Exotic hadrons in heavy ion collisions

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Aim

- A brief overview on the state-of-art of exotic states
- The exotics in a HIC: dependence on their interpretation
- Molecular, tetraquark and triangle singularities interpretations in HICs?

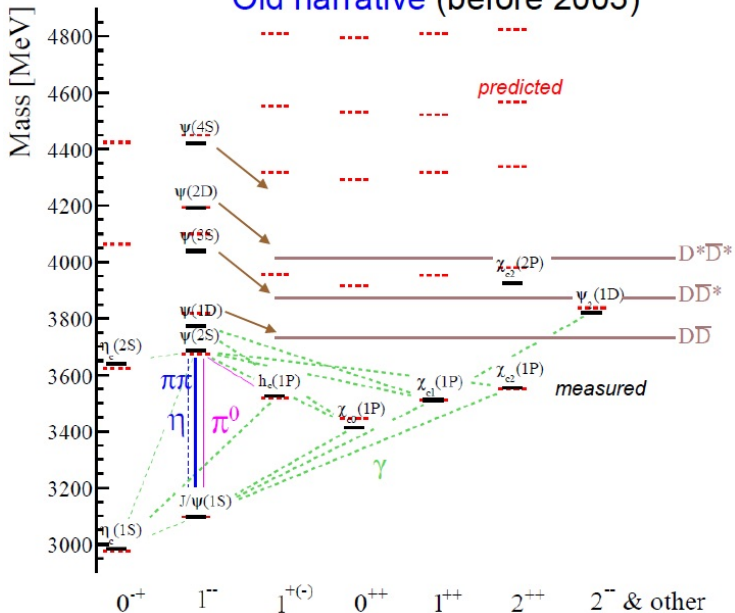Case study of some of the most prominent exotic states

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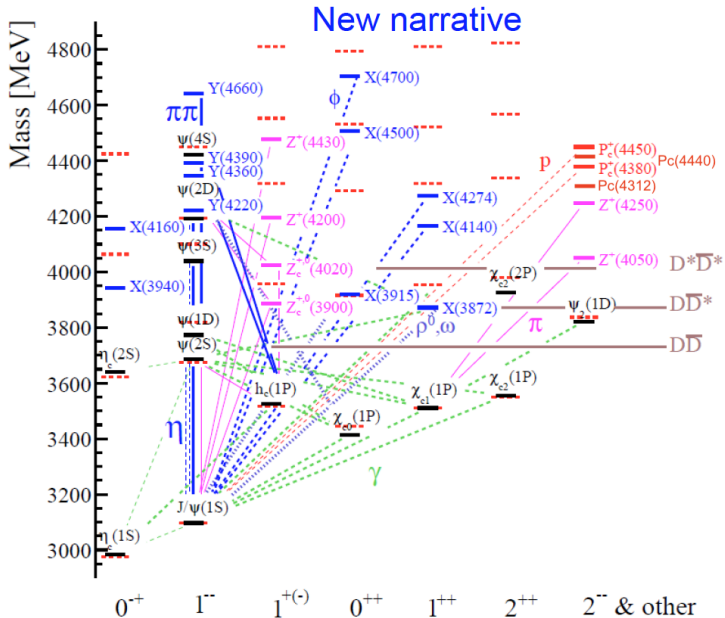Case study of some of the most prominent exotic states

Figures from Olsen, Skwarnicki, Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

New narrative

(Skwarnicki, 2018)

Why exotic hadron states?

- Proliferation of new states in the $c\bar{c}$, $b\bar{b}$ and ccq sectors
- Properties do not match standard quark-model predictions
- Decay properties require > 3 valence quarks

Ex.1: Z's are manifestly 4-quark states (J/ψ not produced from $|0\rangle$)

$$Z_c^+(3900) \to J/\psi \pi^+$$

Ex.2: isospin violation (if $X(3872) \sim c\bar{c}$: decay highly suppressed)

$$X(3872) \to \rho^0 J/\psi \to \pi^+ \pi^- J/\psi$$

The heavy exotics collection (2101.08241 [hep-ph], PDG2020)

- 44 observed
- 17 confirmed with complete assignment by PDG
- Estimations: about a hundred to be discovered in near future

