Test of Lepton Flavour Universality using B_s semileptonic decays: normalization channel selection

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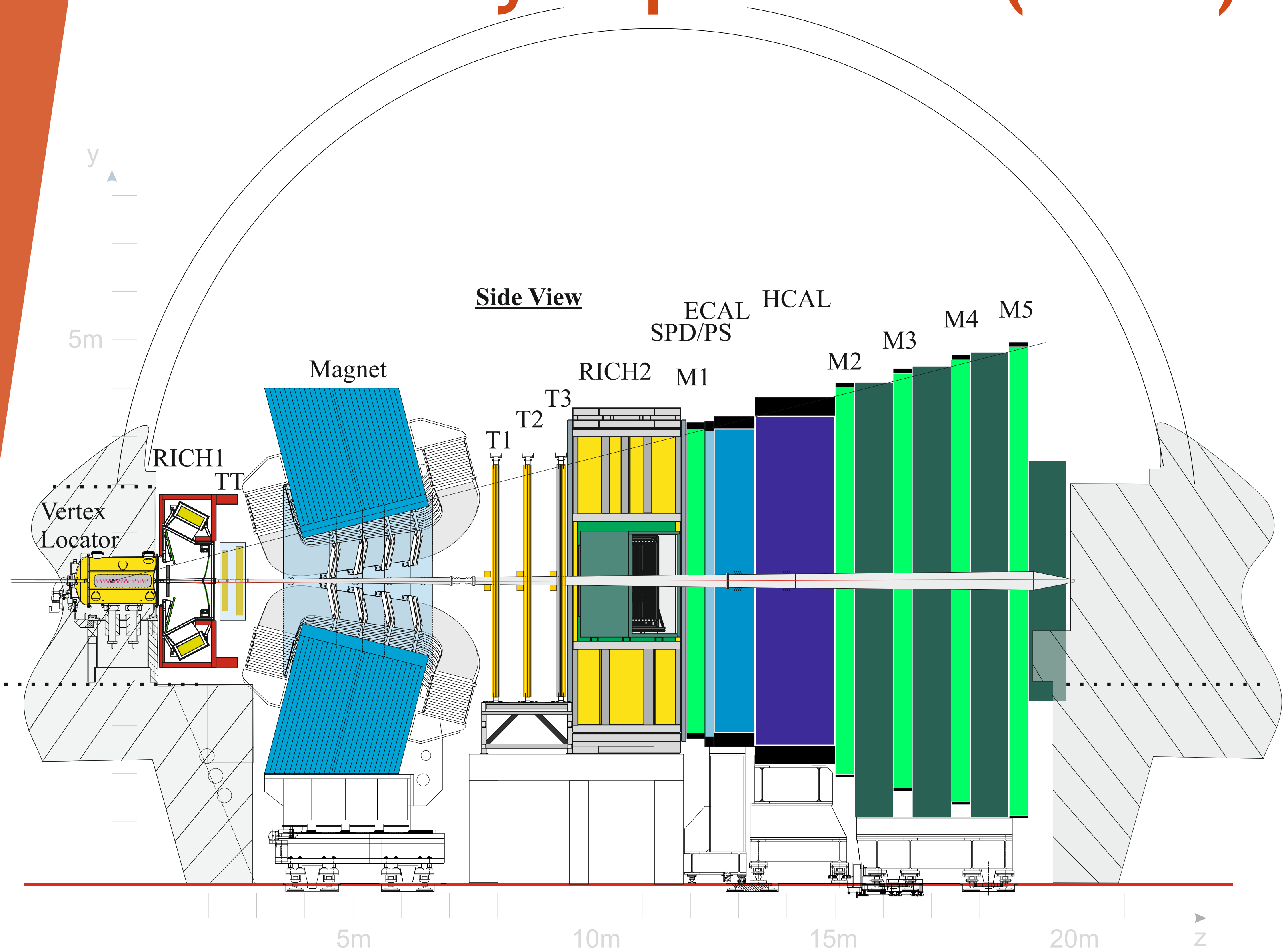
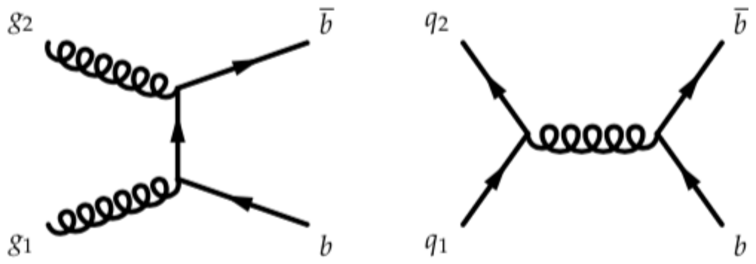
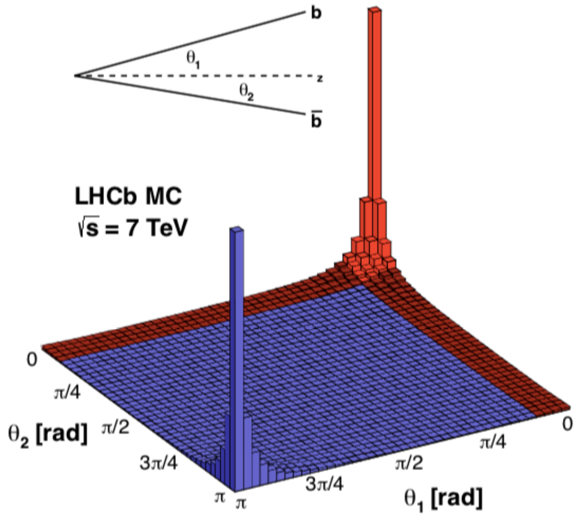
LHC beauty experiment (LHCb)



