# $B_s^0 \to \phi\mu^+\mu^-$ from LHCb

12th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"

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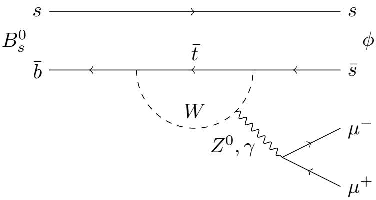
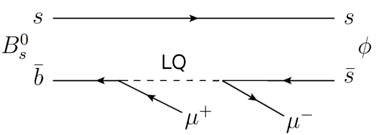
DESY Hamburg, November 27, 2018

# Introduction to $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$



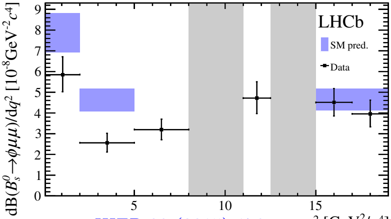

flavor-changing neutral current (FCNC) forbidden at tree level in SM

- rare decay
- sensitive to new virtual, heavy particles
- accessible scales of $\mathcal{O}(100\text{TeV})$ [A. Buras, arxiv:1505.00618]
- can affect $\mathcal{B}$ and angular observables

key quantity

$$q^2 = m^2(\mu^+\mu^-)$$

- tensions up to $3.3\sigma$ for $\mathcal{B}(B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-)$
  - Run 2 update by S. Kretzschmar
- $\mathcal{B}$ measurements
  - SM theory uncertainty large (e.g. form factors)
  - other systematic uncertainties (e.g. normalization channel)
- angular analysis:
  - observables are phasespace ratios $\rightarrow$ smaller theory uncertainties
  - Run 1 analysis statistically limited $\rightarrow$ Run 2 update

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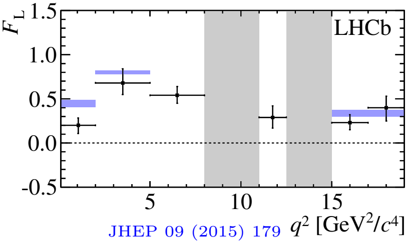


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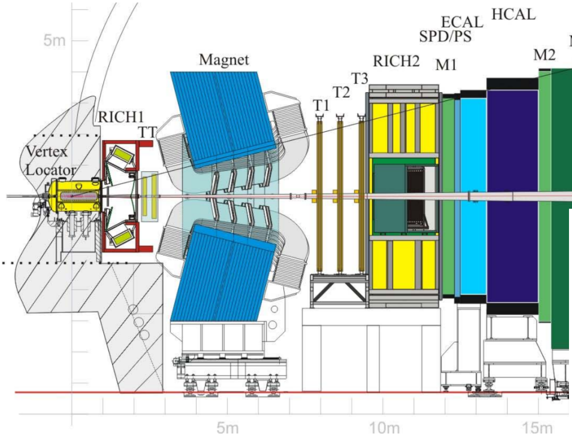
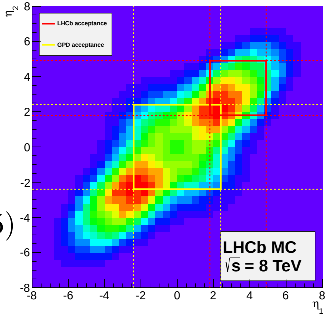
# LHCb Detector

