華中師範大學

CENTRAL CHINA NORMAL UNIVERSITY

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Institute of Particle Physics

Quark Matter 2018 Review

Open Heavy Flavour

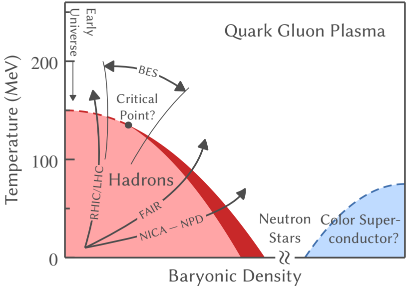
Caio A. G. Prado (博开友)

2018 年 5 月 31 日，武汉

Outline

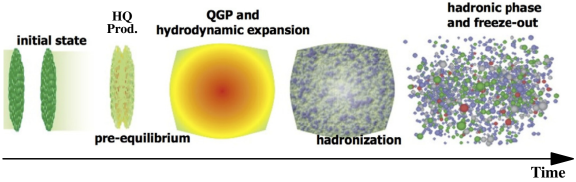
Introduction

Heavy quarks in heavy ion collisions



- Goal: understand the structure of universe (is it too much?)
- Heavy Ion Collisions
  - Experimental assessment of nuclear matter
  - Quark Gluon Plasma (everyone talks about it!)
- Collision systems (pp, pA, AA)
  - Not only baseline!
  - Different effects in play
- Probes
  - Soft: low-p_T light flavor particles
  - Hard: high-p_T and heavy flavour particles

Heavy quarks in heavy ion collisions



- The case for heavy flavor:
  - Pre-equilibrium production (hard scattering)
  - Long relaxation times
  - $m_Q > \Lambda_{QCD} \Rightarrow$ pQCD calculations
  - Strongly affected by QGP
  - Weakly affected by late time evolution
  - Hard fragmentation

- "Markers of the medium:"
  - Medium constituents
  - Transport coefficients
  - Mean free path

Heavy quarks in heavy ion collisions

Investigate QGP with heavy flavor probes

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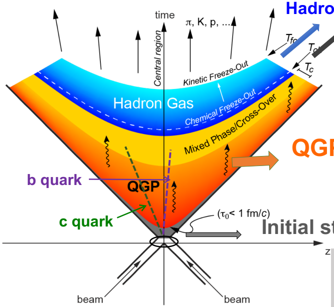

Hadronic phase

Hadronization

Fragmentation vs recombination

QGP/partonic phase

Microscopic interaction with medium constituents

Initial stages

Produced in initial high-Q^2 processes
→ calculable with pQCD

Large mass → short formation time
→ experience medium evolution

Interplay of different mechanisms

crucial to understand the observed results (R_{AA}, v_2,…)

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Heavy quarks in heavy ion collisions

Investigate different systems with heavy flavor probes

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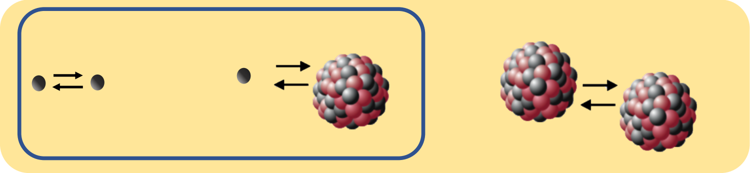

Cold Nuclear Matter effects
HF production mechanisms
Onset of medium-like effects for HF ?

OBSERVABLES

Charm, beauty R_{pPb}
Angular correlations
v_2

2018

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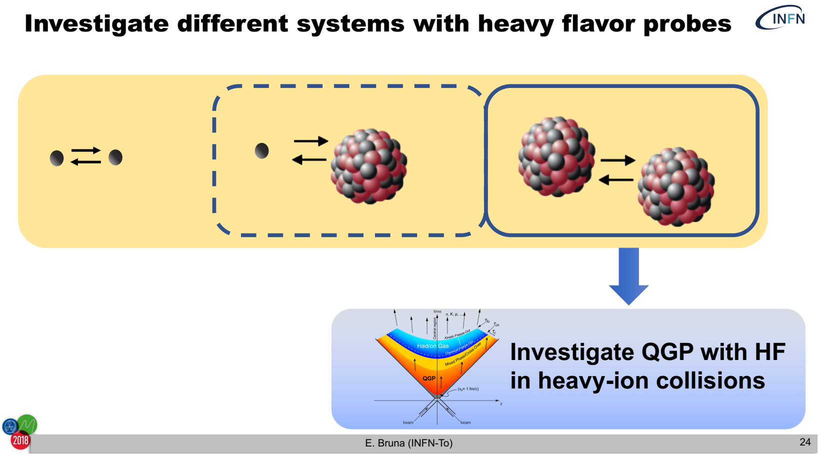
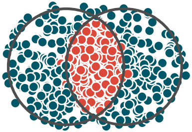
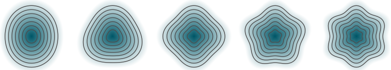
Heavy quarks in heavy ion collisions



