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(ON BEHALF OF CMS COLLABORATION)

FIRST OBSERVATION OF $B^+ \rightarrow \Psi(2S)\Phi K^+$

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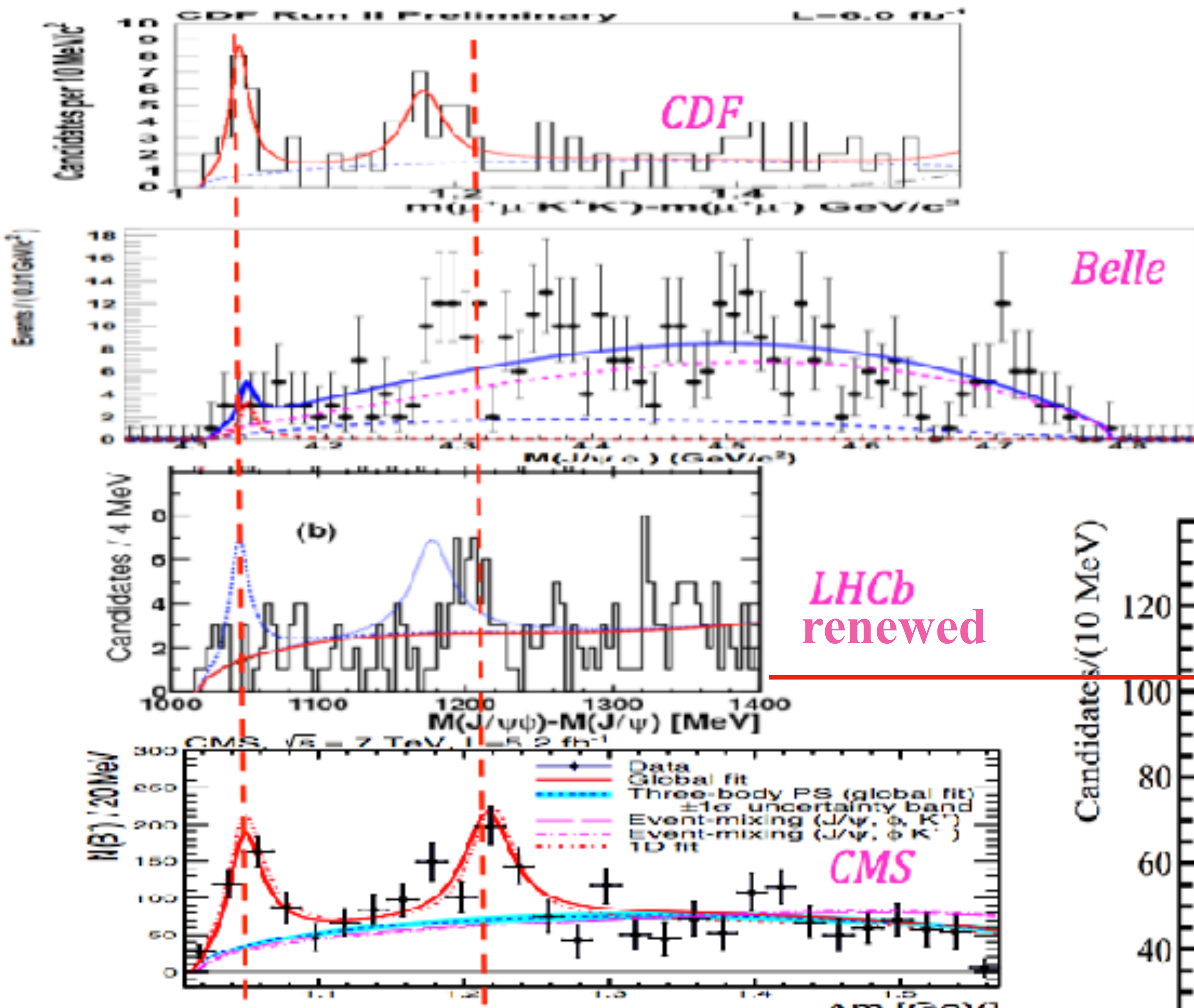
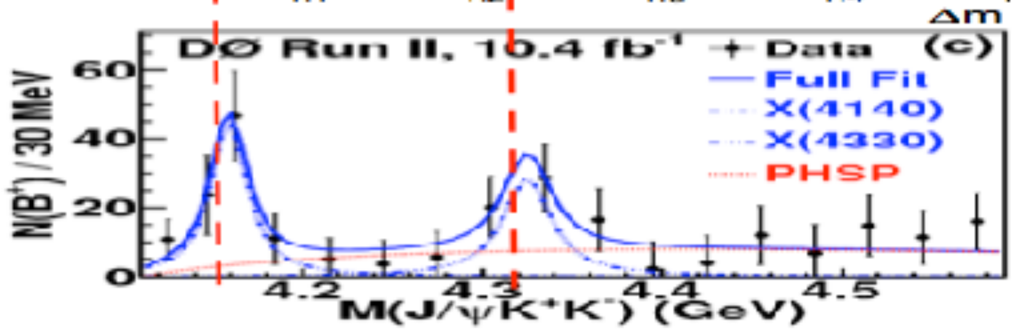
Outline

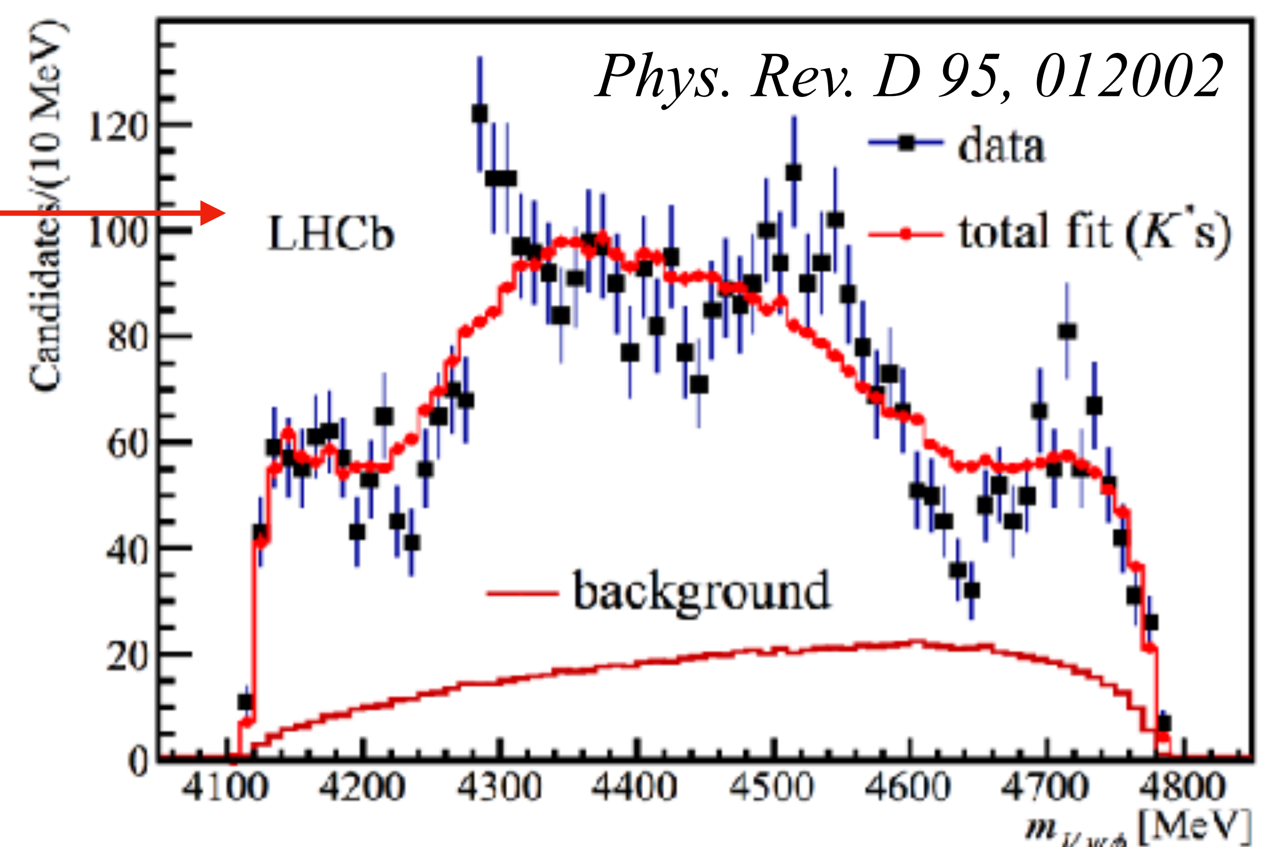
- Motivation
- Introduction
- CMS and Triggers
- Event reconstruction
- Event selection
- Results
- Summary and outlook

