The TORCH Detector

Physics case

Tom Hadavizadeh,
on behalf of the TORCH collaboration

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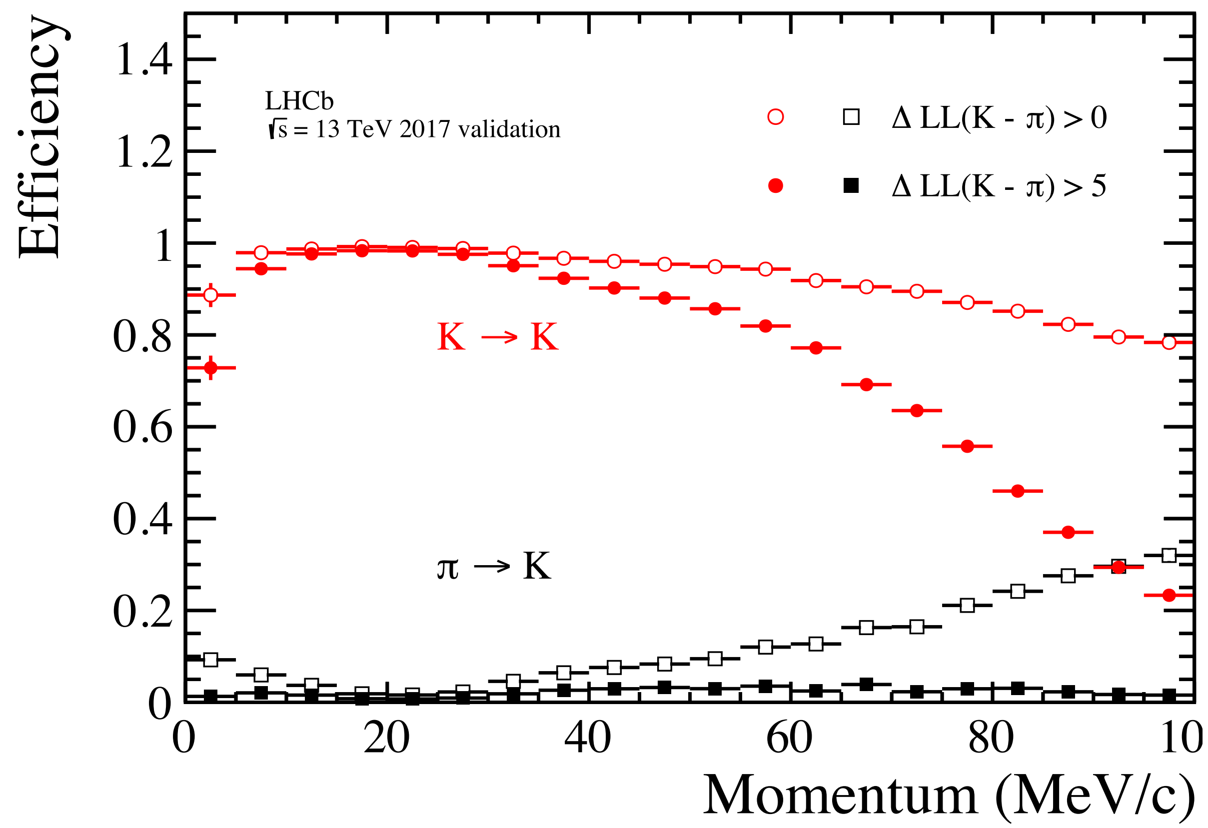
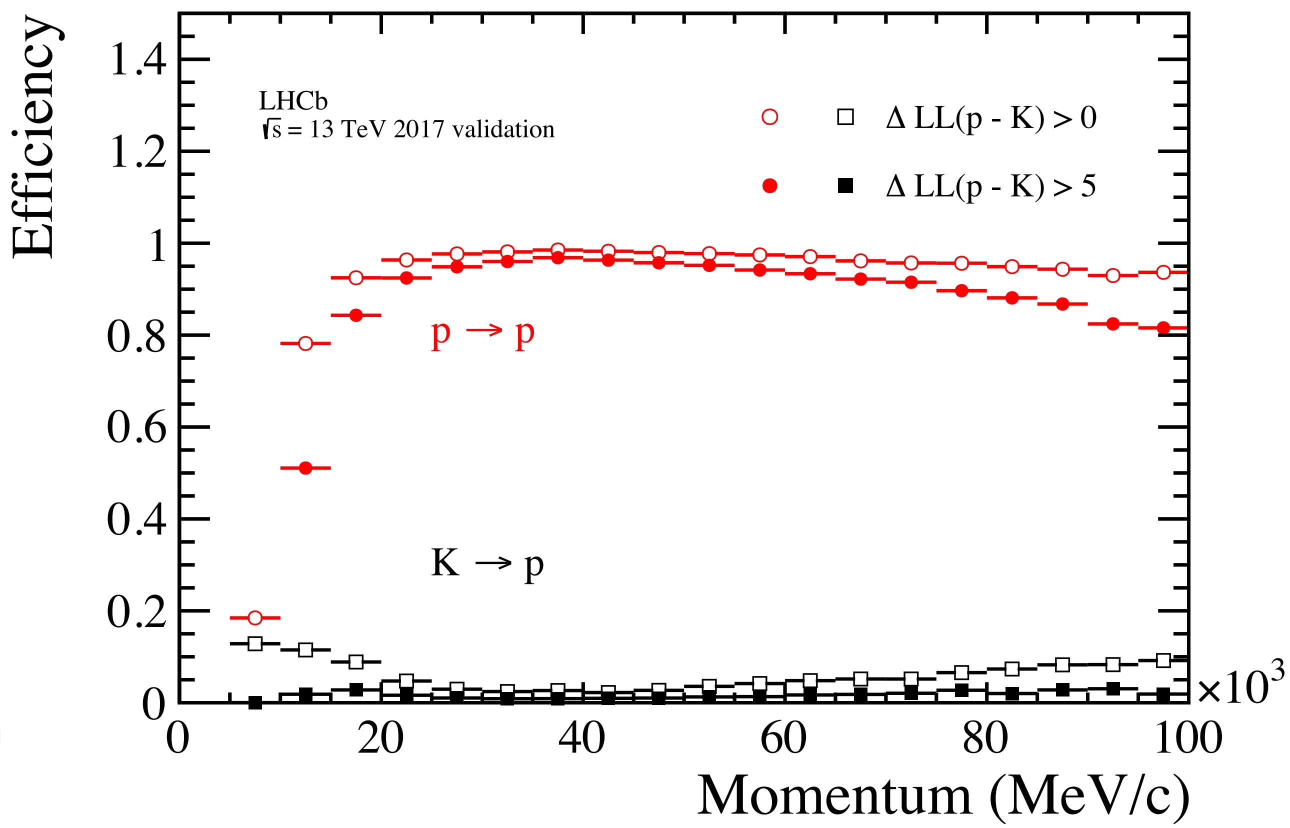
4th Workshop on LHCb Upgrade II

Physics motivation

- The aim of our physics studies are to quantify the improvement in physics performance from the proposed TORCH detector





- The current RICH system provides no positive kaon or proton identification below 10 GeV/c