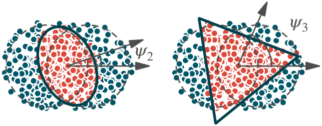
Common observables

- Nuclear Modification Factor: $R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$
    - Compare AA with pp
    - Collision geometry: $\langle T_{AA} \rangle$
    - Energy loss, shadowing and low-p_T flow bump
- Azimuthal anisotropy: $E\frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T\, dp_T\, dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\varphi - \psi_n)\right]\right)$
    - Initial spatial anisotropy
    - Heavy quark coupling with medium
    - Particle correlations
    - Event-by-event fluctuations





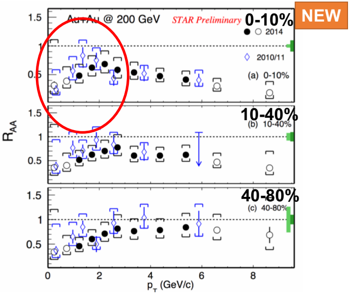
$n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$

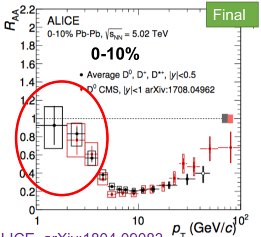


What’s new?

Experimental new results

D mesons at RHIC and LHC





ALICE, arXiv:1804.09083
CMS, arXiv:1708.04962

S. Radhakrishnan (Tue 15:50)
X. Peng (Wed 09:20)
Z. Shi (Wed 14:40)

D^0 R_{AA}<1 down to **p_T=0 at RHIC** (2014 data +re-analysis 2010/2011)
High p_T: similar suppression at RHIC and LHC
Low p_T: $R_{AA}(D)_{RHIC} \lesssim R_{AA}(D)_{LHC}$ → interplay of p_T shapes, radial flow, recombination

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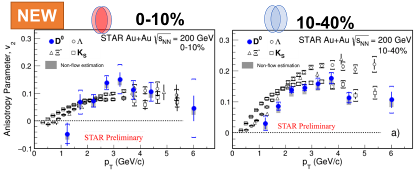
Experimental new results

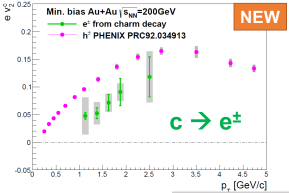
Charm elliptic flow

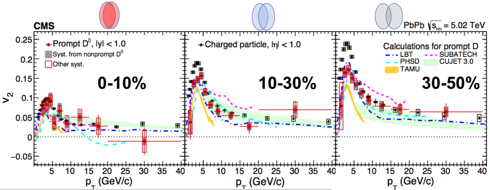


Significant charm v_2 at both RHIC and LHC

v_2 decreases with increasing centrality

Low p_T: v_2 (charged particles) $\gtrsim$ v_2 (D)
High p_T: v_2 (charged particles) ≈ v_2 (D)





arXiv: 1708.03497

R. Xiao (Wed 09:00), S. Singha (Wed 09:40), T. Hachiya (Tue 16:00)

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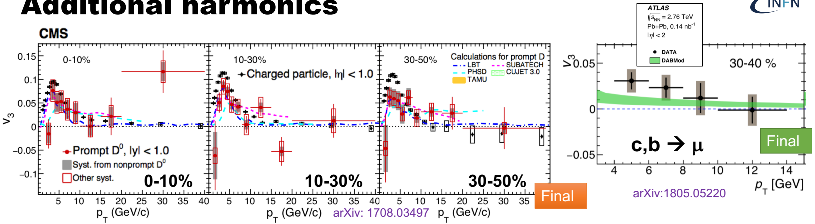
Experimental new results

Additional harmonics



R. Xiao (Wed 09:00), Q. Hu (Wed 15:00)

Positive v_3 for HF !