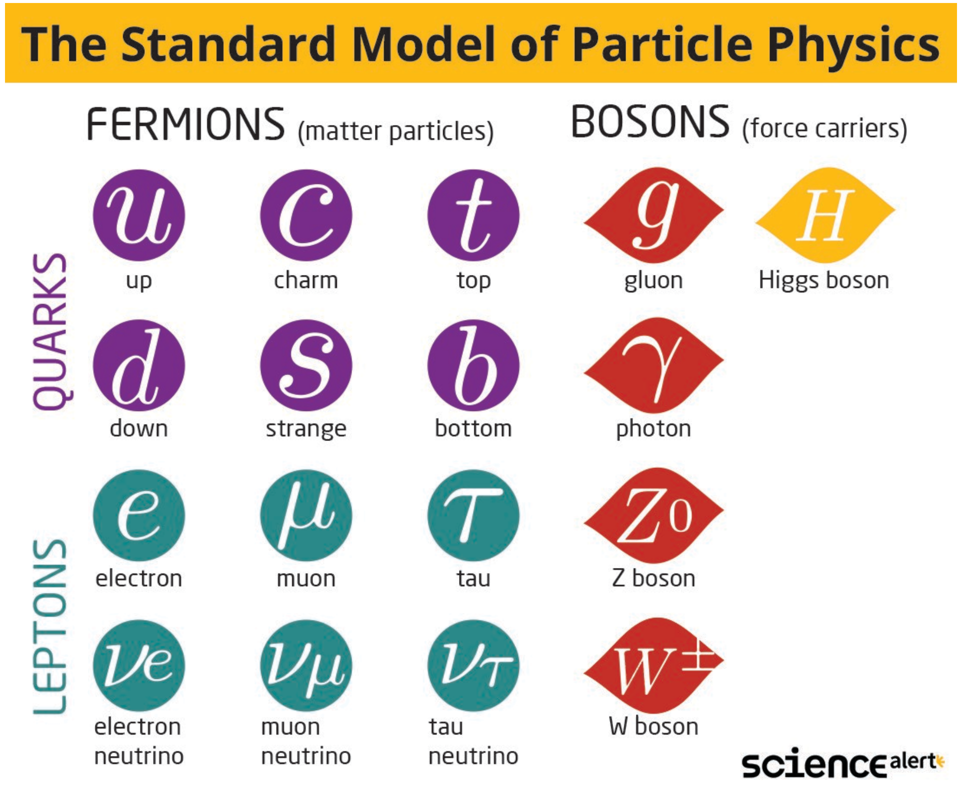
b-quark production





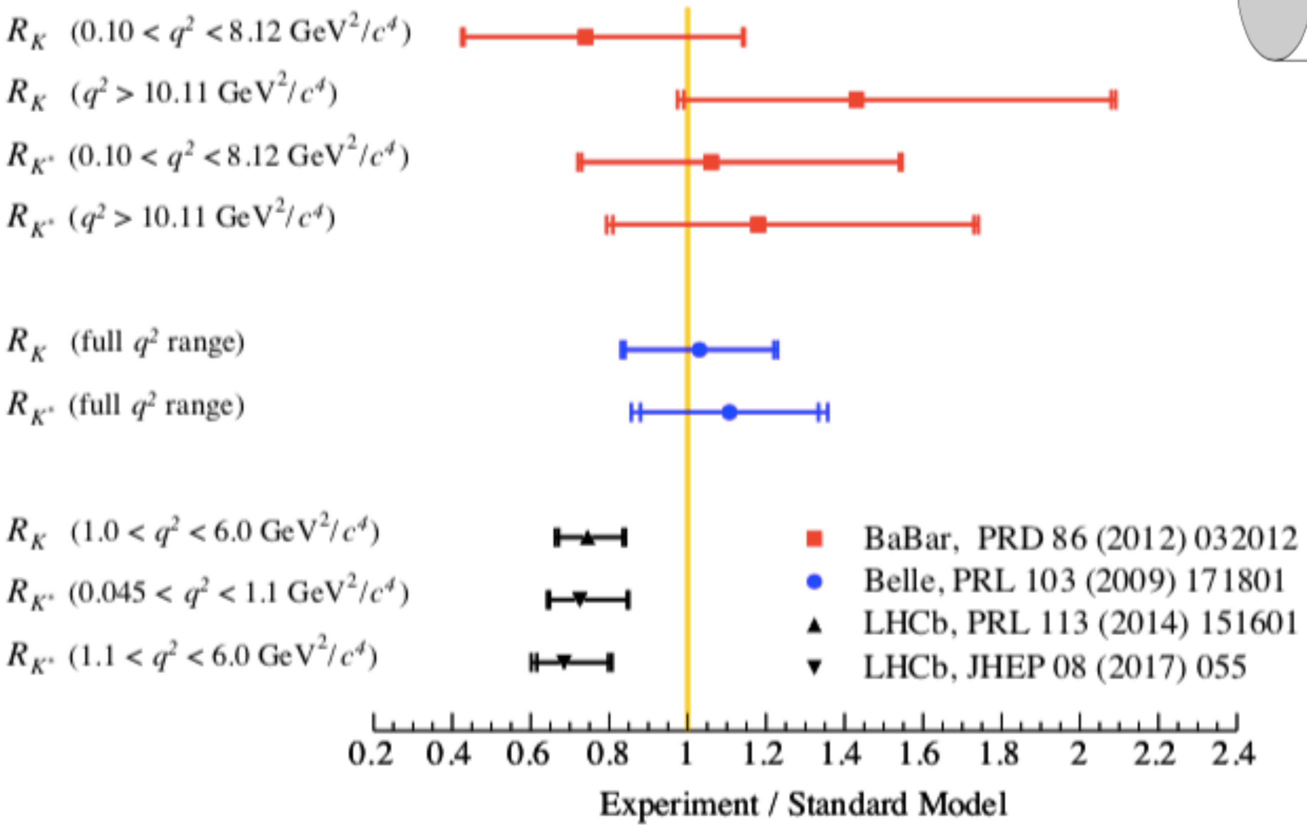
Lepton Flavour Universality (LFU) in the SM

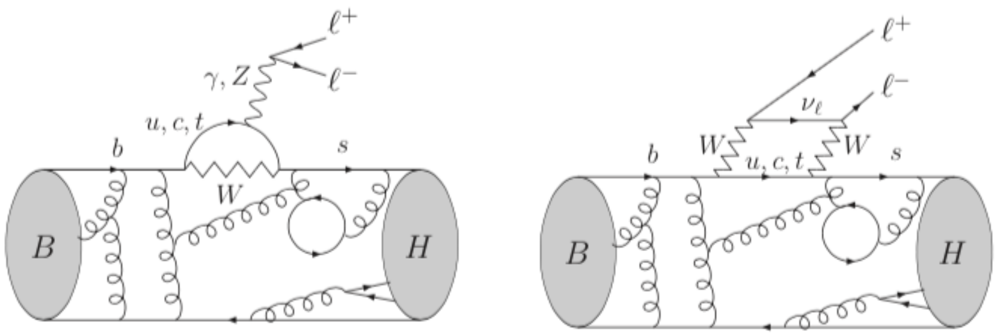
The photon, the W and the Z bosons couple in exactly the same manner to the three lepton generations.



Decay Ratio	Precision	Deviation from SM
$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}}$	0.3 %	$<1\ \sigma$
$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}}$	0.3 %	$<1\ \sigma$
$\frac{\mathcal{B}(W^-\to e^-\bar{\nu}_e)}{\mathcal{B}(W^-\to\mu^-\bar{\nu}_\mu)}$	0.08 %	$<1\ \sigma$
$\frac{2\Gamma_{W^-\to\tau^-\bar{\nu}_\tau}}{\Gamma_{W^-\to e^-\bar{\nu}_e}+\Gamma_{W^-\to\mu^-\bar{\nu}_\mu}}$	2.3 %	$2.6\ \sigma$
$\frac{\Gamma_{K^-\to e^-\bar{\nu}_e}}{\Gamma_{K^-\to\mu^-\bar{\nu}_\mu}}$	0.4 %	$1.2\ \sigma$
$\frac{\Gamma_{\pi^-\to e^-\bar{\nu}_e}}{\Gamma_{\pi^-\to\mu^-\bar{\nu}_\mu}}$	0.3 %	$1.3\ \sigma$
$\frac{\Gamma_{D_s^-\to\tau^-\bar{\nu}_\tau}}{\Gamma_{D_s^-\to\mu^-\bar{\nu}_\mu}}$	6.1 %	$<1\ \sigma$
$\frac{\Gamma_{J/\psi\to e^+e^-}}{\Gamma_{J/\psi\to\mu^+\mu^-}}$	0.3 %	$<1\ \sigma$

LFU experimental tests: FCNC $H_b \to H_s \ell^+ \ell^-$



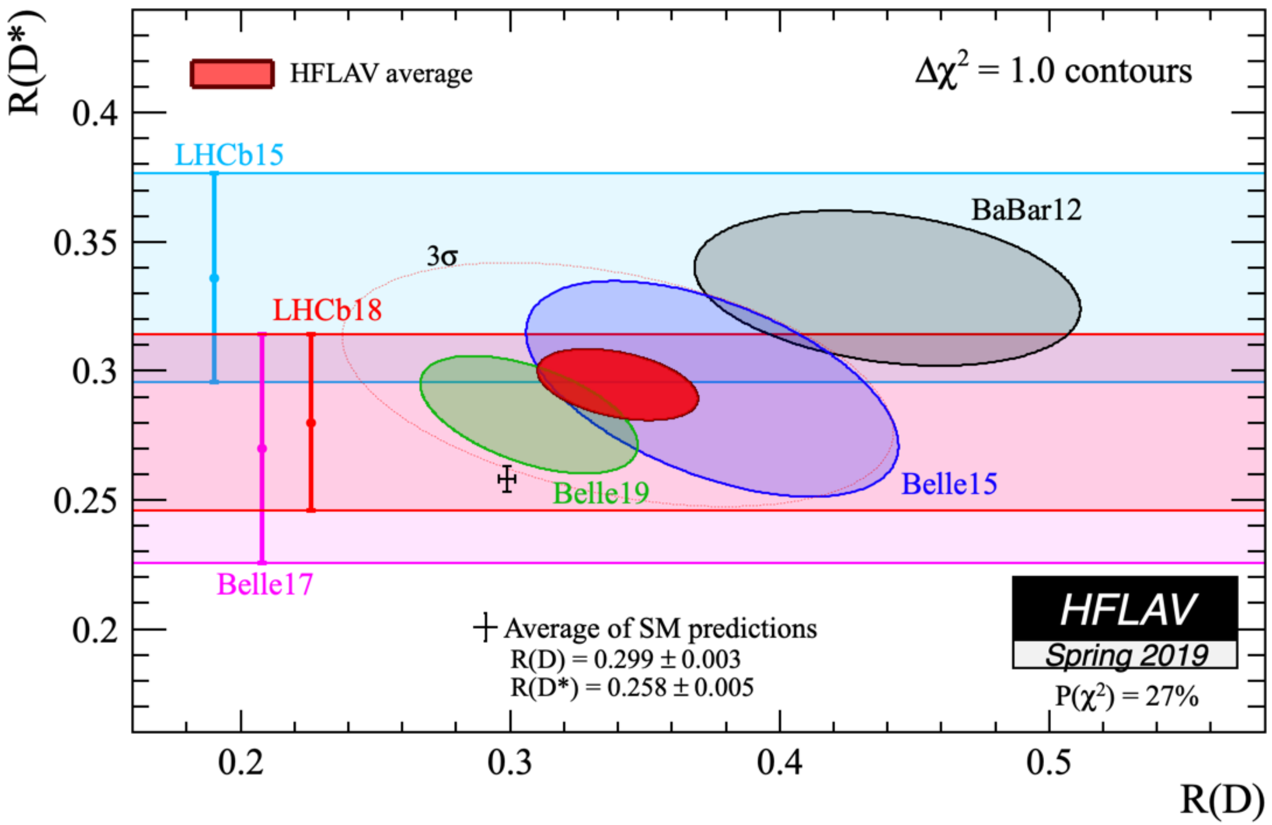


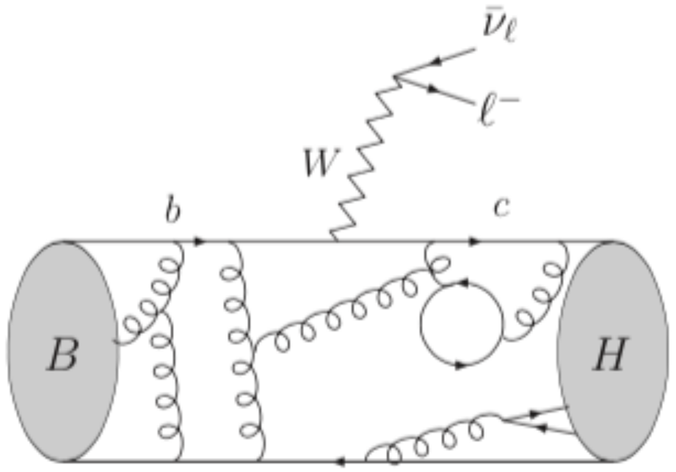
$$R(H_s) = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(H_b \to H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(H_b \to H_s e^+ e^-)}{dq^2} dq^2},$$

