THE OHIO STATE UNIVERSITY

X(3872) production

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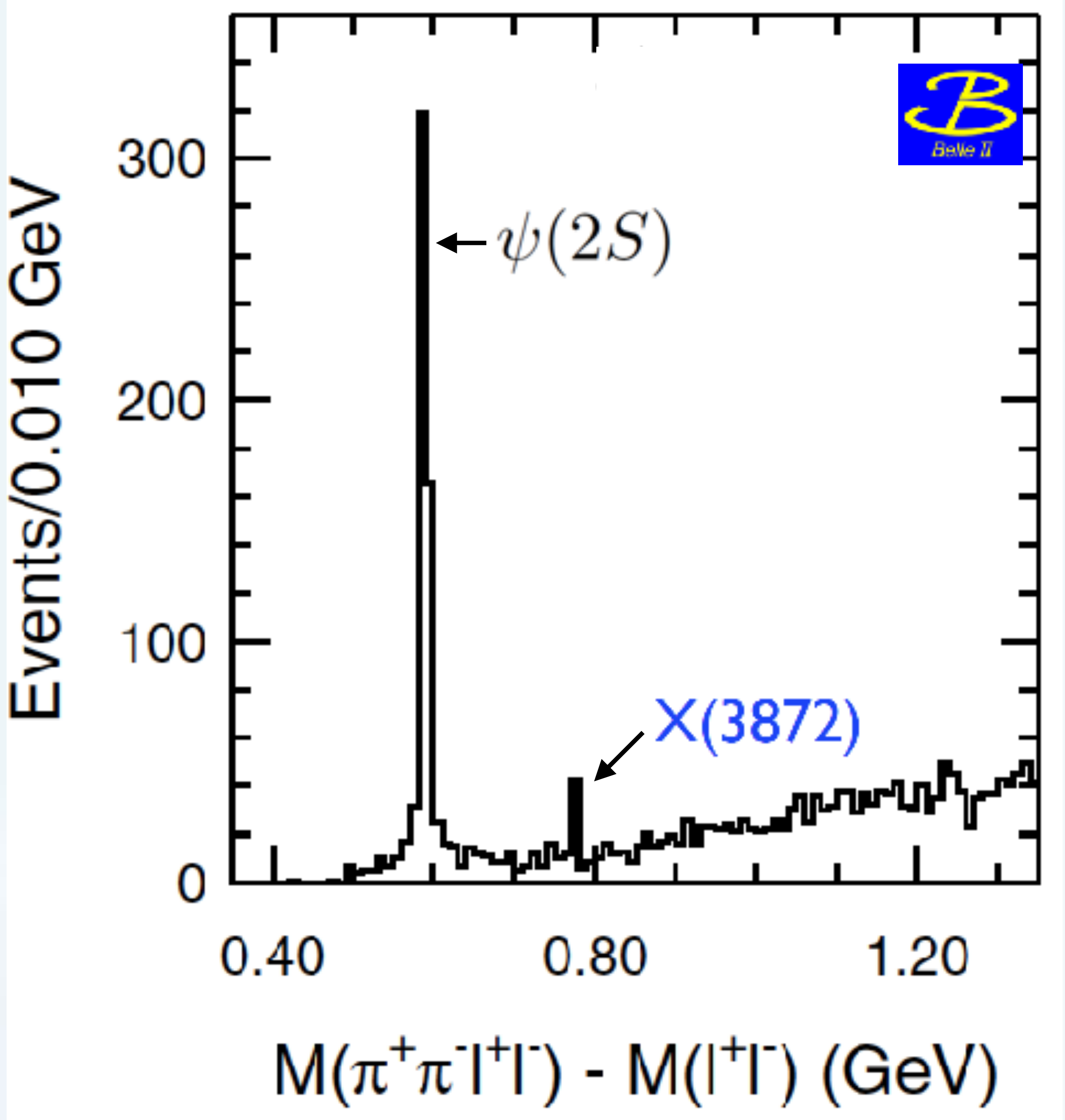
International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA 12 / ATHOS 7) [Sept. 6-10, 2021]

Outline

- Brief review of X(3872)
- Production of X(3872)
  - charm-meson triangle singularity
    - e^+e^- annihilation [PRD100, 031501(2019), PRD101, 014021(2020), PRD101, 096020(2020)]
    - B meson decay [PRD100, 074028(2019)]
    - prompt production in hadron collisions [PRD100, 094006(2019)]
  - prompt production in hadron collisions [PRD100, 094024(2019)]
  - multiplicity dependence in hadron collisions [PRD103, L071901(2021)]
  - heavy-ion collisions
- Summary

Brief review of X(3872) (≡ $\chi_{c1}(3872)$)



- ☑ discovery at e⁺e⁻ collider [Belle (2003)]:

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

- ☑ confirmation at $p\bar{p}$ collider [CDF (2003)]:

  $p\bar{p} \to X + \text{anything}$

- quantum numbers [LHCb (2013)]:

  $J^{PC} = 1^{++}$

- mass [LHCb (2020)]:

  $E_X = M_X - (M_{D^{*0}} + M_{D^0}) = (-0.07 \pm 0.12)$ MeV $\quad$ $|E_X| < 0.22$ MeV at 90% CL

- first measurement of width (Breit-Wigner) [LHCb (2020) average]:

  $\Gamma_X = (1.19 \pm 0.19)$ MeV

- 7 observed decay modes: $J/\psi\, \pi^+\pi^-$, $J/\psi \pi^+\pi^- \pi^0$, $J/\psi\, \gamma$, $\psi(2S)\gamma$, $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$, $\chi_{c1}\pi^0$

see also Chun Hua Li's talk on Tuesday

Brief review of X(3872) (≡ χ_{c1}(3872))

What is the X(3872)?

$J^{PC} = 1^{++}$ → S-wave coupling to $D^{*0}\bar{D}^0$/ $\bar{D}^{*0}D^0$

$|E_X| < 0.22$ MeV → resonant coupling

S-wave loosely bound charm-meson molecule!!

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

other components of wave functions have small probabilities:

- at long distances: $D^0\bar{D}^0\pi^0$
- at short distances:
  - χ_{c1}(2P)?
  - charged charm mesons?
  - compact tetraquark [cq][$\bar{c}\bar{q}$]?

Brief review of X(3872) ($\equiv \chi_{c1}(3872)$)

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

Universal properties determined by the binding energy $|E_X|$

- large scattering length: $|a| = \pm 1/\sqrt{2\mu\,|E_X|}$, $|a| >> \text{range}$
- large mean separation: $\langle r \rangle = a/2$, $|E_X| < 0.22$ MeV implies $\langle r \rangle > 5$ fm
- scattering amplitude at $E \ll 1/(2\mu\,\text{range}^2)$: $f(E) = 1/\left(-1/a + i\sqrt{2\mu E}\right)$
- wavefunction: $\psi(r) = e^{-r/a}/r$

XEFT

effective field theory for charm mesons and pions

Fleming, Kusunoki, Mehen & van Kolck [PRD 76, 034006(2007)]

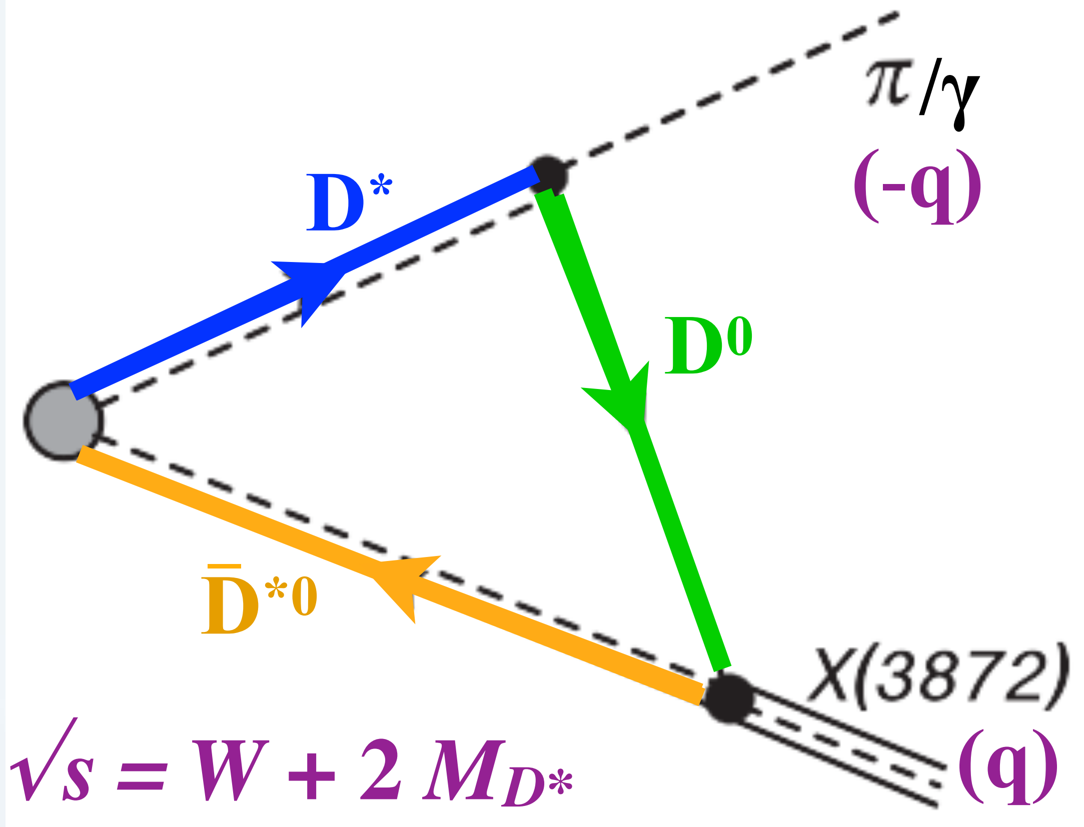
Galilean-invariant XEFT

Braaten [PRD 91, 114007(2015)]

