Search for hadron exotics in new decay modes of B^0 meson at LHCb

Graduate physics seminar 2025

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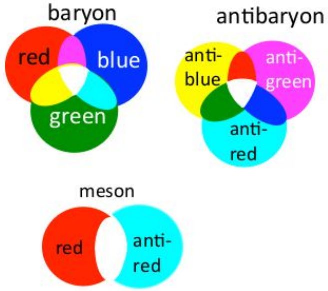
NCBJ

A brief history of Hadron spectrum

- **Gell-Mann and Zweig (1964)**: hadrons described as composites of fractionally charged fermions, Quarks with baryon number B = ⅓.
- **Original Quark Model** : u,d and s quarks and Baryons (qqq, B = 1) & Mesons ($q\bar{q}$, B = 0).
- **1965, Han and Nambu** : strong-interaction "charges"
- 3 color charges (r-b-g) & 3 anti color charges (y-m-c).
- Baryon and Meson : color neutral



Quantum Chromodynamics : Generalization to a gauge theory with quarks of fractional electric charge. (1973)

SCHEMATIC MODEL OF BARYONS AND MESONS *

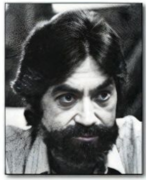
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), etc. It is assuming that the lowes

AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN – Geneva



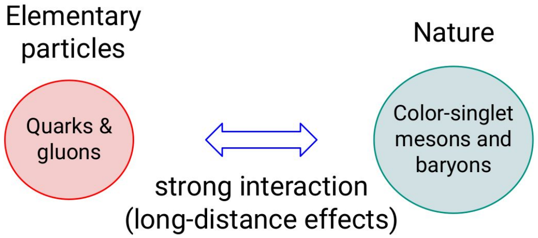
In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAAA\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

Gell-Mann, M. 1964. "A Schematic Model of Baryons and Mesons". Physics Letters 8 (3): 214–15
An SU₃ model for strong interaction symmetry and its breakingCERN-TH-412 (21 Feb 1964)

Why are multi-quark states important?

- X(3872), in 2003 accidental discovery by Belle as a narrow peak in the $J/\psi\pi^+\pi^-$ invariant mass distribution.

Asymptotic freedom
Perturbation theory
Not accessible experimentally



Confinement
Effective theories approximate QCD
Accessible to Experiment

No rigorous description of hadrons and their spectrum, as bound-quark systems from the QCD Lagrangian

Muti-quark states are the bridge!!

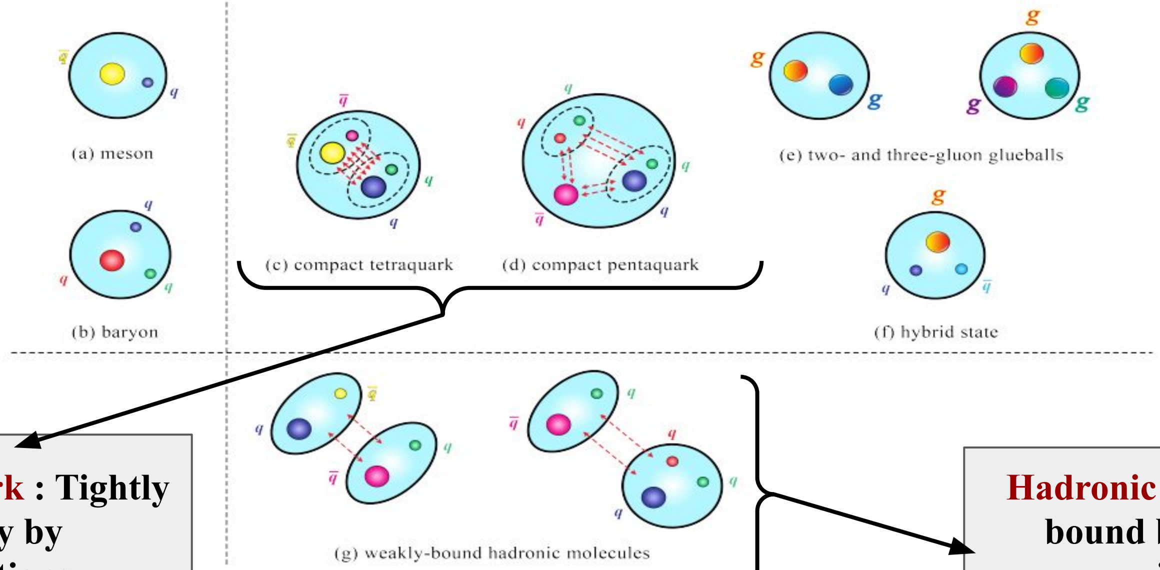
- **Exotic hadrons live exactly in the transition region:** sensitive to multi-quark interactions, gluonic excitations, and strong-coupling dynamics, invisible in ordinary mesons/baryons.
- Involve **diquarks, multi-body color structures, hadronic molecules, and gluonic degrees of freedom**, can probe aspects of QCD that ordinary hadrons do not.
- **Studying them tests how the same QCD Lagrangian produces both perturbative and non-perturbative behavior**, helping build a more unified picture of hadronic structure.

Exotics

- **Conventional States** : states well understood phenomenologically in the Quark Model i.e. $q\bar{q}$ and qqq
- **Exotic states** : 4-5 quark states, unconventional quantum numbers ,….

Conventional

Exotic



Rep. Prog. Phys. 86 026201(2023)

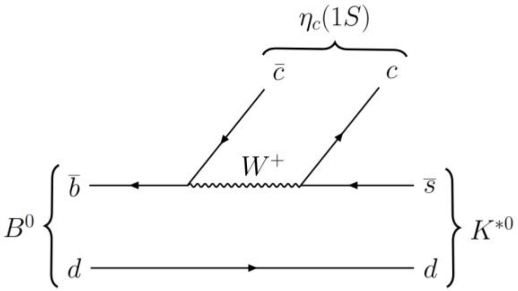
Compact multi-quark : Tightly bound directly by strong interactions

Hadronic Molecular : Weakly bound by residual strong interaction

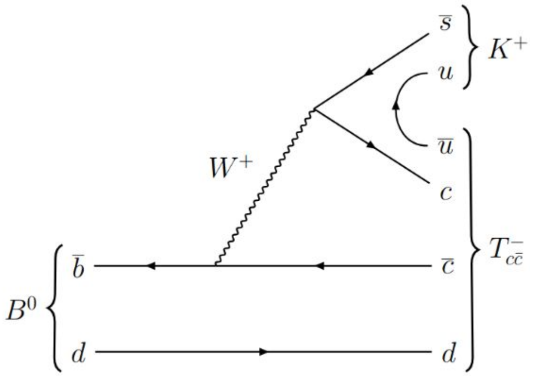
Exotics and B-decays

- $b\bar{b}$ pair produced in high-energy collisions, hadronizes separately.
- B meson are a **$\bar{b}$** and **u,d,s, or c** quark : **B^+, B^0, B_c, and B_s**
- Decay via generation-changing processes : **$b \rightarrow cW^-$**
- Forms charmed mesons or **$c\bar{c}$** (charmonium).

