Analysis of the rare decay $B^+ \to \pi^+\mu^+\mu^-$ with LHCb

by Hendrik Jage

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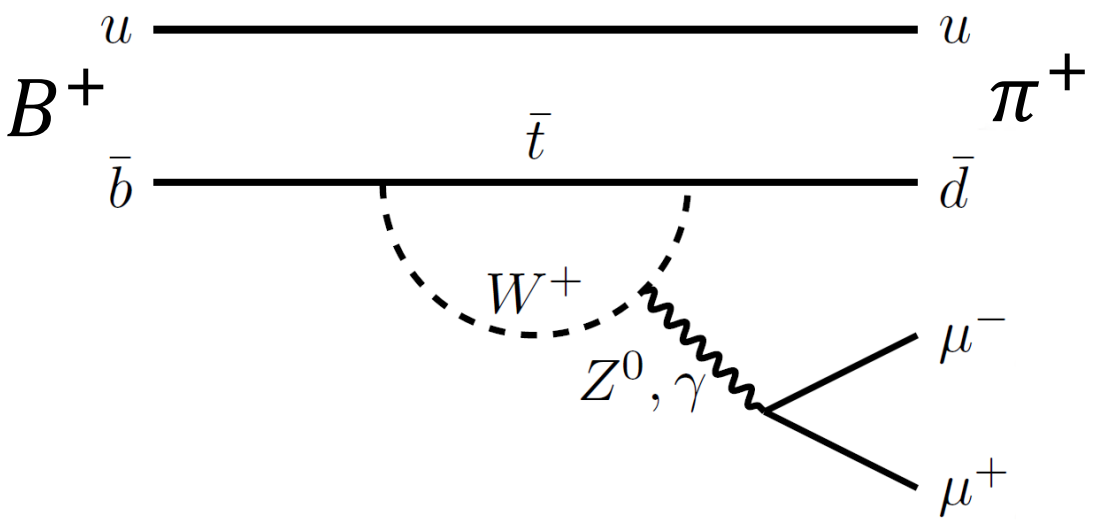
The $B^+ \to \pi^+\mu^+\mu^-$ decay

- Flavour Changing Neutral Current ($b \to d l^+ l^-$)
- More suppressed than $b \to s l^+ l^-$ ($|V_{td}/V_{ts}|^2 \approx 1/22$)

→ Search for New Physics



- First observed in 2012 at LHCb [JHEP12(2012)125]
- Analysis with Run 1 dataset in 2014 [LHCb-ANA-2014-092]

→ No significant deviations from Standard Model predictions

Analysis strategy

- Measurement of $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)$ via $B^+ \to J/\psi\,(\to \mu^+\mu^-)\pi^+$

(Control channel)

$$\frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\pi^+)} = \frac{N_{\pi\mu\mu}}{N_{J/\psi\,\pi}} \cdot \frac{\varepsilon_{J/\psi\,\pi}}{\varepsilon_{\pi\mu\mu}} \cdot \mathcal{B}_{PDG}(J/\psi \to \mu^+\mu^-)$$

  - Yield measurement
    - Background rejection
    - Fit
  - Efficiency calculation
    - Data-simulation agreement

→ Determination of $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)$

Selection

- Complete LHCb Run 1 dataset ($3\ \mathrm{fb}^{-1}$)
- Trigger & Stripping

<u>Backgrounds</u>

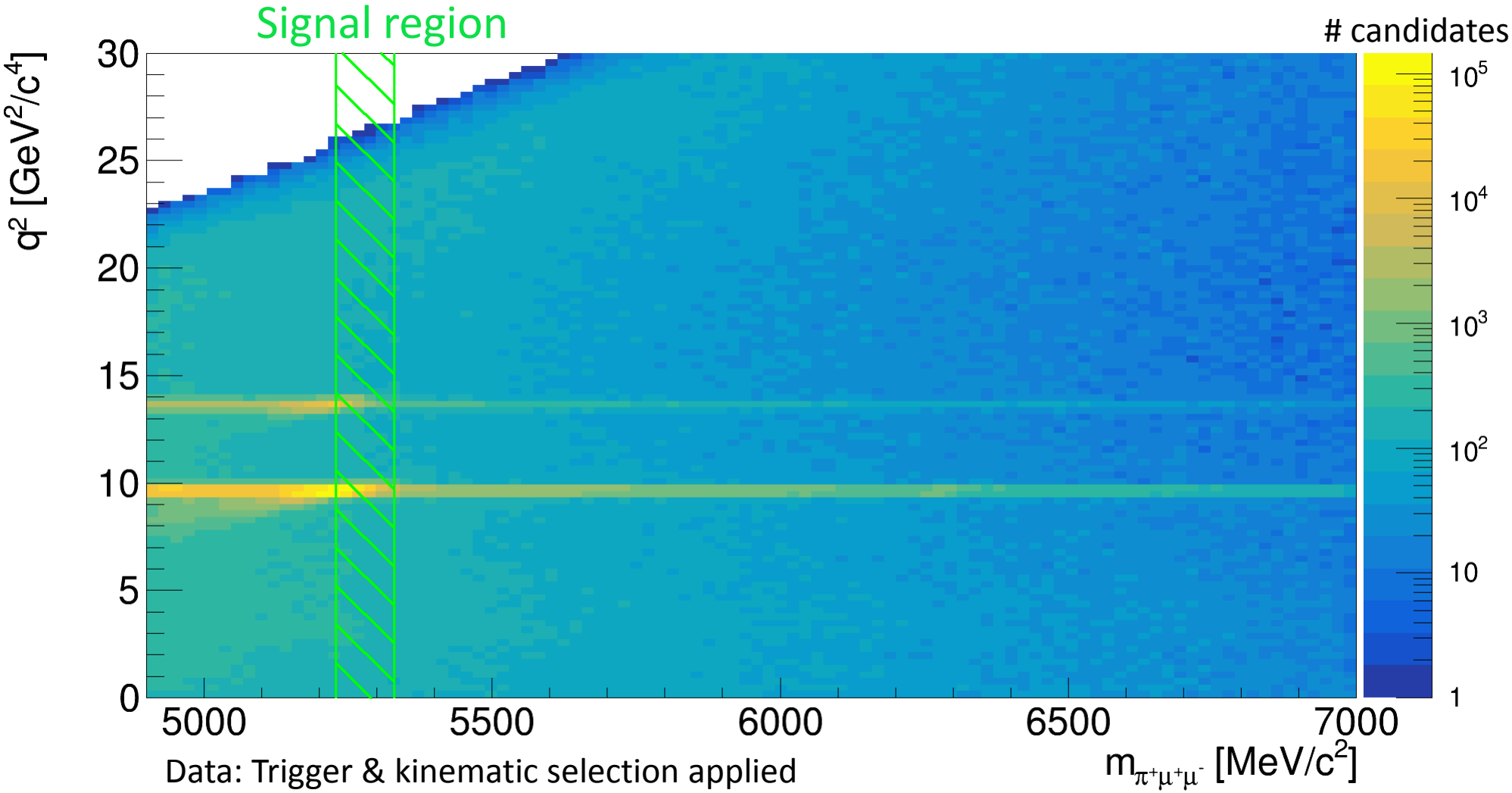
- Physical peaking background
  - Misidentifications (Mis-ID)
    $B^+ \to K^+\mu^+\mu^-$ ($K^+ \to \pi^+$)
  - Partially reconstruction (part. reco.)
    $B^0 \to \cancel{\pi^-}\pi^+\mu^+\mu^-$

} Kinematic selection
PID requirement

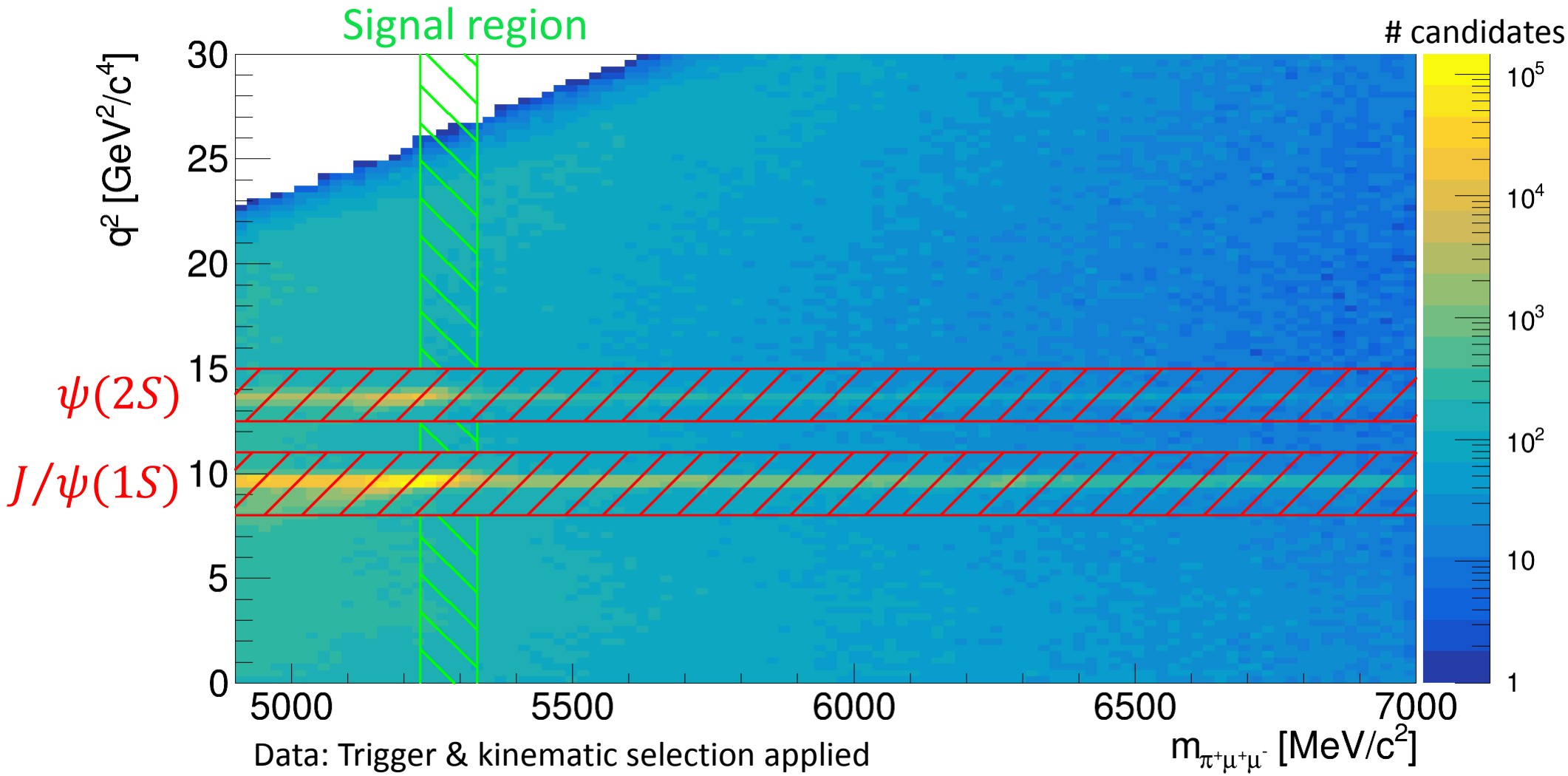
- Combinatorial background
  - Random tracks

} Multivariate classifier

Charmonium veto

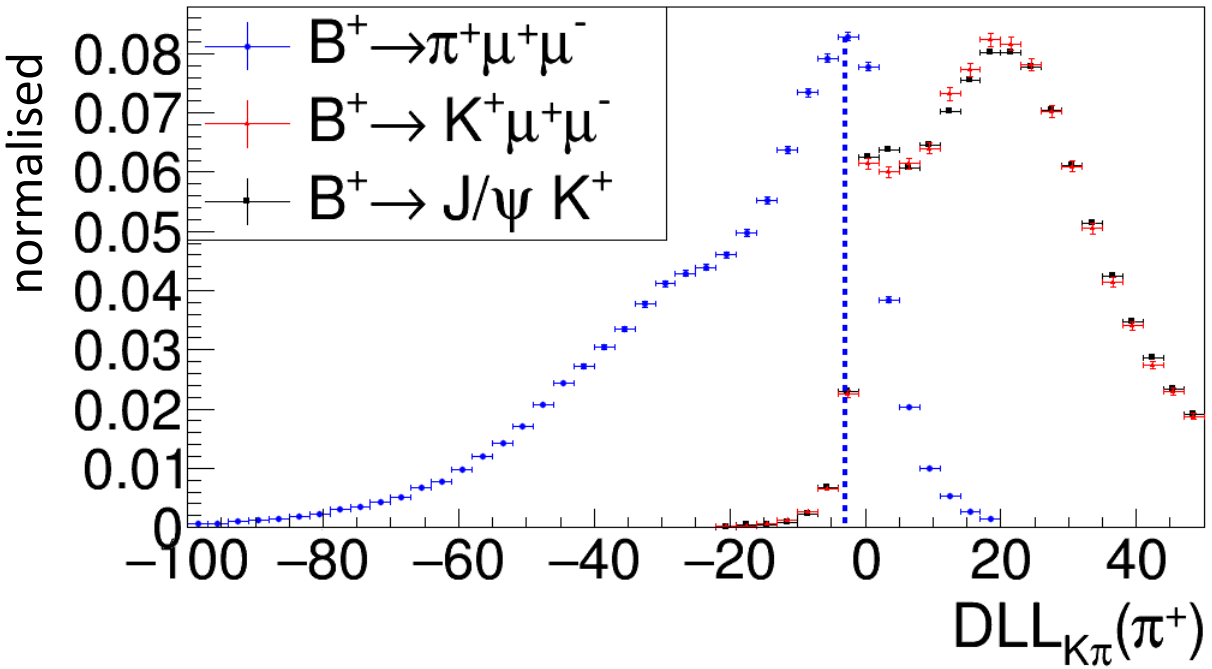


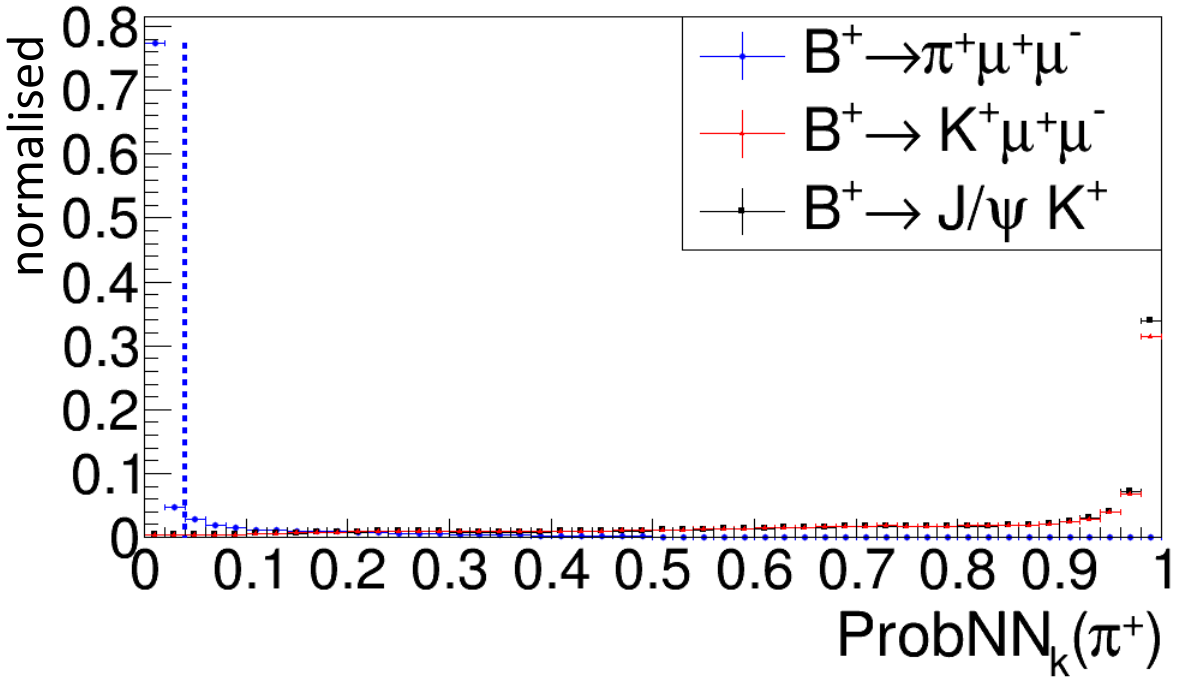
Charmonium veto



PID selection

- Main mis-ID background: $B^+ \to K^+\mu^+\mu^-$ $(K^+ \to \pi^+)$
  - Comparison of $\mathrm{DLL}_{K\pi}$ (old analysis) and $\mathrm{ProbNN_k}$ performance
  - Corrected simulation (via PID resampling)

