Triangle Singularities in the Production of $T_{cc}^{+}(3875)$

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Triangle Singularities in the Production of $T_{cc}^{+}(3875)$

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BHIJ = Braaten, He, Ingles & Jiang

Triangle Singularities in the Production of $T_{cc}^{+}(3875)$

- S-wave near-threshold molecules: $T_{cc}^{+}(3875)$ and $X(3872)$
- Single Parton Scattering and Double Parton Scattering
- Triangle singularities
- Multiplicity dependence

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

discovery by Belle 2003

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

- mass 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 LHCb 2020

  $E_X > -0.22$ MeV at 90% CL

- quantum numbers $J^{PC} = 1^{++}$ LHCb 2013

  ⇒ S-wave coupling to the charm mesons

Conclusion:

X is a loosely bound charm-meson molecule !

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

with universal properties determined by binding energy

$T_{cc}^{+}(3875)$

discovery by LHCb 2021

$p\,p \rightarrow T_{cc}^{+}$ + anything, $T_{cc}^{+} \rightarrow D^0\,D^0\,\pi^{+}$

- mass extremely close to $D^{*+}D^0$ threshold

  $E_T \equiv M_T - (M_{D^{*+}} + M_{D^0}) = (-0.27 \pm 0.06)$ MeV LHCb 2021

- quantum numbers $J^P = 1^+$?

  ⇒ S-wave coupling to the charm mesons

Conclusion:

T_{cc}^{+} is a loosely bound charm-meson molecule !

$$T_{cc}^{+}(3875) = D^{*+}D^0$$

(plus small mixture of $D^{*0}D^{+}$)

with universal properties determined by binding energy

S-wave Resonance near Threshold

has universal properties determined by binding energy $|E_X|$

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

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

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

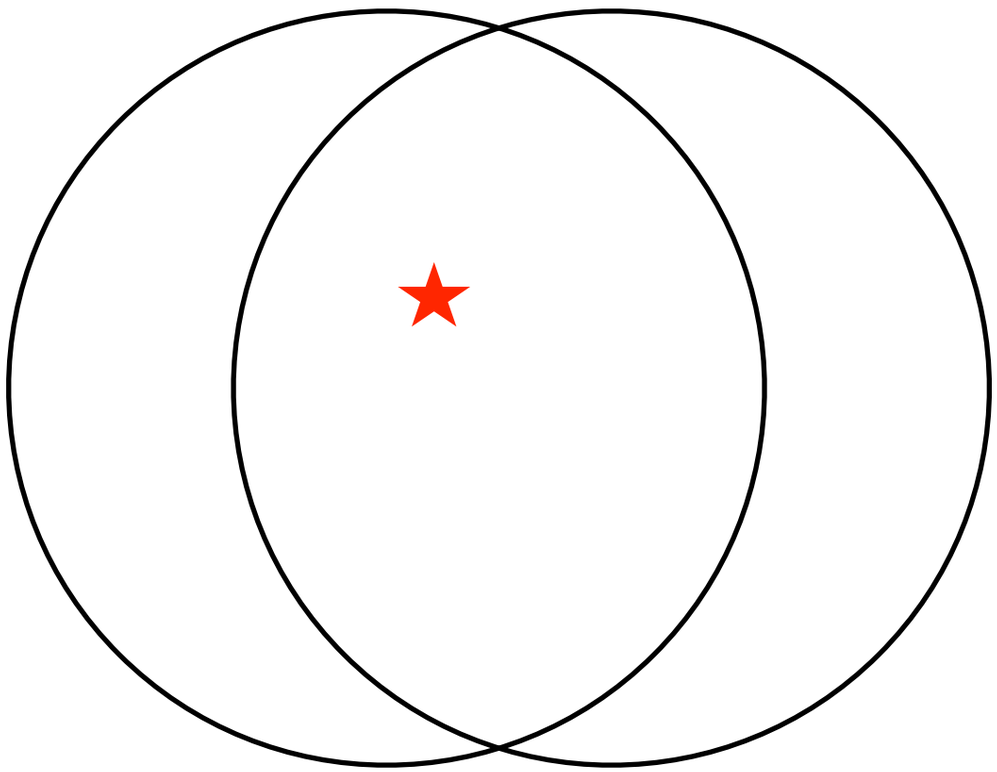
X(3872): $|E_X| < 0.22$ MeV $\implies$ $\langle r \rangle > 4.8$ fm

T_{cc}^{+}*(3875)*: $|E_X| = 0.27 \pm 0.06$ MeV $\implies$ $\langle r \rangle = 4.3 \pm 0.6$ fm

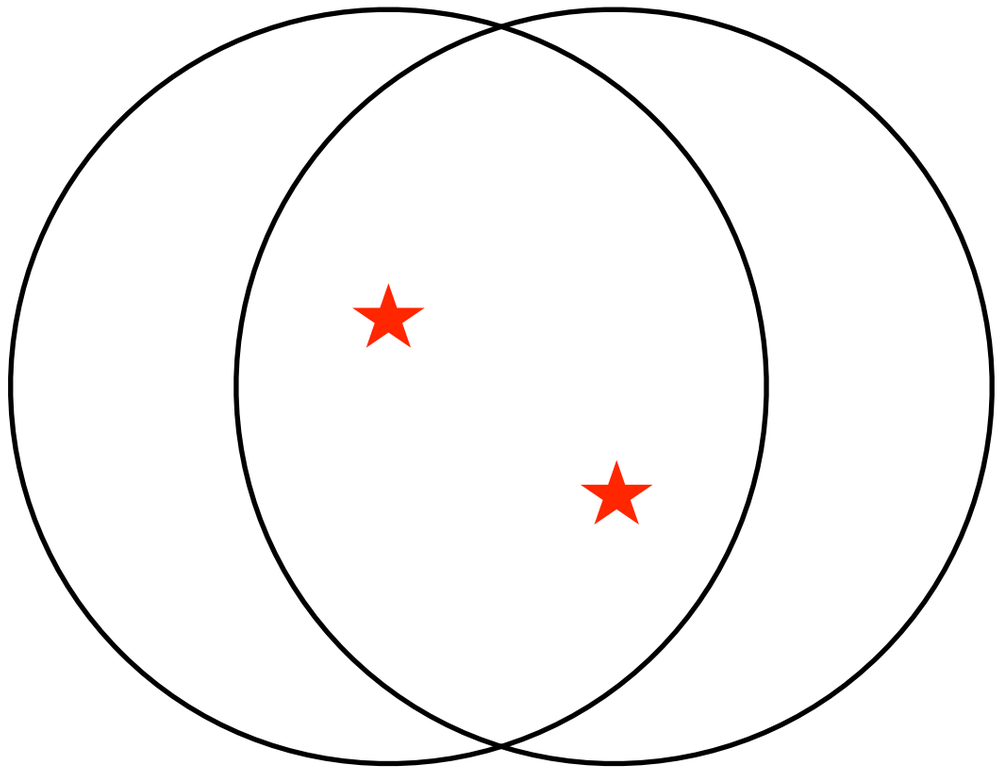
Proton-Proton Collisions at LHC

- protons are Lorentz contracted to thin disks
- disks collide with variable impact parameter

