The rediscovery of Zc(3900) with QSVM

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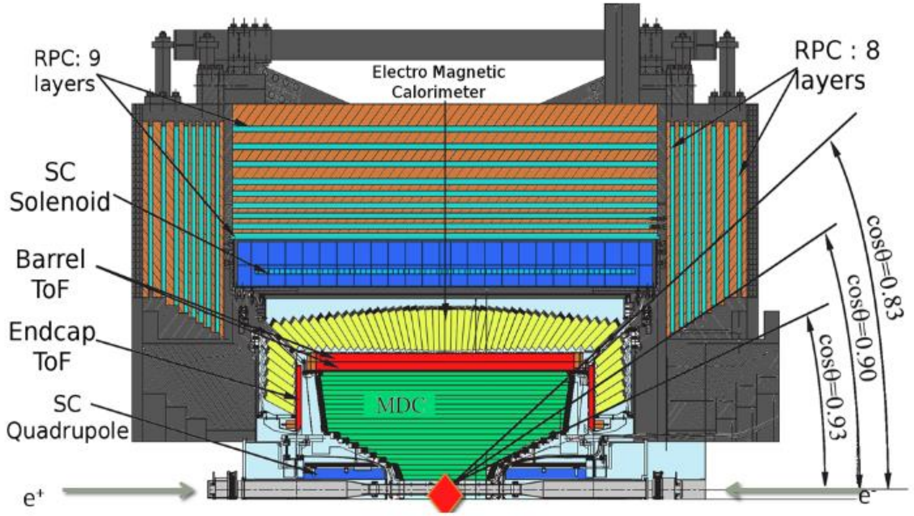
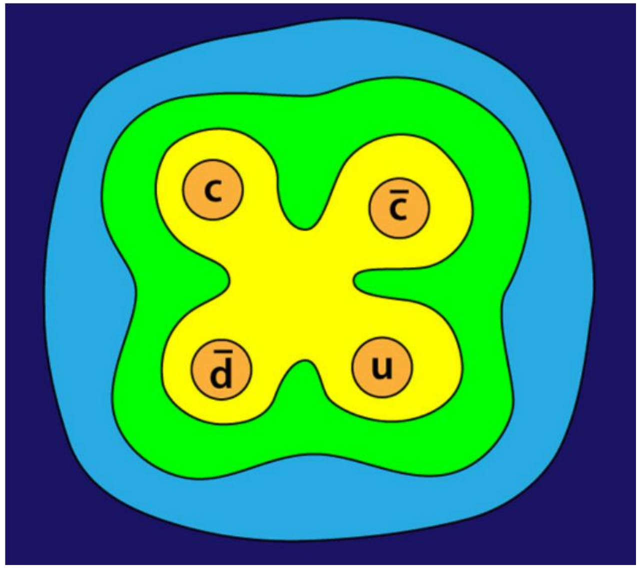
Outline

- Background Introduction
- QSVM/SVM Study
  - Dataset selection
  - Training and optimization
  - Results
- Summary and Outlook

Zc(3900) @ BESIII

- The BESIII experiment
  - BEPCII running at a cms of 2.0-5.0GeV
  - Sub-detectors: MDC, TOF, EMC, MUC
  - τ-charm physics
- The discovery of Zc(3900)
  - Initially discovered by BESIII at 2013
  - Possibly the first tetra-quark state observed in experiment
  - 美国物理学会《物理》2013年国际物理学领域十一项重要成果之首
  - 2013年度“中国科学十大进展”



