Production of the X(3872) at the Tevatron and the LHC

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work in collaboration with
Eric Braaten [arxiv:0911.2016]

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What is the X(3872) ?

- EXP: *Resonance* discovered by the Belle Collaboration in 2003 through the decay $B^+ \to K^+ + X$ and $X(3872) \to J/\psi\pi\pi$, confirmed by many other experiments (Babar, CDF, D0)

- TH: no common agreement has been reached so far about the nature of this state. Several interpretations have been proposed (charm-meson molecule, tetraquark state, charmonium, ...)

- Subject of the talk: production of the X(3872) in hadron collisions

two aspects

Can we learn something about the nature of the X(3872) from the measured production rate ?	Given the Tevatron data, can we predict accurately the production rate at the LHC?

OUTLINE

- **The X(3872) as a loosely-bound charm-meson molecule**

  Ingredient: large scattering length a in the C=+1 $D^{*0}\bar{D}^0$ scattering channel.

- **In the molecule picture, what is the typical production rate expected at a hadron collider ?**

  framework: factorized expression of the cross section that takes advantage of the very large scattering length:

$$1/a \ll m_\pi, m_c, p_T$$

- **Given the Tevatron data on the X(3872), can we predict accurately the production rate at the LHC ?**

  framework: NRQCD factorization to separate the perturbative and nonperturbative momentum scales:

$$1/a, m_\pi \ll m_c, p_T$$

The X(3872) as a loosely-bound charm-meson molecule

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The argument is based on two experimental facts:

- $J^{PC}=1^{++}$ → the X(3872) has an S-wave coupling to $D^{*0}\bar{D}^0$ and hence should manifest itself as a pole in the $D^{*0}\bar{D}^0$ S-wave scattering amplitude

- $M_X - M_{D^{*0}} - M_{D^0} = -0.42 \pm 0.39\ \mathrm{MeV}$.

→ due to the tiny energy of the X(3872) relative to the $D^{*0}\bar{D}^0$ threshold, we can consider an expression of the S-wave partial amplitude at low relative momentum

$$f(k) = \frac{1}{k\cot[\delta_0(k)] - ik} \approx \frac{1}{-1/a - ik}$$

where $\delta_0(k)$ is the S-wave phase shift, and a is the scattering length.

Unique pole at $k = i/a$

- $a < 0$: virtual state
- $a > 0$: bound state, $E_X = 1/(2M_{D^*D}a^2)$
  mean separation: $\langle r \rangle_X = a/2$

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The X(3872) as a loosely-bound charm-meson molecule

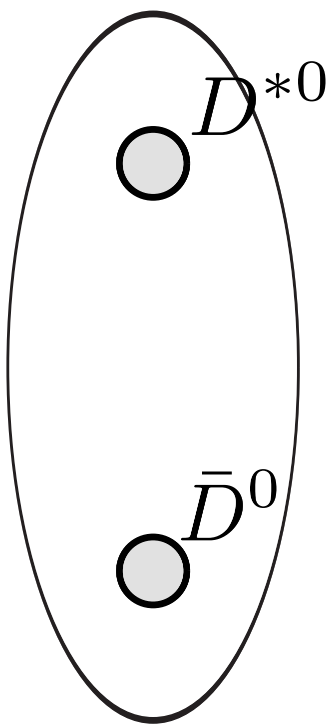
- Measured binding energy (in the $J/\psi\pi\pi$ decay channel)

$$E_X = M_{*0} + M_0 - M_X = 0.42 \pm 0.39 \text{ MeV}$$

$\Rightarrow$ X(3872) ≡ bound state is favored by the data.

- Predicted mean separation

$$\langle r \rangle_X = 4.9^{+13.4}_{-1.3} \text{ fm}$$



$\Rightarrow$

1. the mean separation of the constituents of the X(3872) is larger than for ordinary hadrons by an order of magnitude.

2. the scattering length a is much larger than the range set by the interaction between the charm mesons

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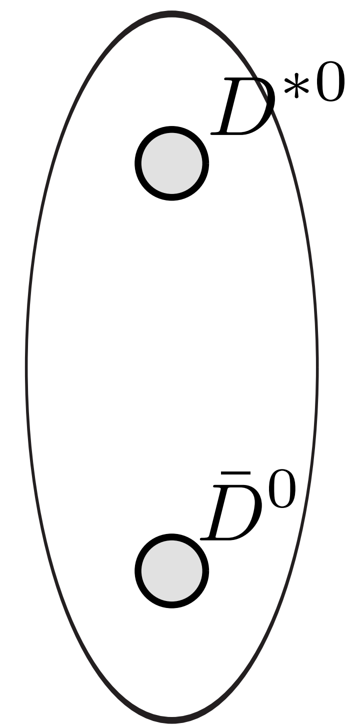

