Working Group 3

Reunião de 22/05/24

Alberto Martinez

Fernando Navarra

Renato Higa

WG3 : aprender física de hadrons no LHC (QCD, QGP, CGC, espectros...)

Sub-produto: melhorar o nível de discussão dentro do grupo e do IFUSP

O que aconteceu entre 06/23 e 05/24 ?

10 Artigos Publicados

inspirehep.net

$\chi_{c1}(4274)$ multiplicity in heavy-ion collisions #1

L.M. Abreu (Bahia U. and Sao Paulo U.), A.L.M. Britto (Bahia U.), F.S. Navarra (Sao Paulo U.), H.P.L. Vieira (Bahia U.) (Oct 5, 2023)

Published in: *Phys.Rev.D* 109 (2024) 1, 014041 • e-Print: 2310.03948 [hep-ph]

pdf DOI cite claim reference search 1 citation

Unveiling the properties of the dimuonium at the energies available at the Large Hadron Collider at CERN #2

C.A. Bertulani (Darmstadt, Tech. Hochsch.), D. Bhandari (Texas A-M, Commerce), F.S. Navarra (Sao Paulo U.) (Jul 23, 2023)

Published in: *Eur.Phys.J.A* 60 (2024) 2, 43 • e-Print: 2307.12387 [hep-ph]

pdf DOI cite claim reference search 2 citations

Charmonium production in high multiplicity pp collisions and the structure of the proton #3

R. Terra (Sao Paulo U.), F.S. Navarra (Sao Paulo U.) (Jun 25, 2023)

Published in: *Phys.Rev.D* 108 (2023) 5, 054002 • e-Print: 2306.14298 [hep-ph]

pdf DOI cite claim reference search 2 citations

Two- and three-photon fusion into charmonium in ultraperipheral nuclear collisions #4

R. Fariello (Unlisted, BR and Sao Paulo U.), D. Bhandari (Texas A-M, Commerce), C.A. Bertulani (Texas A-M, Commerce and Darmstadt, Tech. Hochsch.), F.S. Navarra (Texas A-M, Commerce and Sao Paulo U.) (Jun 18, 2023)

Published in: *Phys.Rev.C* 108 (2023) 4, 044901 • e-Print: 2306.10642 [hep-ph]

pdf DOI cite claim reference search 4 citations

Leading Λ production in future electron-proton colliders #5

F. Carvalho (Diadema, Sao Paulo Fed. U.), K.P. Khemchandani (Diadema, Sao Paulo Fed. U.), V.P. Gonçalves (Munster U., ITP), F.S. Navarra (Sao Paulo U.), D.S. Spiering (Sao Paulo U.) et al. (Jun 16, 2023)

Published in: *Phys.Rev.D* 108 (2023) 9, 094034 • e-Print: 2306.09813 [hep-ph]

pdf DOI cite claim reference search 0 citations

Interactions of the $\chi_{c1}(4274)$ state with light mesons #6

A.L.M. Britto (Bahia U.), L.M. Abreu (Bahia U.), F.S. Navarra (Bahia U.) (Jun 12, 2023)

Published in: *Phys.Rev.D* 108 (2023) 9, 096028 • e-Print: 2306.07446 [hep-ph] inspirehep.net

Four-boson first excited state near two-body unitarity

#1

Feng Wu (Arizona U.), T. Frederico (Sao Paulo, Inst. Tech. Aeronautics), R. Higa (Sao Paulo U.), U. van Kolck (IJCLab, Orsay and Arizona U.) (Oct 25, 2023)

Published in: *Phys.Rev.A* 109 (2024) 4, 043301 • e-Print: 2310.17079 [physics.atom-ph]

pdf DOI cite claim reference search 0 citations

Multiplicity of $Z_{cs}(3985)$ in heavy ion collisions

#7

L.M. Abreu (Bahia U. and Valencia U., IFIC), F.S. Navarra (Sao Paulo U.), M. Nielsen (Sao Paulo U.), H.P.L. Vieira (Bahia U.) (Mar 10, 2023)

Published in: *Phys.Rev.D* 107 (2023) 11, 114013 • e-Print: 2303.05990 [hep-ph]

pdf DOI cite claim reference search 3 citations

$\phi(2170)$ decaying to $\phi\eta$ and $\phi\eta'$

#3

Brenda B. Malabarba (Sao Paulo U.), K.P. Khemchandani (Sao Paulo U.), A. Martinez Torres (Sao Paulo U.) (May 5, 2023)

Published in: *Phys.Rev.D* 108 (2023) 3, 036010 • e-Print: 2305.03885 [hep-ph]

pdf DOI cite claim reference search 2 citations

Theoretical study of the $\gamma d \to \pi^0 \eta d$ reaction

#11

A. Martinez Torres (Sao Paulo U. and Valencia U., IFIC), K.P. Khemchandani (Sao Paulo U. and Valencia U., IFIC), E. Oset (Valencia U., IFIC) (May 2, 2022)

Published in: *Phys.Rev.C* 107 (2023) 2, 025202 • e-Print: 2205.00948 [nucl-th]

pdf DOI cite claim reference search 5 citations

5 Artigos Submetidos

The $X(3872)$ to $\psi(2S)$ yield ratio in heavy-ion collisions #1

L.M. Abreu, F.S. Navarra, H.P.L. Vieira (Jan 20, 2024)

e-Print: 2401.11320 [hep-ph]

pdf cite claim reference search 0 citations

Can femtoscopic correlation function shed light on the nature of the lightest, charm, axial mesons? #2

K.P. Khemchandani, Luciano M. Abreu, A. Martinez Torres, F.S. Navarra (Dec 18, 2023)

e-Print: 2312.11811 [hep-ph]

pdf cite claim reference search 0 citations

Interaction of exotic states in a hadronic medium: the $Z_c(3900)$ case #3

L.M. Abreu, R.O. Magalhães, F.S. Navarra, H.P.L. Vieira (Oct 28, 2023)

e-Print: 2310.18747 [hep-ph]

pdf cite claim reference search 1 citation

Production of meson molecules in ultra-peripheral heavy ion collisons #1

F.C. Sobrinho (Sao Paulo U.), L.M. Abreu (Sao Paulo U. and Bahia U.), C.A. Bertulani (Texas A-M, Commerce and Darmstadt, Tech. Hochsch.), F.S. Navarra (Sao Paulo U.) (May 4, 2024)

e-Print: 2405.02645 [hep-ph]

pdf cite claim reference search 0 citations

Strangeness $+1$ light multiquark baryons: a jinx? #3

Brenda B. Malabarba, K.P. Khemchandani, A. Martinez Torres, Seung-il Nam (Apr 5, 2024)

e-Print: 2404.04078 [hep-ph]

pdf cite claim reference search 0 citations

4 Proceedings

Novel aspects of particle production in ultra-peripheral collisions

#1

F.C. Sobrinho (Sao Paulo U.), I. Danhoni (Darmstadt, Tech. Hochsch.), C.A. Bertulani (Texas A-M, Commerce and Darmstadt, Tech. Hochsch.), L.M. Abreu (Sao Paulo U. and Bahia U.), F.S. Navarra (Sao Paulo U.) (May 18, 2024)

Contribution to: UPC 2023 • e-Print: 2405.11283 [hep-ph]

pdf cite claim reference search 0 citations

Remarks on charmonium production in ultra-peripheral collisions

#2

R. Fariello (Unlisted, BR), F.S. Navarra (Sao Paulo U.), C.A. Bertulani (Texas A-M, Commerce), D. Bhandari (Texas A-M, Commerce) (Feb 19, 2024)

Published in: *Nucl.Part.Phys.Proc.* 343 (2024) 28-31 • Contribution to: QCD23

DOI cite claim reference search 0 citations

Intriguing aspects of light baryon resonances

#1

K.P. Khemchandani (Sao Paulo U.), A. Martinez Torres (Sao Paulo U.), Sang-Ho Kim (SoongSil U.), Seung-il Nam (Pukyong Nat. U.), A. Hosaka (Osaka U., Res. Ctr. Nucl. Phys.) et al. (May 3, 2024)

Contribution to: Cocoyoc 2024 • e-Print: 2405.02116 [hep-ph]

pdf cite claim reference search 0 citations

The properties of $\phi(2170)$ and its three-body nature

#2

A. Martinez Torres (Sao Paulo U.), Brenda B. Malabarba (Sao Paulo U.), K.P. Khemchandani (Sao Paulo U.) (Apr 26, 2024)

Contribution to: Cocoyoc 2024 • e-Print: 2404.17664 [hep-ph]

pdf cite claim reference search 0 citations

5 Teses concluidas

Breno Garcia (mestrado - Renato Higa)

Murilo Soares de Godoy (mestrado - Renato Higa)

Brenda Malabarba (doutorado – Alberto Martinez)

Richard Terra (mestrado – Fernando Navarra)

Fernando César Sobrinho (mestrado – Fernando Navarra)

9 Participações em Conferências

The present and future of flavour and exotic hadron spectroscopy
26/05 - 02/06 (2023) Munique, Alemanha (Alberto Martinez))

QCD 2023, 06/07 – 10/07 (2023) Montpellier, França (F. Navarra)

Extreme QCD 2023, 28/07 -30/07 (2023) Coimbra, Portugal (F. Navarra)

1st Inha – Pukyong Workshop on Hadron Physics and Chiral Dynamics, 11/08 -15/08 (2023)
Inha, Coréia (Alberto Martinez))

HADRONS 2023, (2023) Genova, Itália (Alberto Martinez)

Nagoya Workshop on Exotic Hadrons, 13/11 – 17/11 (2023) Nagoya, Japão (F. Navarra)

UPC 23 International Workshop on the Physics of Ultra-peripheral Collisons,
12/12 – 15/12 (2023), Playa del Carmen, México (F. Navarra)

XLV Symposium on Nuclear Physics, Cocoyoc, México,
08/01 - 11/01 (2024) Cocoyoc, México (Alberto Martinez))

1 Workshop on Baryon Dynamics from RHIC to EIC, 22/01 – 24/01 (2024)
Stony Brook, EUA (F. Navarra)

Organização de Eventos Científicos

POETIC 2023 IFT-UNESP (Fernando Navarra)

LIGHT CONE 2023 CBPF (Fernando Navarra)

RETINHA 31 2024 CBPF (Fernando Navarra)

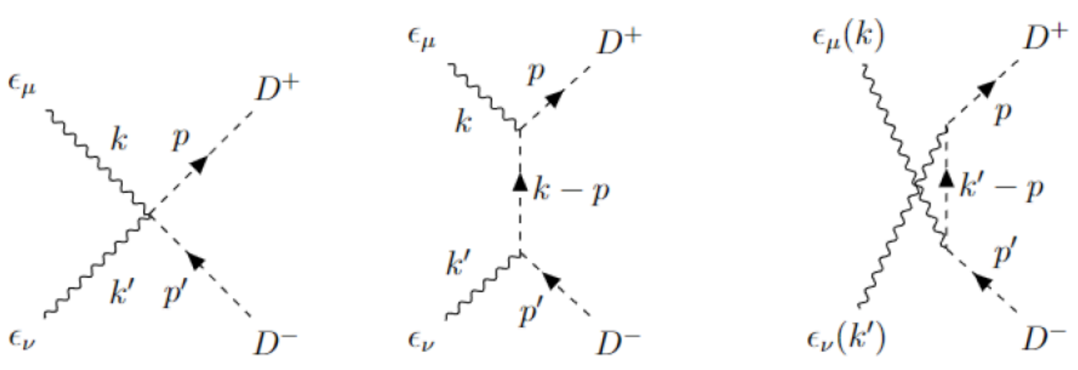
Qualitativamente

Progresso na pesquisa da produção de exóticos em UPCs :

2 papers publicados, 2 Proceedings, um paper submetido

Production of meson molecules in ultra-peripheral heavy ion collisons

F.C. Sobrinho[1], L.M. Abreu[1,2], C.A. Bertulani[3,4], F.S. Navarra[1]
[1]Instituto de Física, Universidade de São Paulo, Rua do Matão 1371 - CEP 05508-090, Cidade Universitária, São Paulo, SP, Brazil



Molécula :

$$\sigma(Pb\,Pb \to Pb\,Pb\,B) = 3.0^{+0.8}_{-1.2}\ \mu b$$

Tetraquark:

$$\sigma(Pb\,Pb \to Pb\,Pb\,B) = 0.18\ \mu b$$

A. Esposito, C. A. Manzari, A. Pilloni and A. D. Polosa, Phys. Rev. D **104**, 114029 (2021)

Método geral para criar moléculas hadrônicas em colisões fóton-fóton

Progresso na pesquisa da produção de exóticos em colisões AA centrais

Continuação da colaboração com o Prof. Luciano Abreu

O Prof. Luciano Abreu visitou o IFUSP por 6 meses

The $X(3872)$ to $\psi(2S)$ yield ratio in heavy-ion collisions #1

L.M. Abreu, F.S. Navarra, H.P.L. Vieira (Jan 20, 2024)

e-Print: 2401.11320 [hep-ph]

pdf cite claim reference search 0 citations

Can femtoscopic correlation function shed light on the nature of the lightest, charm, axial mesons? #2

K.P. Khemchandani, Luciano M. Abreu, A. Martinez Torres, F.S. Navarra (Dec 18, 2023)

e-Print: 2312.11811 [hep-ph]

pdf cite claim reference search 0 citations

Interaction of exotic states in a hadronic medium: the $Z_c(3900)$ case #3

L.M. Abreu, R.O. Magalhães, F.S. Navarra, H.P.L. Vieira (Oct 28, 2023)

e-Print: 2310.18747 [hep-ph]

pdf cite claim reference search 1 citation

Teoria efetiva para as interações do Psi(2S) : artigo em redação

Femtoscopia

The $X(3872)$ to $\psi(2S)$ yield ratio in heavy-ion collisions

L. M. Abreu[1,2,*] F. S. Navarra[2,†] and H. P. L. Vieira[1‡]
[1]*Instituto de Física, Universidade Federal da Bahia, Campus Universitário de Ondina, 40170-115, Bahia, Brazil and*
[2]*Instituto de Física, Universidade de São Paulo, Rua do Matão, 1371, CEP 05508-090, São Paulo, SP, Brazil*
(Dated: January 23, 2024)

In this work we evaluate the $X(3872)$ to $\psi(2S)$ yield ratio ($N_X/N_{\psi(2S)}$) in Pb Pb collisions, taking into account the interactions of the $\psi(2S)$ and $X(3872)$ states with light mesons in the hadron gas formed at the late stages of these collisions. We employ an effective Lagrangian approach to estimate the thermally-averaged cross sections for the production and absorption of the $\psi(2S)$ and use them in the rate equation to determine the time evolution of $N_{\psi(2S)}$. The multiplicity of these states at the end of mixed phase is obtained from the coalescence model. The multiplicity of $X(3872)$, treated as a bound state of ($D\bar{D}^* + c.c.$) and also as a compact tetraquark, was already calculated in previous works. Knowing these yields, we derive predictions for the ratio ($N_X/N_{\psi(2S)}$) as a function of the centrality, of the center-of-mass energy and of the charged hadron multiplicity measured at midrapidity [$dN_{ch}/d\eta\,(\eta < 0.5)$]. Finally, we make predictions for this ratio in Pb Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV to be measured by the ALICE Collaboration in the Run 3.

$$\frac{N_X}{N_{\psi(2S)}} \simeq 5 \qquad \text{for molecules}$$

$$\frac{N_X}{N_{\psi(2S)}} \simeq 0.1 \qquad \text{for tetraquarks}$$

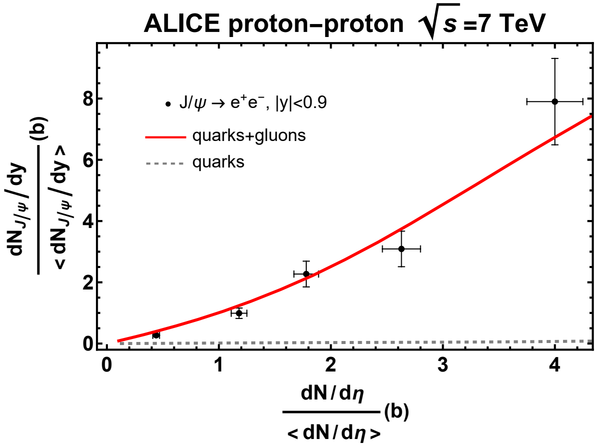
Previsão para pequeno p_T !

CMS: R ~ 1 para p_T grande !

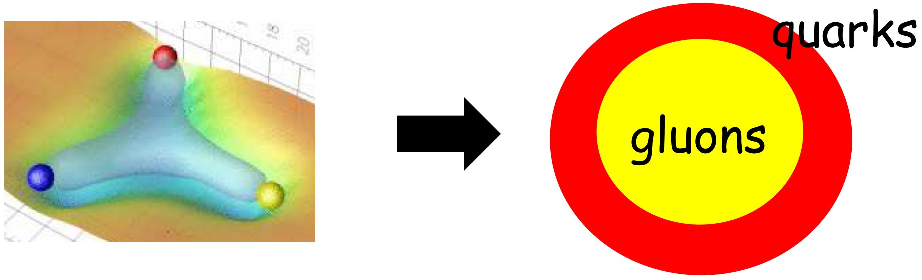
Produção de charmonium em colisões proton - proton

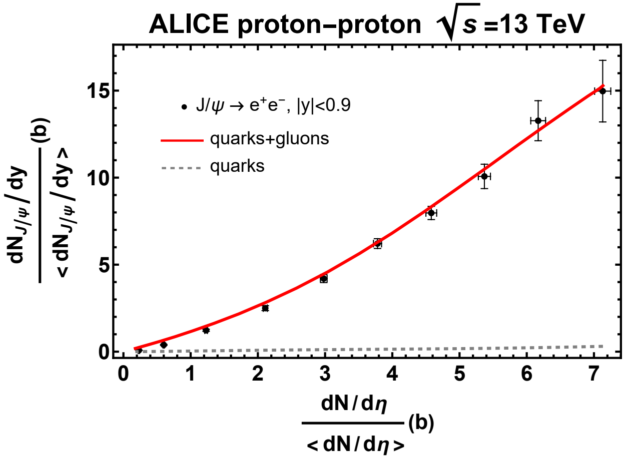
1 paper publicado sobre pp e um em conclusão sobre pPb

mestrado do Richard Terra



Estrutura do proton: core-corona





$$\sigma(gg \rightarrow c\bar{c}) >> \sigma(q\bar{q} \rightarrow c\bar{c})$$

Busca experimental da junção bariônica !

