# Searches for $D^{*0}$ and $B_{(s)}^{*0} \rightarrow \mu^+\mu^-$ decays

Fernando Abudinén, Tom Blake, Ulrik Egede, Tim Gershon

MWAPP meeting
March 15, 2023

- Results of the search for $D^{*0} \rightarrow \mu\mu$
- Ongoing searches for $B_{(s)}^{*0} \rightarrow \mu^+\mu^-$ and $B_c^+ \rightarrow \mu^+\mu^-\pi^+$decays

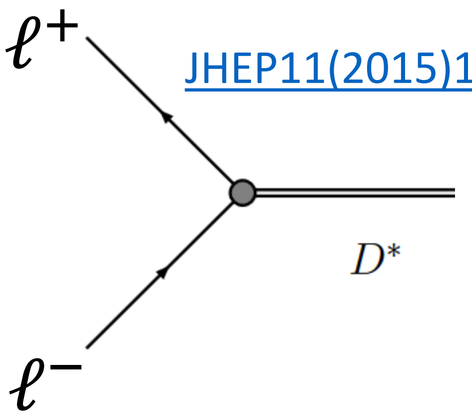
MONASH University

WARWICK
THE UNIVERSITY OF WARWICK

# Recap

## Goal:

Perform a dedicated searches for $D^{*0} \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$decays and $B^{*0}_{(s)} \to \mu^+\mu^-$ in $B_c^+ \to \mu^+\mu^-\pi^+$decays




JHEP11(2015)142

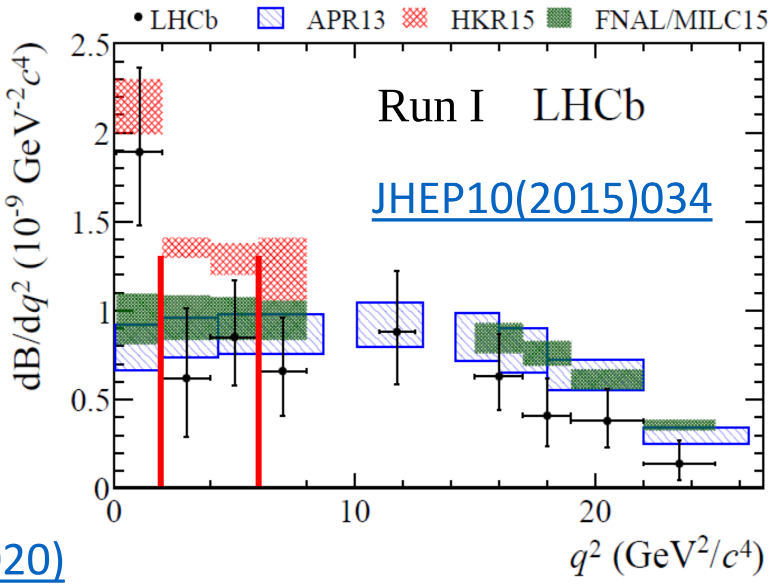
## Motivation:

- $V \to \mu\mu$ decays probe same operators as pseudo-scalar decays, but not helicity suppressed
- $D^{*0}$ ($B^{*0}_{(s)}$) decay via strong (EM) transitions

$\Rightarrow$ Very small $V \to \mu\mu$ BFs predicted in the SM ($\lesssim 10^{-11}$)

- $B^+_{(c)} \to \pi^+\mu^+\mu^-$decays provide most promising way to keep bkg. low through displaced vertex signature EPJC82(2022)459
- LHCB Run I sensitivity for $D^{*0} \to \mu^+\mu^-$ better than world's best limit by CMD-3:

$$\mathcal{B}(D^{*0} \to e^+e^-) < 1.7 \cdot 10^{-6}$$ PAN83.954(2020)




JHEP10(2015)034

$\Rightarrow$ Perform analyses exploiting Run I + II sample (9 fb$^{-1}$)

# Analysis steps

## Reconstruction and selection

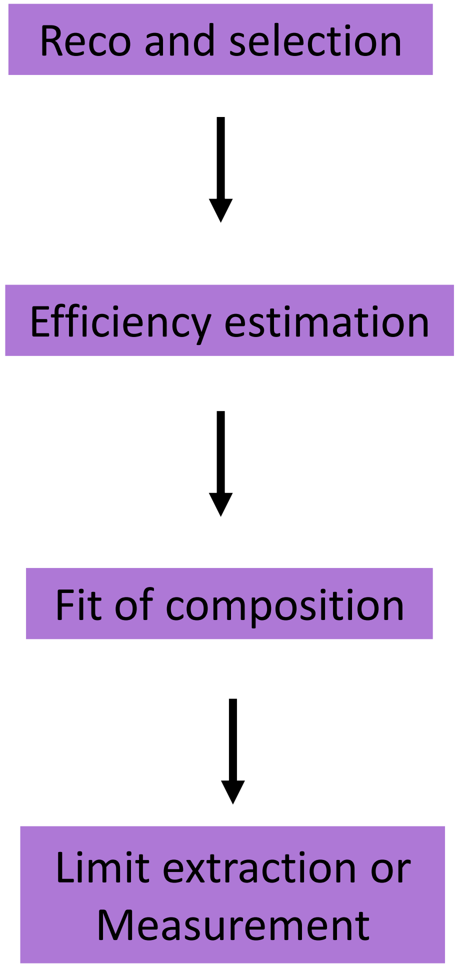
- Aligned across $B^+ \to \mu^+\mu^-\pi^+$ analyses: stripping, baseline and trigger selection, BDT classifier (dedicated BDT for $B_c^+$)
- Dedicated optimization: hadron ID and BDT selection, $B_{(c)}^+$-mass constraint to improve $M(\mu\mu)$ resolution (in $D^{*0}/B_{(s)}^{*0}$ searches)

## Determination of efficiency

- Obtained from MC and corrected for particle ID, track reco., trigger effcy., and $B_{(c)}^+$ kinematics (in common framework)
- Systematic uncertainty by varying all corrections

## Fit of sample composition

- Dedicated fit for each analysis using $M(\mu\mu\pi)$ and $M(\mu\mu)$
- Confidence intervals based on Feldman-Cousins approach