Braaten, He & Jiang [PRD 103, 036014(2021)]

Charm-meson triangle singularity

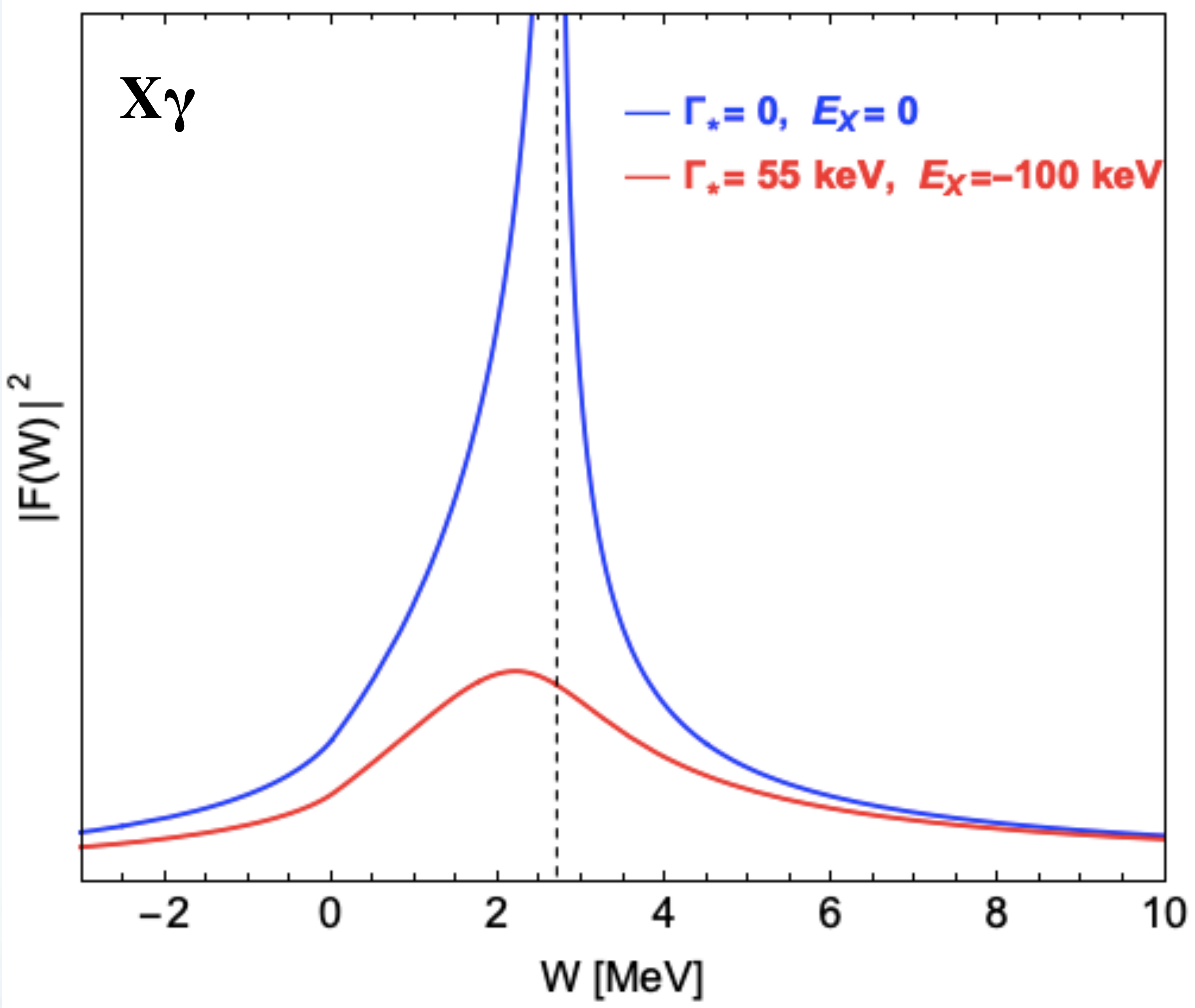
three charm mesons can be on shell simultaneously → $\log^2(s/s_\triangle)$ divergence in reaction rate at $s_\triangle$ determined by masses



loop amplitude near singularity:

$$F(W) \propto \log \frac{\sqrt{M_* W} + (M_*/M_X)q}{\sqrt{M_* W} - (M_*/M_X)q}$$

$(M_* = M_{D^*})$



divergence at energy W above D*D̄* threshold:

- Xγ: $(M_{D^{*0}}/M_X^2)(M_{D^{*0}} - M_{D^0})^2 = 2.7$ MeV
- Xπ⁰: $(m_{\pi^0}/2M_{D^0})(M_{D^{*0}} - M_{D^0} - m_{\pi^0}) = 0.3$ MeV
- Xπ±: $(m_{\pi^0}/2M_{D^0})(M_{D^{*+}} - M_{D^0} - m_{\pi^+}) = 0.2$ MeV

BUT
- * nonzero decay width for D*
- * nonzero binding energy (-Ex) for X

→
$$F(W) \propto \log \frac{\sqrt{2\mu E_X + i\mu\Gamma_*} + \sqrt{M_*(W + i\Gamma_*)} + (M_*/M_X)q}{\sqrt{2\mu E_X + i\mu\Gamma_*} + \sqrt{M_*(W + i\Gamma_*)} - (M_*/M_X)q}$$

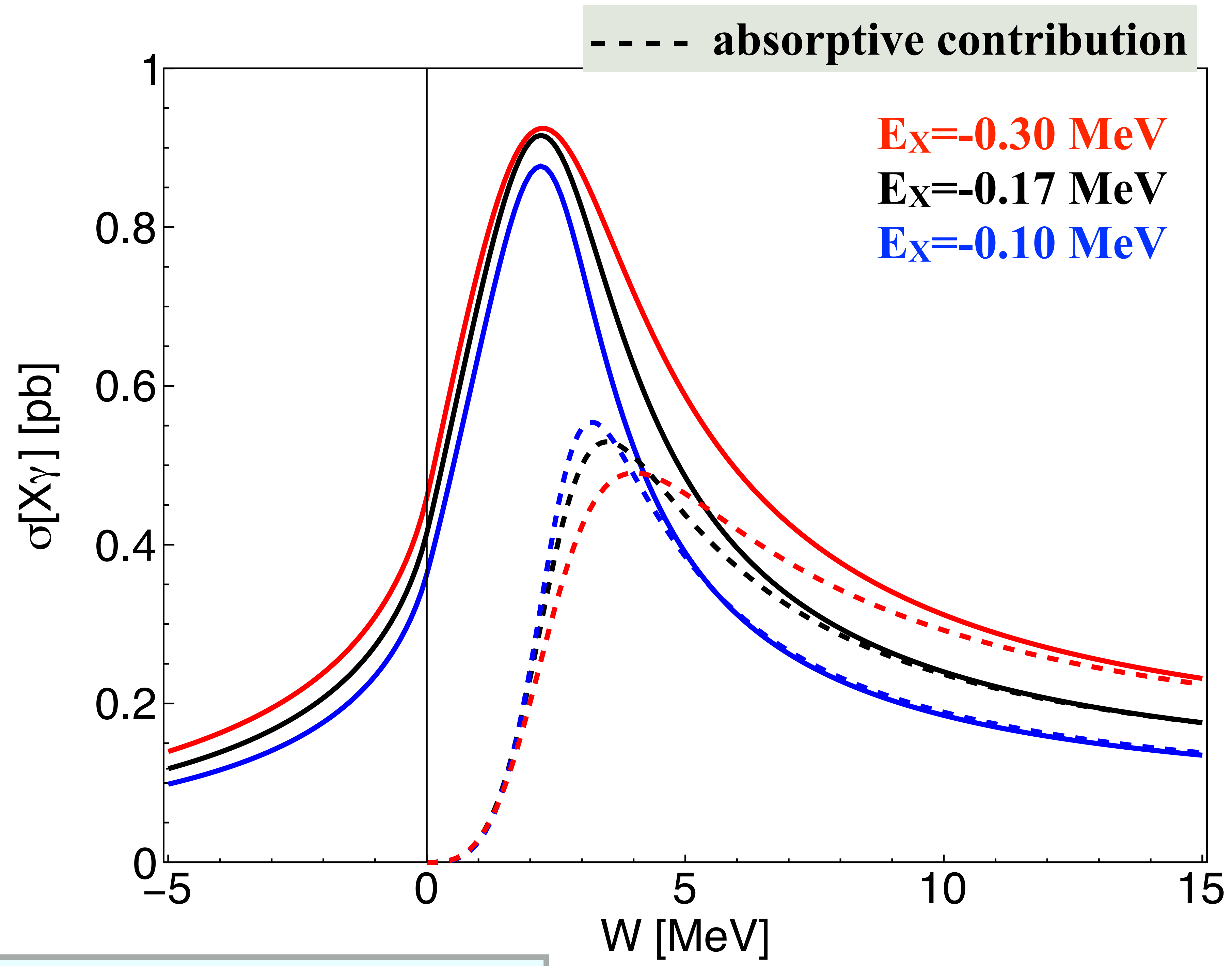
→ narrow peak in reaction rate

review on TS: Guo, Liu, Sakai [Prog. Part. Nucl. Phys. 112, 103757 (2020)]

production of X(3872) + γ in e^+e^- annihilation

$e^+e^- \longrightarrow X\gamma$

- Dubinskiy & Voloshin (2006)
- BHI (2019), BHIJ(2020): narrow peak near 4016 MeV