1 Workshop on Baryon Dynamics from RHIC to EIC

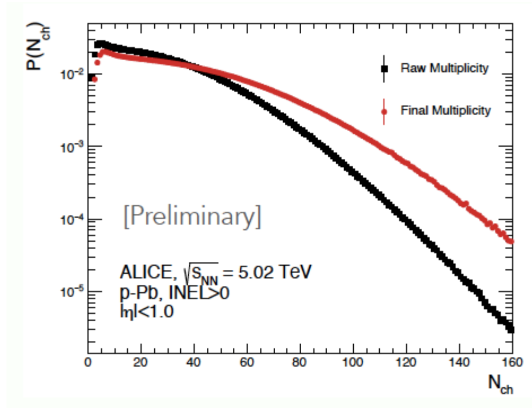
Distribuição de multiplicidade

Distribuição de multiplicidade de mesons em colisões proton-chumbo

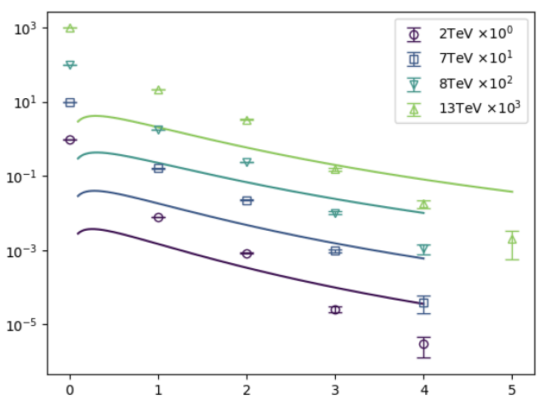
Mestrado da Eliana Marroquin

Mestrado do Henrique Martins Fontes

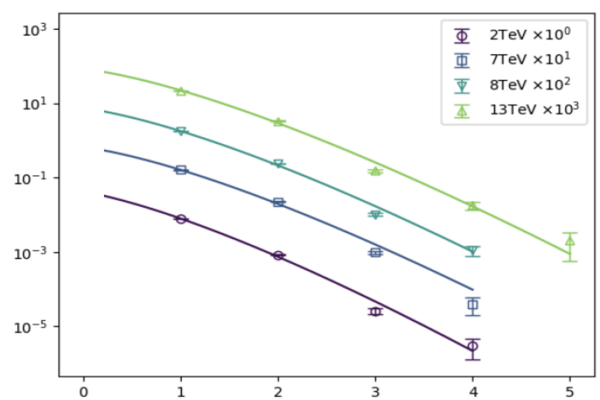
(dependência com A e com a energia)



Jhoão Arneiro e Guilherme Germano (PYTHIA + Fits)



Binomial Negativa não funciona



Poisson funciona

Previsão do PYTHIA : charme tem outra dinâmica !

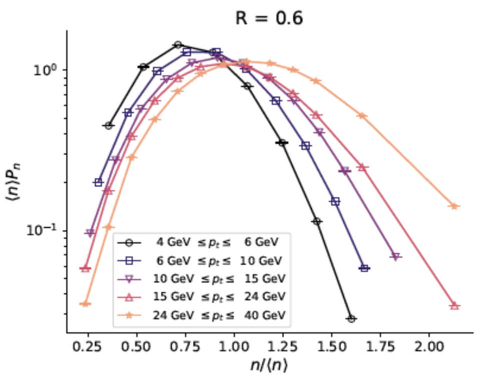
algum dia vai...

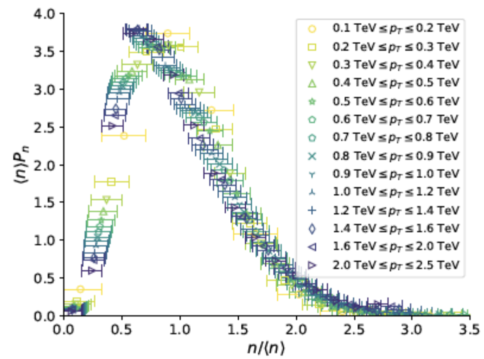
Emergence of KNO scaling in multiplicity distributions in jets produced at the LHC

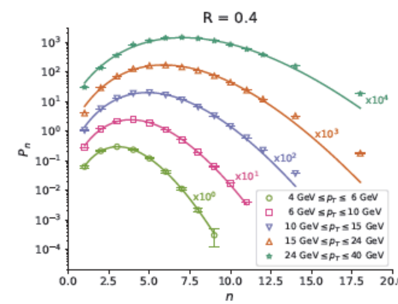
G. R. Germano* and F. S. Navarra†
Instituto de Física, Universidade de São Paulo, Rua do Matão, 1371, CEP 05508-090, Cidade Universitária, São Paulo, SP, Brazil.

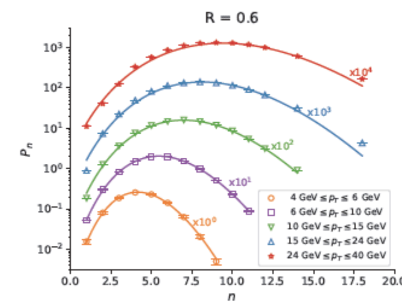
G. Wilk‡
National Centre For Nuclear Research, Pasteura 7, Warsaw 02-093, Poland.

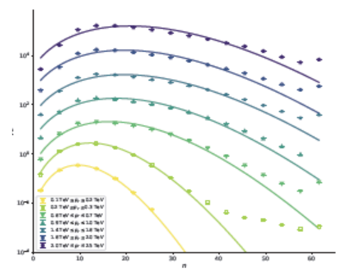
Z. Wlodarczyk§
Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland.

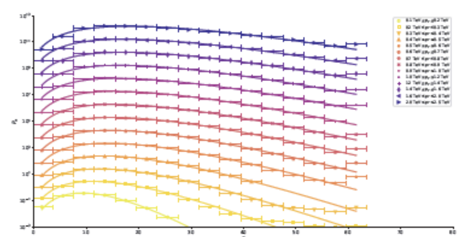


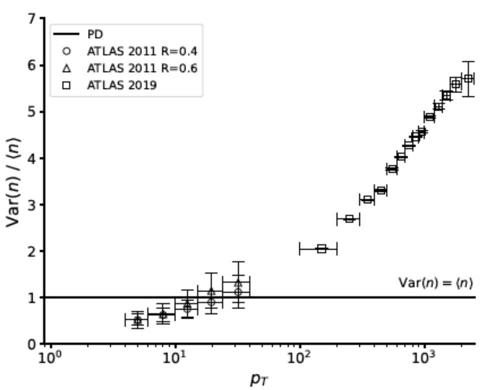










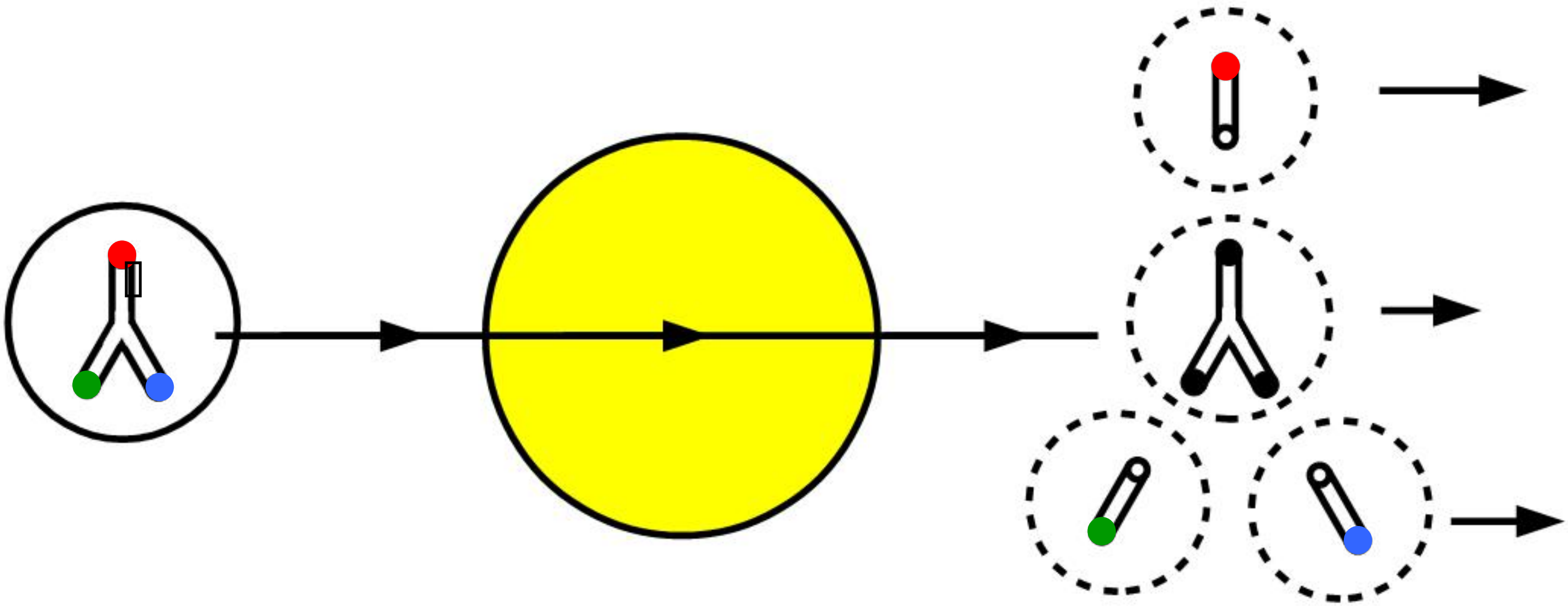


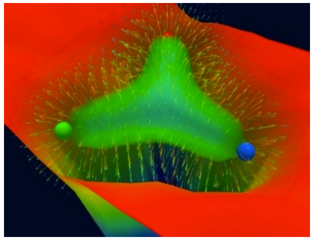
Mudança de dinâmica na cascata de partons !

FIM

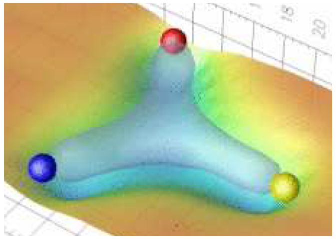
Baryon junction excitation

Kharzeev, PLB (1996)





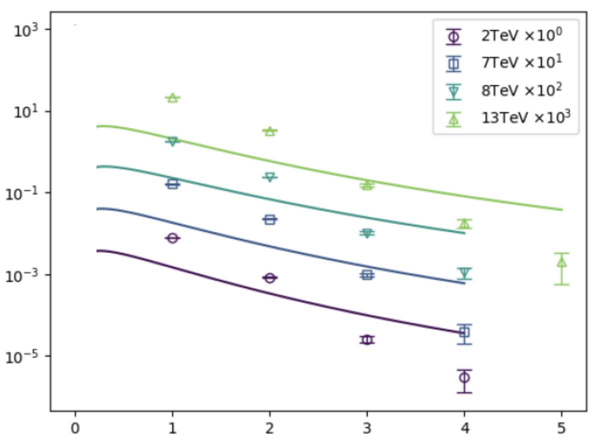
Suganuma et. al
hep-lat/0006005
hep-lat/0204011



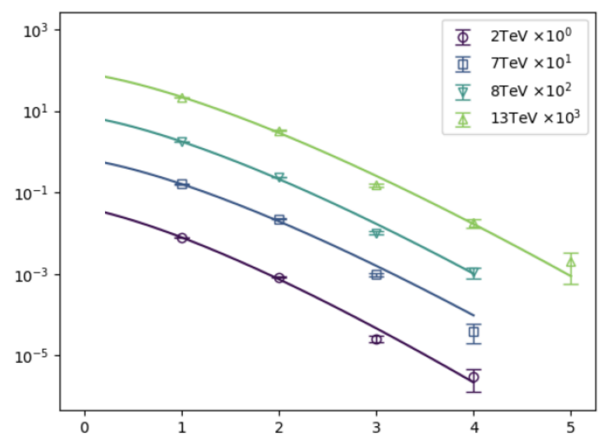
Leinweber et al.
hep-lat/0606016]

Distribuição de multiplicidade de mesons com charme em proton-proton

Jhoão Arneiro e Guilherme Germano (PYTHIA + Fits)



Binomial Negativa não funciona



Poisson funciona

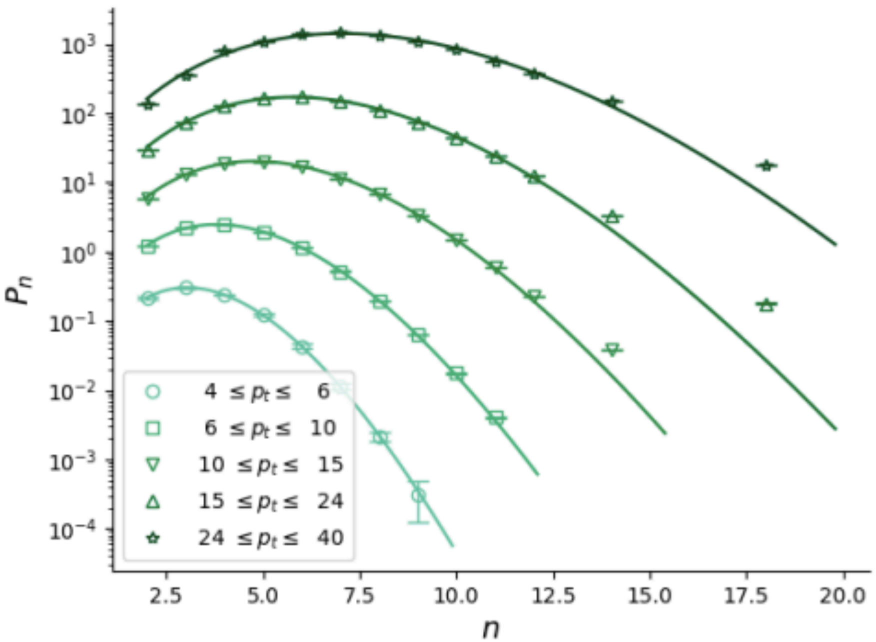
Previsão do PYTHIA : charme tem outra dinâmica !

algum dia vai...

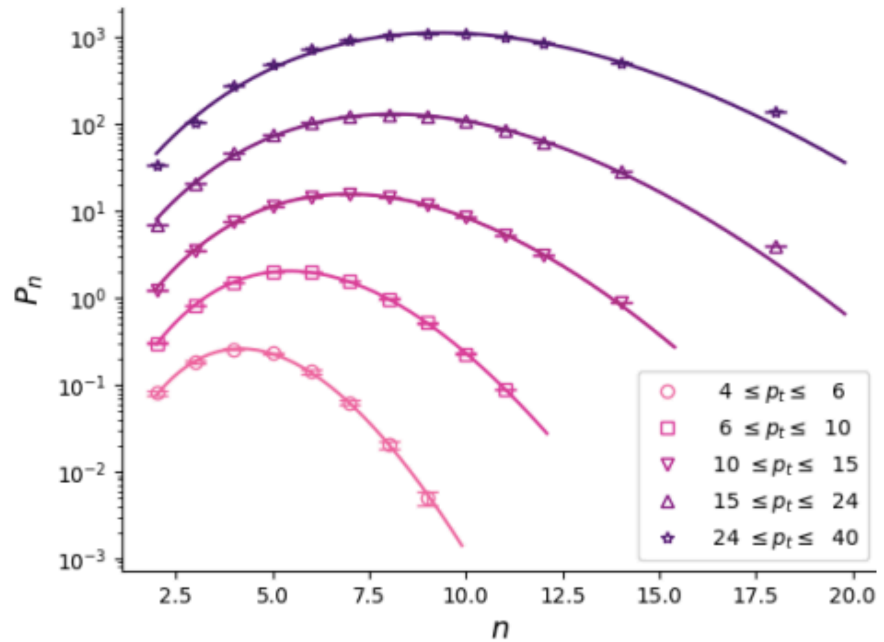
Distribuição de multiplicidade em jatos

Guilherme Germano

Sub Poisson funciona !



