Bulk evolution for MC@sHQ + EPOS & HADRONIZATION

EMMI RRTF - GSI July 2016

Marlene Nahrgang, Jörg Aichelin, Pol Bernard Gossiaux, Klaus Werner

July 18, 2016

Duke University & Subatech Nantes

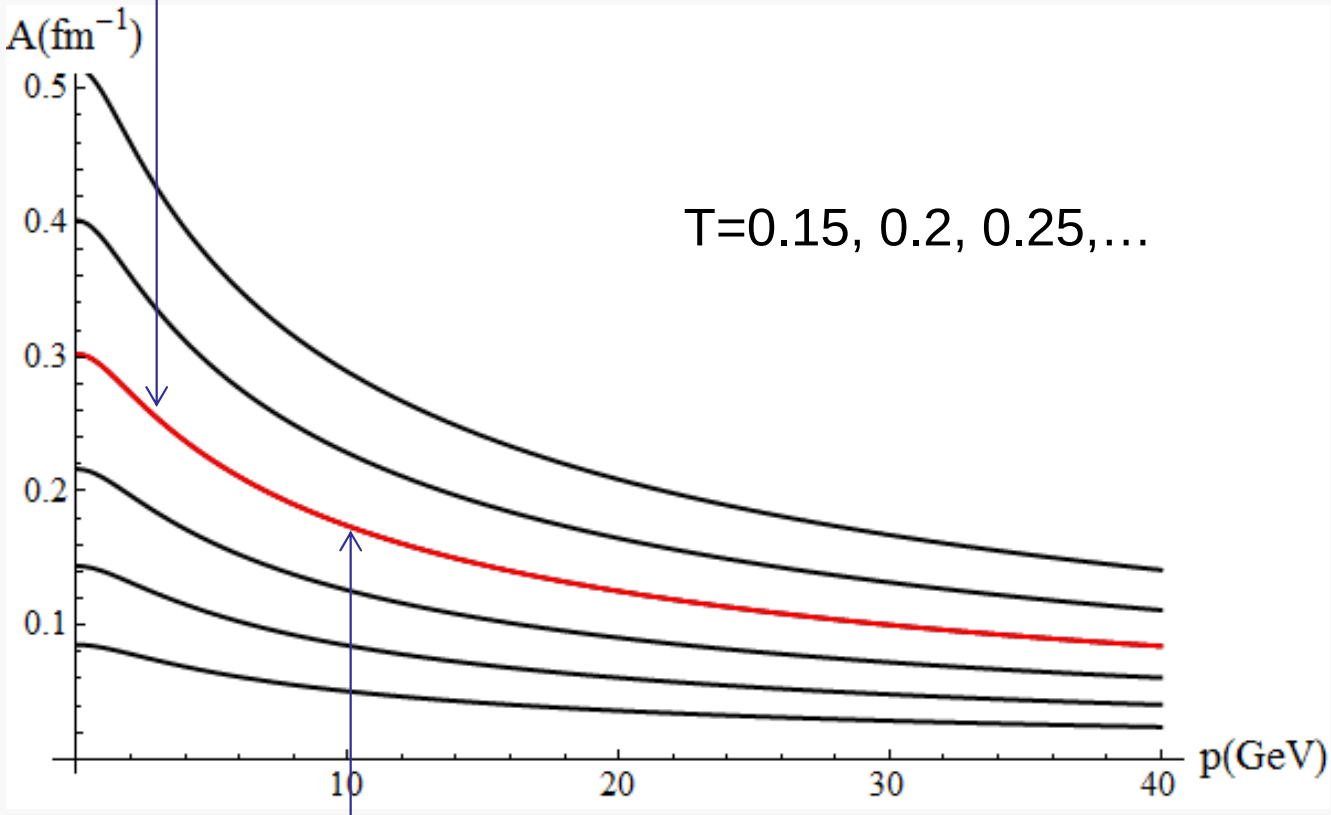
Previously: MC@sHQ + Kolb Heinz (RHIC & LHC)

↑

(« use at your own risks »)