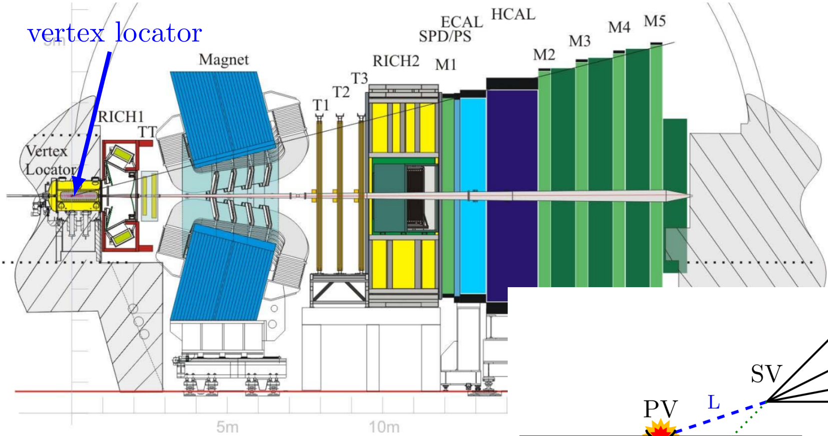


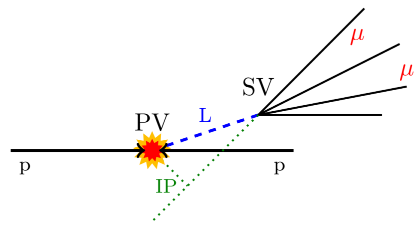




- single-arm forward spectrometer ($2 < \eta < 5$)
- $b\bar{b}X$ production dictates detector geometry

LHCb Speakersbureau

# LHCb Detector

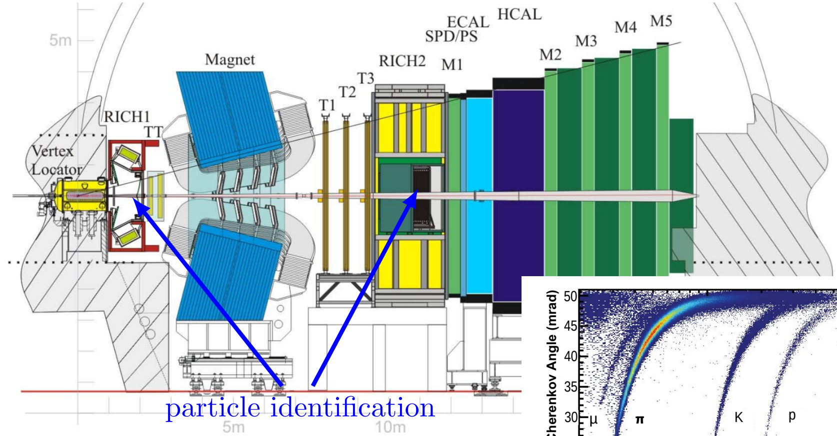


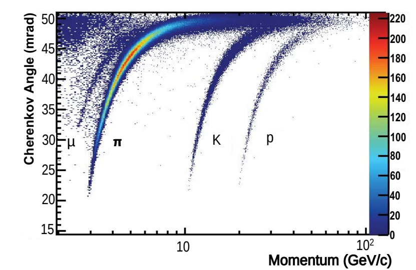




- $B_s^0$ longlived, $\tau(B_s^0) = 1.527 \pm 0.011\text{ps}$
- flight distance $\mathcal{O}(\text{cm})$
- IP resolution $(15 + 29/p_T[\text{GeV}])$ $[\mu\text{m}]$

# LHCb Detector






- separation using Cherenkov angle
- Kaon ID 95% ($\approx$5% $\pi \to K$ mis-id)

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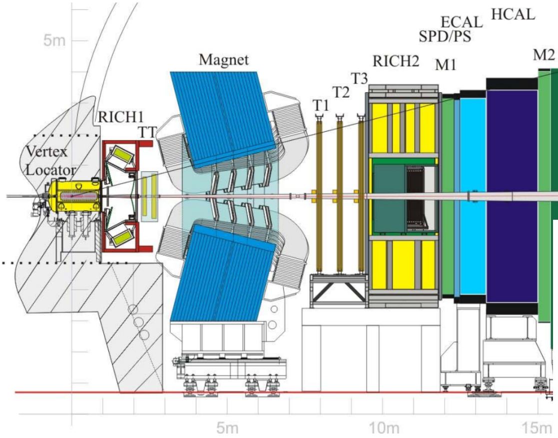


