Deciphering the (3872) via its polarization in prompt production at the CERN LHC

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Phys.Rev.Lett. 123,032001,

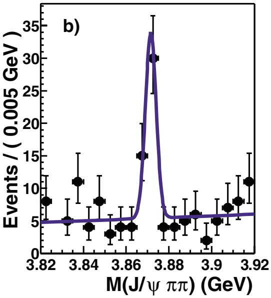
XVIII International Conference on Hadron Spectroscopy and Structure
August 16-21 2019, Guilin, China

Outline

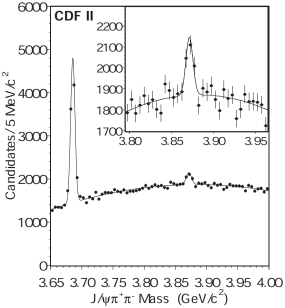
1. Background
2. The polarization of $X(3872)$
3. Summary

The discovery of $X(3872)$

- In 2003, $X(3872)$, which is the first exotic state, was discovered by Belle Collaboriation in the final states of $J/\psi + \pi\pi$ through B meson decay. Soon afterward, it was confirmed by CDF Collaboration.



Belle 2003



CDF 2004

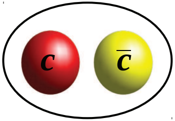
- After 10 years, it is quantum number J^{PC} is established to be 1^{++}. (LHCb 2013)

The discovery of $X(3872)$

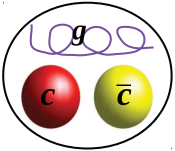
- Since then dozens of exotic states, named as X, Y, Z, have been discovered at hadron and e^+e^- colliders in both $c\bar{c}$ and $b\bar{b}$ sectors.
- Theoretically, more than one thousand papers have devoted to understand their natures or explain their properties.
- These make hadron spectrum and structure become the center stage of high energy physics once more.
- However, 16 years later, for the very first state-$X(3872)$, its nature is still mysterious.
- Now, to lift the veil of $X(3872)$, people perform the investigation mainly from the aspects of its spectrum, decay modes and production mechanism with different hypothsis.

The Content of $X(3872)$ I

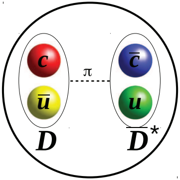
- On the market, the models that still stay firm are:



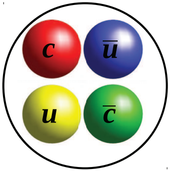
charmonium



hyperid



Molecule

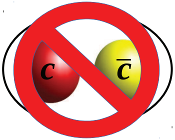


four quark

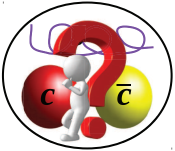
Or, maybe it is a mixture of all the options above.

The Content of $X(3872)$ II

- After we analzed $X(3872)$ prompt production data, we conclude that the $\chi_{c1}(2P)$ component can not be dominant inside $X(3872)$. (Butenschoen et al. 2013)



charmonium



hyperid

Molecule

four quark

$X(3872)$ hadroproduction in molecule picture

- It was first found that in molecule picture the cross section of $X(3872)$ prompt production is one order of magnitute less than CDF measurement.(Bignamini et al. 2009)
- Later, it was pointed out that after including the rescattering mechanism, the cross section of $X(3872)$ in molecule model can be compatible with its hadroproduction data. (Albaladejo et al. 2017)
- Now whether the molecule picture can describe $X(3872)$ hadropoduction results is still under debate.
- To solve the puzzle, a new production channel, namely $X(3872) + \pi^{\pm}$, is suggested to measure at hadron collider. (Braaten et al. 2018)

Why study the polarization of $X(3872)$?

- $X(3872)$ is a spin 1, axial vector state.
- Similar to J/ψ case, the polarization parameters in prompt production may be very sensitive to its production mechansim and its internal structure.
- What's more, if the decay of $X(3872) \to J/\psi\pi^+\pi^-$ preserves heavy quark spin symmtry. The polarization of J/ψ from $X(3872)$ decay can tell us the important information of $c\bar{c}$ pair inside $X(3872)$.
- Our hypothsis is that the prompt production of $X(3872)$ is via its $\chi_{c1}(2P)$ component, although such component is not majority inside $X(3872)$.
- We implement NRQCD factorization formalism to calculate its polarization.