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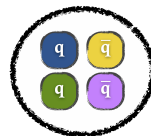# Intepretations for composition and binding mechanisms?
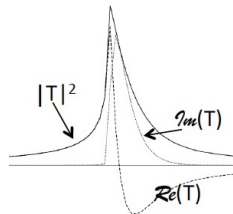
- Hadron Molecules
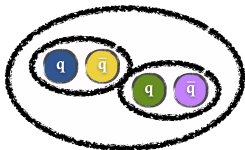
- Hybrids

- Glueballs

- Tetraquarks

- Kinematical effects (TS's)

Theoretical perspective

A compelling and unified understanding has not yet emerged

- No single theoretical framework explains all exotic candidates
- Candidates: different interpretations
- In some cases, properties (masses, decay widths) are well explained by different models or quantum-mechanical superposition of them

- Necessity of more observables to distinguish its internal structure

- Let us focus on some emblematic states

The heavy exotics collection

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$X(3872)$: features

$X(3872)$ story

74 years ago

K-mesons discovered -- *associated production – strangeness – SU(3)* -- **quark model**

Dec. 1947 ←————— **16 years** —————→ Jan 1964

18 years ago

X(3872) discovered -- *molecule?* *charmonium?* *molecule?* – *charmonium?* – *diquark?* – *molecule?* *charmonium?* *molecule?* -- **????**

Aug. 2003 ←————— **18 years** —————→ today

(Adapted from S. Olsen, SCGP Workshop on Exotic Hadrons and Flavor Physics, May 2018)

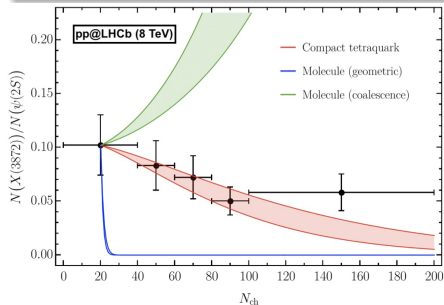# Recent dispute on Prompt production of $X(3872)$

Esposito et al., 2006.15044

- Comover interaction model:

$$\tau \frac{N_{\mathcal{Q}}}{d\tau} = -\langle v\sigma \rangle_{\mathcal{Q}} \rho_c N_{\mathcal{Q}};$$

$\langle v\sigma \rangle_{4q} \sim \pi r_{4q}^2 \simeq 11.6\,\mathrm{mb}$;
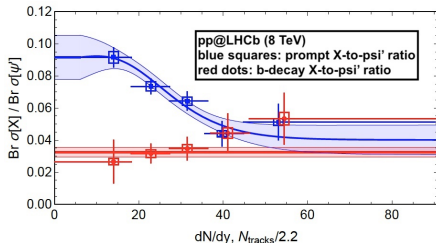$\langle v\sigma \rangle_{Mol} \sim \pi r_{Mol}^2 \simeq 1197\,\mathrm{mb}$

- Findings $\Rightarrow$ tetraquark nature

Braaten et al., PRD (2021); 2012.13499

- $\langle v\sigma \rangle_{Mol}$: probability-weighted sum of $\langle v\sigma \rangle (\pi D^{(*)})$
- Insensitive to $E_b^{(X)}$
- $f_{out,\mathcal{Q}}^{(prompt)}$: out of reach of comoving pions
- Findings $\Rightarrow$ molecular picture

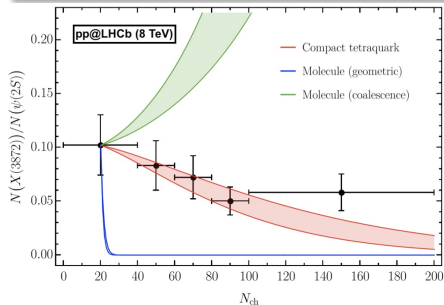# Recent dispute on Prompt production of $X(3872)$

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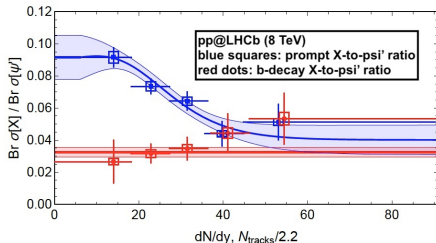$$\langle v\sigma \rangle_{Mol} \sim \pi r_{Mol}^2 \simeq 1197 \,\mathrm{mb}$$

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Promising alternative: exotics in HICs

pp collisions

- Esposito et al., 2006.15044 $\rightarrow$ Geometrical Cross sections:
  $\langle v\sigma \rangle_Q \sim \pi r_Q^2 (1 - E_Q^{Thr}/E_\pi)^n$
- Braaten et al., 2012.13499 $\rightarrow$ non-relativistic XEFT for $D^{(*)}\pi$

Relevance of hadronic medium interactions

Artoisenet and Braaten (PRD, 2011), Esposito et al. (JMP, 2013), Cho and Lee (PRD, 2013), LMA et al. (PRD, 2014), Guerrieri et al. (2014), ...

