THE OHIO STATE UNIVERSITY

Quarkonia as Tools 2021

$X(3872)$ Production and Suppression

(in pp collisions)

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General overview

- Brief review of *X(3872)*
- Production of *X(3872)* at hadron colliders
- Suppression of *X(3872)*

Brief Review of $X(3872)$

- Discovered at e^+e^- collider in $B^+ \to K^+X,\ X \to J/\psi\pi^+\pi^-$ [Belle (2003)]
- Confirmed at $p\bar{p}$ collider [CDF (2003)]
- Observed at pp collider [ATLAS (2013), CMS (2011), LHCb (2011)]
- Most precise mass and first width [LHCb (2020)]:

$$M_X = 3871.695 \pm 0.096\ \text{MeV},\ \Gamma_X^{BW} = 1.19 \pm 0.19\ \text{MeV}$$

- 7 observed decay channels
  - $J/\psi\pi^+\pi^-$ [Belle (2003)]
  - $J/\psi\pi^+\pi^-\pi^0$ [BaBar (2010)]
  - $J/\psi\gamma$ [BaBar (2006)]
  - $\psi(2S)\gamma$ [BaBar (2009)]
  - $D^0\overline{D}^0\pi^0$ [Belle (2006)]
  - $D^0\overline{D}^0\gamma$ [Belle (2010)]
  - $\chi_{c1}\pi^0$ [BESIII (2019)]

Brief Review of $X(3872)$

- Tiny binding energy [LHCb (2020)]:

$$E_X = M_X - (M_{D^{*0}} + M_{\bar{D}^0}) = -0.07 \pm 0.12\ \text{MeV}$$

- Quantum numbers: $J^{PC} = 1^{++}$ [LHCb (2013)]
- Imply $X(3872)$ is S-wave loosely-bound charm-meson molecule

$$X = \frac{1}{\sqrt{2}}\left(|D^{*0}\bar{D}^0\rangle + |\bar{D}^{*0}D^0\rangle\right)$$

- Universal properties determined by binding energy E_X (or scattering length $a_X = 1/\gamma_X$) [Braaten, Kusunoki (2003)]

$|E_X| < 0.22\ \text{MeV}$ at 90% C.L. $\qquad \gamma_X = \sqrt{2\mu_{D^*\bar{D}}|E_X|} < 21\ \text{MeV}$

  - Wavefunction:

$$\psi_{X(r)} = \frac{1}{\sqrt{8\pi\gamma_X}}\frac{e^{-\gamma_X r}}{r}$$

  - Huge mean separation:

$$\langle r\rangle_X = \frac{1}{2\gamma_X} > 4.5\ \text{fm}$$

Brief Review of $X(3872)$

- Other possibilities for X [Ali, Lange, Stone (2017)]:
  - Cusp: discontinuity in differential cross section across threshold
  - Hadroquarkonia: heavy charmonium core $c\bar{c}$ surrounded by light meson $q\bar{q}$ bound by QCD analog of van der Waals force
  - Hybrid: combination of heavy quarks and a constituent gluon
  - Compact tetraquark: diquark and anti-diquark bound by color interactions
  - Charmonium: $\chi_{c1}(2P)$
- Regardless, the coupling of X to $D^{*0}\bar{D}^0$ transforms it into a large charm-meson molecule
- Production and suppression mechanisms help to determine X true nature