NRQCD Factorization formalism

NRQCD factorization formula for the spin density matrix:

$$d\sigma_{ij}(AB \to X(3872) + \mathrm{anything}) = \sum_{k,l,n} \int dxdy f_{k/A}(x)$$

$$f_{l/B}(y)\, d\hat{\sigma}_{ij}(kl \to c\bar{c}[n] + \mathrm{anything}) \times \langle \overline{\mathcal{O}}^{X(3872)}[n] \rangle,$$

- $f_{k/A}(x)$ –parton distribution function.
- $d\hat{\sigma}_{ij}(kl \to c\bar{c}[n] + \mathrm{anything})$–short distance coefficient
- $\langle \overline{\mathcal{O}}^{X(3872)}[n] \rangle = \langle \mathcal{O}^{\chi_{c1}(2P)}[n] \rangle |\langle \chi_{c1}(2P)|X(3872)\rangle|^2$.
- At v^2 LO, only the Fock states n=${}^3S_1^{[8]}$ and n=${}^3P_1^{[1]}$ are involved in.

The short distant coefficients are calculated at QCD NLO. The non-perturbative parts $\langle \overline{\mathcal{O}}^{X(3872)}[n] \rangle$ are fit to $X(3872)$ yield data.

The prediction power of NRQCD factorization

The difference between *S*-wave and *P*-wave results at QCD NLO:

1. At QCD NLO, all the leading power contribution, which behaves as $1/p_T^4$, shows up for χ_{cJ}. However, for J/ψ an important integredient from CS channel is still missing.
2. The ${}^3P_J^{[8]}$ channel, which contribute to J/ψ but not to χ_c prodution, is sensitive to the NNLO corrections.
3. When $p_T^{J/\psi} > 7$ GeV, the disagreement between NRQCD predictions and experimental measurements is reduced to a tolerable level.

The failure of NRQCD prediction to J/ψ polariztion will not influence on the prediction power for *P*-wave case.

How to measure the polarization of $X(3872)$?

- For J/ψ, its polarization is measured through the angular distribution of l^+ in $J/\psi \to l^+ l^-$ as:

$$W_\psi(\theta) \propto 1 + \lambda_\theta^\psi \cos^2\theta, \quad \text{where } \lambda_\theta^\psi = \frac{\sigma_{11}^\psi - \sigma_{00}^\psi}{\sigma_{11}^\psi + \sigma_{00}^\psi}$$

- Similarly, the polarization of $X(3872)$ can also be measured through the angular distribution of its decay products, for instance that of J/ψ in the $X(3872) \to J/\psi + \pi^+\pi^-$ decay channel.
- Note that because it is a different decay mode, we should first derive out the relation between λ_θ^X and the spin density matrix, σ_{11}^X and σ_{00}^X.

$X(3872)$ polarization parameter I:

- It is observed by CMS and ATLAS Collaboration that the $\pi^+\pi^-$ originate from ρ meson decay predominately.
- Therefore the decay amplitude for $X(3872) \to J/\psi\pi^+\pi^-$ can be expressed as following in good approximation:

$$\mathcal{M}(X(3872) \to J/\psi + \pi^+\pi^-) = \mathcal{A}_\mu(X(3872) \to J/\psi\rho) \times \\ (-g^{\mu\nu} + p_\rho^\mu p_\rho^\nu/m_\rho^2)\mathrm{BW}_\rho(p_\rho^2)\mathcal{A}_\nu(\rho \to \pi^+\pi^-)$$

  - $\mathrm{BW}_\rho(p_\rho^2)$– The propagator of ρ meson in Breit-Wigner form.
  - $\mathcal{A}^\nu(\rho \to \pi^+\pi^-) = f_{\rho\pi\pi}(p_{\pi^+}^\nu - p_{\pi^-}^\nu)$.

$X(3872)$ polarization parameter II:

- Due to J^{PC} conservation, generally, $\mathcal{A}_\mu(X(3872) \to J/\psi\rho)$ is a linear combination of 2 independent Lorentz invariant forms:

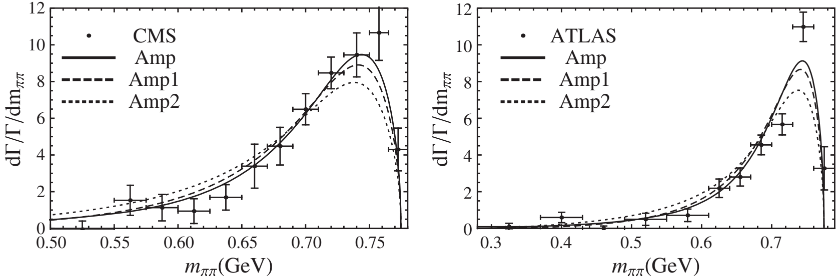
$$\mathcal{A}_{\mu_1}(X(3872) \to J/\psi\rho) \propto \varepsilon_{\mu_1\mu\nu\sigma}\epsilon_X^\mu \epsilon_\psi^{*\nu}(\frac{p_\rho^\sigma}{m_\rho} + g\frac{p_\psi^\sigma}{m_\psi})$$

- Choosing $m_X = 3.8717$, $m_{J/\psi} = 3.0969$, $m_{J/\psi} = 0.7753$, $m_{\pi^\pm} = 0.1396$ GeV, $\Gamma_\rho = 0.1491$ GeV, $\mathrm{BW}_\rho(p_\rho^2) = (p_\rho^2 - m_\rho^2 + i\Gamma_\rho\sqrt{p_\rho^2 - 4m_\pi^2})^{-1}$, and integrating out the $\pi^+\pi^-$ phase space numerically, we get:

$$\lambda_\theta^X = \frac{f(1-R)}{2-f+R} \text{ with } R = \frac{\sigma_{00}^X}{\sigma_{11}^X}, f = \frac{-0.56 + 1.28g + 3.12g^2}{13.7 + 30.6g + 18.2g^2}$$

$X(3872)$ polarization parameter III:

- The value of the weight factor $g = -0.51 \pm 0.10$ is fitted to the $\pi^+\pi^-$ spectrum measured by CMS and ATLAS Collaborations.



- Setting $\sigma_{00}^X = 0$ and $\sigma_{11}^X = 0$, we get the allowed window $-0.066 \leq \lambda_\theta^X \leq 0.141$.

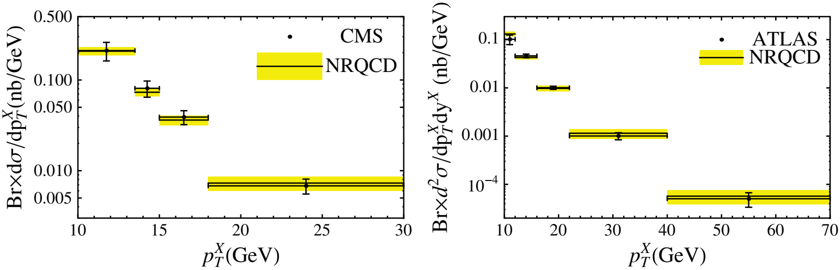
The above results depend on the phase space of $\pi^+\pi^-$, so f must be recalculated according to experiment acceptance cut.

Determine the LDMEs

- The non-perturbative parameters can be obtained by fitting to $X(3872)$ yield data measured by CDF,LHCb,CMS and ATLAS Collaborations after calculating the corresponding short distance coefficients up to QCD NLO.
- The numerical input in our NLO calculation is:
  - PDF, α_s running– CTEQ6M set with $\Lambda^4_{QCD} = 326$ MeV for 2-loop running.
  - Scales of renormalization (μ_r), factorization (μ_f), and NRQCD (μ_Λ)– $\mu_r = \mu_f = \xi\sqrt{4m_c^2 + p_T^2}$, $\mu_\Lambda = \eta m_c$ with $m_c = 1.5$ GeV.
  - Theoretical uncertainties–varying ξ and η from $1/2$ to 2 independently around their default value 1.
- Only the product of $\langle \overline{\mathcal{O}}^X[n] \rangle$ and branching function ($\mathcal{B}$) of $X(3872) \to J/\psi\pi^+\pi^-$ can be determined.

The fit results

- The fit quantify is very good with $\chi^2/d.o.f. = 7.25/9 = 0.81$ yielding $\langle\overline{\mathcal{O}}^X[{}^3P_1^{[1]}]\rangle\mathcal{B} = 0.34^{+0.12}_{-0.15} \times 10^{-2}\mathrm{GeV}^5$ and $\langle\overline{\mathcal{O}}^X[{}^3S_1^{[8]}]\rangle\mathcal{B} = 0.83^{+0.12}_{-0.16} \times 10^{-4}\mathrm{GeV}^3$.
- Comparison between fit results with CMS and ATLAS measurements of p_T^X spectra:



The fit results

- The integrated cross section measured by CDF and LHCb Collaborations are $\sigma^{\mathrm{prompt}}_{\mathrm{CDF}}(p\bar{p} \to X(3872) + X)\mathcal{B} = 3.1 \pm 0.7\mathrm{nb}$ and $\sigma^{\mathrm{prompt}}_{\mathrm{LHCb}}(pp \to X(3872) + X)\mathcal{B} = 4.26 \pm 1.23\mathrm{nb}$, which are also in agreement with our fitting results within error
  $\sigma^{\mathrm{fit}}_{\mathrm{CDF}}(p\bar{p} \to X(3872) + X)\mathcal{B} = 2.2 \pm 0.8\mathrm{nb}$
  $\sigma^{\mathrm{fit}}_{\mathrm{LHCb}}(p\bar{p} \to X(3872) + X)\mathcal{B} = 5.8 \pm 1.5\mathrm{nb}.$
- If we only include CMS and ATLAS data, in which p_T^X >10 GeV, we get a slightly different results, $\langle \overline{\mathcal{O}}^X[^3P_1^{[1]}]\rangle\mathcal{B} = 0.34^{+0.12}_{-0.15} \times 10^{-2}\mathrm{GeV}^5$ and $\langle \overline{\mathcal{O}}^X[^3S_1^{[8]}]\rangle\mathcal{B} = 0.83^{+0.12}_{-0.16} \times 10^{-4}\mathrm{GeV}^3$.

Excluding data from $p_T^X < 10\mathrm{GeV}$ region leads to a tiny effect on our predictions below!!

Impact on $\chi_{cJ}(2P)$ production

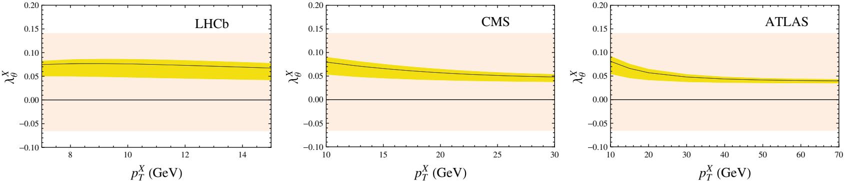
- For $n = {}^3P_1^{[1]}$ and $n = {}^3S_1^{[8]}$, the branching function $\mathcal{B}$ and overlap of the wave functions $|\langle\chi_{c1}(2P)|X(3872)\rangle|^2$ are common factors.
- With the help of heavy quark spin symmetry, we thus get the identity:

$$r = \frac{m_c^2\langle\overline{\mathcal{O}}^X[{}^3S_1^{[8]}]\rangle}{\langle\overline{\mathcal{O}}^X[{}^3P_1^{[1]}]\rangle} = \frac{m_c^2\langle\overline{\mathcal{O}}^{\chi_{c_1}(2P)}[{}^3S_1^{[8]}]\rangle}{\langle\overline{\mathcal{O}}^{\chi_{c_1}(2P)}[{}^3P_1^{[1]}]\rangle} = \frac{m_c^2\langle\overline{\mathcal{O}}^{\chi_{c_J}(2P)}[{}^3S_1^{[8]}]\rangle}{\langle\overline{\mathcal{O}}^{\chi_{c_J}(2P)}[{}^3P_J^{[1]}]\rangle}$$

- It is interesting to observe that the center value of r is 0.055, which is consistent with that in $1P$ case, $r(1P) = 0.045 \pm 0.010$.
- Once the CS LDMEs for $2P$ states is known, for example from potential model calculation, we can then predict $\chi_{c_J}(2P)$ production in various environments.

$X(3872)$ polarization at LHC

- We consider 3 setups at LHC, namely
  - LHCb: $\sqrt{S} = 7$ TeV, $2.0 < y^X < 4.5$;
  - CMS: $\sqrt{S} = 7$ TeV, $|y^X| < 1.2$;
  - ATLAS: $\sqrt{S} = 8$ TeV, $|y^X| < 0.75$.
- Predictions of λ_θ^X in helicity frame (HX) as function of p_T^X for the 3 setups:

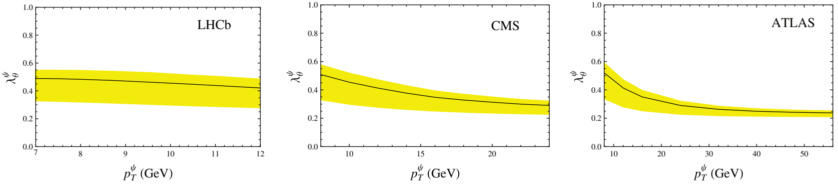


Conclusion

The $X(3872)$ is largely longitudinal polarized for all the 3 setups. However the value of λ_θ^X is too close to 0.

