

Heavy-flavor flow and energy loss in the quark-gluon plasma

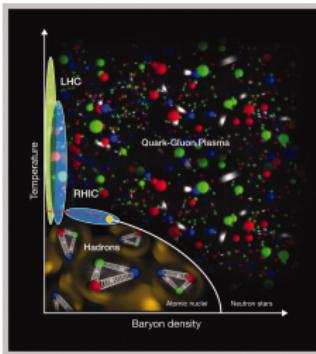
Marlene Nahrgang
Duke University

October 7th 2015, Osaka University



Probes of the quark-gluon plasma

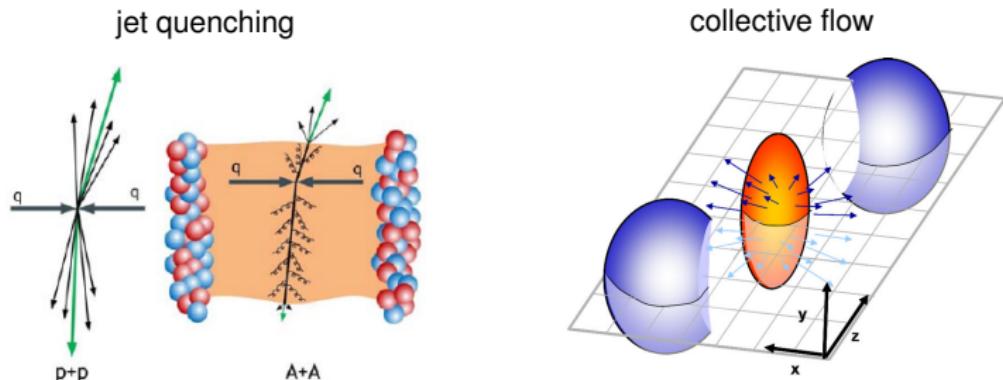
- Study of properties of strongly interacting many-body systems via ultra-relativistic heavy-ion collisions.
- Probes should not thermalize with the medium, e.g. dileptons, high-pT jets,...



- The mass of heavy quarks (HQ) sets another scale: m_c , m_b
- HQ vacuum shower terminates much earlier: E / Q_H^2 with $Q_H = \sqrt{Q_0^2 + m_Q^2}$.
- Number of thermally excited HQ is negligibly small.
- Contributions from gluon-splitting are negligible for charm quarks at current p_T -range.
- HQ as leading parton is always tagged.

Quark-gluon plasma and its properties

Formation of QGP, which evolves fluid dynamically as a nearly perfect fluid.



observable: nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{N_{\text{coll}}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

sensitive to jet quenching parameter \hat{q}

observable: Fourier coefficients of

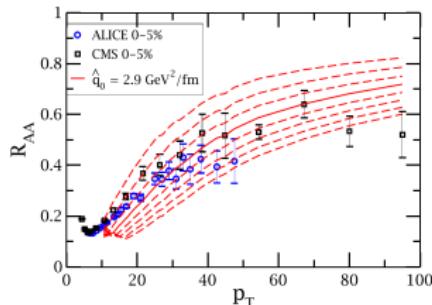
$$\frac{d^2N}{dp_T dy} \propto \sum_n v_n \cos(n\phi)$$

sensitive to viscosity η/s

Quark-gluon plasma and its properties

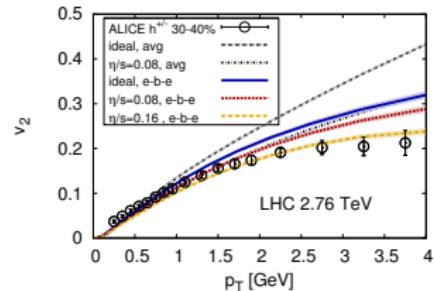
Formation of QGP, which evolves fluid dynamically as a nearly perfect fluid.

jet quenching



Jet Collab. PRC90 (2014)

collective flow



B. Schenke et al. PLB702 (2011)

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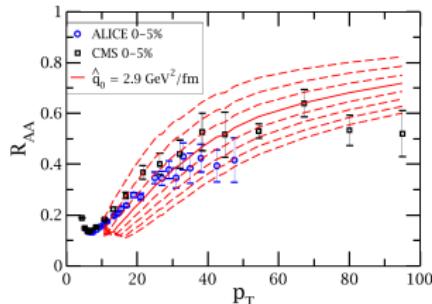
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Quark-gluon plasma and its properties

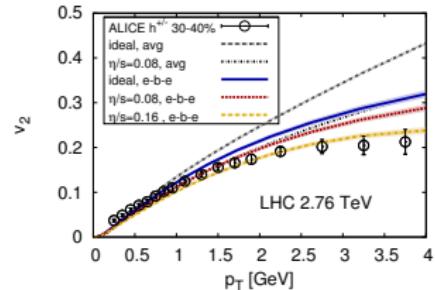
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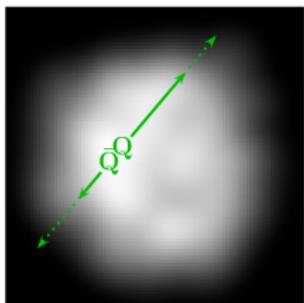
Learn from the success in the light hadron sector for heavy-flavor studies!

Modeling of heavy-quark dynamics in the QGP

production

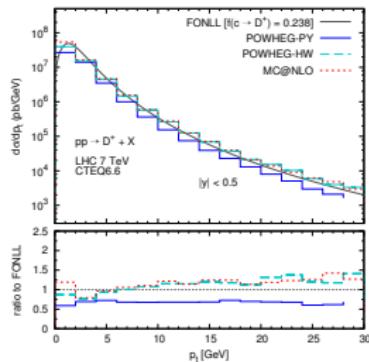
interaction with the medium

hadronization



- LO pQCD → including resummation of logs:
FONLL → inclusive spectra ⇒ back-to-back initialization, no information about the azimuthal $Q\bar{Q}$ correlations

M. Cacciari et al. PRL 95 (2005), JHEP 1210 (2012)



- NLO pQCD matrix elements plus parton shower,
e.g. POWHEG or MC@NLO ⇒ exclusive spectra,
like $Q\bar{Q}$ correlations

S. Frixione et al. JHEP 0206 (2002), JHEP 0308 (2003)

- Cold nuclear matter effects, i.e. shadowing, p_T broadening aka Cronin effect, etc.