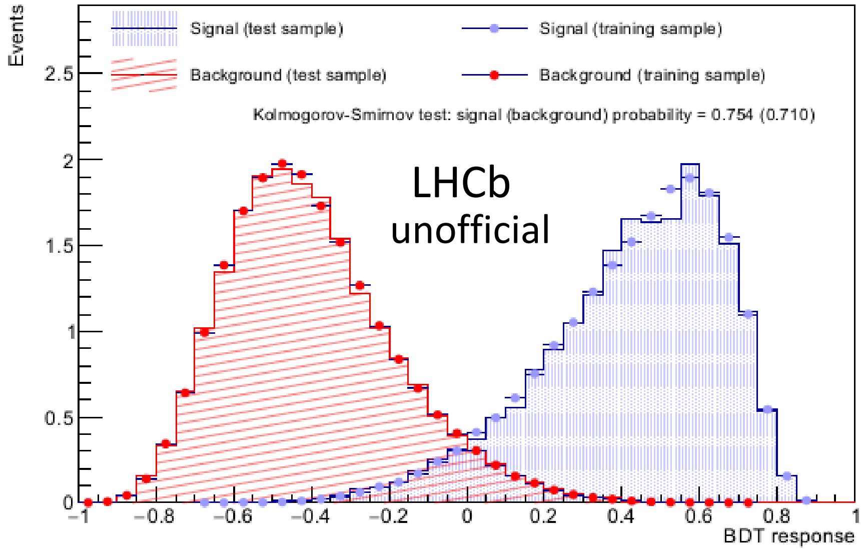
# Reconstruction and selection

Currently aligned across $B^+ \to \mu^+\mu^-\pi^+$ analyses:
JHEP10(2015)034

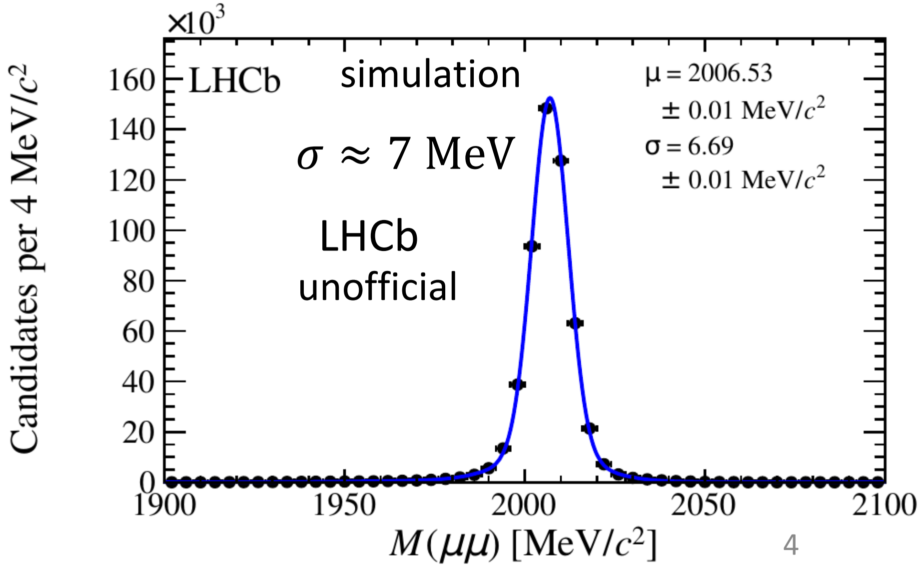
- Baseline selection using topological and muon ID info
- Trigger selection
- Multivariate (BDT) selection exploiting topological, kinematic and vertex info
- Muon and hadronic particle ID selection
- Apply $B$-mass constraint to improve dimuon mass resolution (by factor $\approx 1.5$ )

Performed dedicated optimisation

**BDT response**



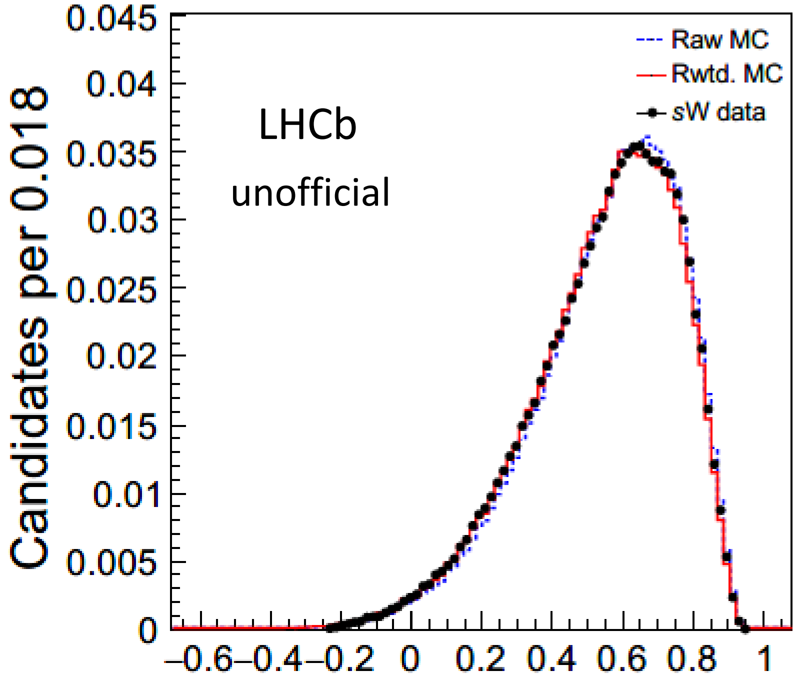

**Dimuon mass with $B$-mass constraint**



# Determination of efficiencies

- Obtain efficiencies from correctly associated candidates reconstructed in simulation.
- Correct for data/MC discrepancies associated with
  - PID selection (PID Calib)
  - Muon-ID selection (dedicated MC and PID Calib)
  - Track reconstruction (Track Calib)
  - Trigger selection (TIS-TOS method)
  - $p_{\mathrm{t}}$ and track multiplicity

**Example of data/MC comparison**

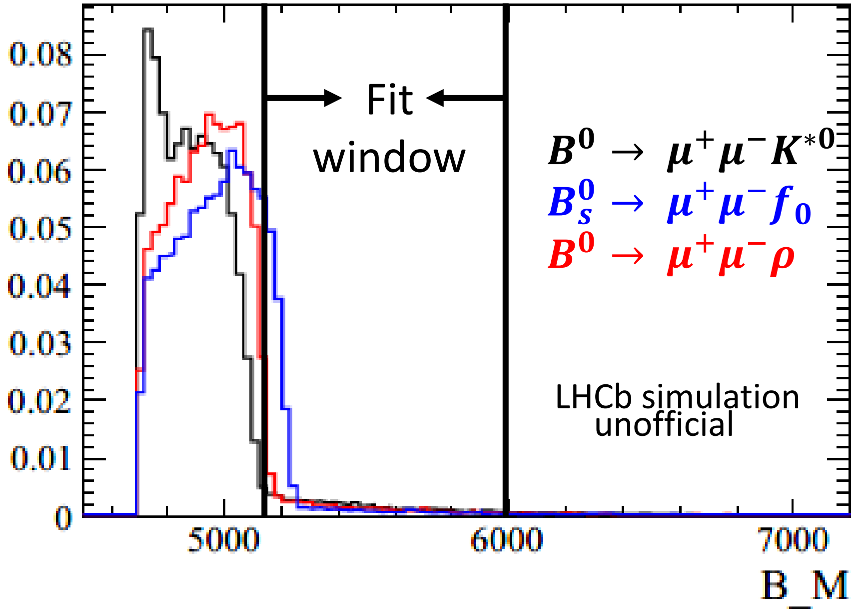



**BDT output**

$\Rightarrow$ Good agreement between simulation and data after all corrections

# Background studies

- Combinatorial background $\widehat{=}$ dominant source
- Non-resonant $B^- \to \pi^-\mu^+\mu^-$
- Misidentified $B^- \to K^-\mu^+\mu^-$
- Partially reconstructed decays such as $B^0_{(s)} \to \mu^+\mu^-(\rho, f_0)$ are negligible and not peaking inside fit region




JHEP10(2015)034

## New!

- Doubly misidentified decays such $B^- \to \pi^+\pi^-\pi^-$ expected to be negligible (Run I analysis)

PRD.101.012006

$\Rightarrow$ Performed dedicated study using simulation based on observed Dalitz distribution

$\varepsilon(B^+ \to \pi^+\pi^-\pi^+) = (8 \pm 1) \cdot 10^{-11}$ $\Rightarrow$ using PDG info expect $10^{-3}$ events in fit region

