Search for $B^0 \to J/\psi\phi$ decay

LHCb-PAPER-2020-033

Wenhua Hu

Central China Normal University

The 6th China LHC Physics Workshop

Experimental measurements

- $\mathcal{B}(B^0 \to J/\psi K^+ K^-) = (2.53 \pm 0.31 \pm 0.19) \times 10^{-8}$ [3]
- Upper limits of $B^0 \to J/\psi\phi$ at 90% CL

Experiment	$\mathcal{B}(B^0 \to J/\psi\phi)$
BaBar	$< 9.2 \times 10^{-6}$ [1]
Belle	$< 9.4 \times 10^{-7}$ [2]
LHCb	$< 1.9 \times 10^{-7}$ [3]

Measured using 1 fb^{-1} data collected at LHCb in 2011

[1] [PRL91 (2003) 071801]

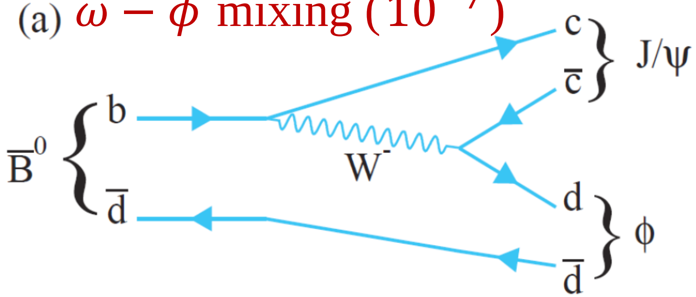
[2] [PRD78 (2008) 011106]

[3] [PRD88 (2013) 072005]

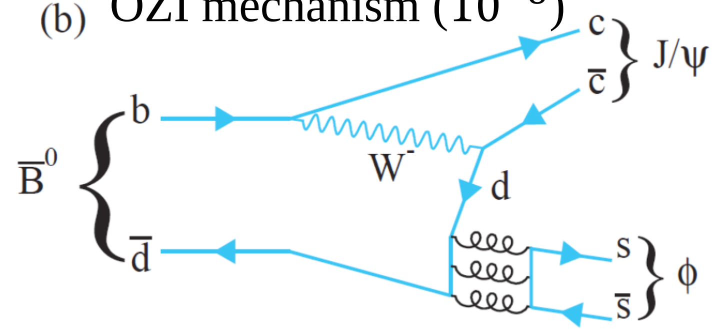
Motivation

- $B^0 \to J/\psi\phi(\phi \to K^+K^-)$ is a rare decay
  - ✓ OZI and CKM suppressed, possible contributions [PLB677 (2009) 278]

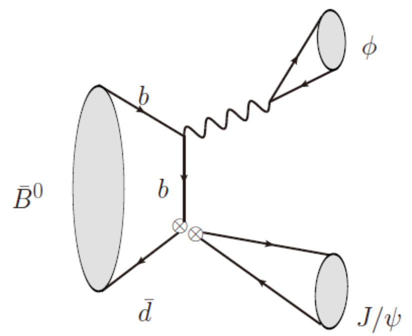
(a) $\omega - \phi$ mixing (10^{-7})



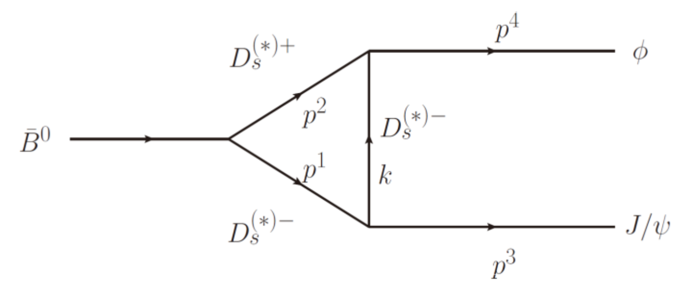
(b) OZI mechanism (10^{-8})



(c) photoproduction (10^{-11})