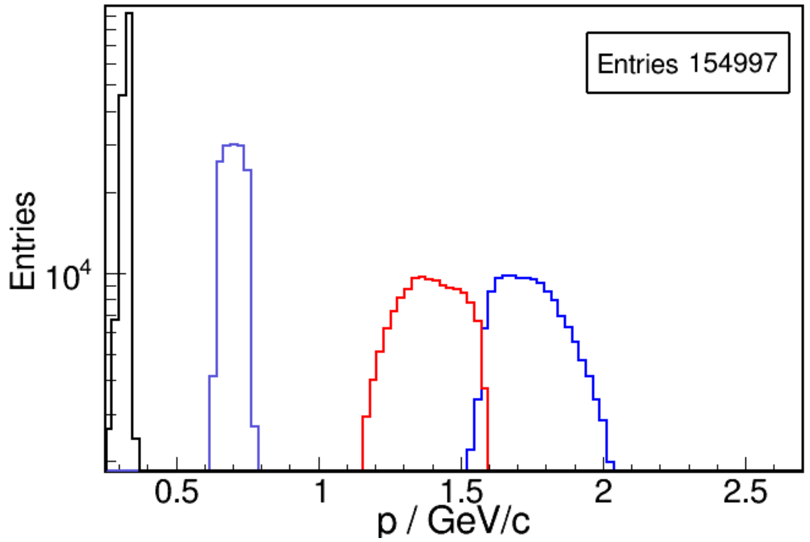


The Traditional Physics Analysis Method

- Initially observed via the following decay mode with 4.26GeV data

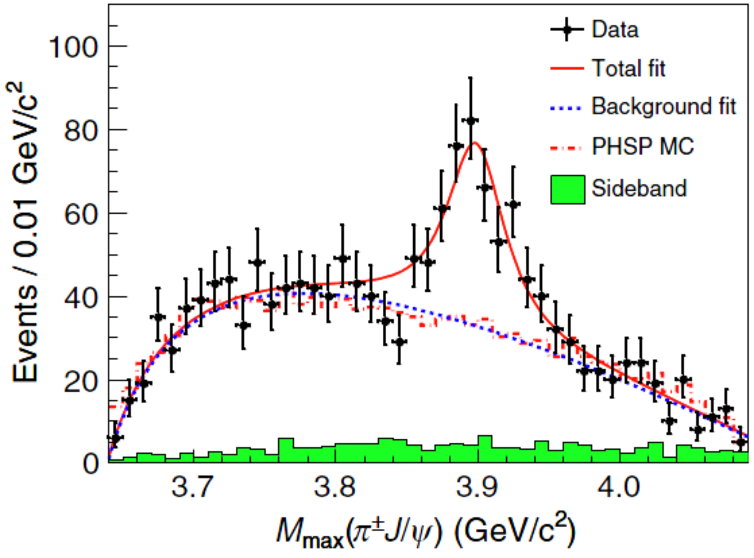
$$e^+e^- \rightarrow Zc(3900)\pi^\pm$$
$$Zc(3900) \rightarrow J/\psi\, \pi^\mp$$
$$J/\psi \rightarrow e^+e^- \quad or \quad J/\psi \rightarrow \mu^+\mu^-$$

- The final state consists of 4 charged tracks
  - The leptons and pions are separated clearly by the momentum
  - As shown in the picture (MC data)



Cut-based Event Selection

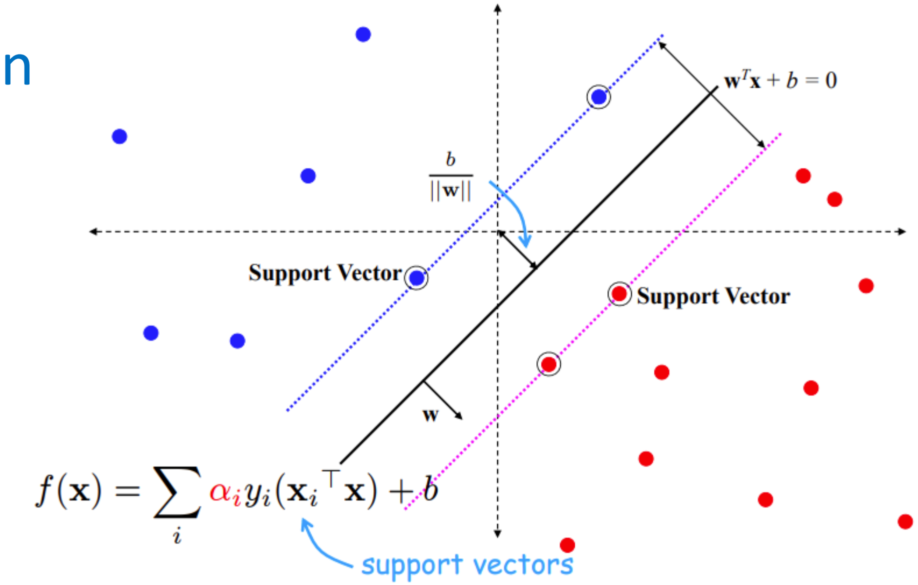
- 4 good charged tracks with netcharge = 0
  - Sorted in descending order by momentum
  - Track 1 and 2 are assumed to be the leptons
  - Momentums
    - The 2 leptons: p1 > 1.0GeV, p2 > 1.0GeV
    - The 2 pions: p3 < 1.0GeV, p4 < 1.0GeV
  - Energy deposition in EMC
    - ee mode: $E1_{emc}$>1.1GeV & $E2_{emc}$>0.8GeV, mumu mode: $E1_{emc}$<0.35GeV & $E2_{emc}$<0.35GeV
  - Angles between the tracks
    - For ee mode: $\cos(\theta_{e^+\pi^-}) < 0.98$ && $\cos(\theta_{e^-\pi^+}) < 0.98$ && $\cos(\theta_{\pi^+\pi^-}) < 0.98$
    - For mumu mode: $cos(\theta_{\pi^+\pi^-}) < 0.98$
- Kinematic fit chisq < 60
- 3.077 < InvariantMass(1, 2) < 3.117



Support Vector Machine (SVM & QSVM)

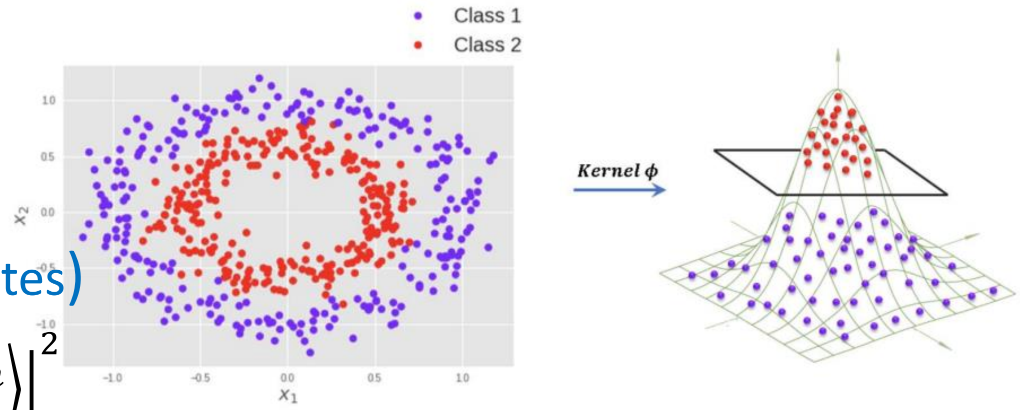
- Supervised machine learning for binary classification
- Find the optimal hyperplane that separates data points in the feature space

$$\frac{1}{2}||w||^2 \quad subject\ \ to\ \ y_i(w \cdot\ x_i + b) \geq 1\,, \ldots, m,$$

