Search for Exotics in B decays at LHCb

Graduate Physics Seminar

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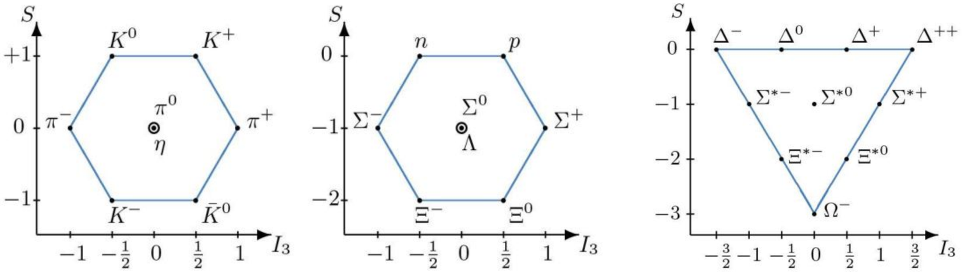
NCBJ

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 (qq, B = 0).



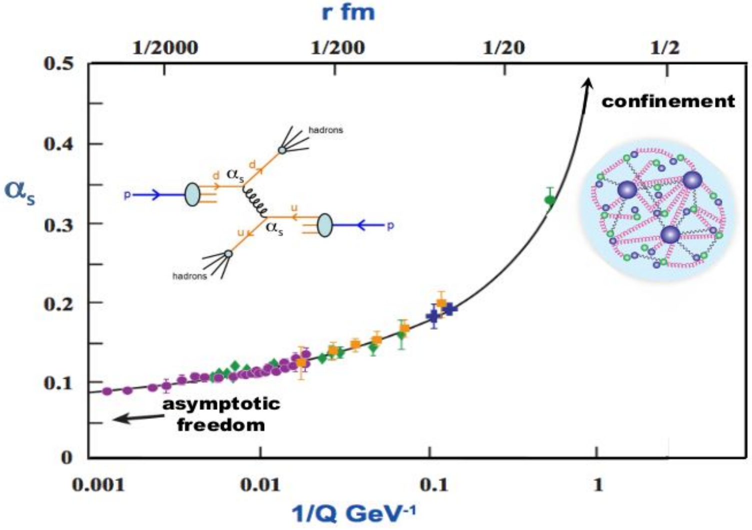
Quantum Chromodynamics : Generalization to a gauge theory with quarks of fractional electric charge. (1973)

- J = 3/2 Ω^- baryon as (sss) ➪ Pauli Exclusion principle Violated!
- Solution : Hidden quantum number
- **1965, Han and Nambu propose** : each of the quarks are SU (3) triplets in flavor-space and with strong-interaction "charges" that are a triplet in another SU (3) space.
- 3 color charges (**r**-**b**-**g**) & 3 anti color charges (**y**-**m**-**c**).
- Baryon and Meson : color neutral

A brief history of Hadron spectrum

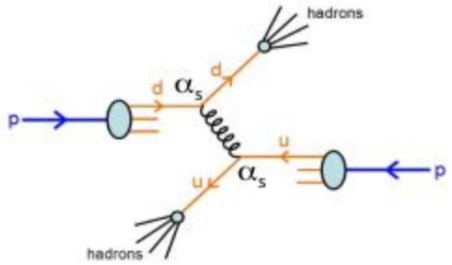
- Color force is mediated by eight massless vector particles called Gluons.
- Gluons have color charges ⇒ interact with each other.
- The vacuum polarization diagram, modify the coupling strength (α_s) : decreases at short distances and increases at long distances.

- Consequences :
  - **Asymptotic Freedom :** small coupling strength at short distances
  - Use Perturbation theory for high-momentum (P_T) transfer processes.
  - Distance scales : r ~ 1 fm (characteristic of the sizes of hadrons), α_s ~ O(1) and perturbation expansions do not converge.
  - **Confinement :** increase in the coupling strength ⇒ only color-charge-neutral isolated hadrons can exist.



r : quark separation
1/Q : inverse-mom transfer
α_s : coupling strength

A brief history of Hadron spectrum



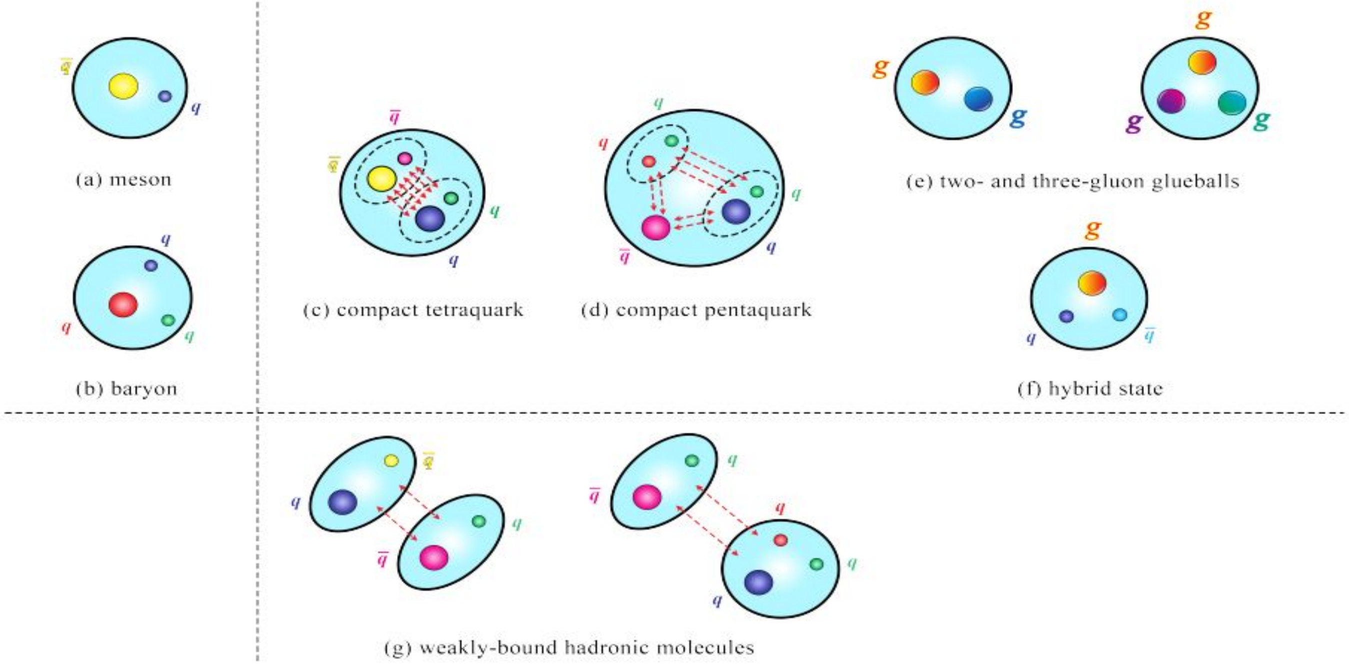
- Confinement : no free quark-gluons in experiments.
- $\alpha_s \sim 1 \Rightarrow$ q-g tightly bound inside hadrons.
- P_T distribution of quarks inside hadron governed by long-distance QCD.
- Quark-quark elastic scattering : description based on perturbative QCD.
    - **Experiments** : two high transverse momentum jets of hadrons.
- No rigorous description of these hadrons and their spectrum, as bound-quark systems from the QCD Lagrangian.

QCD Dilemma : **Nearly total disconnect between the hadrons that we observe in experiments and the quarks and gluons that appear in the theory**.

- Effective theories/models approximate QCD by simplifying the complexity but may not capture **"ALL"** detailed properties of hadrons.
- Experiments can identify patterns in hadron physics - study hadrons with substructures more complex than the baryons & mesons of the original quark model :
    - Powerful insights : Masses, decay channels, widths and lifetimes
    - Testing the Boundaries of the Quark Model : richer hadron spectrum than predicted!
    - Probing Confinement and Color Dynamics
    - Insights into Hadronization Mechanisms

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 ,….