Single Parton Scattering
hard scattering of 2 partons
at 1 point in overlapping disks



Double Parton Scattering
hard scattering of partons
at 2 separate points



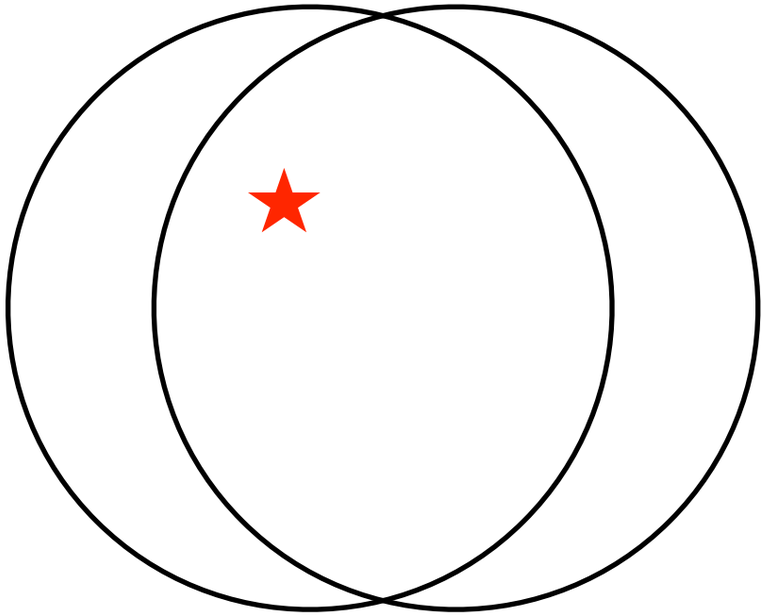
Double Parton Scattering is expected to produce events
with higher multiplicities than Single Parton Scattering

Production of *X(3872)*

- requires production of charm mesons $D^{*0}\bar{D}^{0}$ or $D^{0}\bar{D}^{*0}$
  with small relative momentum

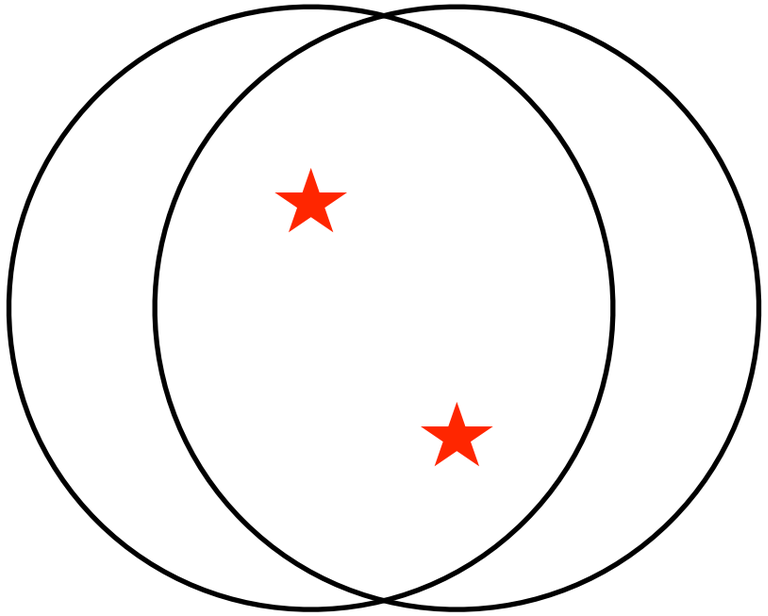
- requires creation of charm quark and antiquark $c\,\bar{c}$
  with small relative momentum

Single Parton Scattering



★ $g\,g \longrightarrow \boxed{c\,\bar{c}} + g$ order α_s^3

Double Parton Scattering



★ $g\,g \longrightarrow \boxed{c} + \bar{c}$ order α_s^2

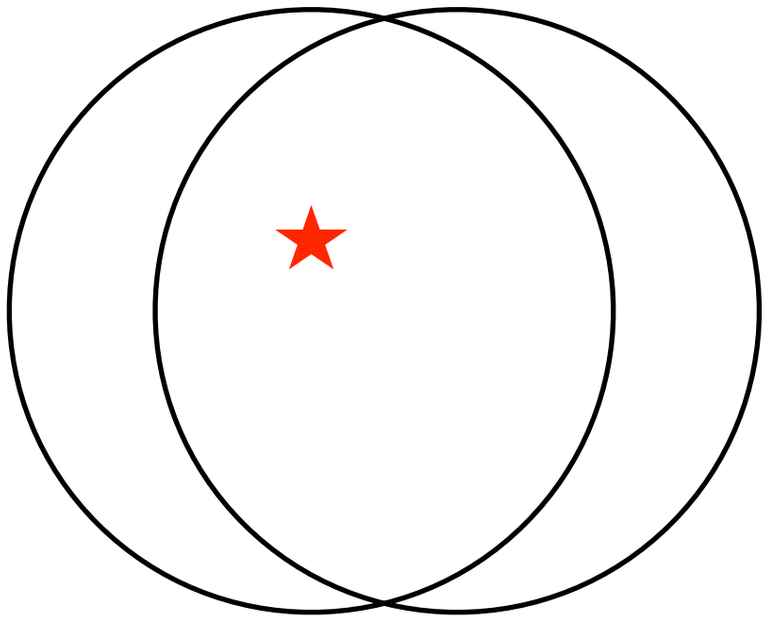
★ $g\,g \longrightarrow \boxed{\bar{c}} + c$

Production of $T_{cc}^{+}(3875)$

- requires production of charm mesons $D^{*+}D^{0}$ (or $D^{*0}D^{+}$) with small relative momentum