With H_b b-hadrons such as B^0 and $B^{\pm}$ and H_s hadrons containing an s-quark such as K and K^* mesons

LHCb measurements are **~2.5 σ** lower than the SM expectations

LFU experimental tests: FCCC $H_b \to H_c \ell^- \bar{\nu}_\ell$





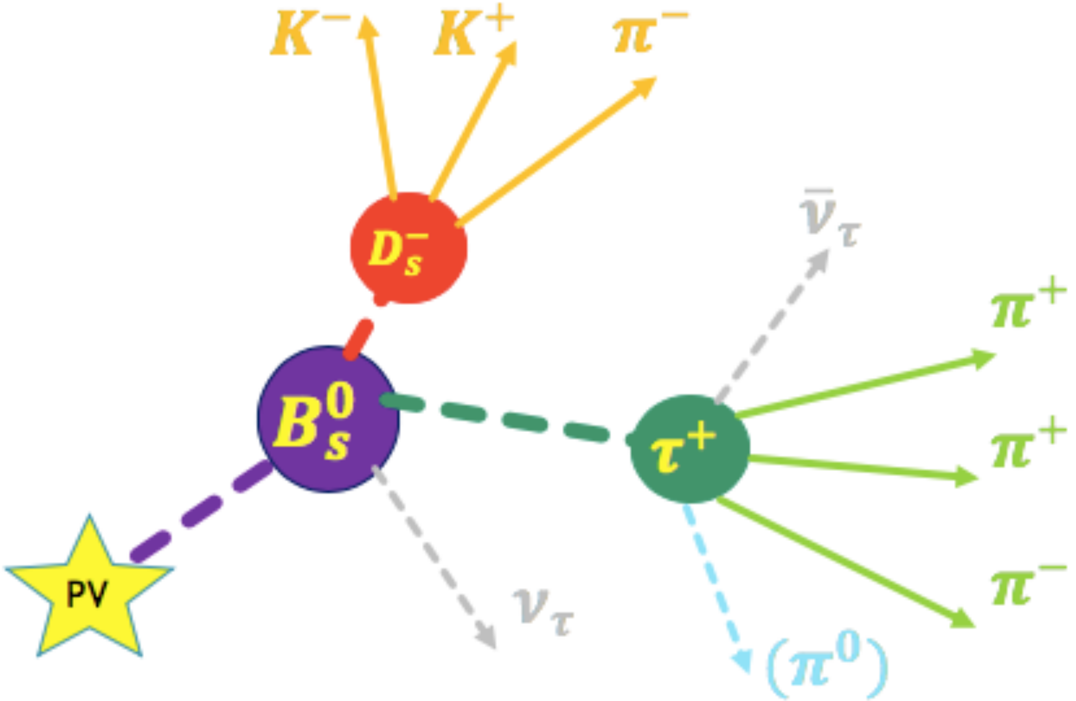
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell^- \bar{\nu}_\ell)}.$$

With H_b b-hadrons such as B^0 and $B^\pm$ and H_c hadrons containing an c-quark such as D, D^* and J/ψ mesons

The overall difference with the SM predictions corresponds to **3.08 σ**

The $R(D_s)$ measurement

- Study of the semileptonic $B_s^0 \to D_s^- \ell^+ \nu_\ell$ decay ratio
- $R(D_s) = \dfrac{BF(B_s^0 \to D_s^- \tau^+ \nu_\tau)}{BF(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$



- $B_s^0 \to D_s^- \tau^+ \nu_\tau$ with:
  - $\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0)\, \bar{\nu}_\tau$ 3-prong hadronic decay
  - $D_s^- \to K^+ K^- \pi^-$

R(D_s) measurement technique

- Introducing a normalization channel:

- $$R(D_s) = \frac{BF(B_s^0 \to D_s^- \tau^+ \nu_\tau)}{BF(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \underbrace{\frac{BF(B_s^0 \to D_s^- \tau^+ \nu_\tau)}{BF\ norm.}}_{\boldsymbol{K}} \underbrace{\frac{BF\ norm.}{BF(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\boldsymbol{\alpha}}$$

- $$K = \frac{N_{sign}}{\varepsilon_{sign}} \frac{\varepsilon_{norm}}{N_{norm}} \frac{1}{BF(\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0)\, \bar{\nu}_\tau) \times BF(D_s^- \to K^+ K^- \pi^-)}$$

  - N_{sign}, N_{norm} : signal and normalization yield
  - ε_{sign}, ε_{norm} : signal and normalization efficiency

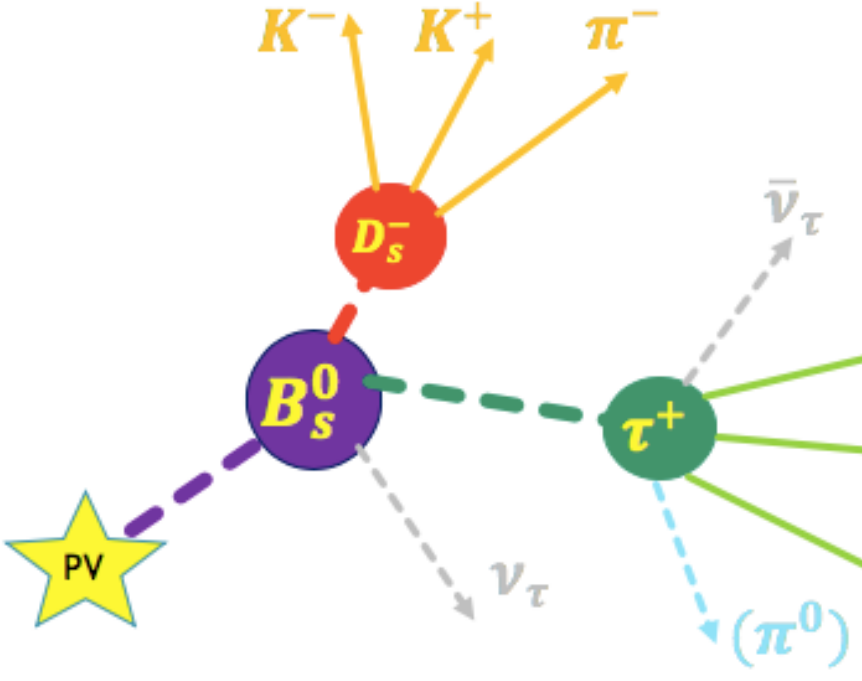
SIGNAL:

$B_s^0 \rightarrow D_s^- \tau^+ \nu_\tau$

with

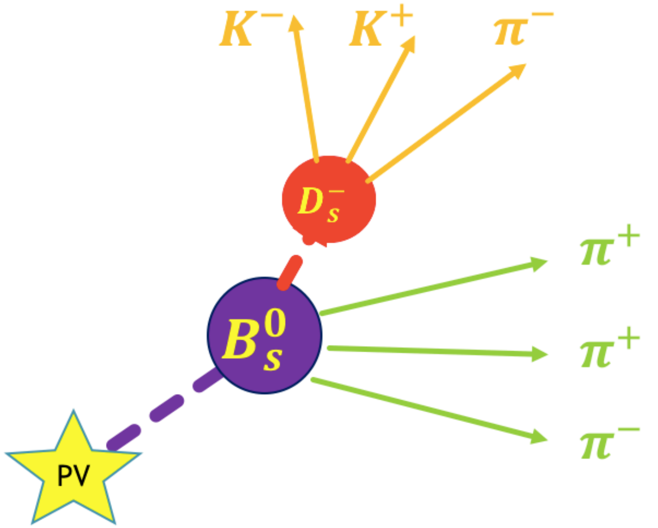
$\tau^+ \rightarrow \pi^+\pi^-\pi^+(\pi^0)\,\bar{\nu}_\tau$