HICs

- End of the QGP phase: XYZ states interact with hadronic medium
- Absorption by comoving mesons or production from heavy mesons
  ($D^{(*)}\bar{D}^{(*)} \rightarrow X\pi, \rho, ...$)
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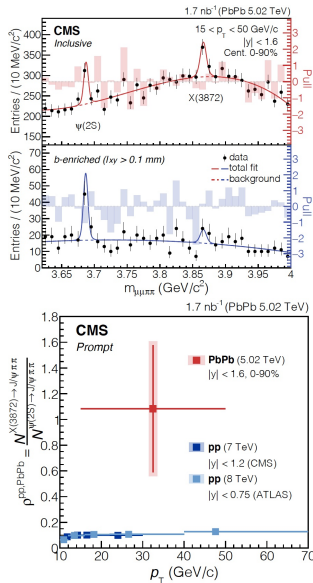# Breaking news: first evidence for $X(3872)$ in HICs!

CMS-LHC, arXiv:2102.13048

- Prompt $X(3872)$-production in $PbPb$ collisions, $\sqrt{s} = 5.02$ TeV

$$X(3872) \quad \rightarrow \quad J/\psi \pi^+ \pi^-$$
$$\rightarrow \quad \mu^+ \mu^- \pi^+ \pi^-$$

- $\rho^{(PbPb)} = \dfrac{N_{X(3872)}}{N_{\psi(2S)}} = 1.08 \pm 0.9 \pm 0.52$

$\rho^{(PbPb)} \simeq 10 \, \rho^{(pp)}$

Unique experimental input of the $X(3872)$ production mechanism and its nature

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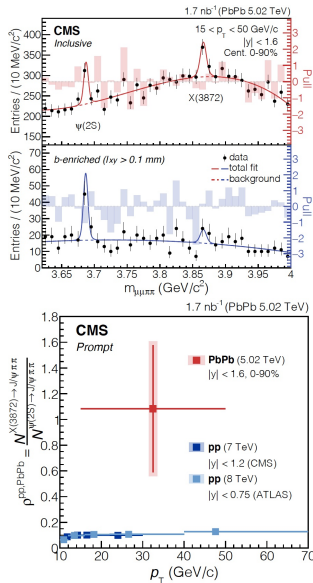
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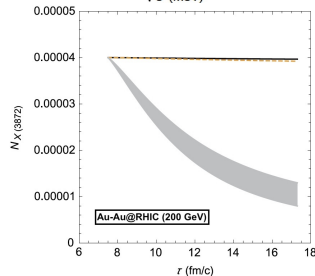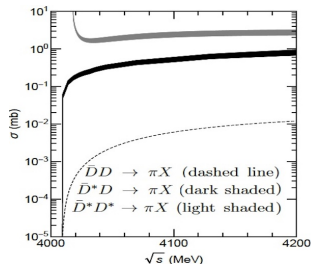
Hadronic effects on $N_{X(3872)}(\tau)$

- Use of Eff. Lagrangians based on relevant symmetries
- Inclusion of $g_{X D^{\pm} D^{*\mp}}$
- Anomalous: $\mathcal{L}_{\pi D^* \bar{D}^*}$, $\mathcal{L}_{X D^* \bar{D}^*}$
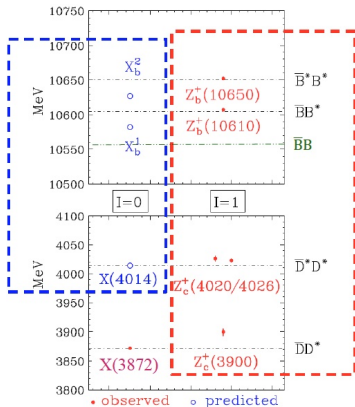- Internal structure: coalescence