Both v_2 and v_3 smaller for charm wrt light quarks: different degree of thermalization, recombination?

Very little centrality dependence: constant triangularity from geometrical fluctuations

Models (including charm re-scattering) qualitatively describe v_2 and v_3 data
→ **confirm that charm takes part in collective motion**

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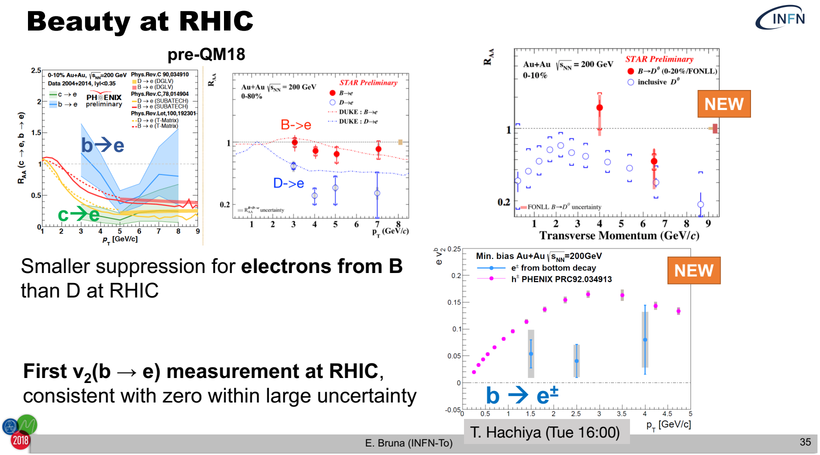
Experimental new results



Experimental new results

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A. Dubla (Tue 15:00)
T-W. Wang (Wed 16:20)
Q. Hu (Wed 15:00)

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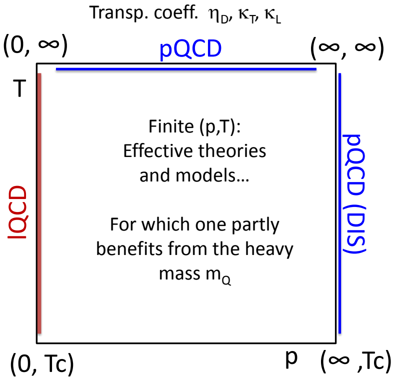
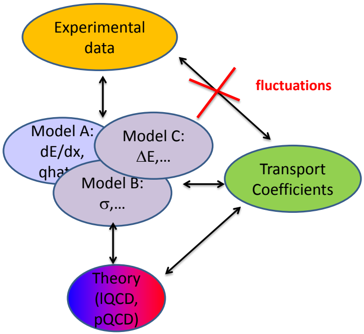
What’s up with the models?

Lanscape of HF theory and modeling in URHIC





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What's up with the models?

Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coeff based (LV,…)	TAMU POWLANG HTL Catania LV	Duke	ASW	ADS/CFT POWLANG lQCD *DABMOD* *(poster R. Katz)* *S. Li et al*, *arXiv:1803.01508*
Cross section (or$\|M\|^2$) based (Boltzmann,…)	AMPT MC@sHQ el URQMD PHSD Catania BM	Djordjevic et al MC@sHQ el + rad BAMPS CUJET3 Abir and Mustafa LBL-CCNU VNI/BMS *LIDO* *(DUKE; poster W. Ke)*	$SCET_{G,M}$	

Red: Transport models

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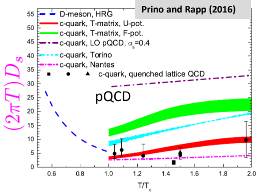
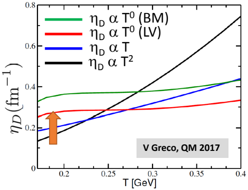
What's up with the models?

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail



$$\tau_{\mathrm{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{m_Q}{2\pi T^2}$$

S.K. Das et al, Physics Letters B747 (2015) 260

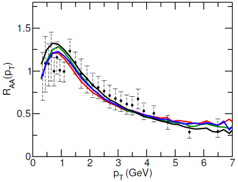


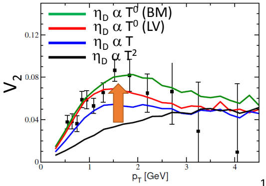
$\eta_D \propto T^2$: pQCD (fixed α_s), AdS/CFT

$\eta_D \propto T$: pQCD (running α_s)

$\eta_D \propto T^0$: QPM, DQPM, U potential (TAMU)

Tuned to reproduce R_{AA} => Larger coupling with the bulk near T_c (when the hydro v_2 has fully developped) => Larger v_2





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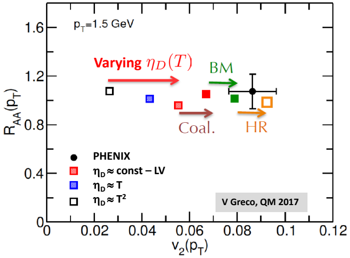
What's up with the models?

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail



Nice guideline but need:

- To consider extra ingredients (bulk, initial v_2,..)
- To assess the uncertainties on « Coal » and « HR »
- … before one can think of ruling out other trends for η_D.

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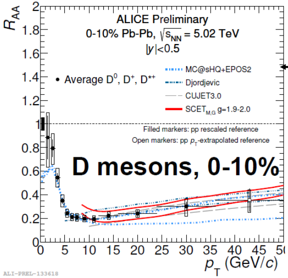
What’s up with the models?

Status of high p_T HQ

Over the past years, steady development of several sophisticated pQCD-based radiative Energy loss schemes in order to cope with the radiation of energetic partons: BDMPSZ, AMY, higher twist, DGLV, SCET… some of them leading to successful comparison with the data in their numerical implementation…



BDMPS (« infinite » path length regime)

Although some « extra ingredients » differ…

pQCD e-loss MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro	nPDF
CUJET3.0 JHEP 02 (2016) 169	✔	✔	✘	✘	✘
Djordjevic PRC 92 (2015) 024918	✔	✔	✘	✘	✔
MC@sHQ+EPOS PRC 89 (2014) 014905	✔	✔	✔	✔	✔
SCET JHEP 03 (2017) 146	✔	✔	✘	✘	✔

… Overall success of pQCD for describing the gluon radiation from a hot medium.

Beware : $\hat{q}$ is « just » an indirect result in some of those formalisms

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What's up with the models?

Status of high p_T HQ: prospects

Other challenges:

- Better understanding of heavy mass effect and medium properties in the radiation (especially on the coherence effects)
- Embedding in a realistic medium
- In a « jetty » picture: Combination of induced Eloss affecting the « initial » DGLAP evolution and the final « on shell » HQ

"Drag Induced Radiation and Multi-Stage Effects in Heavy-Flavor Energy Loss"

S. Cao et al, arXiv:1711.09053 **// talk S. Cao**

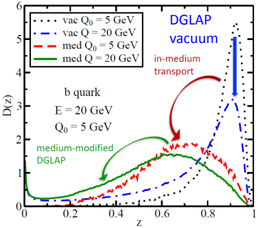
Also poster G-Y Qin

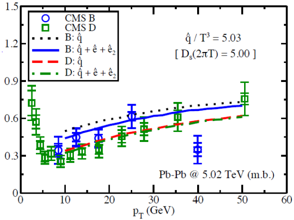
Hard scale $Q=p_T$

Modified DGLAP evolution (virtuality ordered)

Low scale $Q_0=m_Q$

« Usual » time ordered LBL-CCNU evol. (Higher twist with $\hat{e}$ and $\hat{e}_2$ corrections)





Good agreement with CMS data for D and B, some influence of higher order term at intermediate p_T

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What's up with the models?

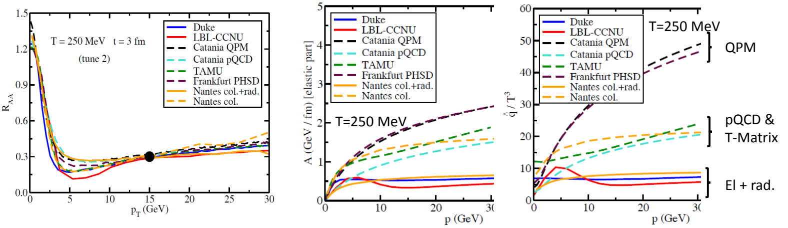
HQ-Working Group (convener: X-N Wang)

The goal is to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
- Estimate some systematics + uncertainties

Best controled QGP ever: uniform fixed temperature for all models (with same initial condition FONLL-like @ RHIC)

1) Rescale the coefficients to match R_{AA}=0.3 at p=15 GeV & « final time » 3 fm/c

2) Compare them !



Main result: Nice structuration of the transport coefficients in different classes. For each class, the work illustrates the maximal accuracy reachable for each class once all other ingredients are either fixed or chosen commonly

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What looks exciting?

New observables

Directed flow v_1 with open heavy flavours

INFN

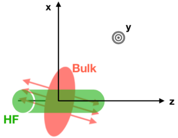
Interplay of two main sources for v_1:

- Initial **tilt of fireball** (hydro based)
  - **independent of charges**
  - expected to give larger effect for HQ

  (produced according to N_{coll} profile, symmetric in rapidity)

  → **slope $v_1\,(y)_{HQ}$ > slope $v_1\,(y)_{LQ}$?**

  Chatterjee, Bozek, arXiv: 1804.04893



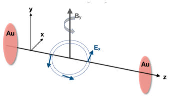
- **Varying magnetic field** influences moving charges
  - **charge-dependent v_1**
  - expected to give larger effect for HQ

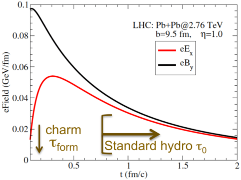
  (produced when magnetic field is maximum)

  → slope $v_1\,(y)_{HQ}$ > slope $v_1\,(y)_{LQ}$?

  → **$v_1(D) - v_1(\bar{D})$?**

  Das, Greco et al., Phys.Lett. B768 (2017) 260





S. Plumari (Tue 15:20)
S. Chatterjee (Wed 10:20)

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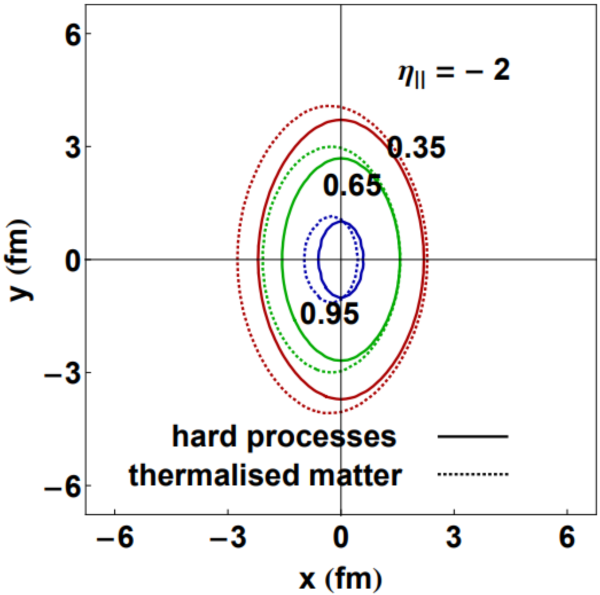
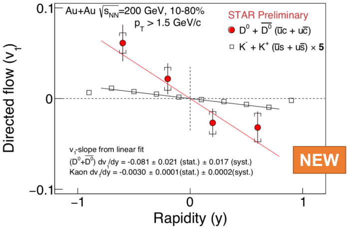
New observables

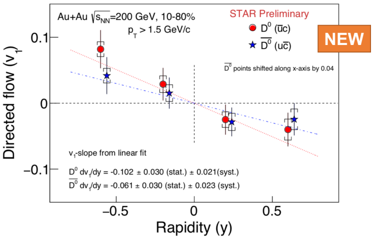


New observables

Directed flow v_1 with open heavy flavours

INFN





First observation of non-zero D^0 v_1

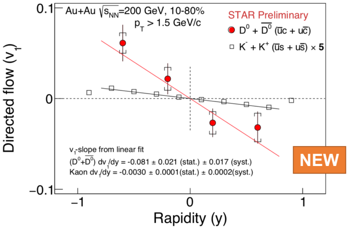
D^0 v_1-slope much larger than the kaons

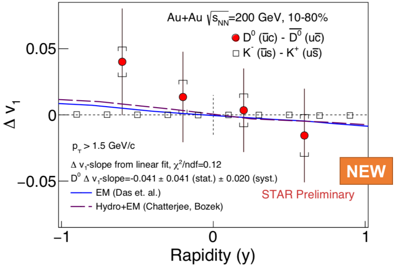
S. Singha (Wed 09:40)

New observables

Directed flow v_1 with open heavy flavours

INFN





First observation of non-zero D^0 v_1

D^0 v_1-slope much larger than the kaons

No firm conclusion yet on possible magnetic field induced splitting $\Delta v_1 = v_1(D) - v_1(\overline{D})$

Very promising **sensitivity to the effect of the early time magnetic field in heavy-ion collisions**, can help constrain QGP properties

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New observables

New Observables are coming

Short term, mid-term, long term,…

What	Good for ?	Caviat
Event shape engineering	Strength and T dependence of the interaction	Might be sensitive to the bulk and initial stage => play collective
Heavy light - correlations	b/c-jet substruture, nature of the interaction **Poster Rohmoser**	Might be sensitive to various HF creation in pp, to be calibrated **Poster Vermunt**
Λ_c, D_s, B_s,…	Understanding hadronization esp. Recombination (if generic enough not to require 1 new free parameter per state) or limits of statistical models	Dynamical treatment of confinement ? Inputs from lQCD probably needed
$v_1(y)$ **// Chatterjee Poster Coci**	Constrain (E,B), vorticity, initial tilt of matter initial distribution of HQ in transverse plane	Isn't it a bitt too much for this poor observable ?

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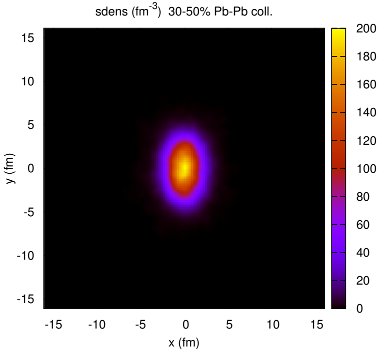
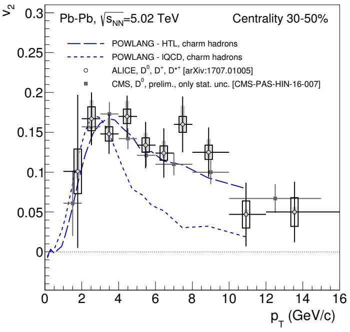
Are you cheating?

New results at 5.02 TeV: D-meson v_2 and v_3 in Pb-Pb





Transport calculations carried out in JHEP 1802 (2018) 043, with hydro background calculated via the ECHO-QGP code (EPJC 73 (2013) 2524)

Are you cheating?

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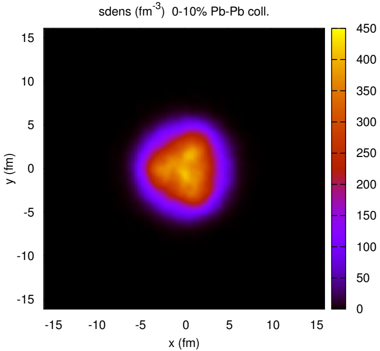
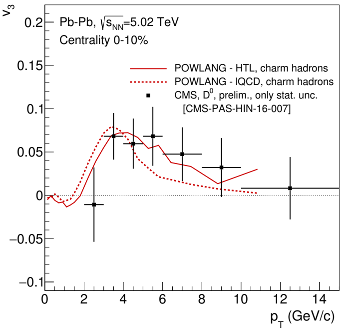
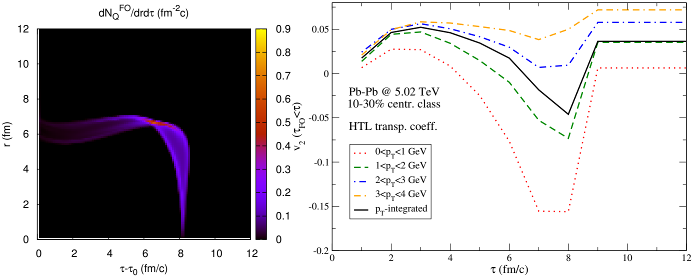




Transport calculations carried out in JHEP 1802 (2018) 043, with hydro background calculated via the ECHO-QGP code (EPJC 73 (2013) 2524)

Are you cheating?

Time development of azimuthal anisotropies



- Most of the HQ's decouple quite late ($\sim$ 50% after 8 fm/c);
- Final elliptic flow from a complex interplay of contributions from the whole medium history;
- HQ v_2 correlated with the one of the fluid cell;
- supplementary information from p_T-differential analysis;

Conclusions

Conclusions

- A lot of new results from the experiments!
- Huge amount of physics pertaining all the processes: do you feel kinda lost?
- Aim at quantitative rather than qualitative predictions... How? New observables...?
- Quark Matter in Wuhan: what is waiting for us there?