THE OHIO STATE UNIVERSITY

Charm 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 [LHCb (2011), CMS (2011), ATLAS (2016)]

Most precise mass and first width [LHCb (2020)]:

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

7 observed decay channels

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

Brief Review of $X(3872)$

Decays into $J/\psi\pi^+\pi^- = J/\psi\rho$ and $J/\psi\pi^+\pi^-\pi^0 = J/\psi\omega$ indicate severe isospin violation

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

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

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

$|E_X| < 0.22$ MeV at 90% C.L.

$$\gamma_X = \sqrt{2\mu_{D^*\bar{D}}|E_X|} < 21 \text{ MeV}$$

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:

- Hybrid: combination of heavy quarks and a constituent gluon
- Hadroquarkonia: heavy charmonium core $c\bar{c}$ surrounded by light meson $q\bar{q}$ bound by QCD analog of van der Waals force
- Compact tetraquark: diquark and anti-diquark bound by color interactions
- Charmonium: $\chi_{c1}(2P)$
- Cusp: discontinuity in differential cross section across threshold

Regardless, the coupling of X to $D^{*0}\bar{D}^0$ transforms it into a large charm-meson molecule

Much past research has tried to use decay-channel predictions to determine the nature of X but without much success

More recently production and suppression mechanisms have been used to help determine X nature

Production of $X(3872)$ at hadron colliders

Production of $X(3872)$ at hadron colliders

Two contributions to inclusive production

- Prompt production at primary collision vertex
- Production by b hadron decay at secondary vertex

Convenient to benchmark $X(3872)$ against $\psi(2S) = \psi(3686)$

- Both are observed in $J/\psi\pi^+\pi^-$ channel
- They have similar masses

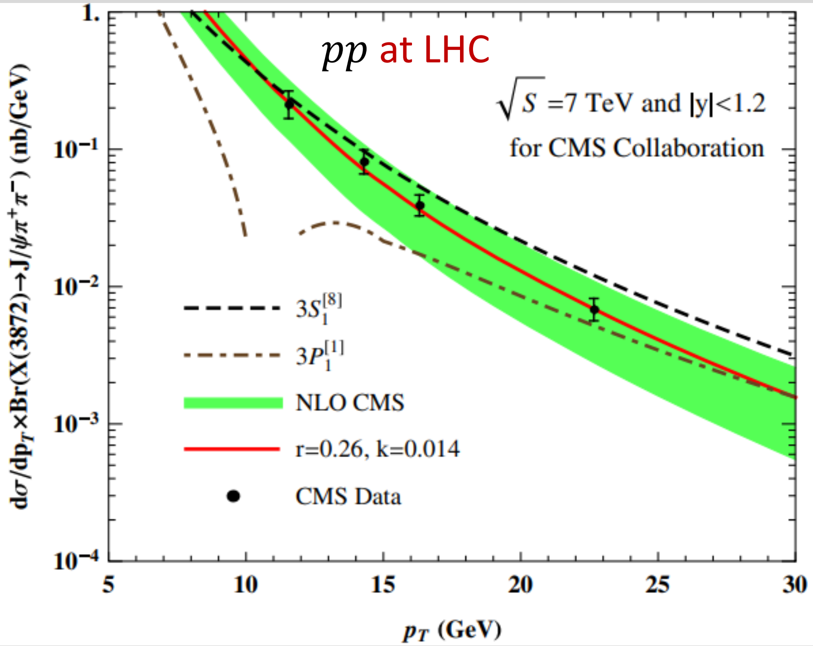
Production of $X(3872)$ at hadron colliders in NRQCD

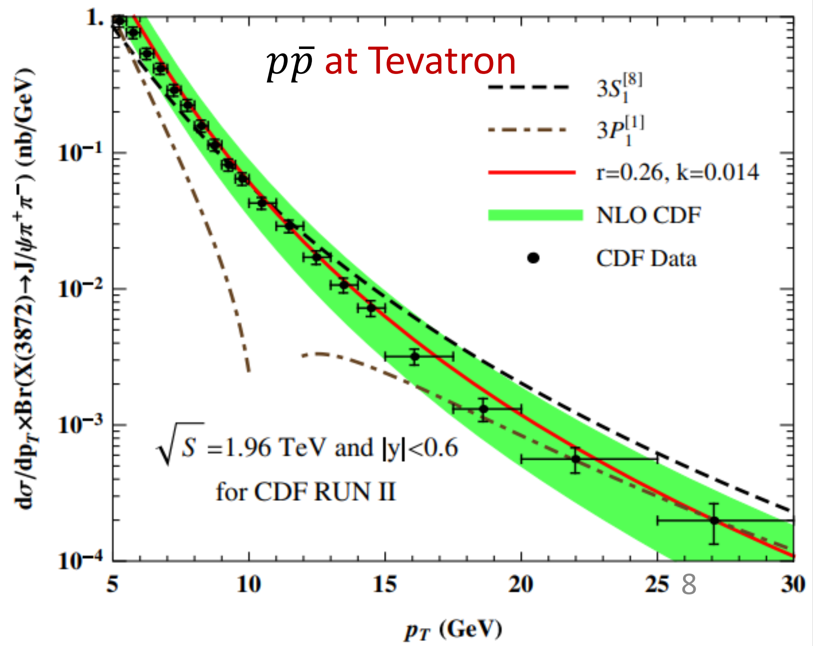
Cross section for producing X related to cross section for creating $c\bar{c}$ at short distances through Long Distance Matrix Elements (LDMEs)