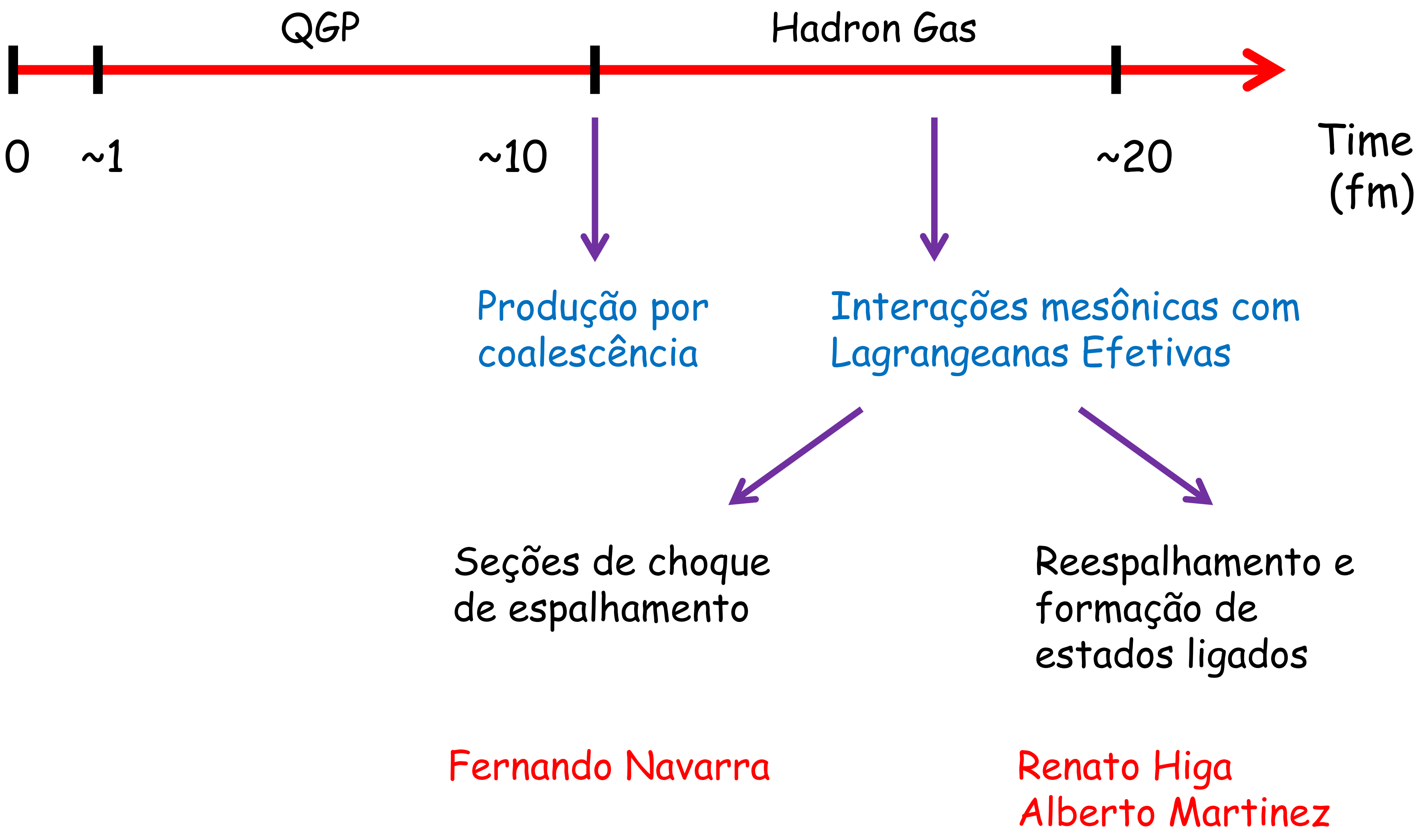
R = 0.4



R = 0.6

$$P(N) = c\frac{\alpha^N}{(N!)^{1+\delta}}$$

Linha do tempo de uma colisão de ions pesados

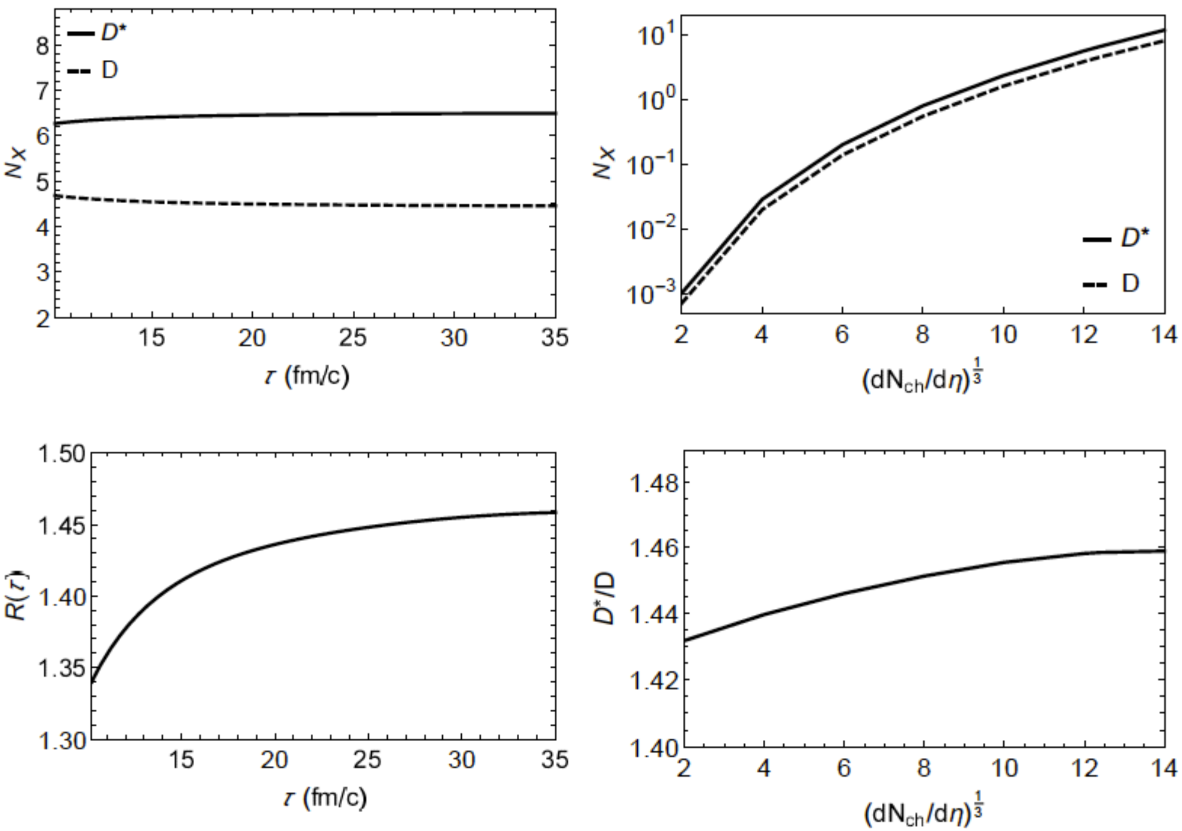


Fernando Navarra

Trabalhos e andamento e publicados

Estudo da produção e interações do Zcs (3985) : em andamento

Estudo da produção e interações do D* e D : concluido e publicado



Interação melhorada com regras de soma da QCD

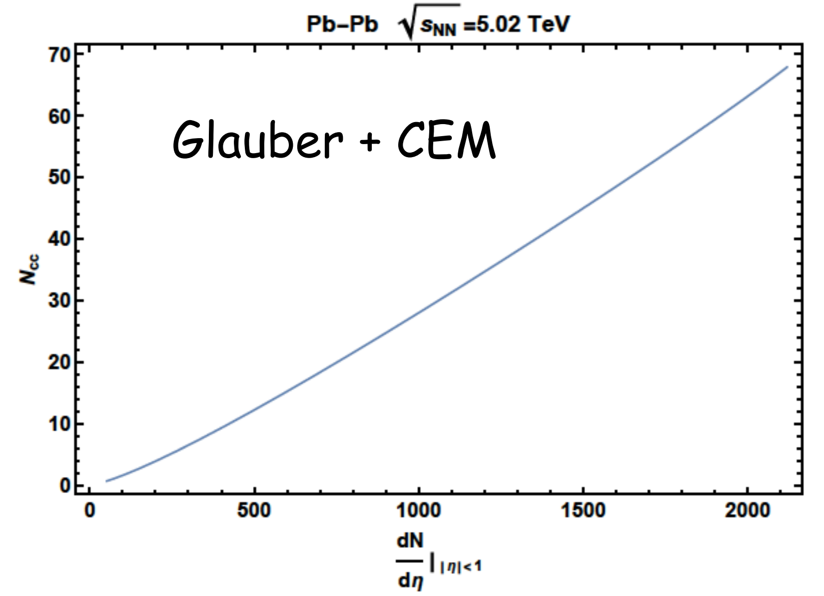
Abreu, FSN and Vieira,
Phys. Rev. D 106, 074028 (2022)

Produção de exóticos com charme no modelo de coalescência

Trabalho de mestrado de Richard Terra

Número de pares c-cbar em função do tamanho do sistema

Melhoria do trabalho da colaboração EXHIC



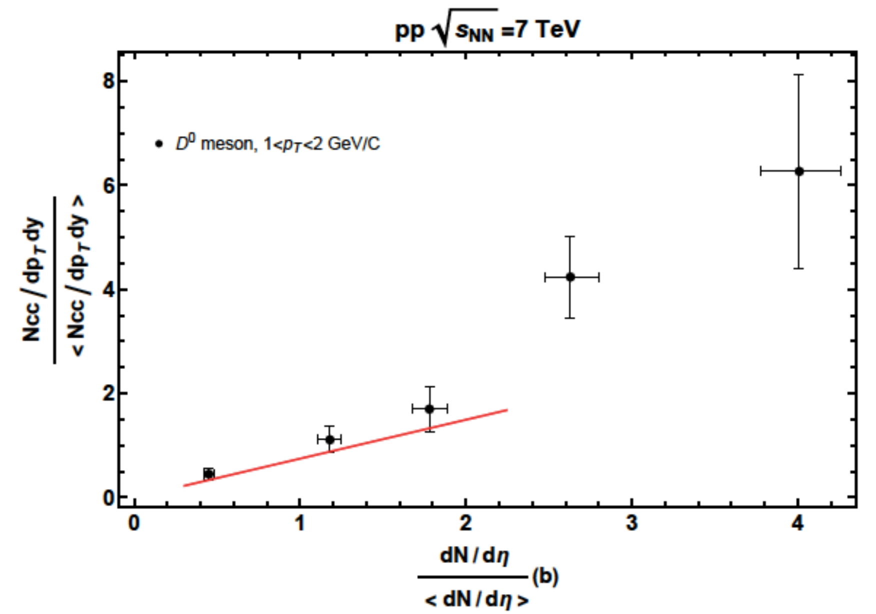
Produção de charme em proton - proton

Crescimento mais rápido do que o esperado

Color Glass Condensate?

Hidrodinâmica?

Multiple parton scattering?



Distribuição de multiplicidade de mesons com charme em proton-proton

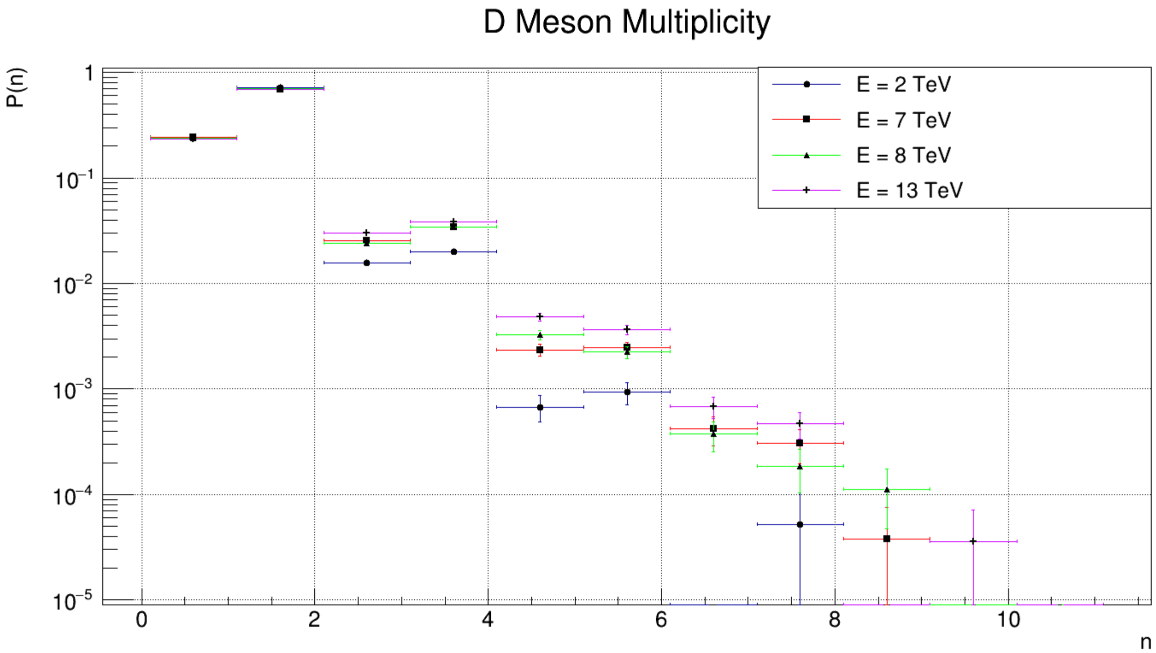
Trabalho de Jhoão Arneiro (doutorando do Suaide)

Simulação com PYTHIA

Comparação com NBD

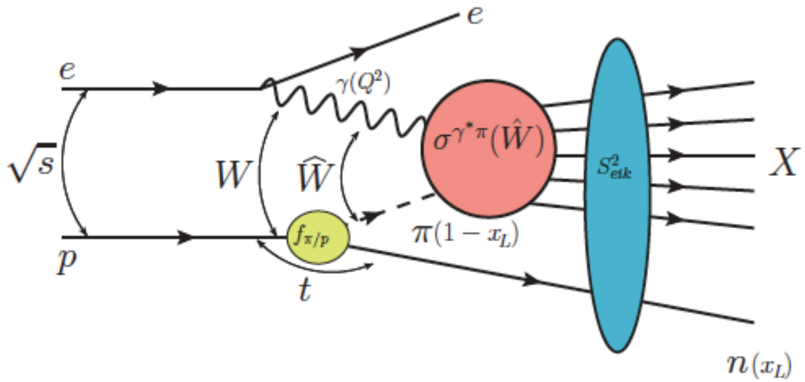
Altas densidades ?

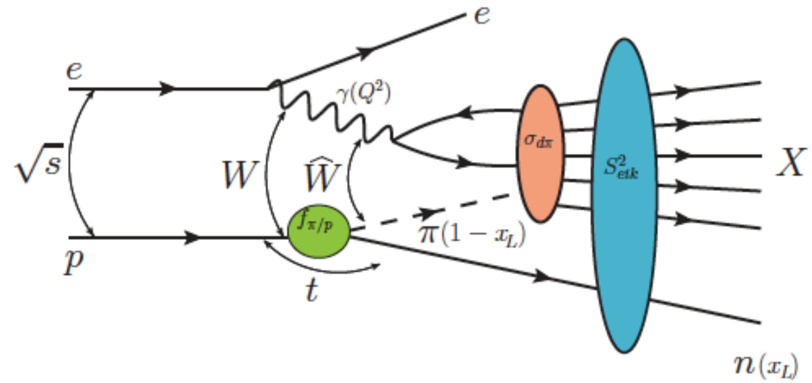
Multiple parton scattering ?

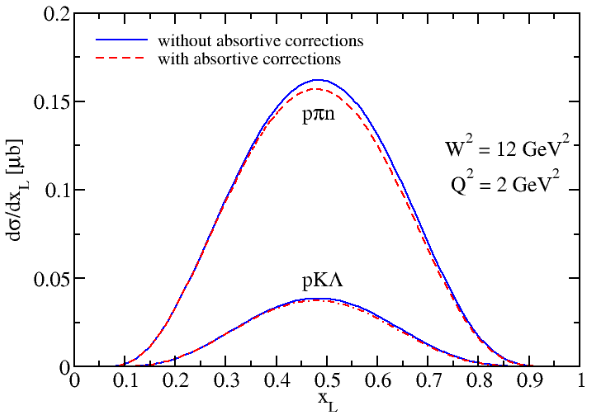


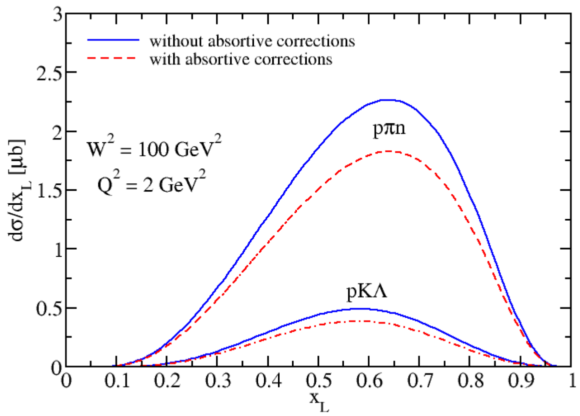
Leading neutrons e leading Lambdas no Electron Ion Collider

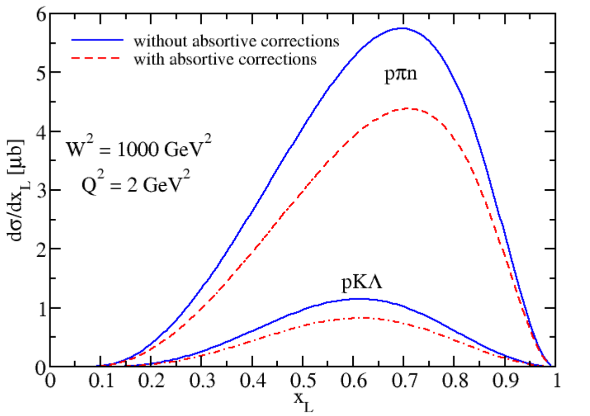
Trabalho de Diego Spiering (pós-doc)











Renato Higa

Participação em conferências

Reunião de Trabalho em Física Nuclear no Brasil

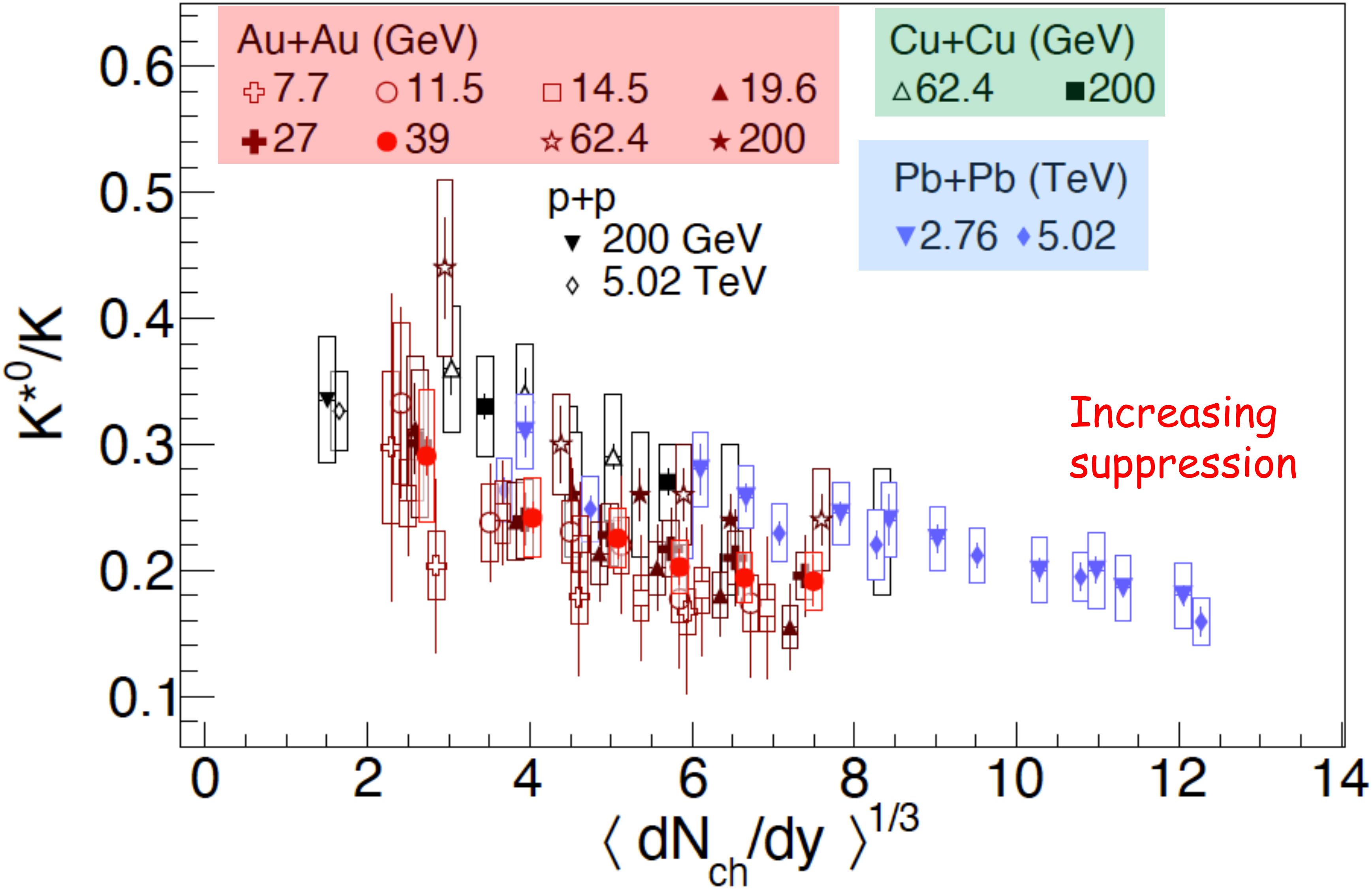
Simpósio do INCT-FNA

Orientações

Alberto Fernandez (iniciação científica)

Efeito de canais acoplados e estrutura analítica da matriz S aplicada ao X(3872)

...to a wealthy of data



STAR, arXiv:2210.02909

What can we learn from this ratio?

