FIAS Frankfurt Institute for Advanced Studies

LOEWE Exzellente Forschung für Hessens Zukunft

Di-electron production at ultra-relativistic energies

J. Manninen[1] & E. Bratkovskaya[1]
O. Linnyk[2] & W. Cassing[2]
P.B. Gossiaux[3] & J. Aichelin[3]
C. M. Ko[4] & T. Song[4]

[1]Frankfurt Institute for Advanced Studies
[2]Institut für Theoretische Physik, Universität Giessen
[3]SUBATECH, UMR 6457, Laboratoire de Physique Subatomique et des Technologies Associées University of Nantes
[4]Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University

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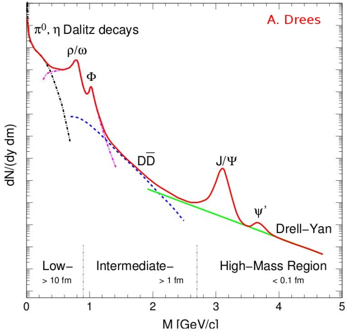
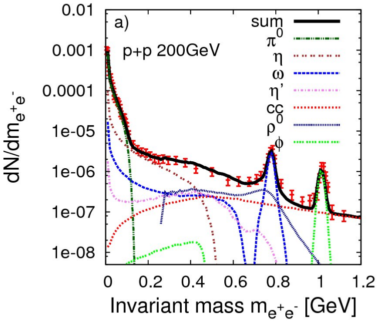
Outline

1. Introduction
2. Di-electron radiation
   - Freeze-out decay cocktail
   - In-medium effects
   - Heavy flavour
   - QGP radiation
   - Predictions for LHC
3. Summary

Introduction

Invariant mass spectrum of di-lepton pairs carry plenty of information





p+p well understood in terms of CFO cocktail

Deviations from cocktail in A+A: dynamics, energy loss, quarkonia melting, in-medium modification, QGP

Electromagnetic signals survive the evolution and are "separable" → offers windows to look into all stages of evolution (QGP!)

Different models for different stages of the evolution

Process	Model	M Region	Time (LHC)
◇ Initial state Drell-Yan†	$pQCD_1$	IMR/HMR	< 0.03 fm
◇ Quark-gluon-plasma radiation	PHSD	IMR/HMR	few - 5 fm
◇ Quarkonia	data	HMR	few - 10 fm
◇ Quarkonia suppression	$pQCD_2$	HMR	few - 5 fm
◇ Charm and beauty continuum	$MC@_sHQ$	IMR/HMR	5 - 10 fm
◇ In-medium effects	PHSD	LMR	5 - 10 fm
◇ Freeze-out decay cocktail	SHM/PHSD	LMR	≈10 fm

† not important at LHC

$pQCD_1$=next to leading order collinear factorisation approach

$pQCD_2$=NLO $c + \bar{c} + p \to J/\psi + p$ with non-equilibrium $c, \bar{c}$

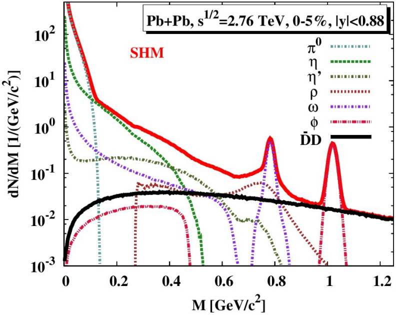
$MC@_sHQ$=pQCD + hydro based model for heavy-quark propagation

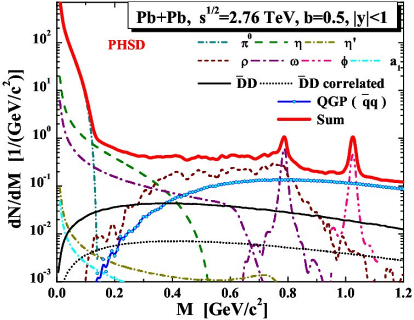
PHSD=off-shell parton-Hadron transport with dynamical quasi-particles

SHM=statistical hadronization model

Low invariant mass region in Pb+Pb at 2.76 TeV

Low invariant mass region is dominated by the freeze-out decay cocktail
→ SHM and PHSD in fair agreement in Pb+Pb, very good in p+p
Contribution from QGP is fairly large (might be difficult to separate)





SHM: T=170MeV ; $\gamma_S = 0.95$; V_0=70fm^3 (measured p_T spectrum) +
$\sigma^y_{clust}(\sqrt{s}) = \ln(\sqrt{s}/2m_p)$ | $\langle p_T \rangle = \sqrt{2/3} M_{clust}$ with $\sigma_{p_T} = M_{clust}/2$
PHSD: No tuning, internal switches as at RHIC

