Probing the Quark-Gluon Plasma with heavy quarks

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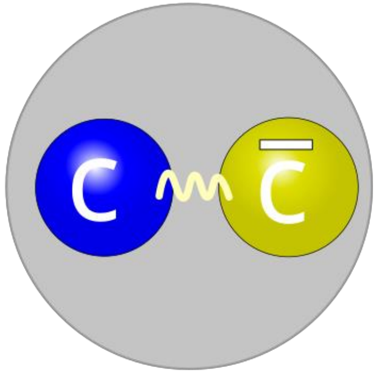
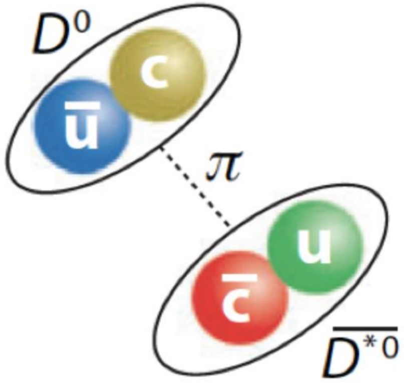
Exotic States and X(3872)

- Hadrons: particles made of quarks and gluons.
  - **mesons** and **baryons**
  - **exotic states**: tetraquarks, pentaquarks, glueballs, hybrids and XYZ states

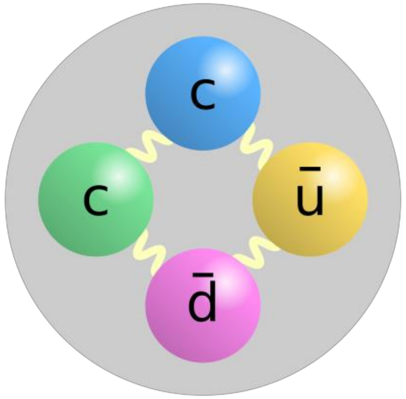
- **X(3872):** the first exotic state discovered in 2003 by the Belle experiment.
  - different explanations for its structure:
    - **charmonium** state
    - D0 and anti-D0* **molecule**
    - **tetraquark**
    - their admixture



charmonium state



molecule

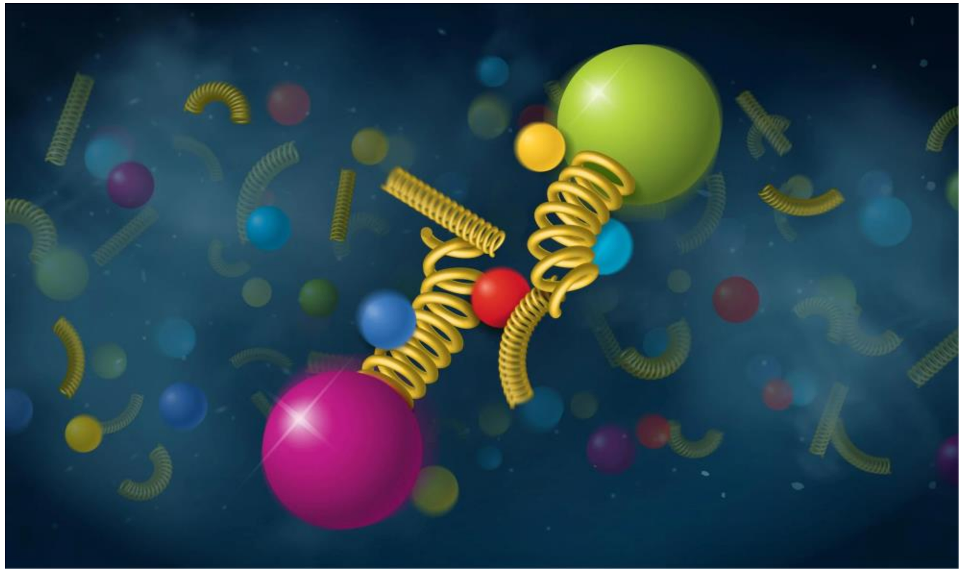


tetraquark

X(3872) as Probes of the QGP

- The interaction between QGP and X(3872)
  - **Coalescence**
    - Coalescence mechanisms could enhance the X(3872) production yield.
  - **Screening**
    - Due to Screening effects**, a** longer distance between the quarks and antiquarks of X(3872) could lead to a higher dissociation rate.

- **Why** do we want to study the X in HIC?
  - Learn about the nature of X(3872):
    - a compact tetraquark configuration with a radius ~0.3 fm?
    - a molecular state with a radius greater than 1.5 fm?
  - Establish the **first observation** of X(3872) in Pb-Pb collisions
  - Explore the QGP mechanisms



screening effects

Study Procedure

➢ How to study the interaction between QGP and X(3872)?

- preparation: **data** & **simulation**
- **event selection**: single variable optimization & multi-variable ML
- **efficiency** correction
- **cross section** measurement
- **Nuclear Modification Factor** (RAA) calculation

$$\frac{d\sigma}{dp_T} = \frac{1}{\varepsilon L B}\frac{Y_s}{\Delta p_T}$$

$$R_{AA}(p_T) = \frac{1}{\langle N_{col}\rangle}\frac{\left(\frac{d\sigma}{dp_T}\right)_{PbPb}}{\left(\frac{d\sigma}{dp_T}\right)_{pp}}$$

