Exotic Hadrons

Graduate Physics Seminar

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Overview

Bit of a history!

- Gell-Mann and Zweig - hadrons as composites of fractionally charged fermions - quarks (u,d,s) with baryon number B $= 1/3$.
- producing B$=0$ mesons as $q\bar{q}$ and B $= 1$ baryons as qqq
- Han and Nambu proposed - quarks carries strong-interaction charges - 3 color dof - rbg and anti charges - Brayons and Mesons are color neutral.
- Generalization to a gauge theory with quarks of fractional electric charge gave Quantum Chromodynamics : More complex structures!

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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes

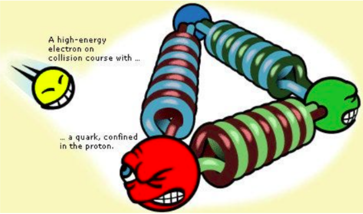
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

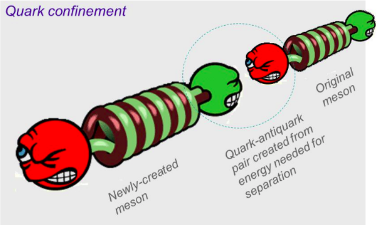
G. Zweig *)
CERN – Geneva

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

QCD

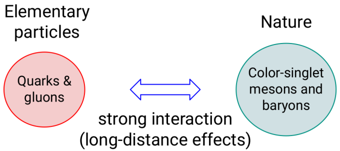
- In QCD,three interaction charges, called colors, are carried by elementary strongly interacting spin-1/2 particles called quarks
- And the color force is mediated by eight massless gauge bosons - gluons, themselves carry color charges and interact with each other.
- Two main properties:
  - Asymptotic freedom : the QCD coupling strength α_s, decrease at short distances and increase at long distances.
  - Confinement : isolated colored particles cannot exist.





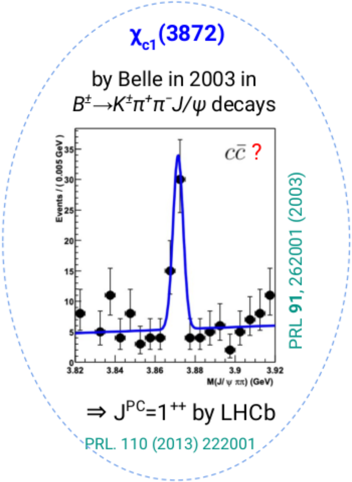
QCD

- SU(3) structure of the gauge symmetry describing the 3 color charges produces possible color-singlet combinations (Hadrons).
- The rule : Any net number of quarks ($N_q - N_{\bar{q}}$) that is divisible by 3, plus any number of valence gluons can form a color singlet.
- Valence : the total gluonic field of the hadron—affecting the overall J^{PC} of the hadron.
- Conventional : states well understood phenomenologically in the Quark Model.
- Exotic states : 4-5 quark states, unconventional Q no, glue balls...etc called XYZ states.



Distinguishing Conventional from Exotic Hadrons

- How does one know that a sufficiently long-lived state has been observed?
- Charged state : long track in a detector, neutral state : measurable gap between its production point and its decay via charged particles/absorption in a calorimeter.
- Kinematical reconstruction : identified as a resonant peak in the production amplitude and E, P and M of the particle are determined.
- Not every bump in a cross section is a new resonance!



Distinguishing Conventional from Exotic Hadrons

- How does one know that it is exotic?
- Quantum numbers (J^{PC}) : qqq, exhaust all but not $q\bar{q}$
- Unreachable: $J^{P=(1)^J, C=(1)^{J+1}} \in [0^{+-}, 1^{-+}, ...]$

n: radial quantum #
S: total spin of quarks
L: orbital ang. mom. btw quarks - S,P,D...

$$n^{(2S+1)}L_J$$

J=L+S
$P=(-1)^{L+1}$
$C=(-1)^{L+S}$

L	S	J^{PC}	L	S	J^{PC}	L	S	J^{PC}
0	0	0^{-+}	1	0	1^{+-}	2	0	2^{-+}
0	1	1^{--}	1	1	0^{++}	2	1	1^{--}
			1	1	1^{++}	2	1	2^{--}
			1	1	2^{++}	2	1	3^{--}

Allowed quantum numbers for $q\bar{q}$. eg. cannot have 1^{-+}

- Charges of quarks and quark flavor:
  - Bosonic +2 Hadron, not $q\bar{q}$ state but tetraquark.
  - $c\bar{c}$ with nonzero charge, must contain more valence quarks.
- If same J^{PC} and charge as conventional: states mix quantum-mechanically, making identification even trickier.