Production of $X(3872)$ at hadron colliders

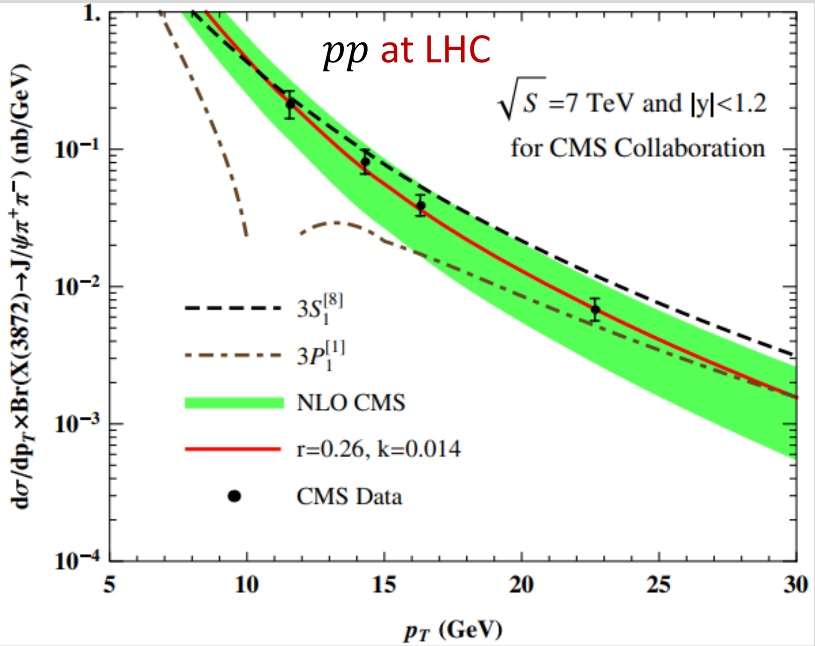
Production of $X(3872)$ at hadron colliders

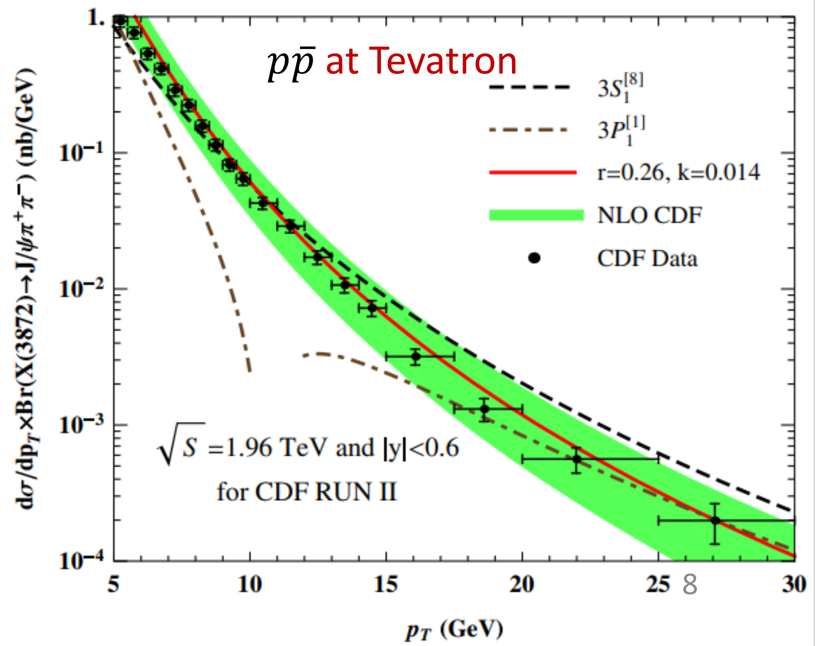
- Two contributions at hadron colliders
  - Prompt production $pp \to X + \text{anything}$
  - b hadron decays
- Convenient to benchmark $X(3872)$ against $\psi(2S) = \psi(3686)$
  - Both are observed in $J/\psi\pi^+\pi^-$ channel
  - They have similar masses
- Field theoretic tools include
  - Non-relativistic QCD [Bodwin, Braaten, Lepage (1995)]
  - Potential Non-relativistic QCD [Brambilla, *et al.* (2000)]
  - XEFT [Fleming, *et al.* (2007)][Braaten (2015)]

Production of $X(3872)$ at hadron colliders in NRQCD

- Cross section for creating X related to cross section for creating $c\bar{c}$ at short distances through Long Distance Matrix Elements (LDMEs)
- [Meng, Han, Chao (2017)] calculate p_T-distribution assuming production of X at short distances dominated by $\chi_{c1}(2P)$ state
- LDMEs at NLO in NRQCD:
  - $\widehat{O}^{\chi'_{c1}}\left(3S_1^{[8]}\right)$: from fits
  - $\widehat{O}^{\chi'_{c1}}\left(3P_1^{[1]}\right)$: related to $\chi_{c1}(2P)$ wavefunction at origin
  - Normalization factor $k = Z_{c\bar{c}}\mathrm{Br}(X \to J/\psi\pi^+\pi^-)$, where $Z_{c\bar{c}}$ is probability $\langle\chi'_{c1}|X\rangle$

