BRANCHING FRACTION MEASUREMENT OF $B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$ USING RUN 1 AND RUN 2 LHCb DATA

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$B^0 \to \rho^0 \mu^+ \mu^-$ - *Motivation*

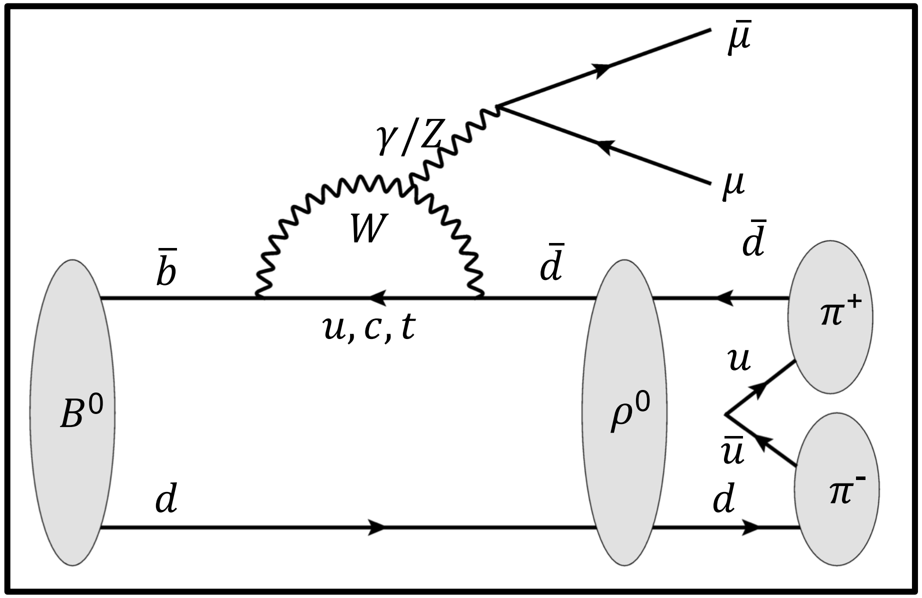
- $B^0 \to \rho^0 \mu^+ \mu^-$ is an example of a b → d Flavour Changing Neutral Current (FCNC) process

- FCNCs can only occur at loop level within the Standard Model (SM)

- Off shell → Sensitive to up to $\mathcal{O}$(100TeV) energy scale

- New Physics (NP) could enter these processes at the loop level and effect physical observables such as BFs, angular observables.

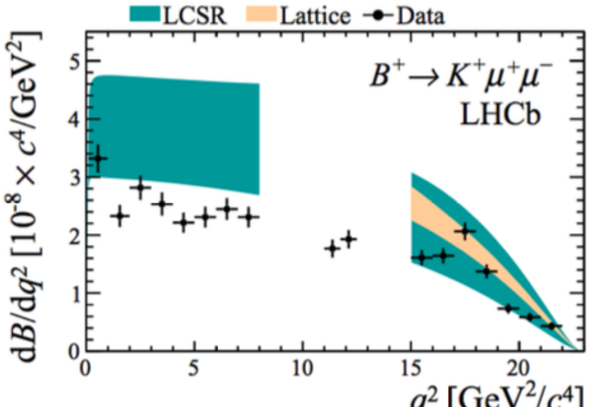
- As a b → d transition suppressed by small size of V_{td} meaning more suppressed than similar b → s transitions



b → s processes at LHCb

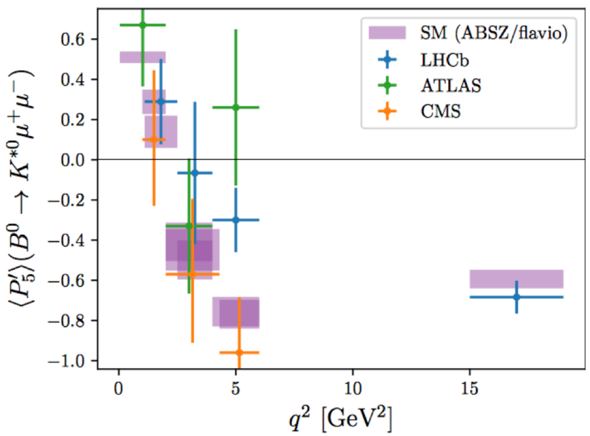
- Large number of analyses on processes involving b → s transitions. Several interesting tensions found so far between measurements and SM predictions:

[LHCb,JHEP 06 (2014) 133]



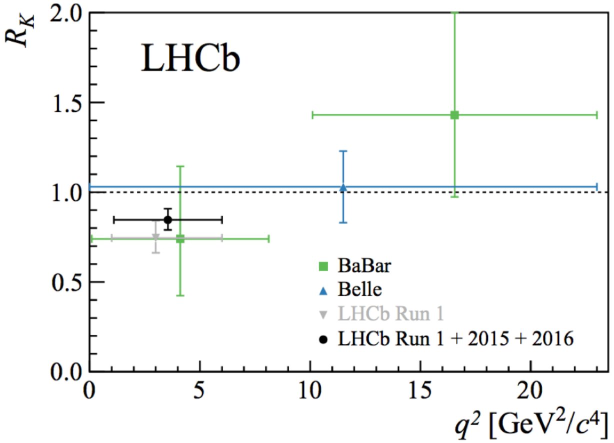
Branching Fractions (BF) are systematically lower than SM predictions

[LHCb, JHEP 02 (2016) 104]



P5' discrepancy in $B^0 \to K^{*0}\mu^+\mu^-$

[arXiv:1903.09252]



Possible hints of Lepton Non-Universality e.g. (R_K & R_{K^*})

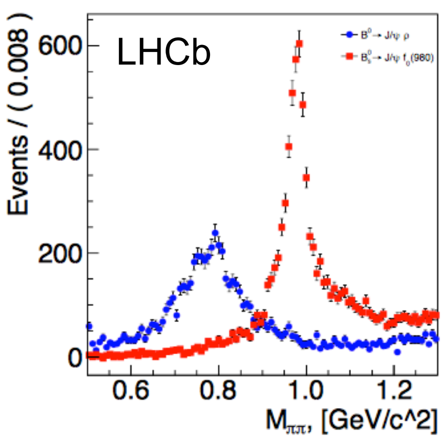
- Perhaps point to NP contribution that destructively interferes with SM. Want to probe flavour structure of NP and see if also present in b → d decays

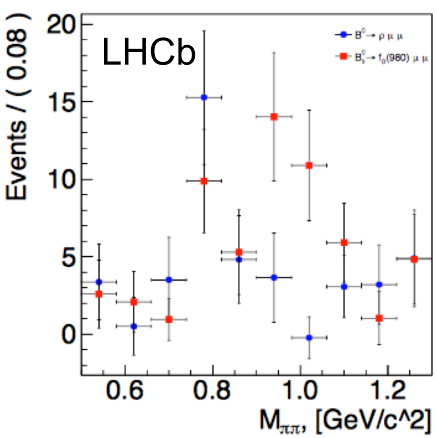
$B^0 \to \rho^0 \mu^+ \mu^-$ - Run 1 analysis

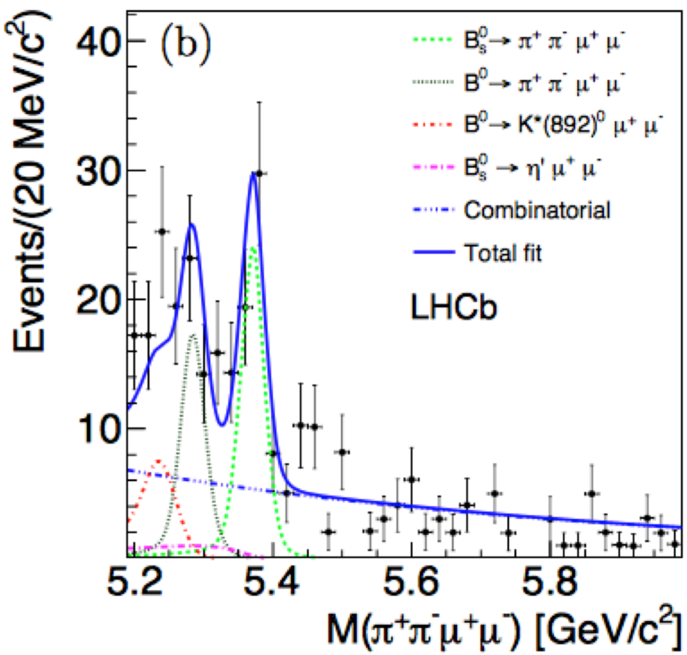
- Previous branching fraction analysis using only Run 1 data completed by LHCb [Phys. Lett. B743 (2015) 46]
- Measured **BF**s:

$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.1 \pm 0.5(stat) \pm 0.7(system) \pm 0.7(norm)) \times 10^{-8} \quad 4.8\sigma$$
$$\mathcal{B}(B_s^0 \to \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5(stat) \pm 0.7(syst) \pm 0.7(norm)) \times 10^{-8} \quad 7.2\sigma$$

- 55 B_s and 40 B^0 candidates were observed
- Was assumed that the contributions are dominated by the f_0 and ρ^0 resonances







UPDATED ANALYSIS – *aims and strategy*

- Perform and improve ***BF*** Analysis of the B^0 mode using Run 1 + 2015 + 2016 data -- perform differential BF measurement in bins of q^2 – with improved selection methods should provide first observation

- Use control mode $B^0 \to K^{*0} J/\psi$ to normalise the signal and as a large yield proxy

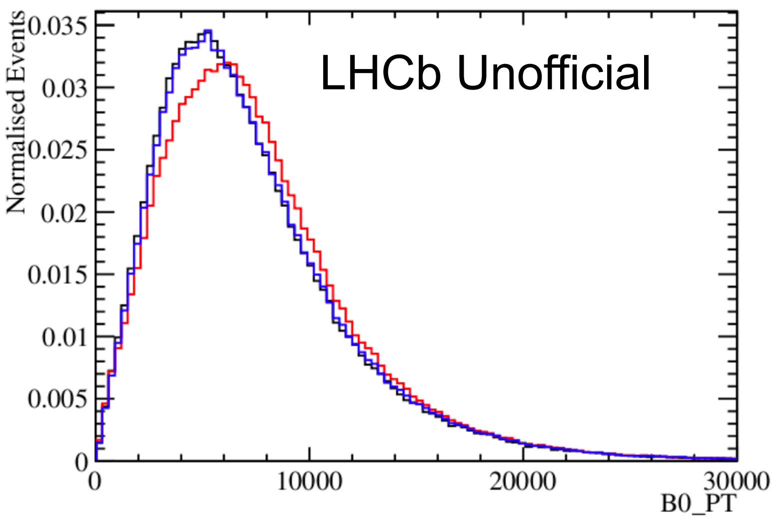
$$\mathcal{B}(B^0 \to \rho^0 \mu^+ \mu^-) = \mathcal{B}(B^0 \to K^{*0} J/\psi) \times \frac{N(B^0 \to \rho^0 \mu^+ \mu^-)}{N(B^0 \to K^{*0} J/\psi)} \times \frac{\epsilon(B^0 \to K^{*0} J/\psi)}{\epsilon(B^0 \to \rho^0 \mu^+ \mu^-)}$$

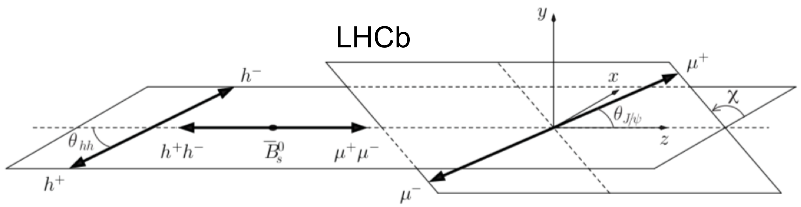
CHALLENGES:

1. ***Monte Carlo inaccuracies:*** MC reweighted in kinematic variables and with helicity models
2. ***Combinatorial Background:*** Multi Variate Analysis (MVA)
3. ***Signal underneath large peaking backgrounds e.g.*** $B^0 \to K^{*0} \mu^+ \mu^-$ ***:*** PID cut selection using toy study – use tight PID cuts as trying to find rare mode
4. ***Rare mode confirmation:*** Show that the $\pi^+ \pi^-$ state originates from ρ^0 in order to compare to SM predictions – mass fits and fits to angular variables
5. ***Angular Analysis:*** Calculate angular observables sensitive to interesting observables

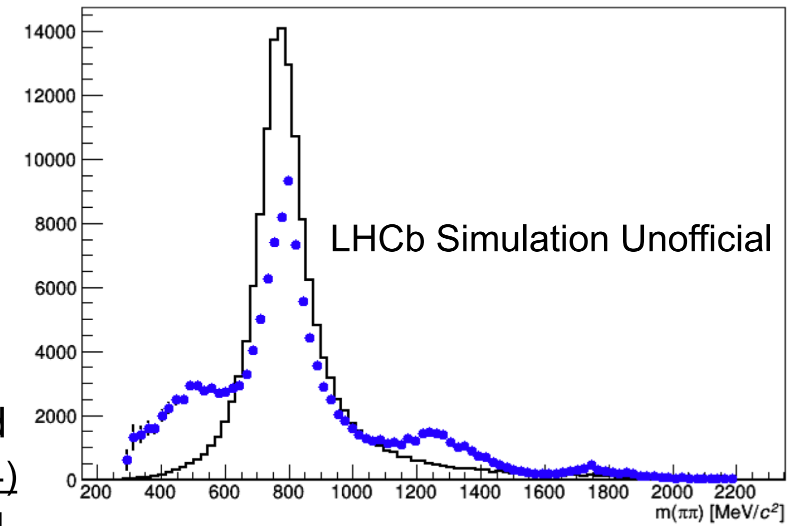
Pre-selection MC Corrections

- MC used throughout analysis: MVA, mass shapes, efficiencies
  ➔ MC/Data agreement is **crucial**
- MC initially reweighted in B^0 P_T, B^0 vertex χ^2 and occupancy which are known to be poorly modelled. ➔ Use sPlot technique to unfold signal using fit to control mode $B^0 \to K^{*0} J/\psi$



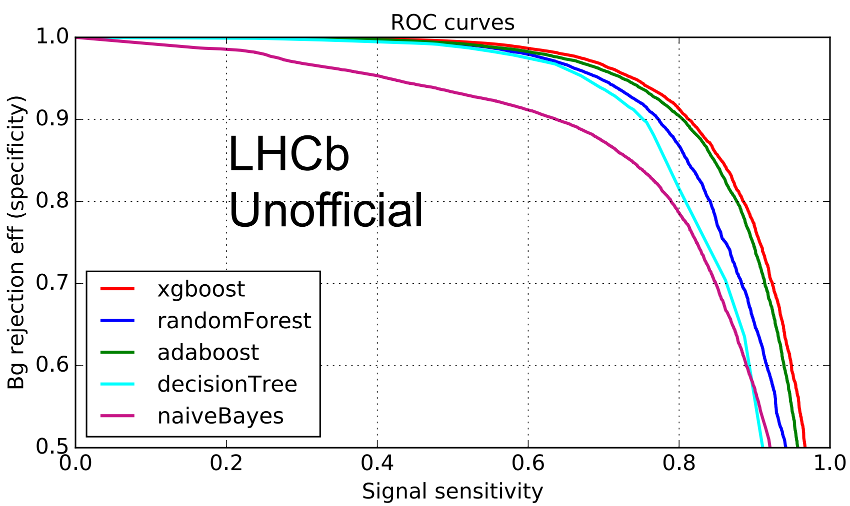


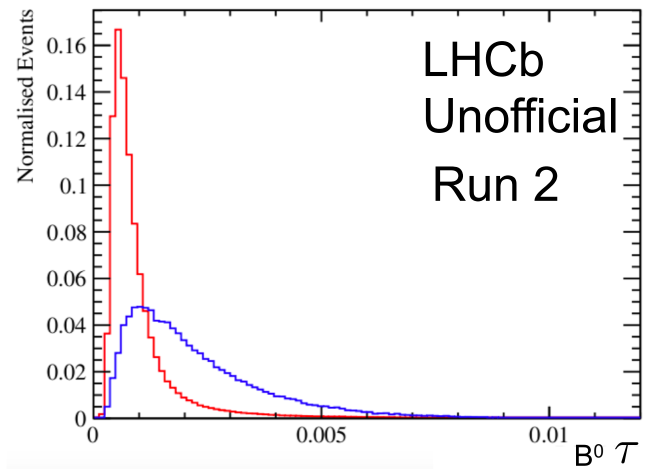
- Include contributions from higher mass $K\pi/\pi\pi$ resonances to improve mass fit accuracy and efficiency accuracy
- Use helicity amplitude models for $\pi\pi$ states described in: Phys. Rev. D90 (2014) 012003 and Phys. Rev. D89 (2014) 092006 and $K\pi$ states from Phys. Rev. D90 (2014), no. 11 112009