Predicting Spectrum

- Complexity : gluon self-coupling and sea-quark production.
- Deficiency of analytical and even reliable numerical solutions for relativistic light-quark sector.
- Heavy-quark sector : Born-Oppenheimer scale separation
  - Typical energies associated with light quarks and glue : $\Lambda_{QCD} = \mathrm{O}(200$ MeV)
  - Production of $q\bar{q}$ sea-quark pairs in hadrons is also known to be suppressed.
  - Non-relativistic color sources interacting with a background field of gluons and sea quarks via $V(r)$: Cornell potential.

$$V(r) = -\frac{\kappa}{r} + br \tag{1}$$

- Solve Schrodinger equation for V(r) : Short-distance Coulomb-like one-gluon exchange interaction (Asymptotic freedom) and joined to a linearly increasing confining term at large distances (Confinement) .

Predicting Spectrum

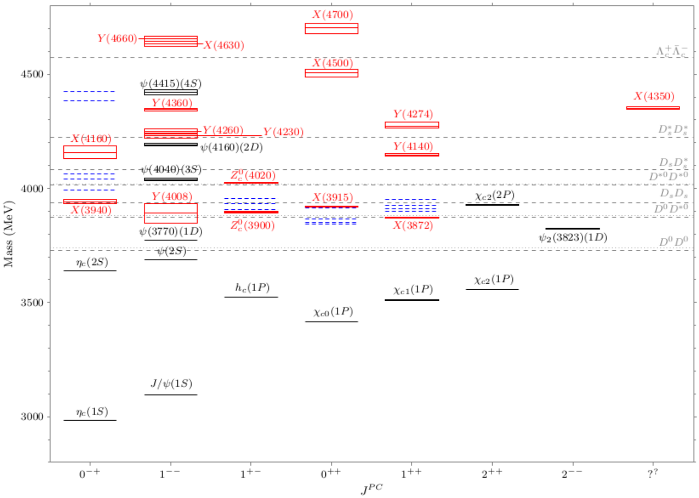


Figure 1: Level diagram for the neutral $c\bar{c}$ sector. Conventional, observed $c\bar{c}$ states are solid (black) lines labeled by Greek letters, the lowest predicted yet-unobserved conventional $c\bar{c}$ states are labeled with dashed (blue) lines (the clusters indicating predictions of several variant model calculations), and the solid (red) lines labeled by X, Y, or Z indicate exotic charmoniumlike candidates. Each measured state mass, including its central value and uncertainty, is presented as a rectangle (lines simply indicating very thin rectangles). Relevant thresholds are given by gray dashed lines; if a gray dotted line is nearby, it indicates the threshold isospin partner to the labeled dashed line. In some cases, likely quantum numbers have been assigned to states for which some uncertainty remains; this is the case, for example, for the $X(3940)$ and $X(4160)$, which have been studied as $\eta_c(3S)$, $\eta_c(4S)$ candidates. The actual known quantum numbers are listed in Table 2.

Predicting Spectrum

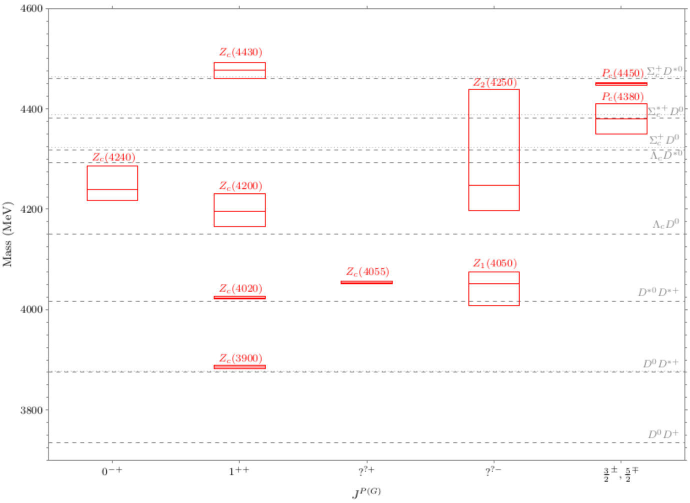
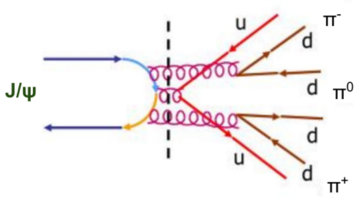


