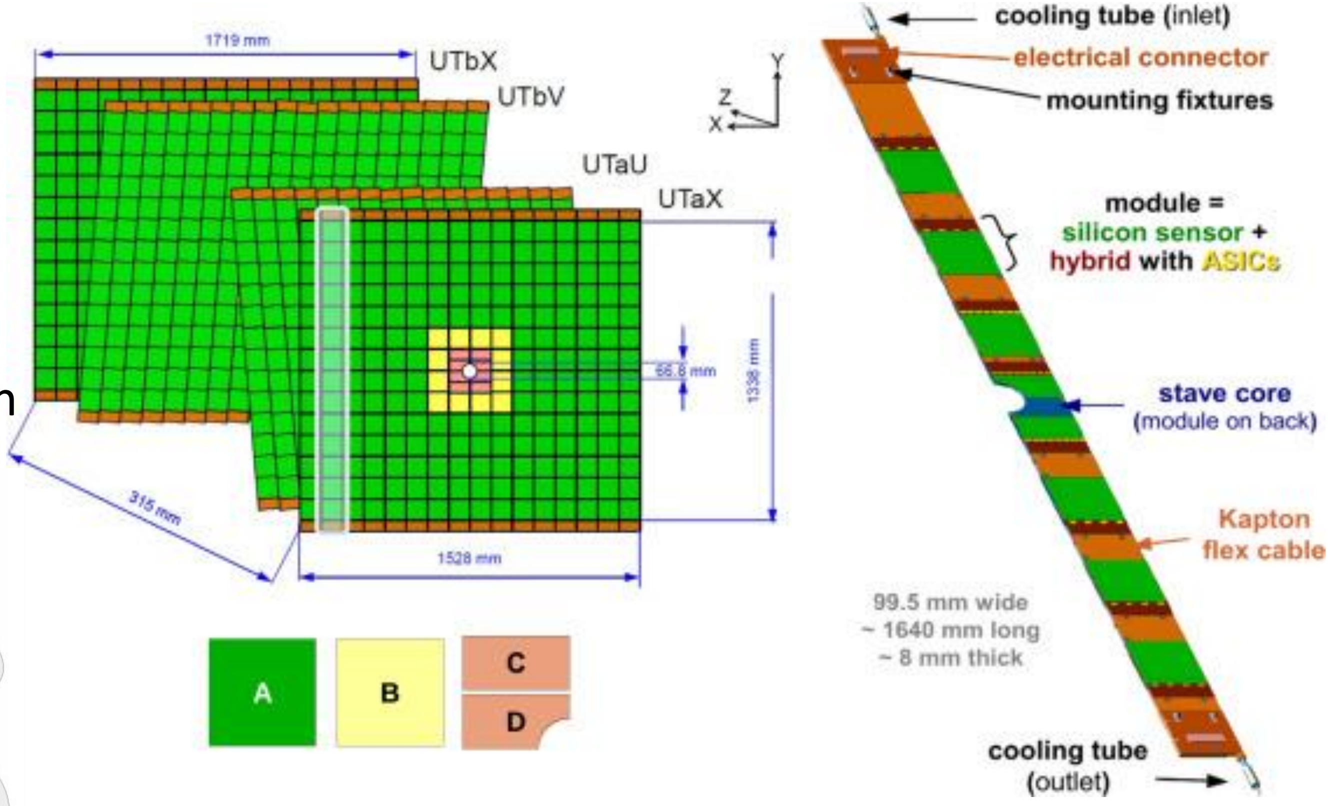




Upstream Tracker

- Critical for upgrade triggering scheme
- Intermediate track information speeds track finding by factor of 3
- 40 MHz readout, improved segmentation and acceptance
- 4 types of silicon sensors mounted on staves with integrated flex and cooling, based on ATLAS design