- The TORCH detector is designed to complement the existing RICH detector discrimination

Review recommendations

A number of recommendations were made during the review of the TORCH proposal

This talk has been updated with respect to the one given in the review session

Recommendations

Today

- ✓ Continue physics studies with full simulation of TORCH integrated into LHCb

Future studies

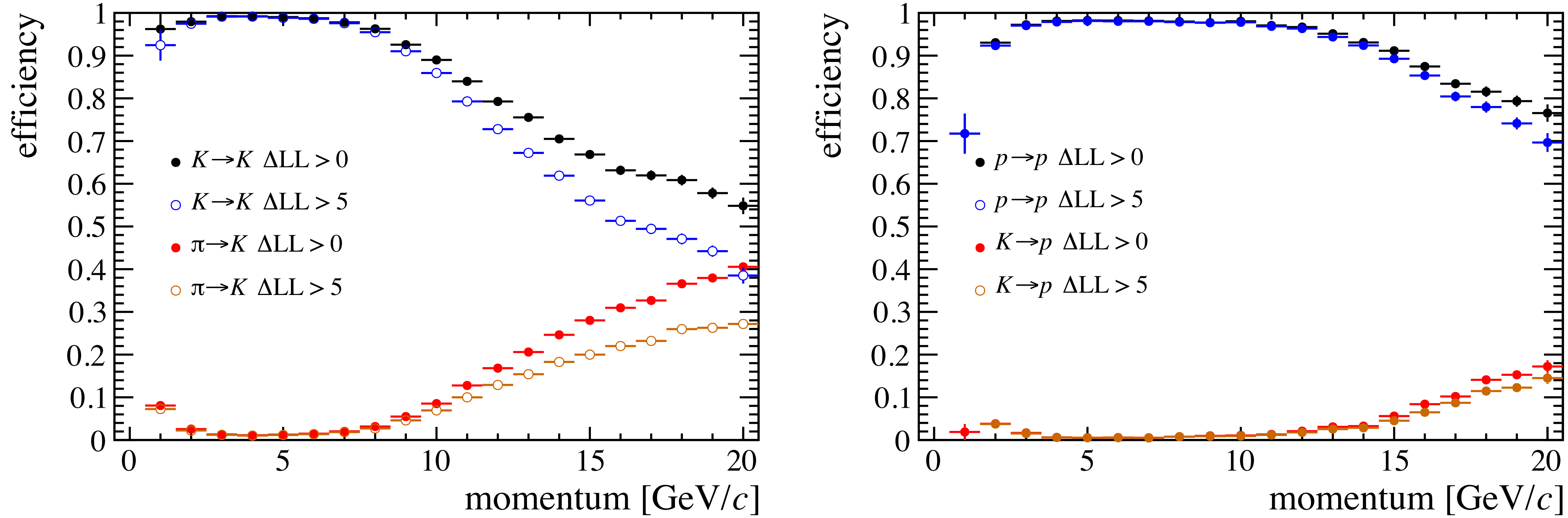
- ➡ Extend TORCH physics studies to Upgrade II conditions
- ➡ Perform physics studies with degraded performance, e.g. time resolution and photon yield
- ➡ Perform realistic studies to determine if there is any degradation in other channels from TORCH
  - We intend to produce samples of $B \rightarrow K^*$ gamma and $B \rightarrow K^*$ ee to check for degradation in ECAL performance

Outline

- PID performance
- Flavour tagging studies
  - Improved low-momentum PID
  - Impact of timing information
- Improvements for specific channels
  - Key modes with protons/kaons
  - Other modes
- Further studies of interest

PID performance

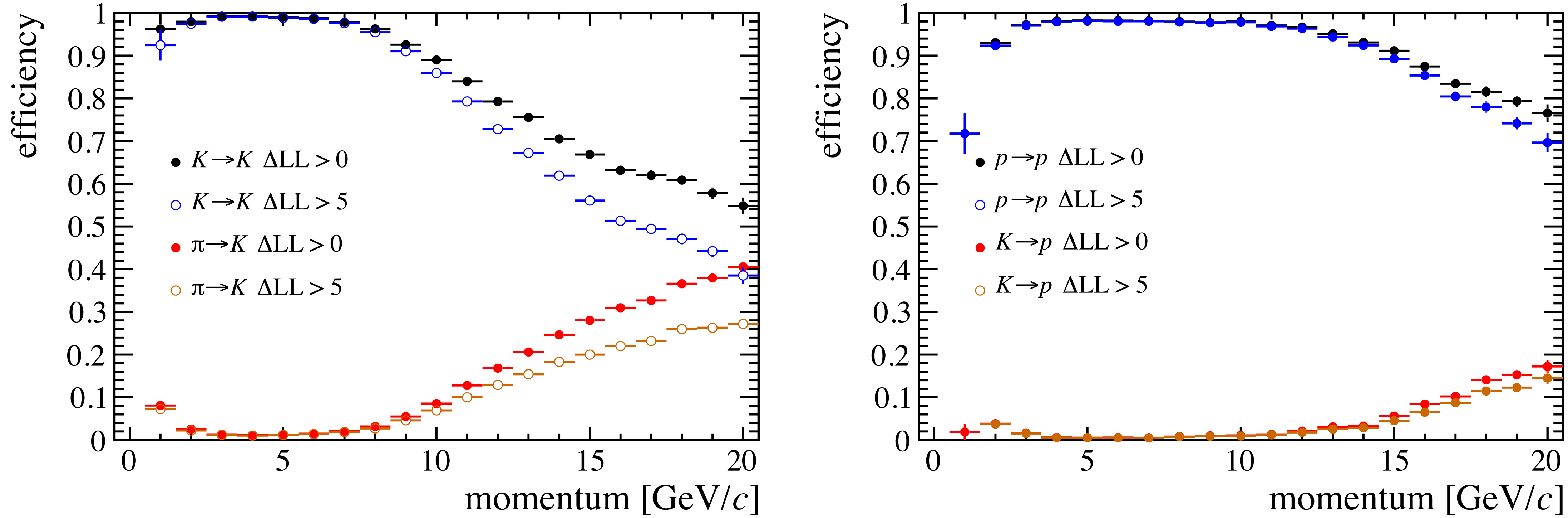
TORCH performance in LHCb



- The TORCH PID performance is determined using full simulations of TORCH in LHCb
- This PID performance is incorporated into existing Upgrade I LHCb MC samples on an analysis-by-analysis basis
    - The simulated TORCH and RICH PID efficiencies are combined for the relevant set of PID requirements