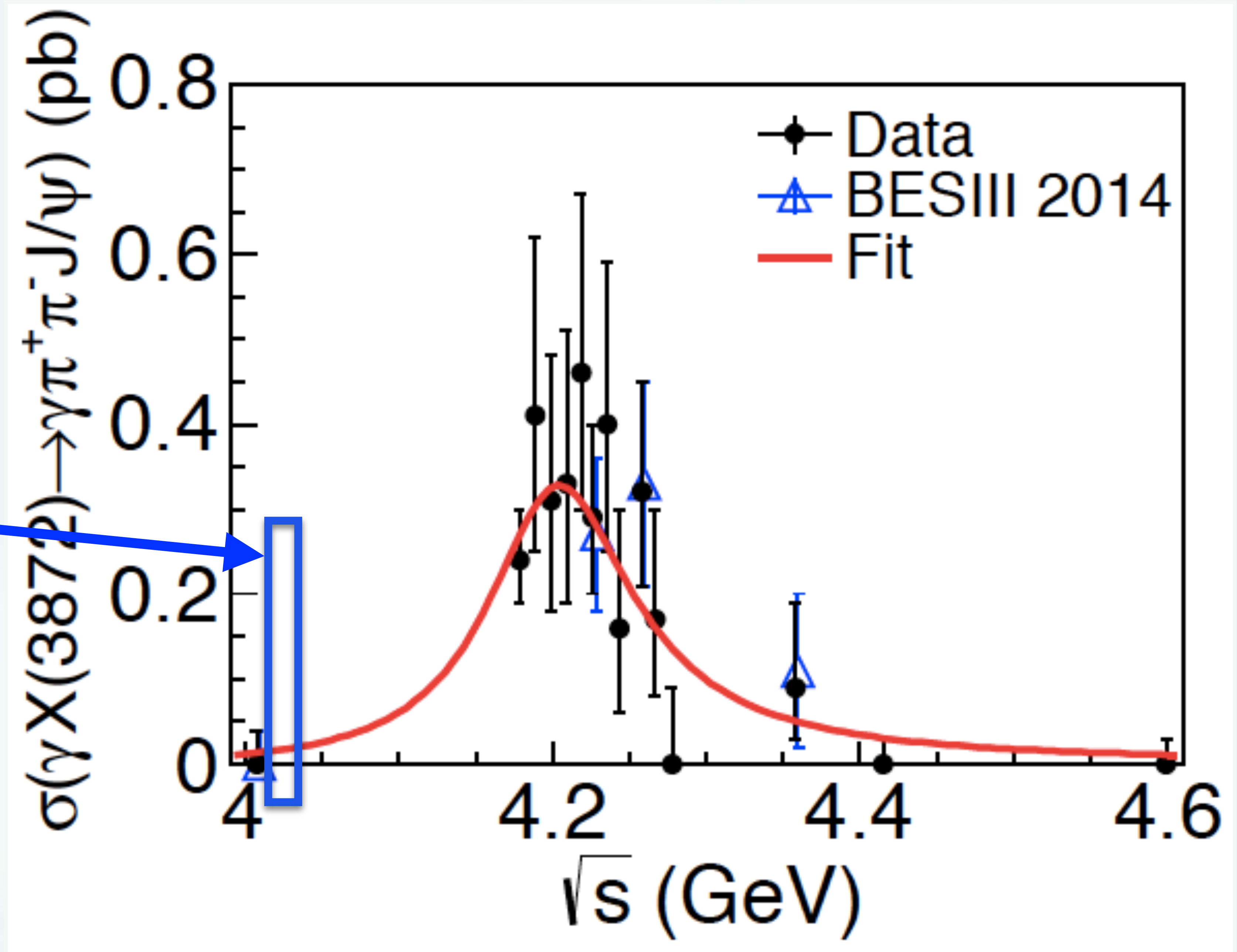


$e^+e^- \longrightarrow \pi + (X\gamma)$

- Guo(2019), Sakai, Jing & Guo (2020)

BESIII data

BESIII: $e^+e^- \rightarrow X\gamma$
[PRL122,232002 (2019)]