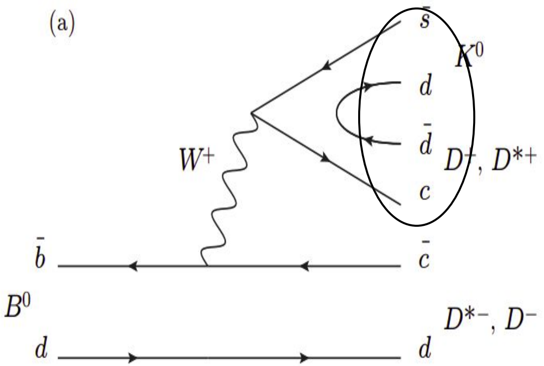
Conventional $c\bar{c}$



Hidden charm: $c\bar{c}$ pairs, zero net charm

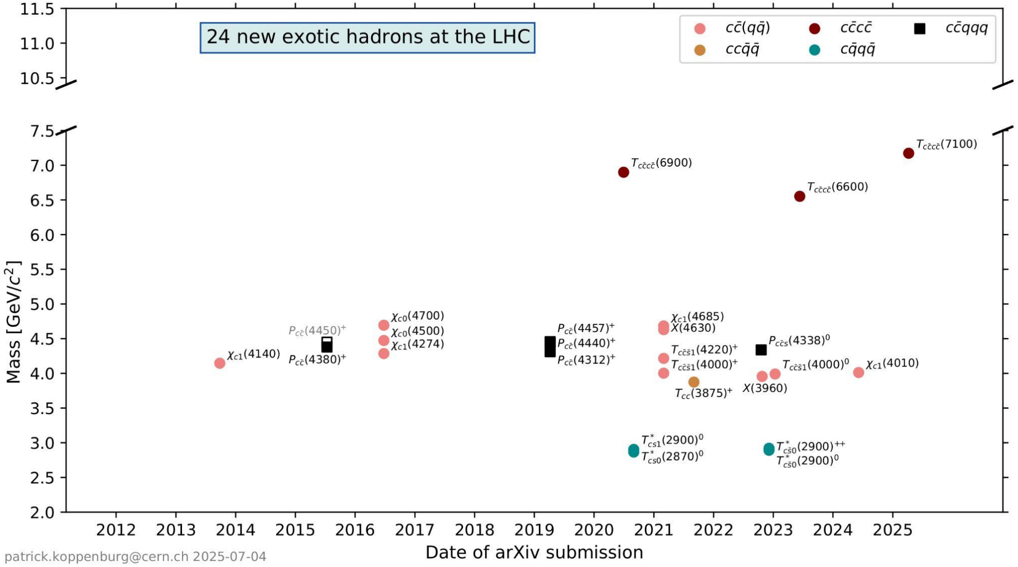


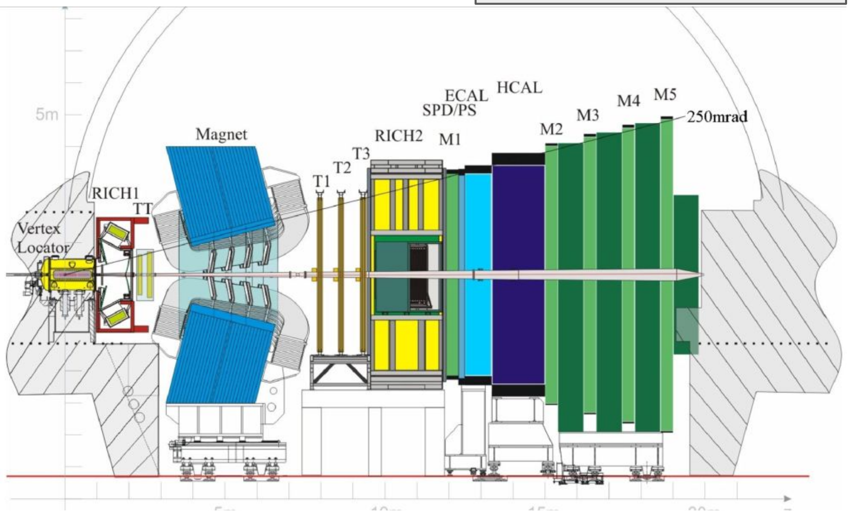
Open charm: Either only c or only $\bar{c}$, non zero net charm



Exotics and LHCb

JINST 3 (2008) S08005,
IJMPA 30:07 (2015) 1530022





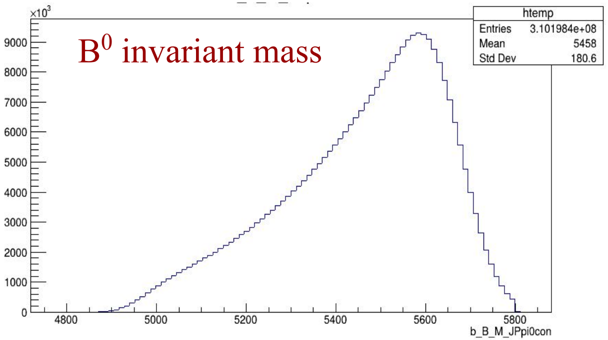
- **Largest data sample** of b and c hadrons
- **Excellent tracking** → mass and lifetime resolutions
- **Particle Identification** → important to deal with charged hadrons in final states

Run	Years	Lum. [fb^{-1}]	$\sqrt{s}$ [TeV]	$\sigma_{b\bar{b}}$ [μb]	$\sigma_{c\bar{c}}$ [μb]
1	2011-12	3.0	7,8	70	1400
2	2015-17	3.8	13	150	2400
2	2018	2.2	13		

Methodology in brief

Reconstruction: B^0 meson from final state particles in data and Monte-Carlo.

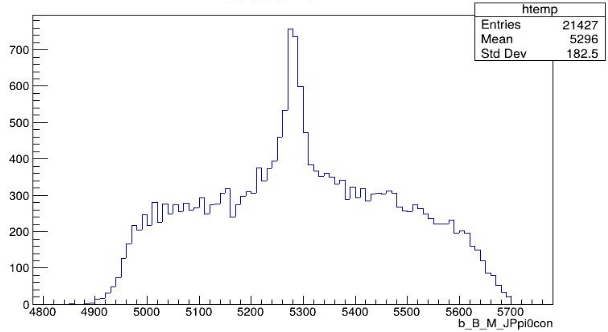
Cut based Selection : Appropriate range around many kinematical variables in order to increase signal(S) to background(B) ratio.