Organisers' suggestion

$$A(T = 0.3, p = 3) = 0.25 \text{ fm}^{-1}$$



$$A(T = 0.3, p = 10) = 0.175 \text{ fm}^{-1}$$

Importance of realistic bulk evolution

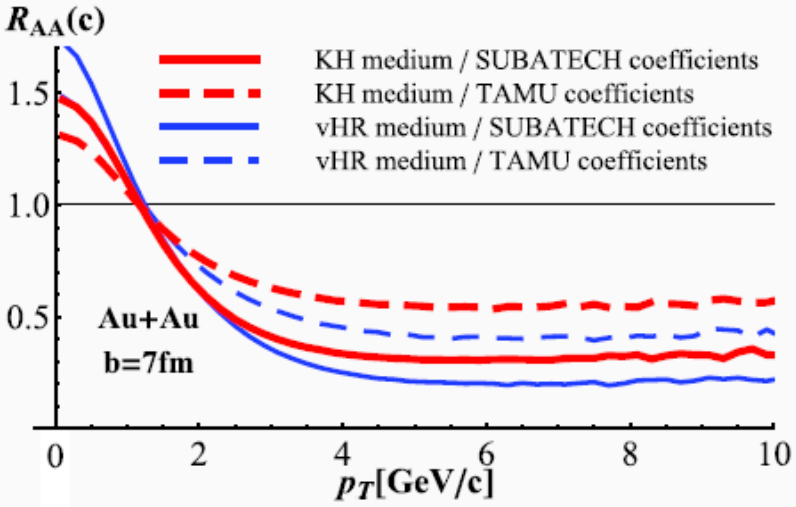
... assumption: QGP is locally thermalized $\Rightarrow$ heavy quarks scatter off thermal medium constituents.

... information about the local medium temperatures, (chemical potentials) and velocities can be obtained from fluid dynamical models.

... modern fluid dynamical simulations of HIC have been extremely successful in describing the bulk evolution, in particular identified p_T spectra and flow.

... any model with $P(\Delta E)$ produces the generic p_T shape of R_{AA}, magnitude depends on details in the Eloss model IN COMBINATION with the bulk evolution model!