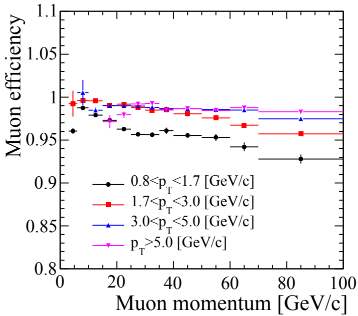


- separation using Cherenkov angle
- Kaon ID 95% ($\approx$5% $\pi \to K$ mis-id)
- muon ID 97% (1-3 % $\pi \to \mu$ mis-id)

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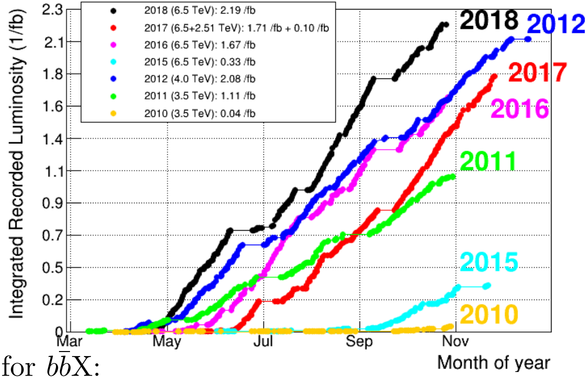
# Data Taken with LHCb



- used in prev. Run 1 analysis: 2011+2012
- planned for this analysis: 2011+2012 and 2016, roughly doubling statistics

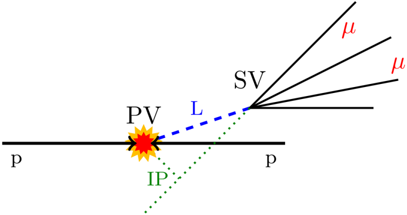



production cross sections for $b\bar{b}X$:

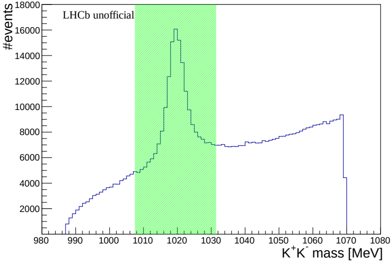
- $72.0 \pm 0.3 \pm 6.8\mu b$ (7 TeV) Phys.Rev.Lett. 118 (2017) no.5, 052002
- $144 \pm 1 \pm 21\mu b$ (13 TeV)

# Cut Based Selection

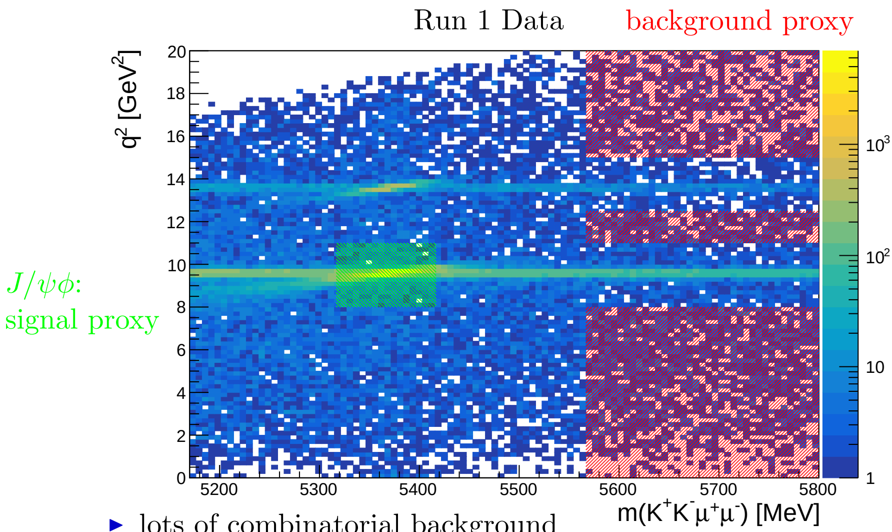
- LHCb-wide preselection
  - good vertex quality ($\chi^2_{vtx}$)
  - $B^0_s$ points back to PV
  - large separation of B decay vertex (significant lifetime)
- within $\phi$ mass window: $|m(K^+K^-) - m(\phi)| < 3 \cdot \Gamma_{\text{pdg}}(\phi)$
- loose Kaon particle ID selection (improved for update)




