Observation of the decays $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ in the ATLAS detector

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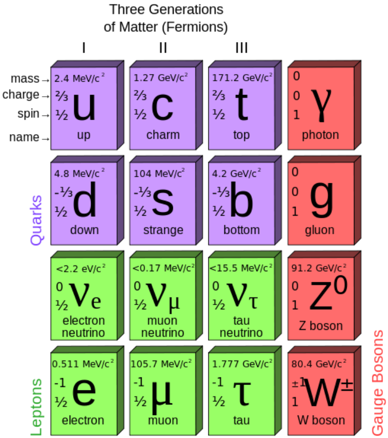
Outline

1. Introduction
2. Motivation and B physics
3. Analysis methodology
4. Study of $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$
5. Summary and conclusions

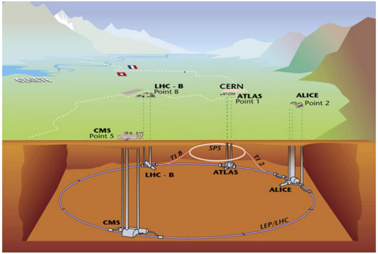
The Standard Model

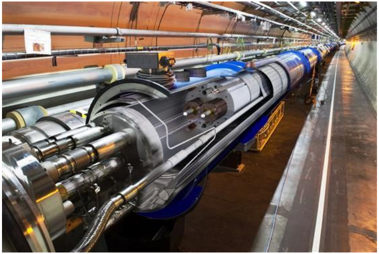
- The Standard Model (SM) is a theory of fundamental matter particles and interactions among them.
- Matter is made up of elementary fermions (leptons and quarks) interacting with each other through fields.
- Fields are force carriers called gauge bosons.
- An additional particle, known as the Higgs boson, must also be included to explain why particles have mass.
- Small-scale investigation requires high energies.



The LHC

- The Large Hadron Collider (LHC) is a proton-proton (*pp*) collider designed to operate with a center-of-mass energy up to 14 TeV.
- Located in a 27 km long, circular tunnel, about 100 m under ground.
- The LHC accelerates two separate beams of protons traveling in opposite directions.
- Beams are guided to intersect at four specific regions along the LHC ring, where head-on collisions take place.
- Four main experiments: ATLAS, CMS, ALICE and LHCb.





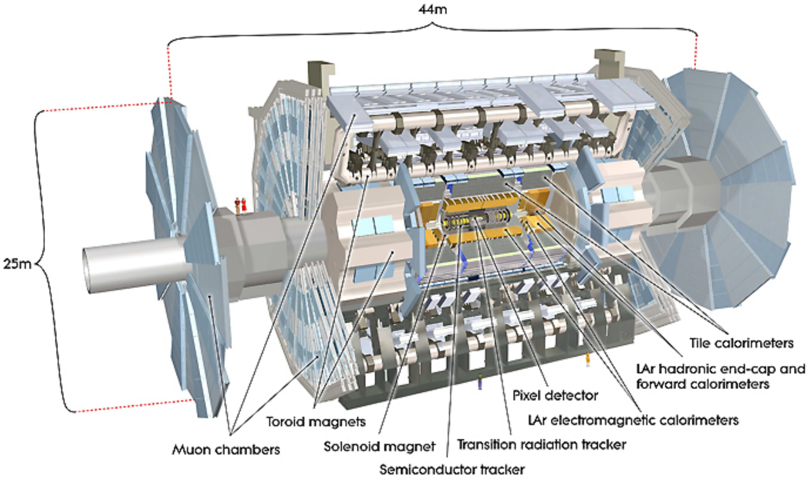


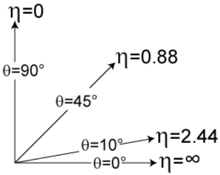
Figure: Cut-away view of the ATLAS detector.