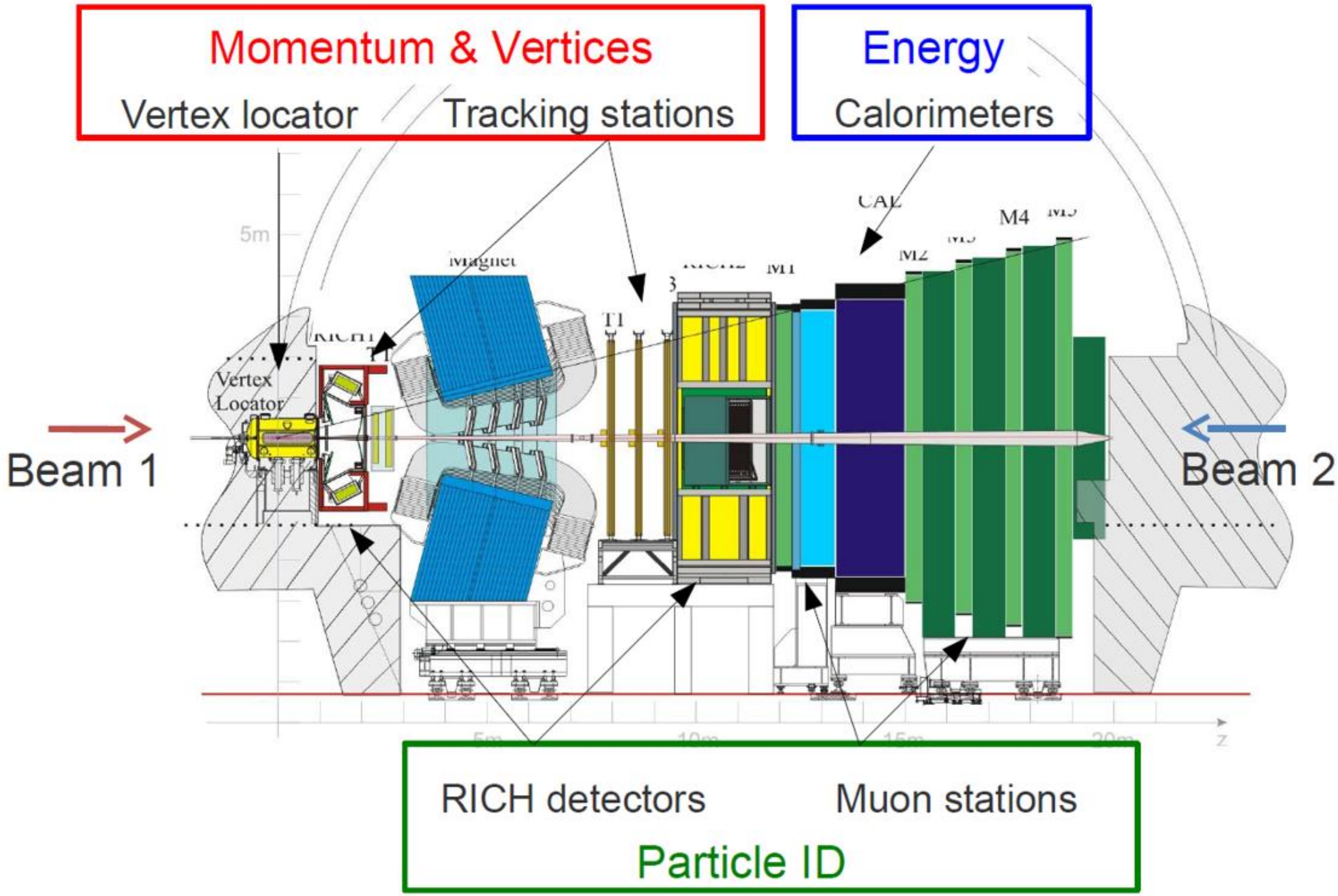
(d) final-state rescattering (10^{-9})



Under the assumption of $\omega - \phi$ mixng dominance, branch ratio is predicted as $(1.0 \pm 0.3) \times 10^{-7}$ [PLB666(2008)185188, PRD88 (2013) 072005]

LHCb detector

- Designed for beauty and charm physics, $2.0 < \eta < 5.0$



Analysis strategy

- Use the full Run 1 and Run 2 data to search $B^0 \to J/\psi\phi$
  - ✓ $B_s^0 \to J/\psi\phi$ is used as normalisation channel

$$N_{B^0}^{\phi} = N_{B_s^0}^{\phi} \times \frac{\mathcal{B}(B^0 \to J/\psi\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} \times \frac{1}{f_s/f_d} \times \frac{\varepsilon_{B^0}}{\varepsilon_{B_s^0}}$$

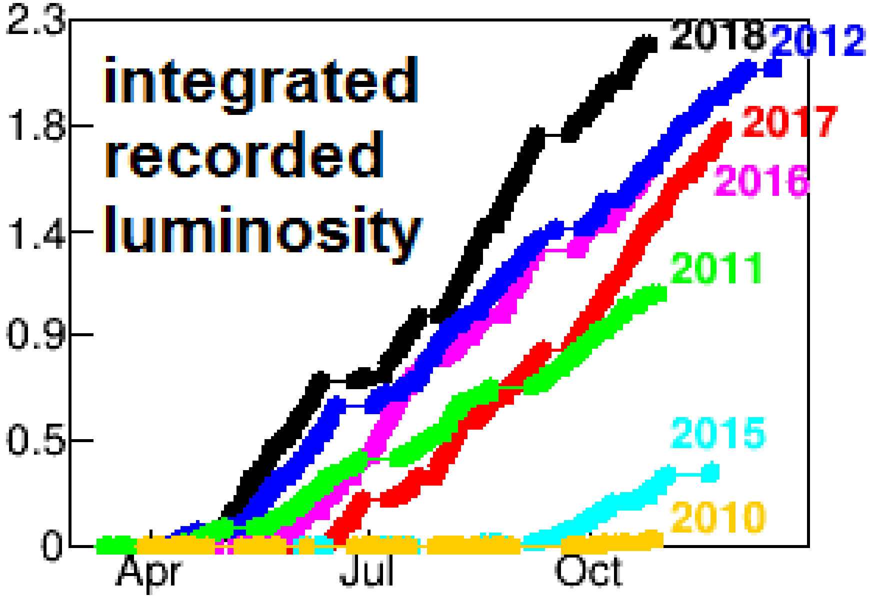
- $\mathcal{B}(B_s^0 \to J/\psi\phi) = (10.50 \pm 0.13 \pm 0.64 \pm 0.82) \times 10^{-3}$ [PRD87.072004]
- $f_s/f_d = 0.259 \pm 0.015$ [JHEP04(2013)001]
- $\varepsilon_{B^0}/\varepsilon_{B_s^0}$, efficiency ratio