Interactions of K and K* in a hot hadron gas

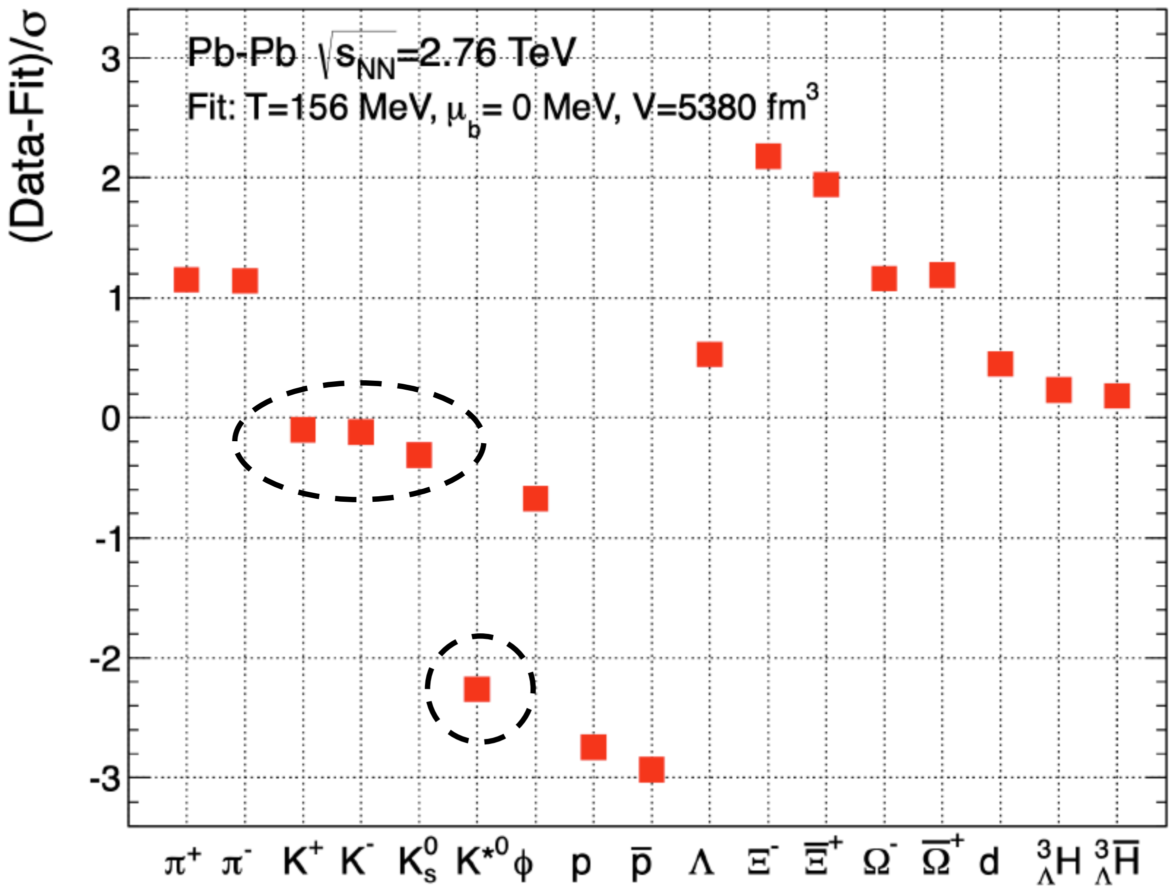
Emergence of chemical equilibrium (freeze-out)

Kinetic freeze-out: lifetime of the hadron gas phase

Confirm the existence of a hot hadron gas

Do we have a good theory ?

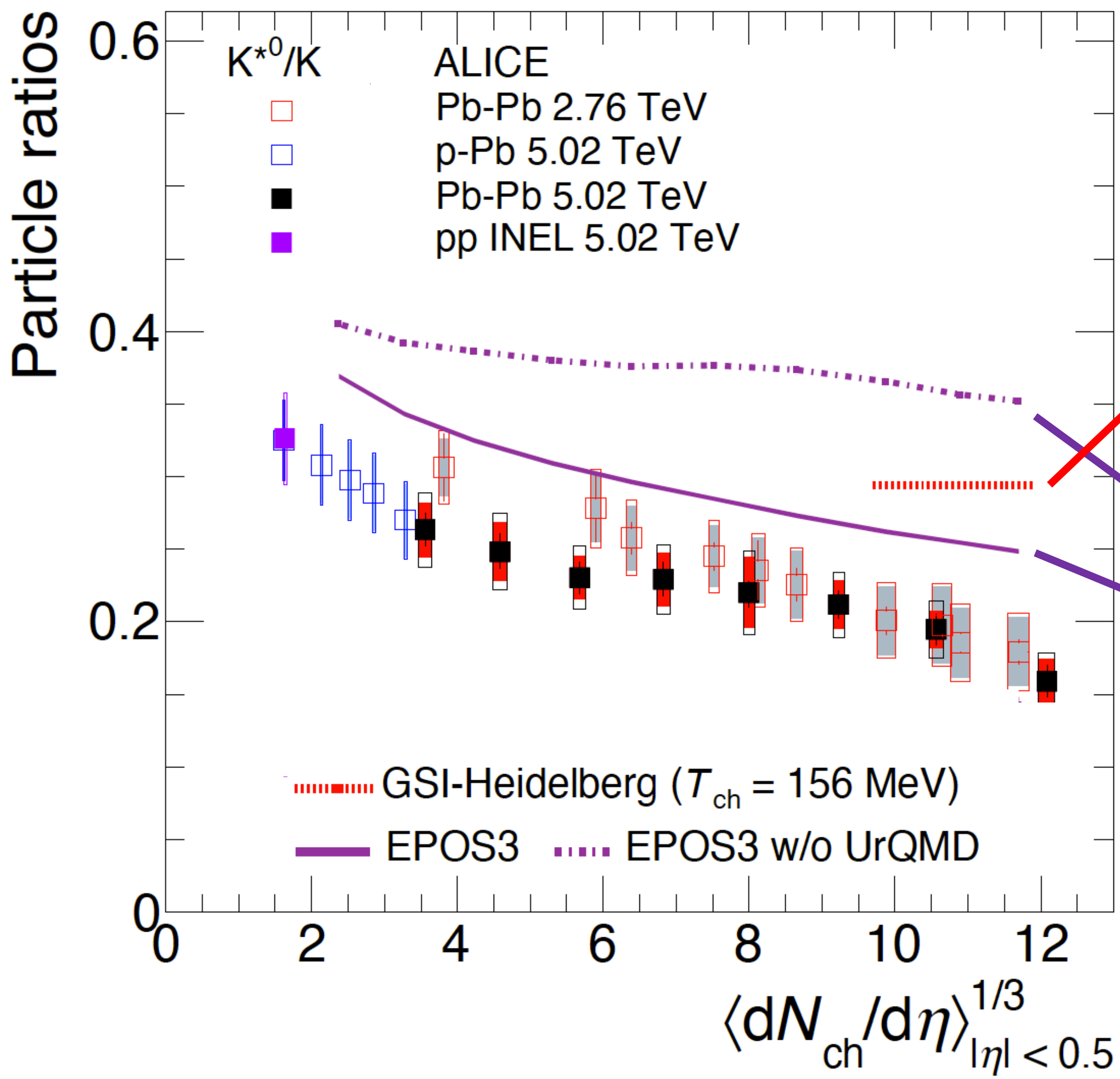
Statistical Hadronization Model fails...



Stachel et al.,
arXiv:1311.4662

We must include rescattering and/or decay !

ALICE, arXiv:1910.14419

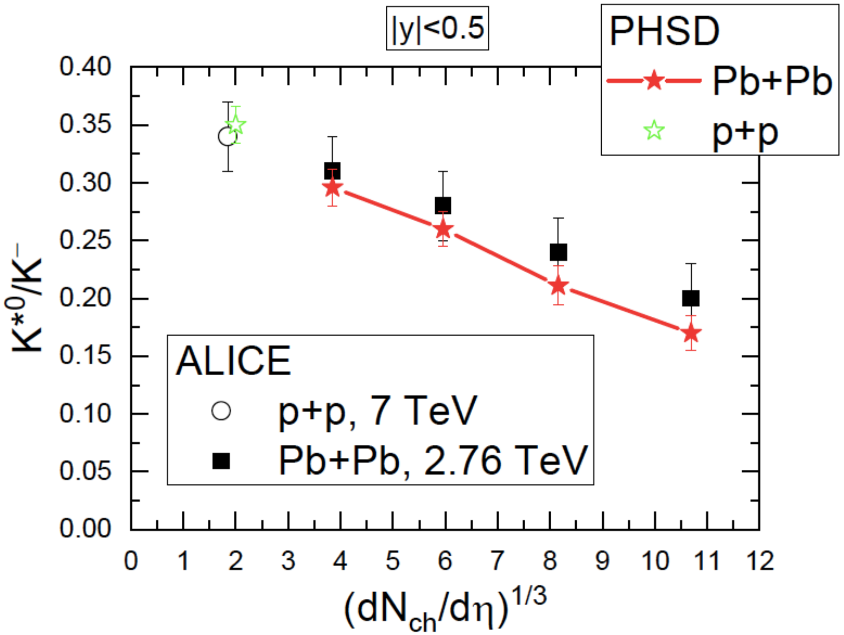


Stachel et al., arXiv:1311.4662

SHM

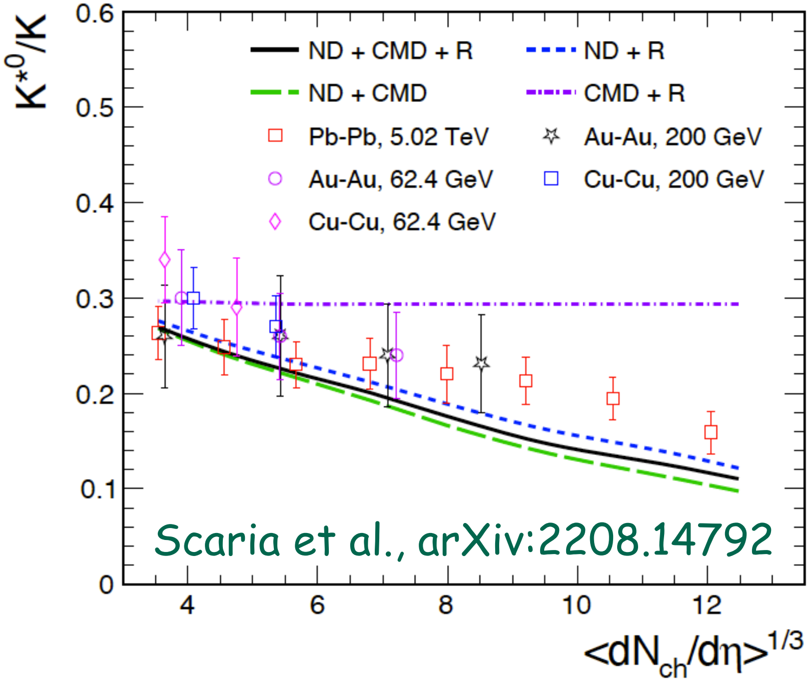
Knospe, Markert, Werner, Steinheimer, Bleicher, arXiv:1509.07895

Interactions with the hadron gas improve agreement with data !

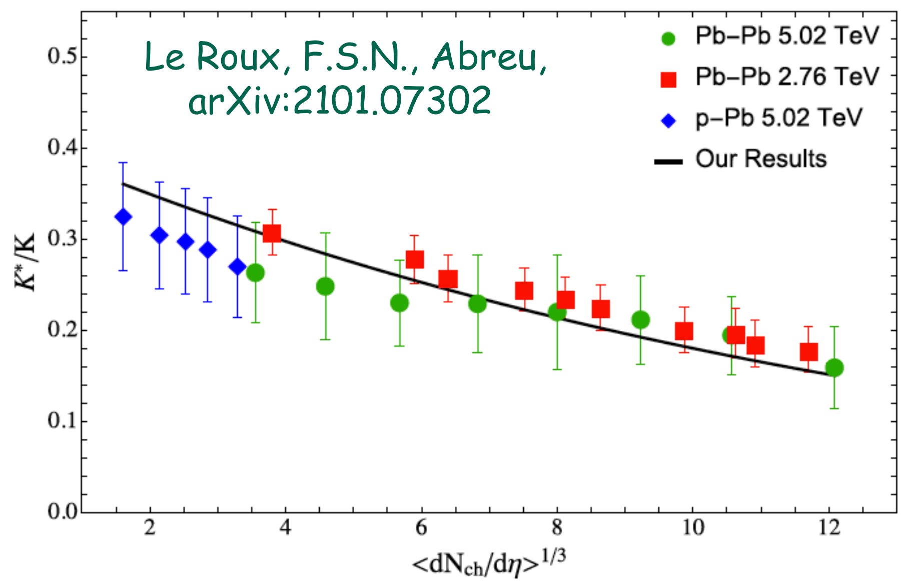


Ilner, Cabrera, Markert, Bratkovskaya, arXiv:1609.02778

Ilner, Blair, Cabrera, Markert, Bratkovskaya, arXiv:1707.00060



Scaria et al., arXiv:2208.14792



Le Roux, F.S.N., Abreu, arXiv:2101.07302

The hadron gas contribution

Start with the multiplicities at the hadronization

Study the changes produced by interactions in the hadron gas

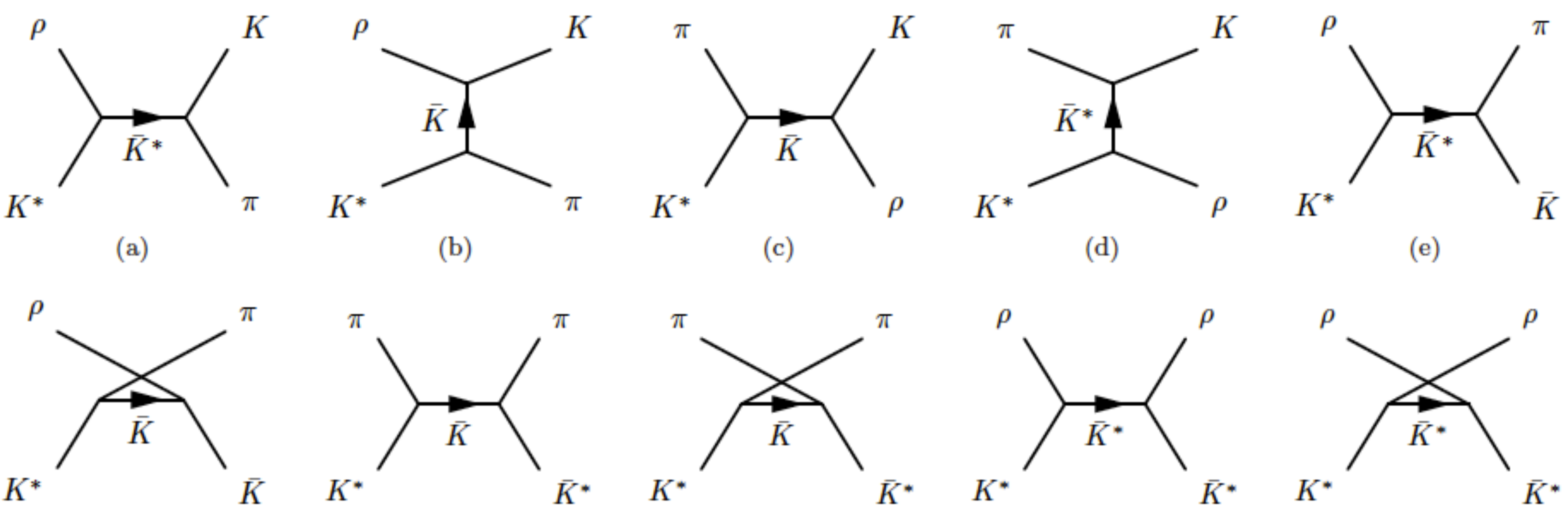
Lagrangians -> Amplitudes -> Cross Sections -> Thermal Cross Sections