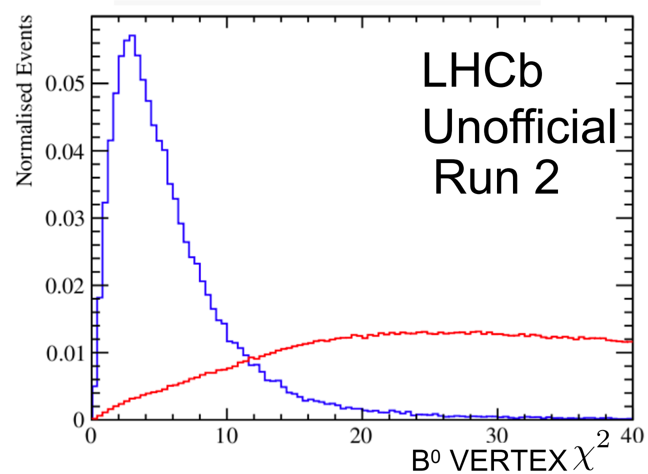
Multivariate Analysis (MVA)

- MVA used to reduce Combinatorial background
- Initially compared performance of several classifiers, ***xGBoost*** (Gradient Boosted Decision Tree) produced best performance
- Use $B^0 \to \rho^0 \mu^+ \mu^-$ MC as signal proxy and upper sideband of data ($m(\pi\pi\mu\mu)$ > 5800 MeV) as background proxy

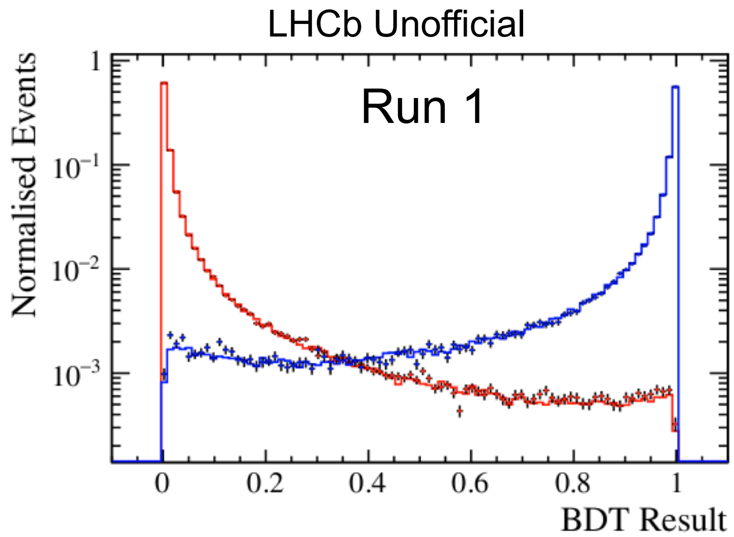


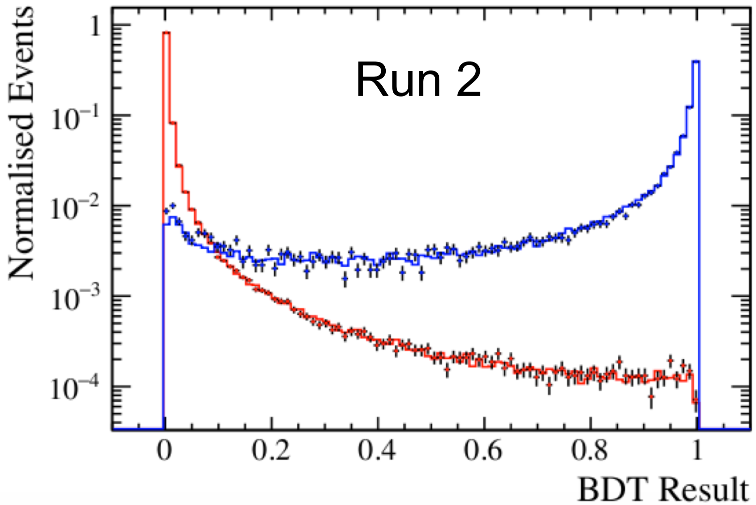


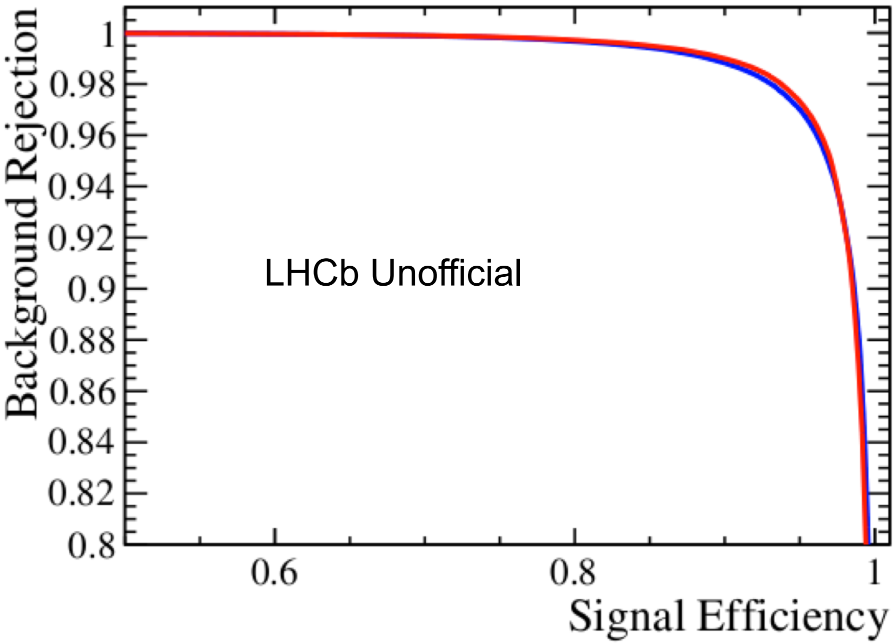
- Train MVA with (12) variables which provide good signal/background separation, e.g. B⁰ Vertex χ^2 where signal like tracks point back to the B0 decay vertex



MVA Performance



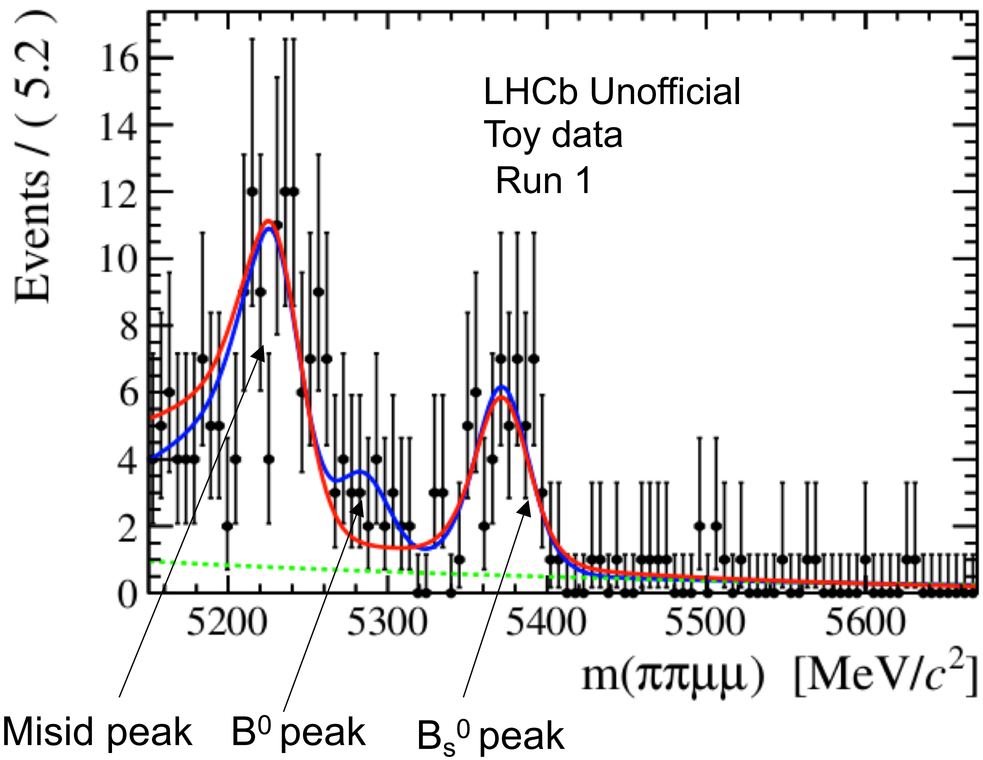




- Classifier provides excellent separation for both Run 1 and Run 2
- Excellent performance: ~99.9% combinatorial background rejection corresponding to ~70% signal efficiency

