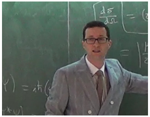
When heavy-ion collisions help distinguish triangle singularities from actual hadrons

Luciano Abreu and Felipe J. Llanes-Estrada†

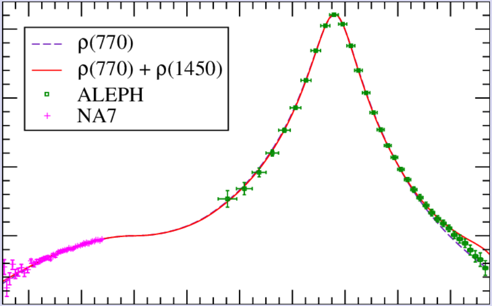


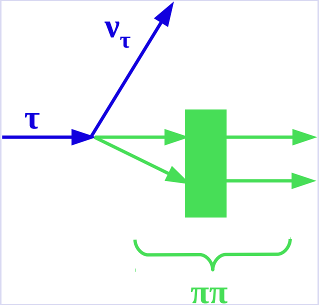
Univ. Complutense de Madrid
Based on Eur.Phys.J.C **81** (2021) 430

Presented at PANIC 2021

record available at https://youtu.be/j59Ooj8SQmg

Traditional resonances came from simple reactions





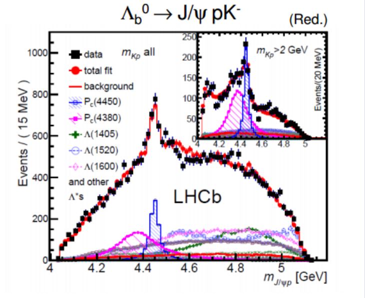
Typically, only two strongly interacting particles in the reaction

Sanz-Cillero, J. & Pich, A. (2003), EPJC. 27. 587-599. 10.1140/epjc/s2002-01128-8.

But many new states appear in multiparticle reactions

Hidden charm pentaquarks?

$$\Lambda_b^0 \to K^- \underbrace{(J/\psi p)}_{\text{LHCb pentaquark}}$$



State	Mass (MeV)	Width (MeV)	Fit fract. (%)	Sig.
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2	9σ

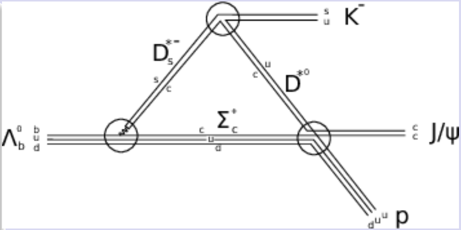
LHCb collaboration 2015

Nonresonant production-amplitude singularities?

Triangle singularity?

$$\Lambda_b^0 \to D_s^{*-}\Sigma^+ \to$$

$$\to K^- \; D^{*0}\Sigma^+ \to K^- \; \underbrace{(J/\psi p)}_{\text{Kinematic accident}}$$



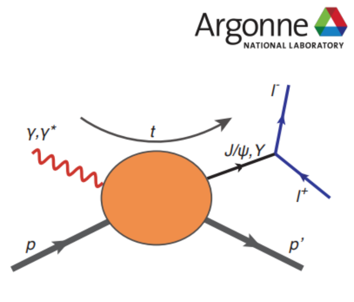
M. Mikashenko 1507.06552

Jlab can cross-check the LHCb pentaquarks

On the works:

$$\gamma/\gamma^* p \to J/\psi p$$

resonant or not?



Joosten@ Jlab users group meeting June 2021

This work

- Many other examples $\Longrightarrow$
- Try RHIC/ALICE to bear in


EPJ.org

NEWS ARCHIVES SCIENTIFIC ADVISORY COMMITTEE

EPJ A B D E AP ST H PLUS C DS PV TI QT

EPJ C

2020 Impact factor 4.590

Particles and Fields

10 most recent | Browse issues | Topical issues | Reviews | Letters

Open Access

Regular Article - Theoretical Physics

Eur. Phys. J. C (2021) **81**: 430

https://doi.org/10.1140/epjc/s10052-021-09216-3

Regular Article - Theoretical Physics

Heating triangle singularities in heavy ion collisions

Luciano M. Abreu[1] and Felipe J. Llanes-Estrada[2b]

[1] Instituto de Física, Universidade Federal da Bahia, 40170-115, Salvador, Bahia, Brazil

[2] Dept. Física Teórica and IPARCOS, Universidad Complutense, 28040, Madrid, Spain