PID performance

TORCH performance in LHCb

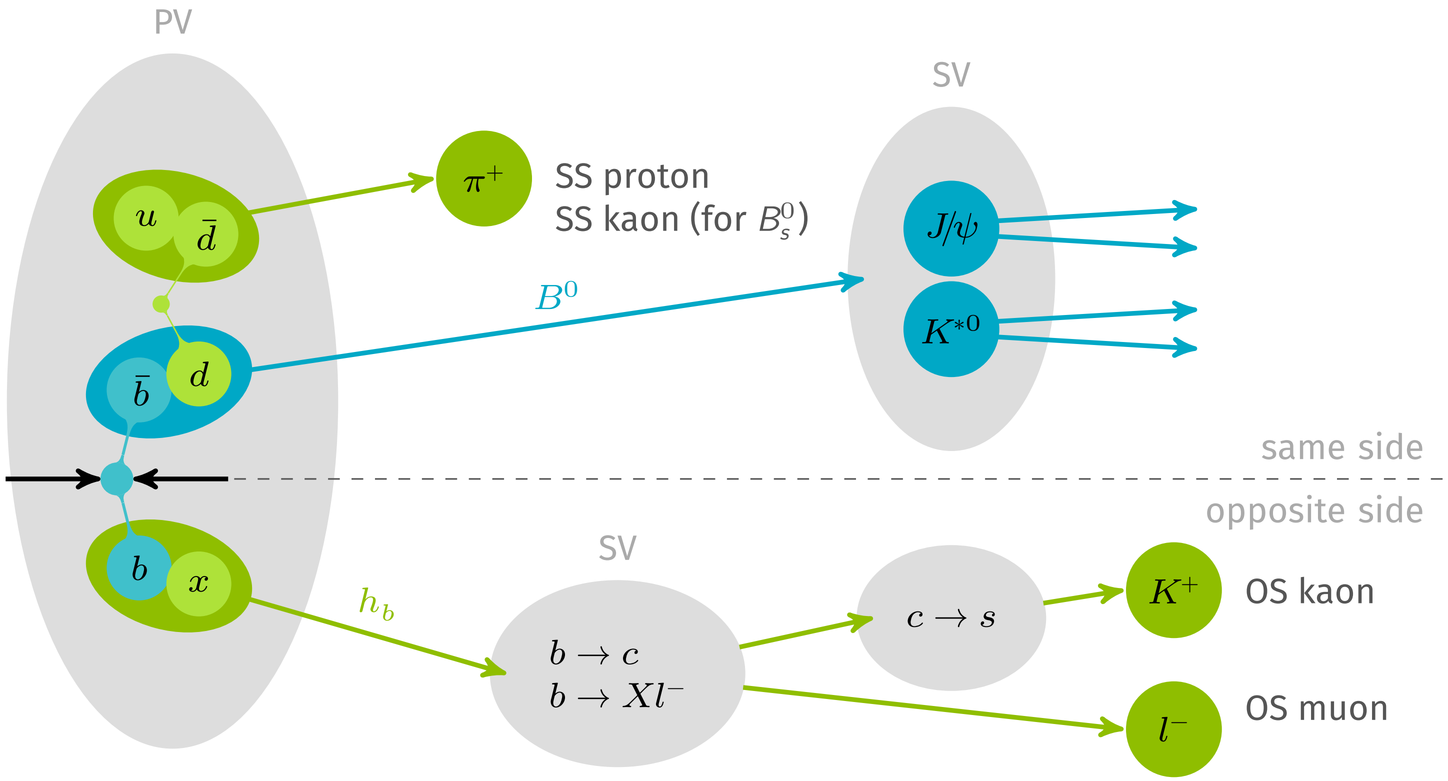


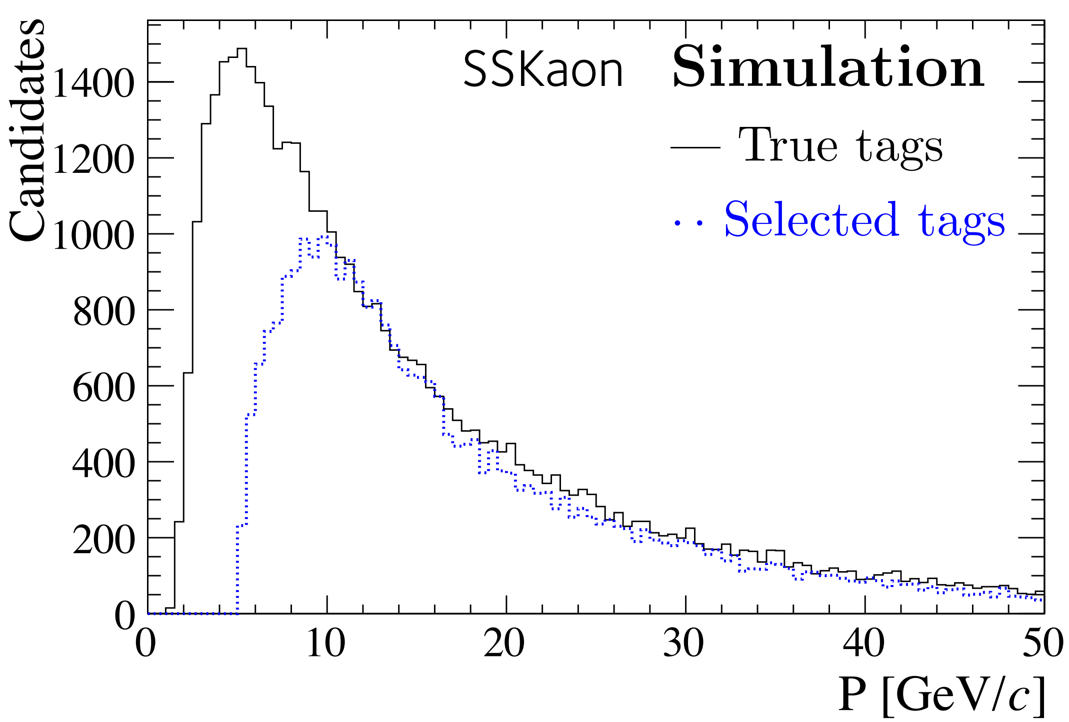
Some clarifications

- The candidates in the LHCb MC are constructed using **reconstructed** tracks
- The RICH PID performance is taken from the MC samples themselves

Flavour tagging

- Two aspects of flavour tagging have been investigated:
  - The effect of **improved low-momentum PID** performance on tagging power
  - The effect of **correct track-PV association** on tagging power as a function of the number of PVs
- To achieve this, simple **cut-based** tagging algorithms have been constructed
- This method has been used to isolate the effect of TORCH





Tagging Part I: PID

- Simple tagging algorithms are developed: **OSKaon** and **SSKaon**
- Three tag track selection methods are used:

Selection	Tracks with p<10 GeV/c	Tracks with p>10 GeV/c
Nominal	Nominal (i.e. p/p_T and RICH PID cuts)	Nominal
TORCH PID	Use TORCH efficiencies/mis-id rates	Nominal
Perfect PID	Only truth matched kaons	Nominal

- **Nominal:** the requirements on (RICH) PID and momentum are applied (selections in backup)
- **TORCH PID:** the TORCH efficiency and mis-id rates from the stand-alone simulations are used with the truth information to select the right fraction of each species for the corresponding RICH PID requirements
- **Perfect PID:** the performance using just the correct particle type (e.g. kaon) is compared as an upper limit of the possible PID-related improvement

Tagging Part I: PID

- The tagging power is compared for the different configurations

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}} \times (1 - 2\omega)^2$$

$$B_s^0 \to D_s^+ \pi^-$$

Tagger	$B_s^0 \to D_s^+ \pi^-$		
	Nominal	TORCH	Perfect
`SSKaon`	$1.20 \pm 0.05\%$	$1.52 \pm 0.05\%$	$1.61 \pm 0.05\%$
`OSKaon`	$1.29 \pm 0.05\%$	$1.73 \pm 0.06\%$	$1.80 \pm 0.06\%$