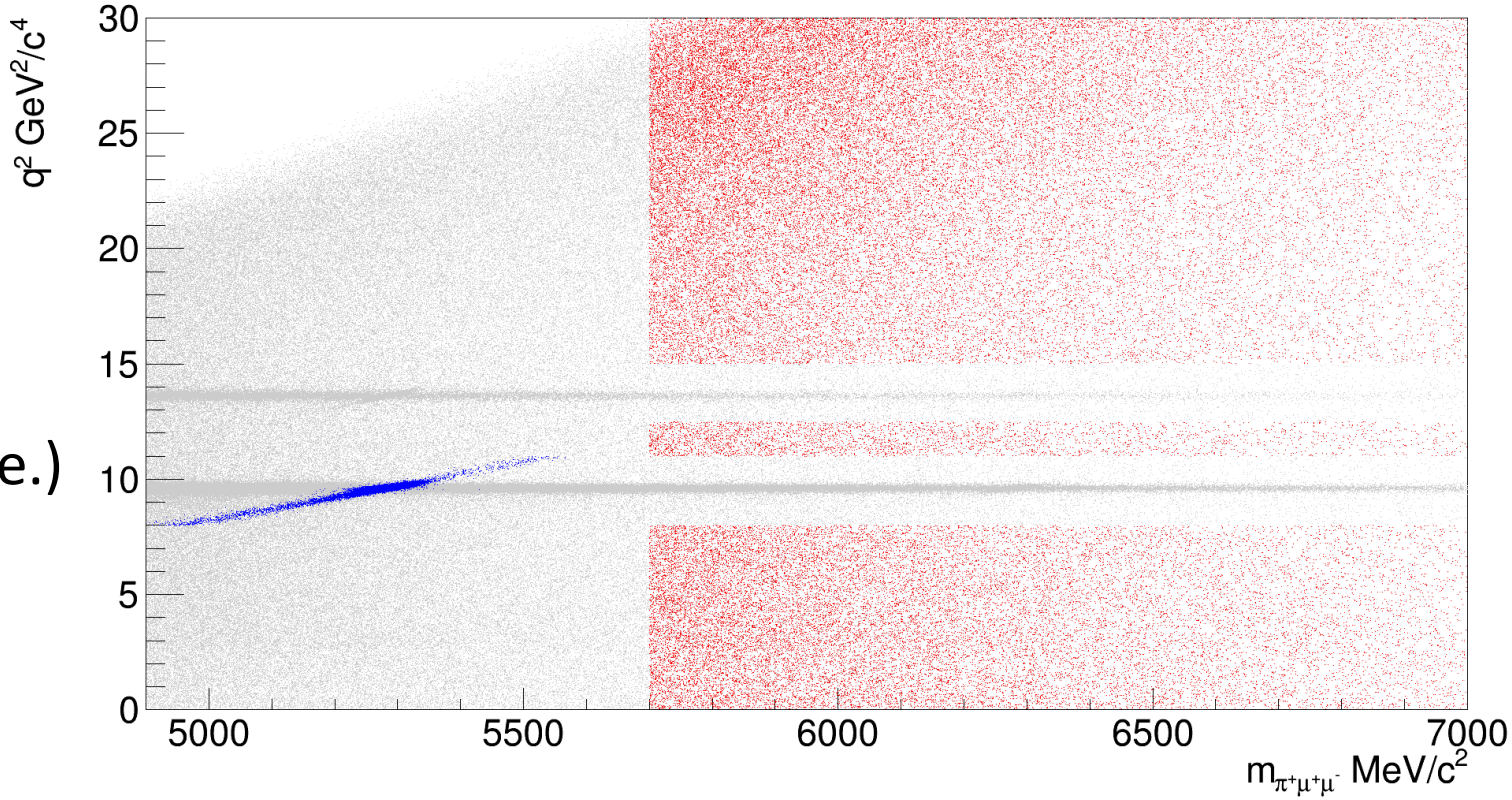




→ Use $\mathrm{ProbNN_k}$ requirement (better performance)

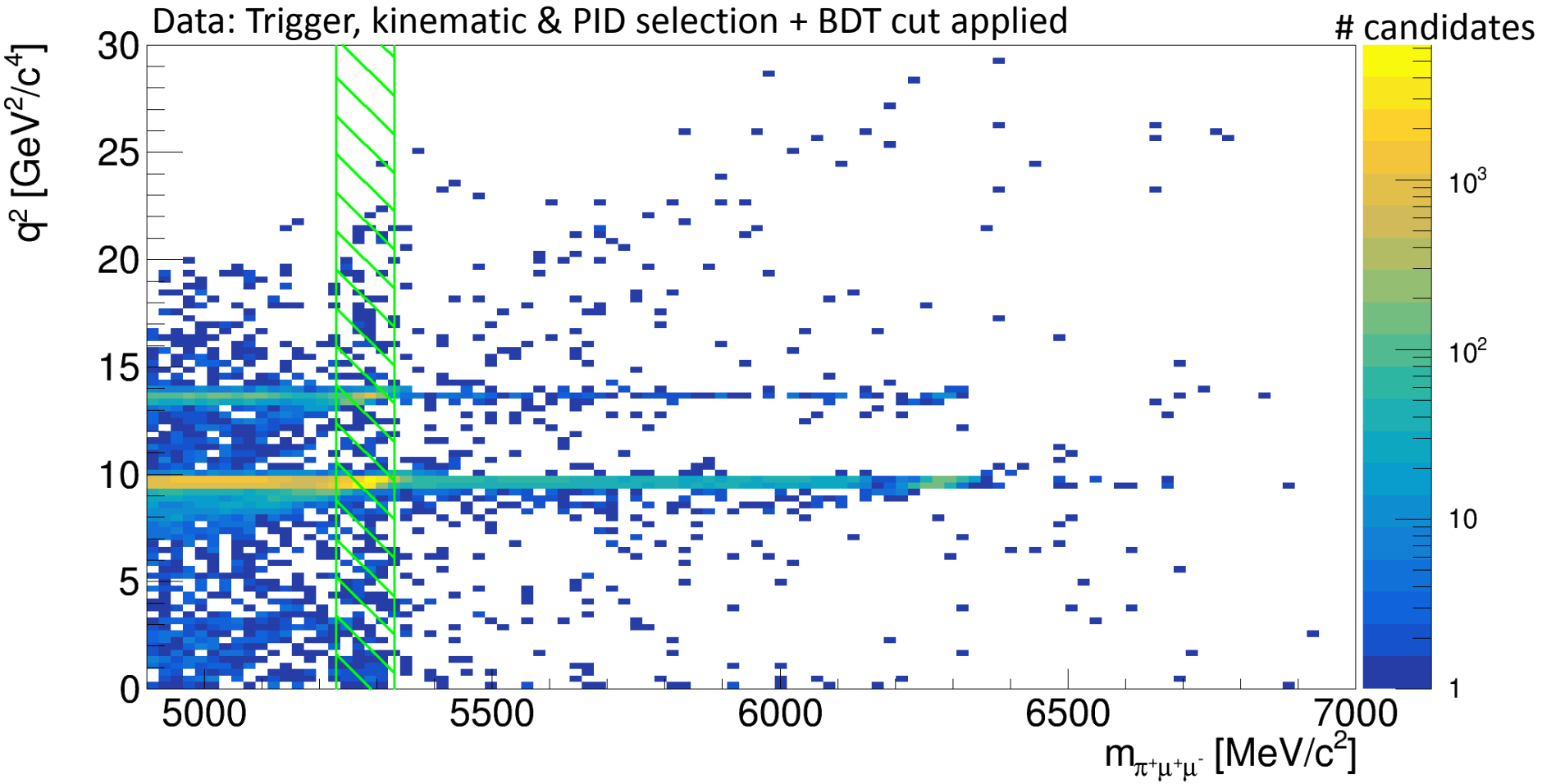
Multivariate classifier

- Combinatorial background reduction
- Boosted Decision Tree (BDT), TMVA software
- Trained on Run 1 dataset
  - Trigger & preselected
  - Background proxy:
    - Upper-mass sideband
  - Signal proxy:
    - Control channel (q^2 require.)
    - B^+- J/ψ constrained mass
    - *sWeighted*
- Improve configuration



BDT

- BDT cut optimised for signal significance

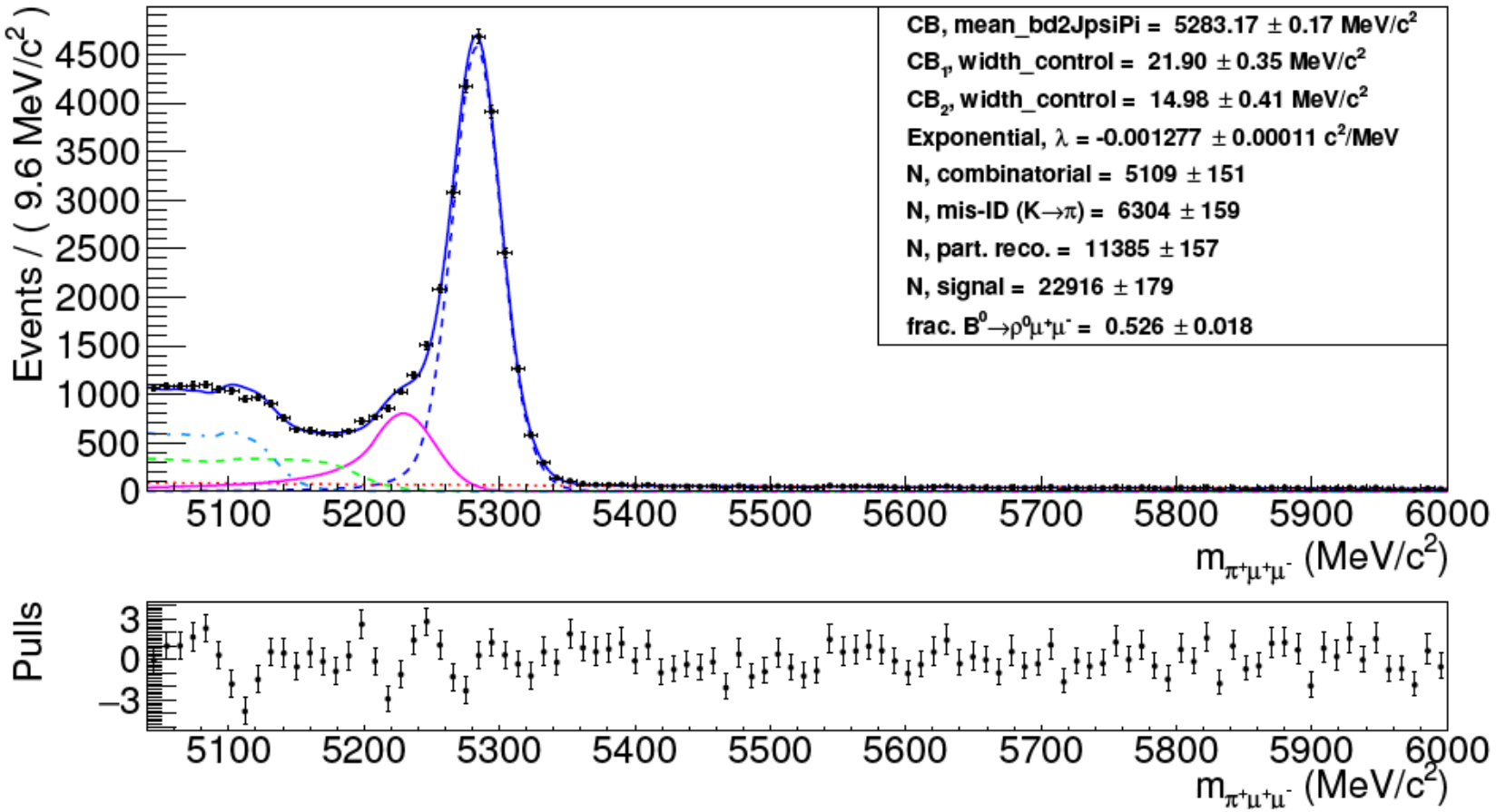


Determination of the yields – control channel

- $B^+ \to J/\psi\,\pi^+$ data
  - Complete selection applied

Signal
Mis-ID ($K^+ \to \pi^+$)
$B^0 \to \rho^0 \mu^+ \mu^-$
$B_s^0 \to f^0 \mu^+ \mu^-$
Comb. background

$$N_{J/\psi\,\pi} = 22916 \pm 179$$



→ Fix width of signal model

→ Fix ratio between part. reco.