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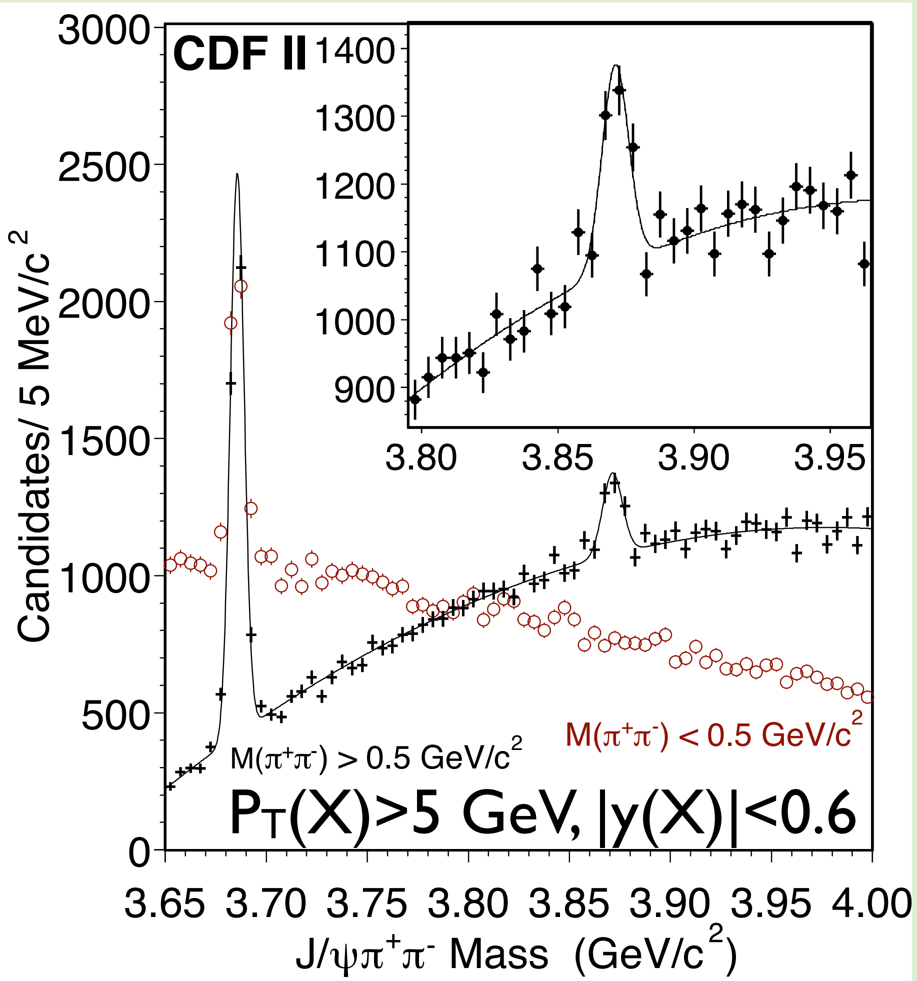
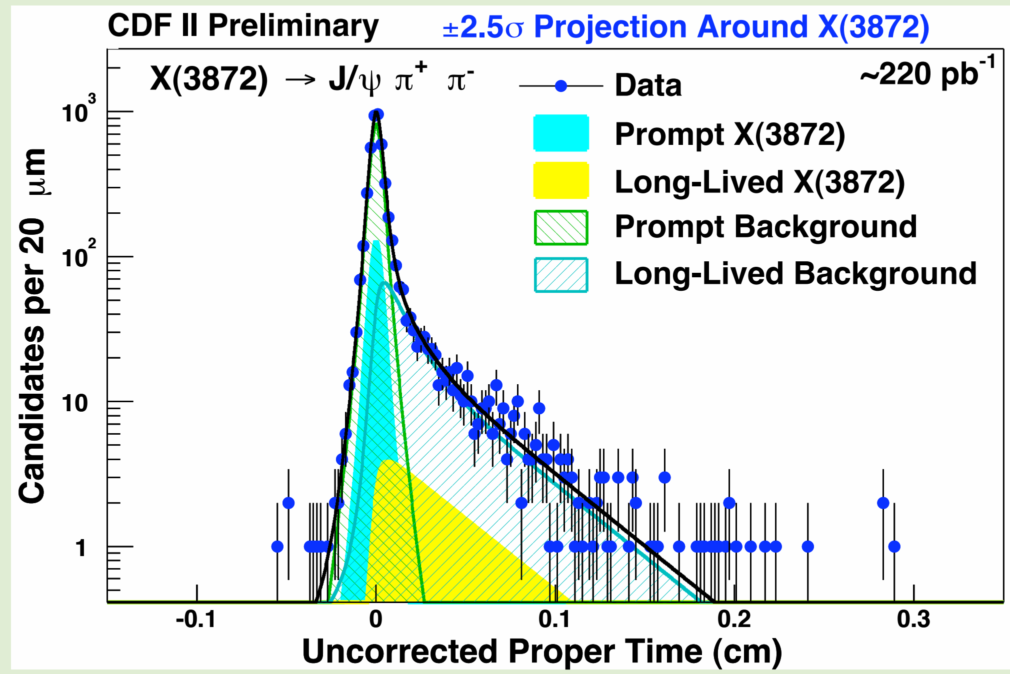
What is the typical production rate at a hadron collider ?