$D_s^- \rightarrow K^+K^-\pi^-$

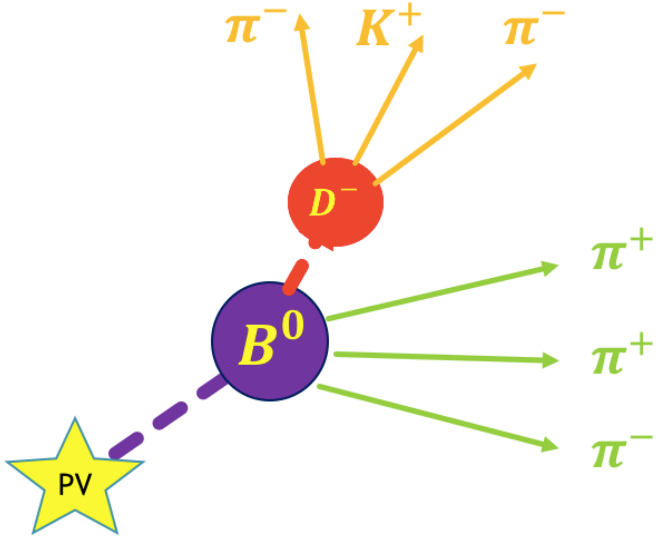


Normalization candidates

$B_s^0 \rightarrow D_s^-(\rightarrow K^+K^-\pi^-)\,\pi^+\pi^-\pi^+$



$B^0 \rightarrow D^-(\rightarrow K^+\pi^-\pi^-)\,\pi^+\pi^-\pi^+$



Uncertainty from external contributions

Normalization: $B_s^0 \rightarrow D_s\, 3\pi$ with $D_s \rightarrow KK\pi$

$$R(D_s) = \frac{N_{sign}}{\varepsilon_{sign}} \frac{\varepsilon_{norm}}{N_{norm}} \frac{1}{BF(\tau \rightarrow 3\pi\, (\pi^0)\nu_\tau)} \frac{\cancel{BF(D_s \rightarrow KK\pi)}}{\cancel{BF(D_s \rightarrow KK\pi)}} \times \frac{BF(B_s^0 \rightarrow D_s\, 3\pi)}{BF(B_s^0 \rightarrow D_s\, \mu\, \nu_\mu)}$$

FROM ANALYSIS

EXTERNAL INPUTS

19.10 % relative uncertainty on R(Ds)

Normalization: $B^0 \rightarrow D\, 3\pi$ with $D \rightarrow K\pi\pi$

$$R(D_s) = \frac{N_{sign}}{\varepsilon_{sign}} \frac{\varepsilon_{norm}}{N_{norm}} \frac{1}{BF(\tau \rightarrow 3\pi\, (\pi^0)\nu_\tau)} \frac{BF(D \rightarrow K\pi\pi)}{\frac{f_s}{f_d} BF(D_s \rightarrow KK\pi)} \times \frac{BF(B^0 \rightarrow D\, 3\pi)}{BF(B_s^0 \rightarrow D_s\, \mu\, \nu_\mu)}$$

FROM ANALYSIS

EXTERNAL INPUTS

14.26 % relative uncertainty on R(Ds)

Common signal-normalization selection

- **Backgrounds**:
  - b-hadrons decays with similar topology or mis-identified final states
  - random combination of tracks (combinatorial)
- **Selection**:
  - Preliminary selection composed trigger cuts and requirements on mass and final states PIDs based on Dalitz Plot and decay mis-identification
  - Multivariate analysis → Boosted Decision Tree (BDT) machine learning technique
- MC samples and Data from 2012

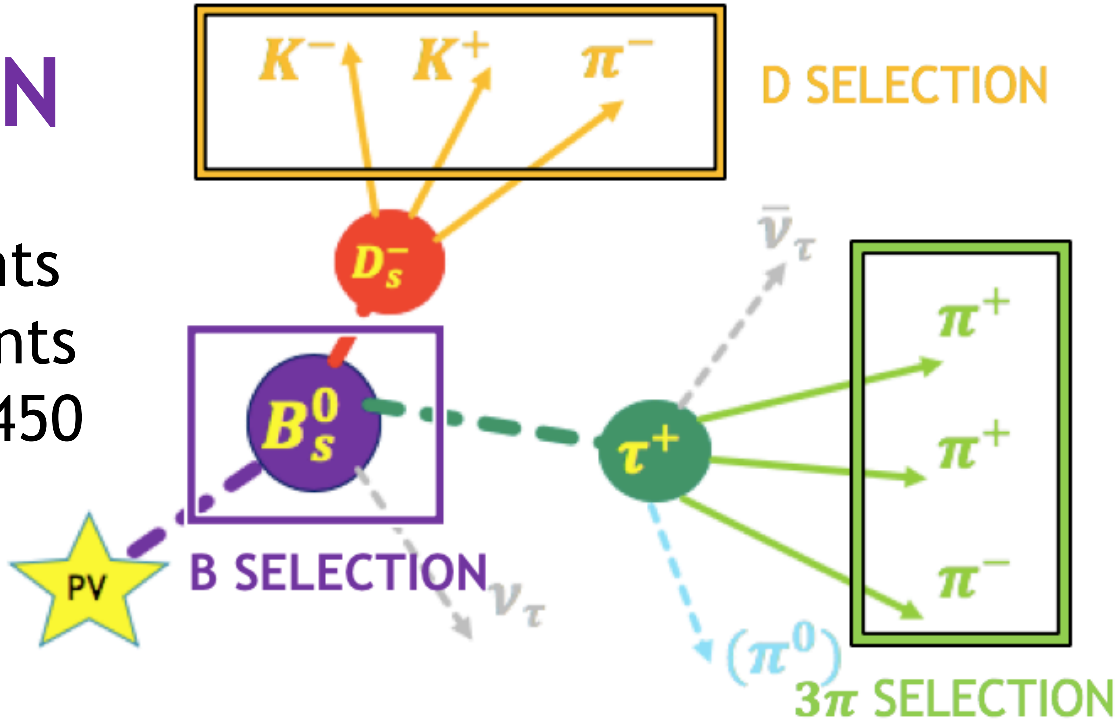
Multivariate common signal-normalization selection: training events

D SELECTION

- Signal: MC selected events
- Bkg: Data events with m(Bs) >5200 MeV/c^2 and Ds mass sidebands

B SELECTION

- Signal: MC selected events
- Bkg: Data events with m(Bs) >5450 MeV/c^2



3π SELECTION

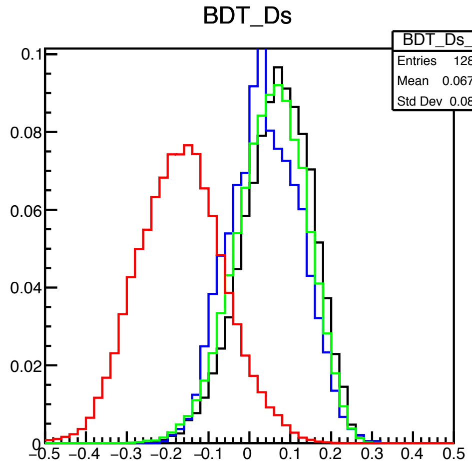
- Signal: MC selected events
- Bkg: Data events with m(Bs) >5450 MeV/c^2

Multivariate selection: BDT outputs

Legend:
- SIGNAL
- BKG
- NORM Bs
- NORM Bd

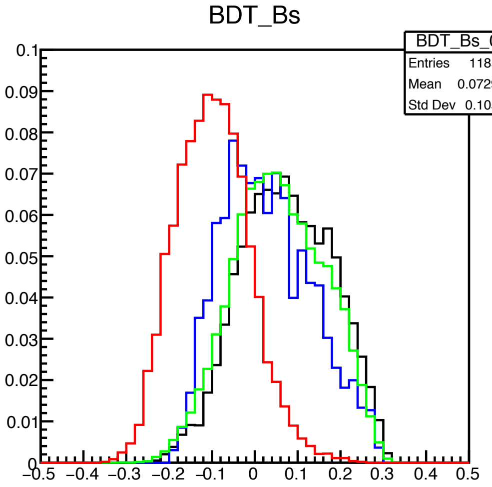
D SELECTION

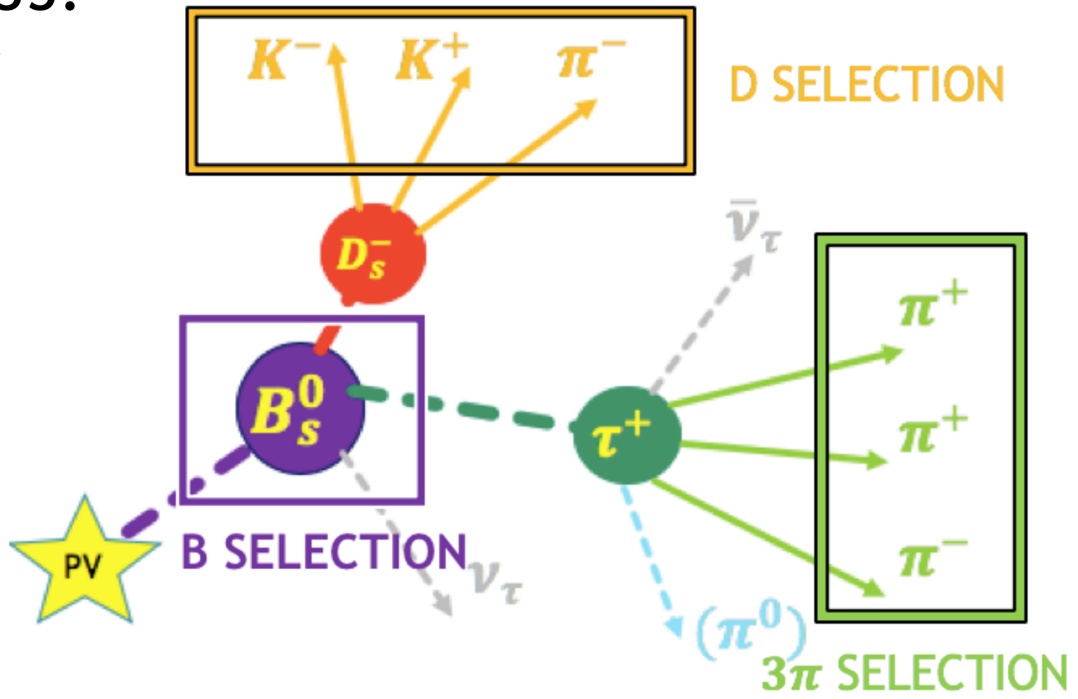
Chosen cut at -0.0876:
- 95 % efficiency
- 77.5 % bkg rejection