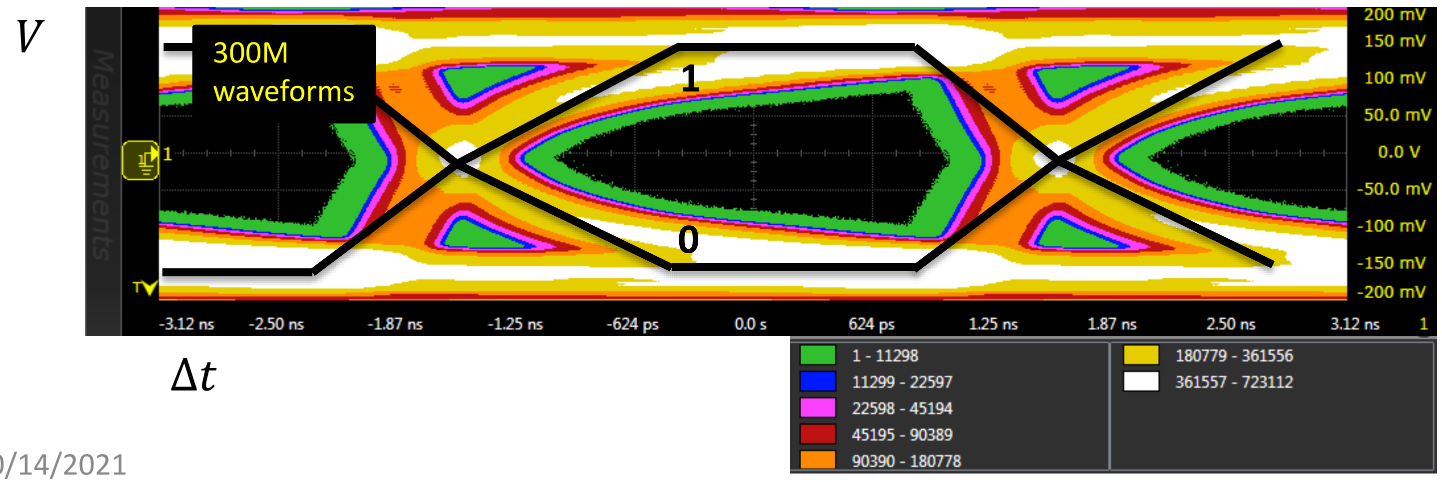


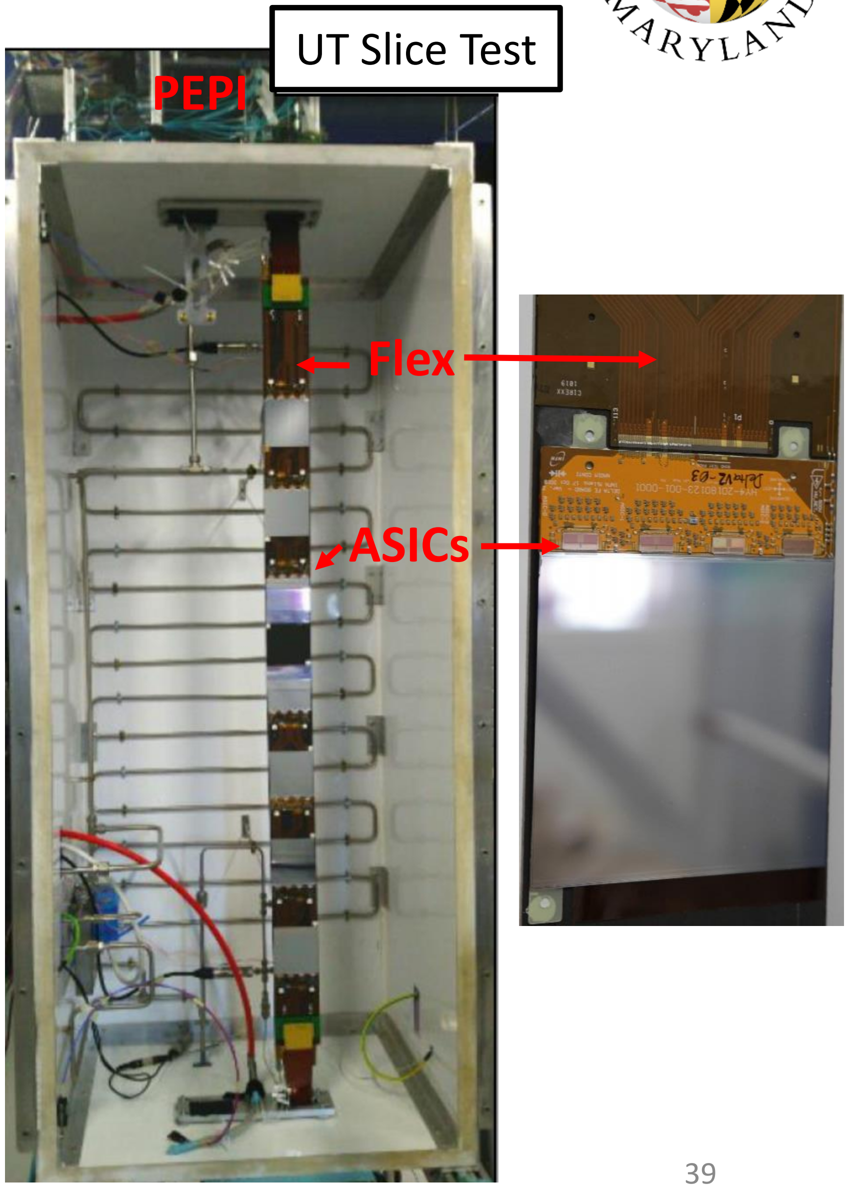


NIM Volume 831, 21 Sept. 2016, 367-369

UT Data Flow

- 4192 custom 128 channel ASICs digitize, zero-suppress, transmit via 3-5 320Mbps output links
- Up to 300 data and control lines transmitted through ~1.2m flexible circuit
- Reorganized and converted to optical signals in Peripheral Electronics Processing Interface
- Cross-talk and attenuation a major concern