- requires creation of two charm quarks $c\,c$ with small relative momentum

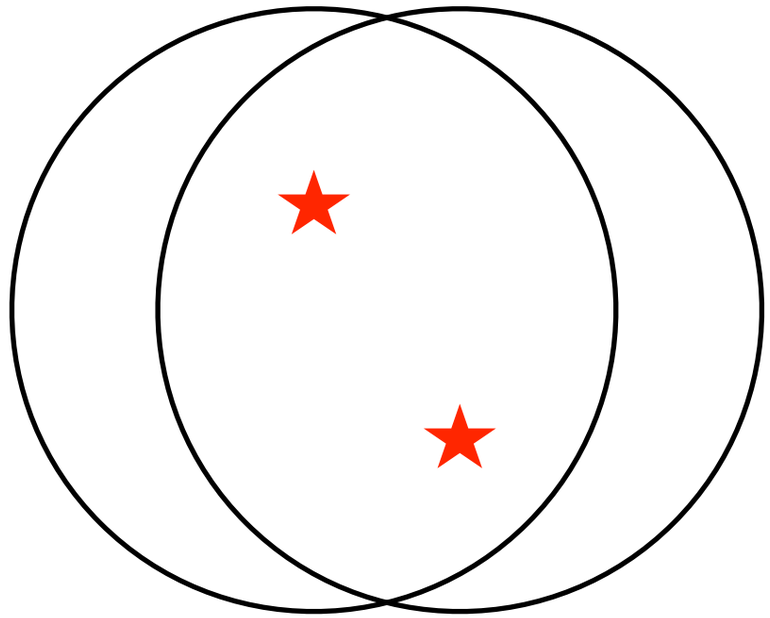
Single Parton Scattering



$\star \; g\,g \longrightarrow \boxed{c\,c} + \bar{c} + \bar{c}$ order α_s^4

suppressed compared to *X(3872)*

Double Parton Scattering



$\star \; g\,g \longrightarrow \boxed{c} + \bar{c}$ order α_s^2

$\star \; g\,g \longrightarrow \boxed{c} + \bar{c}$

comparable to *X(3872)*

Multiplicity Dependence

- number of tracks in LHCb vertex detector N_{tracks}
  strongly correlated with hadron multiplicity *dN/dy*

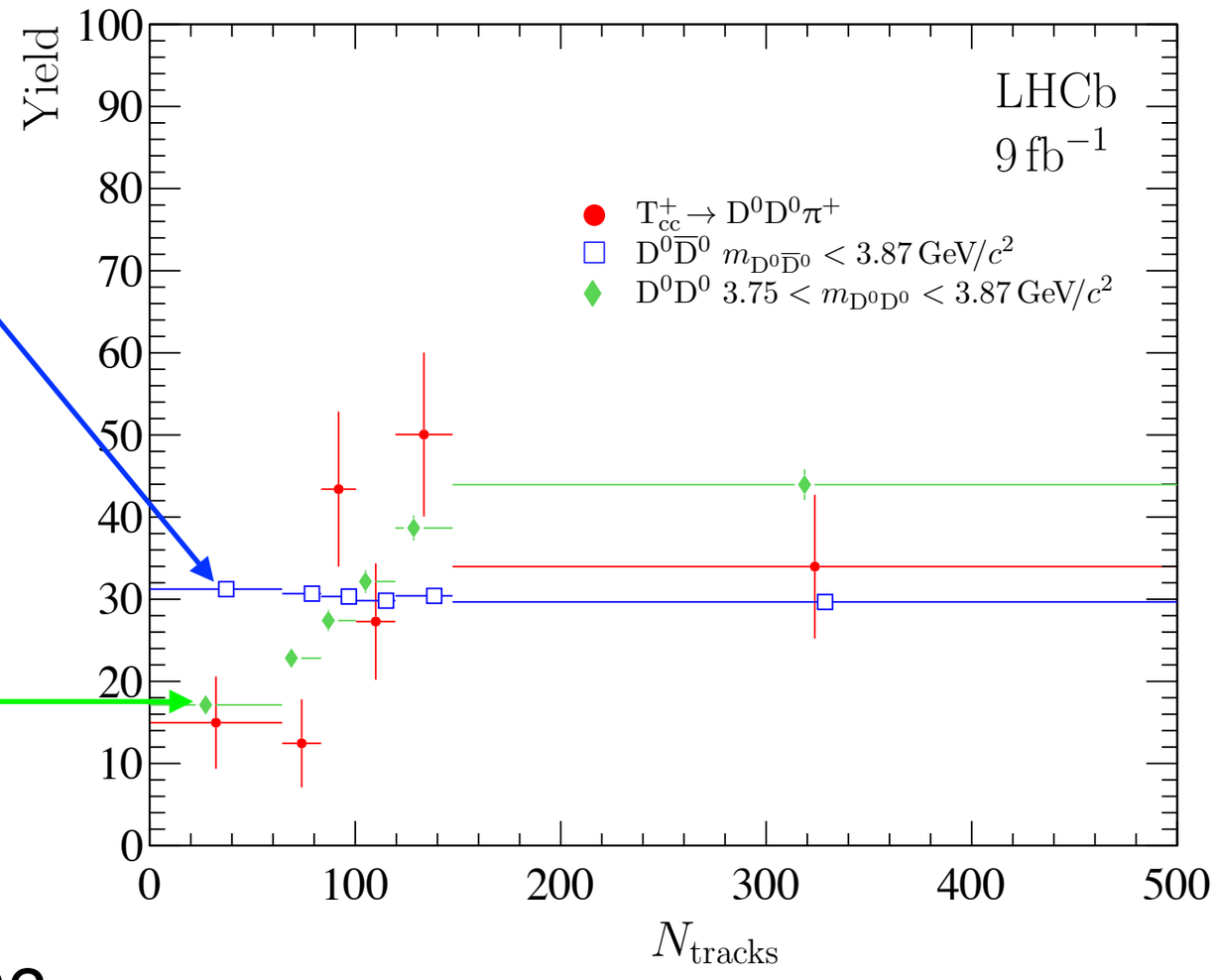
LHCb: arXiv:2109.01056

Low-mass charm+anticharm: $D^0\bar{D}^0$

- independent of N_{tracks}
- dominated by SPS ?
- *X(3872)* dominated by SPS ??

Low-mass double charm: D^0D^0

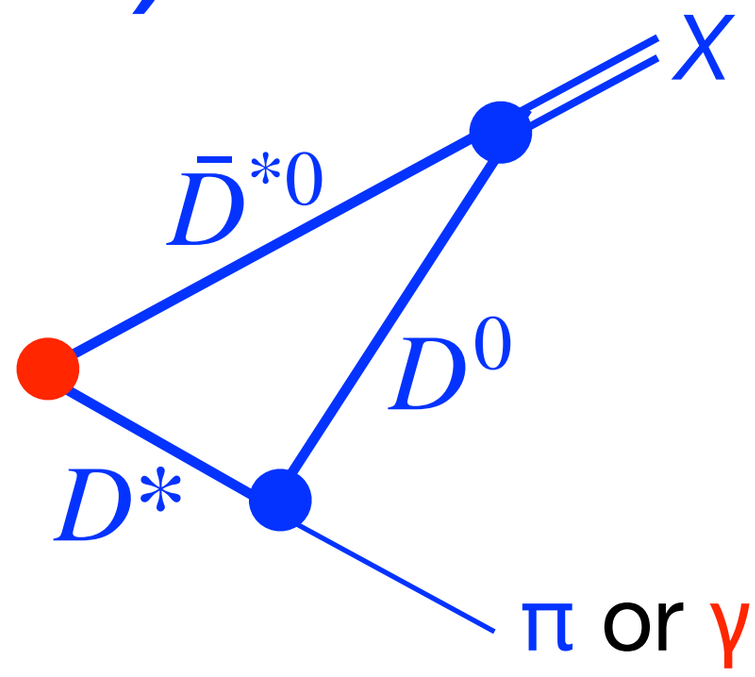
- increasing with N_{tracks}
- dominated by DPS ?
- $T_{cc}^+(3872)$ dominated by DPS ??
- $T_{cc}^+(3872)$ at small N_{tracks} dominated by SPS ???