X(3872) production in hadron collisions (exp.)

- Observation by the CDF collaboration in the $J/\psi\pi\pi$ decay channel

[Bauer, 2005 (CDF collaboration)]





In high energy $p\bar{p}$ collisions most of the high p_T X are produced promptly by QCD mechanisms

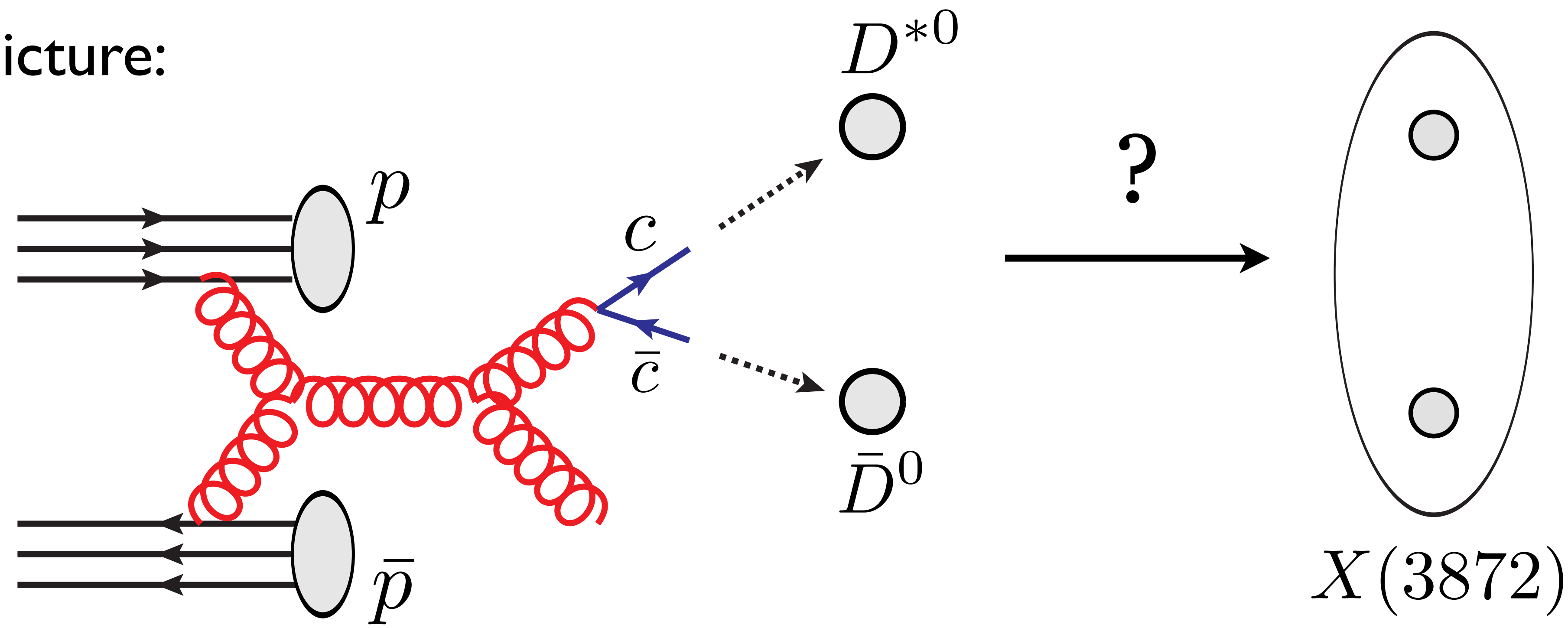
- The measured number of events $X(3872) \to J/\psi\pi\pi$ relative to the number of events $\psi(2S) \to J/\psi\pi\pi$ implies the estimates

$$\sigma_{\text{prompt}}[X(3872)]\ \text{Br}[X \to J/\psi\pi^+\pi^-] \approx 3.1 \pm 0.7\ \text{nb},$$

$$\sigma_{b\text{-decay}}[X(3872)]\ \text{Br}[X \to J/\psi\pi^+\pi^-] \approx 0.59 \pm 0.23\,\text{nb}.$$

