Investigating the Flavour Anomalies with Machine Learning at LHC

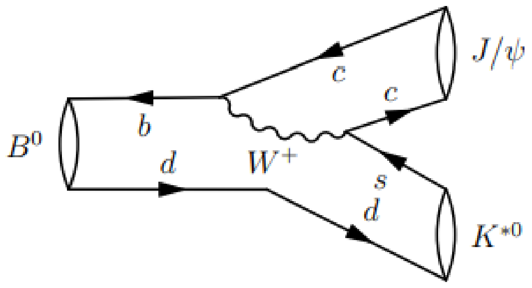
João Bernardo, Madalena Blanc | Alessio Boletti, Nuno Leonardo

LIP Internship Program Workshop, 8/9/2023

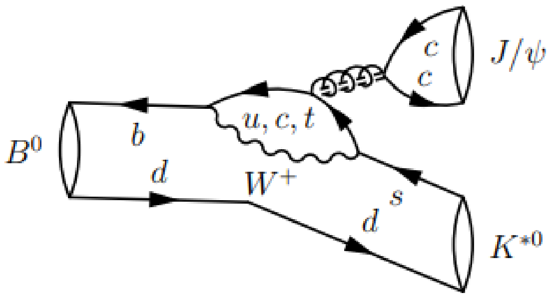
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Physics Process: B^0 meson decay to $K^+ \pi^- \mu^+ \mu^-$

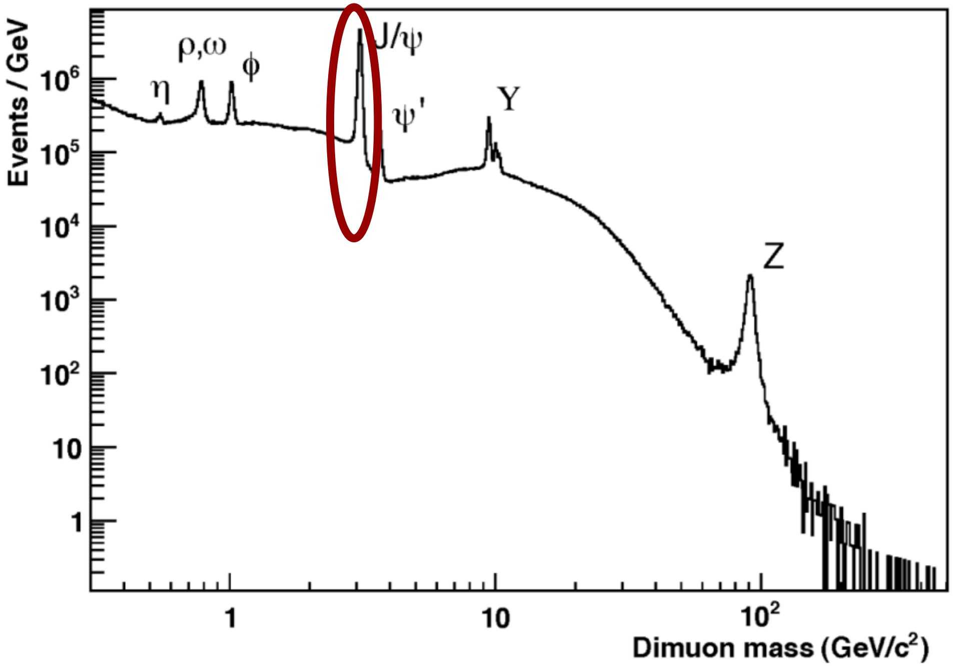
$B^0 \rightarrow K^{*0} J/\Psi \rightarrow K^+\pi^- \mu^+\mu^-$ [resonant channel]



(a) Tree



(b) Penguin



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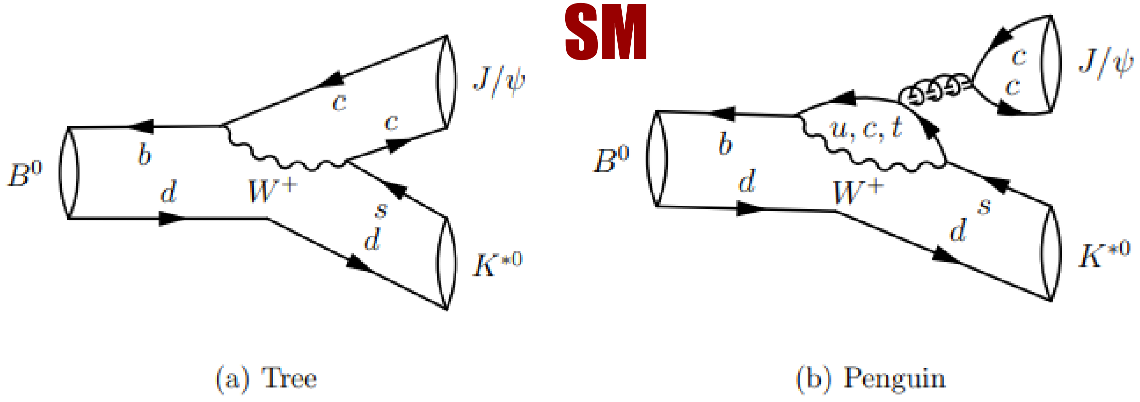

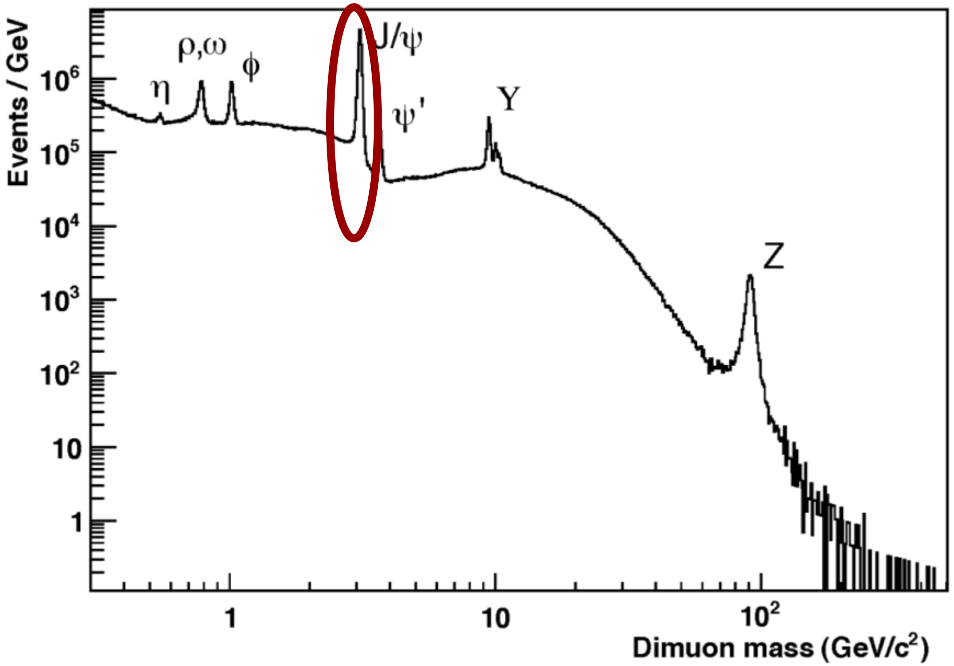

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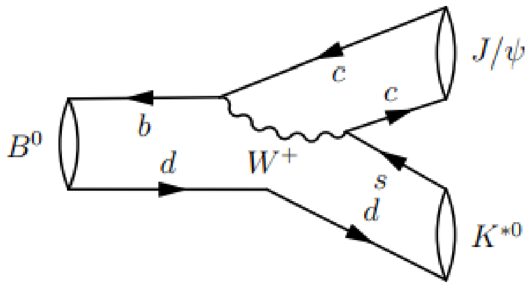

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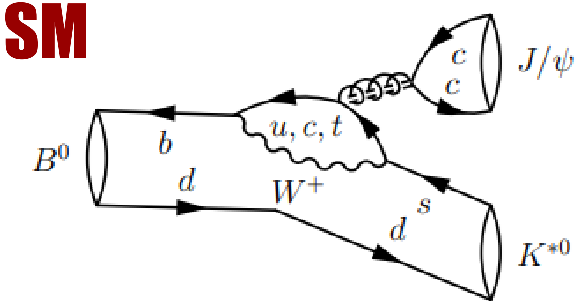

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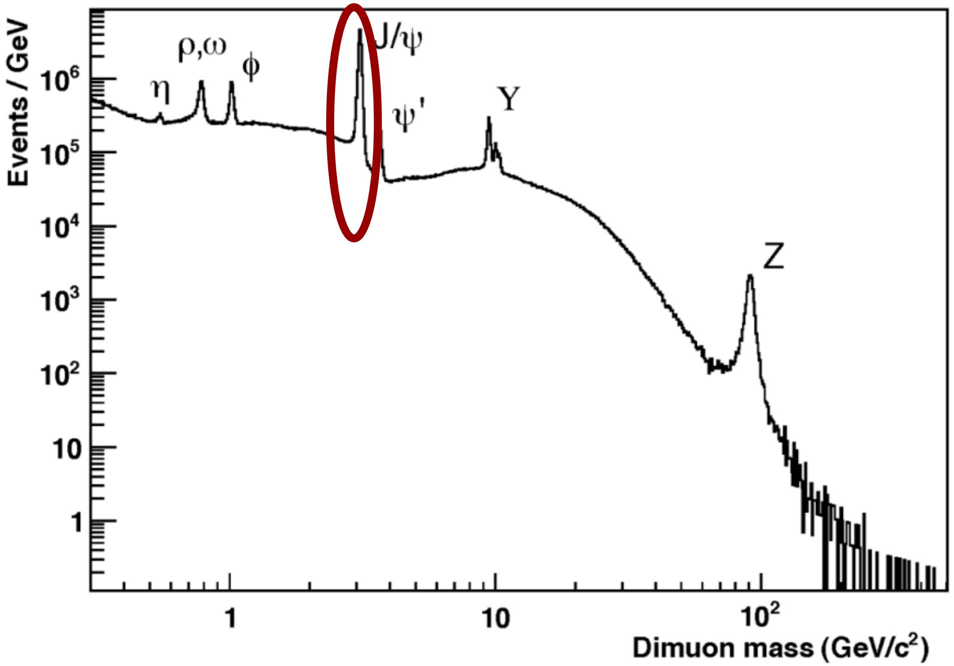
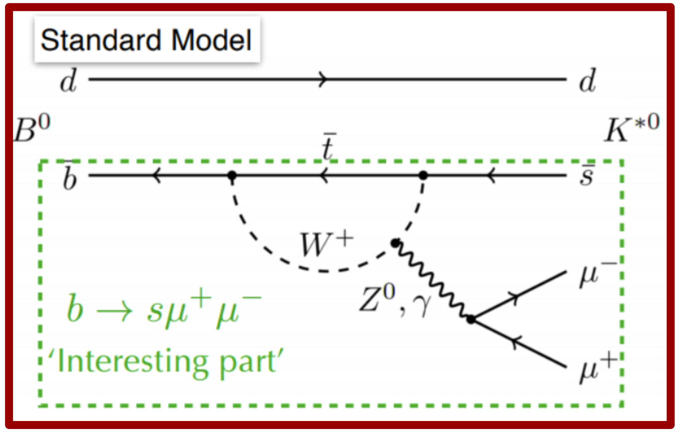


$B^0 \rightarrow K^{*0} \mu^+\mu^- \rightarrow K^+\pi^- \mu^+\mu^-$ [non-resonant channel]



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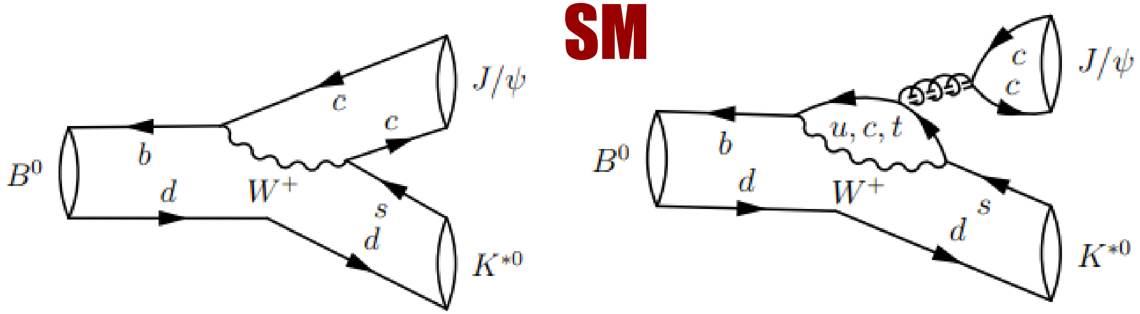

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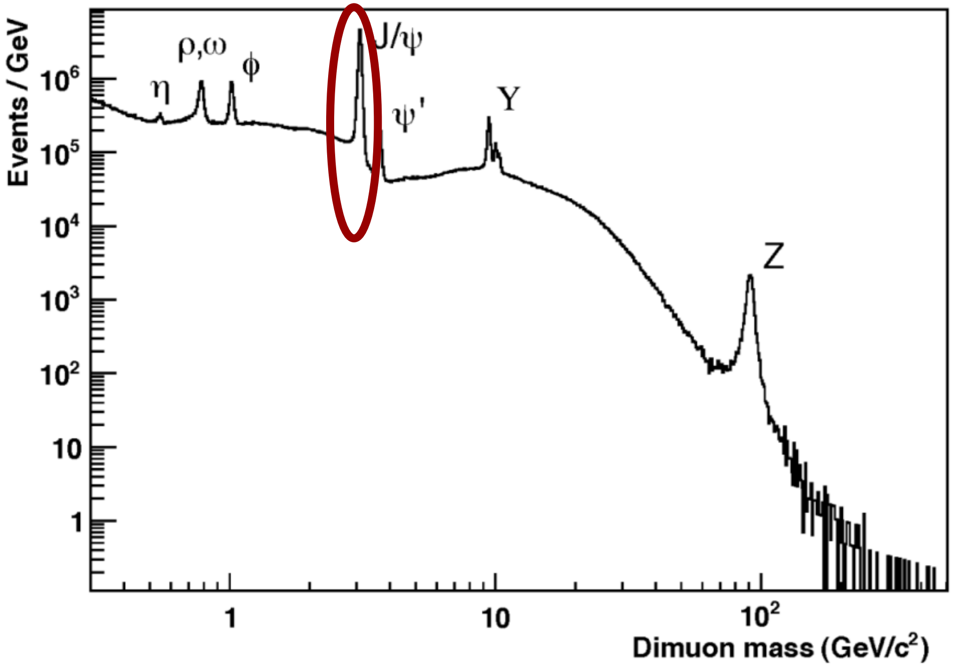

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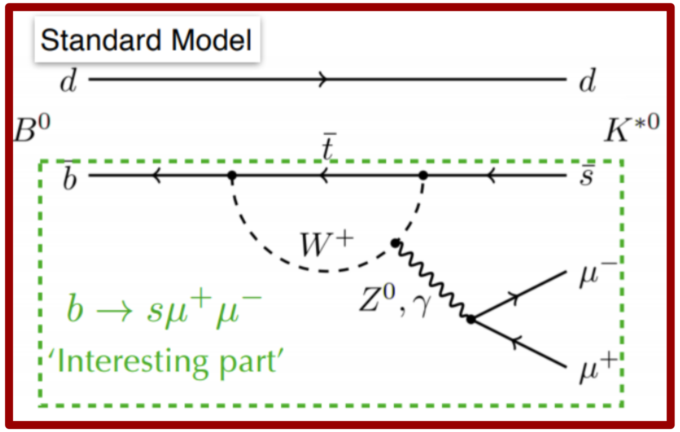
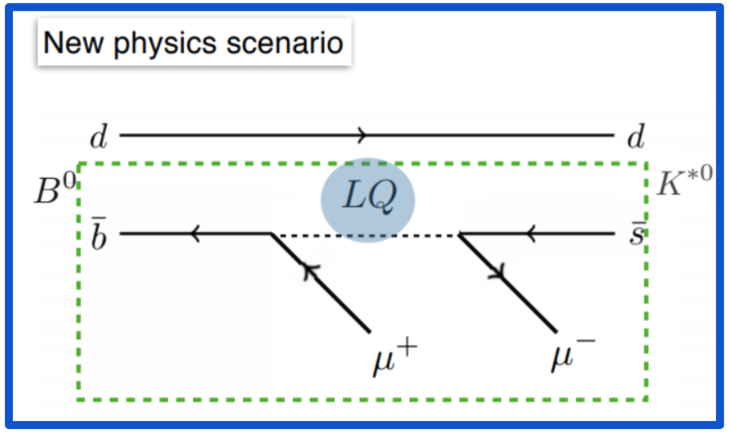
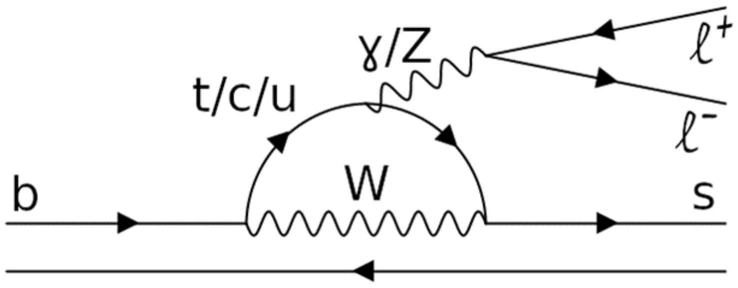




Flavour Anomalies (b→sll)

$$\frac{1}{\mathcal{B}(B\to KJ/\psi)}\frac{d\mathcal{B}(B\to K\mu\mu)}{dq^2}$$



SM: Loop-level

[arXiv:2206.03797]

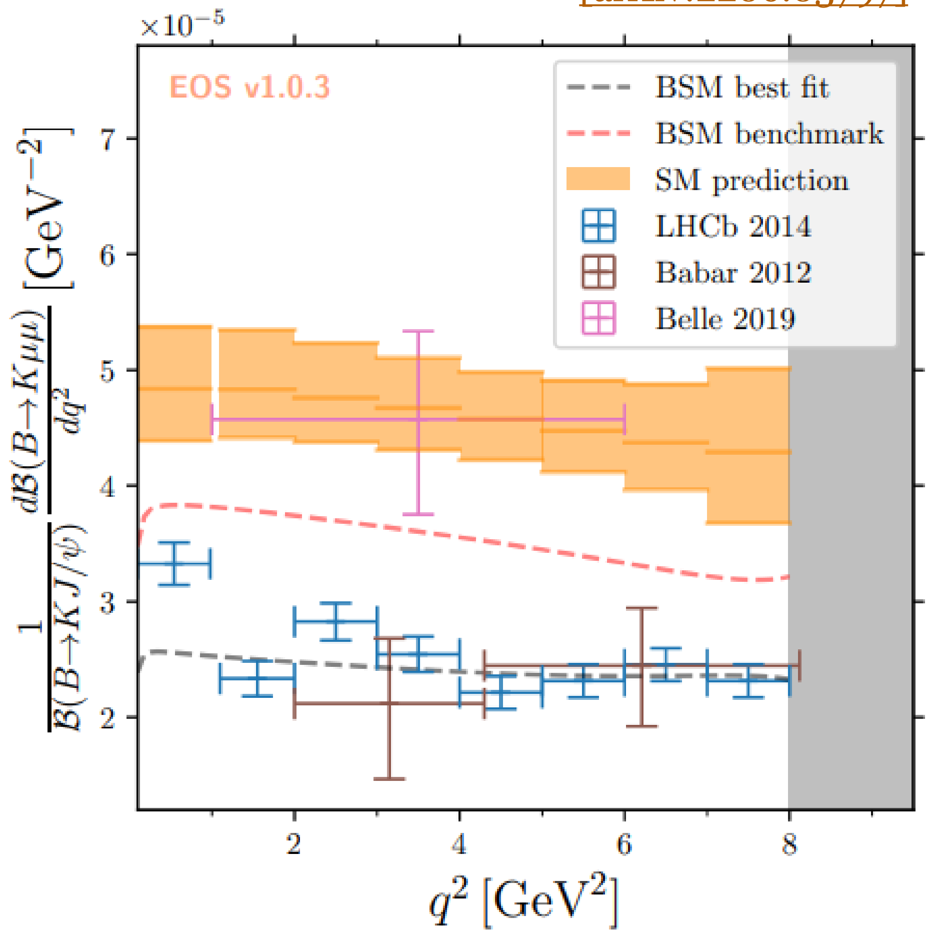


Fig.1: Substantial tensions between the SM predictions and the available experimental data.

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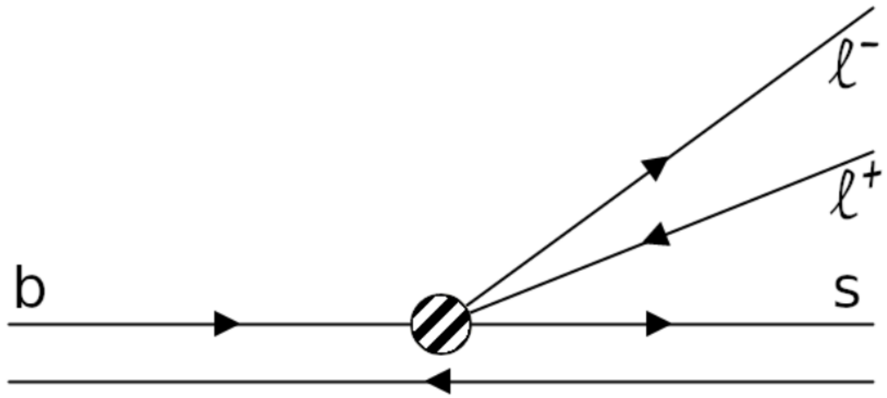

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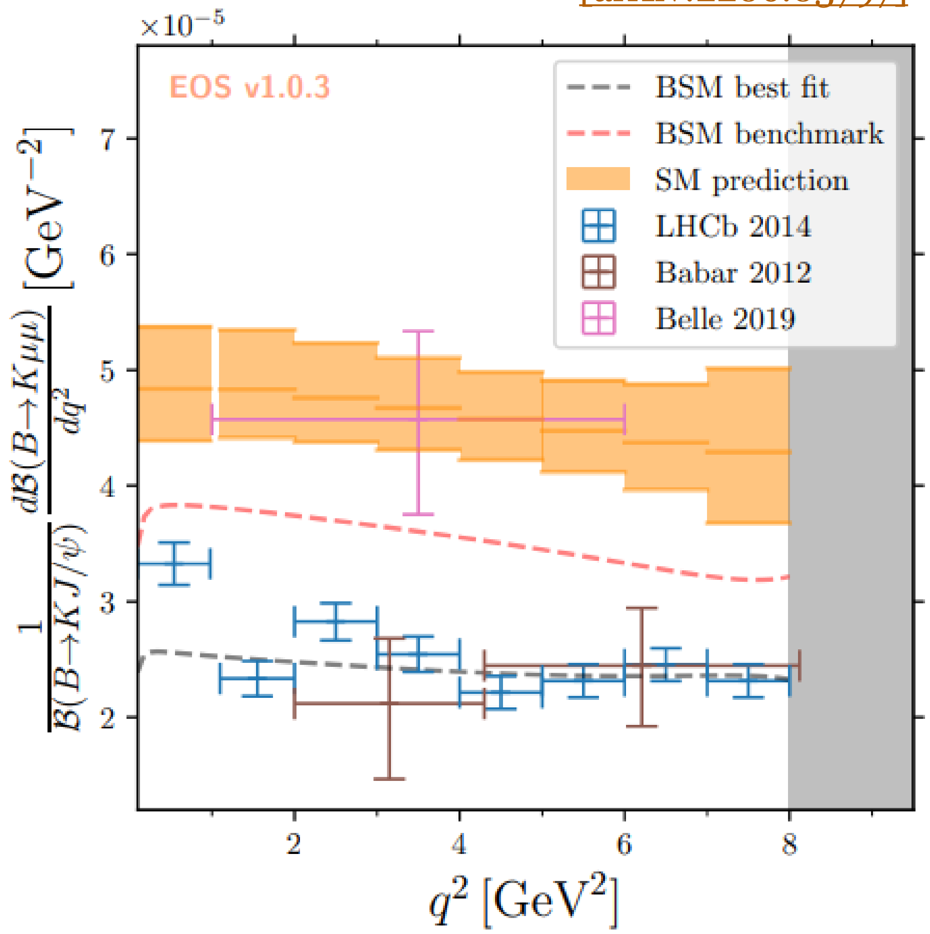

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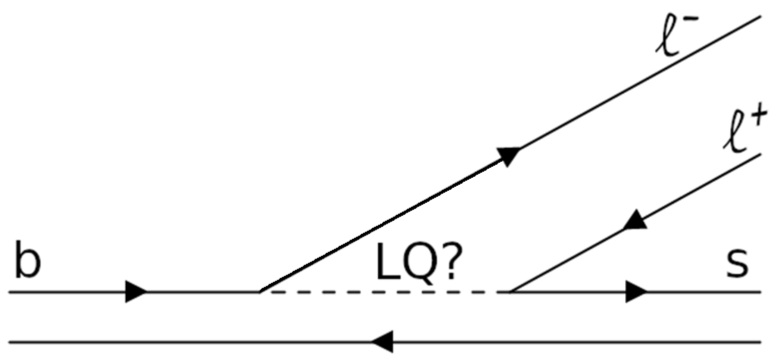

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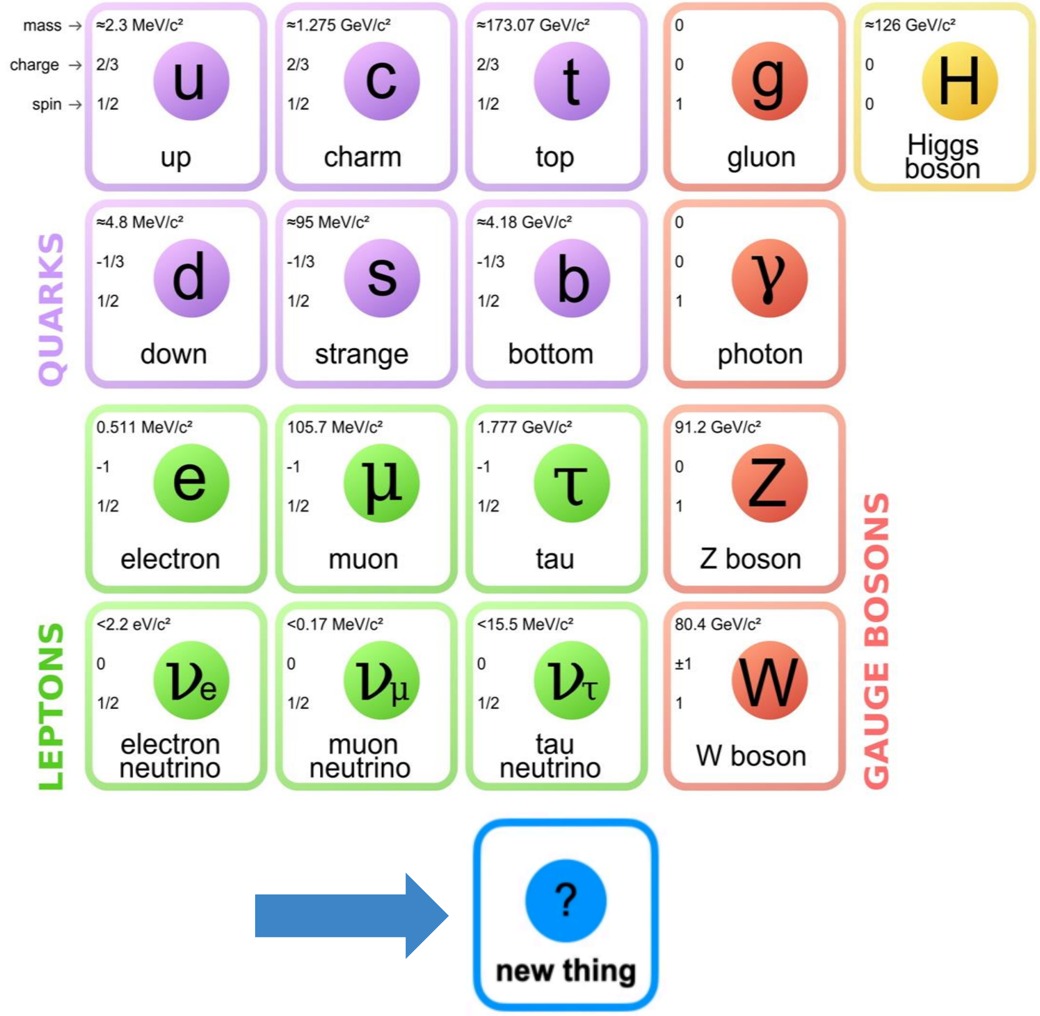
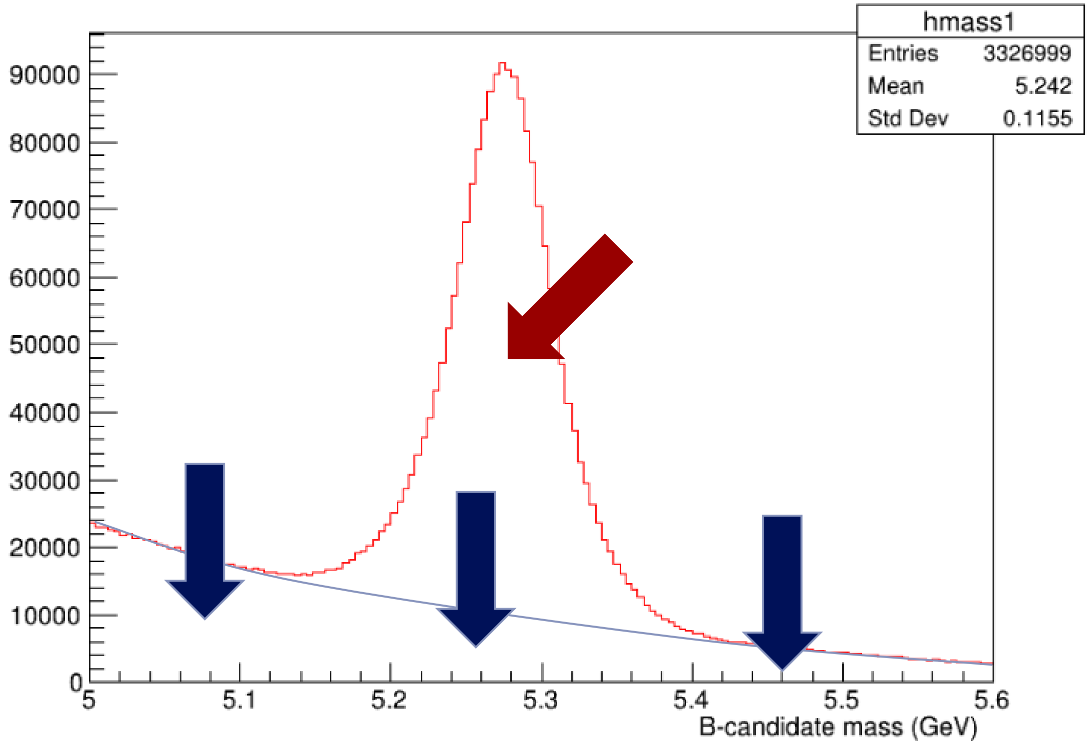


Project Goal: $B^0 \rightarrow K^{*0}\, J/\Psi \rightarrow K^{+}\pi^{-}\, \mu^{+}\mu^{-}$

Apply Single and Multivariate Analysis to discriminate signal from background

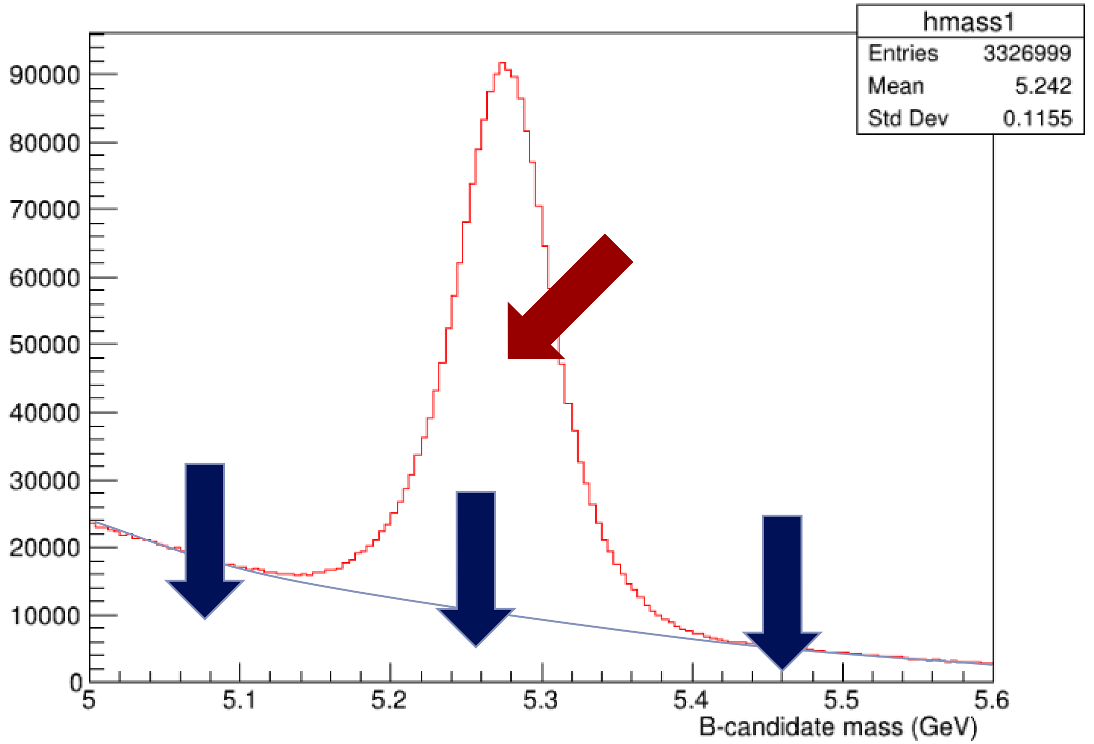


Signal: final state particles coming from the B^0-meson

Background: final state particles coming from other processes

Project Goal: $B^0 \to K^{*0}\, J/\Psi \to K^+\pi^-\, \mu^+\mu^-$

Apply Single and Multivariate Analysis to discriminate signal from background



$m(K^+\pi^-\mu^+\mu^-)$ (GeV)

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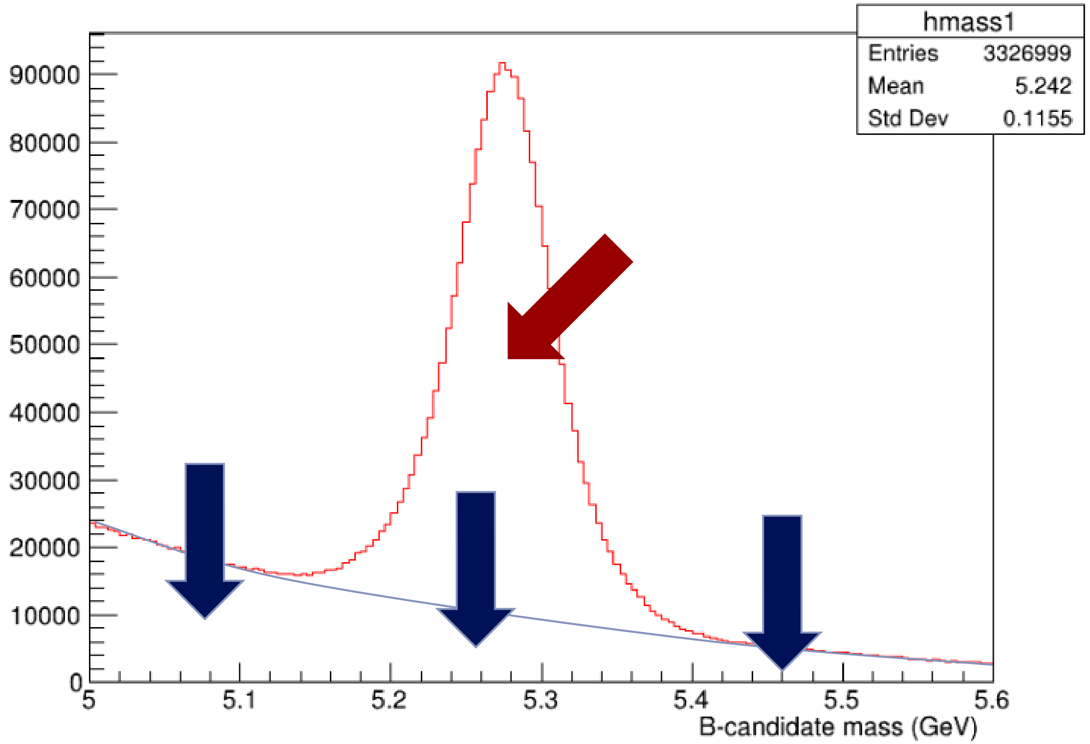


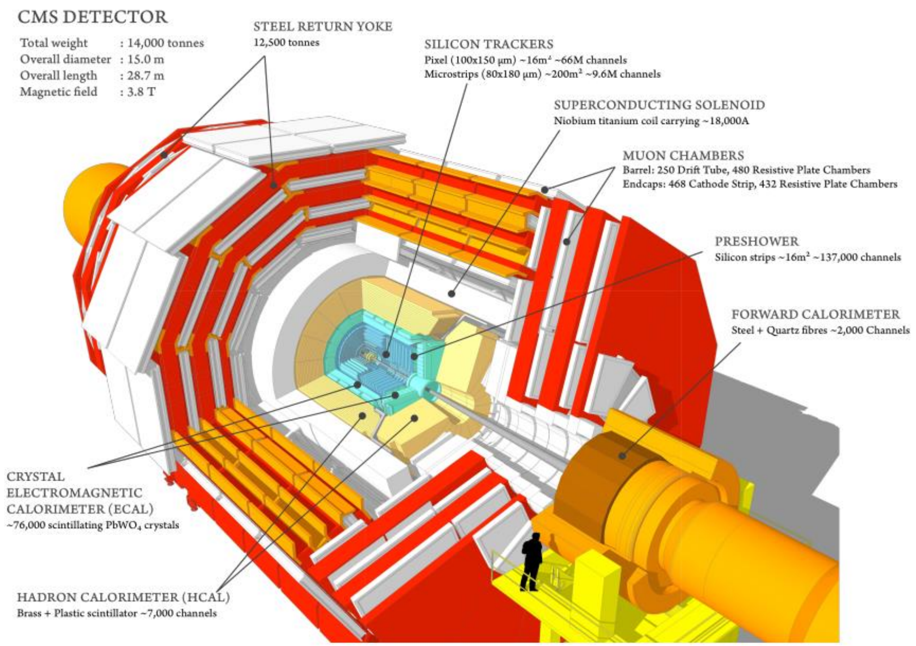
$m(K^+\pi^-\mu^+\mu^-)$ (GeV)

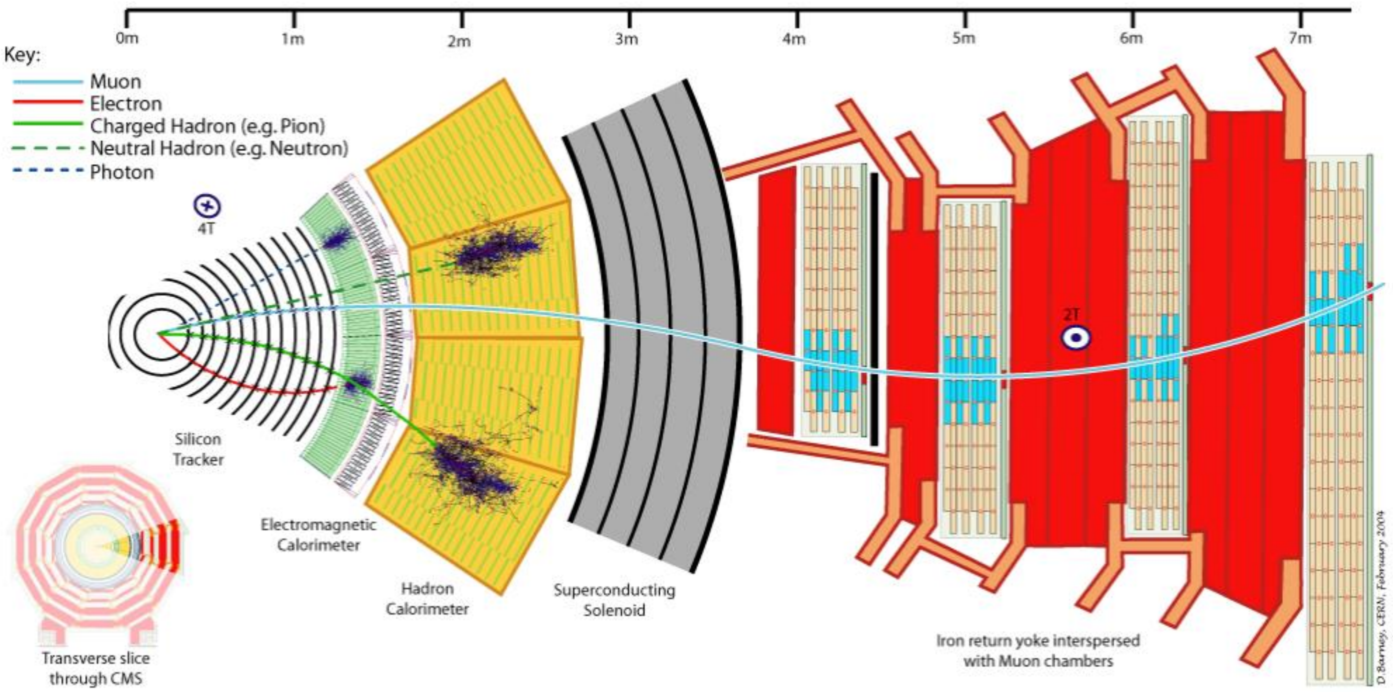
Compare the performance

and the figure of merit

$$FOM = \frac{S}{\sqrt{S+B}}$$

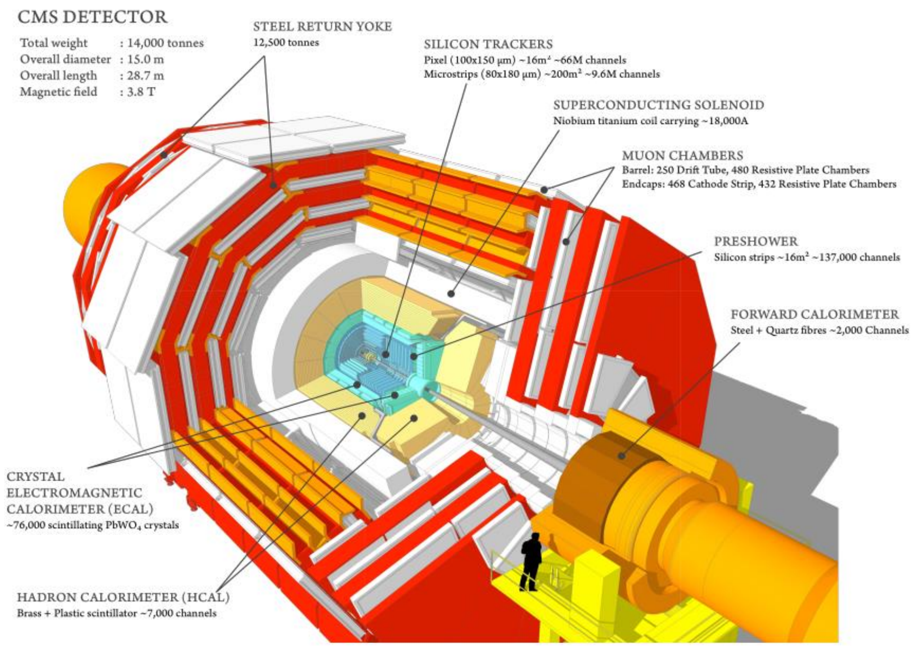
CMS Detector

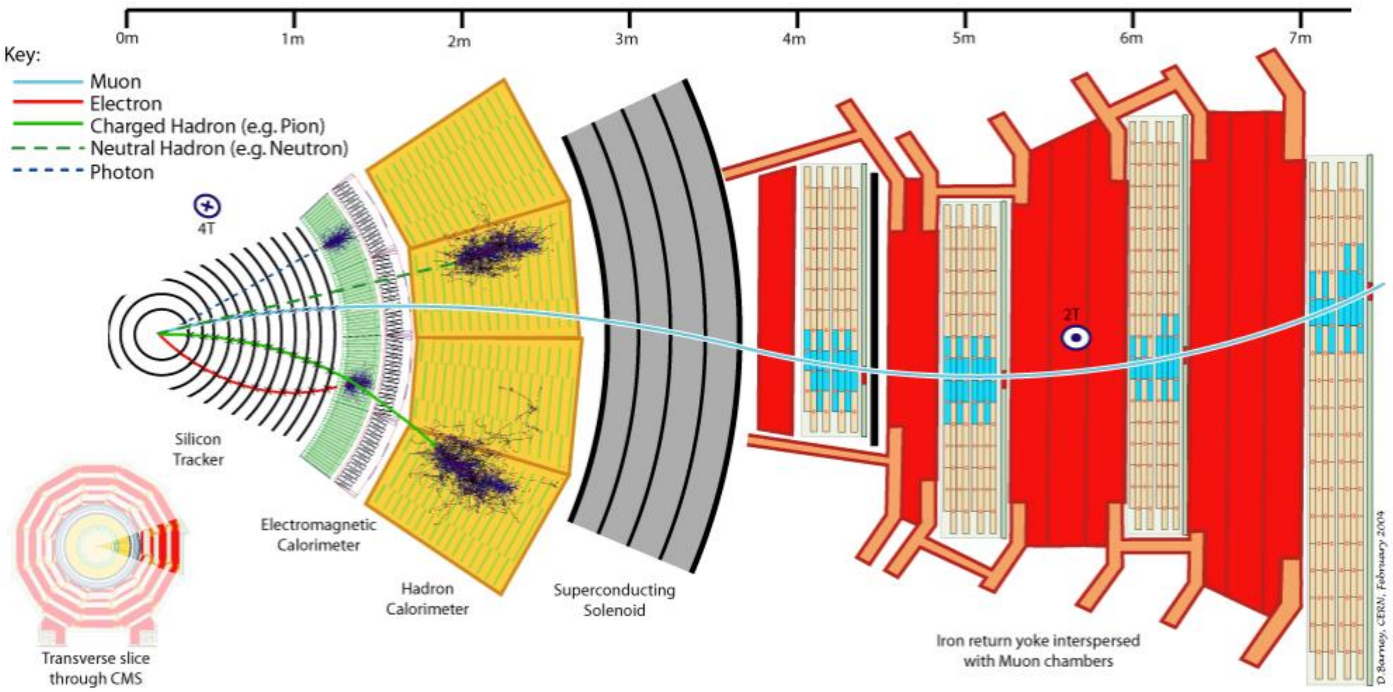




- Silicon Trackers
- ECAL
- HCAL
- Muon Chambers

CMS Detector





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$B^0 \rightarrow K^{*0}\, J/\Psi \rightarrow K^+\pi^-\, \mu^+\mu^-$

- Silicon Trackers
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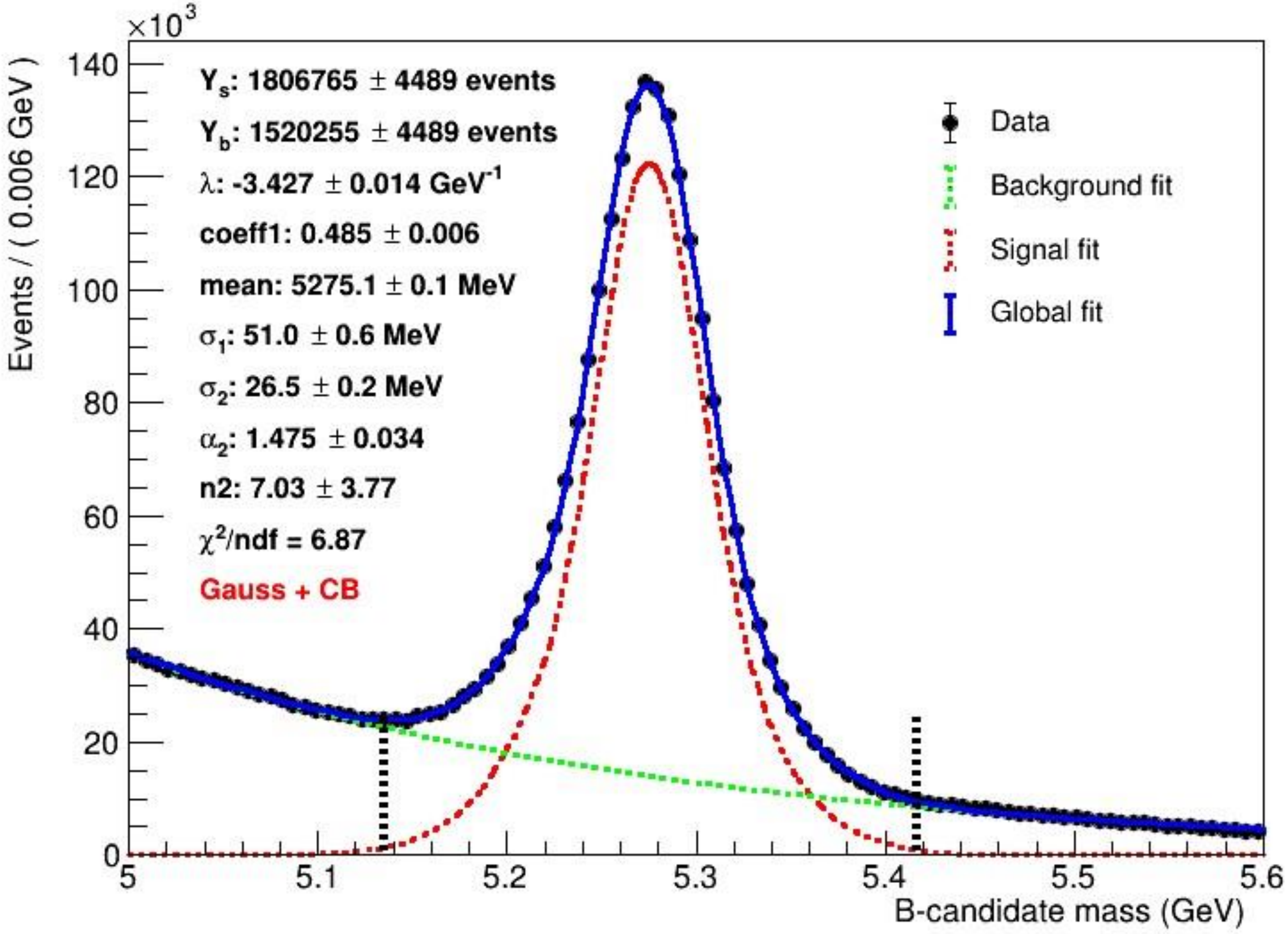
$B^0 \rightarrow K^{*0}\ J/\Psi$ (dimuon triggers)



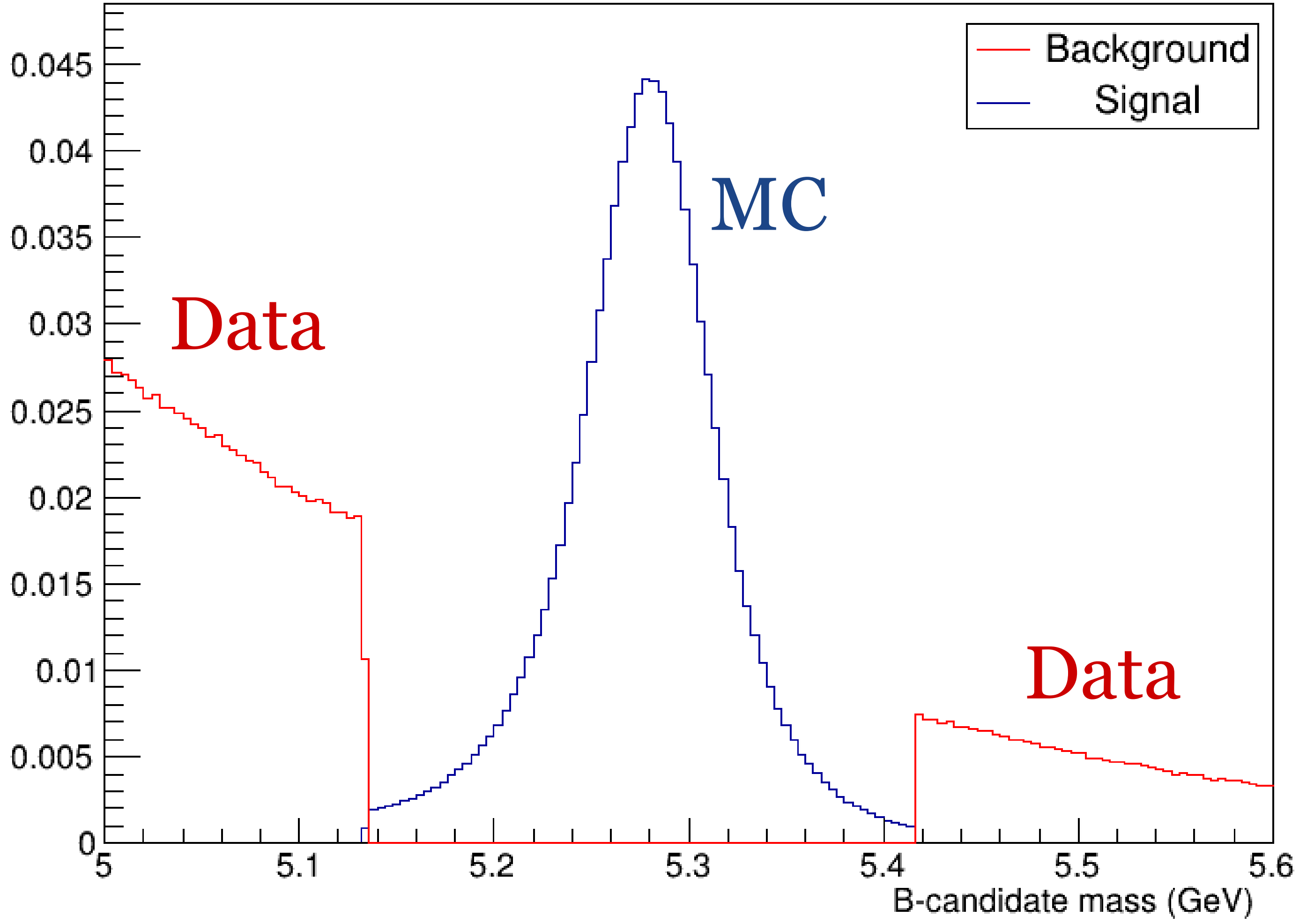
Binned Likelihood Fit

Signal PDF:
Gaussian + Crystal Ball: $\mathcal{P}_S$
Background PDF:
Exponential: $\mathcal{P}_B$

$$\mathcal{P}_G = Y_S\, \mathcal{P}_S + Y_B\, \mathcal{P}_B$$

Right and left sideband edges correspond to a 3.5σ:
less than 0.3% signal contamination

Signal/Background samples for ML training



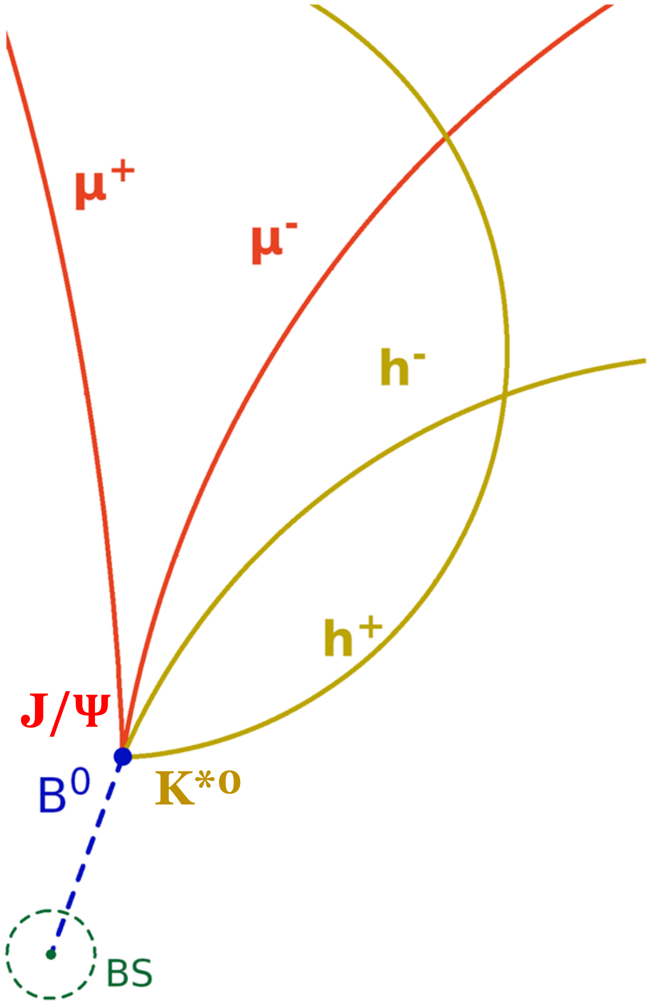
Background:
Left and right sidebands of the data sample ($B^0 \rightarrow K^{*0}\ J/\Psi$ channel collected with dimuon triggers in 2018)

Signal:
Peak region of the Monte Carlo simulation

B^0 Meson Variables

Variables chosen:

- Flight length
- Flight length significance
- Cos(**α**)
- Vertex confidence level
- Negative track DCA from beamspot
- Positive track DCA from beamspot
- Leading muon p_T
- Trailing muon p_T
- Negative track p_T
- Positive track p_T
- B-candidate tag



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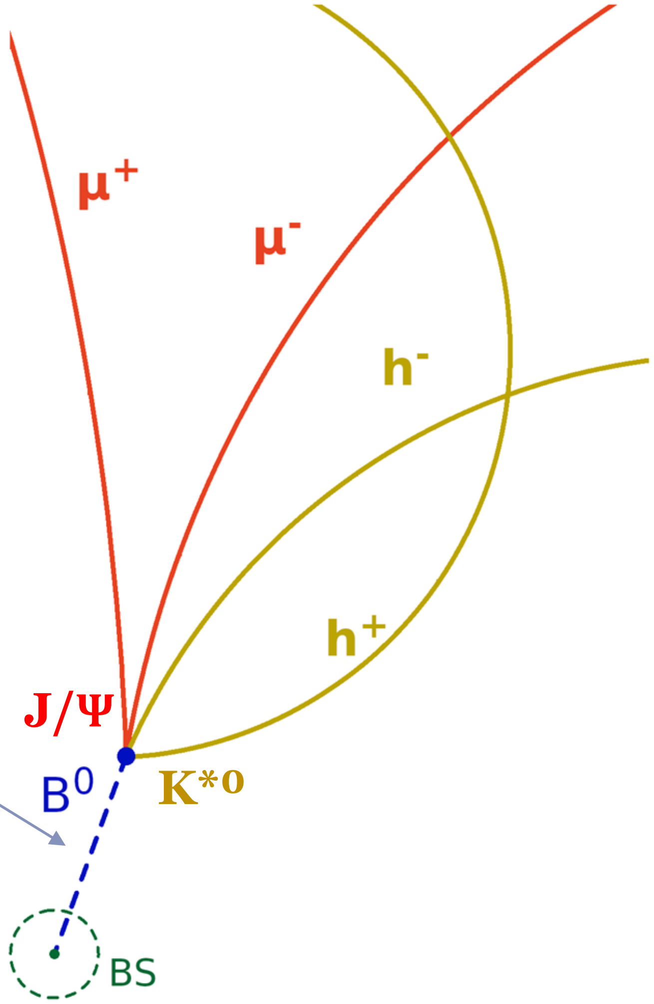

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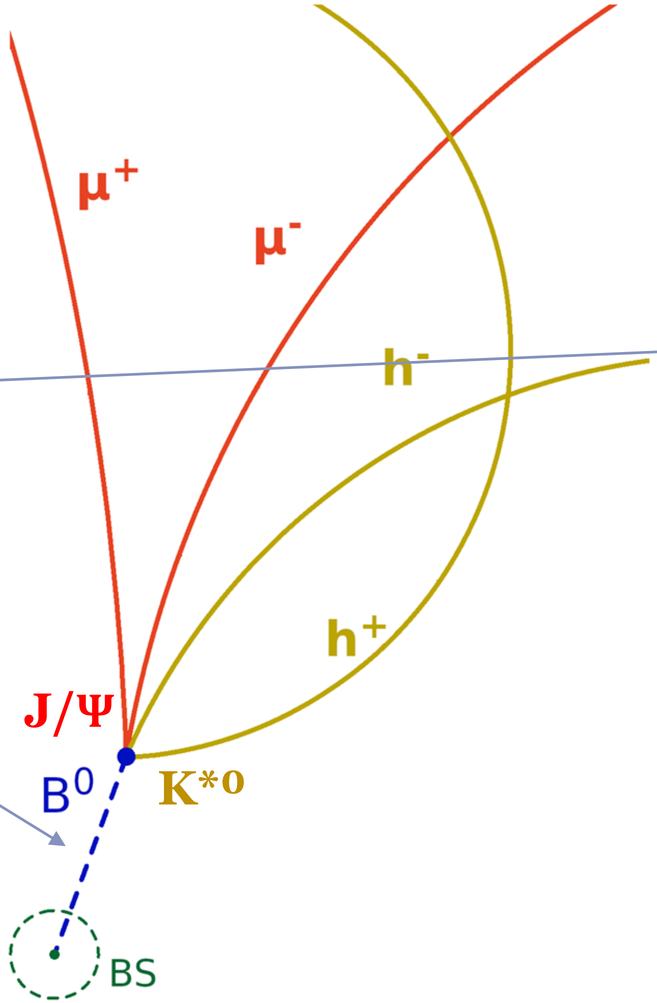

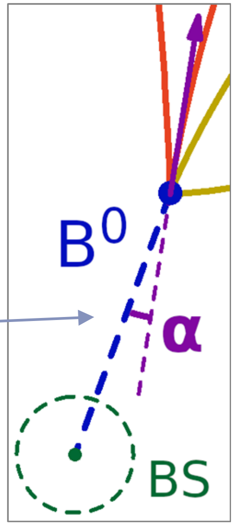

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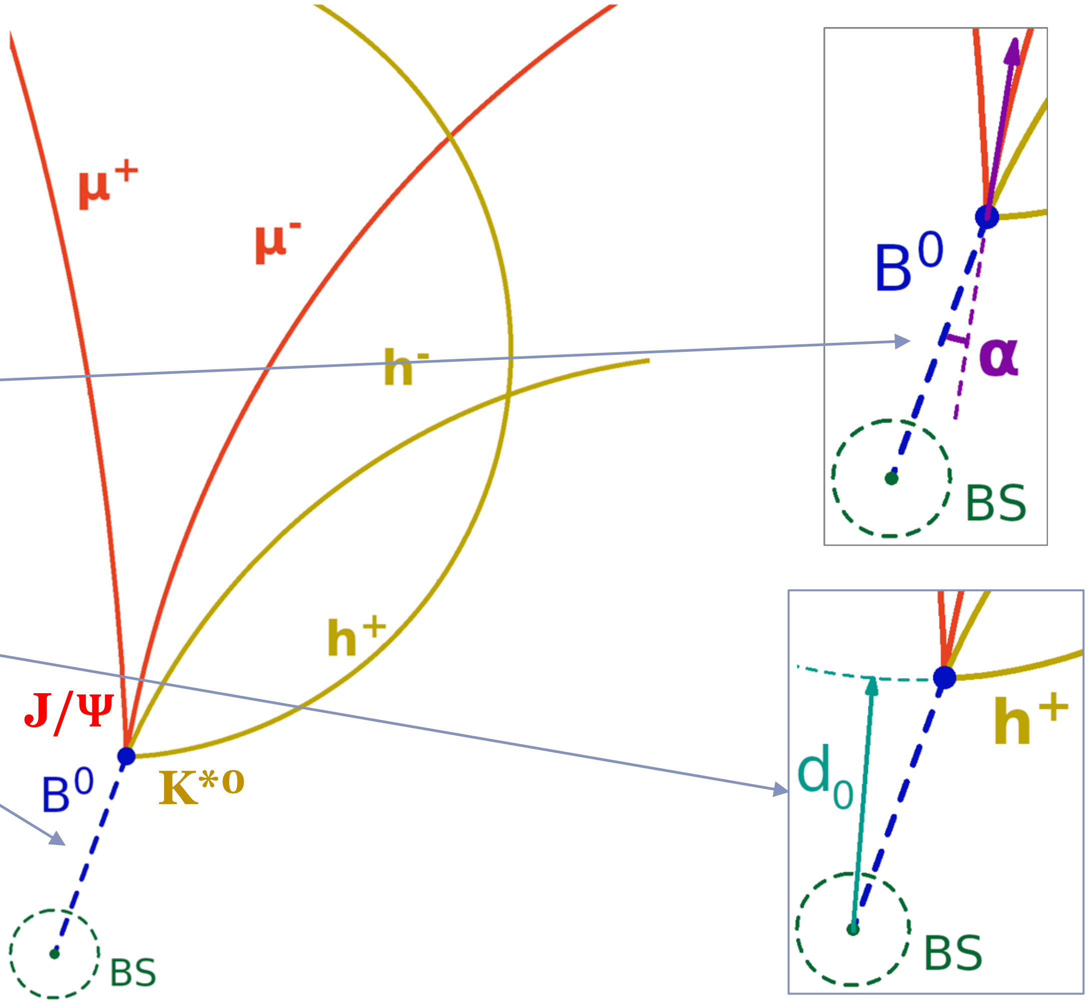

B^0 Meson Variables

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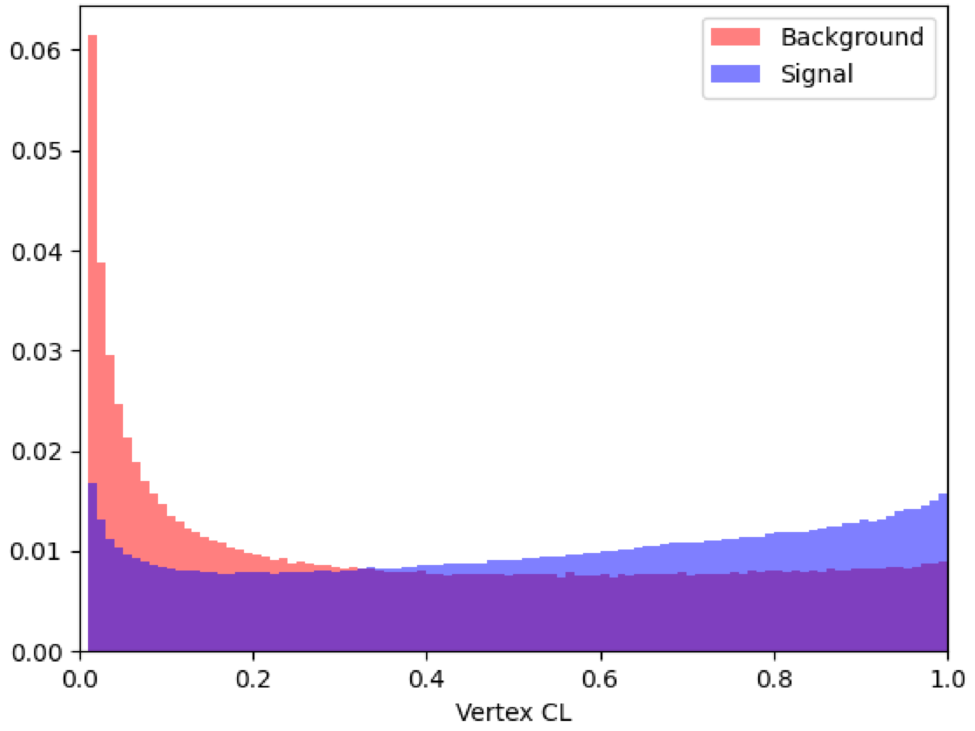

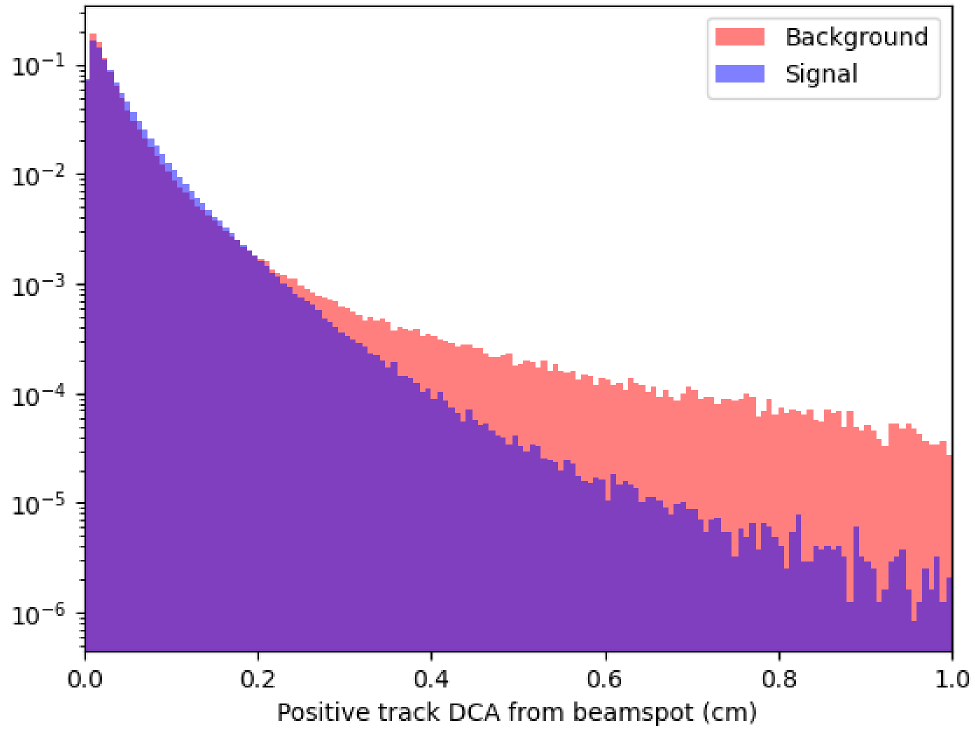

B⁰ Meson Variables

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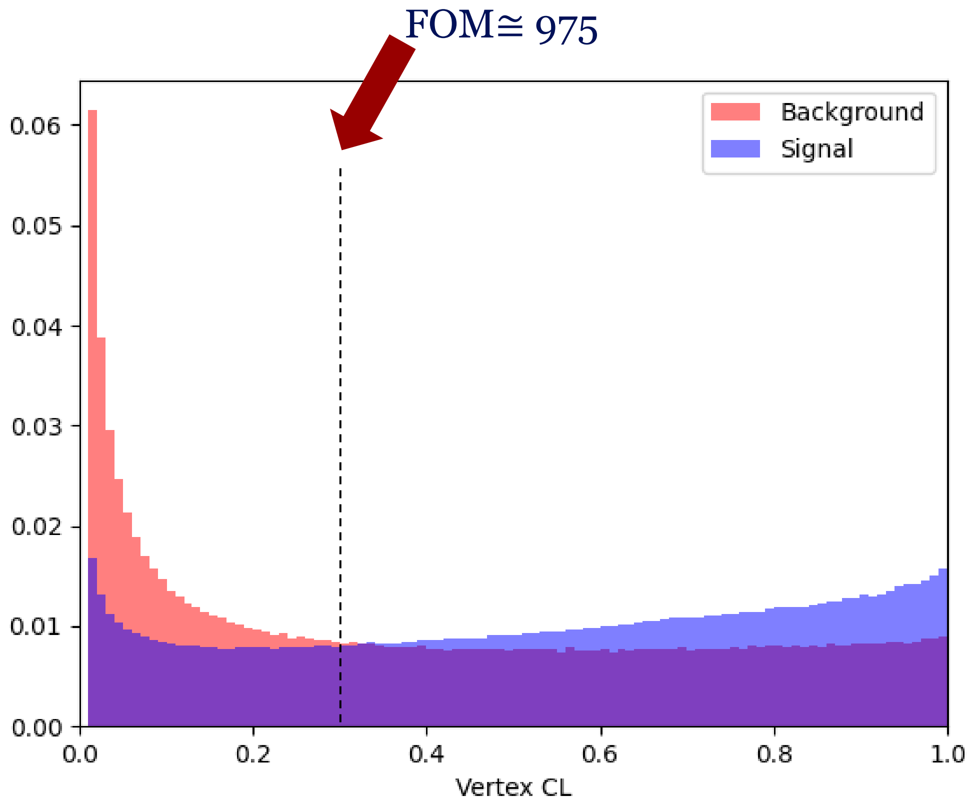

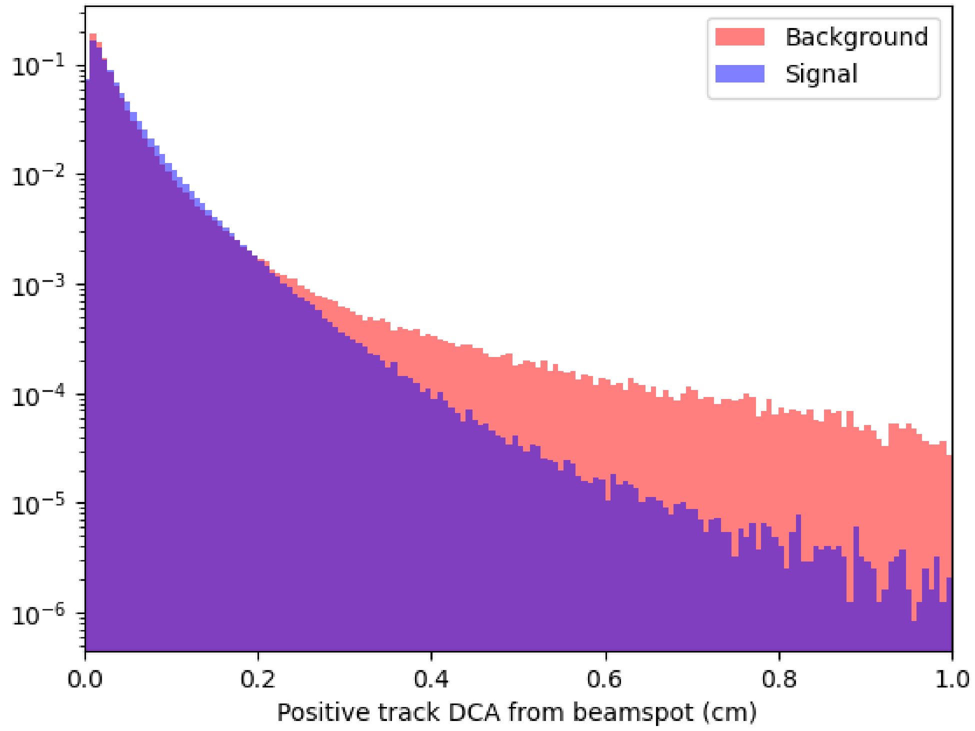

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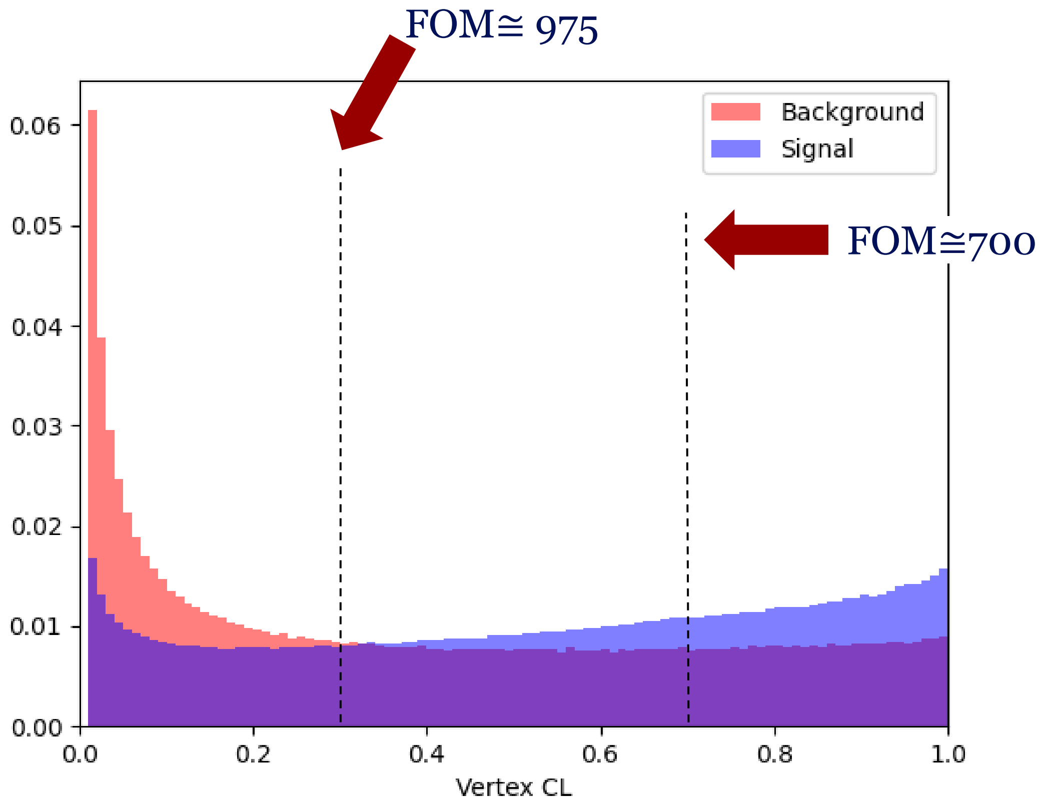

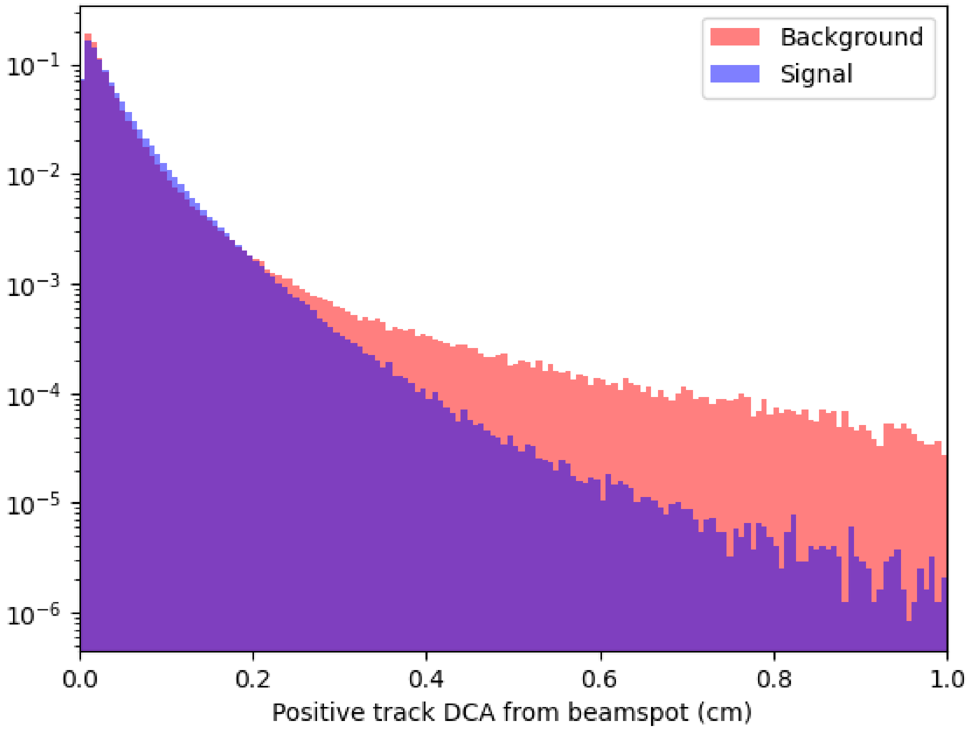

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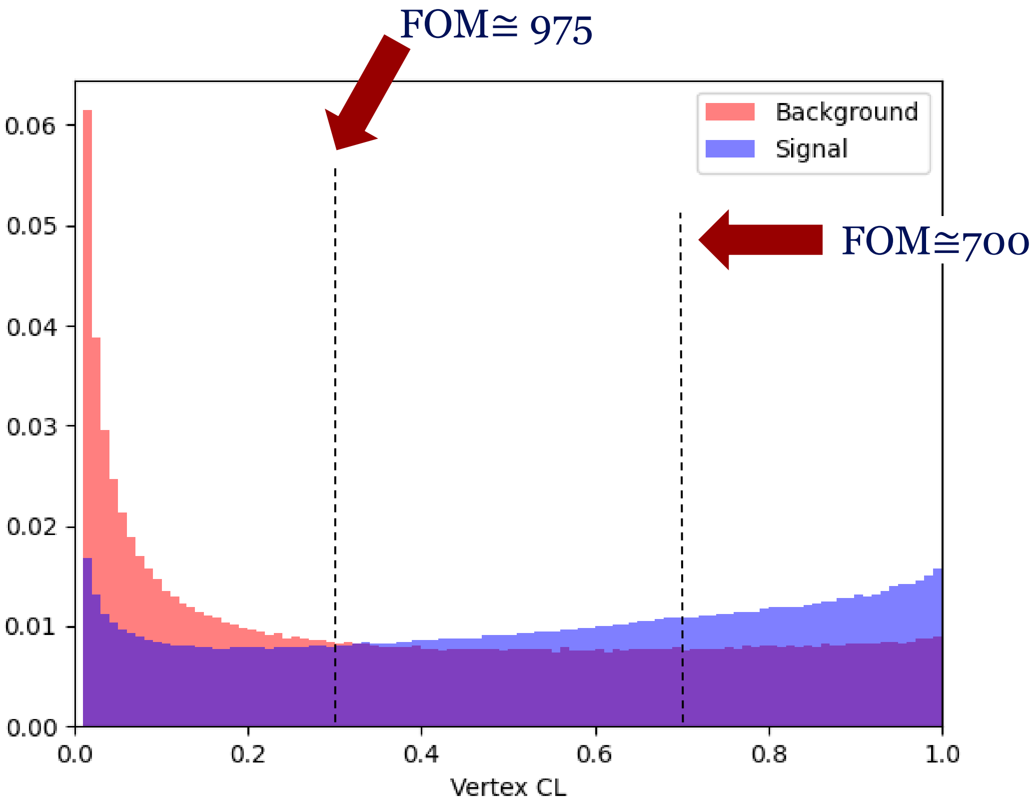

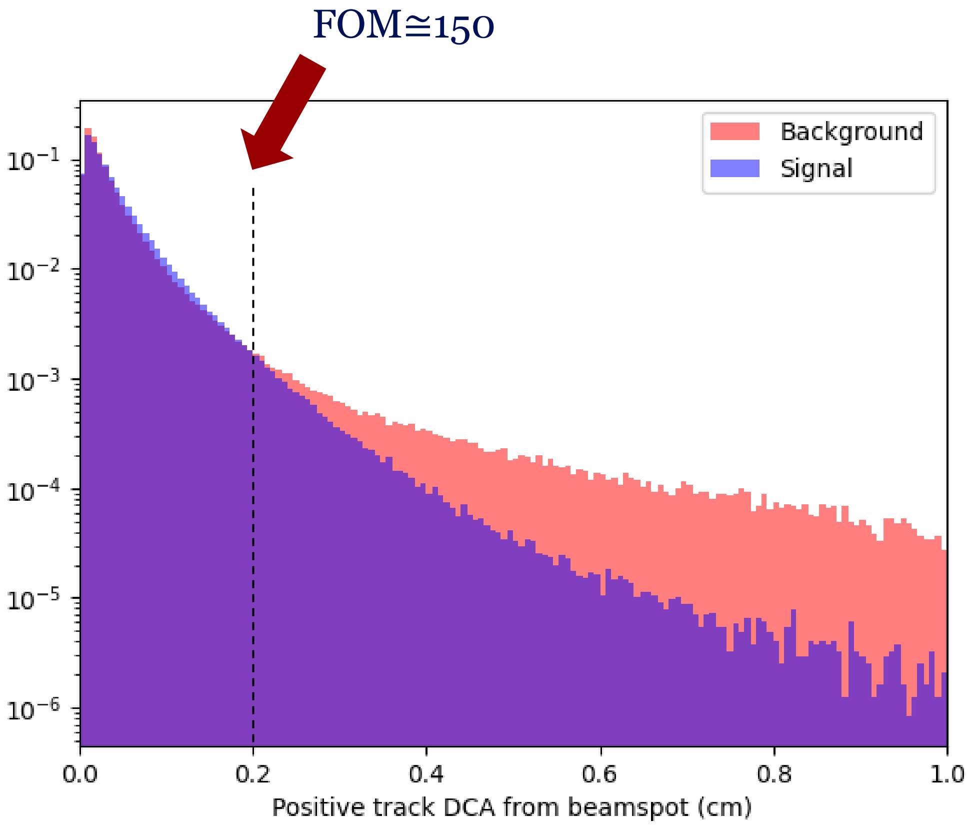

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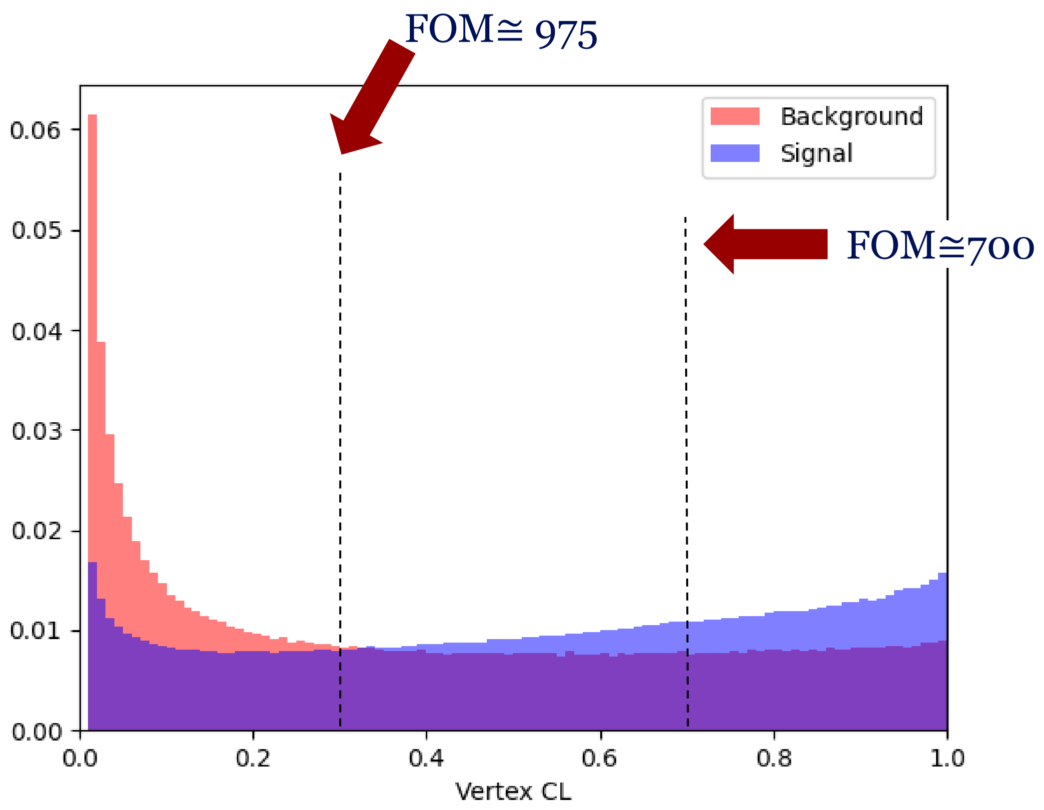
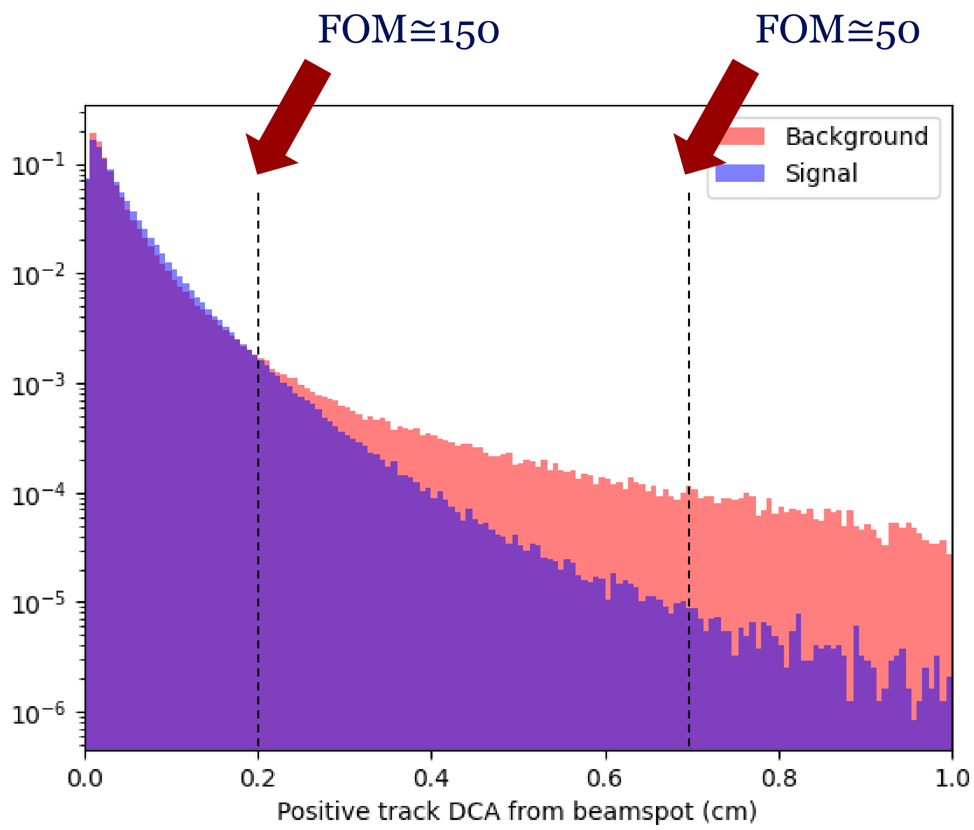
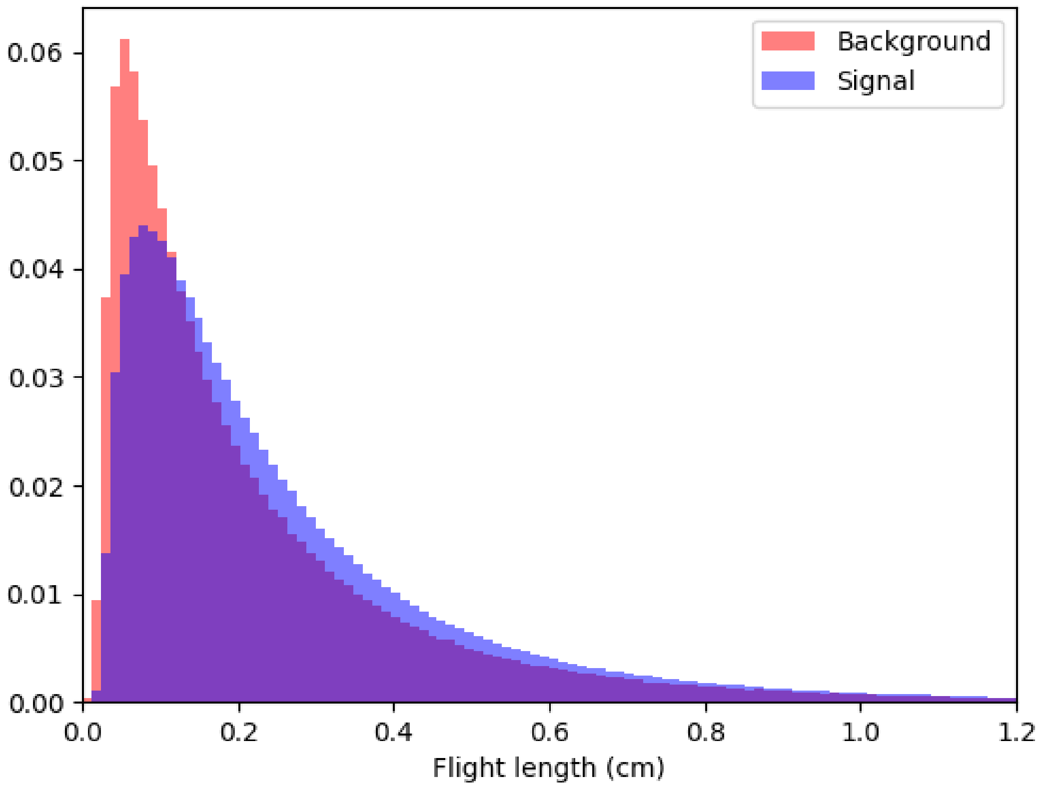
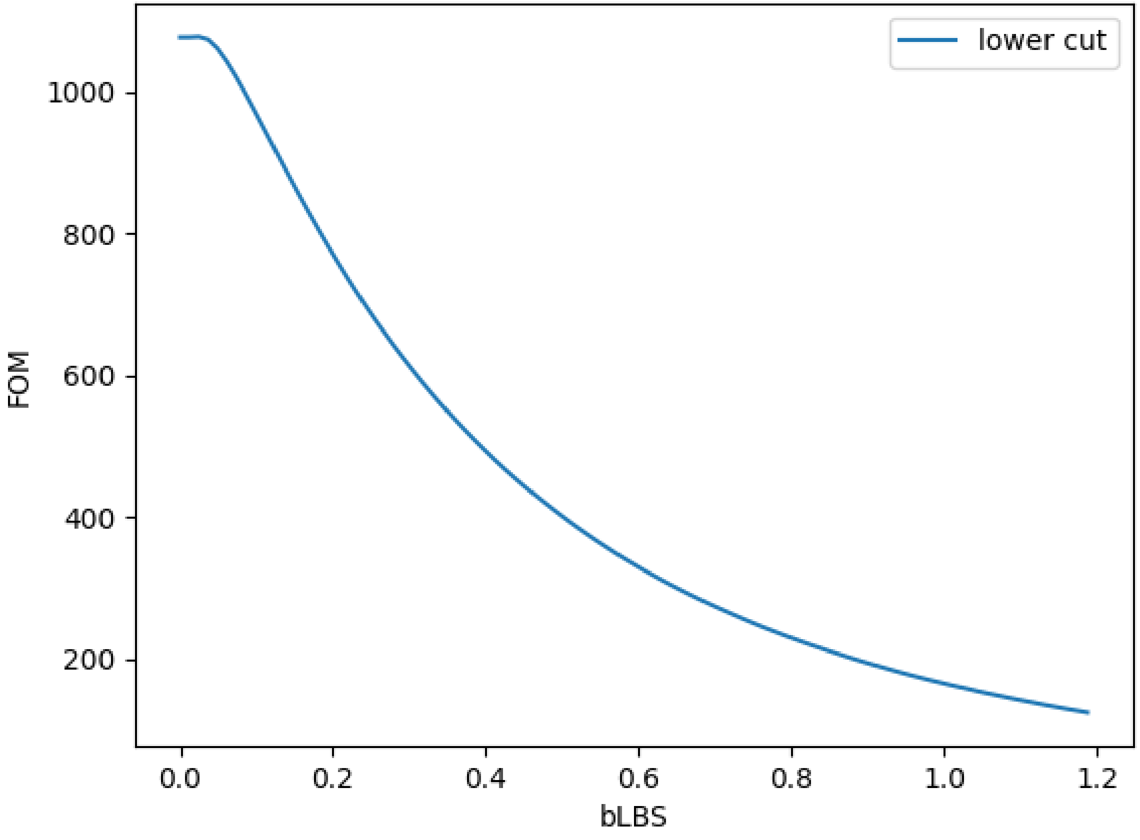




Single Variate Analysis





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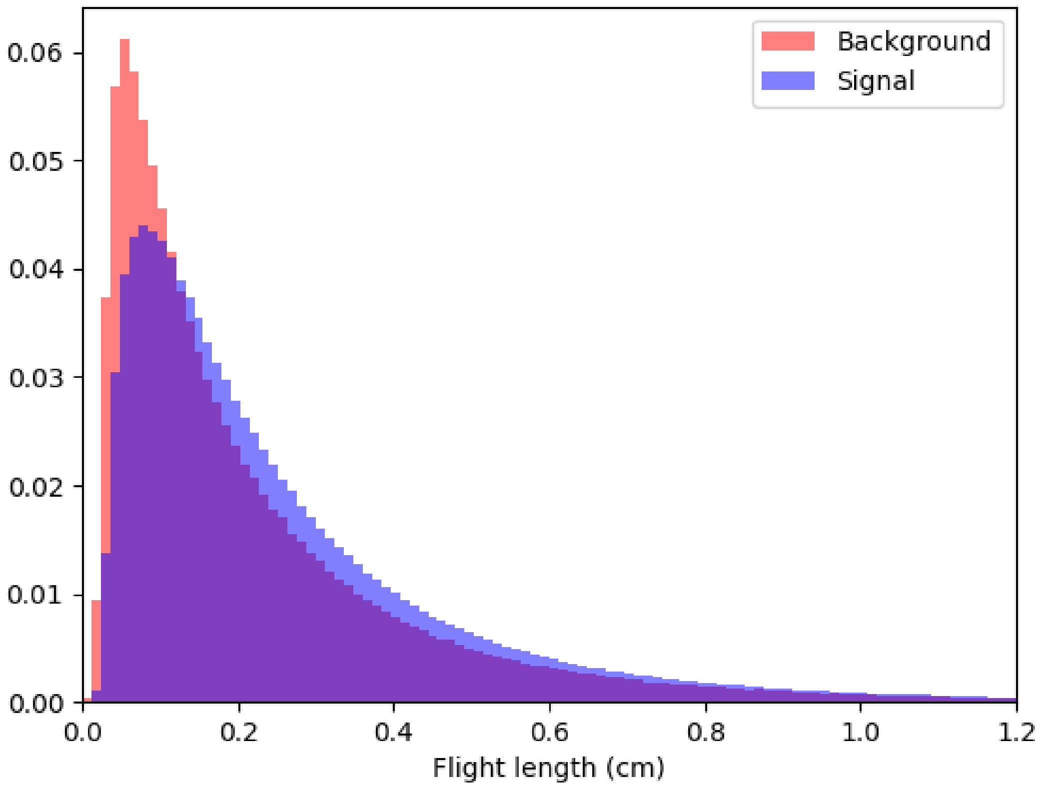
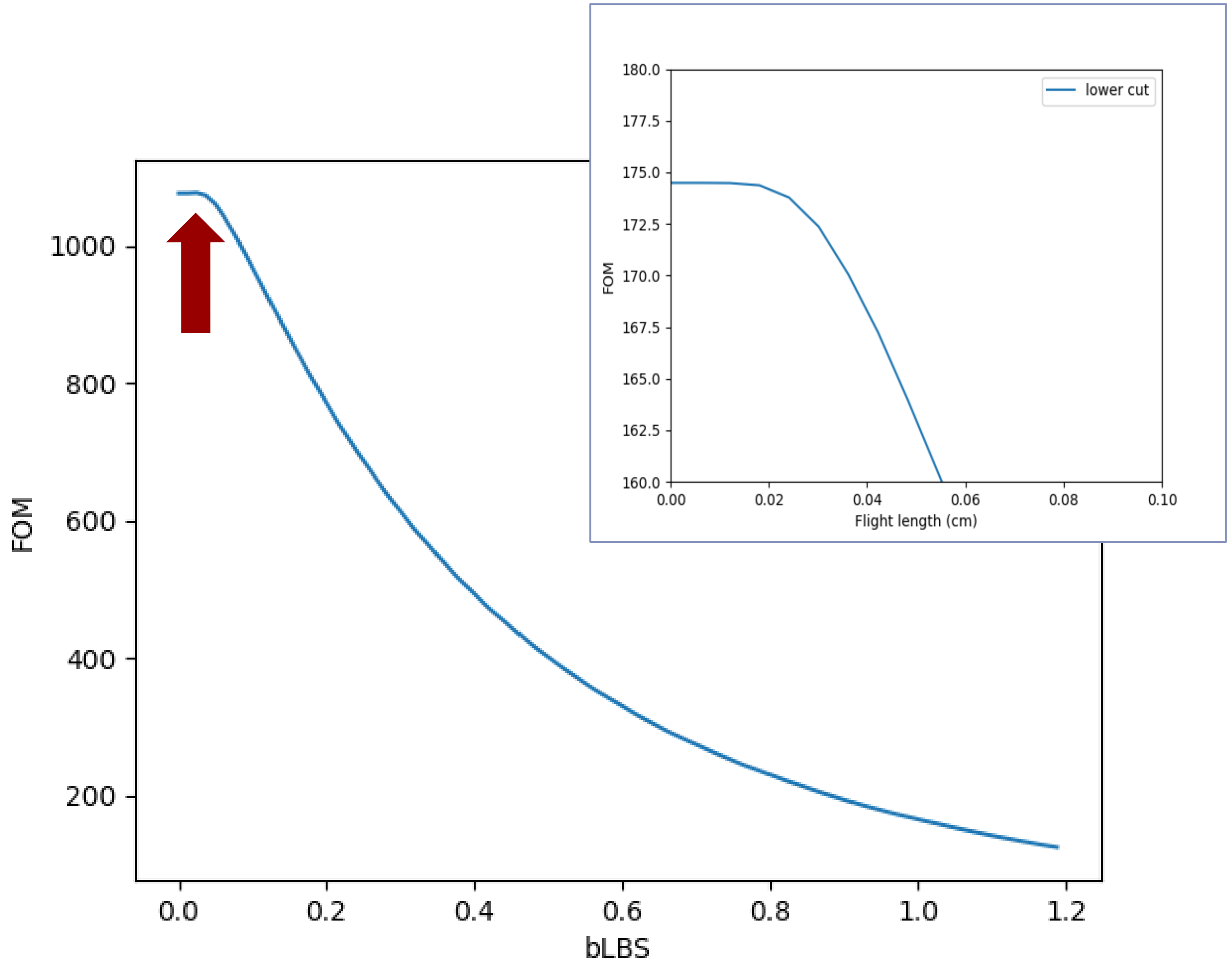


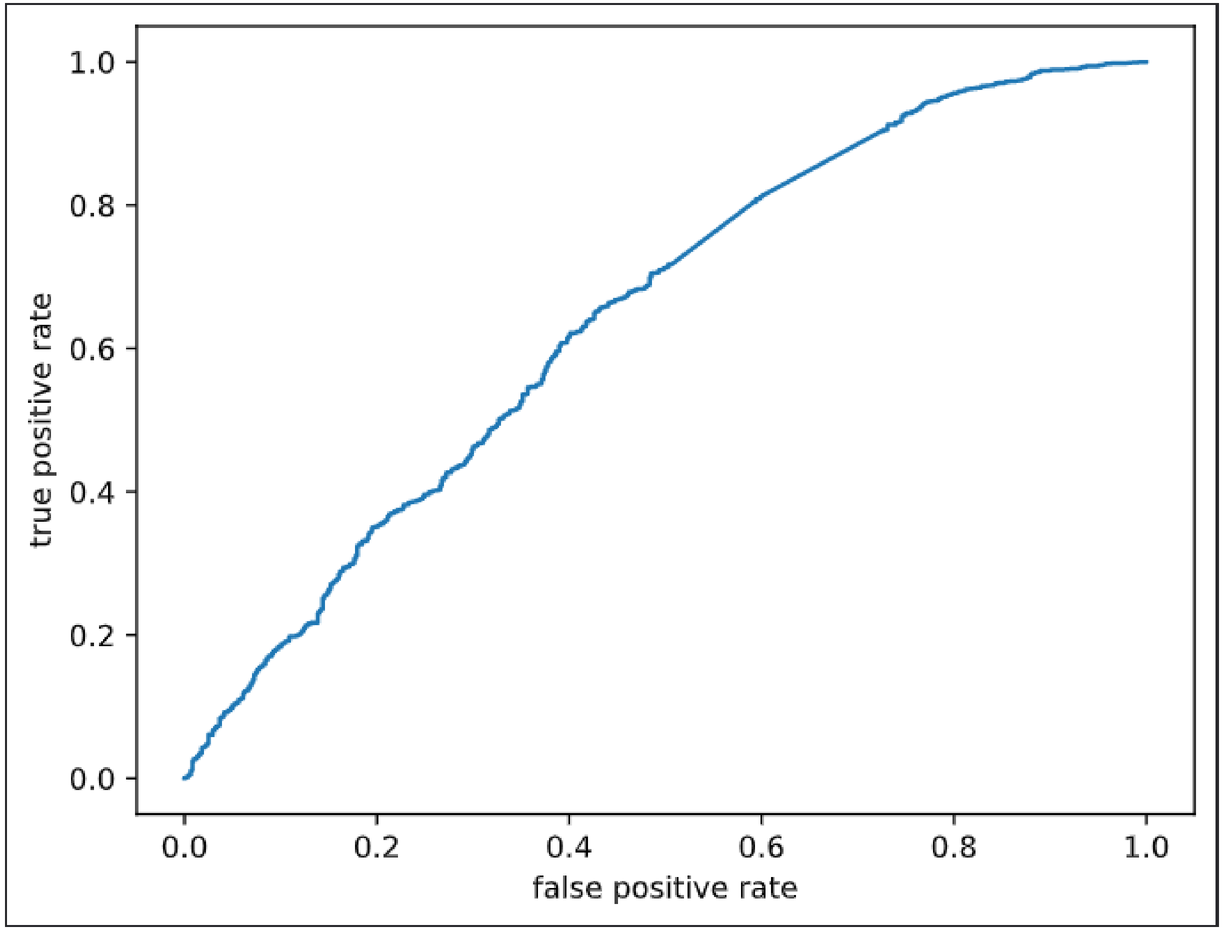


Multivariate Analysis (NN)

Neural Network Parameters

- Number of layers: 3
- Number of hidden layers: 64
- Non-linear activation: relu
- Dropout
- Number of epochs: 50

Final accuracy: 0.8012



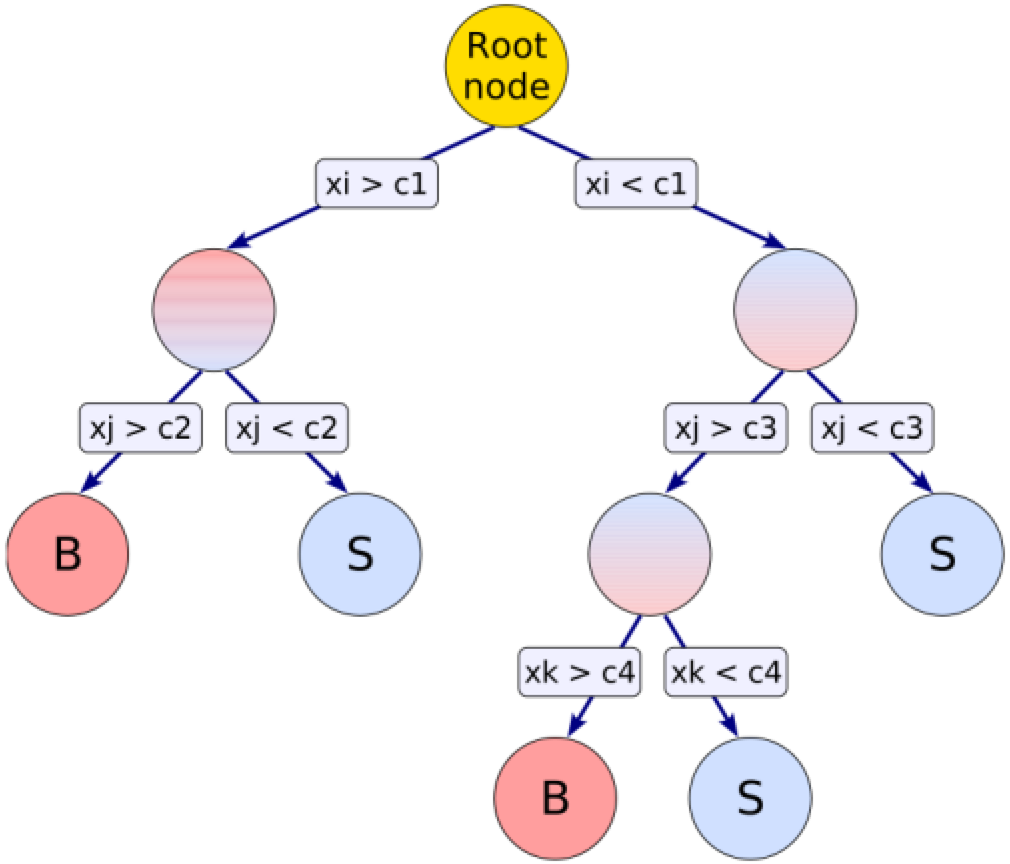
Multivariate Analysis (BDT)

Discriminating variables:

- Flight length
- Cos(**α**)
- Vertex confidence level
- Negative (positive) track DCA from BS
- Leading (trailing) muon pT
- Negative (positive) track pT
- B-candidate tag

Hyperparameters:

- Number of trees=250
- Minimal node size: 2.5%
- Maximum depth: 5
- Number of cuts: 30



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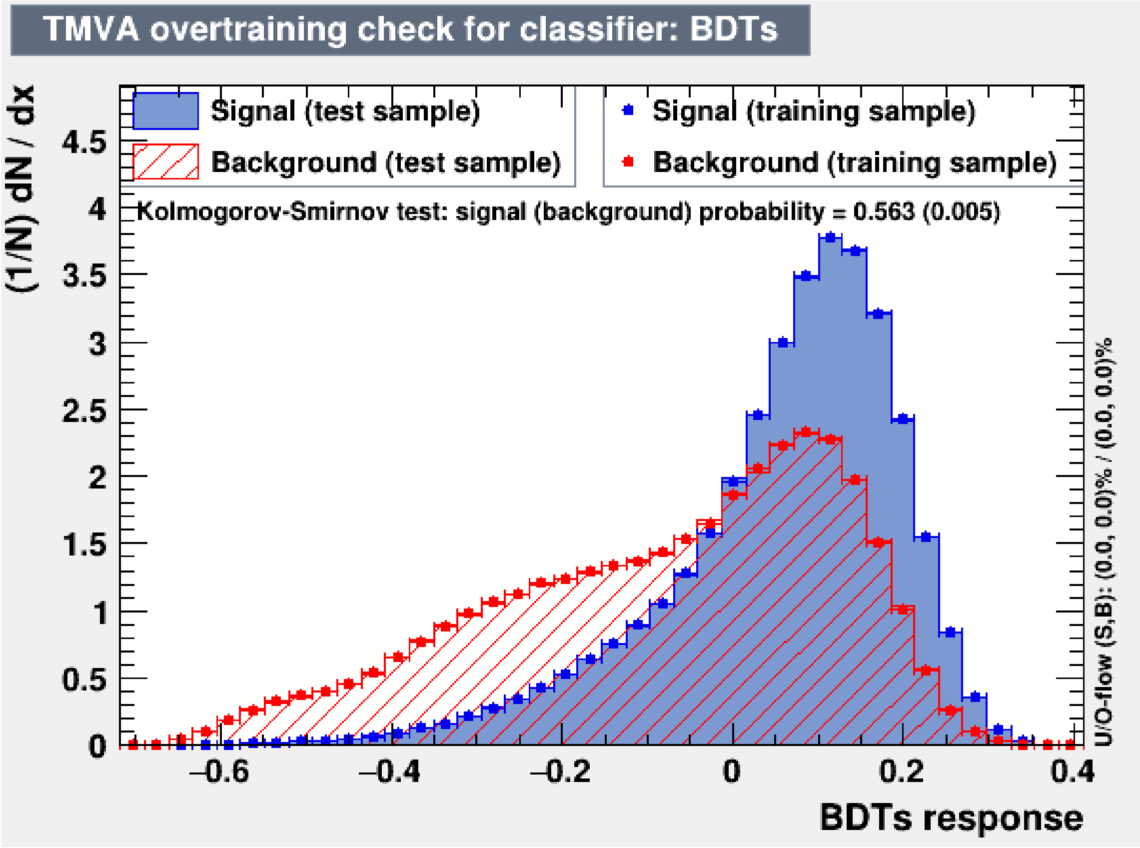

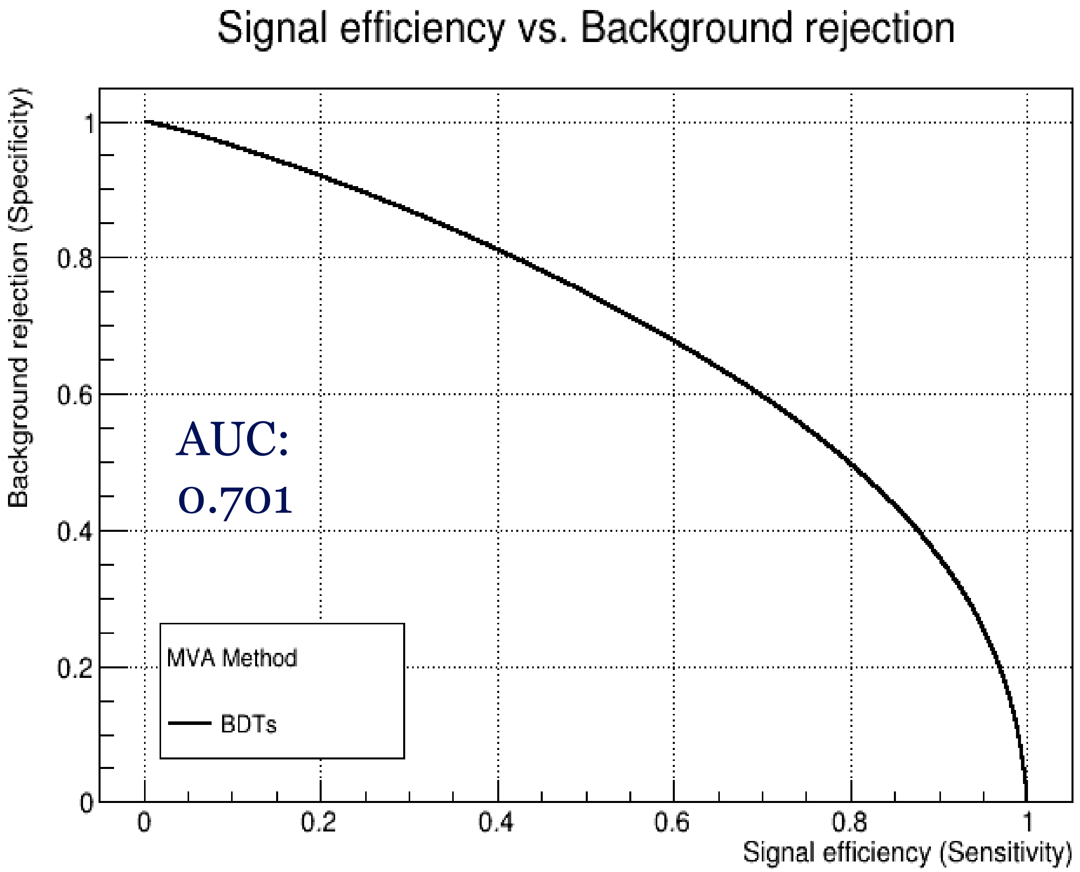

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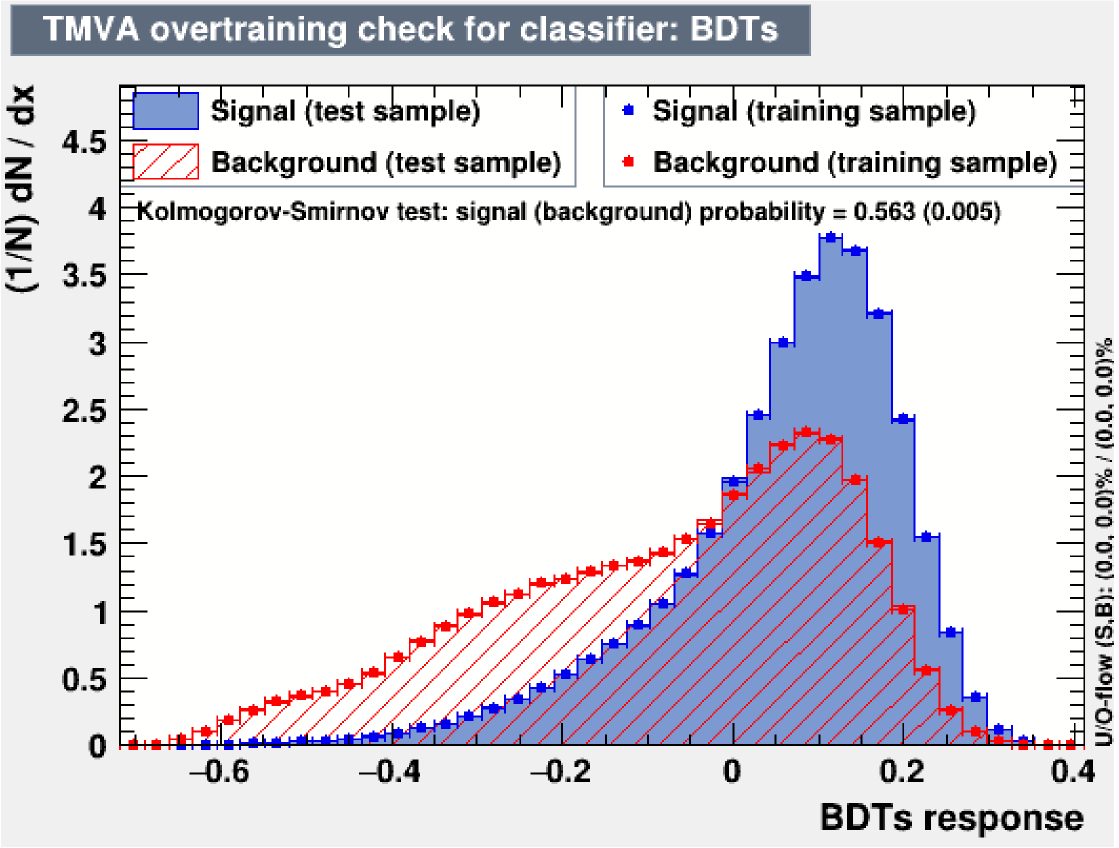
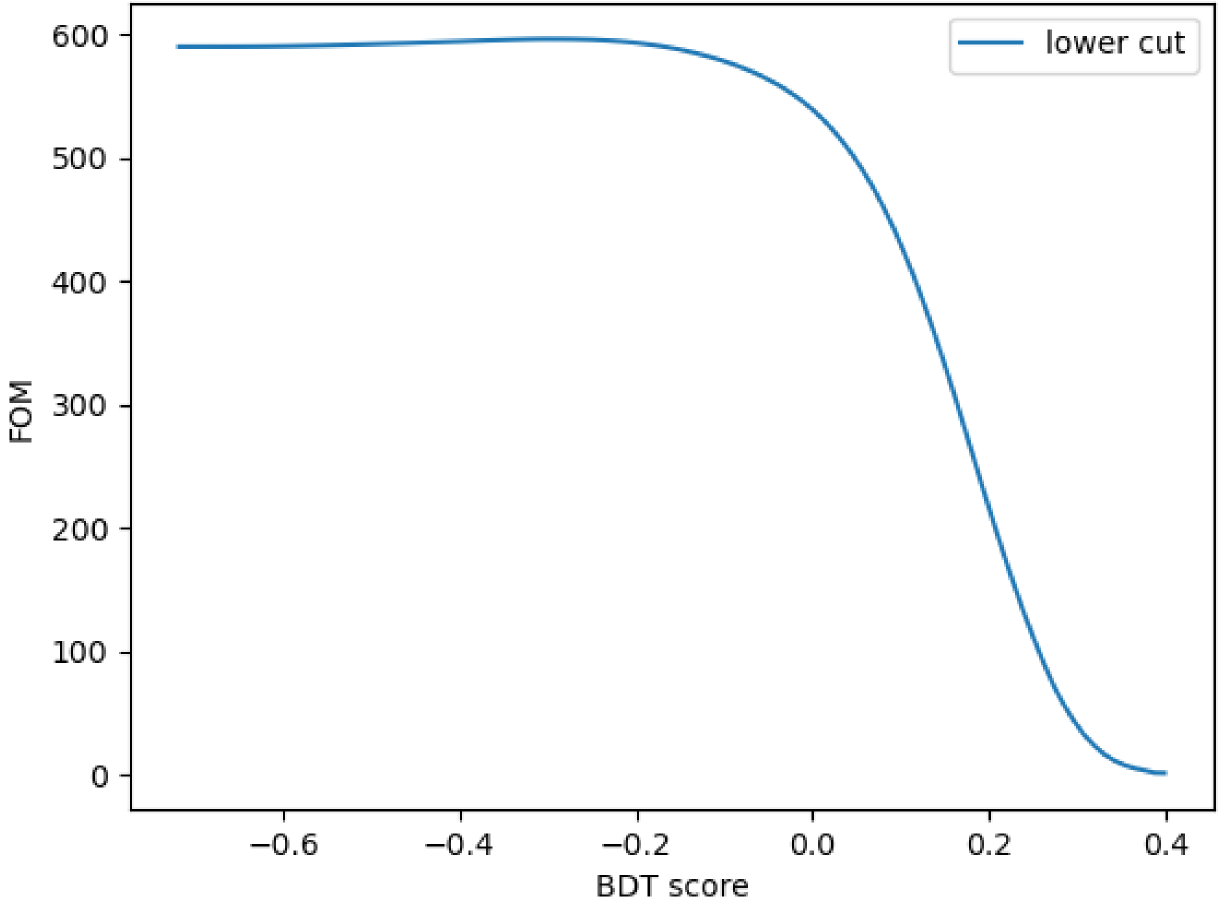
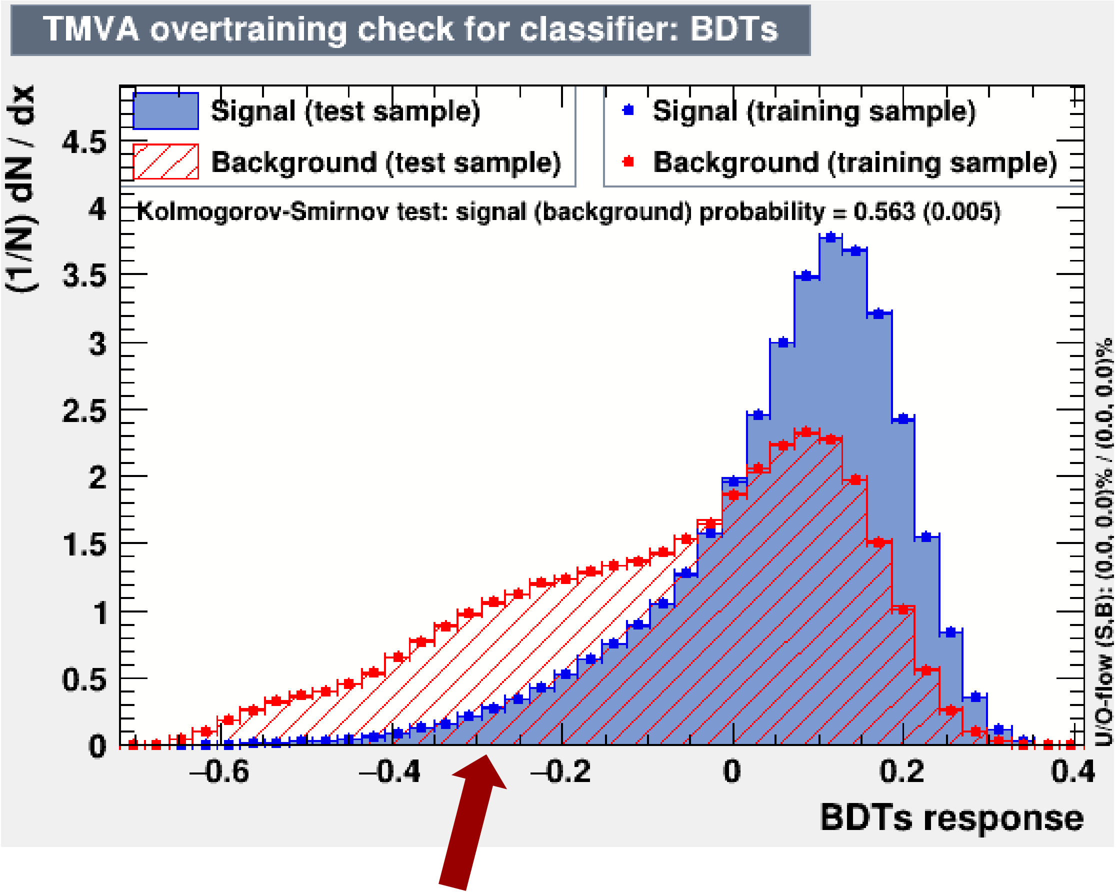
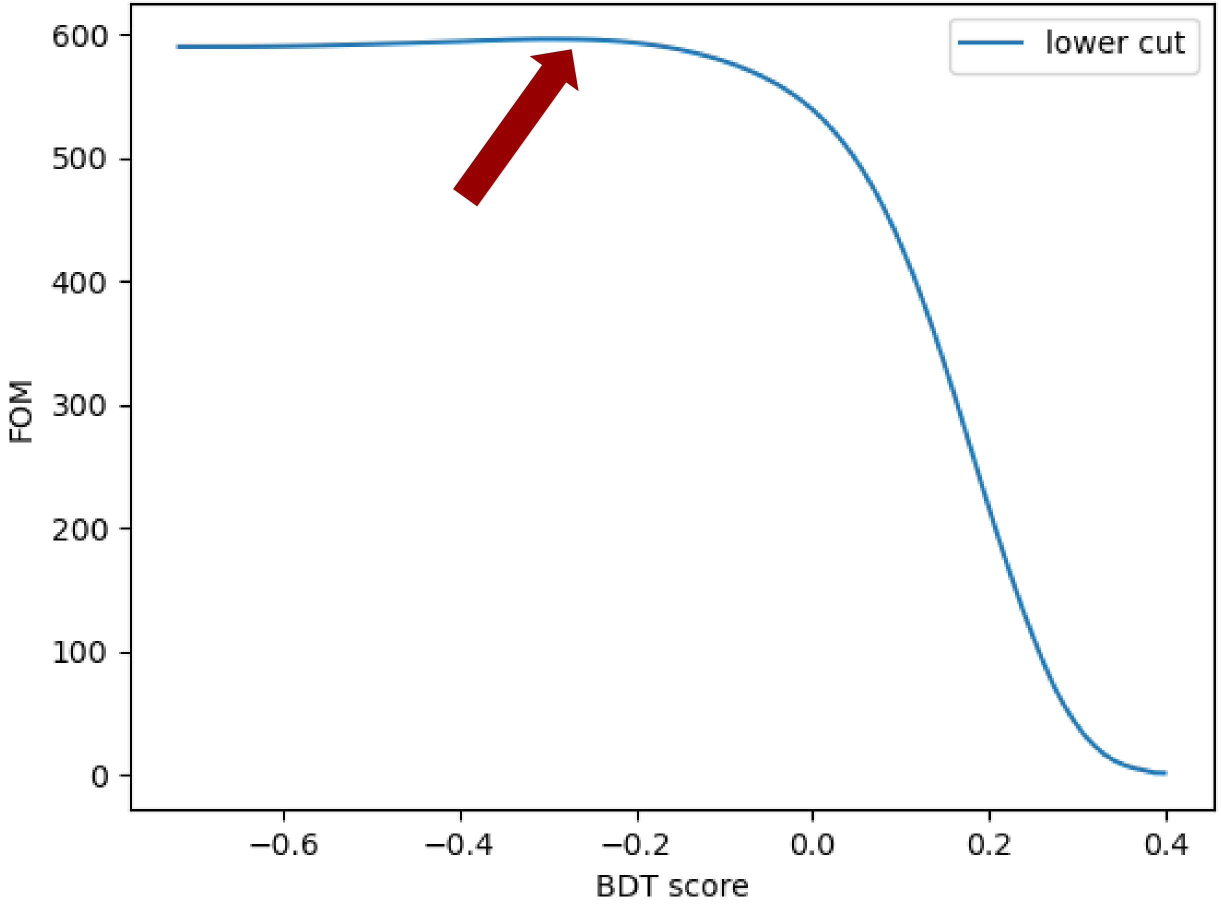




Multivariate Analysis (BDT)

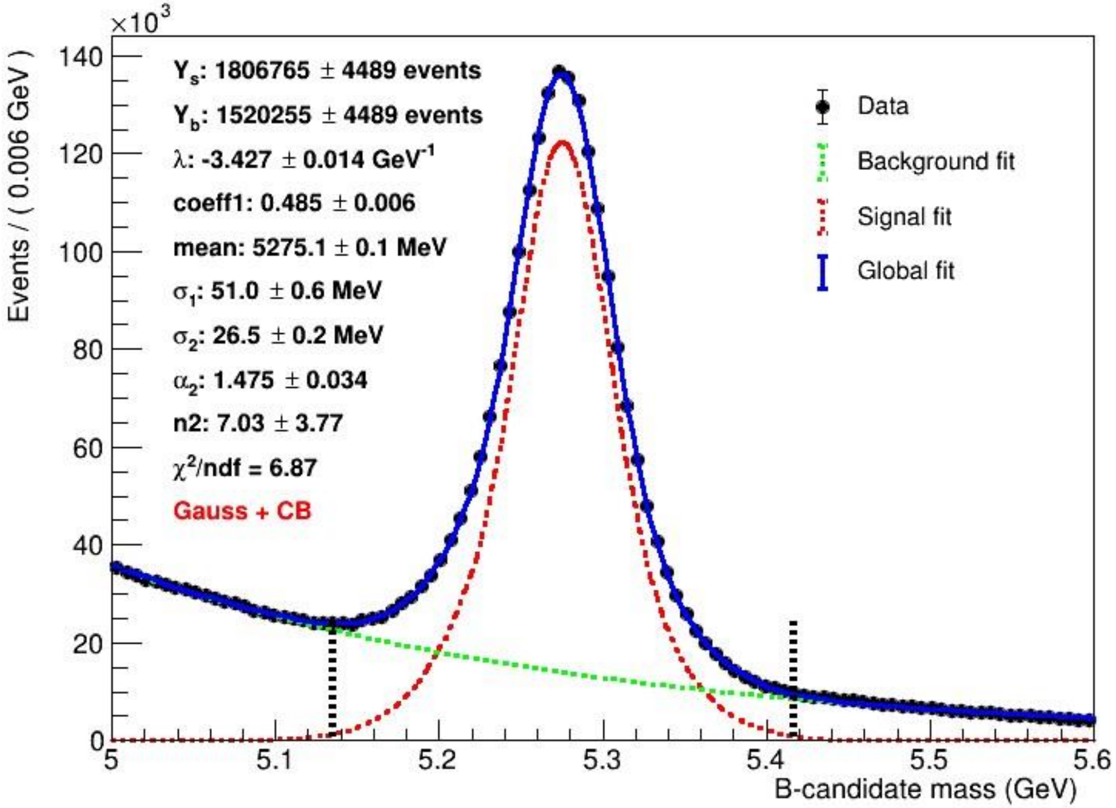
Best cut ~ -0.296



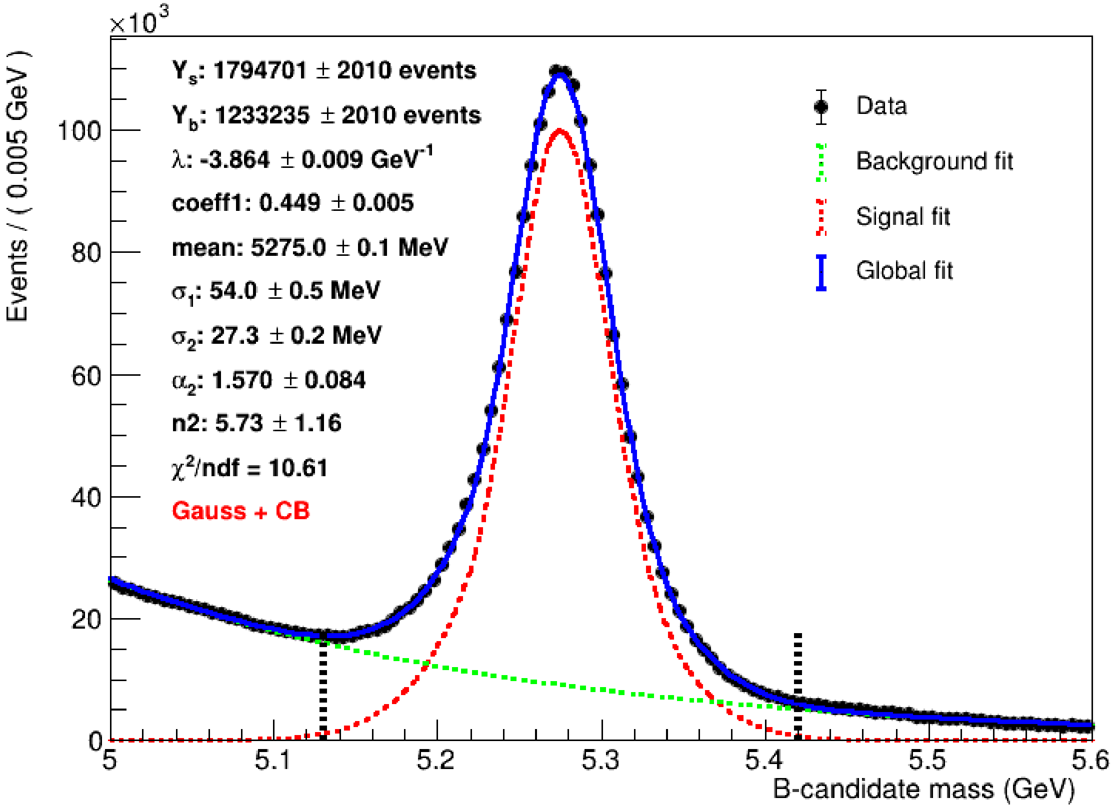


Results Comparison

Before (BDT)



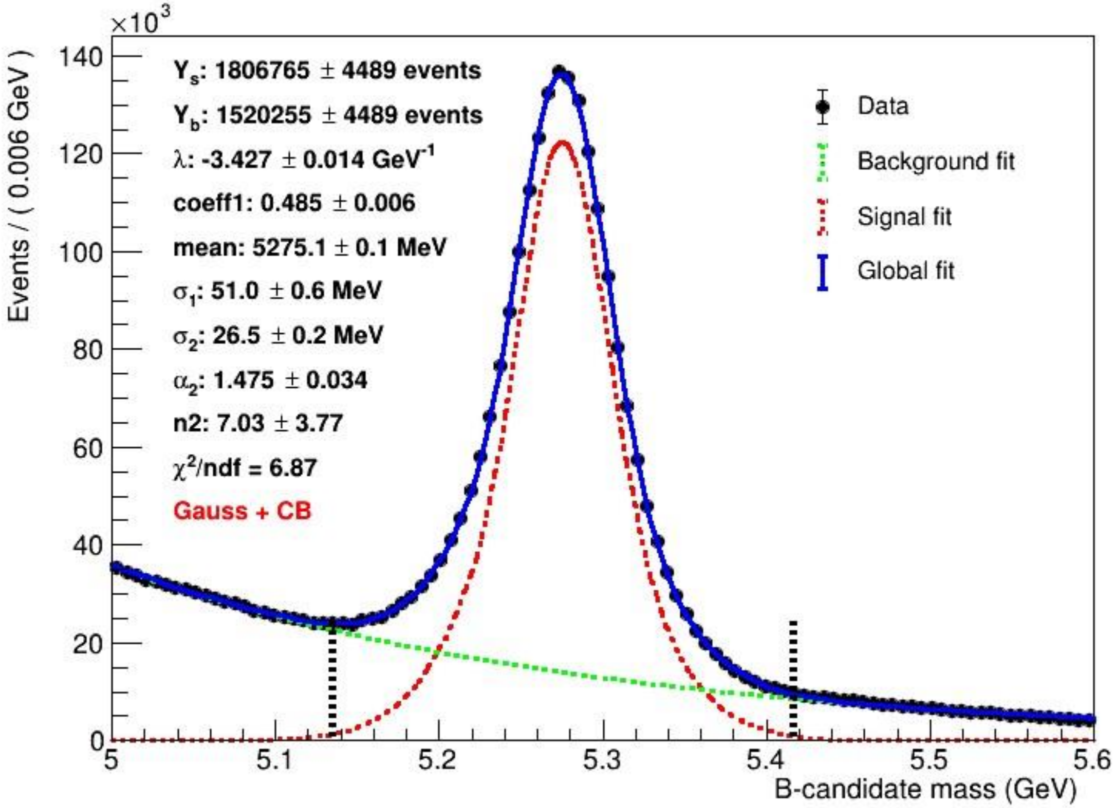
After (BDT)

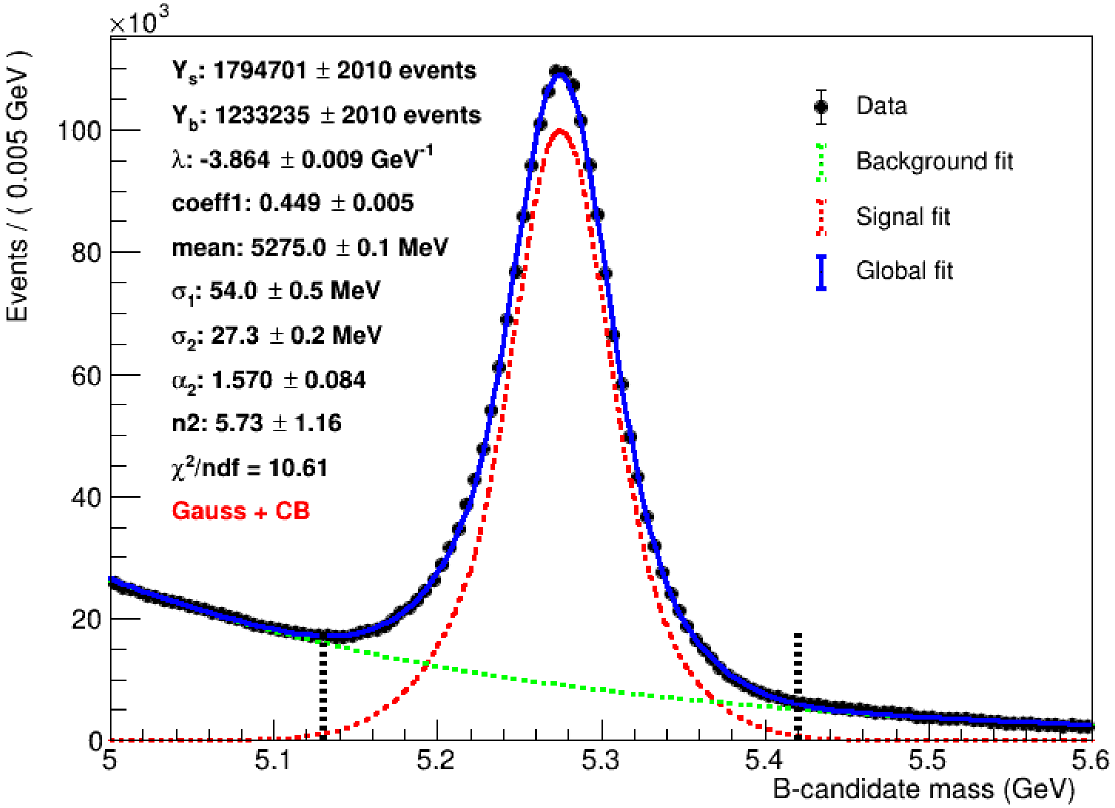


Results Comparison

Before (BDT)

Signal reduction ~ 1%
Background reduction ~ 20%





Conclusions

- Project integrated in the exploration of Flavour Anomalies in LHC data with CMS
- Studied features of the B^0 meson decay that allow to discriminate signal from background
- Explored Machine Learning methods (BDT & NN algorithms) to optimally correlated input features

Next steps:

- Apply the developed tools to the rare B^0 decay channel (non-resonant) for exploring Flavour-Anomaly dedicated datasets collected by CMS

Thank you!

Any questions?

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Backup Slides

LABORATÓRIO DE INSTRUMENTAÇÃO
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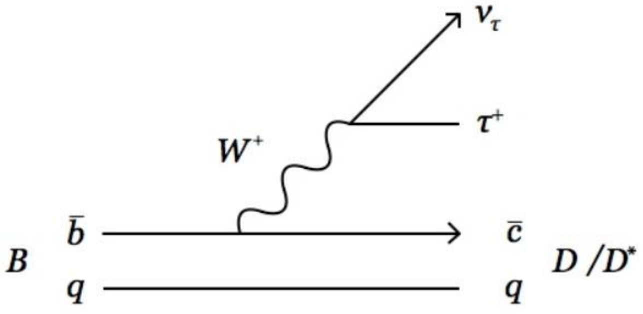
Flavour Anomalies (b→cτν)

$$R(X) = \frac{\mathcal{B}(\bar{B} \to X\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to Xl\bar{\nu})} \qquad \begin{array}{l} X = D, D^* \\ l = \mu, e \end{array}$$



Tree-level

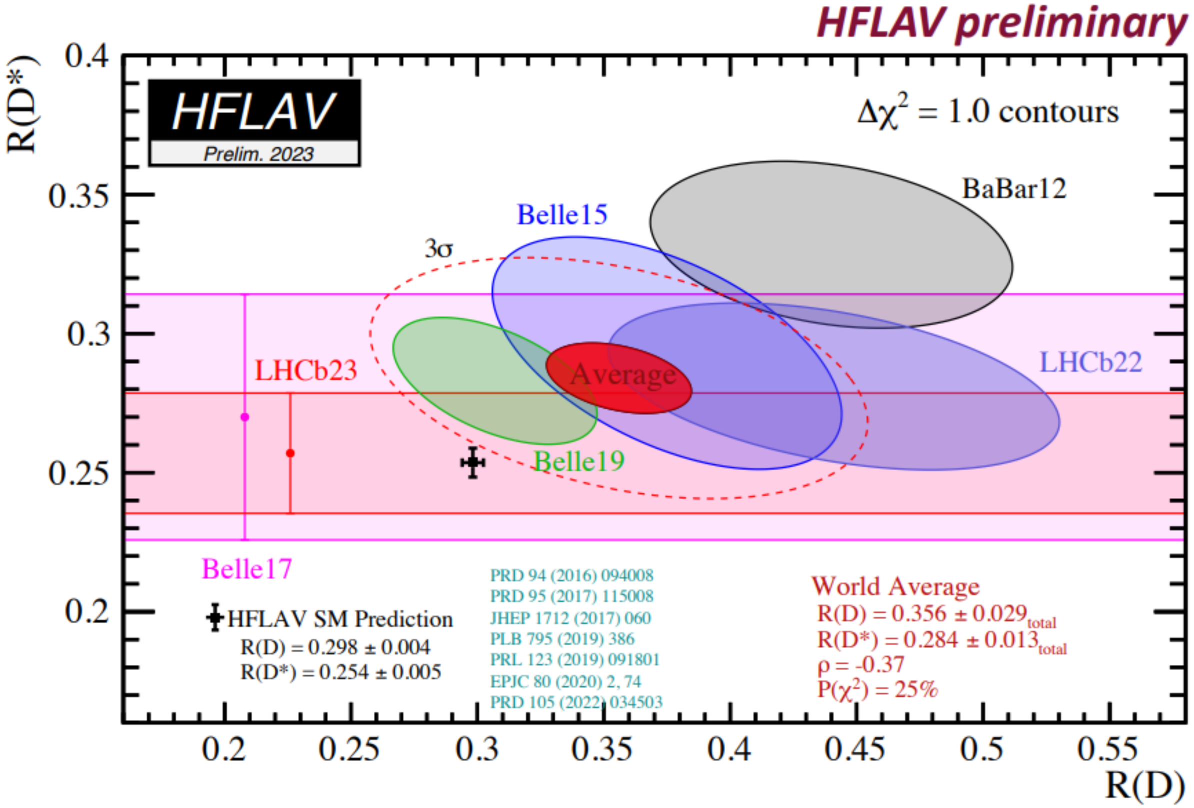
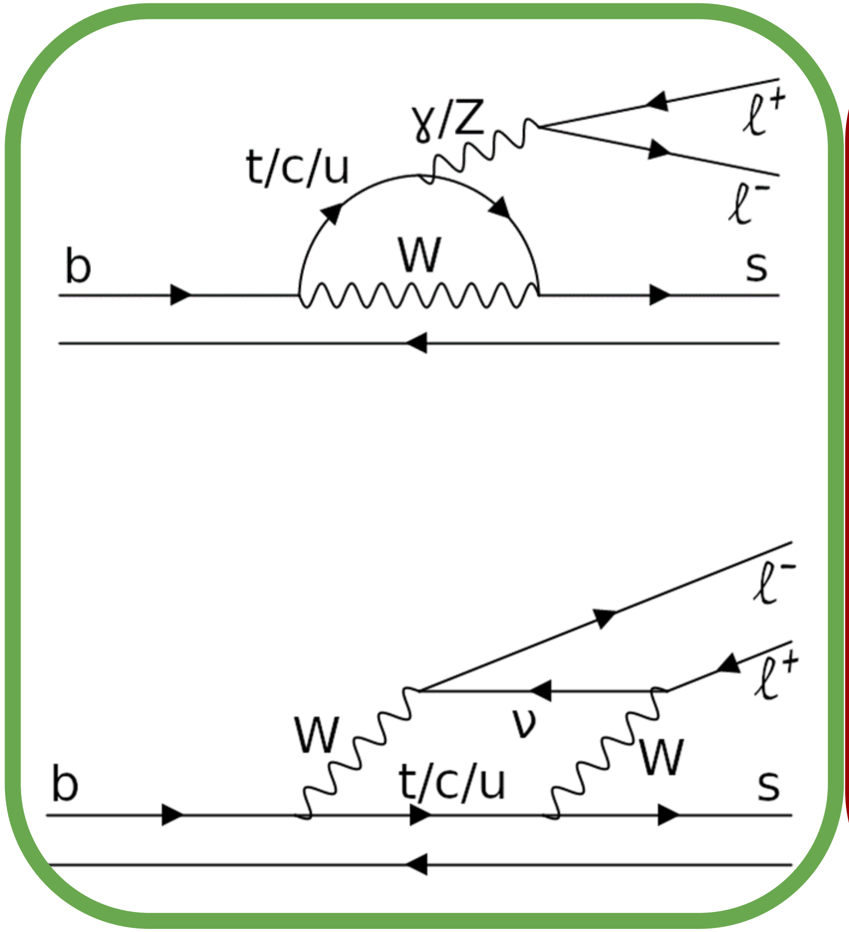


Fig.1: The SM predictions are in tension with the experimental world average at the 3.2σ level (ALpine Particle physics Symposium 2023).

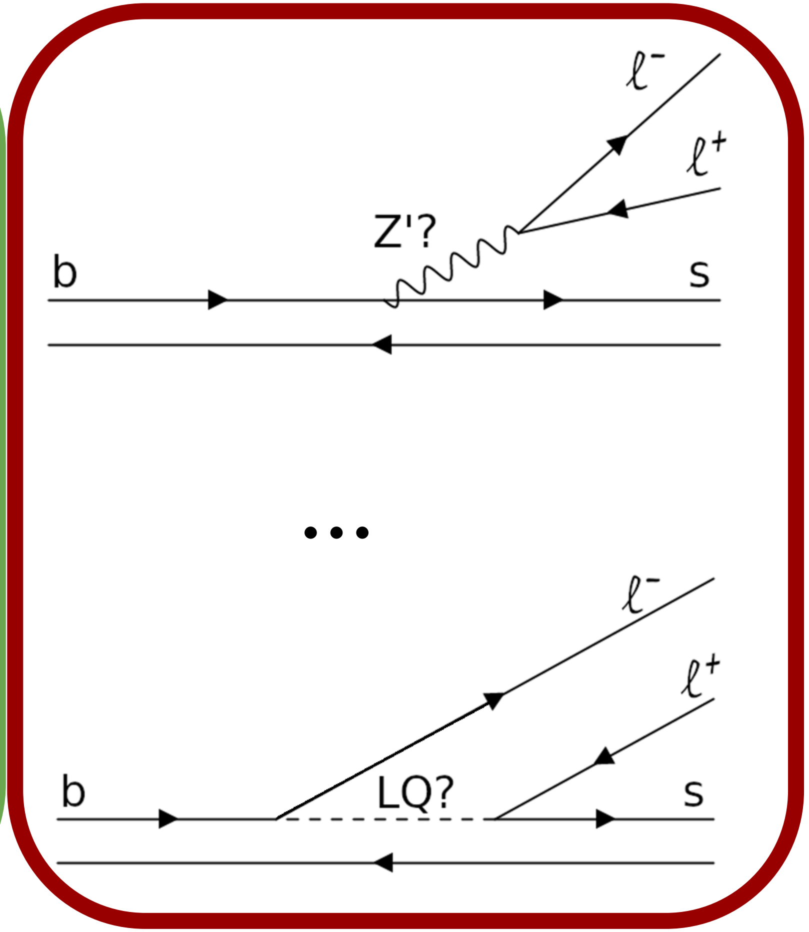
Effective Field Theory (b→sll)

Effective Field Theory (b→sll)

SM

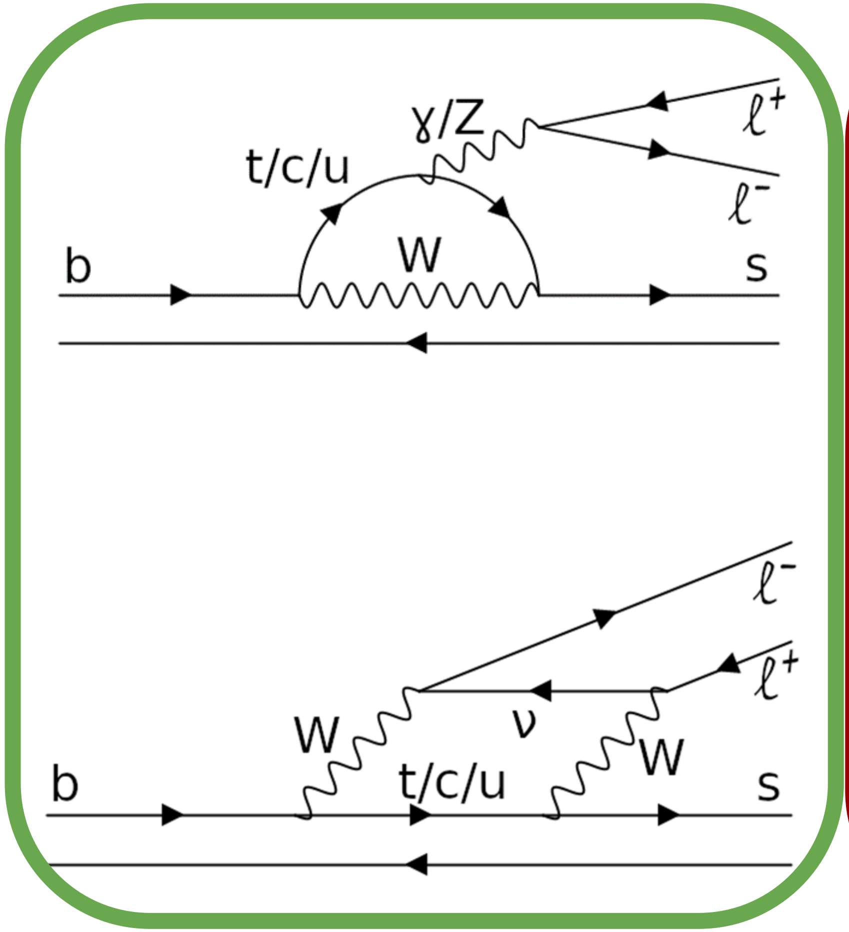


NP



Effective Field Theory (b→sll)

SM



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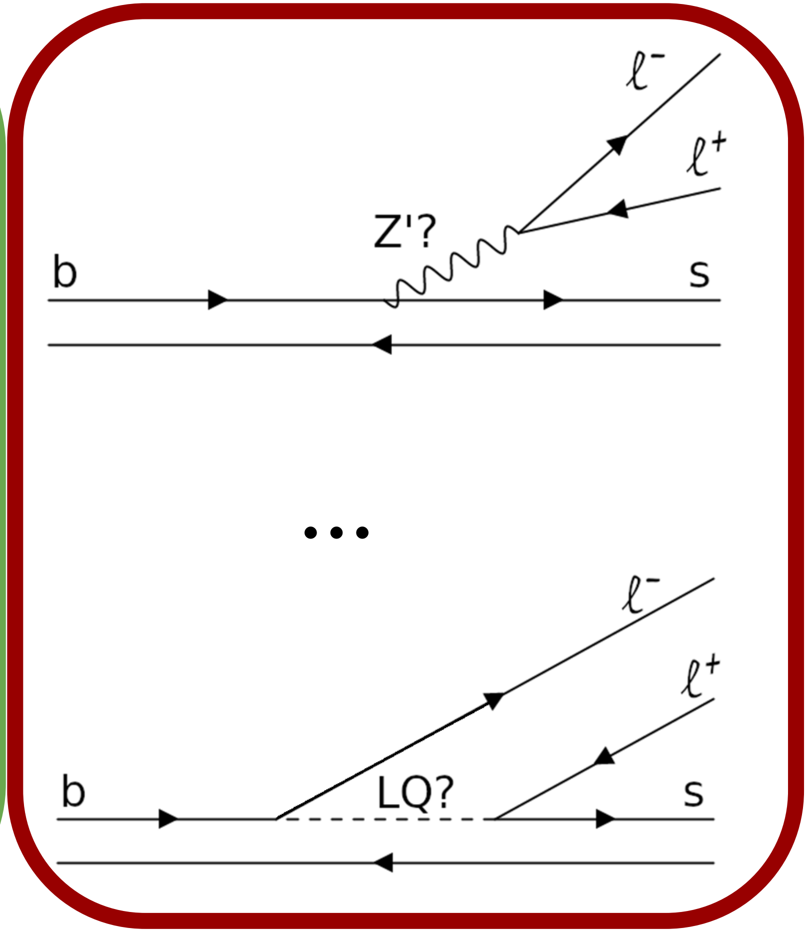
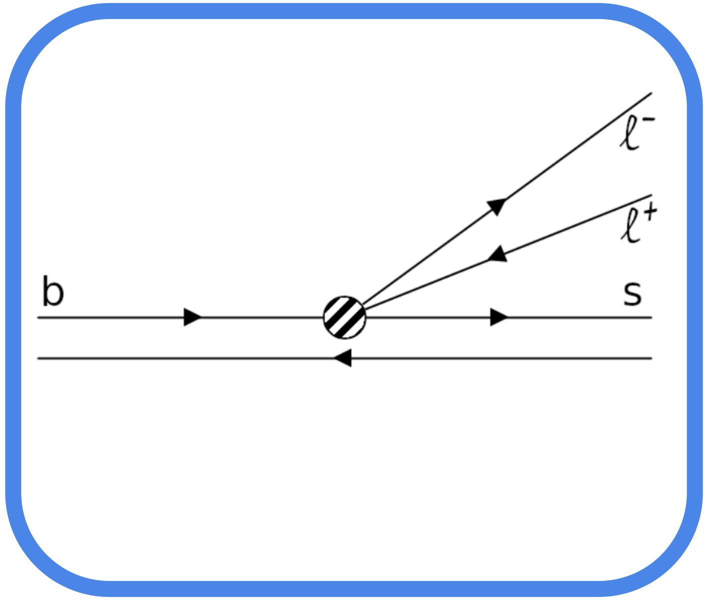
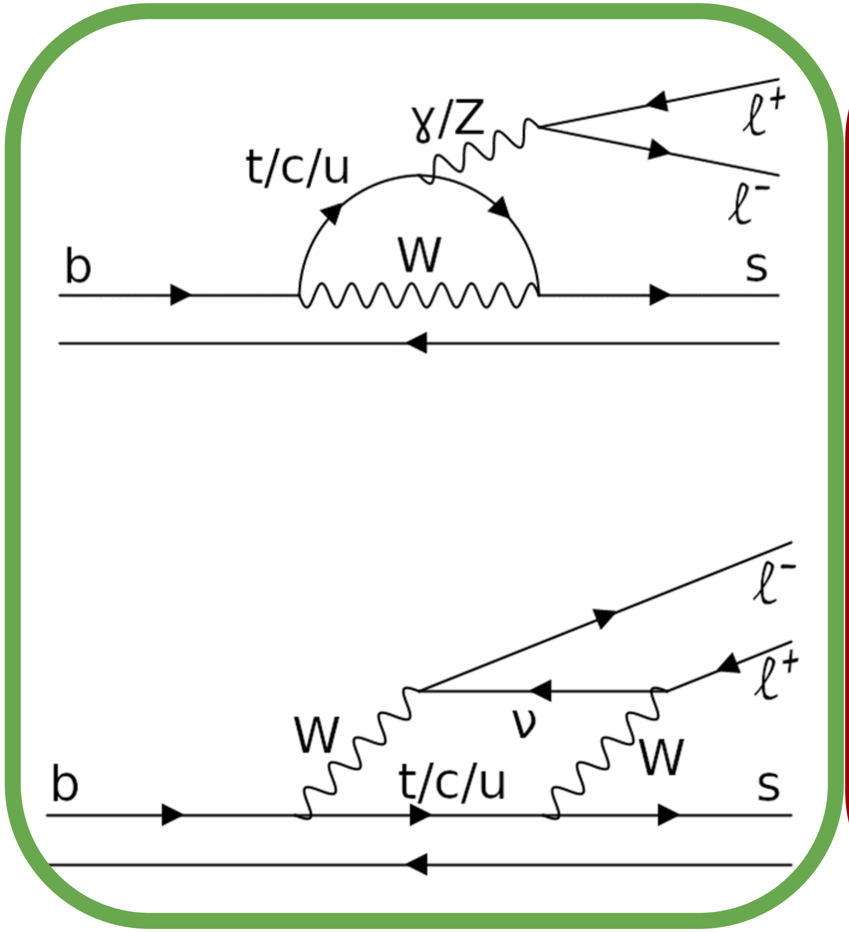




Effective Field Theory (b→sll)

SM



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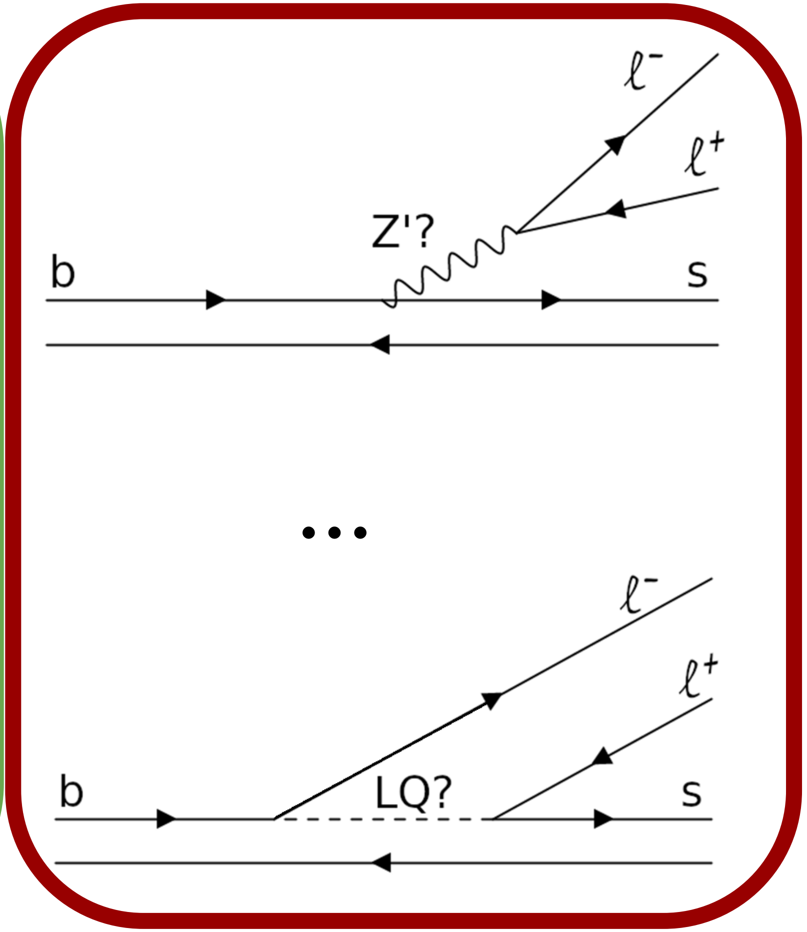
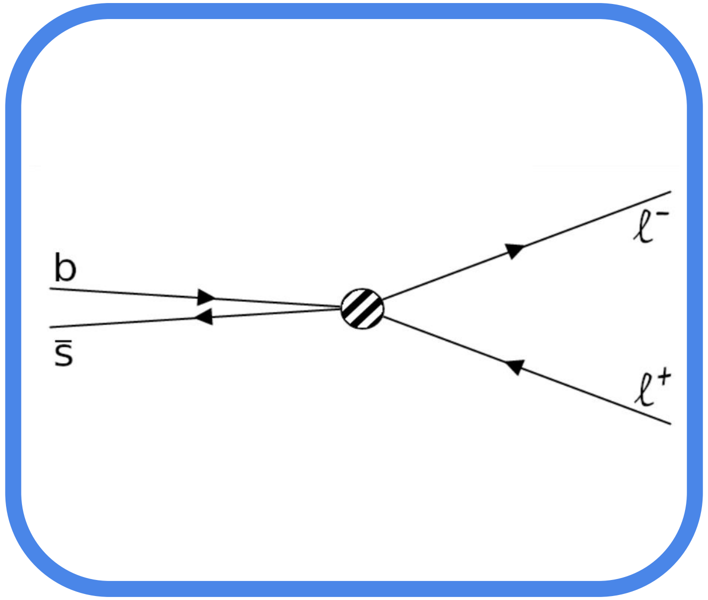
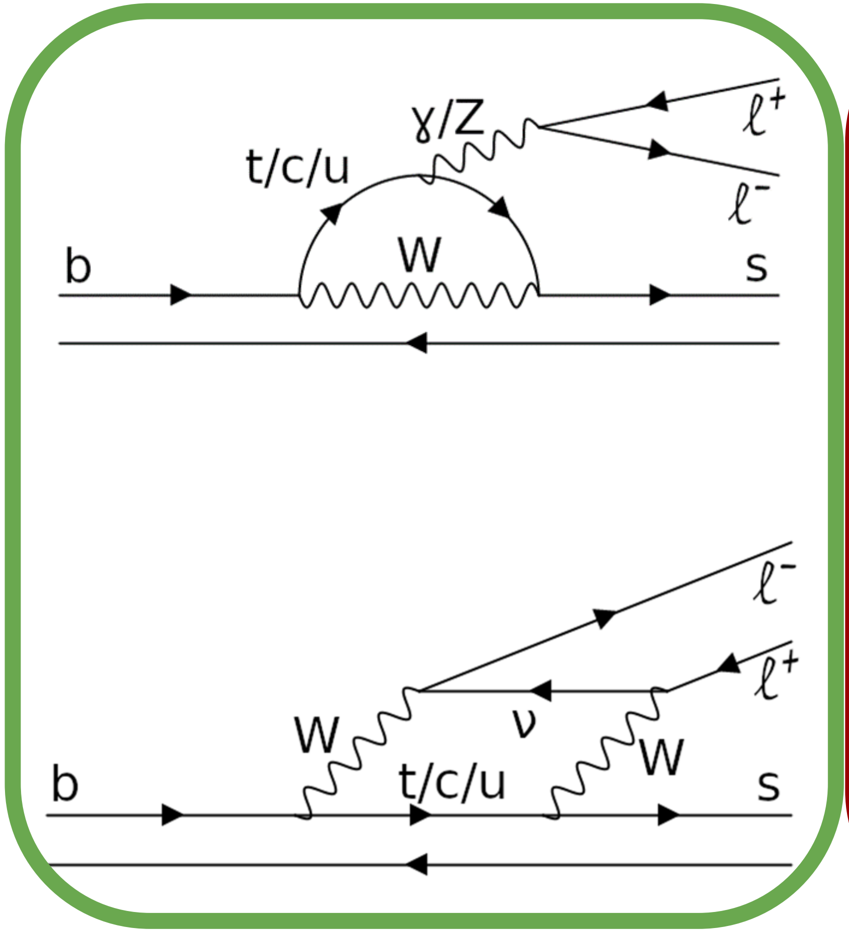


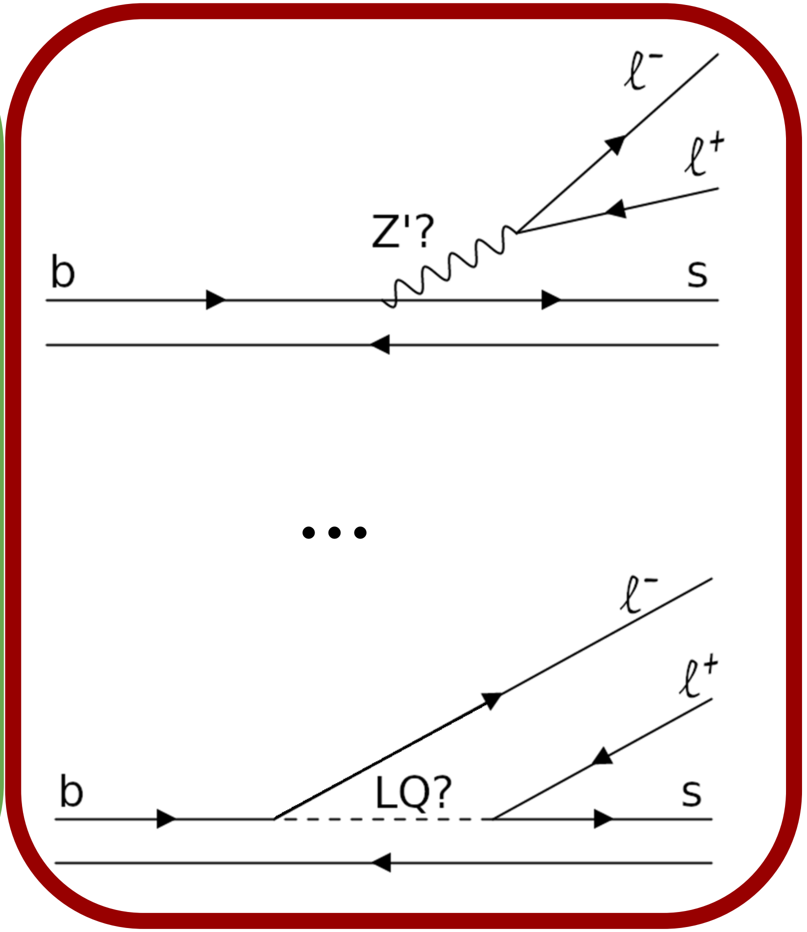


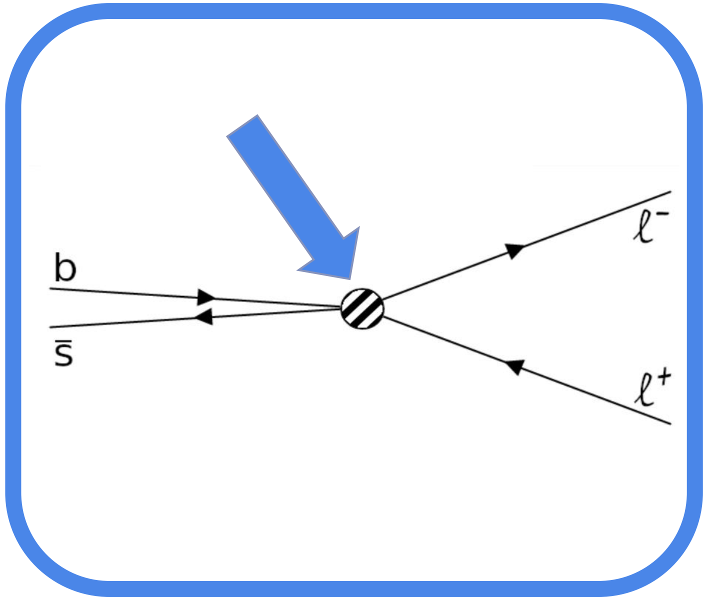
Effective Field Theory (b→sll)

SM



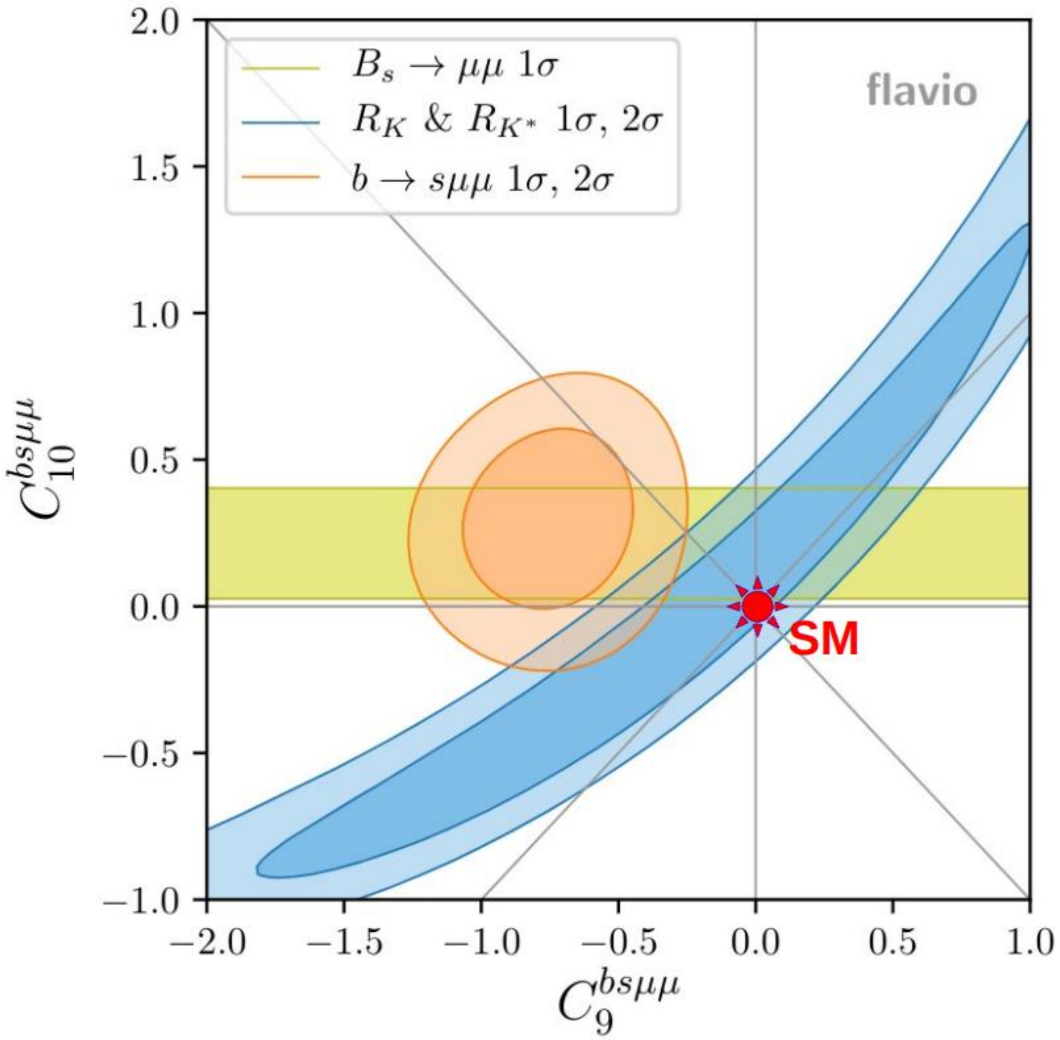
NP





Effective Field Theory (b→sll)

[arXiv:2212.10497]



Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \sum_i C_i \mathcal{O}_i$$

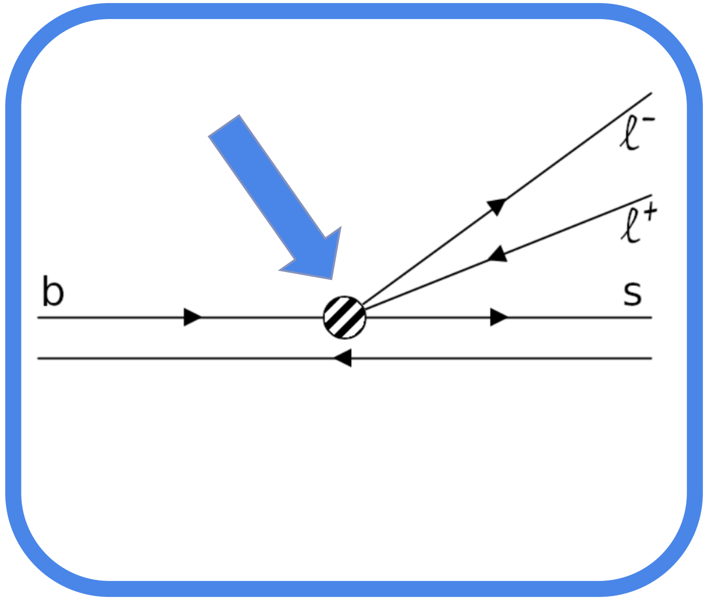
(model independent)

Operators: O_i

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Semi-leptonic decays



Future Project Goals (samples)

1. Apply machine learning classifiers (BDT and NN) to discriminate signal from background

1. Samples:
   1. $B^0 \rightarrow (K^{*0})(J/\Psi)$ signal channel collected with **dimuon** triggers
   2. $B^0 \rightarrow (K^{*0})(\mu\mu)$ signal channel collected with **dimuon** triggers
   3. $B^0 \rightarrow (K^{*0})(J/\Psi)$ signal channel collected with special "**B-parking**" triggers (*)
   4. $B^0 \rightarrow (K^{*0})(\mu\mu)$ signal channel collected with special "**B-parking**" triggers (*)

1. Compare the performance and the figure of merit obtained

$$FOM = \frac{S}{\sqrt{S+B}}$$

$B^0 \rightarrow K^{*0}\ J/\Psi$ (Binned Likelihood Fit)

Signal PDF:
Gaussian + Crystal Ball

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{x-\bar{x}}{\sigma}\right)^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha|,$$

$$N = \frac{1}{\sigma(C+D)},$$

$$C = \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$D = \sqrt{\frac{\pi}{2}}\left(1 + \operatorname{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right).$$

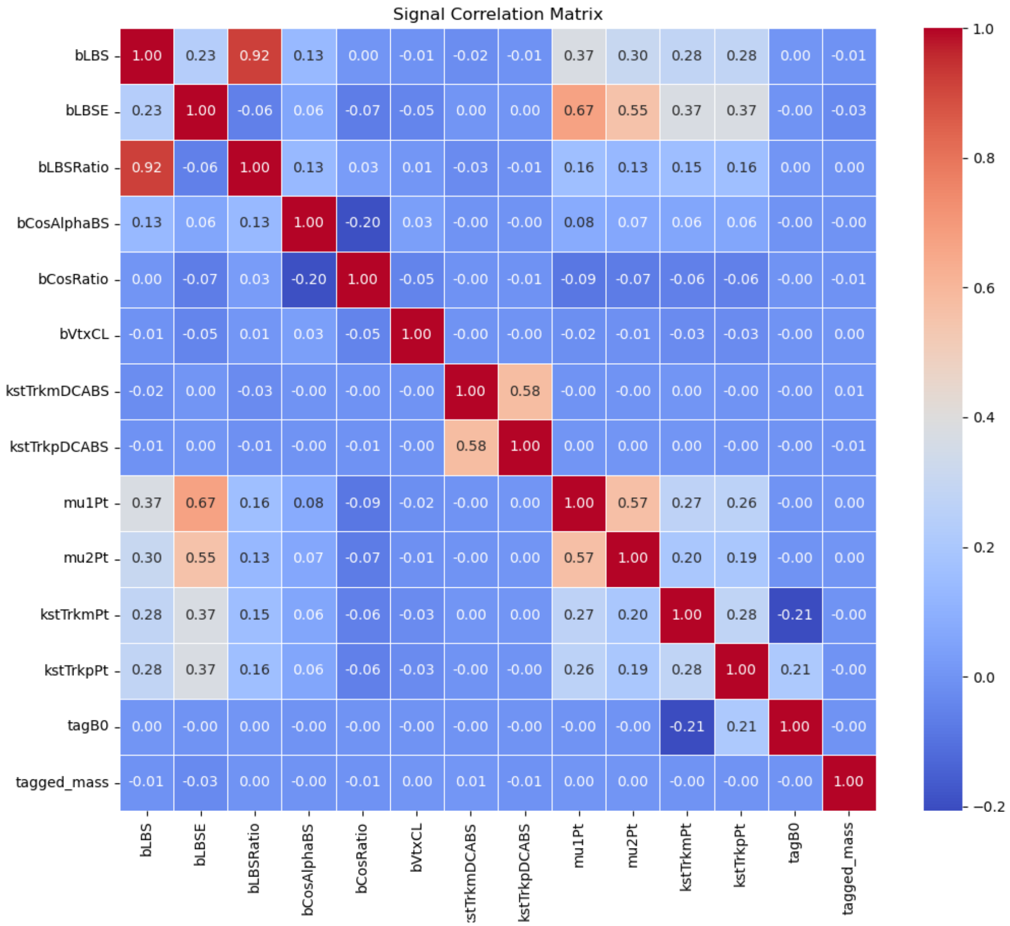
$$\operatorname{erf} z = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2}\,\mathrm{d}t$$

Background PDF:
Exponential

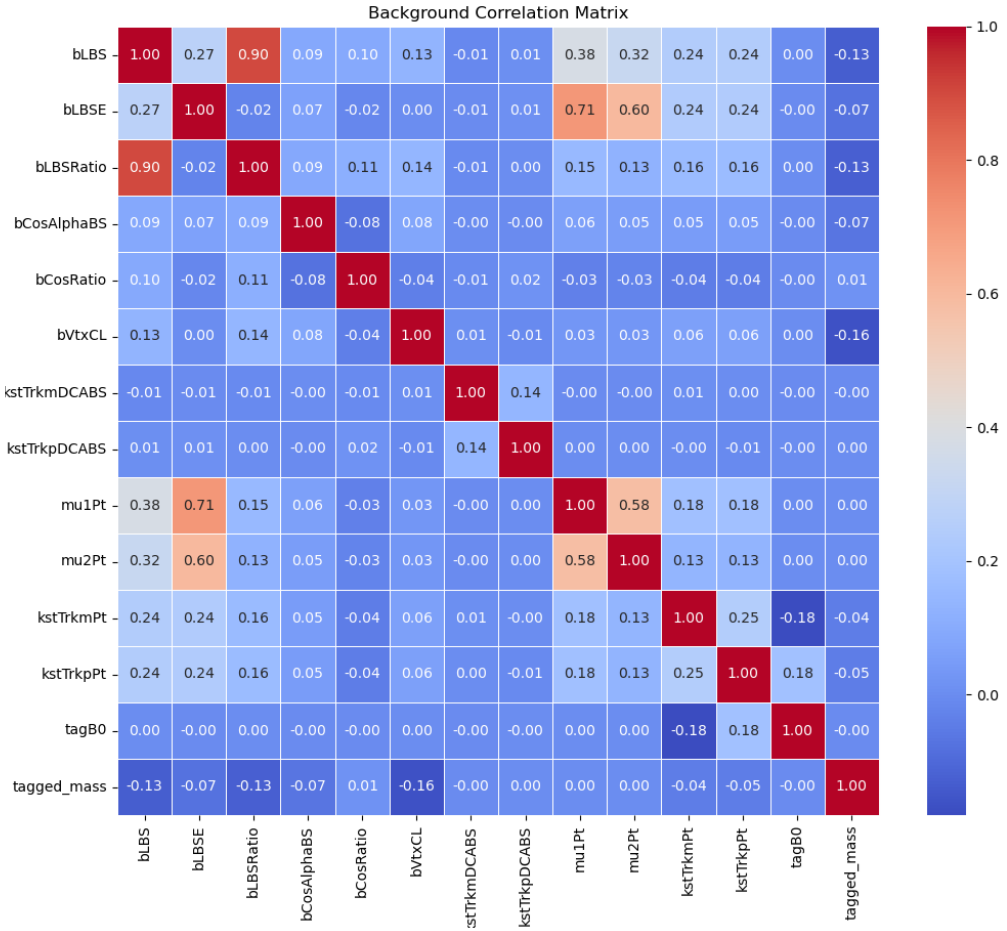
$$\mathrm{RooExponential}(x, c) = \mathcal{N} \cdot \exp(c \cdot x)$$

Correlation Matrix

Signal



Background



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