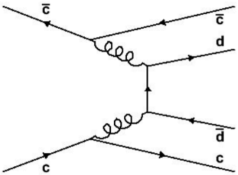
Figure 2: Charged charmoniumlike states, both bosonic and fermionic. Each measured state mass, including its central value and uncertainty, is presented as a rectangle. Relevant thresholds are given by gray dashed lines; if a gray dotted line is nearby, it indicates the threshold isospin partner to the labeled dashed line.

Why Charmonium?

- Why were exotics first discovered in the charm system?
- Decays of conventional $c\bar{c}$ states with masses below open charm threshold $m_{D\bar{D}}$ are OZI suppressed - states are narrow and well separated



OZI-suppressed



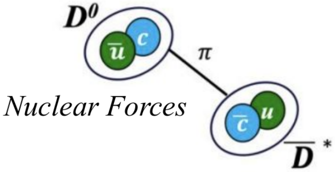
OZI-allowed

- Above the open charm threshold OZI allowed processes dominate - wider resonances but still significantly narrower than light quark states
- Charm is the lightest 'heavy' quark - $m_c >> \Lambda_{QCD}$- can determine $c\bar{c}$ spectrum with simple non-relativistic Q-M treatment.

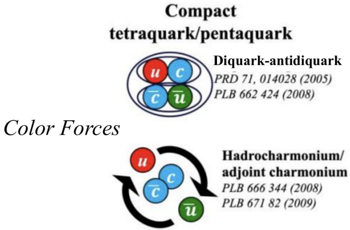
Models

Four largely considered exotic configurations are:

- Hybrids : An excited gluon combining with a $\bar{q}q$ in an octet representation.
- Molecules : Yukawa like force binding 2 or more constituent Hadrons.



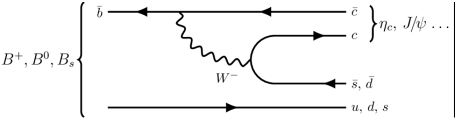
- Compact Tetraquarks : tightly arranged qq diquark and $\bar{q}\bar{q}$ anti di- quark.
- Hadro-Quarkonium : Hadron core with $q\bar{q}$ cloud orbitting it.

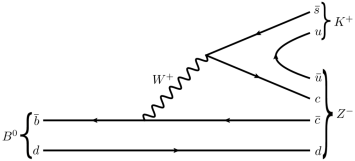


No single configuration explains all aspects of data, which one then?

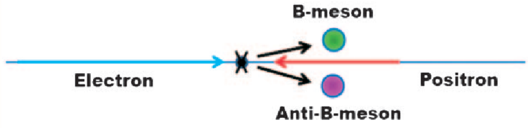
Production Mechanisms for Exotics

- Hadron Collisions : The CDF and D0 (Fermilab) and LHCb, CMS, ATLAS (CERN) : high-energy $p\bar{p}$ and pp collisions.
- Prompt and non-prompt production (B/Λ_b decays) separated using the position of the decay vertex.



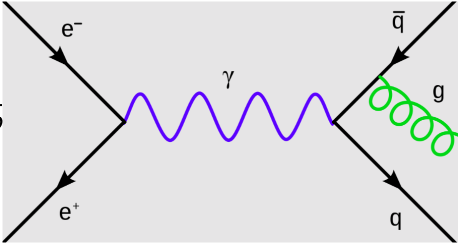


- B meson/Λ_b baryon decays : in (pp) LHCb and (e^+e^-) BaBar, Belle.
- Weak decay $\bar{b} \to W^- \bar{c}$ generating $B \to K(XYZ)$

