Production of *X(3872)* at High Multiplicity

Eric Braaten
Ohio State University

Li-Ping He, Kevin Ingles (Ohio State University)


Jun Jiang (Shandong University)

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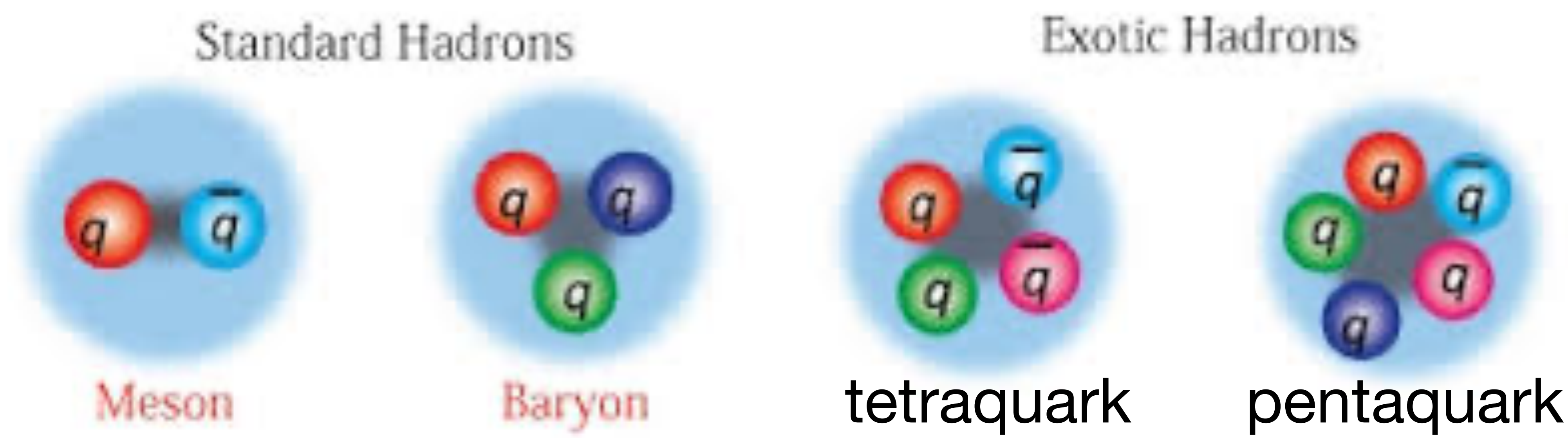
Exotic Heavy Hadrons

heavy: contains charm or bottom quarks
exotic: not predicted by quark model



tetraquark meson?

pentaquark baryon?

dozens of exotic heavy hadrons have been discovered beginning with *X(3872)* in 2003

<u>challenge to particle theory</u>
explain the exotic heavy hadrons that have been discovered
predict those that remain to be discovered

$X(3872) \equiv \chi_{c1}(3872)$

discovered at e^+e^- collider Belle 2003

$B^+ \to K^+ X, \quad X \to J/\psi\, \pi^+\pi^-$

confirmed at $p\bar{p}$ collider CDF 2003

- quantum numbers $J^{PC} = 1^{++}$ LHCb 2013
- mass LHCb 2020
  extremely close to $D^{*0}D^0$ threshold
  $E_X \equiv M_X - (M_{D^{*0}} + M_{D^0}) = (-0.07 \pm 0.12)$ MeV
  $|E_X| < 0.22$ MeV at 90% CL
- width (Breit-Wigner) LHCb 2020
  $\Gamma_X = (1.19 \pm 0.19)$ MeV
- 7 observed decay modes
  $J/\psi\, \pi^+\pi^-$, $J/\psi\, \pi^+\pi^-\pi^0$, $J/\psi\, \gamma$, $\psi(2S)\, \gamma$, $\chi_{c1}\, \pi^0$, $D^0\bar{D}^0\gamma$, $D^0\bar{D}^0\pi^0$