Multivariate analysis :

- ML techniques separate S from B using "discriminating variables".
- **Boosted decision trees** (BDT)
- **Signal**: extracted from simulation
- **Background**: extracted from real data
- **2 Trainings:**
  - Combinatorial background
  - Dedicated to neutral pion background

  → **Optimized to reduce background**
- **Additional selections:**
  - Mass Vetoes : ex - $\psi(2S)\rightarrow J/\psi\pi^{+}\pi^{-}$
  - Internal clone removal
  - Kinematical reweighting
  - Multiplicity correction



Perform Fits :

- Extended maximum likelihood fits using appropriate modelling of B^0 meson invariant mass.
- Extract yields for branching fraction calculation and weights search for exotics.

First observation of $B^0 \to J/\psi\, \pi^+ \pi^- \pi^0\, \pi^+ K^-$ decay

- Several vector states observed in $e^+e^- \to$ charmonium+hadrons, cross sections near (4.2- 4.6) GeV
- **ψ(4230)** exhibits non-conventional properties.
- Hadronic transitions to lower charmonia are sensitive probes to internal structure.
- $\psi(4230) \to J/\psi\, \pi^+\pi^-\pi^0$ provides a direct test of the coupling of ψ(4230) to the J/ψω system
- Measure branching fraction of a **new decay mode** of B^0 meson.

[Phys. Rev. Lett. 122 (2019) 232002]

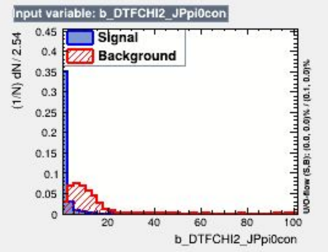
BESIII results at DPF 2015 [arXiv:1509.08042]

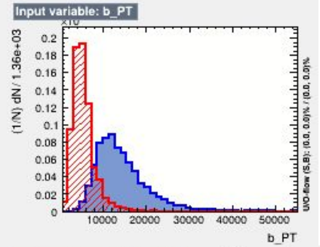
Reconstruction :

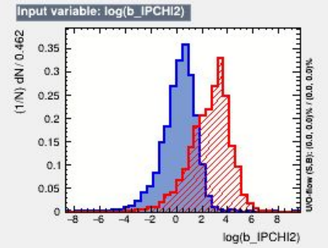
- $B^0 \to J/\psi\, \pi^+ \pi^- \pi^0\, \pi^+ K^-$ full range of $m_{(\pi+\pi-\pi0)}$
- $J/\psi \to \mu^+\mu^-$, $\pi^0 \to \gamma\gamma$
- **MC**: $B^0 \to J/\psi\, \pi^+\pi^-\, \pi^0\pi^+K^-$ (PHSP)

Pi0 BDT Variables	
π^0	P_T M CL
(γ_1, γ_2)	$min(P_T)$, $max(P_T)$ $min(CL)$, $max(CL)$ ΣP_T $\lvert (P_{T1} - P_{T2})/(P_{T1} + P_{T2}) \rvert$

Combinatorial BDT Variables	
$\mu^\pm$	ΣP_T
(γ_1, γ_2)	$min(P_T)$, $max(P_T)$ $min(CL)$, $max(CL)$
$K^\pm$, $\pi^\pm$	ΣP_T $log(min(\chi^2_{IP}))$
B^0	χ^2DTF ($J\psi, \pi^0$ constrained) $log(\chi^2_{IP})$ P_T $(log\chi^2_{FD})$ $-log(DIRA)$ VCHI2NDOF







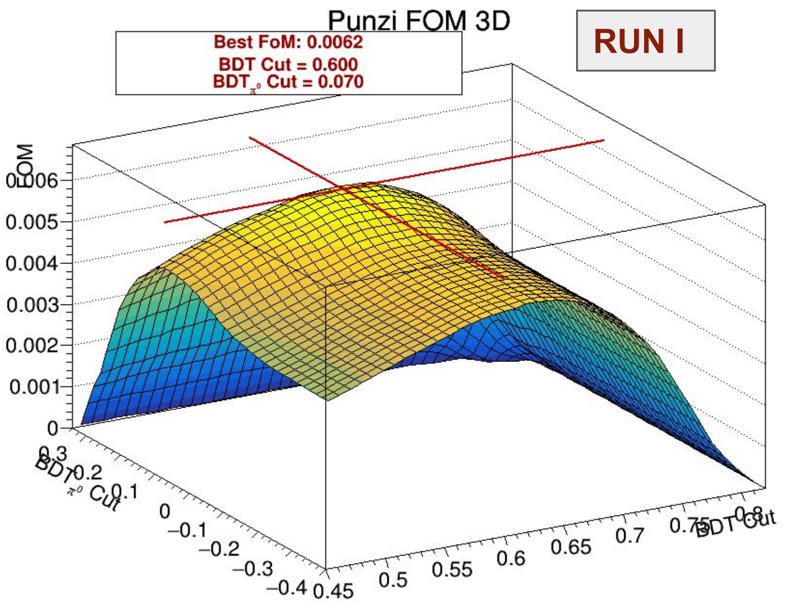
First observation of $B^0 \to J/\psi\, \pi^+ \pi^- \pi^0\, \pi^+ K^-$ decay

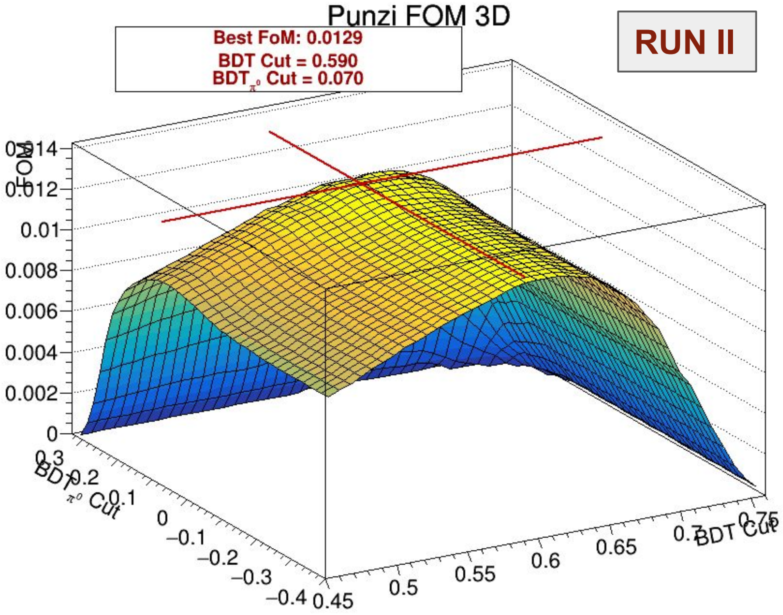
FoM :