Motivation - J/ψϕ System



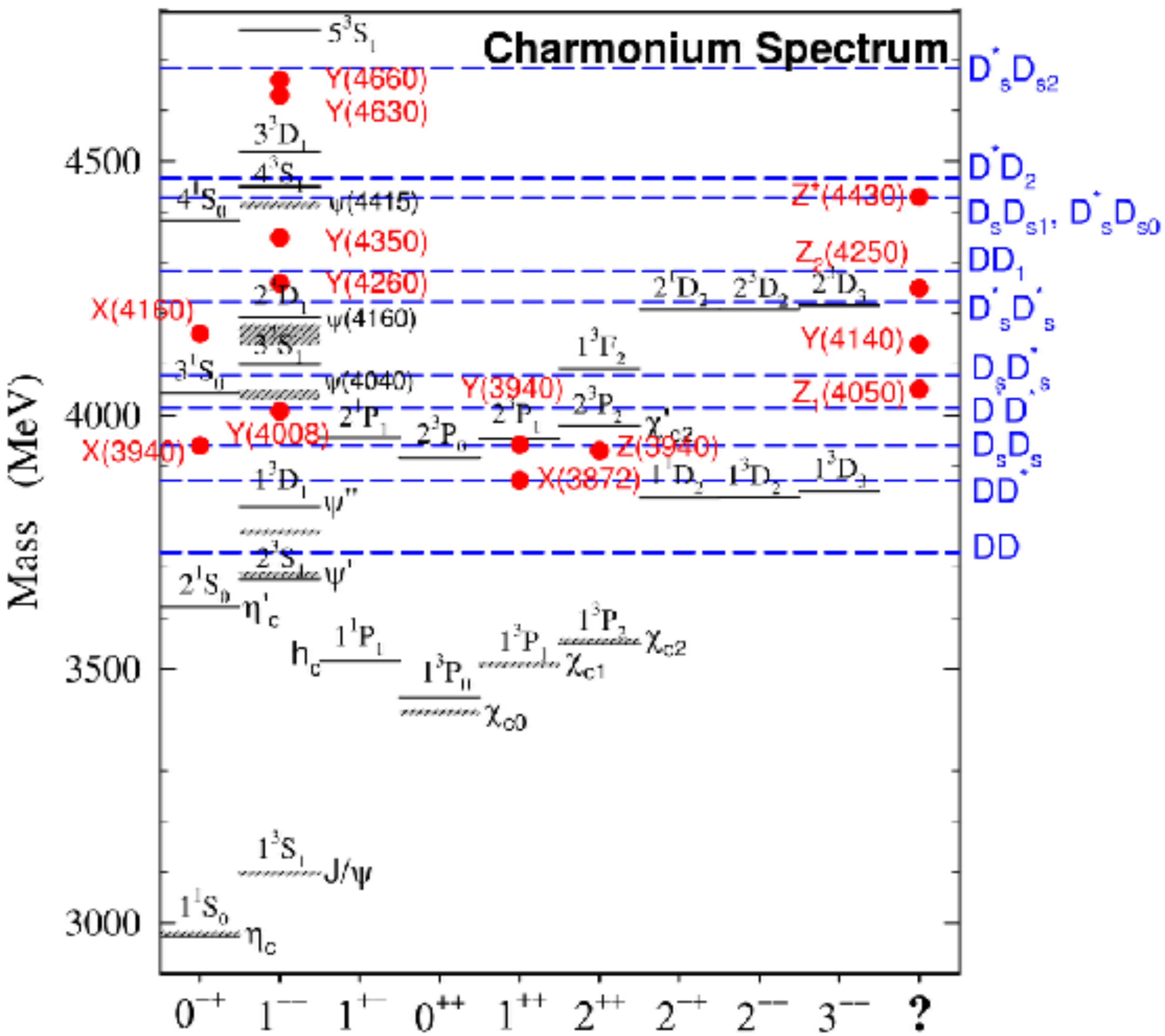


First amplitude analysis from LHCb confirms the particle(s)

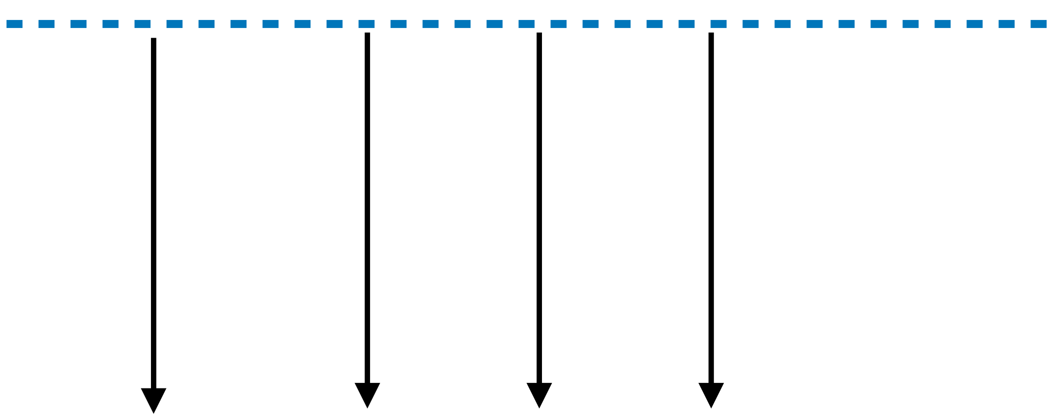


Kai Yi, Joint Experimental-Theoretical Physics Seminar Fermilab, Oct 18, 2013

What is interesting?