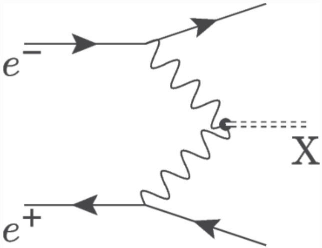


Production Mechanisms

- e^+e^- Annihilation : Direct production through a virtual photon
- $c\bar{c}$ (BESIII and CLEO-c) and $b\bar{b}$ (BaBar, Belle II)
- Double-charmonium production process ($J/\psi X$)



- $\gamma\gamma$ Collisions : e^+e^- experiments with com energies in the $b\bar{b}$ region explore collisions in the $c\bar{c}$ region through $e^+e^- \to e^+e^-X$.
- BaBar, Belle, and Belle II



The notorious X(3872)

- X(3872) : found by Belle as a narrow peak in the $\pi^+\pi^- J/\psi$ invariant mass distribution in B $\to$ KX(3872).
- $J^{PC} = 1^{++}$, $I^G = 0^+$.
- Narrow width and mass indistinguishable from the $D^0 \bar{D}^{*0}$ threshold : cannot easily be explained within a standard $q\bar{q}$ picture - Isospin violating $J/\psi\rho^0$.
- Lattice QCD - disfavor a diquark interpretation.
- No charged partners in B decays - disfavours tetra-quark model.

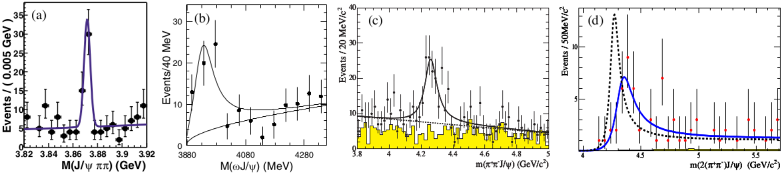


Figure 6: Earliest observations of the XYZ. (a) The $X(3872)$ was discovered in $B \to KX(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$ [4]. The $\pi^+\pi^- J/\psi$ mass spectrum is shown (from [4]). (b) The $Y(3940)$ was discovered in $B \to KY(3940)$ with $Y(3940) \to \omega J/\psi$ [106], as part of a search for $X(3872) \to \omega J/\psi$. The $\omega J/\psi$ mass spectrum is shown (from [106]). (c) The $Y(4260)$ was discovered in $e^+e^- \to Y(4260)$ with $Y(4260) \to \pi^+\pi^- J/\psi$ [29], following a search for $e^+e^- \to X(3872)$. The $\pi^+\pi^- J/\psi$ mass spectrum is shown, along with the background estimation from J/ψ sidebands (from [29]). (d) The $Y(4360)$ was discovered in $e^+e^- \to Y(4360)$ with $Y(4360) \to \pi^+\pi^-\psi(2S)$ [108], as part of a search for $Y(4260) \to \pi^+\pi^-\psi(2S)$. The $\pi^+\pi^-\psi(2S)$ mass spectrum is shown (from [108]). The solid curve is the $Y(4360)$ and the dotted curve is how the $Y(4260)$ would appear if it decayed to $\pi^+\pi^-\psi(2S)$.

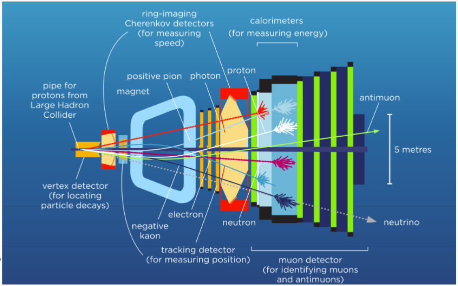
Motivation to study X(3872) $\rightarrow \chi_{cJ}\pi^0$

- $\chi_{cJ}\pi^0$ coupling to $D\bar{D}^*$ components are OZI-allowed and stronger than $c\bar{c}$.
- The ratio of X(3872) decaying to $\chi_{cJ}\pi^0$ with $J = 0, 1, 2$ is suggested to be sensitive to the internal structure of X(3872) so measuring pionic transitions could distinguish between various interpretations.
- If the X(3872) were a conventional $c\bar{c}$ state, transitions to the χ_{cJ} should be very small ; in contrast to tetra-quark or molecular state.
- BESIII : First observation to a P-wave charmonium state in $e + e^- \rightarrow \gamma X(3872)$ with $X(3872) \rightarrow \pi^0\chi_{cJ}$.
- Belle searches for X(3872) and X(3915) decaying to $\pi^0\chi_{c1}$, did not find a significant signal.