Bjorken picture - Rate equation:

$$\frac{dN_X(\tau)}{d\tau} = \sum_{\varphi} \Big[\langle \sigma_{\bar{M}M' \to \varphi X} v_{\bar{M}M'} \rangle n_{\bar{M}}(\tau) N_{M'}(\tau)$$
$$- \langle \sigma_{\varphi X \to \bar{M}M'} v_{\varphi X} \rangle n_{\varphi}(\tau) N_X(\tau) \Big].$$

$N_{X(3872)}^{(4q)}$ reduced by a factor of 4

$\bar{D}D \to \pi X$ (dashed line)
$\bar{D}^* D \to \pi X$ (dark shaded)
$\bar{D}^* D^* \to \pi X$ (light shaded)

Au-Au@RHIC (200 GeV)

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24-46$	$J/\psi\,\pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	$8-25$	$J/\psi\,\pi$	783	$\bar{D}^*D^*$	6
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$Z_c^{\pm,0}(3900),\ Z_c^{\pm,0}(4020)$

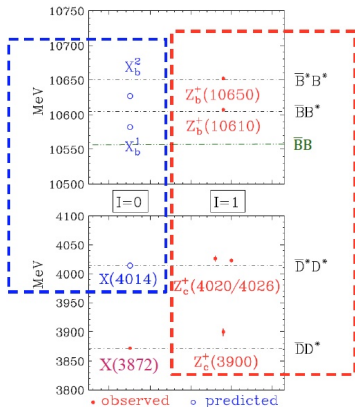- $(D\bar{D}^*)^{\pm,0}, (D^*\bar{D}^*)^{\pm,0}$

$Z_b^{\pm,0}(10610),\ Z_b^{\pm,0}(10650)$

- $(B\bar{B}^*)^{\pm,0}, (B^*\bar{B}^*)^{\pm,0}$

- $I(J^{P(C)}) = 1(1^{+(-)})$
- CHARGED: no confusion with quarkonia $Q\bar{Q}$ states!
- The only clear "spectroscopy" so far

Exotic states with $I = 1$

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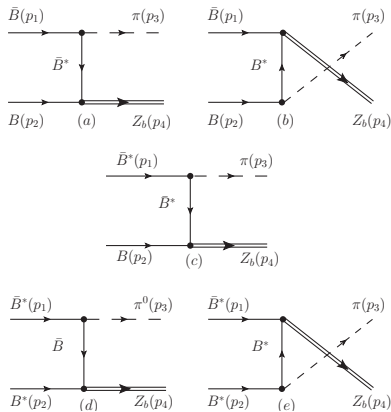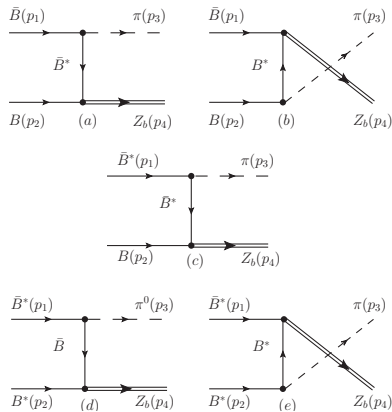# Bottomonium sector: $Z_b(10610)$ and $Z_b'(10650)$

LMA, Kamchandani, Torres, Nielsen, Navarra, Vasconcellos; (PRD, 2017; EPJ C, 2018, ...)

- $N_{Z_b^{(\prime)}}(\tau)$ in HIC enviroment
- Rate equation (Bjorken picture): absorption and regeneration effects in hadron gas phase
- Inclusion of the coupling:

  $Z_b^+(B^+\bar{B}^{*0} + \bar{B}^0 B^{*+})$

- Inclusion of the term
 $-\Gamma_{Z_b} N_{Z_b}(\tau)$
  ($\Gamma_{Z_b} \approx 20$ MeV)

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Time evolution of the $Z_b(10610)^{\pm,0}$ abundance

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- Suppression by a factor two of the final yield
- Smaller suppression that than the one found for $X(3872)$