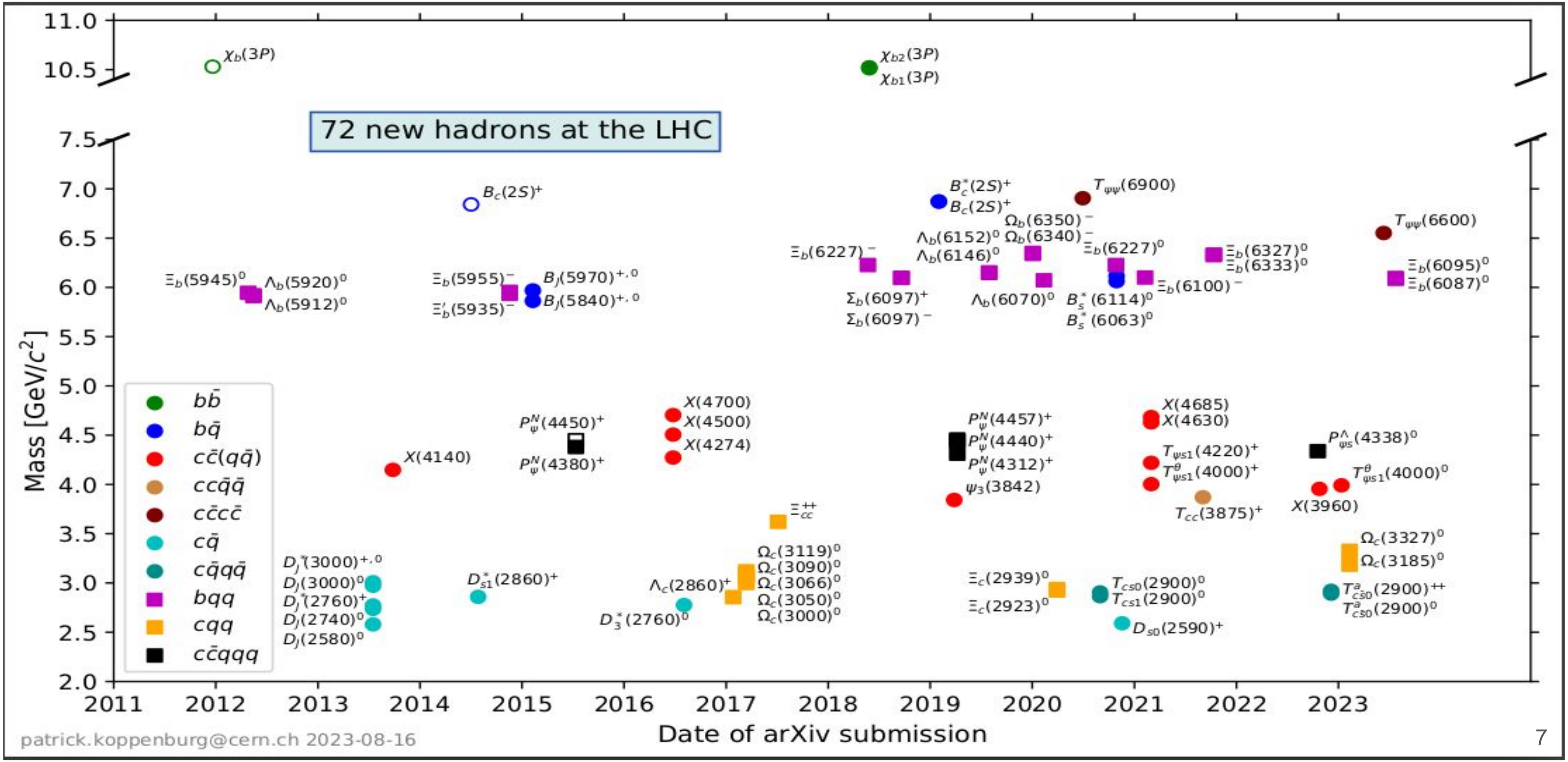
Exotic Hadrons : Models

- Simplified models motivated by the color structure & general features of QCD

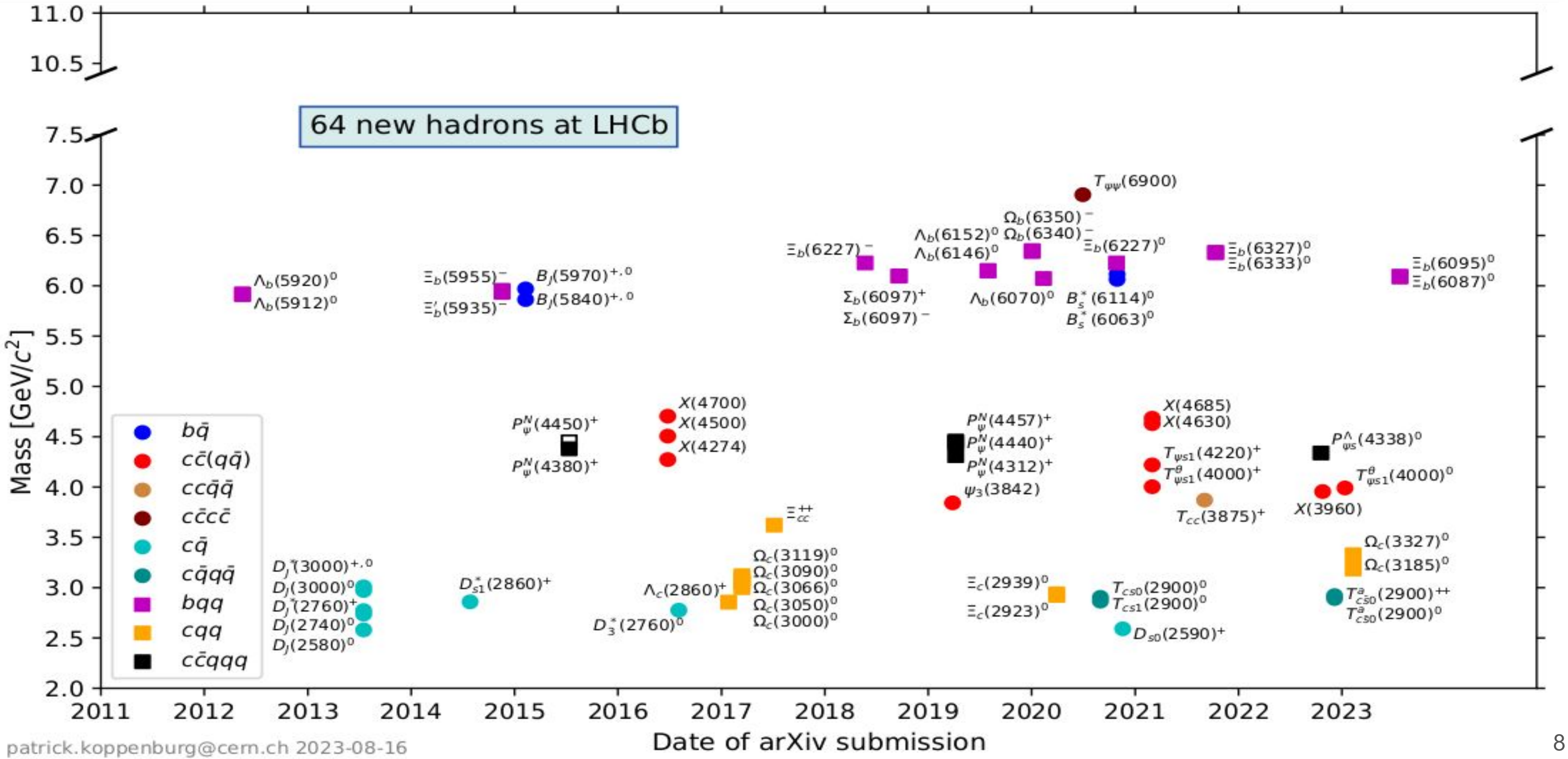
  - **QCD-color-motivated models**
    - **QCD diquarks** : formed from tightly bound colored diquarks
    - **QCD hybrids** : color singlet combinations of quarks and one or more "valence" gluons;
    - **Glueball mesons** : comprised only of gluons

  - **Other models**
    - **Hadronic molecules** : mesons and baryon forming molecule-like systems that are bound via Yukawa-like nuclear forces
    - **Hadrocharmonium** : comprised of quarkonium cores surrounded by clouds of light quarks and gluons

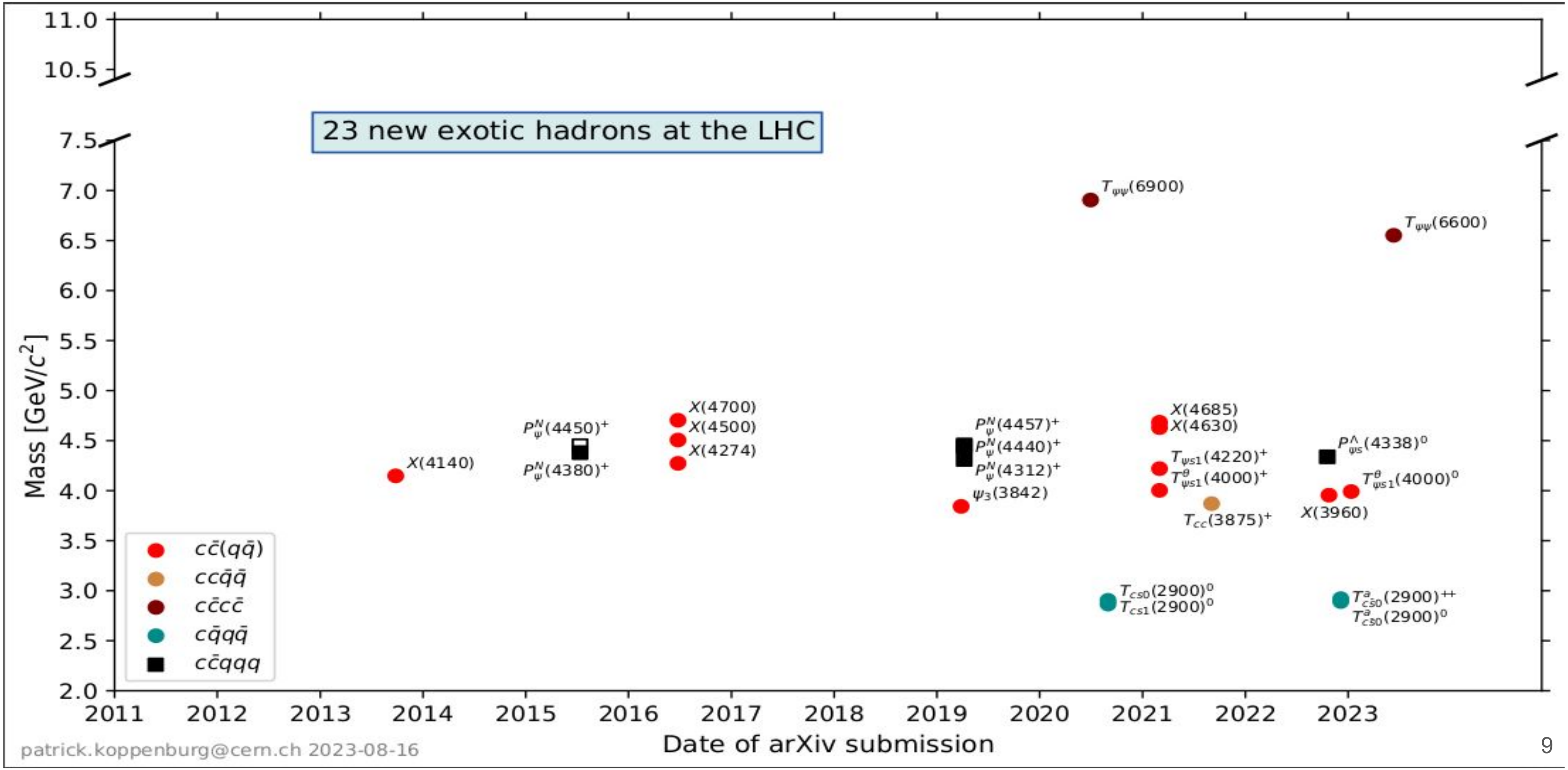
Hadron Spectroscopy at LHC



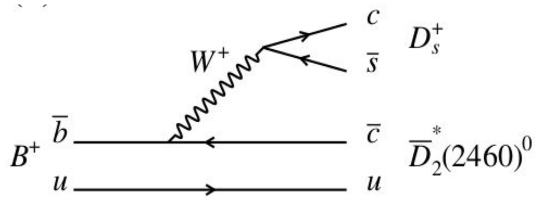
Hadron Spectroscopy at LHCb



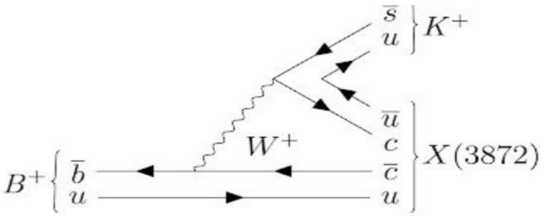
Exotic Hadrons at LHC



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).



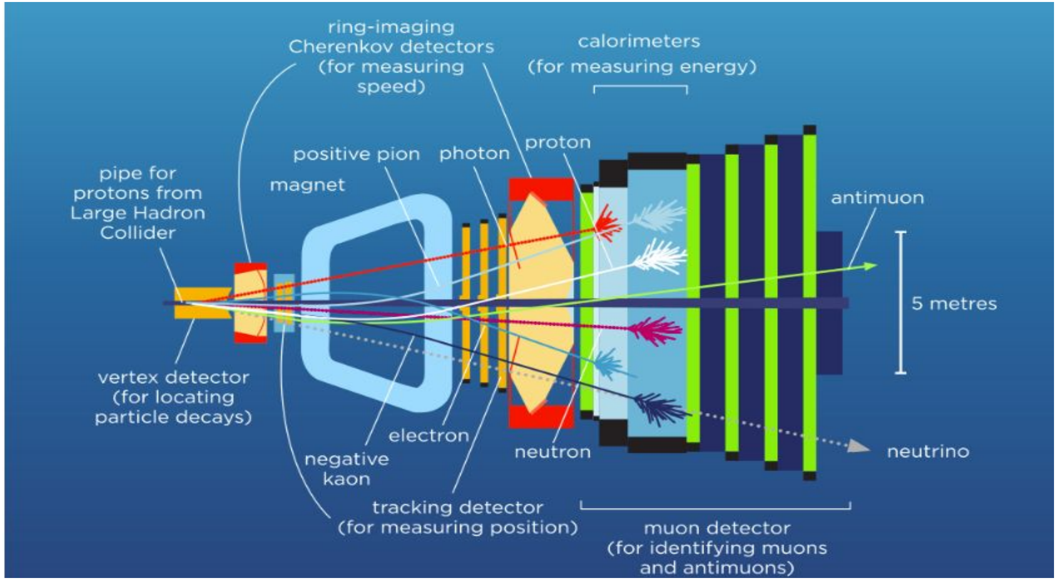
My PhD work is dedicated to search for exotics in charmonimum ($c\bar{c}$) sector at LHCb.

Why Charmonium?

- **Charm :** lightest 'heavy' quark ($m_c >> \Lambda_{QCD}$) can determine $c\bar{c}$ spectrum with simple non-relativistic Q-M treatment.
- Decays of conventional $c\bar{c}$ states are OZI suppressed - states are narrow and well separated.
- Above the open charm ($m_{D\bar{D}}$) threshold OZI allowed : wider resonances but still significantly narrower than light quark states.
- Have reliable predictions of expected conventional states.

Why LHCb?

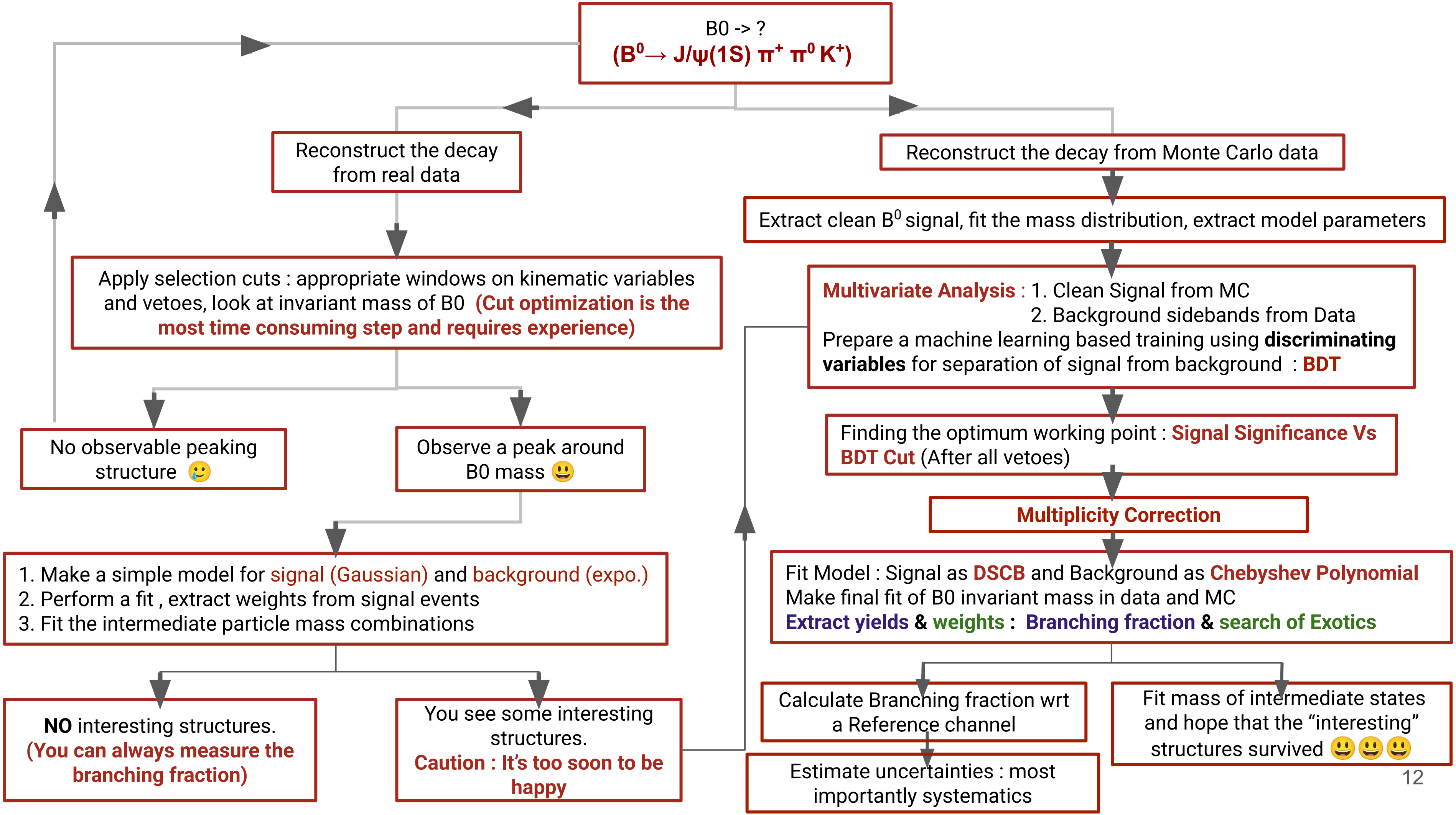
- Largest data sample of b and c hadrons
- Triggers optimised for final state particles J/Ψ(1S) and Ψ(2S).
- Dedicated computational tools available for thorough search of exotics.



Run	Years	Lum. $[\mathrm{fb}^{-1}]$	$\sqrt{s}$ [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		

- Single arm forward spectrometer : $2 < \eta < 5$
- Impact parameter resolution: $\sigma_{IP} \approx 20\mu m$
- Momentum resolution:
  - $\frac{\Delta P}{P} \backsim 0.5 - 1\%$

- Efficient hadronic identification.
- PID separation K , p from π:
  - $\epsilon(K \to K) \approx 95\%$ and $\epsilon(\pi \to K) \approx 5\%$
  - $\epsilon(p \to p) \approx 95\%$ and $\epsilon(\pi \to p) \approx 5\%$


B0 -> ?
($B^0 \to J/\psi(1S)\ \pi^+\ \pi^0\ K^+$)
Reconstruct the decay from real data
Reconstruct the decay from Monte Carlo data
Extract clean B^0 signal, fit the mass distribution, extract model parameters
Apply selection cuts : appropriate windows on kinematic variables and vetoes, look at invariant mass of B0 (Cut optimization is the most time consuming step and requires experience)
Multivariate Analysis : 1. Clean Signal from MC
2. Background sidebands from Data
Prepare a machine learning based training using discriminating variables for separation of signal from background : BDT
No observable peaking structure 🥲
Observe a peak around B0 mass 😃
Finding the optimum working point : Signal Significance Vs BDT Cut (After all vetoes)
Multiplicity Correction
1. Make a simple model for signal (Gaussian) and background (expo.)
2. Perform a fit , extract weights from signal events
3. Fit the intermediate particle mass combinations
Fit Model : Signal as DSCB and Background as Chebyshev Polynomial
Make final fit of B0 invariant mass in data and MC
Extract yields & weights : Branching fraction & search of Exotics
NO interesting structures.
(You can always measure the branching fraction)
You see some interesting structures.
Caution : It's too soon to be happy
Calculate Branching fraction wrt a Reference channel
Estimate uncertainties : most importantly systematics
Fit mass of intermediate states and hope that the "interesting" structures survived 😃😃😃

We have observed 3 new decay modes of B^0 meson

$B^0 \rightarrow (J/\psi\, \pi^+ \pi^- \pi^0\,)\pi^+ K^-$

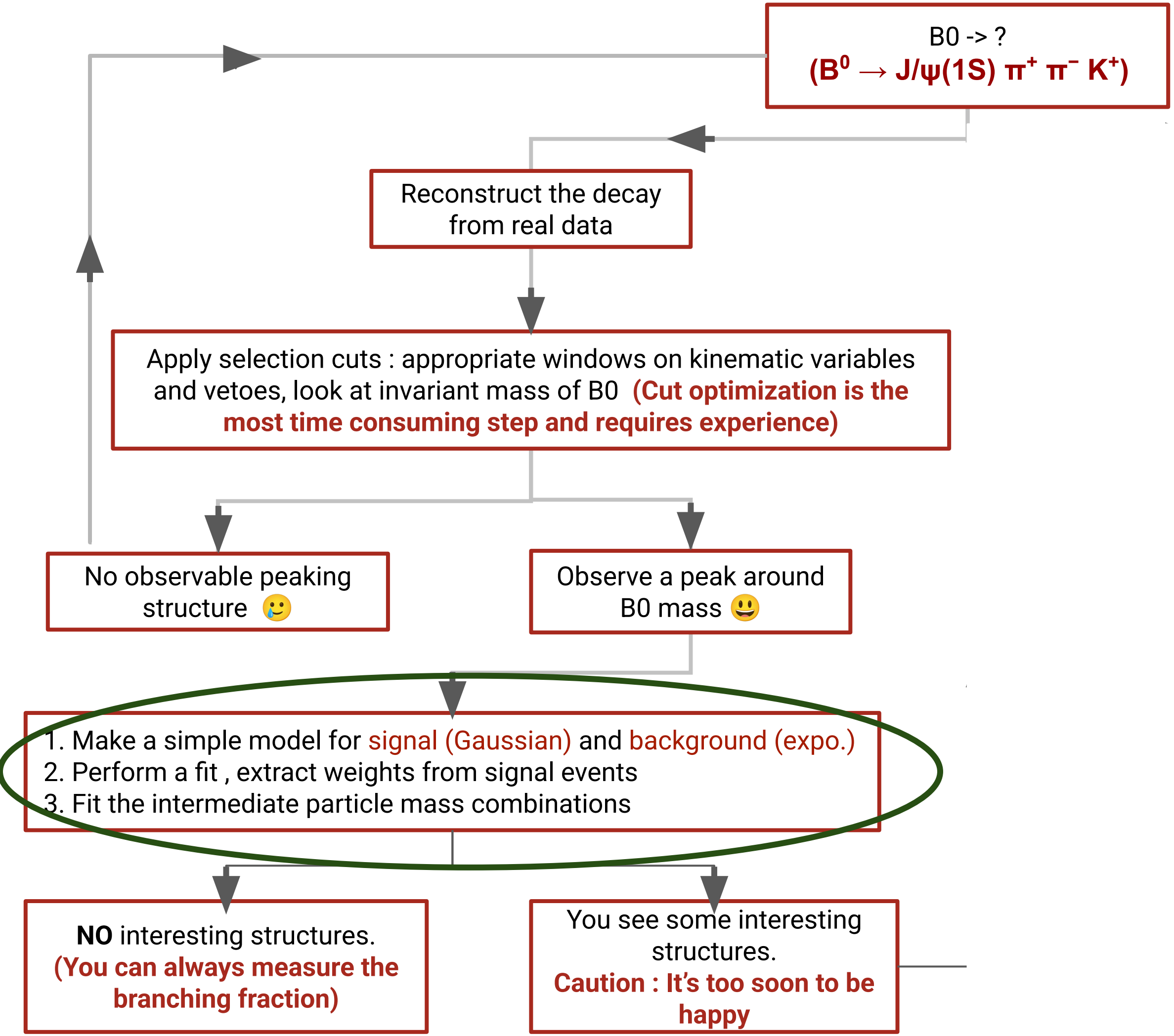
- Search for **$\psi(4230)$**$\rightarrow J/\psi\, \pi^+\, \pi^-\, \pi^0$
- Measure Branching fraction

$B^0 \rightarrow J/\psi \omega \pi^+ K^-$

- Search for **X(3940)**$\rightarrow J/\psi\omega$
- Measure Branching fraction

$B^0 \rightarrow (\psi(2S)\pi^0)\pi^- K^+$

- Measure Branching fraction



B0 -> ?
(B⁰ → J/ψ(1S) π⁺ π⁻ K⁺)
Reconstruct the decay from real data
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No observable peaking structure
Observe a peak around B0 mass
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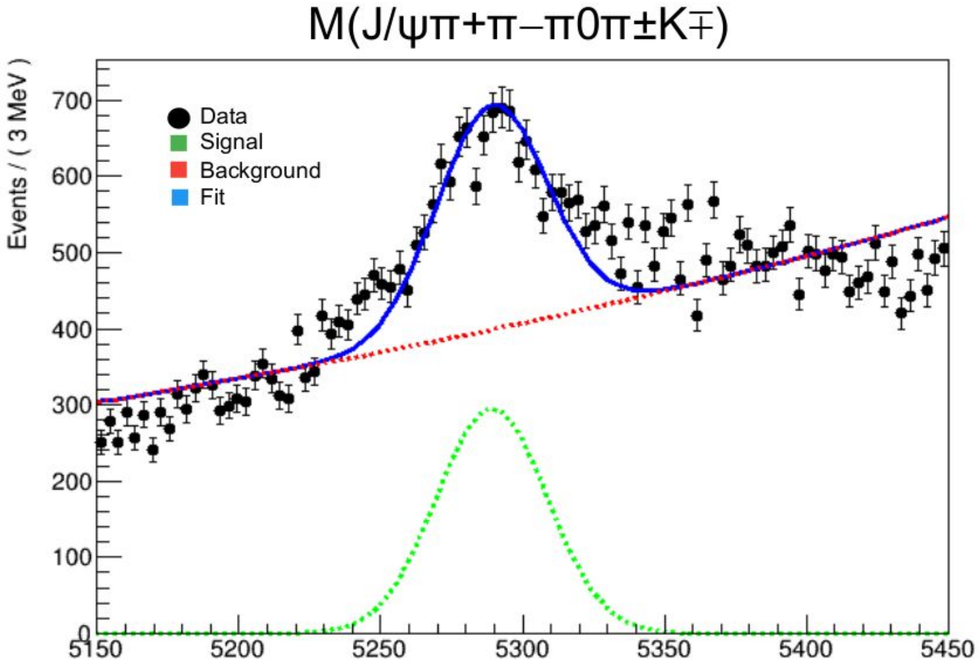
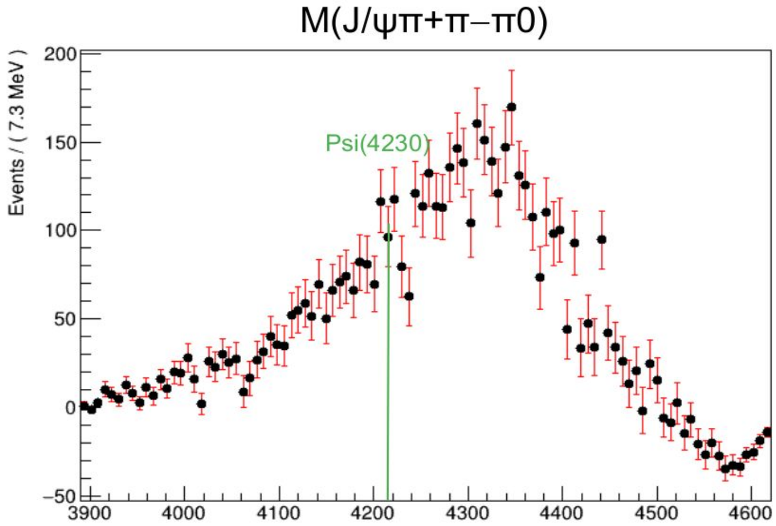
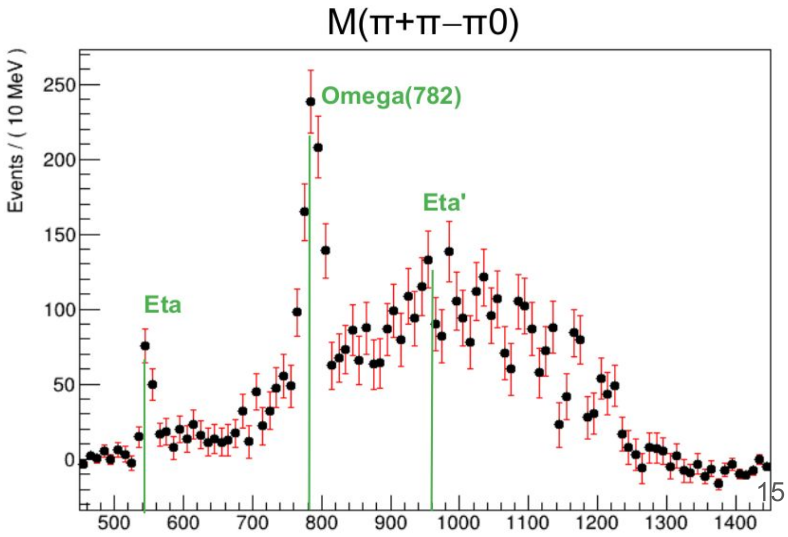
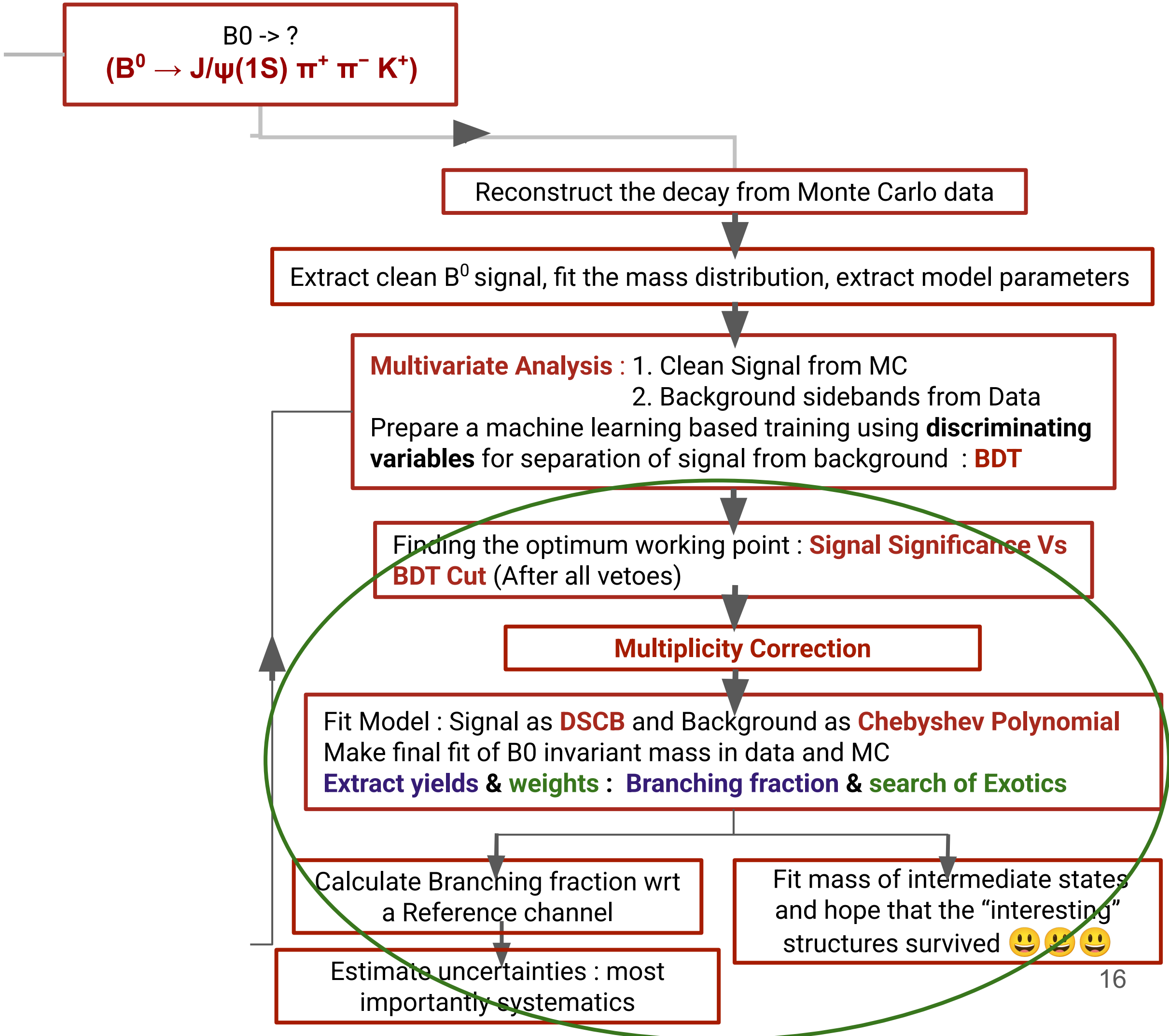
DATA : $B^0 \rightarrow (J/\psi\pi^+\pi^-\pi^0)\pi^+K^-$





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Prepare a machine learning based training using **discriminating variables** for separation of signal from background : **BDT**
Finding the optimum working point : **Signal Significance Vs BDT Cut** (After all vetoes)
Multiplicity Correction
Fit Model : Signal as **DSCB** and Background as **Chebyshev Polynomial**
Make final fit of B0 invariant mass in data and MC
Extract yields & weights : Branching fraction & search of Exotics
Calculate Branching fraction wrt a Reference channel
Estimate uncertainties : most importantly systematics
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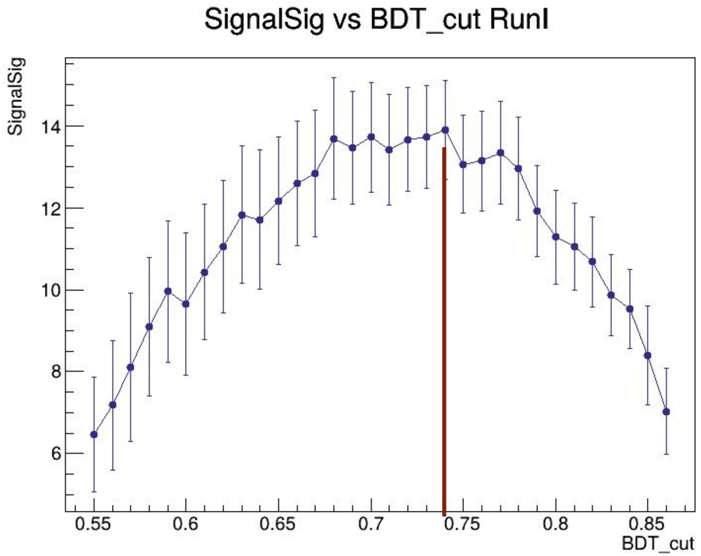
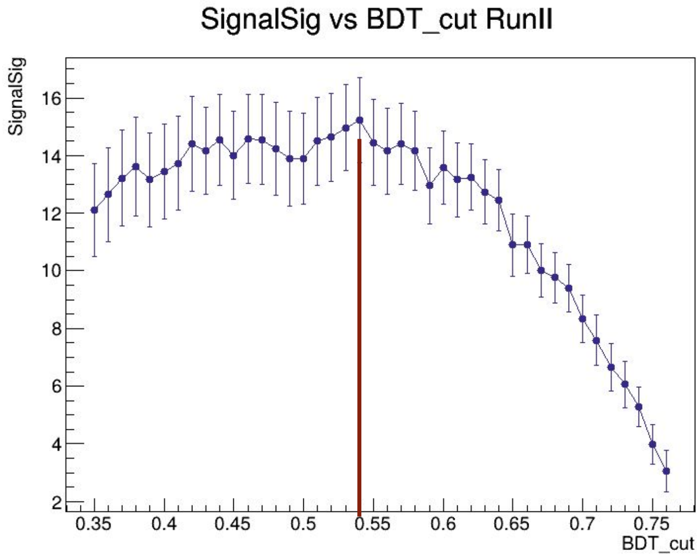
Figure of Merit or **Signal Significance**

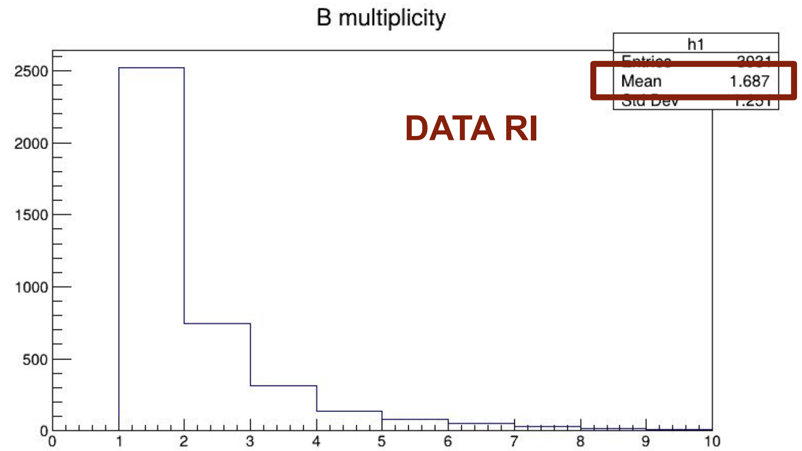
$$\text{FoM} = S/\sqrt{(S+B)}$$

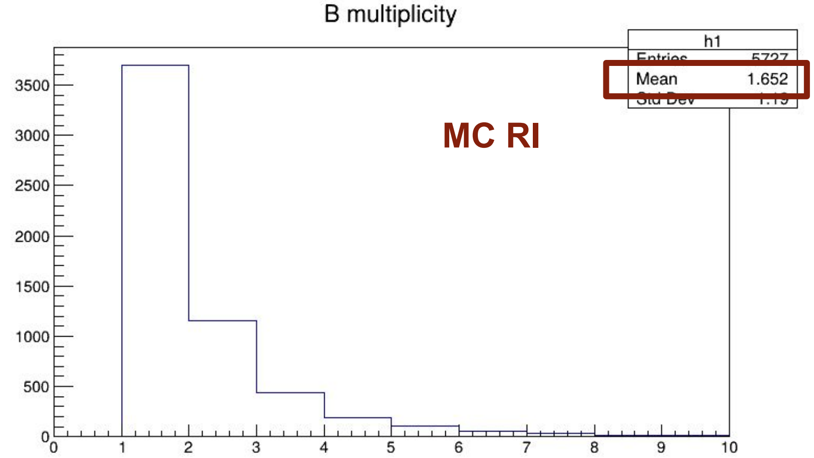
- Apply a cut : BDT > x
- Fit invariant mass of B meson :
  - Signal : DSCB
  - Background : exponential
- Extract signal and background events and evaluate FoM at different x values.
- Optimum working point : BDT value corresponding to maximum FoM.

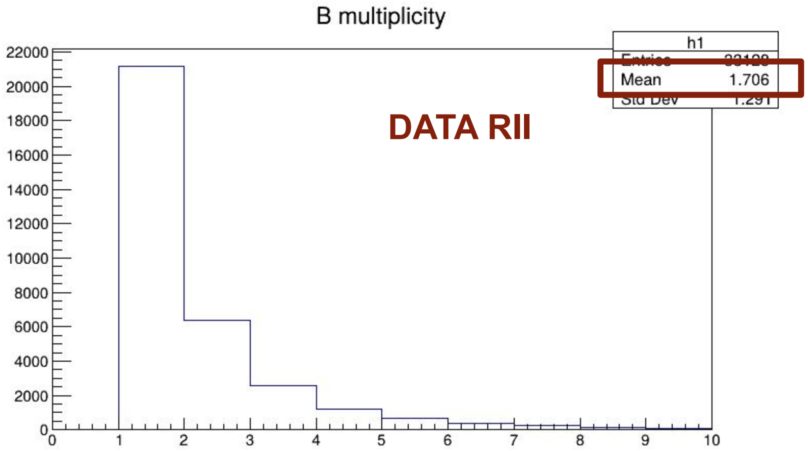


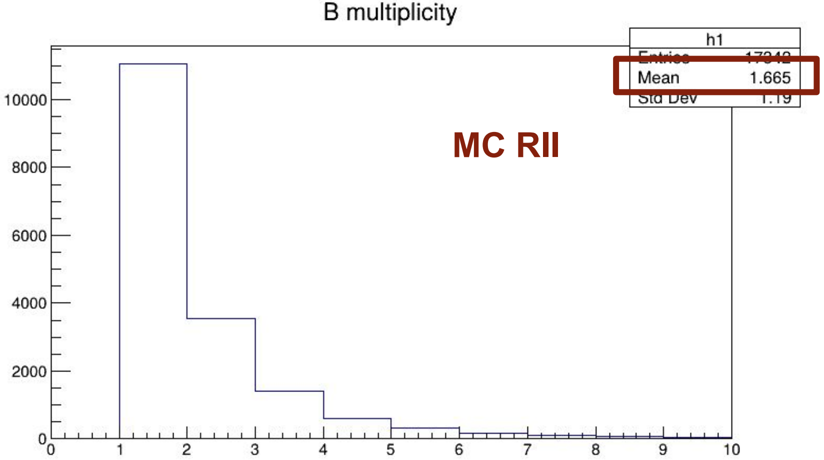


Multiplicity Correction : Random Selection

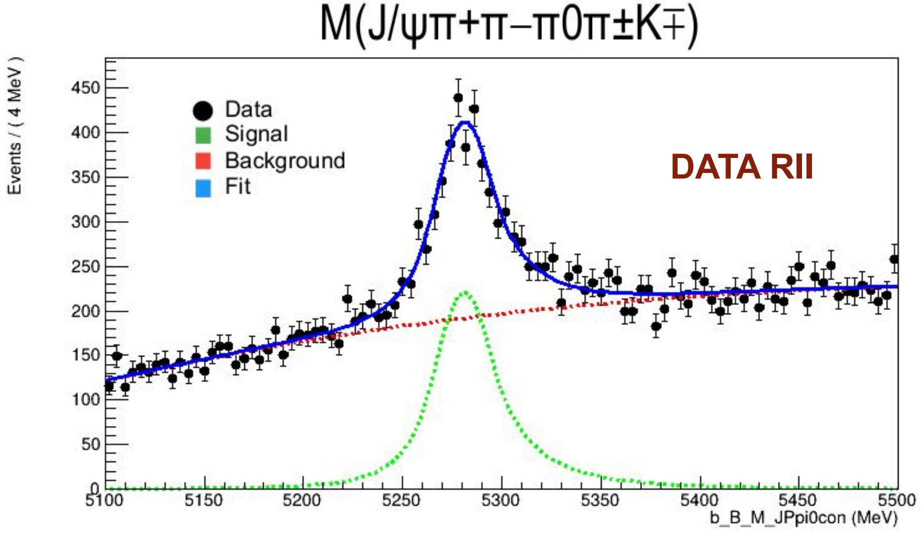


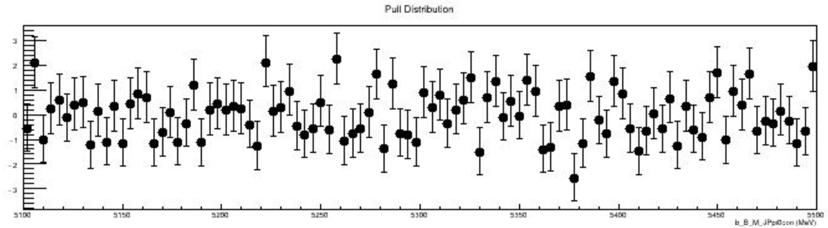




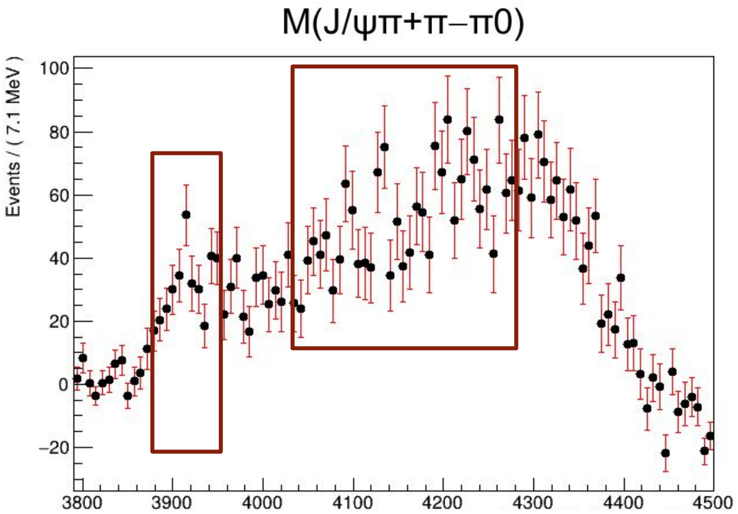


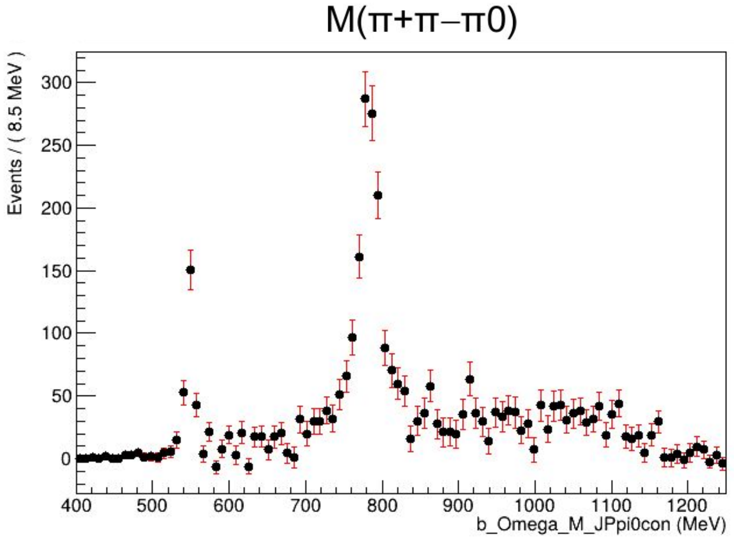
DATA : $B^0 \rightarrow (J/\psi\pi^+\pi^-\pi^0)\pi^+K^-$

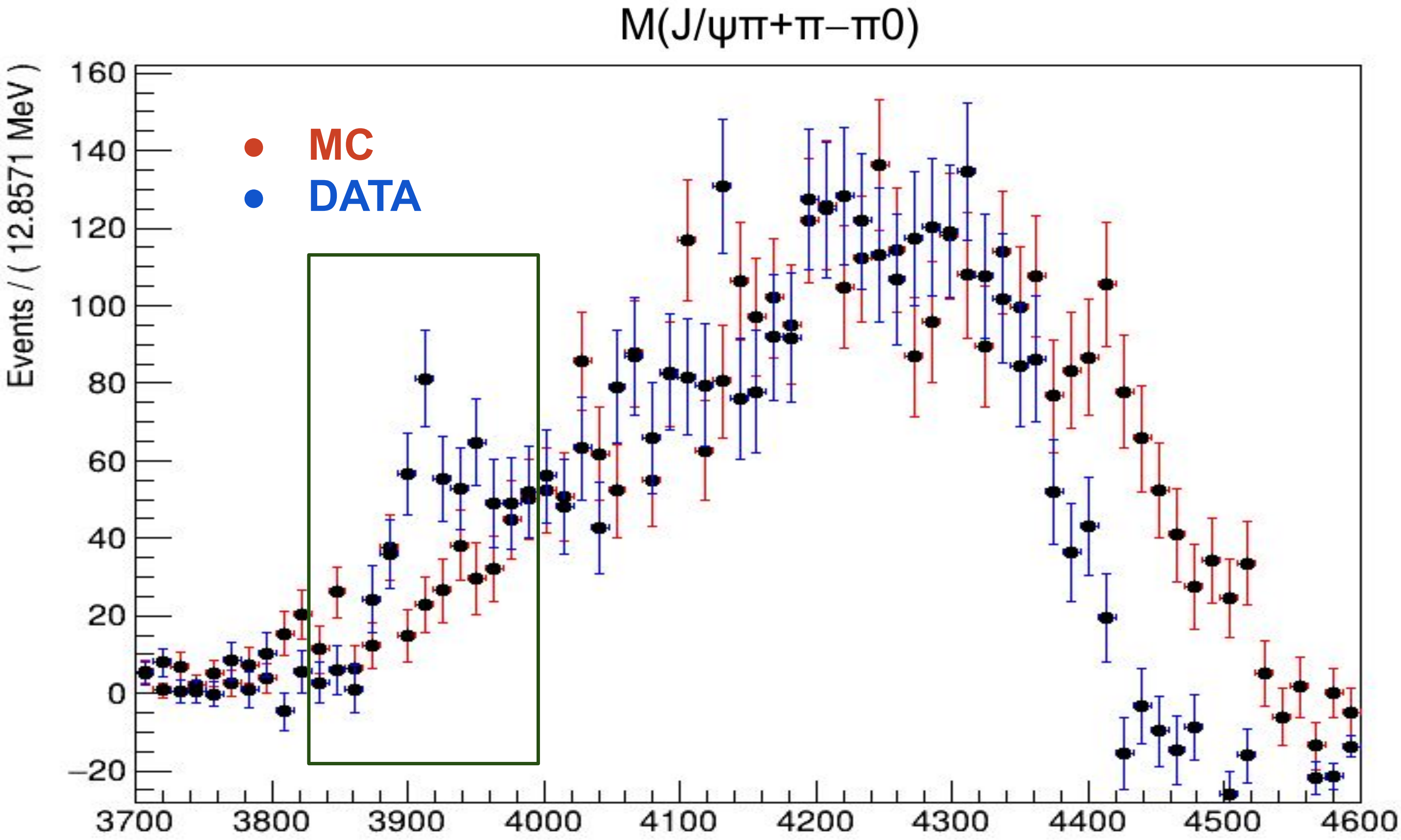




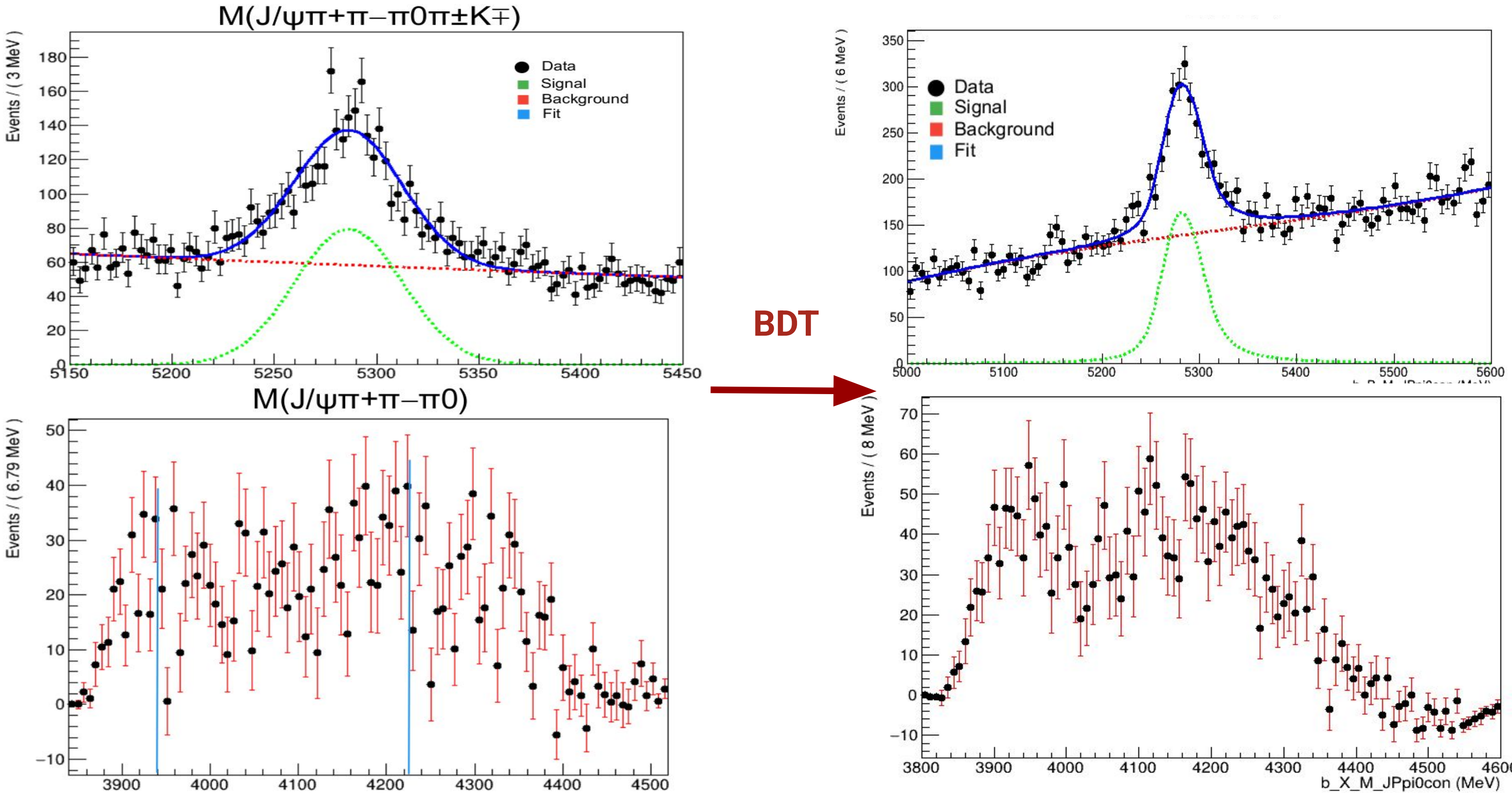
Yield = 2658 +/- 90.44






M(J/ψπ+π−π0)
Events / (12.8571 MeV)
MC
DATA
160
140
120
100
80
60
40
20
0
−20
3700
3800
3900
4000
4100
4200
4300
4400
4500
4600

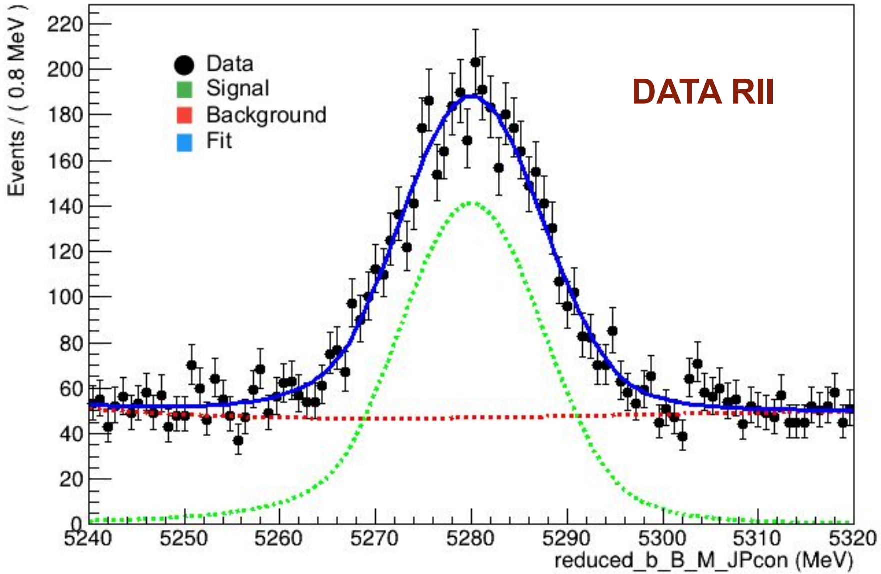
DATA : $B^0 \rightarrow J/\psi\omega\pi^+K^-$



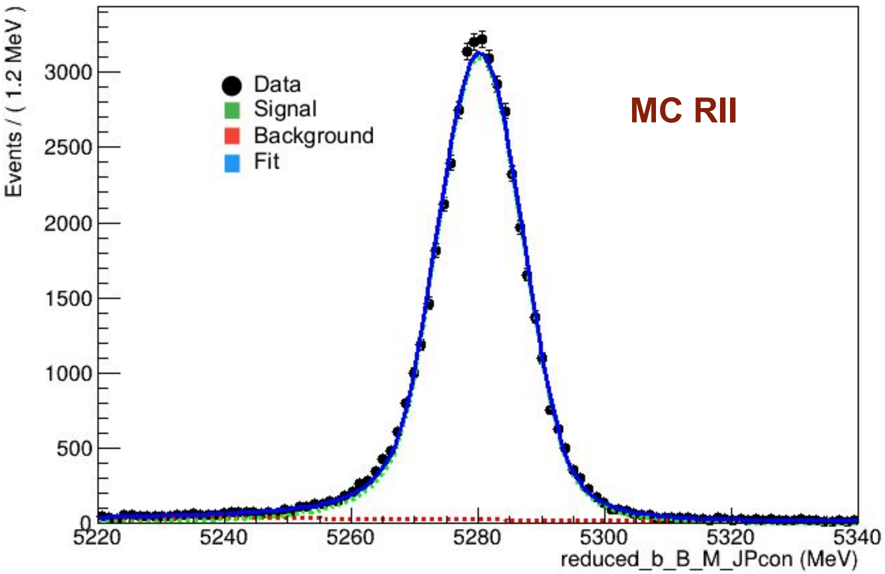
Reference Channel

- Reference channel : **$B^0 \to J/\psi\ \pi^+\pi^-\ \pi^+\pi^-$**
- B.F. measurement by LHCb for run I only : **Phys. Rev. Lett. 112, 091802 (2014)**

$$\frac{Br\,(B^0 \to J/\psi\ \pi^+\pi^-\ \pi^+\pi^-)}{Br\,(B^0 \to J/\psi\ \pi^+\pi^-)} = 0.361 \pm 0.017 \pm 0.021$$



Yield = 3452 +/- 85.74



Yield = 46538 +/- 235.9

Branching fraction measurement

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

- **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 :

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

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

Branching fraction measurement

- $$\frac{Br\,(B^0 \rightarrow J/\psi \pi^+ \pi^- \pi^0 \pi^+ K^-)}{Br\,(B^0 \rightarrow J/\psi \pi^+ \pi^- \pi^+ \pi^-)}$$

$B^0 \rightarrow (J/\psi\ \pi^+ \pi^- \pi^0\ )\pi^+ K^-$

Combined RI & RII : B.F = 27.0 +/- 1.3

Run I : 22 +/- 2.54
Run II : 27.62 +/- 1.437

- $$\frac{Br(B^0 \rightarrow \psi(2S)\rho^+ K^-)}{Br(B^0 \rightarrow J/\psi \pi^+ \pi^- \pi^+ \pi^-)} = \frac{(N1 * E2)}{(E1 * N2) Br(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-) * Br(\rho^+ \rightarrow \pi^+ \pi^0)}$$

Run I : 42.27 +/- 4.68
Run II : 41.85 +/- 1.81

$B^0 \rightarrow \psi(2S)\rho^+ K^-$

Combined RI & RII : B.F = 41.9 +/- 1.7

Conclusions

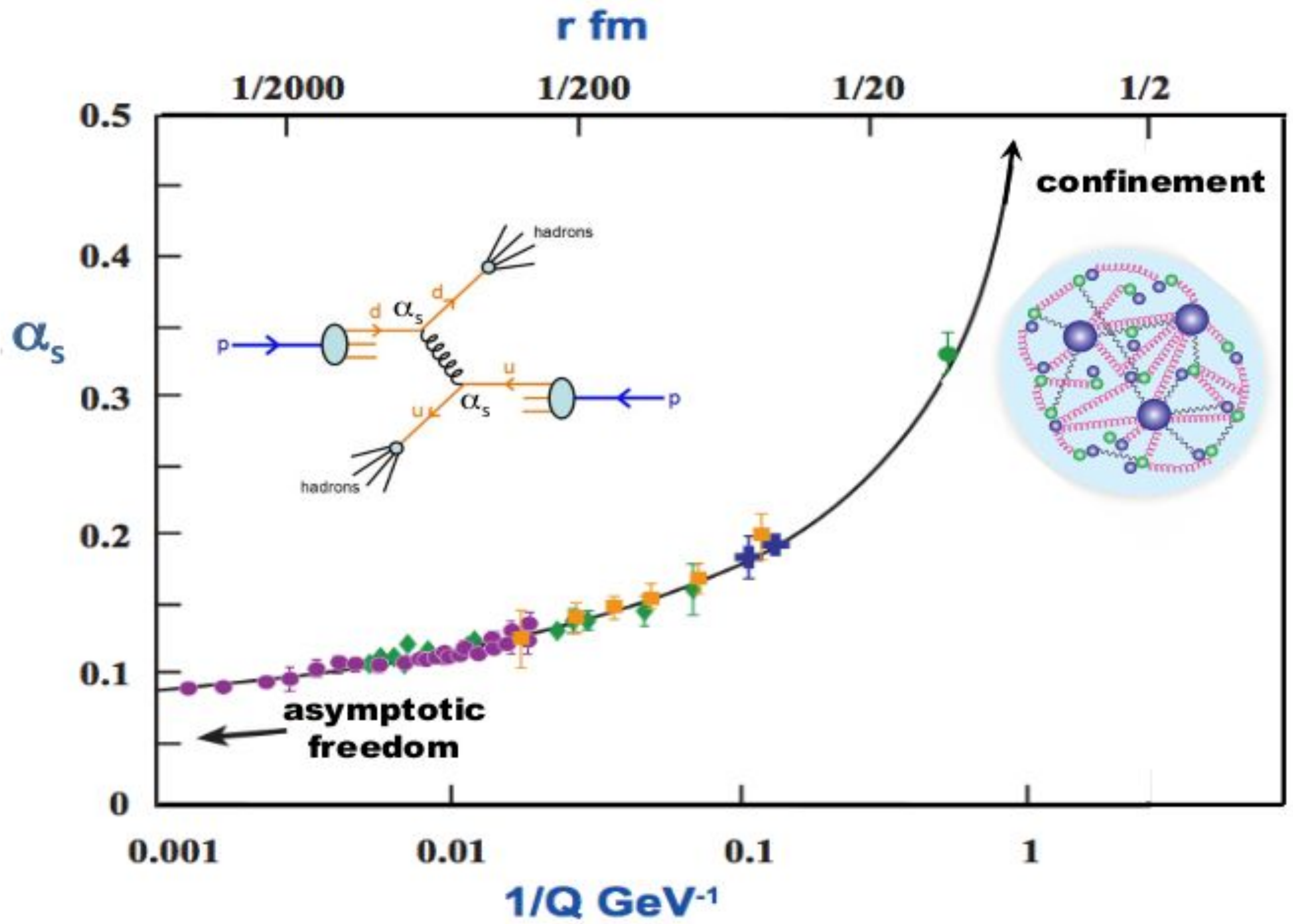
- We have made observation of 3 new decay modes of B0 meson along with presence of signatures from exotic tetraquarks as intermediate states.
- We measure their relative branching fraction.

Next steps in analysis

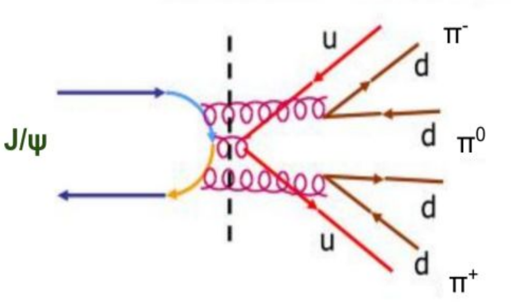
- For each decay mode, estimate systematic uncertainty.
- To claim observation of exotics an amplitude analysis would be needed : **Not enough time to do that now!**

BACK-UP

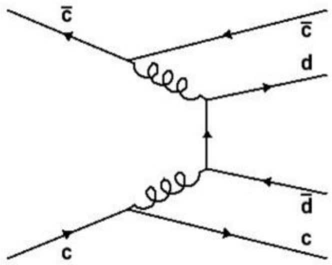
A brief history of Hadron spectrum



OZI rule : Hadronic decays that require quark-antiquark annihilation and reformation into different flavors are strongly suppressed.



OZI-suppressed



OZI-allowed

- Require the cc pair to annihilate and then hadronize into light quarks.
- Involve **loop-level diagrams** or require multiple gluons and are thus higher-order and rarer.
- The decay amplitude is **much smaller** because it involves **"disconnected diagrams"**.

- Involve **intermediate gluons** which **do not disconnect** the quark lines : **"connected diagrams"**.
- Processes are **leading-order** in perturbation theory
- Often involve gluon-rich final states.

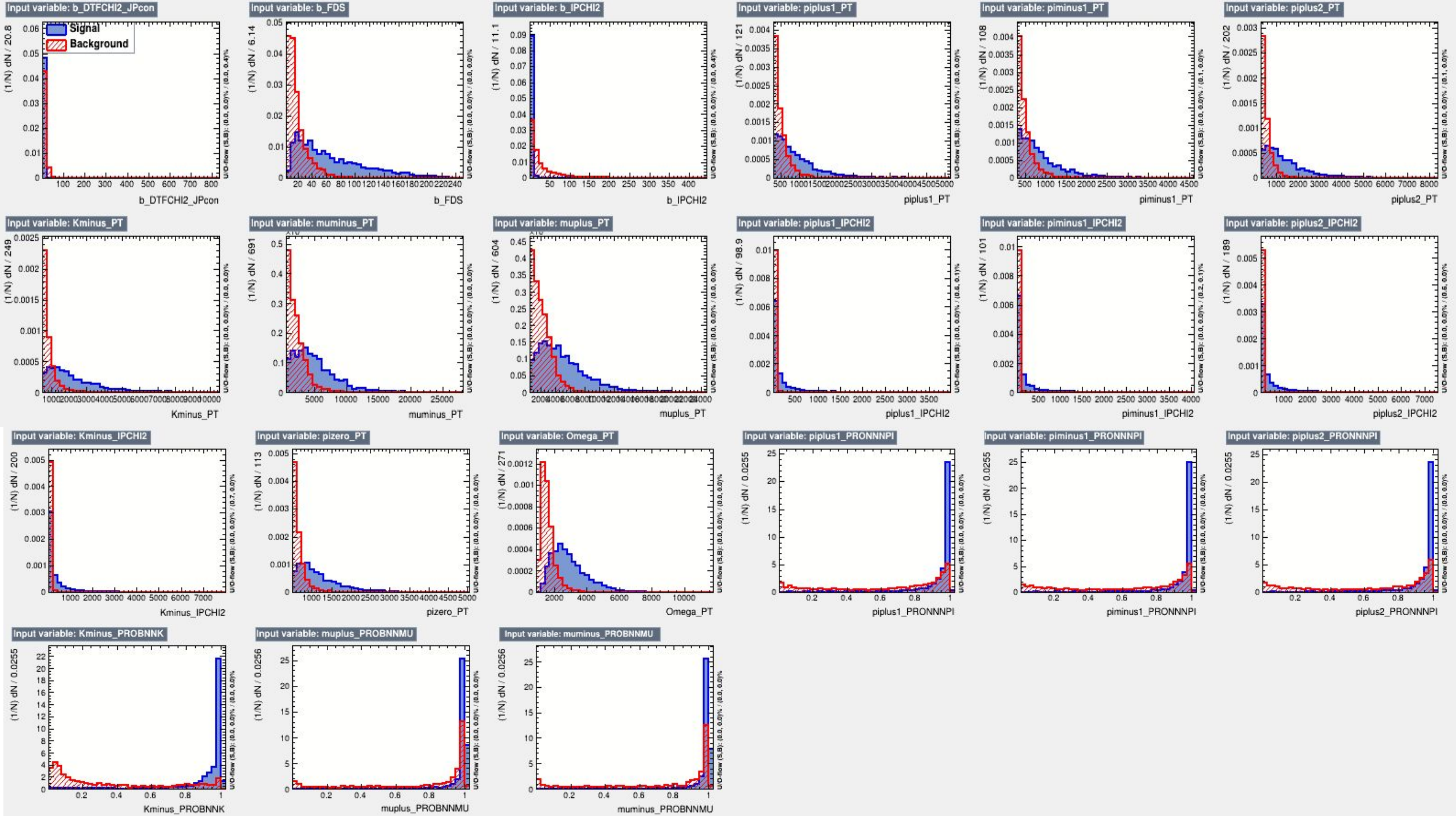
Selection Cuts		
Particle	Parameter	Selection
$\mu^{\pm}$	PROBNNMU	> 0.5
	χ^2 IP	> 10
$\pi^{\pm}$	PROBNNPI	> 0.4
	p_T	> 400 MeV
	P	> 3200 MeV
	χ^2 IP	> 4
π^0	p_T	> 1000MeV
$K^{\pm}$	η	2 - 5
	P	> 3200 MeV
	PROBNNK	> 0.15
	χ^2 IP	> 4
B_0	M (J/ψ constrained)	5150 - 5450 MeV
	χ^2DTF (J/ψ constrained)	< 5
	χ^2 IP	< 9
	FDS	> 5

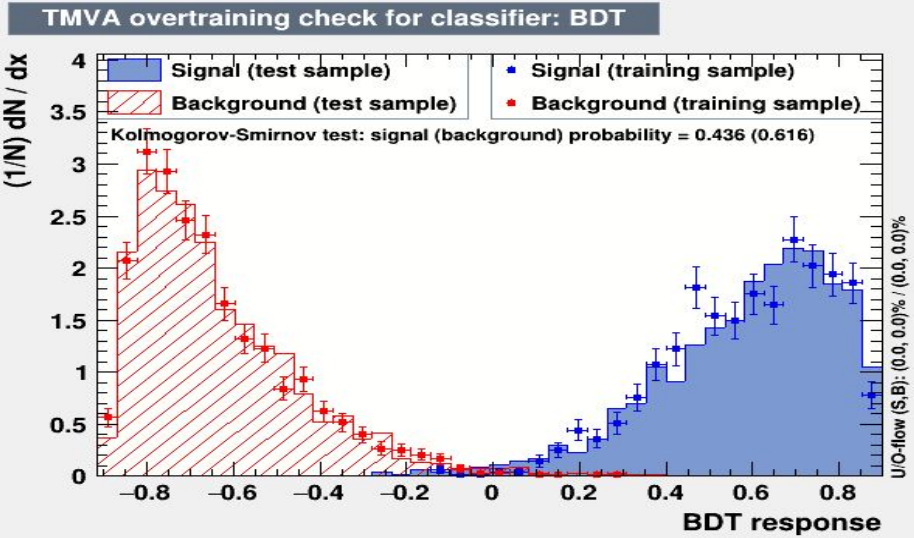
Boosted Decision Tree (BDT)

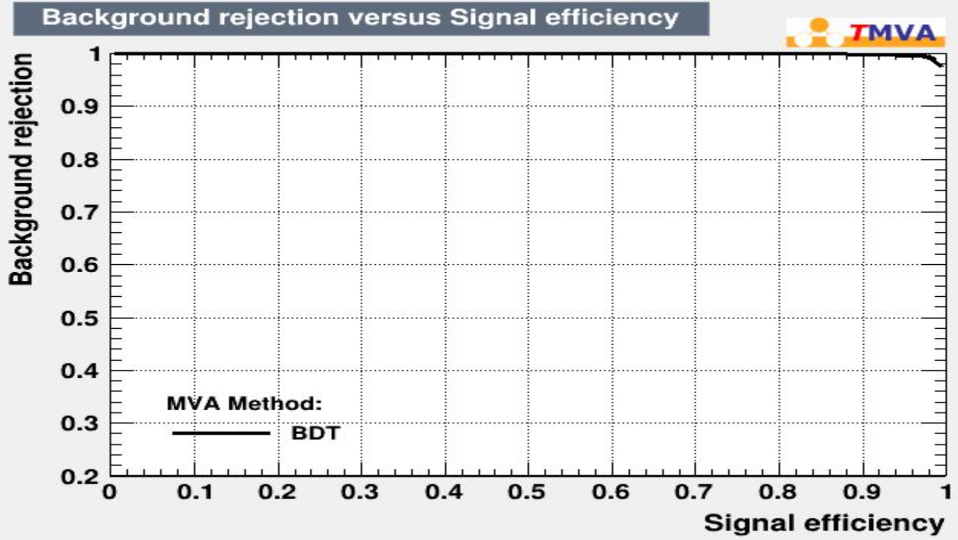
- **Decision trees** employ sequential cuts to perform the classification task.
- At each step in the sequence, the best cut is searched for and used to split data.
- This process is continued recursively on the resulting partitions until a given terminal criterion is satisfied.
- The training data set containing signal and background events.
    - **Signal : Monte Carlo** data for the signal
    - **Background :** Sideband events excluding signal region in raw data
    - **Discriminating Variables**
- Difficult to make a very good discriminant, but simpler, more error-prone (high bias) i.e. **Weak Classifiers.**
- **Boosting** : goal is to combine weak classifiers into a new, more stable one, with a smaller error rate and better performance

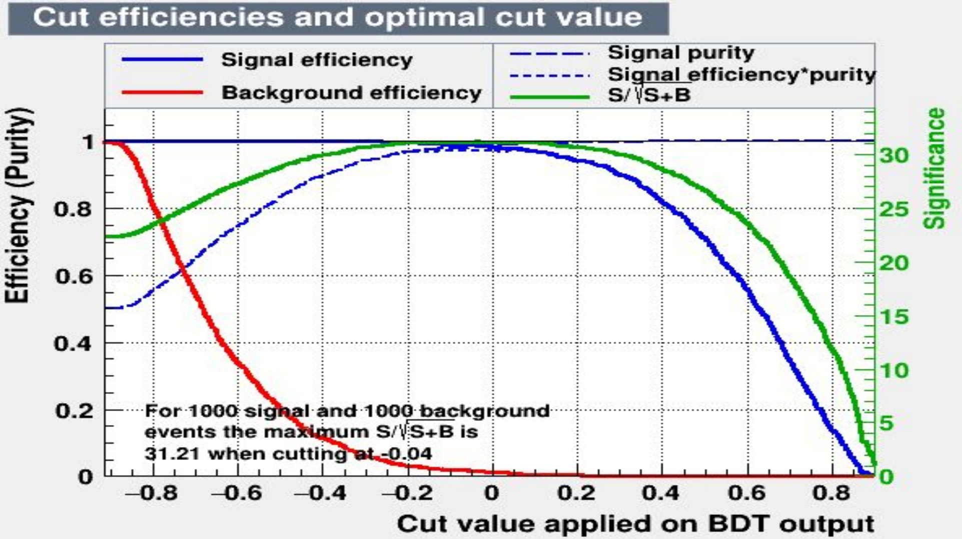
How to do it ?

- Reconstruct MC data for each year on the same code as detector data (keep preselections same).
- Extract pure signal by using variable BKGCAT = 0.
- Extract sideband from reconstructed data (each year): 5150 < B mass > 5450
- Signal region : 5200 < B mass < 5400
- Divide both into 2 data sets : Training and Testing .
- Randomisation is important !!!
- Applying various machine learning algorithms, easy!
- The tediously lengthy part : design and optimisation of the model itself, and how to pick the best one.
- Variable selection : No tricks!
- How to optimise classifier ? : No tricks!


Signal
Background
Input variable: b_DTFCHI2_JPcon
Input variable: b_FDS
Input variable: b_IPCHI2
Input variable: piplus1_PT
Input variable: piminus1_PT
Input variable: piplus2_PT
Input variable: Kminus_PT
Input variable: muminus_PT
Input variable: muplus_PT
Input variable: piplus1_IPCHI2
Input variable: piminus1_IPCHI2
Input variable: piplus2_IPCHI2
Input variable: Kminus_IPCHI2
Input variable: pizero_PT
Input variable: Omega_PT
Input variable: piplus1_PRONNNPI
Input variable: piminus1_PRONNNPI
Input variable: piplus2_PRONNNPI
Input variable: Kminus_PROBNNK
Input variable: muplus_PROBNNMU
Input variable: muminus_PROBNNMU



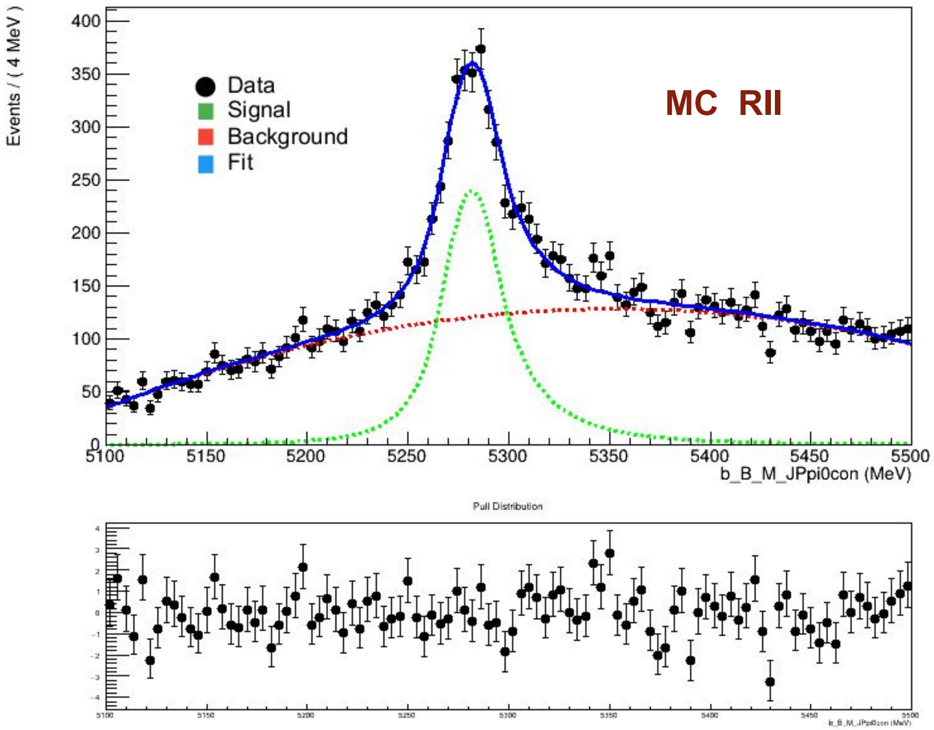




- Apply training on whole data set, each run separately.
- “Friend” this training output event by event with data.
- New variable produced : BDT variable associated with every event.
- Values vary between : 0 and 1

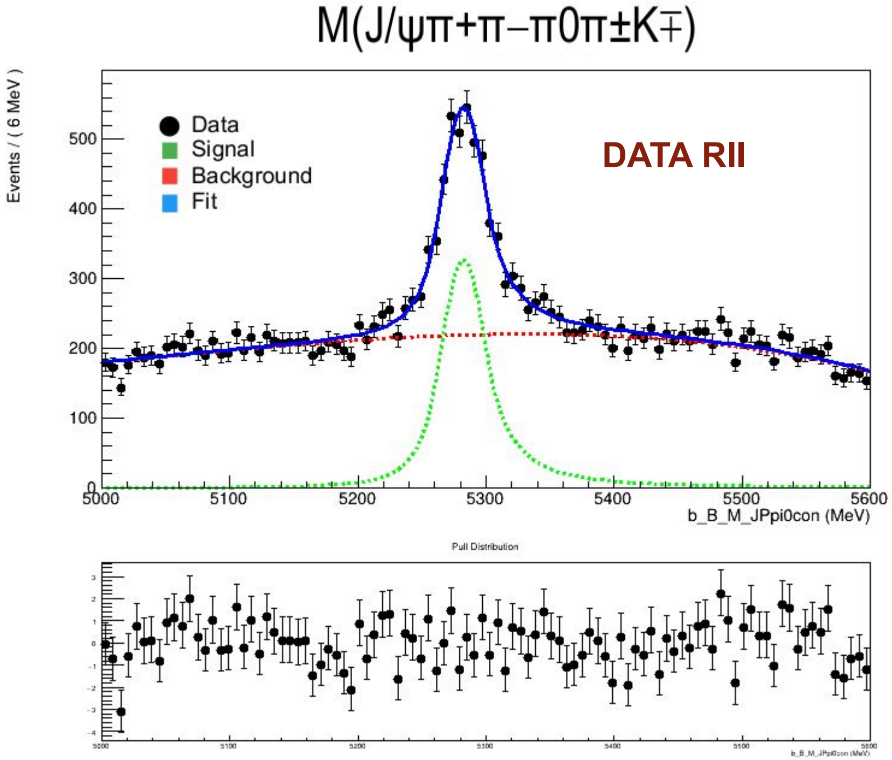
FINAL FIT MC

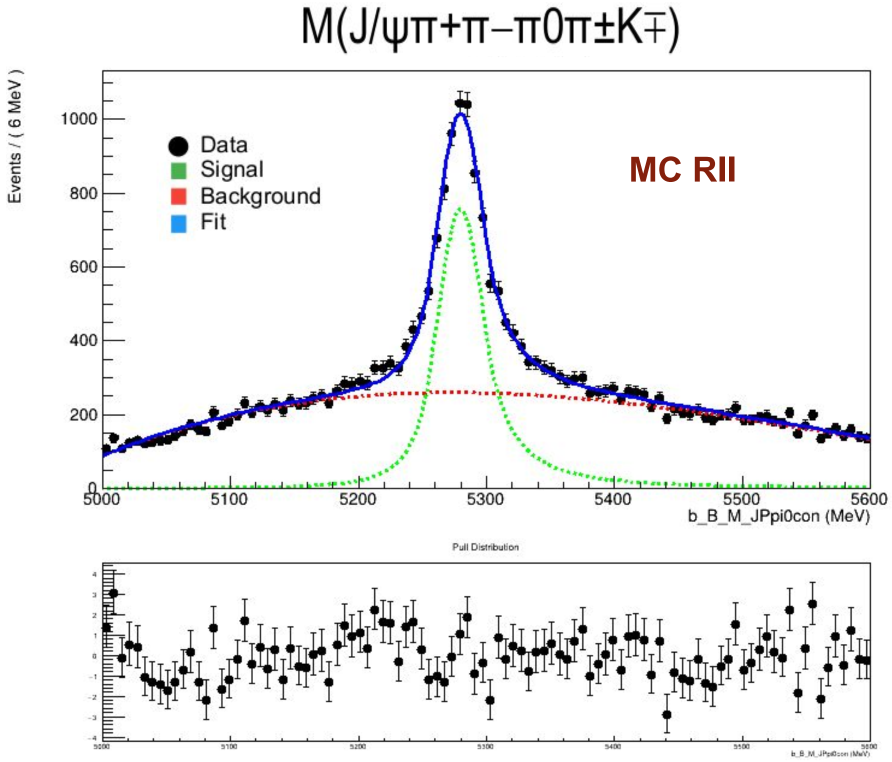
- Apply BDT training on MC
- Cut at optimum working point
- Apply all vetoes
- Perform multiplicity correction
- Use same model to make a fit and extract signal yield

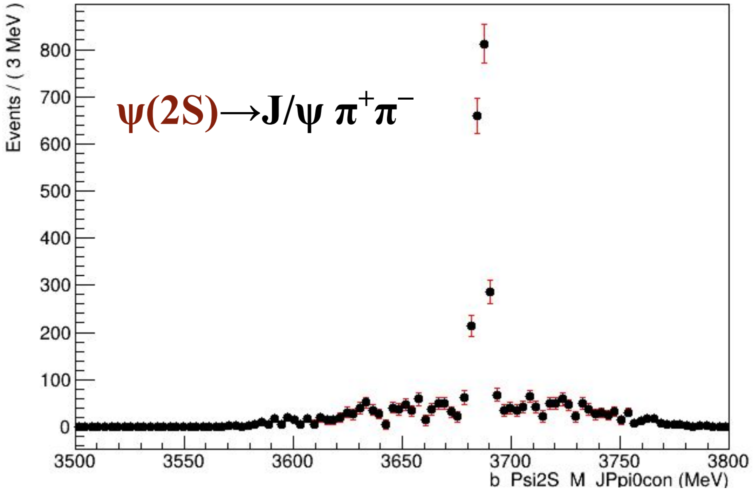


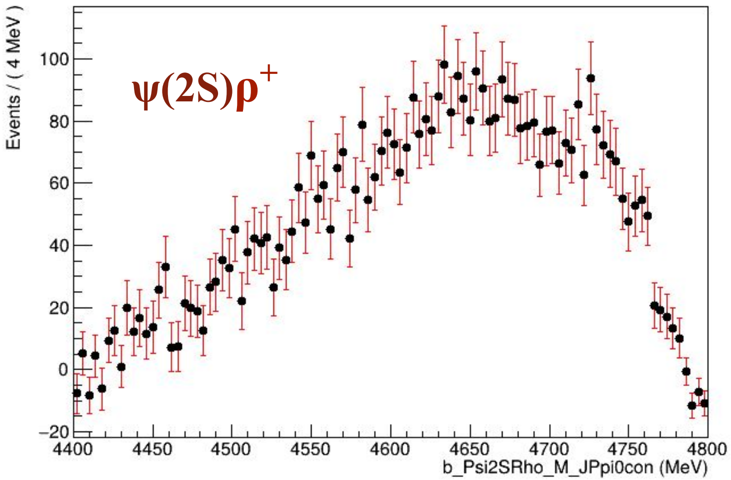
Yield = 3263 +/- 87.46

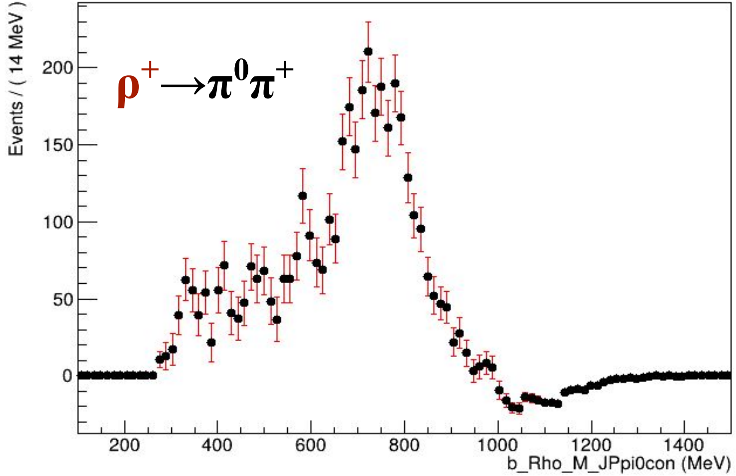
FINAL FITS : $B^0 \rightarrow \psi(2S)\rho^+K^-$

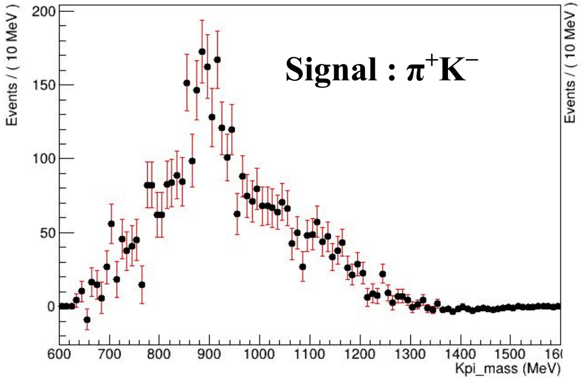


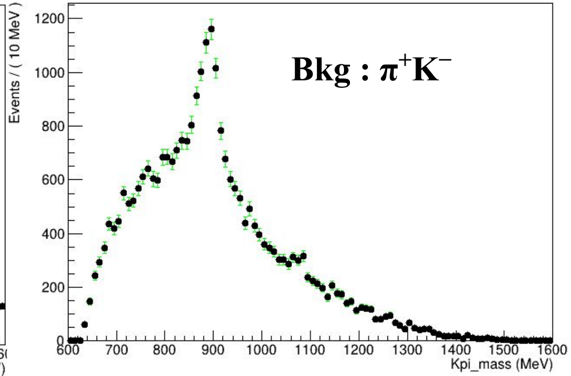



ψ(2S)→J/ψ π⁺π⁻
Events / (3 MeV)
b_Psi2S_M_JPpi0con (MeV)


ψ(2S)ρ⁺
Events / (4 MeV)
b_Psi2SRho_M_JPpi0con (MeV)


ρ⁺→π⁰π⁺
Events / (14 MeV)
b_Rho_M_JPpi0con (MeV)


Signal : π⁺K⁻
Events / (10 MeV)
Kpi_mass (MeV)


Bkg : π⁺K⁻
Events / (10 MeV)
Kpi_mass (MeV)