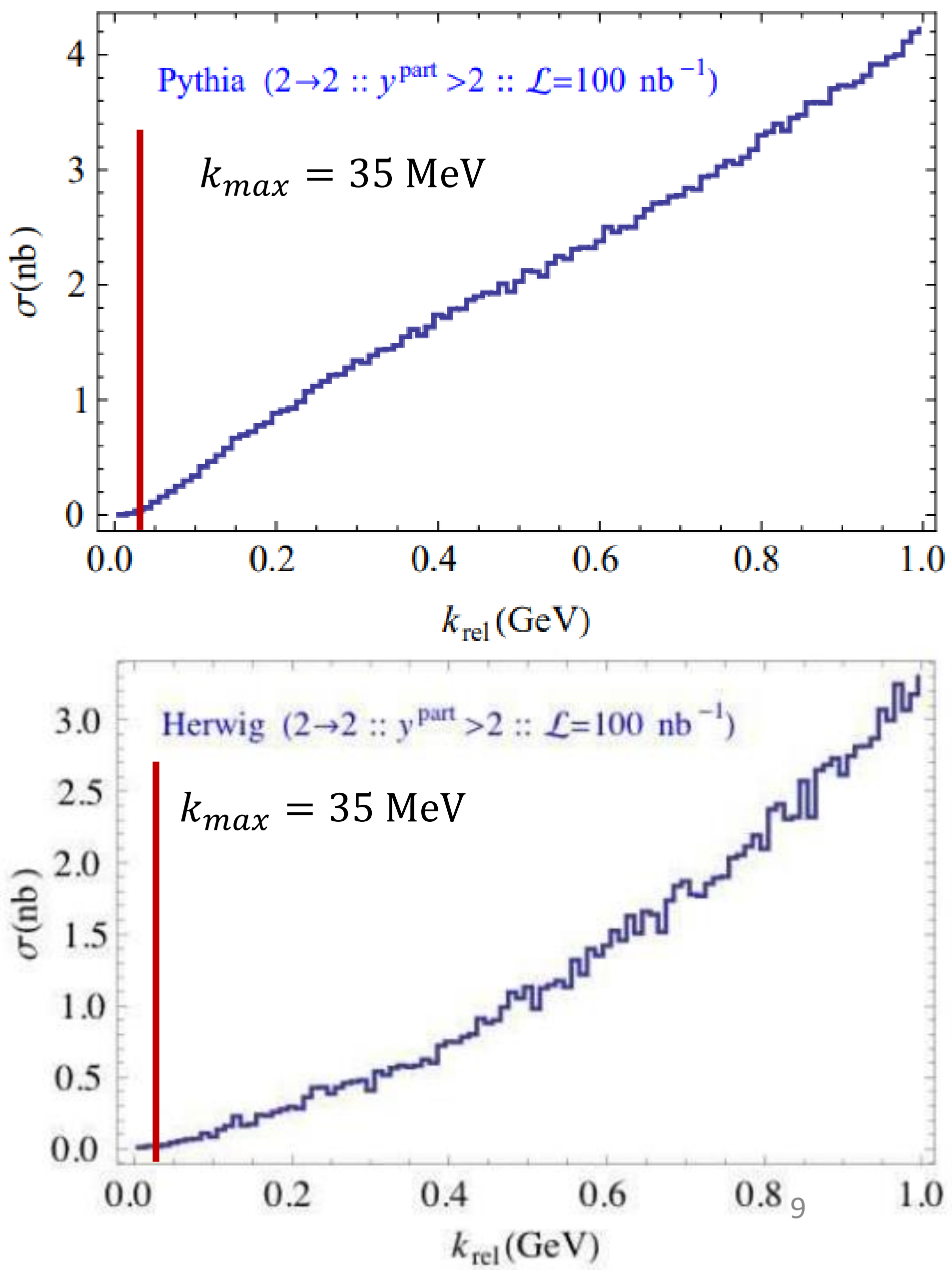
$$k = 0.014$$





Production of $X(3872)$ at hadron colliders

- [Bignamini *et al.* (2009)] If X is a loosely bound charm-meson molecule with relative mom k
$$\sigma[X] = \sigma[D^{*0}\bar{D}^0(k < k_{max})]$$
$$k_{max} \approx \gamma_X, \qquad \gamma_X = \sqrt{2\mu_{D^{*0}\bar{D}^0}|E_X|}$$
- Calculated $\sigma[D^{*0}\bar{D}^0]$ using event generator PYTHIA and HERWIG
- Weak lower bound on $p\bar{p}$ collisions from CDF at Tevatron