- Well above the open-charm threshold.
- Expect tiny BF to J/ψφ
- Expect larger widths
- Does not fit into conventional charmonium.
- **Quarkonium-like** states



- well-known mesons

Quarkonium : a bound state of any heavy quark and its antiquark

Introduction

- High luminosity and the large cross section of the b quark production enable us to study B decays at LHC.

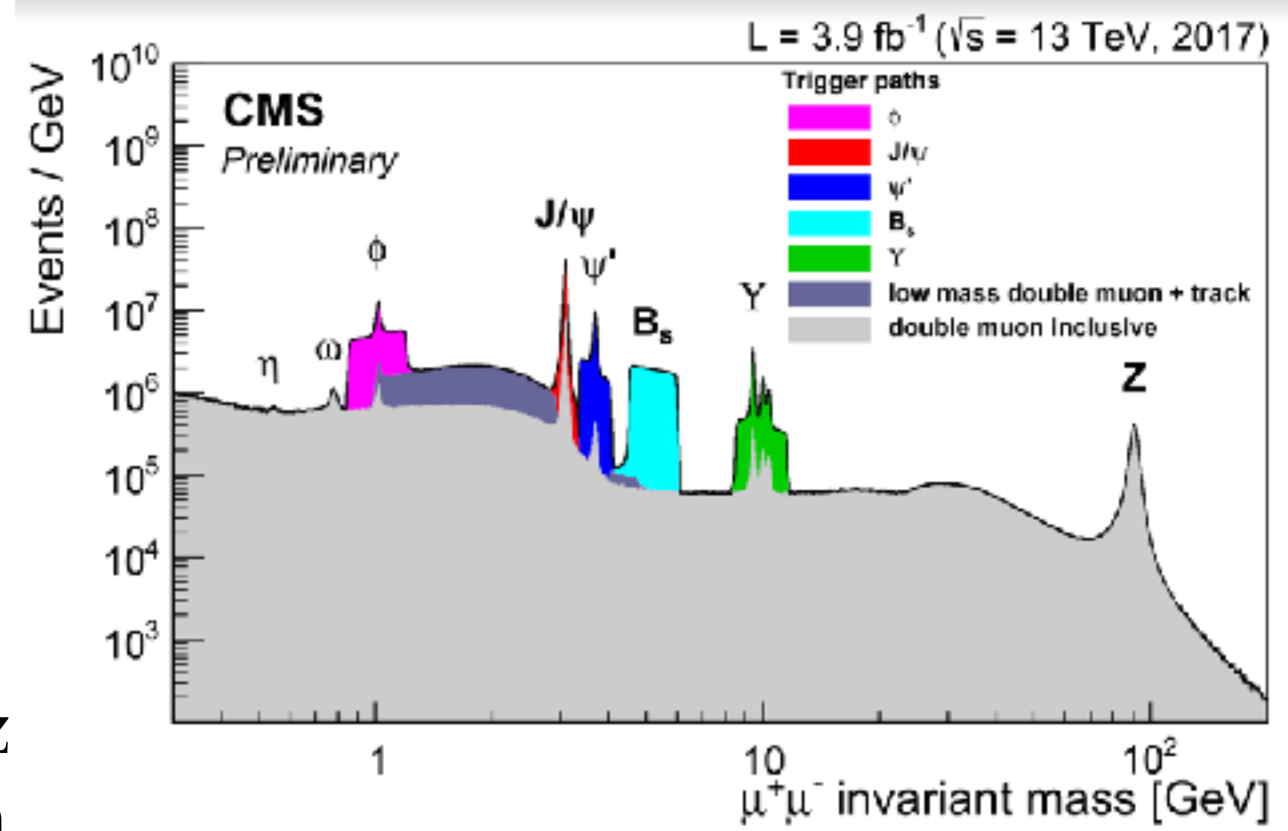
- Several experiments(CDF, Belle, D0, LHCb) study the likely presence of structures in the $J/\psi\phi$ mass scale.

  - CMS reported on the peaking structures in the $J/\psi\phi$ spectrum from exclusive $B^{\pm} \rightarrow J/\psi\phi K^{\pm}$
    Phys. Lett. B(2014)

  - A natural extension of these results is to study the $\psi(2S)\phi(1020)K^{\pm}$ and the $\psi(2S)\phi(1020)$ mass spectra
    Phys.Lett.B(2017)

CMS & trigger system

- Fast hardware processors, information from the muon detectors to select dimuon candidates: L1
- Software modules, reconstruction of physics objects and vertex: HLT
  - Highly flexible - paths dedicated to particular analysis
  - Event rate from ~100 kHz to ~1 kHz
- Data parking advantage of ~100 Hz on top of the stream ~20-30 Hz.