[b] fllanes@fis.ucm.es

Received: 2 November 2020

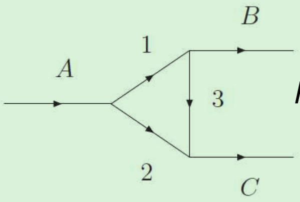
Accepted: 5 May 2021

Published online: 18 May 2021

Abstract

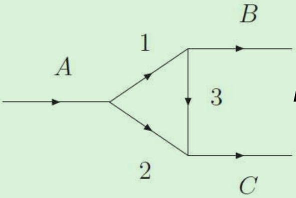
We predict that triangle singularities of hadron spectroscopy can be strongly affected in heavy ion collisions. To do it we examine various effects on the singularity-inducing triangle loop of finite temperature in the terminal hadron phase. It appears that peaks seen in central heavy ion collisions are more likely to be hadrons than rescattering effects under two conditions. First, the flight-time of the intermediate hadron state must be comparable to the lifetime of the equilibrated fireball (else, the reaction mostly happens *in vacuo* after freeze out). Second, the medium effect over the triangle-loop particle mass or width must be sizeable. When these (easily checked) conditions are met, the medium quickly reduces the singularity: at T about 150 MeV, even by two orders of magnitude, acting then as a spectroscopic filter.

How do triangle singularities come about?



$$I_\triangleleft = i\int \frac{d^4q}{(2\pi)^4}\frac{1}{(P-q)^2-m_1^2+i\epsilon)} \cdot \frac{1}{[(q^2-m_2^2+i\epsilon][(P-q-k)^2-m_3^2+i\epsilon]}$$

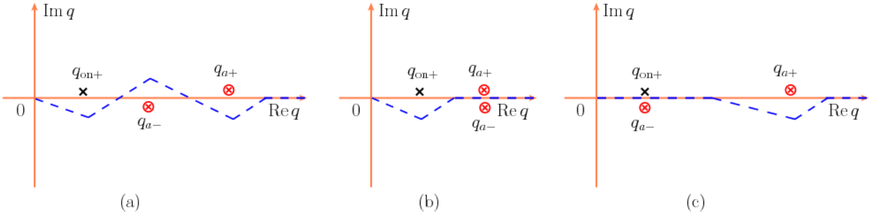
How do triangle singularities come about?



$$I_{\triangleleft} = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_1^2 + i\epsilon} \cdot \frac{1}{[(q^2 - m_2^2 + i\epsilon]\,[(P-q-k)^2 - m_3^2 + i\epsilon]}$$

- All particles on-shell
- Classically allowed triangle scattering

Poles in complex q^0 plane



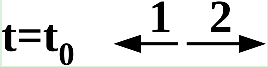
No singularity upon integrating

Threshold singularity

Triangle singularity

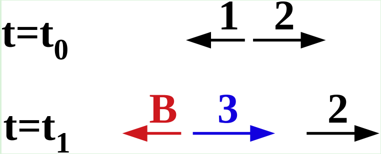
Bayar, Aceti, Guo and Oset, Phys.Rev.D 94 (2016) 7, 074039

Coleman-Norton theorem



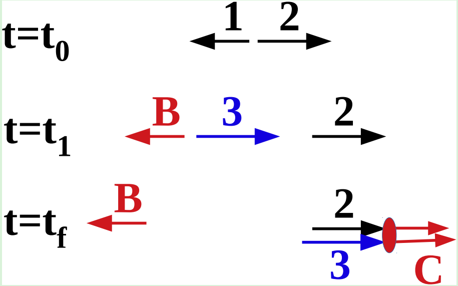
Particles 1 & 2 in the loop fly off

Coleman-Norton theorem



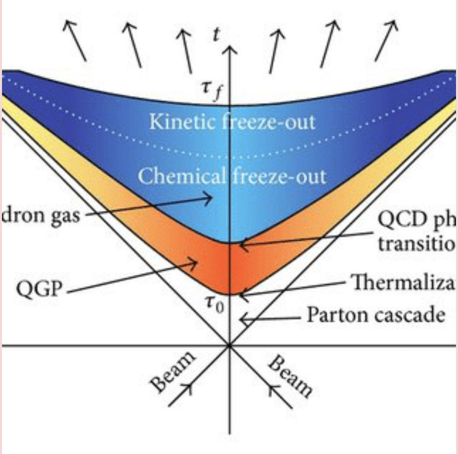
Particle 1 decays collinearly; $v_3 > v_2$