$$\frac{\varepsilon_s}{5/2 + \sqrt{(S+B)}}$$

Scan on 2 BDT's simultaneously

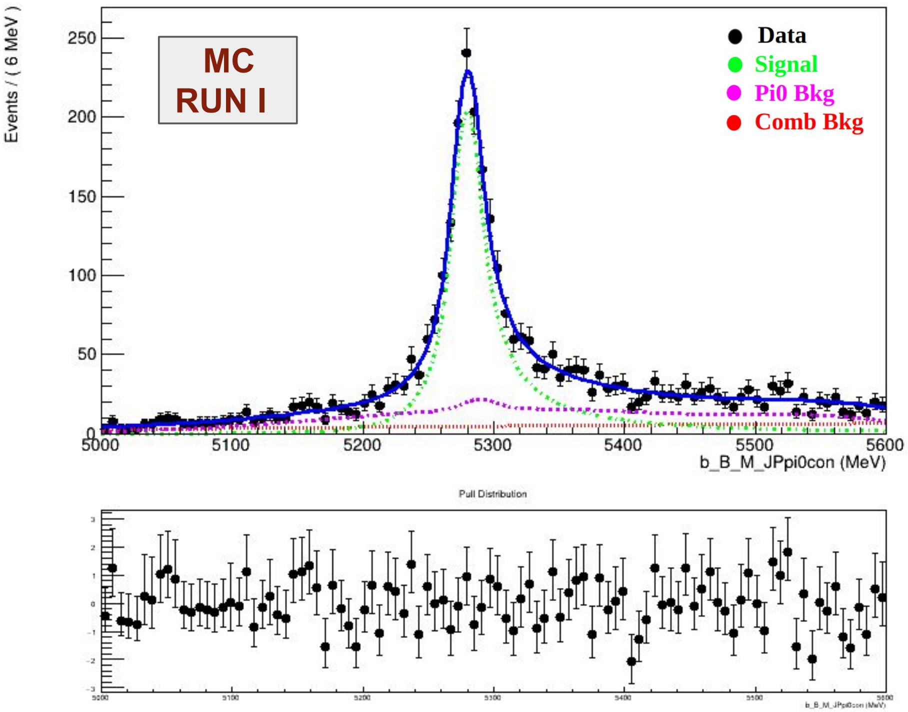
- Efficiency (ε_s) for each pair (MC): (No. events pass cuts)/(Total events)
- **S+B** for each pair (Data)**:** 5250 < count events in data < 5310



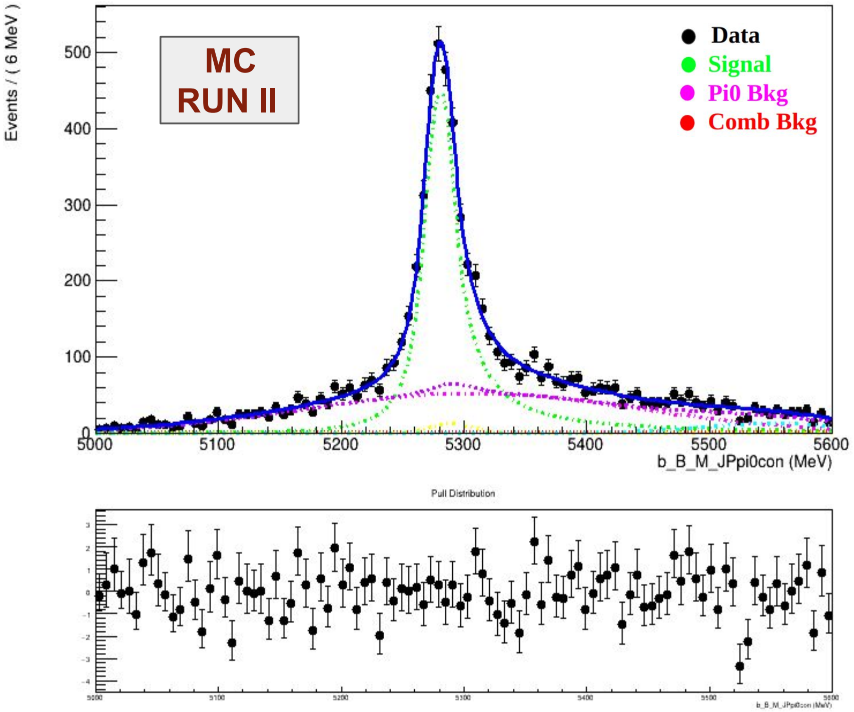


First observation of $B^0 \to J/\psi\, \pi^+ \pi^- \pi^0 \pi^+ K^-$ decay

Extended likelihood fit : **Signal**: DSCB, **Pi0 Bkg**: 3 gaussians, **Comb. Bkg**: Chebyshev Polynomial