B SELECTION

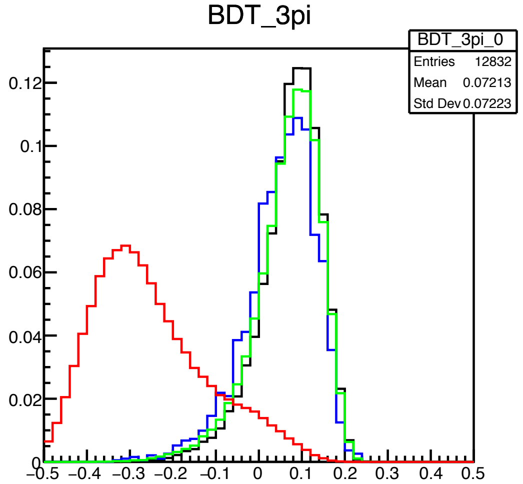
Chosen cut at -0.0655:
- 90 % efficiency
- 65.63 % bkg rejection





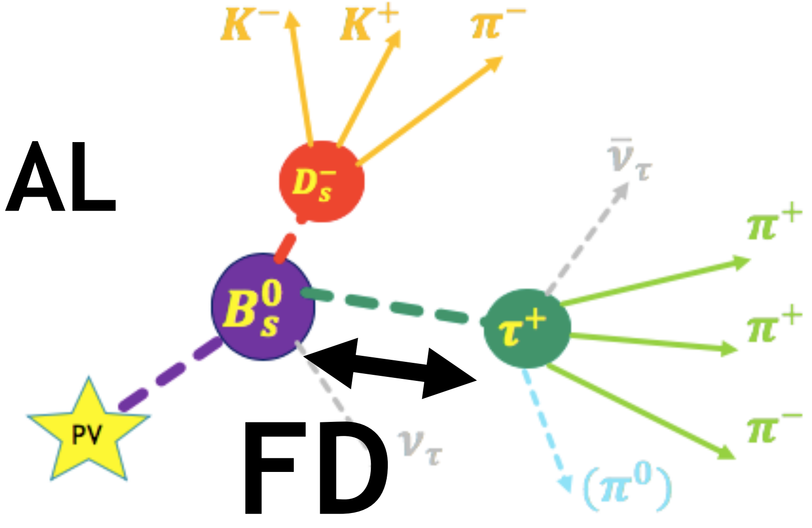
3π SELECTION

Chosen cut at -0.0727:
- 95 % efficiency
- 87.75 % bkg rejection



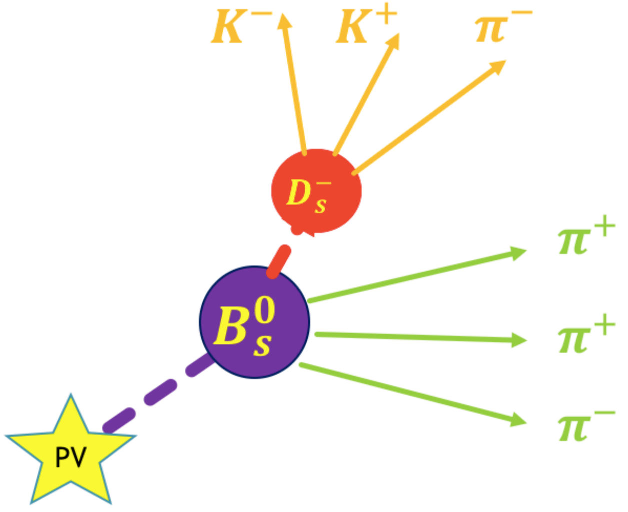
Normalization separation from signal

SIGNAL

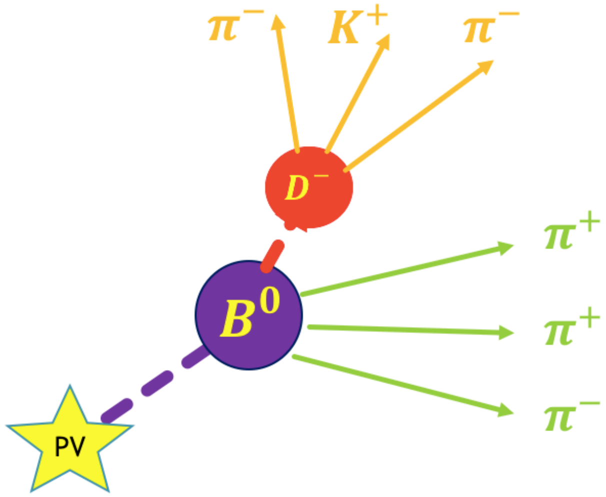


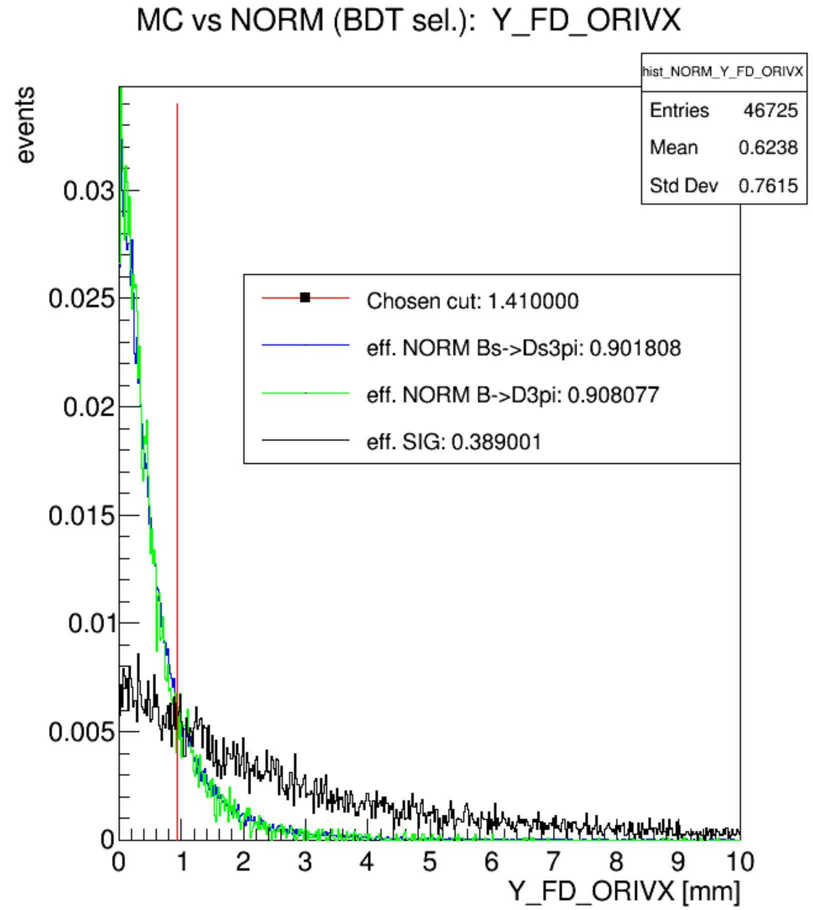
CHOSEN CUT 1.41 mm:
NORM Efficiency 90%

NORM B_s



NORM B_d





Efficiencies

Decay	$B_s \to D_s\tau\nu$	$B_s \to D_s3\pi$	$B \to D3\pi$
	ϵ_{sig} [%]	ϵ_{norm} [%]	ϵ_{norm} [%]
Generation	14.878 ± 0.017	3.414 ± 0.005	15.40 ± 0.02
Filtering	0.245 ± 0.001	2.459 ± 0.007	0.47 ± 0.003
Stripping	51.9 ± 0.2	75.67 ± 0.12	70.5 ± 0.3
MC truth	61.9 ± 0.3	75.17 ± 0.14	68.1 ± 0.3
Trigger	96.89 ± 0.14	96.90 ± 0.07	97.32 ± 0.14
D-D_s sel.	82.6 ± 0.3	81.36 ± 0.15	55.31 ± 0.43
BDTs	83.5 ± 0.3	78.14 ± 0.18	67.6 ± 0.5
FD cut	61.0 ± 0.5	90.07 ± 0.14	90.1 ± 0.4
Total	$(4.57 \pm 0.06)\times10^{-5}$	$(26.43 \pm 0.13)\times10^{-5}$	$(11.39 \pm 0.17)\times10^{-5}$