Evolution equations -> Expansion and cooling -> Freeze-out

K and K* interactions with light hadrons

$$
\begin{aligned}
\mathcal{L}_{\pi K K^*} &= i g_{\pi K^* K} K^{*\mu} \vec{\tau} \cdot (\bar{K} \partial_\mu \vec{\pi} - \partial_\mu \bar{K} \vec{\pi}) \\
\mathcal{L}_{\rho K K} &= i g_{\rho K K} (K \vec{\tau} \partial_\mu \bar{K} - \partial_\mu K \vec{\tau} \bar{K}) \cdot \vec{\rho}^{\mu}, \\
\mathcal{L}_{\rho K^* K^*} &= i g_{\rho K^* K^*} \left[(\partial_\mu K^{*\nu} \vec{\tau} \bar{K}^*_\nu - K^{*\nu} \vec{\tau} \partial_\mu \bar{K}^*_\nu) \cdot \vec{\rho}^{\mu} \right. \\
&+ (K^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu K^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu) \bar{K}^{*\mu} \\
&+ \left. K^{*\mu} (\vec{\tau} \cdot \vec{\rho}^{\nu} \partial_\mu \bar{K}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^{\nu} \bar{K}^*_\nu) \right],
\end{aligned}
$$

S. Cho and S.H. Lee,
arXiv:1509.04092



Cross Sections :
$$\sigma = \frac{1}{64\pi^2 s g_1 g_2} \frac{|\vec{p}_f|}{|\vec{p}_i|} \int d\Omega \overline{|\mathcal{M}|^2} F^4$$

Form Factors :
$$F_{u,t}(\vec{q}) = \frac{\Lambda^2 - m_{ex}^2}{\Lambda^2 + \vec{q}^2} \qquad \Lambda = 1.8\,\mathrm{GeV}$$

Thermal Cross Sections :
$$\langle \sigma_{ab\to cd}\, v_{ab} \rangle = \frac{\int d^3\mathbf{p}_a d^3\mathbf{p}_b\, f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b)\, \sigma_{ab\to cd}\; v_{ab}}{\int d^3\mathbf{p}_a d^3\mathbf{p}_b\, f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b)}$$

$$f_i(\vec{p}_i) = \frac{1}{e^{\sqrt{\vec{p}_i^{\,2} + m_i^2}/T} - 1} \qquad v_{ab} = \sqrt{(p_a \cdot p_b)^2 - m_a^2 m_b^2}/(E_a E_b)$$

Inverse processes with detailed balance:
$$g_a g_b |\vec{p}_{ab}|^2 \sigma_{ab\to cd}(s) = g_c g_d |\vec{p}_{cd}|^2 \sigma_{cd\to ab}(s)$$

$$\frac{dN_{K^*}}{d\tau} = \langle\sigma_{K\rho\to K^*\pi} v_{K\rho}\rangle n_\rho(\tau)N_K(\tau) - \langle\sigma_{K^*\pi\to K\rho} v_{K^*\pi}\rangle n_\pi(\tau)N_{K^*}(\tau) + \langle\sigma_{K\pi\to K^*\rho} v_{K\pi}\rangle n_\pi(\tau)N_K(\tau)$$
$$- \langle\sigma_{K^*\rho\to K\pi} v_{K^*\rho}\rangle n_\rho(\tau)N_{K^*}(\tau) + \langle\sigma_{\pi\rho\to K^*\bar{K}} v_{\pi\rho}\rangle n_\pi(\tau)N_\rho(\tau) - \langle\sigma_{K^*\bar{K}\to\rho\pi} v_{K^*\bar{K}}\rangle n_{\bar{K}}(\tau)N_{K^*}(\tau)$$
$$+ \langle\sigma_{\pi\pi\to K^*\bar{K}^*} v_{\pi\pi}\rangle n_\pi(\tau)N_\pi(\tau) - \langle\sigma_{K^*\bar{K}^*\to\pi\pi} v_{K^*\bar{K}^*}\rangle n_{\bar{K}^*}(\tau)N_{K^*}(\tau) + \langle\sigma_{\rho\rho\to K^*\bar{K}^*} v_{\rho\rho}\rangle n_\rho(\tau)N_\rho(\tau)$$
$$- \langle\sigma_{K^*\bar{K}^*\to\rho\rho} v_{K^*\bar{K}^*}\rangle n_{\bar{K}^*}(\tau)N_{K^*}(\tau) + \langle\sigma_{K\pi\to K^*} v_{K\pi}\rangle n_\pi(\tau)N_K(\tau) - \langle\Gamma_{K^*}\rangle N_{K^*}(\tau),$$

$$\frac{dN_K}{d\tau} = \langle\sigma_{\pi\pi\to K\bar{K}} v_{\pi\pi}\rangle n_\pi(\tau)N_\pi(\tau) - \langle\sigma_{K\bar{K}\to\pi\pi} v_{K\bar{K}}\rangle n_{\bar{K}}(\tau)N_K(\tau) + \langle\sigma_{\rho\rho\to K\bar{K}} v_{\rho\rho}\rangle n_\rho(\tau)N_\rho(\tau)$$
$$- \langle\sigma_{K\bar{K}\to\rho\rho} v_{K\bar{K}}\rangle n_{\bar{K}}(\tau)N_K(\tau) + \langle\sigma_{K^*\pi\to K\rho} v_{K^*\pi}\rangle n_\pi(\tau)N_{K^*}(\tau) - \langle\sigma_{K\rho\to K^*\pi} v_{K\rho}\rangle n_\rho(\tau)N_K(\tau)$$
$$+ \langle\sigma_{K^*\rho\to K\pi} v_{K^*\rho}\rangle n_\rho(\tau)N_{K^*}(\tau) - \langle\sigma_{K\pi\to K^*\rho} v_{K\pi}\rangle n_\pi(\tau)N_K(\tau) + \langle\sigma_{\pi\rho\to K^*\bar{K}} v_{\pi\rho}\rangle n_\pi(\tau)N_\rho(\tau)$$
$$- \langle\sigma_{K^*\bar{K}\to\rho\pi} v_{K^*\bar{K}}\rangle n_{\bar{K}}(\tau)N_{K^*}(\tau) + \langle\Gamma_{K^*}\rangle N_{K^*}(\tau) - \langle\sigma_{K\pi\to K^*} v_{K\pi}\rangle n_\pi(\tau)N_K(\tau).$$

$$n_i(\tau) = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2dp}{e^{\sqrt{p_i^2+m_i^2}/T(\tau)} - 1} \simeq \frac{g_i}{2\pi^2} m_i^2 T(\tau) K_2\left(\frac{m_i}{T(\tau)}\right) \qquad N_i = n_i V$$

Expansion and Cooling :

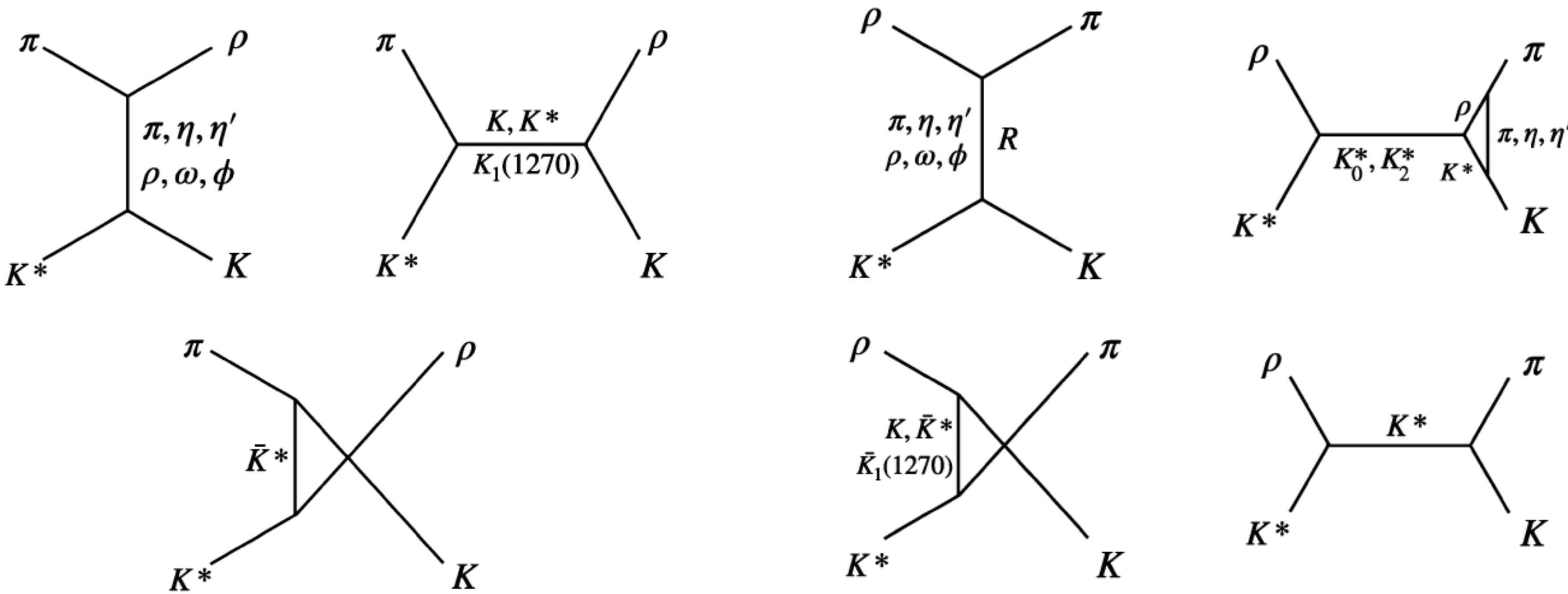
$$\begin{cases} V(\tau) = \pi[R_c + v_c(\tau-\tau_c) + a_c/2(\tau-\tau_c)^2]^2\tau c, \\ T(\tau) = T_c - (T_h - T_f)\left(\frac{\tau-\tau_h}{\tau_f-\tau_h}\right)^{4/5}, \end{cases}$$

K and K* interactions with light hadrons improved

Martinez Torres, Khemchandani, Abreu, F.S.N., Nielsen, arXiv:1708.05784

Inclusion of anomalous parity VVP interactions

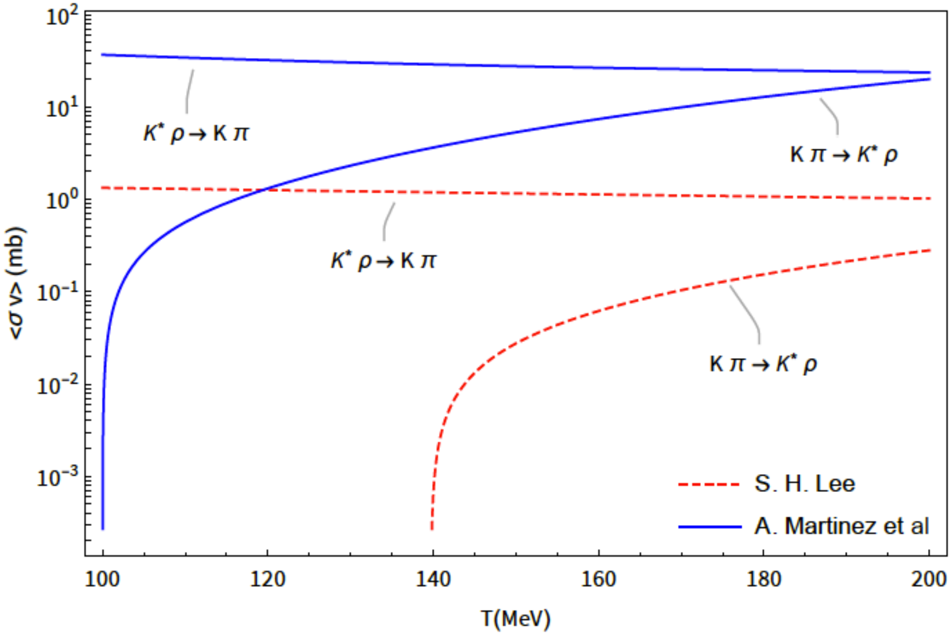
Exchange of axial resonances



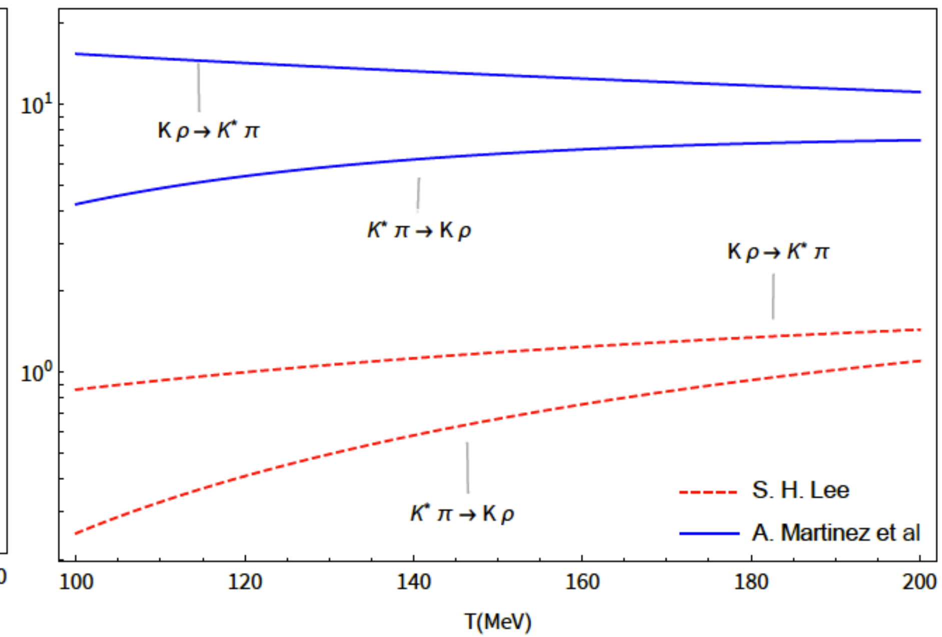
Many processes but only 3 are really important:

$$\left\{ \begin{array}{l} K^* \rho \leftrightarrow K \pi \\ K^* \pi \leftrightarrow K \rho \\ K^* \leftrightarrow K + \pi \end{array} \right.$$

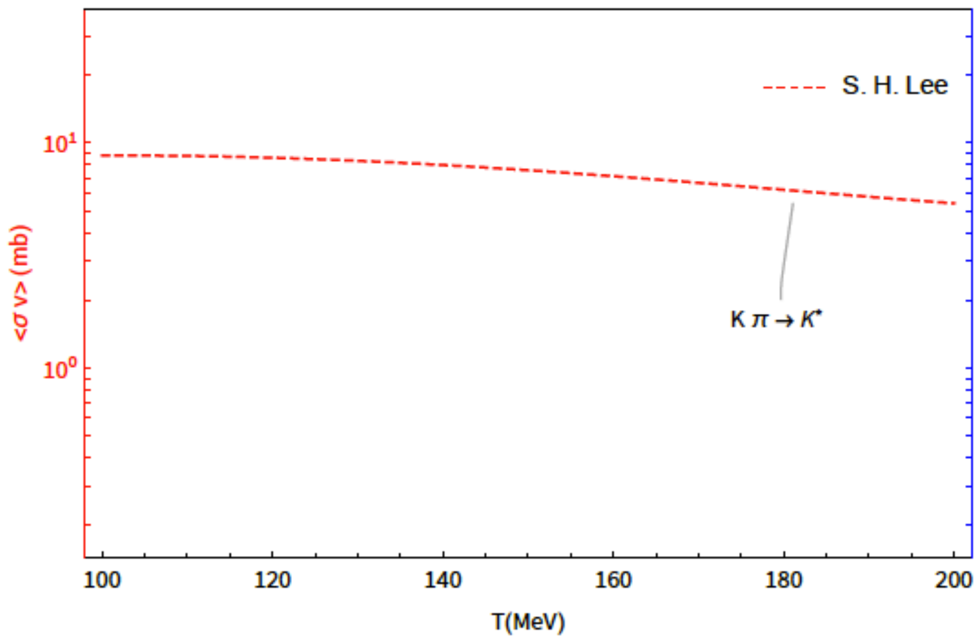
$K^* \rho \leftrightarrow K \pi$



$K^* \pi \leftrightarrow K \rho$



$K^* \leftrightarrow K + \pi$



Simplified evolution equations :

$$
\begin{cases}
\dfrac{dN_{K^*}(\tau)}{d\tau} = \gamma_K N_K(\tau) - \gamma_{K^*} N_{K^*}(\tau), \\
\dfrac{dN_K(\tau)}{d\tau} = -\gamma_K N_K(\tau) + \gamma_{K^*} N_{K^*}(\tau),
\end{cases}
$$