$$\sigma[X]\mathrm{Br}[\mathrm{X} \to J\psi\pi^+\pi^-] > 3.1 \pm 0.7 \text{ nb}$$
- Observed cross section at Tevatron and LHC are orders of magnitude too large



Production of $X(3872)$ at hadron colliders

- [Artoisenet, Braaten (2010)] If X is a loosely bound charm meson molecule with relative mom k

$$\sigma[X] = \sigma[D^{*0}\bar{D}^0(k < k_{max})]$$
$$\sigma[D^{*0}\bar{D}^0(k < k_{max})] \propto k_{max}^3, \qquad k_{max} \approx m_\pi$$

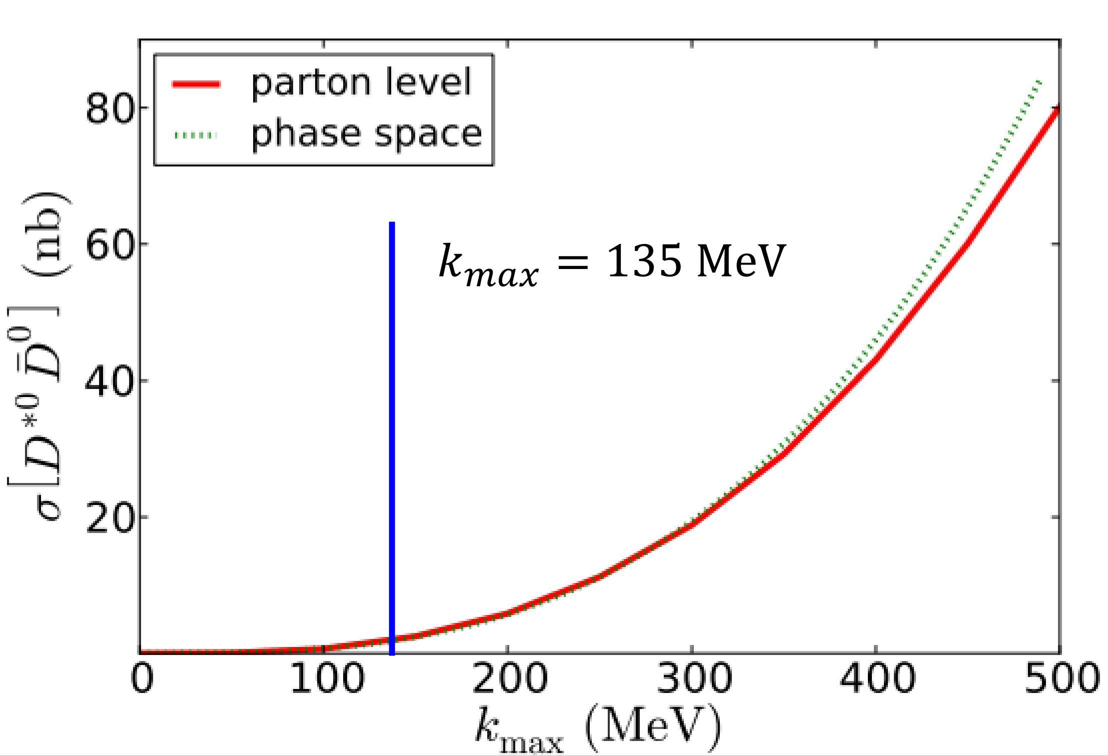
- Calculated $\sigma[D^{*0}\bar{D}^0]$ using event generator PYTHIA