- Role played by the medium: "filtering" of the particles produced at the end of QGP
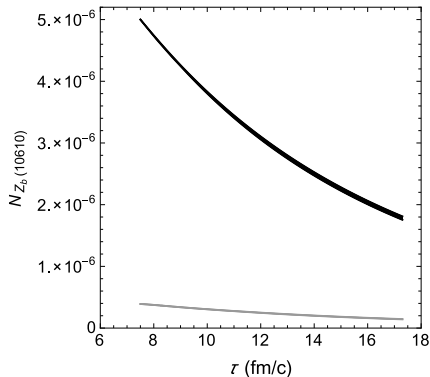
LHC ($\sqrt{s_{NN}} = 2.76$ TeV)
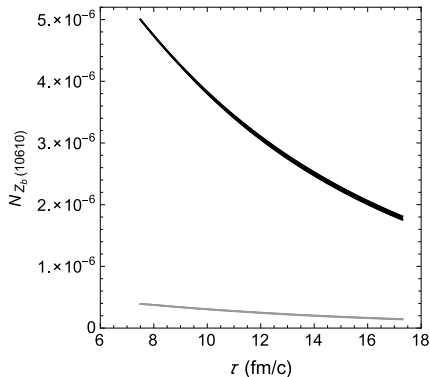
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$X_J(2900)$: first fully open-charm exotic hadrons

LHCb, PRL **125**, 242001 (2020)

- Invariant mass spectrum of the $B^+ \to D^+ D^- K^+$ decay:

  0^+ : $M = 2866\text{MeV}$, $\Gamma = 57\text{MeV}$

  1^- : $M = 2904\text{MeV}$, $\Gamma = 110\text{MeV}$

- Minimum valence quark contents: $\bar{c}\bar{s}ud$

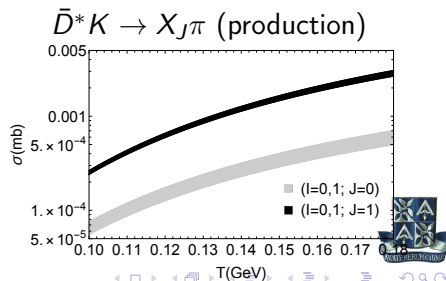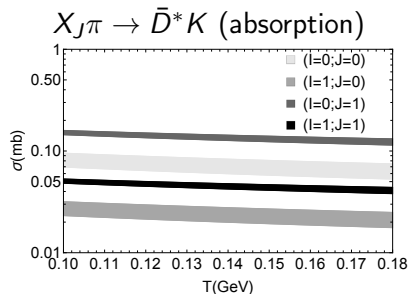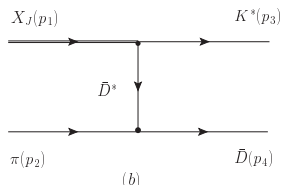First observed unconventional hadrons which are fully open charm tetraquarks
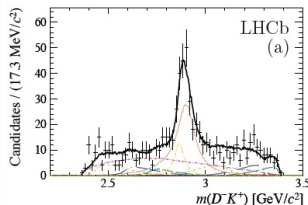
- HIC: how they are affected by the medium during the expansion?

- Possible interpretations?

- Hadronic molecular states ($J = 0$ as a S-wave and $J = 1$ as a P-wave)?

- Tetraquark states?

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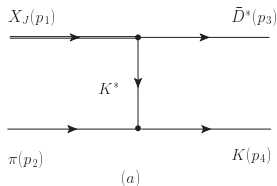First observed unconventional hadrons which are fully open charm tetraquarks
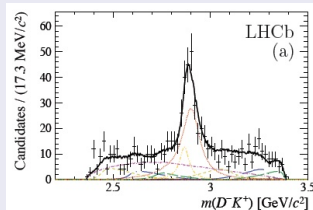
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$X_J(2900)$: hadronic interactions in HICs

LMA, PRD**103**, 036013(2021)