LHCb

The LHCb experiment is designed to study properties and decays of heavy flavored hadrons produced from pp collisions at the LHC

- Largest data sample of b and c hadrons, enabling precision spectroscopy studies
- Gaudi framework : Provides components and interfaces to build event data processing in HEP exp.
- LHCb software projects : DaVinci, which provides lots of Algorithms and Tools for physics analysis
- We use ROOT Framework : Python, C++

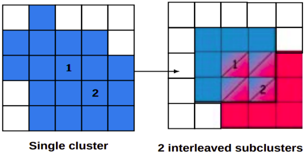


Kinematical Reconstruction

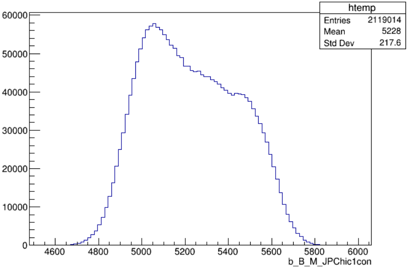
- Take stable final state particles such as $K^{\pm}$,$\mu^{\pm}$,$\pi^{\pm}$,π^{0},η,$e^{\pm}$.... write a code to add them to create intermediate particles involved in the decay.
- $\mu^{+} + \mu^{-} \rightarrow J/\psi + \gamma \rightarrow \chi_{c1} + K^{\pm} \rightarrow B^{\pm}$
- Constraints on mass range, transverse mom., flight time, identification algorithms, confidence level, etc.
- LoKi Functors : used for selections and saving variables of interest in root files.
- Use DaVinci application first to test our code locally on small set of data files.
- Run code on the Grid using Ganga interface and collect processed data as root files.

Neutral Particles are a Nightmare!

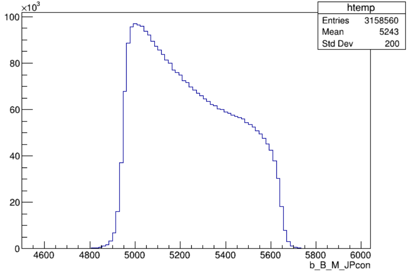
- $[B^+ \to (X(3872) \to (\chi_{c1} \to (J/\Psi \to \mu^+\mu^-)\gamma)\pi^0)K^+]CC$
- Three types of pions used :
  - Resolved Pions : $\pi^0 \to \gamma\gamma$
  - Merged Pions : $\pi^0 \to \gamma\gamma$
  - Dalitz Pions : $\pi^0 \to e^+e^-\gamma$



- Selections applied :
  - $\mu^\pm$: PT > 550 MeV, and $M_{J/\psi}$: $3056 < M_{\mu^+\mu^-} < 3136$ MeV
  - γ : PT > 500 MeV , CL> 0.1
  - $3400 < M_{\chi_{c1}} < 3700$ MeV, PT > 2000 MeV
  - $K^\pm$: PT > 500 MeV , $M_X < 5000$ MeV
  - $105 < M_{\pi^0} < 165$ MeV, PT > 300 MeV
  - BPVLTIME > 0.25 ps, $4950 < M_B < 5650$ MeV
- Constraints on B meson mass from $M_{\chi_{c1},J/\psi}$ and $M_{J/\psi}$: DecayTreeFitter algorithm used for this task.



$M_{B\pm}$ constrained by $M_{\chi_{c1},J\psi}$: Resolved π^0

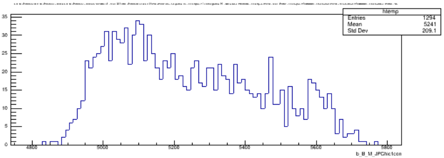


$M_{B\pm}$ constrained by $M_{J\psi}$: Resolved π^0

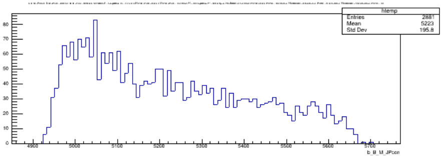
- Once you have made a hypothesis on the chain of decays that lead to your final state,
- Assumption that the daughters form parent with a specific invariant mass : mass constraint