$\Rightarrow$ No peaking dimuon mass distribution inside fit region

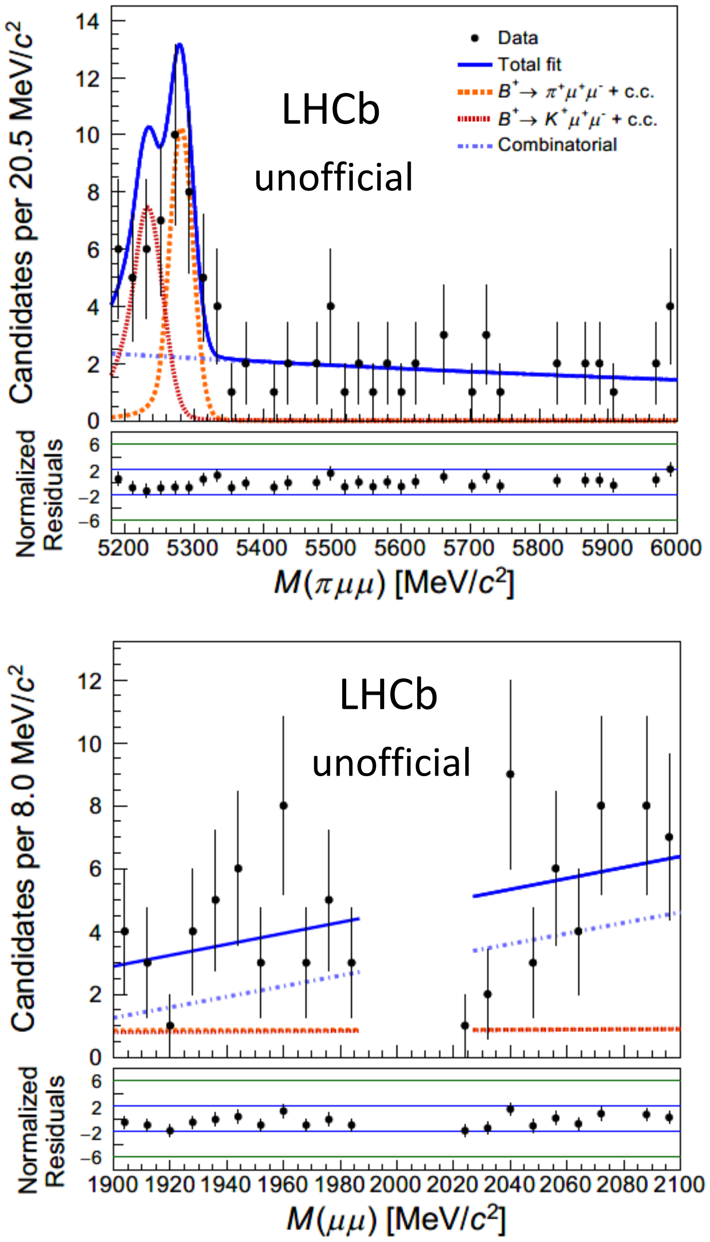
# Fit of sample composition

- 2D fit to $M(\mu^+\mu^-)$ and $M(\pi^-\mu^+\mu^-)$
- Fit includes signal, nonresonant $B^- \to \pi^-\mu^+\mu^-$ and misID $B^- \to K^-\mu^+\mu^-$ decays, and combinatorial background
- Signal and nonresonant peaking bkg. models fixed from simulation
- Combinatorial background model varies freely
- Resolution effects taken into account by incorporating global shift and width scaling factors estimated from data using normalization channel

$\Rightarrow$ Perform pseudoexperiments (toys) to assess sensitivity

$\Rightarrow$ Background expectation obtained from fit to sideband data

**Fit to sideband data**



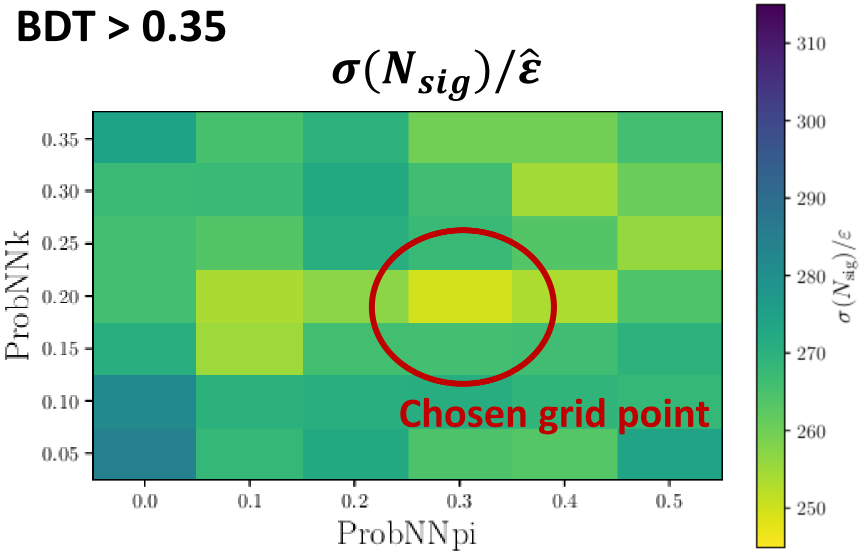
# Selection optimization

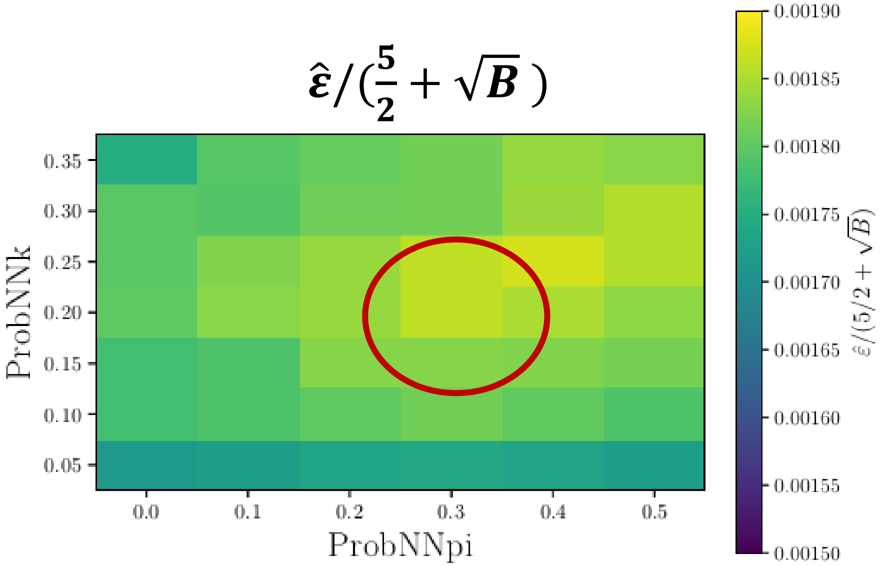
- Vary BDT and hadron PID requirements (3D Grid)
- Perform sets of pseudoexperiments for each working point

  Generated without signal and fitted with full fit model
- Checked that pulls are unbiased for all fit components
- FoM: $\sigma(N_{\text{sig}})/\hat{\varepsilon}$ and cross check with $\hat{\varepsilon}/(\frac{5}{2}+\sqrt{B}\ )$