- Analysis of the processes:
  $X_J\pi \leftrightarrow \bar{D}^*K, K^*\bar{D}$

$X_J\pi \to \bar{D}^*K$ (absorption)
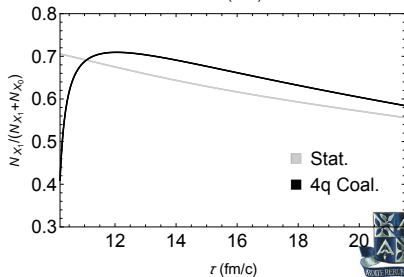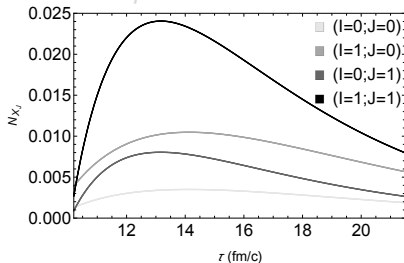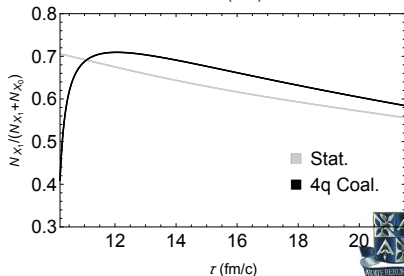
$\bar{D}^*K \to X_J\pi$ (production)

- $4q$ coal.: initial yields ($\tau \sim \tau_C$)
- Hadron coal.: at $\tau \sim \tau_F$

State	$N_{X_J}^{\mathbf{0}(Stat)}(\tau_H)$	$N_{X_J}^{\mathbf{0}(4q)}(\tau_C)$	$N_{X_J}^{(Mol)}(\tau_F)$
$J=0, I=0$	6.9×10^{-3}	1.3×10^{-3}	4.5×10^{-4}
$J=0, I=1$	2.1×10^{-2}	3.9×10^{-3}	1.36×10^{-3}
$J=1, I=0$	1.7×10^{-2}	9.0×10^{-4}	7.2×10^{-3}
$J=1, I=1$	5.0×10^{-2}	2.7×10^{-3}	2.2×10^{-2}

At $\tau \sim \tau_F$:

- $J=0$: $N_{X_0}^{(4q)} \approx 4N_{X_0}^{(Mol)}$
- $J=1$: $N_{X_1}^{(Mol)} \approx 2.5N_{X_1}^{(4q)}$
- HICs: might shed some light on the discrimination of their structure

4q-Coalescence:

N_{X_J} vs τ (fm/c) — (I=0;J=0), (I=1;J=0), (I=0;J=1), (I=1;J=1)

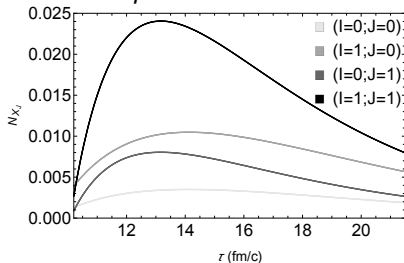$N_{X_J}/(N_{X_J}+N_{X_0})$ vs τ (fm/c) — Stat., 4q Coal.

- $4q$ coal.: initial yields ($\tau \sim \tau_C$)
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$J = 0, I = 0$	6.9×10^{-3}	1.3×10^{-3}	4.5×10^{-4}
$J = 0, I = 1$	2.1×10^{-2}	3.9×10^{-3}	1.36×10^{-3}
$J = 1, I = 0$	1.7×10^{-2}	9.0×10^{-4}	7.2×10^{-3}
$J = 1, I = 1$	5.0×10^{-2}	2.7×10^{-3}	2.2×10^{-2}

At $\tau \sim \tau_F$:

- $J = 0$: $N_{X_0}^{(4q)} \approx 4 N_{X_0}^{(Mol)}$
- $J = 1$: $N_{X_1}^{(Mol)} \approx 2.5 N_{X_1}^{(4q)}$
- HICs: might shed some light on the discrimination of their structure

4q-Coalescence:

$Z_c(3900)$: triangle singularity or a new hadron?
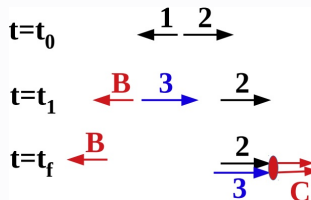
$Y(4260) \to Z_c\pi^\mp \to J/\psi\pi^\pm\pi^\mp$

Guo, NPR **37** (2020), 406

- Possible kinematic accident of the $(D_1^*DD^*)$ triangle satisfying the Coleman-Norton theorem
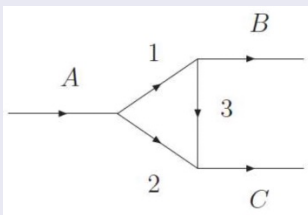
Triangle integral: singular when Coleman-Norton theorem applies

