Analysis of $B_s^0 \to \phi\mu^+\mu^-$ with LHCb data

FSP Meeting, Siegen

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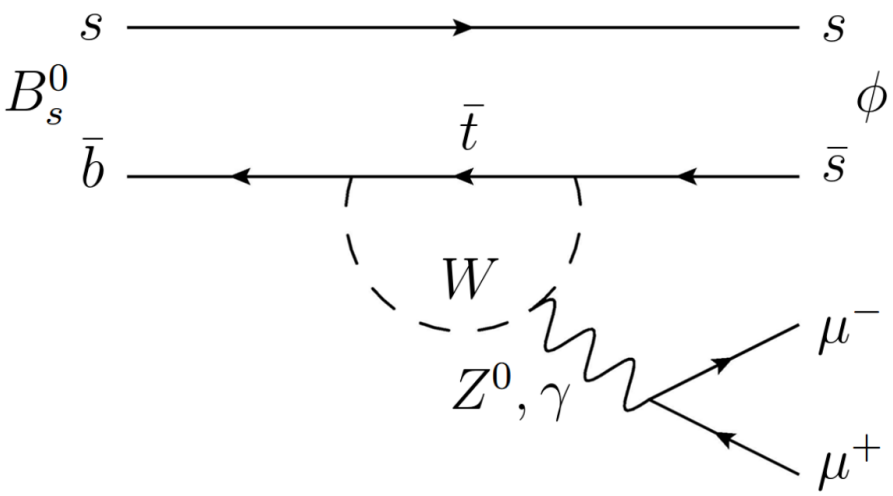
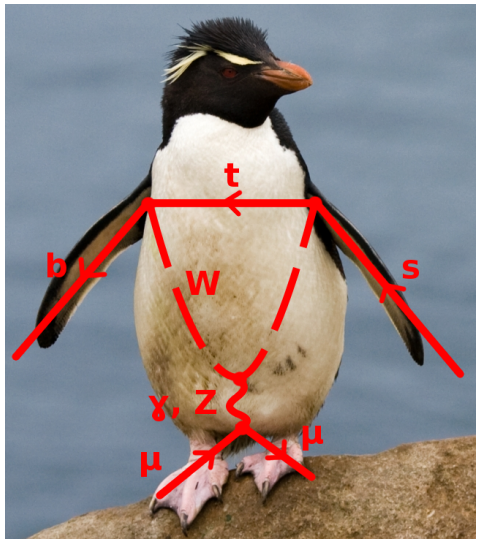
Probing for New Physics with $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$





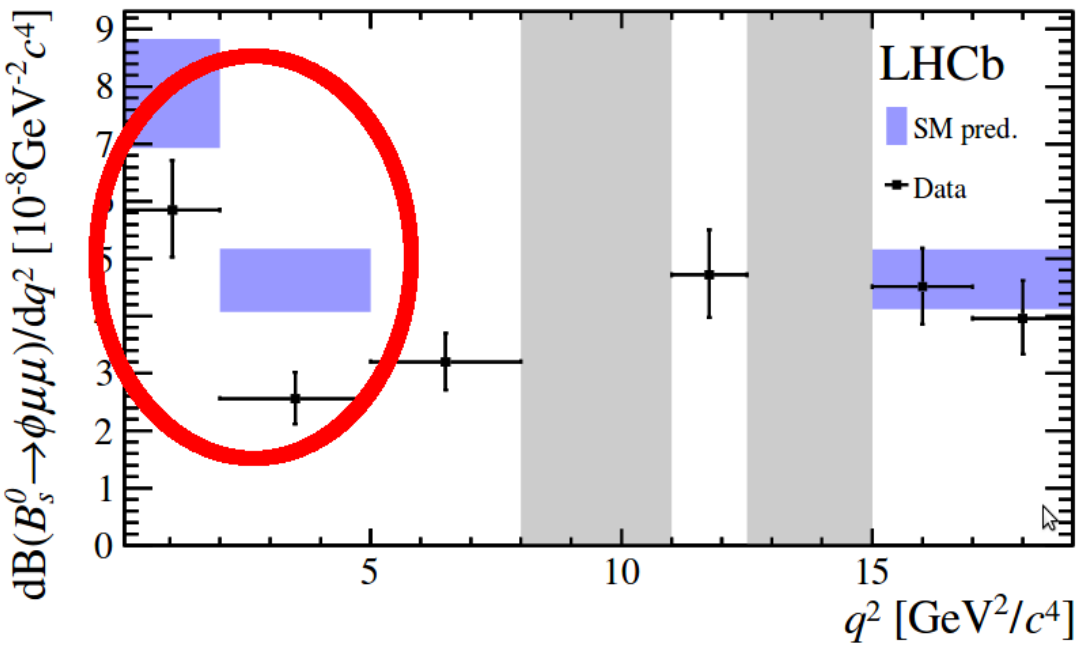
https://en.wikipedia.org/wiki/Southern_rockhopper_penguin

- $b \to s\mu\mu$: Flavour Changing Neutral Current
- Only occurs via higher order diagrams - highly suppressed in the SM
- Sensitive to possible new physics contributions

Run 1 Analysis

- Run 1 analysis in JHEP 09 (2015) 179
  ("Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$")

JHEP 09 (2015) 179



- Result: Branching fraction around $3\,\sigma$ lower compared to Standard Model expectation at low q^2 (invariant dimuon mass squared)
- Goal: Update analysis using Run 2 data

Branching Fraction Analysis Strategy

First reproduce Run 1 analysis, then add Run 2 data.

$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)dq^2} = \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{q^2_{\text{max}} - q^2_{\text{min}}} \cdot \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \cdot \frac{\epsilon^{J/\psi\phi}_{\text{tot}}}{\epsilon^{\phi\mu^+\mu^-}_{\text{tot}}}$$

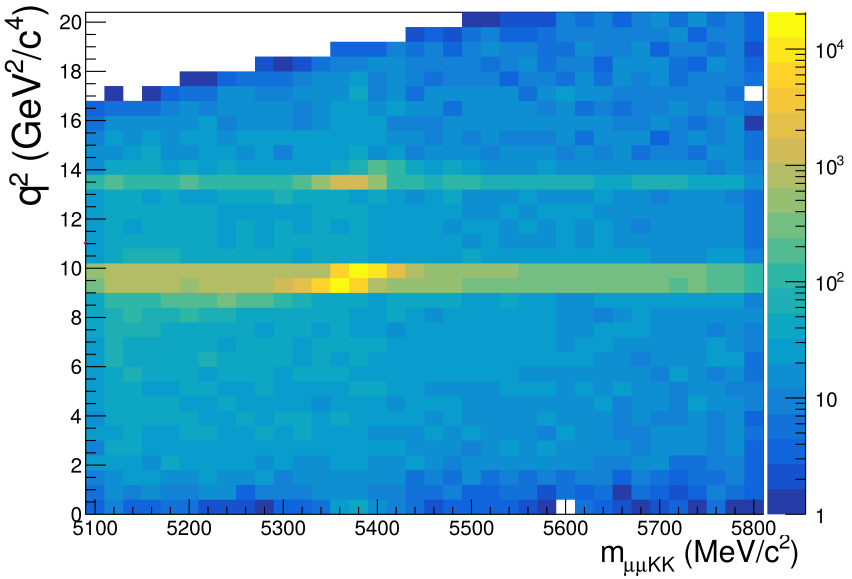
- Trigger, preselection & mis-ID vetoes
- MVA against further combinatorial background
- Fits for event yields
- Efficiency calculations using corrected MC simulations
- Calculation of systematic uncertainties

Trigger, Preselection and Mis-ID Vetoes

Run 1

- Dataset:
  3 fb^{-1} Run 1 (2011/12)
  Run 2 (2015/16) to be added
- Trigger:
  - L0 muon
  - HLT1 muon track
  - HLT2 topo
- Stripping and preselection:
  - Secondary vertex with good quality
  - Cut around $m_{B_s^0}$ and m_Φ
  - daughter PID
- Mis-ID vetoes:
  - $J/\psi\phi \to KK\mu\mu$ double Mis-ID
  - $\Lambda_b^0 \to pK\mu\mu$ background

After preselection and mis-ID vetoes:



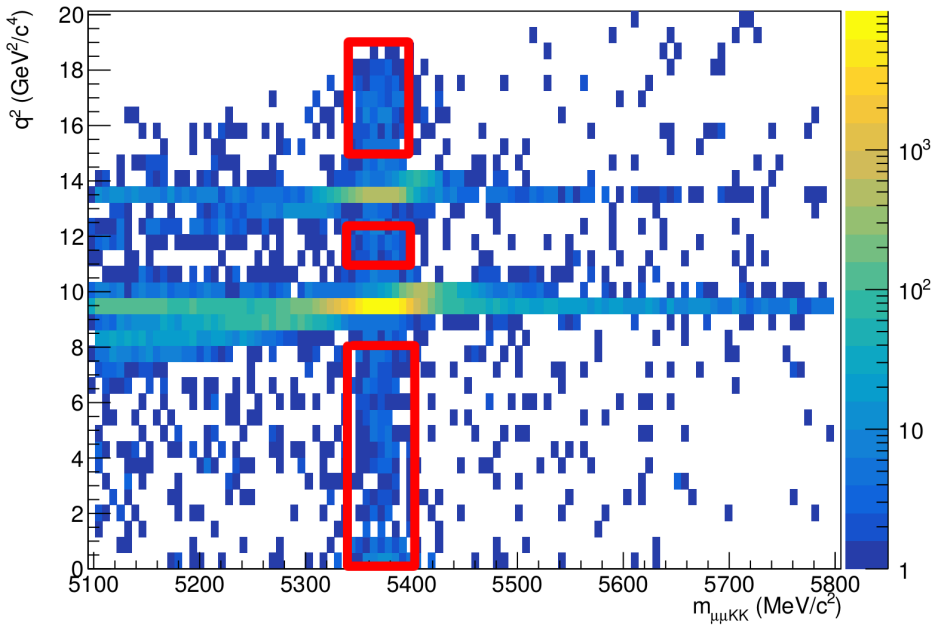
Still lots of combinatorial background...
$\Rightarrow$ BDT

Multivariate Analysis: BDT

Run 1

- Suppress combinatorial background
- 10 kFolds
- Performance checked for different hyperparameter settings
- $J/\psi\phi$ events as signal proxy, higher invariant mass events as background proxy
- Input parameters: B_s^0 kinematics, topology of event and particle identification of daughters
- Optimized BDT cut: 96% bkg. rej. and 98% sig. eff. (Prev. analysis: 95% bkg. rej, 96% sig. eff)

After selection and BDT applied:

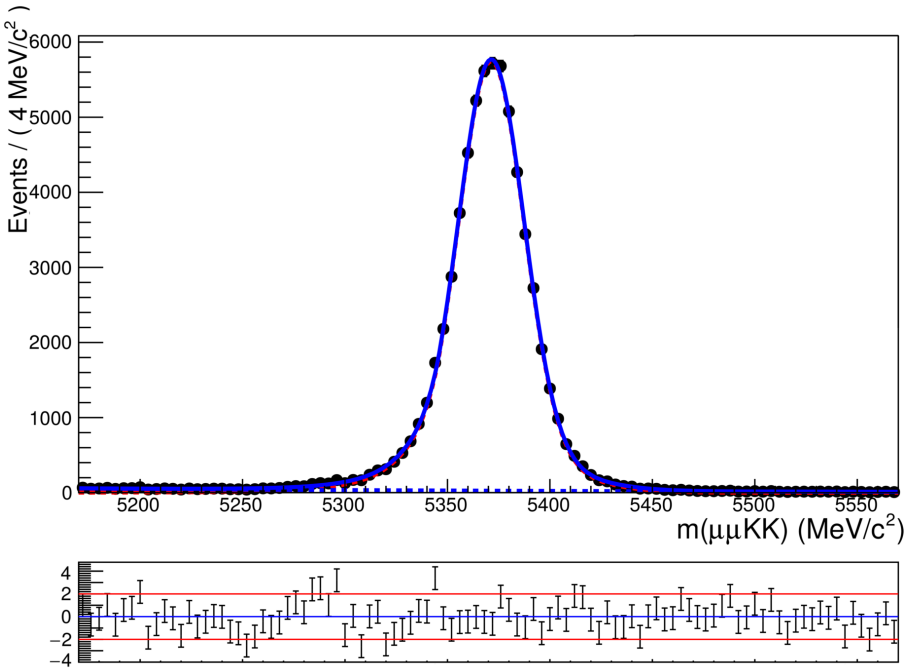


$\Rightarrow$ Rare decay signal visible!

Run 1 Event Yields (after all selection)

Control Channel Decay

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

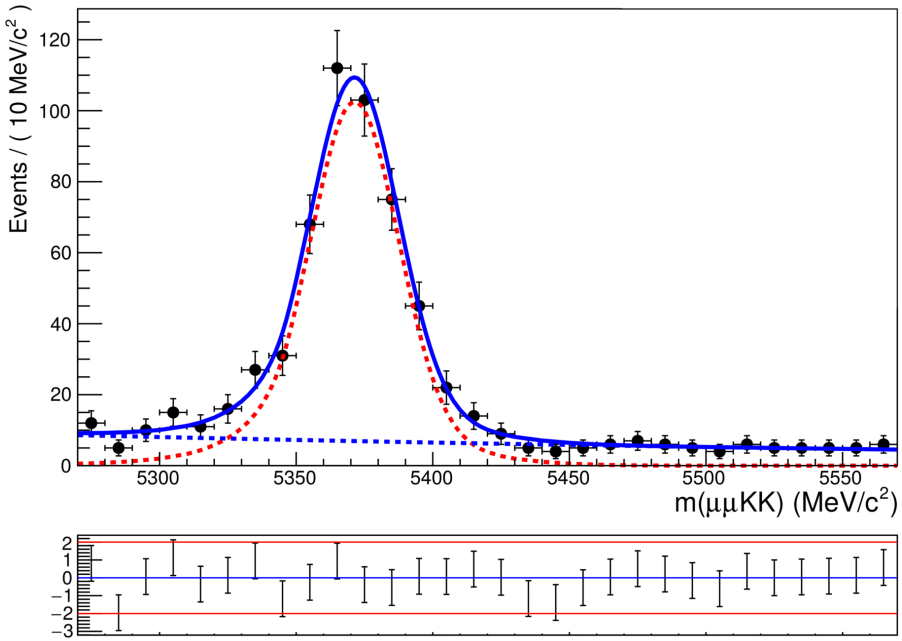


$N_{\text{Control channel}} = 61963 \pm 258$

(Prev. Analysis: 62033 ± 260)

Rare Decay

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



$N_{\text{Rare signal}} = 442 \pm 24$

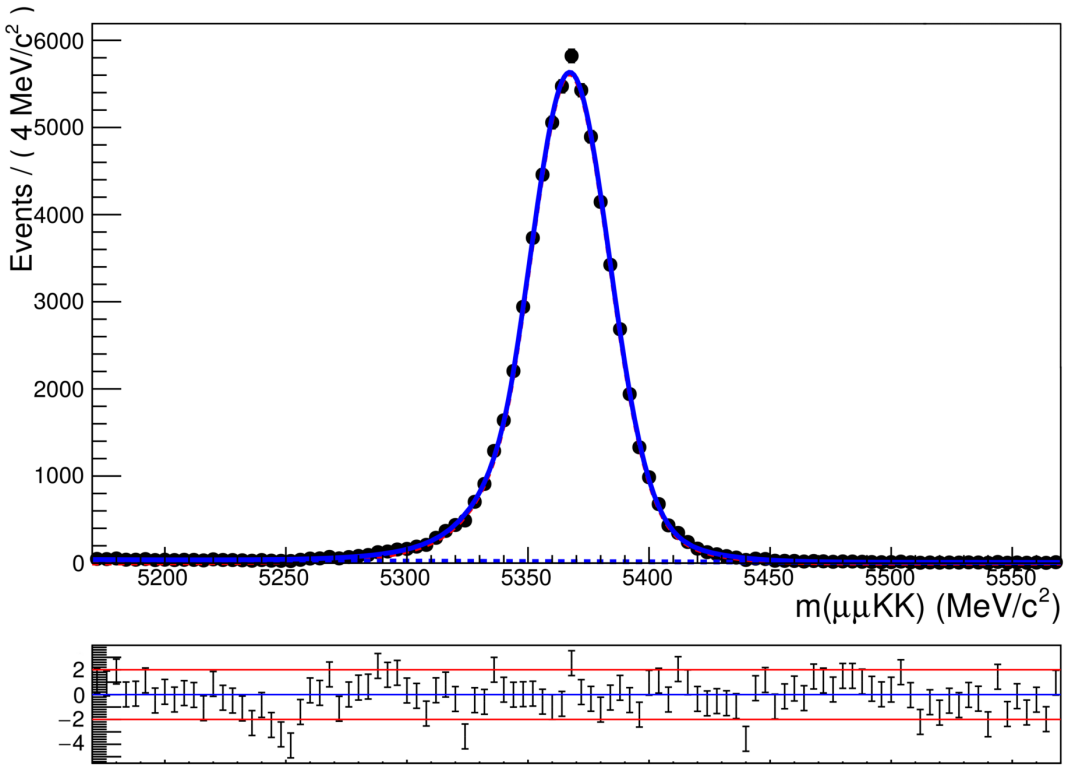
(Prev. analysis: 432 ± 24)

In good agreement with results from previous paper JHEP 09 (2015) 179

Control Channel Yields

Run 2 (2016)

Mostly same trigger, same preselection, same mis-ID vetoes; same MVA hyperparameters as in Run 1



$$N_{\text{Control Channel}} = 61309 \pm 260 \quad (N_{2016\text{ expected}} \approx f \cdot N_{2011/12} \approx 55000)$$

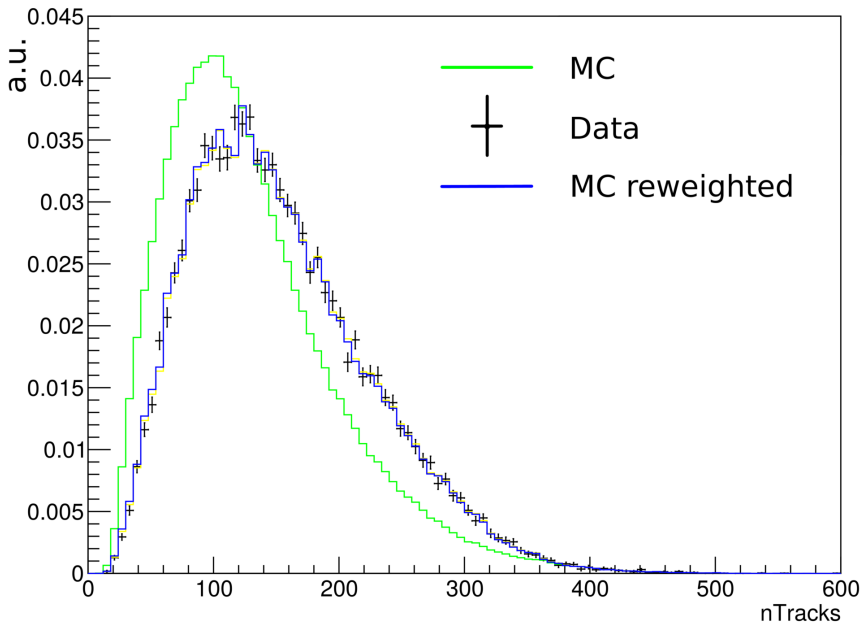
$$f = \frac{13\text{ TeV}\cdot 1.67\text{fb}^{-1}}{7\text{ TeV}\cdot 1.11\text{fb}^{-1} + 8\text{ TeV}\cdot 2.08\text{fb}^{-1}} = 0.89$$

Current stage of the analysis: Efficiency calculations

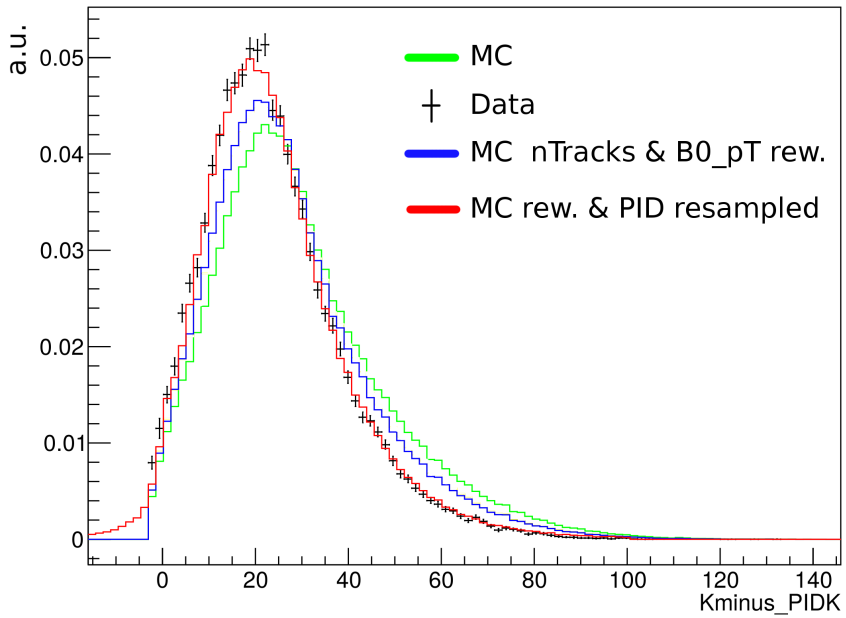
- Use MC simulations (physics + full detector simulation) to determine efficiencies
- Good agreement between data and MC crucial!

$\Rightarrow$ Data-driven correction of simulation ($J/\psi\phi$ events as control channel)

Reweighting, e.g. `nTracks`



PID resampling, e.g. K^- `PIDK`



Summary & Outlook

Run 1 branching fraction analysis of $B_s^0 \to \phi\mu\mu$: Around 3σ devation from expectation

Analysis status:

- Applied trigger, preselection and mis-ID vetoes to Run 1 and Run 2 (2016) data
- Trained BDTs to suppress combinatorial background
- Reproduced Run 1 event yields, first event yields for Run 2 (2016) control channel
- Current stage: Correction of MC for efficiency calculations

Outlook:

- Improve preselection and background vetoes (e.g. study probNNs)
- Calculate efficiencies, obtain branching fraction and see whether anomaly persists...
- Update of angular analysis

BACKUP

Stripping Line and Trigger

Run 1

- 2011 (Stripping21r1) with 1 fb^{-1} at $\sqrt{s} = 7\,\text{TeV}$ + 2012 (Stripping21) with 2 fb^{-1} at $\sqrt{s} = 8\,\text{TeV}$
- `B2XMuMu` stripping line
- Required Trigger:

L0	L0Muon TOS L0DiMuon TOS
HLT1	Hlt1TrackAllL0 TOS, HLT1TrackMuon TOS, Hlt1DiMuonLowMass TOS, Hlt1DiMuonHighMass TOS, Hlt1SingleMuonHighPT TOS
HLT2	Hlt2Topo(2,3,4)BodyBBDT TOS, Hlt2TopoMu(2,3,4)BodyBBDT TOS, Hlt2SingleMuon TOS, Hlt2DiMuonDetached TOS, Hlt2DiMuonDetachedHeavy TOS

Data Set and Preselection

2016 Data

- 2016 (Stripping28) with 1.67 fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$, B2XMuMu Stripping
- Trigger: Mostly same as Run 1 analysis, but
  - ~~Hlt1TrackAllL0 TOS~~, Hlt1TrackMVA TOS, Hlt1TwoTrackMVA TOS
  - ~~Hlt2Topo(2,3,4)BodyBBDT TOS~~ $\Rightarrow$ Hlt2Topo(2,3,4)Body TOS, ~~Hlt2TopoMu(2,3,4)BodyBBDT TOS~~ $\Rightarrow$ Hlt2TopoMu(2,3,4)Body TOS
- Same preselection, same mis-id vetoes
- MVA: Same hyperparameters as for Run 1, but different probNN tunes (MC12TuneV3 $\Rightarrow$ MC15TuneV1),
  slightly changed BDT cut at 0.05 (Run 1: BDT > 0.06)

B2XMuMu Stripping Line

variable	cut value
B_s^0 χ^2_{vtx}	< 8
B_s^0 χ^2_{IP}	< 16
B_s^0 DIRA	< 0.9999
B_s^0 χ^2_{FD}	> 121
$m_{B_s^0}$	$4900\,\text{MeV} < m_{B_s^0} < 7000\,\text{MeV}$
m_ϕ	$0\,\text{MeV} < m_\phi < 6200\,\text{MeV}$
ϕ χ^2_{FD}	> 9
ϕ χ^2_{IP}	> 0
$m_{\mu^+\mu^-}$	$< 7100\,\text{MeV}$
$(\mu^+$ $\mu\text{m})$ χ^2_{FD}	> 9
μ^+, μ^- $\text{DLL}_{\mu\pi}$	> -3
μ^+, μ^- isMUON	true
tracks χ^2_{IP}	> 9
tracks χ^2/ndf	< 5

Preselection and Mis-ID vetoes

Run 1 and Run 2

Preselection:

variable	requirement
$m_{B_s^0}$	$5100\,\text{MeV} < m_{B_s^0} < 5800\,\text{MeV}$
m_Φ	$\lvert m_\Phi - 1019.461\rvert < 12\,\text{MeV}$
K^+, K^-	$\texttt{PIDK} > -3.0$

Mis-id vetoes:

variable	requirement
$\lvert m(\mu^-, K^+ \text{ as } \mu^+) - 3096.916\rvert$ for $\texttt{isMuon}(K^+)$ or $\texttt{PIDmu}(K^+) > 5.$ ($J/\Psi\phi \to KK\mu\mu$ double Mis-ID)	$> 45\,\text{MeV}$
$\lvert m(\mu^-, \mu^+, K^-, K^+ \text{ as } p^+) - 5620.\rvert$ for $(\texttt{PIDp} - \texttt{PIDK})(K^+) > 10.$ ($\Lambda_b^0 \to pK\mu\mu$ background)	$> 50\,\text{MeV}$

Detailed background studies will follow, studies on improving background vetoes are ongoing (e.g. use `probNN` instead of `PID` in future)

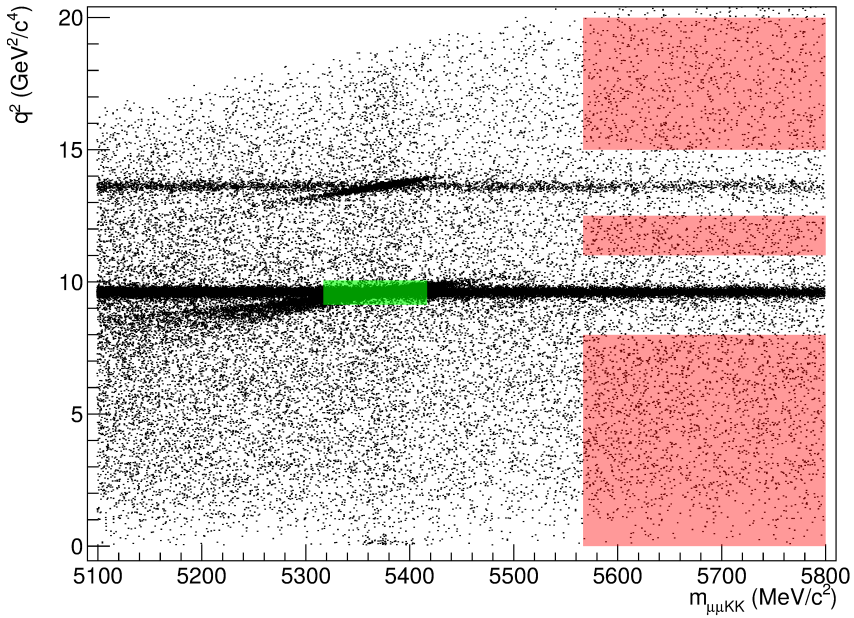
Multivariate Analysis

Run 1

- Suppress combinatorial background
- BDT, kFolding with $k = 10$
- Input variables:

  `B0_ENDVERTEX_CHI2`, `B0_PT`, `B0_IPCHI2_OWNPV`, `B0_FDCHI2_OWNPV`, `B0_DIRA_OWNPV`, min(`K_ProbNNk`), max(`K_ProbNNk`), min(`mu_ProbNNmu`), (`K`,`Mu`)`_IPCHI2_OWNPV`
- Hyperparameters:

  `minNodeSize` $= 7.5\%$, `nCuts` $= 500$, `Boosttype = AdaBoost`, `MaxDepth` $= 2$



Signal Proxy : sWeighted control region (± 50 MeV around $m_{B_s^0}$, ± 75 MeV around $m_{J/\Psi}$)

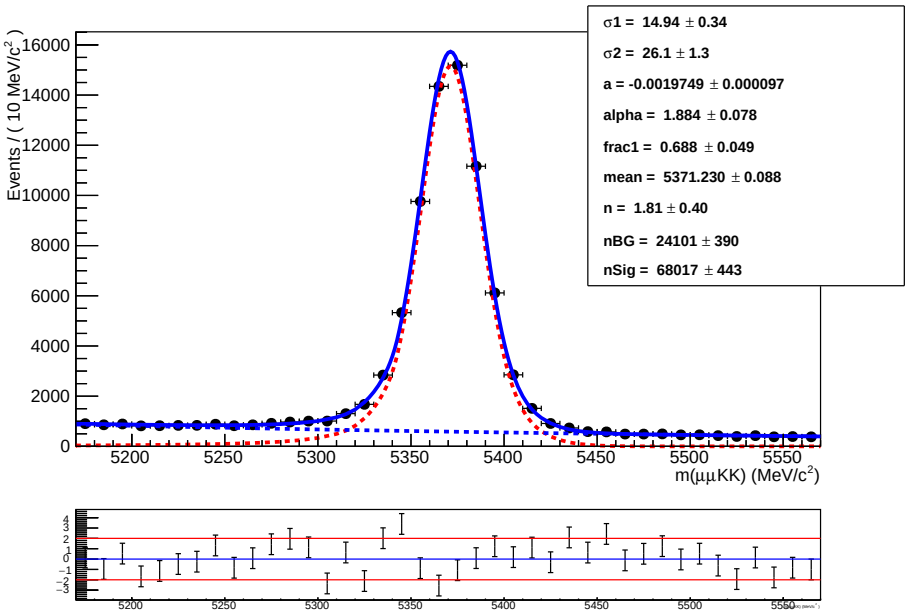
Background Proxy: Upper B_s^0 mass sideband (200 MeV above $m_{B_s^0}$, excluding q^2 of 8-11 GeV^2 and 12.5-15 GeV^2; m_ϕ window of 50 MeV)

sWeighting

Run 1

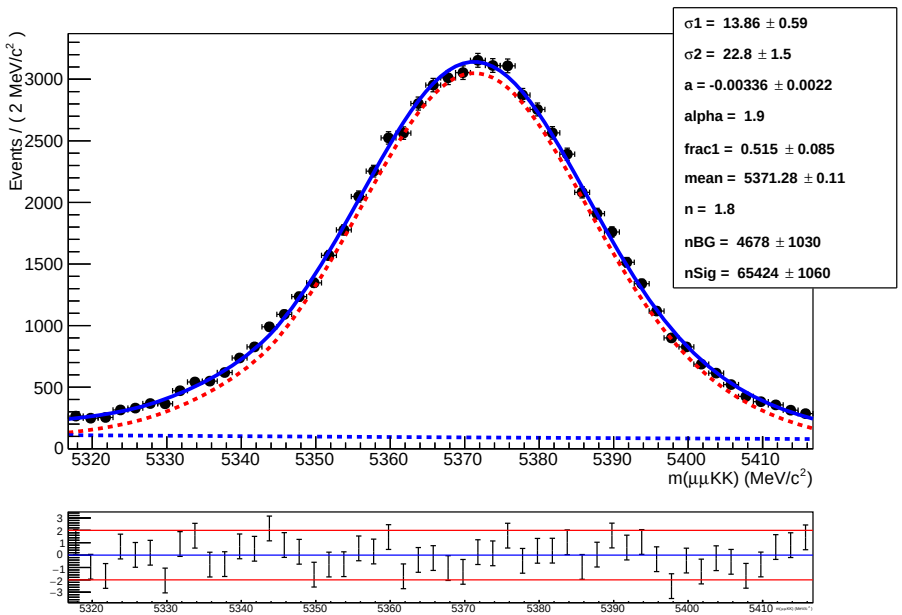
Fit model: Sum of two Crystall-Ball functions with common tail parameters (signal), exponential function (background)

$(8 < q^2 < 11\,\mathrm{GeV}^2)$



Fit to fix tail parameters

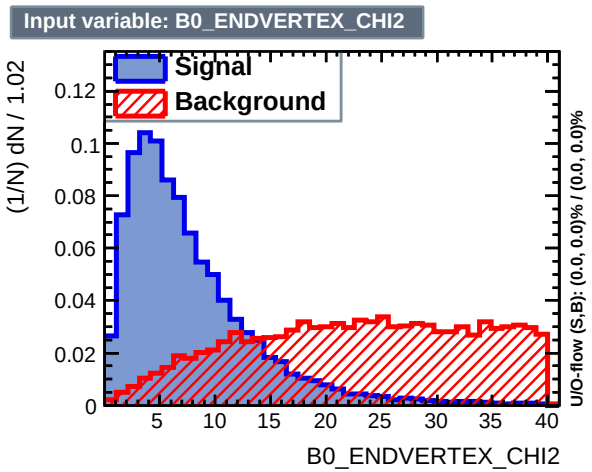
$(|m_{\mu\mu} - m_{J/\psi}| < 75\,\mathrm{MeV})$

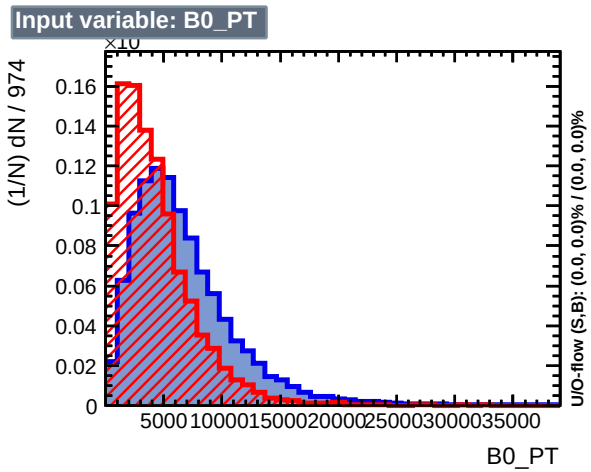


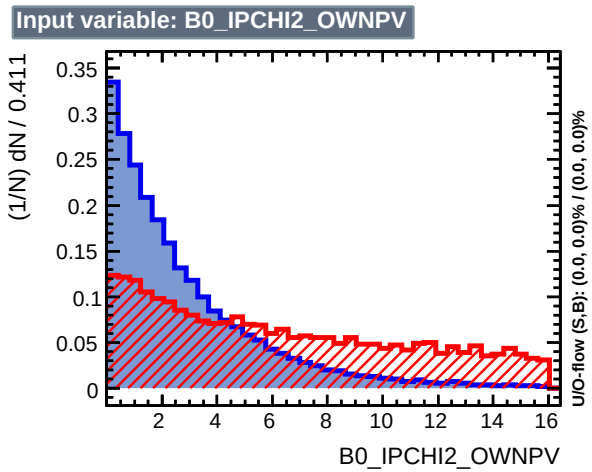
Fit to perform sWeighting

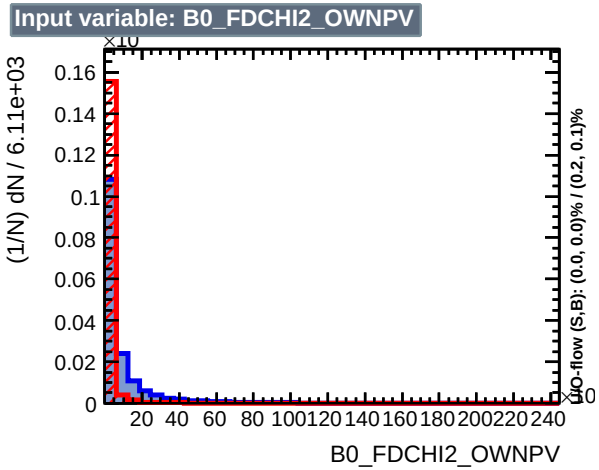
BDT Input Variables (1)

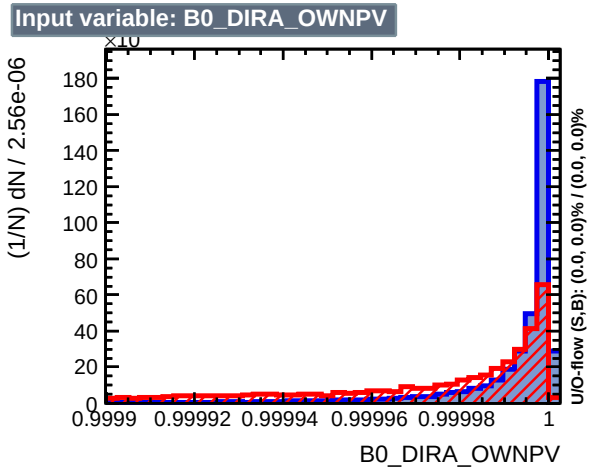
Run 1

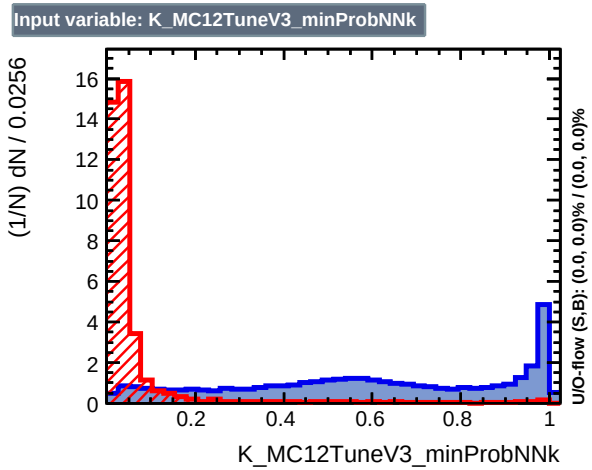






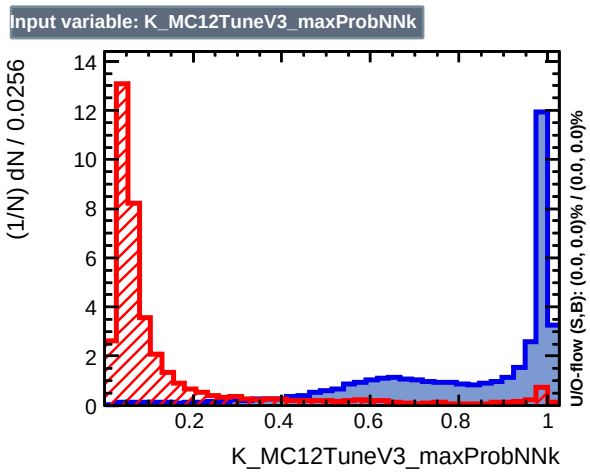


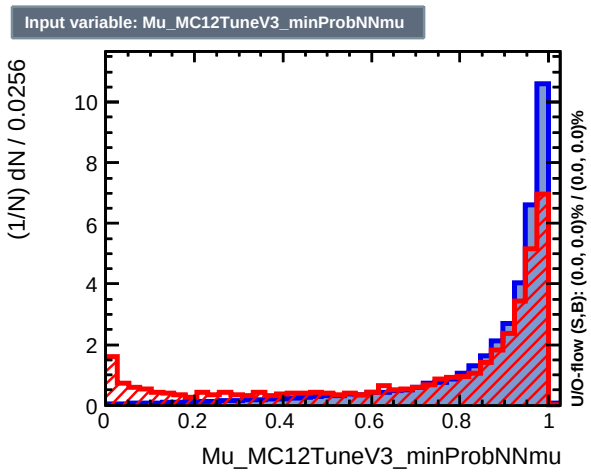


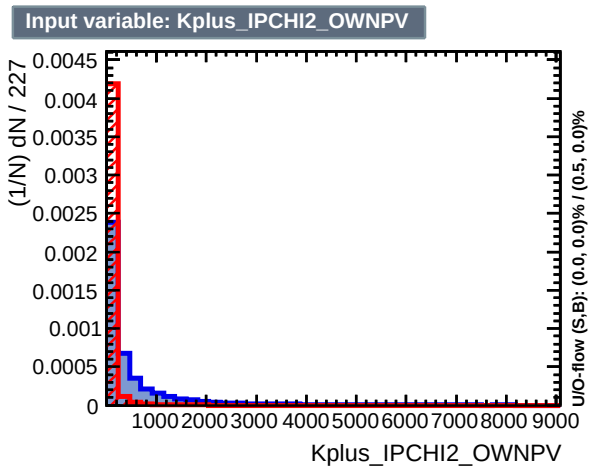


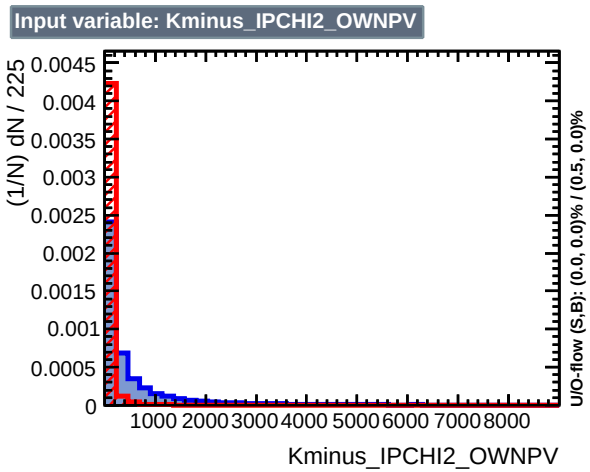
BDT Input Variables (2)

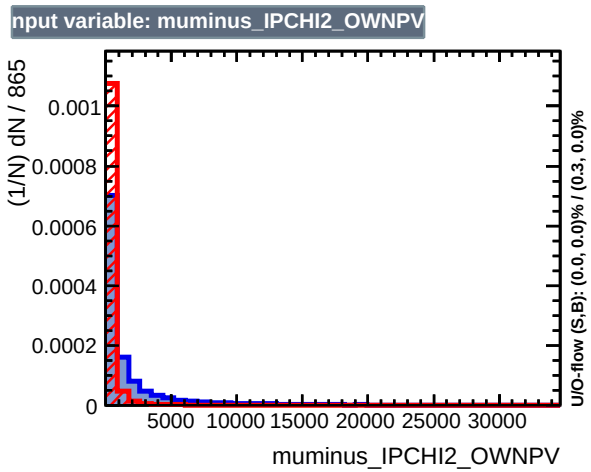
Run 1

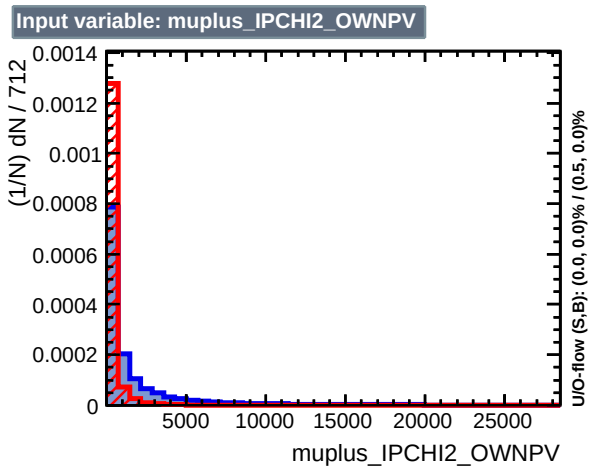








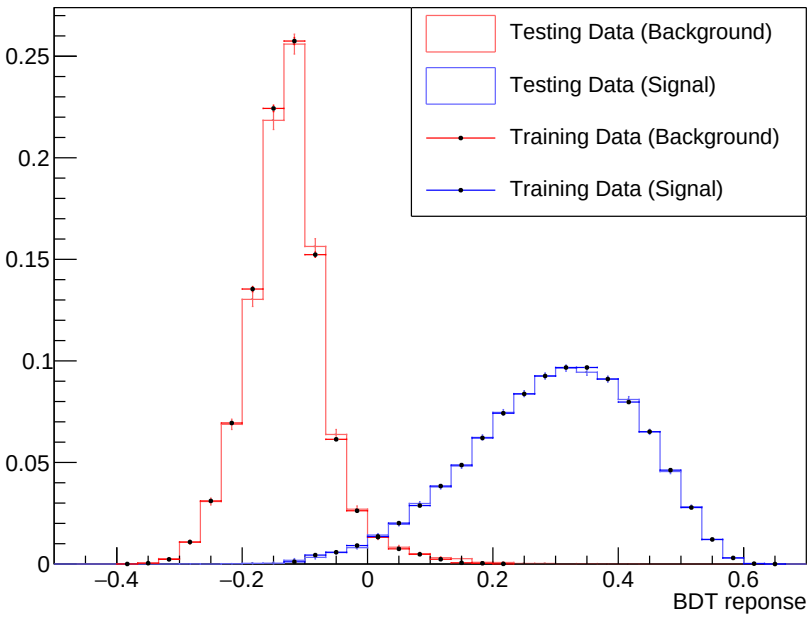




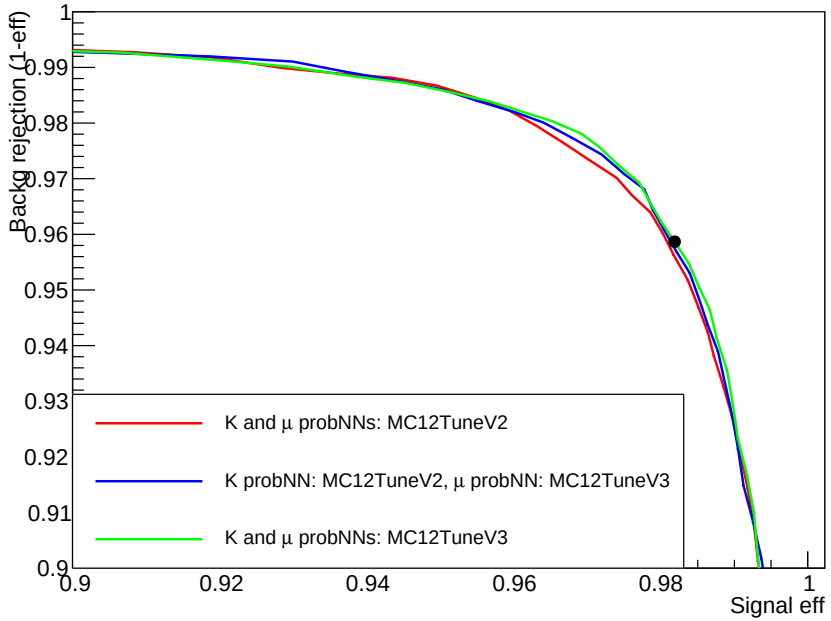
BDT Output

Run 1

Overtraining check



ROC curve

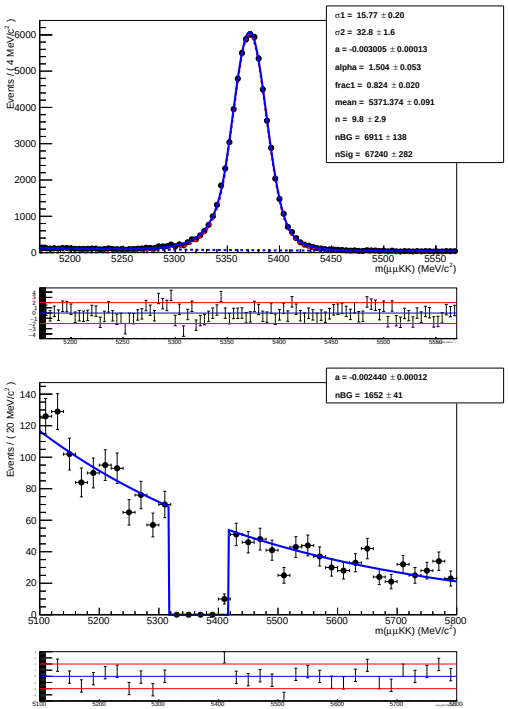


BDT Cut Optimization on Testing kFold

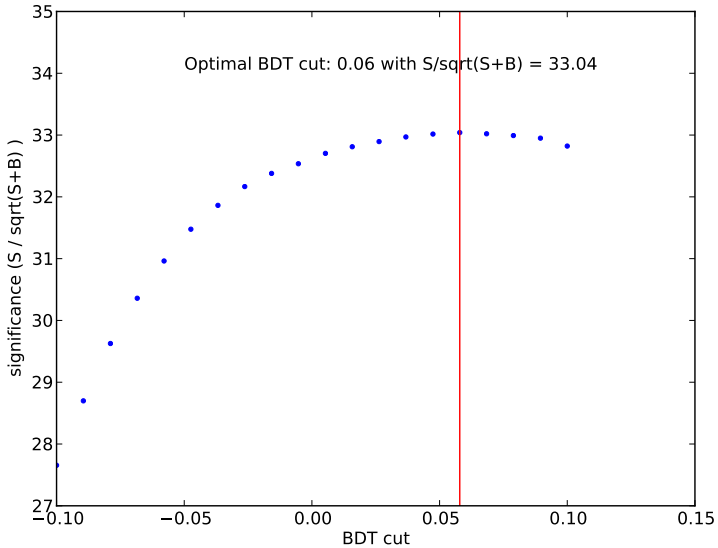
Run 1

- Maximize significance $\frac{N_S}{\sqrt{N_S+N_B}}$, try different BDT cuts

e.g. (BDT response > -0.05):



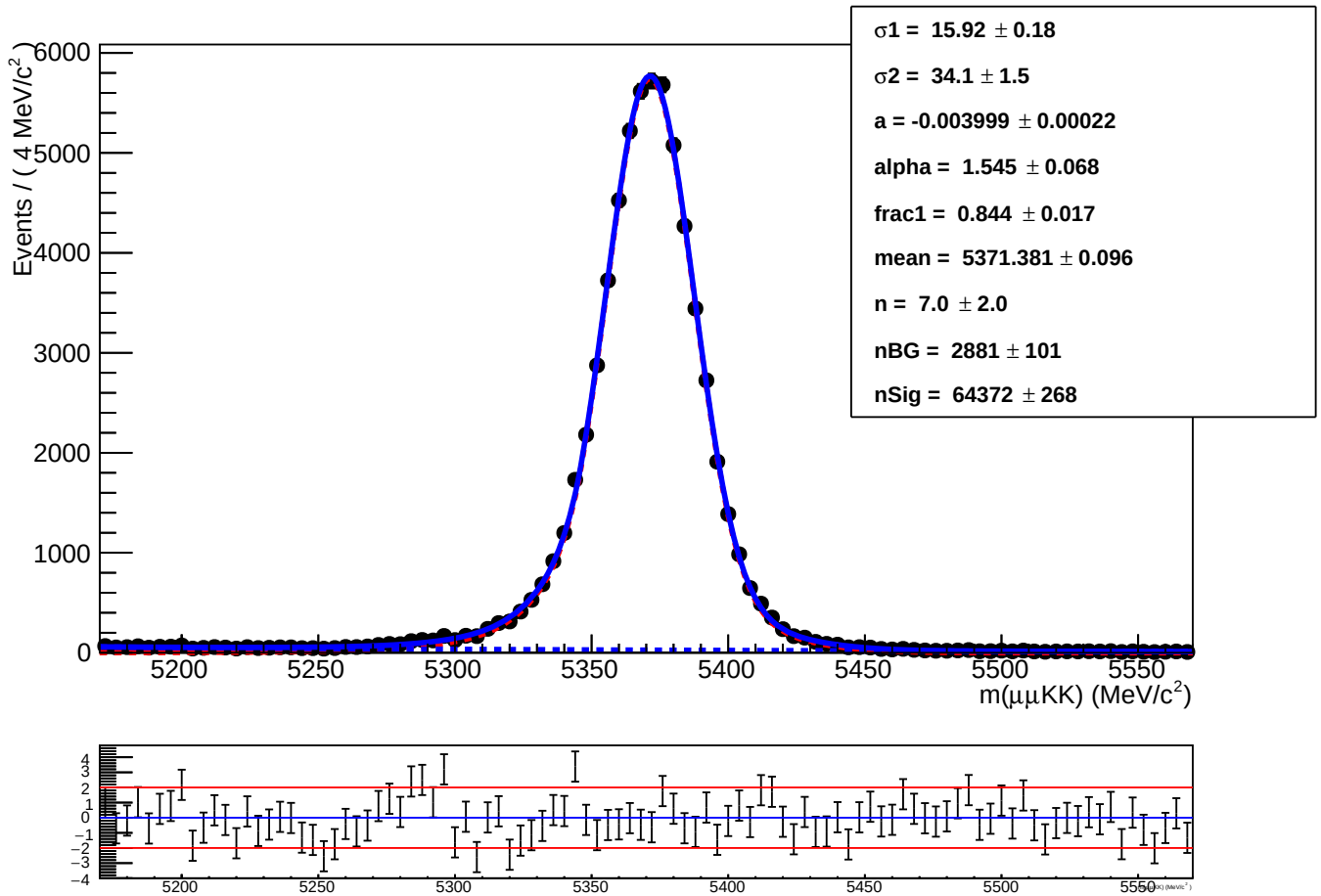
- $N_S = (\text{N}_{\text{sig}} \text{ in CR}) \times \underbrace{\frac{\mathcal{B}(B_s^0 \to \phi\mu\mu)}{\mathcal{B}(B_s^0 \to J/\Psi(\to \mu\mu)\phi)}}_{=0.01896}$
- $N_B = (\text{N}_{\text{background}} \text{ in rare signal region})$ extrapolated from the side bands



Event Yields - Control Channel ($|m_{\mu\mu} - m_{J/\psi}| < 75\,\text{MeV}$)

Run 1 - After All Selection

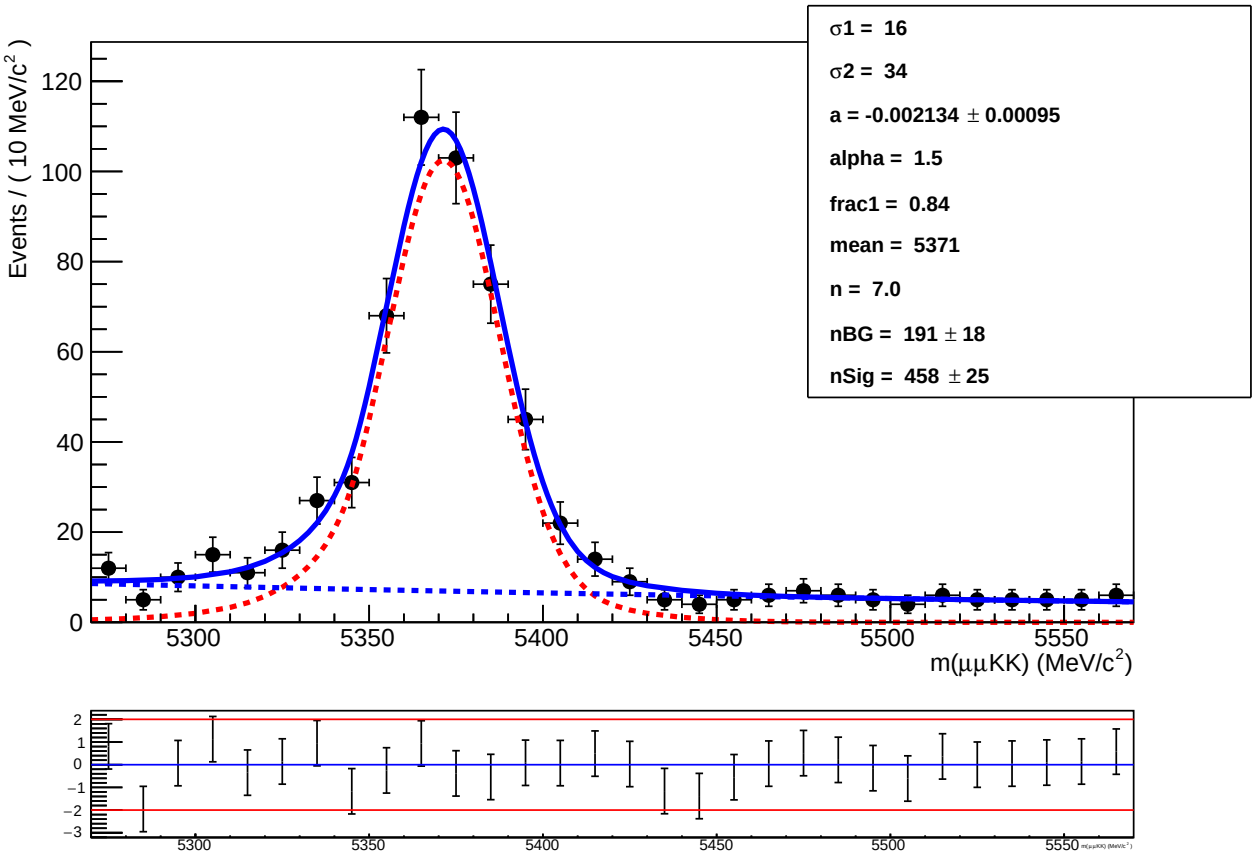
Fit model: Sum of two Crystall-Ball functions with common tail parameters (signal), exponential function (background)



Event Yields - Rare Signal Channel

Run 1 - After All Selection

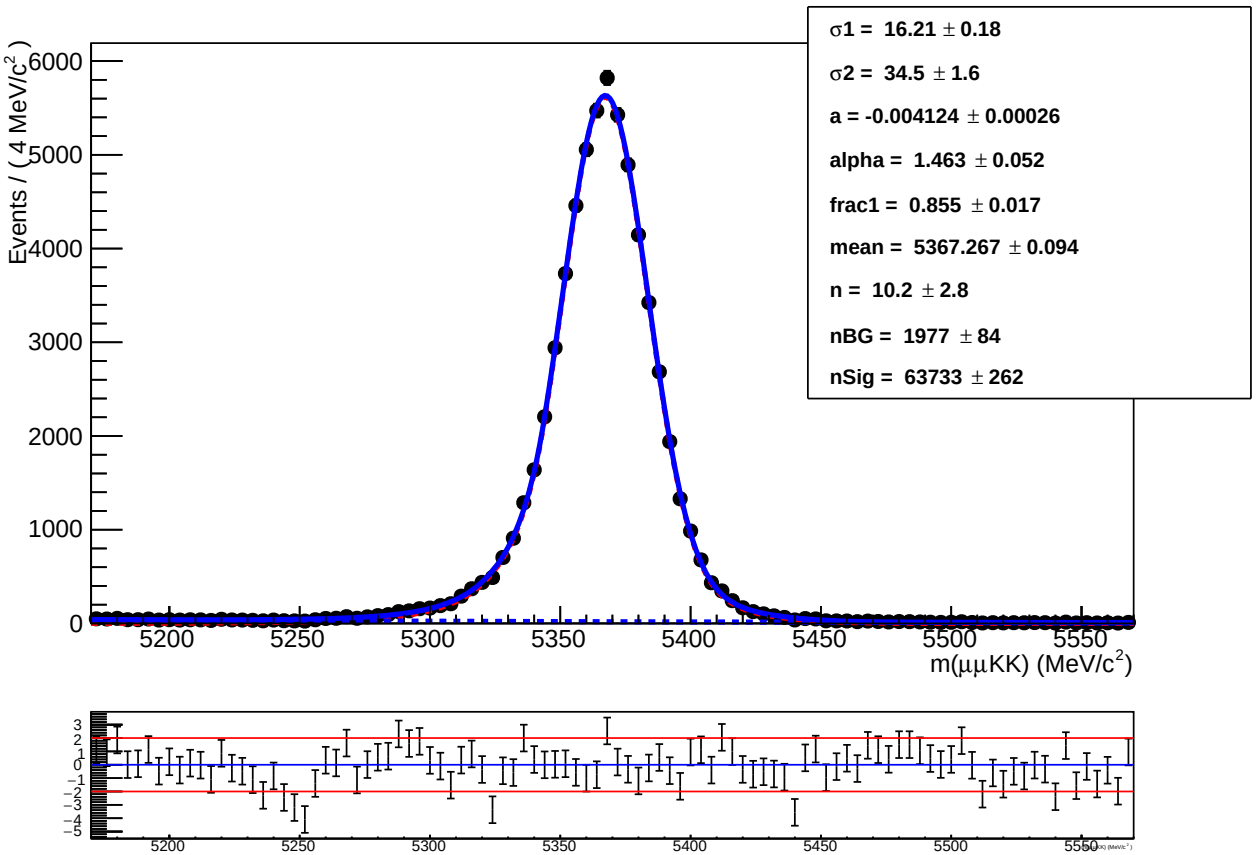
Fit model from Control Channel, only yields and constant from exponential free



$N = 442 \pm 24$ (Paper: 432 ± 24) (in ± 50 MeV around $m_{B_s^0}$)

Control Channel Fit ($|m_{\mu\mu} - m_{J/\psi}| < 75\,\text{MeV}$)

2016 Data



$N = 61309 \pm 26$ (in $\pm 50\,\text{MeV}$ around $m_{B_s^0}$) ($N_{2016\text{ expected}} \approx f \cdot N_{2011/12} \approx 55000$)

$$f = \frac{13\,\text{TeV} \cdot 1.67\text{fb}^{-1}}{7\,\text{TeV} \cdot 1.11\text{fb}^{-1} + 8\,\text{TeV} \cdot 2.08\text{fb}^{-1}} = 0.89$$