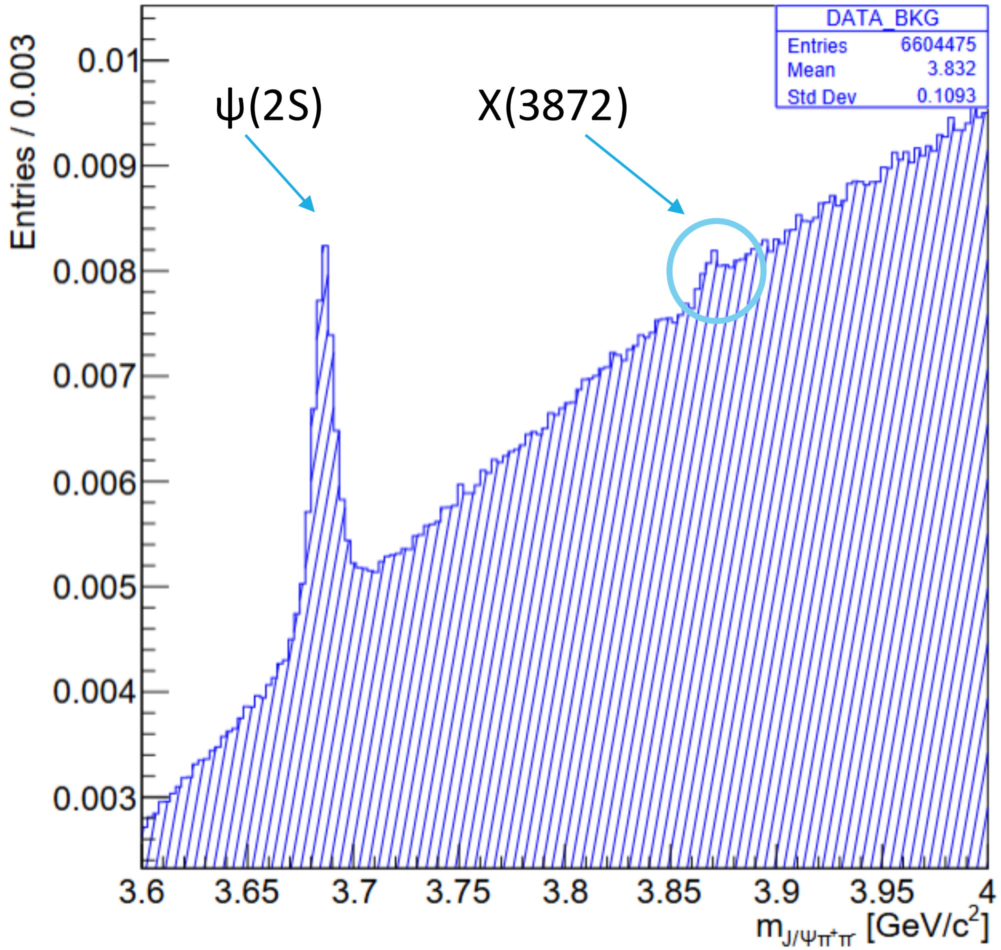
X(3872) & ψ(2S)

Goal: Study exotic particle X(3872) structure and its iteraction with QGP.

First step: Measure Ψ(2S) and X(3872) cross sections in pp collisions.

Decay channels:

- $X(3872) \to J/\psi + \rho \to \mu^+ + \mu^- + \pi^+ + \pi^-$
- $X(3872) \to J/\psi + \pi^+ + \pi^- \to \mu^+ + \mu^- + \pi^+ + \pi^-$
- $\Psi(2S) \to J/\psi + \pi^+ + \pi^- \to \mu^+ + \mu^- + \pi^+ + \pi^-$