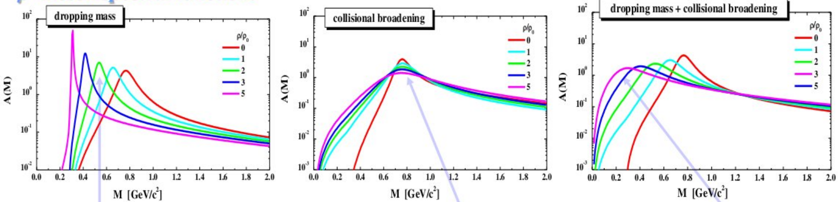
In medium modification of ρ^0

E. Bratkovskaya WW2012

dropping mass	**collisional broadening**	**dropping mass + coll. broad.**
$m^* = m_0(1-\alpha\,\rho/\rho_0)$	$\Gamma(M,\rho) = \Gamma_{vac}(M) + \Gamma_{CB}(M,\rho)$	m^* & $\Gamma_{CB}(M,\rho)$

Collisional width $\Gamma_{CB}(M,\rho) = \gamma\,\rho\,\langle \upsilon\,\sigma_{VN}^{tot} \rangle$

ρ–meson spectral function:

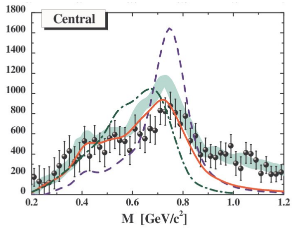


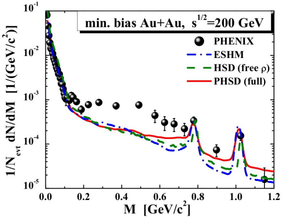
Consequences when increasing the baryon density ρ:

➢ pole position m_0 : shift to low M	➢ pole position m_0 : unchanged	➢ pole position m_0 : shift to low M
➢ spectral function : narrowing	➢ spectral function : broadening	➢ spectral function : broadening

In medium effects: broadening of spectral functions

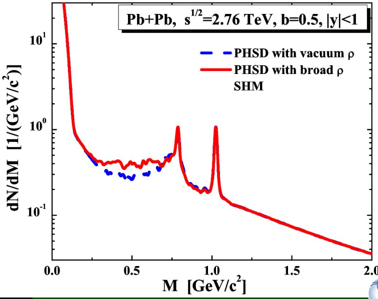
Dynamical broadening of vector mesons important in In+In at 158AGeV ⇒ (short QGP, long HRG) excess only ⇒





⇐ Lesser impact in A+A at RHIC (longer QGP, short HRG)

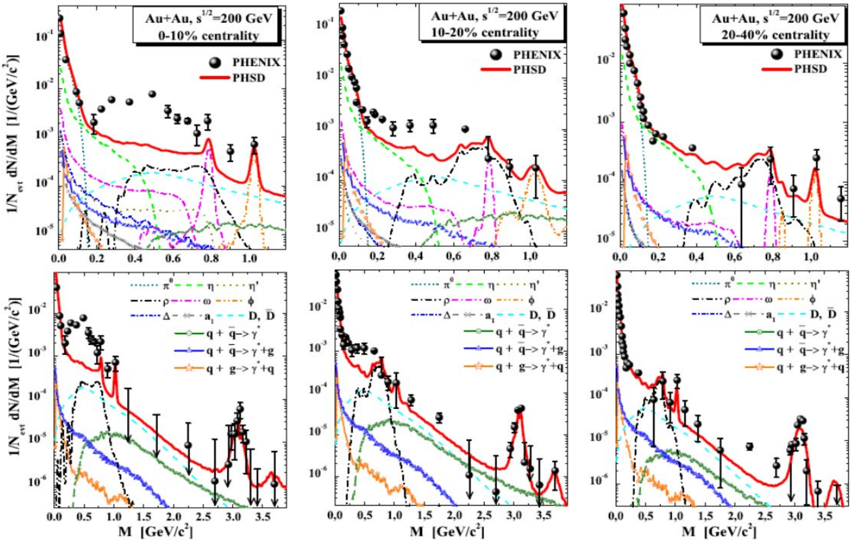
≤20% effect at LHC ⇒ (long QGP, short HRG)



Baryons modify ρ^0 the most ⇒ effects stronger at SPS

The PHENIX excess

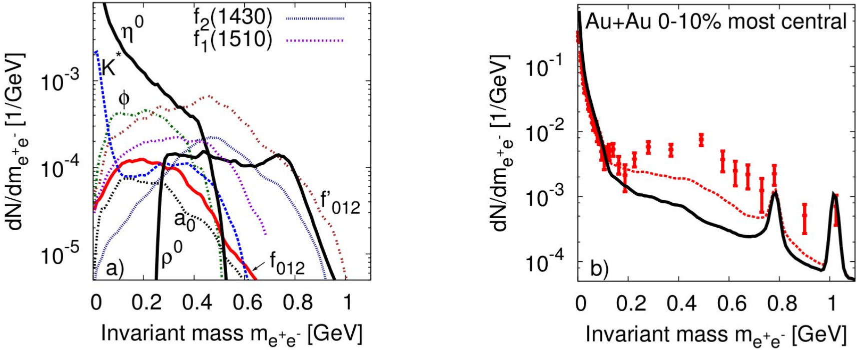
PRC85,024910



(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality

Excited mesons and other exotic contributions

EPJC71,1615



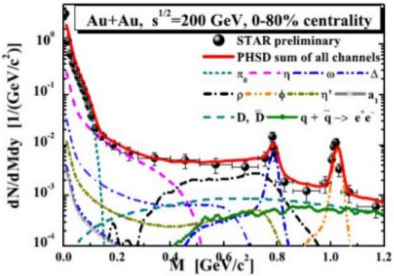
Exotic states may contribute to the PHENIX excess:

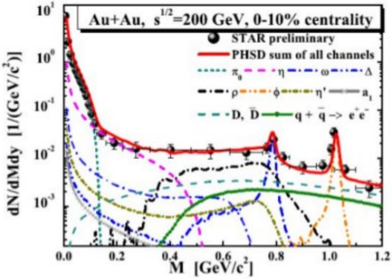
$X \to K\bar{K} \to e^+e^-\nu_e\bar{\nu}_e$

Upper limit estimate still below the PHENIX data

PHSD agree with the STAR data

PRC85,024910





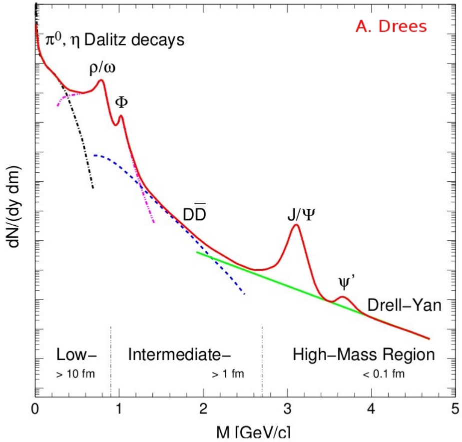
J. Harris, TURIC2012: STAR excess ≈ 2 (preliminary data)...

...with standard cocktail calculation

Broadening of ρ^0 lifts the excess region in PHSD with factor of ≈ 2

$\Rightarrow$ Indication of in-medium effects in action at RHIC

Correlated open heavy flavour feed IMR



Extended SHM for open heavy flavour production

Open heavy flavor is assumed to be in relative chemical equilibrium

Relative yields of 6 (18) lowest D (B) mesons evaluated within SHM with T=170MeV ; γ_S^{hard}=0.3 ; $\mu_{\{B,S,Q\}} = 0$

p+p: $\sigma_{\bar{c}c}^{\mathrm{tot}}$(2.76TeV)=3.6mb (experimental data) (or $\gamma_c \approx 30$)

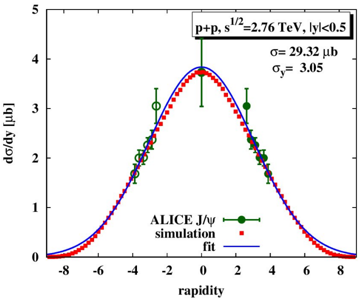
p+p: $\sigma_{\bar{b}b}^{\mathrm{tot}}$(2.76TeV)=1/40 $\sigma_{\bar{c}c}^{\mathrm{tot}}$ (MC@$_s$HQ)

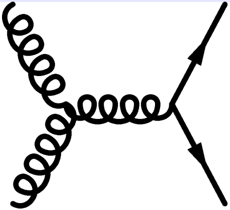
Pb+Pb: $\sigma_{\bar{c}c}^{\mathrm{tot}}$(2.76TeV)=$N_{\mathrm{bin}}\sigma_{\bar{c}c}^{\mathrm{tot}}$(2.76TeV) (also $\sigma_{\bar{b}b}^{\mathrm{tot}}$)

	LHCb	ALICE	T=170 MeV	T=150 MeV
$\frac{D^0}{D^{*+}}$	2.20 ± 0.48	2.09	2.40	2.49
$\frac{D^0}{D^+}$	2.07 ± 0.37	2.08	2.37	2.25
$\frac{D^0}{D_s}$	7.67 ± 1.67		7.98	8.55
$\frac{D^{*+}}{D^+}$	0.94 ± 0.22	1.00	0.99	0.90
$\frac{D^{*+}}{D_s}$	3.48 ± 0.93		3.32	3.44
$\frac{D^+}{D_s}$	3.70 ± 0.84		3.37	3.81

Heavy flavour rapidity distributions in $p + p$ collisions

- Modified BGK model PRC82, 054906
  - $y_{cm} = \mathrm{atanh}(\frac{x_1 - x_2}{x_1 + x_2})$
  - Probability to find parton along the rapidity axis is defined by a triangle whose maximum is at y_{cm} and goes to zero at $y = \mathrm{asinh}(x_1\sqrt{s}/2m_N)$ and $y = -\mathrm{asinh}(x_2\sqrt{s}/2m_N)$.