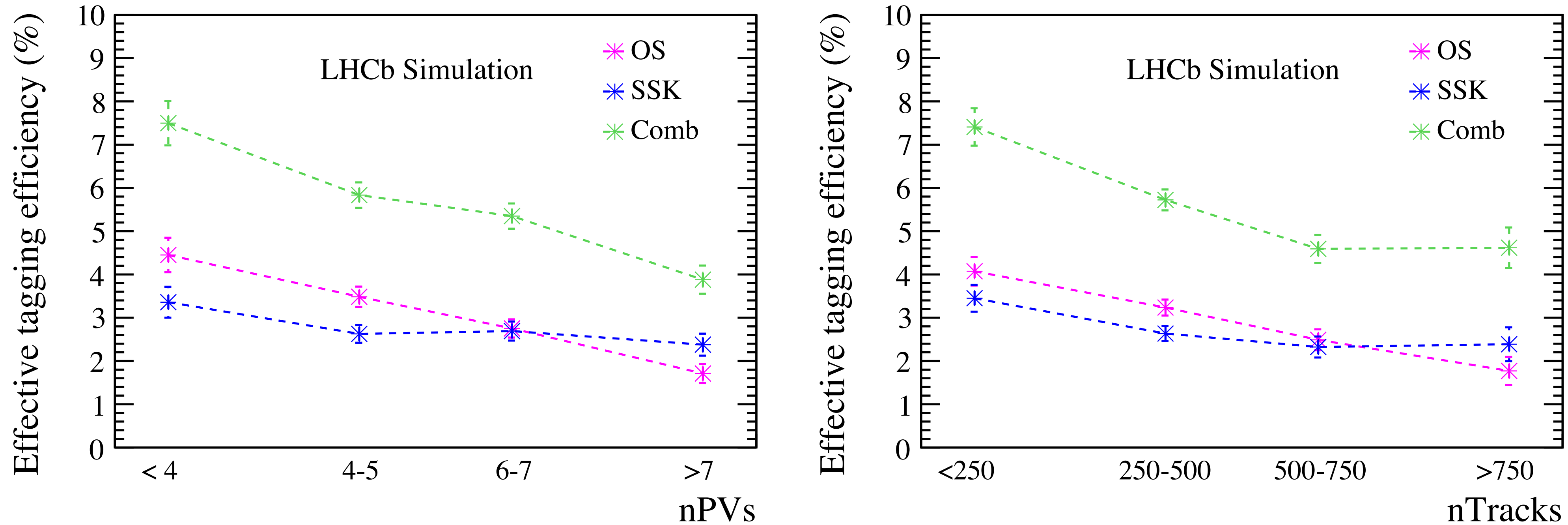
$$B^+ \to J/\psi\, K^+$$

Tagger	$B^+ \to J/\psi\, K^+$		
	Nominal	TORCH	Perfect
`OSKaon`	$1.06 \pm 0.04\%$	$1.51 \pm 0.05\%$	$1.61 \pm 0.05\%$

- TORCH increases the tagging power for both algorithms
- Improvements consistent between the two samples
- Performance approaches upper limit with perfect PID below 10 GeV/c

Tagging Part II: timing

- The TORCH detector could provide information about the timing of tracks to help correctly associate tracks to primary interactions
- Presently, the simulation doesn't model the per-track timing
- The flavour tagging group has already shown that the tagging performance decreases with higher levels of pile up

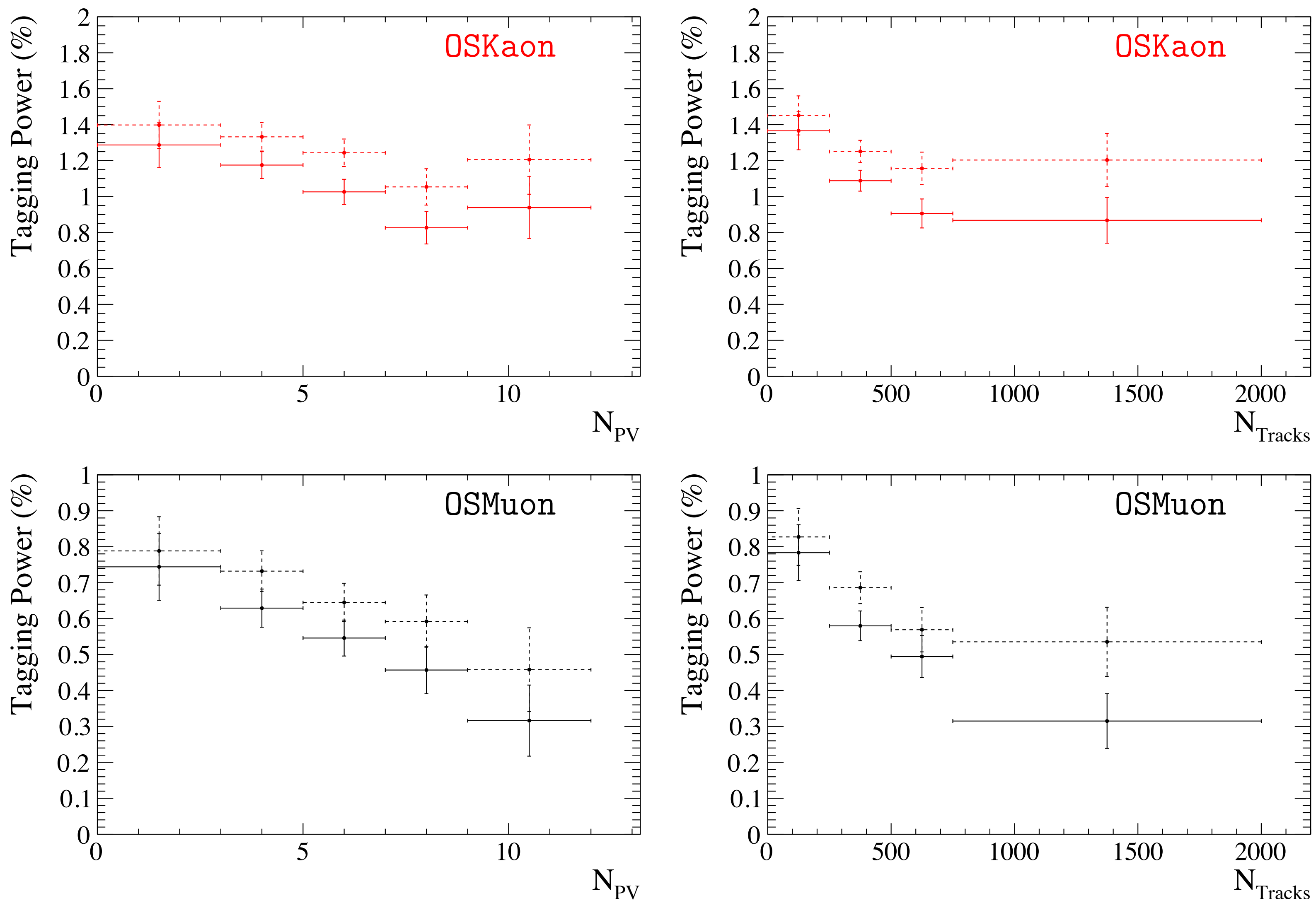


- This TORCH study aims to determine the upper limit of the improvement if tracks could be correctly associated to their PV

LHCb collaboration, R. Aaij *et al.*, *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, arXiv:1808.08865.