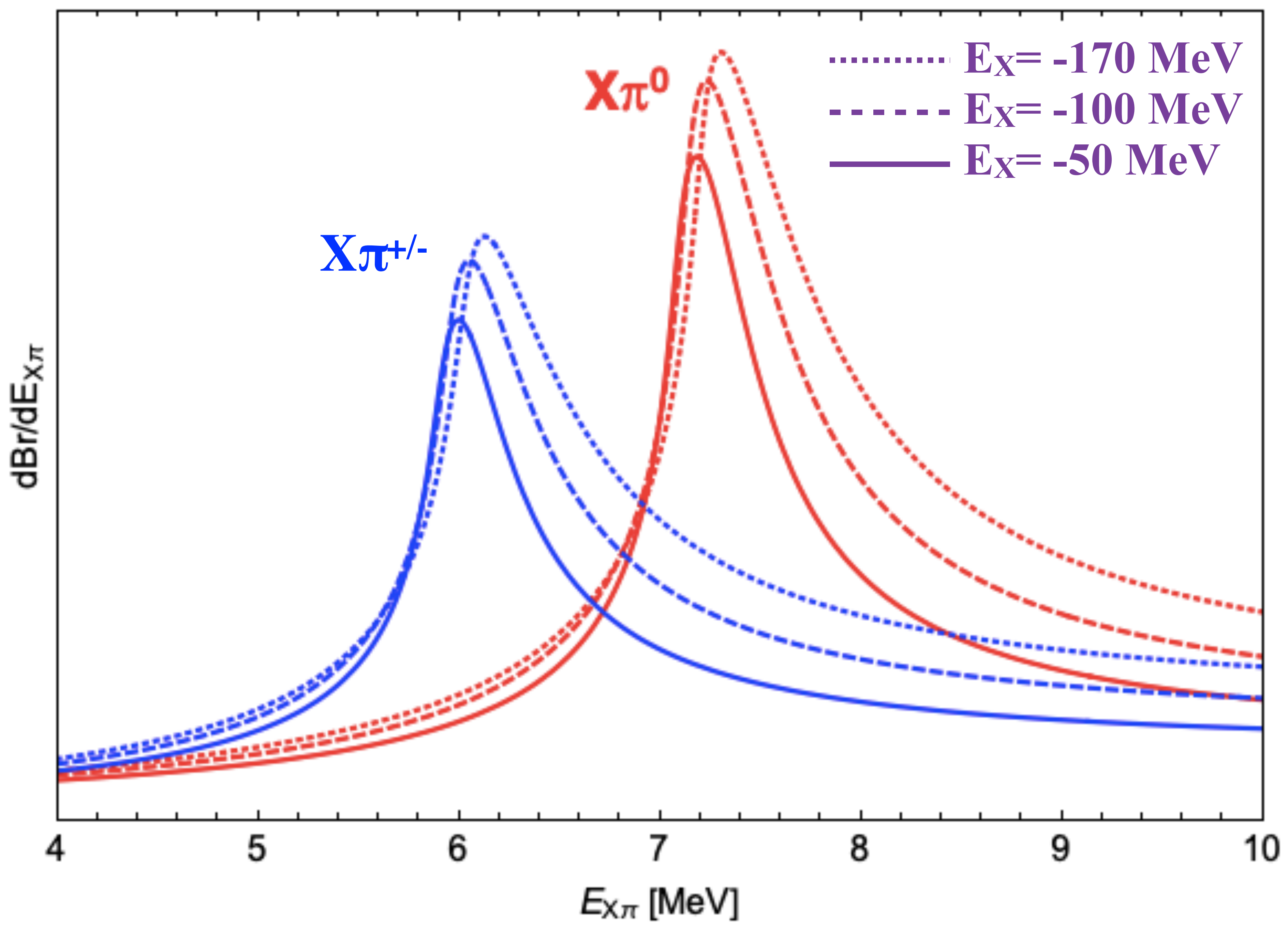


production of X(3872) + π from B meson decay

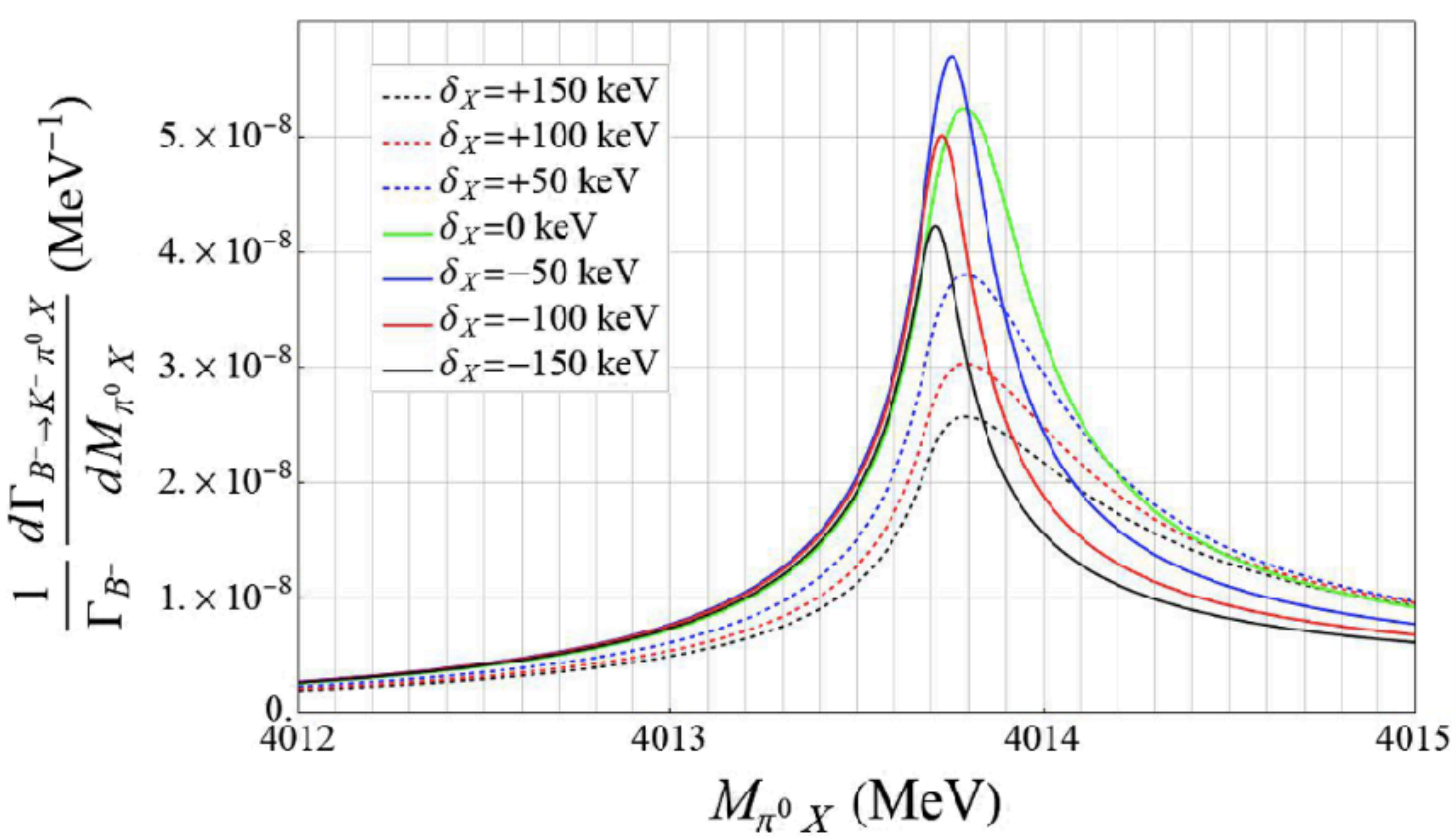
$B \to K\, D^*\bar{D}^* \to K\, X\pi$ decay of B meson into $K+D^*\bar{D}^*$, rescattering of virtual $D^*\bar{D}^*$ into $X\pi$

BHI (2019): triangle singularity produces narrow **peaks** in dBr[$B \to K\, X\pi$]

- $X\pi^\pm$: near 6.1 MeV above $X\pi^+$ threshold with width about 1 MeV
- $X\pi^0$: near 7.3 MeV above $X\pi^0$ threshold with width about 1 MeV



Sakai, Jing & Guo (2020)

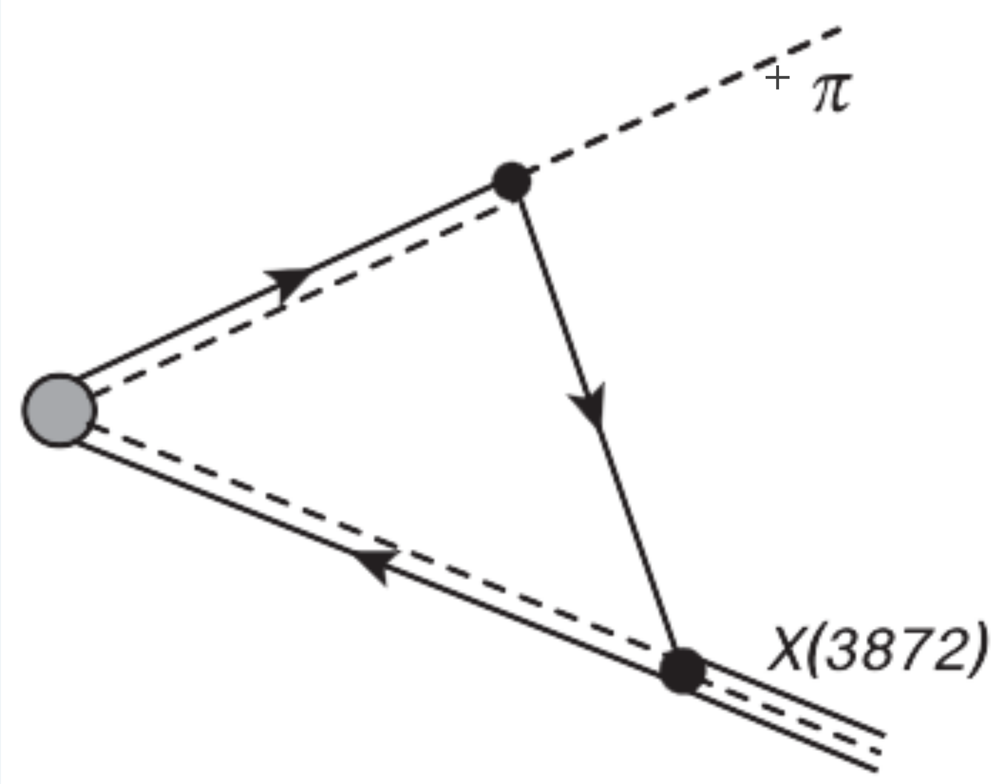


$\delta x = -Ex$

prompt production of X(3872) + π at Hadron colliders

$D^{*+}\bar{D}^{*0} \to X(3872)\pi^+$

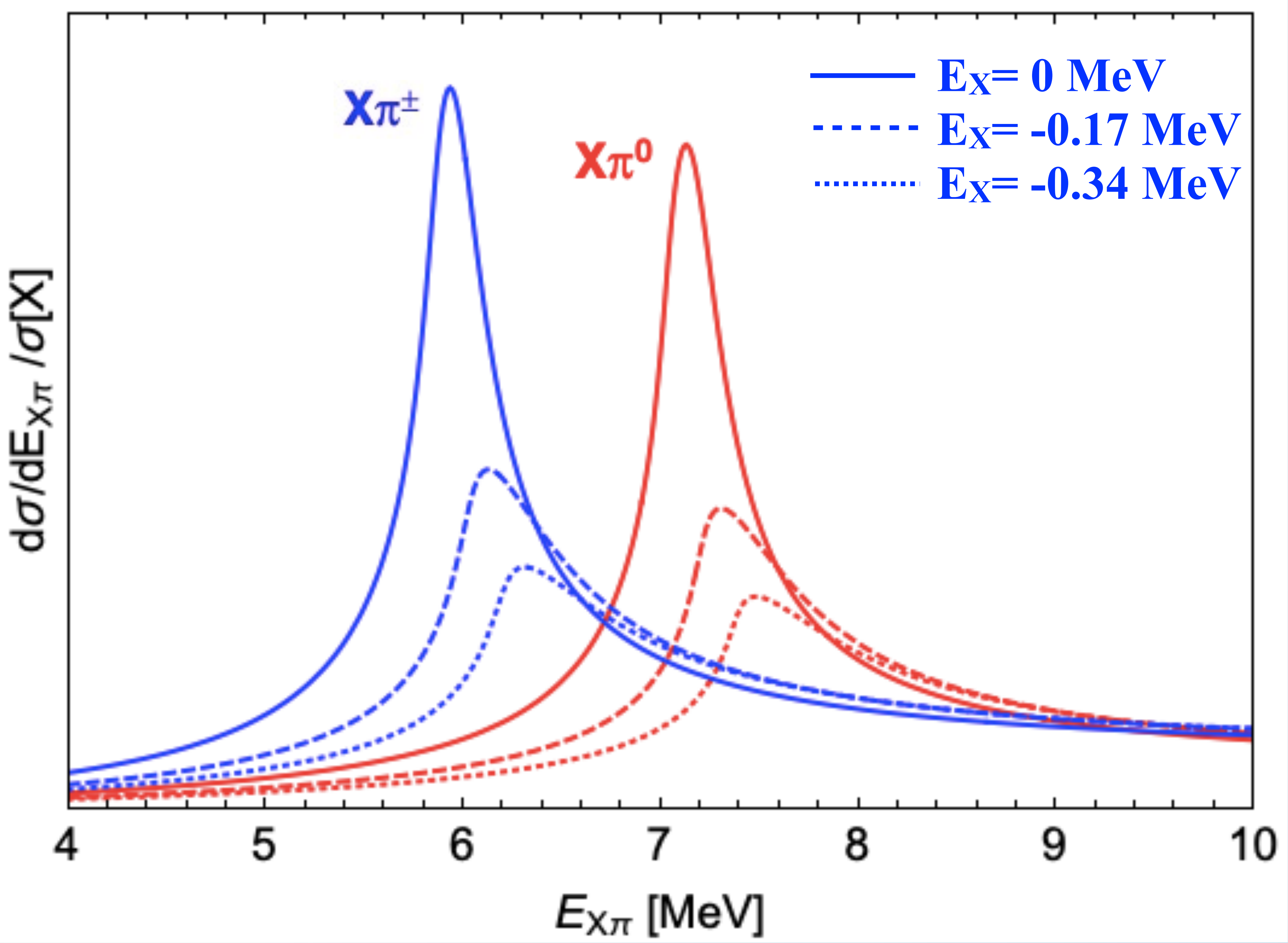
Braaten, He & Ingles [PRD 100, 094006(2019)]