Production of *X(3872)*

Single Parton Scattering

$\Longrightarrow$ charm mesons created at a point



if $D^*\bar{D}^*$ are created at a point
they can rescatter into $X+\pi$ (or $X+\gamma$)
through a triangle diagram

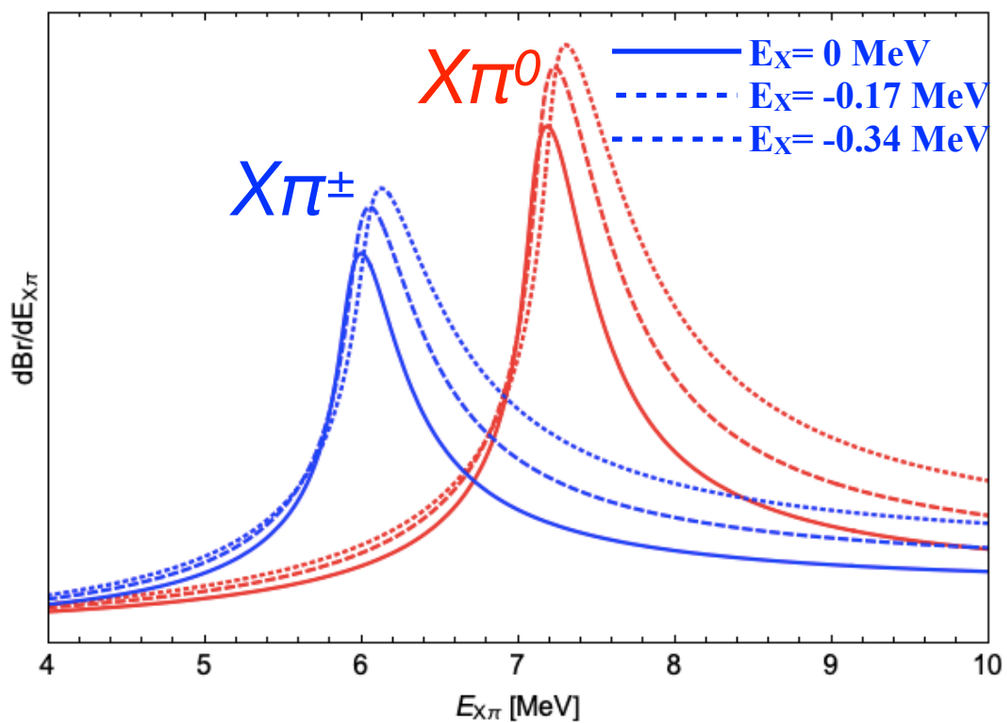
Triangle Singularity

when 3 lines forming triangle can all be exactly on shell
reaction rate has $\log^2|E-E_\Delta|$ divergence
at energy E_Δ determined by masses
when 3 lines forming triangle can all be almost on shell
reaction rate has narrow peak at energy E_Δ

prompt production in *pp* collisions

BHI (2019)

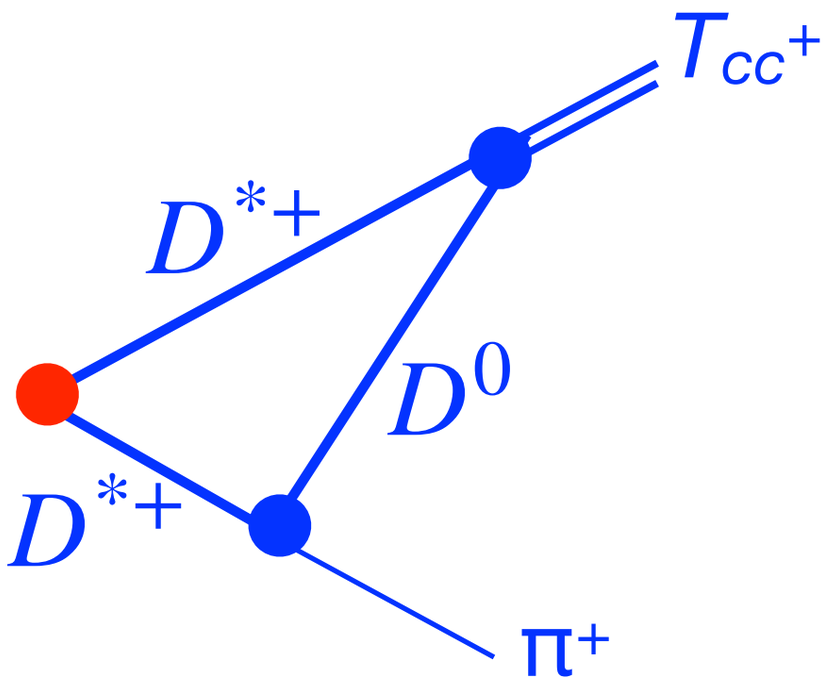
narrow peak in $X\pi^\pm$ invariant mass
6.1 MeV above $X\pi^\pm$ threshold
with width about 1 MeV



Production of $T_{cc}^{+}(3875)$

Single Parton Scattering

$\Longrightarrow$ charm mesons created at a point



if $D^{*+}D^{*+}$ are created at a point
they can rescatter into $T_{cc}^{+} + \pi^{+}$
through a triangle diagram