[Meng, Han, Chao (2017)] calculate p_T-distribution assuming production of X dominated by $\chi_{c1}(2P)$ component

LDMEs at NLO in NRQCD:

- $\widehat{\mathrm{O}}^{\chi'_{c1}}\left(3S_1^{[8]}\right)$: from fits
- $\widehat{\mathrm{O}}^{\chi'_{c1}}\left(3P_1^{[1]}\right)$: 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 $|\langle\chi'_{c1}|X\rangle|^2$
  - ➢ Using $\mathrm{Br}_{X\to J/\psi\pi^+\pi^-} = 4.1\%$ from [Li, Yuan (2019)] I get $Z_{c\bar{c}} \approx 34\%$





Production of $X(3872)$ at hadron colliders

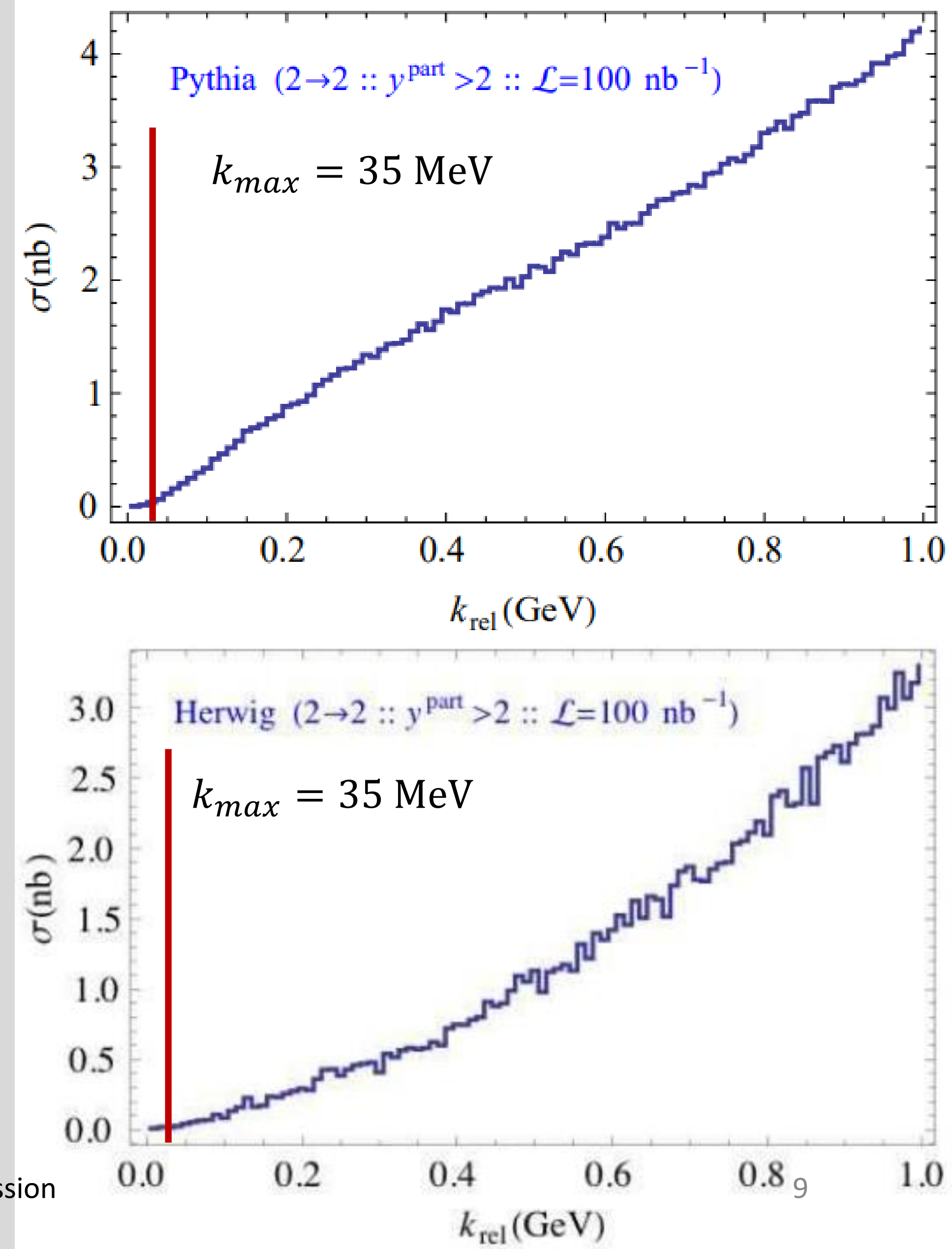
[Bignamini *et al.* (2009)] If X is a loosely bound charm-meson molecule its cross section can be approximated by the cross section for producing $D^{*0}\bar{D}^0$ with relative momentum k less than some k_{max}