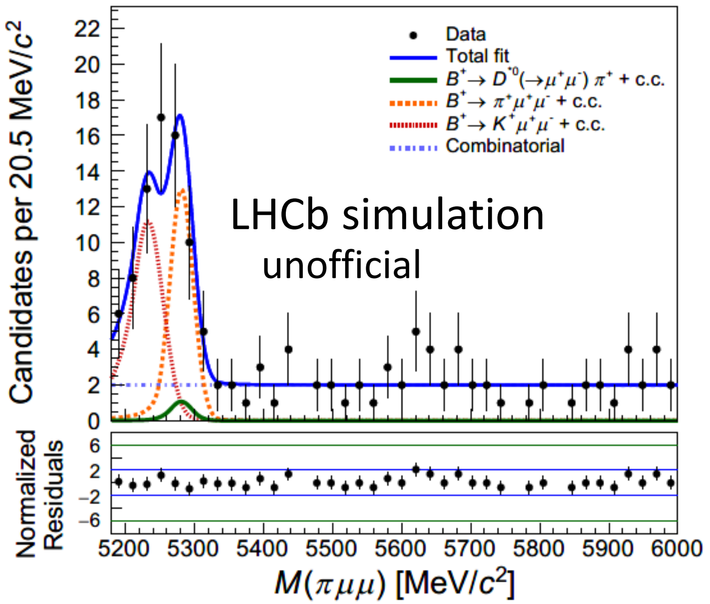
$\Rightarrow$ Both lead to same BDT and similar hadron PID grid points

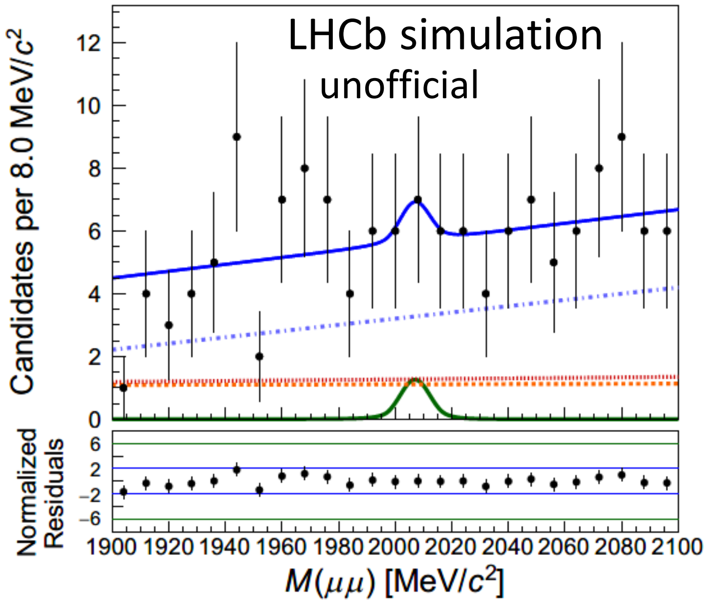
**BDT > 0.35**




**Example pseudoexperiment**



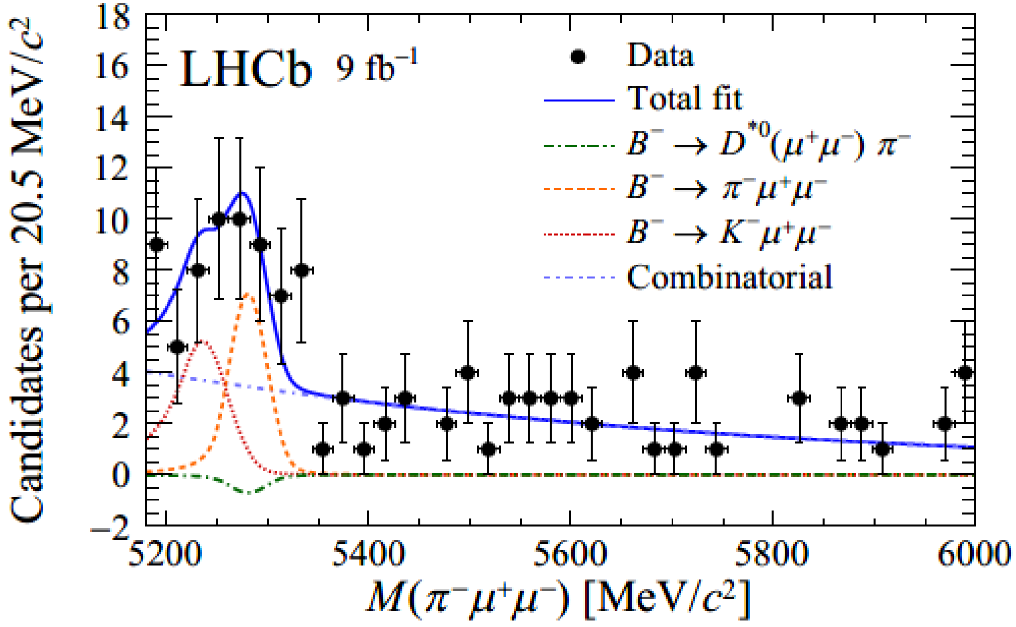
# Unblinded fit to data

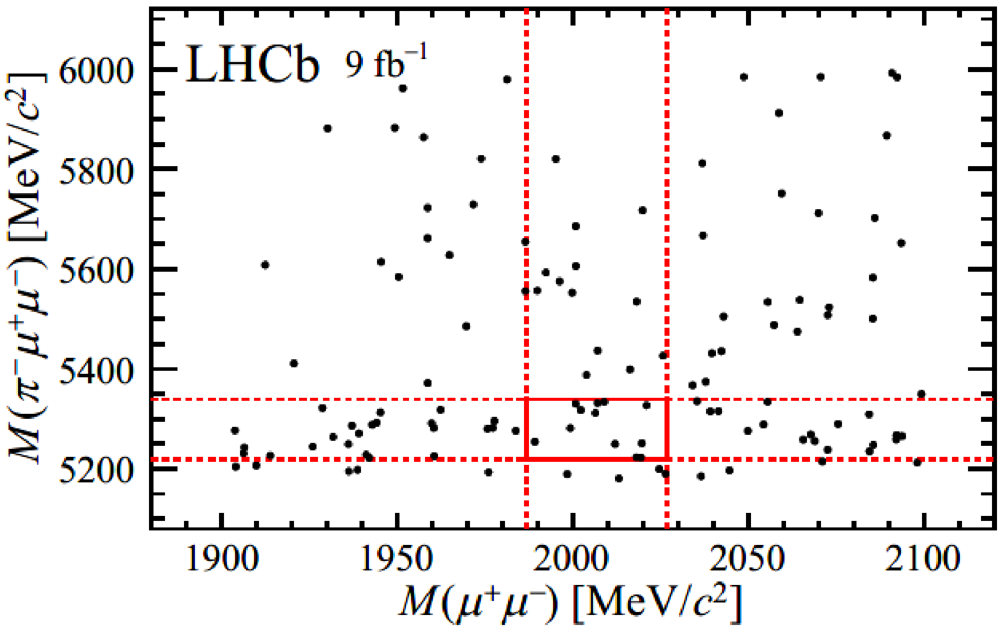
New!