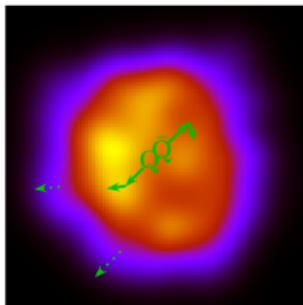
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009)

Modeling of heavy-quark dynamics in the QGP

production

interaction with the medium

hadronization



- Collisional (elastic) cross sections $\Rightarrow \Delta E \sim \log(E)L$
- Incoherent radiation (GB regime) $\Rightarrow \Delta E \sim EL/I_{\text{mfp}}$
- Coherent radiation (BDMPS-Z regime) $\Rightarrow \Delta E \sim \sqrt{EL}$
- Dead cone effect reduces radiative energy loss for heavy quarks.
- For very energetic partons and thin media $\Rightarrow \Delta E \sim L^2$
- Further radiative effects: finite gluon mass and width

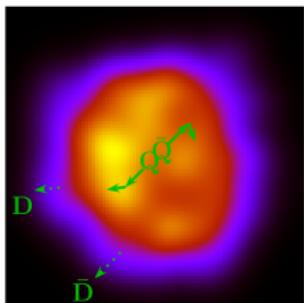
J. D. Bjorken (1982); E. Braaten et al, PRD **44** (1991), PRD **44** (1991); A. Peshier, PRL **97** (2006); S. Peigne et al., PRD **77** (2008) 114017; M. Gyulassy et al, NPB **420** (1994); BDMPS PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952; ibid. **64** (1996) 781; ibid. **65** (1997) 615; ibid. **73** (2001) 49; ibid. **78** (2003) 759; M. Gyulassy et al, PRL **85** (2000); NPB **571** (2000) 197; ibid. **594** (2001); Y. L. Dokshitzer et al., PLB **519** (2001); P. B. Arnold et al., JHEP 0011 (2000), 0305 (2003); N. Armesto et al., PRD **69** (2004); PRCC **72** (2005); B.-W. Zhang et al., PRL **93** (2004); B. Kämpfer et al., PLB **477** (2000); M. Djordjevic et al., PRC **68** (2003) PLB **560** (2003); M. Bluhm et al. PRL **107** (2011); O. Fochler et al. PRD88 (2013); M. Djordjevic, PLB734 (2014); J. Aichelin et al. PRD89 (2014)

Modeling of heavy-quark dynamics in the QGP

production

interaction with the medium

hadronization



- Coalescence/Recombination – predominantly at small p_T .

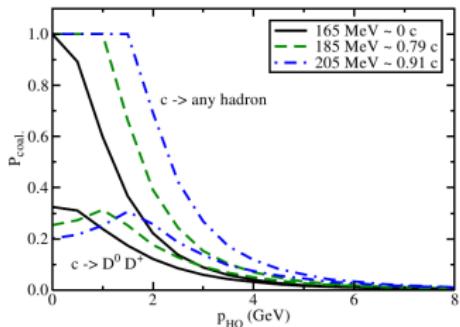
C. B. Dover, U. W. Heinz, E. Schnedermann, J. Zimanyi PRC **44** (1991)

- Fragmentation – predominantly at large p_T .

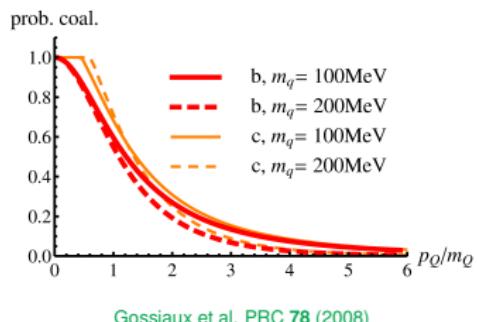
M. Cacciari, P. Nason, R. Vogt PRL **95** (2005)

- After hadronization: final hadronic interactions of D mesons.

L. Tolos et al., PRD88 (2013); J. Torres-Rincon et al., PRD89 (2014)



S. Cao et al. arxiv:1505.01413



Gossiaux et al. PRC **78** (2008)

Modeling of heavy-quark dynamics in the QGP

production

interaction with the medium

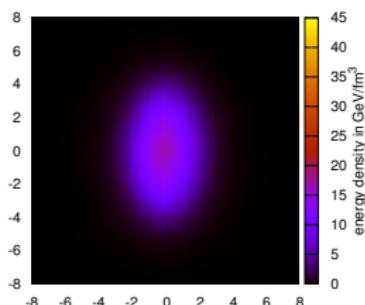
hadronization

medium description

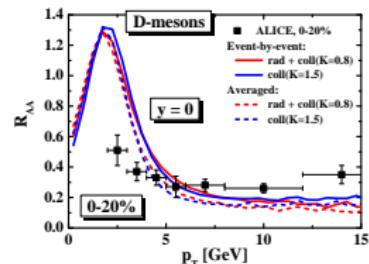
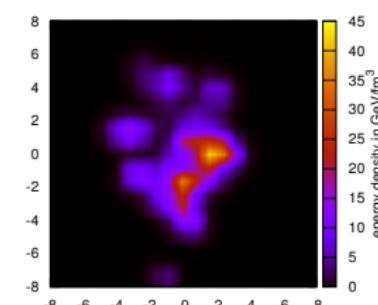
coupling medium - HF sector

- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!

smooth initial conditions



fluctuating initial conditions

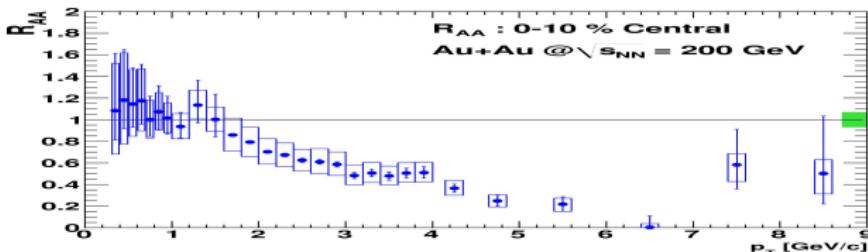


plot by V. Ozvenchuk, Nantes

MN, J. Aichelin, P. B. Gossiaux, K. Werner NPA932 (2014)

What to expect from heavy-quark observables?

PHENIX, PRC84 (2011)



at low $p_T \sim m_Q$

- Very different from light partons.
- Nonperturbative!
- Partial thermalization with the light partons in the QGP?
- Diffusion D mainly via collisional processes?
- Hadronization via coalescence/recombination?
- Initial shadowing and cold nuclear matter effects?

at high $p_T \gg m_Q$

- Similar to light partons.
- Perturbative regime...
- Rare processes, probe the opacity of the matter.
- Energy loss dE/dx via collisional and radiative processes?
- Coherent energy loss \rightarrow jet-quenching parameter \hat{q} ?
- Hadronization via (medium-modified) fragmentation?