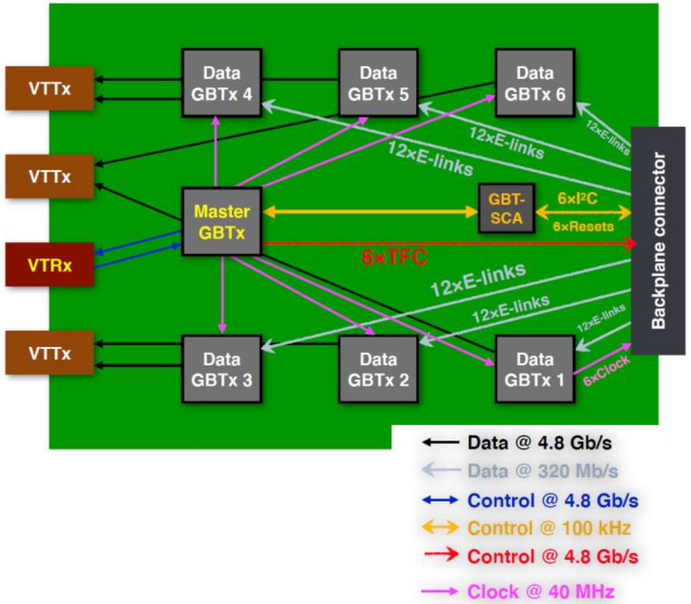




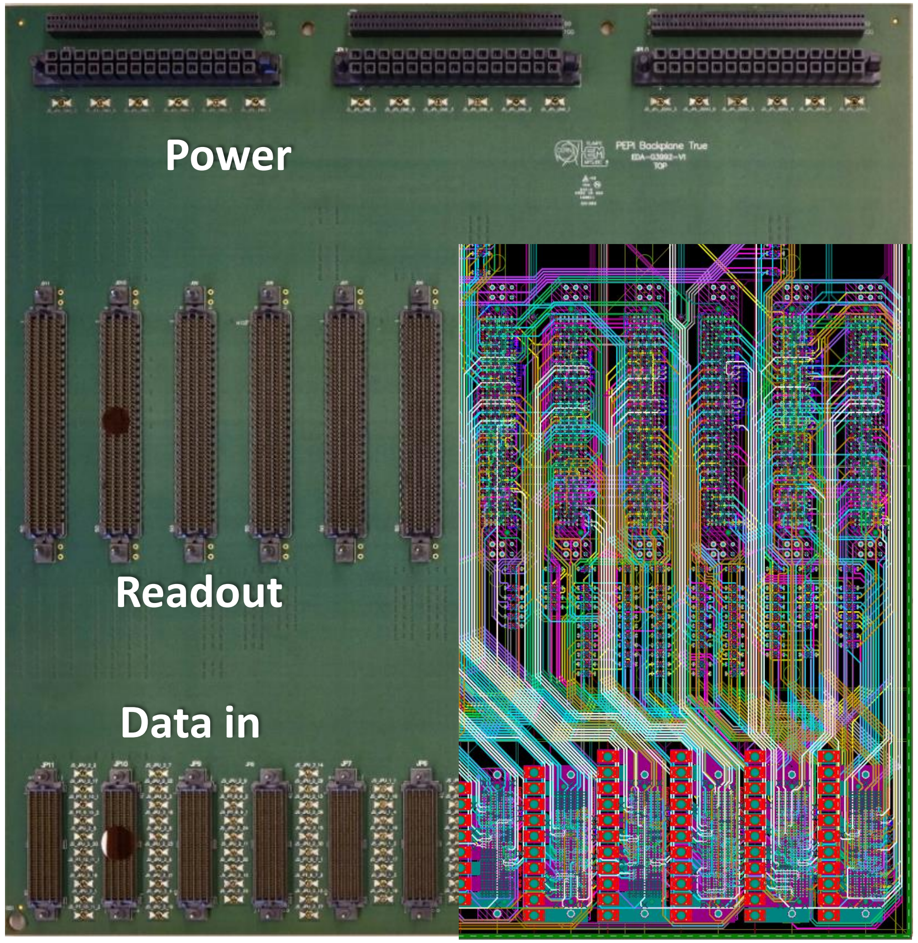
UT Readout Electronics

- All data, control and power routed through backplanes
  - Organize and distribute data
- 248 Data and Control Boards distribute clock and control signals, convert and transmit data optically
  - High-speed rad-hard GBT chip set
  - ~1 TB/s transmitted to control room

Data and Control Board



Backplane



UT Construction

- First staves and all PEPI electronics delivered to CERN
- Frame assembled and aligned
- Now installing backplanes, cooling, and outer flex circuits
- Plan to begin taking data in 2022

$B^+ \to K^+\pi^0$ Upgrade Prospects

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

- Assume simple scaling with luminosity
- Statistical uncertainty with $50\mathrm{fb}^{-1}$: ± 0.005
  - Upgrade I: Expect improved efficiency from trigger but more difficult selection due to higher occupancy
- Dominant sources of systematic uncertainty
  - Modeling of signal tails, can improve with tighter event selection
  - Uncertainty on raw and CP asymmetry in $B \to J/\psi K^+$ currently statistically limited
- Current prediction for $A_{CP}(K^0\pi^0)$: -0.138 ± 0.025
  - Belle II prospective uncertainty: ± 0.018 with $50\mathrm{ab}^{-1}$ (Phys. Rev. D 78, 111501(R))
- Second upgrade under investigation for HL-LHC, could collect $300\mathrm{fb}^{-1}$ with timing and improved granularity in ECAL

Conclusion

- A measurement of direct CP violation in $B^+ \to K^+\pi^0$ decays has been performed
  - Most precise to date
  - Confirms and strengthens the $K\pi$ puzzle
  - Recently published: Phys. Rev. Lett. **126**, 091802
- First measurement of a single track B decay at the LHC
  - An example of LHCb's potential in modes with neutral particles
- A major upgrade of the experiment is close to completion
  - Collect a factor of 5 more data over the next decade
  - Significantly improve the precision of this and many other results
- Similar trigger in place for $B^0 \to K^0\pi^0$