- Use multivariate analysis techniques to select signal and suppress background

- Use sequential fits to $m(J/\psi K^+K^-)$ and m(K^+K^-) to distinguish signal and background

Data samples

Use full Run 1+Run 2 data, 9 fb^{-1}



Run 1 (2011~2012)

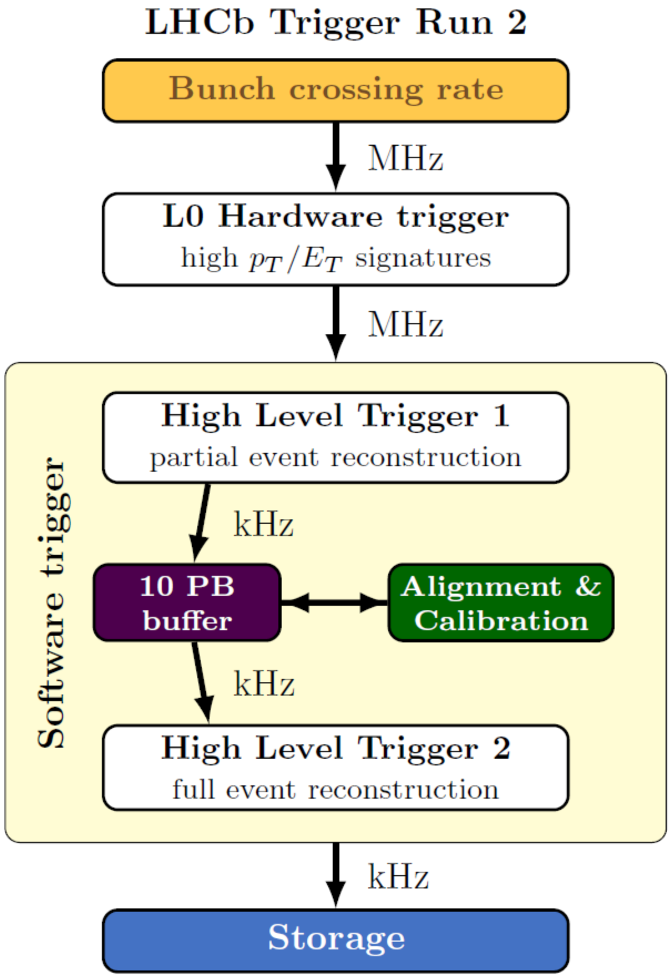
1.0 fb^{-1} of *pp* collisions at 7 TeV

2.0 fb^{-1} of *pp* collisions at 8 TeV

Run 2 (2015~2018)