Set the stage: Transport equations & coefficients

Boltzmann equation for HQ phase-space distribution

$$\frac{d}{dt} f_Q(t, \vec{x}, \vec{p}) = \mathcal{C}[f_Q] \quad \text{with} \quad \mathcal{C}[f_Q] = \int d\vec{k} [\underbrace{w(\vec{p} + \vec{k}, \vec{k}) f_Q(\vec{p} + \vec{k})}_{\text{gain term}} - \underbrace{w(\vec{p}, \vec{k}) f_Q(\vec{p})}_{\text{loss term}}]$$

expanding \mathcal{C} for small momentum transfer $k \ll p$ (in the medium $k \sim \mathcal{O}(gT)$) and keeping lowest 2 terms \Rightarrow Fokker-Planck equation

$$\frac{\partial}{\partial t} f_Q(t, \vec{p}) = \frac{\partial}{\partial p^i} \left(\underbrace{A^i(\vec{p}) f_Q(t, \vec{p})}_{\text{friction (drag)}} + \frac{\partial}{\partial p^i} \left[\underbrace{B^{ij}(\vec{p}) f_Q(t, \vec{p})}_{\text{momentum diffusion}} \right] \right)$$

Recast to Langevin equation (probably good for bottom, but for charm?)

$$\frac{d}{dt} \vec{p} = -\eta_D(p) \vec{p} + \vec{\xi} \quad \text{with} \quad \langle \vec{\xi}^i(t) \vec{\xi}^j(t') \rangle = \kappa \delta^{ij} \delta(t - t')$$

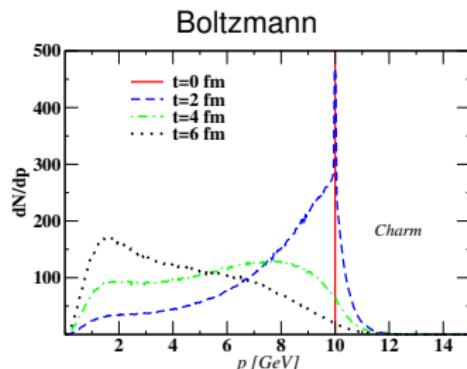
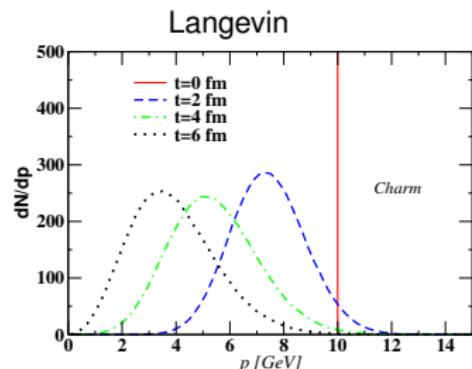
Transport coefficients connected by fluctuation-dissipation theorem (Einstein relation):

$$\eta_D = \frac{\kappa}{2m_Q T}, \quad D_s = \frac{T}{m_Q \eta_D} \quad \text{spatial diffusion}$$

D. Walton et al., PRL84 (2000); G. Moore et al., PRC71 (2005)

Boltzmann vs Langevin dynamics

- Under which conditions should Brownian motion be a valid approximation for relativistic particles?
- Calculations of transport coefficients from the underlying theory do not necessarily fulfil FDT.
- Langevin leads to Gaussian momentum distribution, Boltzmann very different.



S. Das et al, PRC90 (2014)

Boltzmann equation assumes independent scatterings (dilute medium) - is this a correct assumption?

Diffusion coefficient from lattice QCD

Lattice QCD at finite T is performed in Euclidean space \Rightarrow notoriously difficult to calculate dynamical quantities.

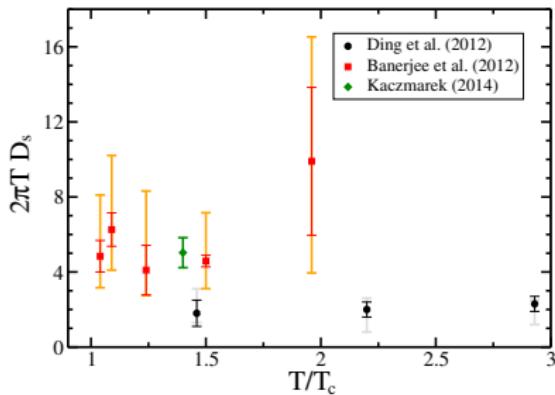
Transport coefficients calculated from correlation function of conserved currents

via slope of spectral function ρ_E at $\omega = 0$ (Kubo formula)

momentum diffusion:

$$\frac{\kappa}{T^3} = \lim_{\omega \rightarrow 0} \frac{2T\rho_E(\omega)}{\omega}$$

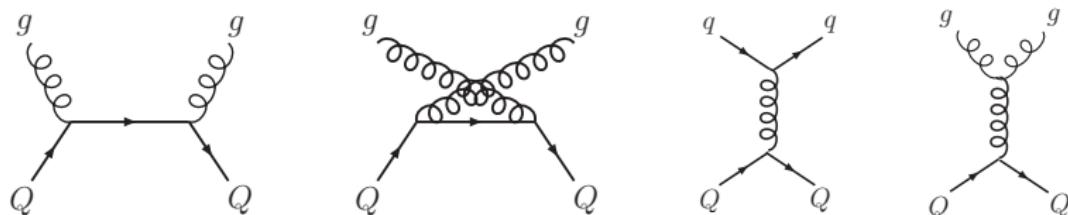
$$\text{spatial diffusion: } D_s = \frac{2T^2}{\kappa}$$



No reliable input from lattice QCD calculations yet...

Collisional (elastic) energy loss

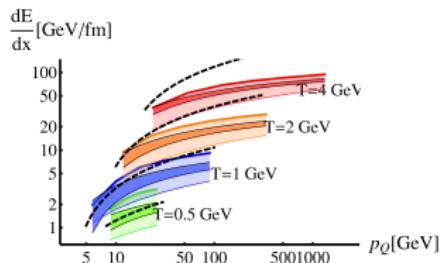
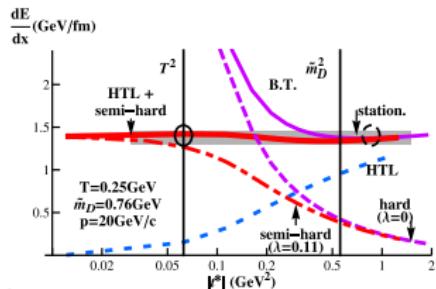
LO Feynmann diagrams for perturbative heavy quark scattering off a light parton



- Dominant contribution from the t -channel
- Well-known IR singularity, regulated by the Debye screening mass m_D
- Gluon propagator: $G(t) = \frac{\alpha_s}{t} \rightarrow \frac{\alpha_s}{t - m_D^2}$ with $m_D \sim \mathcal{O}(gT)$
- Use the Hard-Thermal Loop (HTL) resummed gluon propagator for small $|t| \ll t^*$ and the bare gluon propagator $|t| \gg t^*$ to calculate energy loss.
- For well-separated scales $g^2 T^2 \ll T^2$ results are independent of the intermediate scale t^* .

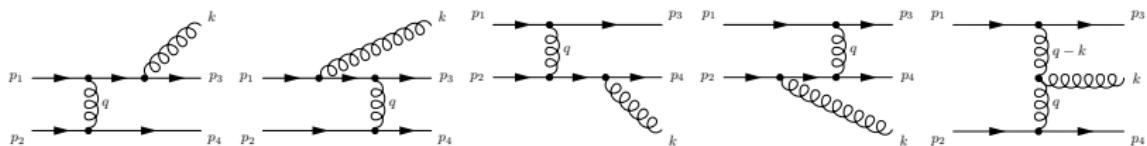
Nantes model

- Relevant separation of scales $g^2 T^2 \ll T^2$ probably not fulfilled in RHIC and LHC experiments.
- Idea: introduce a reduced IR regulator λm_D^2 in the hard part: HTL+semi hard \Rightarrow by tuning λ achieve independence from t^* .
- Calibrate pQCD Born matrix elements with $G(t) = \frac{\alpha_s}{t - \lambda m_D^2}$ to HTL+semi hard energy loss
- Use a running coupling at the scale of the specific process $\alpha_{\text{eff}}(t)$.
- Self-consistently determine the Debye-mass from $m_D^2 = (1 + 6n_f)4\pi\alpha_s(m_D^2)T^2$



A. Peshier, hep-ph/0601119, PRL 97 (2006); P. B. Gossiaux et al. PRC78 (2008), NPA 830 (2009)

Radiative energy loss



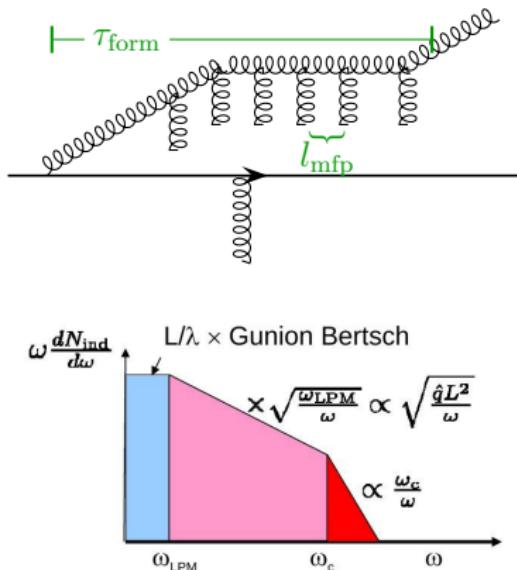
- LO pQCD matrix element for $2 \rightarrow 3$ process Kunszt et al. PRD21 (1980)
- Gunion-Bertsch approximation derived in the high-energy limit, where the radiated gluon k_\perp and the momentum transfer q_\perp are soft $\ll \sqrt{s}$.
- Incoherent radiation off a massless parton, mid-rapidity
- Extension beyond mid-rapidity and to finite mass m_Q (heavy quarks!)
⇒ distribution of induced gluon radiation:

$$P_g(x, \vec{k}_\perp, \vec{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\vec{k}_\perp}{\vec{k}_\perp^2 + x^2 m_Q^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{(\vec{k}_\perp - \vec{q}_\perp)^2 + x^2 m_Q^2} \right)^2$$

- ⇒ $E_{\text{rad}}^{\text{loss}} \propto E L$

J. Gunion, PRD25 (1982); O. Fochler et al. PRD88 (2013); J. Aichelin et al. PRD89 (2014)

Coherent emission - LPM



- coherent emission if $\tau_{\text{form}} = \sqrt{\frac{\omega}{\hat{q}}} > l_{\text{mfp}}$
- QCD analogon to the Landau-Pomeranchuk-Migdal (LPM) effect
- Important in QCD: rescattering of the forming gluon with medium partons \Rightarrow less suppression than in QED
- At large energies in BDMPS-Z: $\Rightarrow E_{\text{rad}}^{\text{loss}} \propto \sqrt{E} L$
- For very energetic partons $\tau_{\text{form}} > L$, then $E_{\text{rad}}^{\text{loss}} \propto L^2$, estimate for the LHC ($L \sim 2\text{ fm}$, $\hat{q} \sim 2 \text{ GeV/fm} \Rightarrow \omega_c \sim 20 \text{ GeV}$)

- Dynamical realization challenging K. Zapp et al. PRL103 (2009), JHEP 1107 (2011), usually implemented effectively.

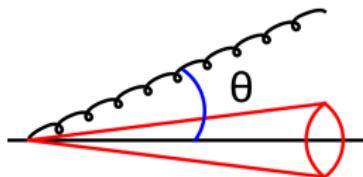
Baier et al. PLB 345 (1995); NPB 483 (1997); ibid. 484 (1997); B. G. Zakharov, JETP Lett. 63 (1996) 952

Dead cone effect

suppression of high-energetic (small angle) gluon emission by the heavy quark mass:

$$\frac{d\sigma_{\text{rad}}}{\theta d\theta} \propto \frac{\theta^2}{(\theta^2 + M_Q^2/E_Q^2)}$$

Dokshitzer et al., PLB 519 (2001)

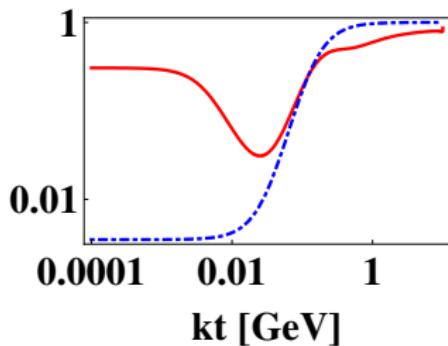


- Suppresses gluon emission in the dead cone $\theta_D = M_Q/E_Q$
- Introduces a mass hierarchy in the radiative energy loss.
- But: assumes hard scatterings!

- When the hard scattering assumption is relaxed, emission at low k_{\perp} is significantly less suppressed:

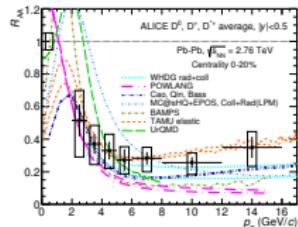
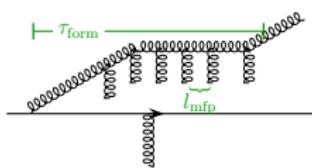
$$\frac{P_g(x, k_{\perp}; M)}{P_g(x, k_{\perp}; 0)}$$

hard-scattering approximation
all scatterings



J. Aichelin et al. PRD89 (2014)

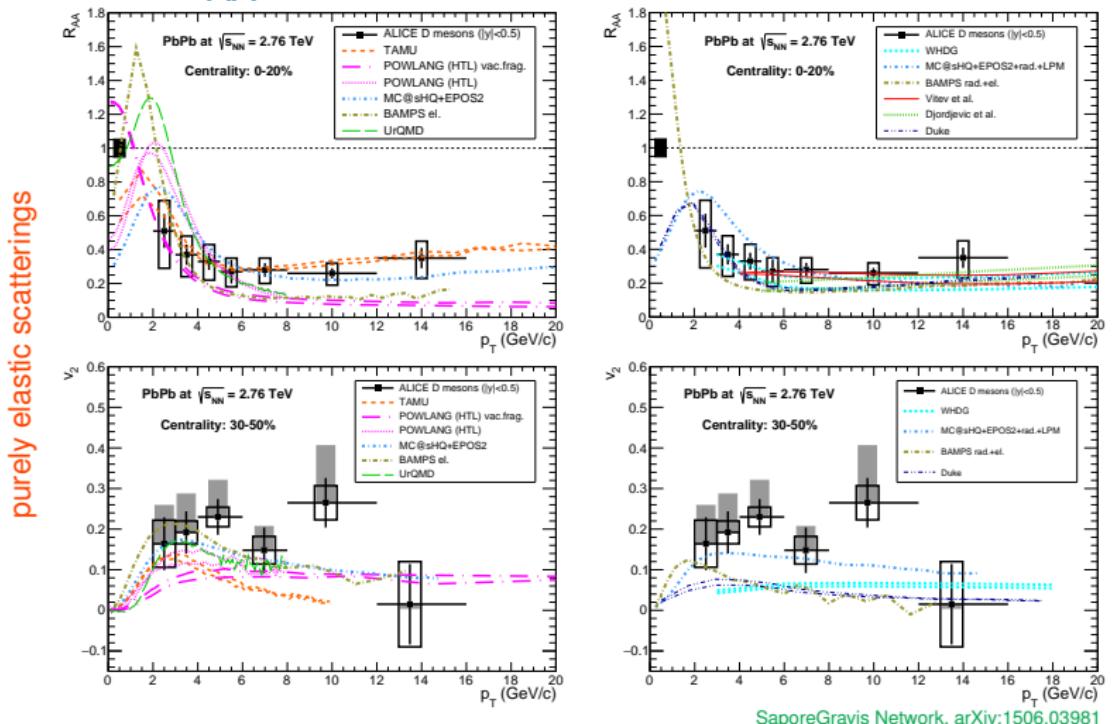
From theoretical input to dynamical modeling



- No reliable input for the HQ diffusion coefficient from lattice QCD calculations.
- Simple approximations are prone to fail in some kinematic region, mostly at intermediate p_T .
- Due to uncertainties all models when compared to data contain (implicit or explicit) parameter tuning.
- Proper modeling of the QGP evolution is important! Should be well tested in the light hadron sector!
- Does the equation of state match the representation of the medium quasiparticles?
- Effects of viscosity, initial state fluctuations, preequilibrium dynamics?

How to get access to fundamental QGP properties from theory to data comparison?

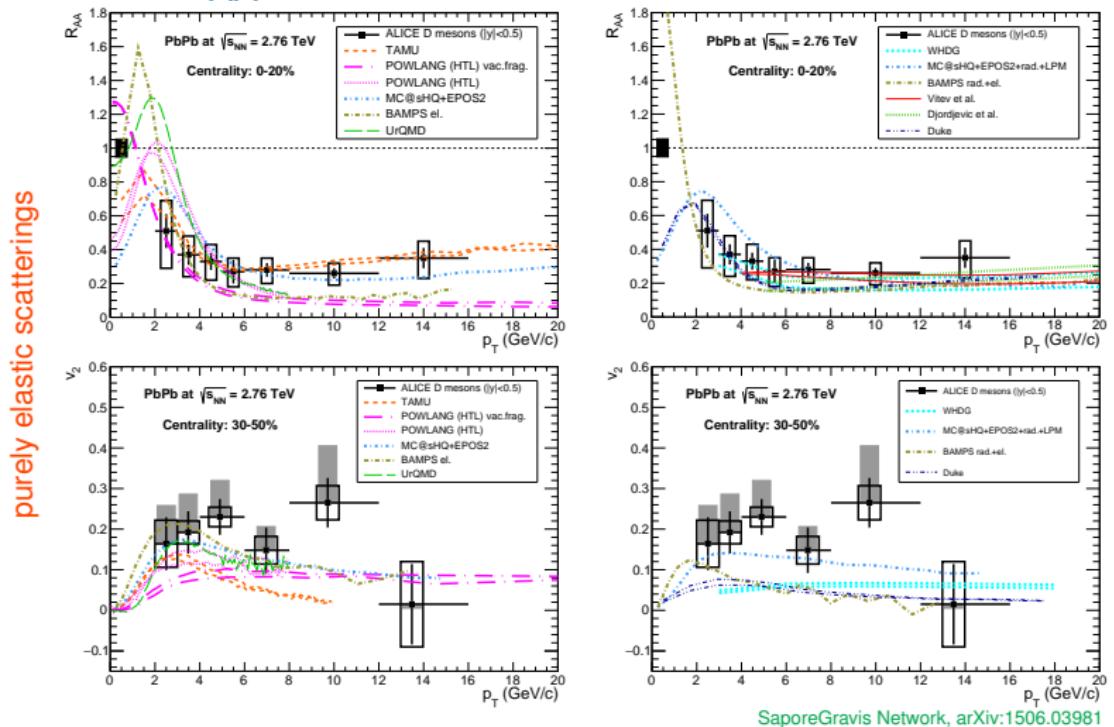
D meson R_{AA} and v_2 in AA at LHC



SaporeGravis Network, arXiv:1506.03981

- The simultaneous description of R_{AA} and v_2 is challenging.

D meson R_{AA} and v_2 in AA at LHC

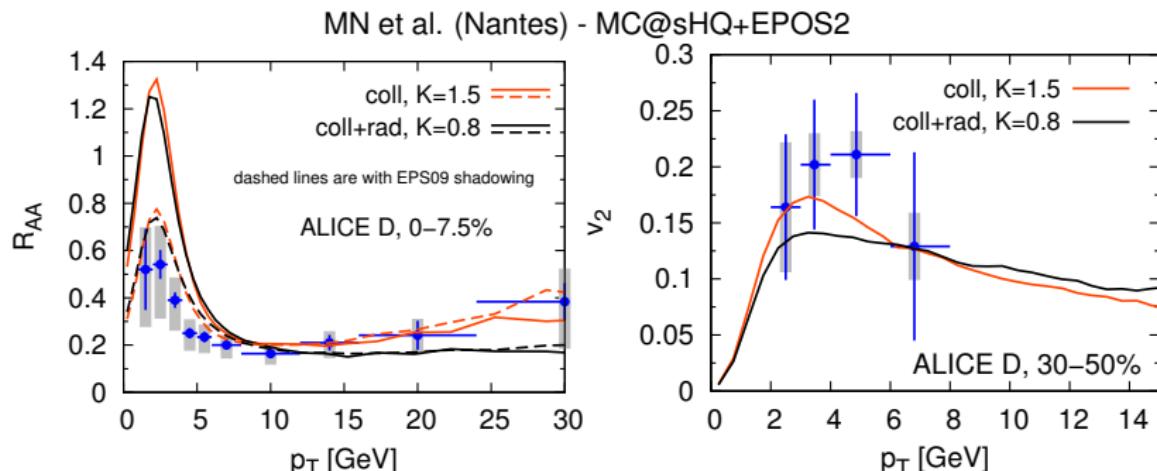


- The simultaneous description of R_{AA} and v_2 is challenging.

(Too?) many models reproduce the R_{AA} and/or the v_2 well.

Nantes model - R_{AA} and v_2

- pQCD-inspired Boltzmann transport in 3 + 1d ideal fluid dynamics (EPOS).

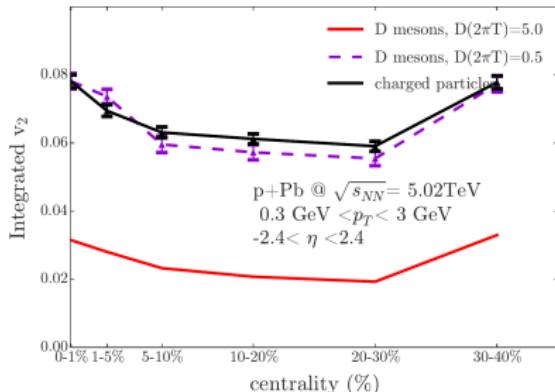
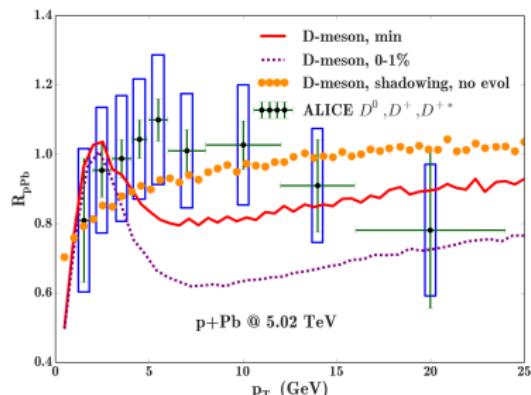


- Rather good description of the R_{AA} and the v_2 .
- Initial shadowing (cold nuclear matter effects) needed to describe the low- p_T region.
- Slight preference for purely collisional energy loss in MC@sHQ+EPOS2.

MN et al. PRC 89 (2014); K. Werner et al. PRC 85 (2012)

Charm production (and diffusion?) in pPb collisions

- 3 + 1d fluid dynamical evolution + Langevin dynamics, initial shadowing.

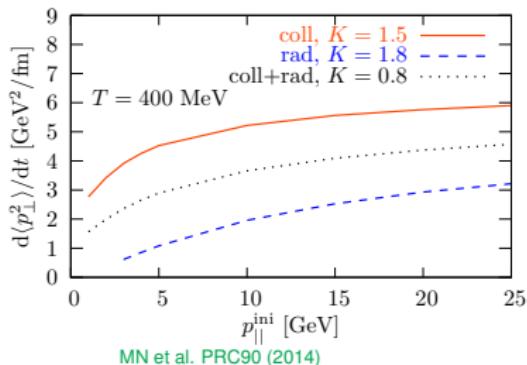


- Centrality dependence of R_{pPb} expected due to energy loss.
(Note, that experimentally Q_{pPb} !)
- Indications that v_2 of D mesons decouples from medium flow - unlike in AA collisions - and decreases with centrality.
- Can HF measurements in pPb help answering the question of initial vs final state effects?

Beyond traditional observables...

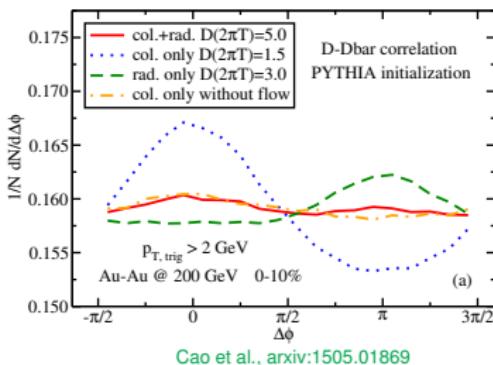
- Observables with high discriminating power between different interaction mechanisms: e.g. azimuthal correlations of $Q\bar{Q}$ pairs.

$\langle p_{\perp} \rangle$ from MC@sHQ+EPOS2:



MN et al. PRC90 (2014)

$D\bar{D}$ correlation plot from Duke model



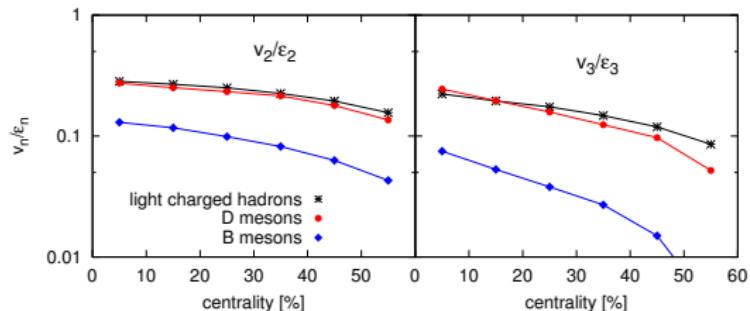
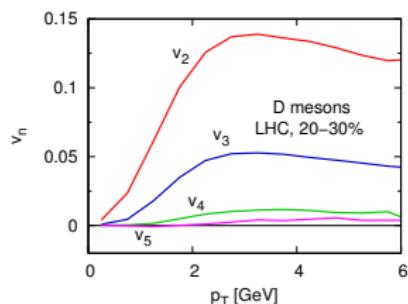
Cao et al., arxiv:1505.01869

- Difficulties: already the $c\bar{c}$ proton-proton baseline is not well understood theoretically and experimental feasibility...

For possible e(HF)-h or D-h correlations models need to couple HF-LF sectors consistently!

Beyond traditional observables...

- Most models give a τ_{relax} for charm quarks much longer than the evolution of the QGP, but $v_2(\text{HF}) \sim v_2(\text{LF})$.
- Higher-order Fourier coefficients were important for understanding charged hadron flow.
- What about heavy-flavor v_3 , v_4 , ...?



- Expectation: v_3 and higher-order coefficients show the incomplete coupling of HQ to the medium.

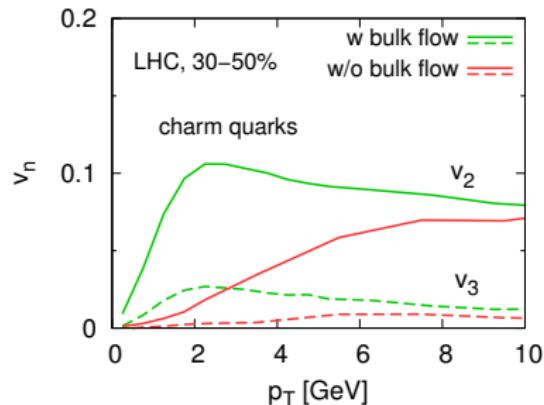
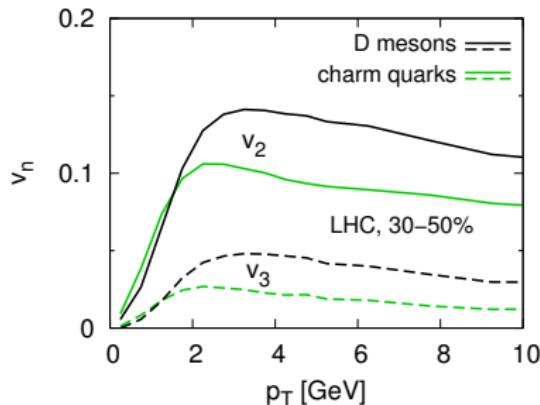
MN et al. PRC91 (2015)

Looking forward to experimental data for v_3 from LHC and RHIC!

Beyond traditional observables...

Charm flow: hadronization and energy loss

collisional+radiative(+LPM), K = 0.8



- Contribution to the flow from hadronization.
- For low p_T the charm flow is predominantly due to the flow of the bulk.

Summary



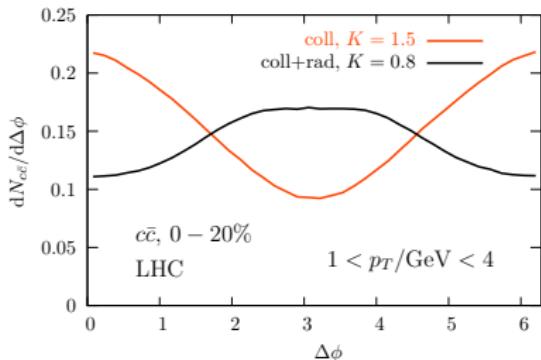
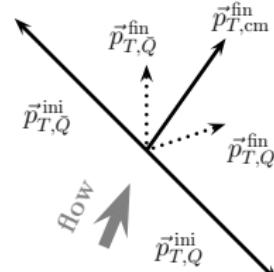
- HQ probe partial **thermalization** at low p_T and **energy loss** at high p_T in the QGP.
- Many effects important at intermediate p_T : onset of coherent gluon emission, gluon thermal mass, finite path length, nonperturbative scatterings,...
- Transport coefficients/scattering cross sections in **Langevin** or **Boltzmann** transport.
- Coupling to a dynamical evolution of the QGP (should be well tested in the light hadron sector!)
- R_{AA} and v_2 are described well by (too?) many models.
- **Learn from the success in the light-flavor sector!**
- Study further observables, like $Q\bar{Q}$ correlations and higher-order flow coefficients, for veri/falsi-fication of models!
- Need to identify most dominant features of HQ-medium interaction: connect data to fundamental properties of QCD!

backup

"Partonic wind" effect

X. Zhu, N. Xu and P. Zhuang, PRL 100 (2008)

- Due to the radial flow of the matter low- p_T $c\bar{c}$ -pairs are pushed into the same direction.
- Initial correlations at $\Delta\phi \sim \pi$ are washed out but additional correlations at small opening angles appear.
- This happens only in the purely **collisional** interaction mechanism!
- No "partonic wind" effect observed in **collisional+radiative(+LPM)** interaction mechanism!



MN et al. PRC90 (2014)

QGP: initial state and bulk flow (1)

- Bulk flow is driven by the initial elliptic or triangular eccentricity ϵ_2 and ϵ_3

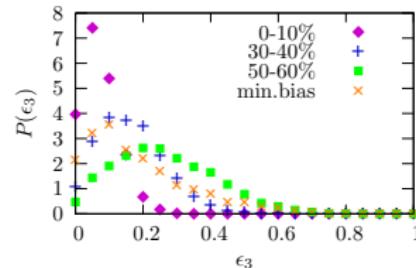
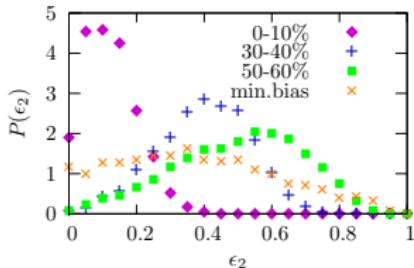
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}$$

- In the light hadron sector the final $v_2 \propto \epsilon_2$ and $v_3 \propto \epsilon_3$ for not too large centralities.
[G.-Y. Qin et al., PRC82 \(2010\); H. Niemi et al., PRC87\(2013\)](#)
- Proportionality depends on viscosity and higher-order flow is more sensitive!

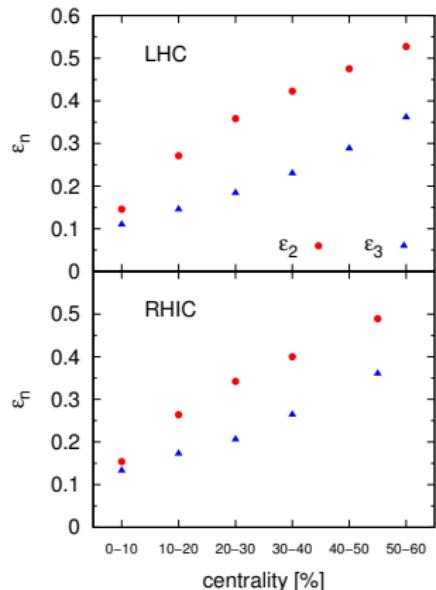
$$\frac{v_n}{\epsilon_n} = \left(\frac{v_n}{\epsilon_n} \right)_{\text{ideal}} (1 - \mathcal{O}(n^m K)) \quad m \sim 1 - 2$$

[B. H. Alver et al., PRC82, \(2010\); P. Staig and E. Shuryak, PRC84 \(2011\); Y. Hatta et al., arXiv:1407.5952](#)

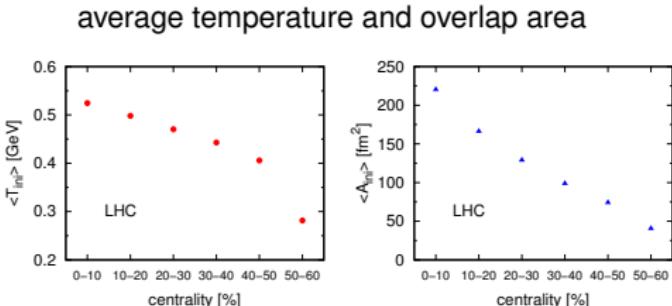
- Dependence on centrality already in the ideal case: FO dynamics, core-corona separation, etc.



QGP: initial state and bulk flow (2)



MN et al. PRC91 (2015)

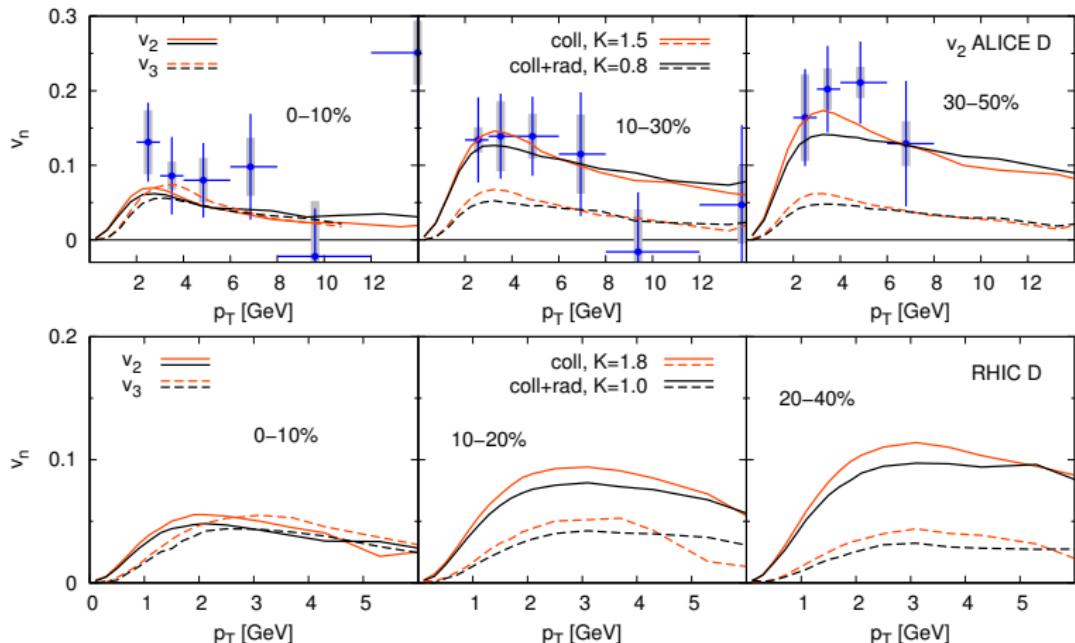


centrality dependence:

- + increase of initial eccentricities
- + decrease of interaction rate and medium size

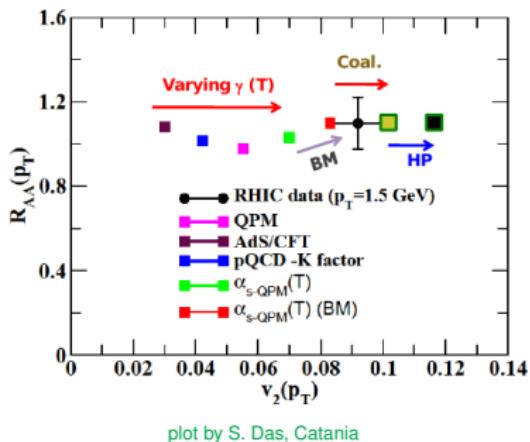
⇒ expectation: heavy-flavor flow shows a weaker dependence on centrality, especially for v_3

D meson v_2 and v_3 at LHC and RHIC

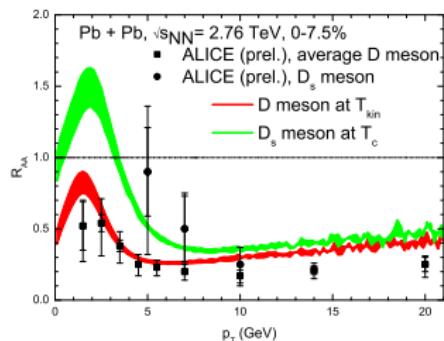


- At small p_T : relative enhancement of flow in purely **collisional** scenario over **collisional+radiative(+LPM)** larger for v_3 than for v_2

D meson R_{AA} and v_2 - miscellaneous



- R_{AA} robust, but v_2 changes significantly:
- affected by interaction details, Langevin vs Boltzmann, coalescence, hadronic final interactions...



- Enhancement of strangeness in the QGP can lead to an enhancement of D_s mesons by coalescence.

Radiative energy loss - spectra

- Incoherent radiation: Gunion-Bertsch spectrum extended to finite quark mass.
- Inclusion of an effective suppression of the spectra in the coherent radiation regime (LPM effect)
- Influence of gluon damping (not in this talk)

M. Bluhm et al., PRL 107 (2011), arXiv:1204.2469