Production mechanism for the prompt fraction

naive picture:



typical relative momentum between D^{*0} and $\bar{D}^0$ produced at high pT in $p\bar{p}$ collisions: $k \approx m_c = 1.5$ GeV

typical relative momentum between D^{*0} and $\bar{D}^0$ bound in the X(3872): $k \approx 1/a \approx 28$ MeV

- Most of the time, the charm mesons are expected to recoil from each other with a momentum much larger that the binding momentum of the X(3872)

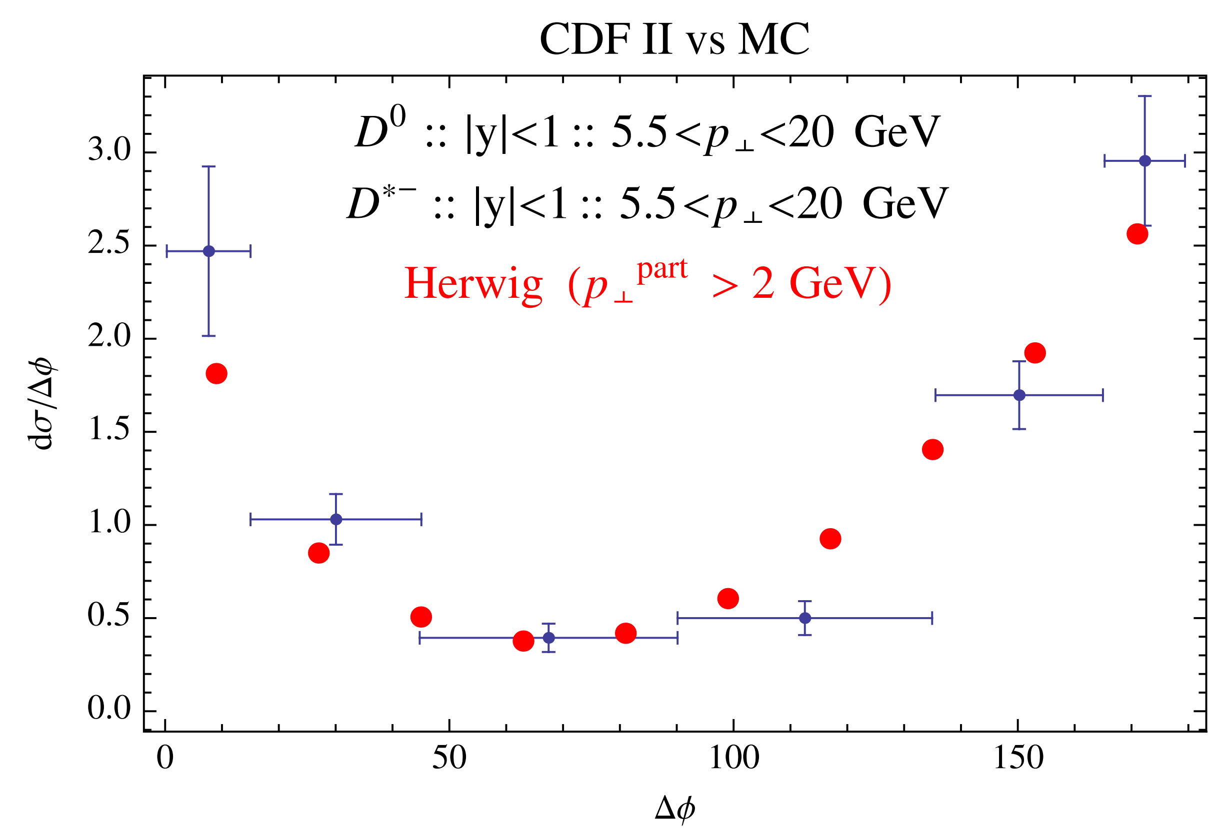
⇒ we would expect a suppressed production rate in the molecule picture