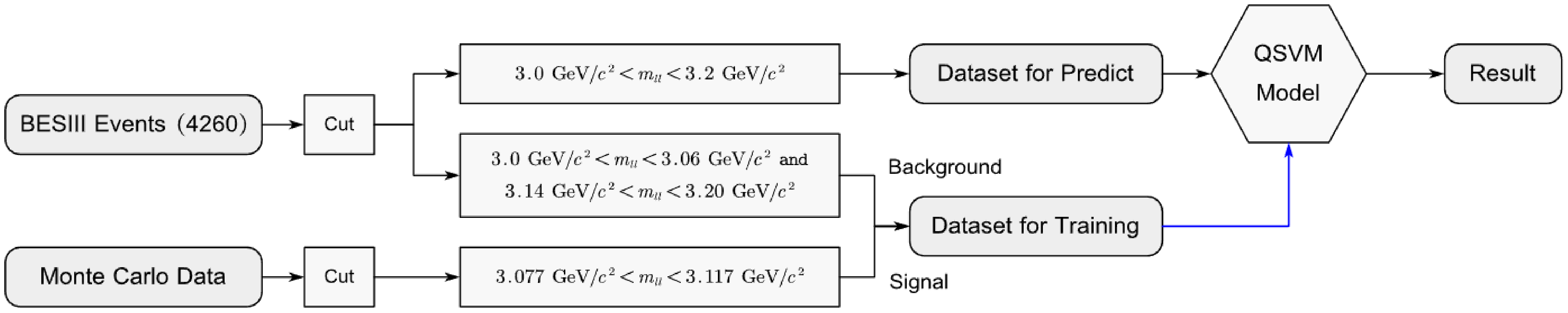


- Kernel method is used to map the original features to a higher dimentional feature space to separate non-linear data
- Traditional kernel
  - Linear kernel, polynomial kernel, Gaussian kernel
- Quantum kernel (the inner product of the quantum states)

$$K\left(\vec{x}_i, \vec{x}_j\right) = |\langle\Phi(\vec{x}_i)|\,\Phi(\vec{x}_j)\rangle|^2 = \left|\left\langle 0^{\otimes n}\left|\mathcal{U}^{\dagger}_{\Phi(\vec{x}_j)}\mathcal{U}_{\Phi(\vec{x}_i)}\right|0^{\otimes n}\right\rangle\right|^2$$



Event Classification with QSVM (and SVM)



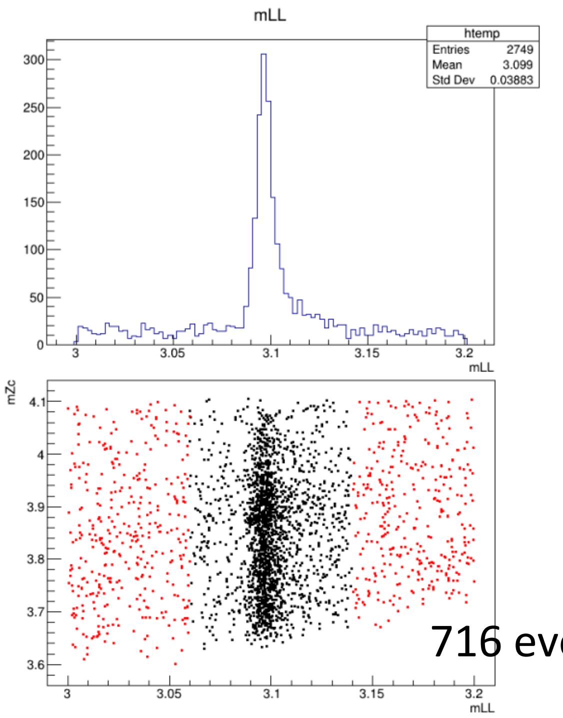
1. Event preselection
    - 4 good charged tracks with netcharge = 0 (the same as the traditional cut-based method)
    - Kinematic fit chisq < 200
    - 3.0 < InvariantMass(1, 2) < 3.2
2. Training dataset selection
3. QSVM/SVM model training and optimization
4. Apply the trained model to the real data
    - The events after event preselection and $m_{j/psi}$ cut

Traditional Computing
+
Quantum Machine Learning

Dataset Selection

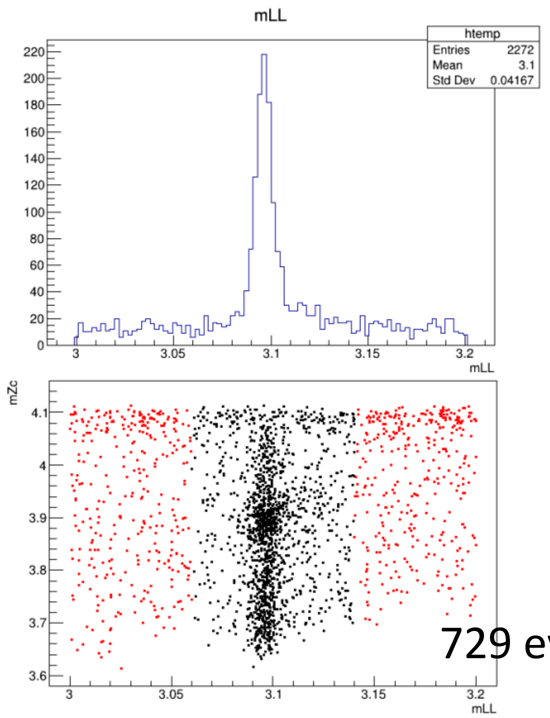
- Background dataset
  - The background can not be well described by the inclusive MC data
  - The background dataset is selected from the real data that after event preselection
  - Limit $m_{J/psi}$ in the range of (3.0, 3.06) and (3.14, 3.20) GeV