What is the $X(3872)$?

given: $J^{PC} = 1^{++}$, $|E_X| < 0.22$ MeV

loosely bound charm-meson molecule !!

$$X(3872) = (D^{*0}\bar{D}^0 + D^0\bar{D}^{*0})/\sqrt{2}$$

+ small admixture of $D^0\bar{D}^0\pi^0$

universal properties

determined by binding energy $|E_X|$

wavefunction $\psi(r) = \mathrm{Exp}[-\gamma_X r]/r$, $\gamma_X = \mathrm{Sqrt}[2\mu|E_X|]$

mean separation of constituents: $r_X = 1/(2\gamma_X)$

$$|E_X| < 0.22 \text{ MeV} \Longrightarrow r_X > 4.8 \text{ fm}$$

What *would* the $X(3872)$ be?

if not for fine-tuning of its mass to $D^{*0}D^0$ threshold

- P-wave charmonium state ?? $\chi_{c1}(2P) = c\,\bar{c}$
- isospin-0 charm-meson molecule ??

  $[\,(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}) + (D^{*+}D^- + D^+D^{*-})\,]/2$
- isospin-1 compact tetraquark ??

  $[\,(cu)(\bar{c}\bar{u}) - (cd)(\bar{c}\bar{d})\,]/\sqrt{2}$
- other ??

In all cases, $X(3872)$ is transformed into charm-meson molecule $(D^{*0}\bar{D}^0+D^0\bar{D}^{*0})/\sqrt{2}$ by resonant coupling to $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$

Production of *X(3872)* at Hadron Collider

production by *b* hadron decay

decay products emerge from displaced secondary vertex

number of charged particles: $N_{ch} < 10$

example: $B^+ \to K^+ X$, $X \to J/\psi\ \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$ ($N_{ch} = 5$)

prompt production by QCD mechanisms

decay products emerge from primary collision vertex

number of charged particles: N_{ch} ~ 100's

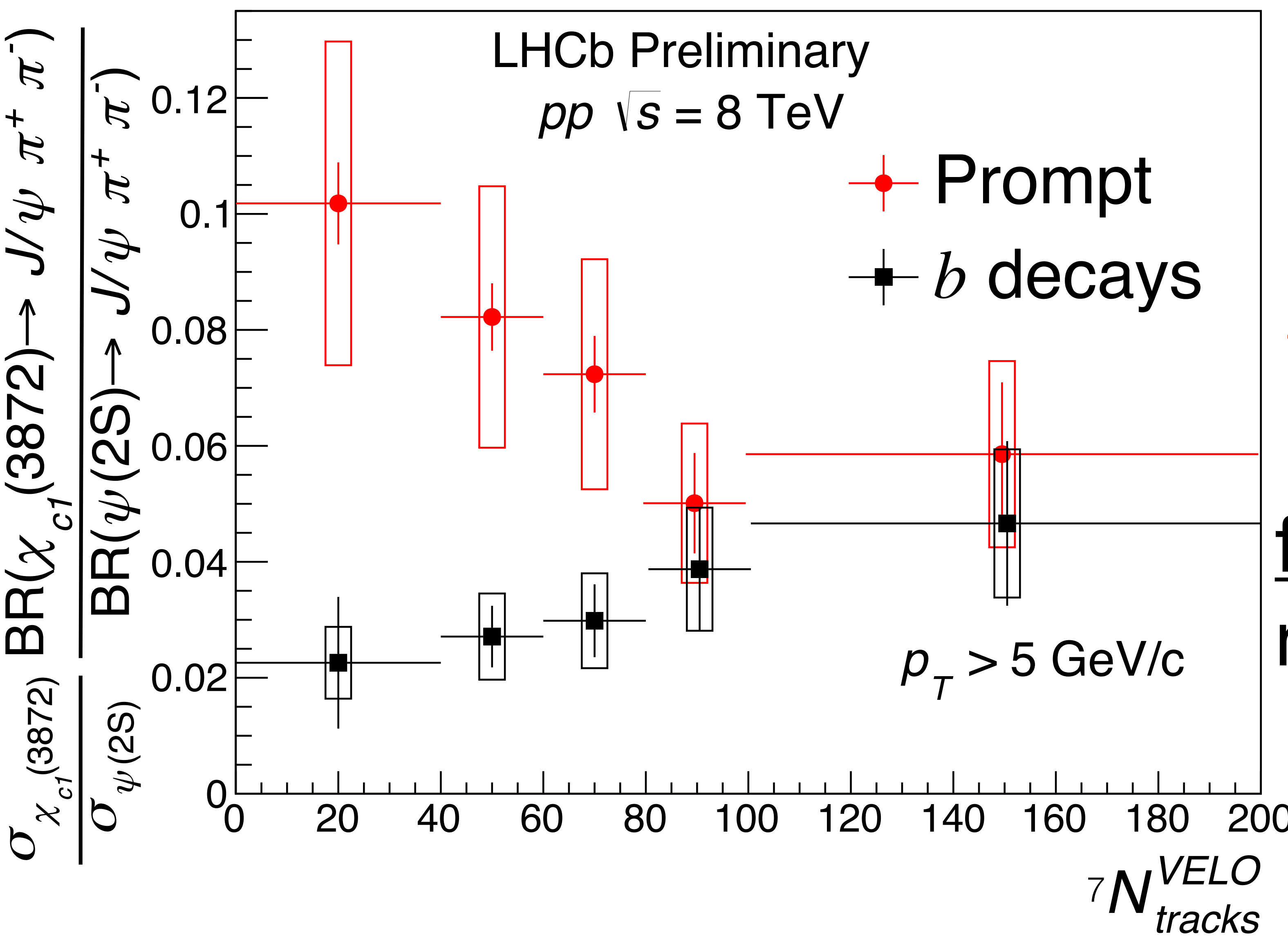
dN_{ch}/dy ~ 10's

Production of *X(3872)*

Dependence on Hadron Multiplicity

pp collisions at Large Hadron Collider LHCb 2020

measure $\frac{\text{Br } \sigma[X(3872)]}{\text{Br } \sigma[\psi(2S)]}$ as function of number of tracks in vertex detector



prompt

ratio decreases with N_{tracks}

from *b* decay

no significant dependence of ratio on N_{tracks}

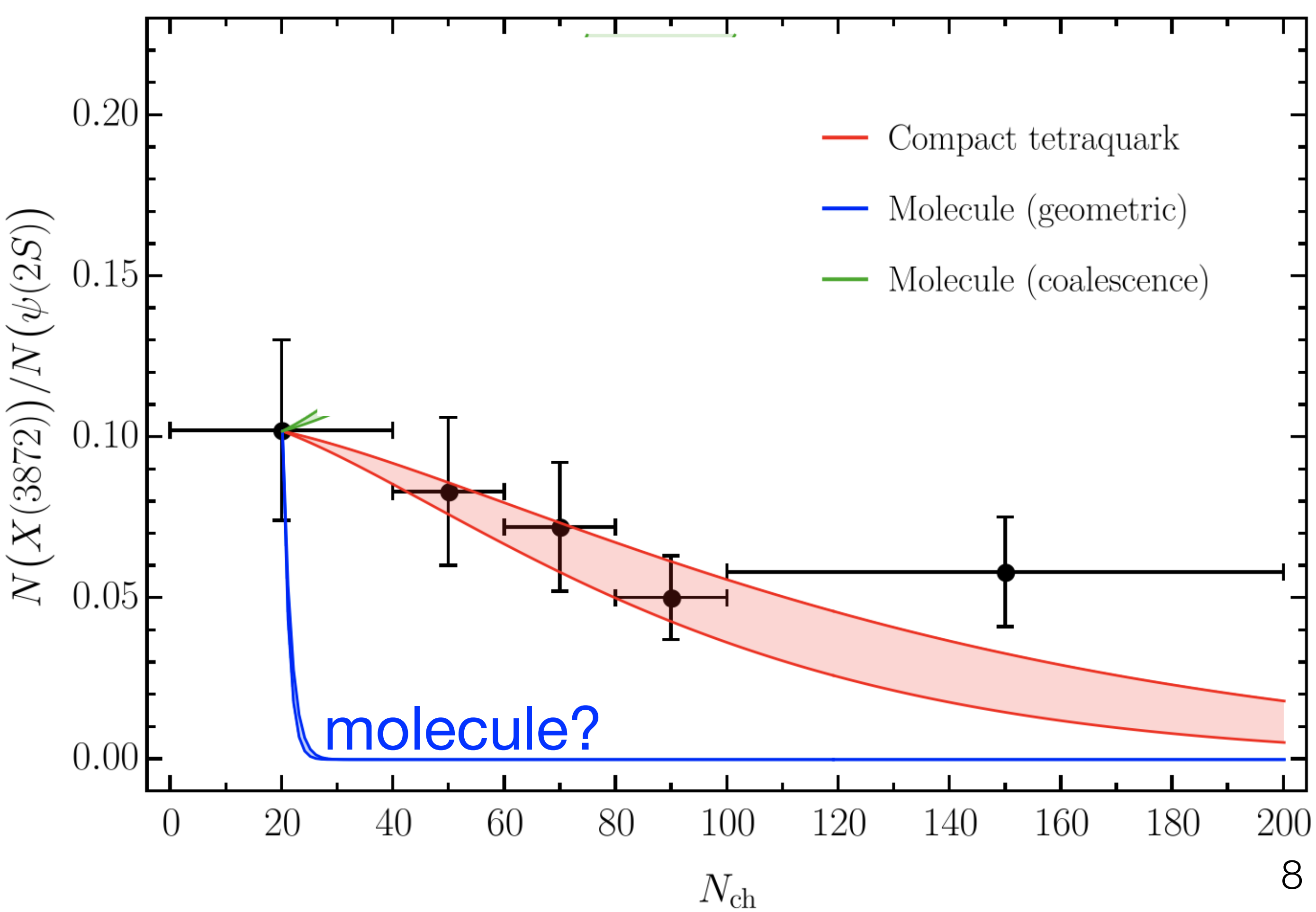
Prompt Production of *X(3872)*

Dependence on Hadron Multiplicity

Esposito et al. arXiv:2006.15044

used Comover Interaction Model to

predict $\frac{N[X(3872)]}{N[\psi(2S)]}$ as function of charged-hadron multiplicity N_{ch}



"clearly supports *X* being a tetraquark state"

"strongly disfavors the molecular interpretation"

Comover Interaction Model

Capella et al., Gavin and Vogt, Kharzeev et al. (1996)
describes suppression of J/ψ and $\psi(2S)$
in *pp*, *p*-nucleus, nucleus-nucleus collisions

- breakup of $c\bar{c}$ meson by collision with comover (gluon OR pion)

Ferreiro & Lansberg 2018
more elaborate version of CI Model
describes suppression of $\Upsilon(2S)$, $\Upsilon(3S)$ compared to Υ

- momentum distribution of comovers:
  Bose-Einstein distribution in rest frame of $b\bar{b}$ meson
  with effective temperature: $T_{\mathrm{eff}} = (250 \pm 50)$ MeV

- cross section for breakup of $b\bar{b}$ meson:
  $\sigma \approx \pi r^2$, r = mean separation of constituents

Prompt Production of *X(3872)*

Dependence on Hadron Multiplicity

Esposito et al. arXiv:2006.15044

applied Comover Interaction Model to *X(3872)* and *ψ(2S)*

Survival Probability

as function of charged-hadron multiplicity dN_{ch}/dy

$$S = \exp\left(- \frac{\langle v\sigma \rangle (dN_{\rm ch}/dy)}{\sigma_{pp}} \log \frac{dN_{\rm ch}/dy}{\sigma_{pp}\rho} \right)$$

σ_{pp}, ρ: phenomenological parameters

$\langle v\sigma \rangle$ = breakup reaction rate averaged over comovers

assume $\langle v\sigma \rangle \approx \pi\, r^2$, r = mean separation of constituents

$r_{\psi(2S)}$ = 0.45 fm

$r_{X(3872)}$ = 0.65 fm if X is compact tetraquark

$r_{X(3872)}$ = 6.6 fm if X is charm-meson molecule with binding energy 116 keV

XEFT

Fleming, Kusunoki, Mehen & van Kolck 2007
Effective Field Theory for charm mesons and pions

XEFT describes $D^*\bar{D}$, $D\bar{D}^*$, $D\bar{D}\pi$, X with total energy near D^*D threshold

XEFT can also describe $D^*\bar{D}^*$, $D^*\bar{D}\pi$, $D\bar{D}^*\pi$, $D\bar{D}\pi\pi$, $X\pi$
with total energy near D^*D^* threshold arXiv:1005.1688
can calculate cross sections for breakup of X
by scattering of low-energy pion:

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

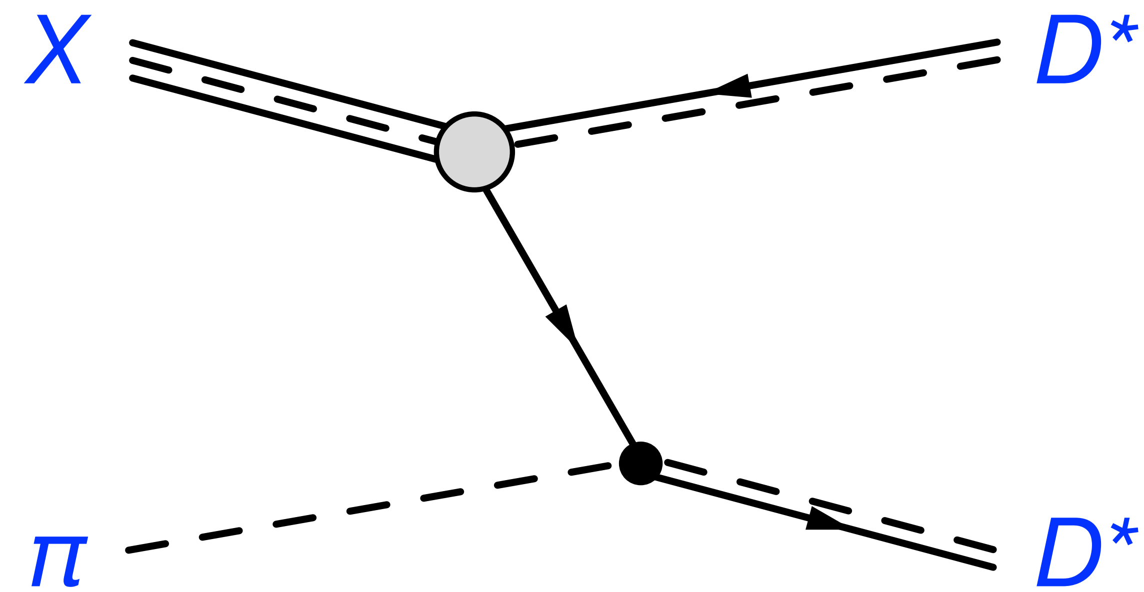
Galilean-invariant formulation of XEFT arXiv:1503.04791
exploits approximate conservation of mass in $D^* \leftrightarrow D\pi$
improved formulation of Galilean-invariant XEFT
Braaten, He & Jiang arXiv:2010.05801

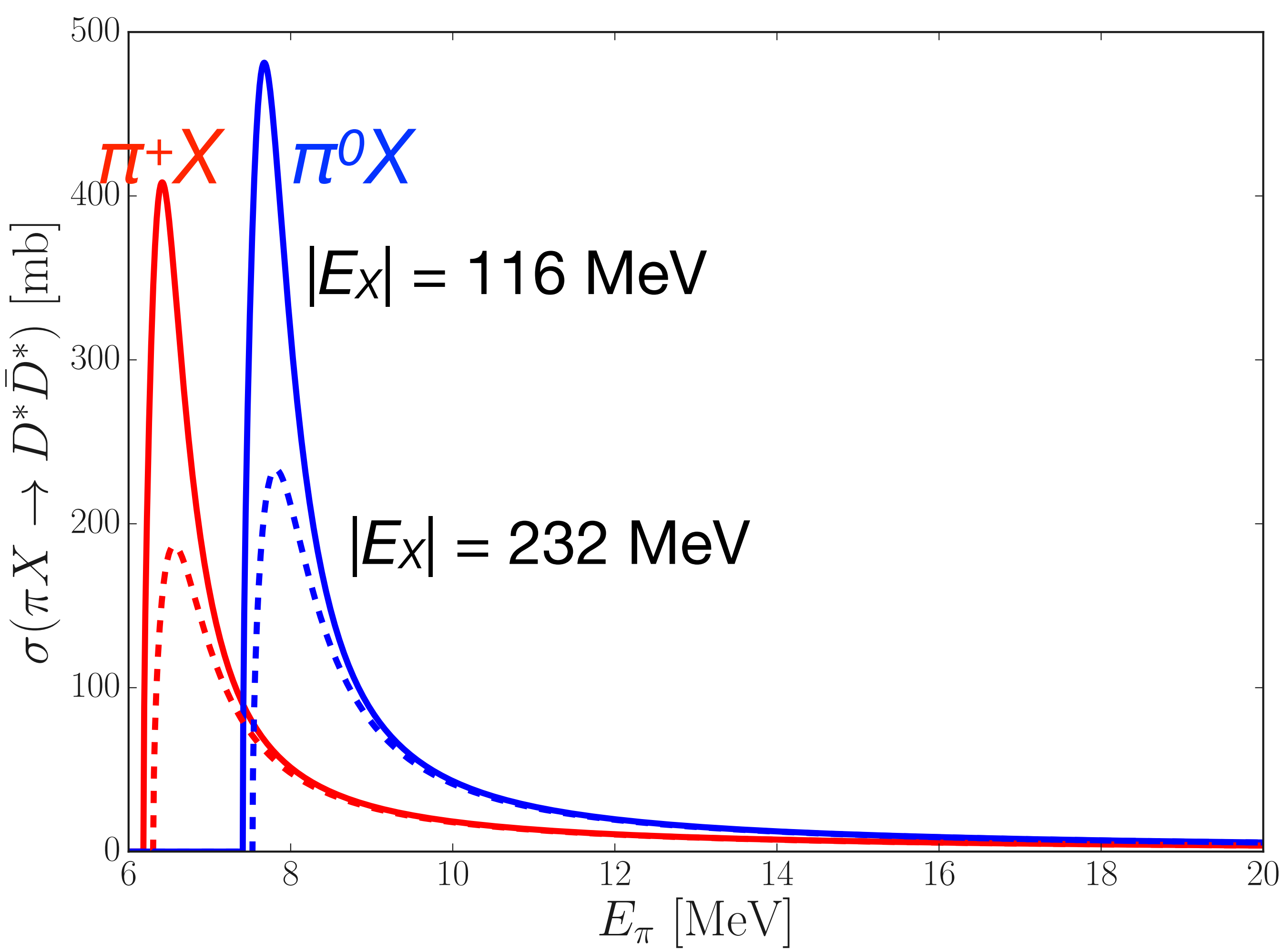
large NLO corrections in XEFT ??
Dai, Guo & Mehen arXiv:1912.04317

πX Breakup Scattering

Low-energy pions

calculate cross section using XEFT





cross sections dominated by D^* resonances (and D resonances ?)

contribution to $\langle v\sigma[\pi X]\rangle$ from D^* resonances:

15^{+14}_{-6} μb if T_{eff} = (250±50) MeV

πX Breakup Scattering

High-energy pions

pions scatter from constituents: D^{*0}, $\bar{D}^0$, D^0, $\bar{D}^{*0}$

$$\sigma[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$

can estimate reaction rates from high energy pions

using Lin, Di & Ko   nucl-th/0006086

hadrons in thermal equilibrium at temperature T up to 200 MeV

reaction rates $\langle v\sigma \rangle$ for πD, πD^* as functions of T

$\langle v\sigma[\pi D]\rangle + \langle v\sigma[\pi D^*]\rangle = (26\pm11)$ mb at $T = 200$ MeV

approximate $\langle v\sigma[\pi X]\rangle$ in X rest frame at $T = (250\pm50)$ MeV

by $\langle v\sigma[\pi D]\rangle + \langle v\sigma[\pi D^*]\rangle$ in thermal frame at $T_{eff} = 200$ MeV

Prompt Production of *X(3872)*
Dependence on Hadron Multiplicity

<u>reaction rates</u> for *X(3872)* and *ψ(2S)* breakup

Esposito et al.

ψ(2S): ⟨$v\sigma$⟩ = (5.2 ± 0.8) mb

X(3872): ⟨$v\sigma$⟩ = (11.6 ± 1.7) mb if *X* is a tetraquark

X(3872): ⟨$v\sigma$⟩ = (1200 ± 170) mb if *X* is a molecule

scattering from *D*, *D** constituents of molecule

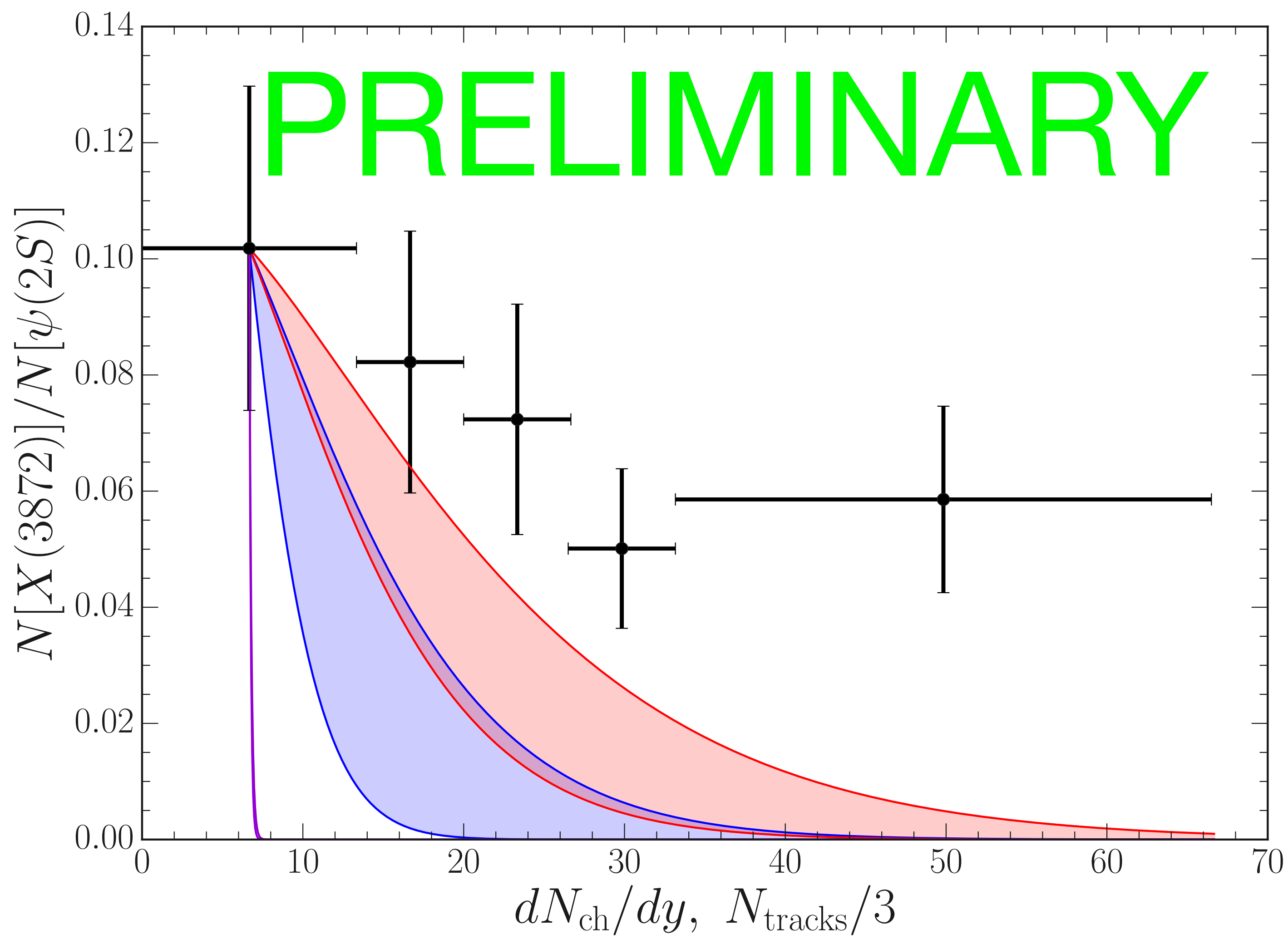
X(3872): ⟨$v\sigma$⟩ = (26 ± 11) mb

$$\frac{\mathrm{N}[X(3872)]}{\mathrm{N}[\psi(2S)]}$$

as function of

charged-hadron multiplicity

dN_{ch}/dy ≈ N_{tracks}/3



Production of $X(3872)$ at High Multiplicity

given $J^{PC} = 1^{++}$, $|E_X| < 0.22$ MeV

$X(3872)$ must be a loosely bound charm-meson molecule
with universal properties determined by $|E_X|$

$$X(3872) = \left(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0} \right)/\sqrt{2}$$

if not for fine-tuning of its mass to $D^{*0}D^0$ threshold

$X(3872)$ could have been

- P-wave charmonium state
- isospin-0 charm-meson molecule
- isospin-1 compact tetraquark
- other

but it is transformed into charm-meson molecule
by resonant interactions with $D^{*0}\bar{D}^0$, $D^0\bar{D}^{*0}$

Production of *X(3872)* at High Multiplicity

X(3872) can be broken up by scattering with comoving pions

- for low-energy pions
  breakup cross section can be calculated using XEFT

- for high-energy pions
  breakup cross section is dominated
  by scattering from constituents D^{*0}, $\bar{D}^0$, D^0, $\bar{D}^{*0}$

- contrary to assumption of Esposito et al.
  πX breakup cross section
  is insensitive to tiny binding energy of X
  (and huge mean separation of its constituents)

Production of *X(3872)* at High Multiplicity

prompt production of *X(3872)* in *pp* collisions
LHCb has observed decrease in ratio *X(3872)*/*ψ(2S)* with increasing multiplicity

dependence on multiplicity
predicted by Comover Interaction Model

- roughly compatible with charm-meson molecule
- compatible with <u>fictitious</u> compact tetraquark that does not couple to $D^{*0}\bar{D}^0$ or $D^0\bar{D}^{*0}$

Esposito et al. arXiv:2006.15044

<u>future</u>

develop quantitative description of dependence on multiplicity of production of *X(3872)* in *pp* collisions
apply to *p*-nucleus and nucleus-nucleus collisions