Coleman-Norton theorem



Particle 3 collides with 2 and they scatter into C

Hadron gas upon cooling of quark-gluon plasma

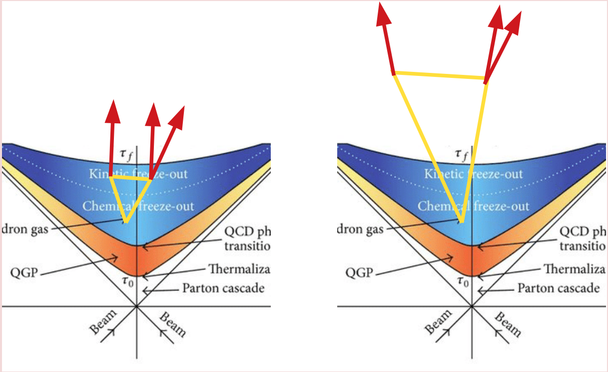


PhD dissertation of Shusu Shi, Univ. of Central China 2010

https://www.bnl.gov/userscenter/thesis/past-competitions/2010/Shi/PhDthesis_ShusuShi.pdf

When should the medium affect the singularity?

- Basically, when the medium's lifetime $\sim$ triangle's lifetime τ_A



Flight time

$$\tau_A = \frac{\gamma(\beta_1)}{\Gamma_1}\frac{\beta_3-\beta_1}{\beta_3-\beta_2}$$

$$\beta_2 = \beta\frac{E_2^* - p_2^*/\beta}{E_2^* - p_2^*\beta},$$

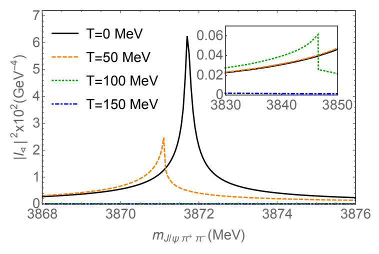
$$\beta = \frac{k}{E_c} \text{ etc.}$$

(Strong) process in medio (Weak) process in vacuo

Example: not enough time

A singularity coincident with $X(3872)$

$$c\bar{c} \to \overbrace{\left(D^{*-}(1)D^{*0}(2)\right)}^{(A)} \xrightarrow{D^0(3)} \overbrace{\pi^-}^{(B)} \overbrace{\left(J/\psi\pi^+\pi^-\right)}^{(C)}.$$



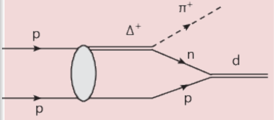
- The singularity would be affected by the medium
- but $\tau_A \simeq 2300$ fm $\gg 10$ fm

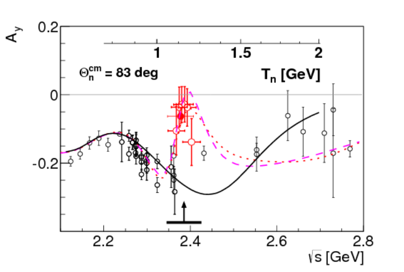
S. X. Nakamura, Phys. Rev. D **102**, 074004 (2020)

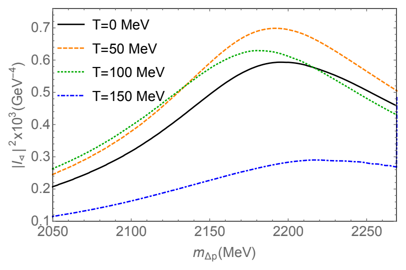
Example: sufficient time

d^* deuteron/hexaquark a triangle singularity?

$$pp(A) \to \underbrace{\Delta(1232)^+(1)}_{\to \pi^+(B) n(3)} p(2) \xrightarrow{(2)+(3)} \pi^+(B) d(C)$$







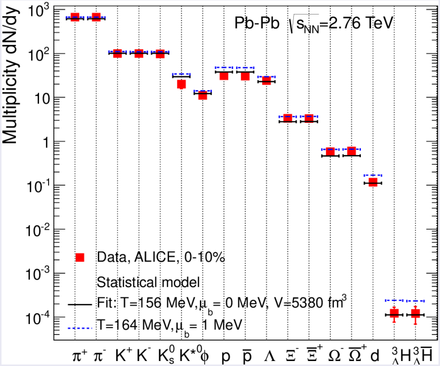
Our $(\mathrm{p}\Delta)$ spectrum, $\tau_A \sim 5$ fm

WASA-at-COSY Coll., P. Adlarson *et al.* PRL **112** (2014) 20, 202301

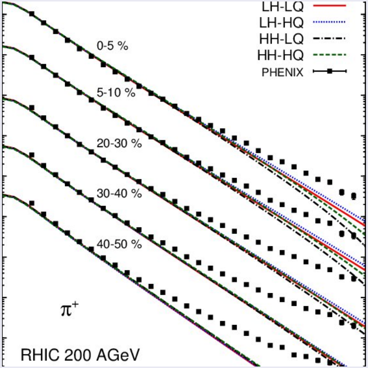
N. Ikeno, R. Molina, E. Oset e-Print: 2103.01712 [nucl-th]