Tagging Part II: timing

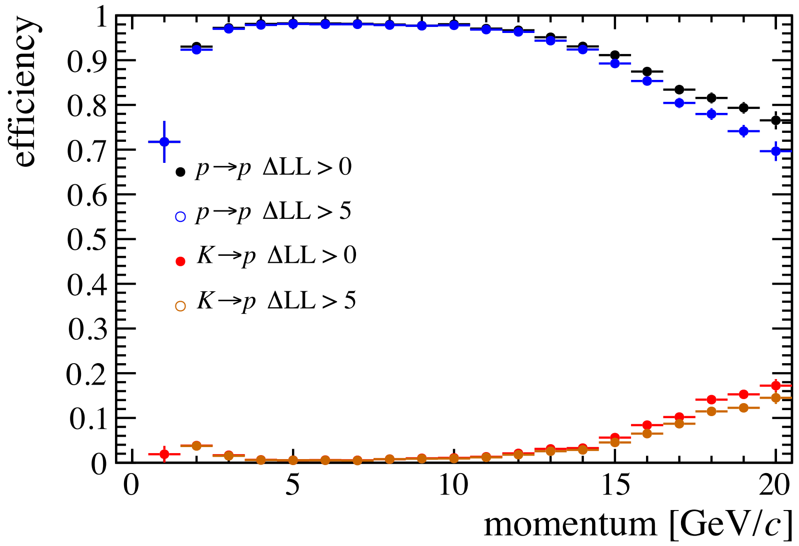
- Two opposite side tagging algorithms, **OSKaon** and **OSMuon**, are constructed
- The performance is compared between the nominal configuration (filled) and the situation in which all tracks originating from a different PV are removed (dashed)

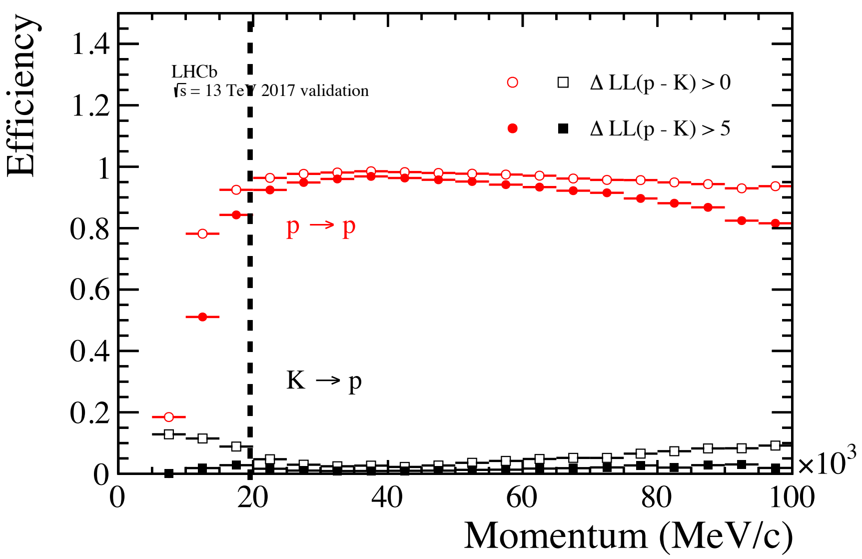


- The tagging power improves, but the dependence on the number of PVs and tracks is not removed entirely

Specific decays

- The second part of the physics studies quantitatively assess the impact of TORCH on specific decay modes:
  - **Signal efficiency:** How much more signal would TORCH select?
  - **Background rejection:** Would TORCH improve the misidentification rate of backgrounds?
  - **Flatness:** Would the dependence of efficiency on phase-space be reduced?





- The RICH and TORCH PID performances are combined by selecting whichever is larger below 20GeV/c (above 20GeV/c just RICH PID is used)
- This PID performance is combined with samples of Upgrade I MC for each mode

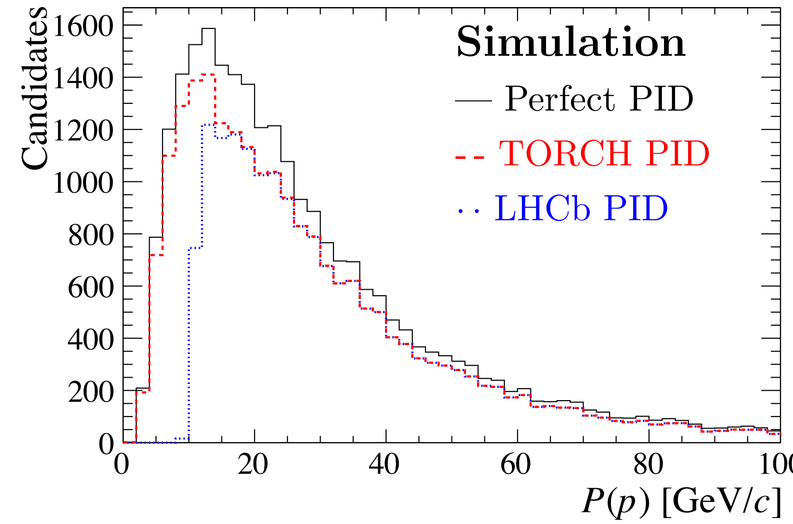
Pentaquark

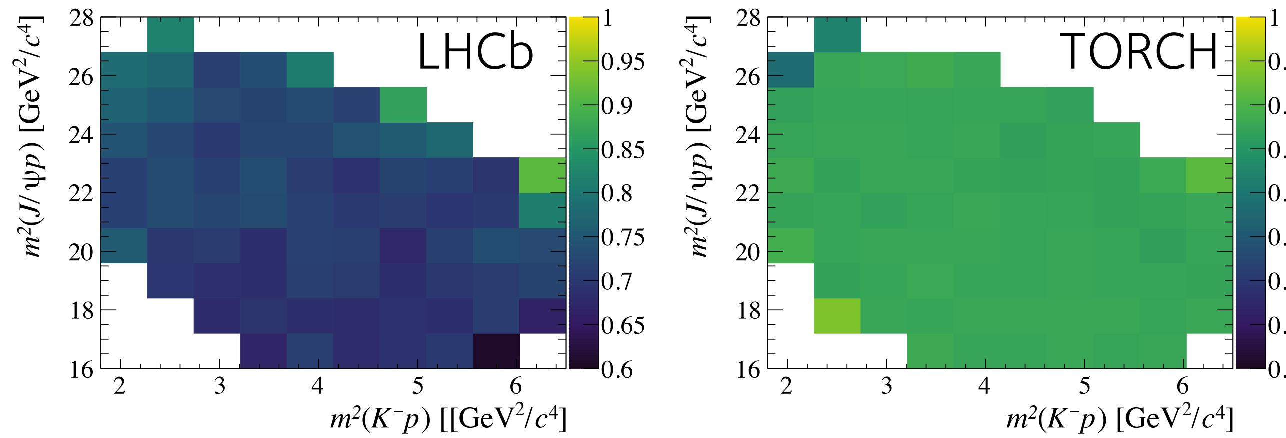
$$\Lambda_b^0 \to J/\psi p K^-$$

- This decay uses PID cuts to reduce misidentification backgrounds

- Including the TORCH performance for the same PID cuts increases the signal yield by 23%