All $c\bar{c}$ ($b\bar{b}$) due to $g + g \to g \to c\bar{c}$

Assume the same model describes all charmed rapidity distributions
Conversion $\sigma_{tot} \leftrightarrow \frac{d\sigma}{dy}_{y\approx 0}$

Heavy flavour p_T and energy loss

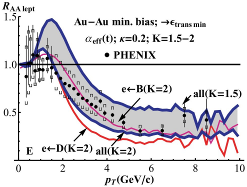
PRC78,014904

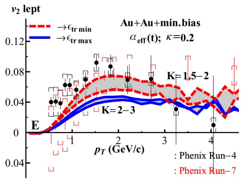
pQCD: c and b quark cross sections & initial momentum

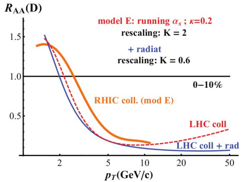
MC@$_s$HQ evolution: running coupling & improved infrared regulator

HQ propagate in Heinz & Kolb hydro background

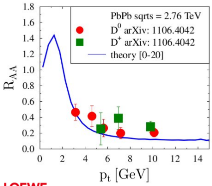
→ simultaneous R_{AA} and v_2 @ RHIC ($K_{coll} = 2$; $K_{coll+rad} = 0.6$)

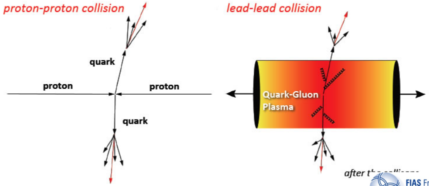






The model is in agreement with preliminary R_{AA} of D mesons at LHC



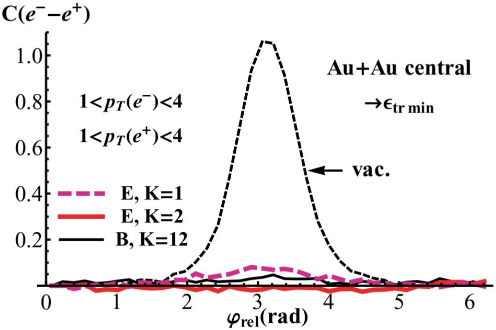


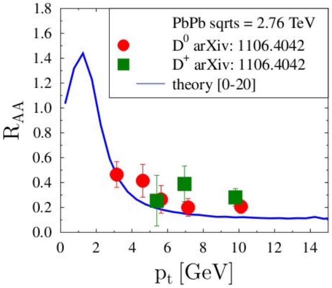
Angular correlations of open heavy flavor mesons at LHC (in)

p+p: π correlations among heavy flavour mesons == hardest (up limit)

central Pb+Pb: correlations are washed out == softest (low limit)

$$P_{corr} \sim R_{AA}^2 < 10\%$$

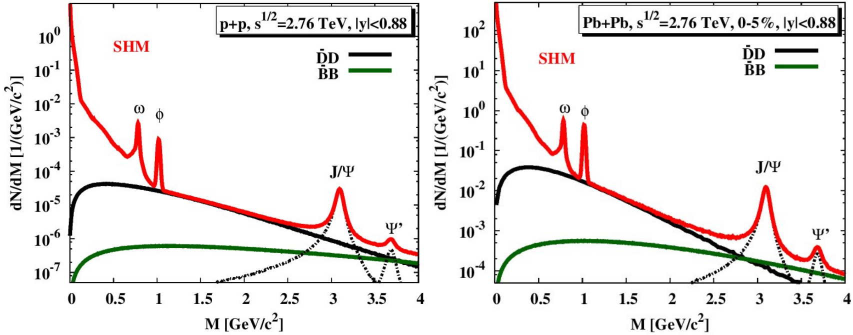




Angular correlations of open heavy flavor mesons (out)

p+p: exact back-to-back correlations among heavy flavour mesons

central Pb+Pb: correlations are washed out ($P_{corr} \sim R_{AA}^2 < 10\%$)



Central Pb+Pb: J/ψ=$0.3 N_{bin} J/\psi^{pp}$; ψ'=$0.4 N_{bin} \psi'^{pp}$ PRC85,054905

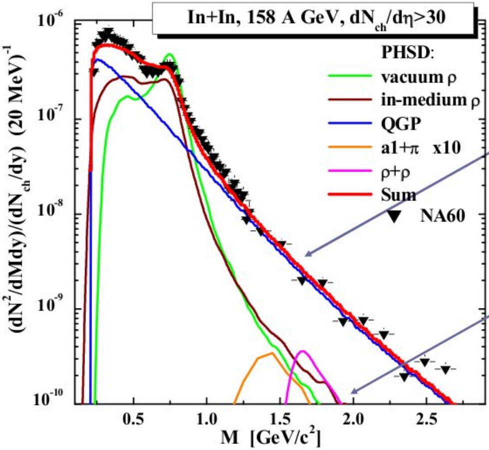
Vanishing correlations in Pb+Pb → softer M spectrum (both D & B)

$m_b > m_c$ → due to, energy loss, D mesons M spectrum softens more than B mesons M spectrum in Pb+Pb (model dependent ×ing)