PID VS BDT OPTIMISATION

- Large $\pi - K$ misid backgrounds present in the analysis reduced with PID cuts PID vs BDT working point determined using optimisation with a toy study
- For different PID and BDT cuts fit resonant J/ψ mode and calculate expected yields with control mode to generate 1000 toys

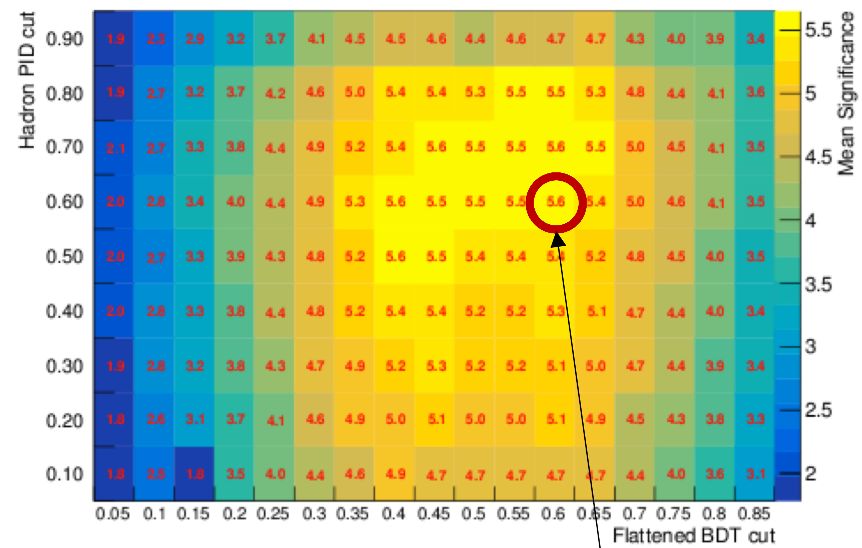


With signal component

Without signal component

Combinatorial Background

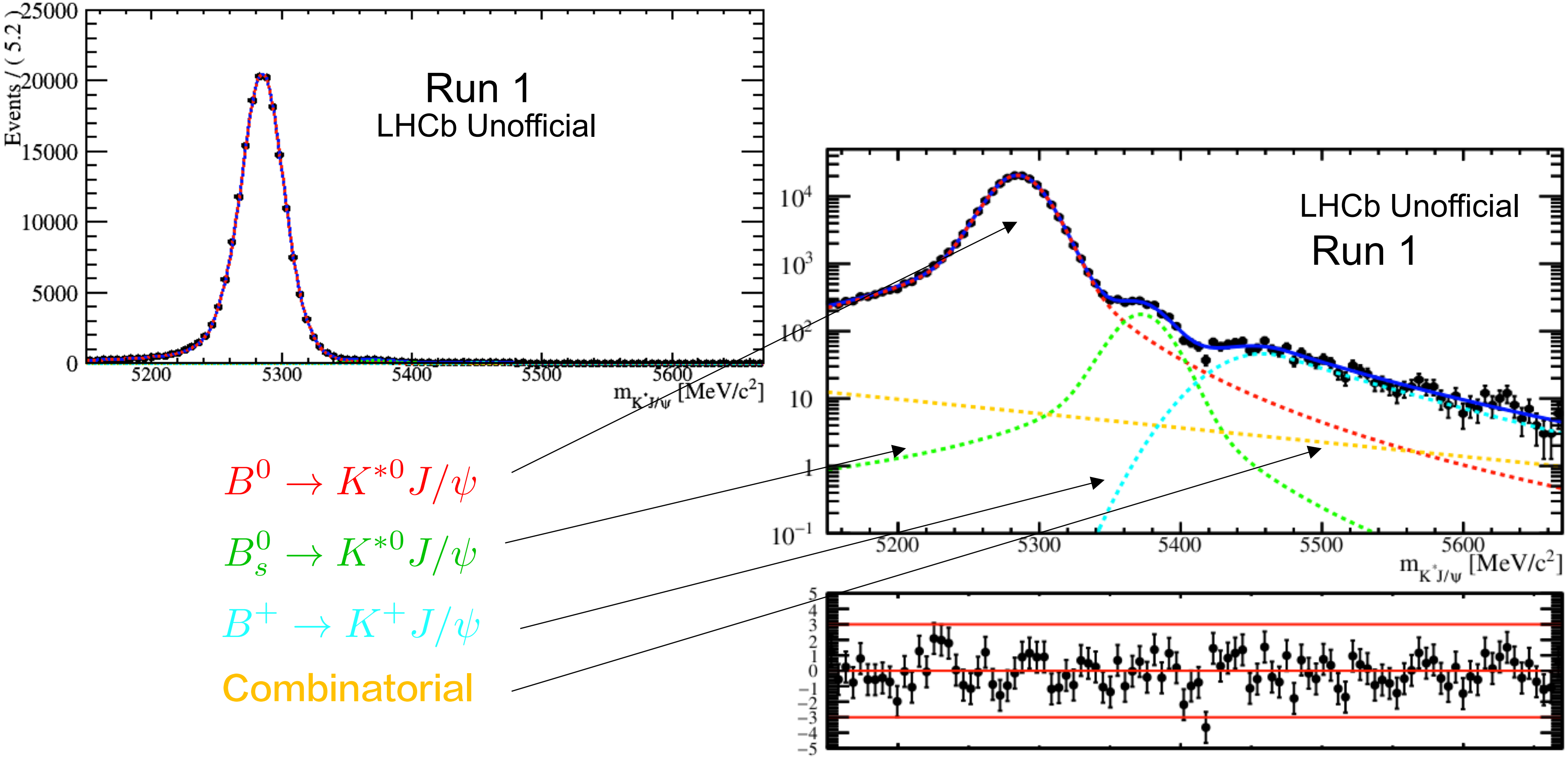
LHCb Unofficial



- Calculate significance using Wilk's theorem
- See peak in significance with optimal cuts corresponding to – 5.6σ Run 1 and 6.4σ Run 2. c.f. Run 1 analysis 4.8σ

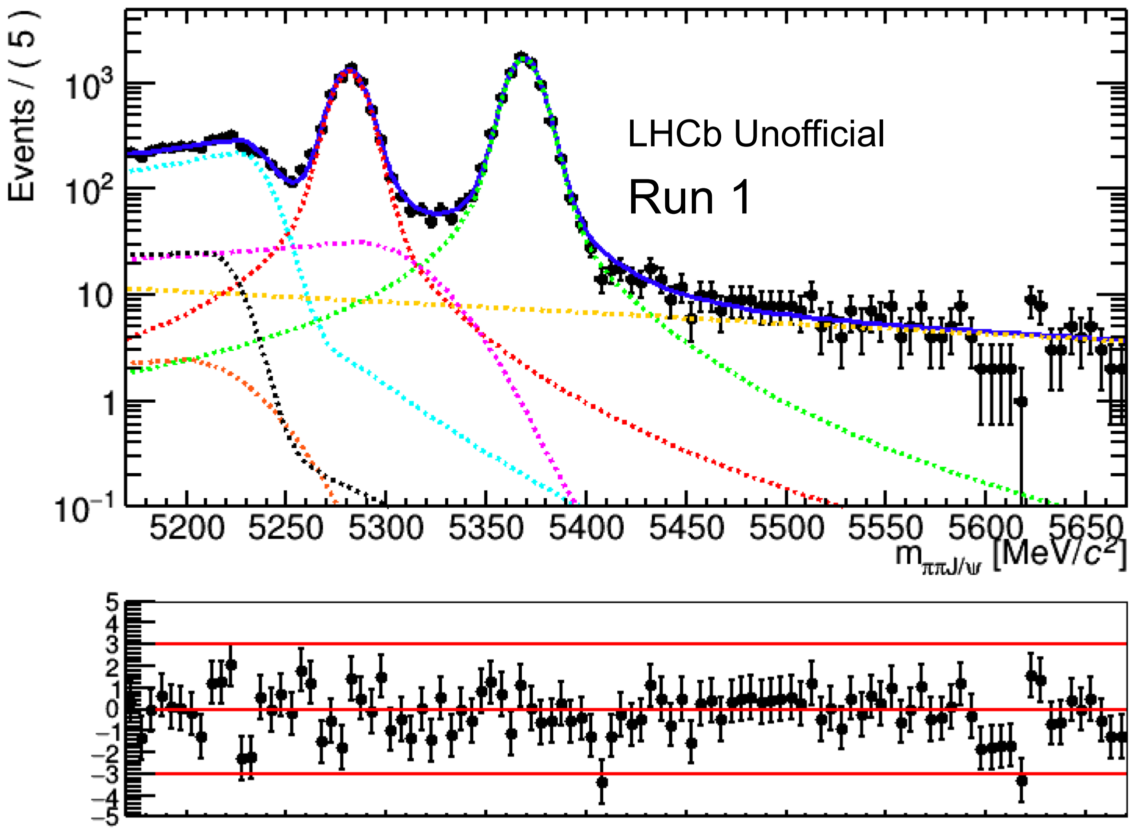
CONTROL MODE FIT

- $B^0 \to K^{*0} J/\psi$ used as control mode due to clean signal and large yield
- Control mode used for normalisation within the BF calculation to cancel systematics
- Fit is very good for both Run 1 and Run 2 with a pure signal.