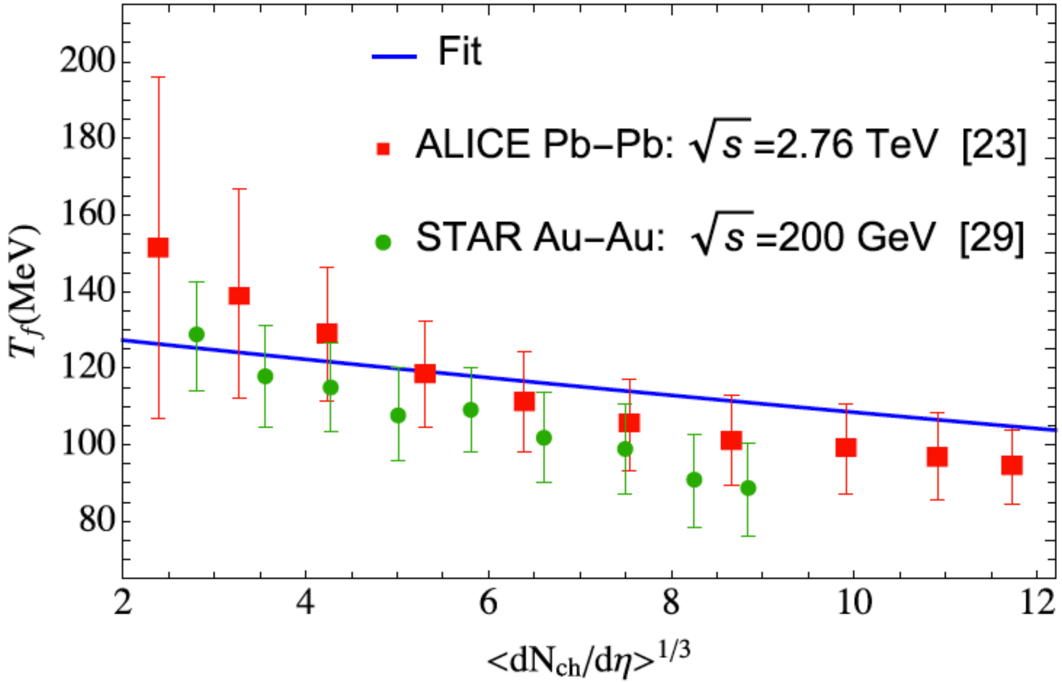
$$
\gamma_K = \langle \sigma_{K\pi\to K^*\rho} v_{K\pi} \rangle n_\pi + \langle \sigma_{K\rho\to K^*\pi} v_{K\rho} \rangle n_\rho + \langle \sigma_{K\pi\to K^*} v_{K\pi} \rangle n_\pi ,
$$

$$
\gamma_{K^*} = \langle \sigma_{K^*\rho\to K\pi} v_{K^*\rho} \rangle n_\rho + \langle \sigma_{K^*\pi\to K\rho} v_{K^*\pi} \rangle n_\pi + \langle \Gamma_{K^*} \rangle .
$$

Bjorken cooling : $T = T_h \left(\dfrac{\tau_h}{\tau}\right)^{1/3} \rightarrow \tau_f = \tau_h \left(\dfrac{T_h}{T_f}\right)^3$

T_f depends on the system size : $T_f = T_f \left(\dfrac{dN}{d\eta}(\eta = 0)\right)$

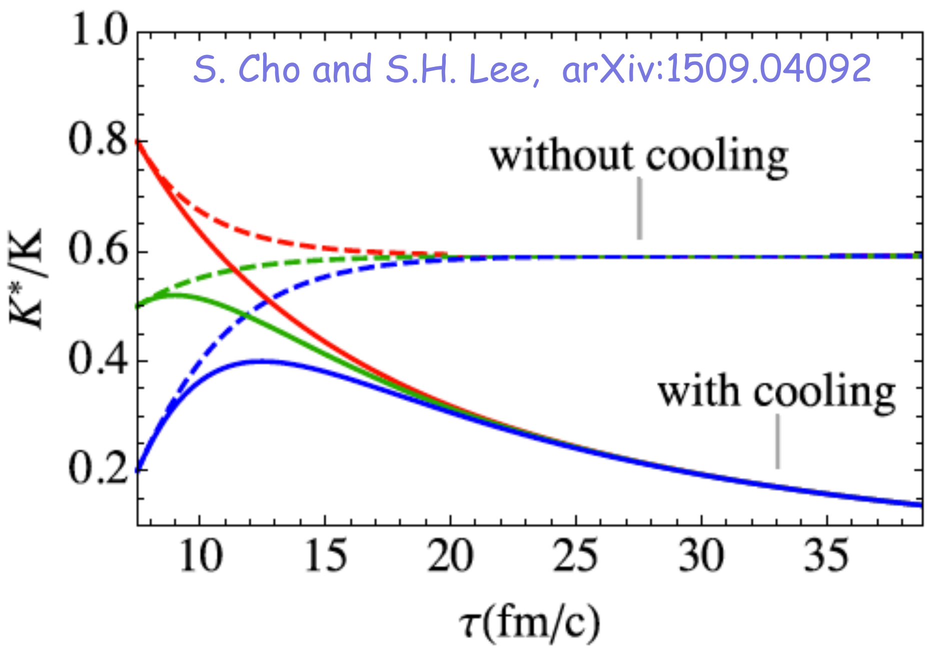
System size dependent freeze-out temperature

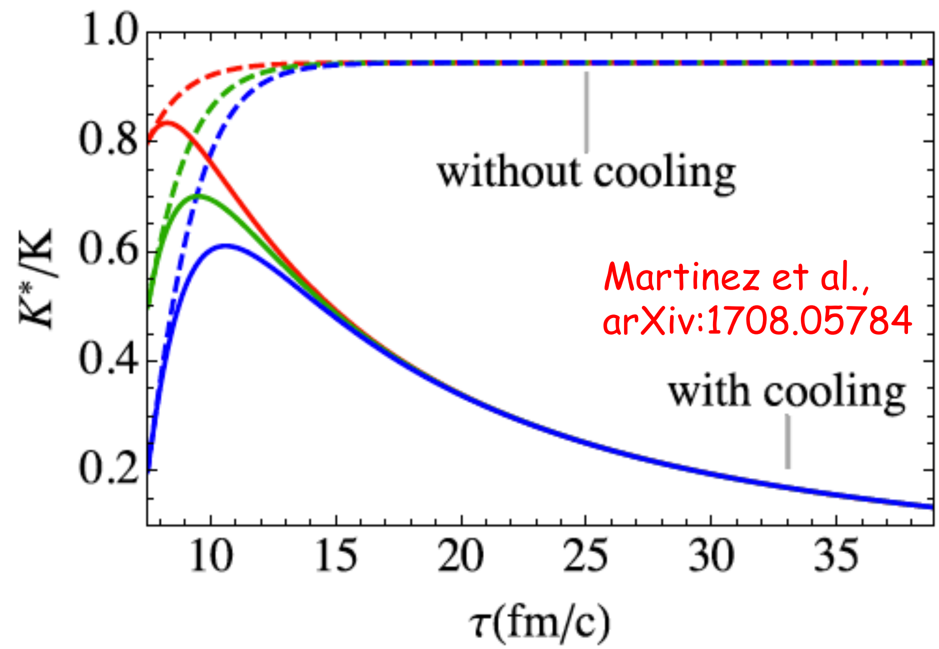


ALICE, arXiv:1303.0737

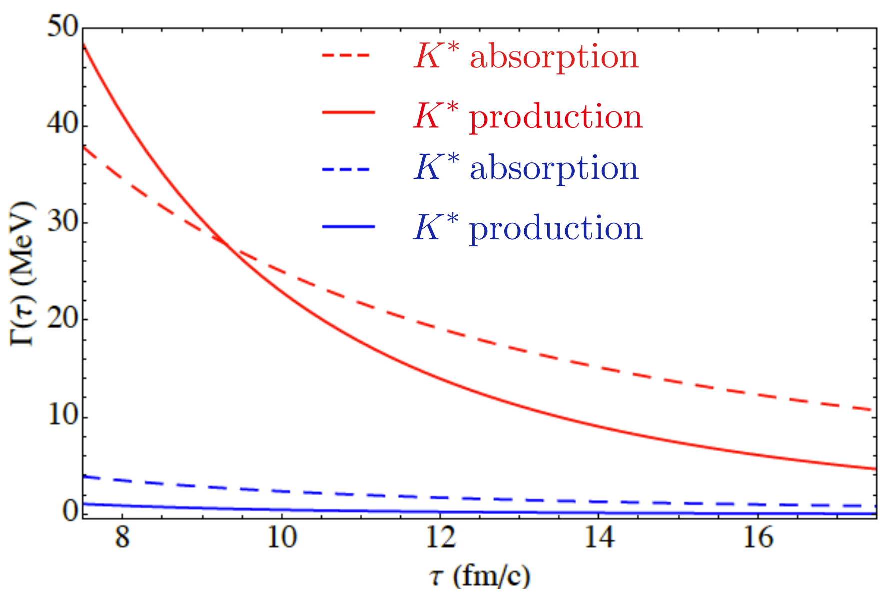
$$T_f = T_{f0}\, e^{-b\mathcal{N}}$$

$$\mathcal{N} = \left[\left(\frac{dN}{d\eta}\right)_{\eta=0}\right]^{1/3}$$





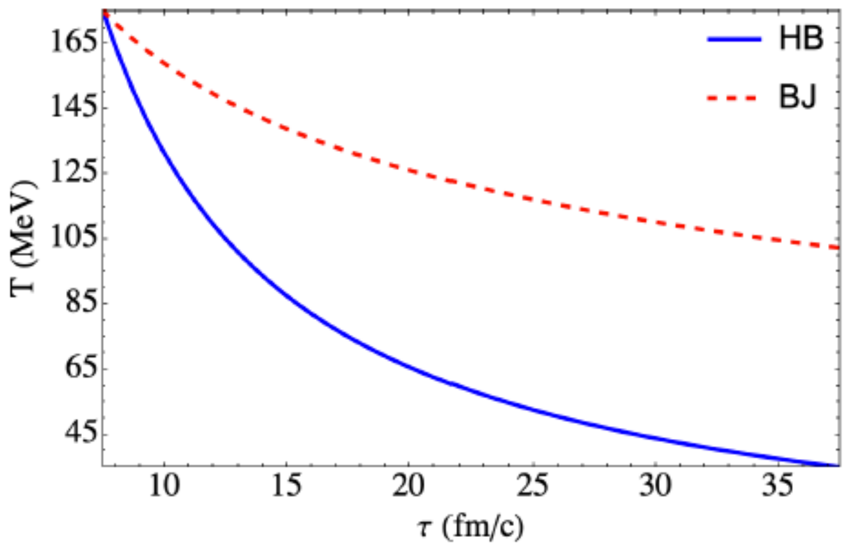
Reaction Rate



Martinez et al., arXiv:1708.05784

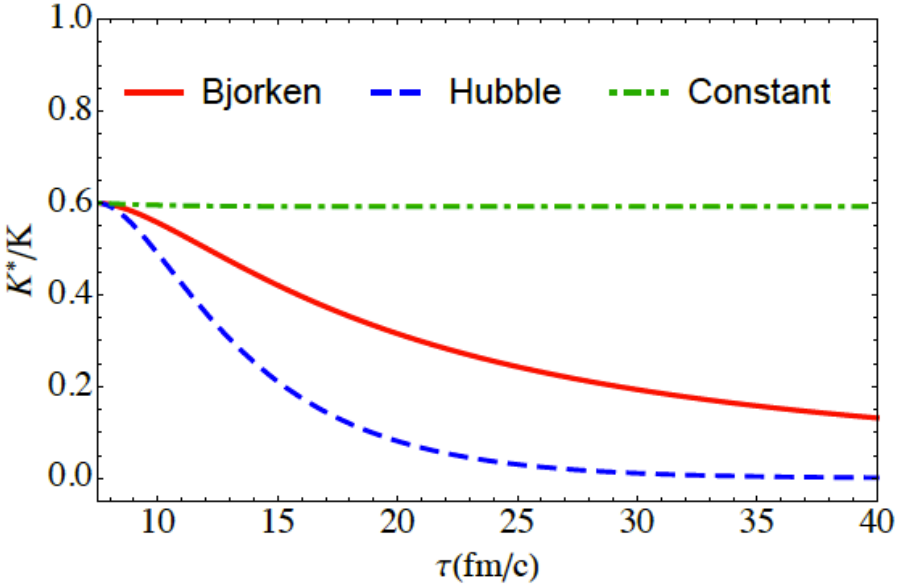
S. Cho,S.H. Lee, arXiv:1509.04092

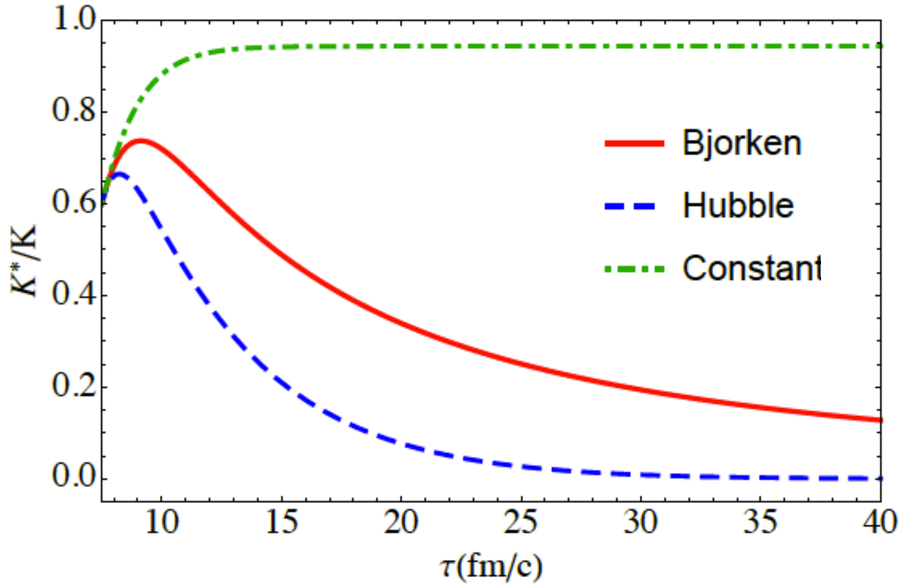
Effect of cooling



$$T(\tau) = T_h \left(\frac{\tau_h}{\tau}\right)^{\frac{1}{3}}$$ Bjorken

$$T(\tau) = T_h \left(\frac{\tau_h}{\tau}\right)$$ Hubble



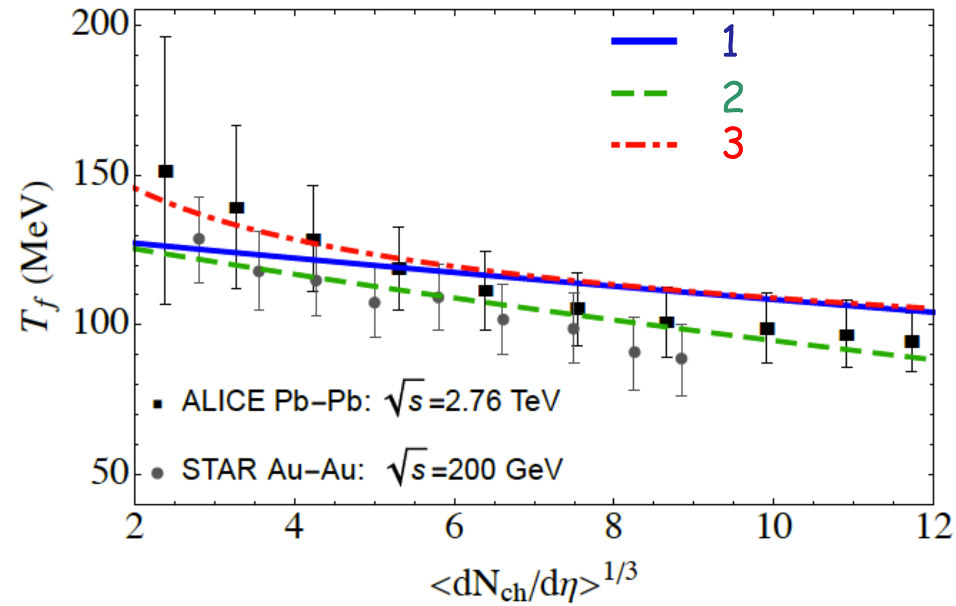


Effect of the parametrization of T_f

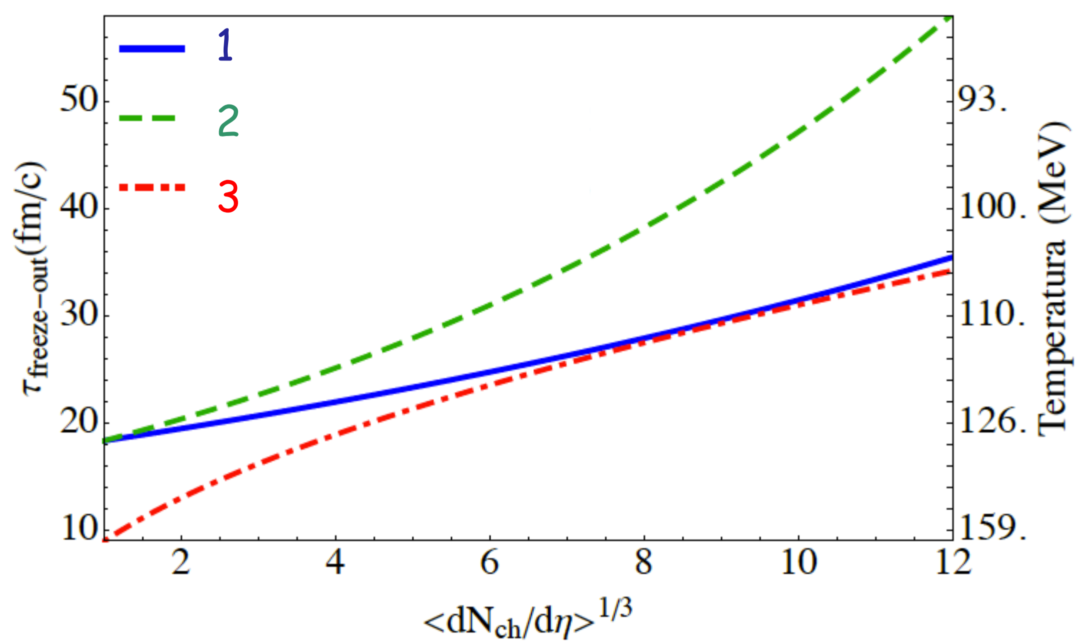
1 $T_f = 132\, e^{-0.02\, \mathcal{N}}$

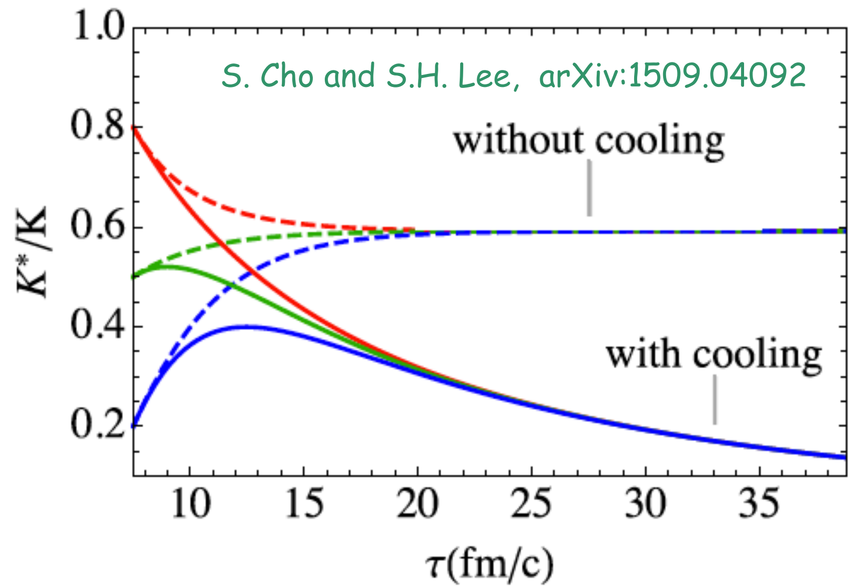
2 $T_f = 134\, e^{-0.035\, \mathcal{N}}$