- Daughters come from same primary vertex: vertex constraint
- leads to new best estimates for the track parameters of the final-state particle : a kinematic refit
- Then apply cut on χ^2 of this DTF : strong

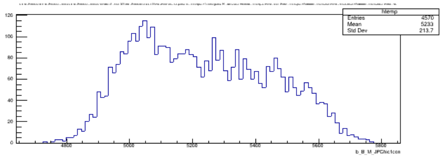
Results : RUN I and II



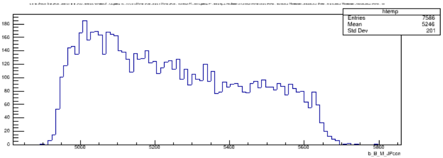
$B^{\pm}$ invariant mass constrained by $\chi_{c1}, J\psi$ mass for Merged π^0



$B^{\pm}$ invariant mass constrained by $J\psi$ mass for Merged π^0



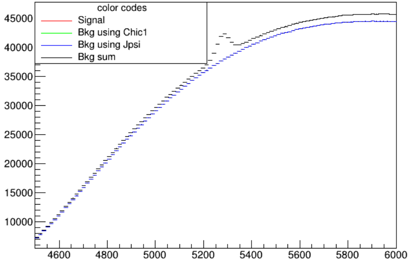
$B^{\pm}$ invariant mass constrained by $\chi_{c1}, J\psi$ mass for Dalitz π^0



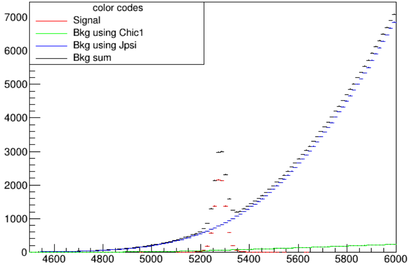
$B^{\pm}$ invariant mass constrained by $J\psi$ mass for Dalitz π^0

Combinatorial Background

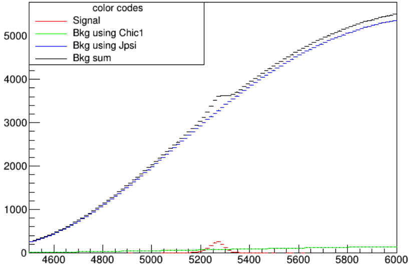
- For Combinatorial bkg : Identify possible sources
- Simulate in Rapid Sim, randomize and combine event by event intermediate particles from simulation with final state particles from data.



Resolved Pions



Merged Pions



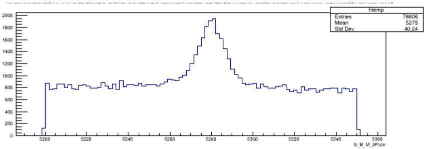
Dalitz Pions

Other channels studied - Disappointing Decays

- $[B^+ \to (X \to (\chi_{c1} \to (J/\Psi \to \mu^+\mu^-)\gamma)\eta)K^+]CC$
- Decay modes of η :
  - $\eta \to \gamma\gamma$
  - $\eta \to \pi^+\pi^-\gamma$
  - $\eta \to \pi^+\pi^-\pi^0$
  - $\eta \to \pi^0\pi^0\pi^0$
- $B^+ \to (X \to (J/\Psi \to \mu^+\mu^-)\pi^+\pi^-\pi^0)K^+$: X candidate were $\chi_{c1}(3872)$ and $\psi(4230)$.
- $\psi(4230)$ decays :
  - $J/\Psi\ \pi^0$
  - $J/\Psi\ \pi^0\ \eta$
  - $J/\Psi\ \eta\ \eta$
  - $\chi_{c1}\ \pi^+\pi^-\pi^0$
- NO SIGNAL!
- Solution : MonteCarlo Simulations

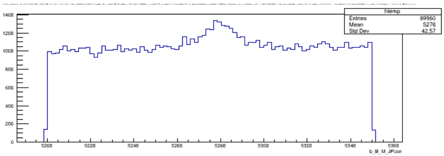
Charged Pions to the rescue....

- $\mathrm{B}^0 \to (X^- \to (Y \to (J/\psi(1S) \to \mu^+\mu^-)\pi^+\pi^-)\pi^-)K^+$
- X and Y? : $\psi(3770)$, $\psi(2S)$, or something else
- RunII data only (16-18)
- Invariant mass distribution for B^0 meson with constraint from J/ψ mass.