Yield = 1794 +/- 65



Yield = 3719 +/- 90

First observation of $B^0 \to J/\psi\, \pi^+ \pi^- \pi^0\, \pi^+ K^-$ decay

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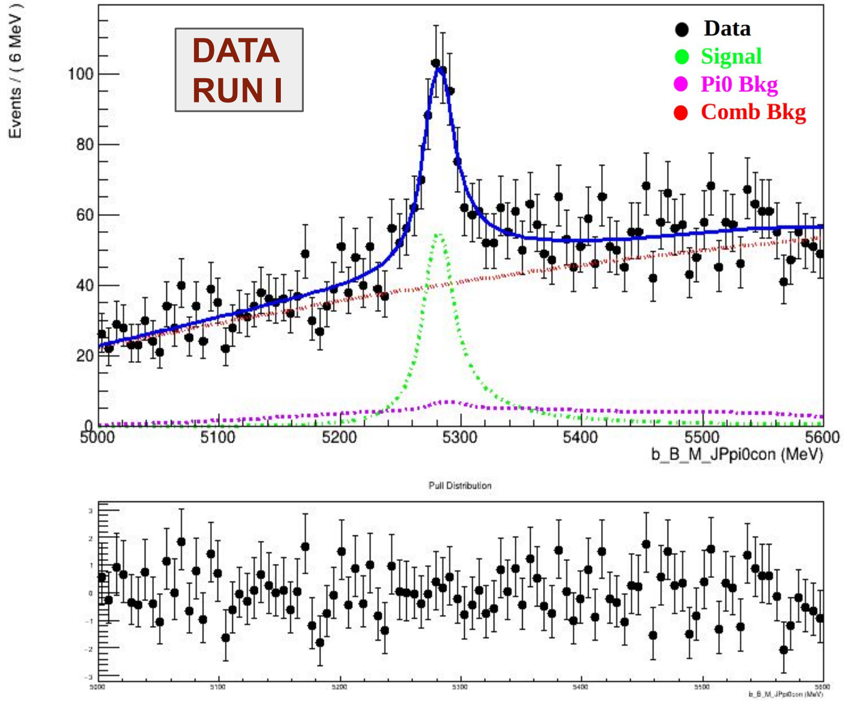
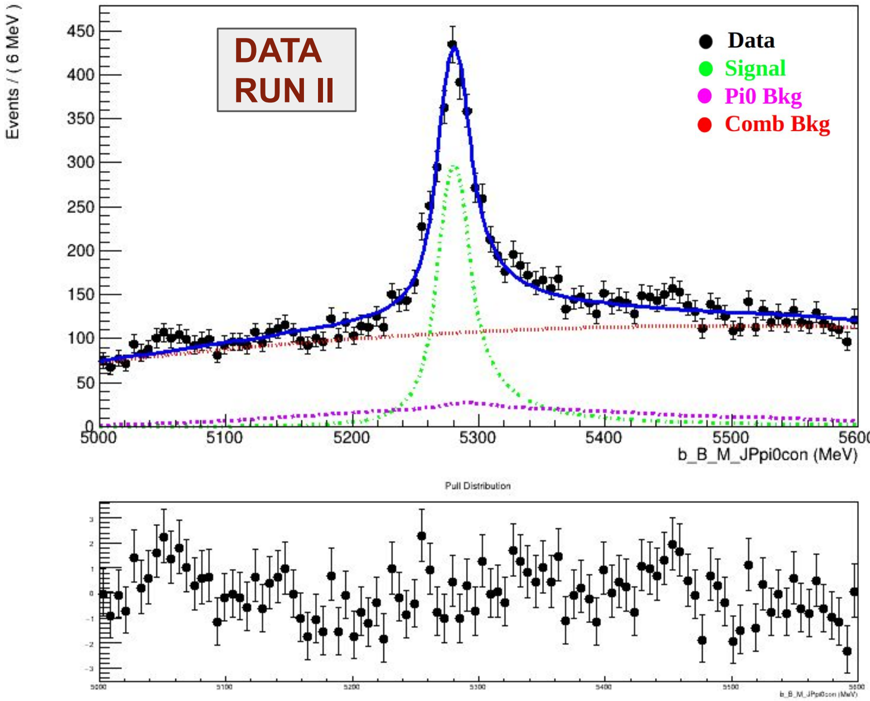
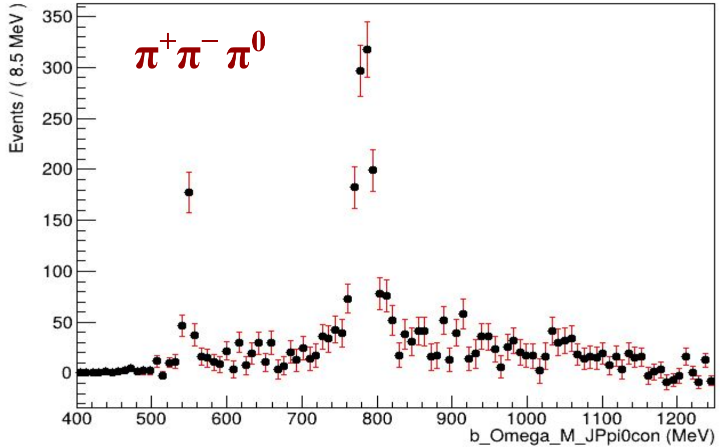


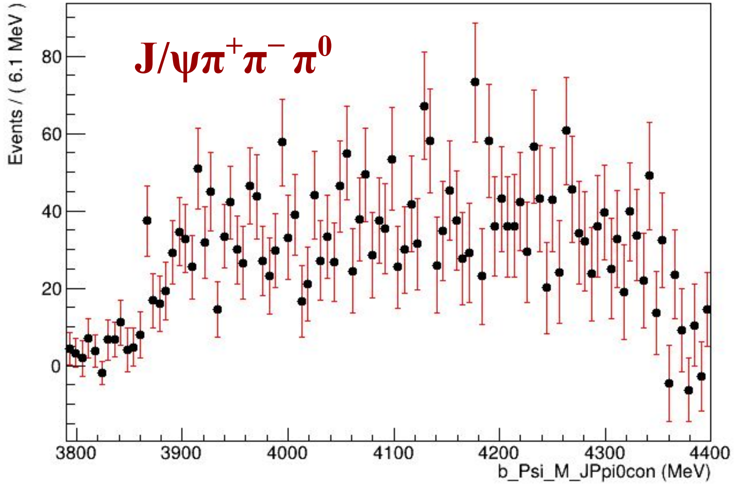


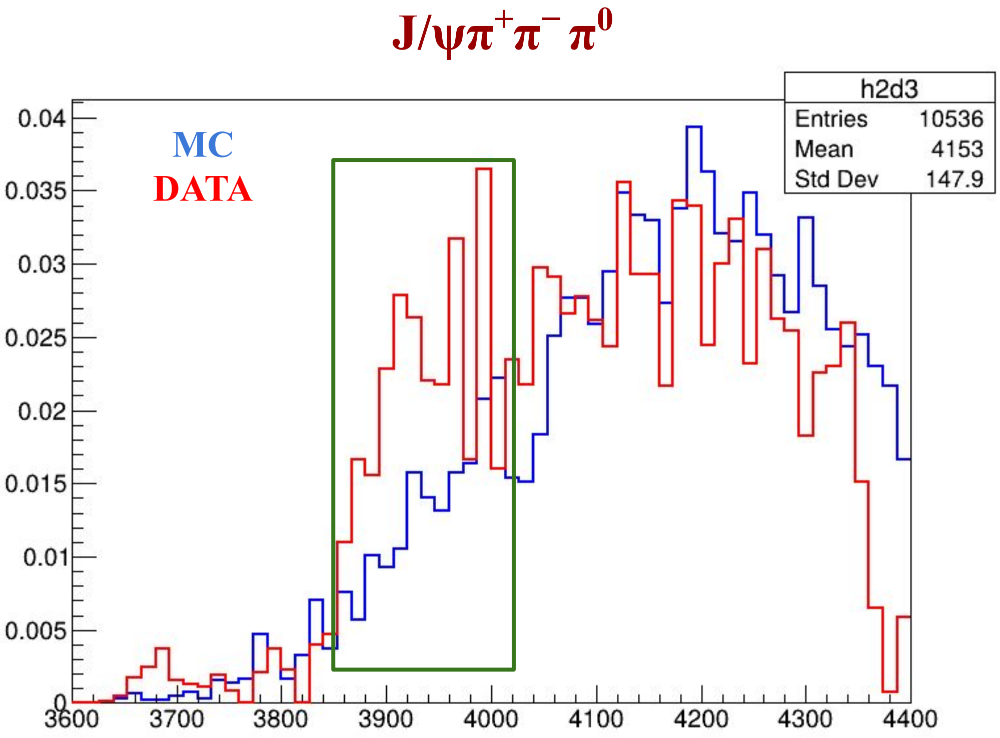
Yield = 489 +/- 41

Yield = 2317 +/- 75

First observation of $B^0 \to J/\psi\, \pi^+ \pi^- \pi^0 \pi^+ K^-$ decay







First observation of $B^0 \to J/\psi\omega\pi^+K^-$ decay

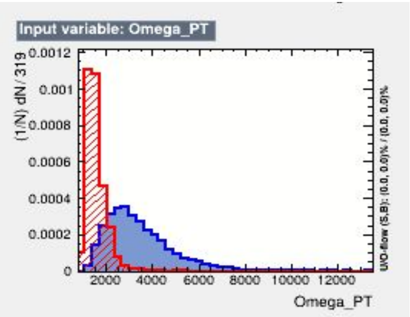
- **X(3940) → J/ψω(782)** in J/ψX and B→KωJ/ψ — Phys. Rev. Lett. 94, 182002(Belle Collaboration), Phys. Rev. Lett. 101,082001(BABAR Collaboration)
- Decay to **J/ψω** => X(3940) is not a conventional state
- Only open charm decays observed yet finding significant **J/ψω** => Compact component
- This final state fixes C-parity and involves an isoscalar light meson : could determine J^{PC}
- Measure branching fraction of a **new decay mode** of B^0 meson.