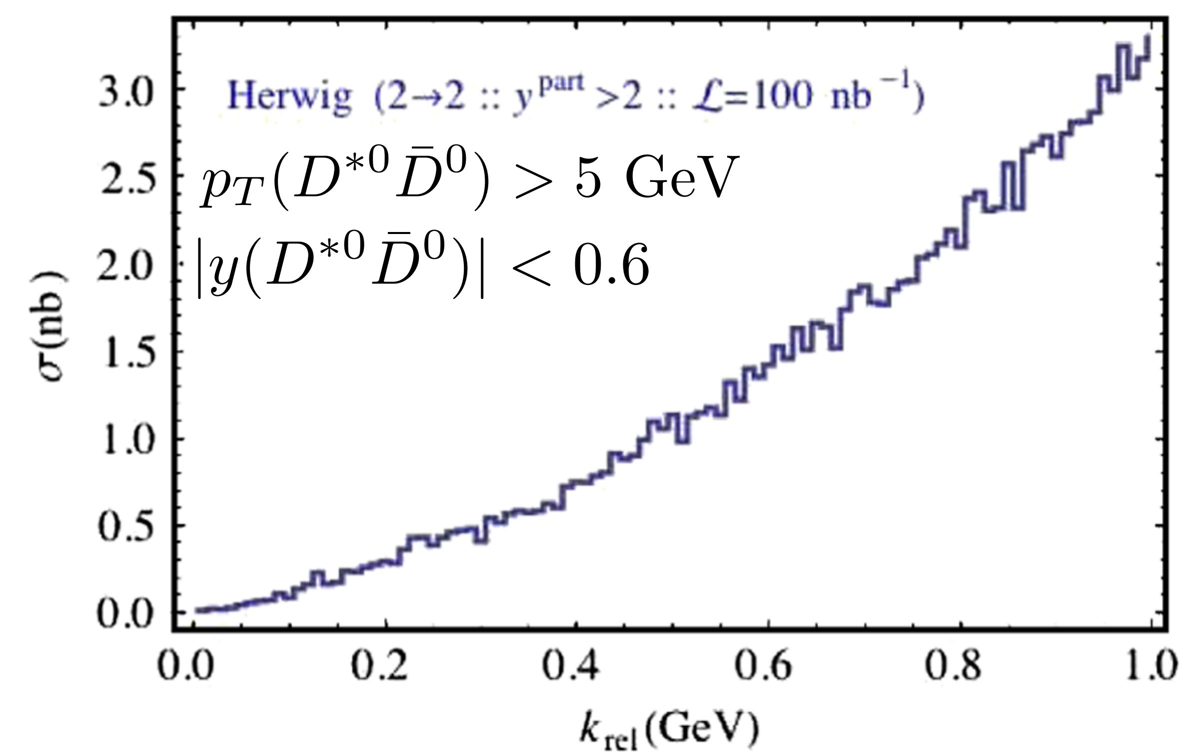
- Is it possible to quantify this suppression and confront it to the experimental number of X(3872) events reported by the CDF collaboration ?

Bignamini, Grinstein, Piccinini, Polosa, Sabelli (2009)

Upper bound on the prompt cross section

- Idea: use Monte-Carlo techniques to predict the number of $D^{*0}\bar{D}^0$ pair with a small relative momentum $k \lesssim 1/a$
- Procedure: - Pythia/Herwig to generate charm-meson events
  - normalization of the distributions using experimental data for $D^0 D^{*-}$ production





- Result: $\sigma[D^{*0}\bar{D}^0(k < k_{\text{max}} = 35 \text{ MeV})] = 0.071 \text{ nb}$
  proposed as an upper bound for $\sigma[X(3872)]$

see Bignamini et al, PRL.103:162001,2009

Production of the X at the Tevatron: (pT>5 GeV, |y|<0.6)

Bignamini et al (th)