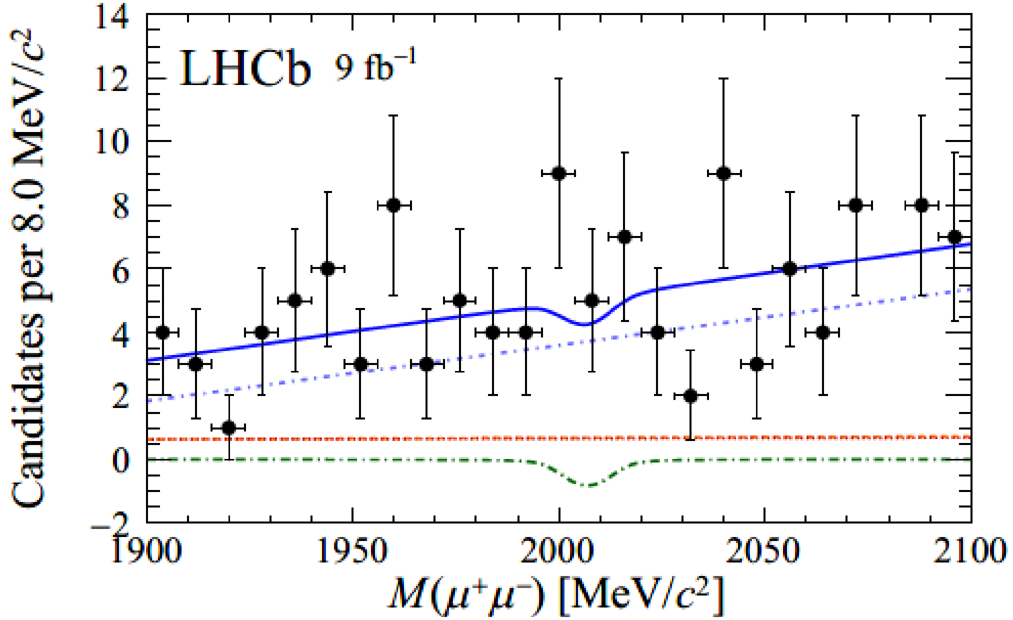
Fit converges to a slightly negative signal yield

$\Rightarrow$ Attributed to under fluctuation of bkg. in sig. box

| Component | Yield |
|---|---|
| $B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-$ | $-2 \pm 3$ |
| $B^- \to \pi^-\mu^+\mu^-$ | $17 \pm 7$ |
| $B^- \to K^-\mu^+\mu^-$ | $17 \pm 8$ |
| Combinatorial bkg. | $90 \pm 13$ |



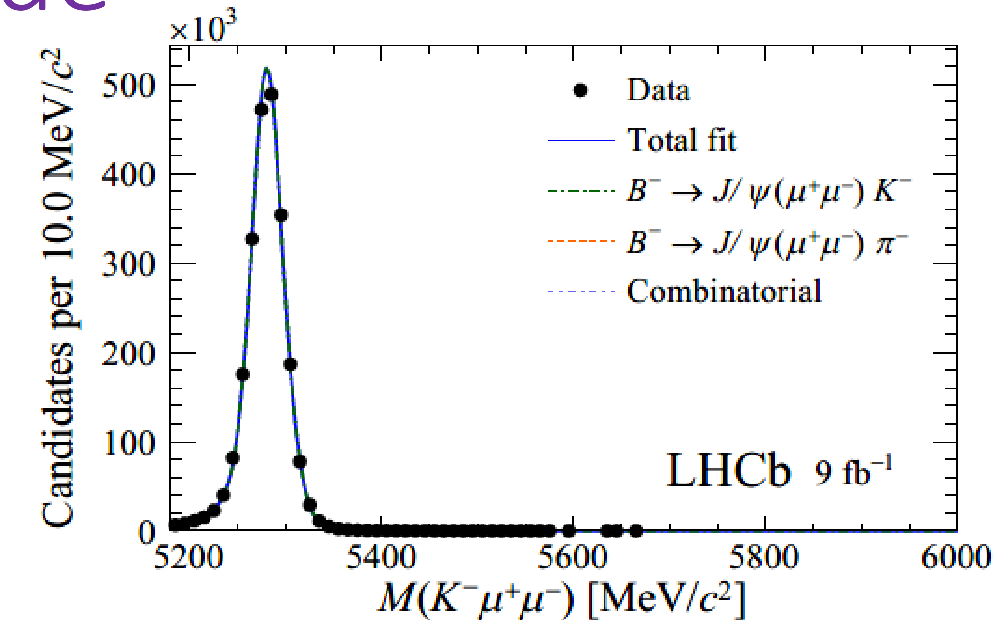
# Fit to data for normalization mode

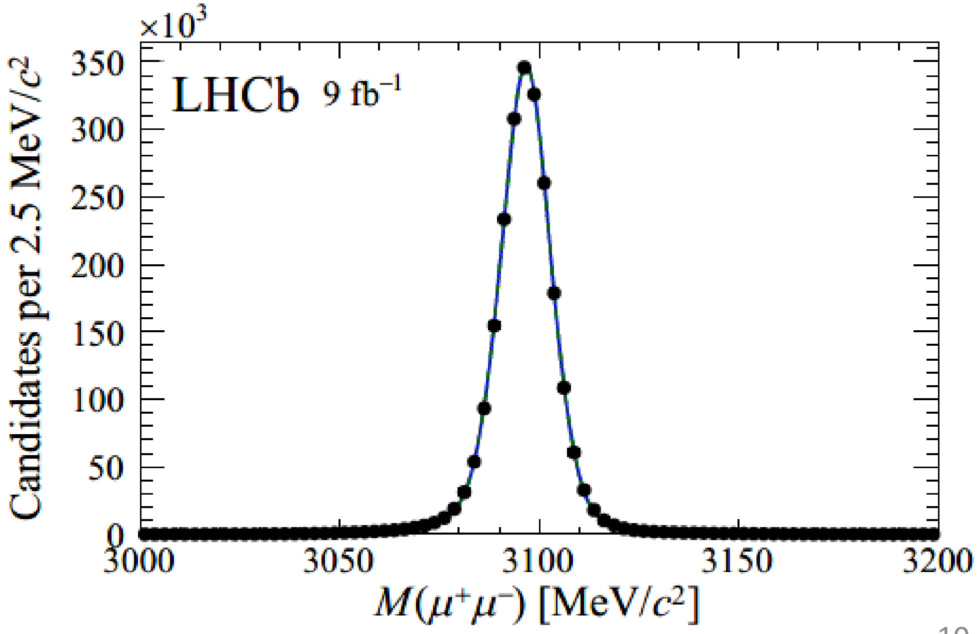
- Obtain norm. yield and shift/resolution factors
- 2 independent 1D fits to $M(\mu^+\mu^-)$ and $M(K^-\mu^+\mu^-)$
  Small correlations in tails might lead to biases in 2D fit due to the large sample size
- Fit includes $B^- \to J/\psi K^-$ and misID $B^- \to J/\psi\pi^-$ decays and combinatorial bkg.
- $B^- \to J/\psi K^-$ and $J/\psi\pi^-$ models fixed from simulation with free global shift and width scaling factor
- Combinatorial background model varies freely
- Same PDFs as in signal mode fit

$\Rightarrow$ Negligible $J/\psi\pi^-$ and comb bkg. contributions

- Cross check performed with alternative signal model
  (Hypathia for $M(K^-\mu^+\mu^-)$ and G+dsCB for $M(\mu^+\mu^-)$)

$\Rightarrow$ Differences between fit results taken as sys. uncty.



# Systematic uncertainties

New!