Run 1 data



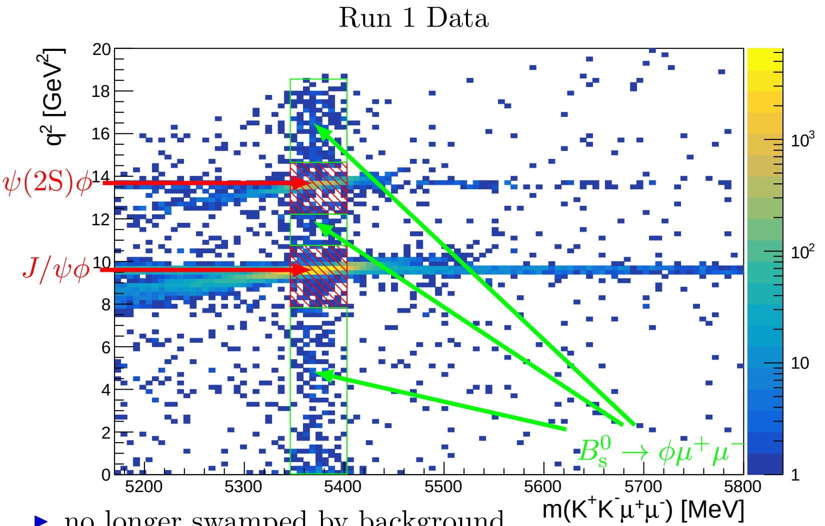
# Need For MVA




- lots of combinatorial background

$\rightarrow$ BDT with training on data

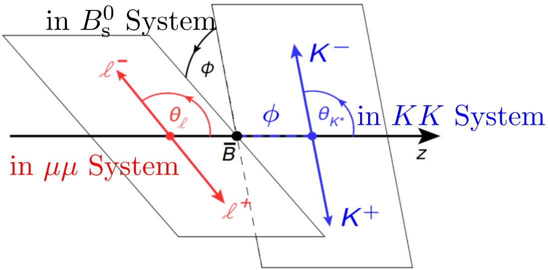
# Effect Of MVA




- no longer swamped by background
- rare mode signal visible as vertical band

$B_s^0$ , $\bar{B}_s^0$ not distinguishable as $\phi \to K^+K^-$

measure $\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\left[\frac{d^3\Gamma(B_s^0\to\phi\mu^+\mu^-)}{d\cos\theta_l d\cos\theta_k d\phi}+\frac{d^3\bar{\Gamma}(\bar{B}_s^0\to\phi\mu^+\mu^-)}{d\cos\theta_l d\cos\theta_k d\phi}\right]$

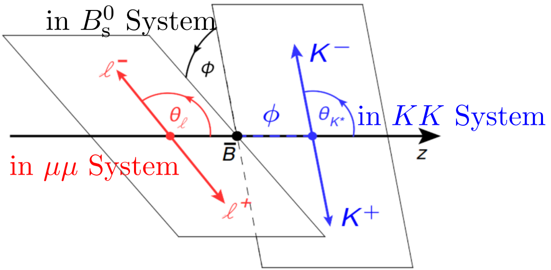


# Angular Observables



$B_s^0$ , $\bar{B}_s^0$ not distinguishable as $\phi \to K^+K^-$

measure $\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{dq}^2}\left[\frac{\mathrm{d}^3\Gamma(B_s^0\to\phi\mu^+\mu^-)}{\mathrm{d}\cos\theta_l \mathrm{d}\cos\theta_k \mathrm{d}\phi} + \frac{\mathrm{d}^3\bar{\Gamma}(\bar{B}_s^0\to\phi\mu^+\mu^-)}{\mathrm{d}\cos\theta_l \mathrm{d}\cos\theta_k \mathrm{d}\phi}\right]$




$$= \frac{9}{32\pi}[\frac{3}{4}(1-F_L)\sin^2\theta_k(1+\frac{1}{3}\cos 2\theta_l) + F_L\cos^2\theta_k(1-\cos 2\theta_l) + S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_k\sin 2\theta_l\cos\phi + A_5\sin 2\theta_k\sin\theta_l\cos\phi + A_6^s\sin^2\theta_k\cos\theta_l$$
$$+S_7\sin 2\theta_k\sin\theta_l\sin\phi + A_8\sin 2\theta_k\sin 2\theta_l\sin\phi + A_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi]$$

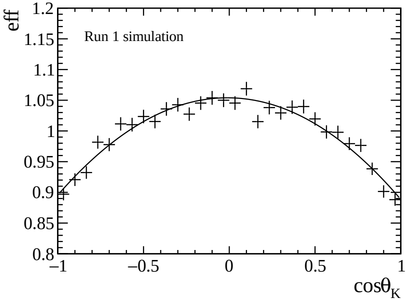
$S_i$ CP-averaged $\quad$ $A_i$ CP-asymmetries

# Determine Detector Acceptance



- trigger, reconstruction and selection distort decay angles and $q^2$ distributions
- angular acceptance accounts for distortion
- parametrize 4D efficiency using Legendre polynomials:

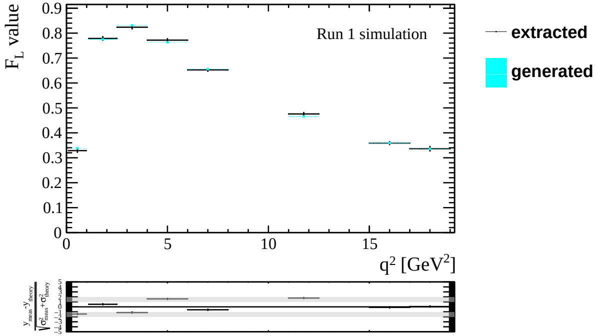
$$\epsilon(\cos\theta_k, \cos\theta_l, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_k) P_l(\cos\theta_l) P_m(\phi) P_n(q^2)$$




extract $c_{klmn}$ via method of moments

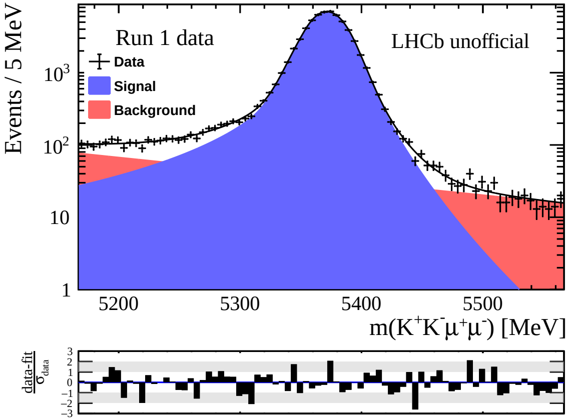
# Checking Acceptance on Simulation

- extract angular observables from $B_s^0 \to \phi\mu^+\mu^-$MC in $q^2$ bins
- compare generated to extracted value
- values agree if acceptance is taken into account correctly




- values compatible within uncertainties for all observables
- check on control mode data with $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$

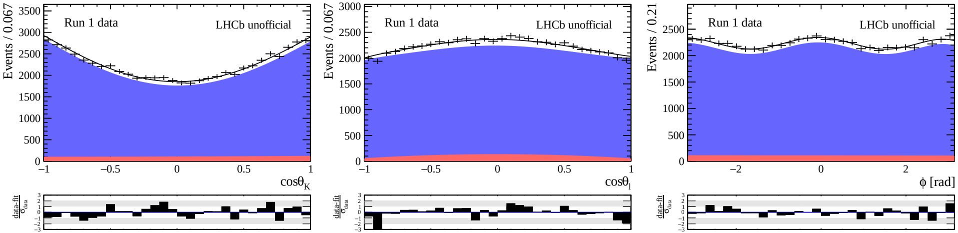
# Mass Fit of $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$




- separation of signal and background using reconstructed $B_s^0$ mass
- fit model: double Crystal Ball + exp

$$f_{sig} \cdot \left(f_1 \cdot \frac{CB_1(m,\alpha_1,n_1,\mu_1,\sigma_1)}{\mathcal{N}(CB_1)} + (1-f_1) \cdot \frac{CB_2(m,\alpha_2,n_2,\mu_2,\sigma_2)}{\mathcal{N}(CB_2)}\right) + (1-f_{sig}) \cdot \frac{\exp(m,a)}{\mathcal{N}(\exp)}$$

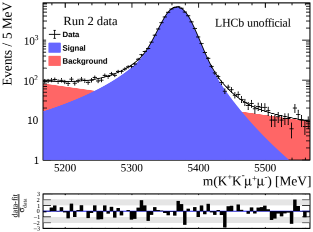
# Angular Fits of $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$

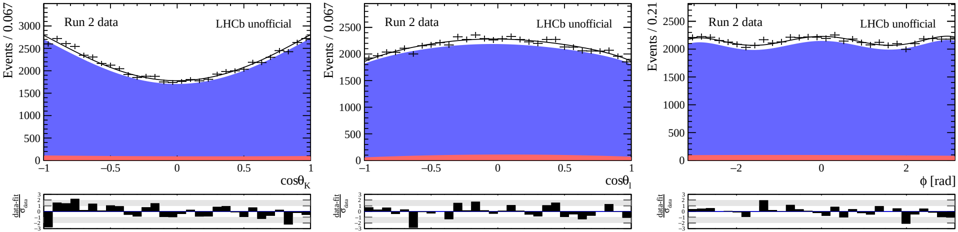



- signal described by $\frac{\epsilon(\cos\theta_k, \cos\theta_l, \phi, q^2)}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l \mathrm{d}\cos\theta_k \mathrm{d}\Phi}$
- background described by Legendre polynomial of order 2
- angular acceptance taken into account
- data well described by fit
- able to reproduce results from Run 1 analysis

# Status Run 2

- derived angular acceptance
- performed fit to $B_s^0 \to J/\psi\phi$
- Run 1 and Run 2 values compatible
- checks still ongoing



# Summary and Outlook

shown today:

- improved selection
- determination of angular acceptance
- validated acceptance with simulation and control mode (Run 1, Run 2)

next steps:

- finalize background study
- develop simultaneous fitting for Run 1 + 2
- evaluate systematics


BACKUP

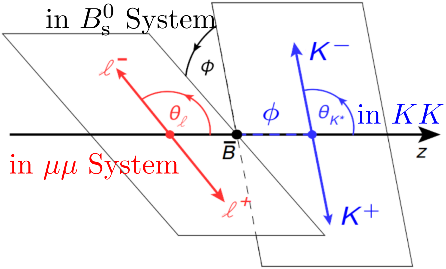
- perform unbinned maximum likelihood fit of mass and 3 angles used to determine angular observables
- probability density function including angular acceptance

$$-\ln \mathcal{L}(\vec{\lambda}) = -\sum_{i}^{N} \ln \left[ f_{\text{sig}} \cdot S(m, \Theta_l, \Theta_K, \phi|\vec{\lambda}) + (1 - f_{\text{sig}}) \cdot B(m, \Theta_l, \Theta_K, \phi|\vec{\lambda}) \right]$$

$$S(m, \Theta_l, \Theta_K, \Phi|\vec{\lambda}) = S(m|\vec{\lambda}) \cdot \left[ \epsilon(\theta_l, \theta_k, \phi, q^2_{\text{bin}}) \cdot S(\Theta_l, \Theta_K, \Phi|\vec{\lambda}) \right] / \mathcal{N}_{\text{sig}}$$

$$B(m, \Theta_l, \Theta_K, \Phi|\vec{\lambda}) = B(m|\vec{\lambda}) \cdot \left[ \epsilon(\theta_l, \theta_k, \phi, q^2_{\text{bin}}) \cdot B(\Theta_l, \Theta_K, \Phi|\vec{\lambda}) \right] / \mathcal{N}_{\text{bkg}}$$

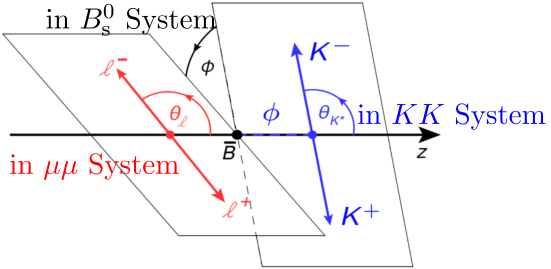
- physics and nuisance parameters $\vec{\lambda}$
- check procedure on $B^0_s \to J/\psi(\to \mu^+\mu^-)\phi$ mode




$B_s^0$ , $\bar{B}_s^0$ not distinguishable as $\phi \to K^+K^-$

$$\frac{d^3\Gamma(B_s^0 \to \phi\mu^+\mu^-)}{d\cos\theta_l d\cos\theta_k d\phi}$$

$$= \frac{9}{32\pi}[\frac{3}{4}(1-J_1^c)\sin^2\theta_k(1+\frac{1}{3}\cos 2\theta_l)+J_1^c\cos^2\theta_k(1-\cos 2\theta_l)+J_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi$$
$$+J_4\sin 2\theta_k\sin 2\theta_l\cos\phi+J_5\sin 2\theta_k\sin\theta_l\cos\phi+J_6^J\sin^2\theta_k\cos\theta_l$$
$$+J_7\sin 2\theta_k\sin\theta_l\sin\phi+J_8\sin 2\theta_k\sin 2\theta_l\sin\phi+J_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi]$$

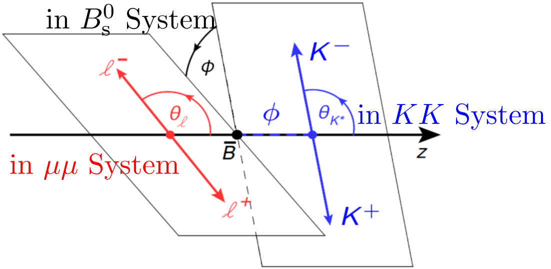



$B_s^0$ , $\bar{B}_s^0$ not distinguishable as $\phi \to K^+K^-$

$$\frac{d^3\bar{\Gamma}(\bar{B}_s^0 \to \phi\mu^+\mu^-)}{d\cos\theta_l \, d\cos\theta_k \, d\phi}$$

$$= \frac{9}{32\pi}\Big[\frac{3}{4}(1-\bar{J}_1^c)\sin^2\theta_k(1+\frac{1}{3}\cos 2\theta_l) + \bar{J}_1^c\cos^2\theta_k(1-\cos 2\theta_l) + \bar{J}_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi$$
$$+ \bar{J}_4\sin 2\theta_k\sin 2\theta_l\cos\phi - \bar{J}_5\sin 2\theta_k\sin\theta_l\cos\phi - \bar{J}_6^s\sin^2\theta_k\cos\theta_l$$
$$+ \bar{J}_7\sin 2\theta_k\sin\theta_l\sin\phi - \bar{J}_8\sin 2\theta_k\sin 2\theta_l\sin\phi - \bar{J}_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\Big]$$

# Angular Observables




$B_s^0$ , $\bar{B}_s^0$ not distinguishable as $\phi \to K^+K^-$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{dq}^2}\left[\frac{\mathrm{d}^3\Gamma(B_s^0\to\phi\mu^+\mu^-)}{\mathrm{dcos}\theta_l\mathrm{dcos}\theta_k\mathrm{d}\phi}+\frac{\mathrm{d}^3\bar{\Gamma}(\bar{B}_s^0\to\phi\mu^+\mu^-)}{\mathrm{dcos}\theta_l\mathrm{dcos}\theta_k\mathrm{d}\phi}\right]$$

$$=\frac{9}{32\pi}[\frac{3}{4}(1-F_L)\sin^2\theta_k(1+\frac{1}{3}\cos 2\theta_l)+F_L\cos^2\theta_k(1-\cos 2\theta_l)+S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_k\sin 2\theta_l\cos\phi+A_5\sin 2\theta_k\sin\theta_l\cos\phi+A_6^s\sin^2\theta_k\cos\theta_l$$

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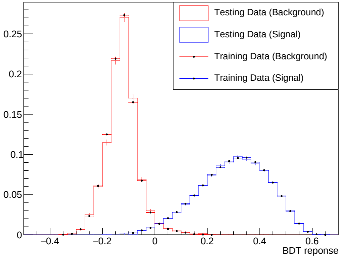
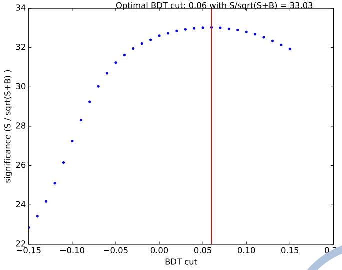
$\frac{J_i+\bar{J}_i}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{dq}^2}=S_i$ CP-averaged $\qquad \frac{J_i-\bar{J}_i}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{dq}^2}=A_i$ CP-asymmetries

Two main approaches for combining PID information

- Likelihood ratio (DLL) $\Delta \ln \mathcal{L}_{K\pi} = \ln \frac{\mathcal{L}(K)}{\mathcal{L}(\pi)}$, with $\mathcal{L}(\text{track}) = \mathcal{L}^{\text{RICH}} \cdot \mathcal{L}^{\text{CALO}} \cdot \mathcal{L}^{\text{MUON}}$
- Neural network classifiers ProbNN$K, \pi, e, \mu$
  - Bayesian probability like output
  - Adds tracking information
  - Separate neural network for every particle type

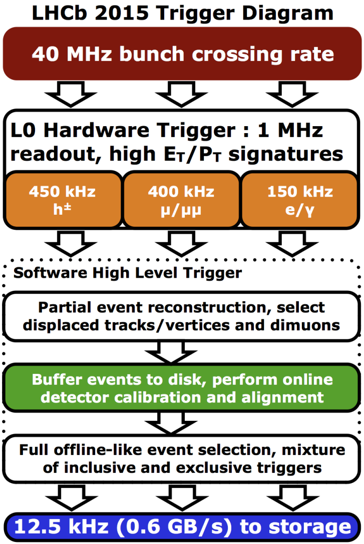
- BDT (from TMVA) with 10 kFolds
- input variables:
  - B0 ENDVERTEX $\chi^2$
  - B0 PT
  - B0 ownPV IPCHI2
  - B0 ownPV FDCHI2
  - B0 ownPV DIRA
  - min(K_probNNk)
  - max(K_ProbNNk)
  - min($\mu$_ProbNNmu)
  - (K,$\mu$)_IPCHI2_OWNPV
- optimize $\frac{S}{\sqrt{S+B}}$ (B from combinatorial)
- working point:
  - 95.5% signal efficiency
  - 98.5% background rejection



used for my analysis:

- hardware:
  - single muon trigger, $p_T$ >1.6GeV
- software:
  - detached high $p_T$ tracks
  - B-like signatures



| Run1 lines | Run2 lines |
|---|---|
| L0Muon<br>L0DiMuon | L0Muon<br>L0DiMuon |
| Hlt1TrackAllL0<br>Hlt1TrackMuon<br>~~Hlt1DiMuonLowMass~~<br>~~Hlt1DiMuonHighMass~~<br>~~Hlt1SingleMuonHighPT~~ | Hlt1TrackMVA, Hlt1TwoTrackMVA<br>Hlt1TrackMuon |
| Hlt2Topo(2,3,4)BodyBBDT<br>Hlt2TopoMu(2,3,4)BodyBBDT<br>~~Hlt2SingleMuon~~<br>Hlt2DiMuonDetached<br>Hlt2DiMuonDetachedHeavy | Hlt2Topo(2,3,4)Body~~BBDT~~<br>Hlt2TopoMu(2,3,4)Body~~BBDT~~<br><br><br>Hlt2DiMuonDetachedHeavy |