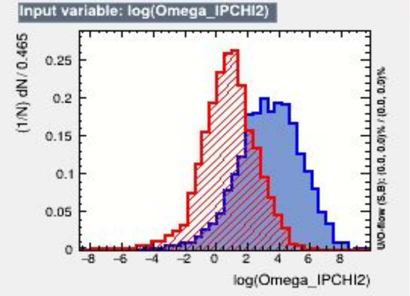
Reconstruction :

- $B^0 \to J/\psi\omega\pi^+K^-$, $\omega \to \pi^+\pi^-\pi^0$
- $J/\psi \to \mu^+\mu^-$, $\pi^0 \to \gamma\gamma$
- **MC**: $B^0 \to J/\psi\omega\pi^+K^-$

Pi0 BDT Variables	
π^0	P_T M CL
(γ_1, γ_2)	$min(P_T), max(P_T)$ $min(CL), max(CL)$ ΣP_T $\|(P_{T1} - P_{T2})/(P_{T1} + P_{T2})\|$
π^0, ω	$P_{T\omega}/P_{T\pi^0}$ $\|(P_{T\pi^0} - P_\omega)/(P_{T\pi^0} + P_\omega)\|$

Combinatorial BDT Variables	
$\mu^\pm$	ΣP_T
(γ_1, γ_2)	$min(P_T), max(P_T)$ $min(CL), max(CL)$
$K^\pm, \pi^\pm$	ΣP_T $log(min(\chi^2_{IP}))$
ω	P_T $log(\chi^2_{IP})$
B^0	χ^2DTF ($J\psi, \pi^0$ constrained) $log(\chi^2_{IP})$ P_T $(log\chi^2_{FD})$ $-log(DIRA)$ VCHI2NDOF





First observation of $B^0 \to J/\psi\omega\pi^+K^-$ decay

FoM :

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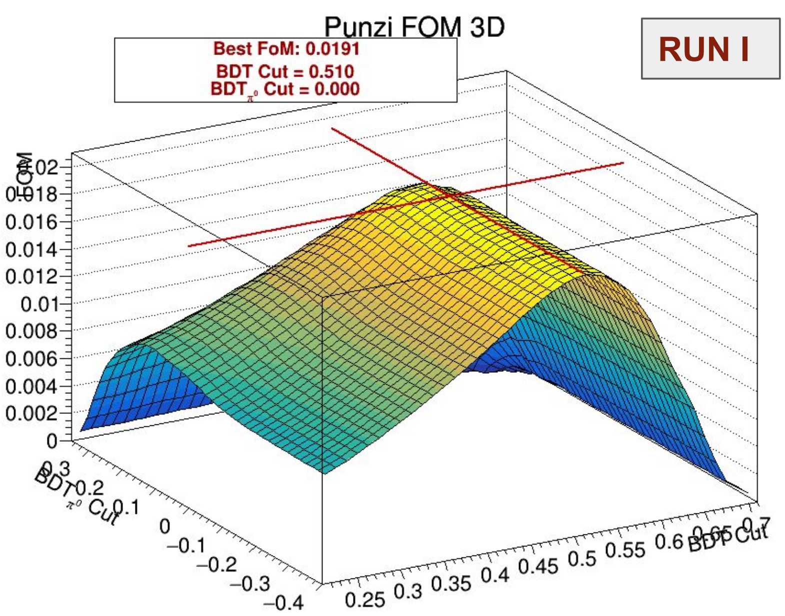
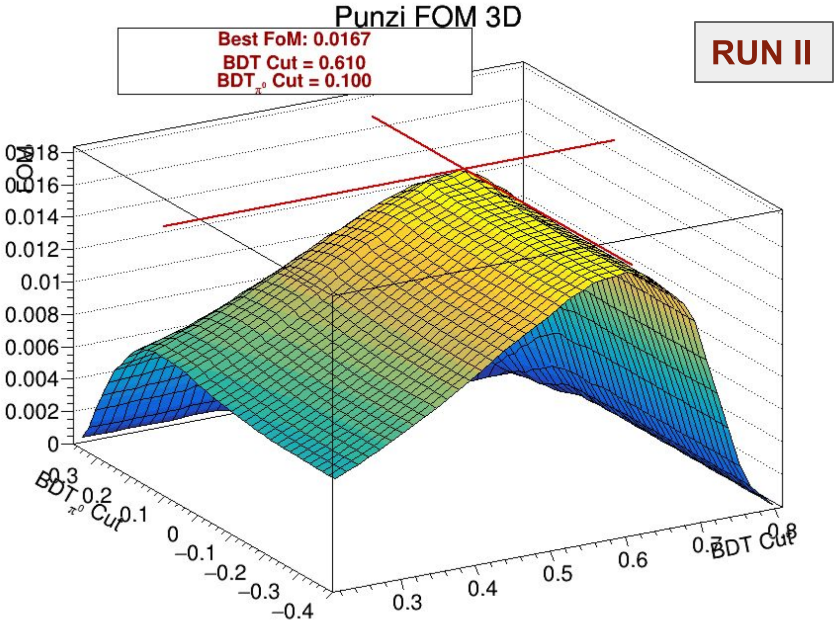
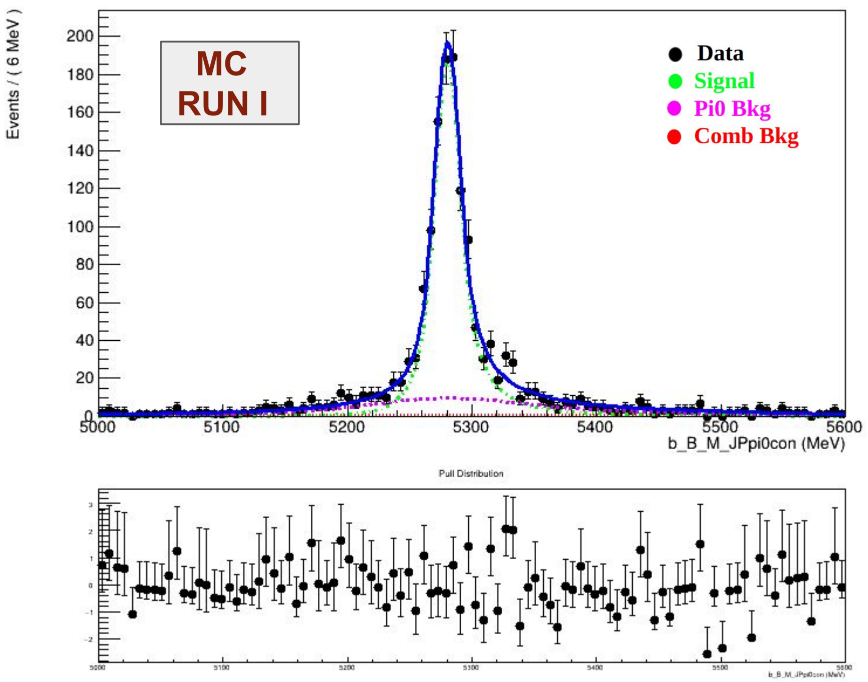
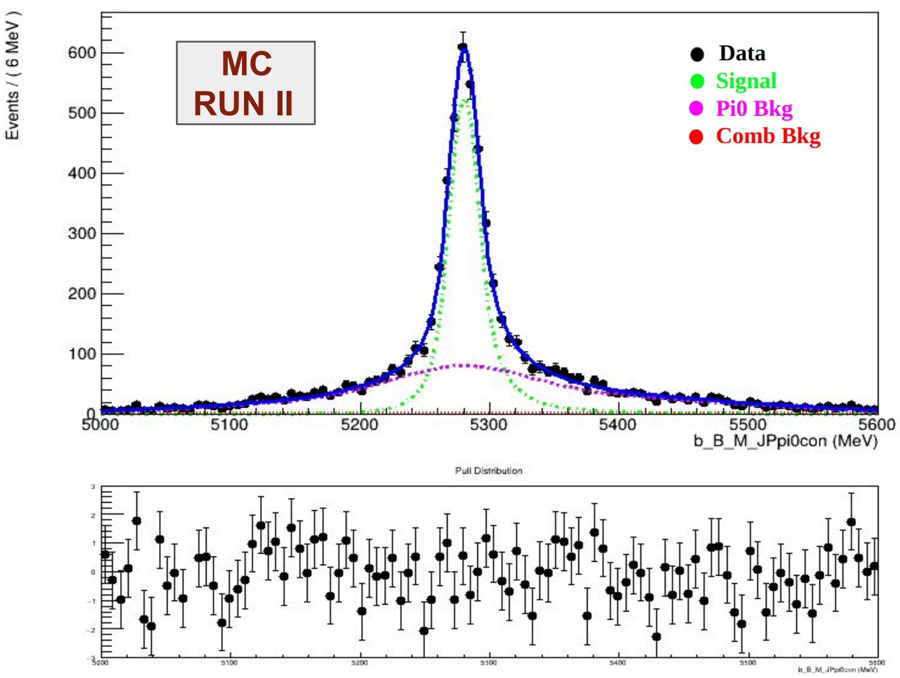