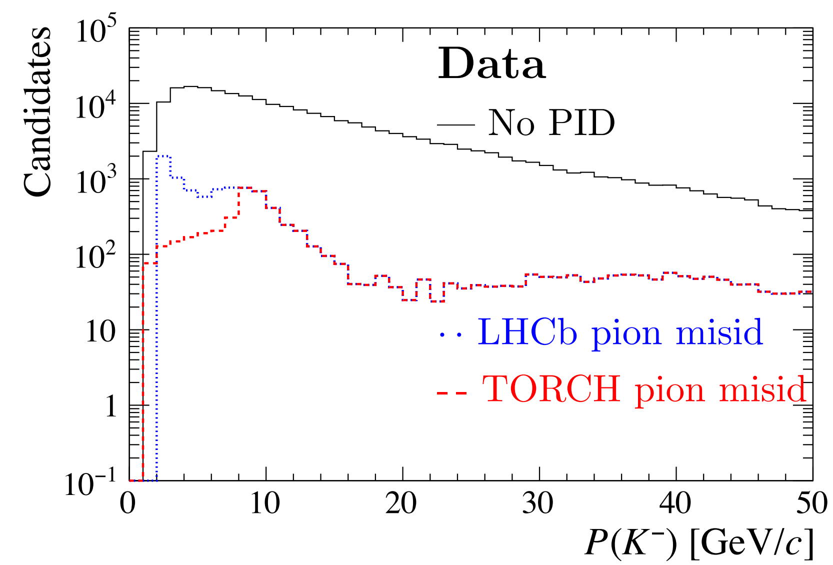
- The variation in PID efficiency across the Dalitz plot significantly reduces





- Run II data is used to qualitatively investigate the level of combinatorial background

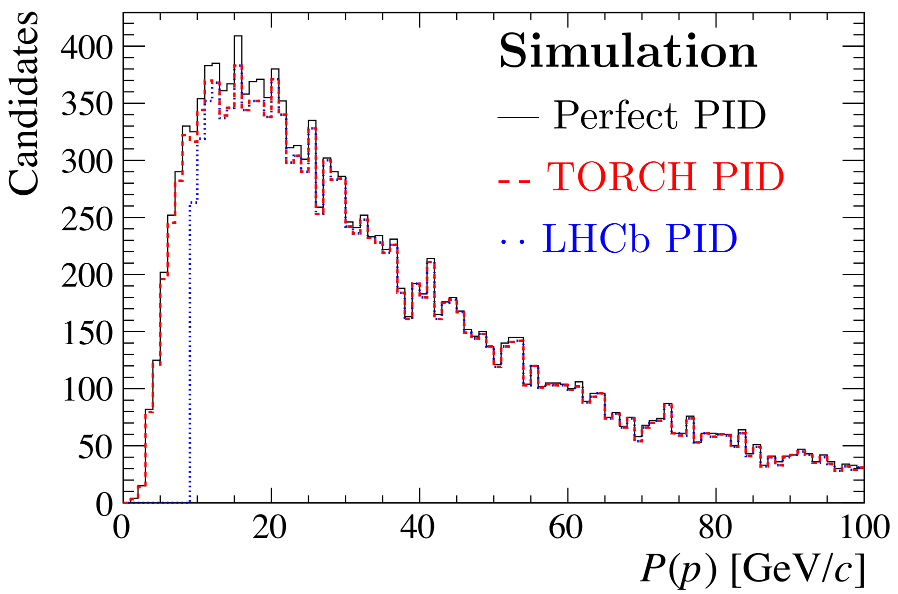
- Assuming the background is composed entirely of pions, TORCH improves the low momentum background rejection



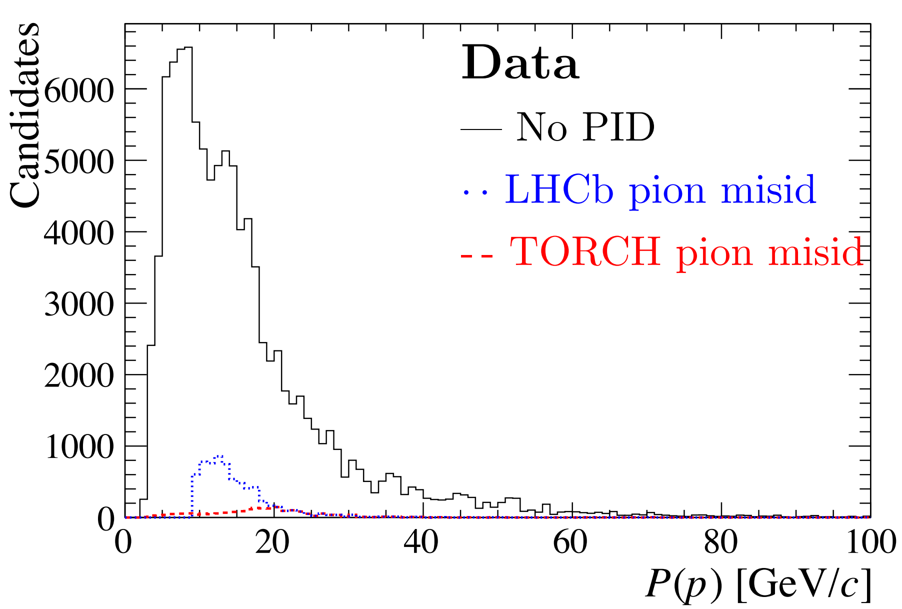
Baryon asymmetry

$$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$$

- Similarly, this mode requires PID requirements to select the proton (using a ProbNNp cut)
- Using a corresponding DLL cut, there is ~10% more signal using the TORCH PID performance



- Run II data has been used to qualitatively investigate the background level
- The TORCH performance shows an improved background rejection, assuming all background are pions