Calculational method

The hadron gas is near thermal equilibrium



Yield of different hadrons



p_t spectra

J. Stachel, A. Andronic, P. Braun-Munzinger, K. Redlich, J.Phys.Conf.Ser. **509** (2014) 012019

H. Niemi *et al.* Phys.Rev.C **86** (2012) 014909

Appropriate to use Thermal Field Theory

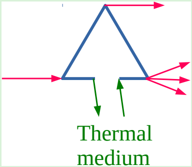
- First effect: Sum triangle over Matsubara frequencies, $\beta := 1/T$

$$q^0 \to i\omega_n = i\frac{2\pi n}{\beta} \qquad\qquad n = 0, \pm 1, \pm 2, \cdots ,$$

$$\int \frac{dq^0}{(2\pi)} f(q^0, \vec{q}) \to S_M \;=\; \frac{i}{\beta} \sum_{n=-\infty}^{\infty} f(\omega_n, \vec{q}),$$

Appropriate to use Thermal Field Theory

Triangle in terms of
Bose-Einstein factors $n_\beta = \frac{1}{e^{E/T}-1}$



$$
\begin{aligned}
I_\triangleleft \;\simeq\; & \frac{1}{2}\int \frac{d^3q}{(2\pi)^3}\frac{1}{8E_1E_2E_3}\frac{1}{\left(P^0-\tilde{E}_1-\tilde{E}_2\right)} \\
\times\; & \frac{1}{\left(P^0-k^0-\tilde{E}_2-\tilde{E}_3\right)}\frac{1}{\left(k^0-\tilde{E}_1+\tilde{E}_3\right)} \\
\times\; & \Big\{\left[1+2n_\beta(\tilde{E}_2)\right]\left(-k^0+\tilde{E}_1-\tilde{E}_3\right) \\
& +\left[1+2n_\beta(P^0-\tilde{E}_1)\right]\left(P^0-k^0-\tilde{E}_2-\tilde{E}_3\right) \\
& +\left[1+2n_\beta(k^0-P^0+\tilde{E}_3)\right]\left(P^0-\tilde{E}_1-\tilde{E}_2\right)\Big\}
\end{aligned}
$$

Effect is small

A singularity relevant for Compass's $a_1(1420)$ production

$$\mathrm{A} \to K^{*+}(1)K^{-}(2)K^{+}(3) \to \pi^0(\mathrm{B})(\pi^+\pi^-)/(\pi^0\eta)(\mathrm{C}).$$

Effect is small

A singularity relevant for Compass's $a_1(1420)$ production

$$\mathrm{A} \to K^{*+}(1)K^{-}(2)K^{+}(3) \to \pi^0(\mathrm{B})(\pi^+\pi^-)/(\pi^0\eta)(\mathrm{C}).$$

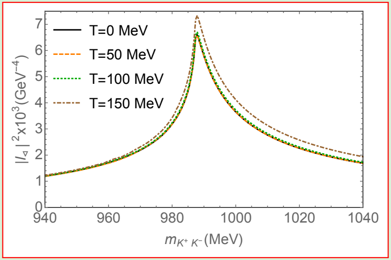
- $a_1(1420)$ too close to $a_1(1260)$ to fit in $q\overline{q}$ approach
- Narrower than typical mesons of that mass

Effect is small

A singularity relevant for Compass's $a_1(1420)$ production

$$\mathrm{A} \to K^{*+}(1)K^{-}(2)K^{+}(3) \to \pi^0(\mathrm{B})(\pi^+\pi^-)/(\pi^0\eta)(\mathrm{C}).$$

- $a_1(1420)$ too close to $a_1(1260)$ to fit in $q\bar{q}$ approach
- Narrower than typical mesons of that mass



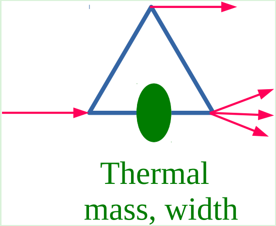
Triangle barely affected by T

COMPASS Coll. M.G.Alexeev *et al.* 2006.05342 [hep-ph]
M. Mikhasenko, B. Ketzer, Andrey Sarantsev Phys.Rev.D **91** (2015) 9, 094015