- All particles need to be on-shell
- All particles collinear
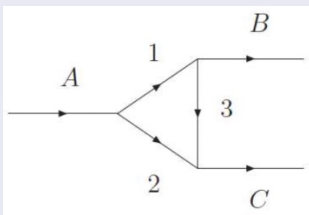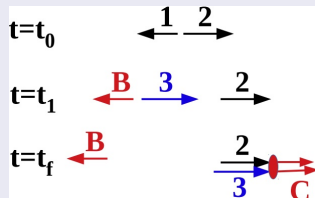- Classically allowed: 3 can reach 2

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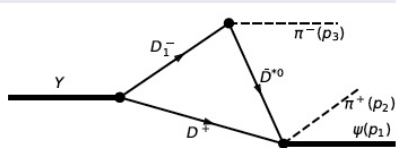

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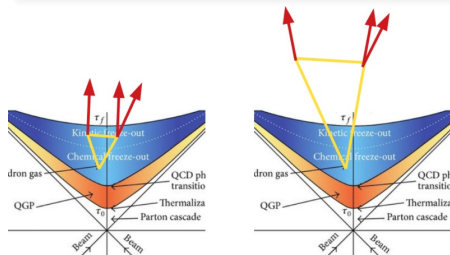- Classically allowed: 3 can reach 2

LMA and Llanes-Estrada, EPJ C **81**, 430 (2021); 2109.01015 [hep-ph] (to appear)

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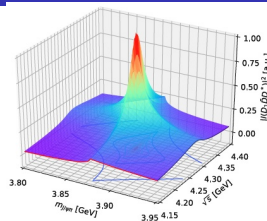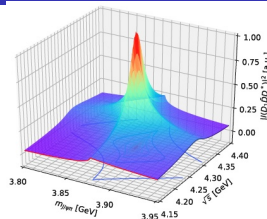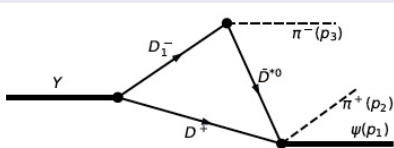

(Guo, NPR 37 (2020), 406)

Can HICs help discern the correct interpretation? Two conditions

- Sufficient time to complete in a HIC
- Mass and/or width are modified from their vacuum values

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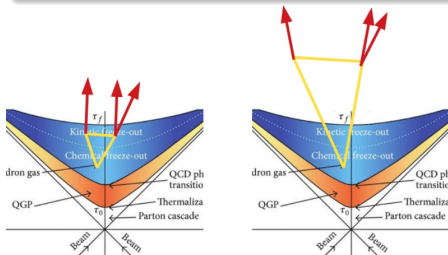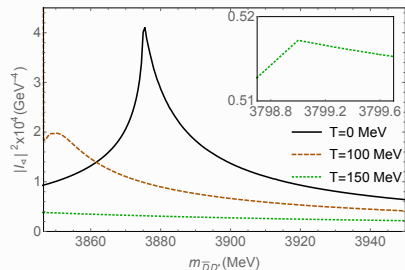- Mass and/or width are modified from their vacuum values

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- Calculations with thermal Matsubara formalism
- Use of Thermal M and Γ

- Singularity disappears at temperatures just below T_H
- HIC: helps discern if $Z_c(3900)$ is an intrinsic state
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$Z_c(3900)$ as a TS in HICs; LMA and Llanes-Estrada, EPJ C **81**, 430 (2021); 2109.01015 [hep-ph] (to appear)
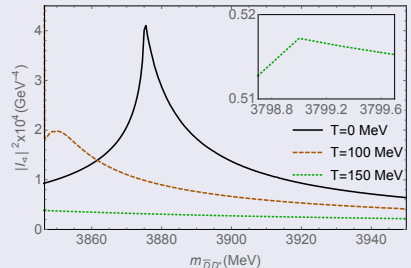
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Summary

- Hadron Spectrum: richer than what we expected
- New particle zoo above $D^{(*)}\bar{D}^*$, $B^{(*)}\bar{B}^*$ thresholds: not $(\bar{q}q, qqq)$

General description of exotic states?

- It remains a great challenge!!!
- More experimental and theoretical investigations are necessary to shed light into their dynamics
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Thank You!!!

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