Reparametrize signal yield in the fit using

Efficiency ratio

$r_{J/\psi K^-/D^{*0}\pi^-}$

$$\mathcal{B}\left(D^{*0}\to\mu^+\mu^-\right) = \frac{N_{B^-\to D^{*0}\pi^-}}{\boxed{N_{B^-\to J/\psi K^-}}}\boxed{\frac{\epsilon_{B^-\to J/\psi K^-}}{\epsilon_{B^-\to D^{*0}\pi^-}}}\boxed{\frac{\mathcal{B}\left(B^-\to J/\psi K^-\right)}{\mathcal{B}\left(B^-\to D^{*0}\pi^-\right)}\mathcal{B}\left(J/\psi\to\mu^+\mu^-\right)}$$

Known BFs

Norm. yield

$\Rightarrow$ incorporate external inputs as Gaussian constraints (width = stat.$\oplus$syst. uncertainties)

- Efficiency ratio uncertainty: consistent variations of data/MC corrections for signal and normalization modes
- Normalization yield: difference between 1D fits
- Dimuon and $B$–mass resolution: diff. in shift and scaling between default and alternative normalization models

$\Rightarrow$ Dominant source: uncertainties on known BFs (PDG)

| Parameter | $\mu\pm\sigma$ |
|---|---|
| $\mathcal{B}\left(B^-\to J/\psi K^-\right)$ $[10^{-4}]$ | $10.20\pm0.19$ |
| $\mathcal{B}\left(B^-\to D^{*0}\pi^-\right)$ $[10^{-3}]$ | $4.90\pm0.17$ |
| $\mathcal{B}\left(J/\psi\to\mu^+\mu^-\right)$ $[10^{-3}]$ | $59.61\pm0.33$ |
| $r_{J/\psi K^-/D^{*0}\pi^-}$ | $1.21\pm0.03$ |
| $N_{J/\psi K^-}$ $[10^3]$ | $2316\pm8$ |
| $M(K\mu^+\mu^-)$ shift $[\mathrm{MeV}/c^2]$ | $0.06\pm0.11$ |
| $M(K\mu^+\mu^-)$ width scale factor | $1.14\pm0.12$ |
| $M(\mu^+\mu^-)$ shift $[\mathrm{MeV}/c^2]$ | $-0.065\pm0.005$ |
| $M(\mu^+\mu^-)$ width scale factor | $1.143\pm0.001$ |

# Limit extraction

New!

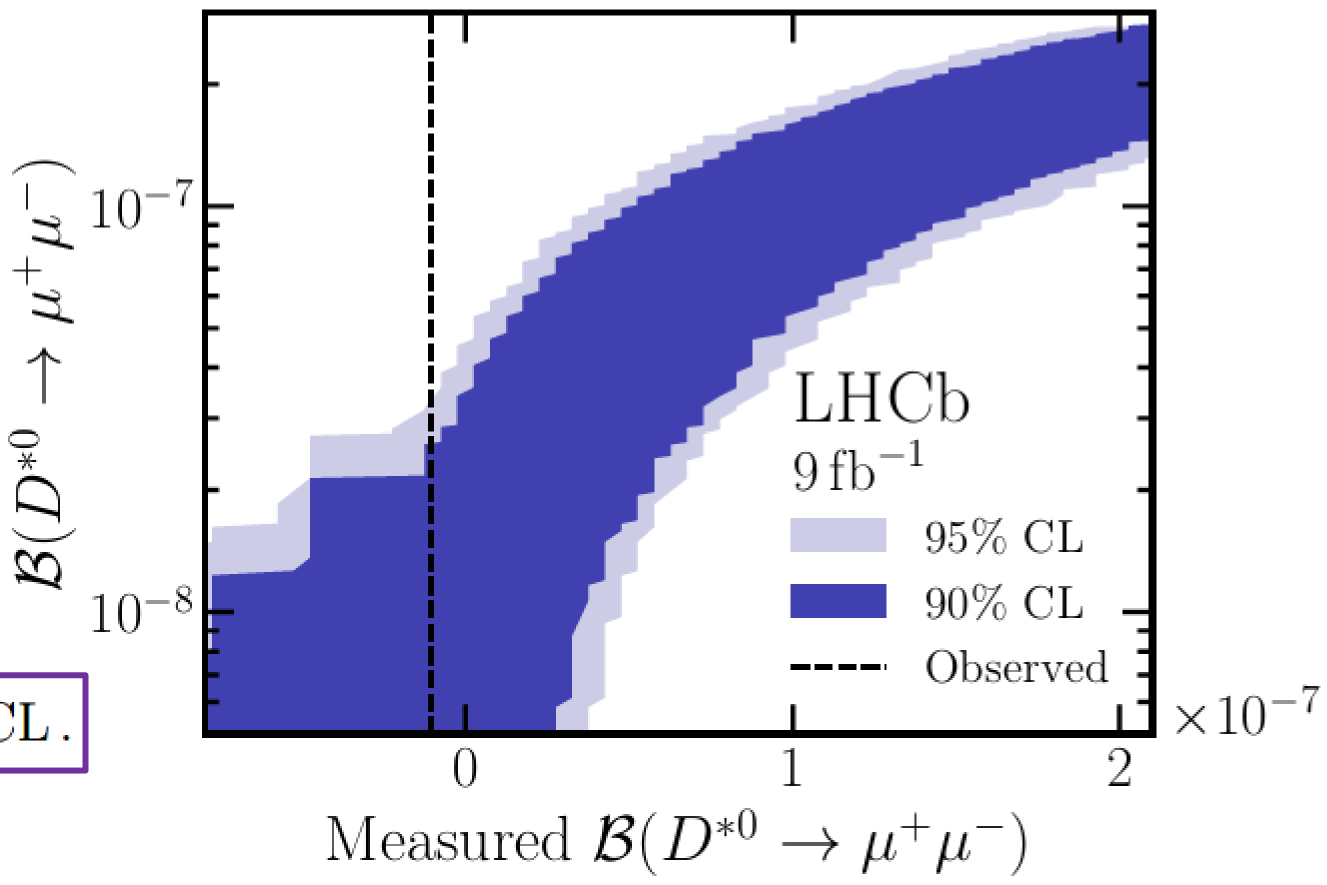
- Perform toys and build conf. band following Feldman-Cousins prescription (PRD.57.3873)
- Results from fit to data

$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = (-1.06 \pm 1.85) \cdot 10^{-8}$$

$$\Downarrow$$

$$\boxed{\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\%\ \text{CL}\,.}$$

$\Rightarrow$ Consistent with expectations




- Repeat procedure with fixed values of external inputs to assess impact of systematic uncertainties

$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.3\,(3.2) \times 10^{-8}$ at 90 (95)% CL. $\Rightarrow$ Results statistically limited

$\Rightarrow$ Repeating procedure restricting signal yield in fit to positive values and also performing counting experiments leads to consistent results

# Search for $B_c^+ \to \mu^+\mu^-\pi^+$ decays

## Goal

Search for nonresonant $B_c^+ \to \mu^+\mu^-\pi^+$ decays (yet unobserved)

$\Rightarrow$ Extend the search then to $B_{(s)}^{*0} \to \mu^+\mu^-$ in $B_c^+ \to \mu^+\mu^-\pi^+$decays

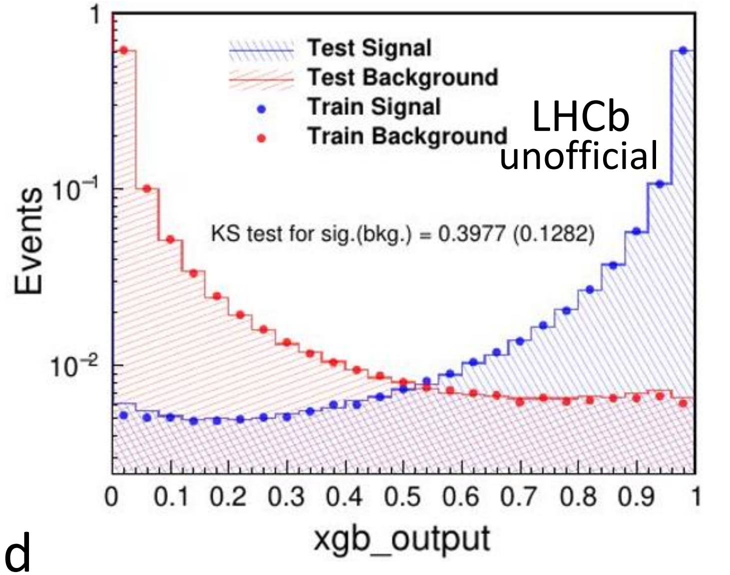
## Strategy

- Perform reconstruction, selection, efficiency determination, and fit based on $D^{*0} \to \mu^+\mu^-$ search
- Perform dedicated optimization where needed (MVA classifier, PID selection, fit model)
- Cross check by measuring $\mathcal{B}(B_c^+ \to \psi(2S)\,\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)$