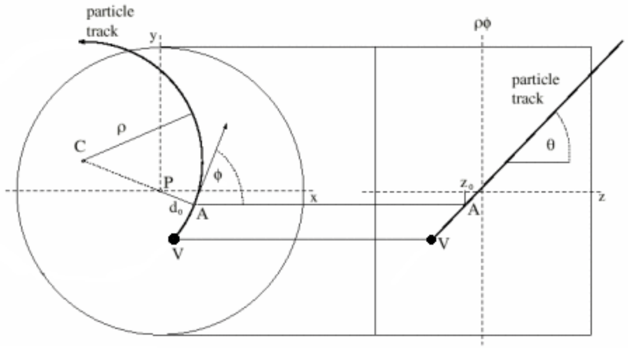
The ATLAS detector

- ATLAS (A Toroidal LHC ApparatuS) is a multipurpose detector having cylindrical geometry.
- It consists of four major parts: the Inner Detector (ID), the calorimeters, the Muon Spectrometer (MS) and the magnet systems.
- **ID** is high granularity system which uses three combined subsystems: pixel and silicon microstrip (SCT) trackers and the Transition Radiation Tracker (TRT). It provides precise measurements for primary and secondary vertices.
- **The calorimeters** are an inner electromagnetic calorimeter (EM) and an outer hadron calorimeter, providing high accuracy energy measurements.
- **MS** provides efficient muon identification and ensures excellent momentum measurement.
- **The magnet system** is used to bend charged particles so that their momenta can be measured.

The ATLAS detector

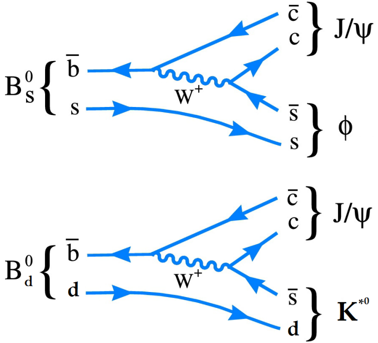
- Azimuthal angle $\phi = \tan^{-1} \frac{p_y}{p_x}$
- Pseudo-rapidity $\eta = -\ln\left[\tan(\frac{\theta}{2})\right]$
- Transverse momentum p_T





Motivation and B physics

- Knowledge of the production rates of B mesons in pp collisions is essential for measurements of branching fractions.
- Rate is determined by the $b\bar{b}$ production cross-section and the fragmentation probability f_i, which is the fraction of B_i^0 mesons amongst all weakly-decaying bottom hadrons ($i = u, d, s, c$).
- Primary example is $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ where improved knowledge of f_s/f_d is needed.



- f_s/f_d can be extracted if B_d^0 and B_s^0 mesons yields and branching fractions are known. For this purpose, channel $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ and $B_d^0 \to J/\psi(\mu^+\mu^-)K^{*0}(K^+\pi^-)$ are suitable and chosen.
- Decays are topologically identical allowing the same analysis methodology.

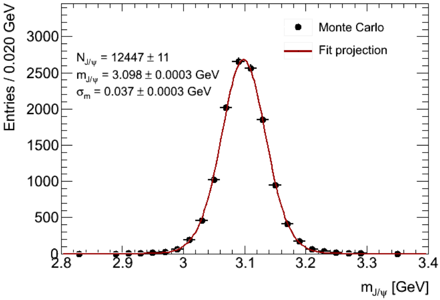
Analysis methodology

- Monte Carlo (MC) study of the decays $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$
  - J/ψ selection
  - Selection specific to $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$
  - Observables for signal and background separation
  - Optimization of the observables
  - Extraction of the invariant mass probability density functions (PDFs) for signal and background
- Data analysis
  - Events selection using optimized selection criteria from MC study
  - Background parameterization validity check with data sidebands
  - Extraction of the B_s^0 and B_d^0 yields and determination of f_s/f_d
- Backgrounds
  - Direct J/ψ (J/ψ decays originating from the pp collisions)
  - $b\bar{b} \to \mu\mu X$ (randomly chosen muons plus 2 oppositely charged tracks)
  - $b\bar{b} \to J/\psi X$ (inclusive decays of b hadrons containing J/ψ)

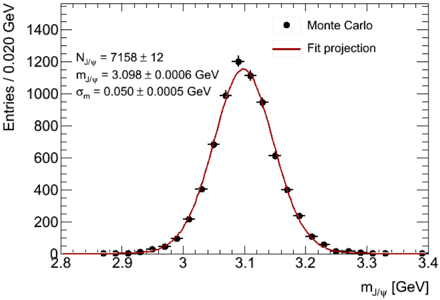
J/ψ selection

- J/ψ candidates are reconstructed by combinig two oppositely charged muons by using two algorithms:
  a) Muons from combined reconstruction (combined tracks from MS+ID)
  b) Muons from ID track tagging (ID tracks extrapolated to MS hits)
- Forward region of the ATLAS detector contains more material. At large $|\eta|$, muons undergo more multiple scattering, which leads to a degradation of the momentum resolution. This leads to a degradation of the J/ψ mass resolution.
- J/ψ candidates are divided into three classes according to the η of the muons. A muon is in the barrel (end-cap) if $|\eta| < 1.05$ ($1.05 < |\eta| < 2.5$).
  a) **BB:** Both muons are in the barrel.
  b) **EB:** One of the muons is in the end-cap and one in the barrel.
  c) **EE:** Both muons are in the end-cap.