- creation of $D^{*+}\bar{D}^{*0}$ at short distance
- rescattering of virtual $D^{*+}\bar{D}^{*0}$ into $X\pi^+$

triangle singularity produces narrow peak in $X\pi^\pm$ invariant mass

peak near 6.1 MeV above $X\pi^+$ threshold



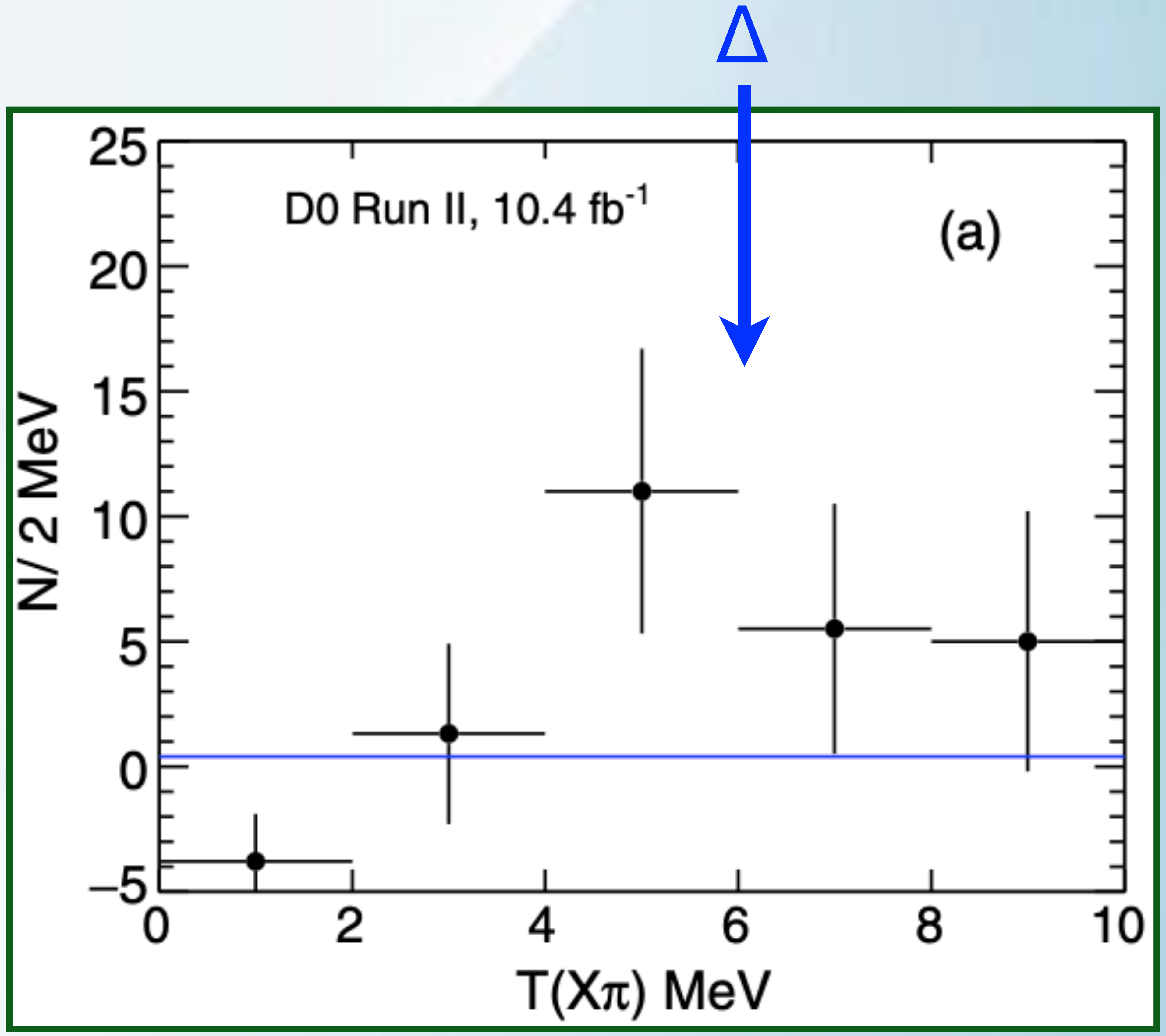
Experimental observation of X(3872) + $\pi^{\pm}$ in $p\bar{p}$ collisions

D0 Collaboration [PRD 102, 072005 (2020)]

prompt and b-hadron decay production of X(3872) + soft $\pi^{\pm}$

a small excess in small $T(X\pi)$ region, significance of 2σ

$T(X\pi) < 11.8$ MeV	observed events	X + random π
prompt production:	18 ± 16	6
b-decay:	27 ± 12	2



conclusions:

* prompt production: no evidence for an enhancement as expected from the triangle singularity
* b-decay: no "significant" evidence for an enhancement as expected from the triangle singularity

questions:

no peak in prompt production??
first hint of narrow peak from triangle singularity in b-decay??

Production of X(3872) in hadron Collisions

convenient benchmark for $X(3872)$: $\psi(2S) = \psi(3686)$

similar mass

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

- **prompt production by QCD mechanisms**

  decay products emerge from primary collision vertex

  number of charged particles: $N_{ch} \sim$ 100's

  $dN_{ch}/dy \sim$ 10's

- **production by b hadron decay**

  decay products emerge from displaced secondary vertex

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

- from production of $X_{c1}(2P)$ component ?
- from creation of charm-meson pairs ?

Production of X through $X_{c1}(2P)$ component

probability for $X_{c1}(2P)$ component: Z_X

if prompt production of $X(3872)$ is dominated by $X_{c1}(2P)$ component

then $\sigma[X(3872)] = Z_X\, \sigma[X_{c1}(2P)]$

prompt production of $X_{c1}(2P)$ at LHC

can be calculated using NRQCD factorization Meng, Han & Chao (2013)

$$Z_X \,\mathrm{Br}[X \to J/\psi\, \pi^+\pi^-] = 0.014 \pm 0.006$$

$4\% < \mathrm{Br}[X \to J/\psi\, \pi^+\pi^-] < 33\%$ [BHI, arXiv:1908:02807] $\Rightarrow$ $4\% < Z_X < 40\%$

Production of X(3872) in hadron Collisions

Production of *X* through *charm mesons*

BGPPS (Bignamini et al, 2009), EGMPP (Esposito et al, 2017)

- if *X(3872)* is a charm-meson molecule,
  prompt production is dominated by creation of charm-meson pairs:
  $\sigma[X(3872)] \approx \sigma[D^{*0}\bar{D}^0(k), k<k_{max}]$ for some relative momentum k_{max}

BGPPS: $k_{max} = \gamma_X, \gamma_X = \sqrt{2\mu E_X}$, $|E_X| < 0.22$ MeV $\Longrightarrow$ $\gamma_X < 20$ MeV

$\Longrightarrow$ predicted production rates are orders of magnitude smaller than observed production rates at Tevatron and LHC

But $\sigma[D^{*0}\bar{D}^0(k), k<k_{max}] \sim k_{max}^3$

estimates of k_{max} informed by physics of loosely bound charm-meson molecule

Artoisenet & B (2010): $k_{max} \sim m_\pi$

BHI (2019) $k_{max} = 7.7\ \gamma_X$

see also AGHMN (Albaladejo et al, 2017)

k_{max} is significantly larger than γ_X

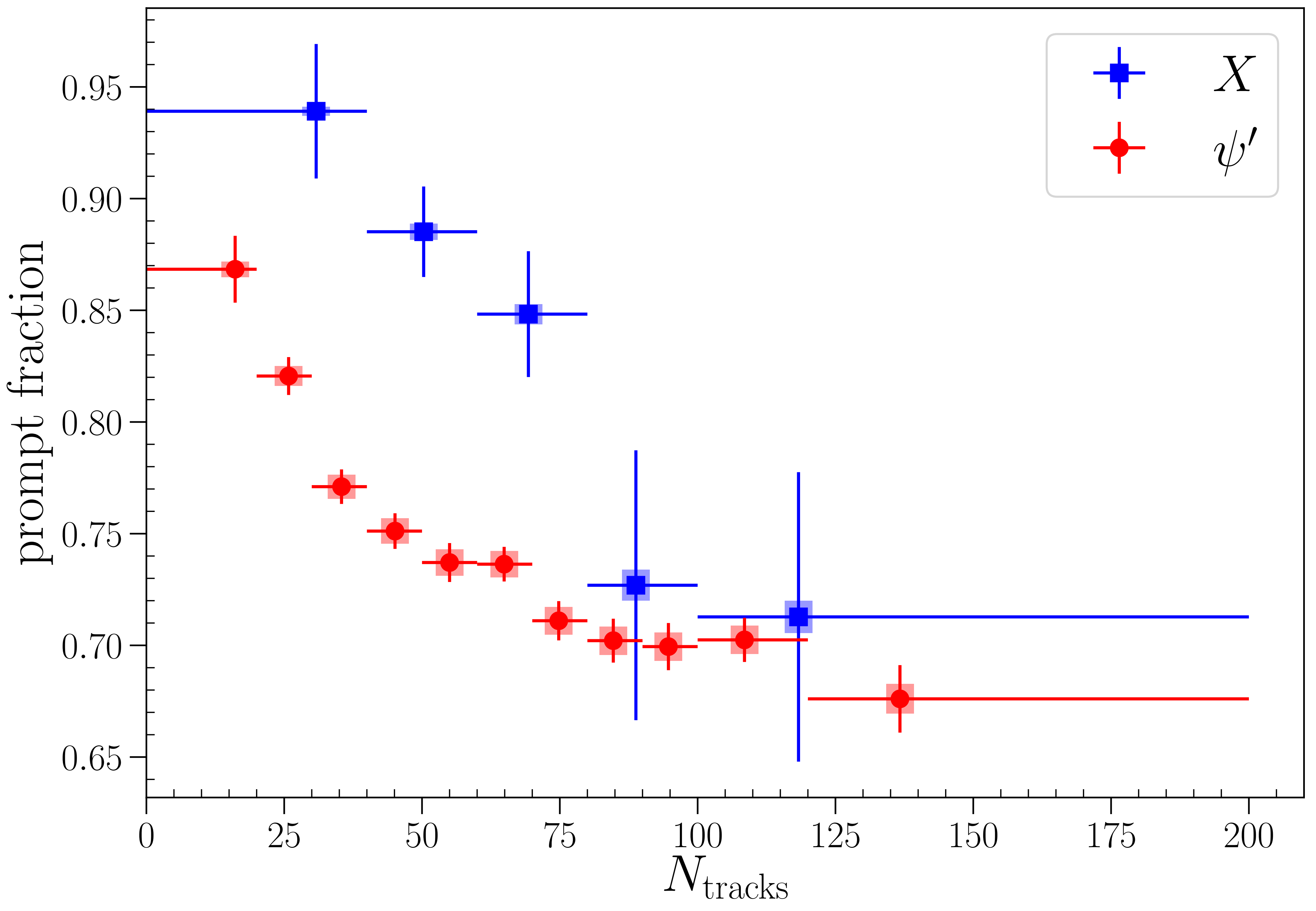
$\Longrightarrow$ predicted production rates can be compatible with observed production rates at Tevatron and LHC