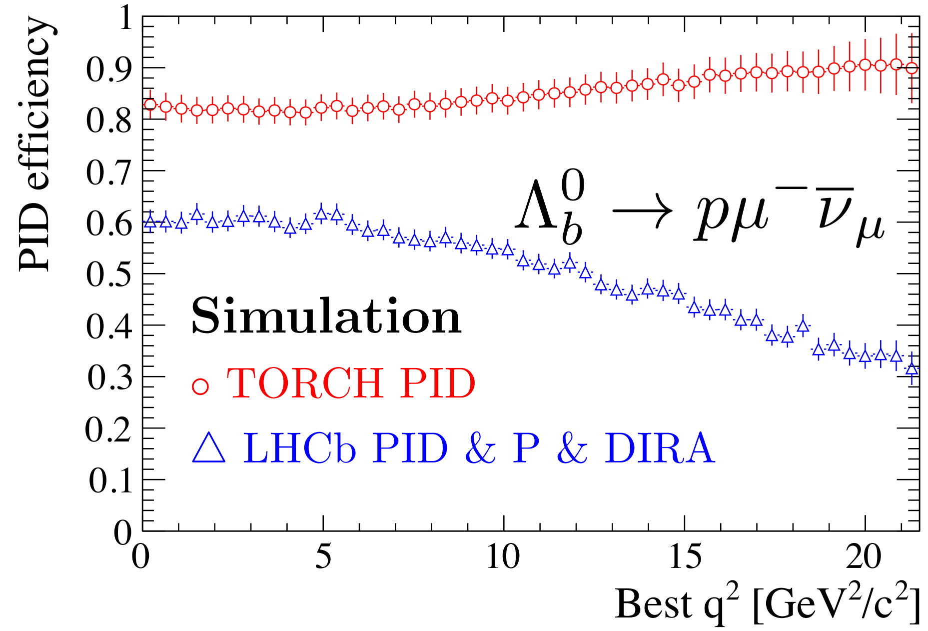
Semi-leptonic V_{ub}

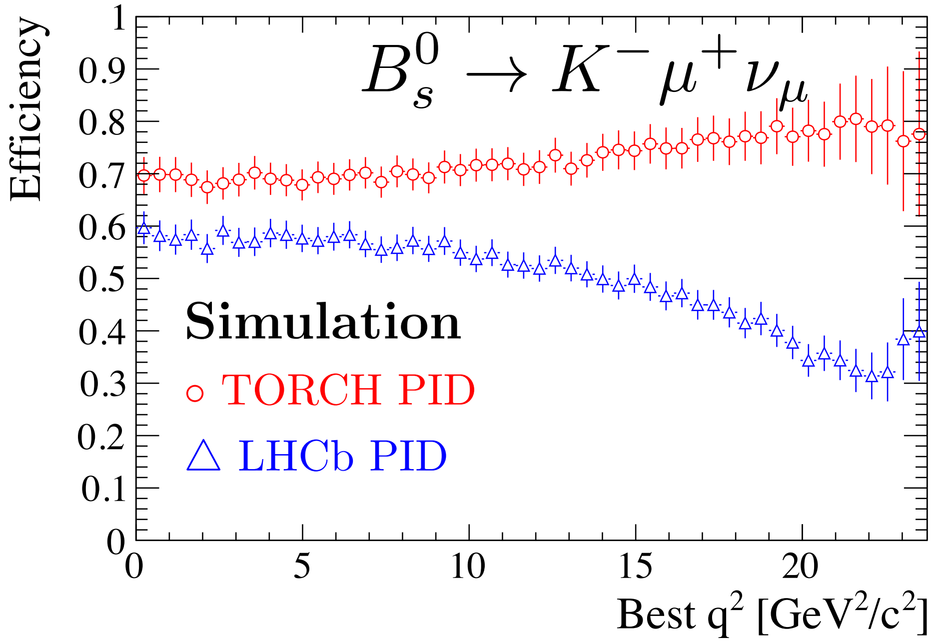
- Semi-leptonic decay modes used to measure V_{ub} will gain from TORCH
- Theoretically predicted form factors are most precise at high q^2, where the experimental efficiency is lowest
- These analyses require tight PID requirements to suppress misidentification backgrounds
- Incorporating the TORCH performance at low momentum leads to substantial improvements in signal yields:

$\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ both $q^2 > 15\,\mathrm{GeV}^2/c^2 \to$ 130% increase

$B_s^0 \to K^-\mu^+\nu_\mu$ all q^2 $\to$ 35% increase

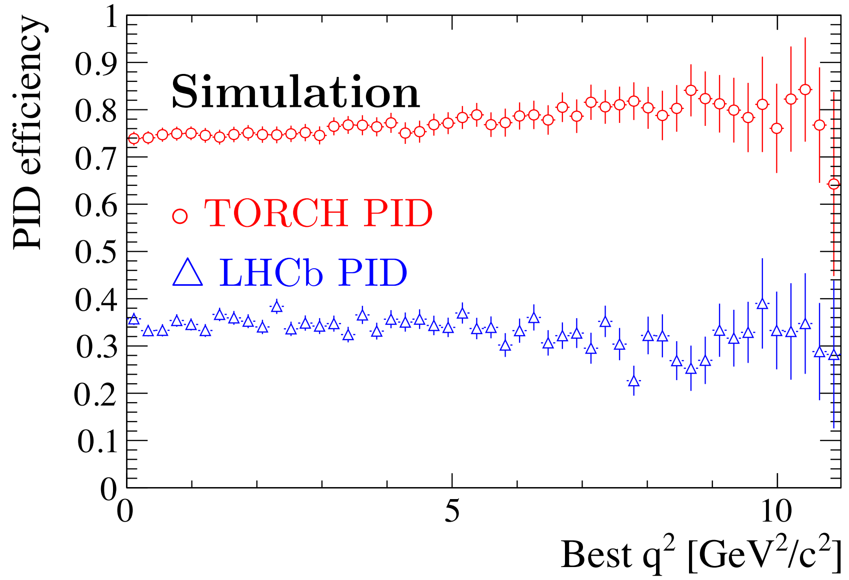
$q^2 > 10\,\mathrm{GeV}^2/c^2$ $\to$ 54% increase





Other modes

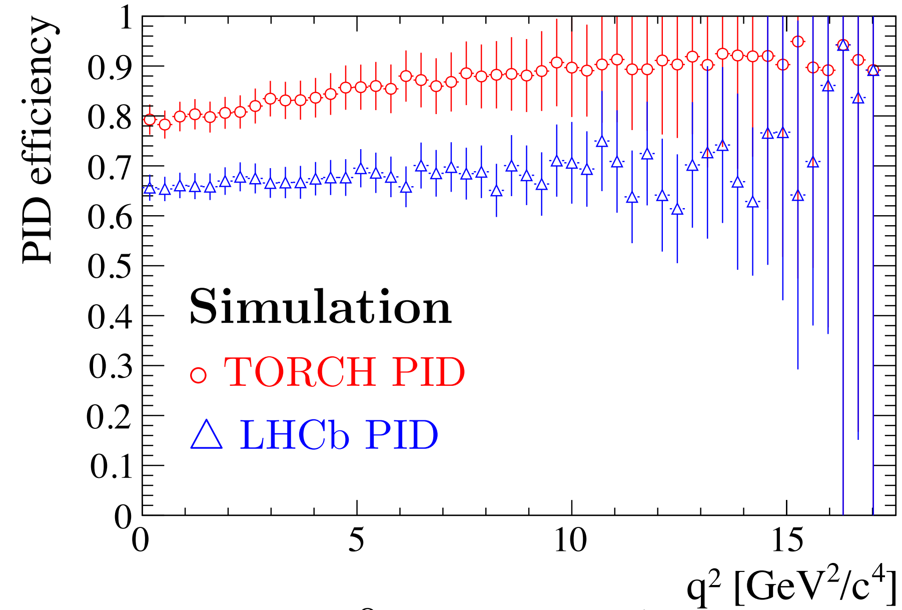
- A range of other modes have been investigated:
  - Generally, the improvements depend on how tight the requirement on kaon-proton separation is