Determination of the yields – signal channel

- $B^+ \to \pi^+\mu^+\mu^-$ data
  - Complete selection applied

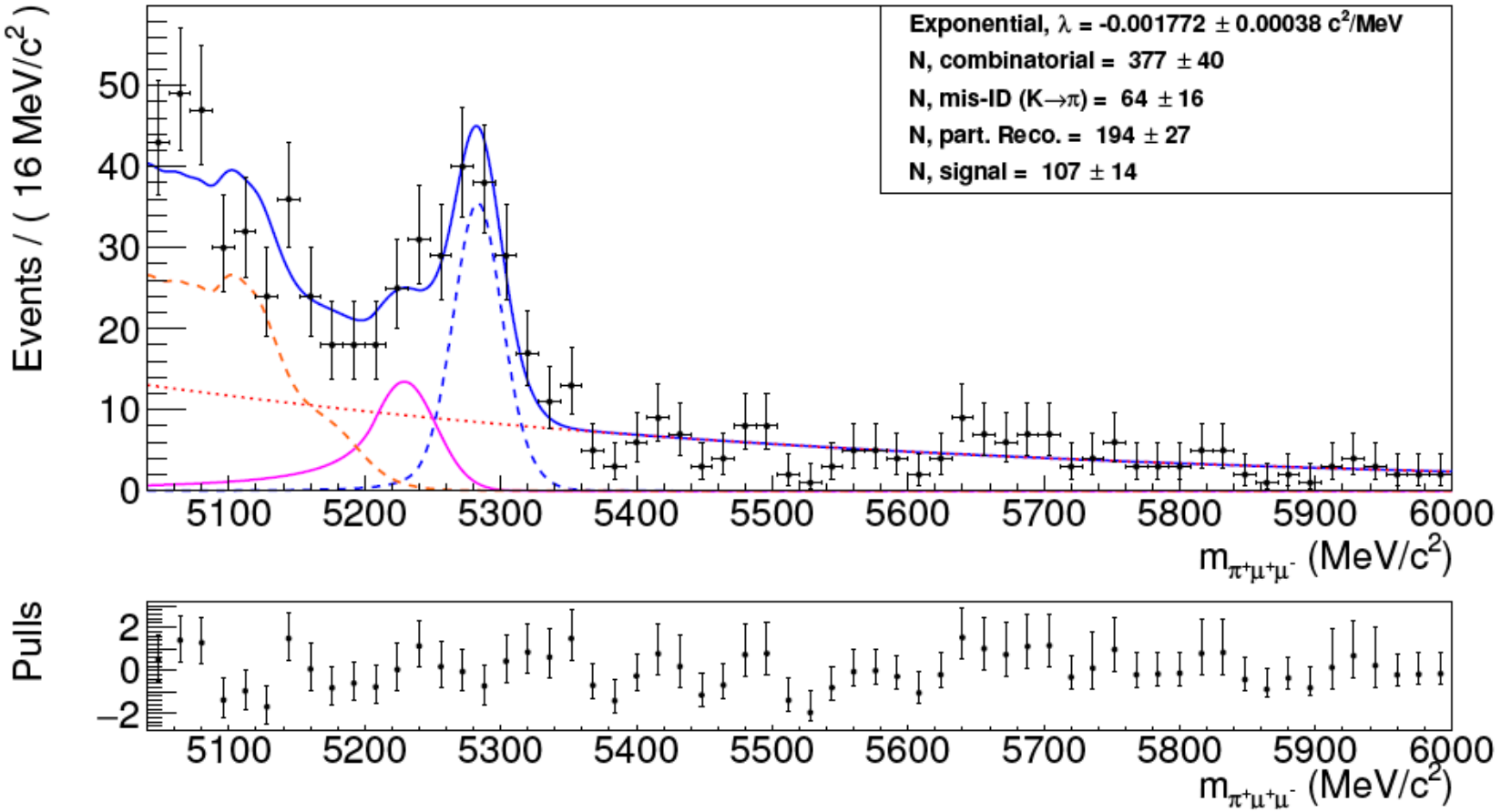
Signal
Mis-ID ($K^+ \to \pi^+$)
Part. reconstructed
Comb. background

$N_{\pi\mu\mu} = 107 \pm 14$

Previous analysis:

$N_{\pi\mu\mu} = 92 \pm 11$

→ Calculate efficiencies



Efficiencies

- Corrected simulated samples
  - PID resampled
  - Reweighted (nTracks & $p_T(B^+)$)

Efficiency [%]	$B^+ \to \pi^+\mu^+\mu^-$	$B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+$
ε_{gen}	16.480 ± 0.033	16.165 ± 0.030
$\varepsilon_{strip\|reco}$	19.61 ± 0.04	20.343 ± 0.025
$\varepsilon_{trigger}$	76.85 ± 0.09	76.57 ± 0.06
ε_{presel}	67.21 ± 0.12	69.27 ± 0.07
ε_{q^2}	72.85 ± 0.14	99.9822 ± 0.0025
ε_{BDT}	58.10 ± 0.18	69.22 ± 0.09
ε^{sel}_{tot}	4.287 ± 0.020	7.466 ± 0.016
ε_{tot}	0.706 ± 0.004	1.207 ± 0.003

- Uncertainties:
  - Stat.: Finite sample size
  - Syst.: Data-simulation differences

$$\frac{\varepsilon_{J/\psi\,\pi}}{\varepsilon_{\pi\mu\mu}} = 1.709 \pm 0.010(stat) \pm 0.031(syst)$$

Results

Relative branching fraction

$$\frac{\mathcal{B}(B^+\to\pi^+\mu^+\mu^-)}{\mathcal{B}(B^+\to J/\psi\pi^+)} = \frac{N_{\pi\mu\mu}}{N_{J/\psi\,\pi}} \cdot \frac{\varepsilon_{J/\psi\,\pi}}{\varepsilon_{\pi\mu\mu}} \cdot \mathcal{B}_{PDG}(J/\psi \to \mu^+\mu^-) =$$

$$(4.755 \pm 0.623(stat) \pm 0.090(syst) \pm 0.026(norm)) \times 10^{-4}$$

Absolute branching fraction

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = \frac{\mathcal{B}(B^+\to\pi^+\mu^+\mu^-)}{\mathcal{B}(B^+\to J/\psi\pi^+)} \cdot \mathcal{B}_{PDG}(B^+ \to J/\psi\,\pi^+) =$$

$$(19.496 \pm 2.555(stat) \pm 0.370(syst) \pm 1.905(norm)) \times 10^{-9}$$

- Previous analysis: [LHCb-ANA-2014-092]

  $(18.337 \pm 2.270(stat) \pm 0.435(syst)) \times 10^{-9}$

- Standard model prediction: [Phys. Rev. Lett. 115 (2015) no. 15, 152002]

  $\mathcal{B}_{SM}(B^+ \to \pi^+\mu^+\mu^-) = (20.4 \pm 2.1) \times 10^{-9}$

Conclusion and outlook

- Selection of $B^+ \to \pi^+\mu^+\mu^-$ improved
  - New PID requirement
  - BDT performance improved
- Measurement of relative & absolute branching fraction
- Good agreement with previous analysis & SM predictions

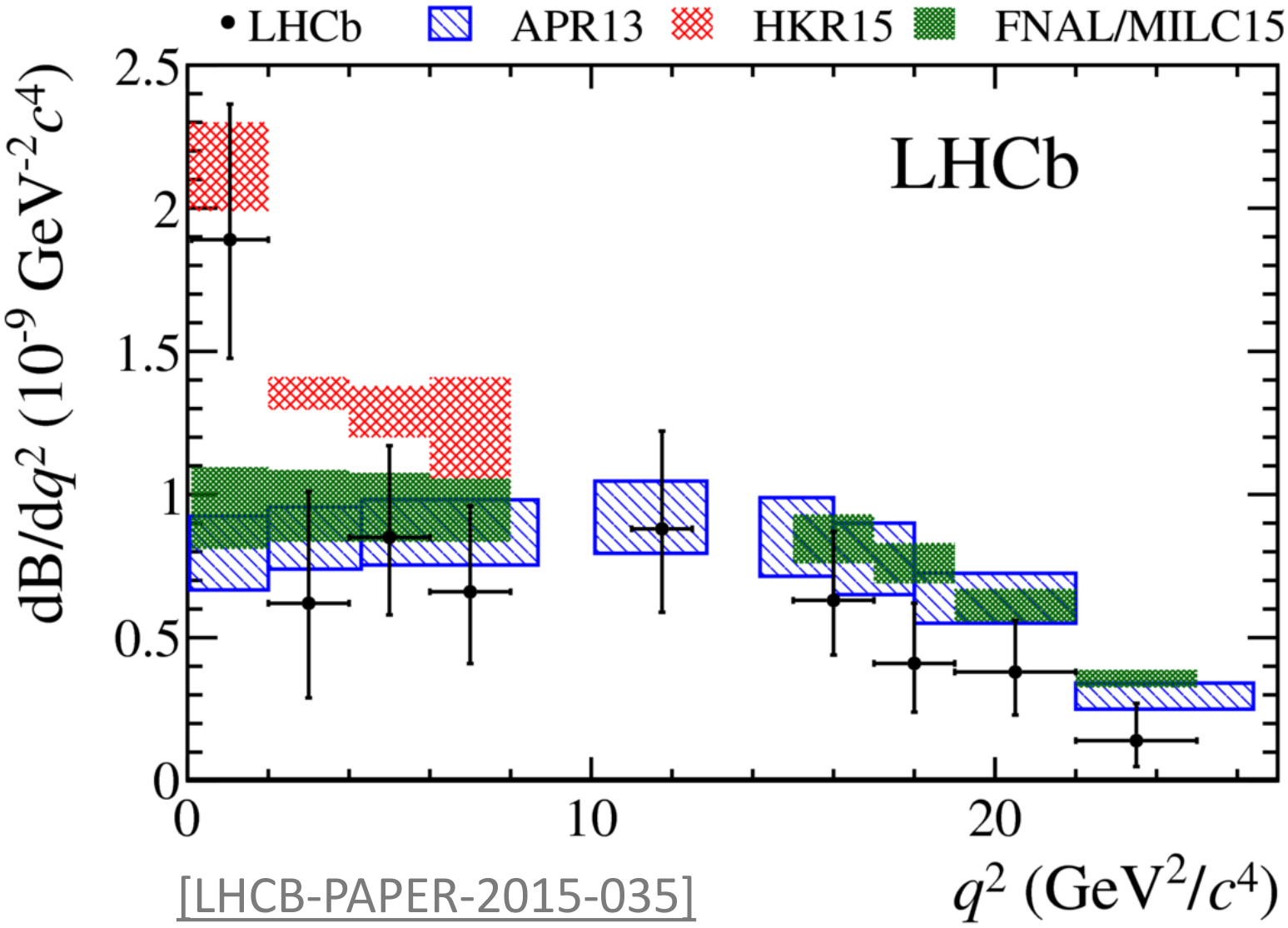
Outlook

- Analysis of LHCb Run 2 datasets
- Improve measurement of $|V_{td}/V_{ts}|^2$ via $\frac{\mathcal{B}(B^+\to\pi^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}$

Thank you
for your attention!

Backup

Standard Model predictions



[LHCB-PAPER-2015-035]

Selection

Candidate	Requirement
B^+	$4900 < m_{\pi^+\mu^+\mu^-} < 7000\,\mathrm{MeV}/c^2$ end vertex $\chi^2/\mathrm{ndf} < 8.0$ $\chi^2_{\mathrm{IP}} < 16.0$ DIRA > 0.9999 (best PV) flight distance $\chi^2 > 121.0$
π^+	track GhostProb < 0.35 min $\chi^2_{\mathrm{IP}} > 6.0$ `hasRICH` = True
$\mu^+\mu^-$	end vertex $\chi^2/\mathrm{ndf} < 12.0$ DIRA > -0.9 flight distance $\chi^2 > 9.0$ $m_{\mu^+\mu^-} < 7100\,\mathrm{MeV}/c^2$
μ^+, μ^-	track GhostProb < 0.35 min $\chi^2_{\mathrm{IP}} > 9.0$ $\mathrm{DLL}_{\mu\pi} > -3.0$ `isMuon` = True
Detector	`nSPDHits` < 600

Candidate	Stage	Trigger line
J/ψ	L0	`MuonDecisionTOS`
		`DiMuonDecisionTOS`
B^+	HLT1	`TrackMuonDecisionTOS`
		`TrackAllL0DecisionTOS`
	HLT2	`Topo2BodyBBDTDecisionTOS`
		`Topo3BodyBBDTDecisionTOS`
		`TopoMu2BodyBBDTDecisionTOS`
		`TopoMu3BodyBBDTDecisionTOS`
		`DiMuonDetachedDecisionTOS`

Candidate	Requirement
π^+	`isMuonLoose` = False
	`inAccMuon` = True
	$p_{\mathrm{T}} > 300$ MeV/c
B^+	$p_{\mathrm{T}} > 300$ MeV/c
μ^+, μ^-	$p_{\mathrm{T}} > 300$ MeV/c

Candidate	Requirement
π^+	$\mathrm{ProbNN}_K < 0.04$
μ^+, μ^-	$\mathrm{ProbNN}_\mu > 0.2$
	$\mathrm{ProbNN}_K < 0.4$

Signal channel		Control channel	
Resonance	Veto	Candidate	Requirement
J/ψ	$8 < q^2 < 11\,\mathrm{GeV}^2/c^4$	J/ψ	$8 < q^2 < 11\,\mathrm{GeV}^2/c^4$
$\psi(2S)$	$12.5 < q^2 < 15\,\mathrm{GeV}^2/c^4$		

Simulation

Decay	Event type	Configuration	Stripping	N_{gen}
$B^+ \to \pi^+\mu^+\mu^-$	12113024	Pythia8 Sim08e	Stripping20	1M
$B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+$	12143010	Pythia8 Sim08a	Stripping20	2.5M
$B^+ \to K^+\mu^+\mu^-$	12113001	Pythia8 Sim08a	Stripping20	0.5M
$B^+ \to J/\psi\,(\mu^+\mu^-)K^+$	12143001	Pythia8 Sim08e	Stripping20	4M
$B^0 \to \mu^+\mu^- K^{*0}$	11114001	Pythia8 Sim08b	Stripping20	0.5M
$B^+ \to \pi^+\pi^-\pi^+$	12103007	Pythia8 Sim08b	Stripping20	2M
$B^0 \to \rho^0\mu^+\mu^-$	11114022	Pythia8 Sim09b	Stripping21	2M
$B_s^0 \to f^0\mu^+\mu^-$	13114011	Pythia8 Sim09b	Stripping21	2M

Signal

Background

- Selection
  - Optimise vetos
- Branching fraction
  - Fit model
  - Efficiency calculation: $\frac{\varepsilon_{J/\psi\,\pi}}{\varepsilon_{\pi\mu\mu}}$

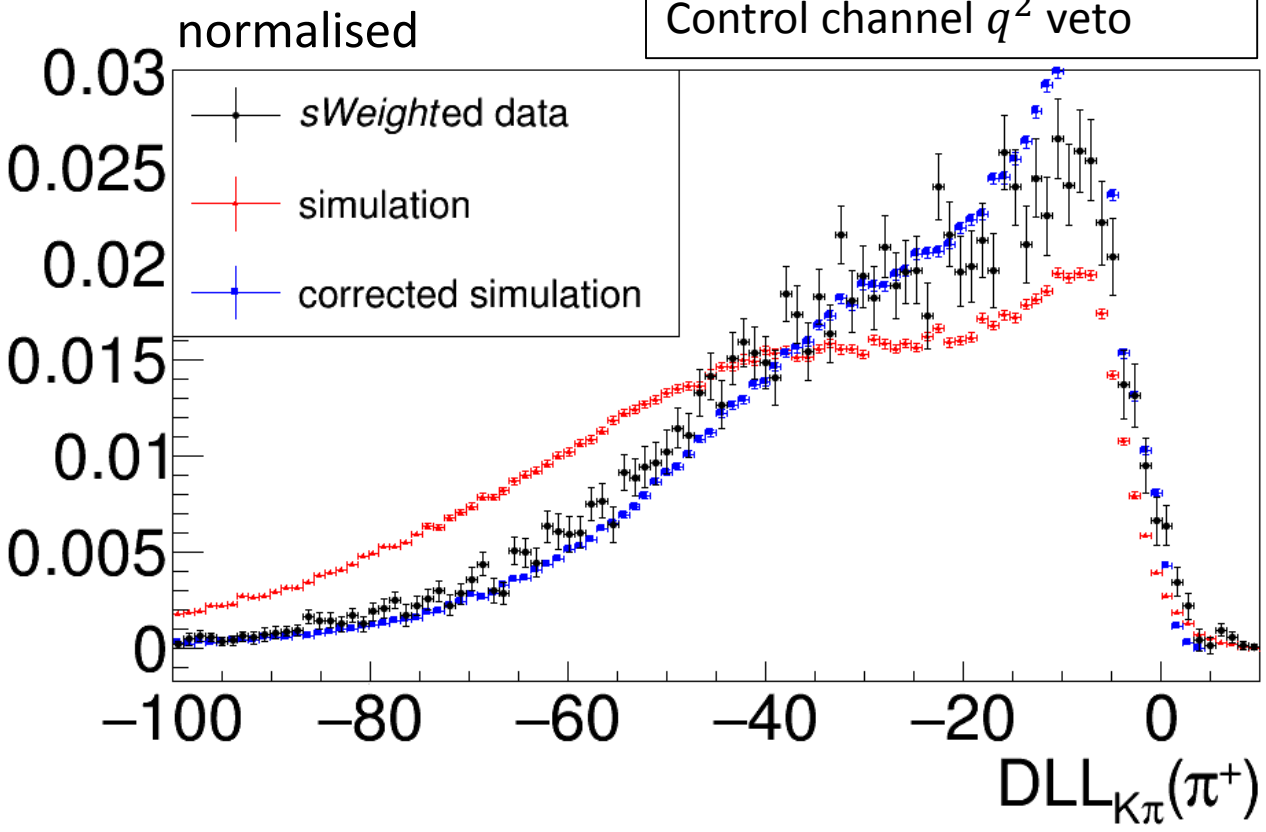
Data-Simulation correction - resampling

- PID variables poorly simulated -> resampling
- Generating new PID values
  - Distribution **p** from calibration data
  - Shape modelled with Meerkat
  - Depending on p, p_T and nTracks

→ $\mathbf{p}(PID|p, p_T, \mathrm{nTracks})$

Comparison: $B^+ \to J/\psi\,\pi^+$
- Simulation
- Data (*sWeighted*)

Trigger & kinematic selected
Control channel q^2 veto

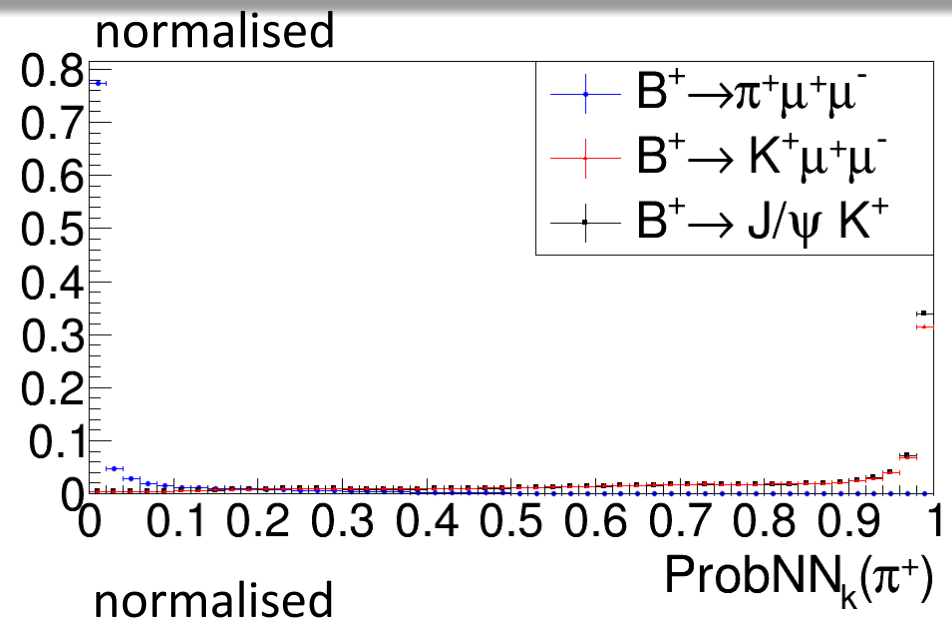


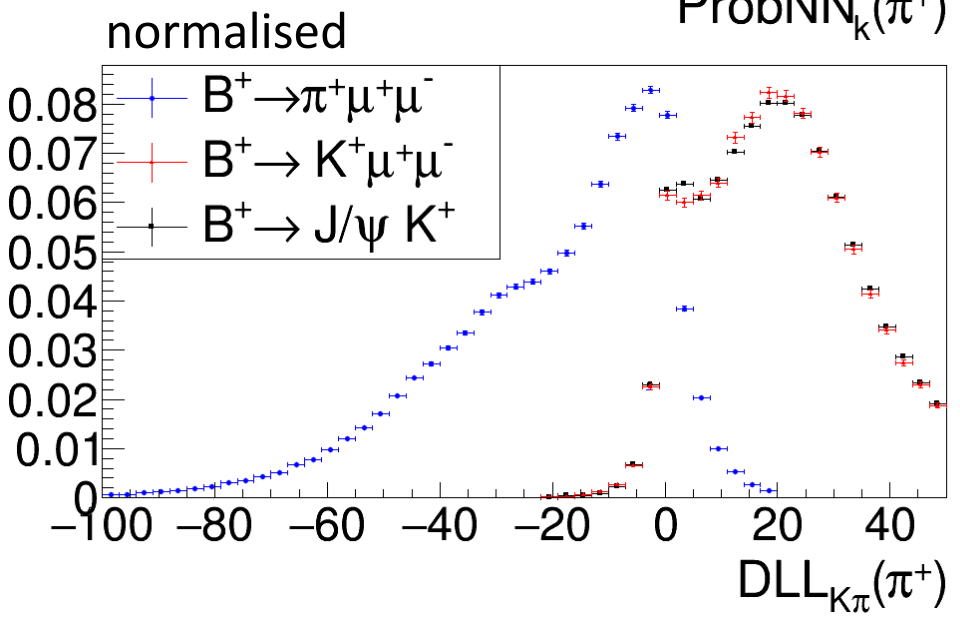
[LHCb-INT-2017-007]

PID selection

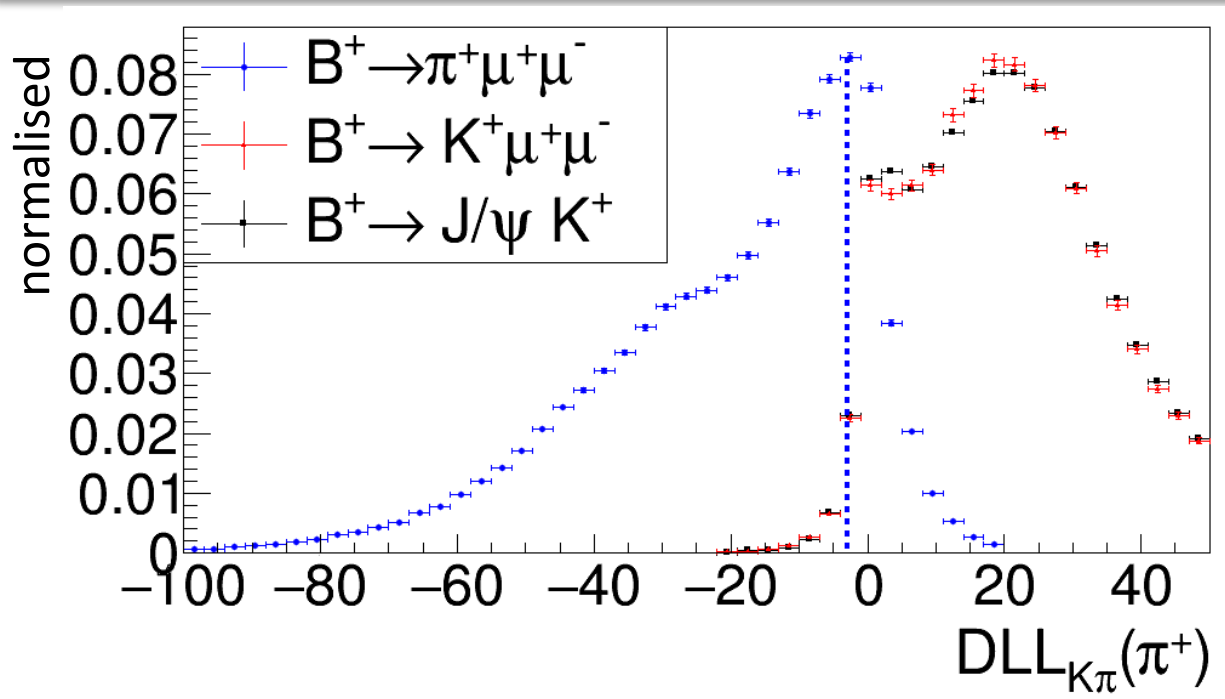
- PID variables:
  - Delta Log Likelihood variables ($\mathrm{DLL}_{X\pi}$)
  - Pseudo-probabilities, neural net ($\mathrm{ProbNN_X}$)
- Previous analysis: Both types
- $K^+ \to \pi^+$ misidentification
- Comparison:
  - Resampled simulated samples:
    - Signal: $B^+ \to \pi^+\mu^+\mu^-$
    - Background: $B^+ \to K^+\mu^+\mu^-$
    - $B^+ \to J/\psi\, K^+$

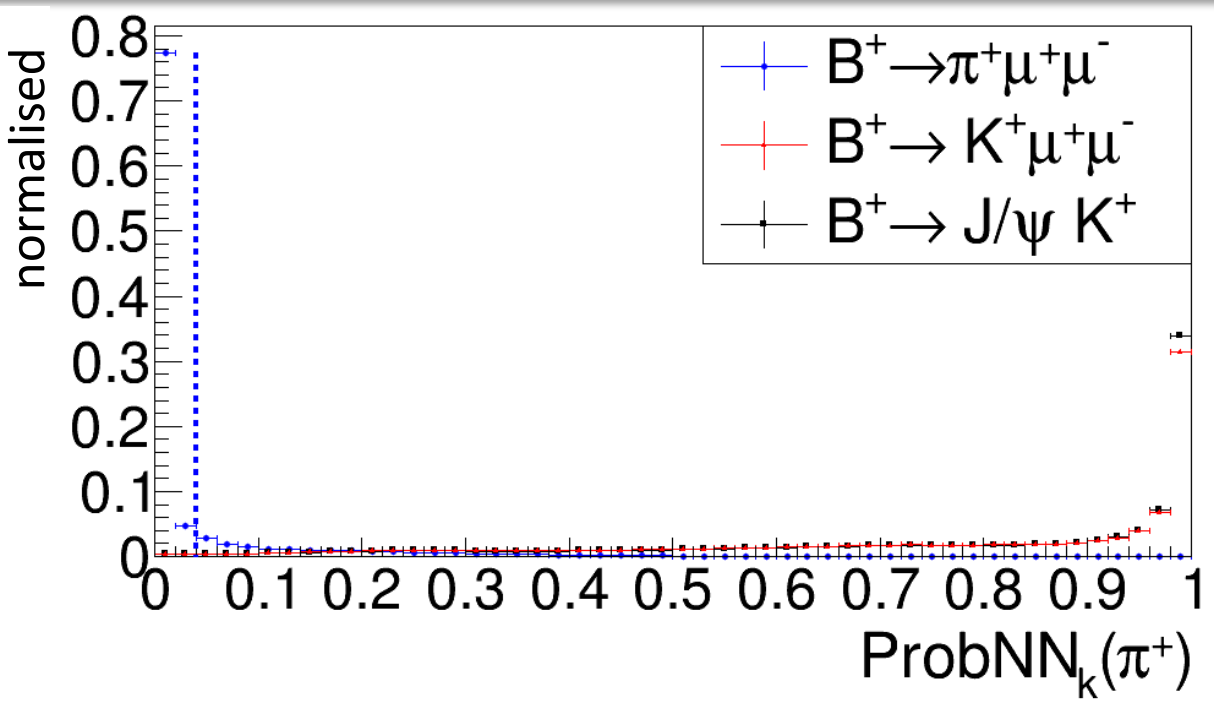
    } Signal q^2 veto
  - Trigger & kinematical selected





PID selection





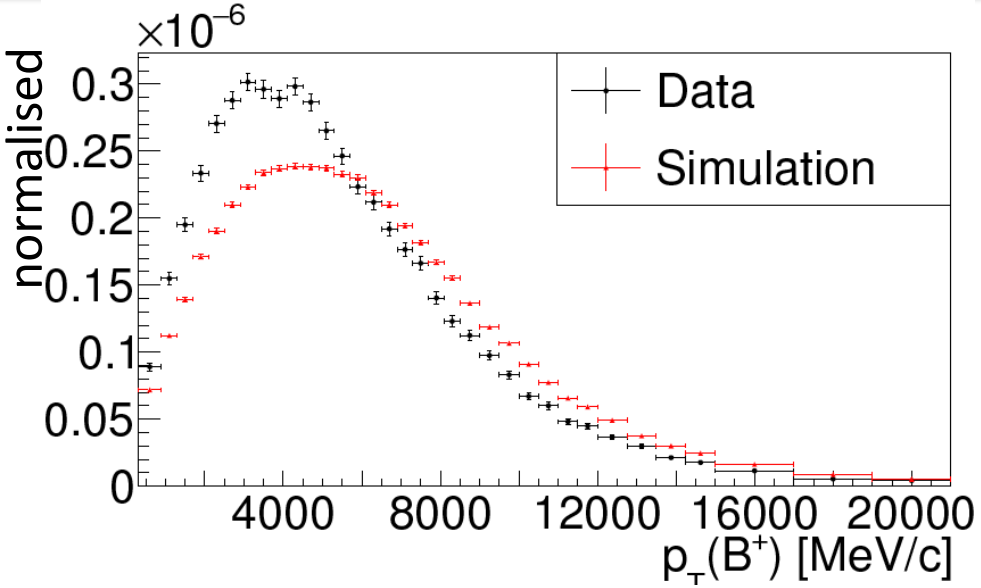
Decay		$\mathrm{DLL}_{K\pi}(\pi^+) < -3$	$\mathrm{ProbNN}_K(\pi^+) < 0.04$
$B^+ \to \pi^+\mu^+\mu^-$	$\varepsilon_{\mathrm{sig}}/\%$	79.903 ± 0.130	80.646 ± 0.128
$B^+ \to K^+\mu^+\mu^-$	$\bar{\varepsilon}_{\mathrm{bkg}}/\%$	98.573 ± 0.056	98.902 ± 0.049
$B^+ \to J/\psi\,(\mu^+\mu^-)K^+$	$\bar{\varepsilon}_{\mathrm{bkg}}/\%$	98.555 ± 0.016	98.929 ± 0.014

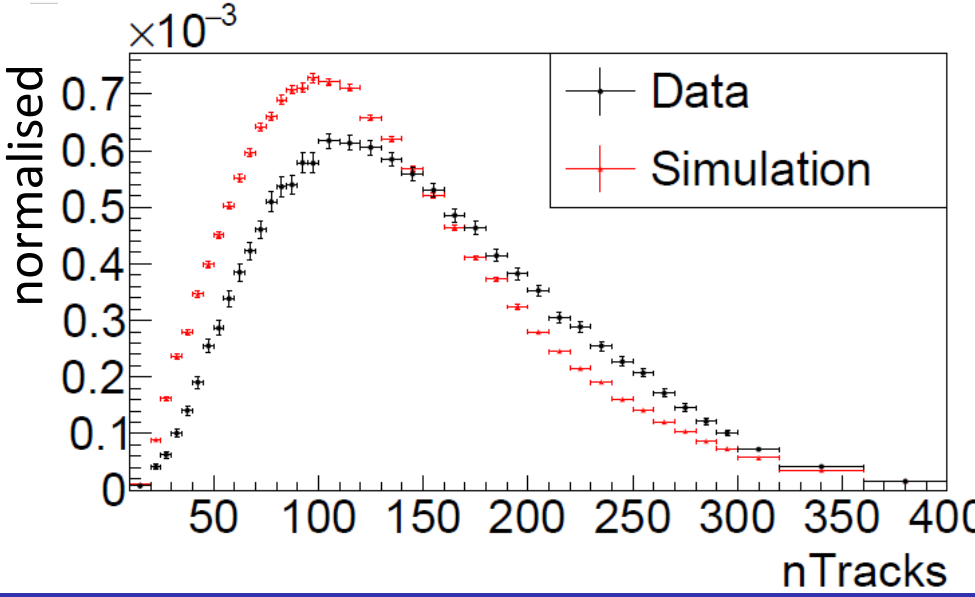
→ Use $\mathrm{ProbNN_k}$ requirement

Data-Simulation correction - reweighting

- Difference in detector occupancy and B^+ transverse momentum
- $B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+$ comparison
  - Control channel data
  - Simulation
  - Complete selection & q^2 requirement
- Binned weights: $w_i = \frac{N_{data}}{N_{sim}}$
- Reweighting nTracks and $p_T(B^+)$:

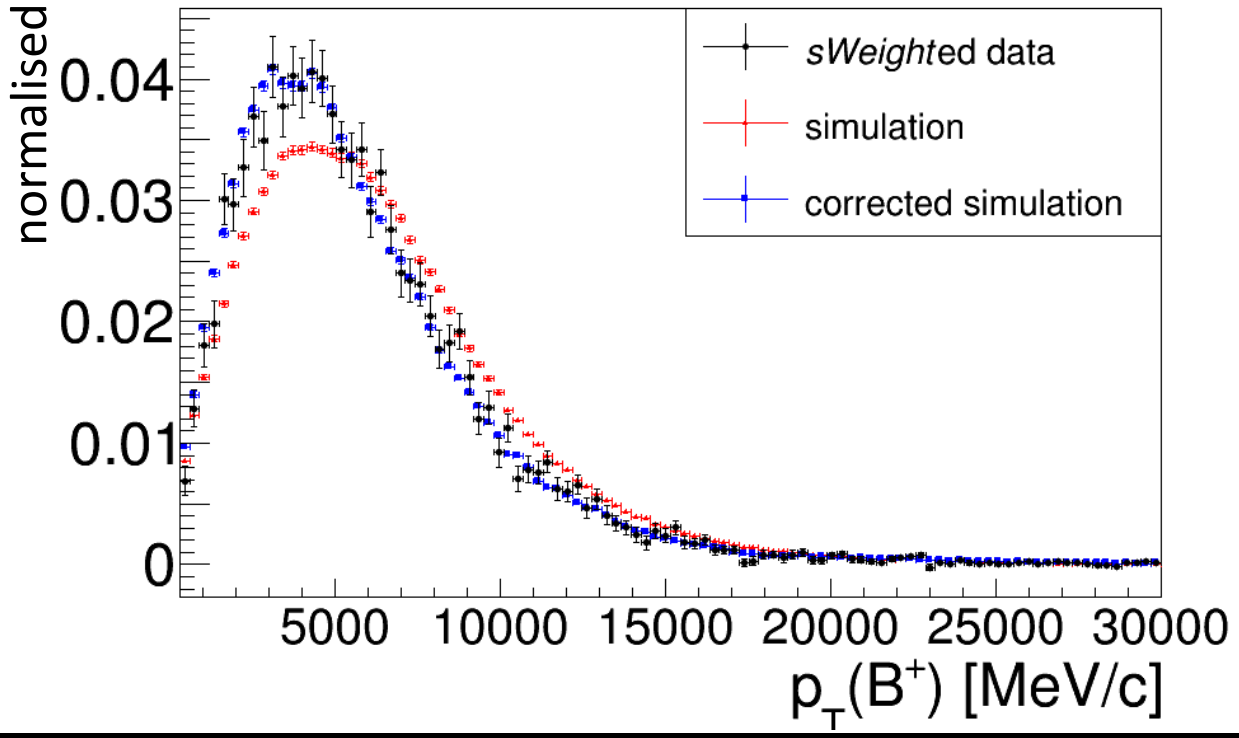
$$w = w_{\text{nTracks}} \cdot w_{p_T(B^+)}$$

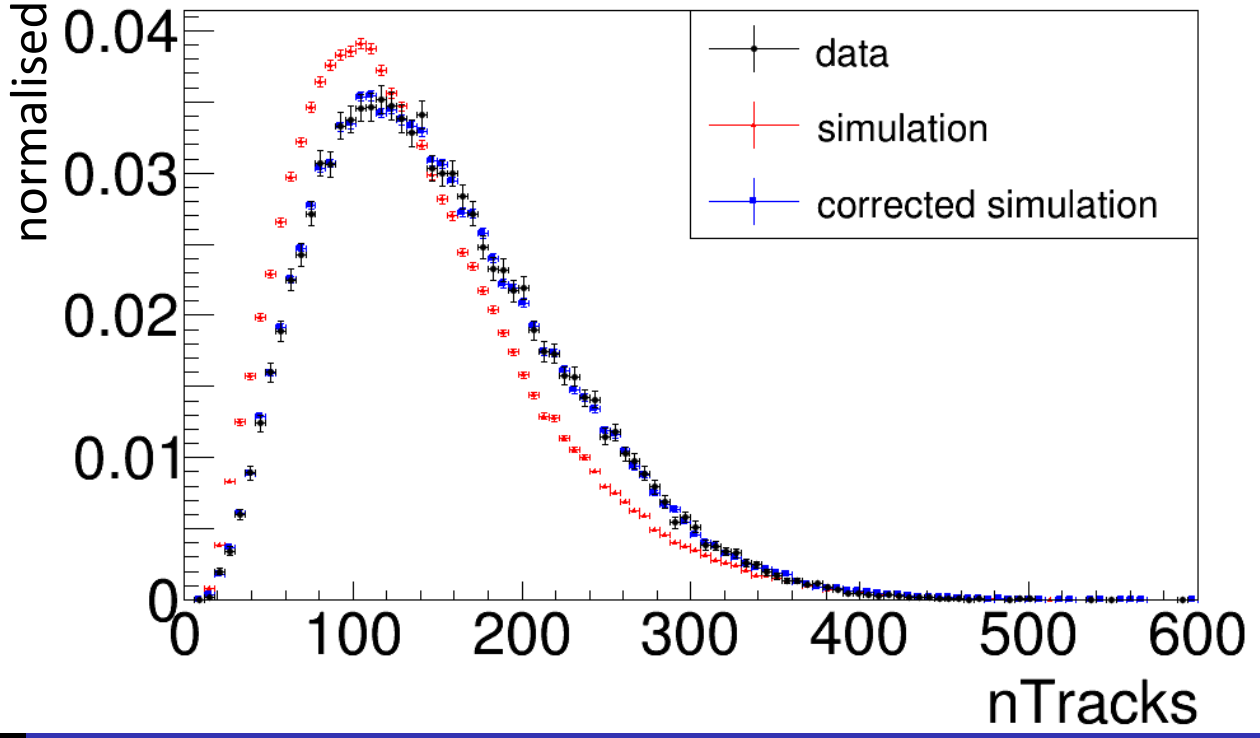




Data-Simulation correction - reweighted

- $B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+$ comparison
  - Control channel data
  - Simulation (before & after reweighting)
  - Complete selection & q^2 requirement



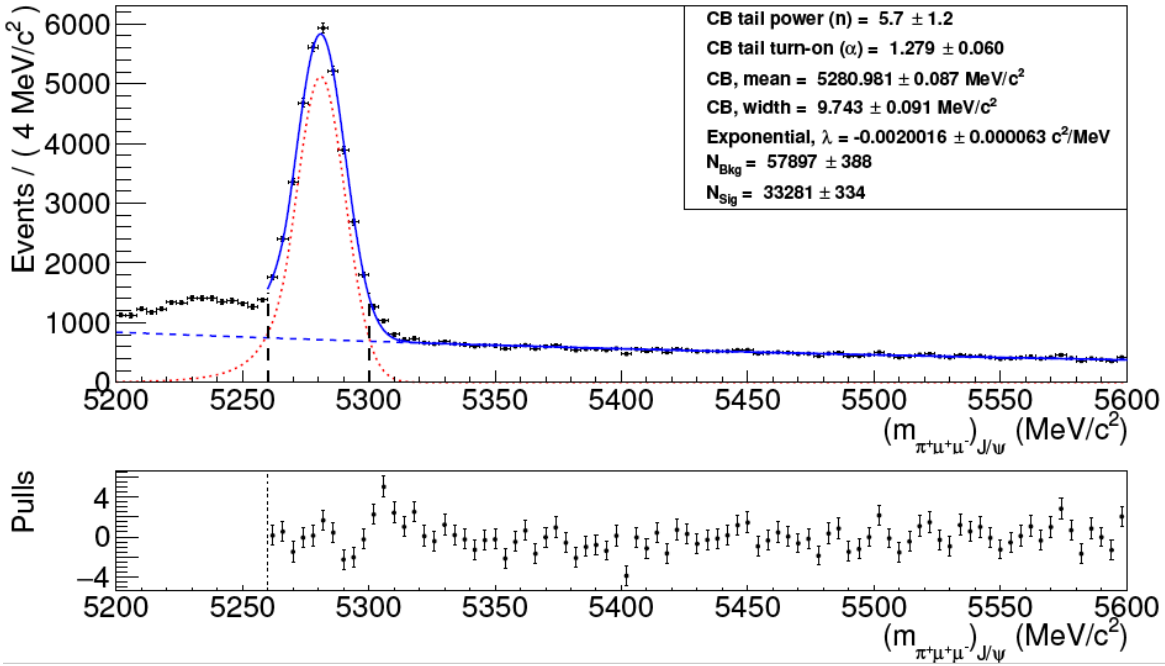


sWeighting

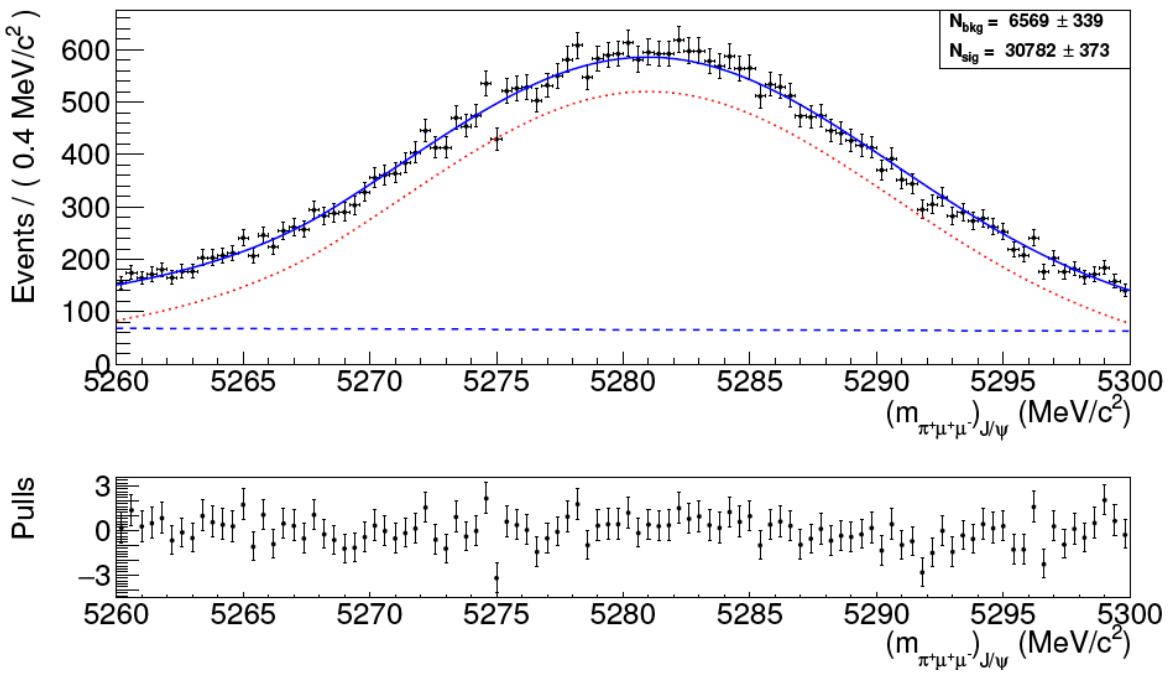
- Apply *sPlot* technique on signal proxy:

[arXiv:physics/0402083]

  - Control variables: BDT input variables
  - Discriminating variable: B^+- J/ψ constrained mass → Fit (*RooFit*)
    - Signal: crystal ball with lower-mass tail
    - Combinatorial background: exponential function



Higher upper $(\pi^+\mu^+\mu^-)_{J/\psi}$ limit: Fix parameters



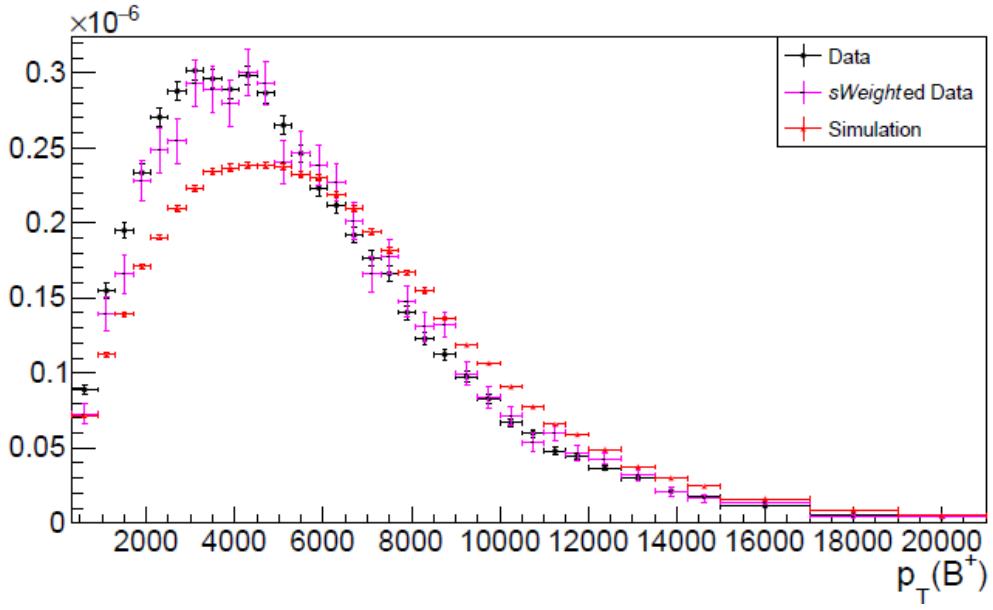
Signal proxy: Fit to calculate *sWeights*

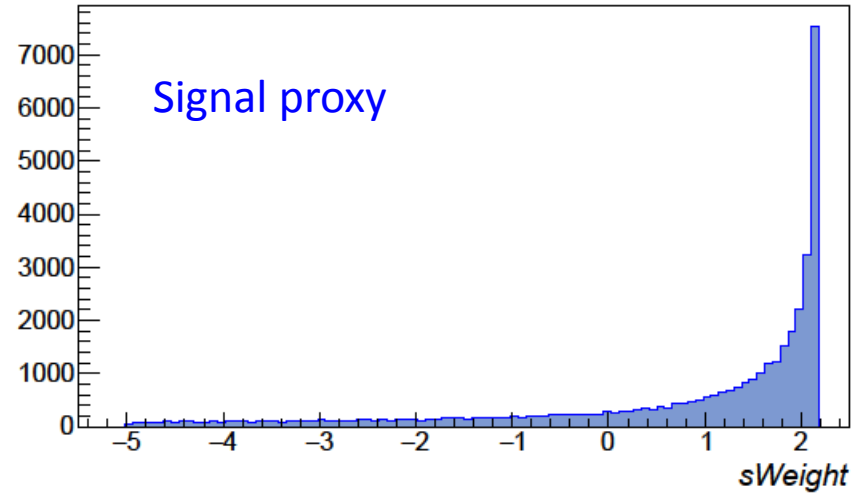
*sWeight*ing

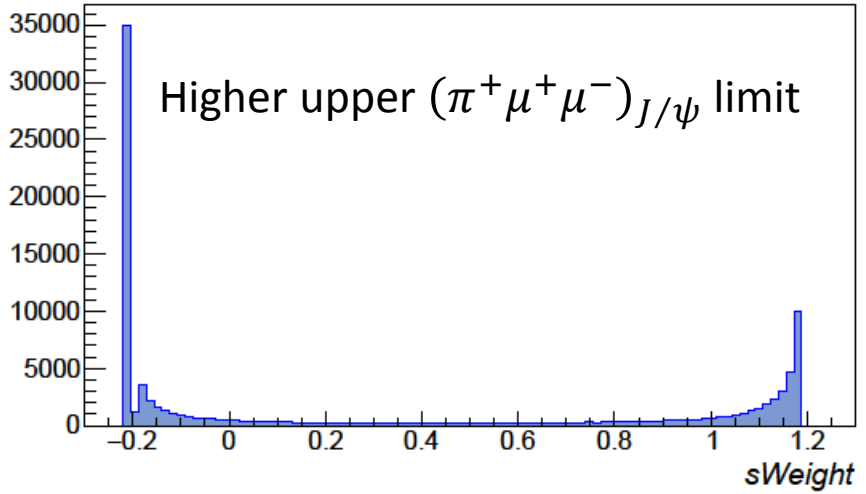
- Broad distribution

  -> Large uncertainties: $\sigma_w = \sqrt{\sum_{i=1}^{N} w_i^2}$

- *sWeight* depend on corr(N_{Sig}, N_{Bg})
- Used during BDT training

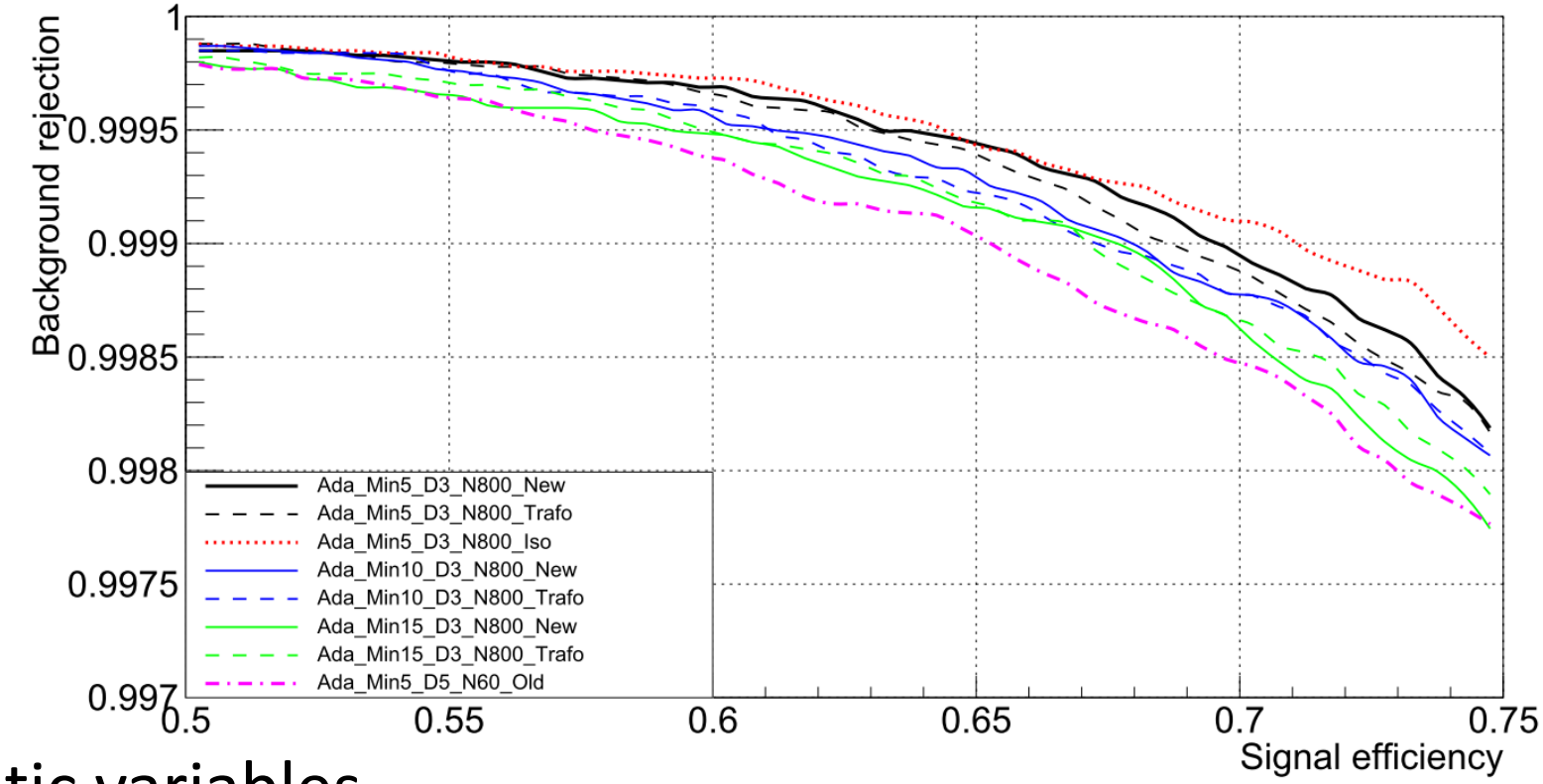






BDT

- kFolding, k = 6:
  - 4/6: Training
  - 1/6: Testing & Optimisation
  - 1/6: Application
- Classifier: Adaboost
- Performance
  - Configuration options
  - Input variables: Kinematic variables
- ROC curves: - Previous analysis
  - Best performance



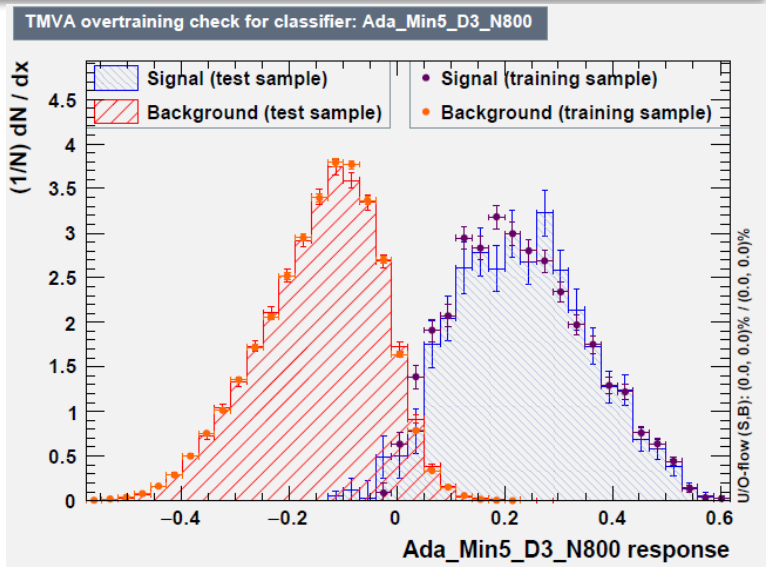
→ use Ada_Min5_D3_N800_New
(Ada_Min[MinNodeSize]_D[MaxDepth]_N[nTrees])

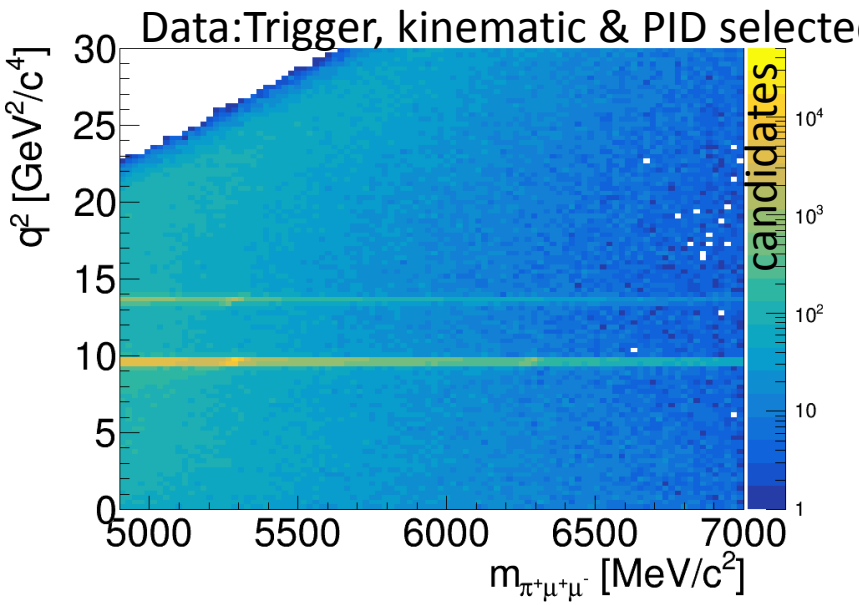
BDT

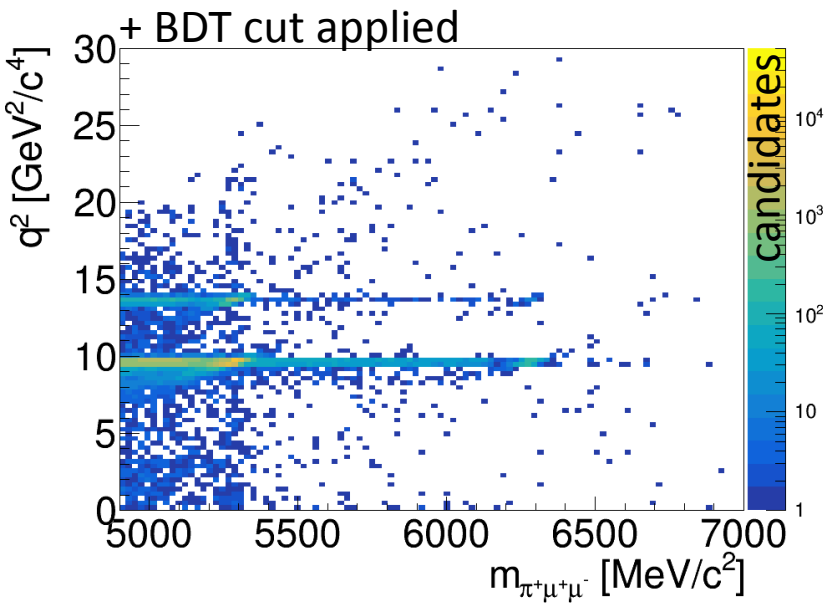
- Optimisation
  - Signal & background yields in signal region

  → maximise significance

  ⇒ BDT variable > 0.15
- Relative efficiency:
  - $\varepsilon_{Sig} = 58.10\%$ (simulated signal)
  - $\bar{\varepsilon}_{Bkg} = 99.91\%$ (background proxy)







BDT - variables

Candidate	Variable
B^+	p_T, χ^2_{IP}
	end vertex χ^2
	flight distance χ^2
	isolation BDT Hard 1st
π^+	p_T, χ^2_{IP}
	track χ^2/ndf
μ^+,μ^-	p_T, χ^2_{IP}
	track χ^2/ndf
	$\lvert p_{\mu^+} - p_{\mu^-} \rvert$

Candidate	Variable
B^+	p_T, χ^2_{IP}
	end vertex χ^2
	flight distance χ^2
	DIRA
π^+	p_T, χ^2_{IP}
μ^+,μ^-	p_T, χ^2_{IP}

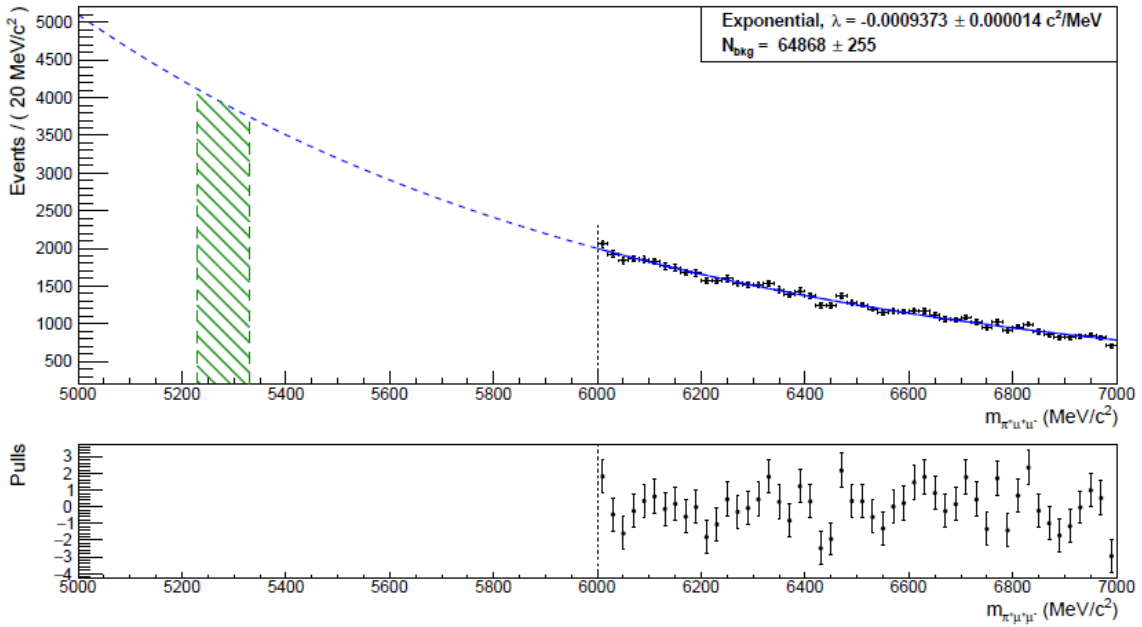
BDT - optimisation

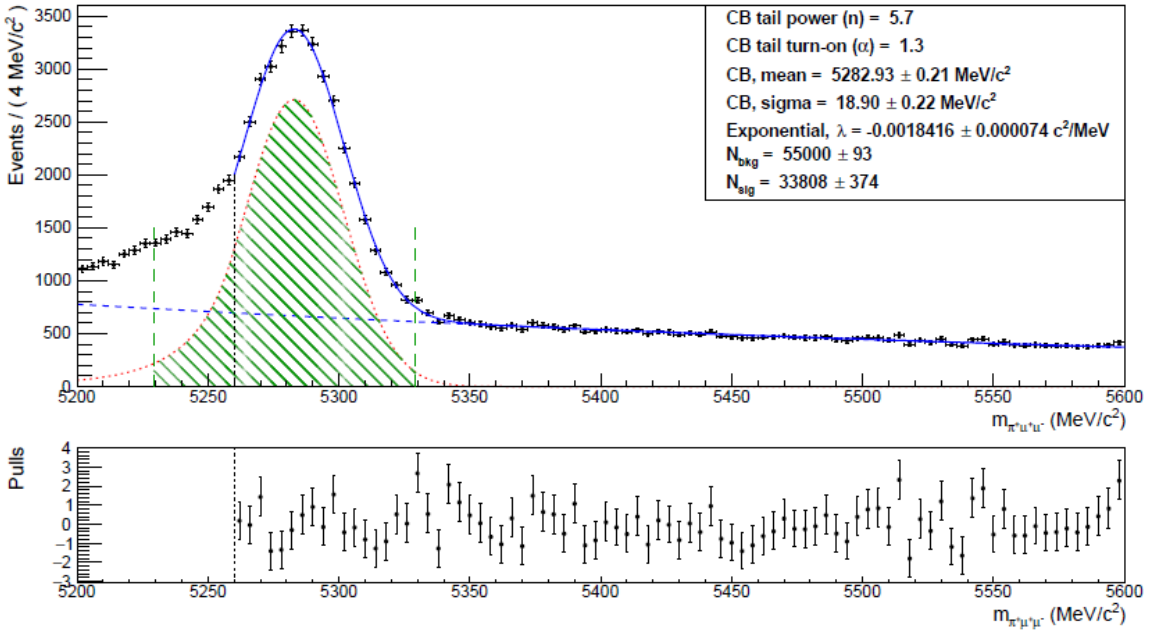
- Maximise significance

$$\mathcal{S} = \frac{\epsilon_S \cdot \mathrm{S}}{\sqrt{\epsilon_S \cdot \mathrm{S} + \epsilon_B \cdot \mathrm{B}}}$$

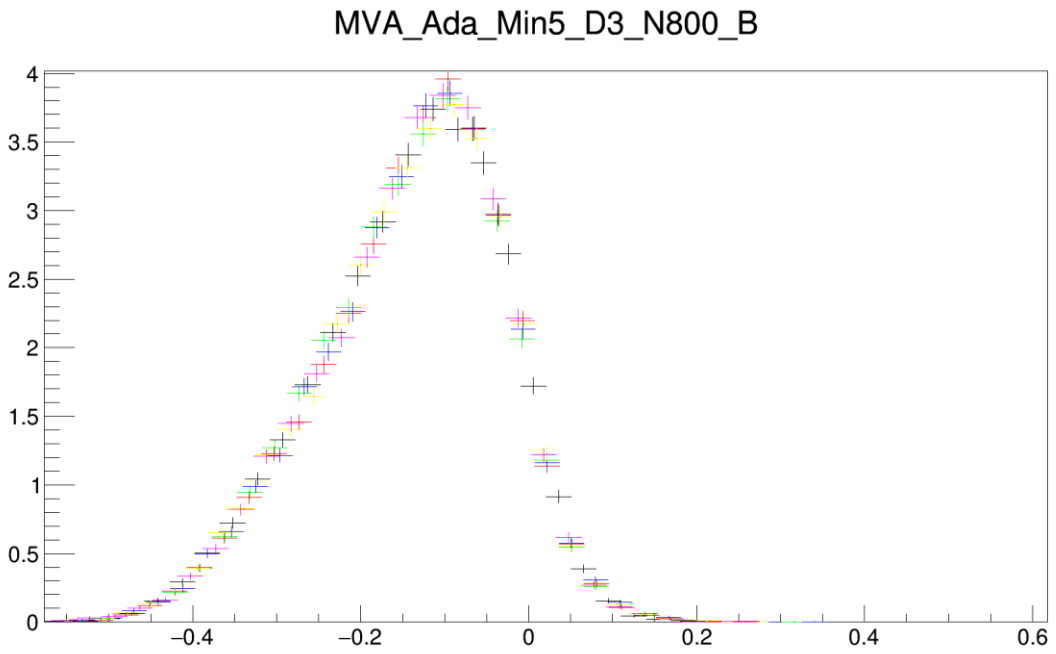
$$\mathrm{S} = \frac{\varepsilon_{\pi^+\mu^+\mu^-}}{\varepsilon_{J/\psi\pi^+}} \frac{\mathcal{B}_{SM}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}_{PDG}(B^+ \to J/\psi(\to \mu^+\mu^-)\pi^+)} \times N_{J/\psi\pi^+}$$

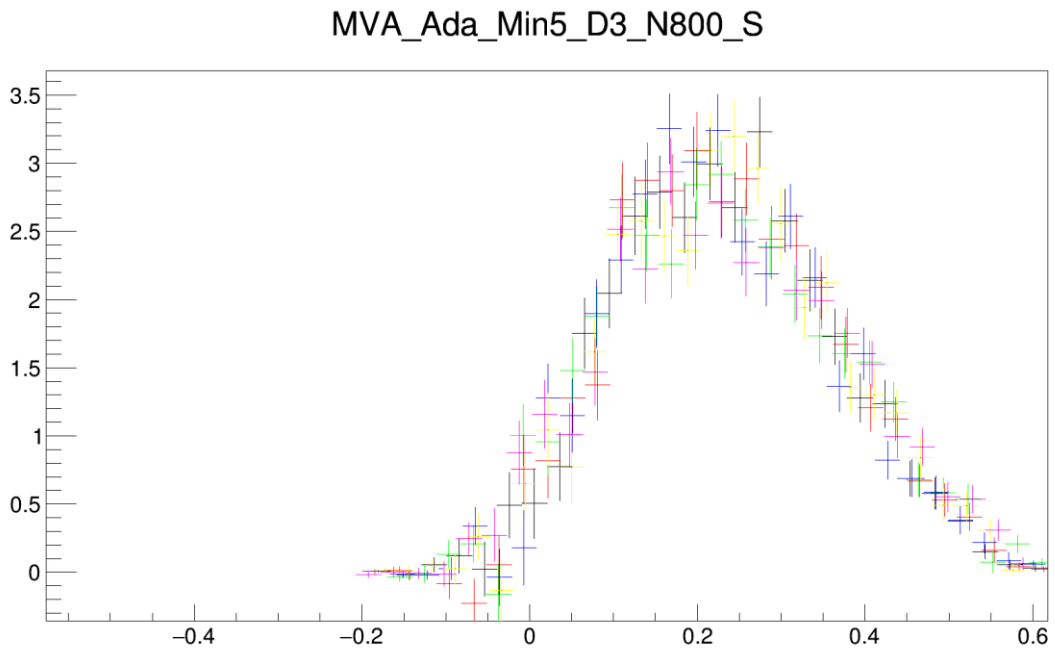
Quantity	Value
$N_{J/\psi}$	34478 ± 346
$\frac{\varepsilon_{\pi^+\mu^+\mu^-}}{\varepsilon_{J/\psi\pi^+}}$	$(69.7 \pm 0.3)\%$
$\frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\pi^+)\mathcal{B}(J/\psi \to \mu^+\mu^-)}$	$(8.2 \pm 1.2) \times 10^{-3}$
$N_{\pi^+\mu^+\mu^-}$	197 ± 28





BDT - kFolding





Physical backgrounds

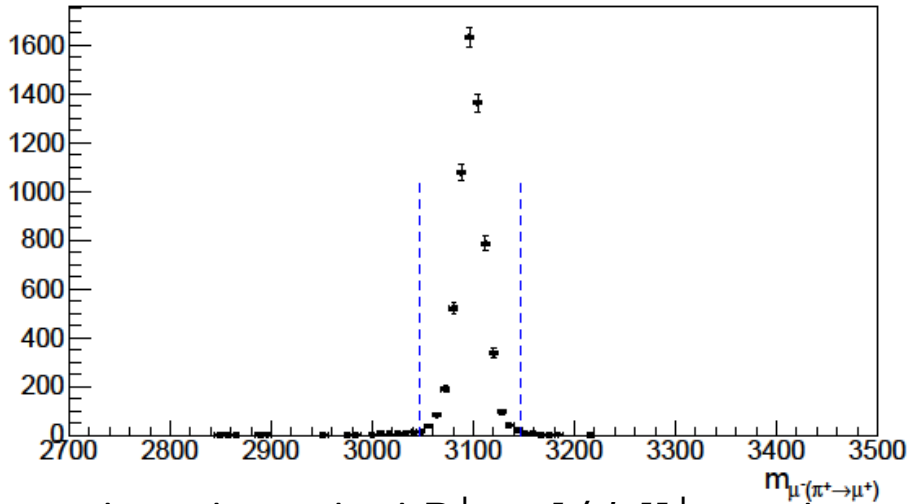
Double Mis-ID:

$$B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+ \quad (\pi^+ \to \mu^+ \;\&\; \mu^+ \to \pi^+)$$
$$B^+ \to J/\psi\,(\mu^+\mu^-)K^+ \quad (K^+ \to \mu^+ \;\&\; \mu^+ \to \pi^+)$$

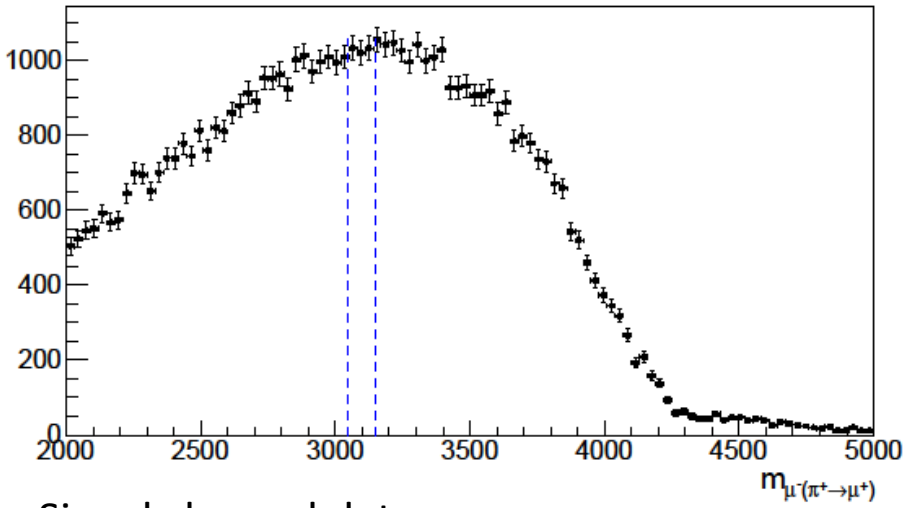
- Resonant decays bypass q^2 veto

->Reconstruct J/ψ mass:

$$m^2_{\mu^-(\pi^+\to\mu^+)} = \left[\begin{pmatrix} E_{\mu^-} \\ \vec{p}_{\mu^-} \end{pmatrix} + \begin{pmatrix} \sqrt{m^2_{\mu} + \vec{p}^{\,2}_{\pi^+}} \\ \vec{p}_{\pi^+} \end{pmatrix}\right]^2$$



Corrected, truthmatched $B^+ \to J/\psi\, K^+$ simulation



Signal channel data

Physical backgrounds – expected yields

- Probability of Mis-ID AND pass selection (p_{tot})
  - simulated samples (truthmatched & corrected)

$$N_{exp} = 2(\mathcal{L}_{2011}\sigma_{b\bar{b},2011} + \mathcal{L}_{2012}\sigma_{b\bar{b},2012}) \cdot f_u \times p_{tot} \cdot B_{PDG}(B^+ \to K^+\mu^+\mu^-)$$

(← Example for $B^+ \to K^+\mu^+\mu^-$)
$\mathcal{L}$: integrated luminosity
$\sigma_{b\bar{b}}$: $b\bar{b}$ production cross section
$f_X, X \in \{u, d, s\}$: fragmentation fraction

Decay	N_{exp}
$B^+ \to J/\psi\,(\mu^+\mu^-)K^+$	$< 1.5 \pm 1.5$
$B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+$	$< 0.09 \pm 0.09$
$B^+ \to K^+\mu^+\mu^-$	27.5 ± 5.0
$B^+ \to \pi^+\pi^-\pi^+$	$< 0.8 \pm 0.8$
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	$< 0.21 \pm 0.21$
$B^0 \to \rho^0(\pi^-\pi^+)\mu^+\mu^-$	27.3 ± 7.9
$B_s^0 \to f^0(\pi^-\pi^+)\mu^+\mu^-$	30.1 ± 7.7

- Significant backgrounds:
  - Mis-ID ($K^+ \to \pi^+$): $B^+ \to K^+\mu^+\mu^-$
  - Part. reconstructed: $B^0 \to \rho^0\mu^+\mu^-$
    $B_s^0 \to f^0\mu^+\mu^-$

→ include in fit model

Rejection efficiencies

Decay	Incorrect reconstruction
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	$K^+ \to \pi^+$
	$K^+ \to \mu^+$ AND $\mu^+ \to \pi^+$
$B^+ \to J/\psi(\mu^+\mu^-)\pi^+$	$\pi^+ \leftrightarrow \mu^+$
$B^+ \to K^+\mu^+\mu^-$	$K^+ \to \pi^+$
$B^+ \to \pi^+\pi^-\pi^+$	$\pi^+ \to \mu^+$ AND $\pi^- \to \mu^-$
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	$\not{K}^-$
	$\not{\pi}^-$ AND $K^+ \to \pi^+$
$B^0 \to \rho^0(\pi^-\pi^+)\mu^+\mu^-$	$\not{\pi}^-$
$B_s^0 \to f^0(\pi^-\pi^+)\mu^+\mu^-$	$\not{\pi}^-$

	$B^+ \to \pi^+\pi^-\pi^+$ $\pi^+ \to \mu^+$ & $\pi^- \to \mu^-$	$B^0 \to \rho^0(\pi^-\pi^+)\mu^+\mu^-$ $\not{\pi}^-$	$B_s^0 \to f^0(\pi^-\pi^+)\mu^+\mu^-$ $\not{\pi}^-$
$\varepsilon_{gen}/\%$	17.000 ± 0.197	15.715 ± 0.041	15.480 ± 0.057
$p_{strip\|reco}/\%$	$(3.06 \pm 1.2) \times 10^{-4}$	6.548 ± 0.017	4.926 ± 0.015
$\bar{\varepsilon}_{trigger}/\%$	-	9.82 ± 0.08	9.91 ± 0.10
$\bar{\varepsilon}_{presel}/\%$	-	32.05 ± 0.14	32.13 ± 0.16
$\bar{\varepsilon}_{q^2}/\%$	-	33.79 ± 0.17	35.70 ± 0.19
$\bar{\varepsilon}_{BDT}/\%$	-	48.50 ± 0.22	41.97 ± 0.25
$p_{tot}/\%$	$< (8 \pm 8) \times 10^{-6}$	0.2150 ± 0.0014	0.1740 ± 0.0013

	$B^+ \to J/\psi(\mu^+\mu^-)K^+$		$B^+ \to J/\psi(\mu^+\mu^-)\pi^+$
	$K^+ \to \pi^+$	$K^+ \to \mu^+$ & $\mu^+ \to \pi^+$	$\pi^+ \leftrightarrow \mu^+$
$\varepsilon_{gen}/\%$	16.660 ± 0.048	16.660 ± 0.048	16.165 ± 0.030
$p_{strip\|reco}/\%$	19.743 ± 0.020	0.2461 ± 0.0025	0.1055 ± 0.0020
$\bar{\varepsilon}_{trigger}/\%$	25.07 ± 0.05	36.4 ± 0.5	28.2 ± 0.9
$\bar{\varepsilon}_{presel}/\%$	99.051 ± 0.013	99.95 ± 0.03	99.92 ± 0.07
$\bar{\varepsilon}_{q^2}/\%$	99.990 ± 0.013	33 ± 26	-
$\bar{\varepsilon}_{BDT}/\%$	-	-	-
$p_{tot}/\%$	$< (4 \pm 4) \times 10^{-6}$	$< (4 \pm 4) \times 10^{-6}$	$< (6 \pm 6) \times 10^{-6}$

	$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$		$B^+ \to K^+\mu^+\mu^-$
	$\not{K}^-$	$\not{\pi}^-$ & $K^+ \to \pi^+$	$K^+ \to \pi^+$
$\varepsilon_{gen}/\%$	16.411 ± 0.052	16.411 ± 0.052	16.980 ± 0.062
$p_{strip\|reco}/\%$	$(3.5 \pm 0.8) \times 10^{-3}$	$(5 \pm 3) \times 10^{-4}$	19.40 ± 0.05
$\bar{\varepsilon}_{trigger}/\%$	90 ± 7	-	27.15 ± 0.14
$\bar{\varepsilon}_{presel}/\%$	68 ± 35	-	99.02 ± 0.04
$\bar{\varepsilon}_{q^2}/\%$	-	-	30.2 ± 1.7
$\bar{\varepsilon}_{BDT}/\%$	-	-	45.0 ± 2.2
$p_{tot}/\%$	$< (3 \pm 3) \times 10^{-5}$	$< (3 \pm 3) \times 10^{-5}$	$(89.9 \pm 5.4) \times 10^{-4}$

Expected yields

Efficiency [%]	$B^+ \to \pi^+\mu^+\mu^-$	$B^+ \to J/\psi\,(\mu^+\mu^-)\pi^+$
ε_{gen}	16.480 ± 0.033	16.165 ± 0.030
$\varepsilon_{strip\|reco}$	19.61 ± 0.04	20.343 ± 0.025
$\varepsilon_{trigger}$	76.85 ± 0.09	76.57 ± 0.06
ε_{presel}	67.21 ± 0.12	69.27 ± 0.07
ε_{q^2}	72.85 ± 0.14	99.9822 ± 0.0025
ε_{BDT}	58.10 ± 0.18	69.22 ± 0.09
ε_{tot}^{sel}	4.287 ± 0.020	7.466 ± 0.016
ε_{tot}	0.706 ± 0.004	1.207 ± 0.003

Quantity	Value
$\mathcal{L}_{2011}$	$(978.6 \pm 0.6) \times 10^{-3}\,\text{fb}^{-1}$
$\mathcal{L}_{2012}$	$(1990.9 \pm 0.7) \times 10^{-3}\,\text{fb}^{-1}$
$\sigma_{b\bar{b},2011}$	$288 \pm 48\,\mu\text{b}$
$\sigma_{b\bar{b},2012}$	$298 \pm 36\,\mu\text{b}$
$f_{u/d}$	$34.4 \pm 2.1\%$
f_s	$11.5 \pm 1.3\%$
$\mathcal{B}(B^+ \to J/\psi\,\pi^+)$	$(4.1 \pm 0.4) \times 10^{-5}$
$\mathcal{B}(B^+ \to J/\psi\,K^+)$	$(1.024 \pm 0.035) \times 10^{-3}$
$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	$(5.09 \pm 0.63) \times 10^{-7}$
$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$	$(1.11 \pm 0.16) \times 10^{-6}$
$\mathcal{B}(B^+ \to \pi^+\pi^-\pi^+)$	$(1.52 \pm 0.06) \times 10^{-5}$
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	$(5.961 \pm 0.033) \times 10^{-2}$
$\mathcal{B}(B^0 \to \rho^0\mu^+\mu^-)$	$(2.11 \pm 0.56) \times 10^{-8}$
$\mathcal{B}(B_s^0 \to f^0\mu^+\mu^-)$	$(8.6 \pm 1.8) \times 10^{-8}$

$$N_{exp} = 2(\mathcal{L}_{2011}\sigma_{b\bar{b},2011} + \mathcal{L}_{2012}\sigma_{b\bar{b},2012}) \cdot f_u \times p_{tot} \cdot B_{PDG}(B^+ \to K^+\mu^+\mu^-)$$

Efficiency calculation

$N_{sig} \equiv$ Number of signal events before cutting

$n_{sig} \equiv$ Number of signal events after cutting

$$\varepsilon_{\text{sig}} = \frac{n_{sig}}{N_{sig}}, \qquad \sigma^2_{\varepsilon_{\text{sig}}} = \frac{\varepsilon_{\text{sig}}(1-\varepsilon_{\text{sig}})}{N_{sig}}$$

$N_{bkg} \equiv$ Number of background events before cutting

$n_{bkg} \equiv$ Number of background events after cutting

$$\bar{\varepsilon}_{\text{bkg}} = \frac{N_{bkg} - n_{bkg}}{N_{bkg}}, \qquad \sigma^2_{\bar{\varepsilon}_{\text{bkg}}} = \frac{\bar{\varepsilon}_{\text{bkg}}(1-\bar{\varepsilon}_{\text{bkg}})}{N_{bkg}}$$

After reweighting:

$$N_{sim} = \sum_{M_{sim}} w, \qquad M_{sim} \equiv \{\text{simulated events before applying the veto}\}$$

$$n_{sig} = \sum_{m_{sim}} w, \qquad m_{sim} \equiv \{\text{remaining events after applying the veto}\}$$

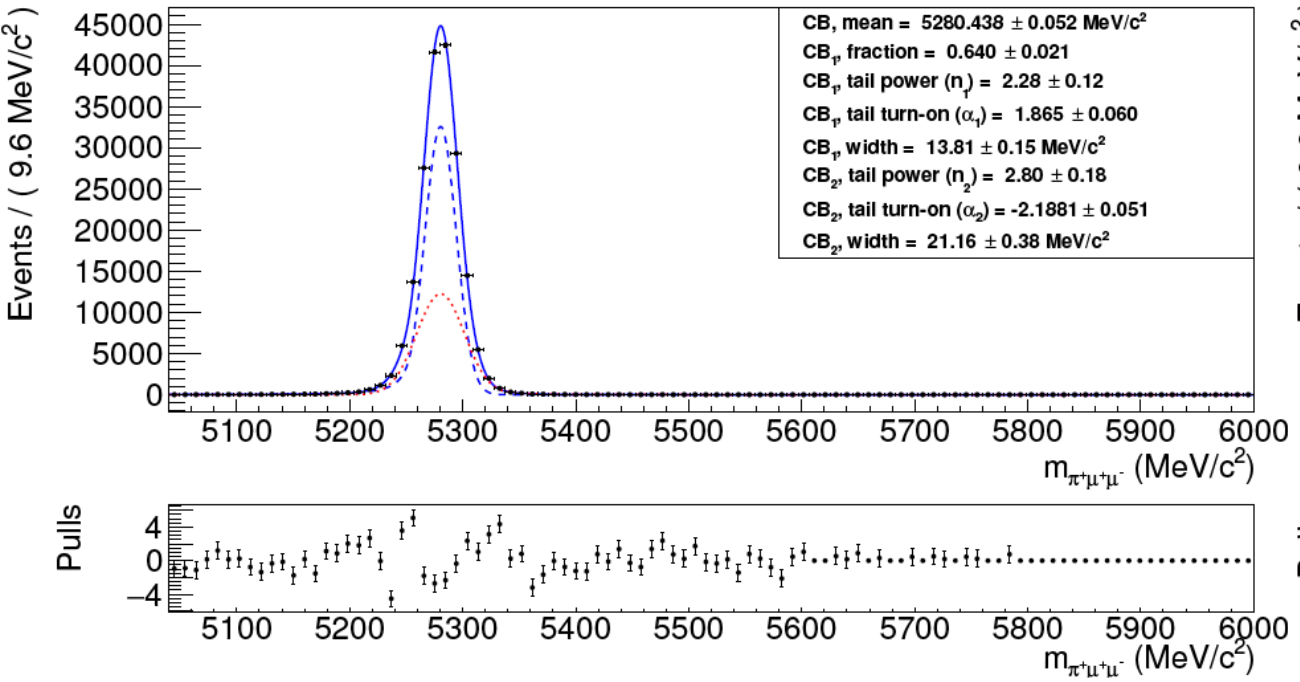
$$\varepsilon_{\text{sig}} = \frac{n_{sig}}{N_{sim}}, \qquad \sigma^2_{\varepsilon_{\text{sig}}} = \frac{\varepsilon_{\text{sig}}(1-\varepsilon_{\text{sig}})}{N_{sim}}$$

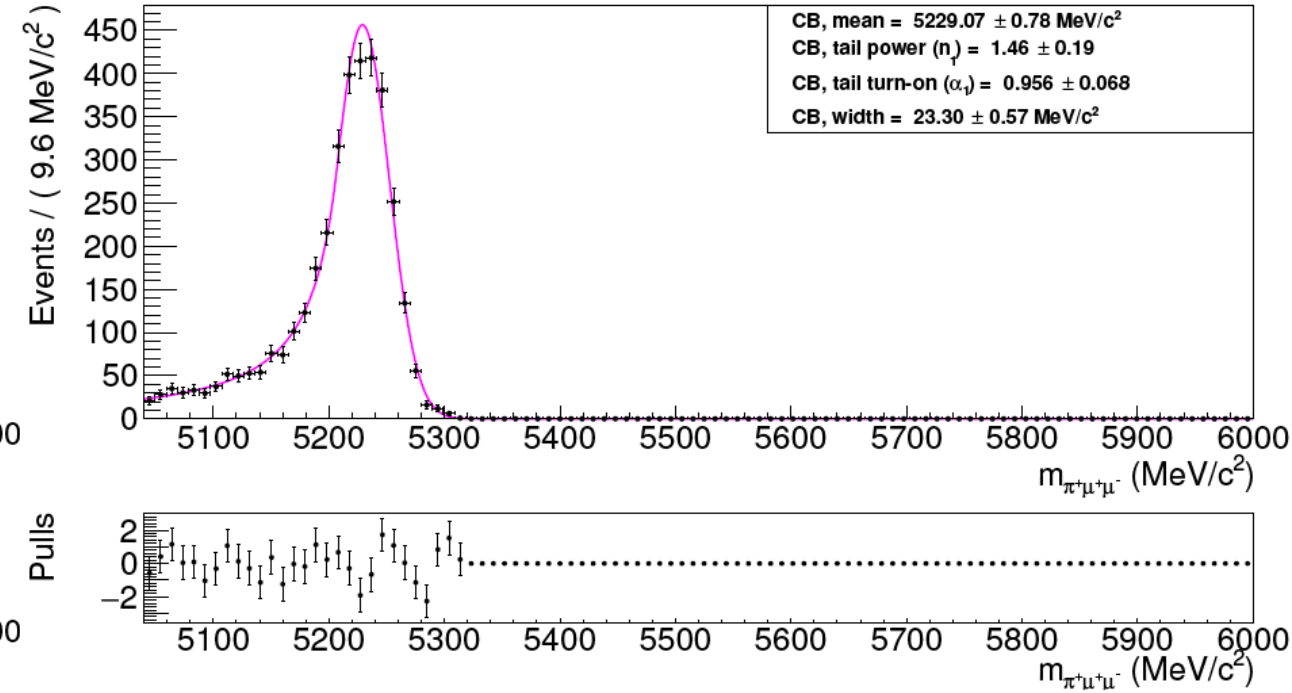
$$n_{bkg} = \sum_{\bar{m}_{sim}} w, \qquad \bar{m}_{sim} \equiv \{\text{events rejected by the veto}\}$$

$$\bar{\varepsilon}_{\text{bkg}} = \frac{n_{bkg}}{N_{sim}}, \qquad \sigma^2_{\bar{\varepsilon}_{\text{bkg}}} = \frac{\bar{\varepsilon}_{\text{bkg}}(1-\bar{\varepsilon}_{\text{bkg}})}{N_{sim}}$$

Determination of the yields – Fit model

- Signal model:
  - Double crystal ball
  - $B^+ \to J/\psi\,\pi^+$ simulation
  - Fix tail parameters & CB fraction
- Mis-ID ($K^+ \to \pi^+$)
  - Crystal ball
  - $B^+ \to J/\psi\,K^+$ simulation
  - Fix all parameters

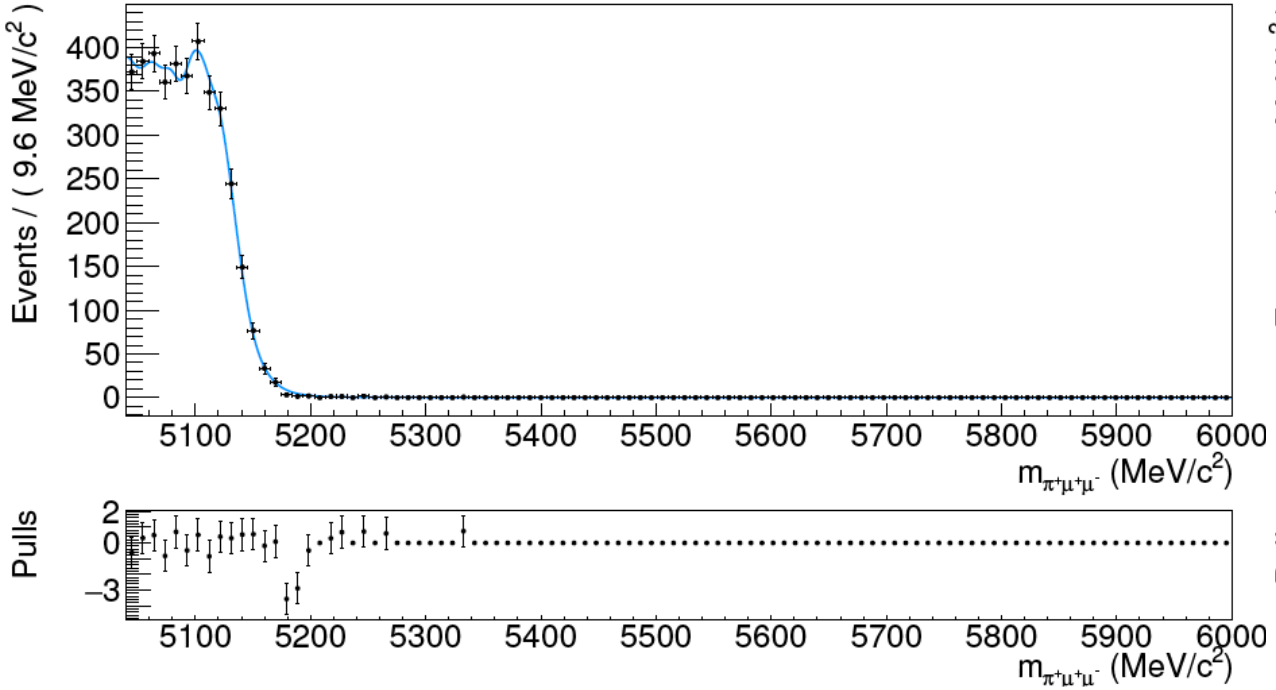




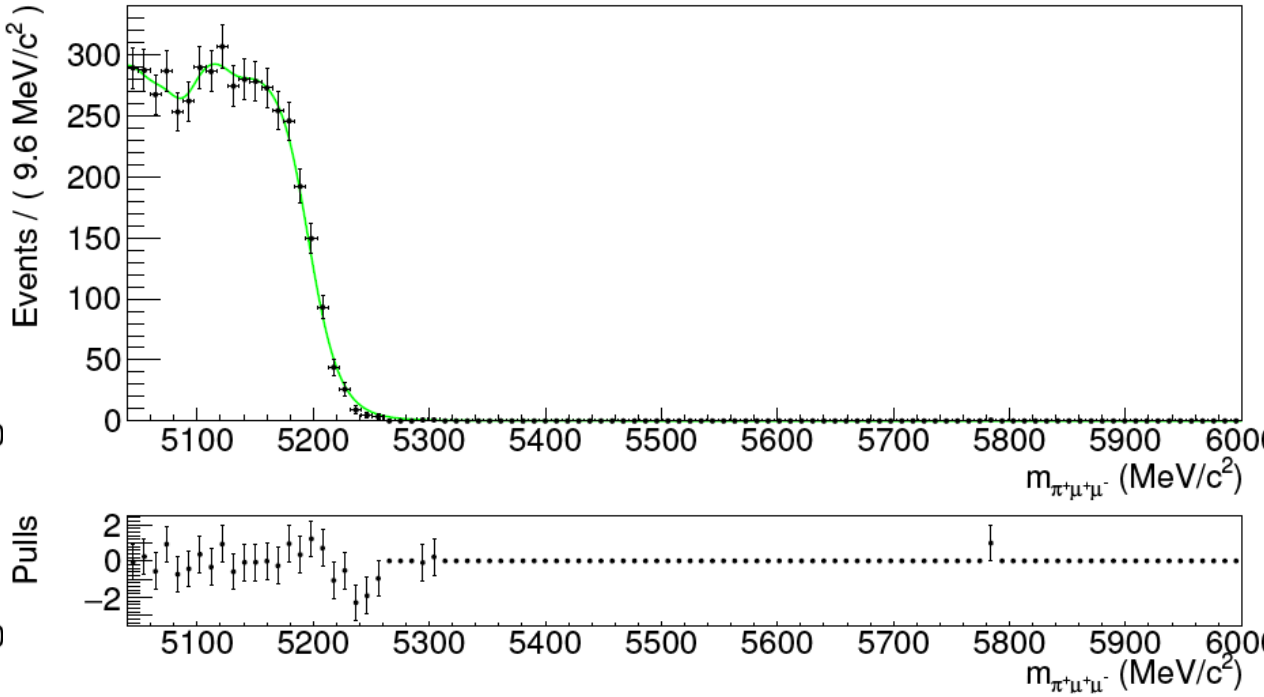
Determination of the yields – Fit model

- Partially reconstructed background: *RooKeysPdf*

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



$B_s^0 \to f^0 \mu^+ \mu^-$



- Combinatorial background:
  - Exponential function with free parameter

Control channel fit