First observation of $B^0 \to J/\psi\omega\pi^+K^-$ decay

Extended likelihood fit : **Signal**: DSCB, **Pi0 Bkg**: 2 gaussians, **Comb. Bkg**: Chebyshev Polynomial



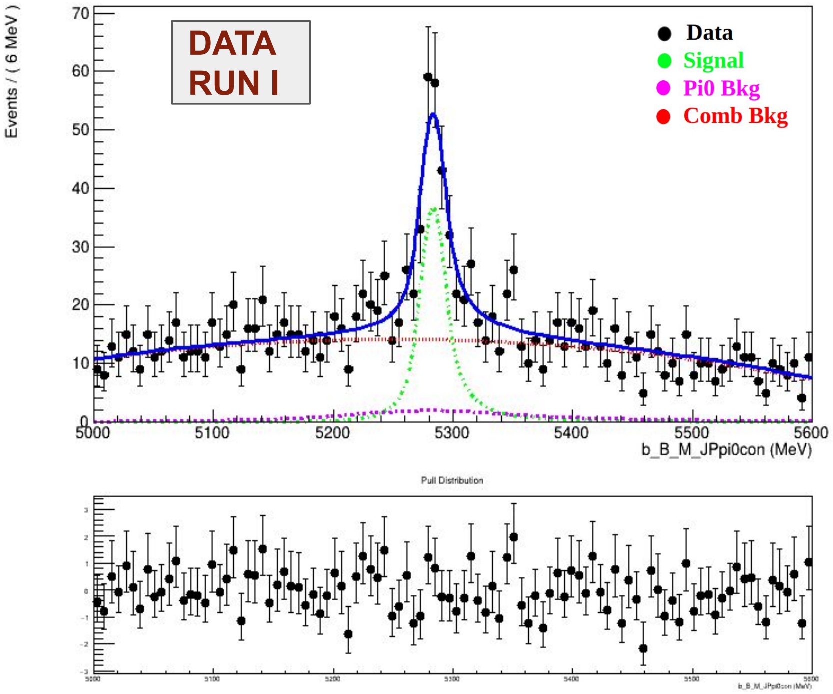


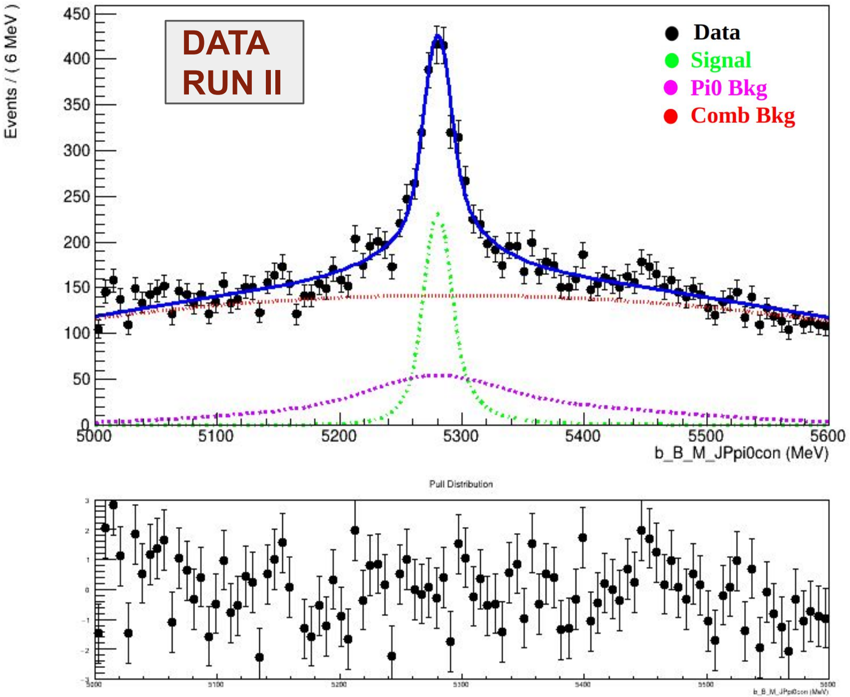
Yield = 1102 +/- 42

Yield = 3243 +/- 78

First observation of $B^0 \rightarrow J/\psi\omega\pi^+K^-$ decay

Extended likelihood fit : Signal: DSCB, Pi0 Bkg: 2 gaussians, Comb. Bkg: Chebyshev Polynomial