$$\sigma[X] \lesssim 0.1 \text{ nb}$$

if we adopt the molecule interpretation

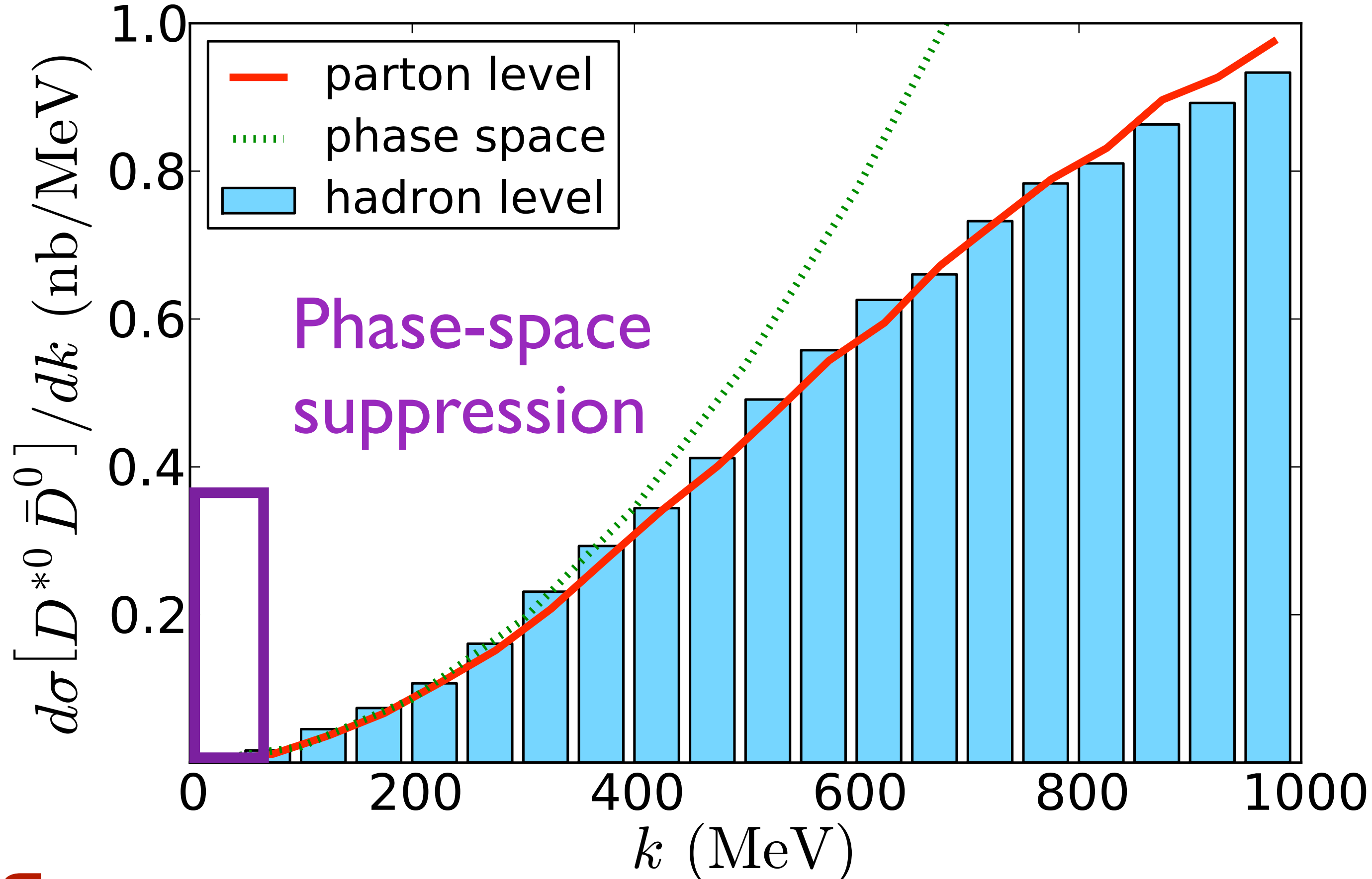
X(3872) as a molecule ruled out ?

CDF data (extrapolated)

$$\sigma[X].Br[X \to J/\psi\pi\pi] \approx 3.1 \pm 0.7 \text{ nb}$$

The suppression has a phase-space origin:

The cross section $\sigma[D^{*0}\bar{D}^0(k < k_{\max})]$ estimated from Herwig or Pythia scales like the phase-space weight $k_{\max}^3$ in the region $k_{\max} < 400$ MeV



implicit assumptions

- that the production amplitude is insensitive to k in that region
- that there is effectively **no effect from charm meson rescattering**

Charm-meson rescattering effects

Reminder: close to threshold, the S-wave $D^{*0}\bar{D}^0$ scattering amplitude is given by

$$f(k) \approx \frac{1}{-1/a - ik}$$

- if $a \approx \Lambda^{-1}$ (= the range of interaction)

⇒ expect no dramatic effect from charm-meson rescattering at small k

- but we have seen that $a \gg \Lambda^{-1}$

⇒ the amplitude has a pole close to threshold

Due to the presence of an S-wave resonance very close to threshold, we expect rescattering to allow charm mesons created with $k \approx \Lambda$ to rescatter into $k \approx 1/a$

Estimate of the cross section

- The large scattering length allows us to derive a factorization formula that determines the dependence of the production rate on the binding energy of the X(3872)

$$\sigma[X(3872)] \approx \underbrace{\sigma_{\text{naive}}[D^{*0}\bar{D}^0(k<\Lambda)]}_{\text{includes the dependence on the momentum scales of order } m_\pi \text{ and larger, can be approximated with Pythia/Herwig}} \times \underbrace{\frac{6\pi\sqrt{2M_{DD^*}E_X}}{\Lambda}}_{\text{dependence on the binding momentum } 1/a = \sqrt{2M_{DD^*}E_X}}$$

The upper bound Λ should be identified to the inverse range of interaction between the charm mesons. For $\Lambda = m_\pi/2, m_\pi, 2m_\pi$, the cross section ranges from 1.5 to 23 nb.