- [Braaten, He, Ingles (2019)] Quantitative estimate on k_{max}

$$\sigma[X] = \sigma[D^{*0}\bar{D}^0](k < 7.7\gamma_X)$$
$$\gamma_X = \sqrt{2\mu_{D^{*0}\bar{D}^0}|E_X|}$$

Note: $7.7^3 \approx 500$

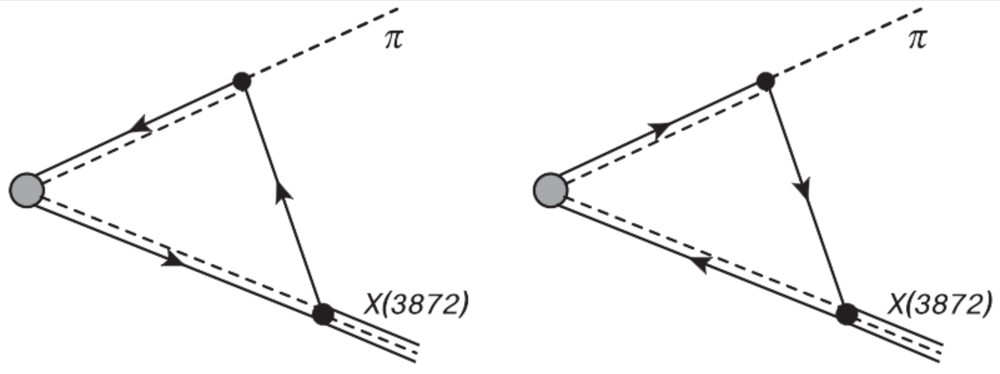
- Observed prompt cross sections for X are compatible with with charm-meson molecule