QGP radiation at SPS with parton transport

O.L. STAR2010

Acceptance corrected NA60 data



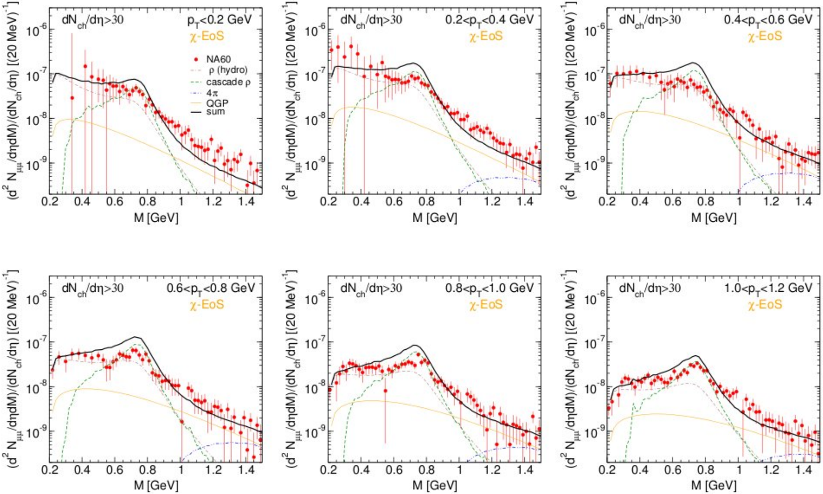
Mass region above 1 GeV is dominated by **partonic** radiation

4π contribution subdominant

Preliminary

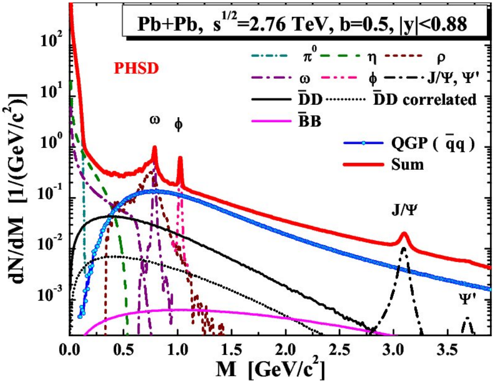
QGP radiation at SPS with hydro partons

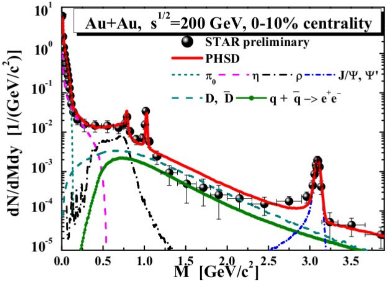
PRC84,014901



Hybrid mode of UrQMD (transport-hydro-cascade) also highlights the role of QGP at SPS

Di-electron radiation from QGP in Pb+Pb 2.76 TeV



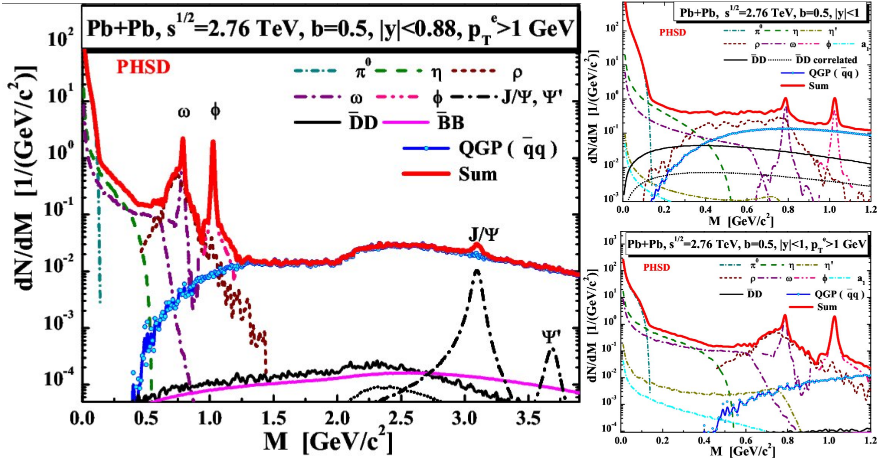


QGP dominates the $M \in [M_\phi : M_{J/\psi}]$ over heavy flavor radiation at LHC

RHIC open charm ≈ QGP
large un-certainty in $\sigma_{\bar{c}c}$
⇒ no strong conclusions

Di-electrons provide a unique window to detect and study properties of QGP at LHC

QGP contribution can be enhanced with p_T cuts



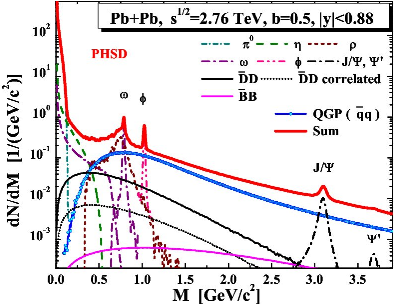
Choose $p_T^e > 1\text{GeV} \Rightarrow$ QGP dominates intermediate/high mass regions

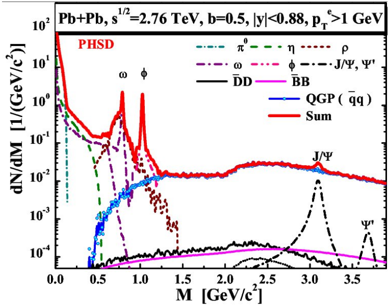
LHC open heavy « QGP within $\sigma_{\bar{c}c}$ un-certainties