- estimate exceeds proposed upper bound of BGPPS by factor of 20-350

- σ approaches 0 as $E_X \to 0$ in accord with naive expectations but only as $E_X^{1/2}$

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- In order to verify the effects from charm-meson rescattering, the authors suggest to search for a loosely-bound X_s (1^{++}) molecule (partner with strange light quarks of the X(3872))

- They also point out that additional hadrons produced in the vicinity of the charm-meson pairs may rescatter with the charm mesons

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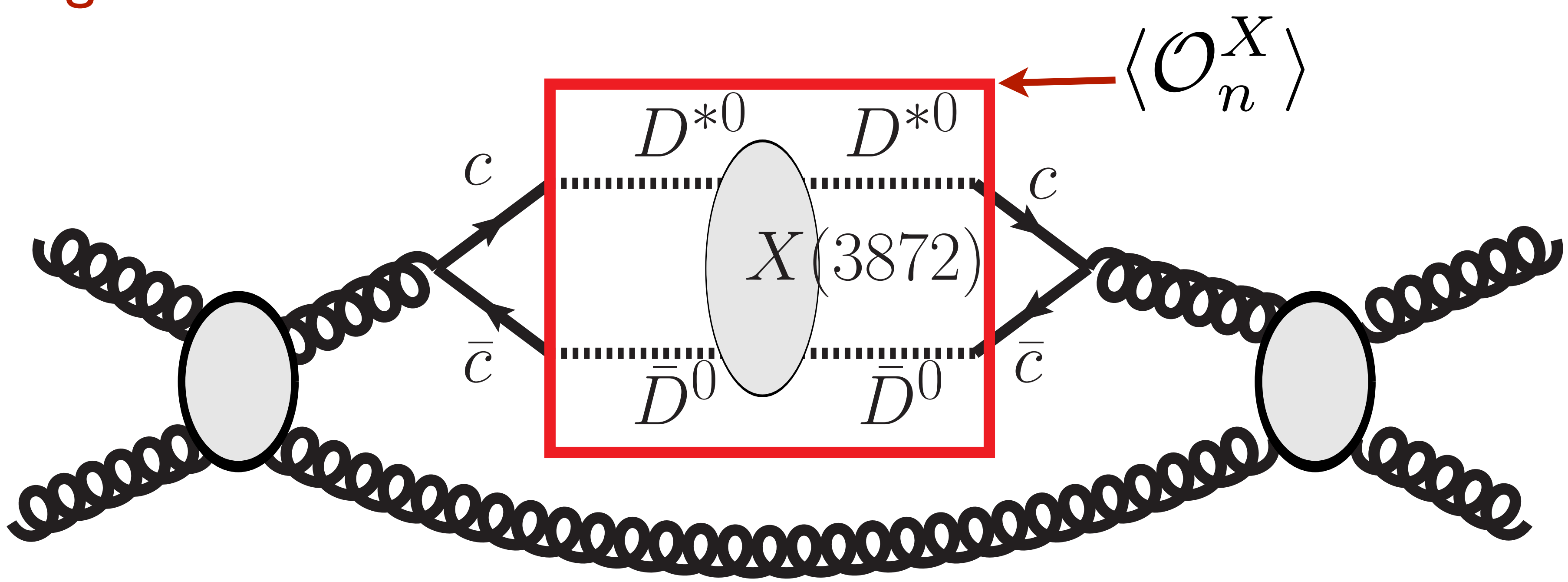
Interesting point, needs to be further investigated

Given the Tevatron data on the X(3872), can we predict accurately the production rate at the LHC ?

NRQCD factorization

- Aim: predict the differential cross section for prompt production of X(3872) at the LHC

- The prompt production of X(3872) proceeds via the production of a charm-quark pair with small relative momentum. Therefore we can use the NRQCD framework to factorize all the effects from momentum scales much smaller than m_c into long-distance matrix elements



$$\sigma[X(3872)] = \sum_n \hat{\sigma}[c\bar{c}_n] \langle \mathcal{O}_n^X \rangle$$