$$\sigma[X] = \sigma[D^{*0}\bar{D}^0(k < k_{max})]$$

Assume that $k_{max} \approx \gamma_X$, $\gamma_X = \sqrt{2\mu_{D^{*0}\bar{D}^0}|E_X|}$

Calculate $\sigma[D^{*0}\bar{D}^0]$ using PYTHIA and HERWIG event generator

Calculated cross section at Tevatron is orders of magnitudes smaller than observed cross section



Production of $X(3872)$ at hadron colliders

$$\sigma[X] = \sigma[D^{*0}\bar{D}^0(k < k_{max})]$$

[Artoisenet, Braaten (2010)]

- Assume that $k_{max} \approx m_\pi$
- Calculated $\sigma[D^{*0}\bar{D}^0]$ using PYTHIA event generator

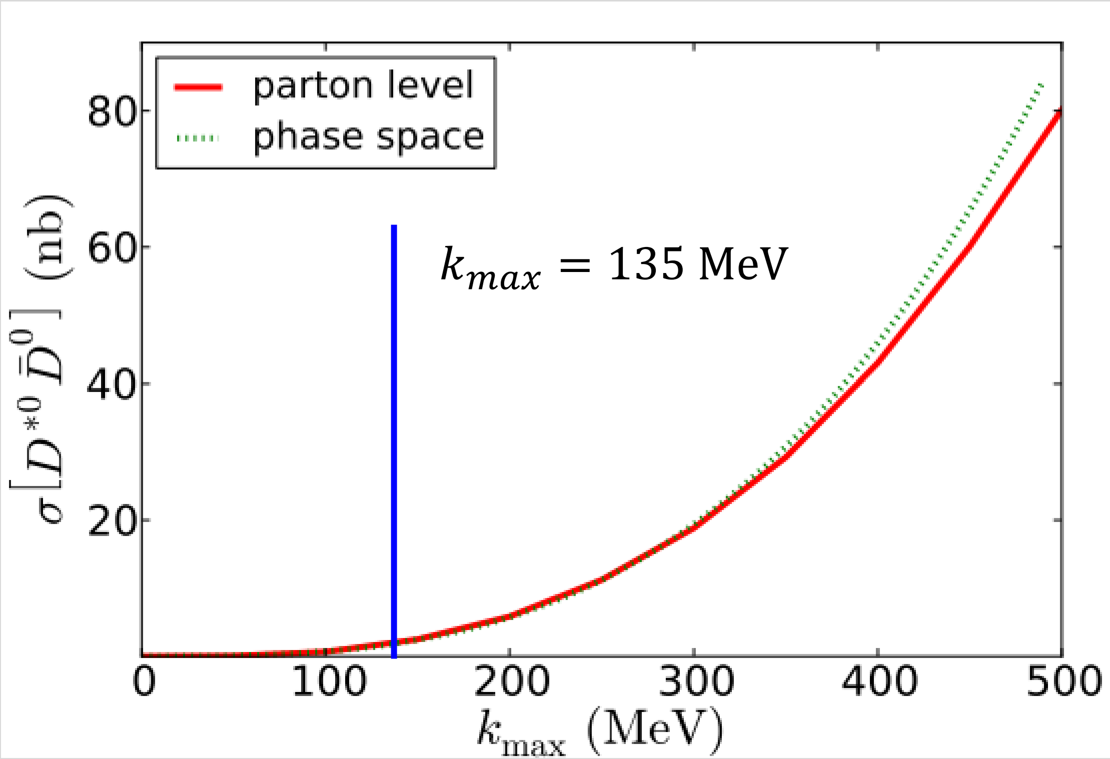
[Albaladejo *et al.* (2017)]

- Used deuteron to show that $k_{max} \sim m_\pi$, similar should be true for $X(3872)$

[Braaten, He, Ingles (2019)]

- Quantitative estimate on $k_{max} = 7.7\gamma_X$, where $\gamma_X = \sqrt{2\mu_{D^{*0}\bar{D}^0}|E_X|}$
  Note: $7.7^3 \approx 500$

Cross section of $X(3872)$ as a molecule reproduces order of magnitude of experiments



LHCb: $2.5 < y < 4.5,\ 5 < p_T < 20$ GeV/c
$\sigma[X]\mathrm{Br}[X \to J\psi\pi^+\pi^-] = 5.4 \pm 1.3 \pm 0.8$ nb

CMS: $y < |1.2|,\ 10 < p_T < 20$ GeV/c
$\sigma[X]\mathrm{Br}[X \to J\psi\pi^+\pi^-] = 1.06 \pm 0.11 \pm 0.15$ nb

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

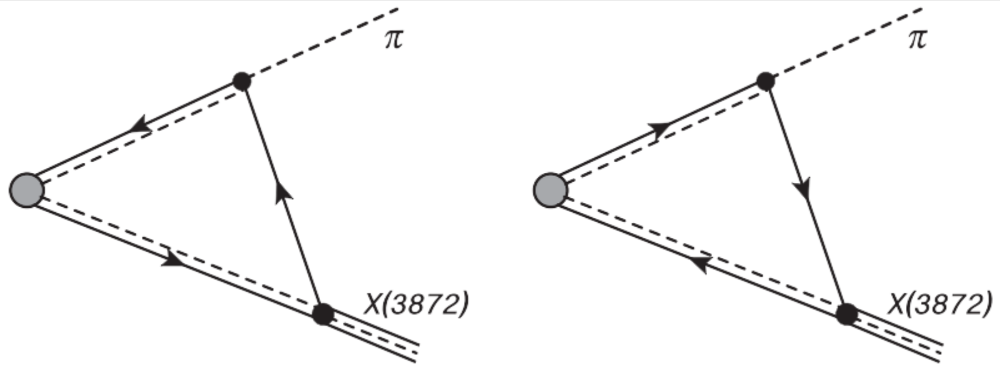
Production of X can come from creation of $\bar{D}^0 D^{*0}, D^0 \bar{D}^{*0}$ at short distances

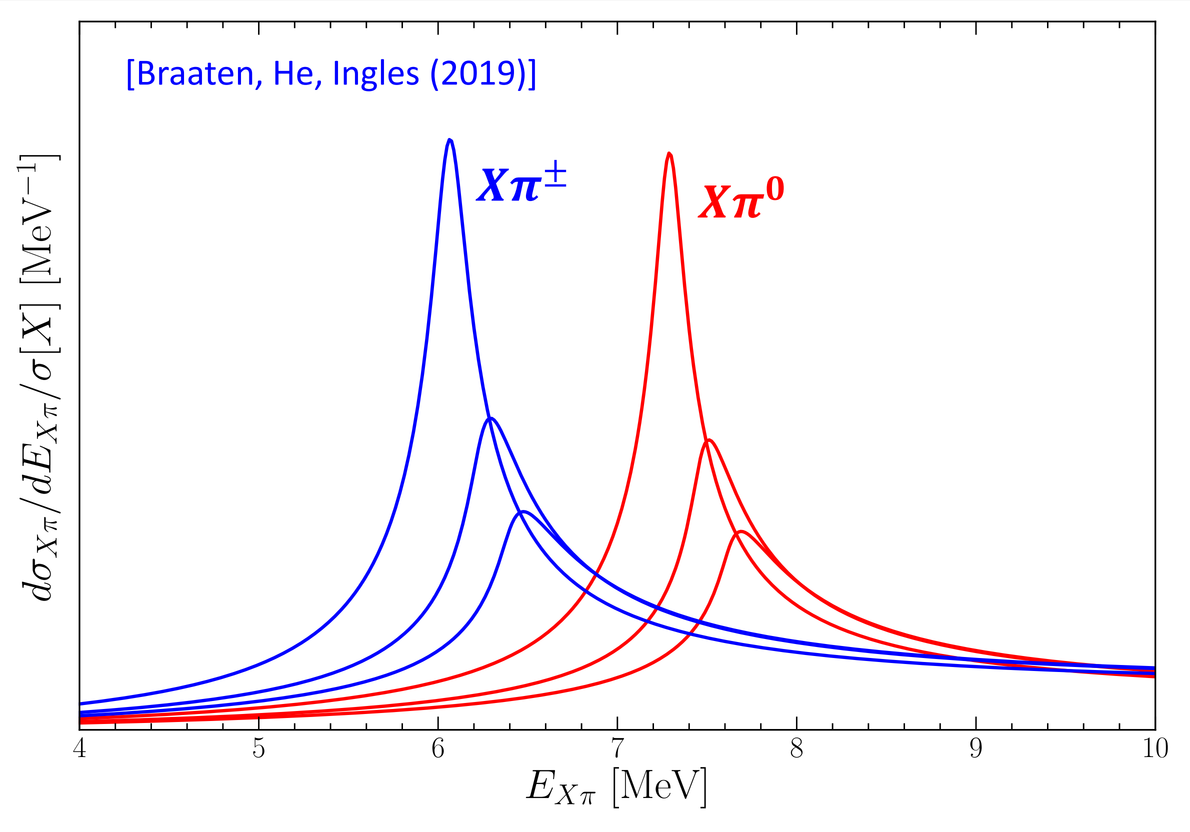
Production of $X\pi^+$ with soft π can come from creation of $D^{*+}\bar{D}^{*0}$ at short distances

- 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 (or pions)
  Comover Interaction Model (CIM)

Proton-nucleus collision:

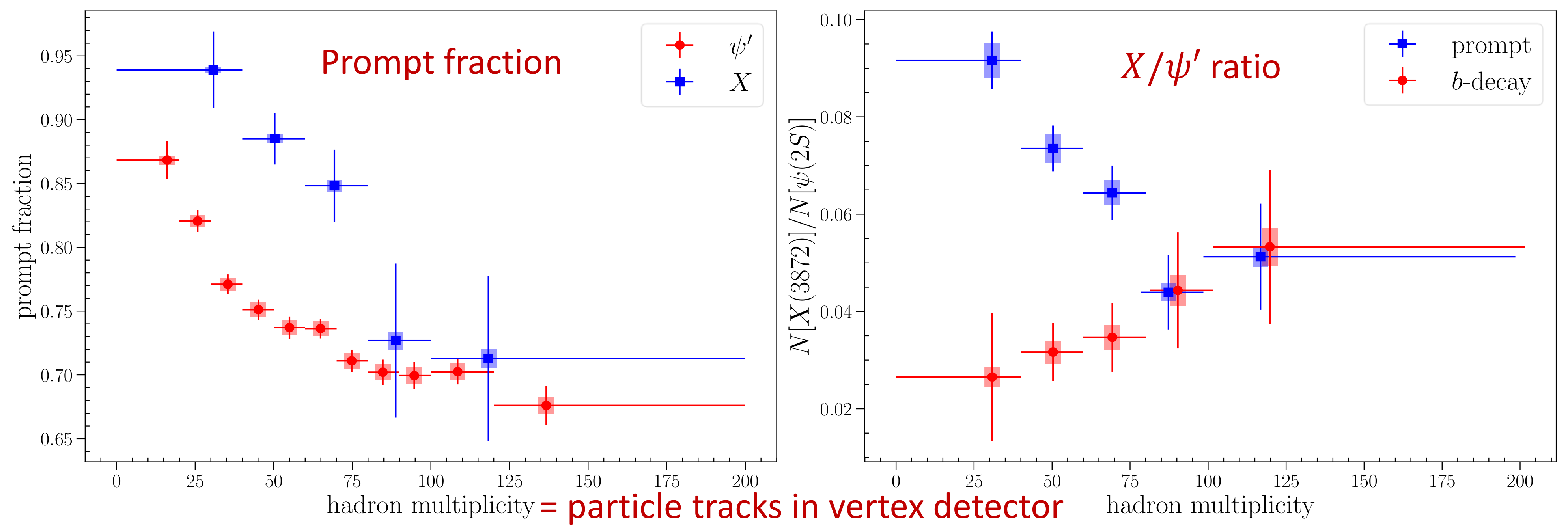
- Interactions with comoving gluons (or pions)
- Cold nuclear matter effects: PDFs of p and n, nuclear shadowing, absorption by nucleons etc.

Nucleus-Nucleus collision:

- Interactions with comoving gluons (or pions)
- Cold nuclear matter effects
- Thermal effects in quark-gluon plasma
- 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



= particle tracks in vertex detector

Prompt fractions for X and ψ' decrease with multiplicity

Prompt fraction for ψ' seems to saturates at large multiplicity

Suppression of $X(3872)$ in pp collision

Survival probability in Comover Interaction Model [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 center-of-mass energy

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

$$\langle v\sigma\rangle = \pi\langle r^2\rangle;$$

r^2: separation squared of constituents
E^{thr}: energy required to break X apart
E: gluon (or pion) relativistic energy

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

$$T_{eff} = (250 \pm 50)\ \mathrm{MeV}$$

Suppression of $X(3872)$ in pp collisions

[Esposito, *et al.* (2020)] estimated X/ψ' ratio assuming CIM and

- X as a tightly bound tetraquark $\langle v\sigma \rangle \sim 10$ mb
- X as charm-meson molecule $\langle v\sigma \rangle \sim 1200$ mb
- X as charm-meson molecule and with processes

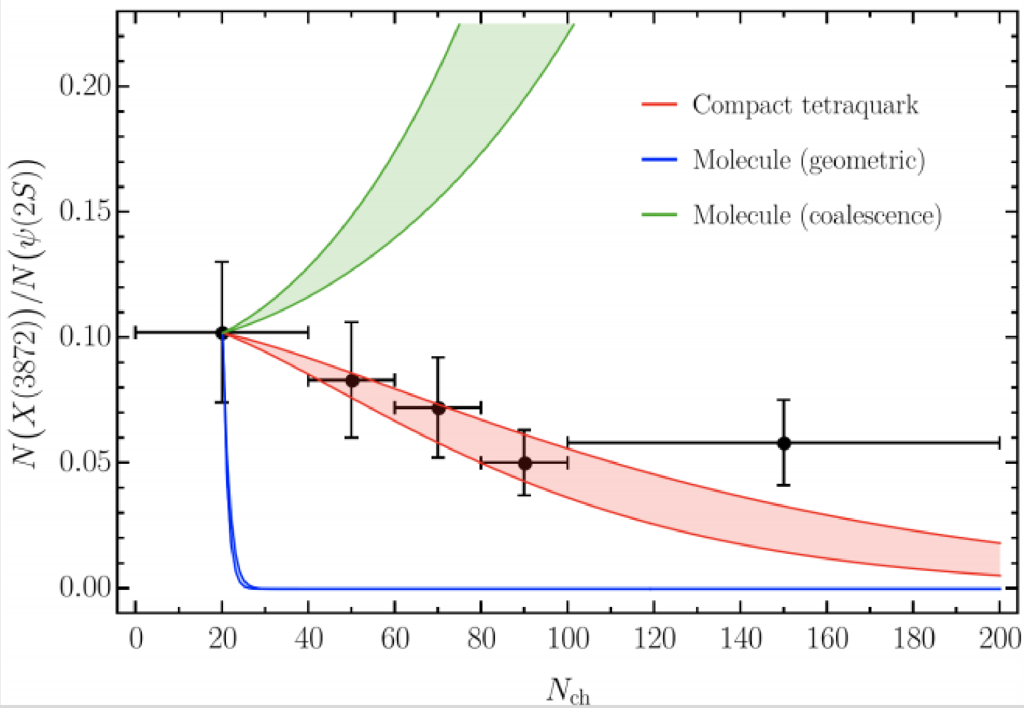
$$\pi \bar{D} D^* \to X\pi$$

Glauber Monte Carlo modeling

- Generate distribution of comovers' momentum and spacetime distributions
- X can only interact with comovers within range r given by geometric cross section $\pi\langle r^2 \rangle$

Authors conclude that CIM favors tetraquark interpretation

Prompt X-to-J/ψ ratio



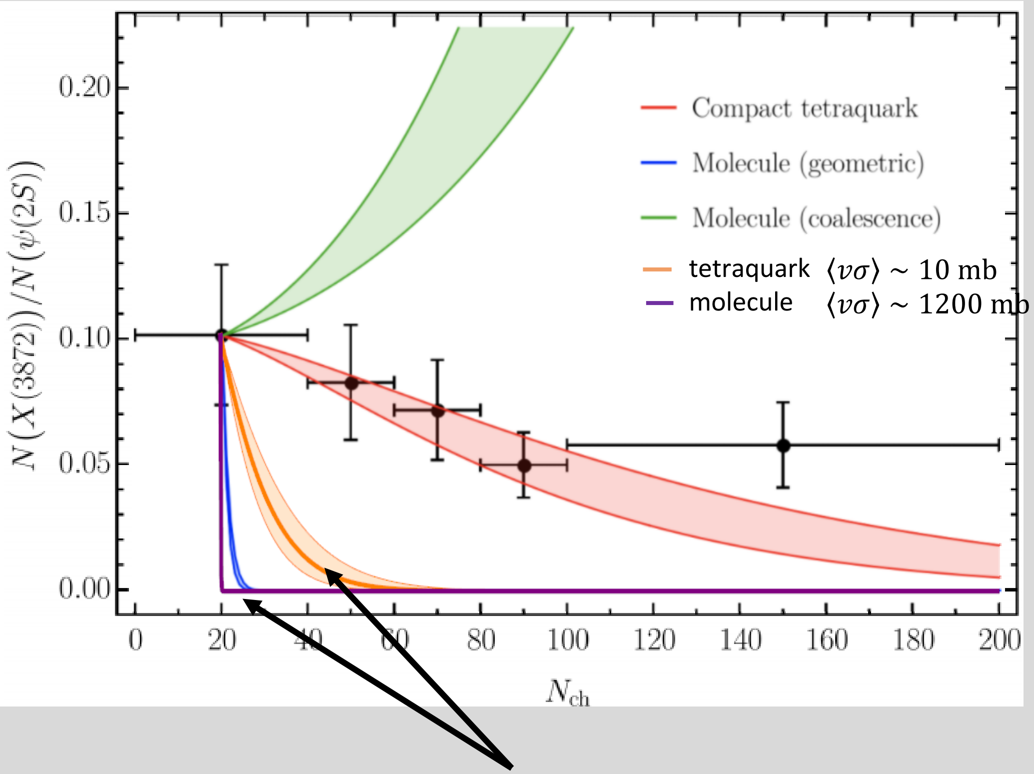
Suppression of $X(3872)$ in pp collisions

Problem with few-body physics from Esposito *et al.* (2020): their breakup reaction rate given by geometric cross section $\pi\langle r^2\rangle$ where $\langle r^2\rangle \propto E_X^{-1}$

But breakup reaction rate in the high energy limit should be given by cross section for scattering with constituents $\sim (m_\pi/f_\pi^2)^2$

Survival probability from CIM gives exponential suppression as function of multiplicity

- LHCb data indicates a saturation



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

Suppression of $X(3872)$ in pp collisions

From LHCb data, prompt fraction for ψ' seems to saturates at large multiplicity

Assumptions of arXiv:2012.13499:

1. prompt cross section is sum of
   - term with survival probability $S = \exp\left[-\frac{\langle v\sigma\rangle(dN/dy)}{\sigma_0}\log\left(\frac{dN/dy}{N_0}\right)\right]$
   - term with survival probability 1
2. b-decay cross section independent of dN/dy

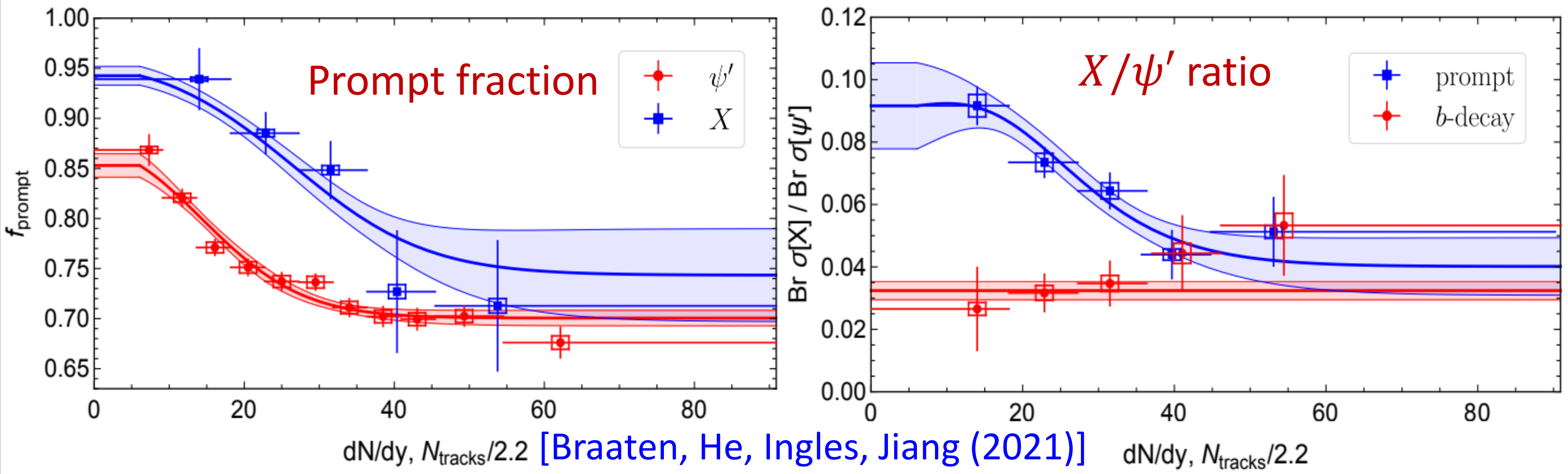
26 data points

7 fitting parameters

$$\chi^2/\mathrm{dof} = 0.99$$

Fitted reaction rates

$$\langle v\sigma\rangle_{\psi'} = 3.9 \pm 0.8\ \mathrm{mb}$$
$$\langle v\sigma\rangle_X = 2.6 \pm 0.7\ \mathrm{mb}$$