Multiplicity Dependence of Production

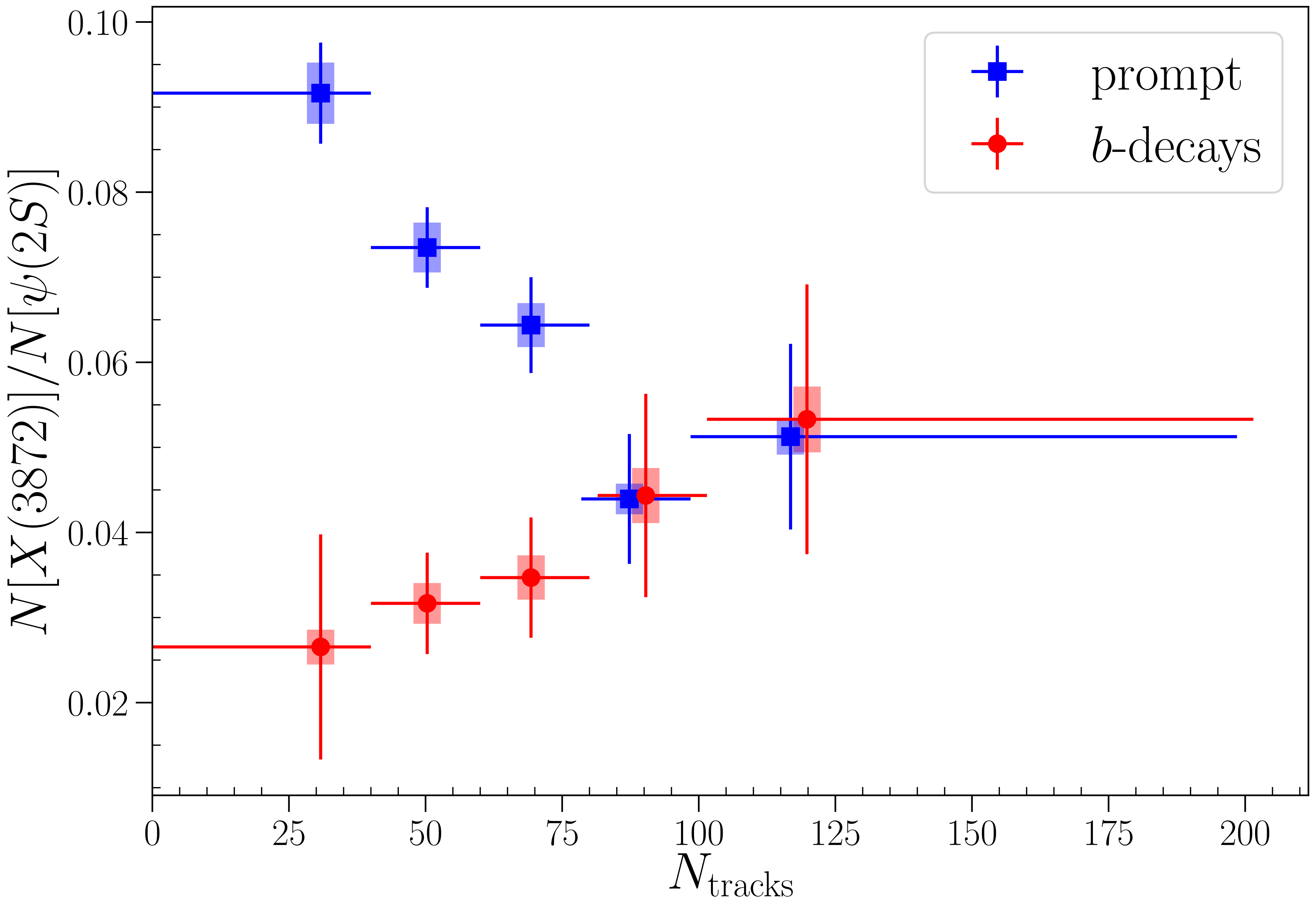
pp **collisions at Large Hadron Collider** **LHCb 2020**

measured prompt fractions for *X* and for *ψ'*
***X*-to-*ψ'* ratios** **for prompt and for *b*-decay as functions of number of tracks in vertex detector**

prompt fraction



***X*-to-*ψ'* ratio**



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

Multiplicity Dependence of Production

quarkonium can be broken up by collisions with comoving hadrons which are more abundant at higher multiplicity

Comover Interaction Model

suppression of J/ψ, $\psi(2S)$ in pp, p-nucleus, nucleus-nucleus collisions

Capella et al., Gavin and Vogt, Kharzeev et al. (1996)

- comovers: gluons ?, pions ?
- breakup cross section from collisions with comovers
  simple-minded model: geometric cross section

  $$\sigma \approx \pi \langle r^2 \rangle, \quad \langle r^2 \rangle$$ = mean square separation of constituents
- Glauber Monte Carlo

suppression of $\Upsilon(2S)$, $\Upsilon(3S)$ compared to Υ Ferreiro & Lansberg (2018)

- momentum distribution ?
  Bose-Einstein distribution with effective temperature: $T_{\rm eff}$ = (250±50) MeV
- breakup cross section: multiply πr^2 by energy-dependent factor

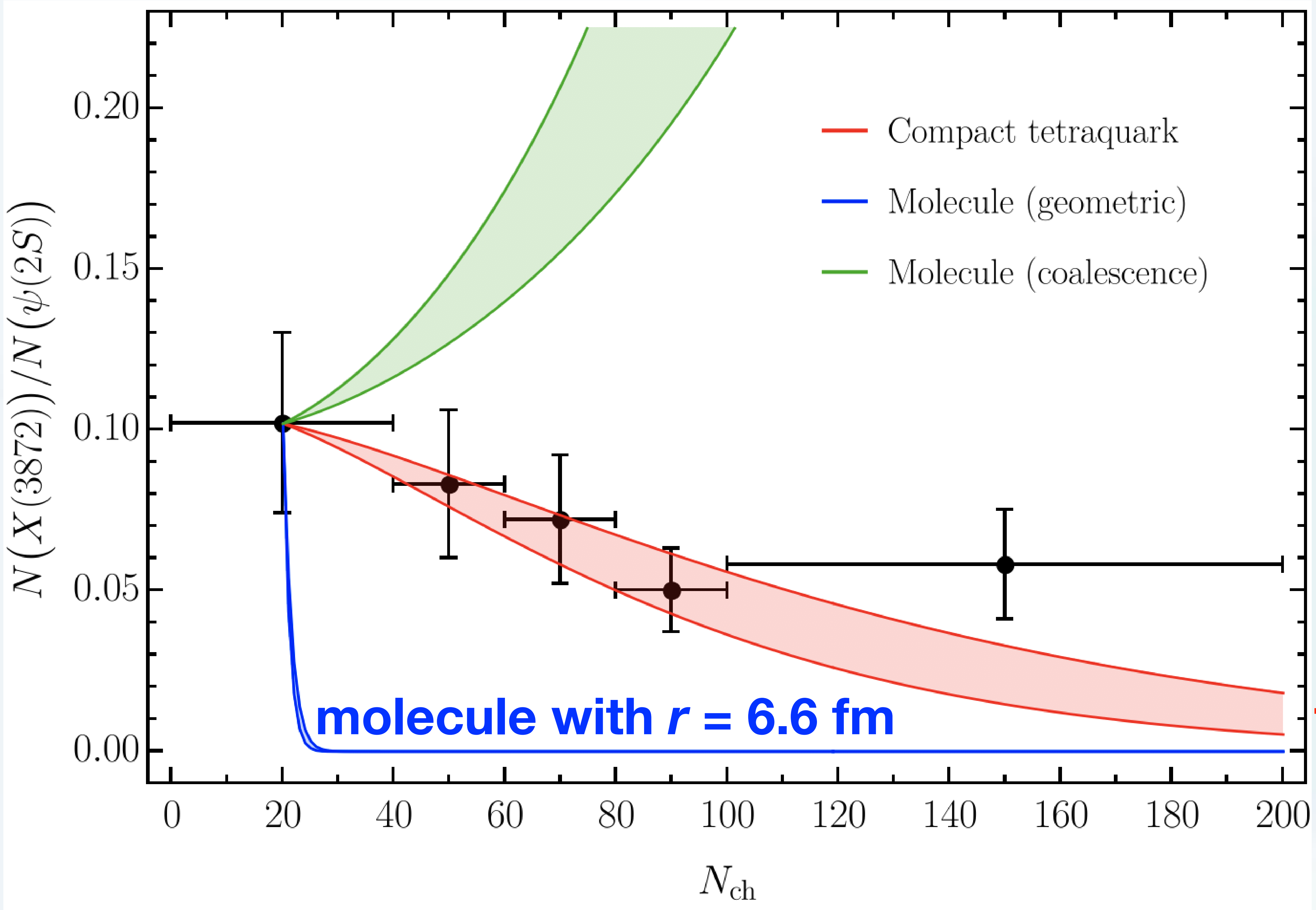
phenomenological model for quarkonium:
does it apply for tetraquark? charm-meson molecule?