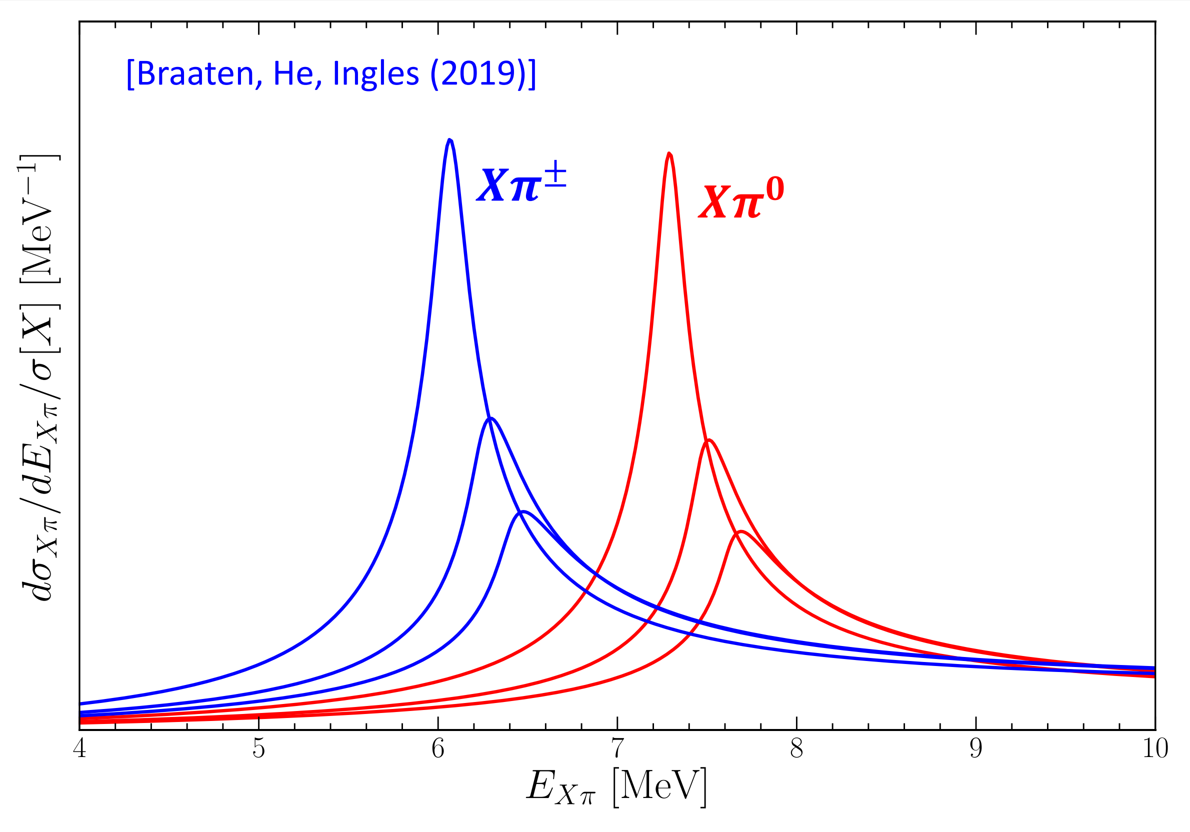


Production of $X(3872)$ at hadron colliders in XEFT

- Production of X can come from creation of $\bar{D}^0 D^{*0}, D^0 \bar{D}^{*0}$ at short distances
- Production of $X\pi^+$ with soft π can come from creation of $D^{*+}\bar{D}^{*0}$ at short distances
  - Triangle singularity in process $D^{*+}\bar{D}^{*0} \to X\pi^+$ gives peak about 6 MeV above $X\pi^+$ threshold with width < 1 MeV

- Charm-meson triangle loop ⇒ triangle singularity
- Decay width of D^* and binding energy of X reduce $\log^2$-divergence to narrow peak





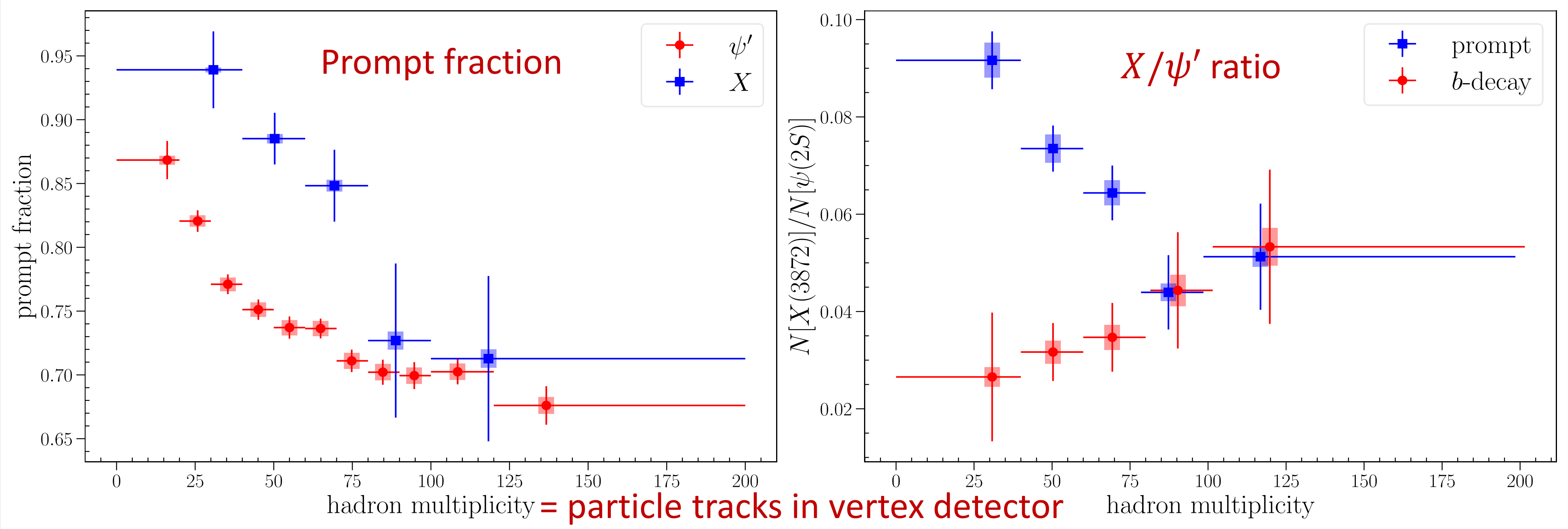
Suppression of $X(3872)$

Suppression of $X(3872)$

- Proton-proton collision:
  - Interactions with comoving gluons and pion
    Comover Interaction Model [Ferreiro (2015)]
- Proton-nucleus collision:
  - Interactions with comoving gluons and pions
  - Cold nuclear matter effects: PDFs of p and n, nuclear shadowing, absorption by nucleons etc. [e.g. Vogt (2015)]
- Nucleus-Nucleus collision:
  - Interactions with comoving gluons and pions
  - Cold nuclear matter effects
  - Thermal effects in quark-gluon plasma [e.g. Rothkopf (2020)]
  - Thermal effects in expanding, cooling hadron gas