$$B^+ \to p\bar{p}\mu^+\nu_\mu$$

Tight momentum and PID requirements

- Gains around 121% extra signal yield



$$\Lambda_b^0 \to pK^-\mu^+\mu^-$$

Medium PID requirements

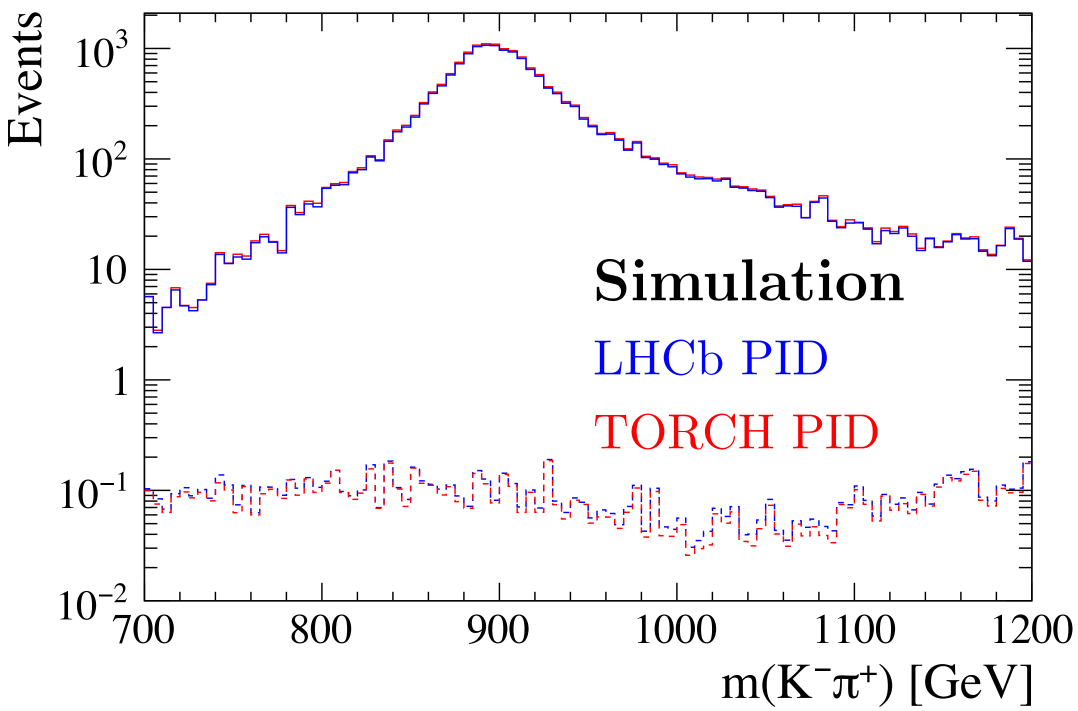
- Gains around 24% extra signal yield

Other modes

- A range of other modes have been investigated:
  - Lots of modes could benefit from TORCH less directly, e.g.

$$B^0 \to DK^{*0}$$

- Used to measure CKM angle gamma
- The K^{*0} mass window is fairly narrow to control K^{*0} double mis-id background
- Improvements from TORCH would mean the mass window could be widened for the same mis-id rate
- Leads to 8% increase in signal yield



Summary

- This selection of analyses discussed here is intended to be a **cross-section** of some interesting modes

- The tagging studies suggest TORCH could improve the tagging power by **25-35%** for algorithms that require kaon identification

- Timing information from TORCH could help reduce the degradation of tagging performance with increased pile up

- A range of decay mode would have signal yields 10-130% larger, depending on the existing tightness of selections

Future outlook

Today

✓ Continue physics studies with full simulation of TORCH integrated into LHCb

- The internal note has been updated with these latest studies
  - A new version will be available shortly
- We intend to further these studies to address the other recommendations of the TORCH review:

Future studies

➡ Extend TORCH physics studies to Upgrade II conditions

➡ Perform physics studies with degraded performance, e.g. time resolution and photon yield

➡ Perform realistic studies to determine if there is any degradation in other channels from TORCH

- We intend to produce samples of $B \to K^*$ gamma and $B \to K^*$ ee to check for degradation in ECAL performance

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Back up

Tagging selections

Variable	SSKaon Nominal	SSKaon TORCH	OSKaon Nominal	OSKaon TORCH
p	>5250 MeV/c	>2000 MeV/c	>2000 MeV/c	>2000 MeV/c
p_{T}	>850 MeV/c	>200 MeV/c	>200 MeV/c	>700 MeV/c
PIDK	>3.5	>15.0	>3.5	>30.0
PIDp−PIDK	<8.5	$<$-5.0	<8.5	<10.0
χ^2_{IP}	< 4.125		> 31.0	
IP			< 1.6	
$\Delta\phi$	< 0.825			
$\Delta\eta$	< 0.6			
ΔR	< 10			
$m(BK) - m(B)$	< 1850 MeV/c^2			
PU χ^2_{IP}	> 3.0		> 31.0	
Dist phi	> 0.005		> 0.005	
χ^2_{Trk}	< 3.0		< 3.0	
Ghost Prob.	< 0.35		< 0.35	

Table 1: Selection requirements used for each of the simple tagging algorithms. The variables PIDK and PIDp refer to the difference in the log-likelikood of the kaon and pion, or proton and pion hypotheses in either the simulation of the Upgrade Ib RICH detectors (nominal), or from the TORCH stand-alone performance (TORCH). The variables IP and χ^2_{IP} are the impact parameter and difference in the best primary vertex fit χ^2 with and without the tag track included. The best primary vertex is the one to which the candidate has the smallest χ^2_{IP}. The variables $\Delta\phi$, $\Delta\eta$ and ΔR describe the difference in direction of the candidate and tag track in the azimuthal angle, pseudo-rapidity, and in their combination $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. The quantity $m(BK) - m(B)$ is the difference between the invariant mass of the candidate and tagging track and the invariant mass of just the candidate. PU χ^2_{IP} is the value of χ^2_{IP} for the second best primary interaction vertex, *i.e.* a pile up (PU) vertex. Dist phi helps remove cloned tracks by comparing the angle between all candidate tracks and the tag. The quantity χ^2_{Trk} describes the quality of the track fit, and Ghost Prob helps discriminate against ghost tracks.

Tagging selections

Variable	`OSMuon`
p_{T}	$>1100\,\mathrm{MeV}/c$
χ^2_{IP}	> 0.0
PU χ^2_{IP}	> 3.0
Dist phi	> 0.005
χ^2_{Trk}	< 3.0
Ghost Prob.	< 0.4
PIDmu	> 3.0
ProbNNmu	> 0.35
ProbNNk	< 0.8
ProbNNe	< 0.8
ProbNNpi	< 0.8
ProbNNp	< 0.8

Table 3: Selection requirements used for the simple `OSMuon` tagging algorithm. The *ProbNN* variables are neural-network based PID variables.