Multiplicity Dependence of Production

Comover Interaction Model

Esposito et al. arXiv:2006.15044

prompt X-to-ψ' ratio



tetraquark with r = 0.65 fm

- **breakup cross section** from collisions with **comovers: geometric cross section** $\sigma \approx \pi\langle r^2\rangle$,

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

- **only information about tetraquark is its size**
- **incorrect few-body physics for molecule: breakup cross section ≈ cross section for scattering from charm meson**

Multiplicity Dependence of Production

Comover Interaction Model

Braaten, He, Ingles & Jiang, arXiv:2012.13499

Survival probability of $Q\bar{Q}$ meson
from scattering with comoving pions
as function of light-hadron multiplicity *dN/dy*

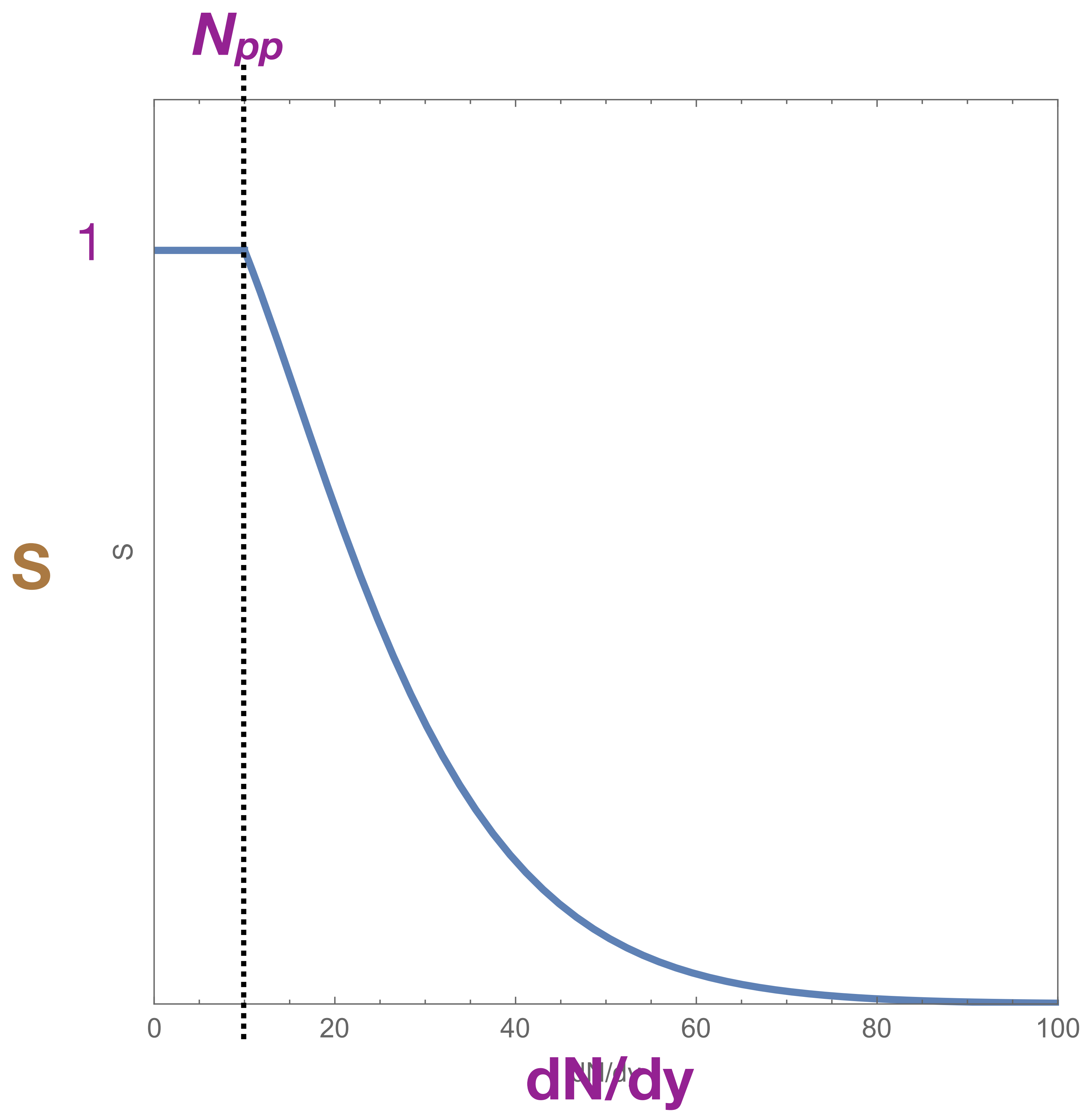
$$S = \exp\left(-\frac{\langle v\sigma\rangle(dN/dy)}{\sigma_{pp}} \log\frac{dN/dy}{N_{pp}}\right) \qquad dN/dy > N_{pp}$$