Suppression of $X(3872)$ in pp collisions

- [LHCb (2021)] measured X and ψ' yields as functions of hadron multiplicity



- Prompt fractions for X and ψ' decrease with multiplicity
- Prompt fraction for ψ' saturates at large multiplicity

Suppression of $X(3872)$ in pp collision

- Survival probability in CIM [Armesto, Capella (1998)]

$$S=\exp\left[-\frac{\langle v\sigma\rangle}{\sigma_0}\frac{dN}{dy}\log\left(\frac{1}{N_0}\frac{dN}{dy}\right)\right]$$

N_0: multiplicity at which interactions stop

σ_0: parameter that depends COM energy

- Model for breakup reaction rate and momentum distribution for comovers [Ferreiro, Lansberg (2018)]

$$\langle v\sigma\rangle = \pi r^2 \left\langle 1 - \frac{E^{thr}}{E_{co}} \right\rangle;$$

r^2: RMS mean separation of constituents

E^{thr}: energy required to break X apart

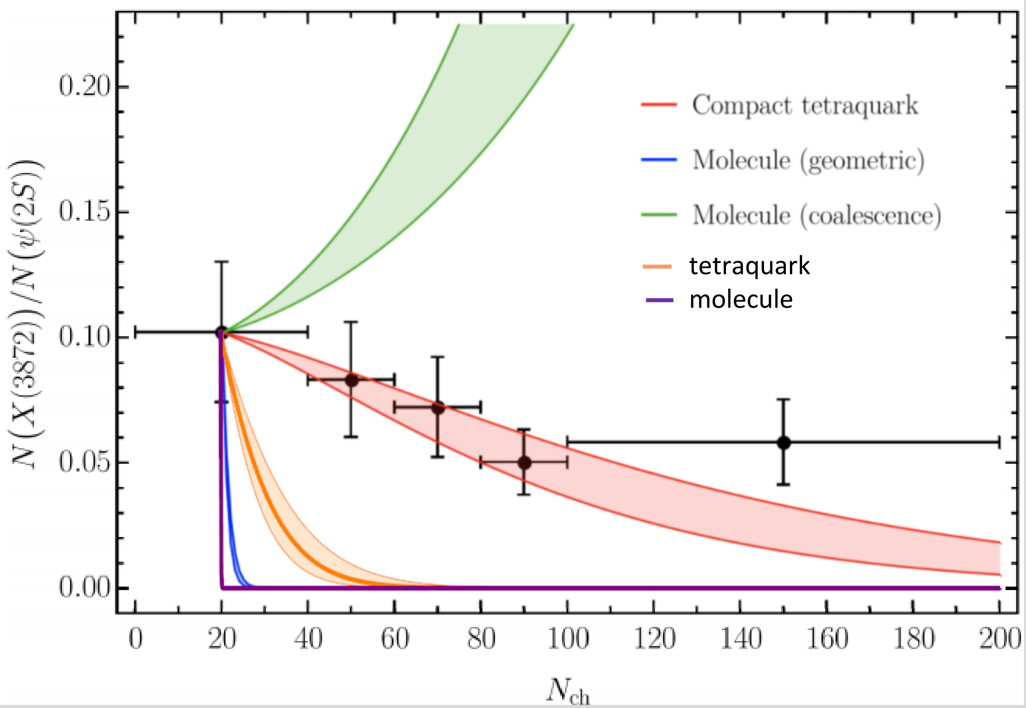
E_{co}: pion(gluon) relativistic energy

$$f(E_{co}) = \left(e^{E_{co}/T_{eff}} - 1\right)^{-1}$$

$$200 < T_{eff} < 300 \text{ MeV}$$

Suppression of $X(3872)$ in pp collisions

- [Esposito, *et al.* (2020)] estimated X/ψ' ratio assuming
  - X as a tightly bound tetraquark
  - X as charm-meson molecule
  - X as charm-meson molecule and with process $\pi\bar{D}D^* \to X$ and $\pi D^*\bar{D}^* \to X\pi$