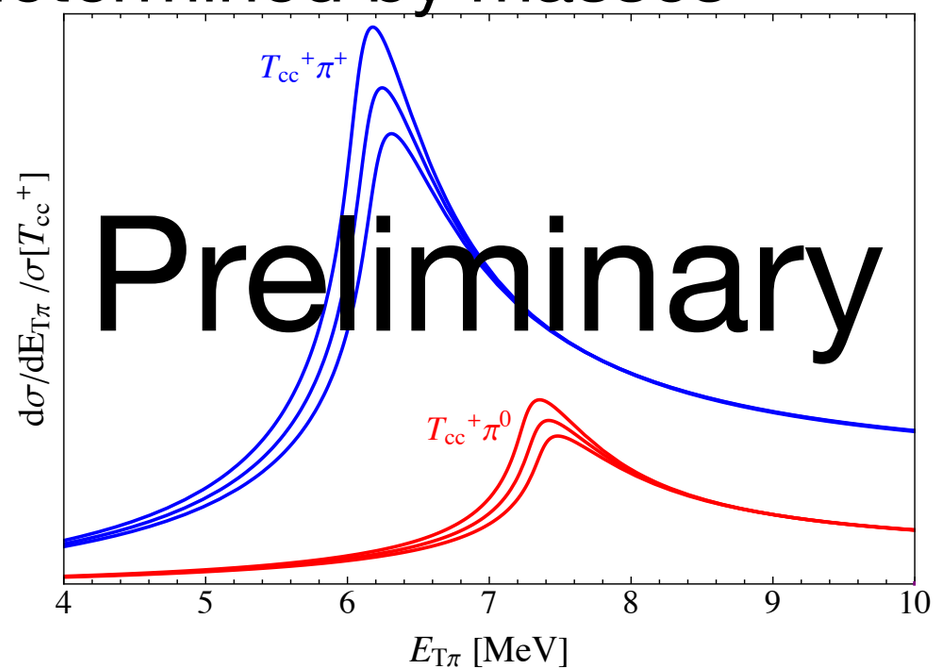
Triangle Singularity

when 3 lines forming triangle can all be almost on shell
reaction rate has narrow peak at energy E_{Δ} determined by masses

prompt production in *pp* collisions

BHIJ (in preparation)

narrow peak in $T_{cc}^{+}\,\pi^{+}$ invariant mass
6.1 MeV above $T_{cc}^{+}\,\pi^{+}$ threshold
with width about 1 MeV
observable at low multiplicity ??



Production of *X(3872)*

other peaks from Triangle Singularities

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

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

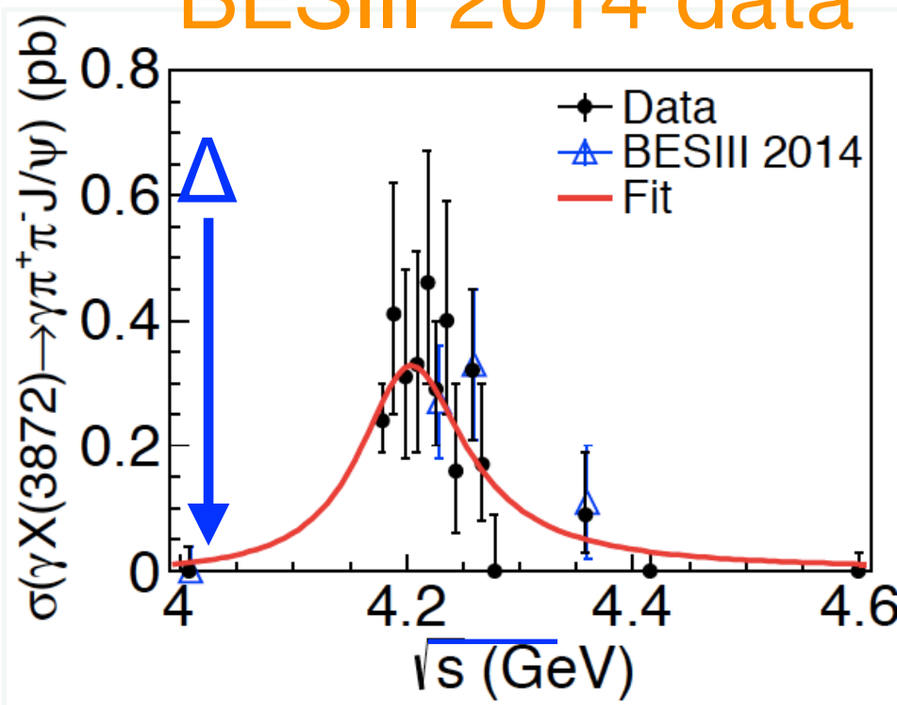
narrow peak near 4016 MeV with width about 2 MeV

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

$e^+e^- \to D^{*0}\bar{D}^0 + \gamma$ BHIJ (2020)

interference effect from triangle singularity

BESIII 2014 data



<u>B meson decay</u>

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

narrow peak in $X\pi$ invariant mass

$X\pi^+$: 6.1 MeV above $X\pi^+$ threshold with width about 1 MeV

$X\pi^0$: 7.3 MeV above $X\pi^0$ threshold with width about 1 MeV

Production of *X(3872)*

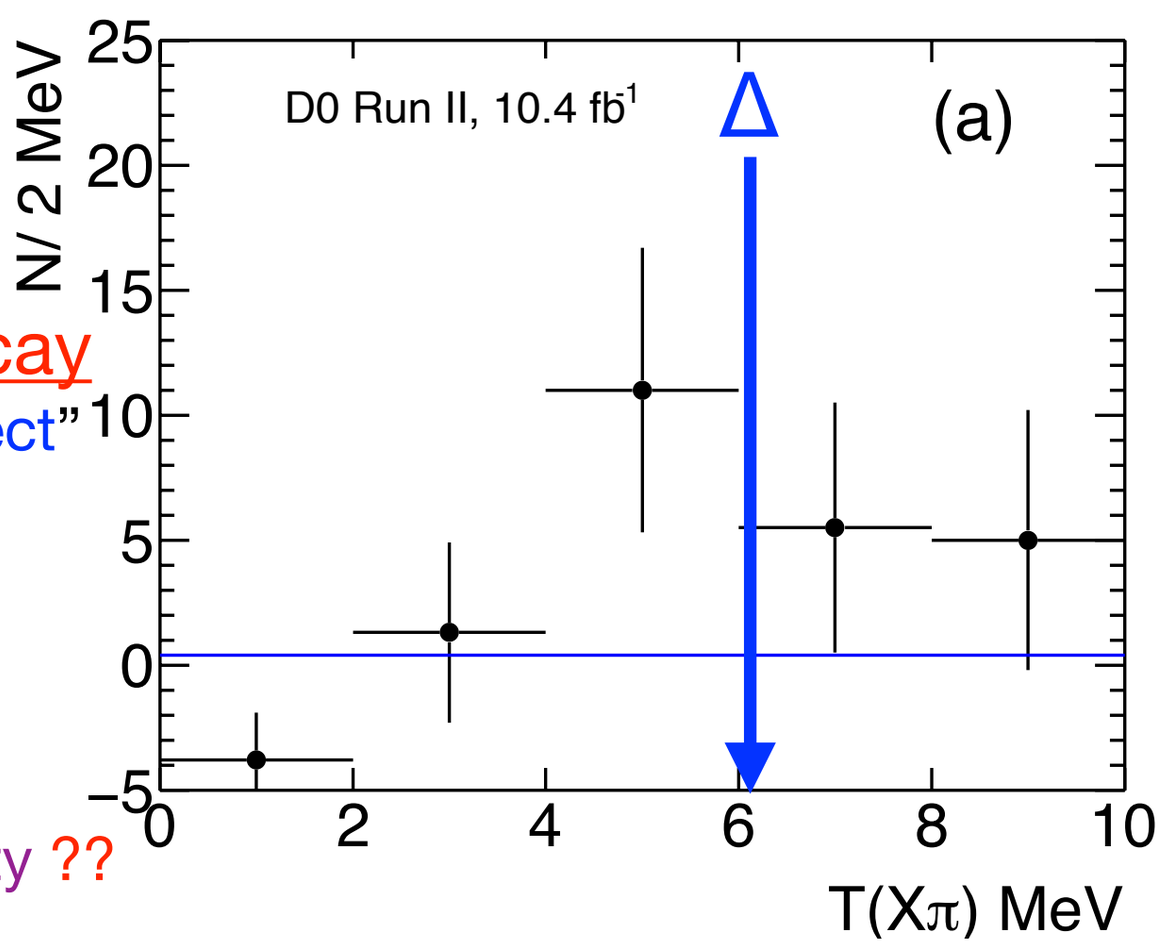
production of $X\pi^{\pm}$ in $p\bar{p}$ collisions at the Tevatron