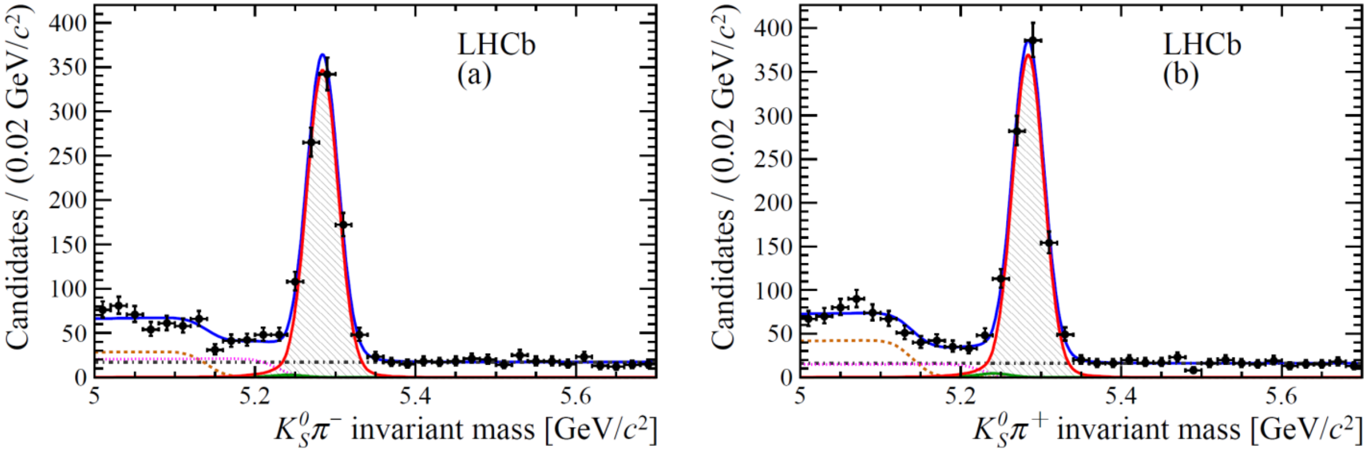
Thank You

Backup

$K\pi$ at LHCb

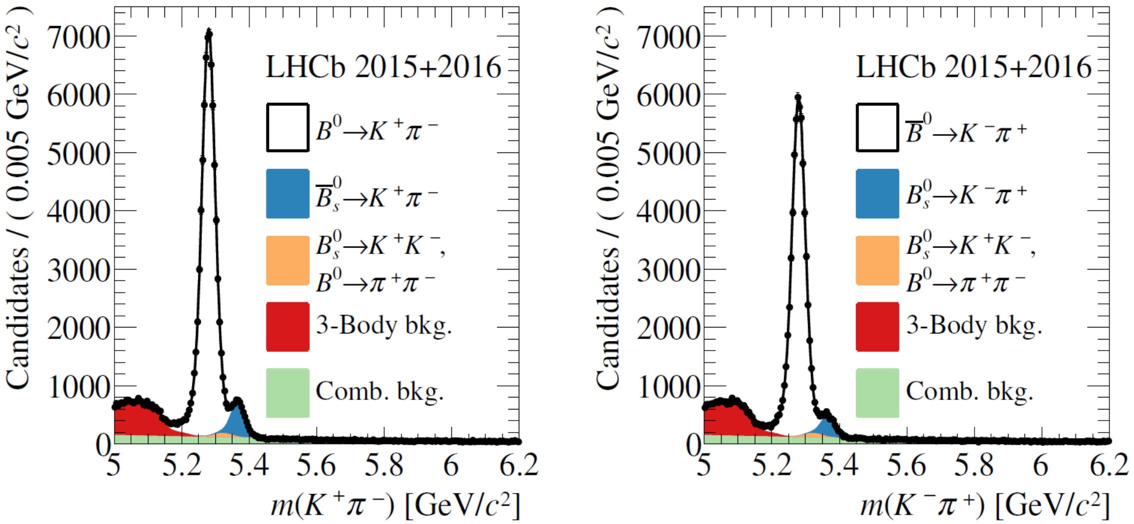
- $A_{CP}(B^+ \to K_S^0\pi^+)$, $A_{CP}(B^+ \to K_S^0 K^+)$, ratio of branching fractions measured with Run I data
- Most precise measurement of $A_{CP}(B^0 \to K^+\pi^-)$ with 1.9fb^{-1} Run II data
  - Also measured A_{CP} in $B_s^0 \to K^+\pi^-, K^+K^-$
- Provide additional information about diagrams related to $K\pi$ system by U-spin symmetry
  - First observation of time-dependent CP violation in B_s^0 decays

