Theoretical perspectives on the LHC heavy-ion program

Nicolas BORGHINI

Universität Bielefeld

Theoretical perspectives on the LHC heavy-ion program

For which kind of audience should this talk be prepared?

- "particle physicists", who wonder whether the runs with heavy ions are not just a waste of LHC time;
- or "heavy-ion practitioners", who want to know if conclusions can already be drawn from the data of Nov.2010.

Theoretical perspectives on the LHC heavy-ion program

To "particle physicists": (where) can Pb-Pb collisions be helpful?

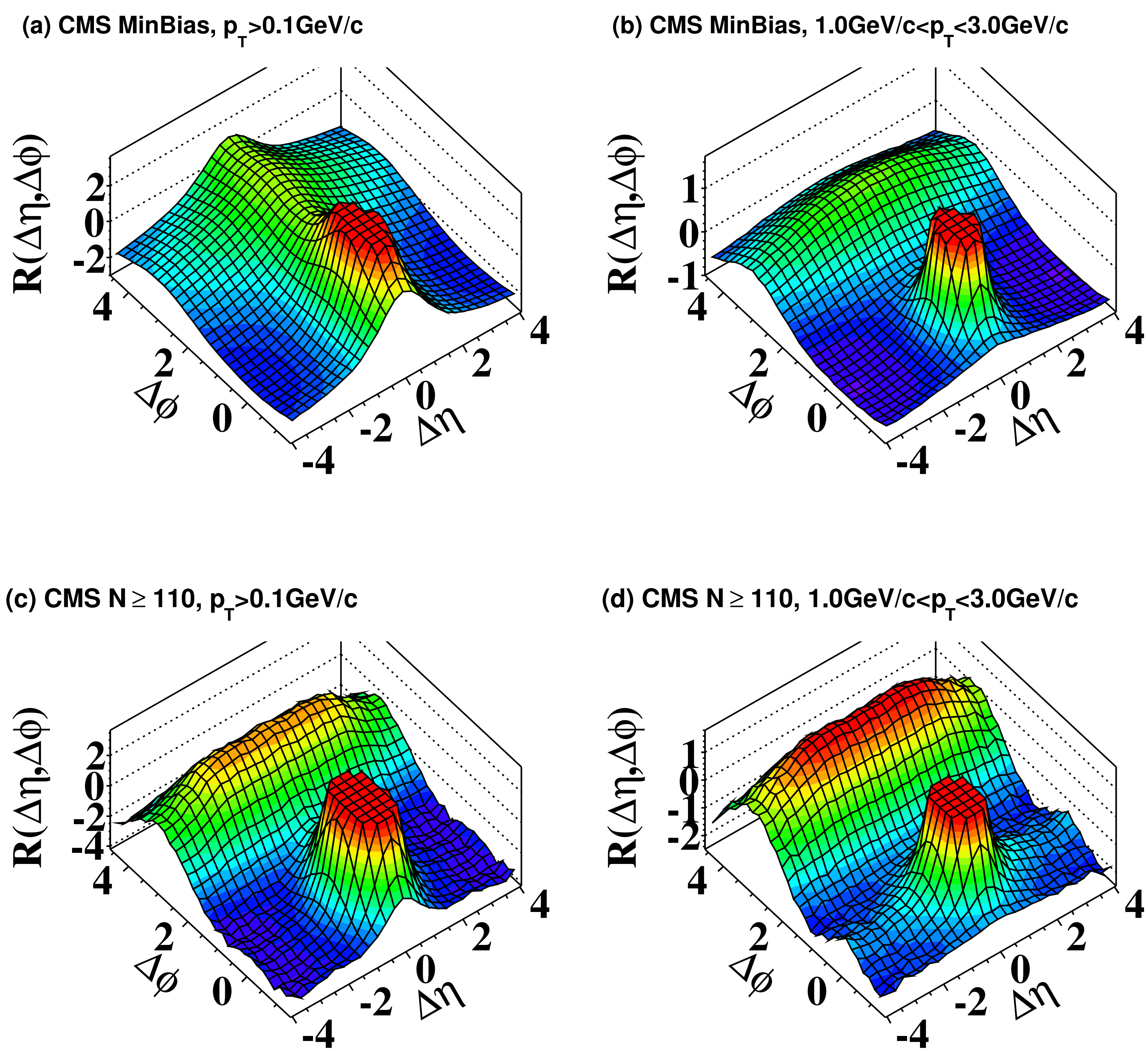
- QCD at small x, $\mathcal{P}$-violation ☞ plenary talk by Dima Kharzeev
- In high-energy pp collisions, large multiplicities are possible: proton-proton events might become "heavy-ion-like".

For instance(?): long-range near-side angular correlations observed

CMS, JHEP 1009 (2010) 091

A similar signal (the "ridge") was previously seen in Au-Au collisions at RHIC...

Long-range near-side angular correlations in pp collisions at 7 TeV:



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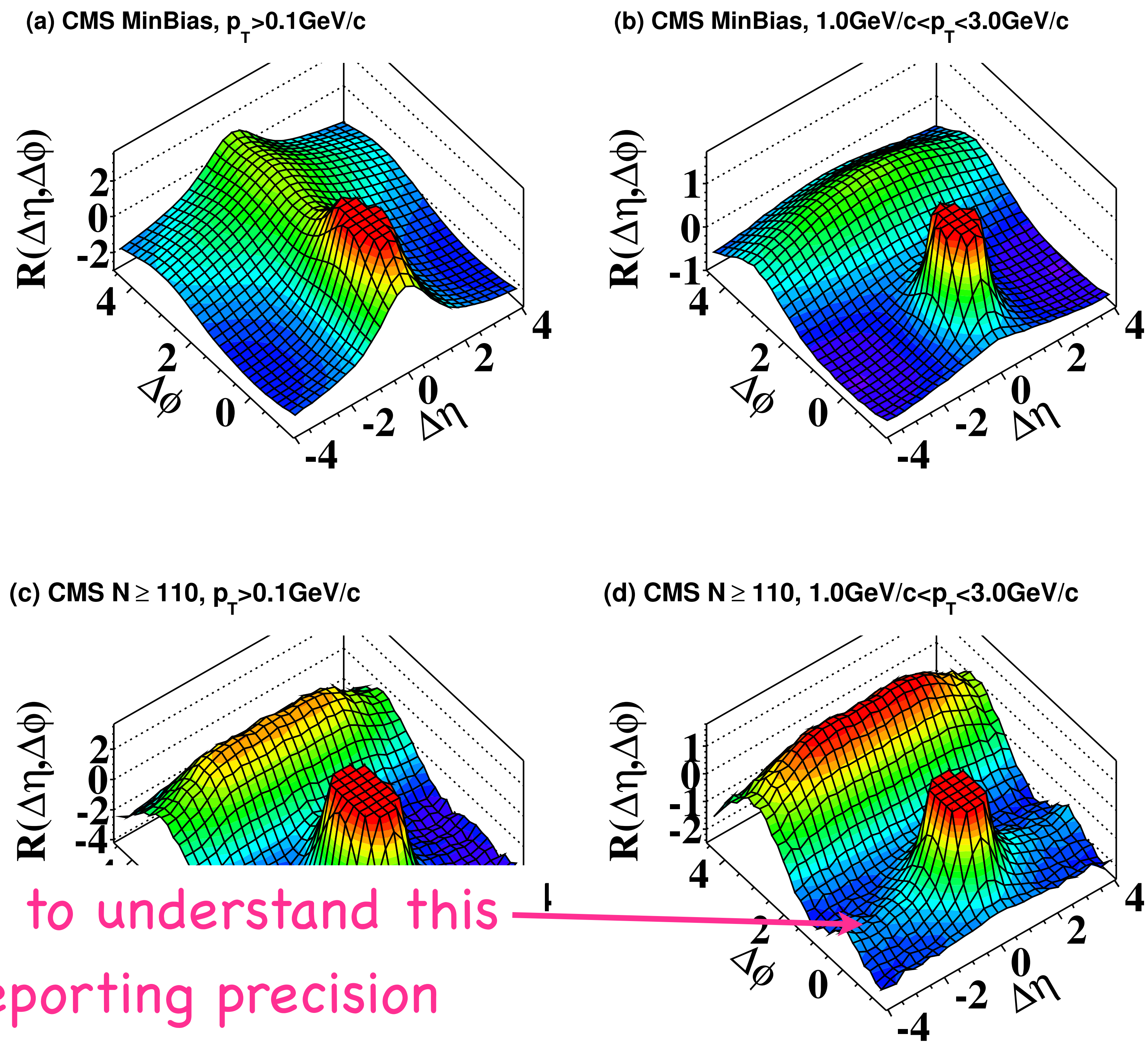


You want to understand this before reporting precision measurements, don't you?

CMS, JHEP 1009 (2010) 091

Theoretical perspectives on the LHC heavy-ion program

An obvious(?) model-independent lesson from the first Pb-Pb data:

- First day measurements:
  - anisotropic flow
  - jet suppression

} ☞ In heavy-ion collisions at the LHC, a hot and dense system with emerging collective behavior is created!

That is universally* accepted in the heavy-ion community, but should perhaps still be stressed to the remainder of particle physicists.

We can focus on the (precise) extraction of quantitative properties of condensed QCD matter.

*Have you heard any dissident voice?

Theoretical perspectives on the LHC heavy-ion program

- Personal ideas / misconceptions on the LHC data presented at QM2011 and their implication for models
  - soft sector
  - hard probes
- A novel idea that could be tested / invalidated at the LHC
  - evolution and dynamics of heavy quarkonia in a QGP

LHC results: soft sector

Various harmonics of anisotropic transverse flow (= the anisotropy in the transverse emission of particles) have been measured: v_1, v_2, v_3, v_4, v_5

$$\frac{\mathrm{d}^2N}{\mathrm{d}^2\mathbf{p}_T} = \frac{1}{2\pi}\frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T}\left[1+\sum_{n=1}^{\infty}2v_n(p_T)\cos n(\varphi-\Psi_n)\right]$$

- The size of these harmonics (especially v_2) are a proof of collective behavior of the emitted particles: each individual N-N collision emits particles isotropically, large anisotropies are due to rescatterings.

- v_3 is large: can only be caused by fluctuations in the initial state of the colliding nuclei — if these were homogeneous (Lorentz-contracted) spheres, v_3 would vanish at midrapidity!

☞ Dissipative fluid dynamics with fluctuating initial conditions does a pretty good job at describing these data ⇒ shear viscosity η of QGP.

LHC results: soft sector

Various harmonics of anisotropic transverse flow (i.e., the anisotropy in the transverse emission of particles) have been measured: v_1, v_2, v_3, v_4, v_5

- Below $p_T \approx 3$ GeV/c, these harmonics seem to account for the larger part of measured angular correlations.

That is, two arbitrary particles are correlated together in azimuth because each of them is correlated to the reaction plane.*

☞ A few bumps and dips which were given fancy names after their "discovery" at RHIC might be trivially explained...

Did we witness at QM2011 the deaths of the (jet-induced) "ridge" and "Mach cone"?

☞ What becomes of the ideas / models developed to explain them?

*up to short-range HBT effects & global momentum conservation

LHC results: soft sector

Dissipative fluid dynamics with fluctuating initial conditions does a pretty good job at describing LHC data on anisotropic flow...

- constraints on the shear viscosity
- other ingredients with varying theoretical status enter the models:
  - which kind of initial condition? and of fluctuations?
  - equation of state of the expanding matter (lattice-QCD-inspired? what is the actual sensitivity of the results to the EoS?)
  - freeze-out prescription, hadronic cascade...
- Probable degeneracy between different choices, even after tuning them: need to include as many experimental results as possible in fits.

How important is the tension between data and models for protons: transverse momentum spectrum, $v_2(p_T)$, abundance ratios?

LHC results: soft sector

Tension between data and models for proton yields...

- From Michele Floris' talk at QM2011: problem for statistical models?

Predictions for the LHC

Ratio	Data	(1)	(2)
p/π^+	0.0454+-0.0036	0.072	0.090
p/π^-	0.0458+-0.0036	0.071	0.091+0.009-0.007
K/π^+	0.156 +- 0.012	0.164	0.180+0.001-0.001
K/π^-	0.154 +- 0.012	0.163	0.179+0.001-0.001

(1) A. *Andronic et al, Nucl. Phys. A772 167 (2006)* — T = 164 MeV, μ_B = 1 MeV

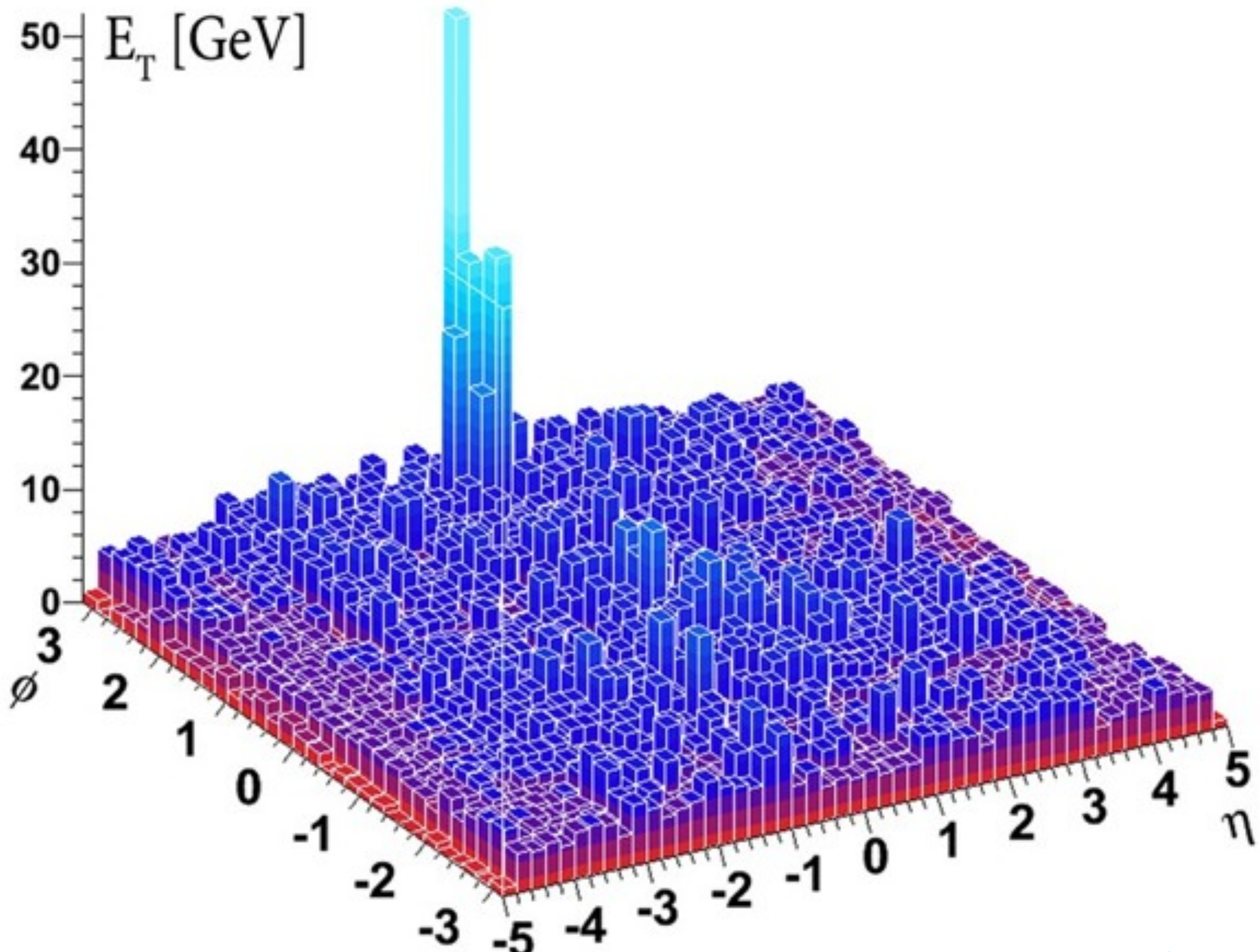
(2) *J. Cleymans et al, PRC74, 034903 (2006)* — T = (170±5) MeV and μ_B =1+4 MeV

- and by the way, if lattice QCD converges towards $T_c \approx$ 147–157 MeV for the transition temperature*, what is the meaning of a hadron gas temperature $T \approx$ 164–175 MeV?

*time should tell... and help shrink the error bars.

LHC results: high-p_T particles

From: ATLAS & CMS heavy-ion groups
To: pp-only practitioners
Subject: We have a dense medium in our detectors!



ATLAS, PRL **105** (2010) 252303

...and no missing E_T: energy / momentum is redistributed at large angles.

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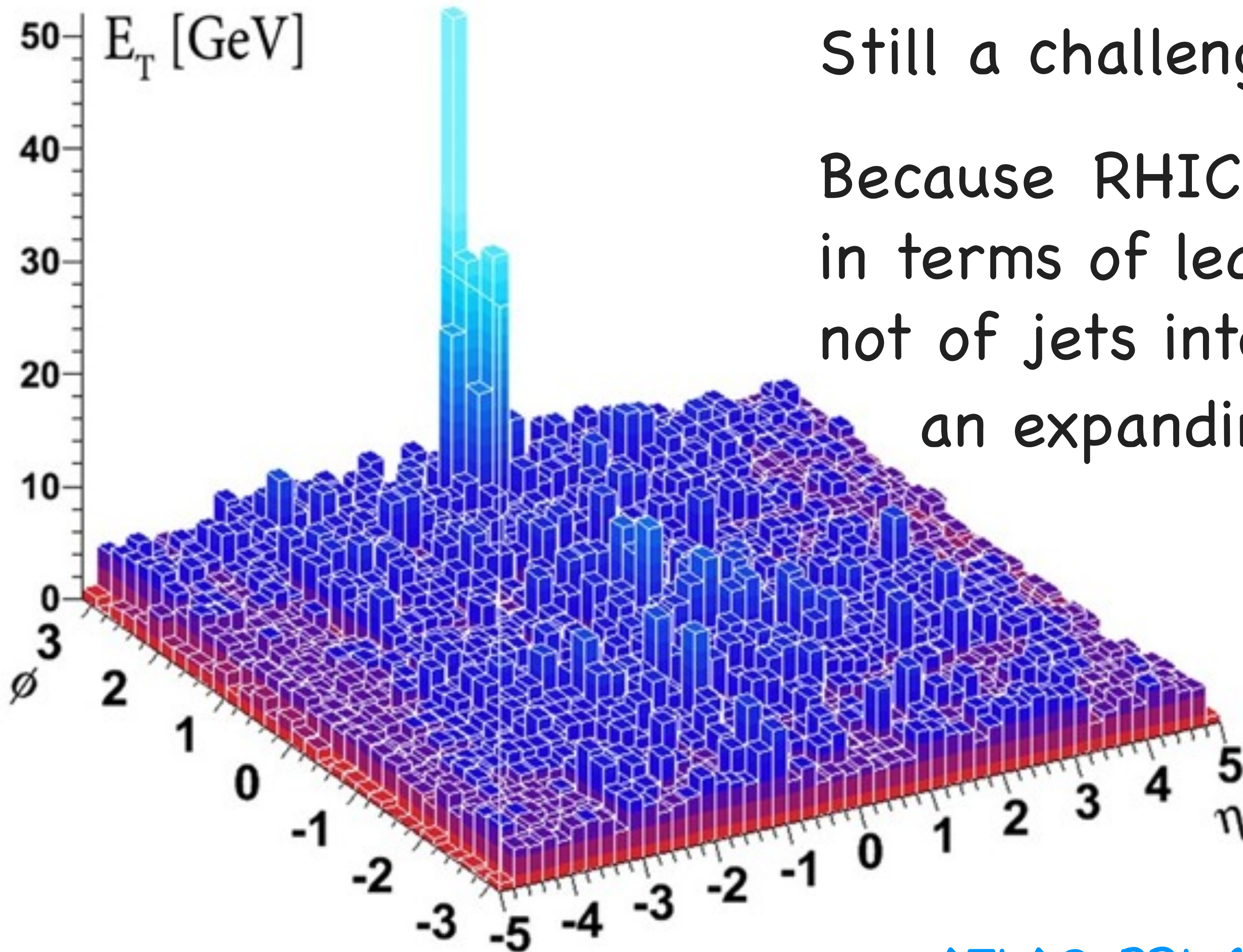


Still a challenge for models!

Because RHIC had us think in terms of leading particles, not of jets intertwined with an expanding medium?

ATLAS, PRL **105** (2010) 252303

...and no missing E_T: energy / momentum is redistributed at large angles.

LHC results: heavy quarkonia

Charmonia are suppressed (long lasting story) and so are the bottomonia!

- For $\Upsilon(1S)$, medium modification factor $R_{\rm PbPb} = 0.62 \pm 0.11 \pm 0.10$

[caveats: preliminary result (CMS) + no p-Pb reference available]

- The excited states are even more suppressed:

$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{\rm pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{\rm PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

CMS, arXiv:1105:4894

Long awaited measurements... We want more!

(Some pieces of heavy-ion folklore: "quarkonia are thermometers of the QGP", "bottomonia at the LHC behave like charmonia at RHIC"...)

…and now, some shameless advertisement for my own work…

N.B. & C.Gombeaud, arXiv:1003.2945 + work in progress

(see also our poster at QM2011 if you are impatient)

Evolution and dynamics of heavy quarkonia in a QGP

Starting remark: the picture of sequential melting of the successive $Q\bar{Q}$ states is static (lattice-QCD inspired).

A simple question: how long does it take for a given $Q\bar{Q}$ bound state, emersed in a QGP, until it is dissociated?

Consider again the question with an expanding finite size QGP fireball: possible interplay of time scales if these are not separated.

Evolution and dynamics of heavy quarkonia in a QGP

Pushing the idea of non-instantaneous processes further:

What happens if transitions between different $Q\bar{Q}$ states are possible in a QGP? (mostly between bottomonia... there are more of them!)

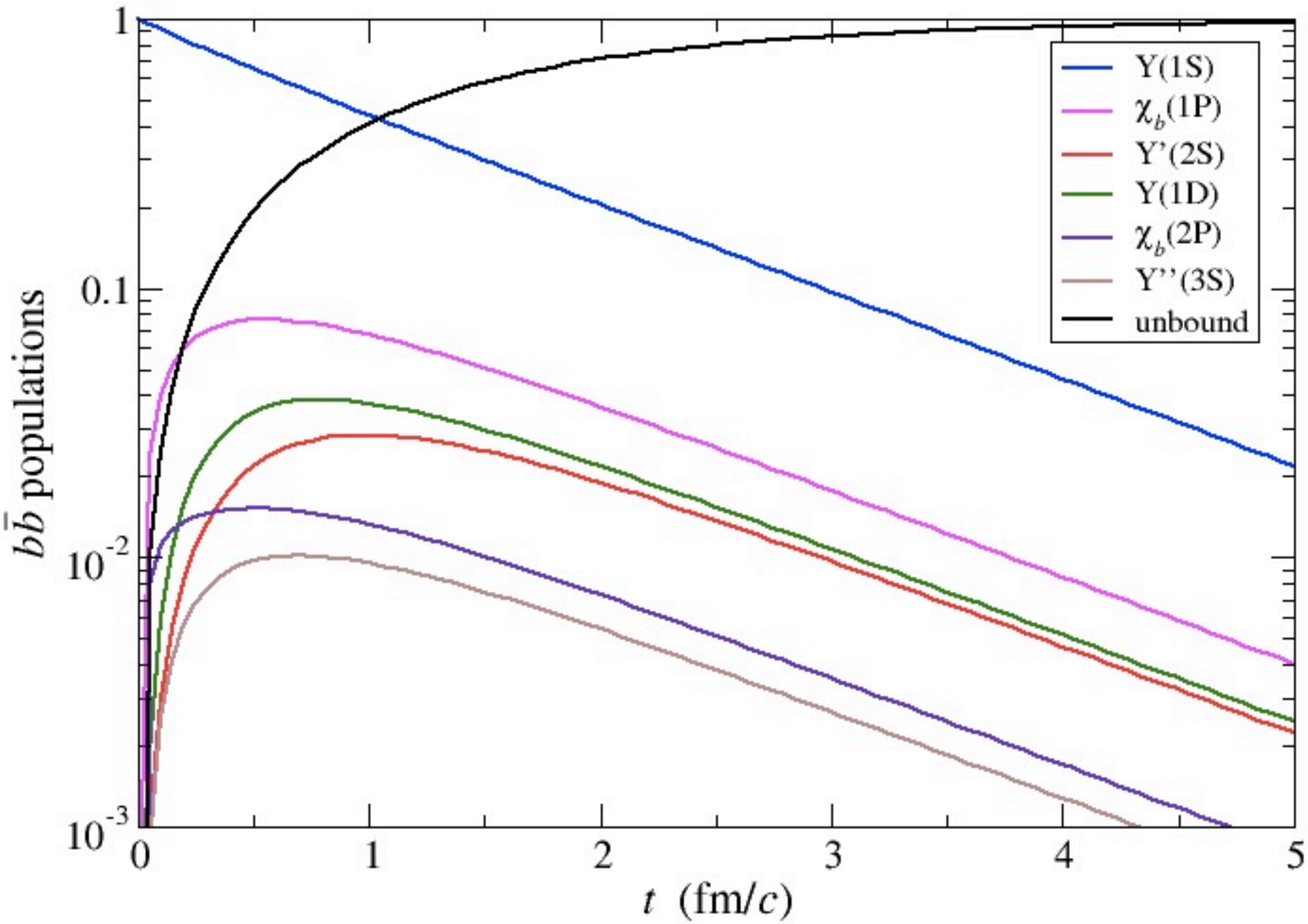
IF this is the case, various model-independent behaviors are to be expected:

(exploratory study within a naïve model in NB & Gombeaud, 2011)

- After some transient time, the different $Q\bar{Q}$ states evolve together: the population of a given state cannot be totally washed out as long as the other states which can transition to it are still populated.

$\neq$ sequential melting

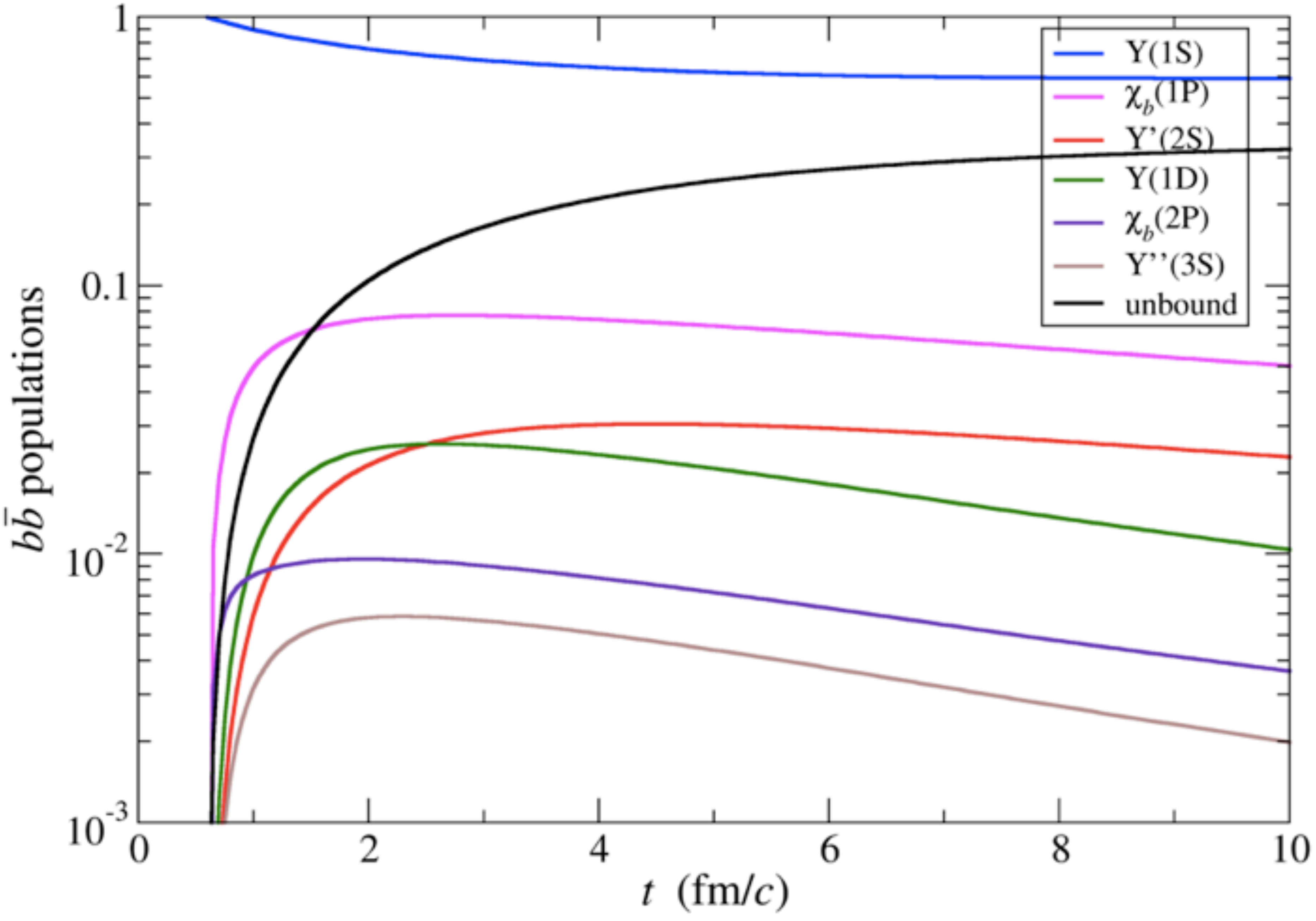
Evolution and dynamics of bottomonia in a QGP at fixed $T = 5T_c$



The numbers are model-dependent!

N.B. & C.Gombeaud, arXiv:1003.2945

Evolution and dynamics of bottomonia in a QGP with evolving temperature



using the time-dependence of temperature as computed by Chen & Heinz

Evolution and dynamics of heavy quarkonia in a QGP

IF the different states can transition to each other:

- After some transient time, the different $Q\bar{Q}$ states evolve together, which gives rise to abundance ratios that differ from those found in statistical models or within the sequential melting picture.
  - ☞ evolution of the internal degrees of freedom

- The quarkonium momentum distribution function does not obey the usual Fokker–Planck equation, but a modified one, in which the friction and diffusion coefficients do not satisfy the fluctuation-dissipation relation.
  - ☞ evolution of the external degrees of freedom

Theoretical perspectives on the LHC heavy-ion program

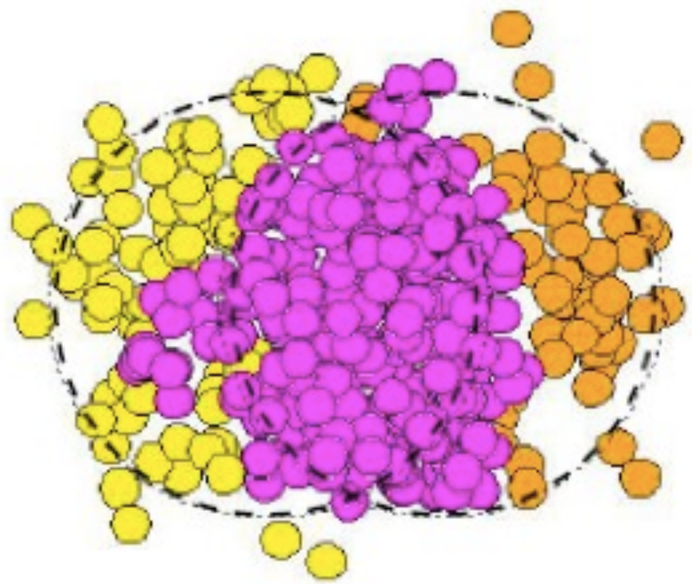
- Personal ideas / misconceptions on the LHC data presented at QM2011 and their implication for models
  - soft sector: dissipative fluid dynamics is quite successful;
    anisotropic flow rules — which initial conditions?
    protons behave bizarrely;
  - hard probes: beautiful data, yet theorists must find how to couple "jets" and the surrounding expanding medium.
- A novel idea that could be tested / invalidated at the LHC
  - evolution and dynamics of heavy quarkonia in a QGP

extra slide

Flow fluctuations

(figure taken from Matt Luzum's talk at QM2001)

$$\frac{\mathrm{d}^2 N}{\mathrm{d}^2\mathbf{p}_T} = \frac{1}{2\pi}\frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T}\left[1+\sum_{n=1}^{\infty}2v_n(p_T)\cos n(\varphi-\Psi_n)\right]$$



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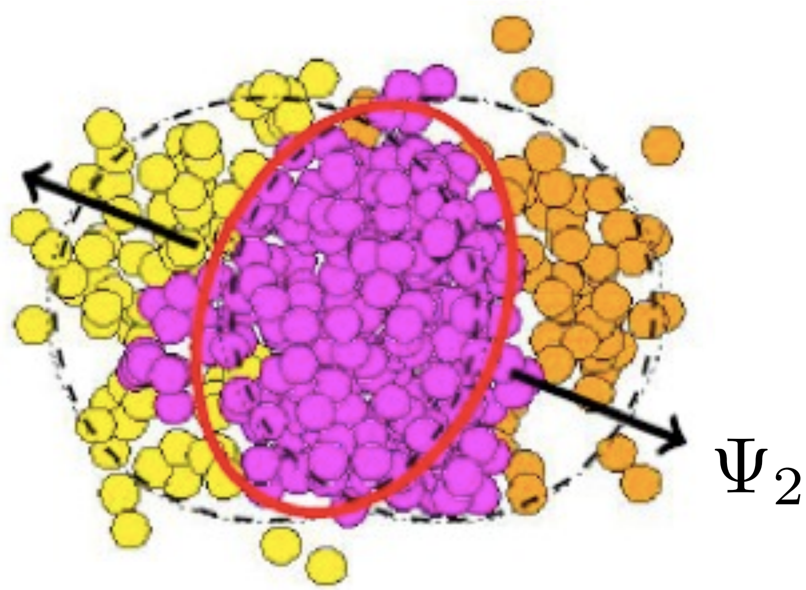

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