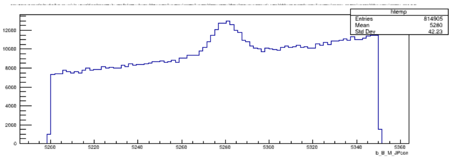


(B^0 mass peak for $\psi(2S)$)

- In reconstruction :
  $B^0 \to Z(4430) \to \psi(3770) \to (J/\psi \to \mu^+\mu^-)\pi^+\pi^-\pi^-K^+$

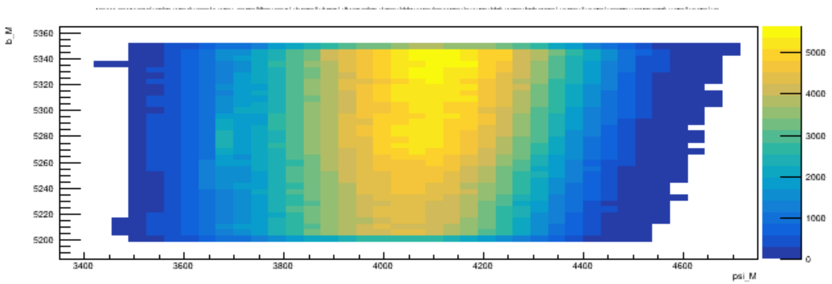


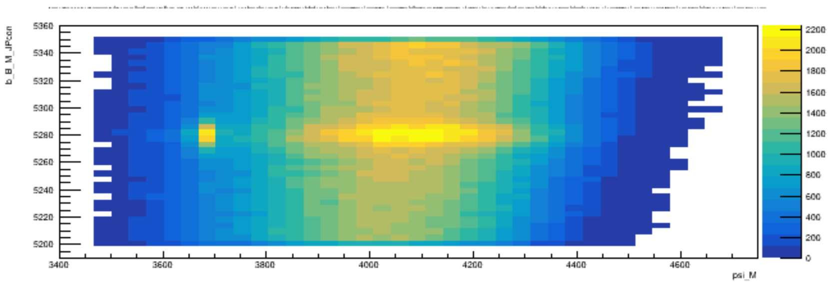
(B^0 mass peak for $\psi(3770)$)



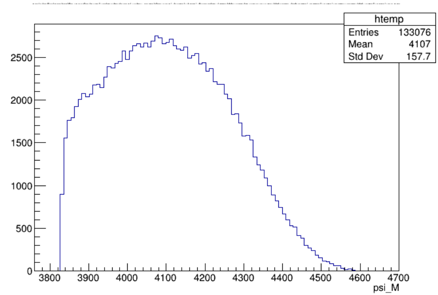
(B^0 mass peak for Y)

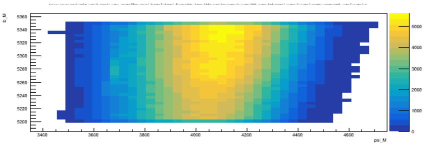
B mass Vs ψ_M full range of ψ_M mass : 2016

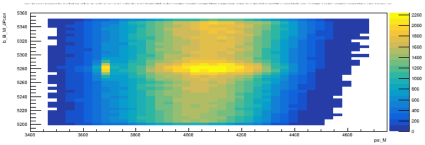




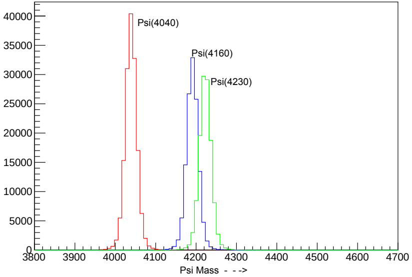
Psi Mass



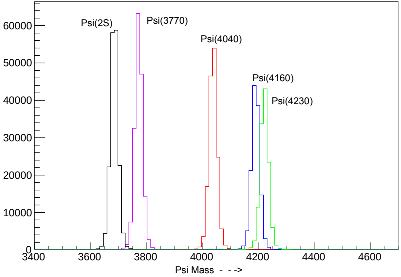




psi_allthree



psi_all



Cherish all the expected and embrace all the unexpected.
Thank You.