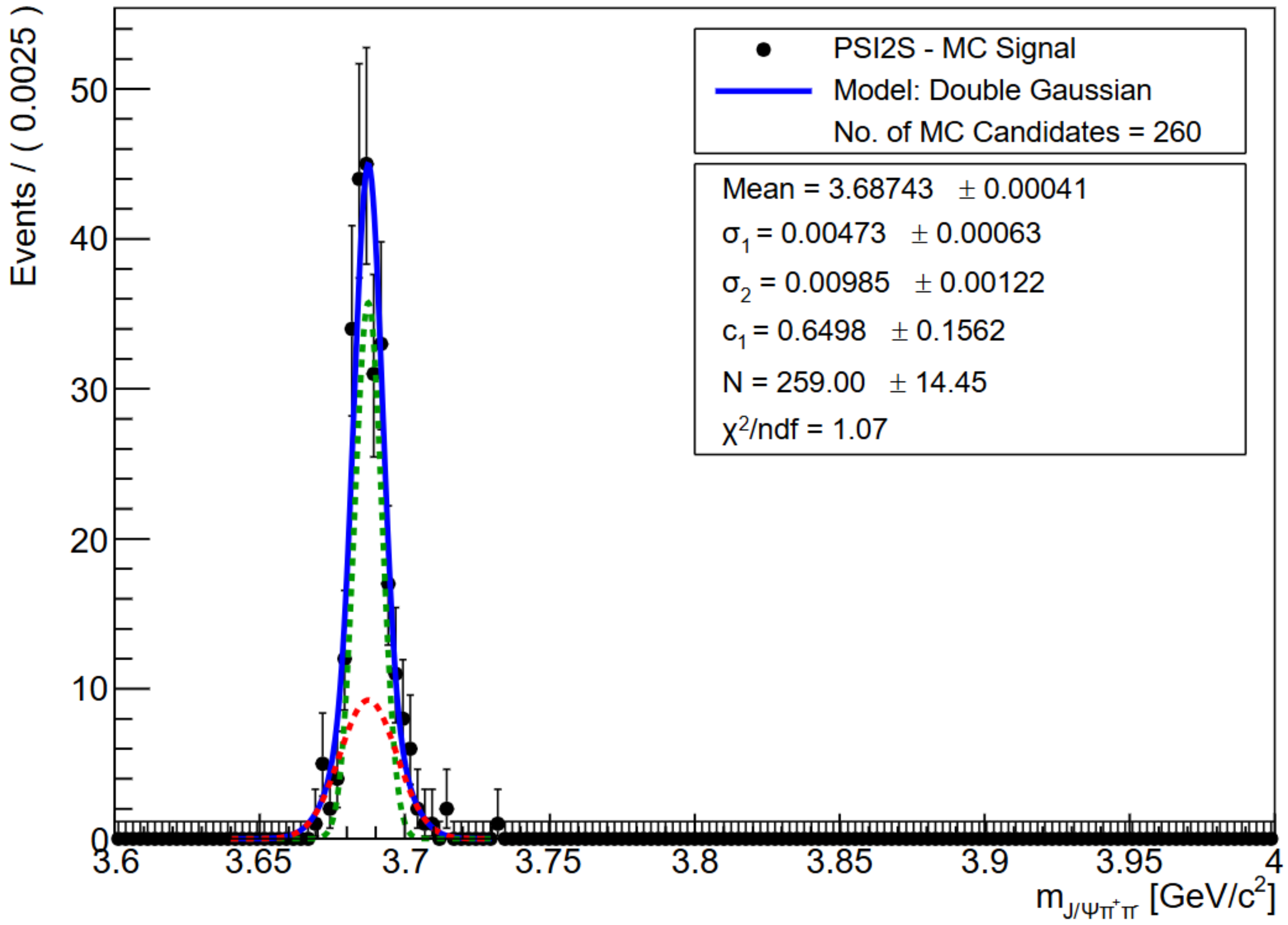


Mass Spectrum of Ψ(2S) and X(3872) before applying any preliminary cuts (pp collision)

Data & Simulation

- pp and PbPb data collected by CMS in LHC Run3
  - pp: 2024 (455/pb)
  - PbPb: 2023 (1.72/nb), 2024 (1.67/nb), 2025 (coming soon)
- Monte Carlo (MC) simulation
  - simulations done with detector conditions of each yearprocess the data
- Candidate reconstruction
  - select pairs of muons (mu+mu-) and pairs of tracks (pi+pi-) originatingfrom a common point
  - jobs submitted to the LHC grid (both to process the data and produceMC)

FITTING MONTE-CARLO SIGNAL [ψ(2S)]

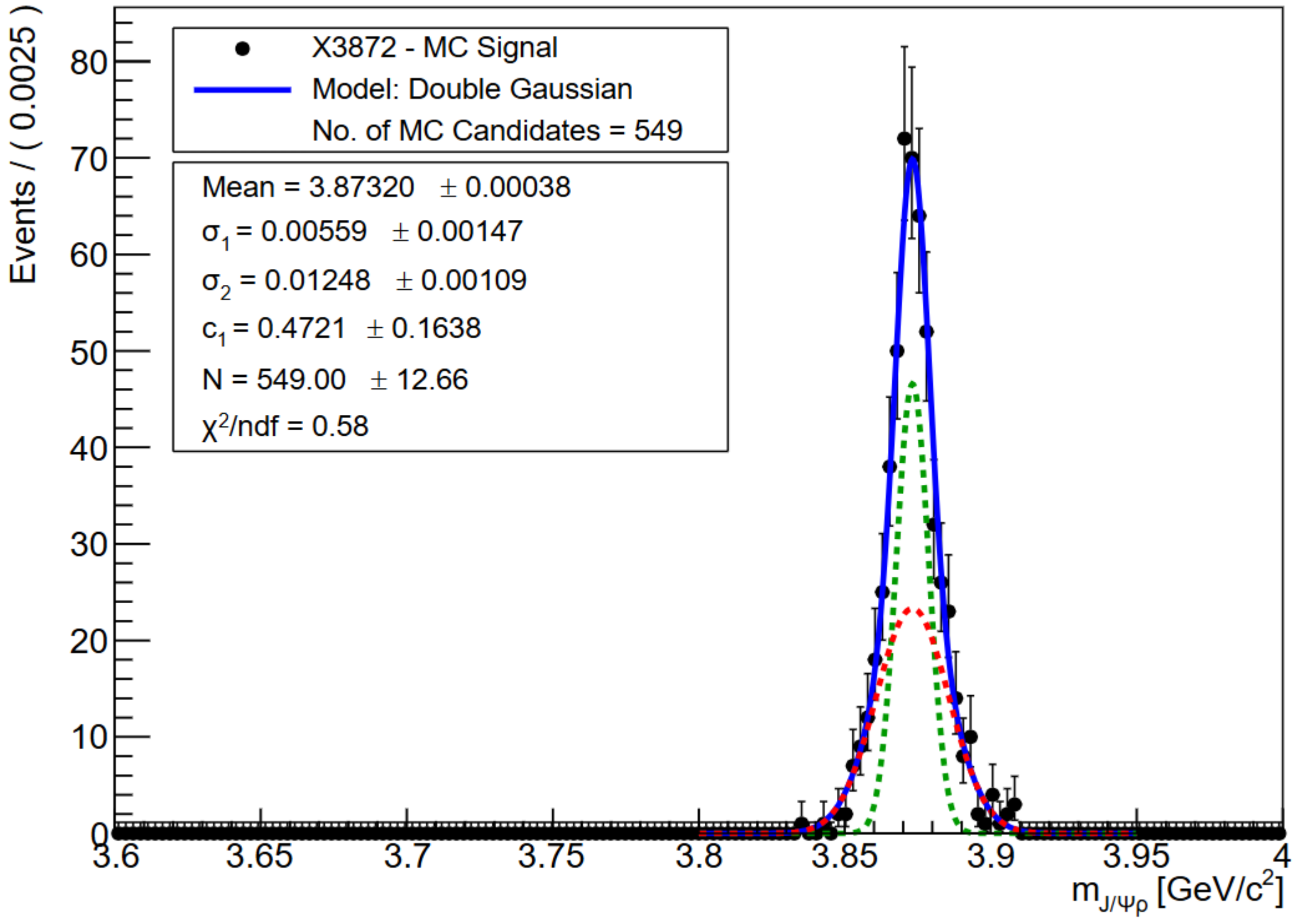


$$\mathscr{L} = N \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

- Define data noise region through sidebands.
- Using the 3σ from the wider gaussian to avoid cutting signal.