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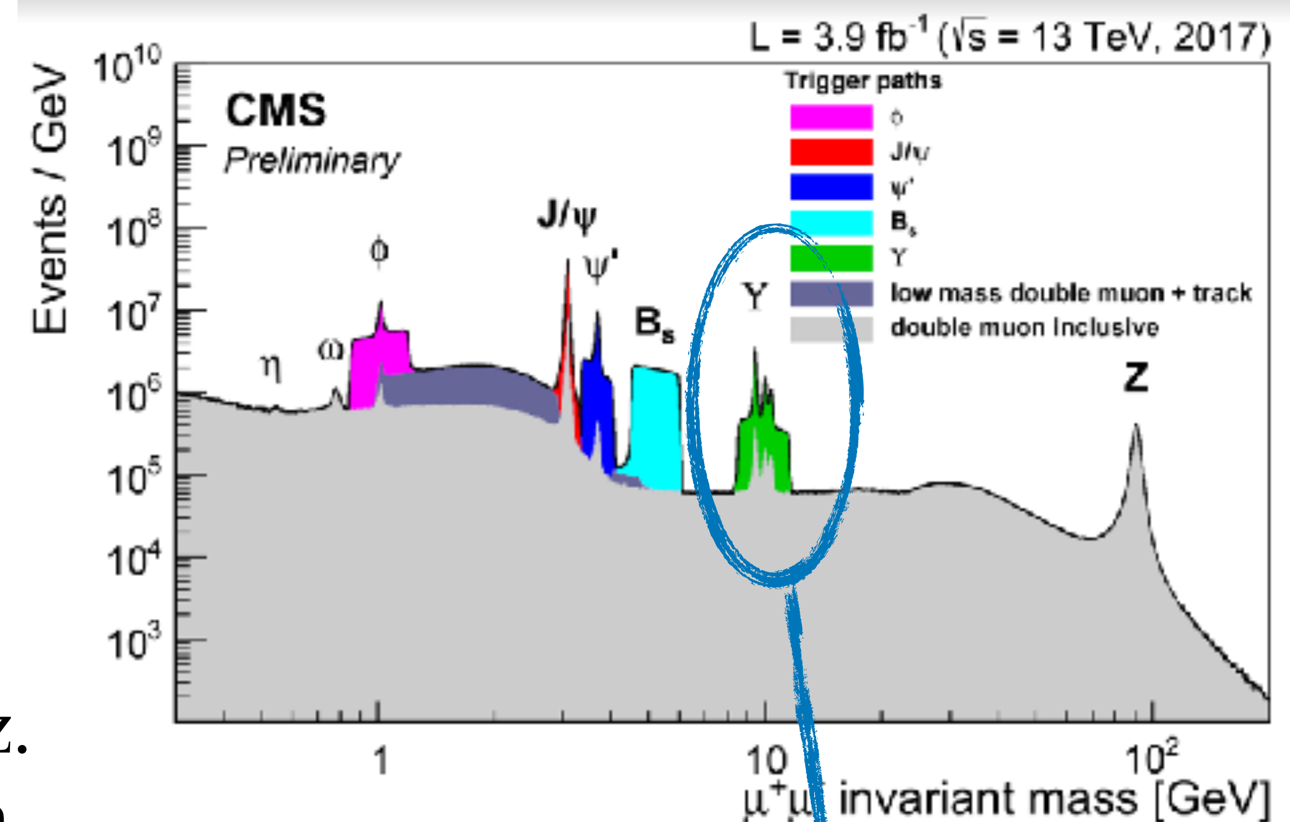
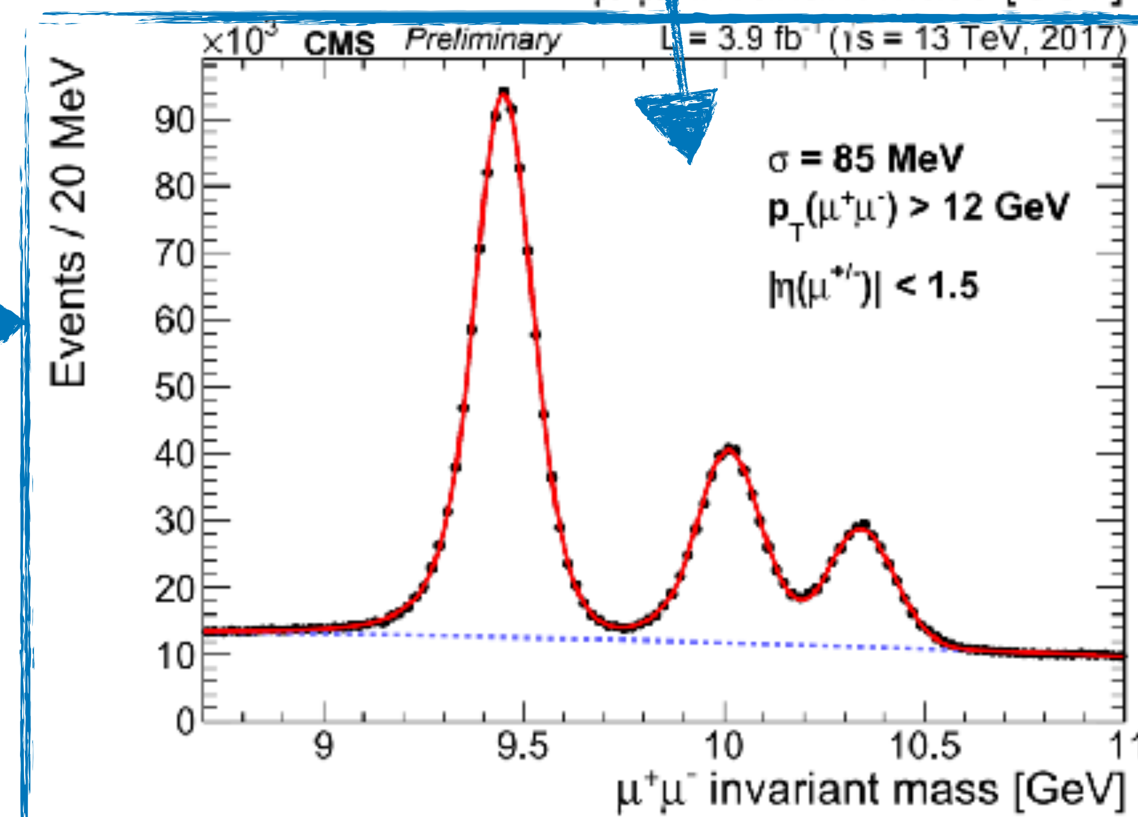
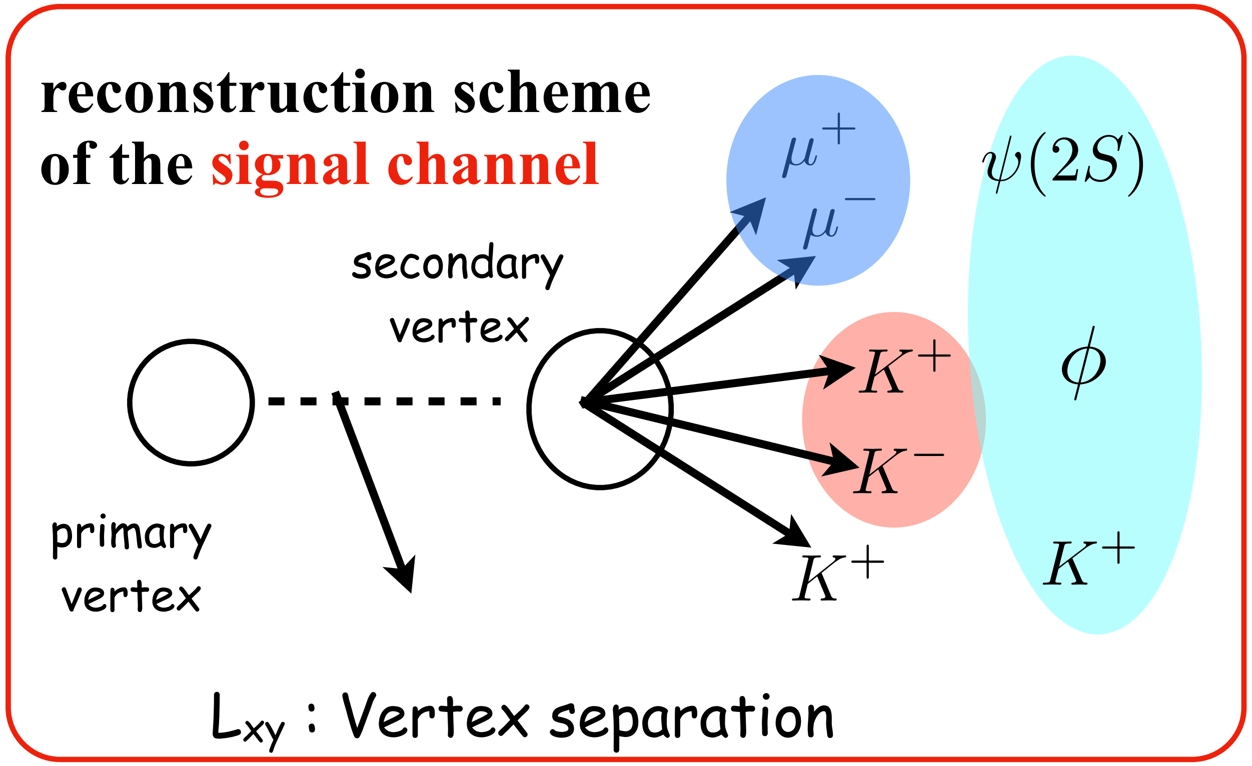
- Excellent dimuon mass resolution (~0.6% - 1.5% depending on |η|)
- Good pT resolution. σ(pT)/pT ~1%
  - results from the matching between the tracks in the muon chambers and in the silicon tracker
- Impact parameter resolution (45–150) μm





Event Reconstruction



➡ **Normalization channel : $B^+ \rightarrow \psi(2S)K^+$**

- Well-known branching fraction.
- Common features, e.g. trigger, decay topology etc. in order to reduce the systematic uncertainties.