5.7 fb^{-1} of *pp* collisions at 13 TeV

Trigger and preselection

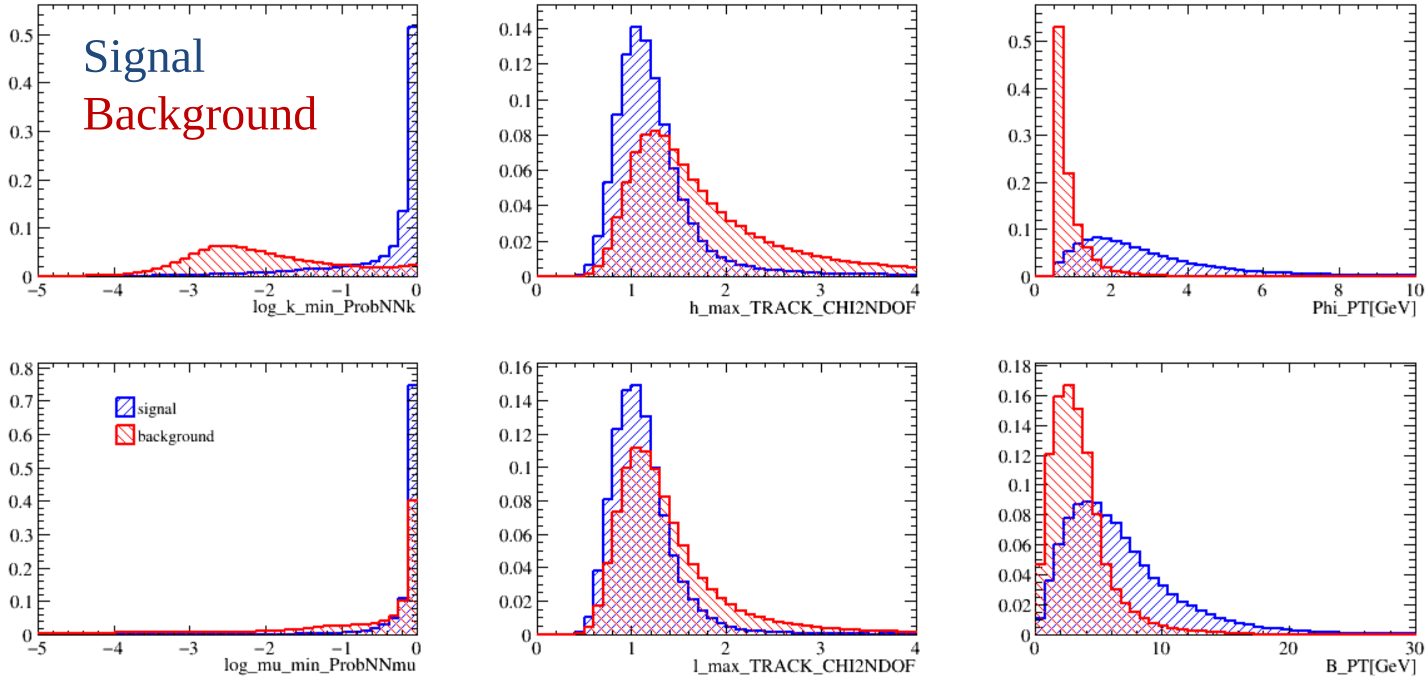


- ✓ Trigger system :
  L0 (hardware) + HLT1, 2 (software)
- ✓ $J/\psi \rightarrow \mu^+\mu^-$
  - **L0Muon** : at least one muon has p_T larger than a given threshold
  - **L0Dimuon** : sum of the two largest p_T of muons is larger than a given threshold
- ✓ Requirements on particle identification, p_T,

  mass ……….

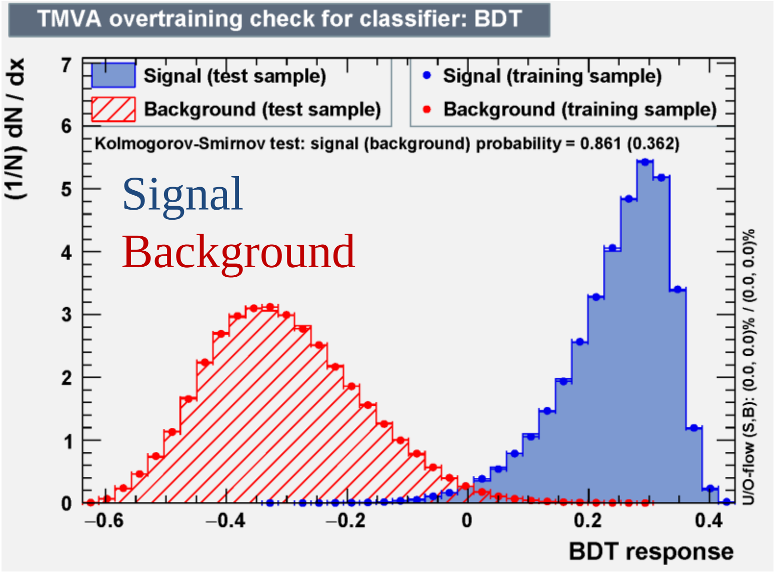
Training samples and variables

- MC sample as signal, data sideband as background
- Training variables
  - ✓ minimum particle identification probabilities of $\mu^{\pm}$ and $K^{\pm}$
  - ✓ minimum track-fit χ^2 of $\mu^{\pm}$ and $K^{\pm}$
  - ✓ p_T of ϕ and B_s^0………



TMVA overtraining check and optimisation

- Trained with BDT (Boosted Decision Tree) method
- The output response has better ability to suppress background



- Optimise the significance for $B^0 \to J/\psi K^+ K^-$ signal

$$\mathrm{F.O.M} = \epsilon/\sqrt{N}$$

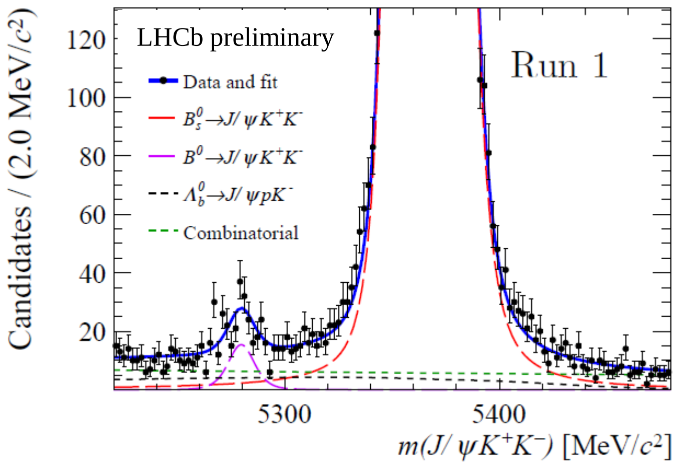
ϵ = signal efficiency for a specific MVA requirement