mumu



716 events

ee



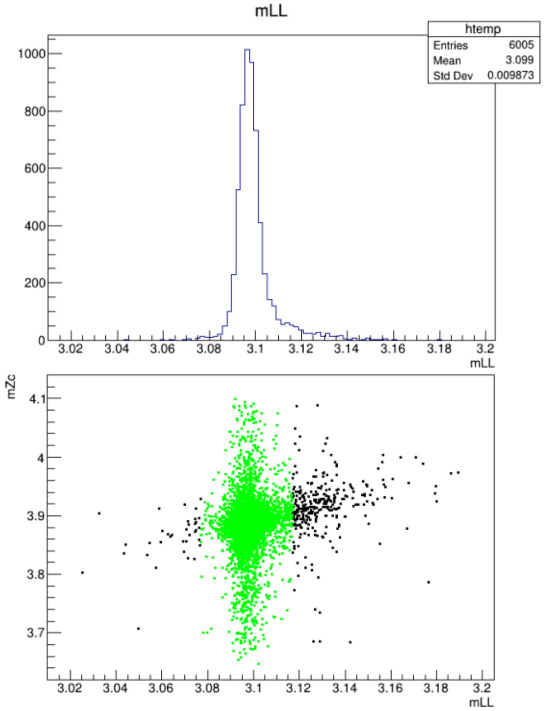
729 events

Dataset Selection

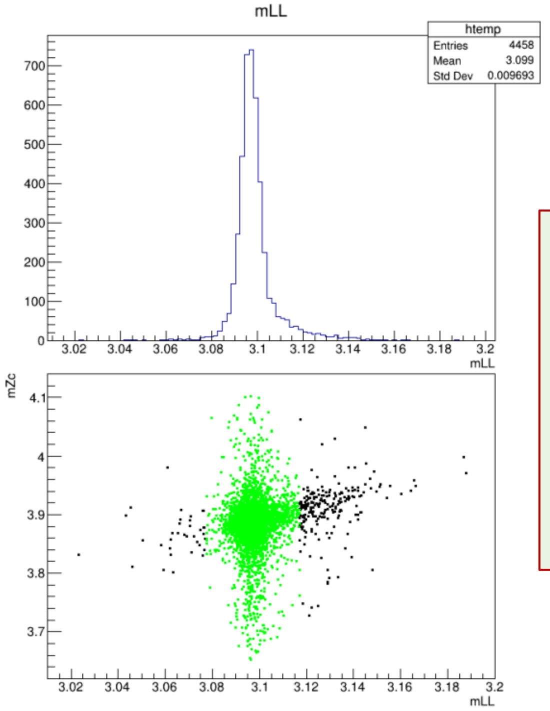
- Signal dataset
  - Zc(3900) MC data after event preselection
  - And no Zc(3900) MC data (PHSP) after event preselection
  - Limit $m_{J/psi}$ in the range of (3.077, 3.117) GeV

$$e^+e^- \to J/\psi\pi^+\pi^-$$

mumu



ee



Zc(3900) and no Zc(3900) events are mixed 1:1

Signal and background events are mixed 1:1

Randomly select 700 + 700 for each mode

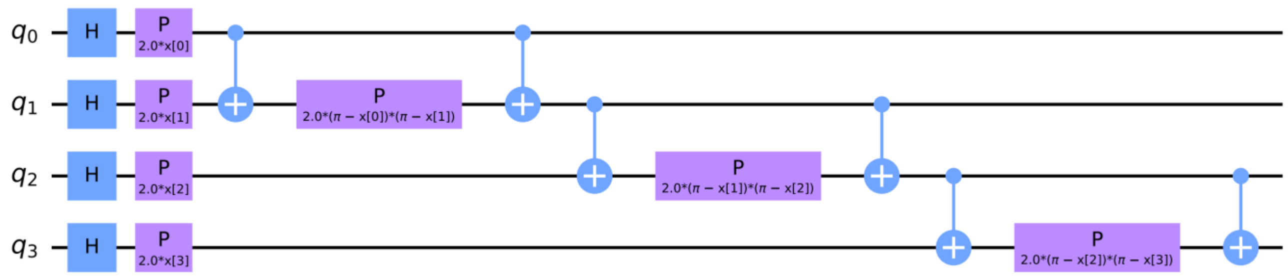
50% training dataset + 50% testing dataset

Data Features and Encoding

- Totally 28 data features are considered to classify the signal and background events

P, P_x, P_y, P_z of the 4 final particles
E_{emc} of the 4 final particles
$\theta_{12}, \theta_{13}, \theta_{14}, \theta_{23}, \theta_{24}, \theta_{34}$
N_γ, E_γ

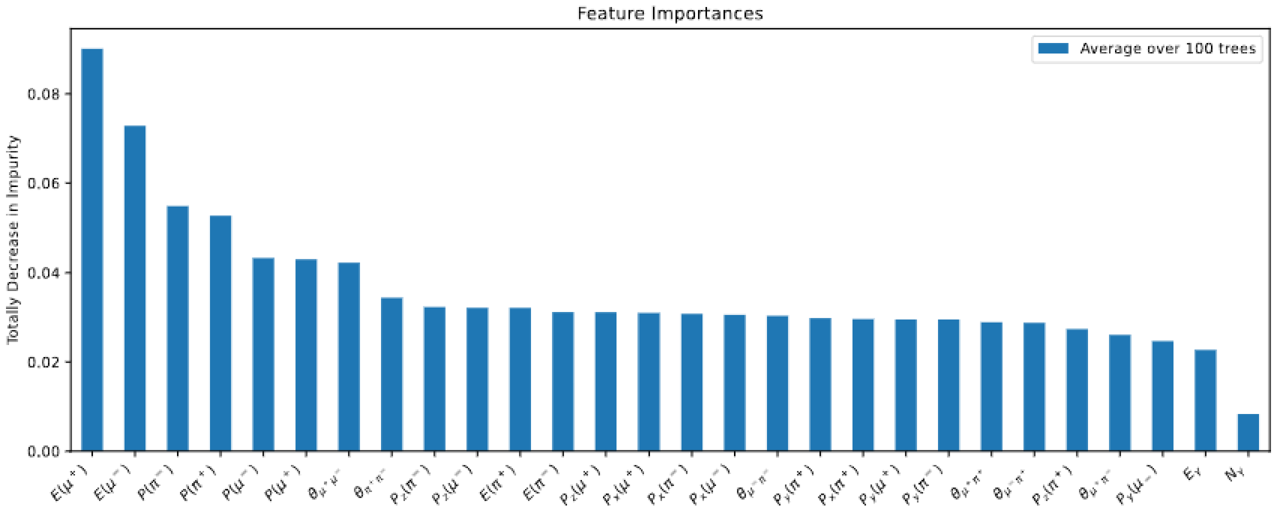
- The embedded ZZFeatureMap in Qiskit is used for data encoding



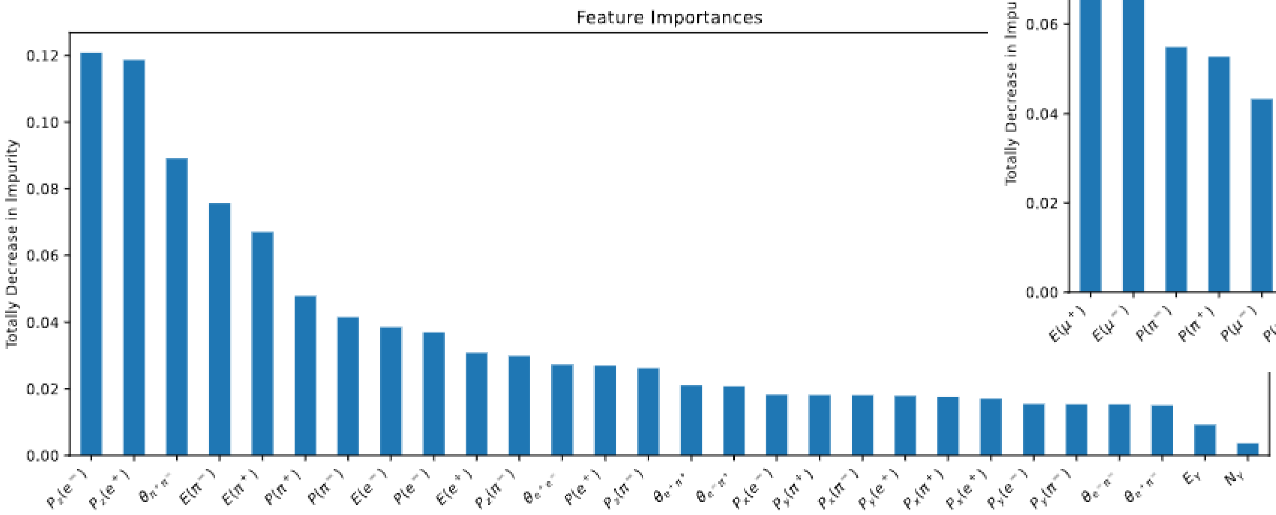
An example of a 4 qubits ZZFeatureMap quantum circuit

Feature Ranking

- Optimize the feature set to get the best result
  - Start with the most discriminative features and gradually expand the feature set
- The ee and μμ modes are processed separately



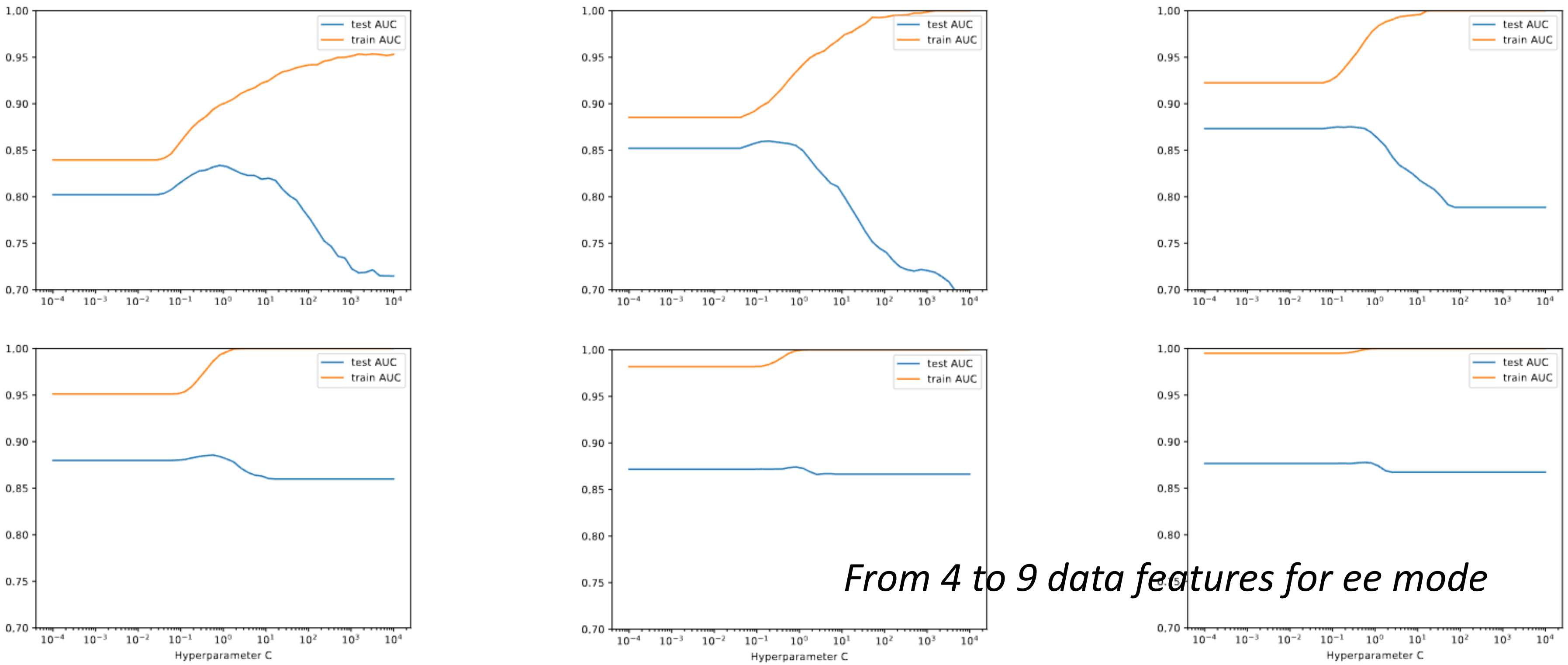
The ranking results for μμ mode



The ranking results for ee mode

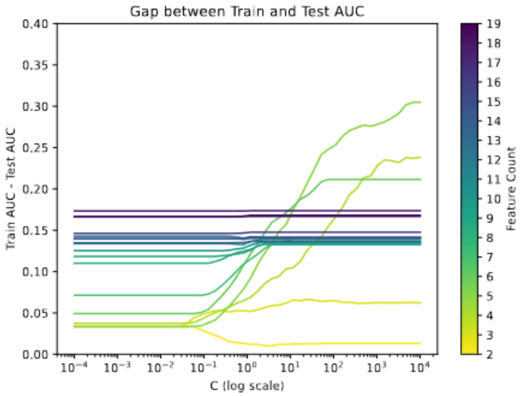
QSVM Training Optimization

- Takes AUC as the main metric, with no obvious overfitting
  - Feature set selection (more features often lead to more severe overfitting)
  - Feature value normalization (0, π)
  - Tuning of the hyperparameter C

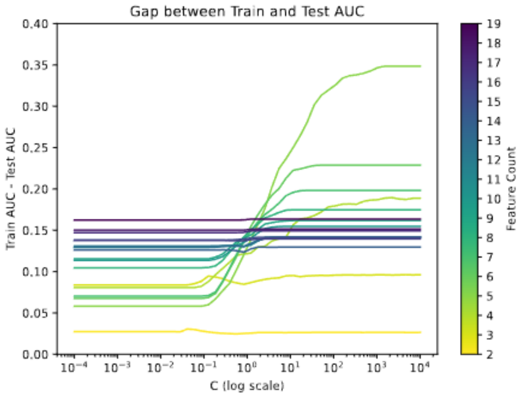


From 4 to 9 data features for ee mode

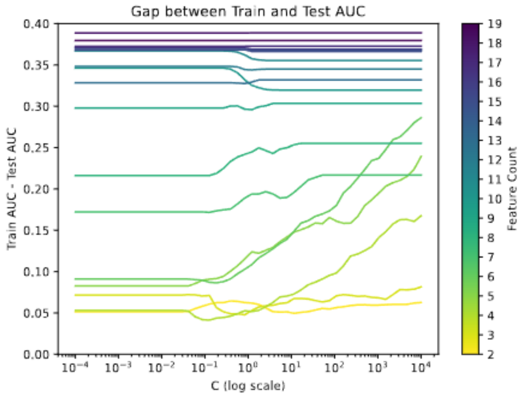
QSVM Training Optimization



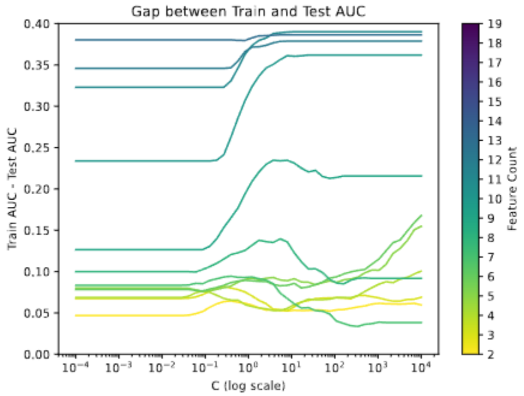
ee with normalizaiton



ee without normalizaiton



μμ with normalizaiton



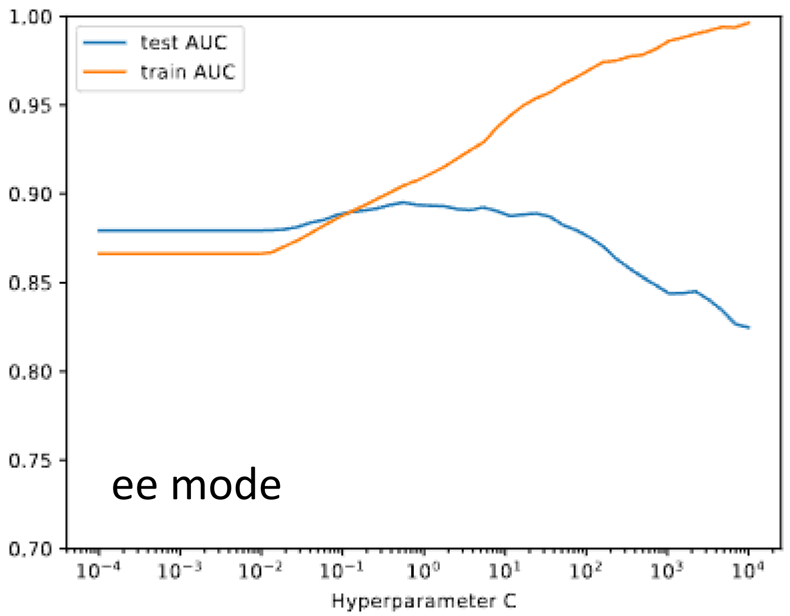
μμ without normalizaiton

The final criteria

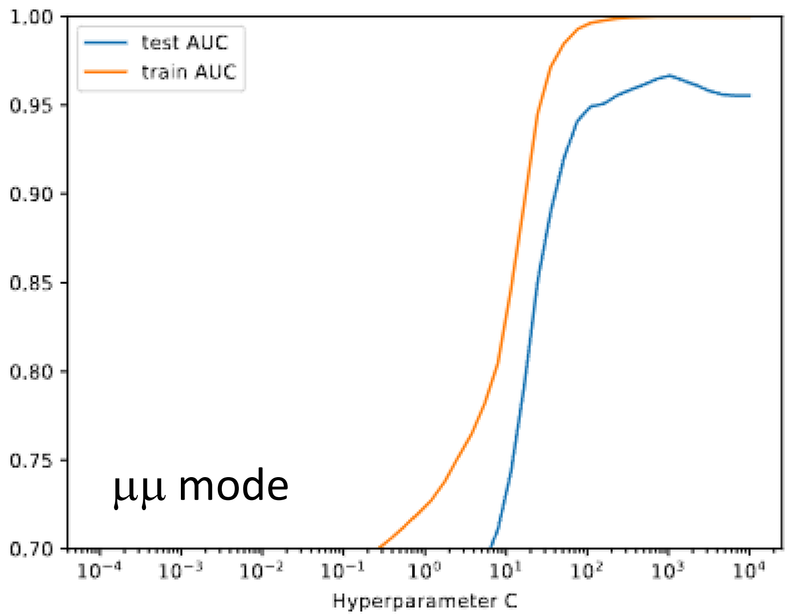
衰变道	选取特征	超参数 C
ee	$P_z(e^-), P_z(e^+), \theta_{\pi^+\pi^-}, E(\pi^-), E(\pi^+), P(\pi^+)$	2.683×10^{-1}
$\mu\mu$	$E(\mu^+), E(\mu^-), P(\pi^-), P(\pi^+), P(\mu^-), P(\mu^+), \theta_{\mu^+\mu^-}$	3.393×10^{2}

Classical SVM Optimization

- Use the same features as QSVM
- Feature values are normalized to (0, π)