➡ **Signal $B^+ \rightarrow \psi(2S)\phi K^+$**

- $\psi(2S)$, ϕ and K mesons fit to a common vertex to reconstruct the B signal.
- Two muons form a common vertex to reconstruct $\psi(2S)$
- K^+K^- pair that has mass closest to the ϕ nominal mass.
- The PV is chosen to be the one that minimizes the angle between the B momentum(3D) and the vector from the collision point to the B decay vertex.

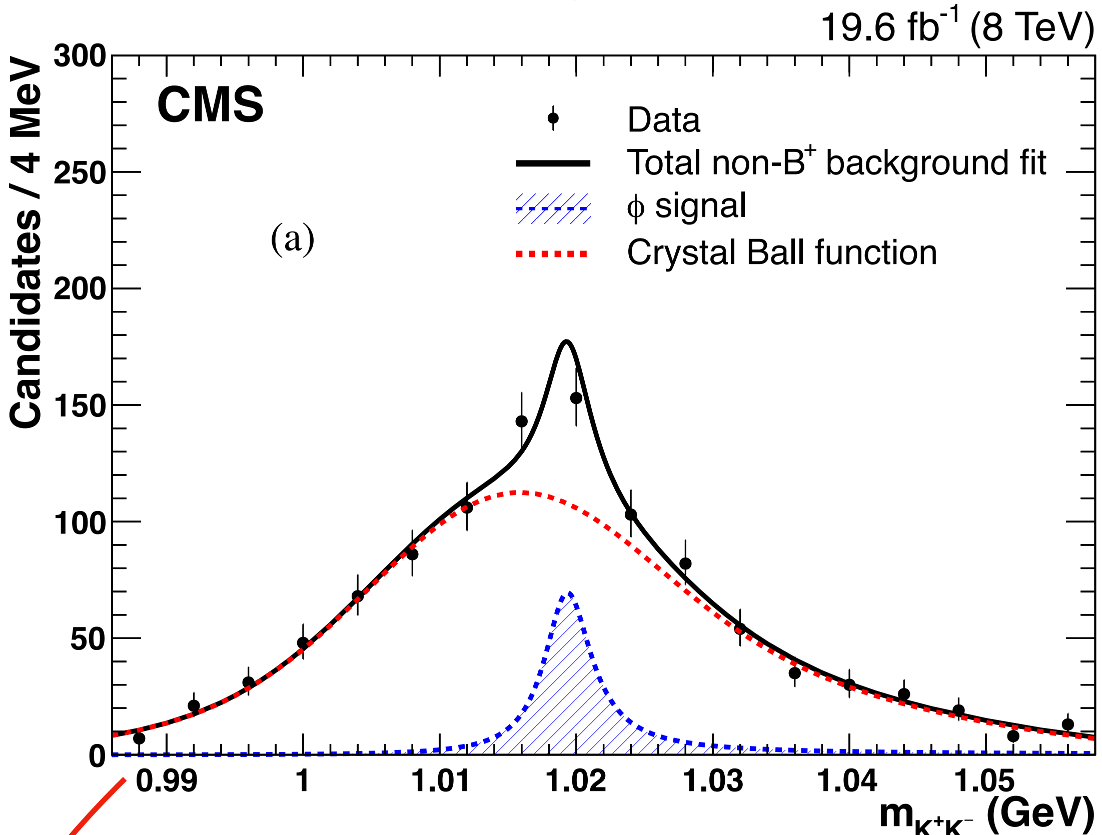
Event Selection

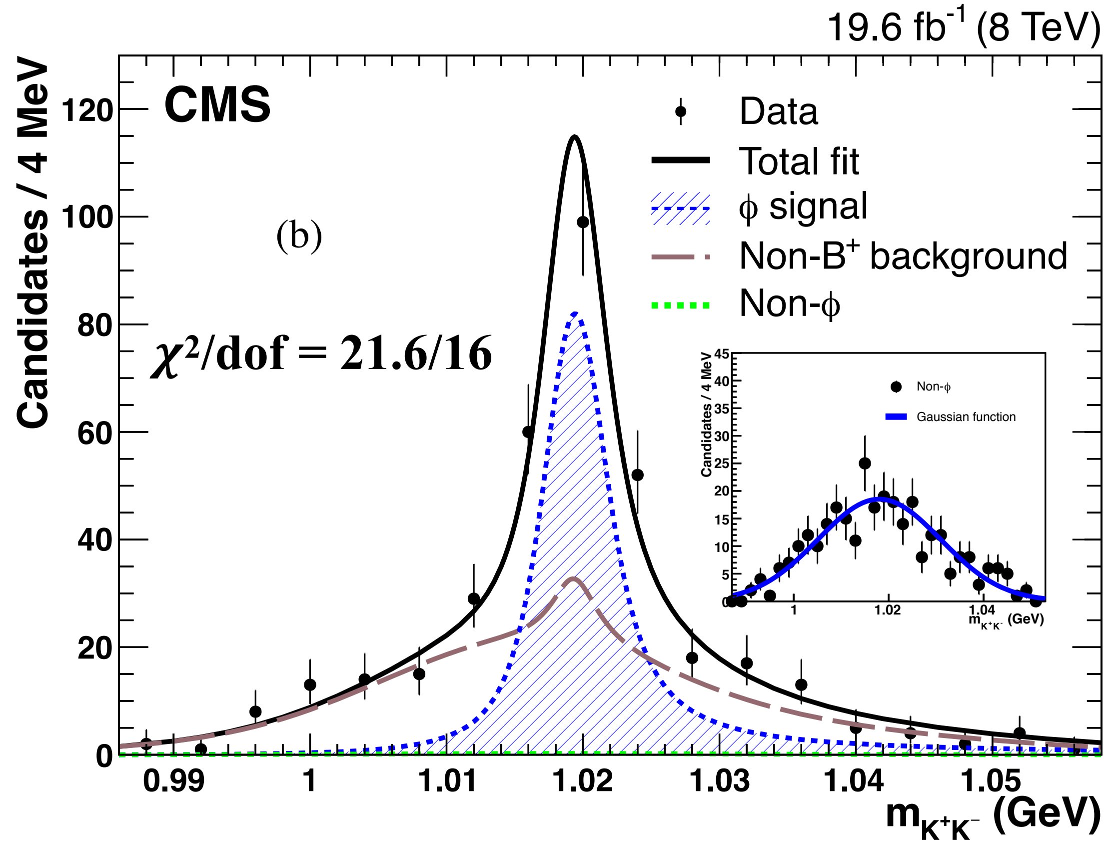
- All kaon tracks to have $p_T > 1.0$ GeV and $|\eta| \leq 2.4$
- The fit probability for $\psi(2S)$ and B^+ vertices > 10%
- Distance between the PV and the SV positions in the transverse plane divided by its uncertainty, $L_{xy}(B^+) / \sigma(L_{xy}(B^+)) > 4$
- Pointing angle > 0.99: the cosine of the angle between the B meson (3D) momentum direction and the direction obtained by the SV and the PV.
- Two K^+K^- pairs(among three K tracks) - choose the pair with its mass to be closest to the φ nominal mass.
  - φ mass window $|m_{K^+K^-} - 1.019| < 8$ MeV.
- $\psi(2S)$ mass $\mp$150 MeV of its PDG mass value.
  - Dimuon pT> 7 GeV