- Unbinned maximum likelihood fit including per-event errors is used to extract the J/ψ mass and corresponding resolutions for three η classes.
- For each η class the signal region is defined as a $\pm 3\sigma_m$ range around the J/ψ mass.

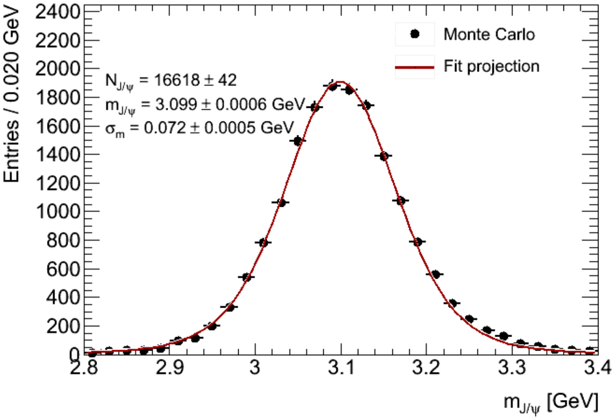


a) **BB:** (2.987 - 3.209) GeV



b) **EB:** (2.948 - 3.248) GeV

J/ψ selection

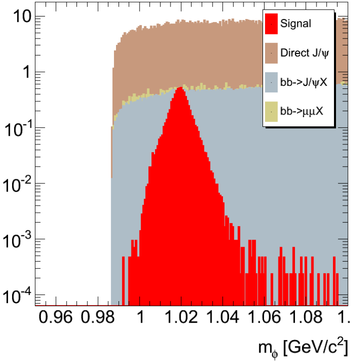


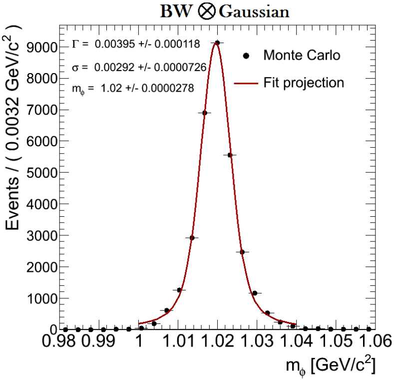
c) **EE:** (2.883 - 3.315) GeV

Selection specific to $B_s^0 \to J/\psi\phi$

- The $\phi \to K^+K^-$ candidates are reconstructed by combining oppositely charged tracks and B_s^0 candidates are formed by fitting J/ψ and ϕ candidates to a common vertex.

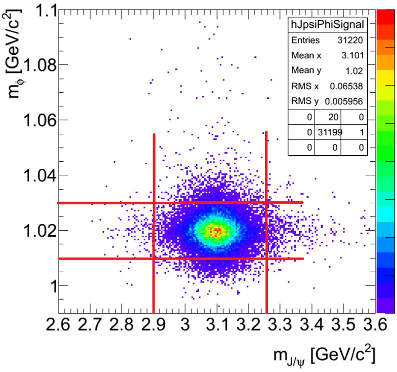
- Invariant mass of ϕ tracks pair falls within interval 1010 MeV $< m_{K^+K^-} <$ 1028 MeV ($\pm 3\sigma$ around the ϕ mass).