Summary

- ◇ STAR excess can be understood with collisional broadening

- ◇ Realistic predictions for all relevant di-electron sources at LHC
- ◇ QGP dominate di-electron radiation in intermediate mass region
- ◇ QGP contribution can be enhanced by suitable p_T cuts





Back-up slides

Relevant channels at RHIC and LHC

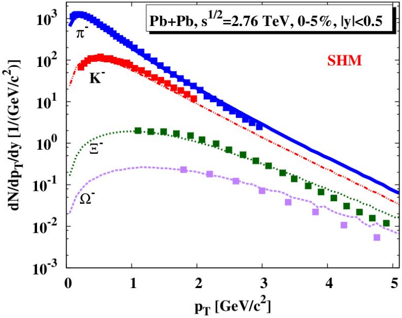
Hadron	direct	Dalitz	other
π^0	-	$\pi^0 \to \gamma\, e^+e^-$	-
η^0	-	$\eta^0 \to \gamma\, e^+e^-$	$\eta^0 \to \pi^+\pi^- e^+e^-$
η'	-	$\eta' \to \gamma\, e^+e^-$	$\eta' \to \pi^+\pi^- e^+e^-$
ρ^0	$\rho^0 \to e^+e^-$	-	-
ω^0	$\omega^0 \to e^+e^-$	-	$\omega^0 \to \pi^0\, e^+e^-$
ϕ^0	$\phi^0 \to e^+e^-$	-	$\phi^0 \to \eta\, e^+e^-$
J/ψ	$J/\psi \to e^+e^-$	$J/\psi \to \gamma\, e^+e^-$	
ψ'	$\psi' \to e^+e^-$	$\psi' \to \gamma\, e^+e^-$	-
D mesons	-	-	$D^\pm \to e^\pm \nu_e + X$
B mesons	-	-	$B \to e^\pm \nu_e + X$

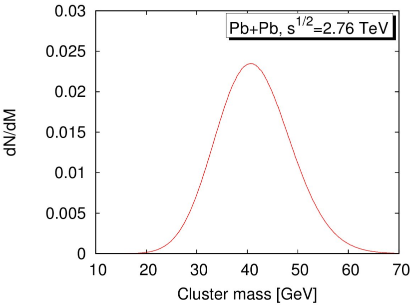
Convention: Only channels with definite BR:s are taken into account

Beyond standard cocktail contributions

Hadron			
$f_0(980)$	K^+K^-	$K^0\bar{K}^0$	-
$f_1(1285)$	-	-	$K\bar{K}\pi$
$f_2(1270)$	K^+K^-	$K^0\bar{K}^0$	-
$f_0'(1350)$	K^+K^-	$K^0\bar{K}^0$	-
$f_1'(1420)$	$K^{*+}K^- +$ c.c	$K^{*0}K^0 +$ c.c	-
$f_2'(1525)$	K^+K^-	$K^0\bar{K}^0$	-
$f_0(1500)$	K^+K^-	$K^0\bar{K}^0$	-
$f_1(1510)$	$K^{*+}K^- +$ c.c	$K^{*0}K^0 +$ c.c	-
$f_2(1430)$	K^+K^-	$K^0\bar{K}^0$	-
ϕ	K^+K^-	$K^0\bar{K}^0$	-
$a_0^0(980)$	K^+K^-	$K^0\bar{K}^0$	-
$K(892)^\pm$	$K^\pm\pi^0$	-	-
$K(892)^0$	$K^0\pi^0$	-	-

SHM transverse momentum spectra in Pb+Pb at 2.76 TeV



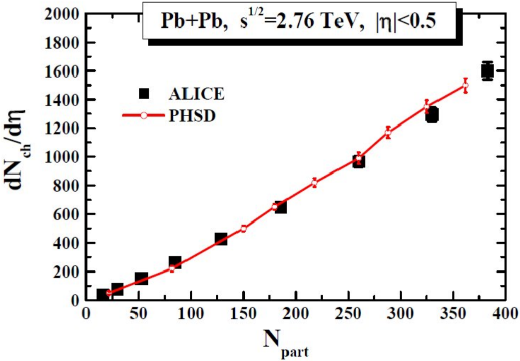


In thermal equilibrium, energy is shared equally among available forms

$\Rightarrow$In each event in the rest frame of the cluster $M_{clust} = \sum_i E_i$

Transverse momentum of the cluster in LAB frame is normally distributed with $\langle|\vec{p}_{clust}|\rangle == M_{clust}$ and $\sigma_{p_T} = M_{clust}/2$