The polarization of J/ψ from $X(3872)$ decay

- Another quantity to describe the polarization is $R = \sigma_{00}^{X}/\sigma_{11}^{X}$.
- The behaviors of R can be obtained through the relation $R = (1 + 15.2\lambda_{\theta}^{X})/(1 - 7.09\lambda_{\theta}^{X})$.
- We find for the 3 setups R behaviors are similar. At $p_T^X = 10$ GeV, R is around 5 and then goes to its asymptotic value 2.2 at large p_T^X.
- Fortunately, unlike λ_{θ}^{X}, the J/ψ polarization parameter λ_{θ}^{X} are well separated from 0.



$X(3872)$ polarization in molecular model

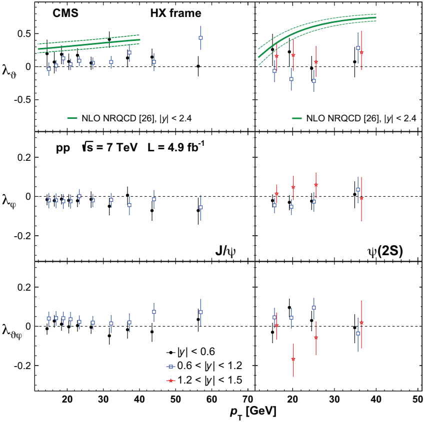
- In molecular model, $X(3872)$ is a loosely S-wave bound state of $D^0\bar{D}^{*0} + c.c.$
- $D^0(\bar{D}^0)$ is spin 0 state, so the polarization information is carried by $D^{*0}(\bar{D}^{*0})$.
- At hadron collider, $D^{*0}(\bar{D}^{*0})$ is predominately produced through the non-perturbative evolution of $c(\bar{c})$-quark.
- We are not aware of any mechanism to in the non-perturbative evolution to result in a polarized $D^{*0}(\bar{D}^{*0})$.
- We, therefore, infer the $D^{*0}(\bar{D}^{*0})$ is unpolarized and so is $X(3872)$.
- Actually, such argument is supported by measurement of $D^{*0}(\bar{D}^{*0})$ polarization at e^+e^- colliders at different center of mass energy.

Conclusion

In molecule model, both $X(3872)$ and the J/ψ from its decay will be unpolarized at LHC!

Feasibility Analysis I

- Experimentally, the polarization of $\psi(2S)$ has been measured by CMS Collaboration in the range of $14 < p_T^{\psi'} < 50$ GeV and $|y^{\psi'}| < 1.2$ using 262 K $\psi(2S)\mu^+\mu^-$ events. (CMS 2013)



Feasibility Analysis II

- In the analysis of $X(3872)$ yield, they used 11.91 K number of events collected at integration luminosity of 4.8 fb^{-1} in almost the same kinematic range, $10 < p_T^X < 50$ GeV and $|y^X| < 1.2$.(CMS 2013)
- By far, the total integration luminosity they accumulated is 29.3 fb^{-1} for Run I and 160 fb^{-1} for Run II.
- If we assume the acceptance and efficiency did not change much during the data taken periods, we can then estimate there will be around 72.7 K (Run I) and 397 K (Run II) prompt $X(3872)$ events available for $X(3872)$ and J/ψ polarization analysis.

Conclusion

During the LHC Long Shutdown 2, there is a chance to obtain the polarization of $X(3872)$ and that of J/ψ from its decay at LHC.

In summary

- In the hypothesis that prompt hdaroproduction of $X(3872)$ is mainly through the $\chi_{c1}(2P)$ component of its short distance wave function, we predict the polarization of $X(3872)$ and that of J/ψ from its decay.
- We find the polarization of $X(3872)(J/\psi)$ is largely longitudinal(transversal) polarized, while the prediction of molecule model is unpolarized for both.
- Such predictions can be examined now by analyzing the current data accumulated at LHC.
- This idea can also be applied to any other X, Y, Z state with non-zero spin.
- If the experimental results agree with our predictions, this would be a strong evidence of both our hypothesis for $X(3872)$ and NRQCD factorization formalism for polarization of P-wave state.

Thank you!