DØ arxiv:2007.13420

Triangle Singularity produces narrow peak in $X\pi^{\pm}$ invariant mass
6.1 MeV above $X\pi^{\pm}$ threshold with width about 1 MeV

prompt production of $X\pi^{\pm}$:
DØ: "no evidence for soft-pion effect"

production of $X\pi^{\pm}$ from *b* hadron decay
DØ: "no significant evidence for soft-pion effect"
but "small excess" with significance of 2σ
at small $X\pi$ energy



first hint of narrow peak from triangle singularity ??

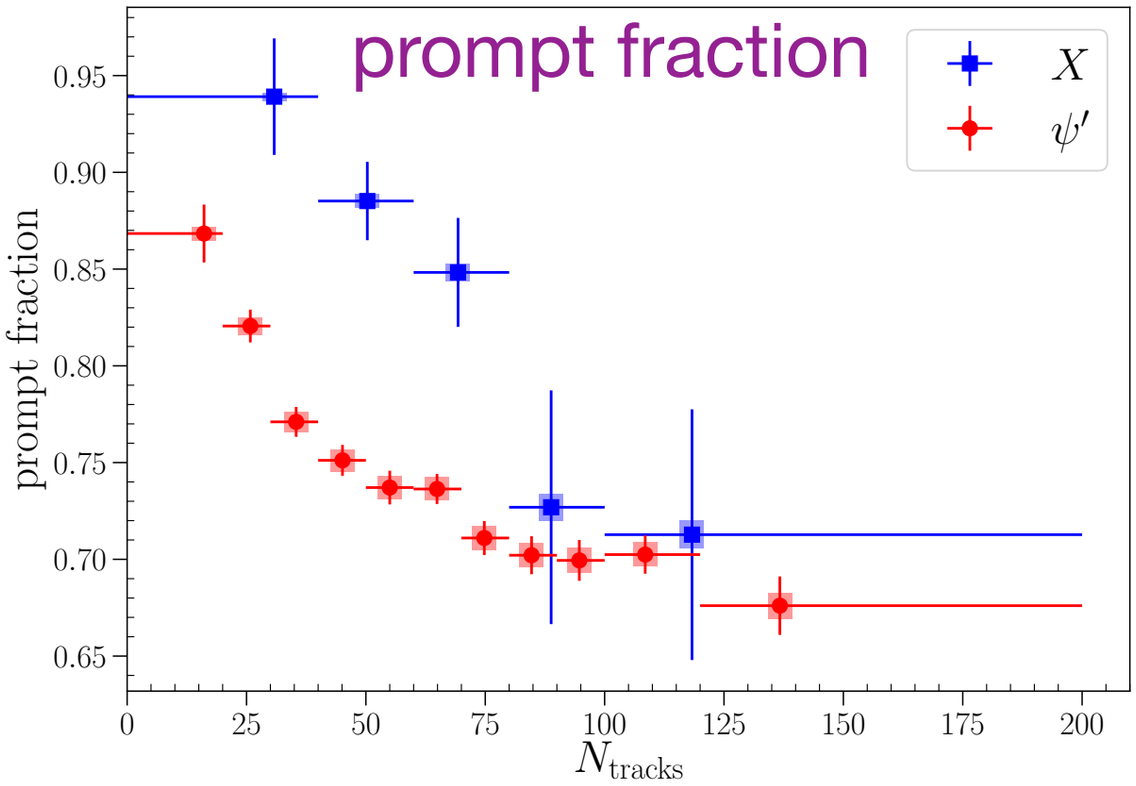
Production of *X(3872)*

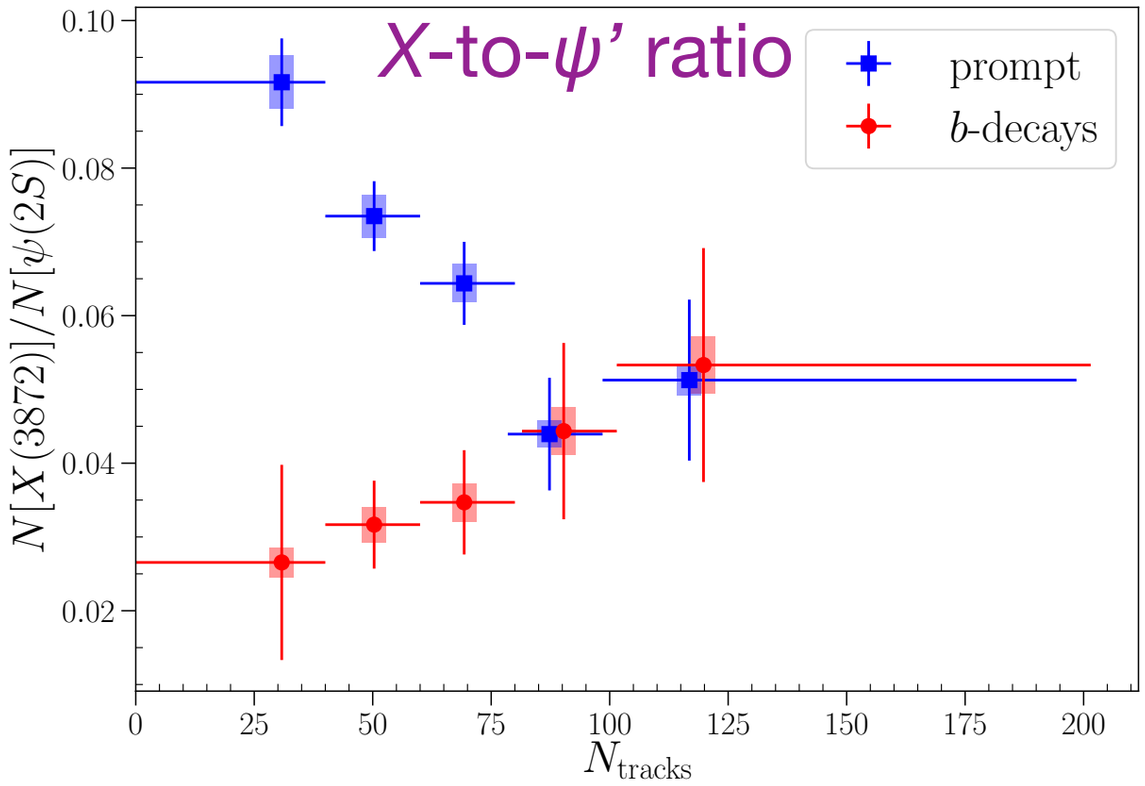
dependence on multiplicity in *pp* collisions LHCb 2020