N = total events in B^0 mass window

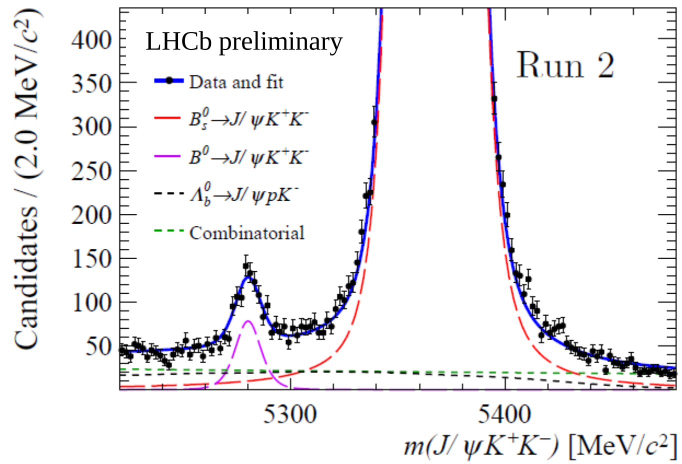
Fit results of m($J/\psi K^+K^-$)

- $B^0_{(s)} \to J/\psi K^+K^-$ & Combinatorial background & $\Lambda_b^0 \to J/\psi p K^-$
- Estimate yields in ± 15 MeV of B^0 and B_s^0 peak

Run 1, $\sigma = 7.67 \pm 0.03$ MeV



Run 2, $\sigma = 7.64 \pm 0.01$ MeV



Data	Category	Full	B_s^0 region	B^0 region
Run 1	$B_s^0 \to J/\psi K^+K^-$	55498 ± 238	51859 ± 220	35 ± 6
	$B^0 \to J/\psi K^+K^-$	127 ± 19	0	119 ± 18
	$\Lambda_b^0 \to J/\psi pK^-$	407 ± 26	55 ± 8	61 ± 8
	Combinatorial background	758 ± 55	85 ± 11	94 ± 11
Run 2	$B_s^0 \to J/\psi K^+K^-$	249670 ± 504	233663 ± 472	153 ± 12
	$B^0 \to J/\psi K^+K^-$	637 ± 39	0	596 ± 38
	$\Lambda_b^0 \to J/\psi pK^-$	1943 ± 47	261 ± 16	290 ± 17
	Combinatorial background	2677 ± 109	303 ± 20	331 ± 21

m(K^+K^-) fit model for each component

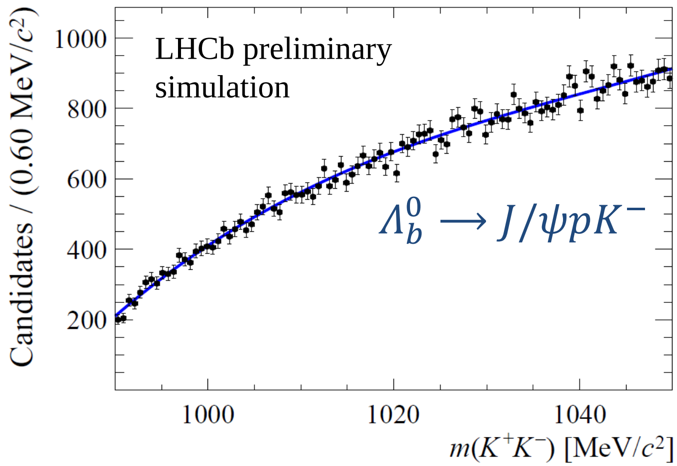
Component	Model
Signal	
$B^0_{s/d} \to J/\psi\phi$	Breit-winger [4]
Background	
$B^0_{s/d} \to J/\psi K^+K^-$	Flatte for $f_0(980)$ /$a_0(980)$ [5] PHSP for nonresonance
B^0_s tail shape under B^0 peak	modified Breit-winger
$\Lambda^0_b \to J/\psi p K^-$	extracted shape from MC
Combinatorial background	extracted shape from data

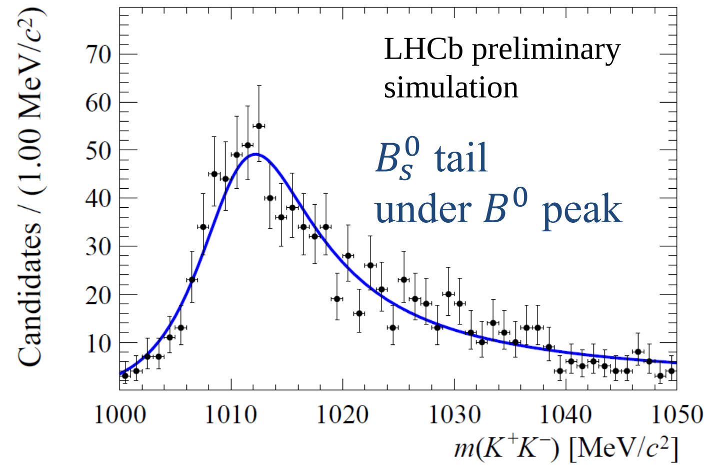
[4] [PRL115 (2015) 072001]