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

Suppression of $X(3872)$ in pp collisions

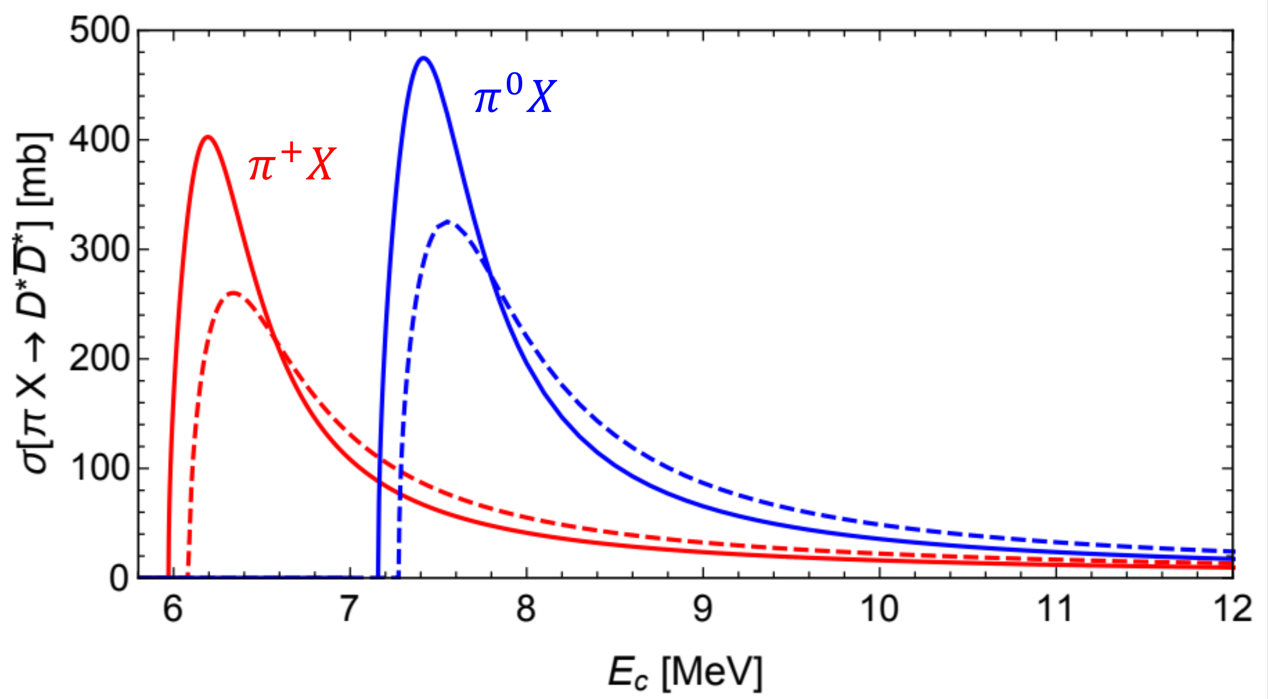
Cross section for πX scattering in XEFT
E_c - comover energy relative to πX threshold

Narrow peak in $\pi^+ X$ 6 MeV above threshold
Narrow peak in $\pi^0 X$ 8 MeV above threshold

Order of magnitude at peak is geometric mean of geometric cross section $\pi\langle r^2\rangle$ and cross section for scattering with constituents $(m_\pi/f_\pi^2)^2$

Cross section for πX scattering decreases to cross section for scattering with constituents $\pi D^{(*)}$ at higher energies

$$\sigma(\pi X) \sim \left(\frac{m_\pi}{f_\pi^2}\right)^2 = 25 \text{ mb}$$



Summary

Still no consensus on nature of $X(3872)$

Studying production and suppression mechanisms will help reveal $X(3872)$ nature

Important to use correct few-body physics for $X(3872)$

Fitted results of multiplicity dependence from LHCb suggest breakup reaction rate for $X(3872)$ from collisions with comoving pions should be of order 3 mb

THANK YOU!