RESONANT MODE FIT

- Use $\rho^0 J/\psi$ mode as a proxy to determine PDF shapes as most peaking backgrounds for rare mode are also present here



- Peaking backgrounds still present after selection are modelled

$B^0 \to J/\psi\pi^+\pi^-$

$B_s^0 \to J/\psi\pi^+\pi^-$

$B^0 \to J/\psi K^+\pi^-$

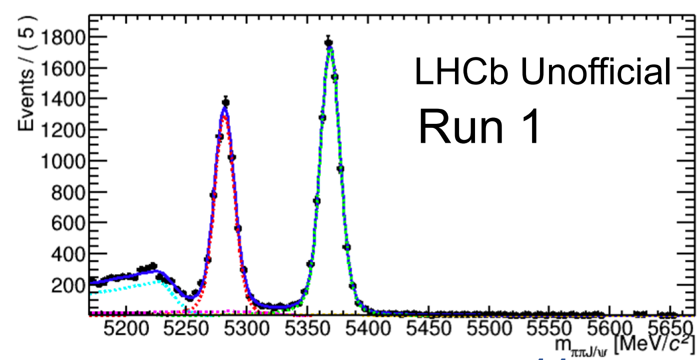
$B_s^0 \to J/\psi(\eta' \to (\rho \to \pi^+\pi^-)\gamma)$

$B^0 \to J/\psi(\eta' \to (\rho \to \pi^+\pi^-)\gamma)$

$B_s^0 \to J/\psi(\phi \to \pi^+\pi^-\pi^0)$

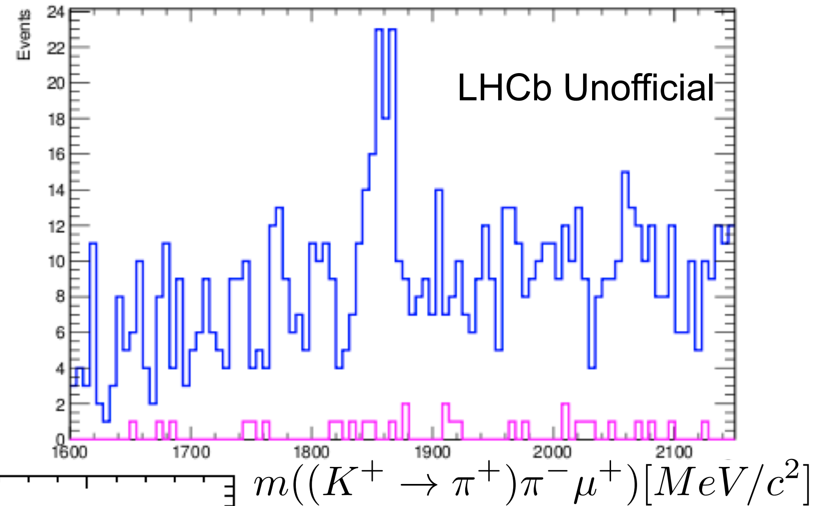
Combinatorial

- Fit version with Jpsi mass constrained to known value to help separate peaks. Find consistent fits without the mass constraint.



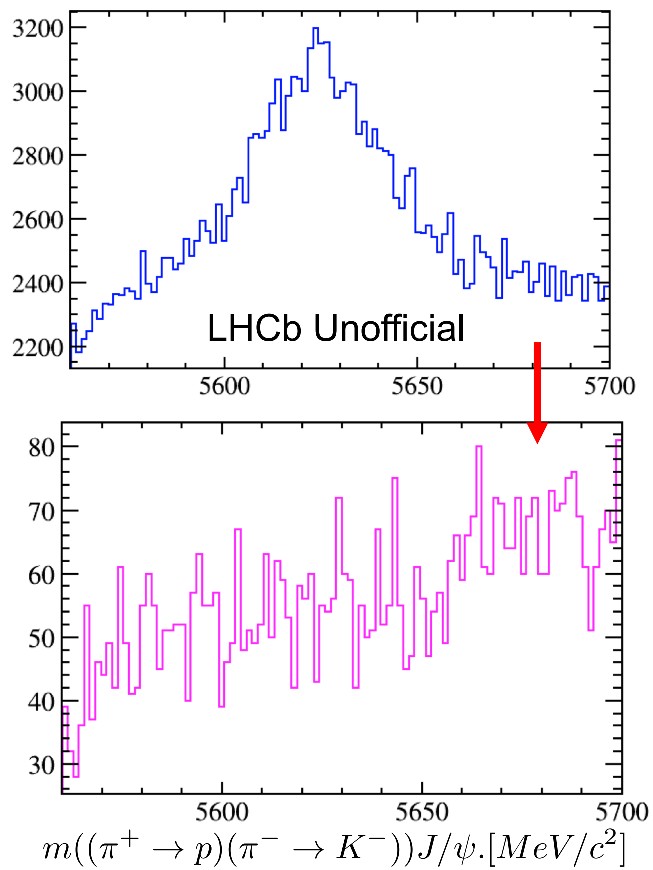
OTHER PEAKING BACKGROUNDS

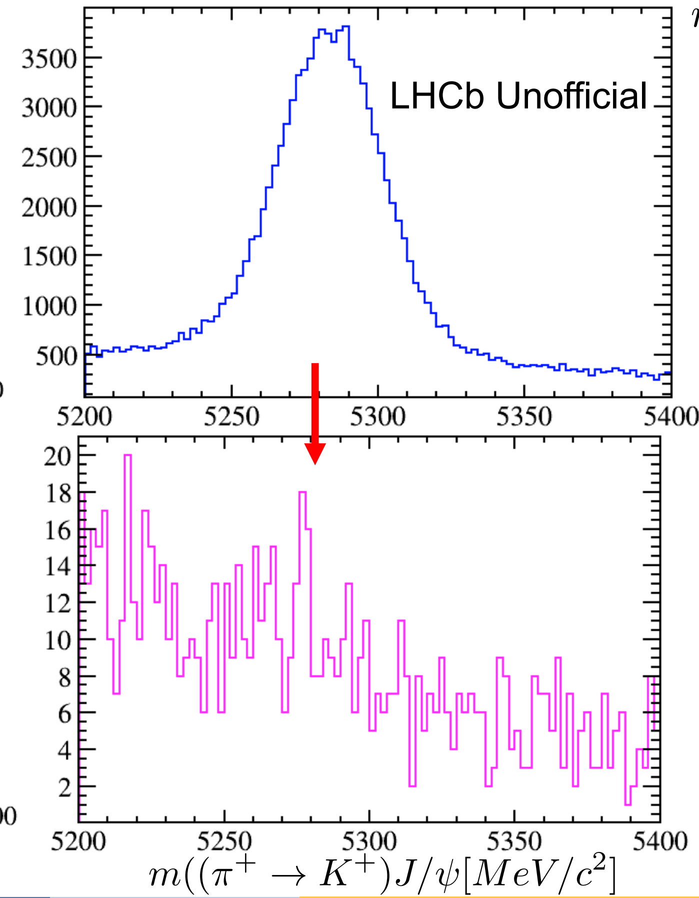
- Many backgrounds are considered and are seen to be effectively removed by the selection