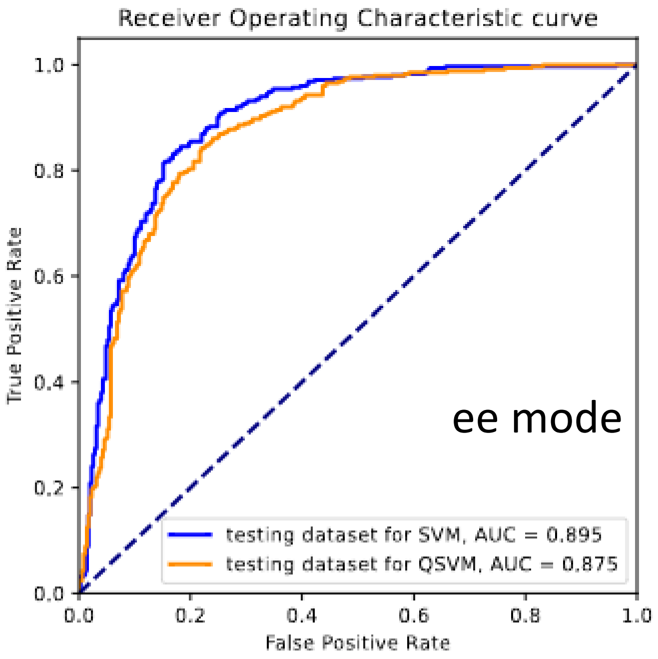
C = 5.690 × 10^{-1}

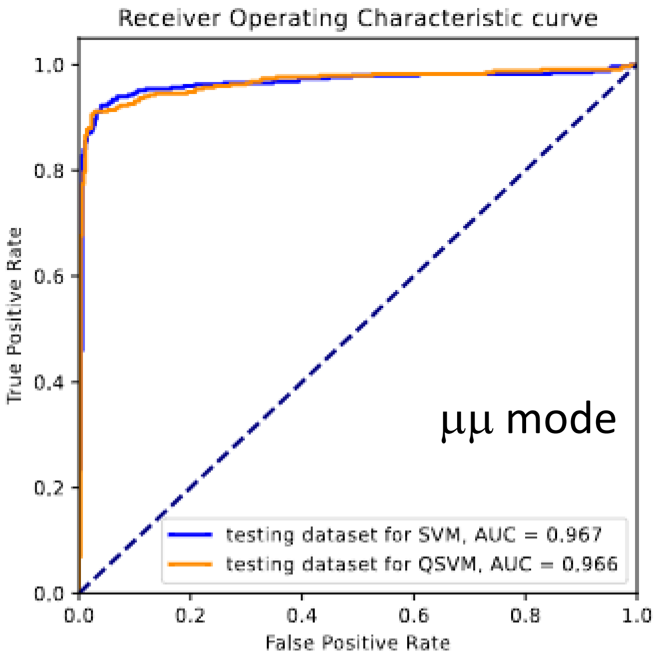


C = 1.048 × 10^{3}

The Performance of QSVM and SVM

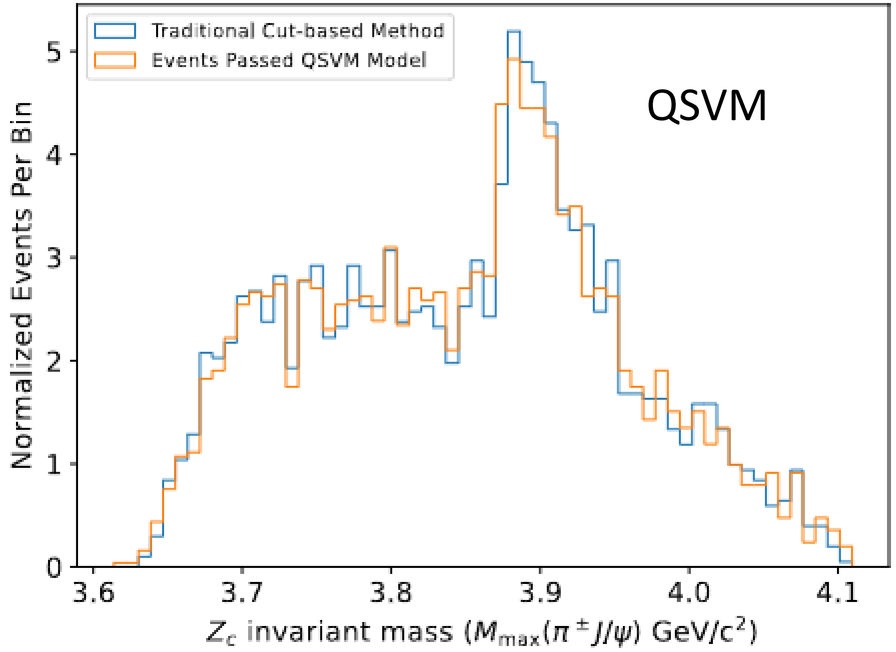
- The ROC of the optimized QSVM and SVM models

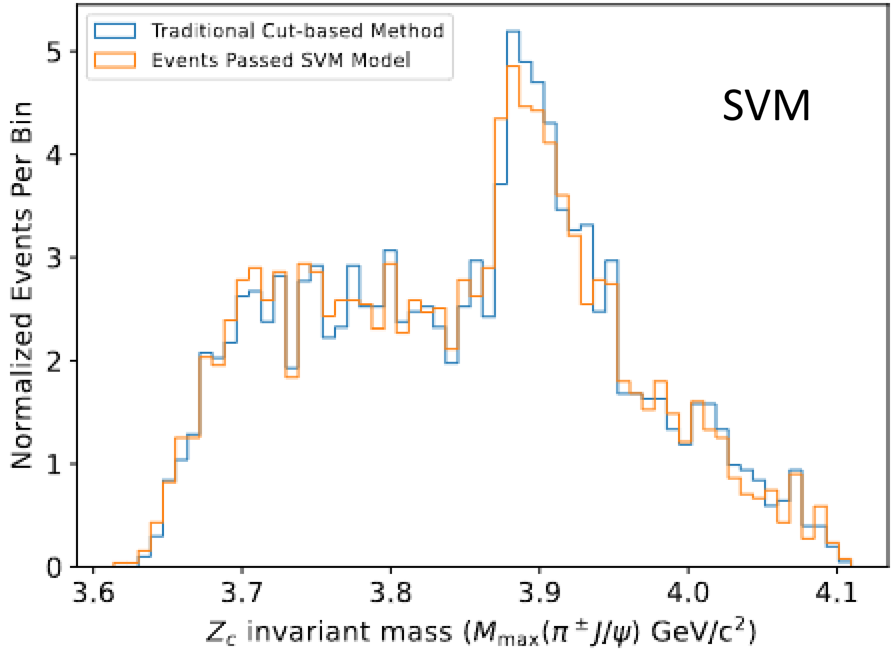




An Informal Result

- The $M_{max}(\pi^{+-}J/\psi)$ distribution
  - Compare with the traditional result
  - The number of events is normalized to enable comparison of the differences in distributions
    - The QSVM/SVM method actually obtains more events since the dataset used is different to the traditional method





Summary and Outlook

- The performance comparison
  - In this study, the performance of QSVM is very close to that of the classical SVM
  - The results of the QSVM/SVM method are also very close to those of the traditional method
- Try on the real quantum equipment
  - 国盾量子
  - 正在协调和研究解决的问题
    - Qiskit量子门的转换
    - 可用机时
    - 保真度对结果的影响

Thanks!