PHSD charged hadron rapidity densities in Pb+Pb 2.76 TeV



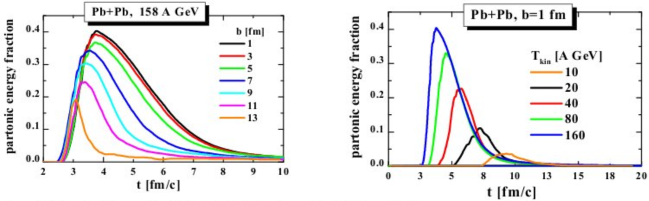
QGP energy fraction at SPS

O.L. STAR2010

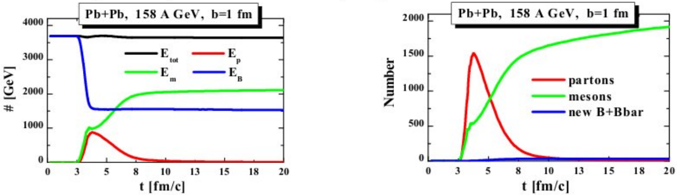
Energy fraction in partonic phase

PHSD

Increase of partonic energy fraction with energy and centrality



In central Pb + Pb at 158 A GeV about 40% of the converted energy goes to partons; the rest is in the ‚large' hadronic corona!



Cassing & Bratkovskaya, NPA 831, 215 (2009)

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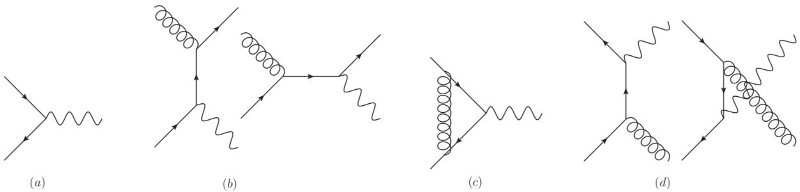
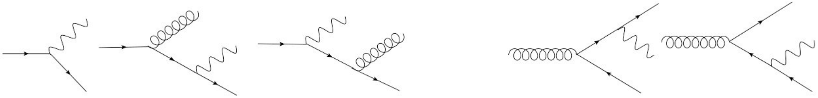
FIAS Frankfurt Institute for Advanced Studies

Di-lepton radiation from quark-gluon-plasma



(a) QGP Drell-Yan — dominates
(b) gluon-Compton scattering — un-important
(c) vertex correction — un-important
(d) gluon bremsstrahlung — 2nd most important

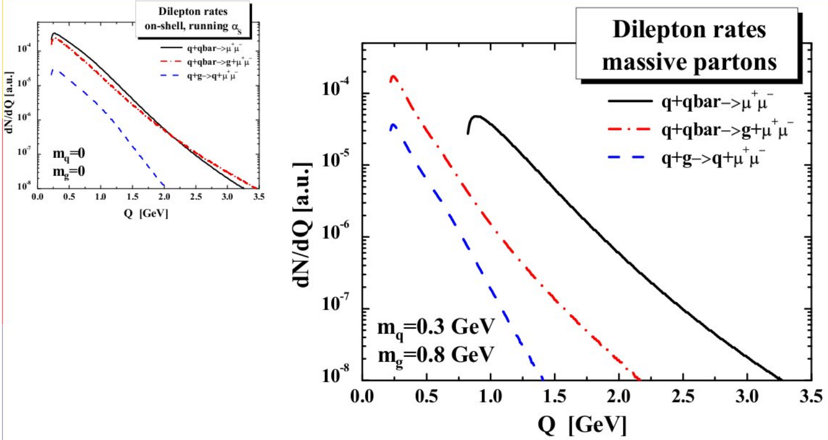
+ radiation from virtual partons



virtual quark decay

virtual gluon decay

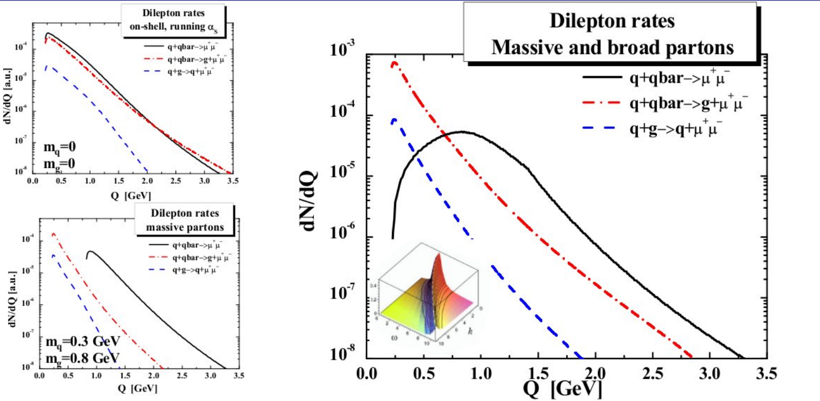
Dilepton rates from massive quarks/gluons



Note: Threshold in the Born contribution due to finite masses of incoming particles.

O. L., arXiv:1004.2591

Massive and broad quarks and gluons



Due to broad spectral functions of partons, the threshold of the Born term is smeared, the contributions of the 2–>2 processes increased.