Charm Decays

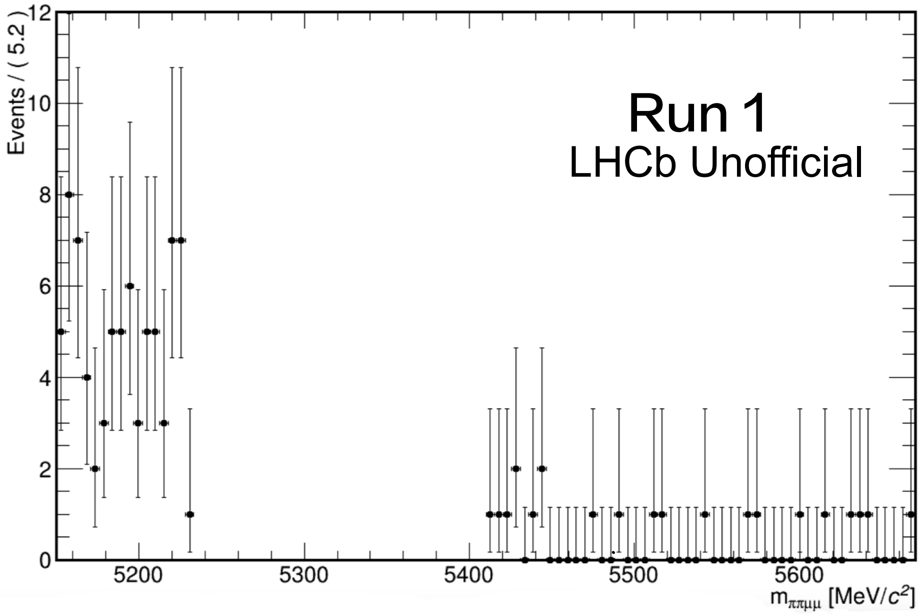
Double-misid decays





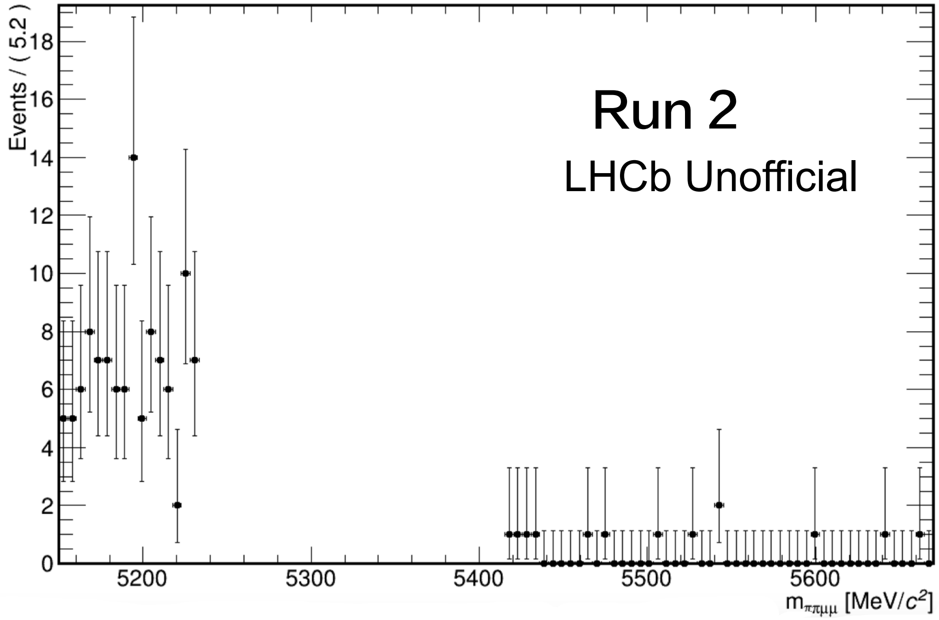
Over reconstructed decays

RARE MODE



- Rare mode is currently blind

- Can see very little combinatorial background remaining after the selection



- Expect ~30 signal events for Run 1 and ~35 signal events for Run 2 c.f. 40 from Run 1 analysis – due to tighter cuts in selection

ANGULAR ANALYSIS

- Final state does not distinguish between B^0 and $\bar{B}^0$. Do not have access to full set of angular variables without a flavour-tagged time-dependent angular analysis (requires upgraded II Dataset)

- Can determine longitudinal polarisation fraction form projection:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_h} = \frac{3}{2}F_{\mathrm{L}}\cos^2\theta_h + \frac{3}{4}(1-F_{\mathrm{L}})(1-\cos^2\theta_h)$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} = \frac{1}{2\pi}(1 + S_3\cos 2\phi + A_{\mathrm{T}}\sin 2\phi)$$

Sensitive to RH currents (photon polarisation at low-q^2)

T-odd observable, sensitive to *CP* violating effects. Can be large due to weak phase differences between diagrams with $u\bar{u}$ and $t\bar{t}$ contributions

FUTURE WORK

- Finalise mass fits and efficiencies
- Systematic errors
- Angular analysis

FIN

BACKUP

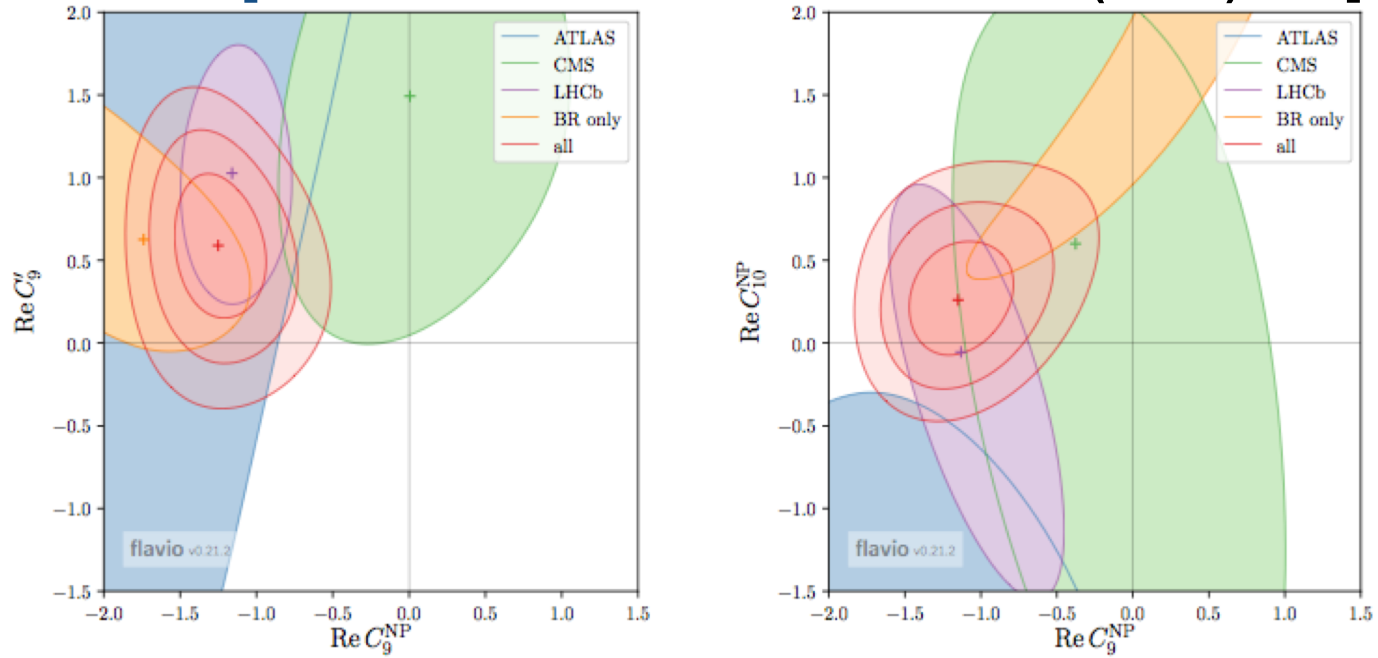
PEAKING BACKGROUNDS

- Major peaking backgrounds are identified within data by swapping mass hypotheses
- Consider backgrounds such as:
  - Misidentified backgrounds
    $$B^0 \to K^{*0}\mu\mu$$
    $$B_s^0 \to (\phi \to K^+K^-)\mu\mu$$
    $$\Lambda_b^0 \to pK\mu\mu$$
  - Partially reconstructed
    $$B_s^0 \to (\eta' \to \rho\gamma)\mu\mu$$
    $$B_s^0 \to (\phi \to \pi^+\pi^-\pi^0)\mu\mu$$
  - Over reconstructed
    $$B^+ \to K^+\mu\mu$$
    $$B^+ \to \pi^+\mu\mu$$
  - Semileptonic backgrounds
    $$B^0 \to (D^- \to (\bar{K}^{*0} \to K\pi)\mu^-\bar{\nu})\mu^+\nu$$
  - Hadronic backgrounds $\mu \to \pi$
- Potential backgrounds which cannot be easily seen within data have yields estimated relative to control mode using BFs, PID eff ratios, fragmentation fractions and mass window efficiency estimated with RapidSim samples