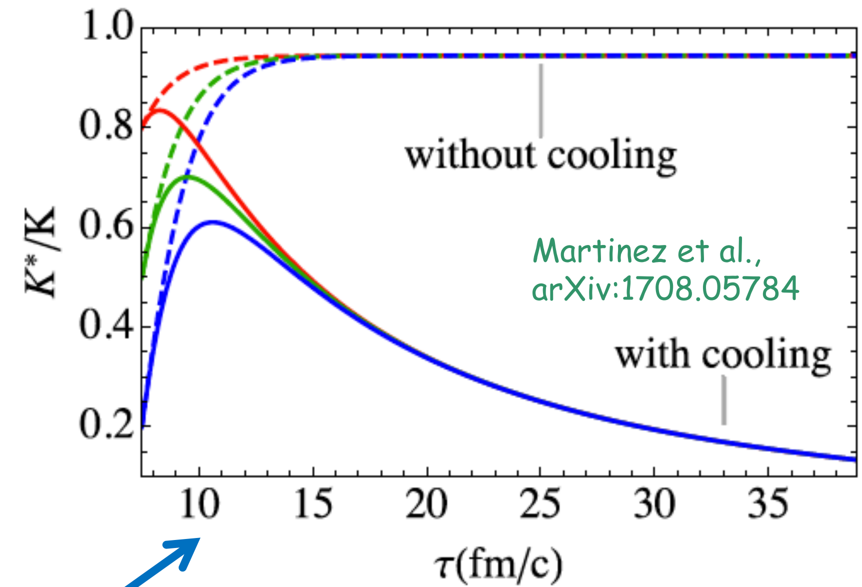
3 $T_f = 165\, e^{-0.18\, \mathcal{N}}$



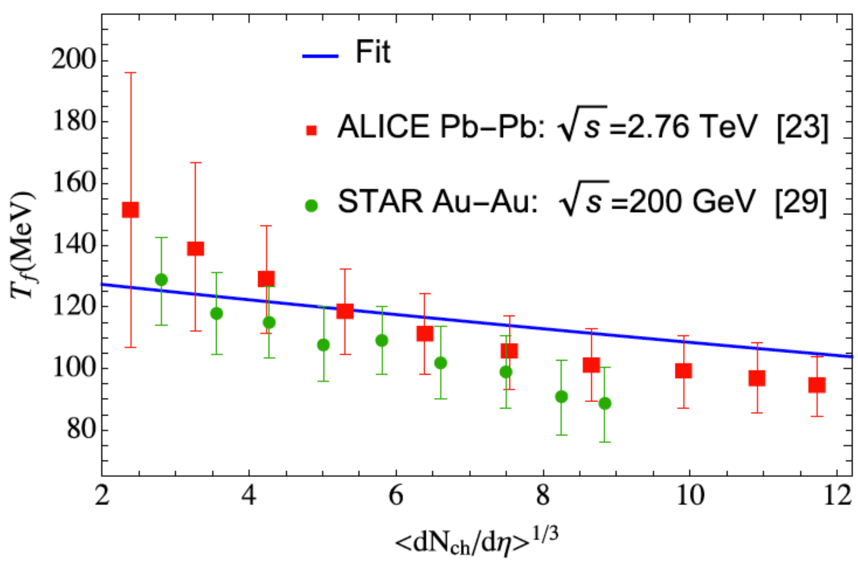
$$\tau_f = \tau_h \left(\frac{T_h}{T_f} \right)^3$$

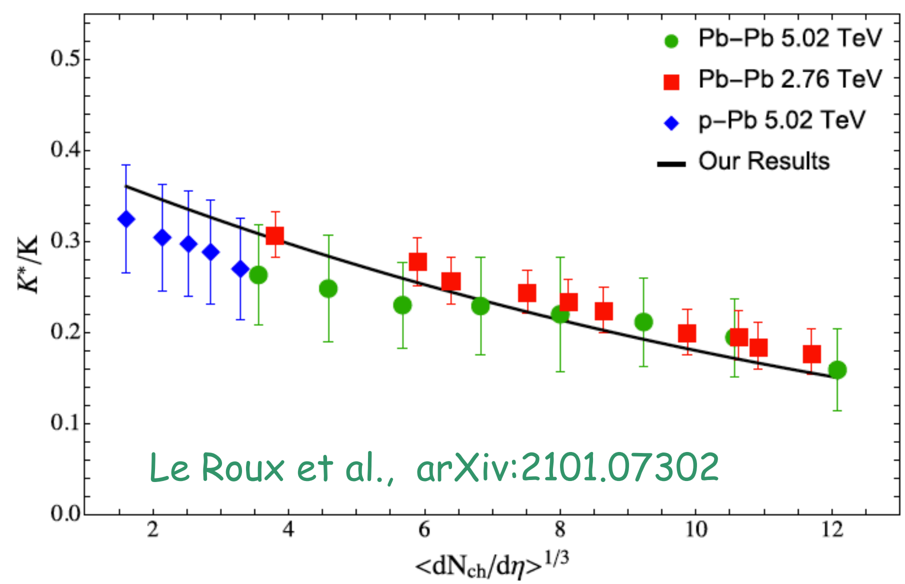






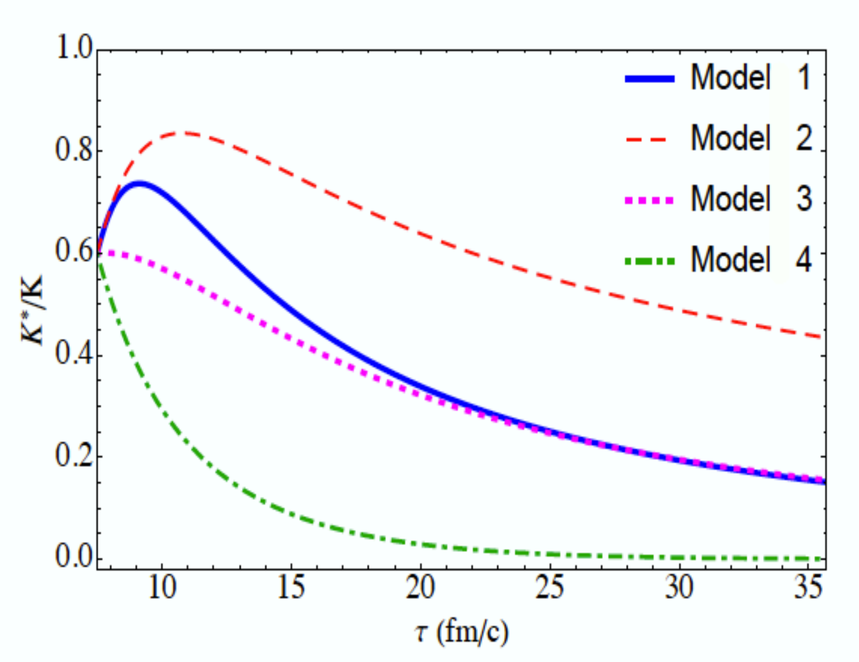
$$\tau_f = \tau_h \left(\frac{T_h}{T_f} \right)^3$$

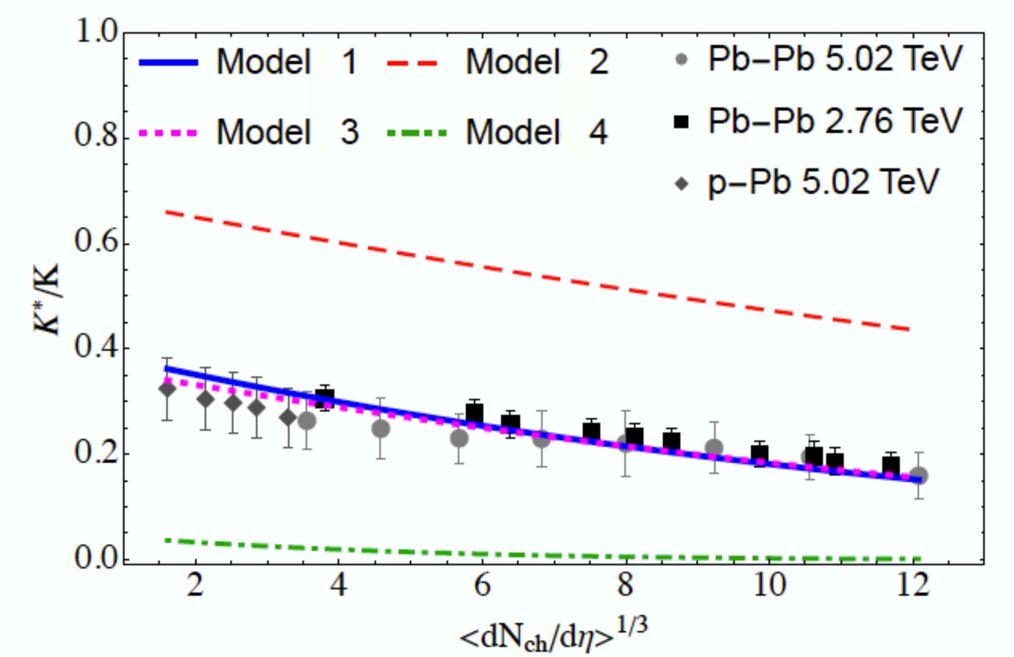




Which reaction is more important?

	$K^*\pi \leftrightarrow K\rho$	$K^*\rho \leftrightarrow K\pi$	$K^* \to K\pi$	$K\pi \to K^*$
Model 1	✓	✓	✓	✓
Model 2	✓	✓		
Model 3			✓	✓
Model 4			✓	





C.~Le Roux and F.~S.~Navarra, J. Phys. Conf. Ser. {2340}, 012010 (2022)

D* / D Ratio

Lagrangians -> Amplitudes -> Cross Sections -> Thermal Cross Sections

Evolution equations -> Expansion and cooling -> Freeze-out

Abreu, FSN and Vieira, arXiv:2209.03814

Decay: $D^* \rightarrow D + \pi$ $\Gamma(D^*) \simeq 1\,\mathrm{MeV}$ $\tau_{life} = \frac{1}{\Gamma(D^*)} \simeq 200\,\mathrm{fm}$

Not relevant !

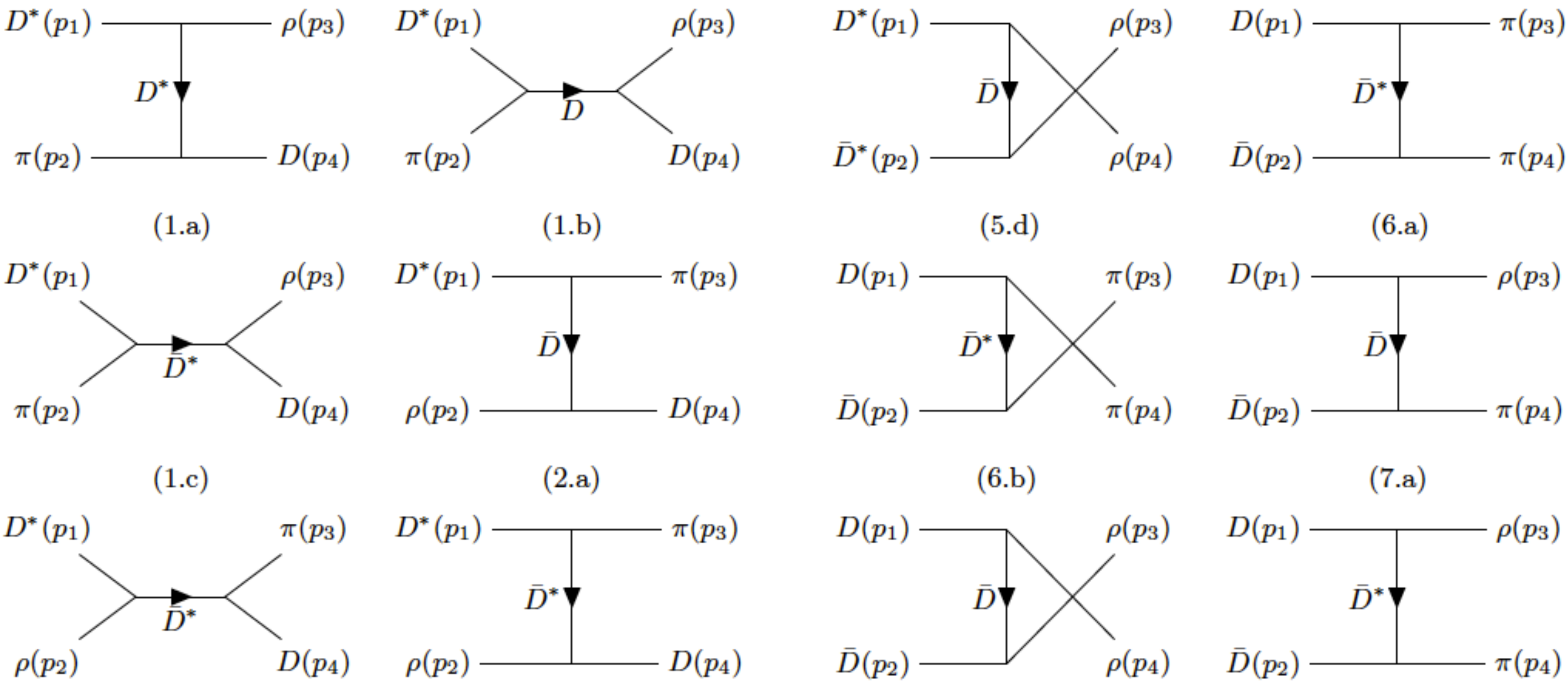
Interactions with rhos and pions

$$
\begin{aligned}
\mathcal{L}_{\pi D D^*} &= i g_{\pi D D^*} D^{*\mu} \vec{\tau} \cdot (\bar{D} \partial_\mu \vec{\pi} - \partial_\mu \bar{D} \vec{\pi}) \\
\mathcal{L}_{\rho D D} &= i g_{\rho D D} (D \vec{\tau} \partial_\mu \bar{D} - \partial_\mu D \vec{\tau} \bar{D}) \cdot \vec{\rho}^\mu, \\
\mathcal{L}_{\rho D^* D^*} &= i g_{\rho D^* D^*} \left[(\partial_\mu D^{*\nu} \vec{\tau} \bar{D}^*_\nu - D^{*\nu} \vec{\tau} \partial_\mu \bar{D}^*_\nu) \cdot \vec{\rho}^\mu \right. \\
&\quad + (D^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu D^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu) \bar{D}^{*\mu} \\
&\quad \left. + D^{*\mu} (\vec{\tau} \cdot \vec{\rho}^\nu \partial_\mu \bar{D}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^\nu \bar{D}^*_\nu) \right], \\
\mathcal{L}_{\pi D^* D^*} &= -g_{\pi D^* D^*} \epsilon^{\mu\nu\alpha\beta} \partial_\mu D^*_\nu \pi \partial_\alpha \bar{D}^*_\beta, \\
\mathcal{L}_{\rho D D^*} &= -g_{\rho D D^*} \epsilon^{\mu\nu\alpha\beta} (D \partial_\mu \rho_\nu \partial_\alpha \bar{D}^*_\beta + \partial_\mu D^*_\nu \partial_\alpha \rho_\beta \bar{D})
\end{aligned}
$$

All couplings and form factors calculated with QCD sum rules!