B_s norm. channel

$$\frac{\epsilon_{norm}}{\epsilon_{sign}} = 5.79 \pm 0.08$$

1.4 % statistical uncertainty on R(Ds)

B_d norm. channel

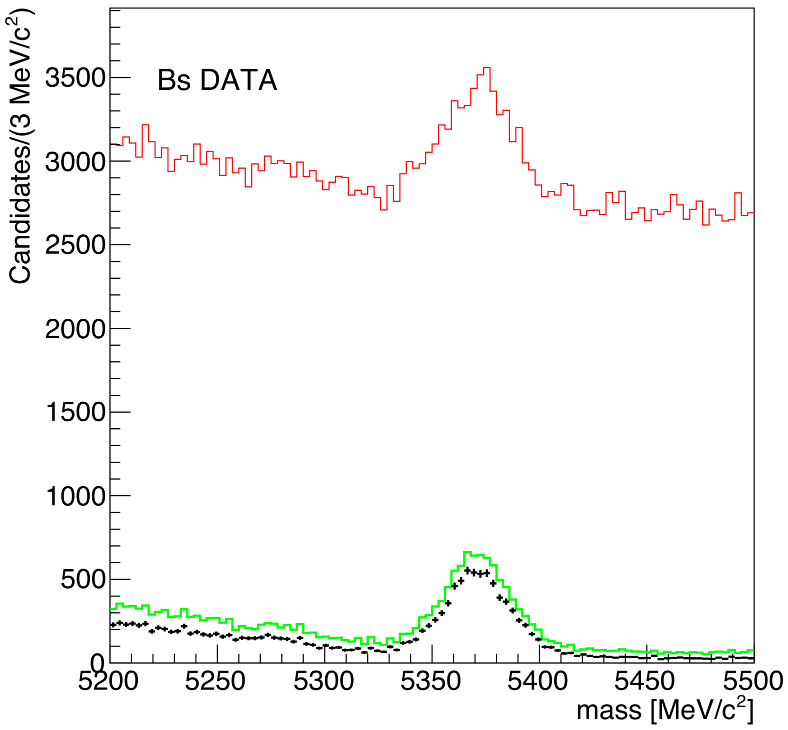
$$\frac{\epsilon_{norm}}{\epsilon_{sign}} = 2.49 \pm 0.05$$

1.3% statistical uncertainty on R(Ds)

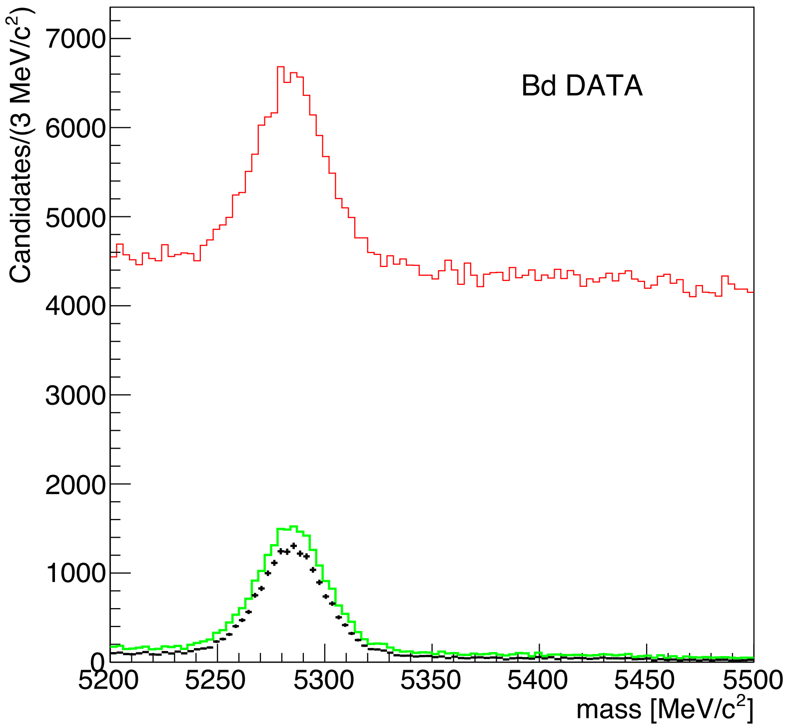
Selection applied on data

- The BDT selection effect on the background suppression is evident
- The signal candidates have a continuous distribution from the B_s mass value down to 3000 MeV/c^2, due to the inclusive reconstruction

B_s DATA



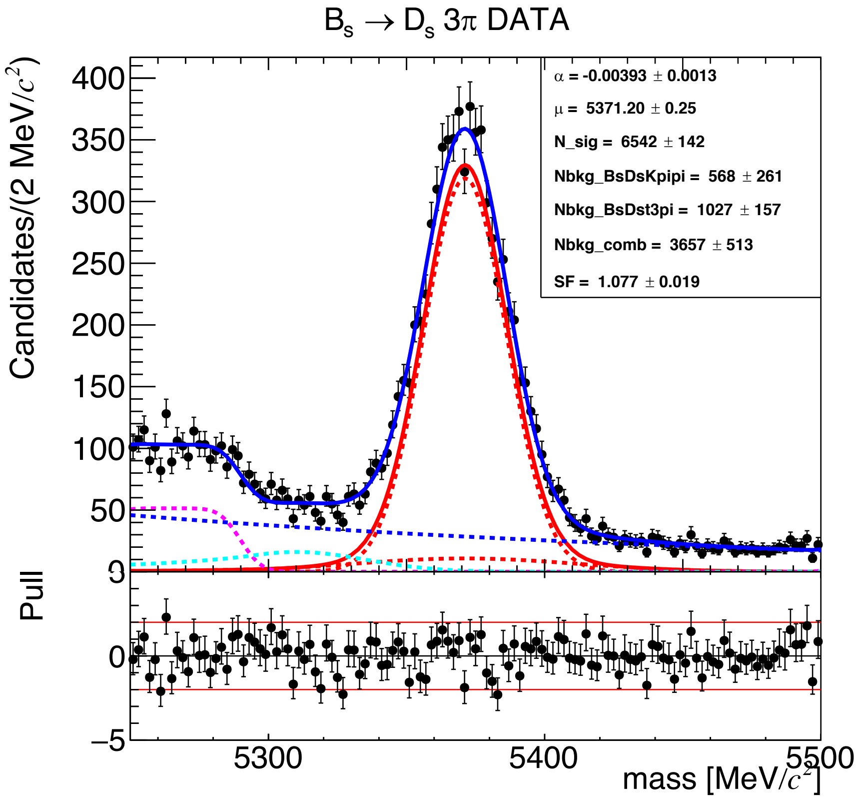
B_d DATA



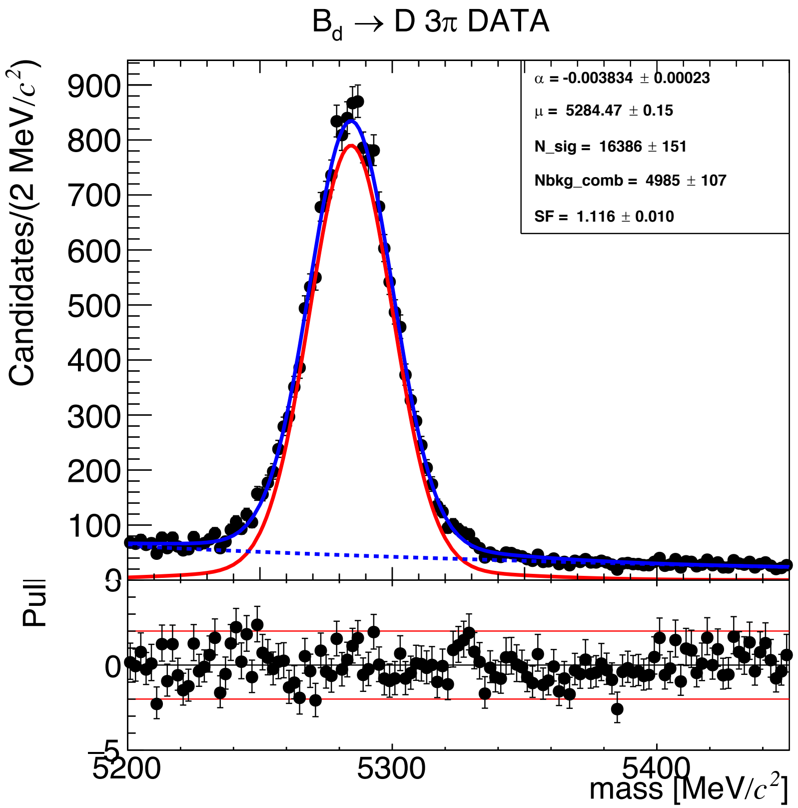
Legend:
- Preliminary selection
- BDT selection
- FD cut

Normalization yields evaluated on data

B_s DATA



B_d DATA



$N_{\text{norm}} = 6542 \pm 142$ → **2.2 %** statistical uncertainty on R(Ds)

$N_{\text{norm}} = 16386 \pm 151$ → **0.9 %** statistical uncertainty on R(Ds)

Summary of systematics

- Systematics on the normalization yield:
  - Choice of the fit model
  - Analysis of background sources from other b-hadrons decays
- Systematics on the selection efficiency ratio:
  - PID calibration on data
  - Trigger selection efficiencies
  - Momentum scale calibration
  - Data-MC differences evaluated from the yields

Contribution	B_s norm. channel [%]	B_d norm. channel [%]
Fit model	1.2	0.9
Particle Identification	0.3	4.4
Trigger	1.0	1.0
Momentum scale calibration	< 0.1	0.4
Data-MC differences	<0.1	1.9
Total	1.6	5.0

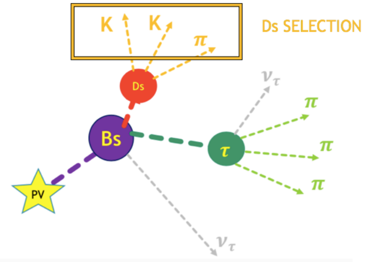
Final results and Conclusions

Contribution	B_s norm. channel [%]	B_d norm. channel [%]
Normalization yield	2.2	0.9
MC statistics	1.4	1.3
Systematic uncertainties	1.6	5.0
External contributions	19.1	14.3
Total	19.3	15.2

- The $B^0 \rightarrow D^-(\rightarrow K^+\pi^-\pi^-)\,\pi^+\pi^-\pi^+$ is the **best normalization channel for the R(Ds) analysis** because it contributes to a smaller total relative uncertainty on the measurement of **15.2 %** compared to the **19.3 %** of the $B_s^0 \rightarrow D_s^-(\rightarrow K^+K^-\pi^-)\,\pi^+\pi^-\pi^+$ norm channel
- This study gives strong directions on how to define the overall analysis strategy and possible uncertainties related to the normalization channels

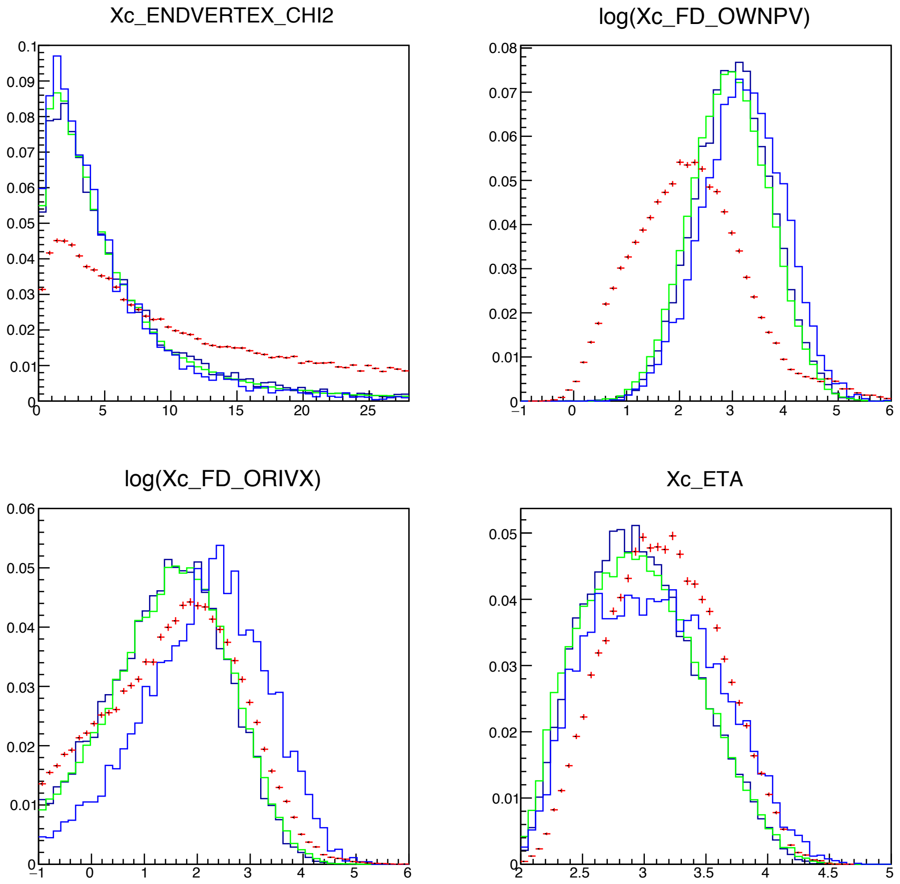
BACKUP

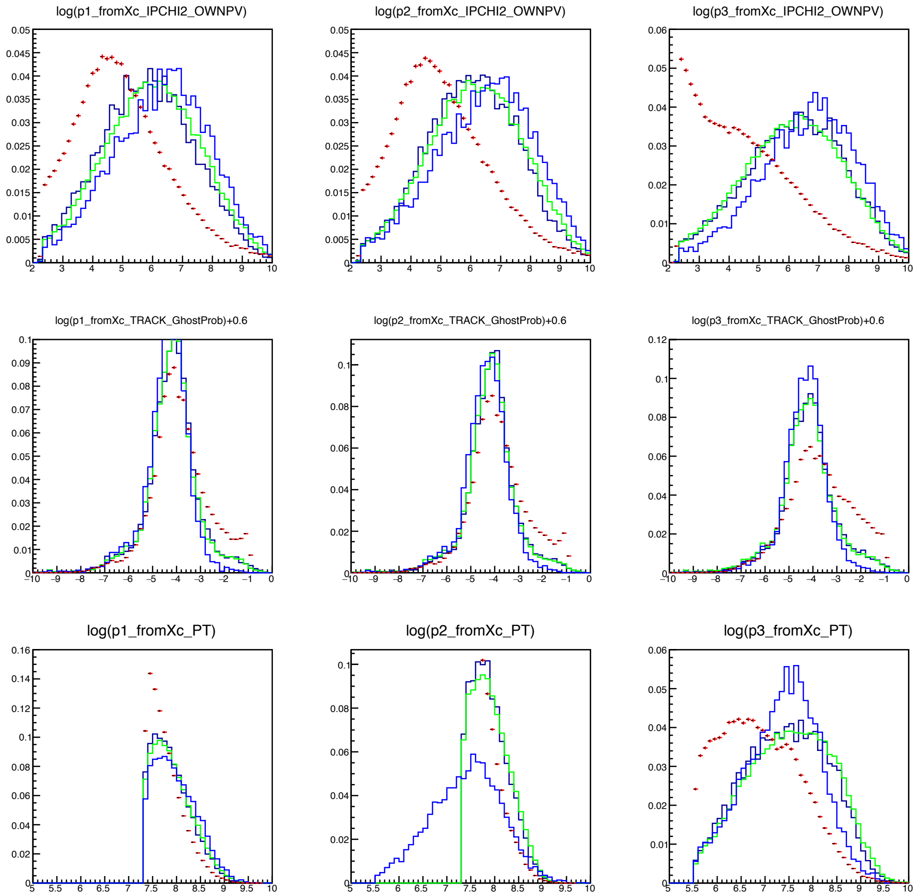
D SELECTION



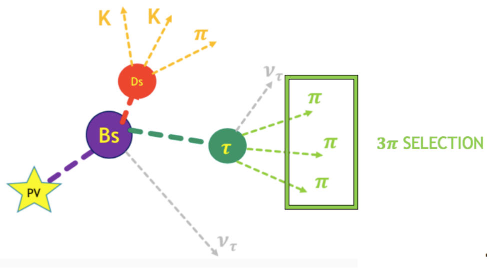
- BDT_D variables:
  - Ds: vertex chi2, flight distance (from PV and Bs), pseudorapidity
  - Ds daughters: PT, impact parameter chi2 (from PV), track ghost prob.