Global fits

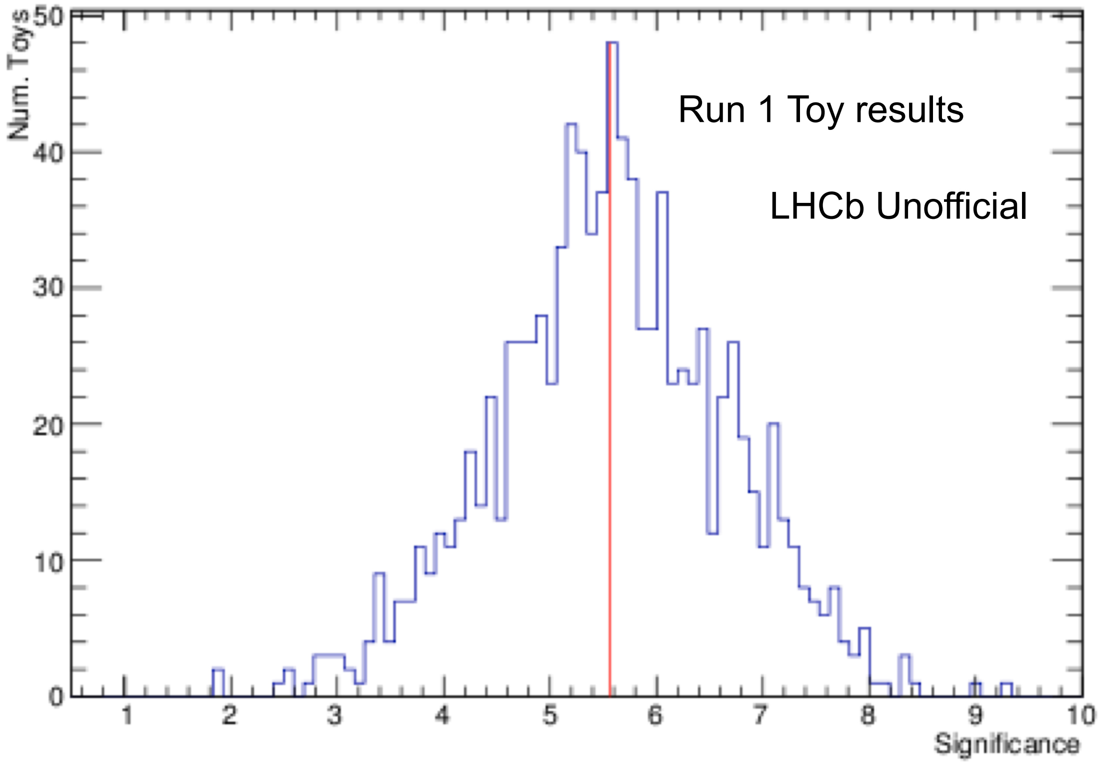
- Several attempts to understand LHCb results using global fits to $b \to s$ data

[W. Altmannshofer et al. EPJC 77 (2017) 377]



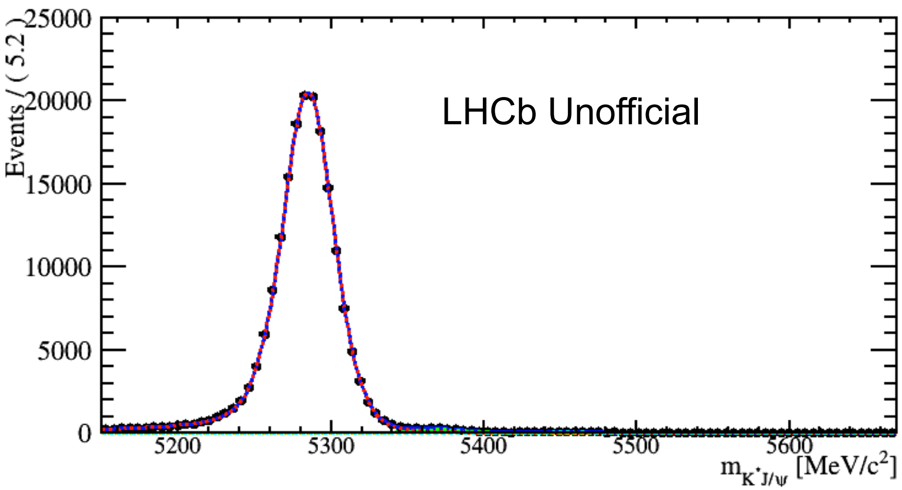
- General pattern of consistency between experiments/measurements.
- Data favours a modified vector coupling ($C_9^{NP} \neq 0$) at 4-5 σ

PID VS BDT OPTIMISATION

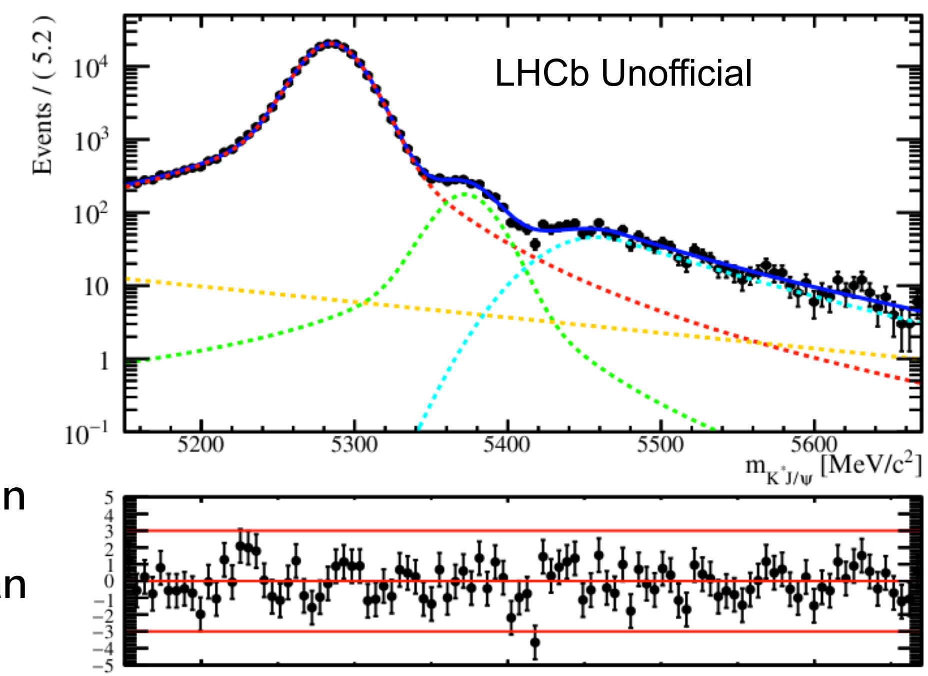


CONTROL MODE FIT

- $B^0 \to K^{*0} J/\psi$ used as control mode due to clean signal and large yield
- Control mode is used for normalisation within the BF calculation to cancel systematics
- Fit with sum of two Crystall Ball functions + Gaussian – lower tail to accomodate FSR and upper to accomodate non-Gaussian tails. Exponential for combinatorial background