φ Signal

Simultaneous fit to the K^+K^- invariant mass closest to the nominal φ mass outside and inside the B window ($3\sigma_B$ - wide).
(Not using the ±8 MeV φ mass window selection.) $\sigma_B = 3$MeV

φ mass outside the B mass window	φ mass inside the B mass window

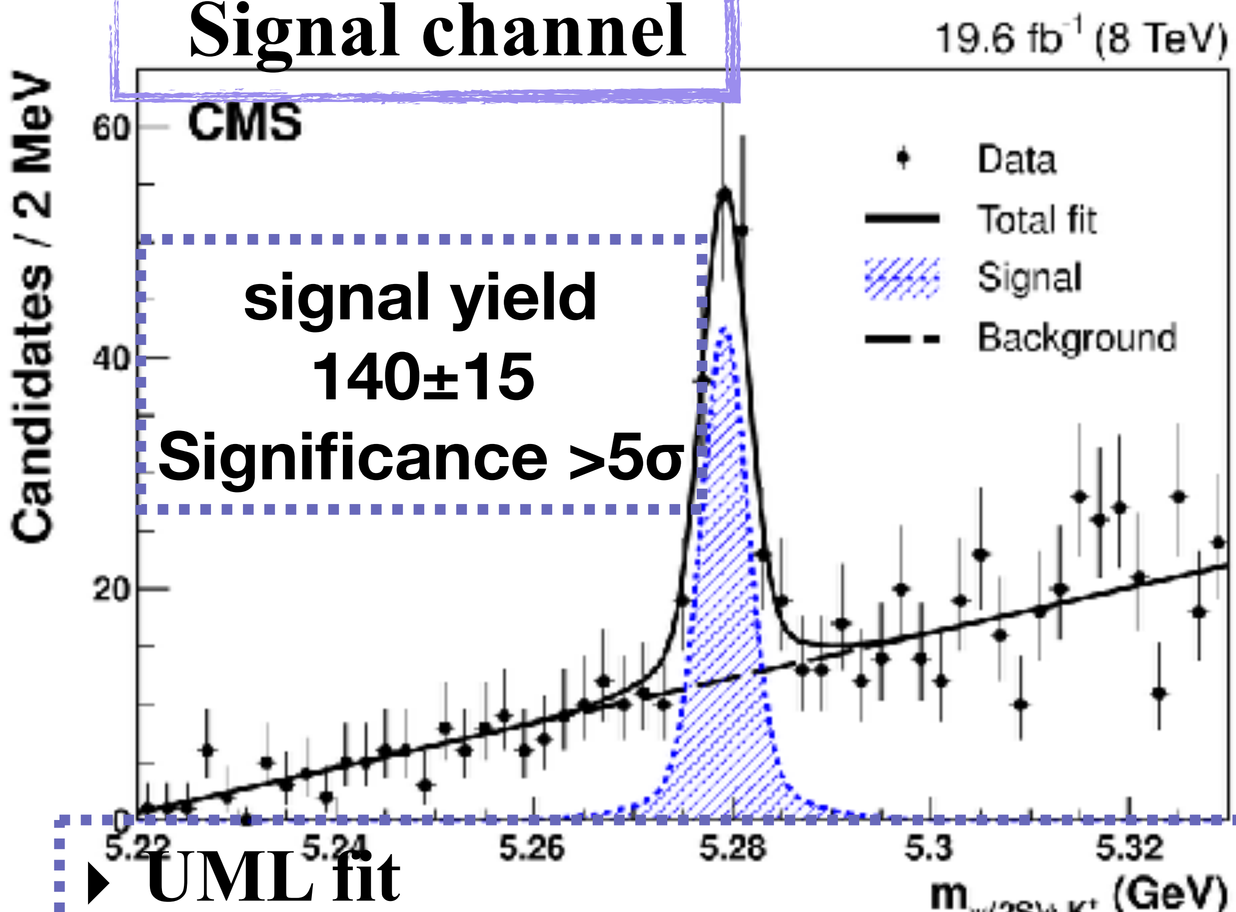




- Non-φ : f0(980) meson and non-resonant K^+K^-
- φ signal : P-wave rel. BW + Gaussian resolution
- Non-B+ bkg : Constrained from ψ(2S)φK^+ sidebands