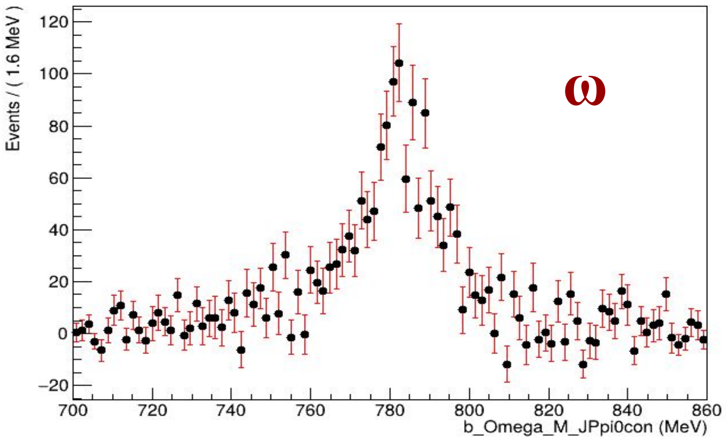


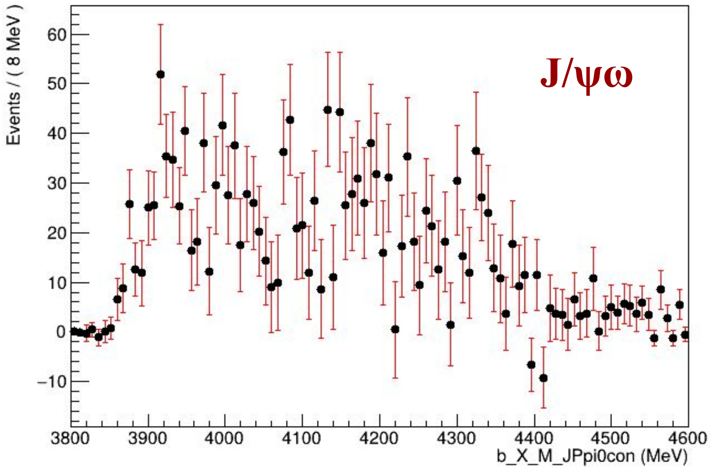


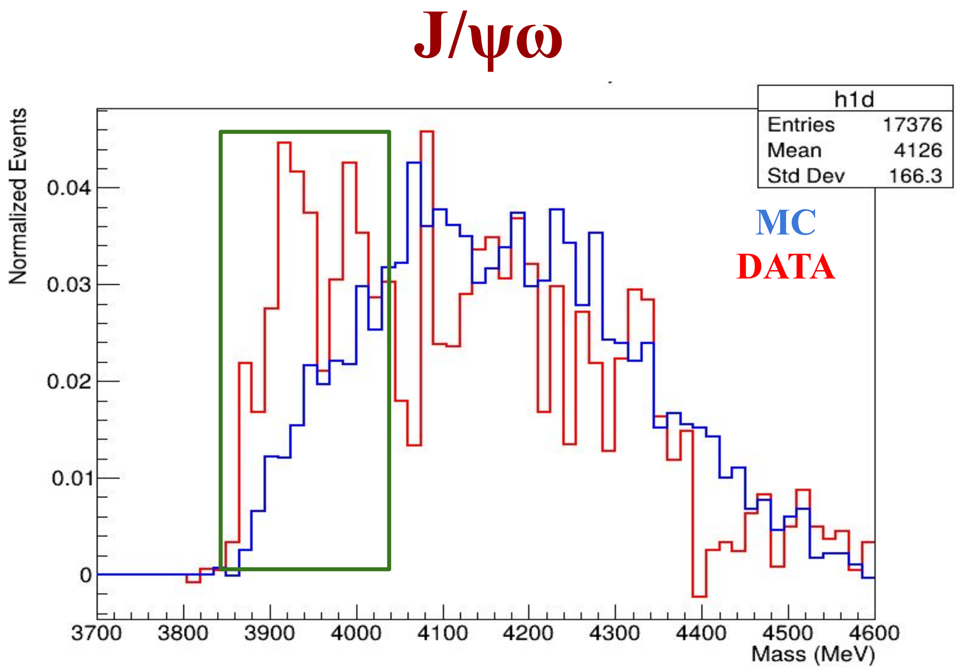
Yield = 218 +/- 21

Yield = 1536 +/- 57

First observation of $B^0 \to J/\psi\omega\pi^+K^-$ decay







Branching fraction measurement

$$\frac{Br(B^0 \to J/\psi \pi^+ \pi^- \pi^0 \pi^+ K^-)}{Br(B^0 \to J/\psi \pi^+ \pi^- \pi^+ \pi^-)} = \frac{\{N1*E2\}}{\{E1*N2\}}$$

$$\frac{Br(B^0 \to J/\psi \omega \pi^+ K^-)}{Br(B^0 \to J/\psi \pi^+ \pi^- \pi^+ \pi^-)} = \frac{\{N1*E2\}}{\{E1*N2\} Br(\omega \to \pi^+ \pi^- \pi^0)}$$

- **N1** = Yield of Signal from data
- **E1** = Efficiency for signal (Ratio of yield from MC to total MC events)
- **N2** = Yield of Reference channel from data
- **E2** = Efficiency for reference channel
- Errors from all variables are added in quadrature.
- Separate calculation for run I and II and combination done by weights :

$$w_{RI} = (1/\sigma^2_{RI}) / (1/\sigma^2_{RII} + 1/\sigma^2_{RI})$$

$$w_{RII} = (1/\sigma^2_{RII}) / (1/\sigma^2_{RII} + 1/\sigma^2_{RI})$$

$$\mathbf{B.F_{comb} = w_{RI}\, B.F_{RI} + w_{RII}\, B.F_{RII}}$$

Results

BF($J/\psi\pi^+\pi^-\pi^0\pi^+K^-$): RUN I = 8.7 +/- 2.0
RUN II = 10.6 +/- 1.4
Combined: 10.0 +/- 1.1

BF($J/\psi\omega\pi^+K^-$): RUN I = 6.7 +/- 1.0
RUN II = 7.4 +/- 0.4
Combined: 7.3 +/- 0.4

Conclusions

- We have made observation of 2 new decay modes of B0 meson along with presence of signatures from exotic tetraquarks as intermediate states.
- We measure their relative branching fraction.
- To do : For each decay mode, estimate systematic uncertainty