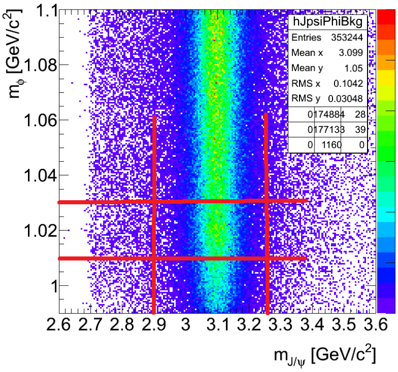




Selection specific to $B_s^0 \to J/\psi\phi$

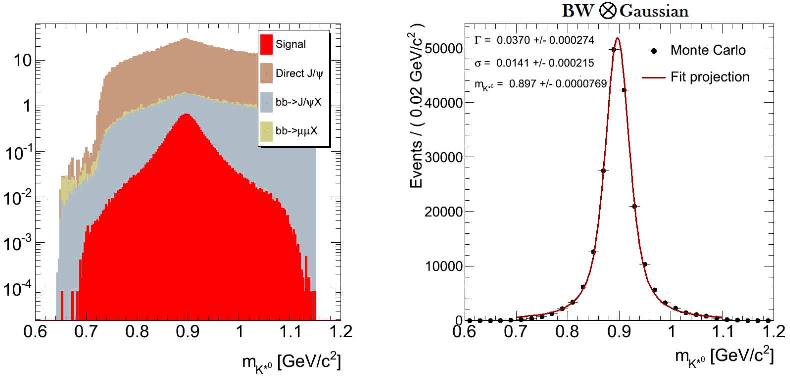
- Constraint on J/ψ and ϕ mass remove large fraction of the background.
- Selection on ϕ rejects peaking background events close to ϕ mass like $B_s^0 \to J/\psi f_0(980)$ and $B_d^0 \to J/\psi K^{*0}$.
- Additional selection criteria must be applied to reject the remaining background content.





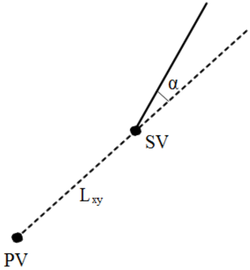
Selection specific to $B_d^0 \to J/\psi K^{*0}$

- The $K^{*0} \to K^+\pi^-$ candidates are reconstructed by combining oppositely charged tracks and B_d^0 cand. are formed by fitting J/ψ and K^{*0} candidates to a common vertex.
- K^{*0} mass falls within interval 853 MeV $< m_{K^{*0}} <$ 938 MeV.
- Each $K^+\pi^-$ combination is tested and closest to K^{*0} mass is chosen.



Observables

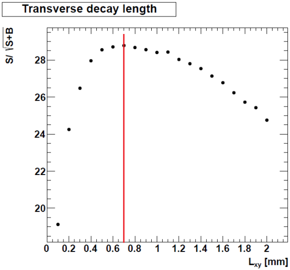
- Remaining backgrounds for the decays $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ are further suppressed by applying constraint on additional observables:
  a) transverse decay length L_{xy}
  b) χ^2 of B_s^0 and B_d^0 vertex
  c) pointing angle α

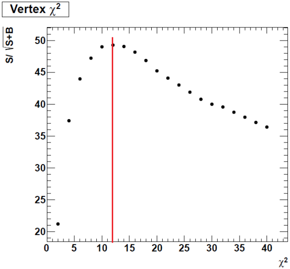


- Selection using discriminating observables have to be optimized.
- Optimization of the signal yields is achieved by using the sensitivity $S/\sqrt{S+B}$ where S is the signal yield and B is the sum of all backgrounds.
- Consider $S/\sqrt{S+B}$ as a function of the discriminating observables.

Observables

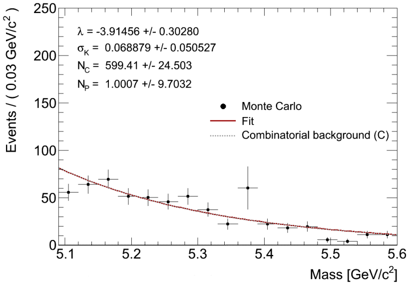
- Signal to background separation is best then $S/\sqrt{S+B}$ is maximal.
- Transverse decay length L_{xy} is most suitable to remove direct J/ψ background.
- After requiring optimal L_{xy} value, remaining backgrounds are summed and optimized for vertex χ^2 observable.
- This selection removes most of the combinatorial background.
- Finally, optimization is performed on α.
- Optimized selection is applied on MC samples to determine PDF shapes for background and signal events.



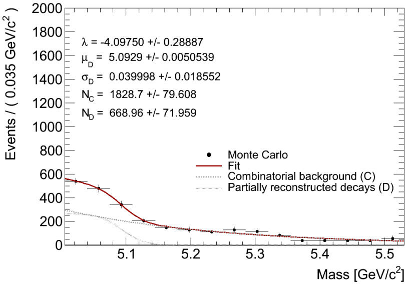


Background modeling

- The background model for B_s^0 consists of an exponential function describing the residual background from inclusive $J/\psi X$ decays and random combinations, plus a Gaussian function accounting for $B_d^0 \to J/\psi K^{*0}$ decays.
- The background model for B_d^0 consists of an exponential function, plus a step function accounting for partially reconstructed decays.



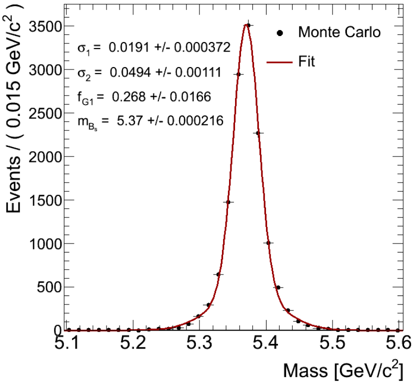
PDF for B_s^0 bkg. (exp.+Gaussian)



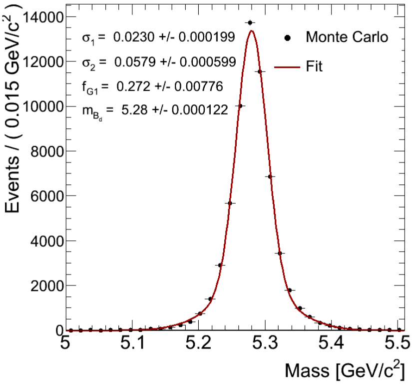
PDF for B_d^0 bkg. (exp.+step)

B_s^0 and B_d^0 signal PDFs

- Consider B_s^0 and B_d^0 candidates selected from MC signal sample.
- Since in the ATLAS mass resolution is better in the barrel than in the end-caps, the invariant B_s^0 and B_d^0 mass can be modeled with two Gaussian distributions.



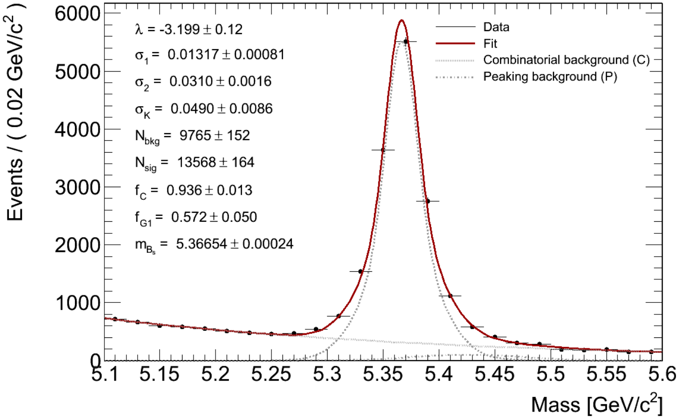
B_s^0 signal PDF



B_d^0 signal PDF

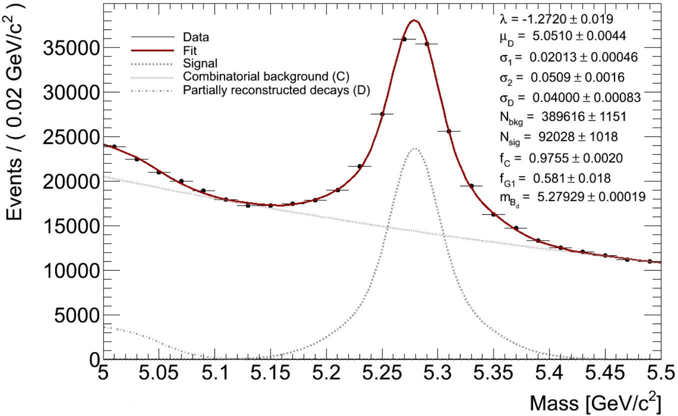
B_s^0 yield extraction

- Analysis is performed using ATLAS data sample of 4.94 fb^{-1} (7 TeV).
- After all requirements perform extended unbinned maximum likelihood fit.
- From fit extracted B_s^0 yield is 13568 $\pm$ 164 (stat) $\pm$ 1072 (syst).



B_d^0 yield extraction

- After all requirements perform extended unbinned maximum likelihood fit.
- From fit extracted B_d^0 yield is 92028 $\pm$ 1018 (stat) $\pm$ 4655 (syst).