- Estimation done using MC Glauber modeling
  - Generate realistic particle distribution
  - X can only interact with comovers within range
- Estimation shows that CIM favors tetraquark interpretation
- Simply plugging in numbers for survival probability gives poor agreement

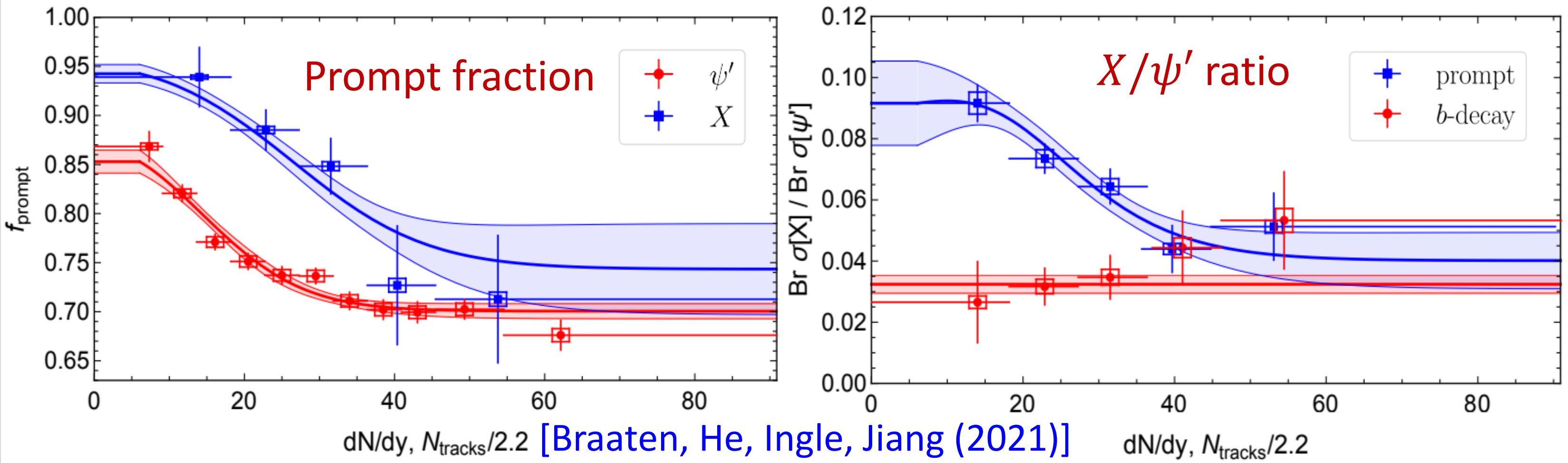


Suppression of $X(3872)$ in pp collisions

- From LHCb data, prompt fraction for ψ' saturates at large multiplicity
- Assumption:
  prompt cross section is sum of
  - term with survival probability S and term with survival probability 1

$$S\left(\frac{dN}{dy}\right) = \exp\left[-\frac{\langle v\sigma\rangle}{\sigma_0}\frac{dN}{dy}\log\left(\frac{1}{N_0}\frac{dN}{dy}\right)\right]$$

- 26 data points
  7 fitting parameters
  $\chi^2/\mathrm{dof} = 0.99$



[Braaten, He, Ingle, Jiang (2021)]

- X as a charm-meson molecule can reproduce LHCb data if

$$\langle v\sigma\rangle_X \sim 2.6 \pm 0.7\ \mathrm{mb}$$

Summary

- Still no consensus on nature of $X(3872)$
- Studying production and suppression will help resolve $X(3872)$ nature
- Theory tools for understanding suppression of $X(3872)$:
  - Comover Interaction Model, *Cold nuclear matter effects…*

THANK YOU!