- Left sideband: [3.60000 ; 3.65788] GeV/c^2
- Right sideband: [3.71698 ; 4.00000] GeV/c^2

FITTING MONTE-CARLO SIGNAL [X(3872)]

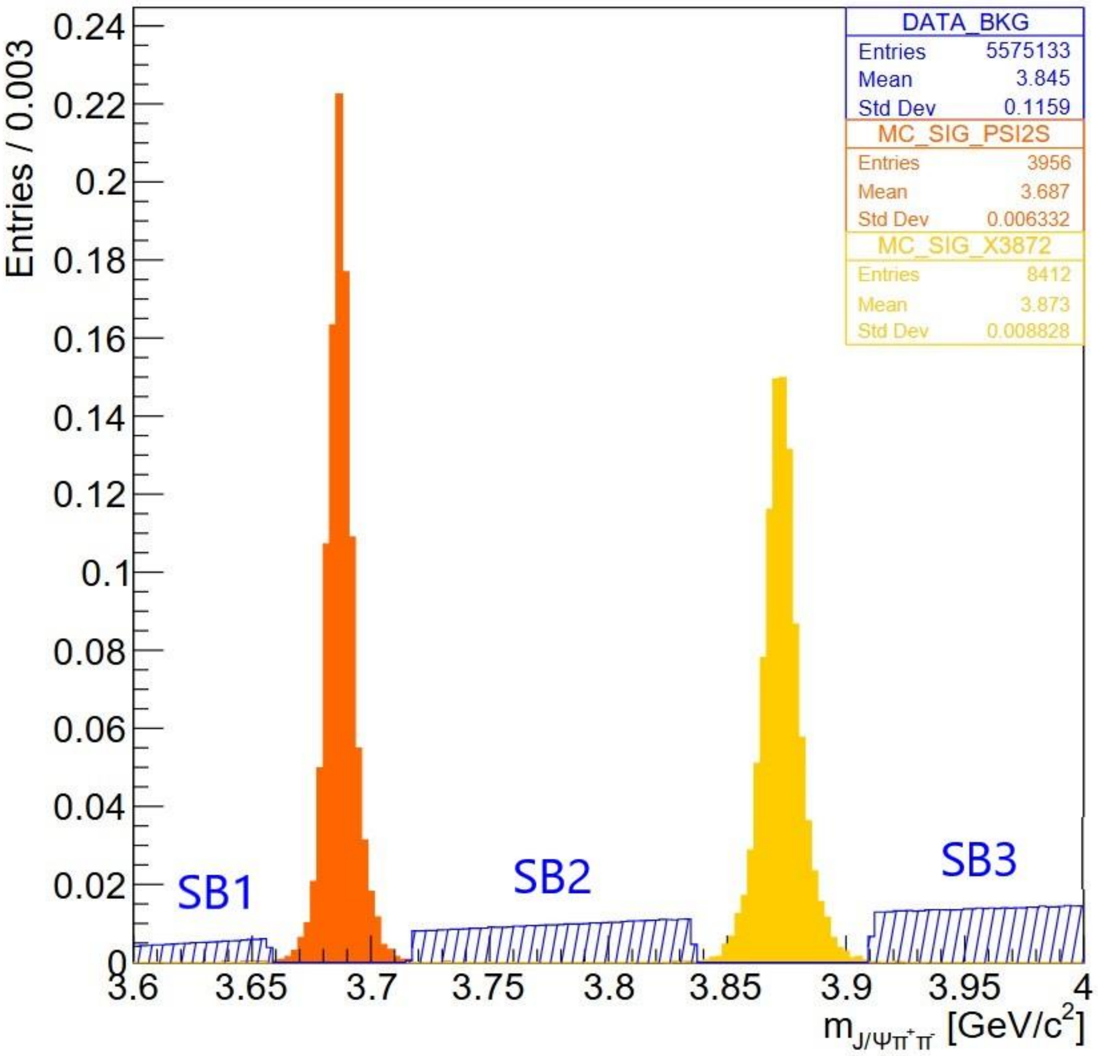


$$\mathscr{L} = N \cdot [c_1 \cdot G_1(\mu, \sigma_1) + (1 - c_1) \cdot G_2(\mu, \sigma_2)]$$

- Define data noise region through sidebands.
- Using the 3σ from the wider gaussian to avoid cutting signal.

- Left sideband: [3.60000 ; 3.83576] GeV/c^2
- Right sideband: [3.91064 ; 4.00000] GeV/c^2

DEFINING THE SIDEBANDS [X(3872) and ψ(2S)]



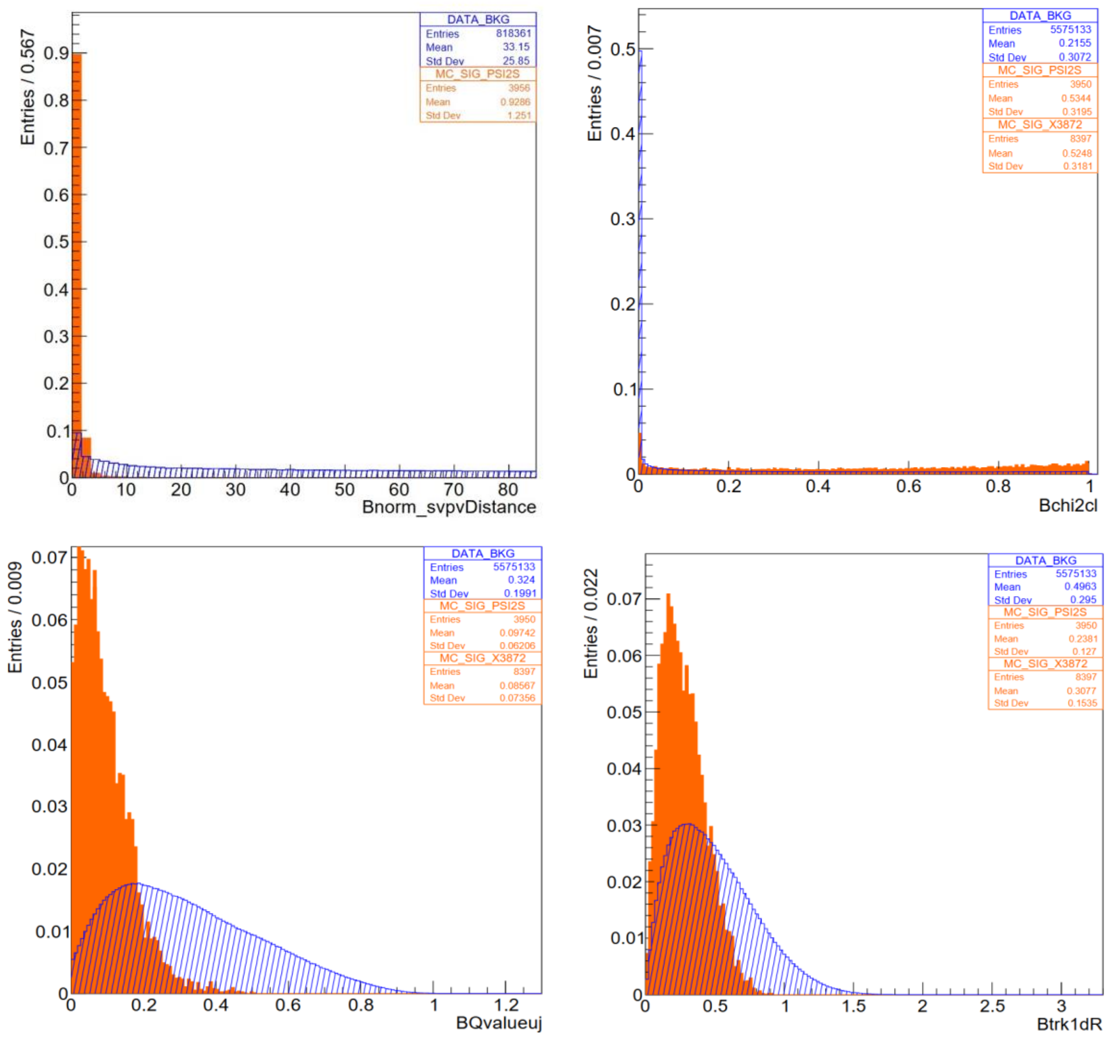
- Sideband 1 (SB1): [3.60000 ; 3.65788] GeV/c^2
- Sideband 2 (SB2): [3.71698 ; 3.83576] GeV/c^2
- Sideband 3 (SB3): [3.91064 ; 4.00000] GeV/c^2

Both X3872 and PSI2S are detected in the same sample, so we have 3 sidebands.

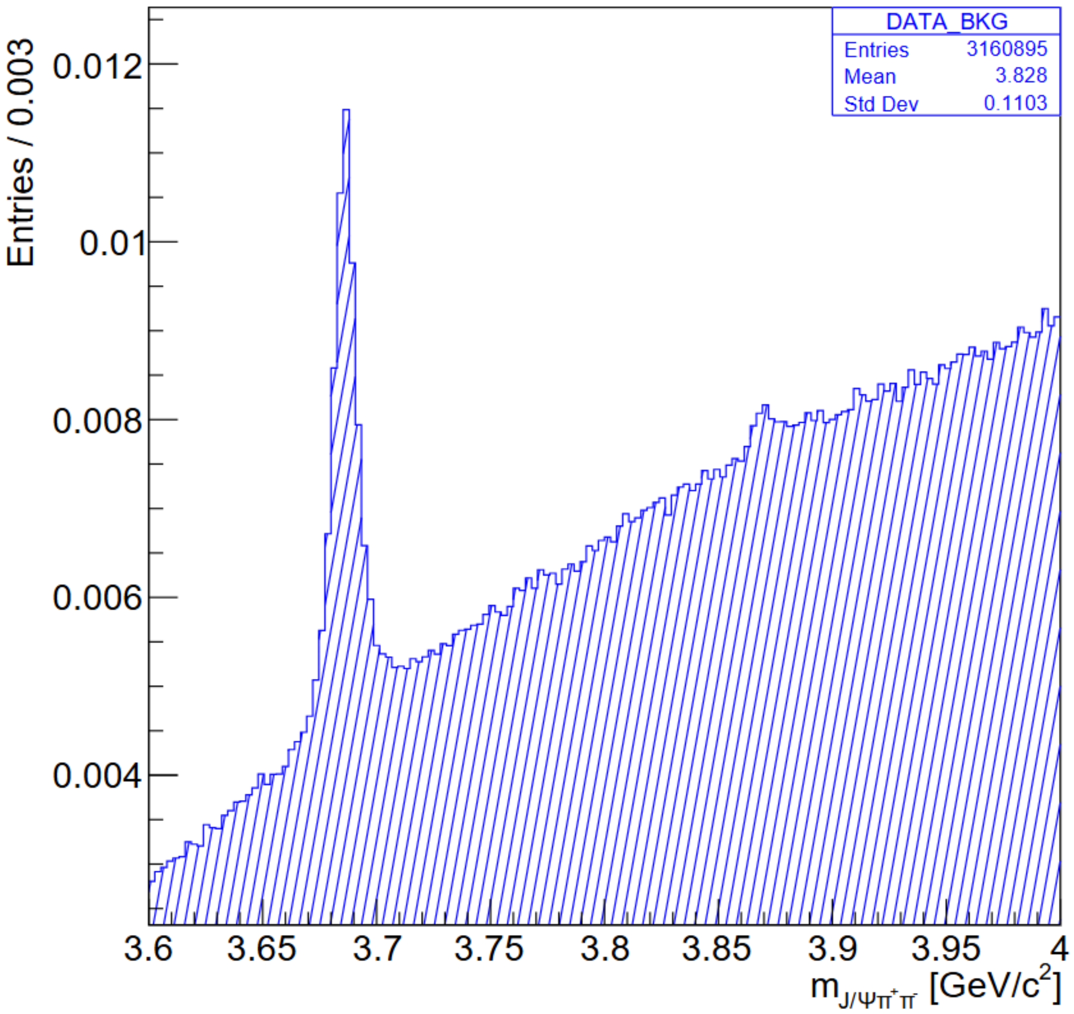
Since we are using a ± 3σ interval around the mean, more than 99% of the signal is inside the peaks, leaving sidebands as almost pure background noise.