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



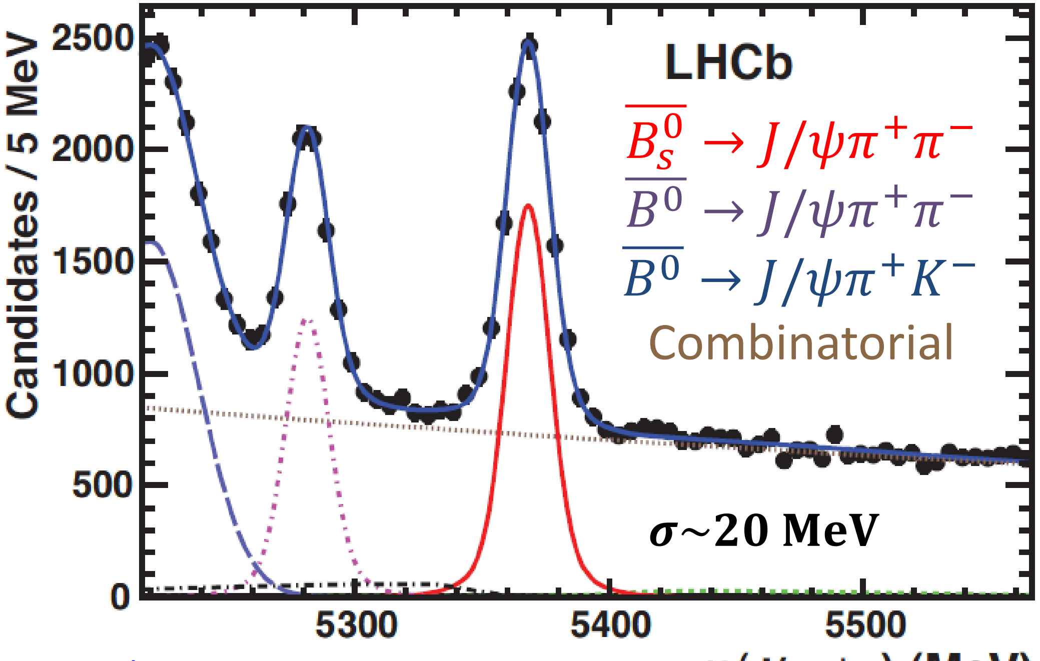
Phys.Lett. B 726 (2013) 646

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

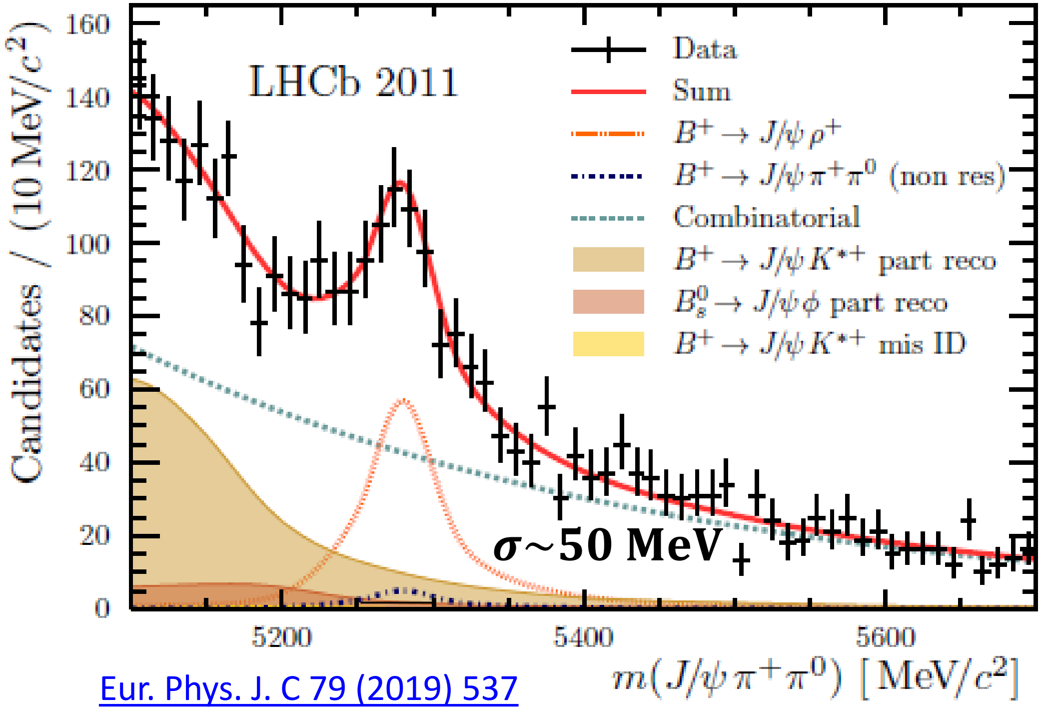


JHEP 03(2021)075

π^0 at LHCb



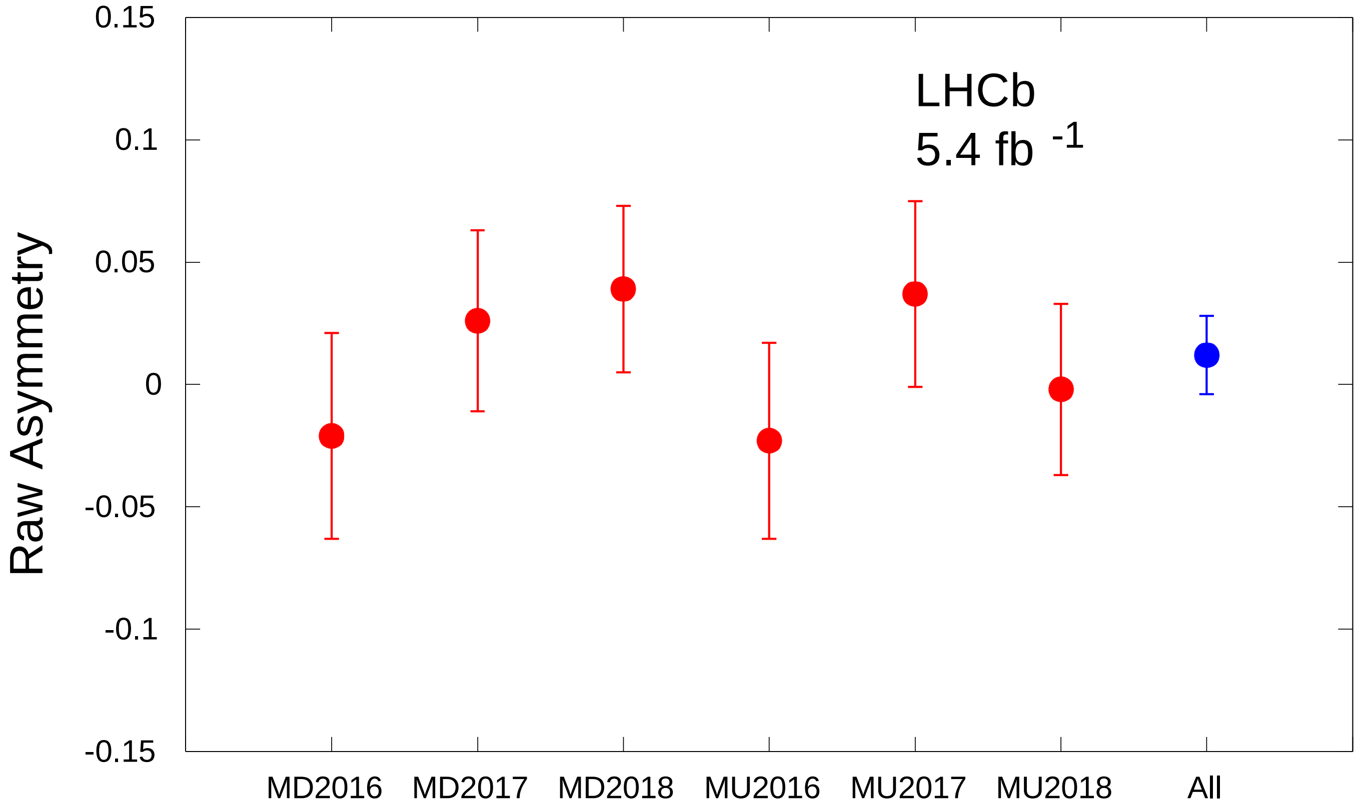
[Phys. Rev. D 86, 052006](#)



[Eur. Phys. J. C 79 (2019) 537](#)

- LHCb analyses of 3- and 4-body decays include modes with π^0
- Wider mass resolution, lower efficiency compared to charged-only modes

Consistency by Year



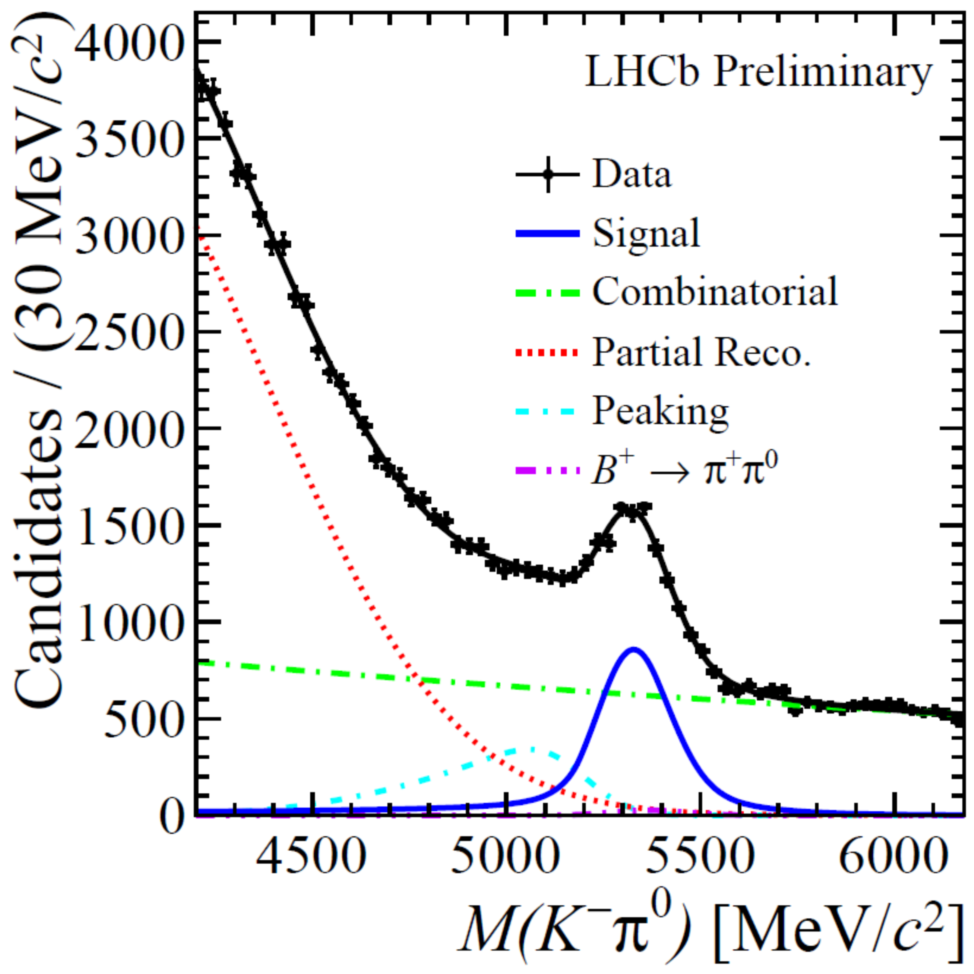
- Consistent between years and magnet polarities
- Additional checks: Binning by kaon p_T and magnet polarity, allowing shape parameters to vary between charges and magnet polarities
- Raw asymmetry consistent in all cases

$B^+ \to K^+\pi^0$ Trigger

Variables	Requirements
K^+ p_{T}	$> 1200\,\mathrm{MeV}/c$
K^+ p	$> 12000\,\mathrm{MeV}/c$
K^+ IP χ^2 PV	> 50
K^+ PIDk	> -0.5
π^0 p	$> 5000\,\mathrm{MeV}/c$
π^0 p_{T}	$> 3500\,\mathrm{MeV}/c$
π^0 mass	$76.0 < m < 195.0\,\mathrm{MeV}/c^2$
$K^+ + \pi^0$ p_{T}	$> 6500\,\mathrm{MeV}/c$
B^+ p_{T}	$> 5000\,\mathrm{MeV}/c$
B^+ mass	$4000 < m < 6200\,\mathrm{MeV}/c^2$
B^+ MTDOCAχ^2	< 8

Invariant Mass Fit

- Signal
  - Crystal Ball function (low mass tail), and Gaussian with exponential tail (high mass tail)
  - Tail shape parameters fixed to values from simulation
- Combinatorial background
  - Exponential
- Partially reconstructed background
  - Gaussian tail
- Partially reconstructed peaking backgrounds
  - Parabolic × Gaussian function (JHEP 06 (2020) 058)
  - Endpoints fixed to $B^+ \to (K^{*+} \to K^+\pi^0)\pi^0$ kinematically allowed values
  - Mass shift fixed to (signal mean – M(B^+))
  - Resolution fixed to signal resolution
  - Rel. height fixed to simulation values (insensitive)
- $B^+ \to \pi^+\pi^0$
  - Gaussian with exp. tail convoluted with π^0 res. Gaussian
  - Shape parameters and offset fixed to simulation values
  - Yield fixed to 2.4% of signal yield



Systematics – Fit Variations

- Signal
  - Crystal Ball + Gaussian w/tail → single Gaussian
- Combinatorial background
  - Exponential → linear
- Partially reconstructed background
  - Gaussian tail → Argus cut off at $M(B-2\pi)$
- Partially reconstructed peaking backgrounds
  - Parabolic × Gaussian function → Argus cut off at $M(B-\pi)$
  - Mass shift fixed to (signal mean – M(B^+)) → floating
  - Resolution fixed to signal resolution → floating
- $B^+ \to \pi^+\pi^0$
  - Yield fixed to 2.4% of signal yield → removed from fit
  - CP asymmetry fixed to 0 → fixed to $\pm 1\sigma$ of measured value
- Events with multiple candidates removed from fit