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 for *ψ'*: seems to saturate at large N_{tracks}

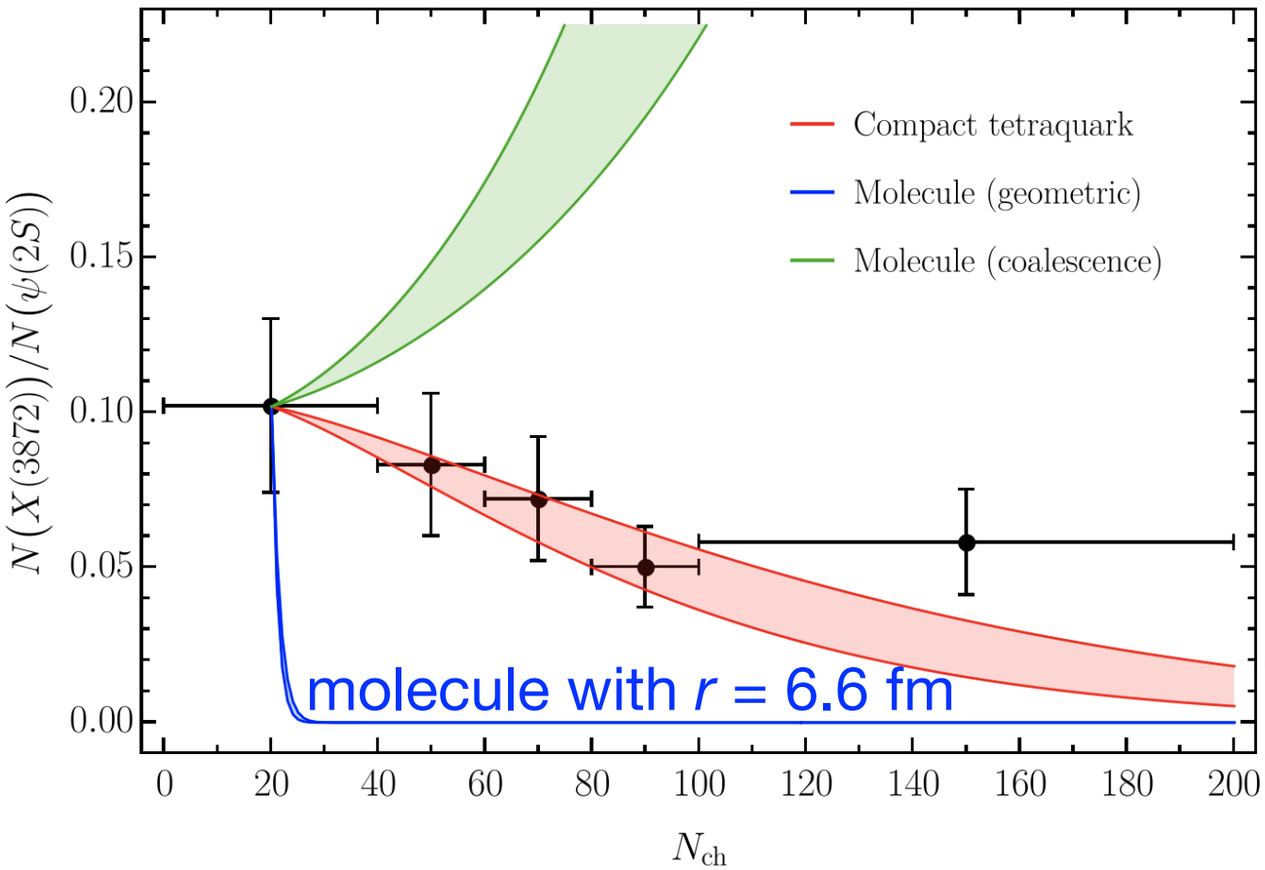
X-to-*ψ'* ratio for prompt: significant decrease with N_{tracks}