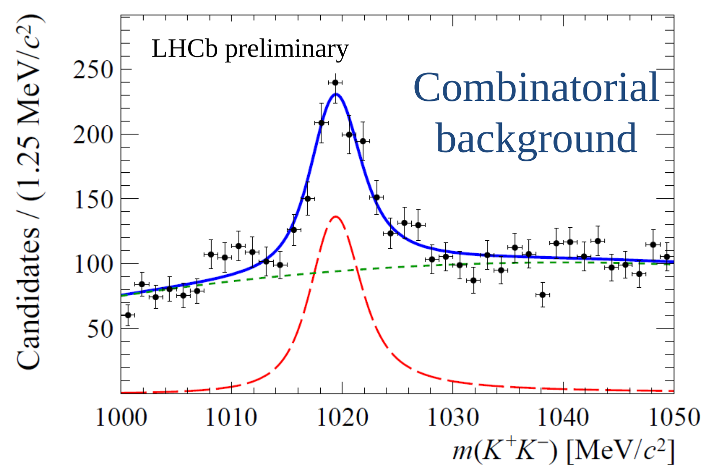
[5] [PLB63 (1976) 228]

m(K^+K^-) shape of backgrounds

- Use MC events for $\Lambda_b^0 \longrightarrow J/\psi p K^-$ and B_s^0 tail shape under B^0 peak
- Use the events in B^0 signal region, applied with inverse BDT, for comb. Bkg.

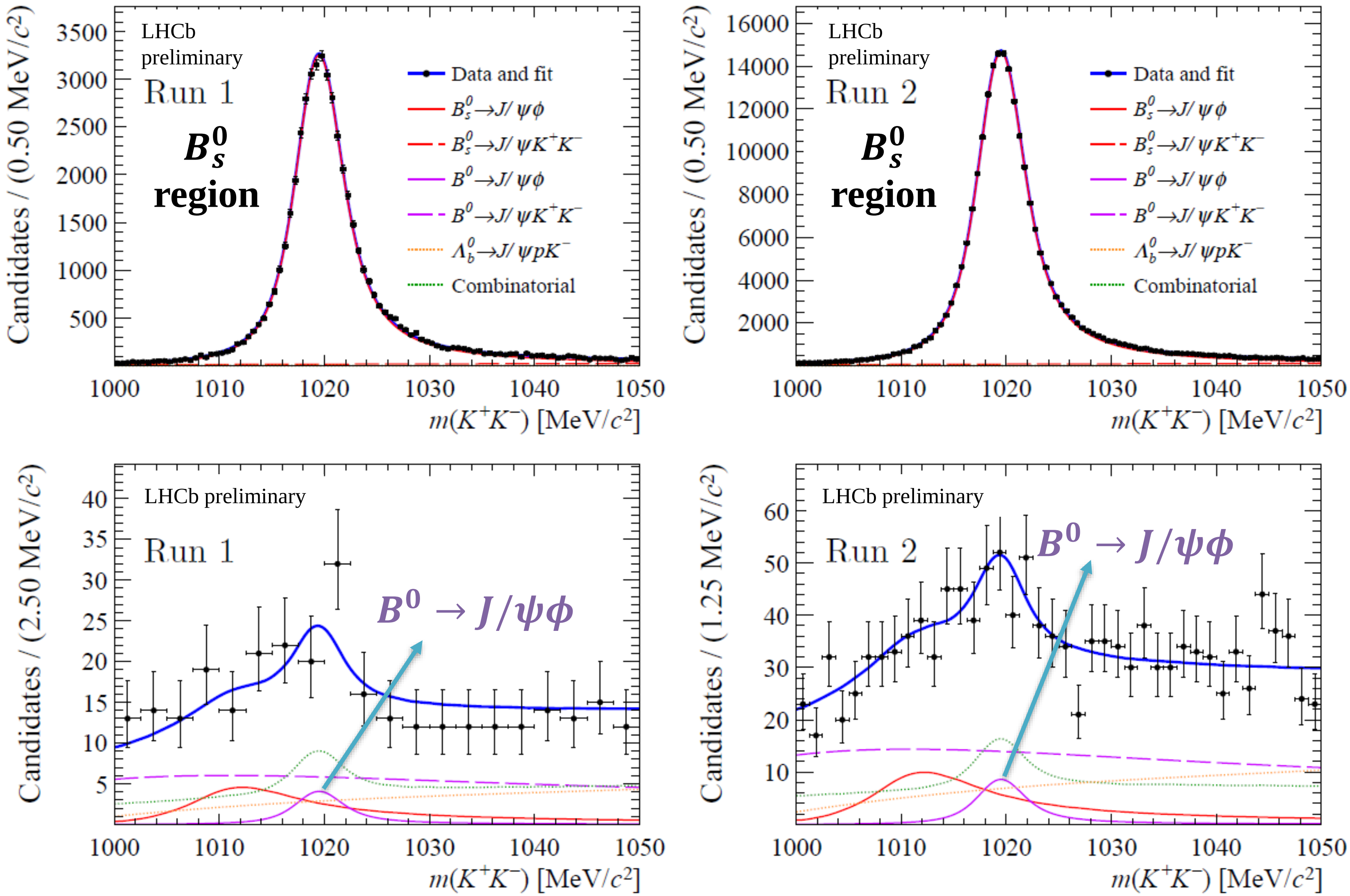






Fit results

- $\mathcal{B}(B^0 \to J/\psi\phi) = (6.8 \pm 3.0) \times 10^{-8}$, significance ~ 2.3σ