T. Renk, PRC85 (2012) arxiv:1112.2503



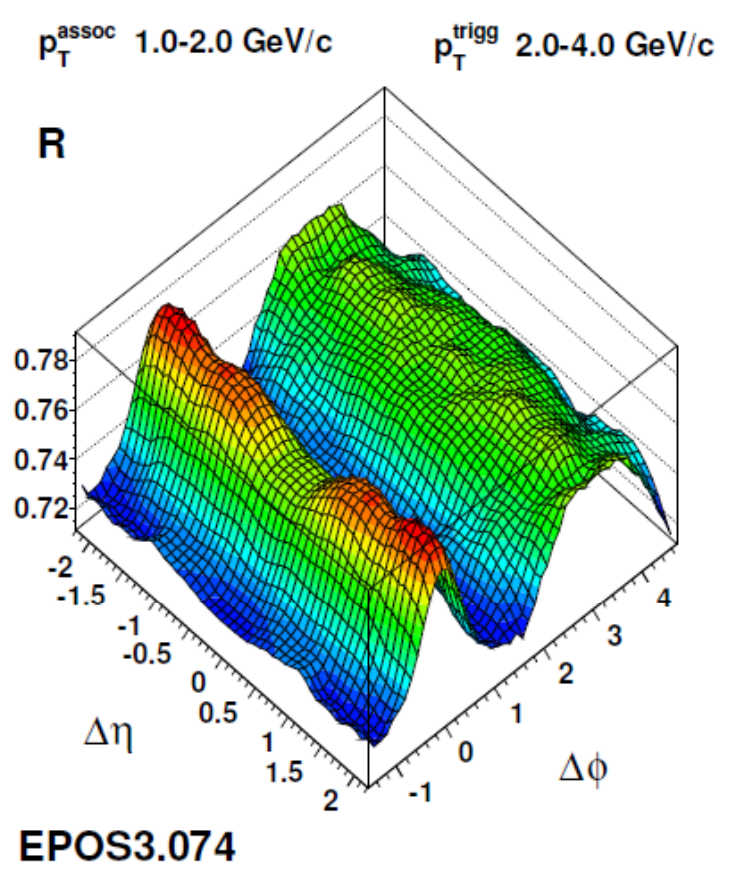
elliptic fireball evolution

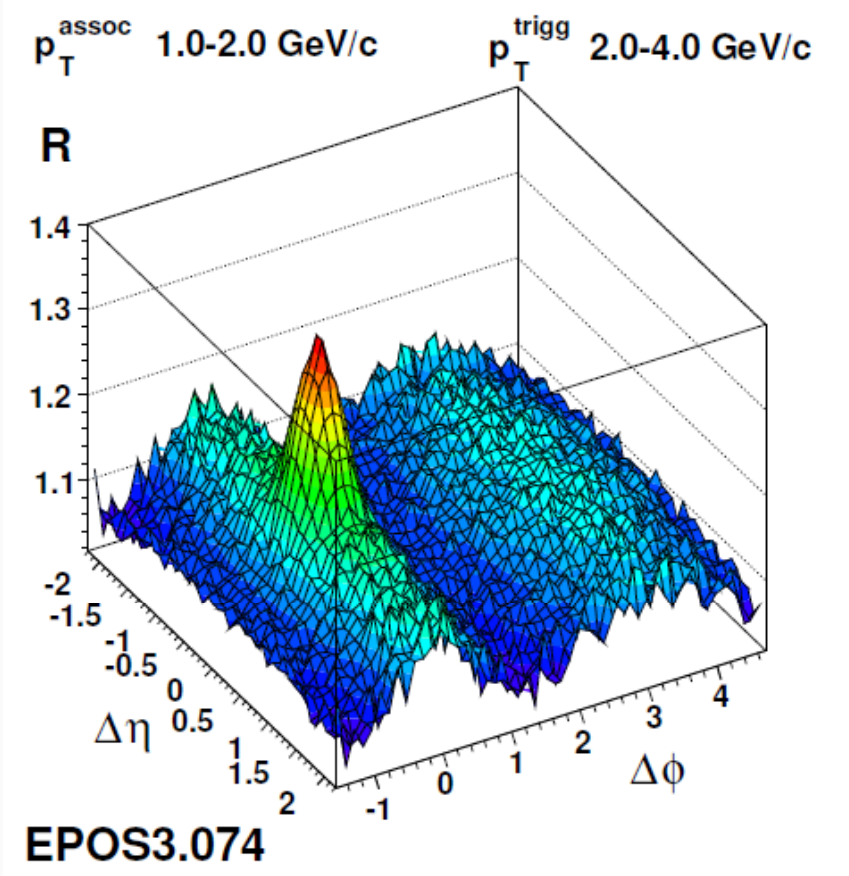
vs.

(simple) hydrodynamics

P.B. Gossiaux et al., arXiv:1102.1114

EPOS model





(pPb at $\sqrt{s} = 5$ TeV, 0 − 20% centrality, left: subtract results for 60 − 80% centrality)

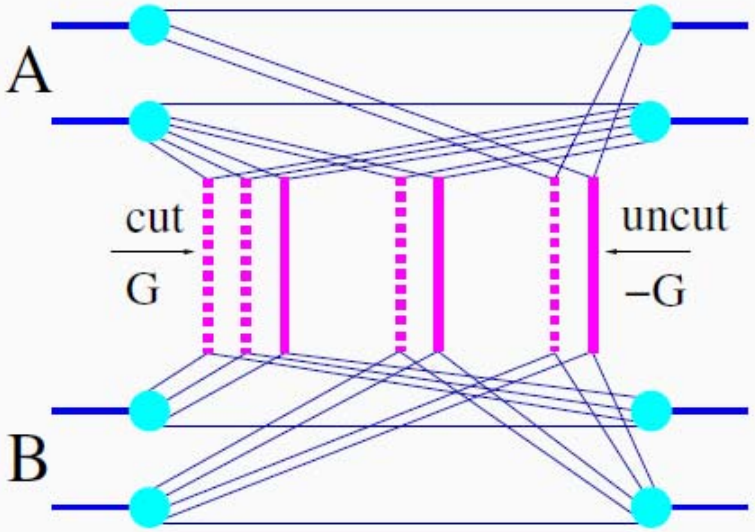
...is an event-by-event MC model for proton-proton, proton-nucleus and nucleos-nucleos collisions.