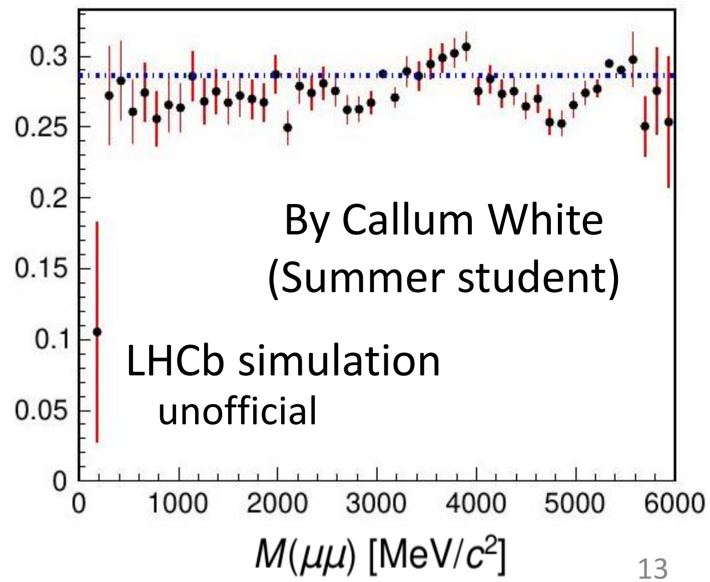
## MVA selection

- Trained dedicated BDT classifier exploiting topology of $B_c^+$ decays
- BDT trained to avoid dependence with $M(\mu\mu)$
- Performed dedicated optimization of hadron ID and BDT selection

**BDT performance**




**BDT efficiency at optimum**



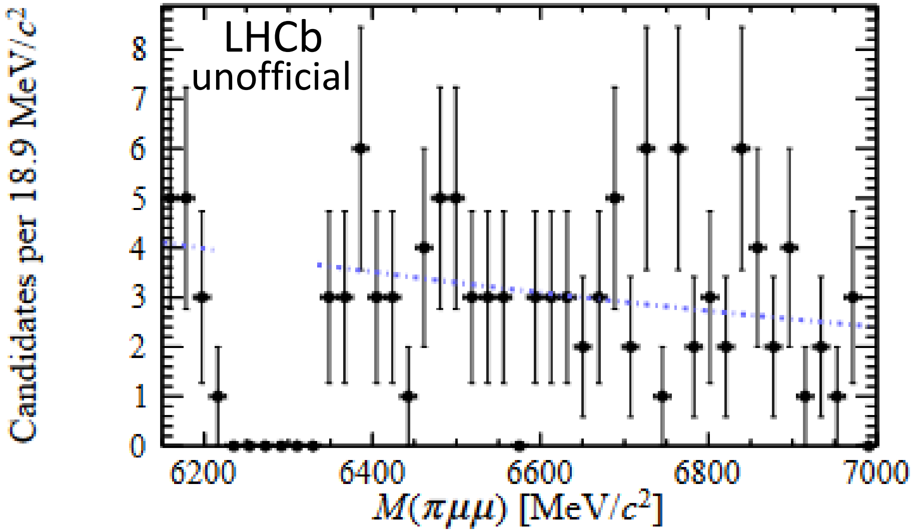
New!

# Selection optimization

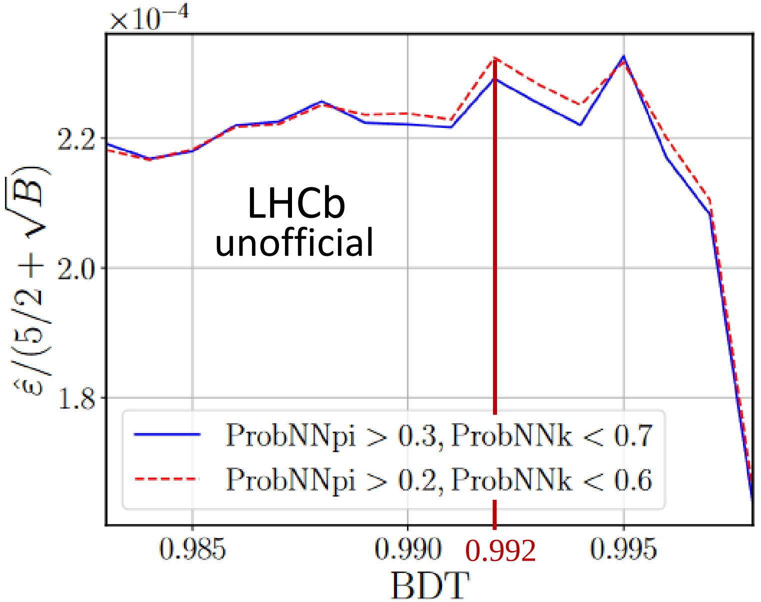
- Maximise sensitivity to search for nonresonant $B_c^+ \to \mu^+\mu^-\pi^+$ decays using FoM = $\hat{\varepsilon}/(\frac{5}{2}+\sqrt{B}\,)$
- Maximise sensitivity for $B_c^+ \to \psi(2S)\,\pi^+$ to update BF ratio using FoM = $S/\sqrt{S+B}$
- Expectations from signal simulation and sideband data

$\Rightarrow$ 2 BDT and PID working points

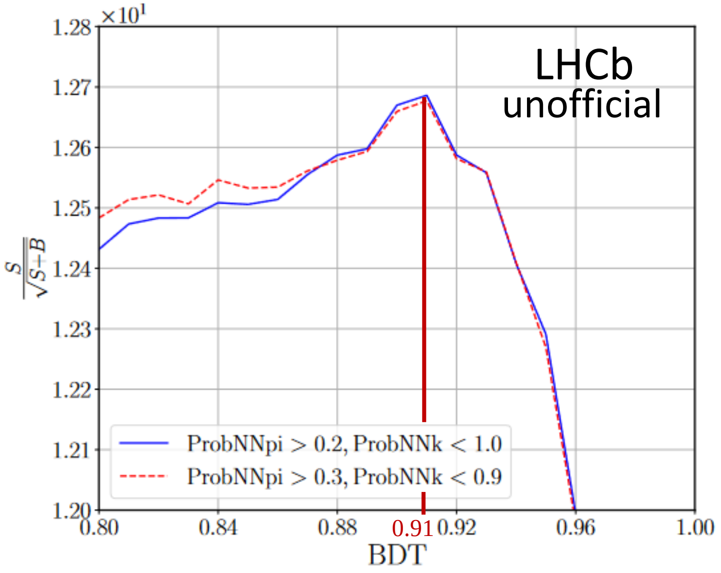
**$B_c^+ \to \mu^+\mu^-\pi^+$ sideband fit at optimum**




**$B_c^+ \to \mu^+\mu^-\pi^+$ optimisation**




**$B_c^+ \to \psi(2S)\,\pi^+$ optimisation**




By Vedanshu Mahajan (Master student)