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

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

1 few-body parameter: ⟨*vσ*⟩

breakup reaction rate averaged over **comovers**



Multiplicity Dependence of Production

Comover Interaction Model

Braaten, He, Ingles & Jiang, arXiv:2012.13499

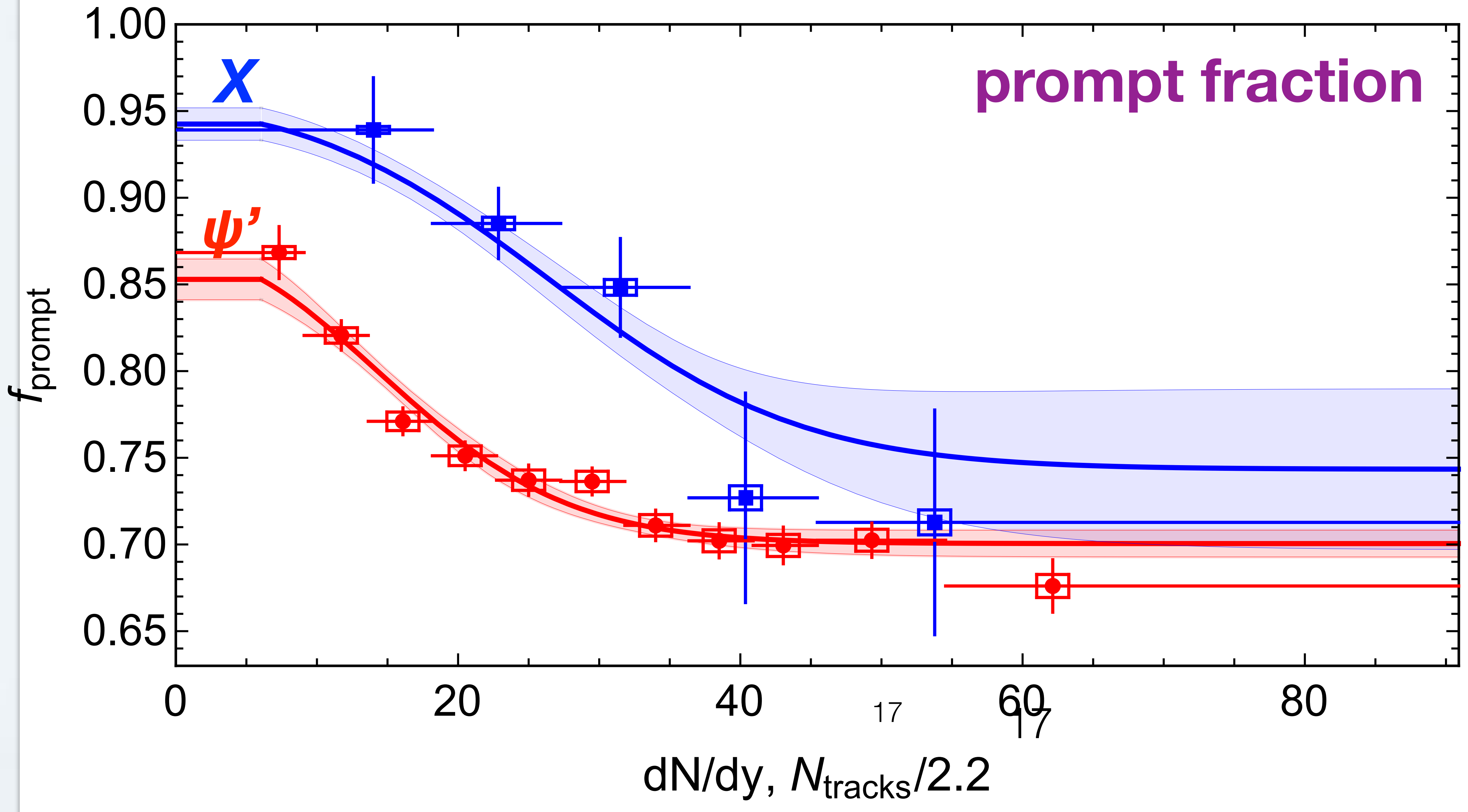
Simple Analysis of LHCb Data

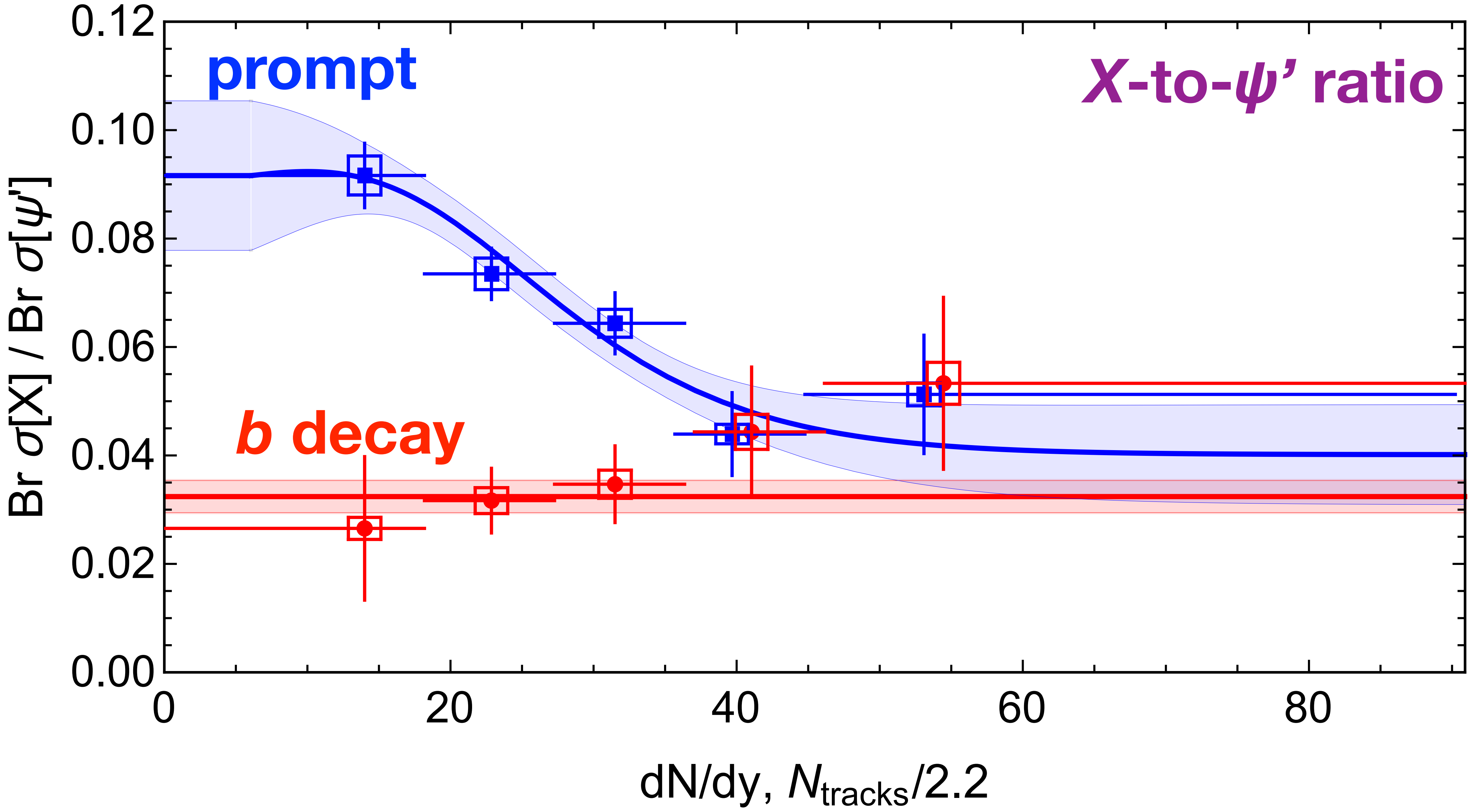
Assumptions

- **prompt cross section is sum of** term with survival probability
  term with survival probability = 1 (constant)

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

- ***b* decay cross section is constant**





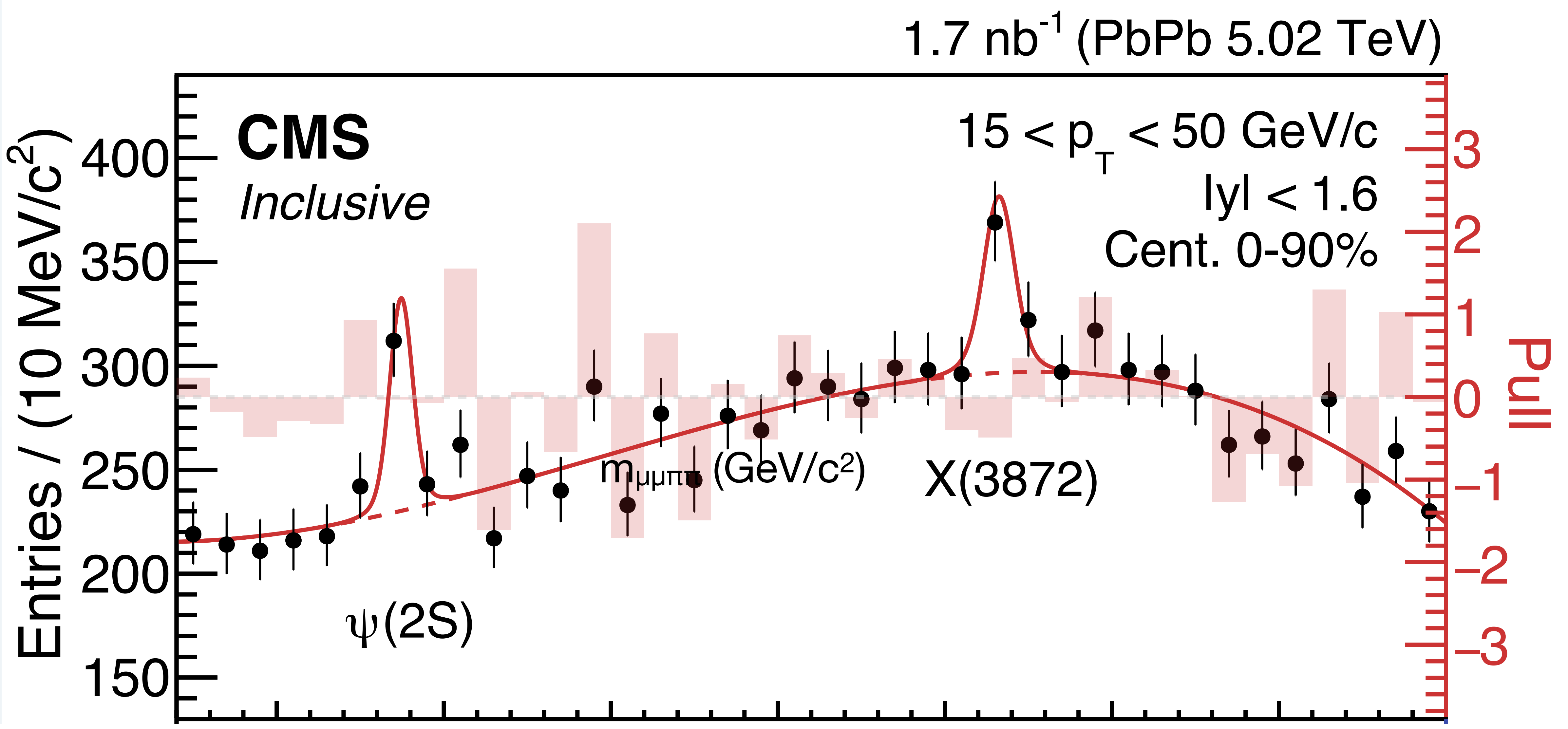
7 fitting parameters, 26 data points, χ²/dof = 0.99

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**

Production of X(3872) in heavy-ion collisions

prompt production in PbPb collisions [CMS arXiv: 2102.13048]



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

enhancement of *X*-to-*ψ'* ratio:
- **from enhancement of *X* ?**
- **from suppression of *ψ'* ?**

recent theoretical work on production in heavy-ion collisions:

- Chen, Jiang, Lui, Liu & Zhao arXiv:2107.00969
- Albaladejo, Nieves & Tolos arXiv:2102.08589
- Wu, Du, Sibila & Rapp arXiv:2006.09945
- Zhang, Liao, Wang, Wang & Xing arXiv:2004.00024
- Fontoura, Krein, Valcarce & Vijande arXiv:1905.03877
- Hong, Cho, Song & Lee arXiv:1804.05336
- Maiani, Polosa & Riquer arXiv:1712.05296

- ***X(3872)* must be produced in expanding hadron gas while *ψ'* may be produced in quark-gluon plasma**
- **It may be essential to treat the few-body physics of a loosely bound charm-meson molecule correctly**

Summary

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

X(3872) must be loosely bound neutral charm-meson molecule $X(3872) = \left(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}\right)/\sqrt{2}$

- charm-meson triangle singularities

  produce narrow peaks in *Xγ* (or *Xπ*) invariant mass near *D*D** threshold

  smoking gun for *X* as charm-meson molecule !!

- prompt production at hadron colliders:

  from $\chi_{c1}(2P)$ component of *X(3872)* *or* from creation of charm-meson pairs?

- multiplicity dependence

  LHCb: production of X in *pp* collisions depends on *dN/dy*

- heavy-ion collisions

  CMS: prompt *X*-to-*ψ(2S)* ratio is order of magnitude larger than in *pp* collisions !

challenge:

develop quantitative description of production of *X(3872)*
in *pp*, *p*-nucleus, and heavy-ion collisions
treating *X(3872)* as charm-meson molecule with correct few-body physics

Thank you!

Backup

$\langle v\sigma \rangle_m \simeq (\Lambda / 150 \text{ MeV})^3 \times 0.51$ mb
and $\langle v\sigma \rangle_{hh} \simeq 4.34$ mb.

$\langle v\sigma \rangle_{hh}$: destruction reaction rate of a molecule