M.~E.~Bracco, M.~Chiapparini, F.~S.~Navarra and M.~Nielsen, arXiv:1104.2864

Amplitudes


$D^*(p_1)$ $\rho(p_3)$ D^* $\pi(p_2)$ $D(p_4)$
(1.a)
$D^*(p_1)$ $\rho(p_3)$ D $\pi(p_2)$ $D(p_4)$
(1.b)
$D^*(p_1)$ $\rho(p_3)$ $\bar{D}$ $\bar{D}^*(p_2)$ $\rho(p_4)$
(5.d)
$D(p_1)$ $\pi(p_3)$ $\bar{D}^*$ $\bar{D}(p_2)$ $\pi(p_4)$
(6.a)
$D^*(p_1)$ $\rho(p_3)$ $\bar{D}^*$ $\pi(p_2)$ $D(p_4)$
(1.c)
$D^*(p_1)$ $\pi(p_3)$ $\bar{D}$ $\rho(p_2)$ $D(p_4)$
(2.a)
$D(p_1)$ $\pi(p_3)$ $\bar{D}^*$ $\bar{D}(p_2)$ $\pi(p_4)$
(6.b)
$D(p_1)$ $\rho(p_3)$ $\bar{D}$ $\bar{D}(p_2)$ $\pi(p_4)$
(7.a)
$D^*(p_1)$ $\pi(p_3)$ $\bar{D}^*$ $\rho(p_2)$ $D(p_4)$
$D^*(p_1)$ $\pi(p_3)$ $\bar{D}^*$ $\rho(p_2)$ $D(p_4)$
$D(p_1)$ $\rho(p_3)$ $\bar{D}$ $\bar{D}(p_2)$ $\rho(p_4)$
$D(p_1)$ $\rho(p_3)$ $\bar{D}^*$ $\bar{D}(p_2)$ $\pi(p_4)$

Expansion, cooling and initial conditions

$$T(\tau) = T_C - (T_H - T_F)\left(\frac{\tau - \tau_H}{\tau_F - \tau_H}\right)^{\frac{4}{5}},$$

$$V(\tau) = \pi\left[R_C + v_C(\tau - \tau_C) + \frac{a_C}{2}(\tau - \tau_C)^2\right]^2 \tau c,$$

TABLE II. Parameters used in Eq. (12) for central $Pb - Pb$ collisions at $\sqrt{s_{NN}} = 5$ TeV [25].

v_C (c)	a_C (c^2/fm)	R_C (fm)
0.5	0.09	11
τ_C (fm/c)	τ_H (fm/c)	τ_F (fm/c)
7.1	10.2	21.5
T_C(MeV)	T_H(MeV)	T_F(MeV)
156	156	115
N_c	$N_\pi(\tau_F)$	$N_\rho(\tau_F)$
14	2410	179
$N_D(\tau_H)$	$N_{D^*}(\tau_H)$	
4.7	6.3	

EXHIC, arXiv:1702.00486

Time evolution and multiplicities

$$\frac{dN_{D^*}}{d\tau} = \langle\sigma_{D\rho\to D^*\pi}v_{D\rho}\rangle n_\rho(\tau)N_D(\tau) - \langle\sigma_{D^*\pi\to D\rho}v_{D^*\pi}\rangle n_\pi(\tau)N_{D^*}(\tau) + \langle\sigma_{D\pi\to D^*\rho}v_{D\pi}\rangle n_\pi(\tau)N_D(\tau)$$
$$- \langle\sigma_{D^*\rho\to D\pi}v_{D^*\rho}\rangle n_\rho(\tau)N_{D^*}(\tau) + \langle\sigma_{\pi\rho\to D^*\bar{D}}v_{\pi\rho}\rangle n_\pi(\tau)N_\rho(\tau) - \langle\sigma_{D^*\bar{D}\to\rho\pi}v_{D^*\bar{D}}\rangle n_{\bar{D}}(\tau)N_{D^*}(\tau)$$
$$+ \langle\sigma_{\pi\pi\to D^*\bar{D}^*}v_{\pi\pi}\rangle n_\pi(\tau)N_\pi(\tau) - \langle\sigma_{D^*\bar{D}^*\to\pi\pi}v_{D^*\bar{D}^*}\rangle n_{\bar{D}^*}(\tau)N_{D^*}(\tau) + \langle\sigma_{\rho\rho\to D^*\bar{D}^*}v_{\rho\rho}\rangle n_\rho(\tau)N_\rho(\tau)$$
$$- \langle\sigma_{D^*\bar{D}^*\to\rho\rho}v_{D^*\bar{D}^*}\rangle n_{\bar{D}^*}(\tau)N_{D^*}(\tau) + \langle\sigma_{D\pi\to D^*}v_{D\pi}\rangle n_\pi(\tau)N_D(\tau) - \langle\Gamma_{D^*}\rangle N_{D^*}(\tau),$$

$$\frac{dN_D}{d\tau} = \langle\sigma_{\pi\pi\to D\bar{D}}v_{\pi\pi}\rangle n_\pi(\tau)N_\pi(\tau) - \langle\sigma_{D\bar{D}\to\pi\pi}v_{D\bar{D}}\rangle n_{\bar{D}}(\tau)N_D(\tau) + \langle\sigma_{\rho\rho\to D\bar{D}}v_{\rho\rho}\rangle n_\rho(\tau)N_\rho(\tau)$$
$$- \langle\sigma_{D\bar{D}\to\rho\rho}v_{D\bar{D}}\rangle n_{\bar{D}}(\tau)N_D(\tau) + \langle\sigma_{D^*\pi\to D\rho}v_{D^*\pi}\rangle n_\pi(\tau)N_{D^*}(\tau) - \langle\sigma_{D\rho\to D^*\pi}v_{D\rho}\rangle n_\rho(\tau)N_D(\tau)$$
$$+ \langle\sigma_{D^*\rho\to D\pi}v_{D^*\rho}\rangle n_\rho(\tau)N_{D^*}(\tau) - \langle\sigma_{D\pi\to D^*\rho}v_{D\pi}\rangle n_\pi(\tau)N_D(\tau) + \langle\sigma_{\pi\rho\to D^*\bar{D}}v_{\pi\rho}\rangle n_\pi(\tau)N_\rho(\tau)$$
$$- \langle\sigma_{D^*\bar{D}\to\rho\pi}v_{D^*\bar{D}}\rangle n_{\bar{D}}(\tau)N_{D^*}(\tau) + \langle\Gamma_{D^*}\rangle N_{D^*}(\tau) - \langle\sigma_{D\pi\to D^*}v_{D\pi}\rangle n_\pi(\tau)N_D(\tau),$$

$$n_i(\tau) \approx \frac{1}{2\pi^2}\gamma_i g_i m_i^2 T(\tau) K_2\left(\frac{m_i}{T(\tau)}\right) \qquad N_i = n_i V$$

$$\tau_f = \tau_h\left(\frac{T_H}{T_F}\right)^3 \qquad T_F = T_{F0}e^{-b\mathcal{N}} \qquad \longrightarrow \qquad \tau_F \propto e^{3b\mathcal{N}}$$

Summary

K* / K ratio can be well understood with a hadron gas phase

K* decay and formation are the dominant reactions

Cooling and system size dependence of the freeze-out are crucial

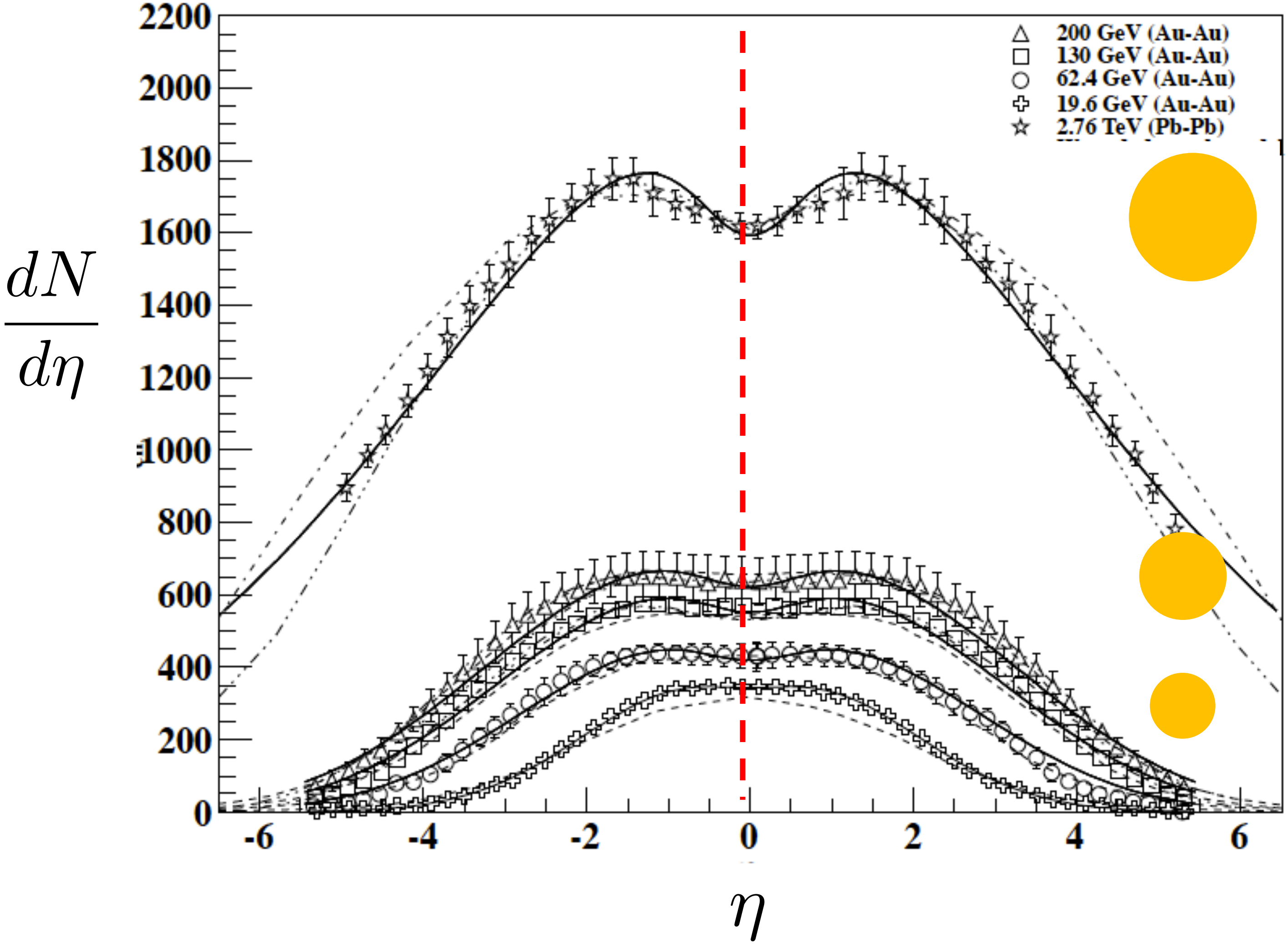
Predictions for the D* / D ratio

Thank you very much !!!

Back-ups

System Size

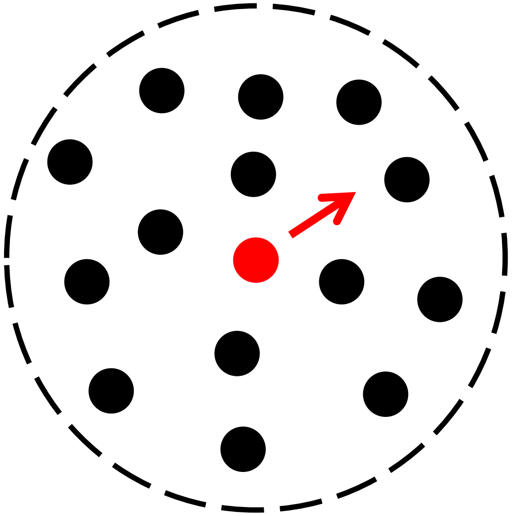
$$\left(\frac{dN}{d\eta}\right)_{\eta=0} \qquad \mathcal{N} = \left[\left(\frac{dN}{d\eta}\right)_{\eta=0}\right]^{1/3}$$



More mesons produced

Larger volume

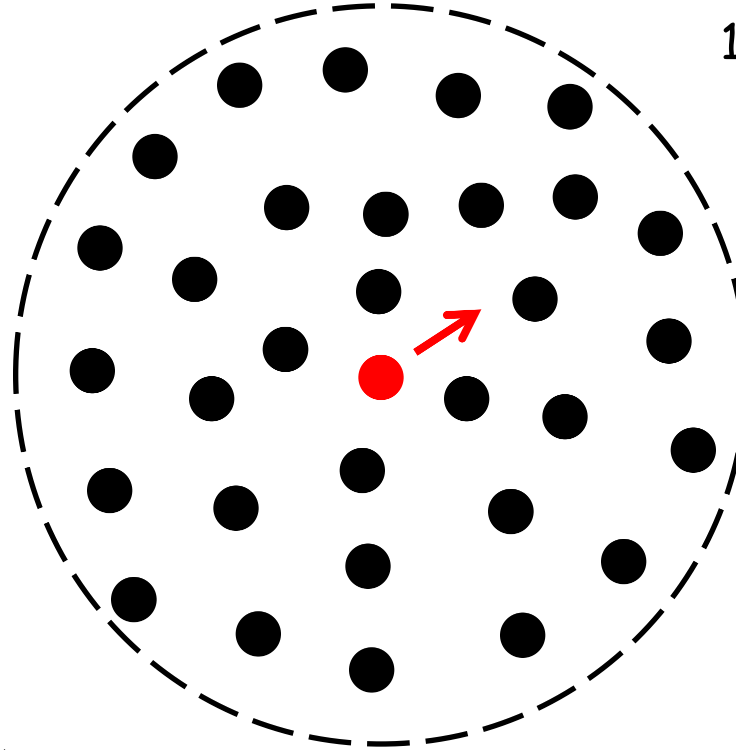
Lives longer



larger volume

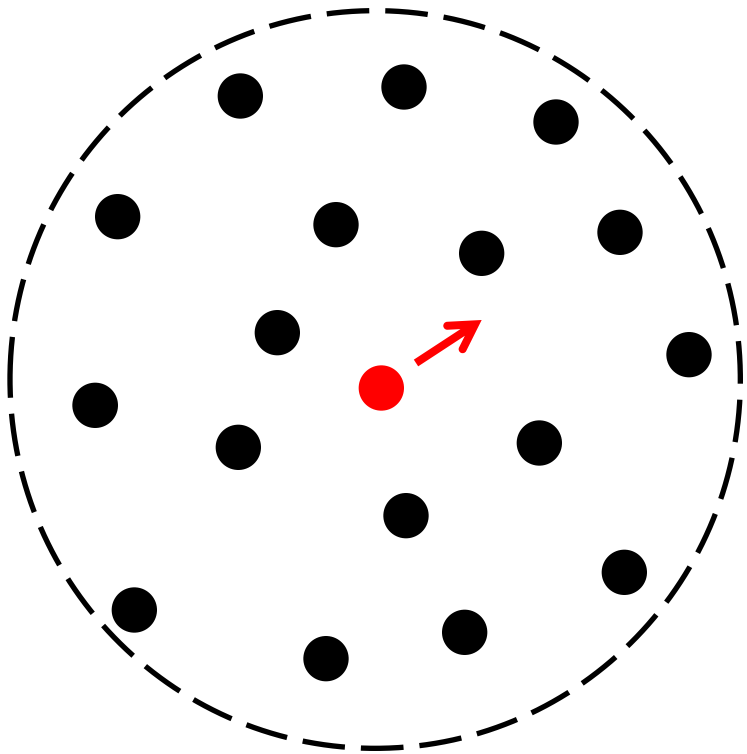
same density

same temperature



Freeze-out:

$$l = \frac{1}{n\,\sigma} = R$$



same volume

lower density

lower temperature

Back to Giorgio

$$\Gamma(D^*) \simeq 1\,\mathrm{MeV} \quad \tau_{life} = \frac{1}{\Gamma(D^*)} \simeq 200\,\mathrm{fm}$$

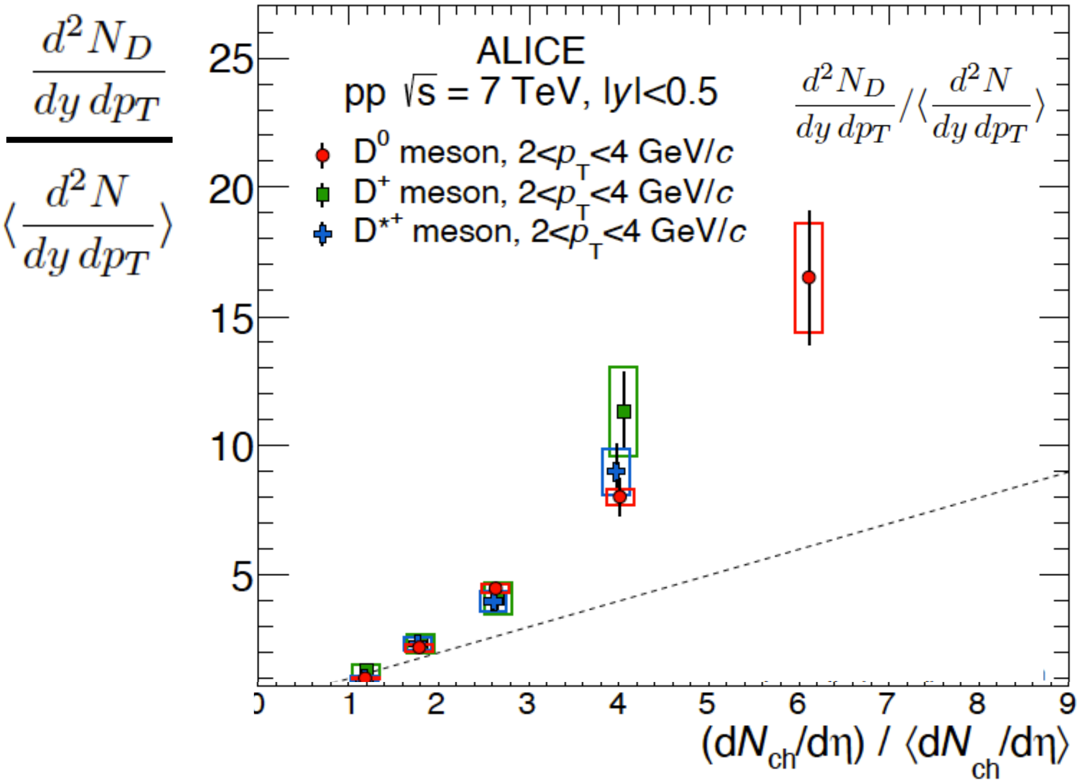
Rapidity and pt dependence of R

Freeze-out e tamanho

SU(4)

Gamma térmico = loops

System size and number of charm quarks



ALICE, JHEP (2015), arXiv:1505.00664

$$\frac{d^2 N_D}{dy\, dp_T} / \langle \frac{d^2 N}{dy\, dp_T} \rangle = \alpha' \left(\frac{dN_{ch}}{d\eta} / \langle \frac{dN_{ch}}{d\eta} \rangle \right)^{\beta}$$

$$\beta = 1.6$$

Assume that:

$$N_D \propto (\mathcal{N}^3)^{\beta}$$

$$N_c \propto (\mathcal{N}^3)^{\beta}$$

Fix the constant using EXHIC estimates:

$$N_c = 7.9 \times 10^{-5} \mathcal{N}^{4.8}$$

Lifetime as a function of the size