Probing the Quark-Gluon Plasma with heavy quarks

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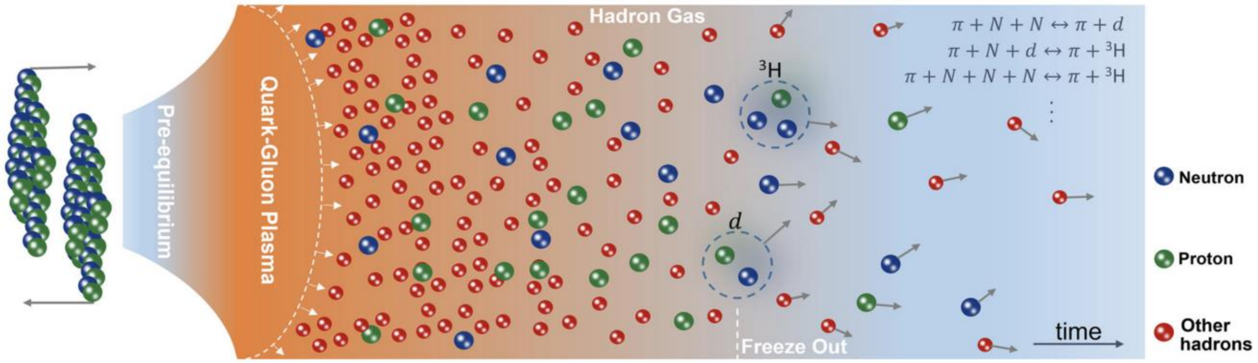
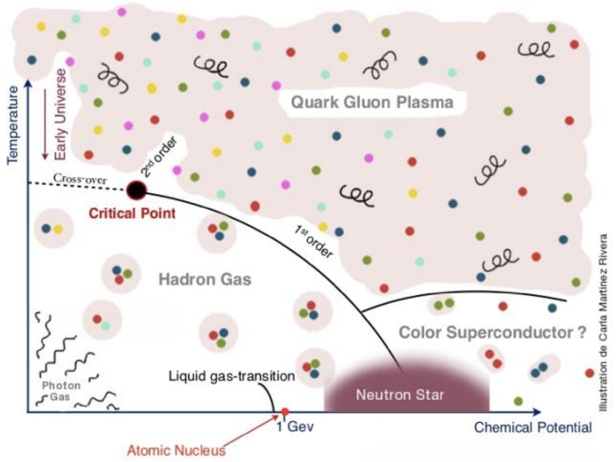
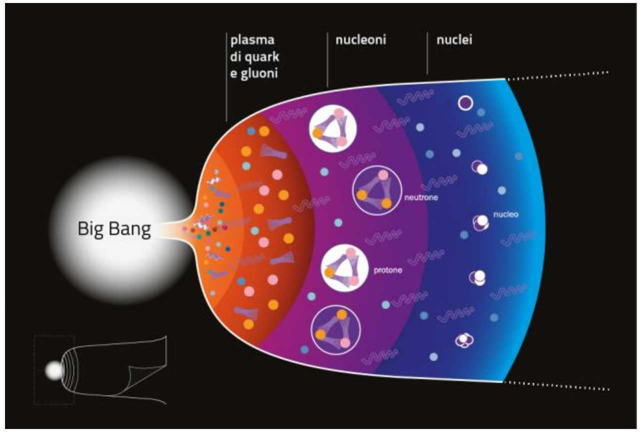
Quark-Gluon Plasma

- The QGP is a state of matter living under extreme conditions of temperature and pressure.
- Constituint quarks melt and form a collective medium with nearly zero viscosity!
- The QGP was the state of the universe right after the Big Bang.
- The underlying theory is the color sector of the Standard Model – Quantum Chromodynamics (QCD).







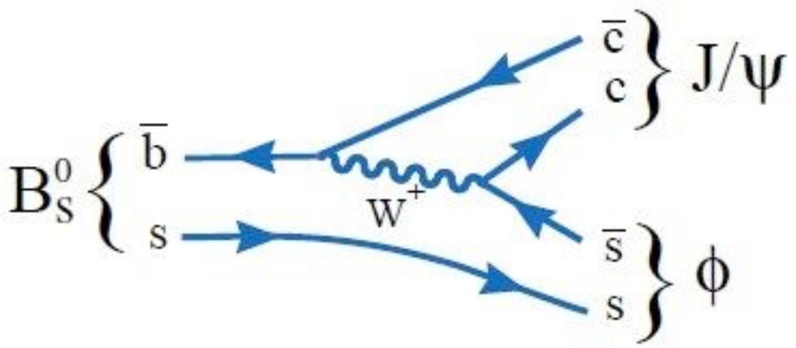
How they are produced on earth? -> Heavy Ion Collisions (PbPb)

QCD Phase Diagram

B Mesons as Probes of the Medium

- B Mesons contain a heavy bottom antiquark bound with a light quark (up, down, etc.).
- Long lived particles, traveling a measurable distance before decaying.
- Produced early in the collision, traversing and interacting with the QGP.
- Not created by the medium, retaining information about its properties.

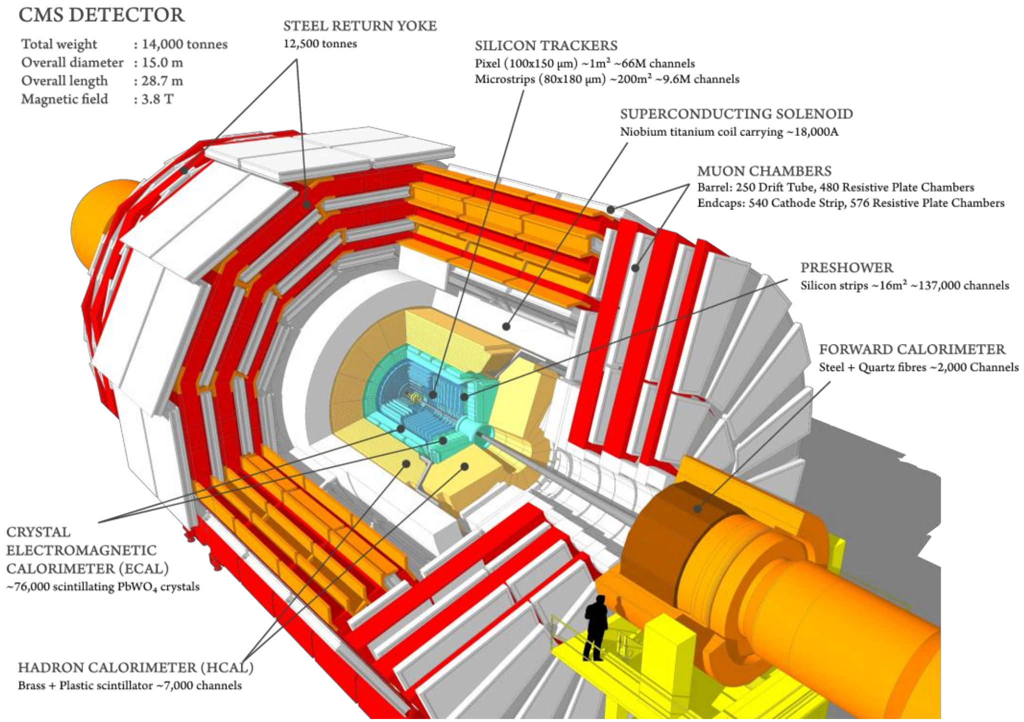
- $B^+ \rightarrow J/\psi + K^+ \rightarrow \mu^+ + \mu^- + K^+$
- $B^0 \rightarrow J/\psi + K^* \rightarrow \mu^+ + \mu^- + \pi^- + K^+$
- $B^0s \rightarrow J/\psi + \Phi \rightarrow \mu^+ + \mu^- + K^- + K^+$

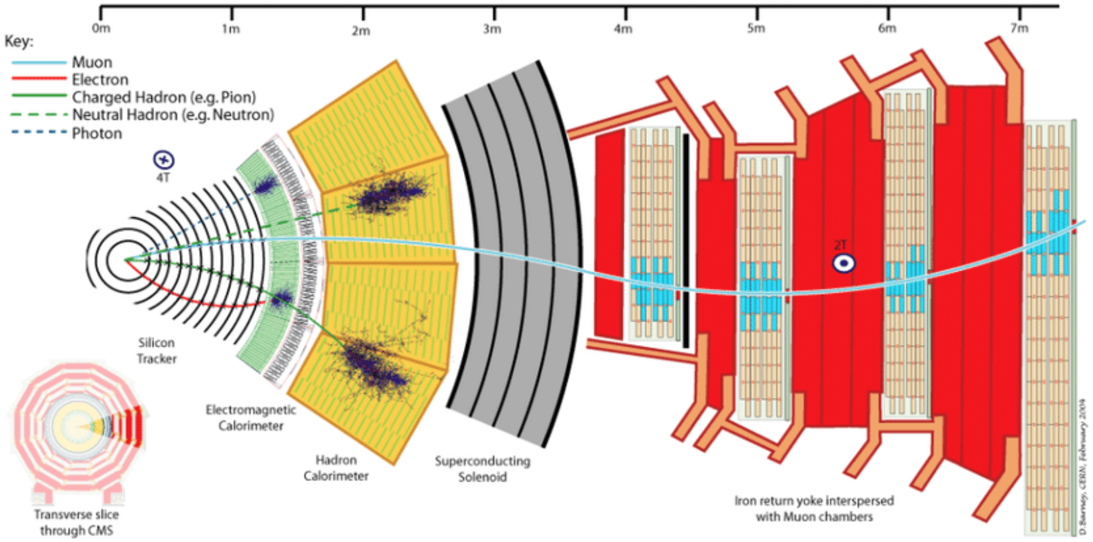


CMS Detector (*Compact Muon Solenoid*)

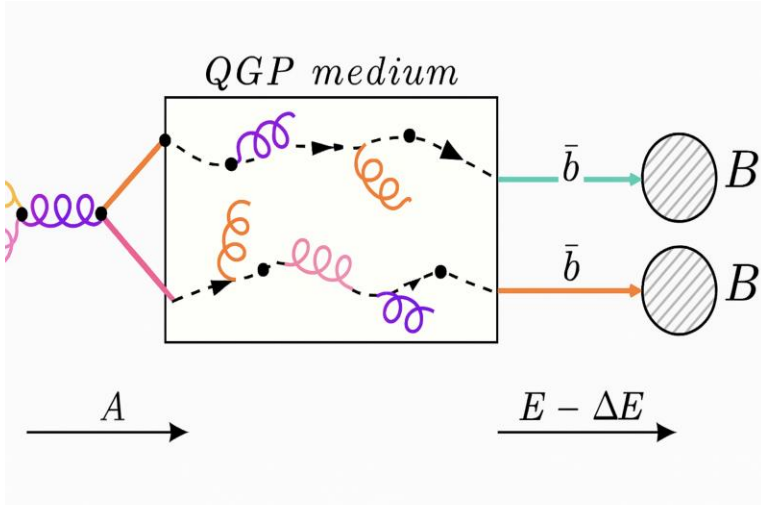
<u>What CMS does?</u>

1. Bending Particles(Lorentz force)
2. Identifying Tracks
3. Measuring Energy
4. Detecting Muons





Physics Objectives



- Study the interference of the Quark-Gluon Plasma in the hadronization of heavy quarks.
- How? -> Measure the **Nuclear Modification Factor** (RAA) of mesons Bs and Bu.
- Also: Establish the **first observation** of **B0** in **Pb-Pb collisions**.

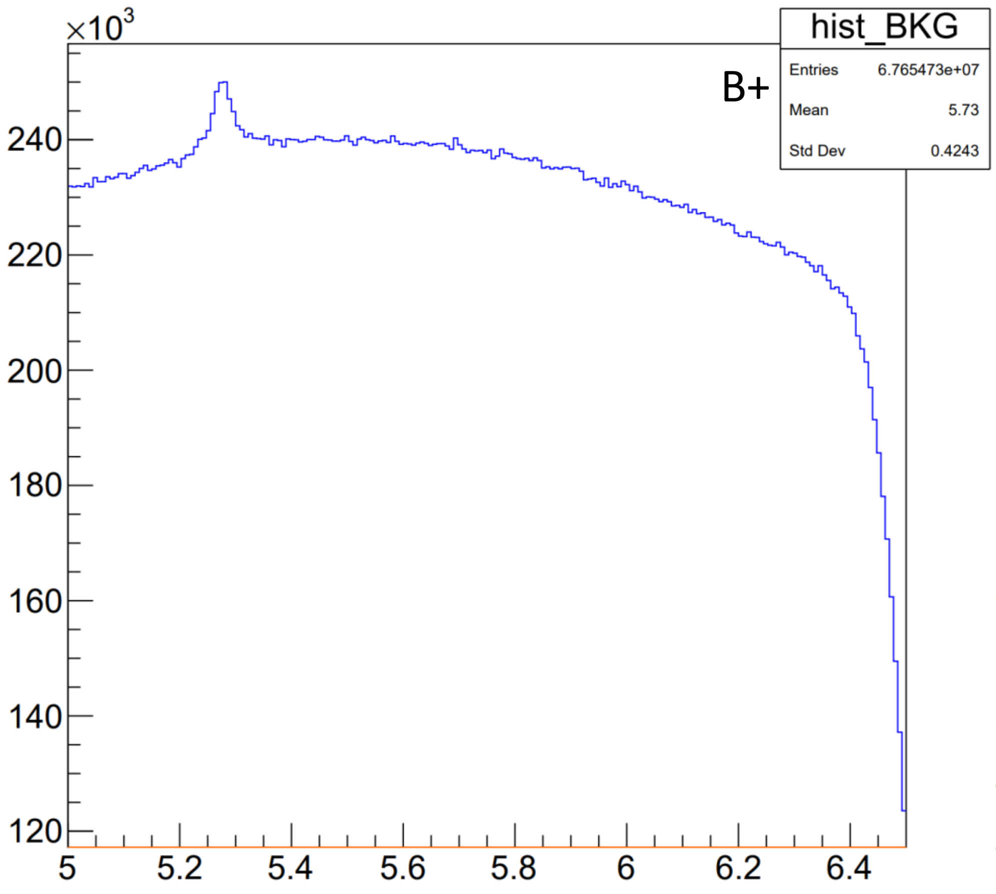
$$R_{AA}(p_T) = \frac{1}{\langle N_{col}\rangle}\frac{\left(\frac{d\sigma}{dp_T}\right)_{PbPb}}{\left(\frac{d\sigma}{dp_T}\right)_{pp}} \qquad \frac{d\sigma}{dp_T} = \frac{1}{\varepsilon LB}\frac{Y_s}{\Delta p_T}$$

PP Collision Data

Run 3 of LHC (2024)
L=455 pb^{-1}

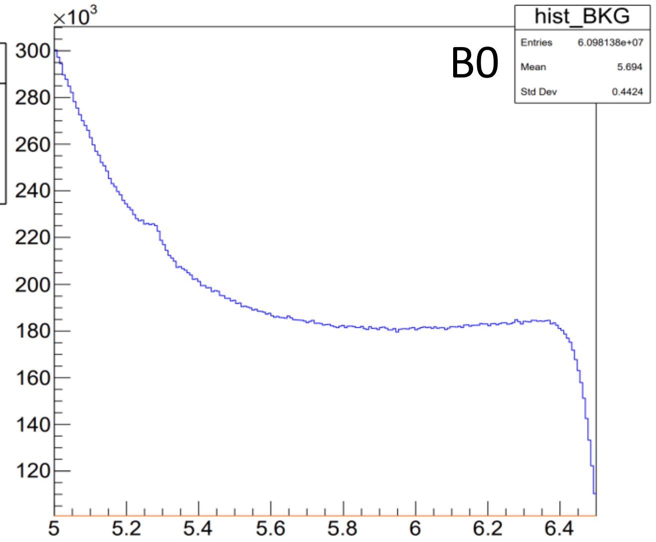
- **Primary Problems of extracting data signal:**

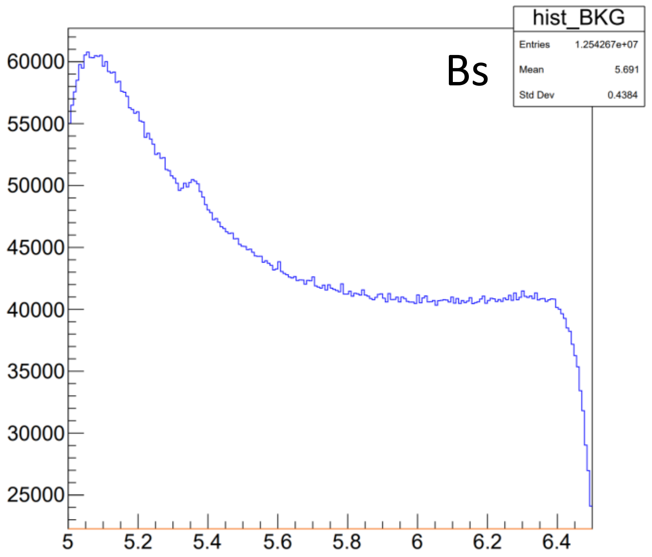
1) **Combinatorial Background**: random combinations of particles that mimic the signal B meson candidate. These combinations do not come from a real B-hadron decay. Since there is no true common parent(B), the invariant mass of such random combinations spreads out as a smooth curve rather than forming a narrow peak.
2) **Partial Reconstructed Background**(B+): Exlusive to B+, for exemplo if B0 decay occured and we didn't detect the π^-, than it could mimic B+ signal but with less invariant mass than B+.



$$m_0^2 c^2 = \left(\frac{E}{c}\right)^2 - \|\mathbf{p}\|^2$$

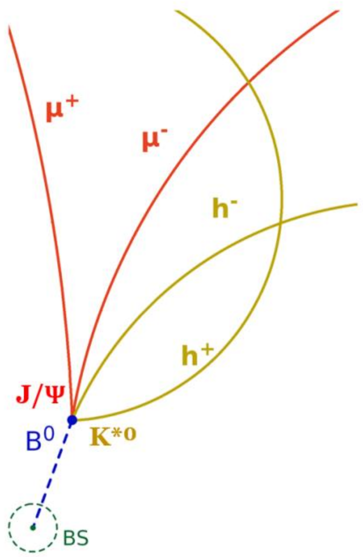
$$E^2 = (pc)^2 + \left(m_0 c^2\right)^2$$

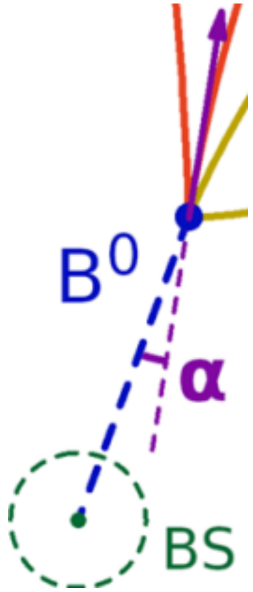


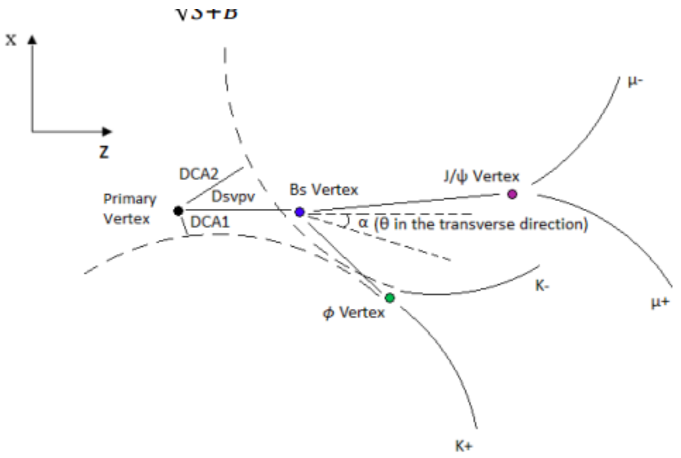


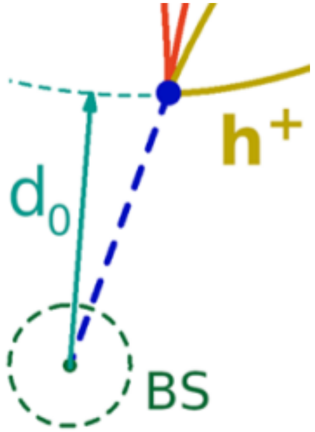
Variables for B mesons selection

- **Normalized Flight length**(Bnorm_svpvDistance): 3D distance between the primary vertex (beamspot) and the secondary vertex (B decay), normalized by its uncertainty
- **α**(Balpha): 3D opening angle between the flight direction and the reconstructed B meson momentum
- **Chi-square Vertex confidence level**(Bchi2cl): probability that the four trajectories (K+,K−,μ+,μ−) are originated in the same secondary vertex
- **ŋ**(BtrkEta): pseudo-rapidity of the non muon track
- **y**(By): rapidity of the reconstructed B meson
- **cos(θ)**(Bcos_dtheta): 2D (projection in the xy direction) opening angle between the 3-momentum and the primary to secondary vertex vector
- **dR**(BtrkdR): angular distance between hadron track and nearest muon track.(for Bs and B0 there are two kaon tracks and for B+ there is only one)
- **Q value**(BQvalue, BQvalueuj, BQvaluemumu): difference between the parent mass and the sum of daughter masses (energy available to be convert into kineti energy), for B+, it is equal to (m(B+) – m(J/ψ)-m(K+))
- **Normalized Flight length in the transverse plane**(Bnorm_svpvDistance_2D): 2D distance between the primary vertex and secondary vertex, normalized by its uncertainty

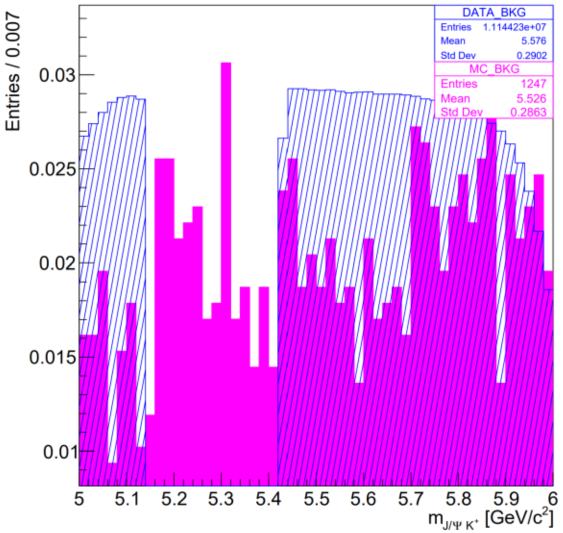


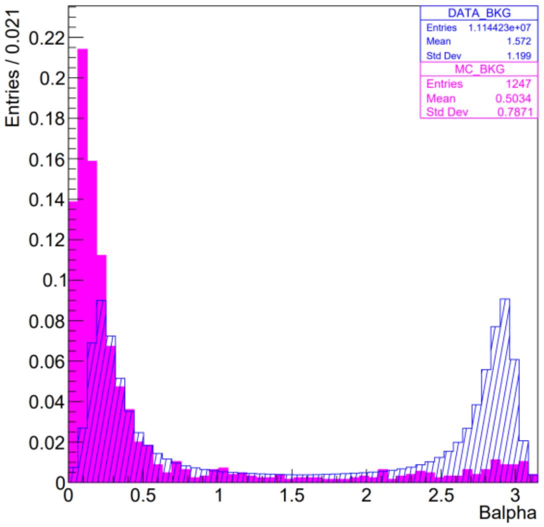


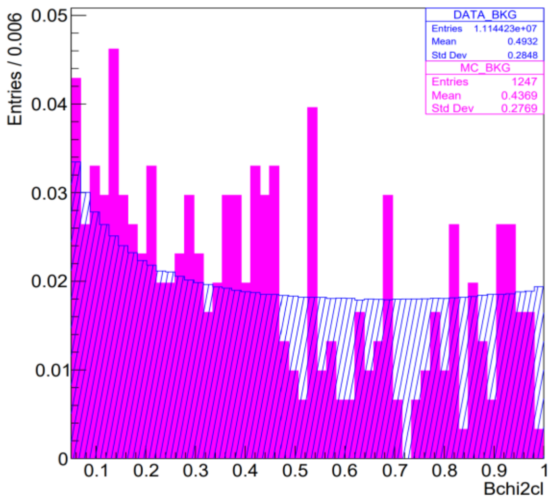


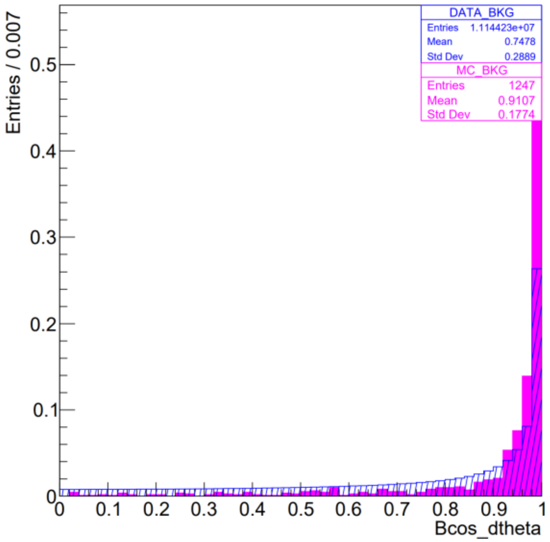


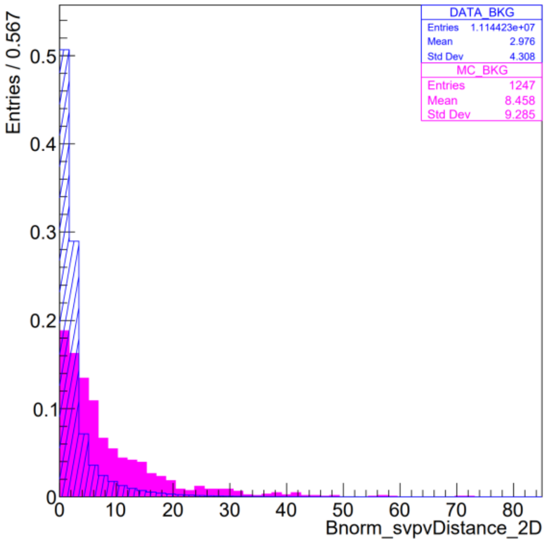
Data Noise Vs MC Noise (B+)

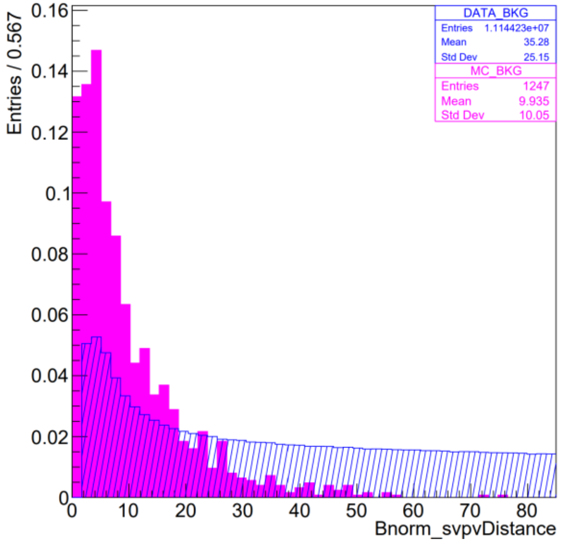










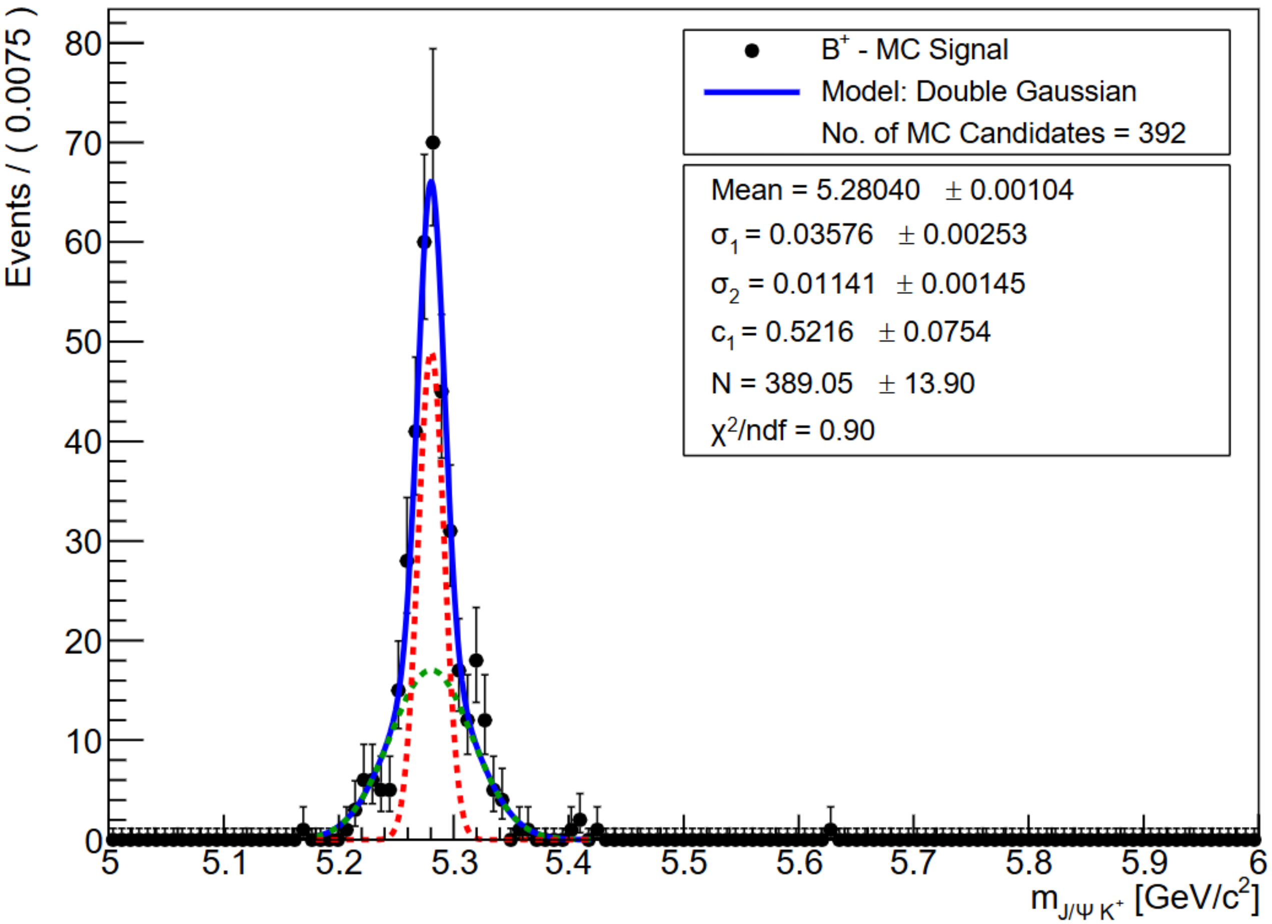


Why not just use MC noise to study?

- Data noise and MC noise are different (ex: lack of symmetry for MC noise in Balpha)
- Therefore, we need to select the sidebands noise in Data to compare variable distributions with MC signal

Fitting Monte Carlo signal (B+)

Double Gaussian Model (L) fitted through the Maximum Likelyhood Method (ROOFIT)



$$\mathscr{L} = N \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

Define data noise region through sidebands

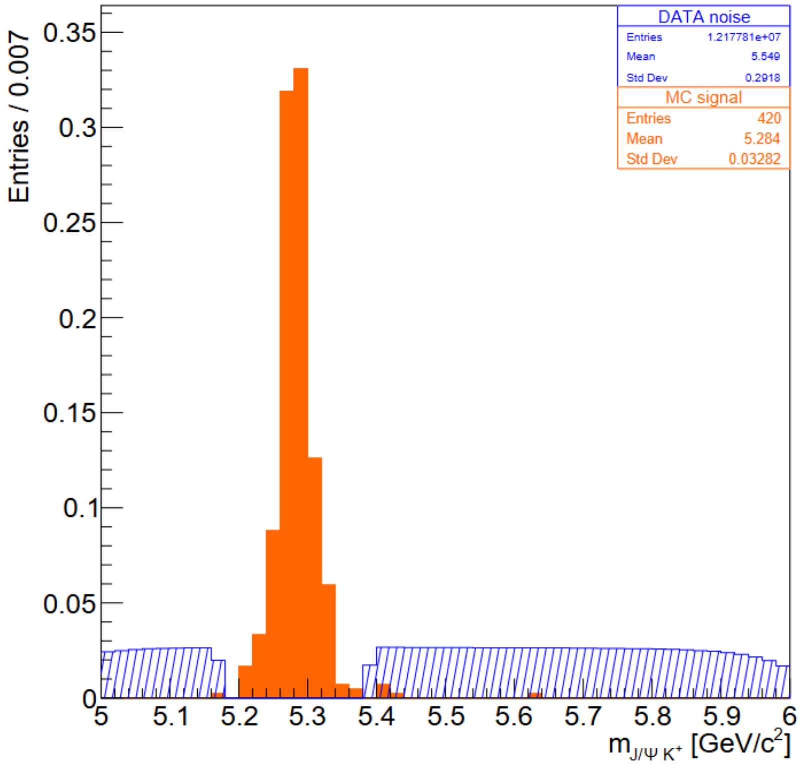
Using the $3\sigma_1$, from the wider gaussian to avoid cutting signal.

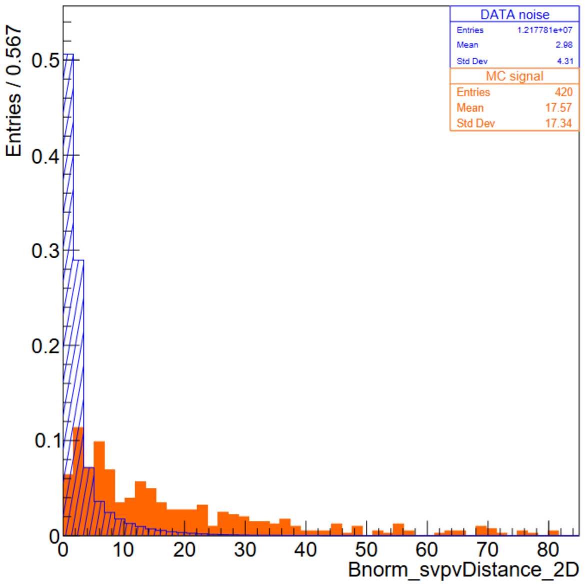
- Left sideband: [5.00000 ; 5.17501] GeV/c^2
- Right sideband: [5.38657 ; 6.00000] GeV/c^2

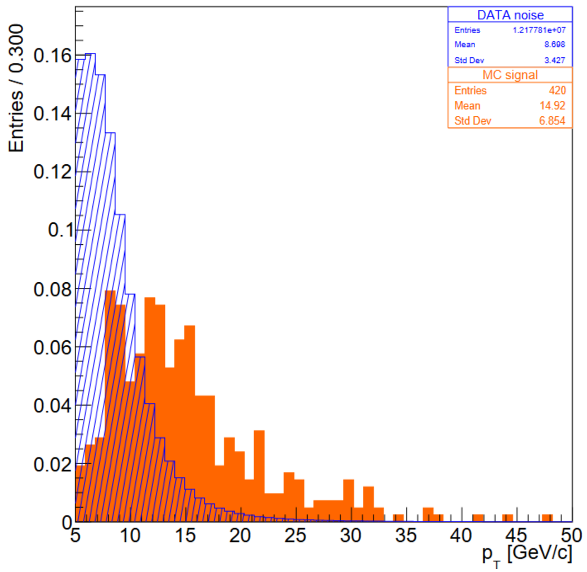
MC Signal Vs Data Noise (B+)

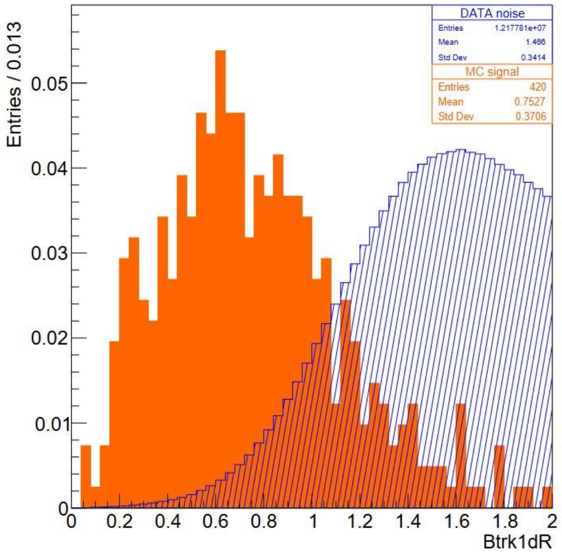
Data Noise Sidebands selected from mass distribution:

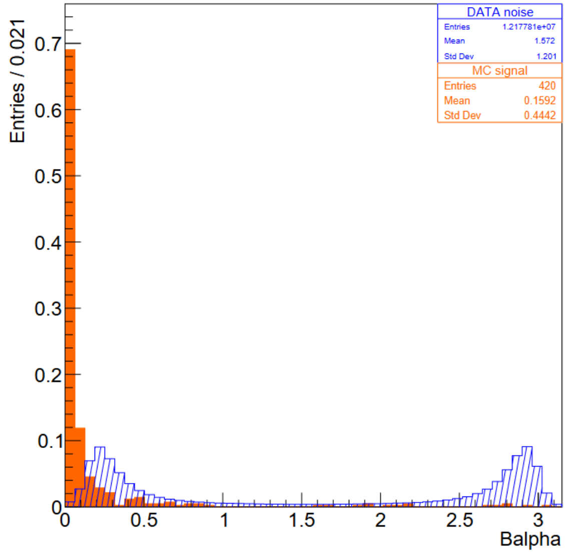
M < 5.17501 || M >5.38657











These are some of the most discriminant variable samples after the sidebands are implemented

ROC curves

A Receiver Operating Characteristic(ROC) curve is a curve of true signal/false positive signal.

Applyed to a variable tells how discriminanting it is.

Why do we use ROC curves:

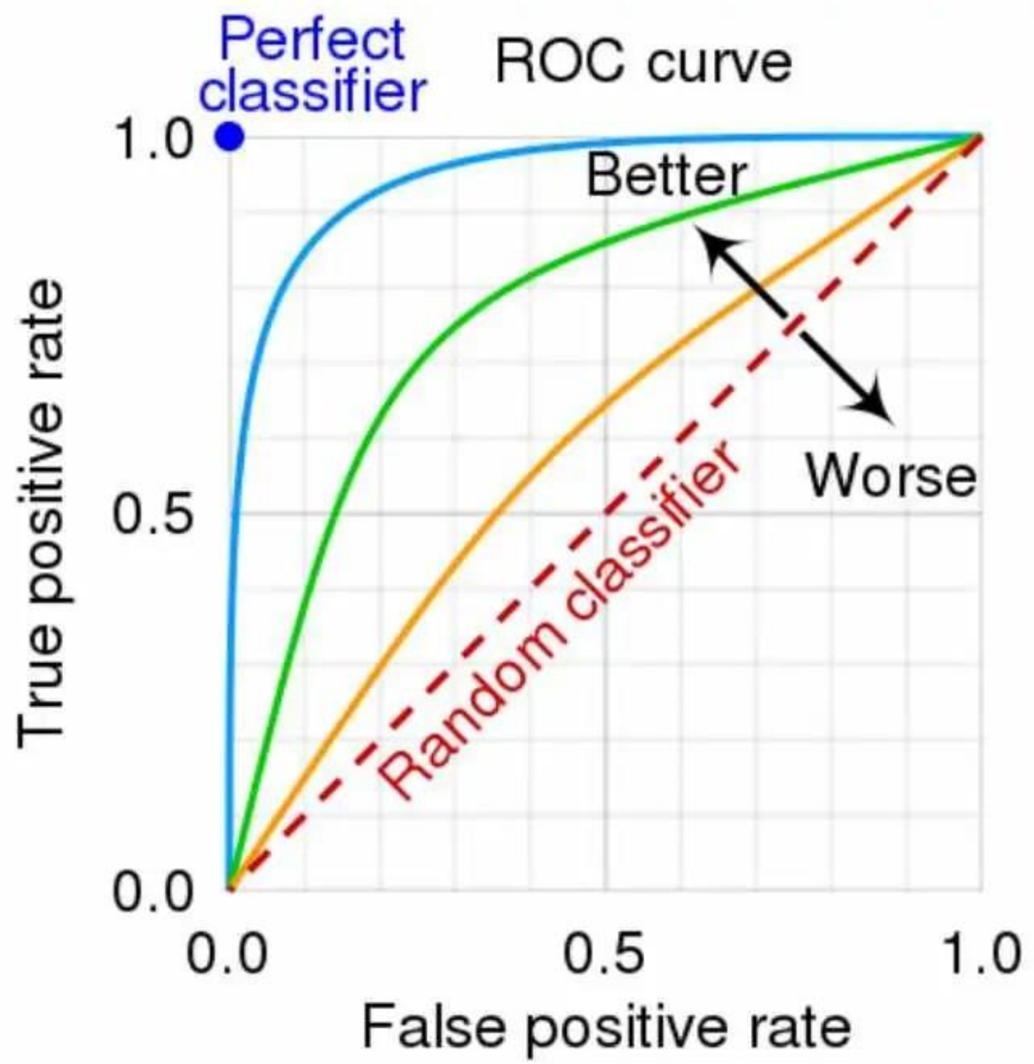
- Determines best cut variables
- AUC score meaures how discriminanting a variable is

How do we use ROC curves:

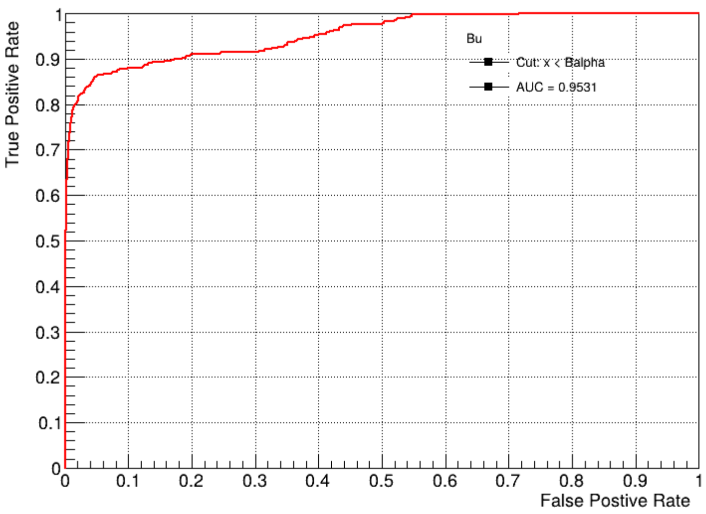
- True positive rate also known as sensitivity
- False poitive rate also known as probability of false alarm and ec to (1-specificity)

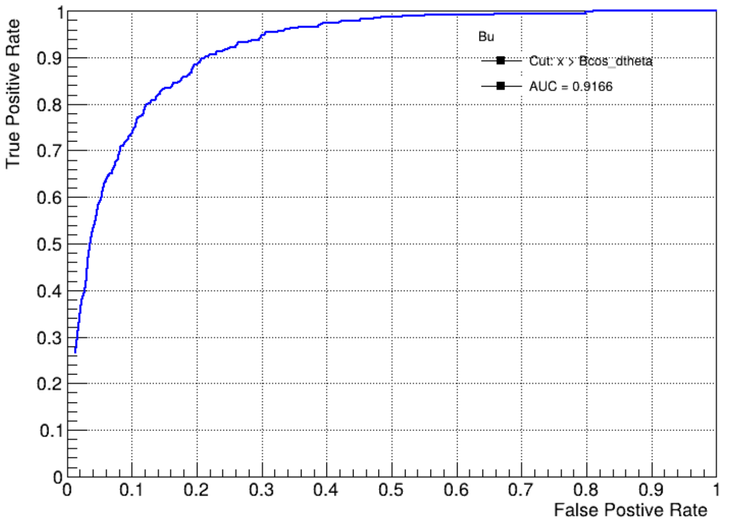
$$TPR = \frac{TP}{FN + TP} = \frac{S(after\ Cut)}{S(before\ Cut)}$$

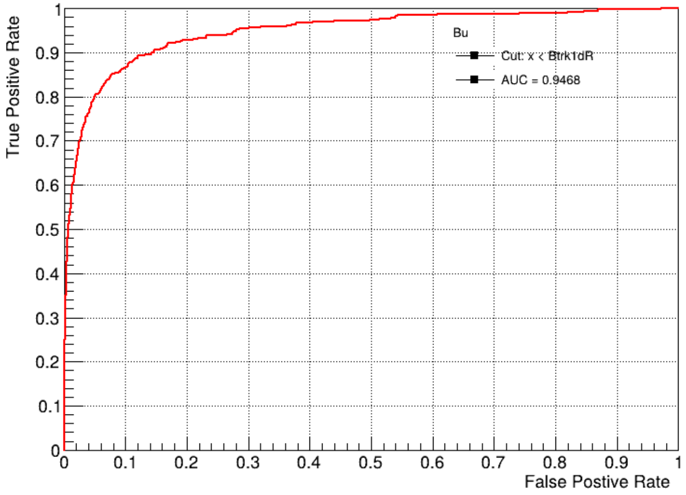
$$FPR = \frac{FP}{FP + TN} = \frac{B(after\ Cut)}{B(before\ Cut)}$$

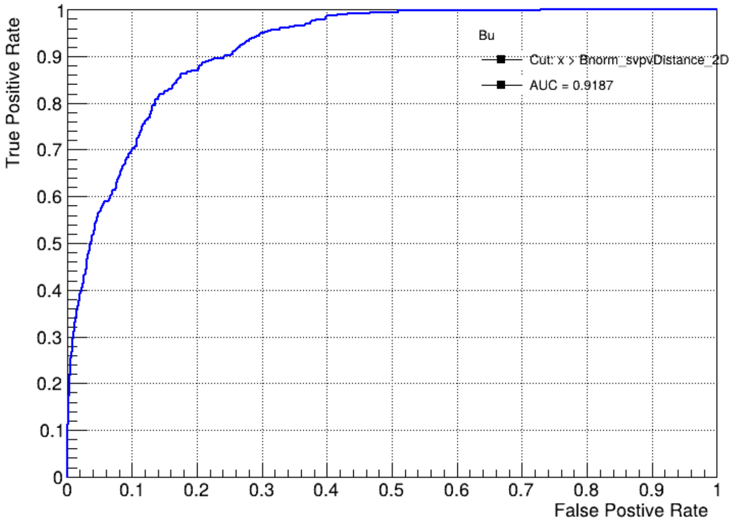


ROC Curves (B+)


Bu
Cut: x < Balpha
AUC = 0.9531
True Positive Rate
False Postive Rate


Bu
Cut: x > Bcos_dtheta
AUC = 0.9166
True Positive Rate
False Postive Rate

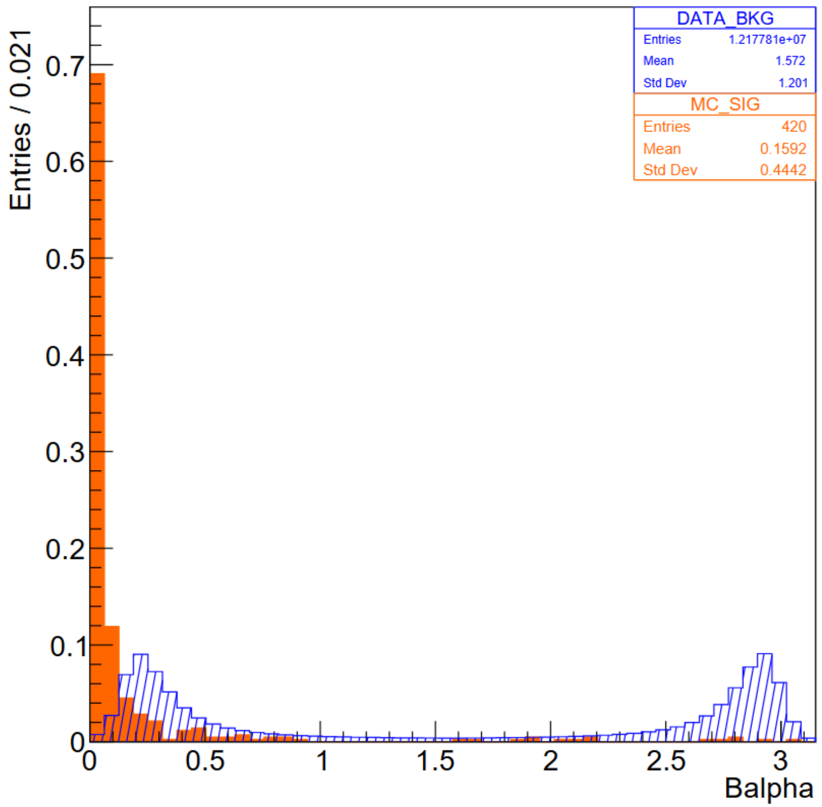

Bu
Cut: x < Btrk1dR
AUC = 0.9468
True Positive Rate
False Postive Rate

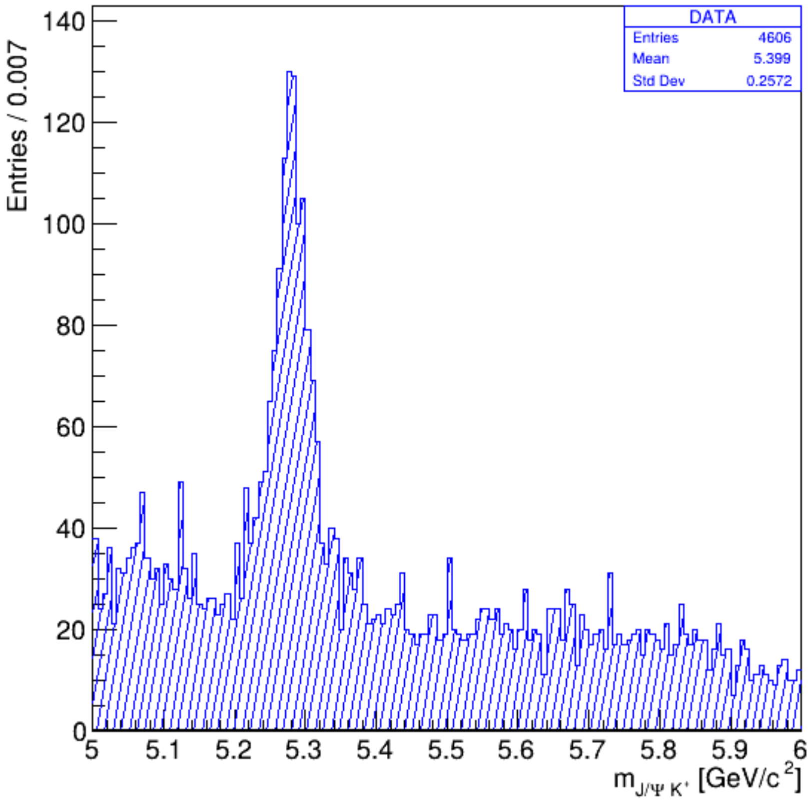

Bu
Cut: x > Bnorm_svpvDistance_2D
AUC = 0.9187
True Positive Rate
False Postive Rate

First cut (B+)

Preliminary CUT:

Balpha>0.008





Why are we applying cuts to the data noise

- Find a peak in the whole data sample
- Fit the data and determine the significance

Poisson Significance (Optimalization of Cut)

We want to preserve as much of signal as possible while cutting as much of noise as possible,

in the signal region 3σ of the widest gaussian, which leads us to calculate the Significance of a cut.

Significance $= \frac{S_{MC}}{\sqrt{B(Sideband)}}$ $(\mathrm{S} \ll \mathrm{B})$

After Cut

Significance $= \frac{S_{MC}}{\sqrt{S_{MC} + B(Sideband)}}$

(A better approximation after preliminary cuts)

- Significance $= FOM = \frac{S_{MC}}{\sqrt{S_{MC} + B(Sideband)}}$
- Significance (Corrected) $= FOM(scaled) = \frac{S_{MC} \cdot f_s}{\sqrt{S_{MC} \cdot f_s + B \cdot f_b}}$

Scaling factors

$$f_s = \frac{S_{data}}{S_{MC}} \qquad f_b = \frac{B(signal\ region)}{B(Sideband)}$$

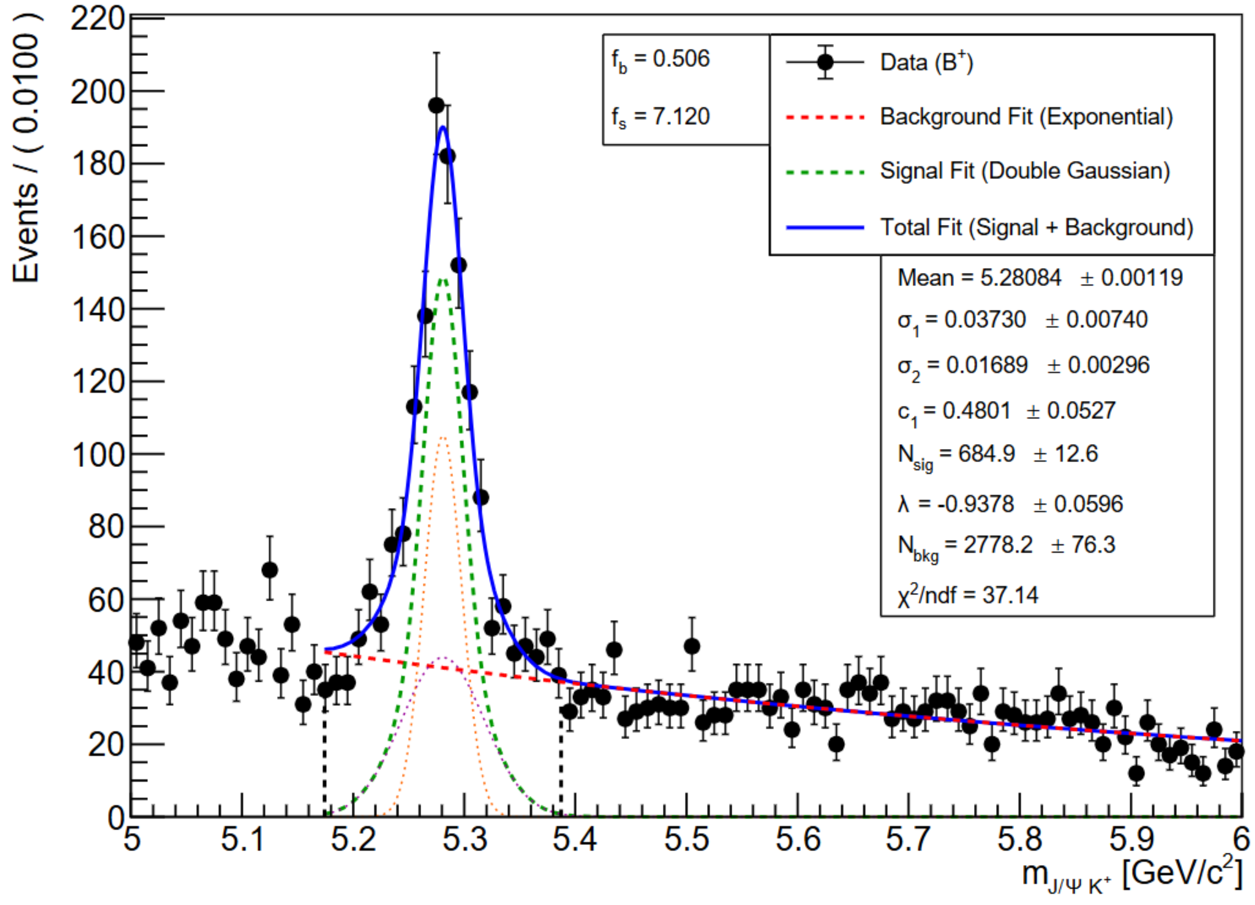
➢ Removes arbitrariness from MC Signal and Data

Why do we want to determine the significance

1. Indicates of best cut value and its direction
2. Finds the best variables to cut

Fitting the data (B+)

Double Gaussian + Expo Bkg model using Extended MLM (Roofit)



Equation of Background Noise:

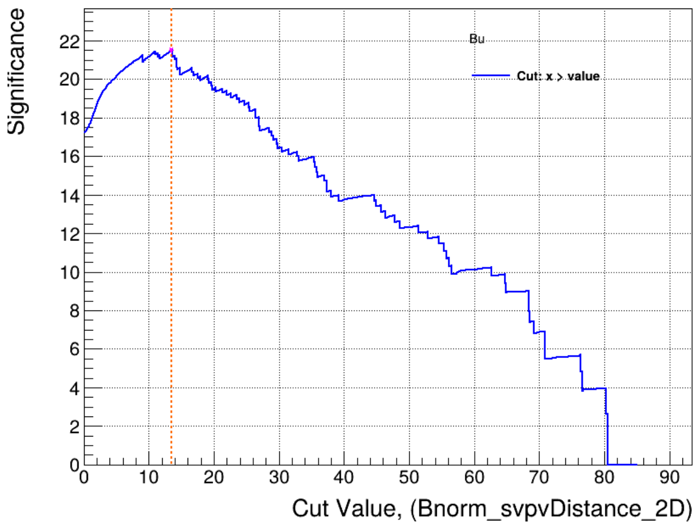
$$\mathscr{L}_{background} = N_{bkg} \cdot e^{\lambda \cdot m}$$

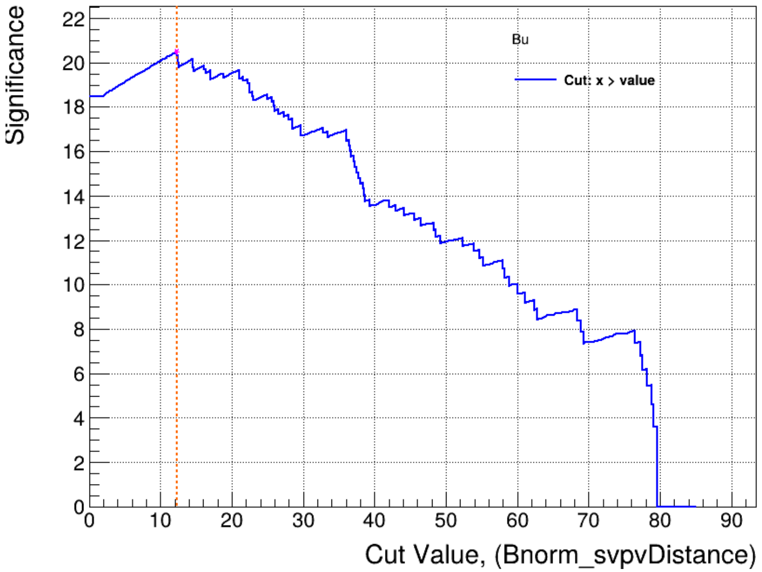
Determine the scaling factors:

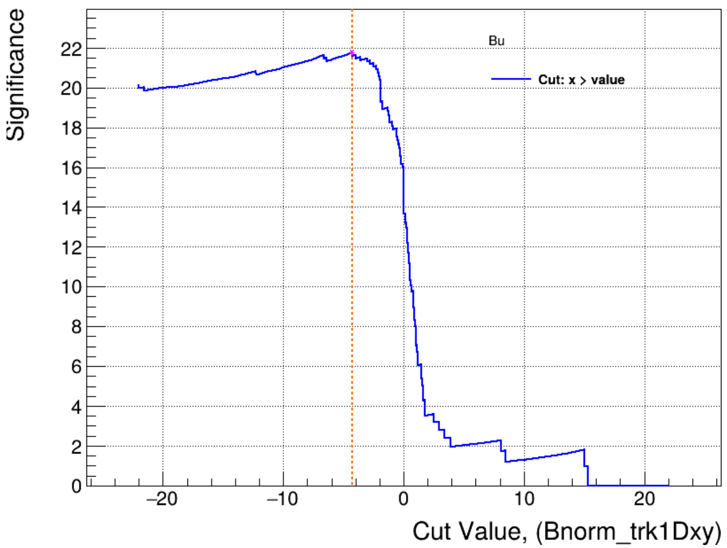
$$f_s = \frac{S_{data}}{S_{MC}} \qquad f_b = \frac{B(signal\ region)}{B(Sideband)}$$

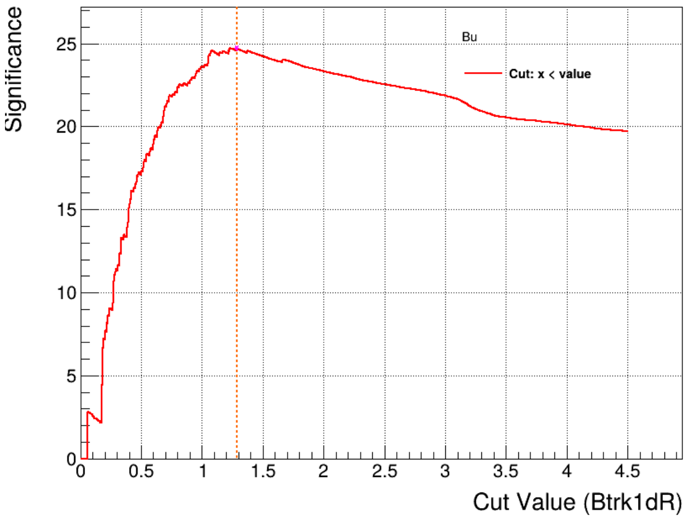
$$\mathscr{L}_{signal} = N_{sig} \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

Max Significance for discriminant variables (B+)





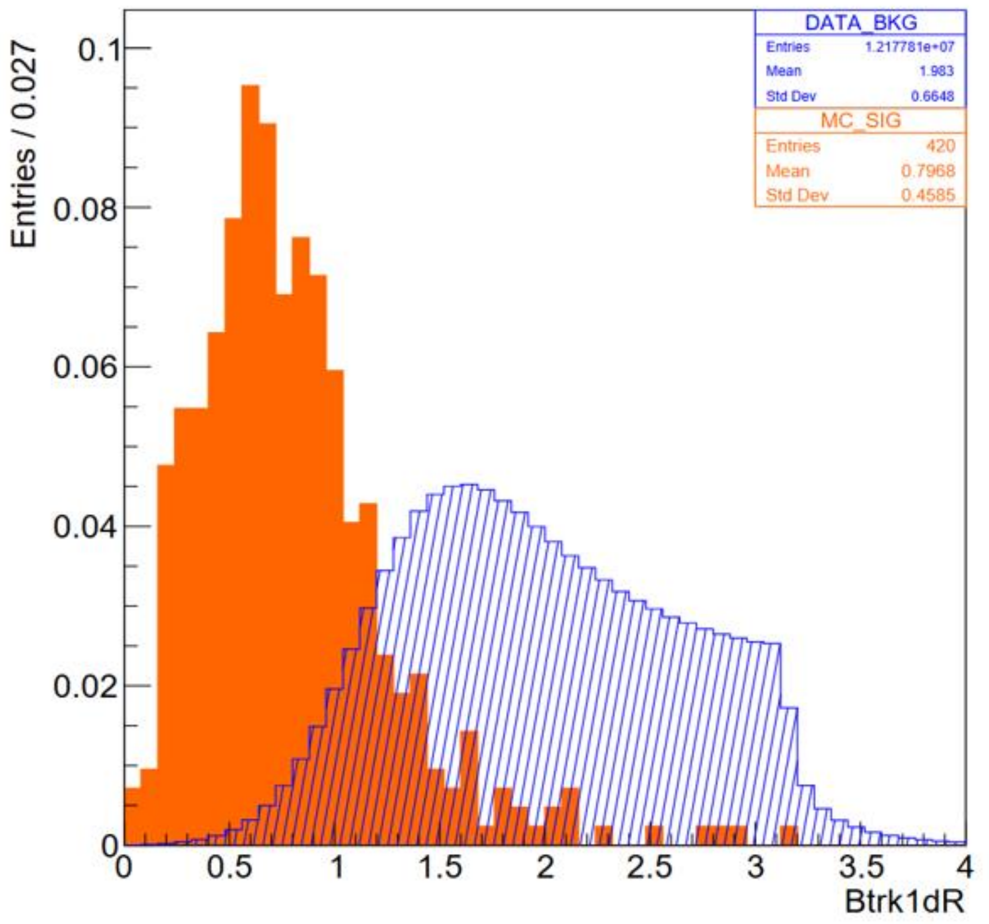




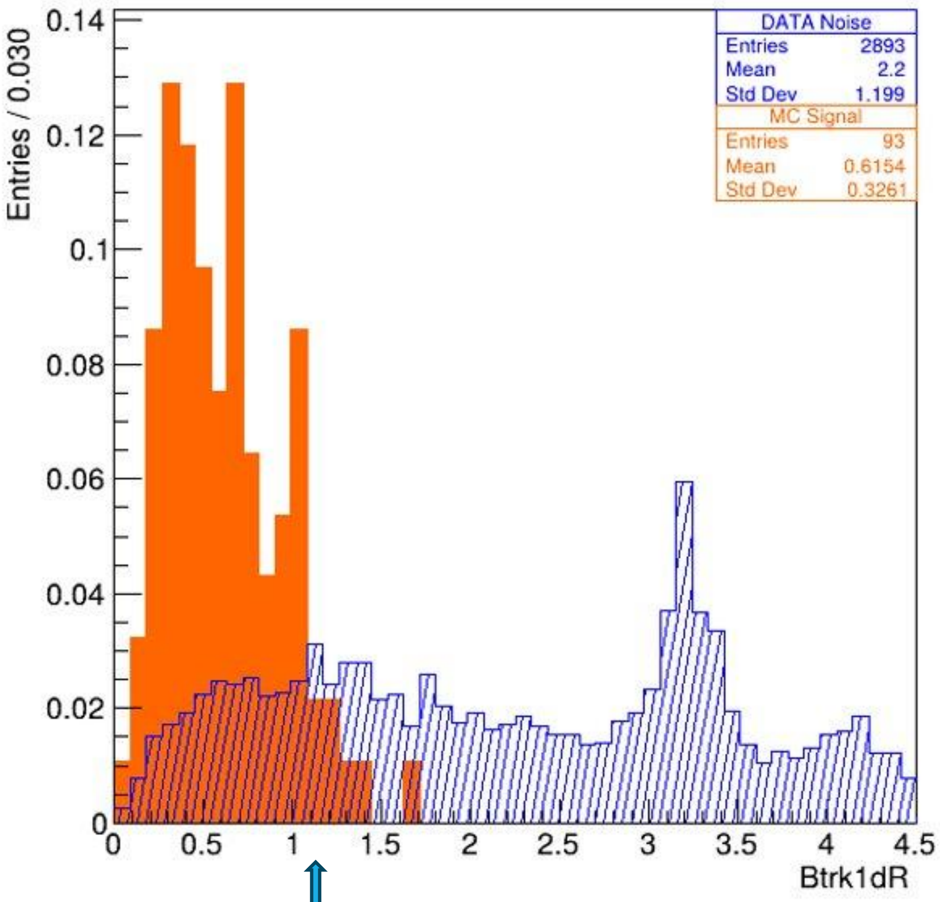
Max Significance = 24.6932
Best Cut: Btrk1dR<1.285

Second Cut (B+) (maximized significance)

Before any preliminary cuts



After the first cut : Balpha>0.008



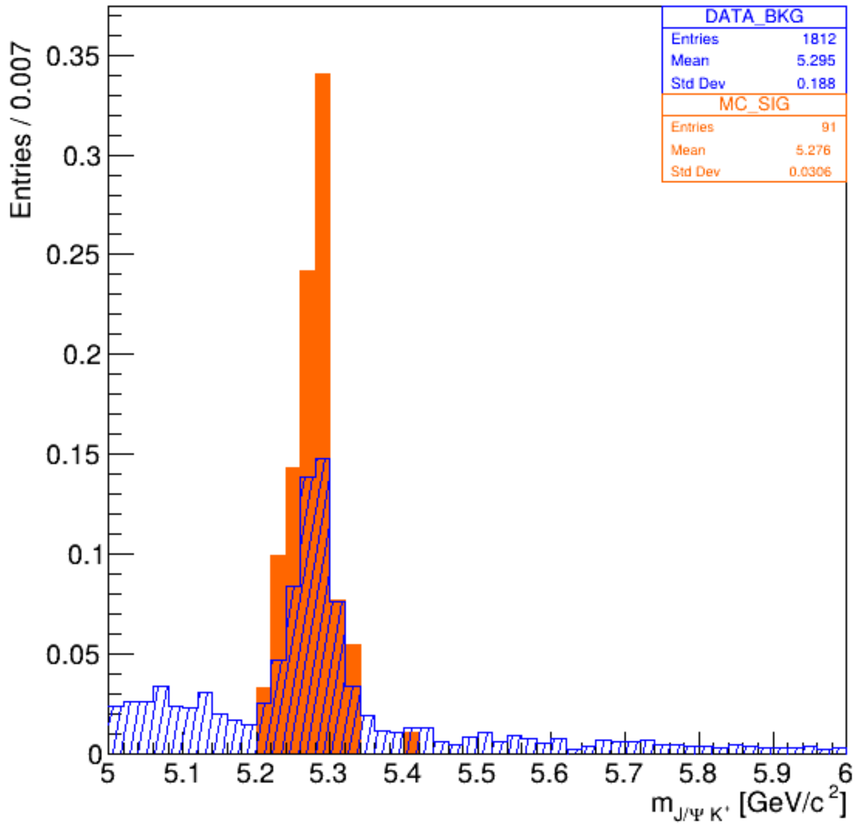
Optimized cut: Btrk1dR>1.285

DATA and Monte Carlo signal (B+)

After applying the cuts:

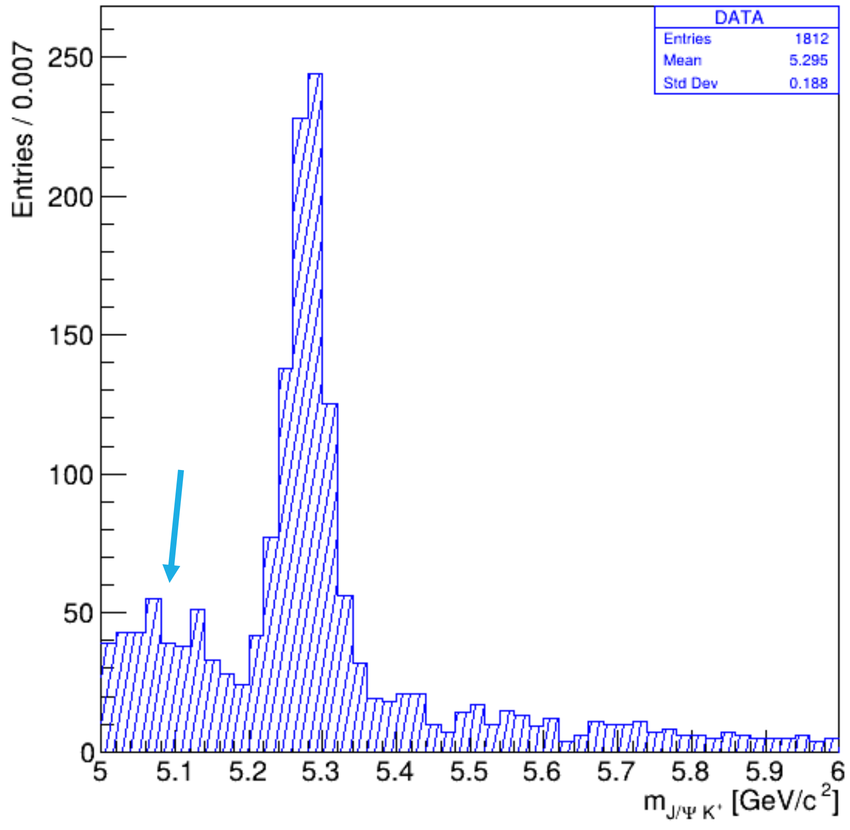
Balpha < 0.008

Btrk1dR < 1.285



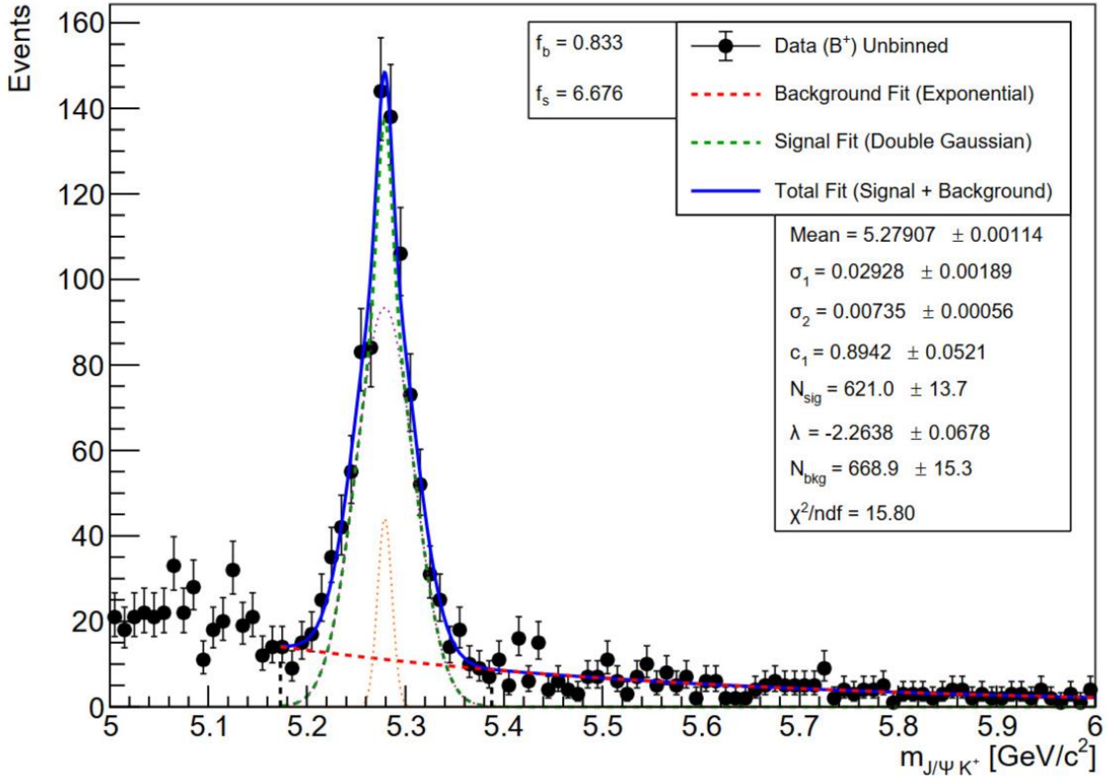
After both cuts not normalized

- Even though after treating the data we arrived at this result, this will not be the end of the B+ data analysis
- After the cuts it is still eas to see a aglomerate to the left of the peak



Unbinned fit to the data (B+)

Double Gaussian Sig +Exponencial BKG Model Extend MLM (Roofit)



Mass range considered:
[5.17501;6.00000]

$$\mathcal{L}_{background} = N_{bkg} \cdot e^{\lambda \cdot m}$$

$$\mathcal{L}_{signal} = N_{sig} \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

Muon & Track Selection ppRef

Muons

- **Soft muons:**
  - **normalized** $\chi^2 <= 1.8$
  - **Hits:**
    - tracker layers ≥ 6
    - pixel Layers ≥ 1
  - **Displacement from vertex:**
    - $dz < 35$
    - $dxy < 4$
- **Acceptance region:**
  - $pT \geq 3.5$ & $|\eta| < 1.2$
  - $pT \geq (5.47 - 1.89 \times |\eta|)$ & $1.2 \leq |\eta| < 2.1$
  - $pT \geq 1.5$ & $|\eta| < 2.4$
- **HLT matching:**
  - **Path:** "*HLT_PPRefL1DoubleMu0_v6* "
  - **Filter:** "*hltL1fL1sDoubleMu0L1Filtered0PPRef*"

Tracks

- **Quality:**
  - High purity tracks
  - $\sigma pT / pT < 0.1$
  - N_{hits} (pixel + tracker hits) ≥ 11
  - $\frac{\chi^2}{ndf} / N_{hits} > 0.18$
- **Acceptance:**
  - $pT > 0.5$
  - $|\eta| < 2.4$

Di-muon system

- Opposite muon charges
- Common vertex probability **> 1%**
- System's mass within $\mathbf{0.15}$ **GeV**$/\boldsymbol{C}$^$\mathbf{2}$ from $\boldsymbol{J/\Psi}$ **mass**

Expected Signal Loss (In Fiducial region)

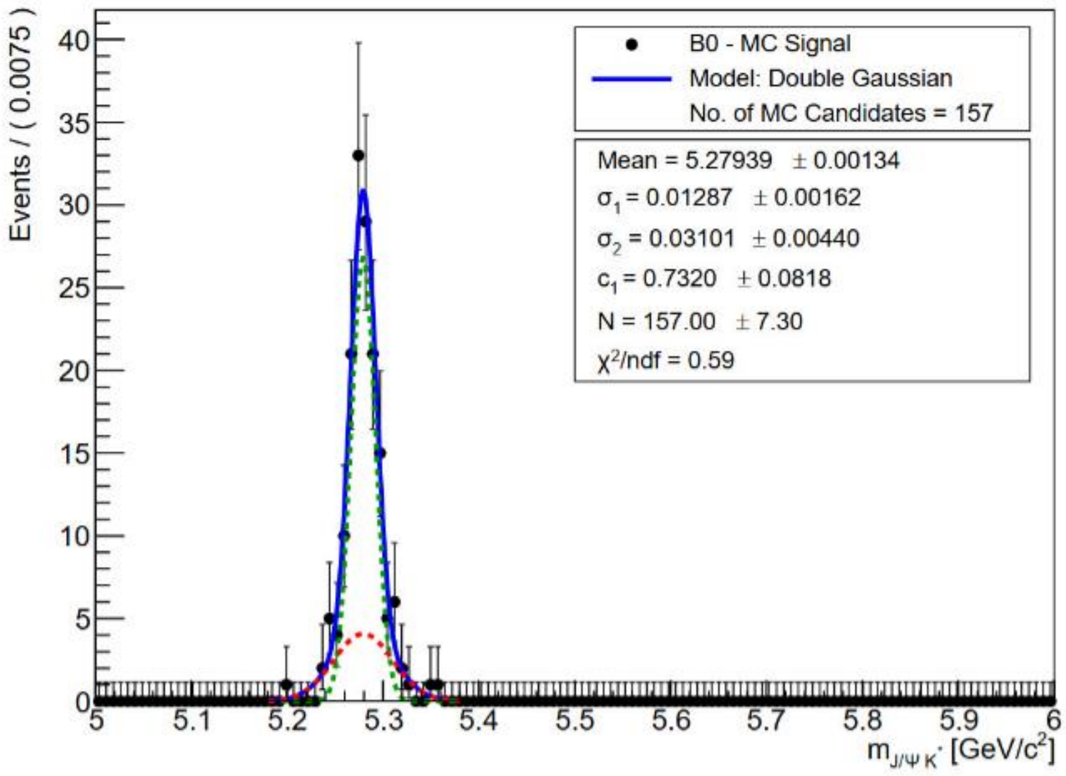
Preliminary efficiency study!

Bu (B+)	**nSignalEntries**	**Signal Loss (%)**
RAW	1661	Not Applicable
ACC	877	47.20
ACC+SEL	558	66.41
ACC+SEL+TRG	420	74.71
Base Selection + Balpha<0.008	93	94.40
Base Selection + Balpha<0.008+Btrk1dR<1.285	91	94.52
Bd (B0)	**nSignalEntries**	**Signal Loss (%)**
RAW	1833	Not Applicable
ACC	853	53.46
ACC+SEL	412	77.52
ACC+SEL+TRG	312	82.98
Bs (Bs)	**nSignalEntries**	**Signal Loss (%)**
RAW	301	Not Applicable
ACC	149	50.50
ACC+SEL	68	77.41
ACC+SEL+TRG	50	83.39

Curcial Study for later measuring of Inclusive Cross Section!

Fitting Monte Carlo signal (B0)

Double Gaussian Model (L) fitted through the Maximum Likelihood Method (ROOFIT)



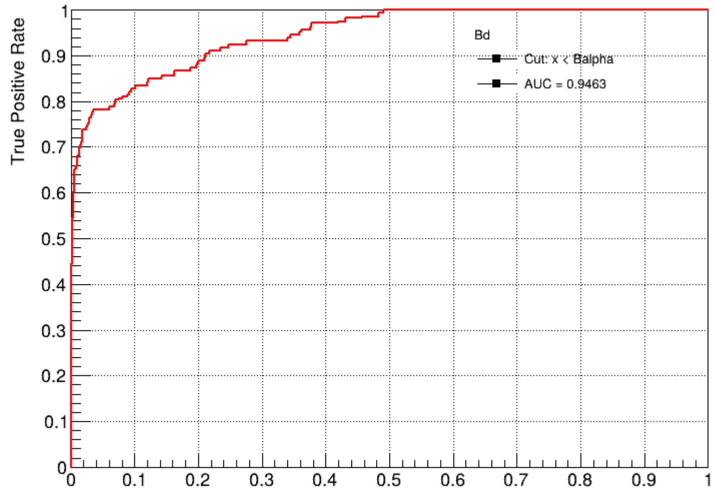
Define data noise region through sidebands:

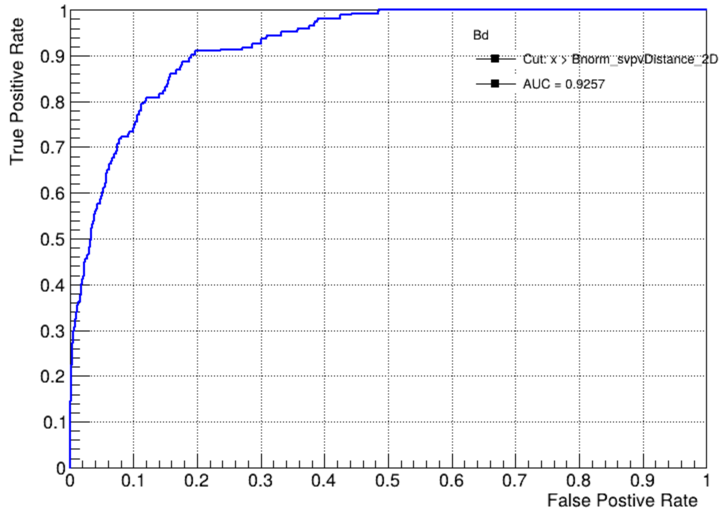
Using 3σ from the wider gaussian in MC fit to avoid cutting signal.

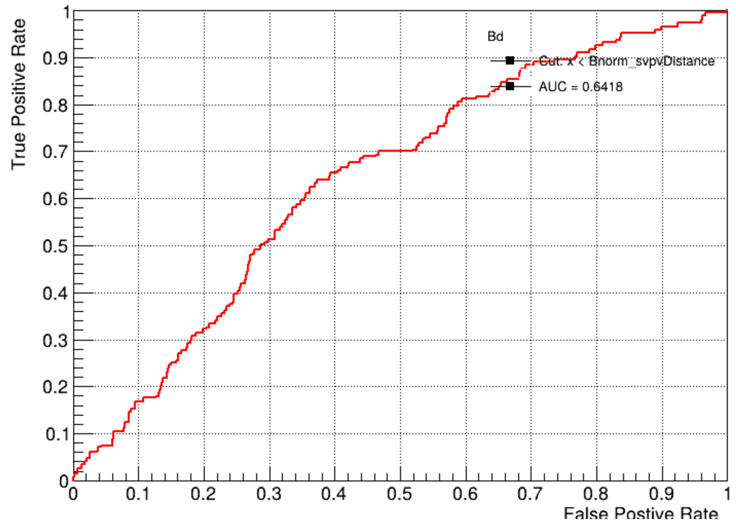
- Left sideband: [5.00000 ; 5.18636] GeV/c^2
- Right sideband: [5.37242 ; 6.00000] GeV/c^2

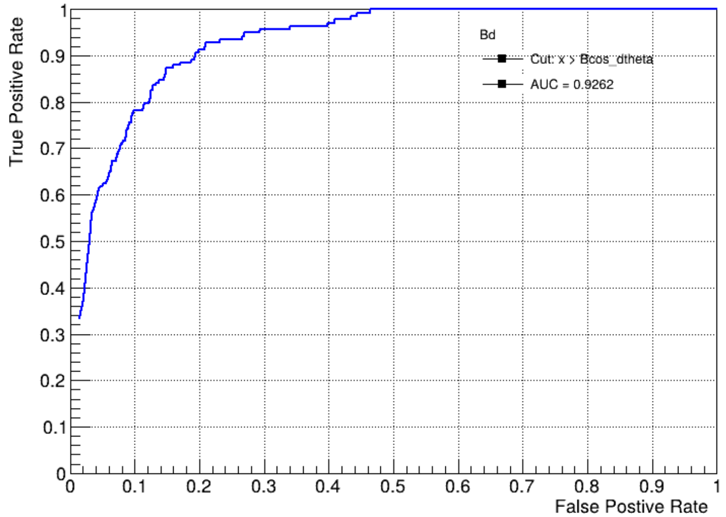
$$\mathscr{L} = N \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

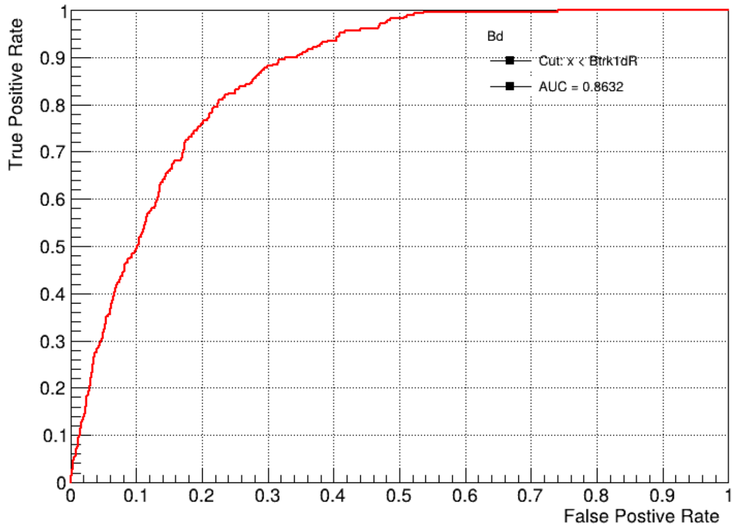
ROC Curves (B0)

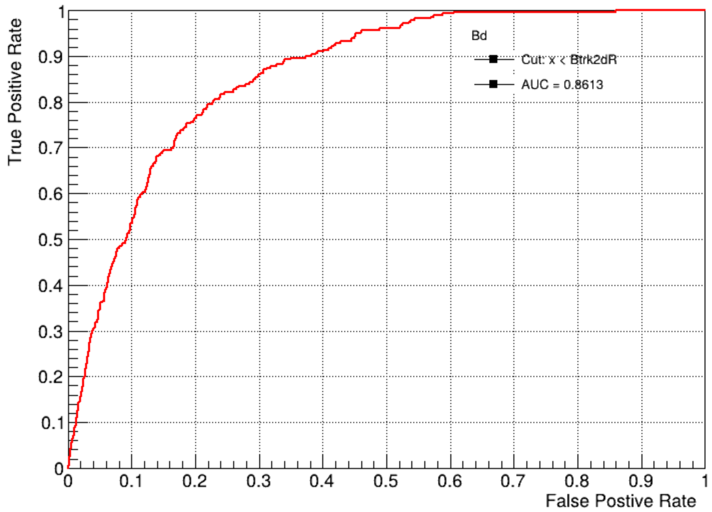






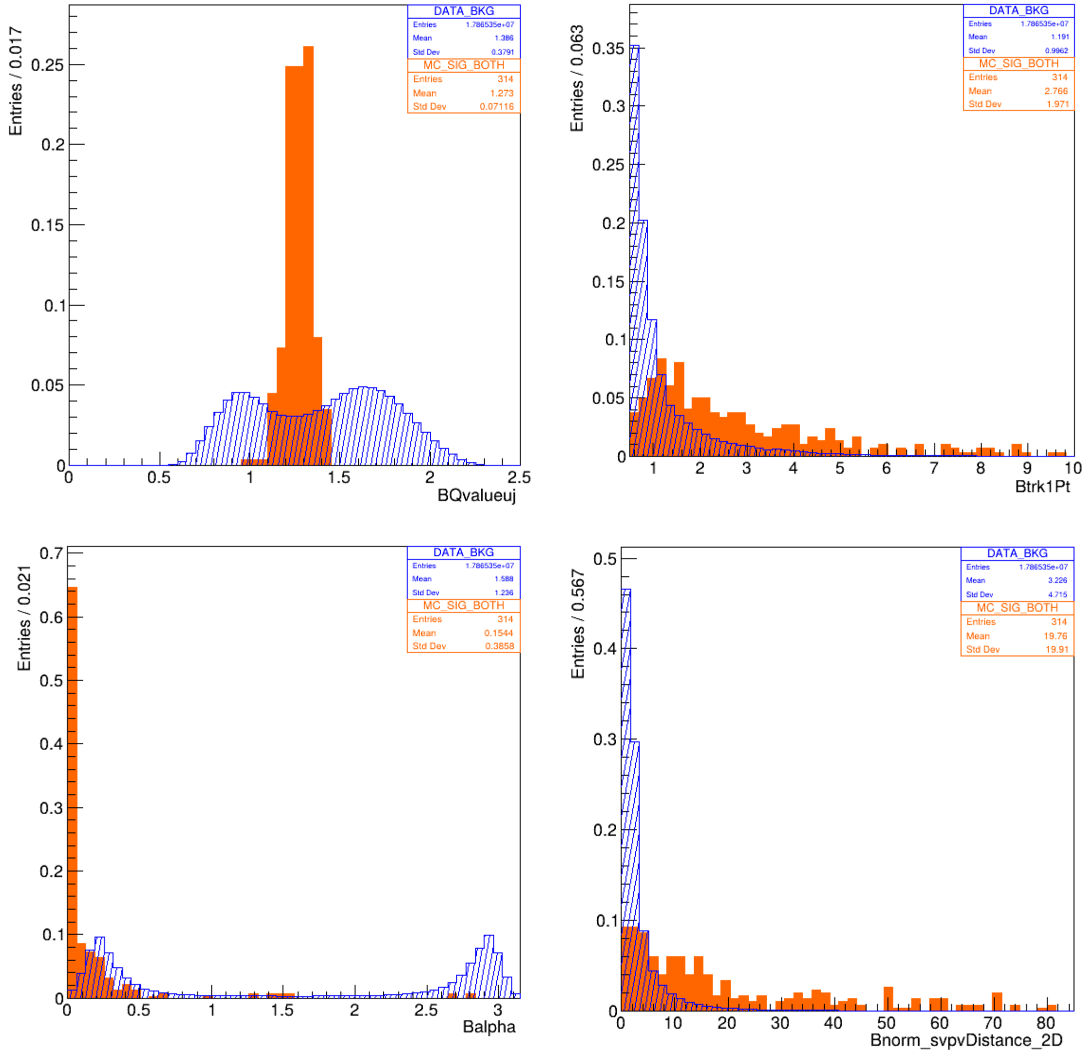




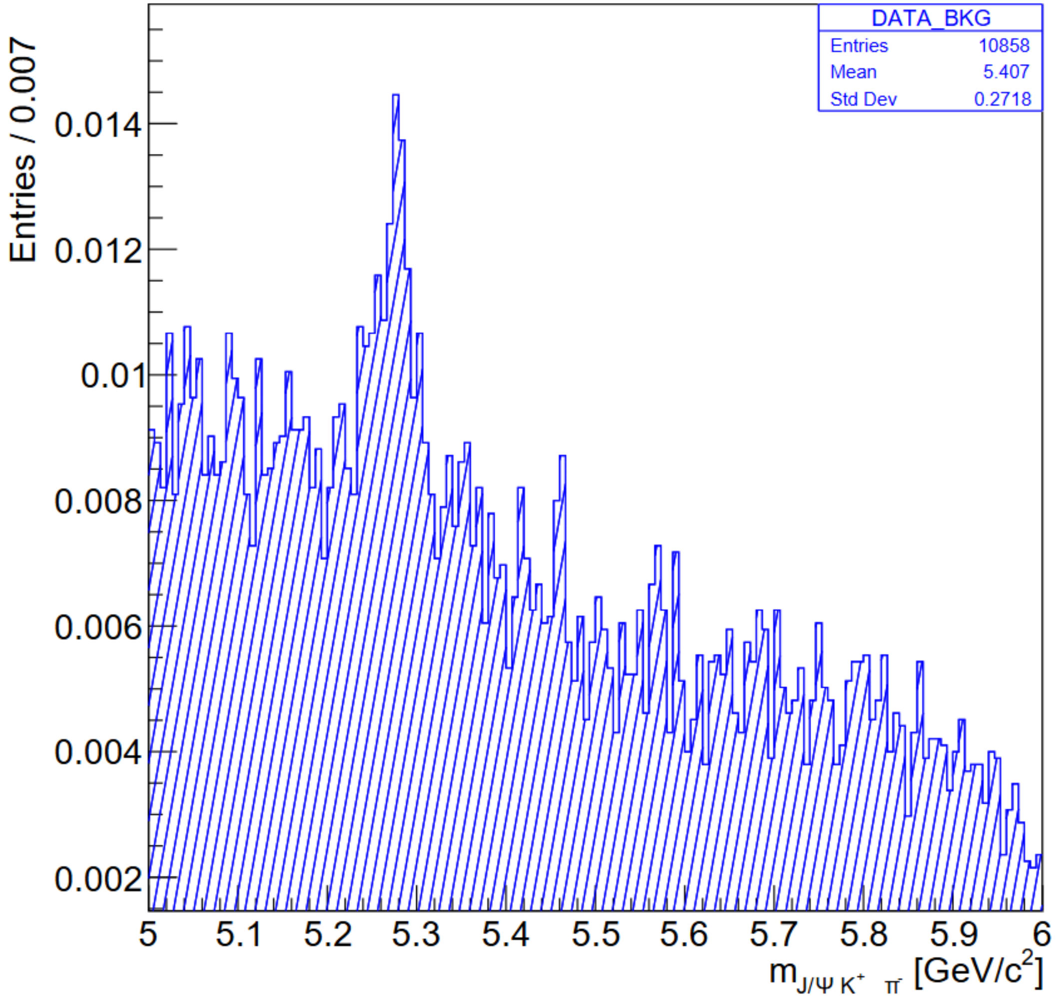


FIRST CUT (B0)

Discriminat variables before cut

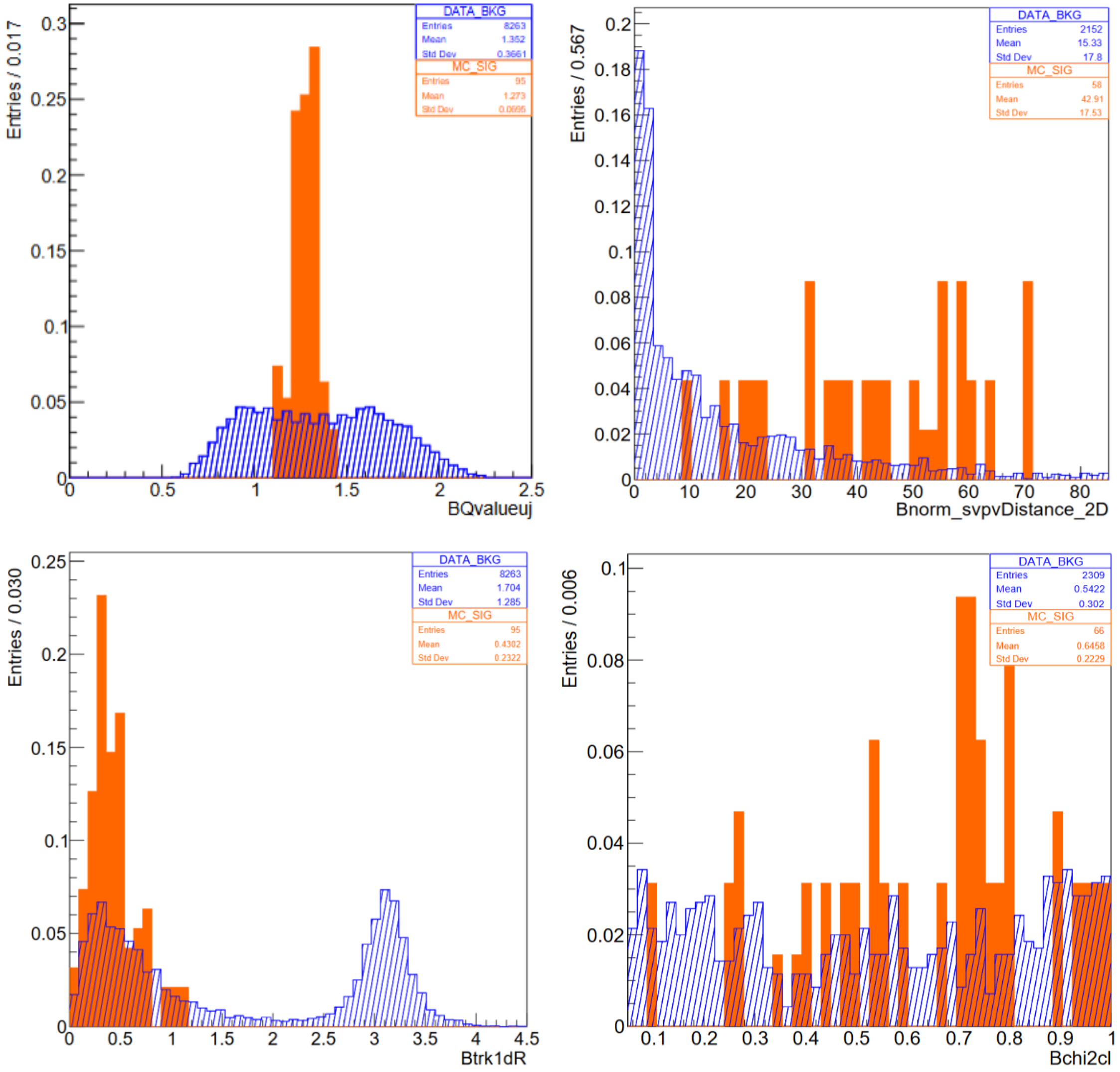


First cut: Balpha<0.01



SECOND CUT (B0)

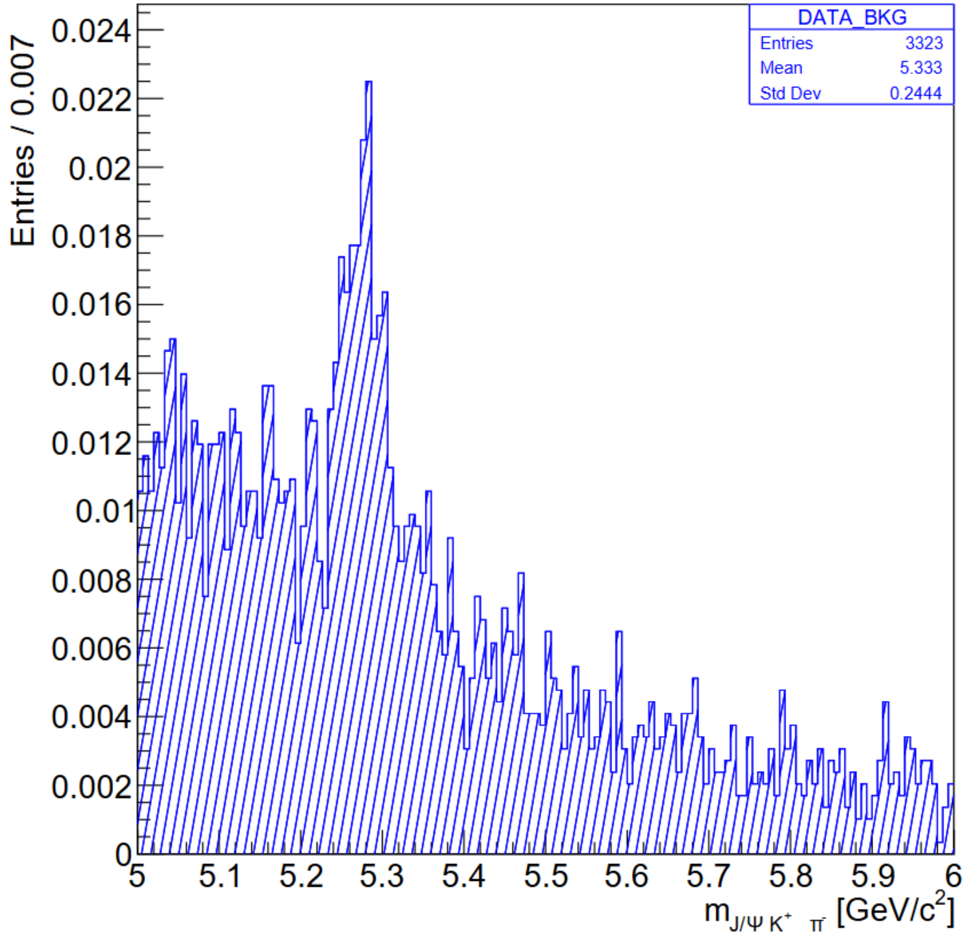
Discriminat variables after first



Second cut:

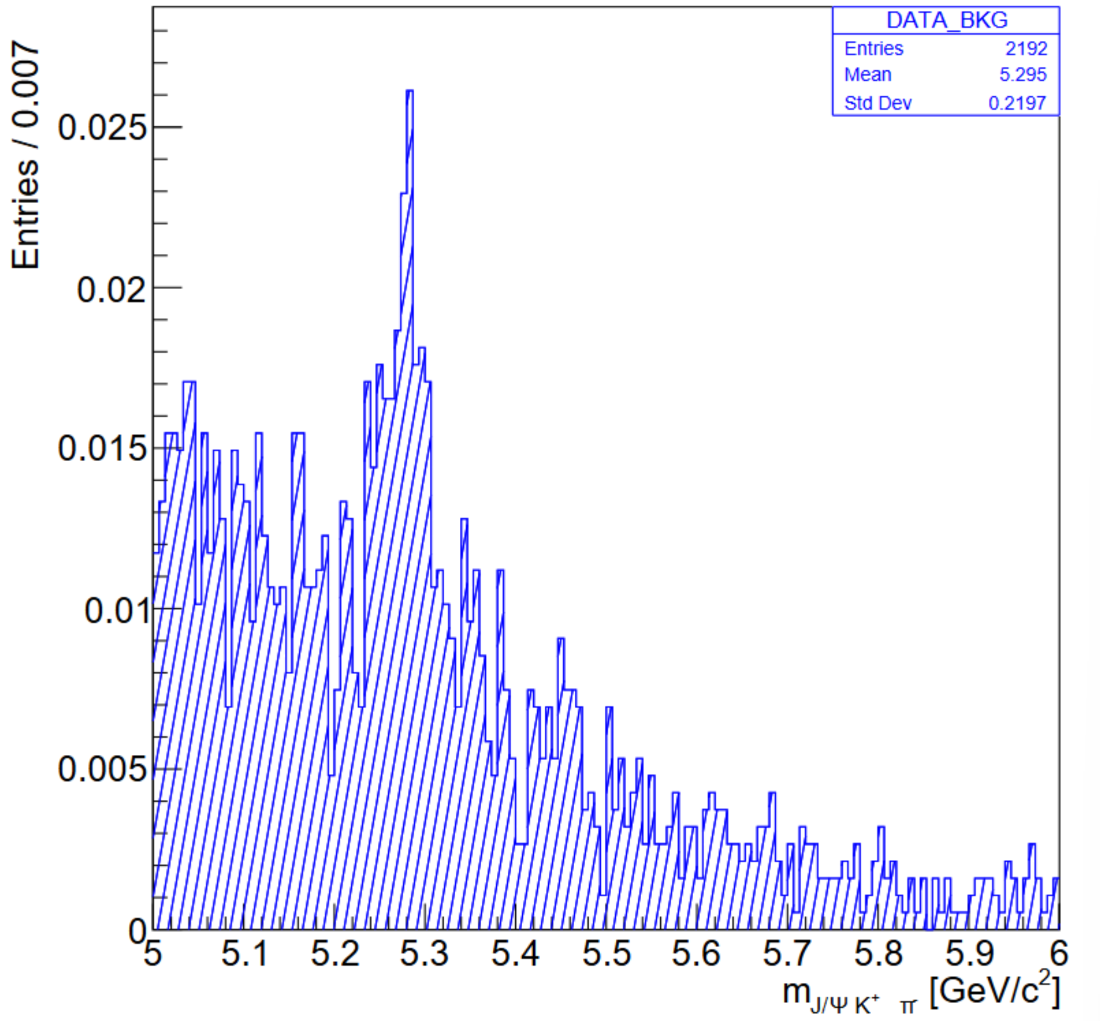
Bnorm_svpvDistance_2D>16

Bnorm_svpvDistance_2D<72



DATA READY TO FIT

Third cut: Btrk2dr<0.6



<u>Data Bmass sample after the cuts:</u>

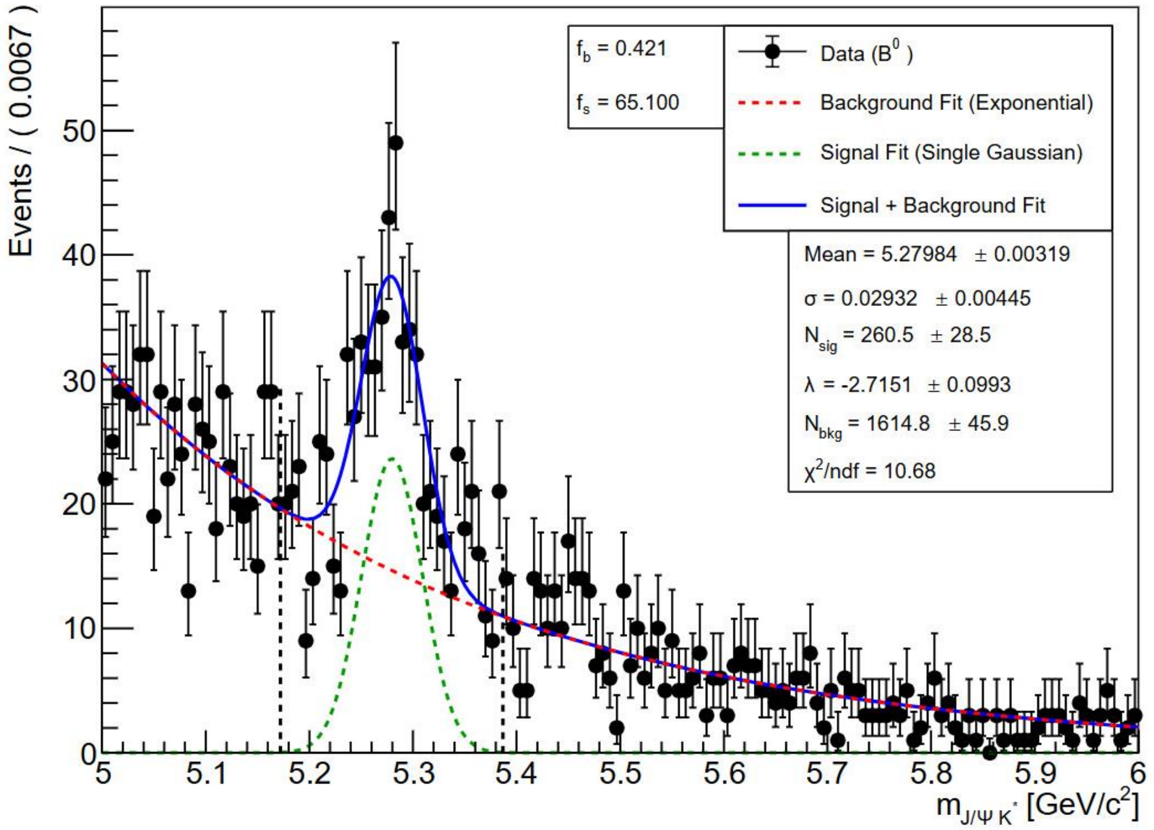
Balpha < 0.01

Bnorm_svpvDistance_2D]16; 72[

Btrk2dR < 0.6

Fitting B0 Data

Double Gaussian Model (L) fitted through the Maximum Likelyhood Method (ROOFIT)



$$\mathscr{L}_{background} = N_{bkg} \cdot e^{\lambda \cdot m}$$

- Left sideband: [5.00000 ; 5.18636] GeV/c^2
- Right sideband: [5.37242 ; 6.00000] GeV/c^2

$$\mathscr{L}_{signal} = N_{sig} \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

Summary

- Conducted selection study for: B+, B0
  - Feature comparison signal (MC) vs background (sideband)
- Single variable optimization, maximizing figure of merit (statistical significance)
- Fits to both data and simulation

Next steps

- pp collision study (ongoing)
    - feature correlations
    - multivariable analysis (machine learning)
    - perform unbinned fits to the selected samples
- PbPb collision analysis (next)
    - Search for the signals (B+,B0) in the more challenging PbPb environment!