Systematic uncertainties

Multiplicative uncertainties	Value (%)
$\mathcal{B}(B_s^0 \to J/\psi\phi)$	6.2
Scaling factor for f_s/f_d	3.4
$\varepsilon_{B^0}/\varepsilon_{B_s^0}$	1.8
Total	7.3

Additive uncertainties	Value (10^{-8})
$m(J/\psi K^+K^-)$ model of combinatorial background	0.03
Fixed yields of Λ_b^0 in $m(K^+K^-)$ fit	0.05
Fixed yields of combinatorial background in $m(K^+K^-)$ fit	0.61
Fixed yields of B_s^0 contribution in $m(K^+K^-)$ fit	0.24
Constant d	0.01
$m(K^+K^-)$ shape of B_s^0 contribution	0.29
$m(K^+K^-)$ shape of Λ_b^0	0.28
$m(K^+K^-)$ shape of combinatorial background	0.16
$m(K^+K^-)$ shape of non-ϕ	0.06
Total	0.80

Relative uncertainties

(1) m($J/\psi K^+K^-$) model
(2) Yields of background

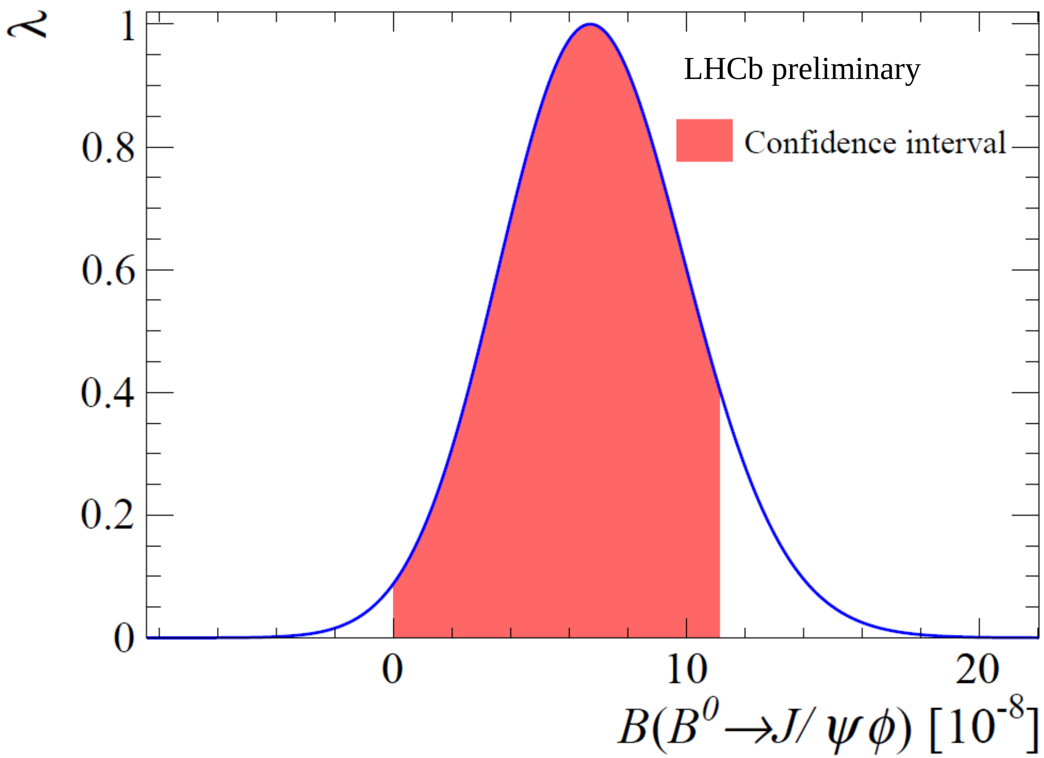
m(K^+K^-) shapes

Compared to statistical uncertainty 3.0×10^{-8}, they are small

Upper limit including systematics

- PLS (Profile Likelihood Scan) on $\mathcal{B}(B^0 \to J/\psi\phi)$ [EPJC71 (2011) 1554]
- Incorporate systematics by smearing PLS curve

$$\lambda(\mathcal{B}) = \int \lambda'(\mathcal{B}')\times G(\mathcal{B}-\mathcal{B}', 0, \sigma_{\text{sys}}(\mathcal{B}'))d\mathcal{B}'$$



$\mathcal{B}(B^0 \to J/\psi\phi) < 1.1 \times 10^{-7}$, $N^{\phi}_{B^0} < 86$ at 90% CL

Summary

- A search for $B^0 \to J/\psi\phi$ has been performed using the LHCb full Run 1 and Run 2 data sample (LHCb-PAPER-2020-033)
  - ☑ $\mathcal{B}(B^0 \to J/\psi\phi) = (6.8 \pm 3.0(stat.) \pm 0.9(syst.)) \times 10^{-8}$
  - ☑ $\mathcal{B}(B^0 \to J/\psi\phi) < 1.1 \times 10^{-7}$, which is improved compared with the previous limit using 1 fb^{-1} data, 1.9×10^{-7}
  - ☑ The measurement is compatible with the theoretical prediction $(1.0 \pm 0.3) \times 10^{-7}$

Backup

m(K^+K^-) fit model of resonance

- Lineshape of resonance [JHEP08(2017)037]

$$\mathcal{A}_R(m) = \sqrt{P_B P_R} F_B^{(L_B)} F_R^{(L_R)} A_R(m) (\frac{P_B}{m_B})^{L_B} (\frac{P_R}{m_R})^{L_R}$$

- P_B, the momentum of J/ψ in the $B_s^0(B^0)$ rest frame
- P_R, is the momentum of either kaon in the K^+K^- rest frame
- $L_{B/R}$, is the orbital angular momentum between J/ψ and dikaon system or K^+ and K^-
- $F_{B/R}$, is Blatt-Weisskopf barrier factor [PRD5 (1972) 624]
- A_R, is a Breit-winger function for $\phi(1020)$ or a Flatte function for $f_0(980)$ /$a_0(980)$
- $m_{B/R}$, the nominal/pole mass of $B_s^0(B^0)$/resonance

Lineshape of ϕ resonance

$$S_\phi(m) \equiv P_B P_R F_R^2(P_R, P_0, d)(\frac{P_R}{m_0})^{2L_R}|A_\phi(m'; m_0, \Gamma_0)|^2 \otimes G(m - m'; 0, \sigma)$$

$$F_R(P_R, P_0, d) = \sqrt{\frac{1 + (P_0 d)^2}{1 + (P_R d)^2}}$$

- A_ϕ is Breit-winger with gaussian constraint on
  $m_0 = 1019.461 \pm 0.016$ MeV and $\Gamma_0 = 4.249 \pm 0.013$ MeV [PDG]
- P_B, the momentum of J/ψ in the $B_s^0(B^0)$ rest frame
- $P_R(P_0)$, is the momentum of kaon in the $K^+K^-(\phi)$ rest frame
- L_R is the orbital angular momentum between K^+ and K^-, $L_R = 1$
- F_R is Blatt-Weisskopf barrier factor [PRD5 (1972) 624], $d = 1.5$ GeV^{-1}
- G is a Gaussian resolution function with floated σ

Lineshape of non-ϕ K^+K^-

$$\mathrm{S}_{non}(m) \equiv P_B P_R {F_B}^2 (\frac{P_B}{m_B})^{2L_B} \left| A_R(m) \times e^{i\delta} + A_{NR} \right|^2$$

- L_B, the orbital angular momentum between J/ψ and dikaon system, L_B = 1
- m_B, the nominal mass of $B_s^0(B^0)$
- F_B, Blatt-Weisskopf barrier factor, F_B = 3.0
- A_R, a Flatte model for $f_0(980)/a_0(980)$
- A_{NR}, a constant for nonresonance
- δ, the relative phase, constrained to -255 ± 35 or 60 ± 26 degrees for $f_0(980)$ or $a_0(980)$, according to the $B_{s/d}^0 \to J/\psi K^+K^-$ amplitude analysis [PRD88.072005, PRD87.072004]

Flatte model[PLB63 (1976) 228.]

$$A_{f_0}(m) = \frac{1}{m_R^2 - m^2 - i m_R(g_{\pi\pi}\rho_{\pi\pi} + g_{KK}\rho_{KK})}$$

$$A_{a_0}(m) = \frac{1}{m_R^2 - m^2 - i(g_{\eta\pi}^2\rho_{\eta\pi} + g_{KK}\rho_{KK})}$$

- m_R, the pole mass for the resonance
- ρ, the Lorentz-invariant phase space factor
- $g_{\pi\pi}(g_{\eta\pi})$ and g_{KK}, the coupling strengths of $f_0(980)$ ($a_0(980)$) to $\pi\pi(\eta\pi^0)$ and KK,

fixed to their mean values according to the Run 1 $B_s^0 \to J/\psi\pi^+\pi^-(K^+K^-)$ analyses [PRD86.052006, PRD87.072004]

Profile Likelihood Scan

Maximum likelihood value with fixed branching ratio

$$\lambda_0(\mathcal{B}) \equiv \frac{L(\mathcal{B}, \widehat{\widehat{\nu}})}{L(\widehat{\mathcal{B}}, \widehat{\nu})}$$

Maximum likelihood value of baseline fit

Relative uncertainties

$$\mathcal{B}(B_s^0 \to J/\psi\,\phi) = \frac{N_{B_s^0}}{N_{B^+}} \times \frac{\varepsilon_{B_s^0}}{\varepsilon_{B^+}} \times \mathcal{B}(B^+ \to J/\psi\,K^+) \times \frac{1}{f_s/f_d}$$

$$= (10.50 \pm 0.13[stat.] \pm 0.64[syst.] \pm 0.82[f_s/f_d]) \times 10^{-4}$$

- ✓ $\mathcal{B}(B_s^0 \to J/\psi\phi)$ is measured with 2011 data [PRD.87.072004]
- ✓ $\mathcal{B}(B^0 \to J/\psi\phi)$ is proportional to $\mathcal{B}(B_s^0 \to J/\psi\phi) \times f_s/f_d$, third uncertainty is canceled with that of the f_s/f_d measurement at 7 TeV
- ✓ scaling factor of 1.068 ± 0.046 is needed for 13 TeV