O. L., arXiv:1004.2591

E.B. WW2012

The Dynamical QuasiParticle Model (DQPM)

Basic idea: Interacting quasiparticles

- massive quarks and gluons (g, q, q_{bar}) with spectral functions :

$$\rho(\omega) = \frac{\gamma}{E}\left(\frac{1}{(\omega - E)^2 + \gamma^2} - \frac{1}{(\omega + E)^2 + \gamma^2}\right)$$

$$E^2 = p^2 + M^2 - \gamma^2$$

- quarks

mass: $m^2(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$

width: $\gamma_q(T) = \frac{N_c^2 - 1}{2N_c}\frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$

- gluons: A. Peshier, PRD 70 (2004) 034016

$M^2(T) = \frac{g^2}{6}\left((N_c + \frac{1}{2}N_f)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$ $N_c = 3, N_f = 3$

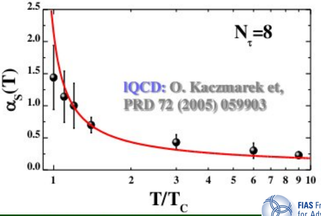
$\gamma_g(T) = N_c \frac{g^2 T}{4\pi}\ln\frac{c}{g^2}$

running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$

➢ fit to lattice (lQCD) results (e.g. entropy density)

with 3 parameters: $T_s/T_c = 0.46$; $c = 28.8$; $\lambda = 2.42$



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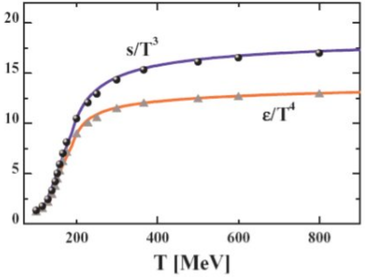
DQPM thermodynamics (N_f=3) and lQCD

entropy $s = \frac{\partial P}{dT}$ → **pressure P**

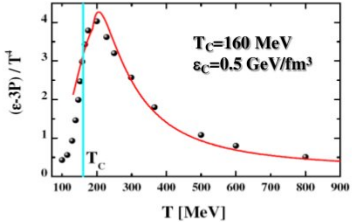
energy density: $\epsilon = Ts - P$

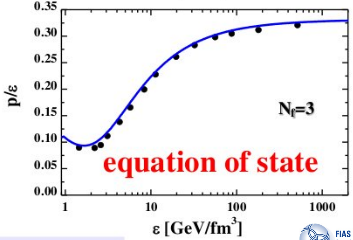
lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088.



interaction measure:

$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$





Meson decay formulae

$$\frac{d\Gamma^{X\to\gamma\ l^+l^-}}{dM} = \frac{\Gamma^{X\to l^+l^-}}{M}\frac{4\alpha}{3\pi}\sqrt{1-\frac{4m_l^2}{M^2}} \times \left(1+\frac{2m_l^2}{M^2}\right)\left(1-\frac{M^2}{m_X^2}\right)^3 |F^{X\to\gamma\gamma}(M)|^2$$

$$F^{\eta\to\gamma\gamma}(M) = \left(1-\frac{M^2}{(0.72\mathrm{GeV})^2}\right)^{-1}$$

$$|F^{\eta'\to\gamma\gamma}(M)|^2 = \frac{(0.75\mathrm{GeV})^4}{((0.75\mathrm{GeV})^2-M^2)^2+(0.105\mathrm{GeV}^2)^2}$$

$$F^{\pi^0\to\gamma\gamma}(M) = 1+\frac{5.5}{\mathrm{GeV}^2}M^2$$

$$|F^{\omega\to\pi^0 l^+l^-}(M)|^2 = \frac{(0.65\mathrm{GeV})^4}{((0.65\mathrm{GeV})^2-M^2)^2+(0.0488\mathrm{GeV}^2)^2}$$

$$\frac{d\Gamma^{\omega\to\pi^0\ l^+l^-}}{dM} = \frac{\Gamma^{\omega\to\pi^0\gamma}}{M}\frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_l^2}{M^2}}\left(1+\frac{2m_l^2}{M^2}\right)$$

$$\times \left[\left(1+\frac{M^2}{m_\omega^2-m_\pi^2}\right)^2-\frac{4m_\omega^2M^2}{(m_\omega^2-m_\pi^2)^2}\right]^{3/2}|F^{\omega\to\pi^0 l^+l^-}(M)|^2$$

Direct decays

$$\Gamma^{V\to l^+l^-}(M) = \frac{m_0^3}{M^3}\Gamma^{V\to l^+l^-}(m_0)$$

$$\Gamma^{\rho^0}_{tot}(M) \simeq \Gamma^{\rho\to\pi\pi} = \Gamma(m_0)\left(\frac{m_0}{M}\right)^2 \frac{(M^2-4m_\pi^2)^{3/2}}{(m_0^2-4m_\pi^2)^{3/2}}$$

J/ψ Dalitz

$$\frac{d\Gamma^{X\to l^+l^-\gamma}}{dM} = \frac{\alpha}{\pi}\frac{2M}{m_X^2-M^2}\left(1+\frac{M^4}{m_X^4}\right)\times\left(\ln\frac{1+r}{1-r}-r\right)\Gamma_0^{X\to l^+l^-}$$

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