Legend:
- SIGNAL
- BKG
- NORM Bs
- NORM Bd



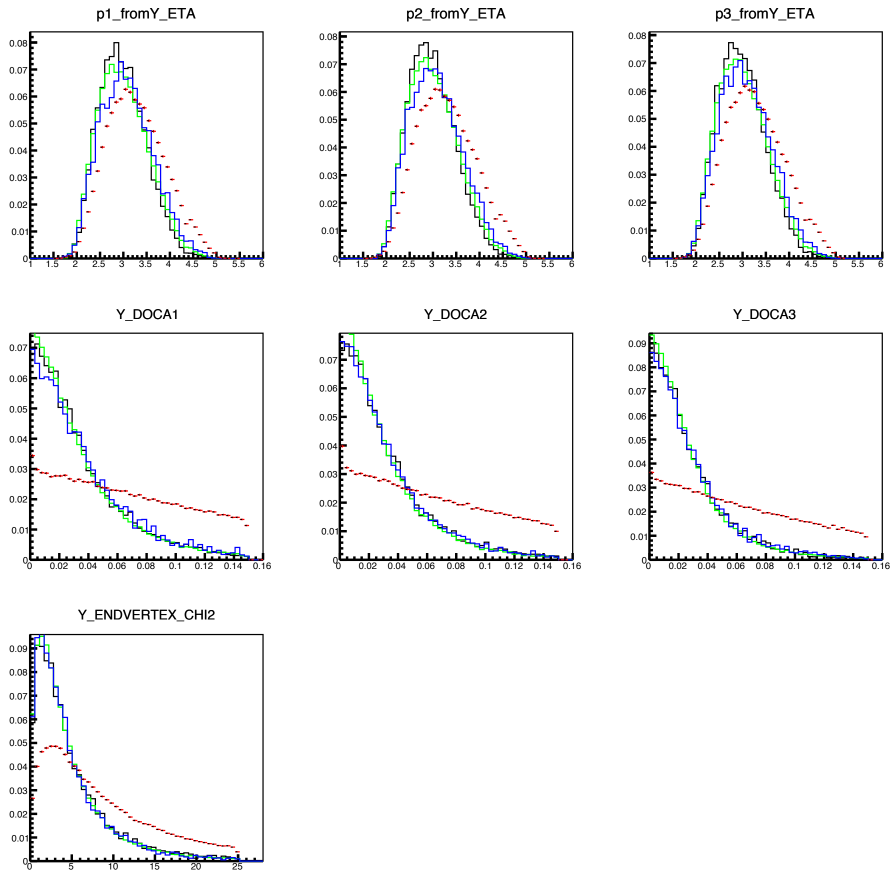


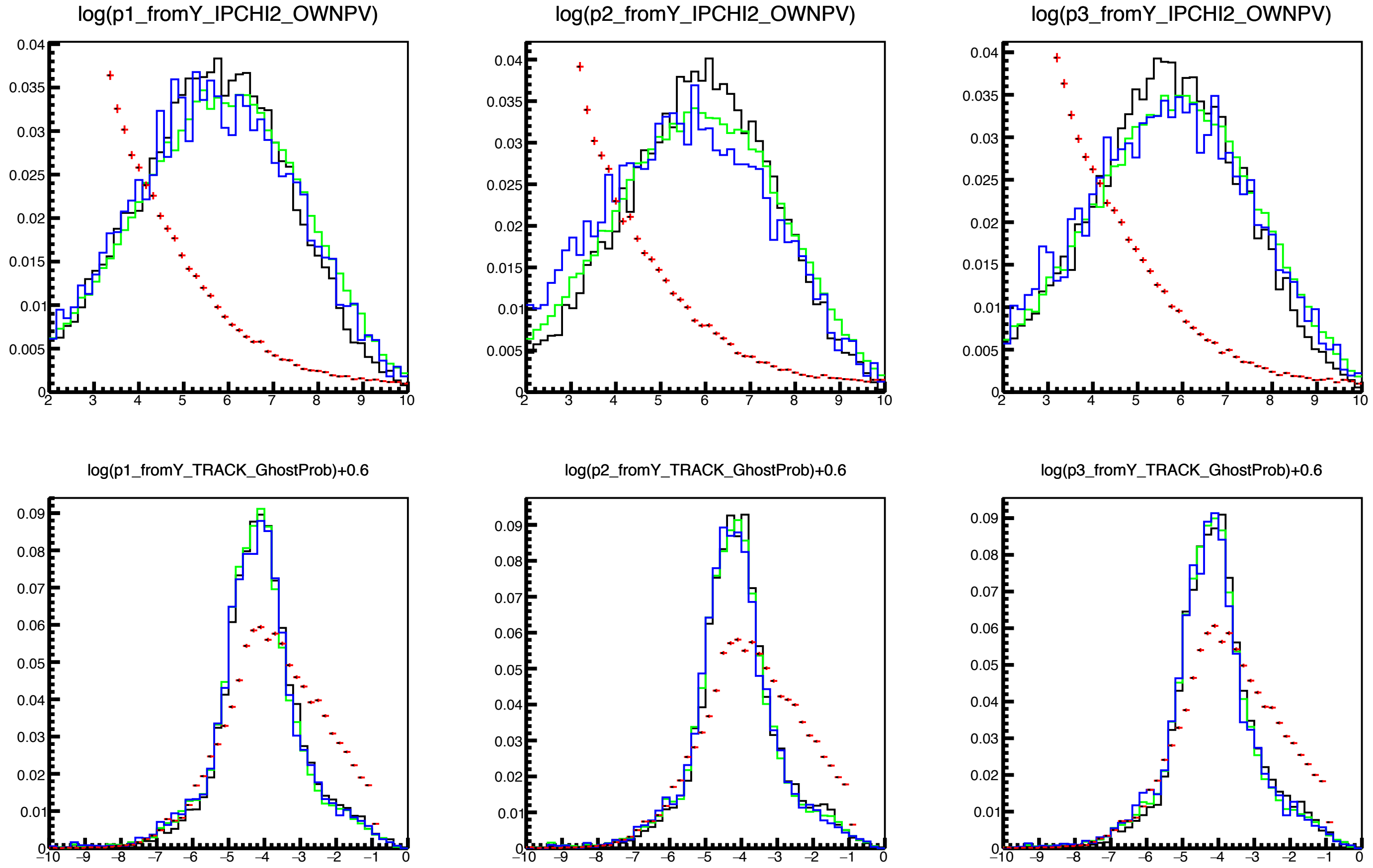
3π SELECTION



- BDT_3pi variables:
  - 3 pions vertex: vertex chi2, DOCA (distance of closest approach)
  - Pions: pseudorapidity, impact parameter chi2 (from PV), track ghost prob.

Legend:
- SIGNAL
- BKG
- NORM Bs
- NORM Bd





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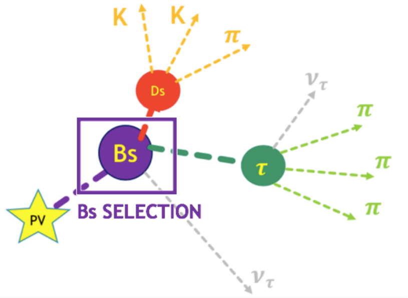
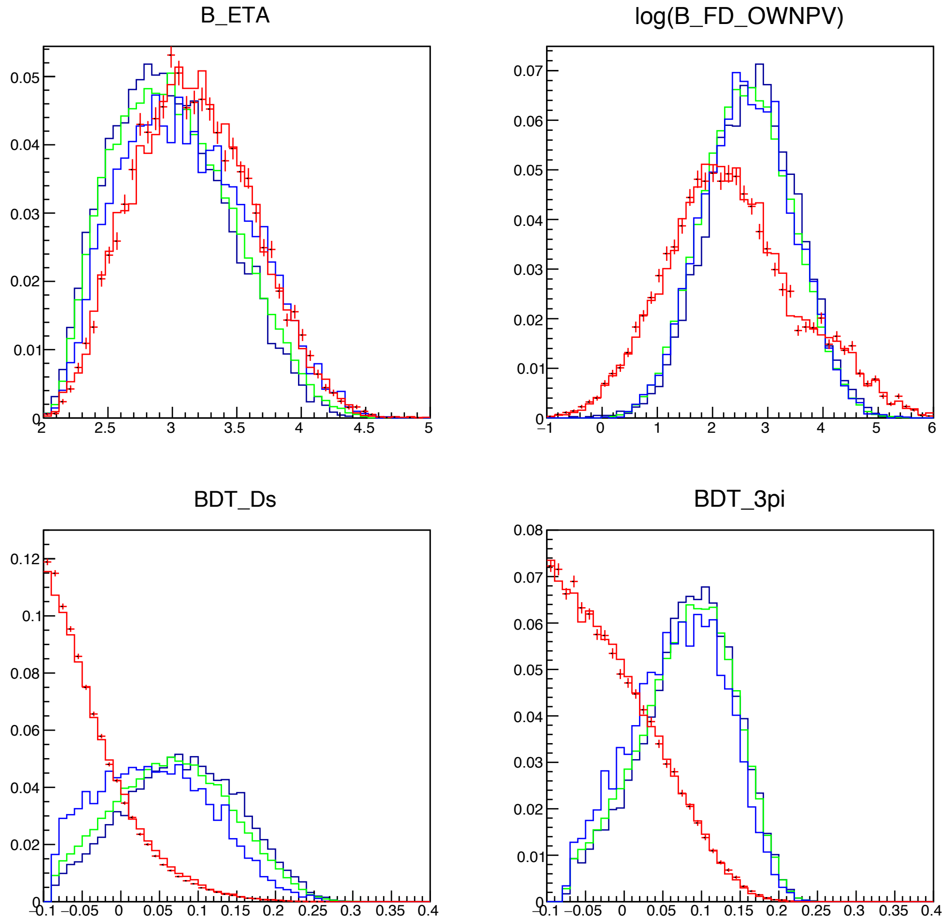
B SELECTION



- BDT_B variables:
  - Bs: pseudorapidity, flight distance from PV
  - BDT outputs: BDT_D, BDT_3pi



Legend:
- **SIGNAL**
- **BKG (right and wrong sign)**
- **NORM Bs**
- **NORM Bd**