FIRST CUT [X(3872) and ψ(2S)]

Discriminant variables

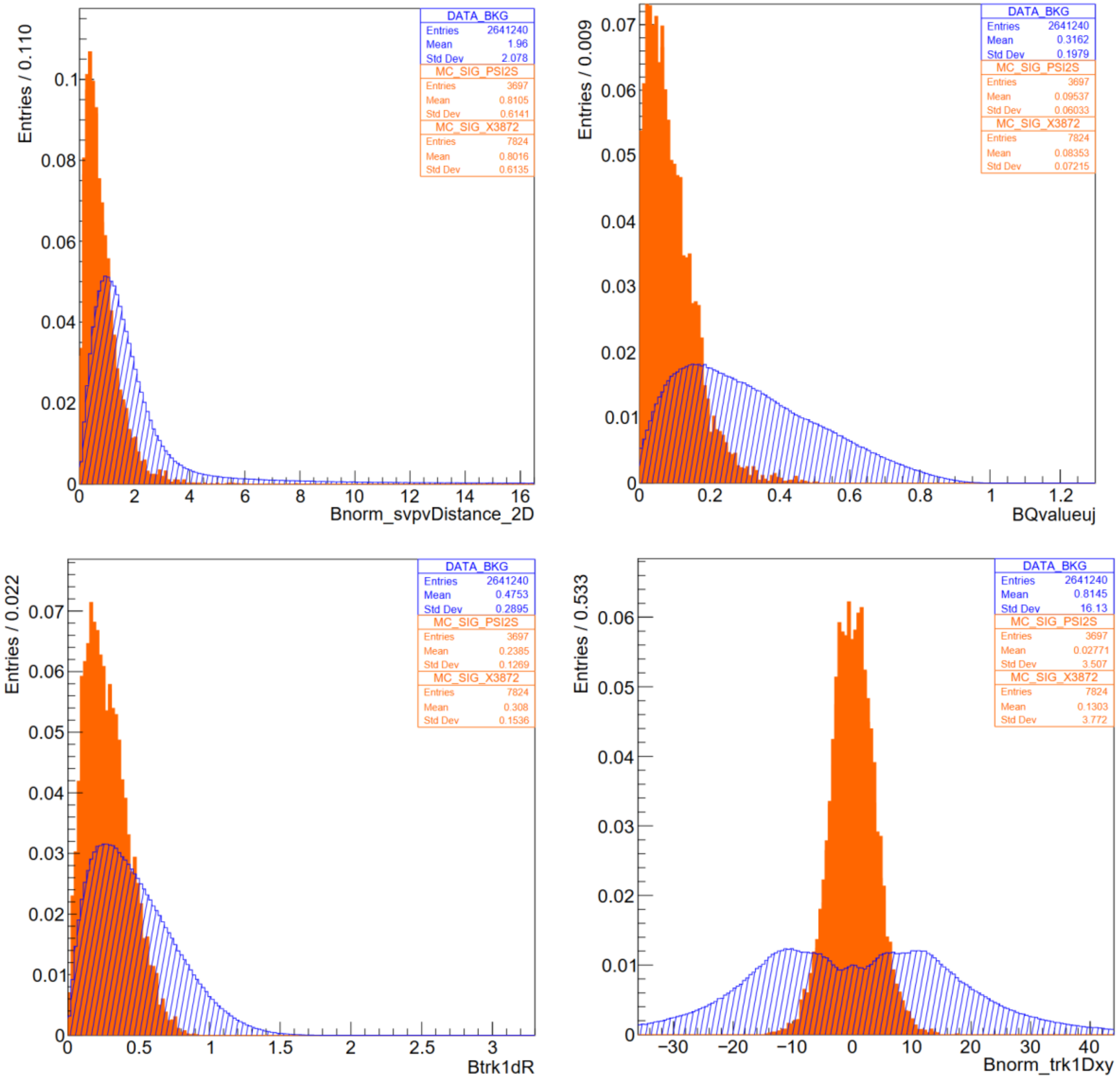


First cut: Bchi2cl>0.02

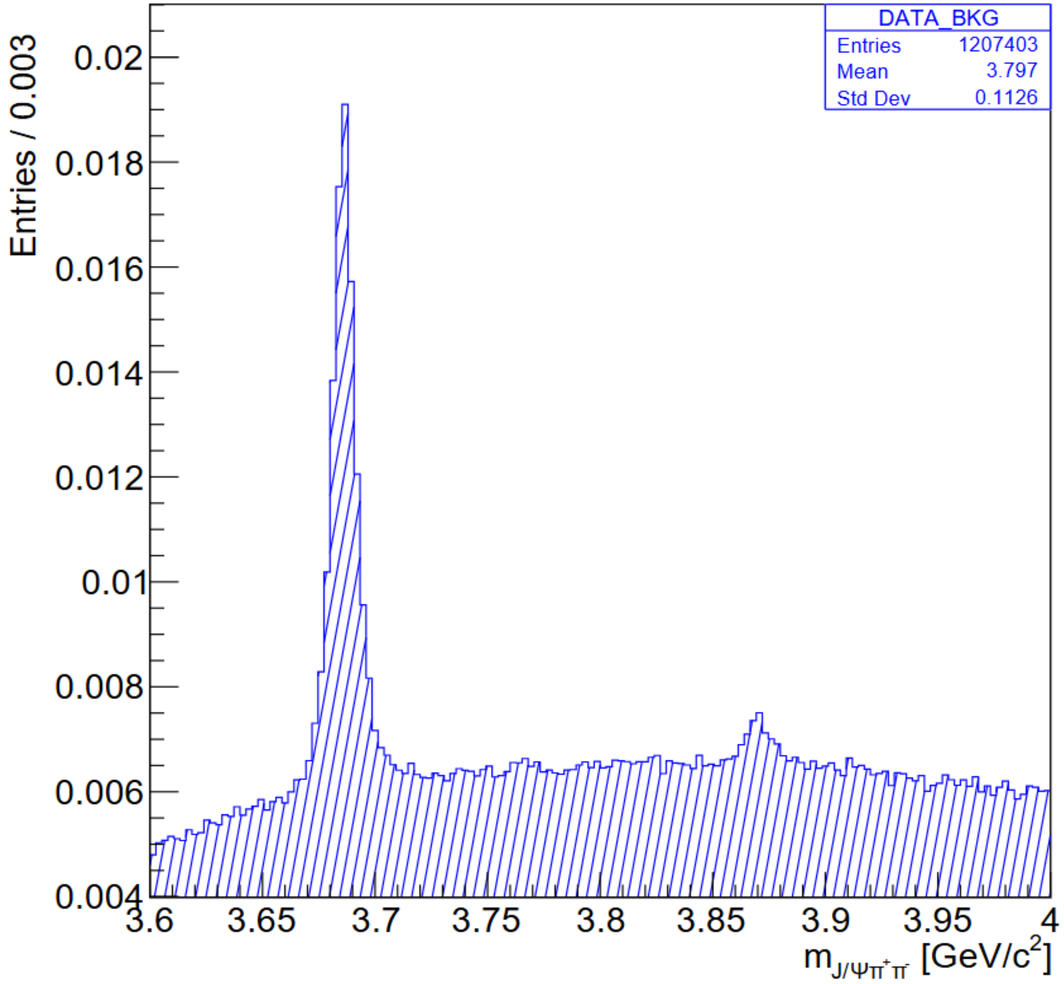


SECOND CUT [X(3872) and ψ(2S)]

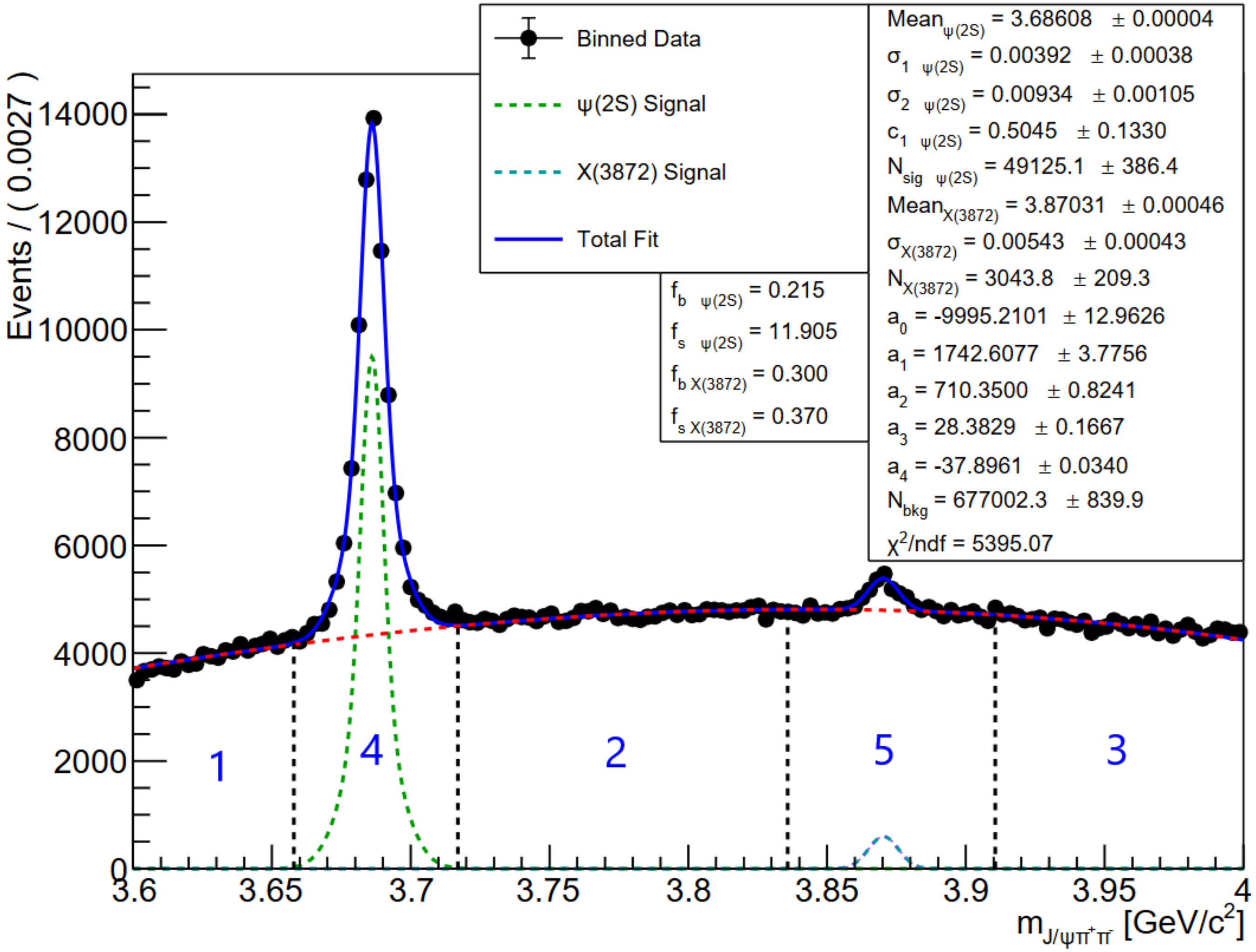
Discriminant variables



Second cut: BQvalueuj <0.2



FITTING THE DATA [X(3872) and ψ(2S)]



$$\mathscr{L}_{\psi(2S)} = N_{\psi(2S)} \cdot [c_{1\psi} \cdot G_1(\mu_\psi, \sigma_{1\psi}) + (1 - c_{1\psi}) \cdot G_2(\mu_\psi, \sigma_{2\psi})]$$

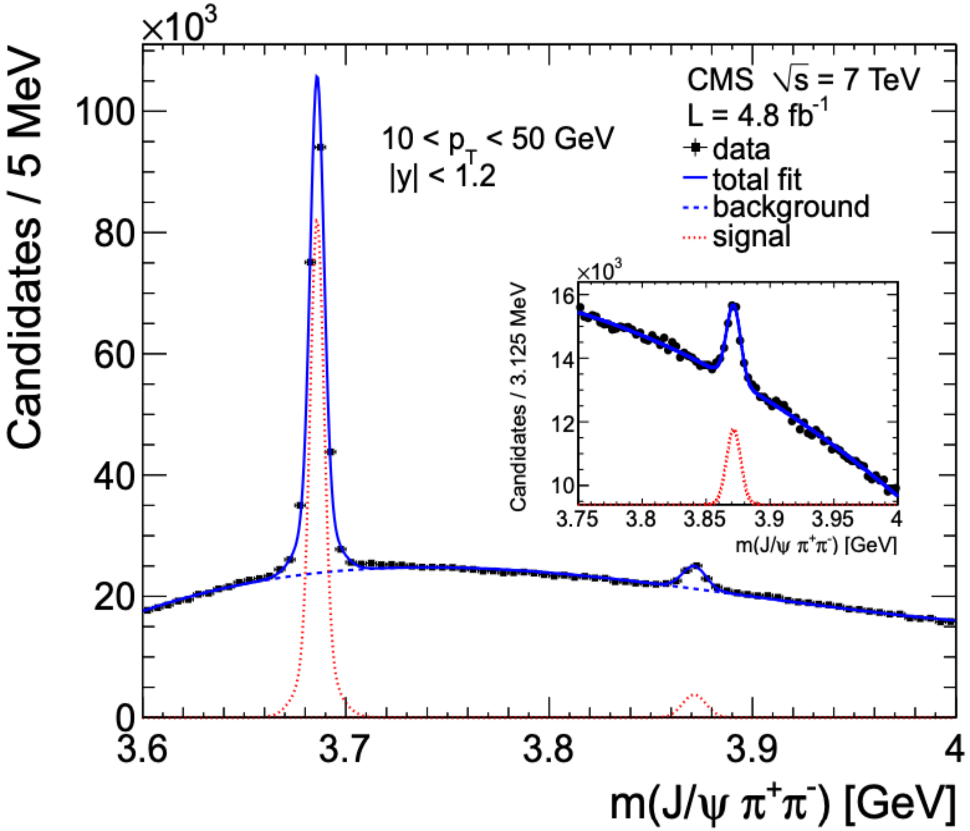
$$\mathscr{L}_{X(3872)} = N_{X(3872)} \cdot G(\mu_X, \sigma_X)$$

$$\mathscr{L}_{\text{bkg}} = N_{\text{bkg}} \cdot [a_0 + a_1 \cdot m + a_2 \cdot m^2 + a_3 \cdot m^3 + a_4 \cdot m^4]$$

$$f_{b,\,\psi(2S)} = \frac{\text{Bkg}_4}{\text{Bkg}_1 + \text{Bkg}_2 + \text{Bkg}_3} \qquad f_{b,\,X(3872)} = \frac{\text{Bkg}_5}{\text{Bkg}_1 + \text{Bkg}_2 + \text{Bkg}_3}$$

$$f_{s,\,\psi(2S)} = \frac{Sig_4}{Sig^{\text{MC}}_{\psi(2S)}} \qquad f_{s,\,X(3872)} = \frac{Sig_5}{Sig^{\text{MC}}_{X(3872)}}$$

Comparison of N(X(3872))/N(ψ(2S))



The J/ψπ+π− invariant-mass spectrum

- pp collisions at √s = 7 TeV (CMS RUN I)
  - N(X(3872)) = 11910 ± 490
  - N(ψ(2S)) = 178540 ± 850
  - N(ψ(2S))/N(X(3872)) = 0.0667 ± 0.0028
- pp collisions at √s = 5.36 TeV (CMS RUN III ppRef, **this research**)
  - N(X(3872)) = 3044 ± 209
  - N(ψ(2S)) = 49125 ± 386
  - N(ψ(2S))/N(X(3872)) = 0.0620 ± 0.0043

Summary

- conducted selection study for: X(3872), ψ(2S)
  - feature comparison signal (MC) vs background (sideband)
- single variable optimization, maximizing figure of merit (statistical significance)
- fits to both data and simulation

Next steps

- pp collision study (ongoing)
  - feature correlations
  - multivariable analysis (machine learning)
  - perform unbinned fits to the selected samples

- PbPb collision analysis (next)
  - Search for the signals X(3872) in the more challenging PbPb environment!