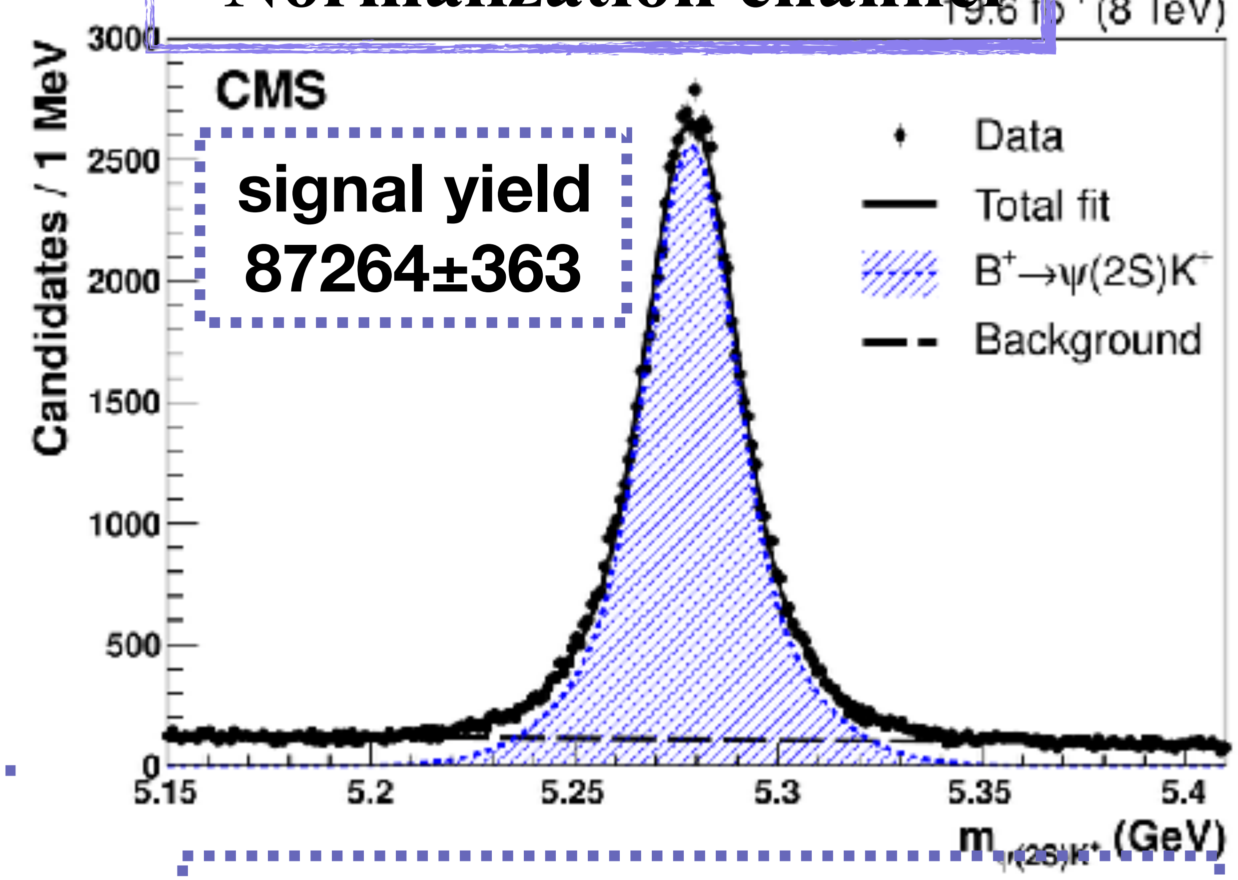
Results

Signal channel



signal yield
140±15
Significance >5σ

Normalization channel



signal yield
87264±363

- UML fit
  - **Signal :** two Gaussian (common mean fixed to B nominal, width and relative fractions fixed to the values from MC.)
  - **Bkg :** 1. order polynomial.

- Normalization Channel
  - Same fit procedure
  - Same event selection as signal decay. (except φ cut)

Limited # of signal events precluded any search for ψ(2S)φ resonances in the current data sample.

Branching Fraction

- BF($B^+ \rightarrow \psi(2S)\phi K^+$) measurement relative to normalization channel
  - $B^+ \rightarrow \psi(2S)K^+$ well-known branching fraction
  - (almost) the same event selection to reduce the uncertainties.

$$BF(B^+ \to \psi(2S)\phi K^+) = \frac{(B^+ \to \psi(2S)\phi K^+)_{\text{data yield}} \times BF(B^+ \to \psi(2S)K^+)_{PDG}}{(B^+ \to \psi(2S)K^+)_{\text{data yield}} \times \epsilon_{relative} \times BF(\phi \to K^+K^-)_{PDG}}$$

$$\epsilon = N_{Reco}/N_{Gen}$$

$\varepsilon_{(signal)} / \varepsilon_{(normalization)}$

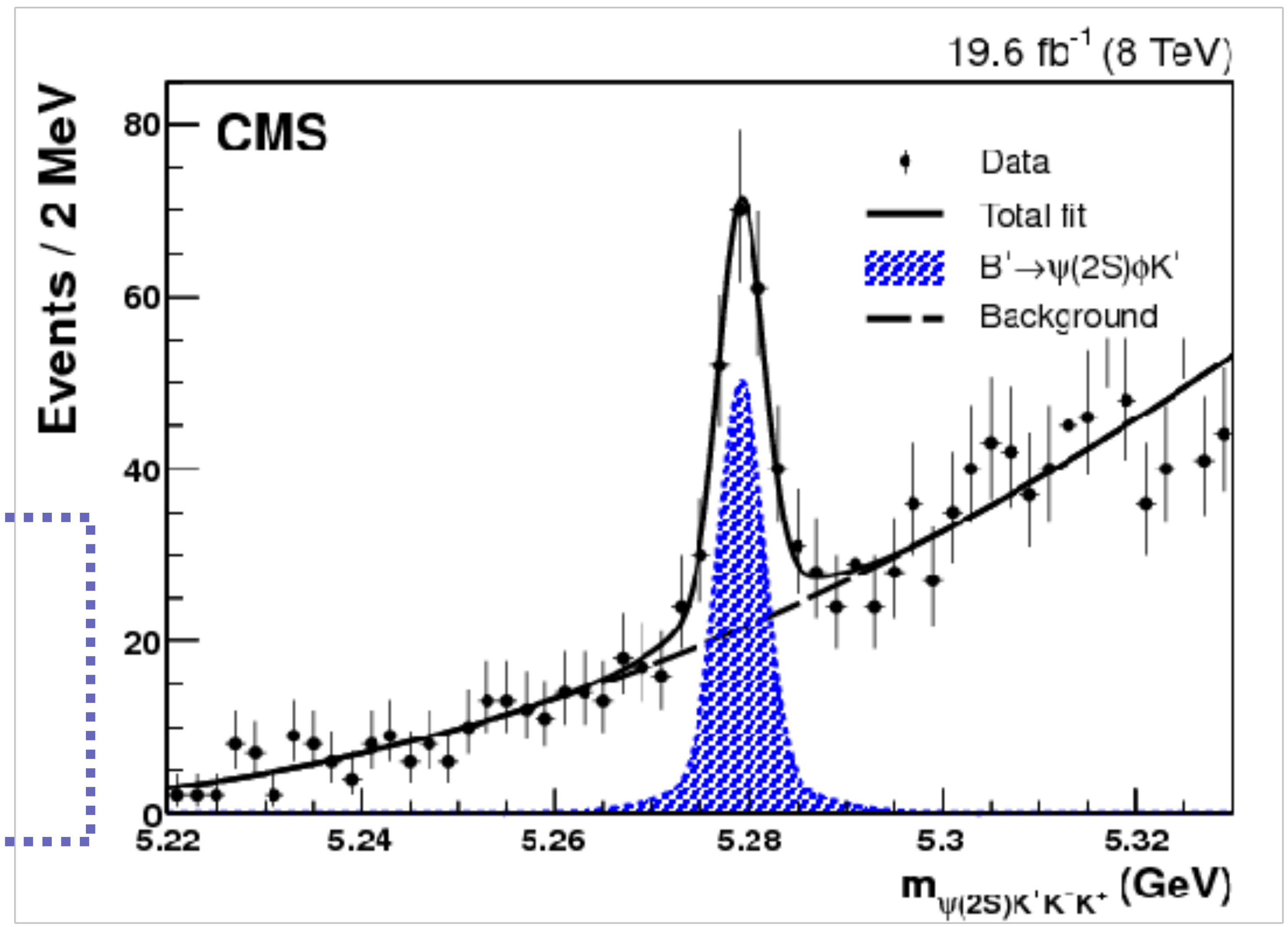
$$BF(B^+ \to J/\psi)\phi K^+ = 4.0 \pm 0.4(stat) \pm 0.6(syst) \pm 0.2(BR) \times 10^{-6}$$

φ Signal - Cross check

The choice of the K⁺K⁻ candidate closest to the nominal φ mass can cause a bias, and, to estimate any systematic contamination of the K⁺K⁻ mass peak from non-φ backgrounds, the analysis is repeated after removing the selection on the K⁺K⁻ mass, being closest to the mass of the φ.