Production of *X(3872)*

dependence on multiplicity in *pp* collisions

Comover Interaction Model
Esposito et al. arXiv:2006.15044

prompt *X*-to-*ψ'* ratio



tetraquark with *r* = 0.65 fm

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

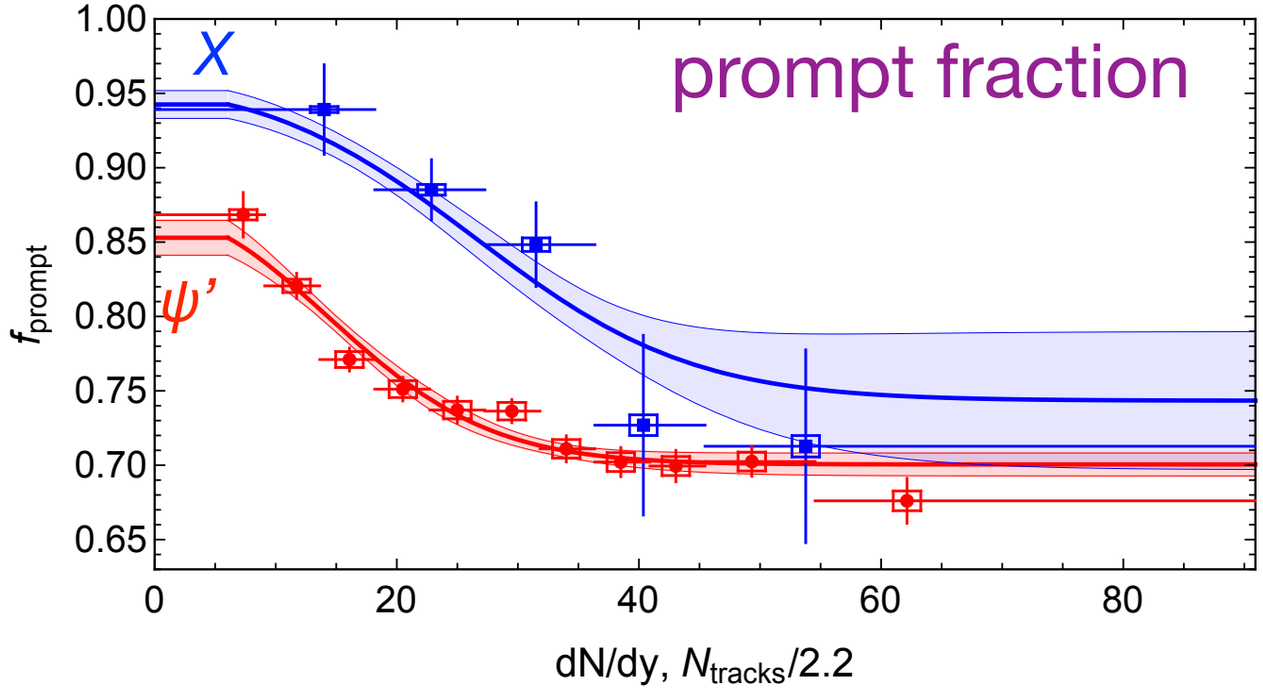
Production of *X(3872)*

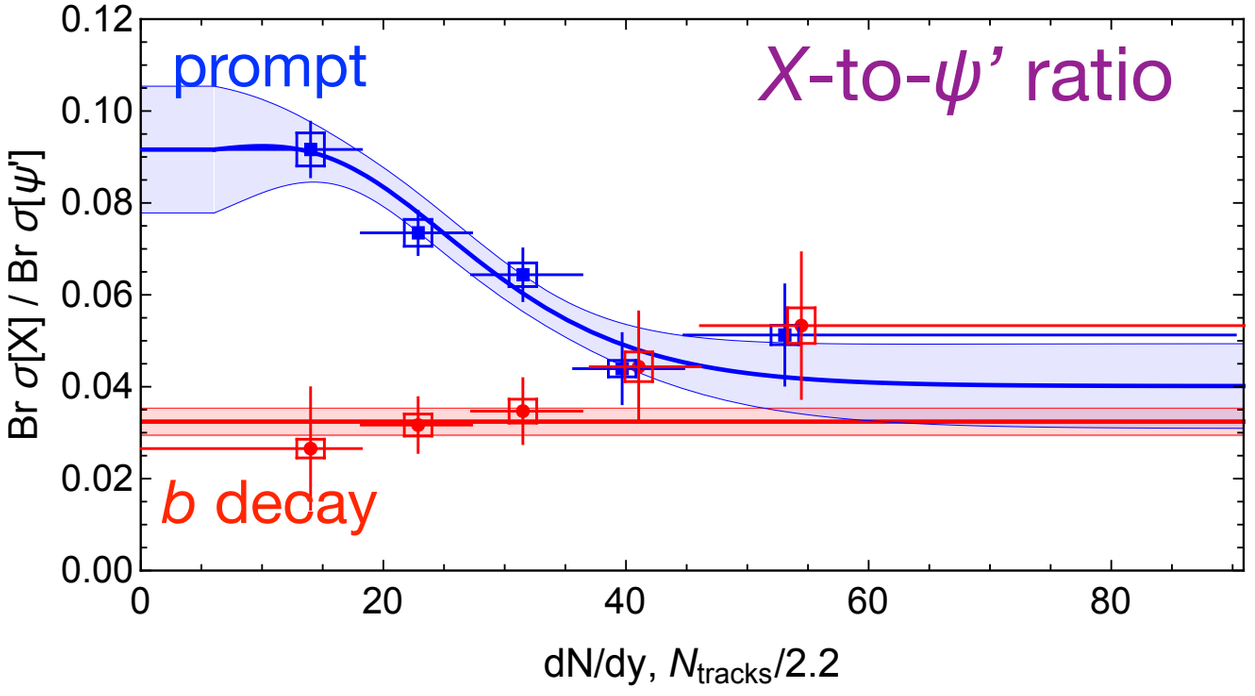
Simple analysis of LHCb data
on multiplicity dependence BHIJ arXiv:2012.13499

<u>Assumptions</u>

- prompt cross section is sum of
  - term with survival probability of comover interaction model
  - term with survival probability = 1 (constant)
- *b* decay cross section is constant

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





7 fitting parameters
26 data points
χ^2/dof = 0.99

fitted breakup reaction rates:

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

$$\langle v\sigma\rangle_{X} = 2.7 \pm 0.7 \text{ mb}$$

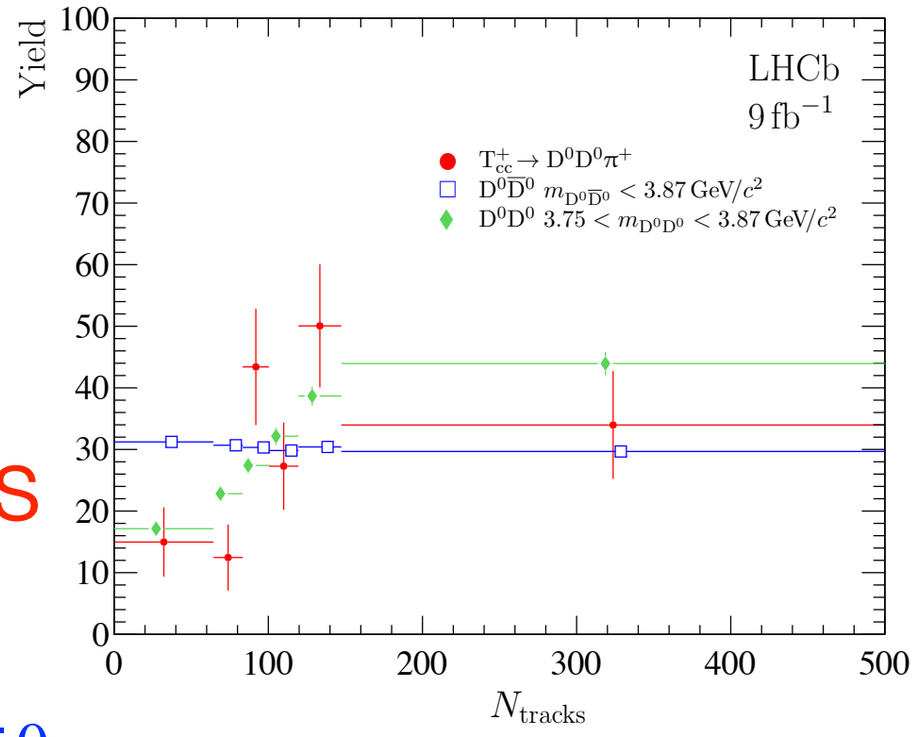
Summary

production of low-mass double charm: D^0D^0
increases with multiplicity

$\Longrightarrow$ dominated by Double Parton Scattering

$\Longrightarrow$ production of $T_{cc}^+(3875)$ dominated by DPS

LHCb arXiv:2109.01056



production of low-mass charm+anticharm: $D^0\bar{D}^0$
does not depend on multiplicity

$\Longrightarrow$ dominated by Single Parton Scattering

$\Longrightarrow$ production of $X(3872)$ dominated by SPS

$\Longrightarrow$ triangle singularity in production of $X\,\pi^\pm$

narrow peak in $X\,\pi^\pm$ invariant mass
6.1 MeV above threshold
smoking gun for loosely bound molecule !