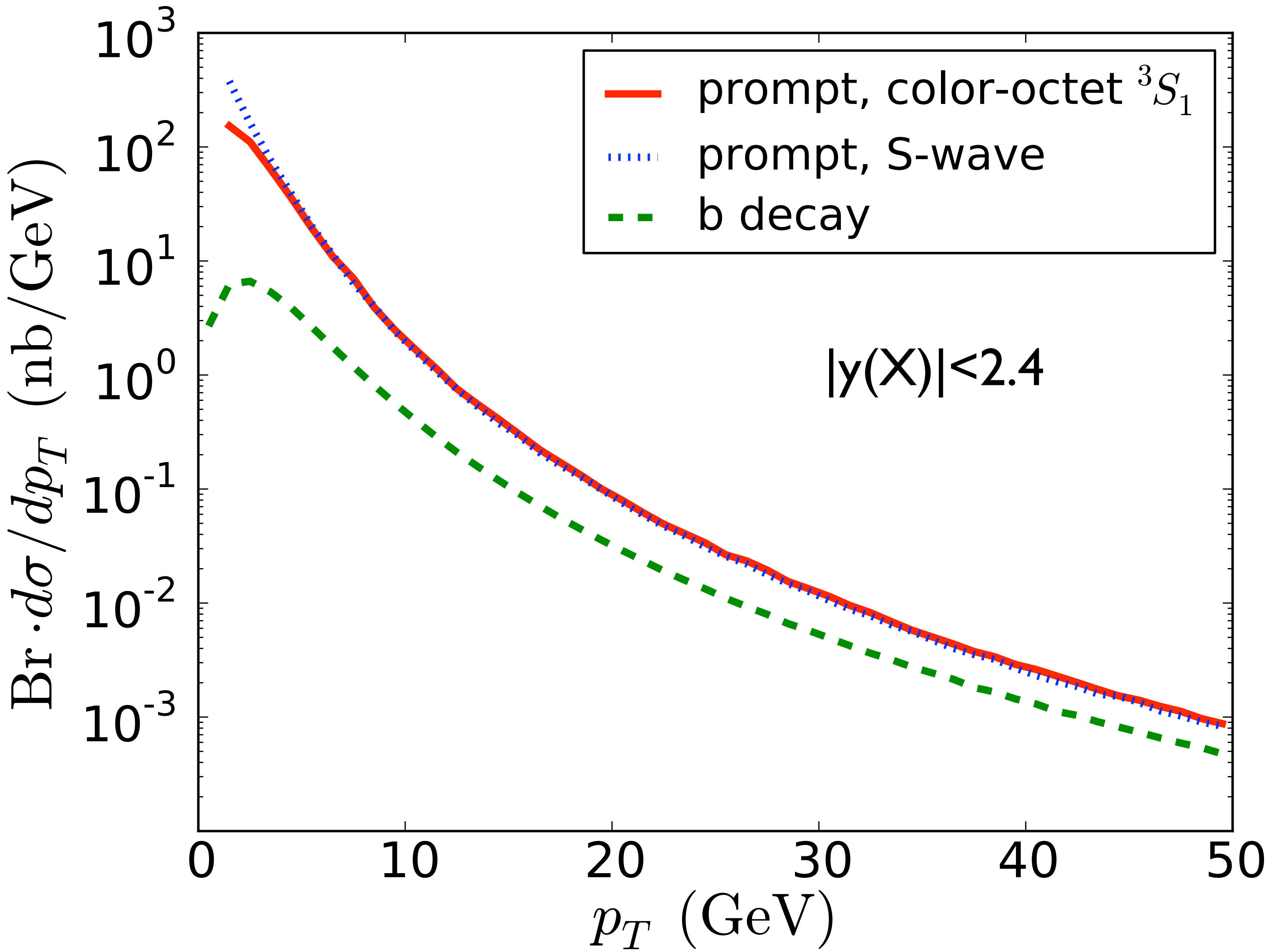
NRQCD factorization

Different hypotheses can be made on the long-distance matrix elements $\langle \mathcal{O}_n^X \rangle$ to reduce them to a single non-perturbative parameter

- **S-wave dominance**. The X(3872) is equally likely to be formed from any $c\bar{c}$ pair that is created with small relative momentum in an S-wave state, regardless of the color or spin state of the $c\bar{c}$ pair.
- **Color-octet $3S^1$ dominance**. The X(3872) can be formed only from a $c\bar{c}$ pair that is created with a small relative momentum in a color-octet $^3S_1$ state.

The resulting non-perturbative parameter can be constrained by the measurement of the prompt cross section at the Tevatron

Predicted rate at the LHC



- The predicted rate is more than an order of magnitude larger than for the CDF detector at the Tevatron, given the same cut on p_T of the X and the same integrated luminosity

- There is a very small sensitivity to the assumption on the long-distance matrix element

Cross section for X(3872)→ J/ψππ in pp collisions at $\sqrt{s} = 7$ TeV

Conclusion

- In the molecule interpretation of the X(3872), the unnaturally large scattering length a has to be taken into account correctly in estimating the production rate at the Tevatron

- The current data on the production rate at the Tevatron is compatible with the interpretation of the X(3872) as a loosely-bound charm-meson molecule

- Given the Tevatron data on the X(3872) production rate, the NRQCD factorization can be used to predict the differential rate at the LHC

- The large data samples of the X(3872) expected at the LHC will allow precise measurements of various properties of the X(3872)