Redetermined the BR, the difference reflected as a systematic uncertainty from possible non-φ backgrounds 5.0%

- UML fit
  - Signal : two Gaussian functions
  - Bkg : 2. order polynomial.



Systematics

Source	Uncertainty (%)
B^+ mass shape for signal mode	8.6
Charged particle track reconstruction efficiency	7.8
Modeling of p_T dependence of B^+ efficiency	5.3
ϕ purity	5.0
Mass distribution for the background in the signal	2.9
Uncertainty in relative efficiency of signal and normalization	2.3
Background distribution in the normalization channel	2.2
Angular distributions of K^+K^- systems	1.9
B^+ mass shape for normalization mode	1.0
$\mathcal{B}(\phi \to K^+K^-)$ uncertainty	1.0
Total	15

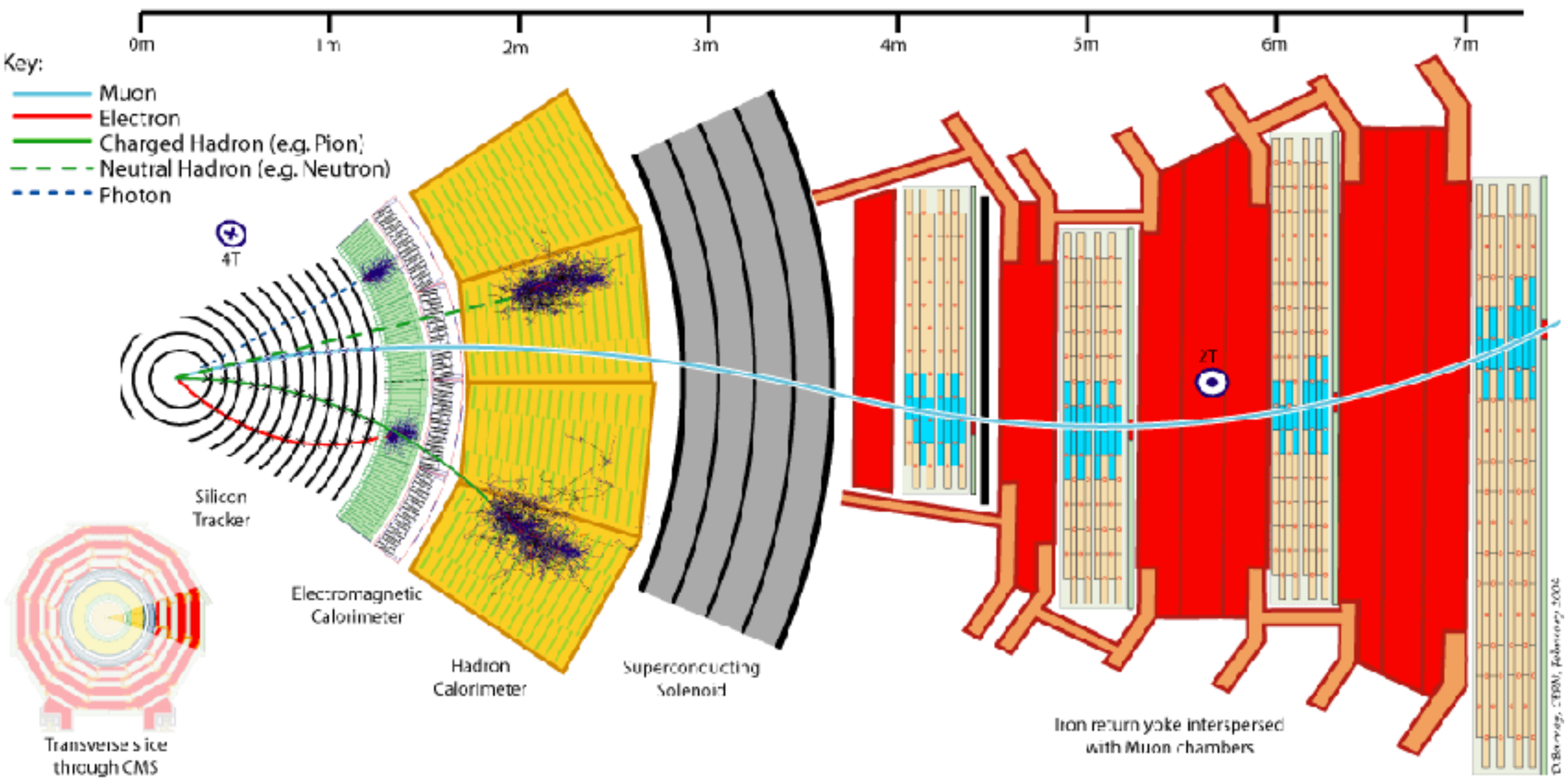
- **B^+ mass shape** uncertainty by allowing the widths of the two Gaussian functions to vary with the background function fixed in the fit.
- The uncertainty on **track reconstruction efficiency** by comparing two-body and four-body D^0 decays in data and simulated events.
- The ratio of efficiencies from the re-weighted MC events is compared to the nominal value to extract a systematic uncertainty of **p_T dependence of B^+**
- **φ purity** systematic uncertainty by removing the closest mass selection on φ as in previous slide.

Summary and Outlook

- The signal $B^+ \to \psi(2S)\phi K^+$ is observed with a significance > 5σ
    - The BR of the decay is present at PDG since 2017.
- The upper limit on the fraction of $B^+ \to \psi(2S)(\text{non-}\phi)K^+$ decays in $B^+ \to \psi(2S)K^+K^-K^+$ channel is found to be 0.26 at 95% confidence.
- The result has been achieved using data from pp collisions at $\sqrt{s}$ = 8 TeV, corresponding to an integrated luminosity of 19.6 fb^{-1}
- Although, there is no resonance search (yet) in the $\psi(2S)\phi$ mass scale, the observation of $B^+ \to \psi(2S)\phi K^+$ offers future opportunities in searches for resonances in the $\psi(2S)\phi$ mass spectrum.

BACKUP

CMS by Layers



Pre-selection

- All kaon tracks to have $p_T > 0.5$ GeV.
- All kaon and muon tracks to have $|\eta| \leq 2.4$.
- The official 'soft muon'criteria are used in the analysis. The muon candidates should at least meet the quality 'TMOneStationTight'.
- All muon tracks to have at least 1 pixel hit and at least 5 silicon hits.
- For each pair of muon with opposite charges, a $\psi(2S)$ candidate is formed within the mass range [3.4, 4.0] GeV.
- A vertex fitting procedure, based on the standard package KinematicVertexFitter, has been applied to the $\psi(2S)$ candidate using the daughter muons. The quality of their common vertex is controlled by requiring the vertex probability to be at least 0.1%.
- Three different tracks with assigned kaon mass, total charge= ± 1 and mass upon combining with $\mu^+\mu^-$ in the range [5.15, 5.45] GeV.
- We have two K^+K^- pairs from three charged kaon tracks. We require the mass of K^+K^- pair with lower mass to be smaller than 1.06 GeV.
- We do a vertex fit to the five tracks and constraint $\mu^+\mu^-$ to nominal $\psi(2S)$ mass and require vertex probability $> 10^{-6}$.