In medio masses and widths

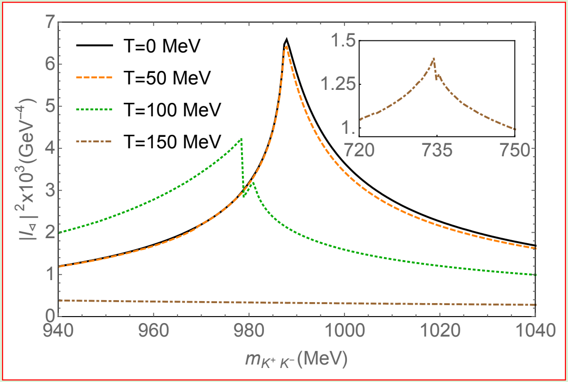
- $M, \Gamma(T)$ Taken from literature (in GeV)

T	0	0.05	0.1	0.15
$m_{K^\pm}$	0.49367	0.49367	0.4906	0.37
$m_{K^{*+}}$	0.89166	0.8877	0.8207	0.508
$\Gamma_{K^{*+}}$	0.0508	0.0509	0.0532	0.0588



and many more...

Medium effects are now large!



Indeed, the singularity is erased at 150 MeV

Medium effects are now large!

- Similarly large effects in other channels as shown earlier
- Exception: π in the triangle loop (barely changes)

Medium effects are now large!

- Similarly large effects in other channels as shown earlier
- Exception: π in the triangle loop (barely changes)

T	0	0.05	0.1	0.15
m_π	0.13957	0.13985	0.141	0.144

A.Schenk, Phys. Rev. D **47** (1993), 5138
A.Gómez Nicola & R. Torres Andrés, Phys. Rev. D **89** (2014), 116009
M.Cheng *et al.* Eur. Phys. J.C **71** (2011), 1564

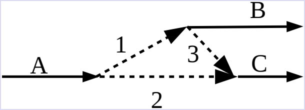
Practical application: $Y(4260) \to \pi^{\pm} \underbrace{(\pi^{\mp} J/\psi)}_{Z_c(3800)}$

- A reaction with two exotics?

Wang, Hanhart and Zhao PRL **111**, 132003 (2013)

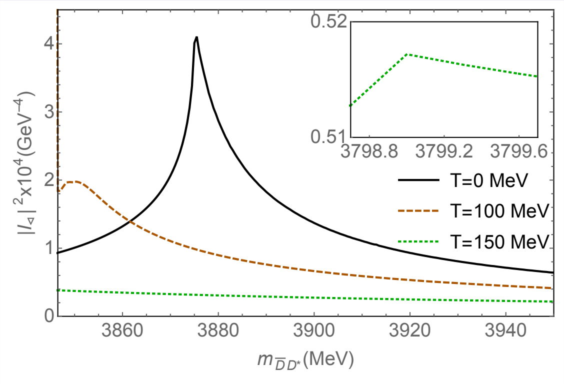
Practical application: $Y(4260) \to \pi^{\pm} \underbrace{(\pi^{\mp} J/\psi)}_{Z_c(3800)}$

- A reaction with two exotics?
- $Y(4260) \sim \psi(4260)$ because 1^{--} conventional $c\bar{c}$
- $Y(4260)$ near s-wave threshold for open charm, at $D_1 D$
- $Z_c(3900)$ a manifest, charged exotic
- Triangle diagram with D_1 (1)D^* (3)D (2)



FLE PRD **72** (2005), 031503 Close, Page, PLB **628** (2005), 215 Wang, Hanhart and Zhao PRL **111**, 132003 (2013)

Heavy Ion Collisions could help



If a triangle singularity, washed out in heavy ion collisions
(but hard to detect $\pi\pi J/\psi$ with the combinatorial background)

Conclusions from this work

- RHIC analysis can help distinguish hadrons (resonances) from triangle singularities by erasing these.

Conclusions from this work

- RHIC analysis can help distinguish hadrons (resonances) from triangle singularities by erasing these.
- Due to the thermal width and mass shifts of particles in loop

Conclusions from this work

- RHIC analysis can help distinguish hadrons (resonances) from triangle singularities by erasing these.
- Due to the thermal width and mass shifts of particles in loop
- Provided triangle's and medium's lifetimes comparable and $M(T)$, $\Gamma(T)$ a significant change from vacuum

Funding acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093; Brazilian CNPq (contracts 308088/2017-4 & 400546/2016-7) and FAPESB (contract INT0007/2016); Spanish MICINN: PID2019-108655GB-I00, PID2019-106080GB-C21; UCM research group 910309 and the IPARCOS institute.

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN