Production of *X(3872)*

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

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

- <u>quantum numbers</u> $J^{PC} = 1^{++}$ LHCb 2013

- <u>mass</u> LHCb 2020

  extremely close to $D^{*0}\bar{D}^0$ 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

- <u>width</u> LHCb 2020

  $\Gamma_X = (1.19 \pm 0.19)$ MeV (Breit-Wigner line shape)

- 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 molecule

of neutral charm mesons !!

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

<u>small additional components</u>

at long distances: $D^0\bar{D}^0\pi^0$

at short distances:

charged charm mesons $D^{*+}D^- + D^+D^{*-}$

P-wave charmonium $\chi_{c1}(2P)$??

compact tetraquark $[cq][\bar{c}\bar{q}]$??

What would the *X(3872)* be?

if its mass was not fine-tuned to $D^{*0}\bar{D}^0$ threshold

- P-wave charmonium state ?? $\chi_{c1}(2P) = c\bar{c}$

- isospin-0 charm-meson molecule ??

$$\left[(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}) + (D^{*+}D^- + D^+D^{*-})\right]/2$$

- isospin-1 compact tetraquark ??

$$\left([cu][\bar{c}\bar{u}] - [cd][\bar{c}\bar{d}]\right)/\sqrt{2}$$

- other ??

In all cases, *X(3872)* is transformed into neutral 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 $D^0\bar{D}^{*0}$

Universal wavefunction

for S-wave molecule near threshold

nontrivial zero-range limit $r_0 \longrightarrow 0$

completely determined by binding energy $|E_X|$

wavefunction: $\psi(r) = \exp(-r/a)/r$

scattering length: $a = 1/\sqrt{2\mu\,|E_X|}$

- large mean separation of constituents: $\langle r \rangle = a/2$

  $|E_X| <$ 0.22 MeV $\implies$ $\langle r \rangle >$ 4.8 fm

- constituents almost always beyond range: $P(r > r_0) \rightarrow 1$ as $r_0 \rightarrow 0$

- wavefunction at origin diverges as $r_0 \rightarrow 0$: $\psi(0) \longrightarrow 1/r_0$

  $P(r < r_0) = r_0/\langle r \rangle$ instead of proportional to $(r_0/\langle r \rangle)^3$

- uncertainty principle: $(\Delta r)(\Delta p) = (a/2)\left(2/\sqrt{\pi r_0 a}\right) = \sqrt{(a/r_0)/\pi}$

  $\rightarrow \infty$ as $r_0 \longrightarrow 0$

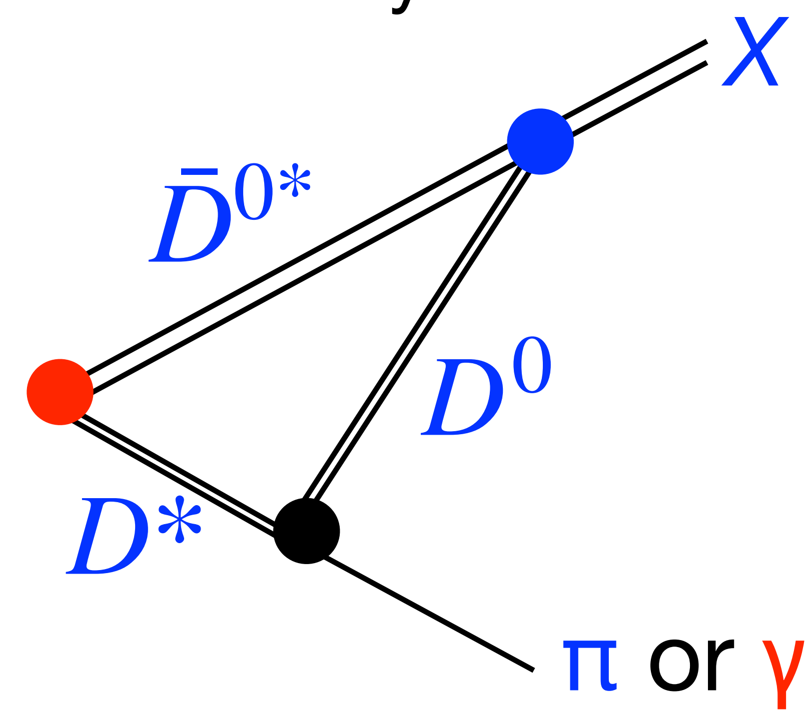
Triangle Singularities in *X(3872)* Production

see talk by Liping He at QWG March 2021

Triangle singularity

kinematic singularity when 3 lines forming triangle can all be on shell

reaction rate has $\log^2(s/s_\triangle)$ divergence at $s_\triangle$ determined by masses



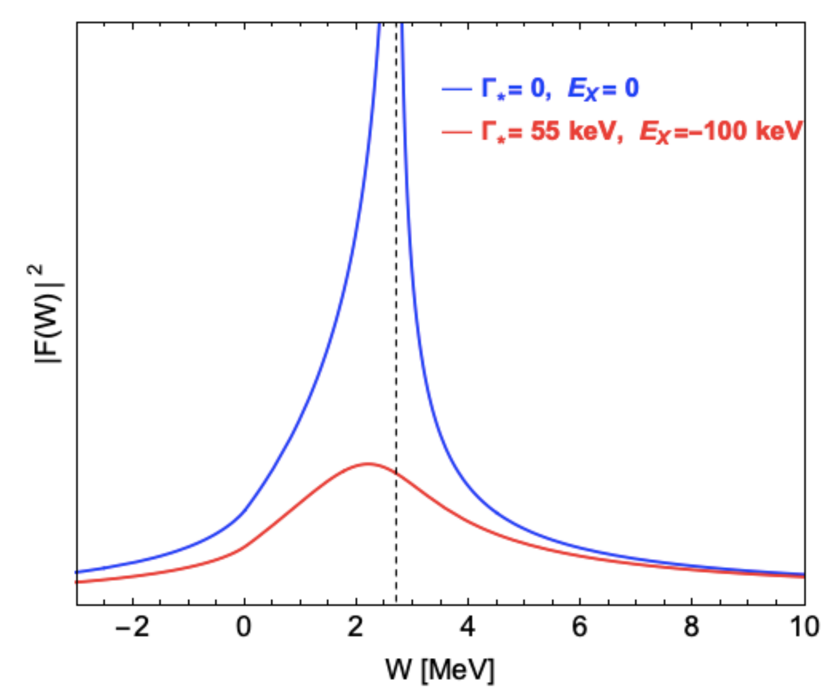
- creation of $D^*\bar{D}^*$ at short distance
- $D^*\bar{D}^*$ rescatter into $X+\pi$ or $X+\gamma$ through Δ

- $\bar{D}^{0*}$ and D^0 can be on shell if $E_X = 0$
- D^* can be on shell if $\Gamma[D^{*0}] = 0$

$|E_X| \approx 100$ keV, $\Gamma[D^{*0}] \simeq 55$ keV

$\log^2(s/s_\triangle)$ divergence is replaced by

narrow peak at $s_\triangle$, width ∼ 1 or 2 MeV



Triangle Singularities in X(3872) Production

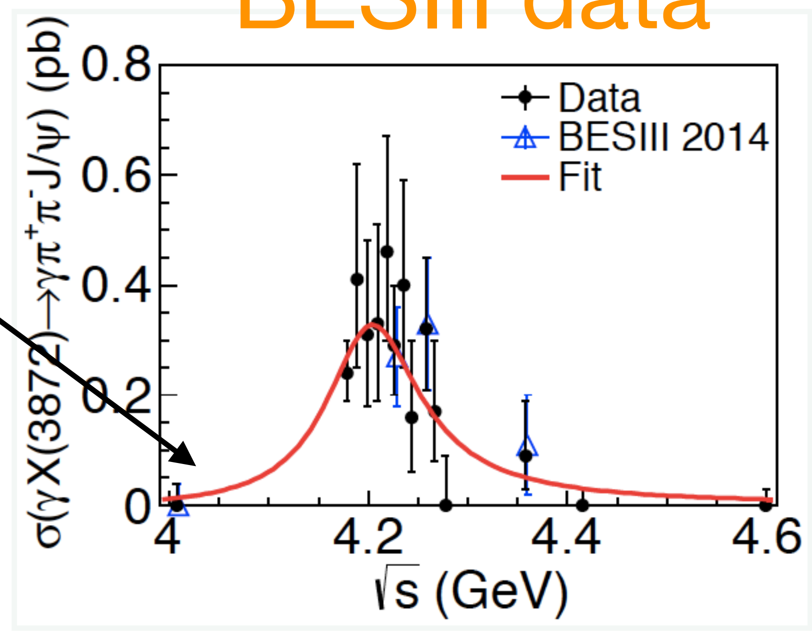
<u>e^+e^- annihilation</u> Dubinskiy & Voloshin (2006)

$e^+e^- \to X + \gamma$ BHI (2019), BHIJ (2020)

narrow peak near 4016 MeV with width about 2 MeV

$e^+e^- \to \pi + (X\gamma)$ Guo (2019), Sakai, Jing & Guo (2020)

BESIII data



<u>B meson decay</u>

$B \to K + (X\pi)$ BHI (2019), Sakai, Jing & Guo (2020)

narrow peak in $X\pi$ invariant mass

about 6 MeV above $X\pi$ threshold with width about 1 MeV

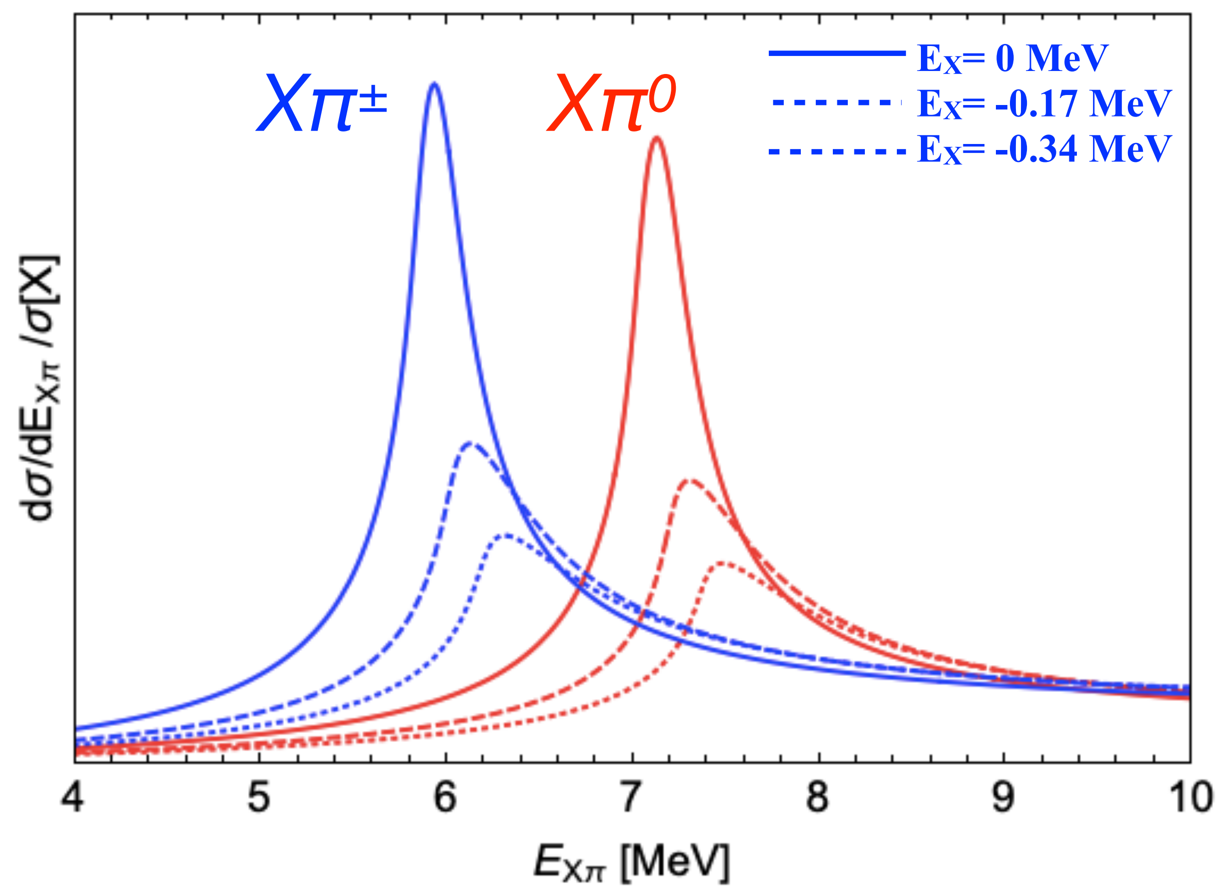
<u>prompt production in *pp* collisions</u>

BHI (2019)

narrow peak in $X\pi^\pm$ invariant mass

about 6 MeV above $X\pi^\pm$ threshold

with width about 1 MeV



Production of *X(3872)* at Hadron Collider

<u>production by *b* hadron decay</u>

decay products emerge from displaced secondary vertex

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

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

<u>prompt production by QCD mechanisms</u>

decay products emerge from primary collision vertex

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

dN_{ch}/dy ~ 10's

comoving hadrons could break up X

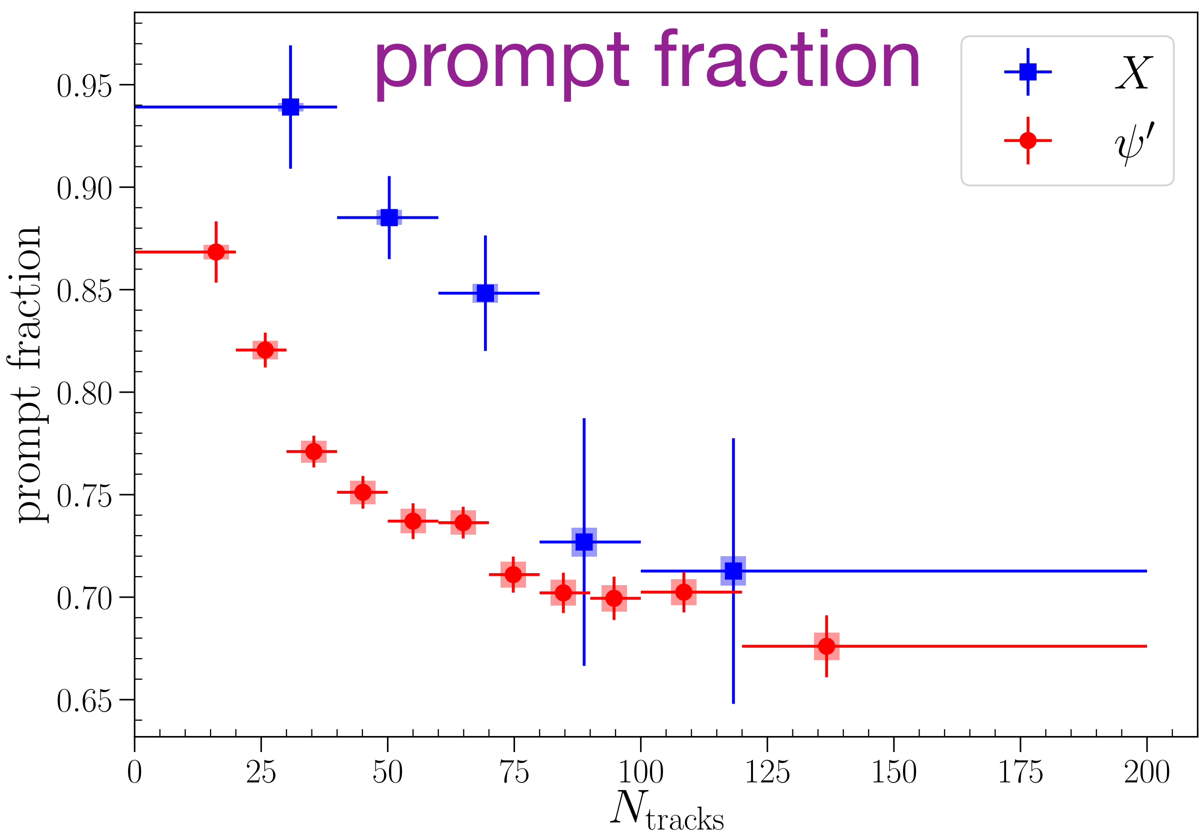
<u>convenient benchmark</u> for $X(3872)$: $\psi(2S) = \psi(3686)$

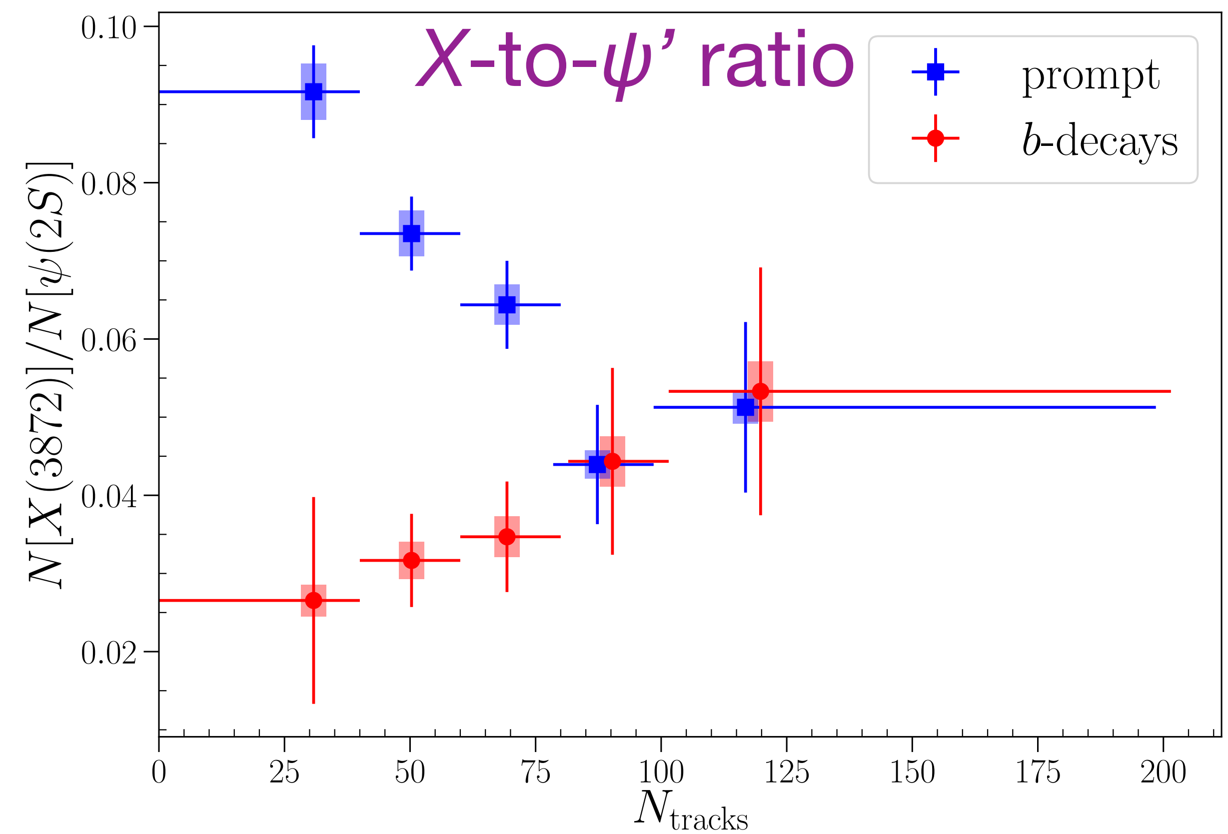
similar mass

both observed in $J/\psi\ \pi^+\pi^-$ decay channel

Dependence of Production on Multiplicity

pp collisions at Large Hadron Collider LHCb 2020
measure prompt fractions for *X* and *ψ'*
X-to-*ψ'* ratios for prompt and *b*-decay
as functions of number of tracks in vertex detector





prompt fraction for *ψ'*: seems to saturate at large N_{tracks}
X-to-*ψ'* ratio for prompt: significant decrease with N_{tracks}

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

- hard-parton collision creates $c\bar{c}$ pair which binds into $c\bar{c}$ meson
- other parton collisions produce gluons
  (or resonances whose decays produce pions)
- comoving gluons (or pions) may break up $c\bar{c}$ meson

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 with effective temperature:
  T_{eff} = (250±50) MeV
- breakup cross section ≈ geometric cross section:
  $\sigma \approx \pi\langle r^2\rangle$, $\langle r^2\rangle$ = mean square separation of constituents

Comover Interaction Model

$Q\bar{Q}$ meson can be broken up
by scattering with comoving pions (or gluons)

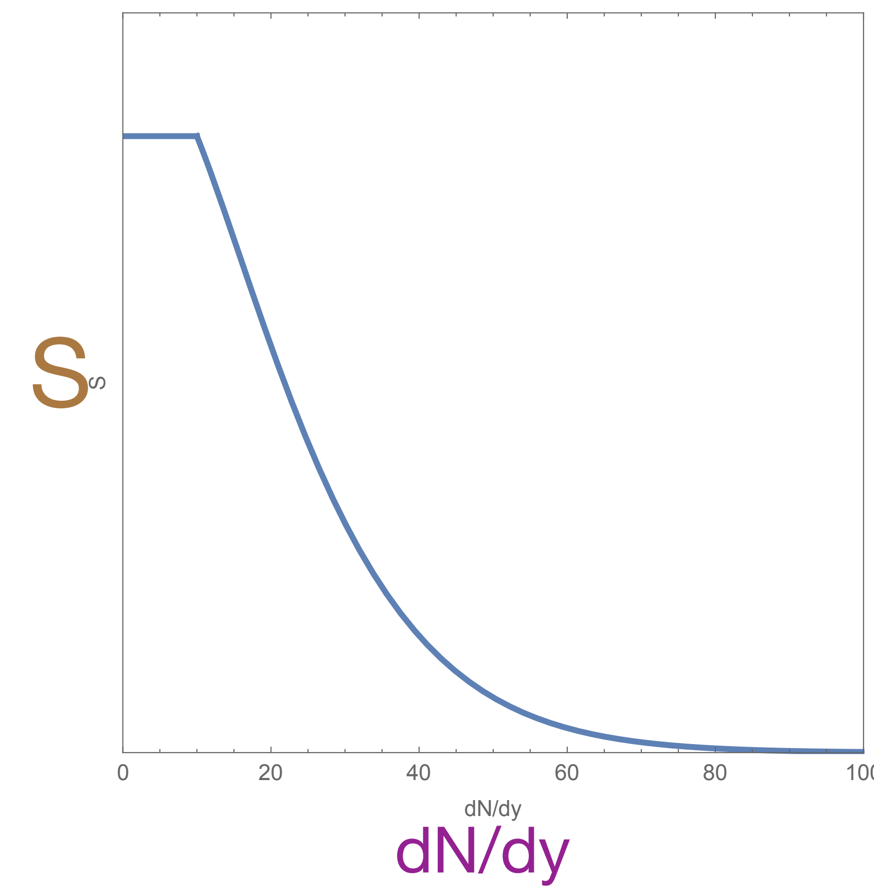
production rate decreases
as light-hadron multiplicity *dN/dy* increases

<u>Survival Probability</u>

of $Q\bar{Q}$ meson as function of *dN/dy*

$$S = \exp\left(-\frac{\langle v\sigma\rangle(dN/dy)}{\sigma_{pp}} \log \frac{dN/dy}{N_{pp}}\right) \qquad dN/dy > N_{pp}$$

$$S = 1 \qquad dN/dy < N_{pp}$$



many-body parameters: $\sigma_{pp}(s), N_{pp}(s, y)$

1 few-body parameter: $\langle v\sigma\rangle$

breakup reaction rate averaged over comovers

Analysis of LHCb Data

BHIJ arXiv:2012.13499

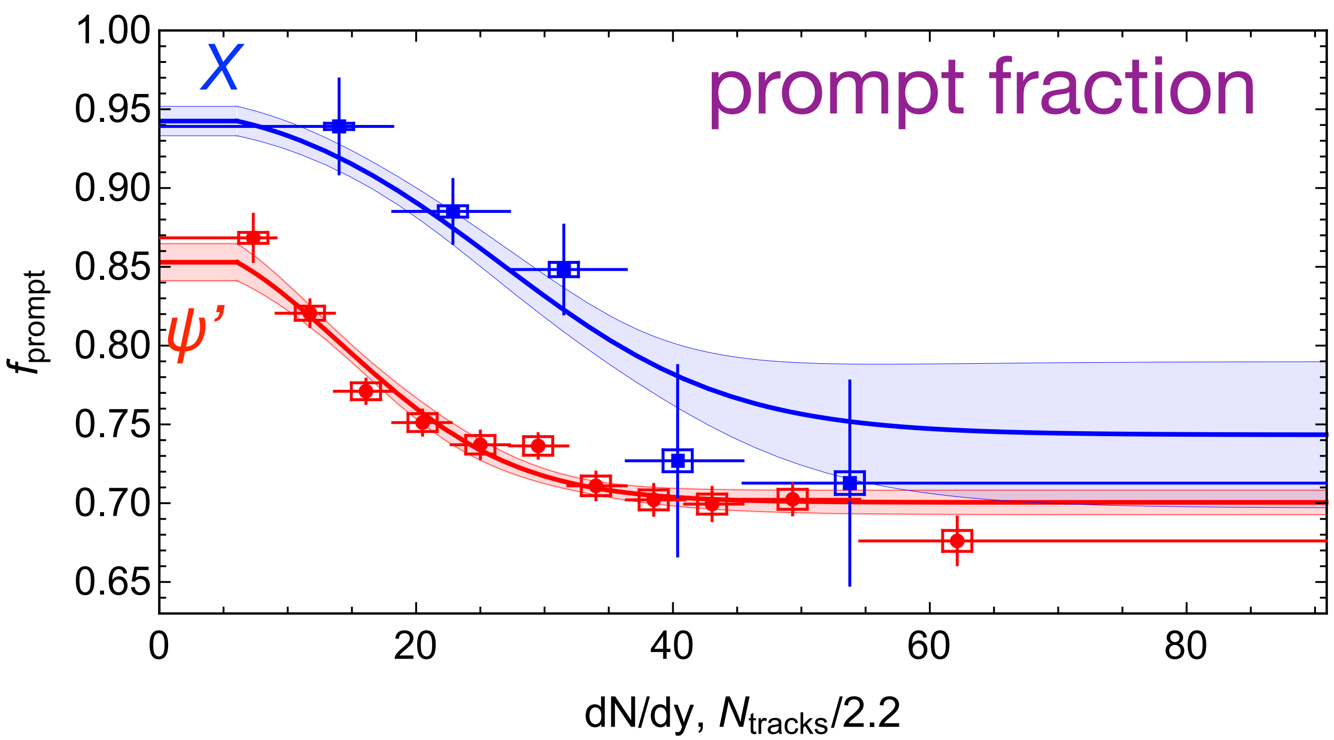
Assumptions

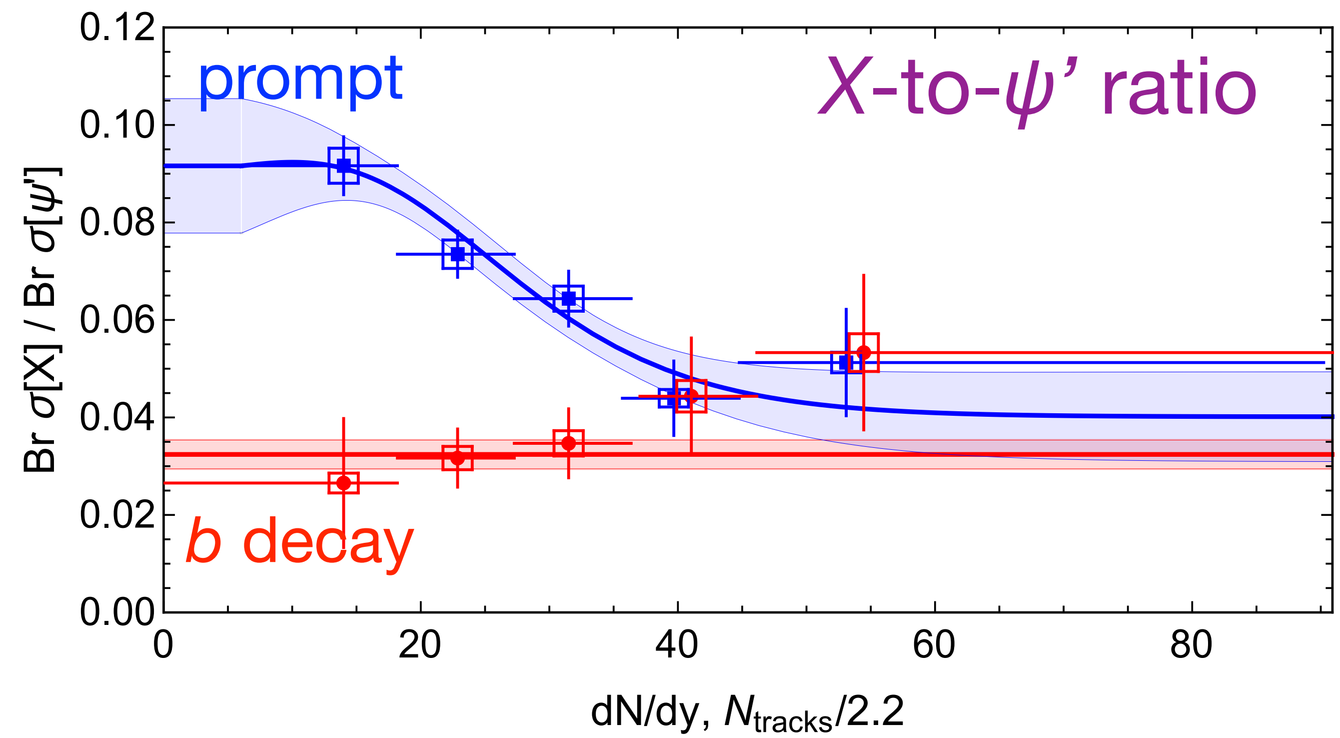
prompt cross section is sum of

term with survival probability $S = \exp\left(-\frac{\langle v\sigma\rangle (dN/dy)}{\sigma_{pp}} \log \frac{dN/dy}{N_{pp}}\right)$

term with survival probability = 1 (constant)

b decay cross section is constant





7 fitting parameters

26 data points

χ^2/dof = 0.99

fitted breakup reaction rates:

$\langle v\sigma\rangle_{\psi'} = 3.9 \pm 0.8$ mb

$\langle v\sigma\rangle_{X} = 2.69 \pm 0.7$ mb

Analysis of LHCb Data

Esposito et al. arXiv:2006.15044 (see talk by Pilloni)

Comover Interaction Model

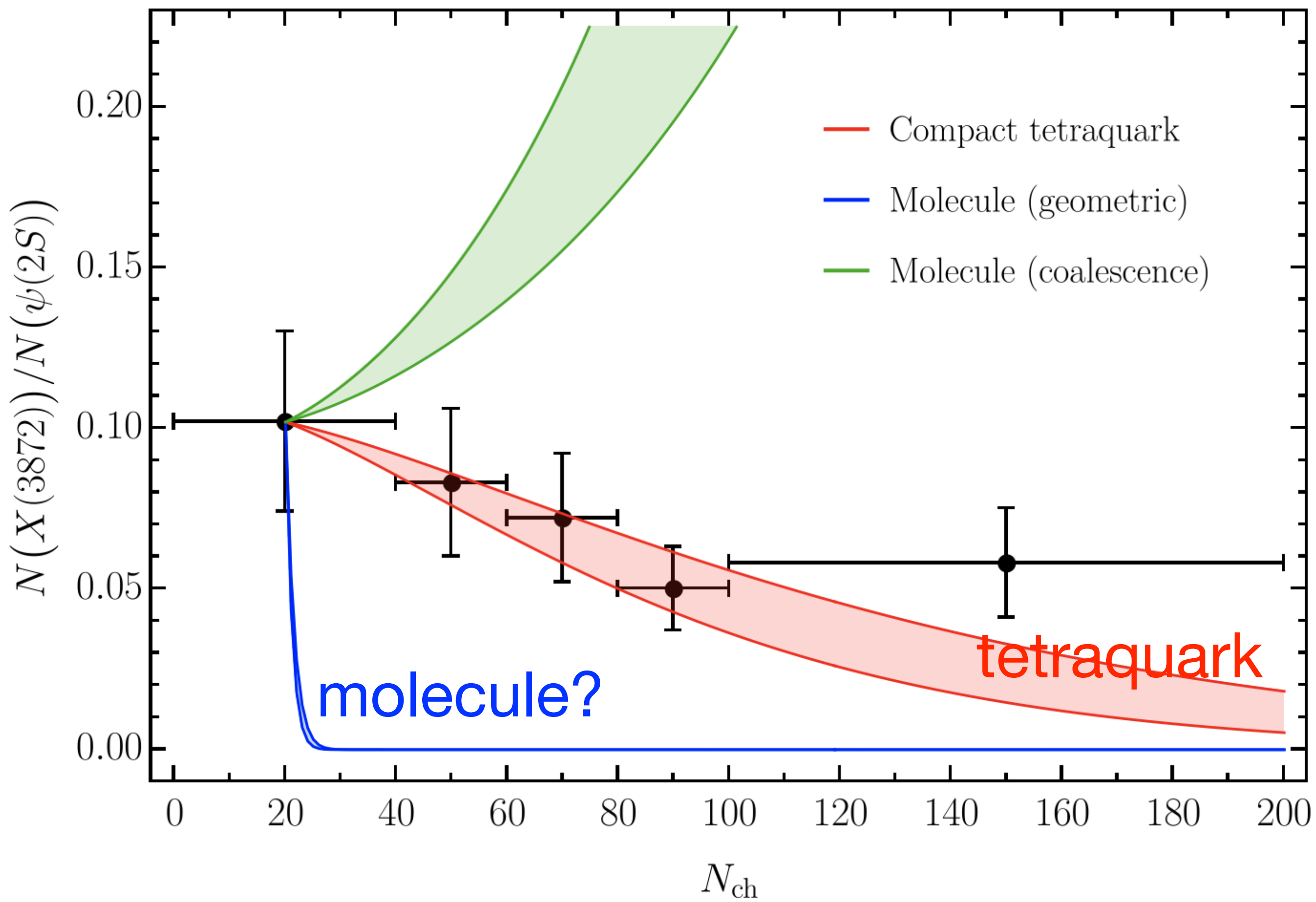
breakup reaction rates: $\langle v\sigma \rangle \approx \pi \langle r^2 \rangle$

ψ(2S): ⟨*vσ*⟩ = (5.2 ± 0.8) mb

X(3872): ⟨*vσ*⟩ = (11.6 ± 1.7) mb if *X* is tetraquark

X(3872): ⟨*vσ*⟩ = (1200 ± 170) mb if *X* is molecule (with binding energy 116 keV)

prompt *X*-to-*ψ'* ratio



- "clearly supports *X* being a tetraquark state"
- "strongly disfavors the molecular interpretation" (based on incorrect few-body physics for molecule)

Analysis of LHCb Data

Esposito et al. arXiv:2006.15044

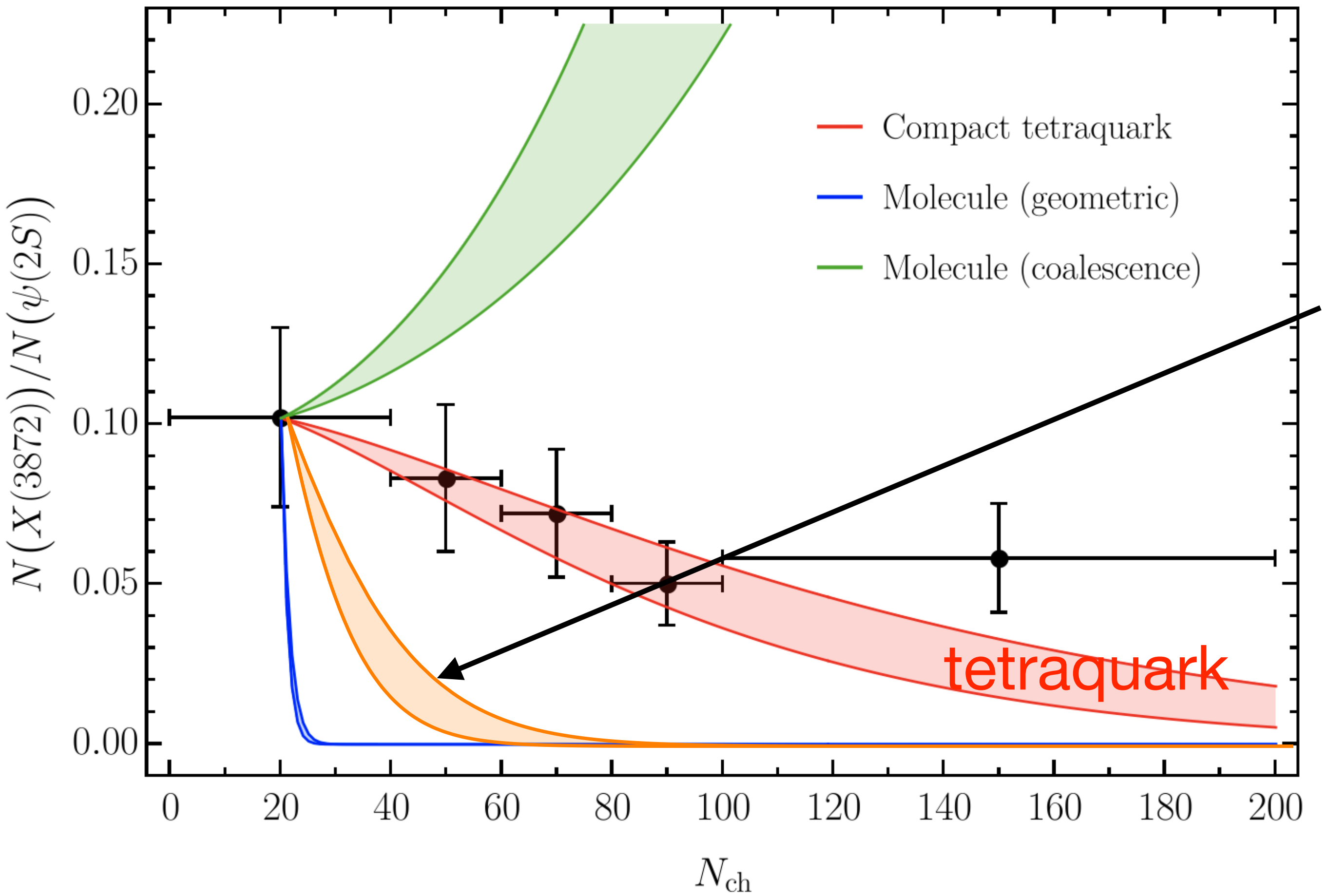
Comover Interaction Model

breakup reaction rates: $\langle v\sigma \rangle \approx \pi \langle r^2 \rangle$

ψ(2S): ⟨vσ⟩ = (5.2 ± 0.8) mb

X(3872): ⟨vσ⟩ = (11.6 ± 1.7) mb if *X* is a tetraqua

prompt *X*-to-*ψ'* ratio



Survival probability for tetraquark

$$S = \exp\left(-\frac{\langle v\sigma\rangle (dN/dy)}{\sigma_{pp}} \log \frac{dN/dy}{N_{pp}}\right)$$

Tetraquark band that fits LHCb data

is dominated by physics not captured by survival probability

many-body physics: Glauber Monte Carlo?, … ??

few-body physics: $\langle v\sigma \rangle$, … ??

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

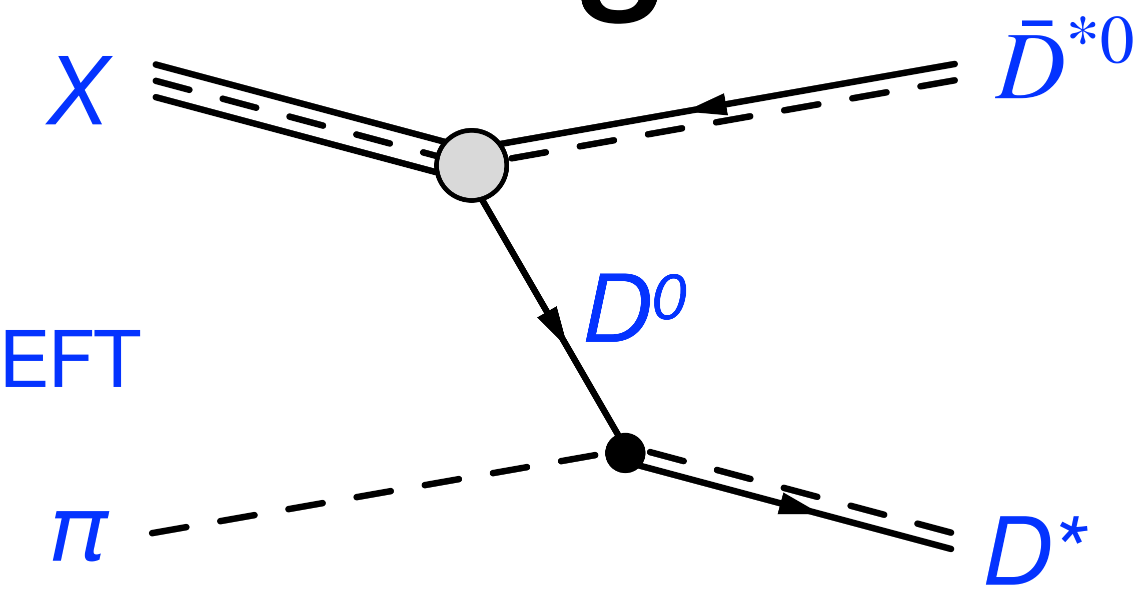
XEFT can also describe D^*D^*, $D^*D\pi$, $DD^*\pi$, $DD\pi\pi$, $X\pi$
with total energy near D^*D^* threshold arXiv:1005.1688
can calculate cross sections for breakup of X
by scattering of low-energy pion: $\pi X \to D^*D^*, D^*D\pi, DD^*\pi, DD\pi\pi$

Galilean-invariant formulation of XEFT arXiv:1503.04791
exploits approximate conservation of mass in $D^* \leftrightarrow D\pi$

improved formulation BHJ arXiv:2010.0580

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

πX Breakup Scattering



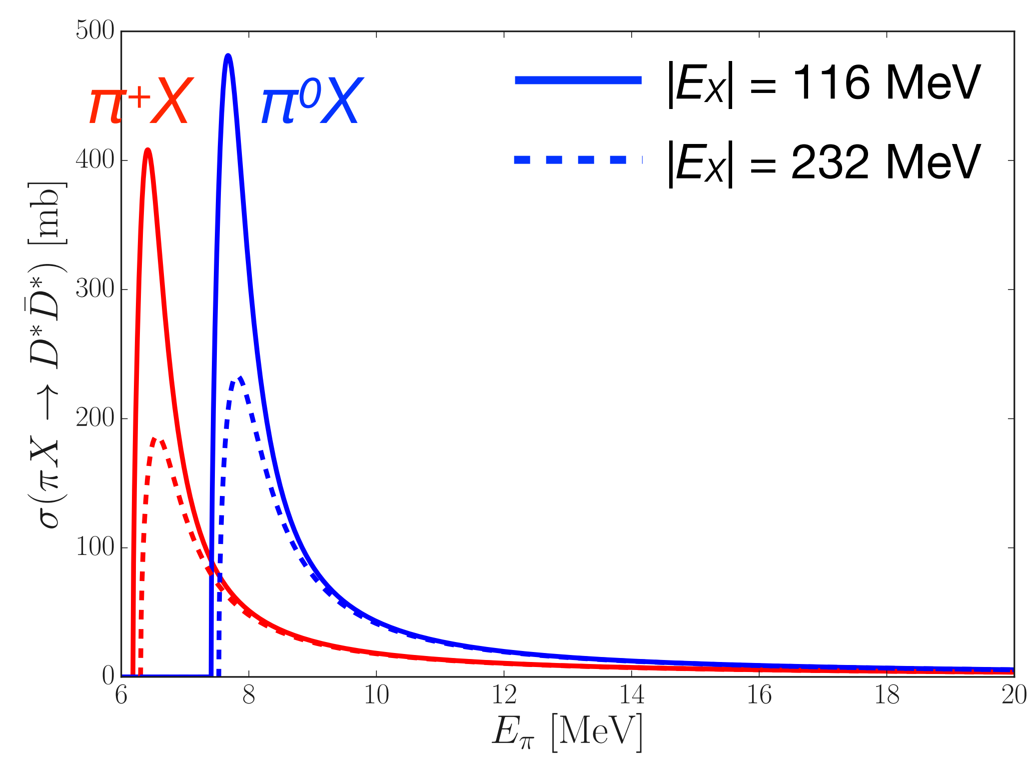
Low-energy pions

calculate breakup cross section using XEFT

narrow peak near threshold

near peak: $\sigma \sim \left[(m_\pi/f_\pi^2)^2\ \pi\langle r^2\rangle\right]^{1/2}$

order of magnitude smaller than geometric cross section $\pi\langle r^2\rangle$



High-energy pions

π scatters from constituents: $D^{*0}, \bar{D}^0, \bar{D}^{*0}, D^0$

breakup cross section: $\sigma \sim (m_\pi/f_\pi^2)^2 = 25$ mb

orders of magnitude smaller than geometric cross section $\pi\langle r^2\rangle$

Summary

given $J^{PC} = 1^{++}$, $|E_X| < 0.22$ MeV
X(3872) must be loosely bound neutral charm-meson molecule
with universal properties determined by $|E_X|$

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

charm-meson triangle singularity

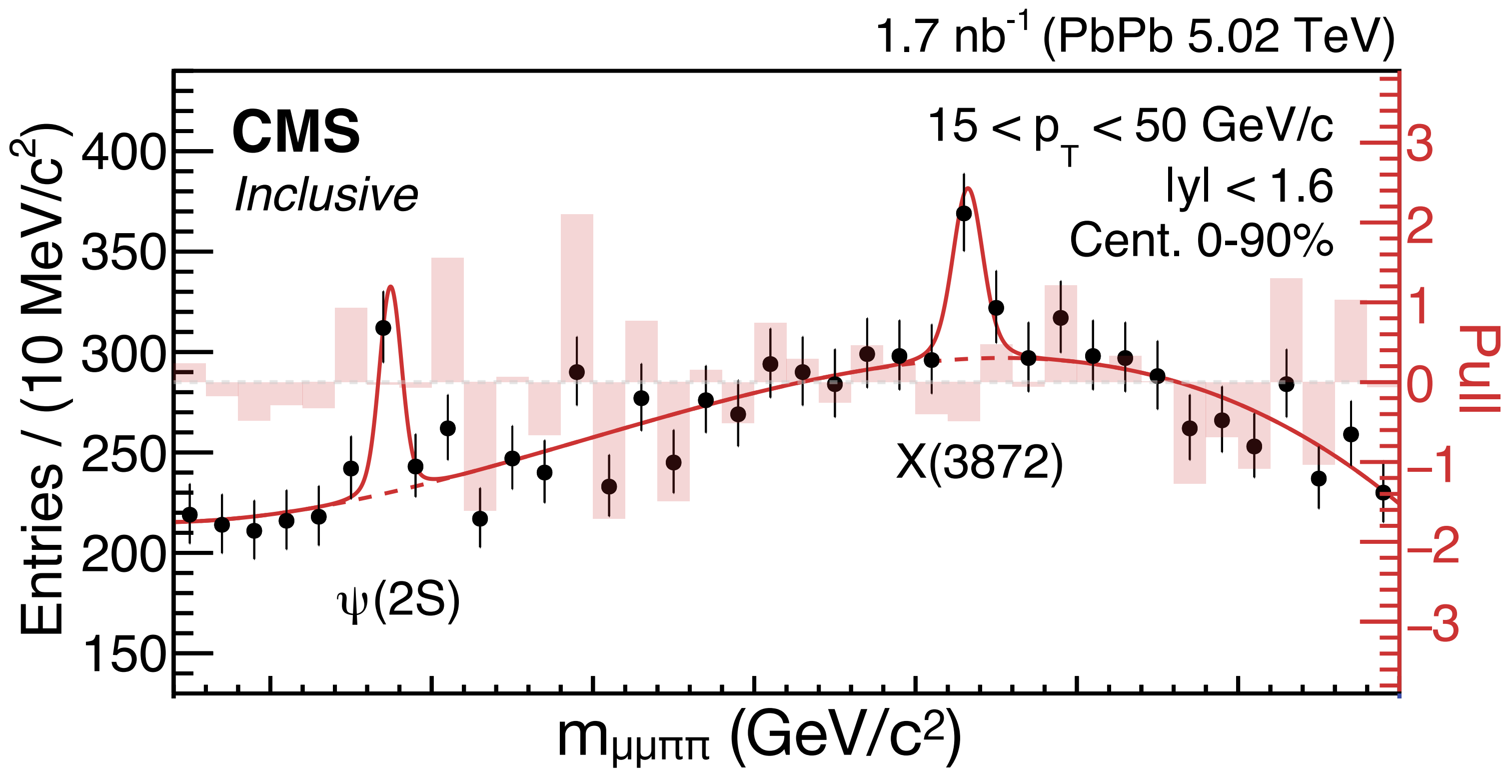
produces narrow peak in $X\pi$ invariant mass (or $X\gamma$ invariant mass)
near D^*D^* threshold with width 1 or 2 MeV
Smoking gun for *X(3872)* as charm-meson molecule !!

multiplicity dependence

LHCb: production of X(3872) in *pp* collisions depends on dN/dy
challenge: develop quantitative description of LHCb data
treating *X(3872)* as charm-meson molecule
with correct few-body physics

Production of *X(3872)*
in heavy-ion collisions

production in PbPb collisions CMS arXiv:2102.13048



prompt *X*-to-*ψ'* ratio = 1.08 ± 0.49 ±0.52
about an order of magnitude larger than in *pp* collisions !!

challenge:
develop quantitative description of production of *X(3872)*
in *pp*, *p*-nucleus, and nucleus-nucleus collisions