# Summary and outlook

### Search for $D^{*0} \to \mu^+\mu^-$ decays

- Analysis converged, results approved, paper draft under review
- No excess over background-only hypothesis observed
- Set most stringent limit on $D^{*0} \to \ell^+\ell^-$ decays

$$\boxed{\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\% \text{ CL}\,.}$$

$\Rightarrow$ To be shown for first time next week at Moriond EW

### Search for nonresonant $B_c^+ \to \mu^+\mu^-\pi^+$ decays

- Trained BDT against combinatorial bkg., optimized selection, prepared fits
- Currently studying agreement between data and simulation
- TODO: study misID and partially reconstructed backgrounds

### Search for $B_{(s)}^{*0} \to \mu^+\mu^-$ decays

- Can use same BDT as for $B_c^+ \to \mu^+\mu^-\pi^+$ search, but needs selection optimisation
- Major limitation are missing denominators $\mathcal{B}(B_c^+ \to B_s^*\pi^+)$ and $\mathcal{B}(B_c^+ \to B^{*0}\pi^+)$

$\Rightarrow$ Will pick up soon analysis started by Matthew Monk et al.

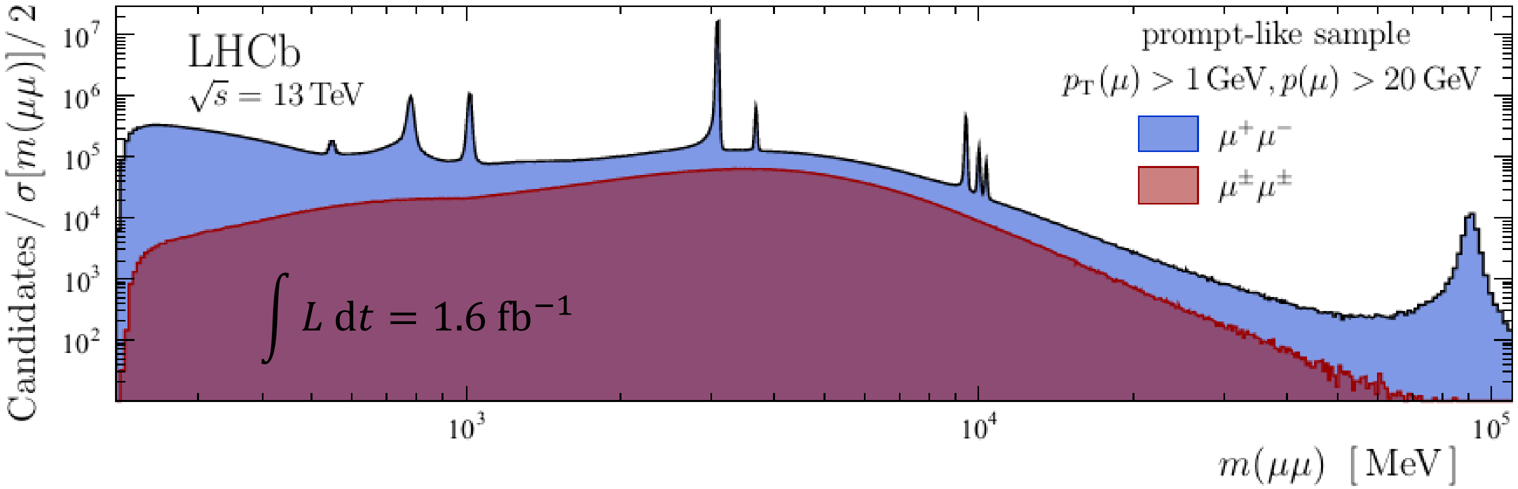
# Backup

# Searches exploiting prompt decays

- $D^{*0}$, $B^{*0}_{(s)}$ produced directly in $pp$ collisions

$\Rightarrow$ Requires respective cross sections (not yet measured)

Dimuon mass spectrum from dark photon search PRL120.061801




- Assuming same cross section for $D^{*+}$ and $D^{*0}$, the exp. single event sensitivity is $\sim 10^{-11}$
- Assuming same background level as for dark photon search, the expected limit at 1.6 $\text{fb}^{-1}$ is

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) \lesssim 10^{-7}$$

$\Rightarrow$ Similar sensitivity as in search through $B^+_{(c)} \to \mu^+\mu^-\pi^+$ decays, but background dominated and missing cross section

# Semi-inclusive searches

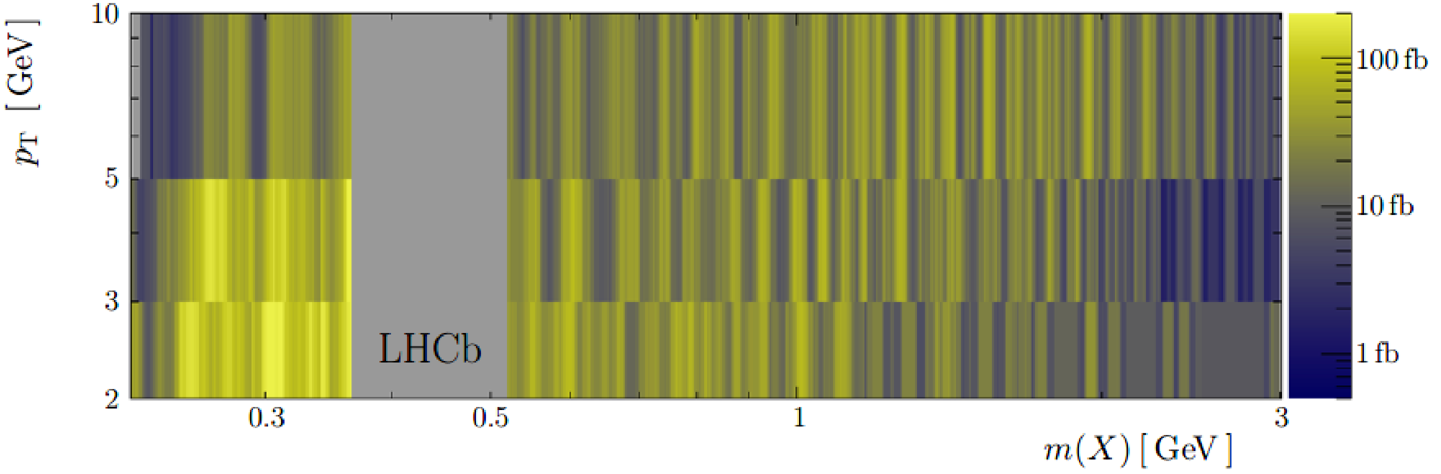
- Search for $D^{*0}$, $B^{*0}_{(s)} \to \mu\mu$ decays from a displaced ($b$-hadron) decay vertex
- Example:

$$N_{D^{*0}\to\mu^+\mu^-} = \mathcal{L}\,\mathcal{B}\left(D^{*0}\to\mu^+\mu^-\right)\sum_i \sigma_{B_i}\,\mathcal{B}\left(B_i\to D^{*0}X\right)\,\epsilon_{B_i\to D^{*0}X}$$

$\Rightarrow$ Production cross sections and inclusive branching fractions known for dominant $B^{\pm(0)}$ hadrons (in the $D^{*0}$ case).

$\Rightarrow$ Analysis in principle possible, but worse dimuon mass resolution and higher irreducible backgrounds

Limit at 90% CL on $\sigma(X)\cdot\mathcal{B}(X\to\mu\mu)$ JHEP10(2020)156




$\Rightarrow$ Most likely less sensitive than exclusive searches