Run 1

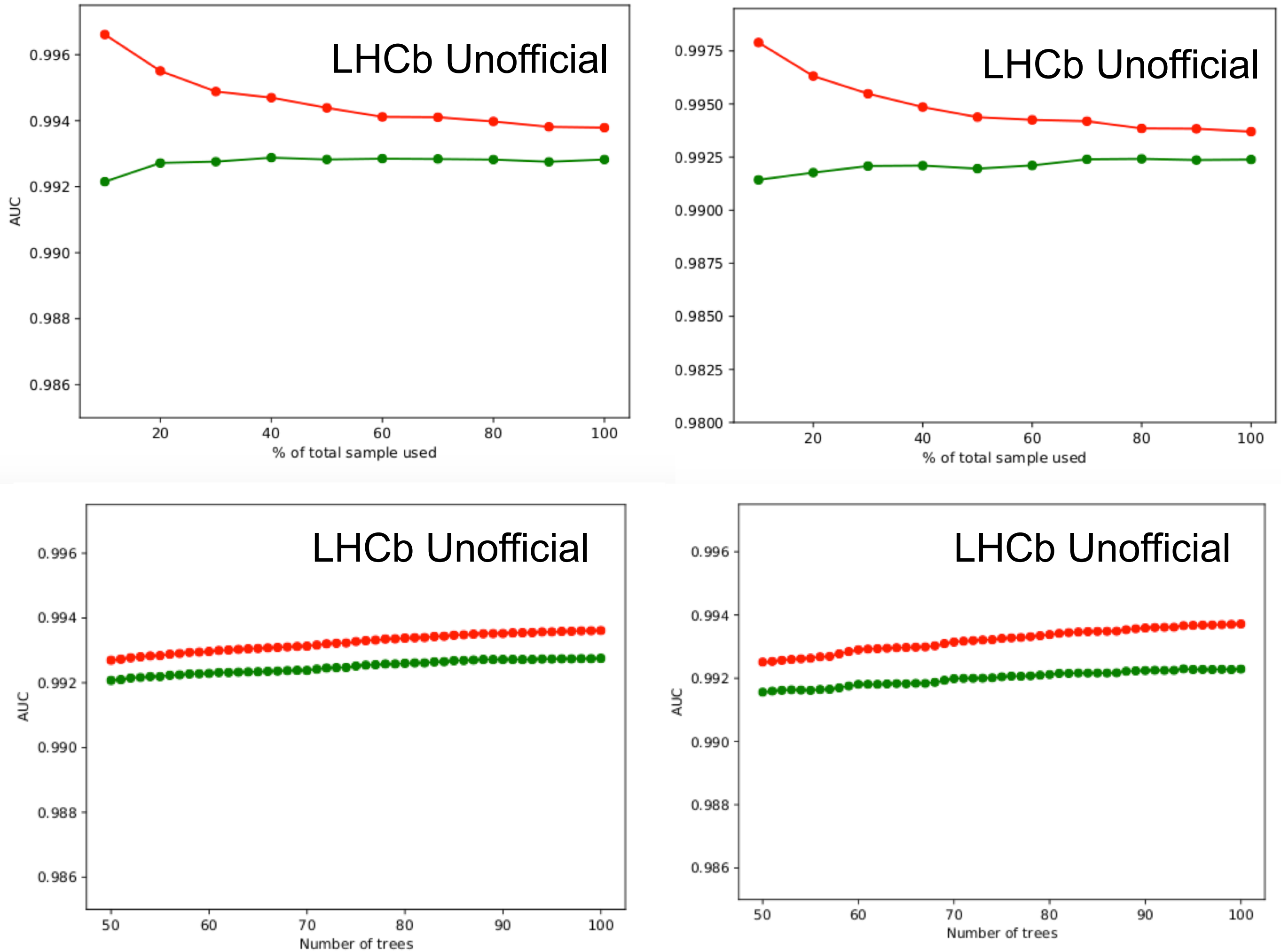


$B^0 \to K^{*0} J/\psi$	Sum of two CBs + Gaussian
$B_s^0 \to K^{*0} J/\psi$	Sum of two CBs + Gaussian
$B^+ \to K^+ J/\psi$	CB
Combinatorial	Exponential

MVA OVERTRAINING CHECKS

Train split
Test split

Run 1 Run 2

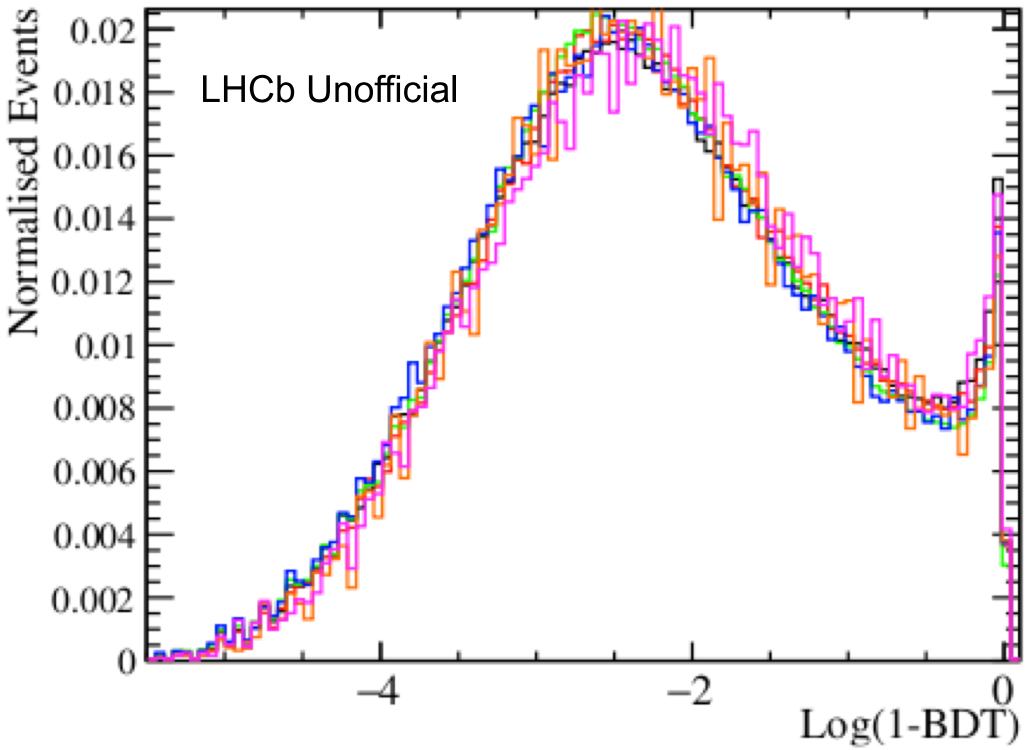


- Use learning curves as test for overfitting and underfitting
- Both Run 1 and 2 show good performance without high variance

MVA Performance

- Compare BDT response for different but kinematically similar MC modes – would expect similar performance in absence of large overtraining

Run 1

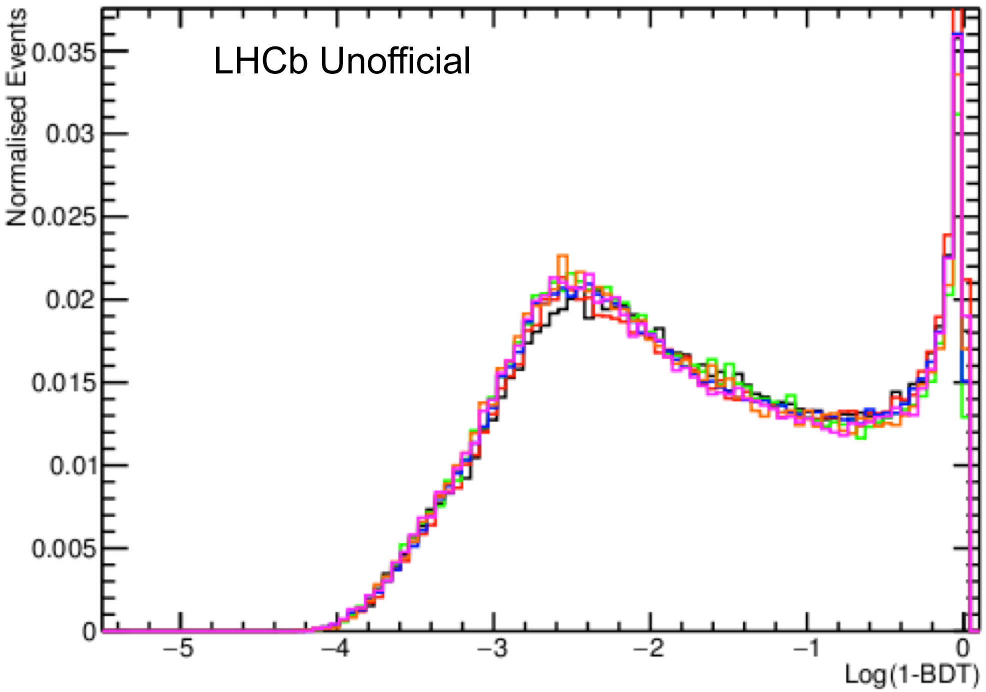


- Black $B^0 \to \rho^0 \mu^+ \mu^-$
- Red $B^0 \to \rho^0 J/\psi$
- Green $B^0 \to K^{*0} \mu^+ \mu^-$
- Blue $B^0 \to K^{*0} J/\psi$
- Orange $B_s^0 \to f^0 J/\psi$
- Pink $B_s^0 \to f^0 \mu^+ \mu^-$

MVA Performance

- Compare BDT response for different but kinematically similar MC modes – would expect similar performance in absence of large overtraining

Run 2



- Black $B^0 \to \rho^0 \mu^+ \mu^-$
- Red $B^0 \to \rho^0 J/\psi$
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- Blue $B^0 \to K^{*0} J/\psi$
- Orange $B_s^0 \to f^0 J/\psi$
- Pink $B_s^0 \to f^0 \mu^+ \mu^-$

PID VS BDT OPTIMISATION

- Run 2 optimisation