Determination of f_s/f_d

- The ratio of fragmentation probabilities f_s/f_d may depend on the collision energy and on kinematic variables as p_T and η of the B meson.
- Assume no dependency (LHCb result) and estimate it in range then $|\eta| < 2.5$.
- The value of fragmentation probabilities f_s/f_d is given by

$$\frac{f_s}{f_d} = \frac{N_{B_s^0}}{N_{B_d^0}} \frac{\mathcal{B}(B_d^0 \to J/\psi K^{*0})}{\mathcal{B}(B_s^0 \to J/\psi \phi)} \frac{\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \frac{\epsilon_{B_d^0}}{\epsilon_{B_s^0}}.$$

- Here $N_{B_s^0}$ and $N_{B_d^0}$ are extracted B_s^0 and B_d^0 yields, and $\epsilon_{B_s^0}$ and $\epsilon_{B_d^0}$ are corresponding MC selection efficiencies.
- Fragmentation probabilities ratio f_s/f_d is estimated to be

$$\boxed{\frac{f_s}{f_d} = 0.294 \pm 0.005^{stat} \pm 0.091^{syst}.}$$

Determination of f_s/f_d

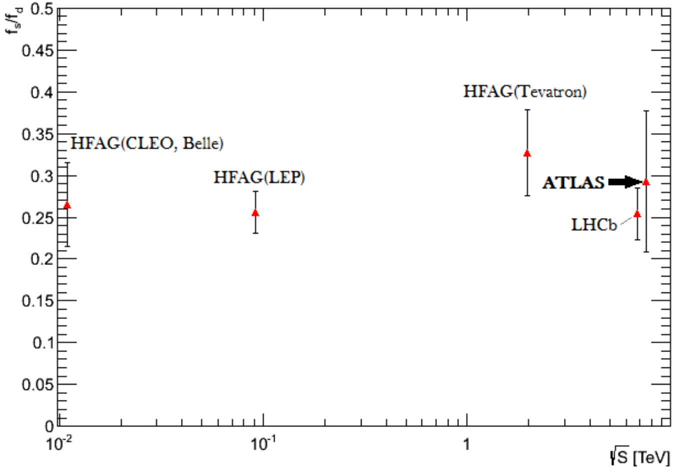


Figure: f_s/f_d as a function of $\sqrt{s}$.

Summary and conclusions

- B_s^0 and B_d^0 mesons were reconstructed using 4.94 fb^{-1} of pp collision data at 7 TeV.
- Analysis was performed using selection criteria obtained from MC simulations. For each decay, background and signal models were determined.
- Acquired mass fit models were used to extract B_s^0 and B_d^0 yields.
- Extracted B_s^0 and B_d^0 yields were used to determine f_s/f_d. Obtained value is $\boxed{f_s/f_d = 0.294 \pm 0.005^{stat} \pm 0.091^{syst}}$ which is compatible with LHCb value of $f_s/f_d = 0.253 \pm 0.017^{stat} \pm 0.017^{syst} \pm 0.020^{theor}$ within the precision of the current measurement.

THANK YOU

$B_s^0 \to J/\psi\phi$ bkg. modeling

- Gaussian function accounting for $B_d^0 \to J/\psi K^{*0}$ decays:

$$P(m_{\mu\mu KK}) = exp(-\frac{(m_{\mu\mu KK} - \mu_K)^2}{2(\sigma_K)^2}).$$

- Exp. function describing the residual background from inclusive $J/\psi X$ decays and random combinations:

$$C(m_{\mu\mu KK}) = exp(\lambda m_{\mu\mu KK}).$$

- Likelihood model:

$$BS(m_{\mu\mu KK}) = \frac{N_C C + N_P P}{N_C + N_P}.$$

- Likelihood function:

$$L = \prod_{i=1}^{N} BS(m^i_{\mu\mu KK}).$$

$B_d^0 \to J/\psi K^{*0}$ bkg. modeling

- Exp. function describing the residual background from inclusive $J/\psi X$ decays and random combinations:

$$C(m_{\mu\mu K\pi}) = exp(\lambda m_{\mu\mu K\pi}).$$

- Background from the partially reconstructed decays is modeled as a step function described by a complimentary error function

$$D(m_{\mu\mu K\pi}) = erfc(\frac{m_{\mu\mu K\pi} - \mu_D}{\sigma_D}),$$

where $erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$ is the complimentary error function.

- Likelihood model: $BD(m_{\mu\mu K\pi}) = \frac{N_C C + N_D D}{N_C + N_D}$.
- Likelihood function:

$$L = \prod_{i=1}^{N} BD(m^i_{\mu\mu K\pi}).$$