K. Werner et al., Phys.Rev. C89 (2014); Phys.Rev.Lett. 112 (2014); Phys.Rev. C85 (2012); Phys.Rev. C82 (2010); ...

EPOS model - initial conditions

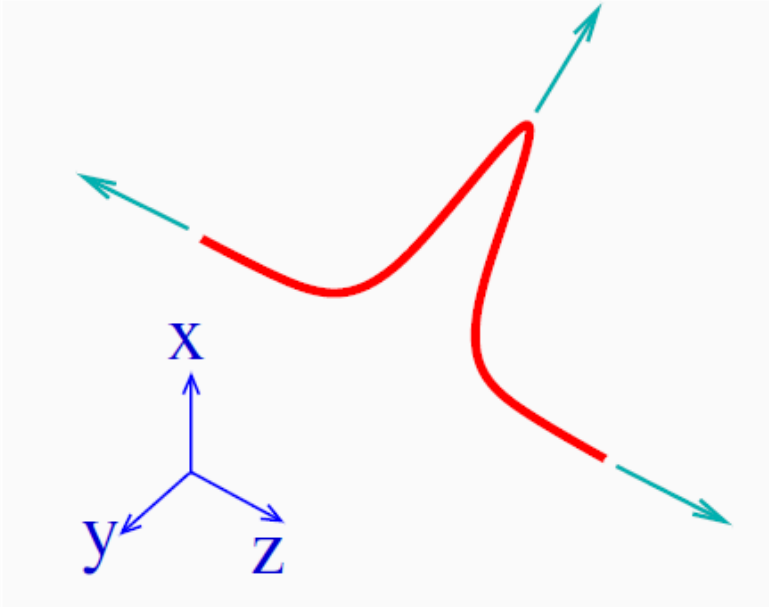
- Gribov-Regge multiple scattering approach with DGLAP parton ladders = pomerons
- saturation scale motivated by a CGC: $Q_s \propto N_{\mathrm{part}} \hat{s}^{\lambda}$

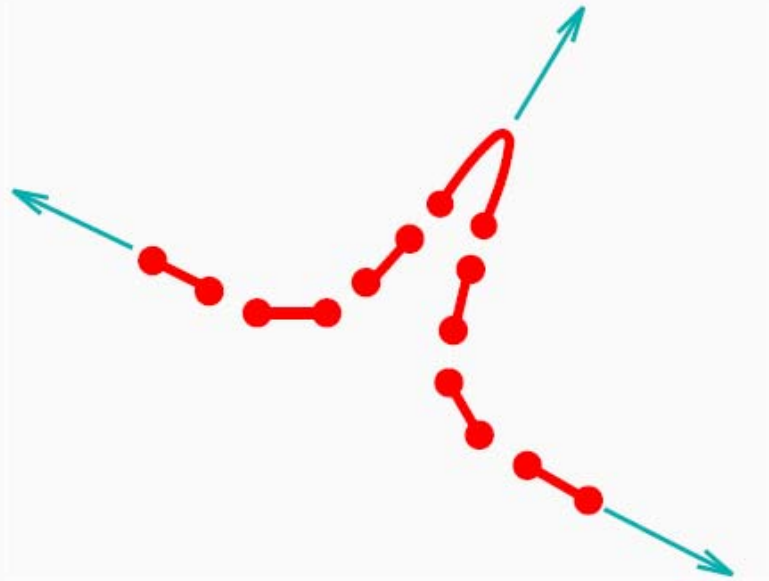
  N_{part} connected nucleons to pomeron, $\hat{s}$ energy of pomeron, $\lambda = 0.25$
- parton ladders are treated as classical, relativistic strings with longitudinal and transverse momentum
- high density of strings (= flux tubes) in AA collisions



EPOS model - core-corona approach

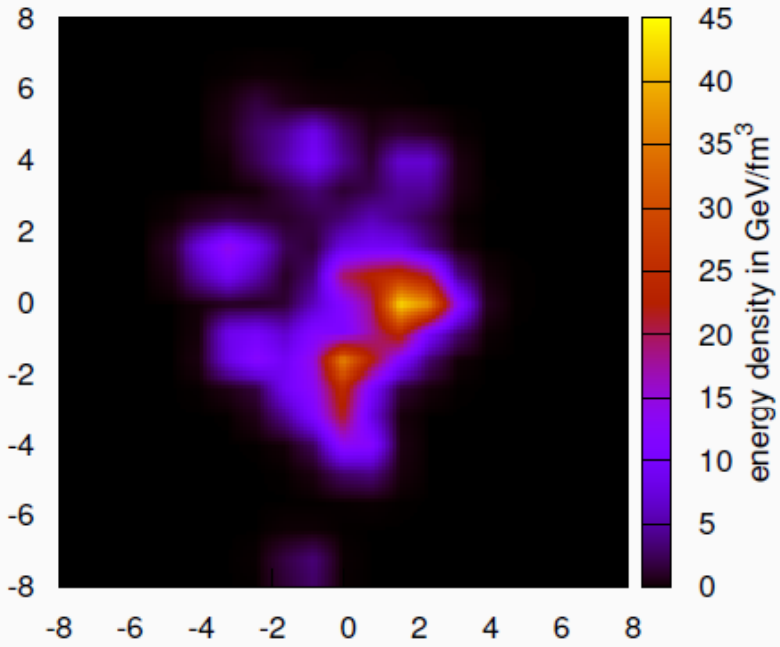
- at τ_0 fluid (core) and escaping hadrons (incl. jet hadrons) (corona)
- criterion based on momentum and density of string segments





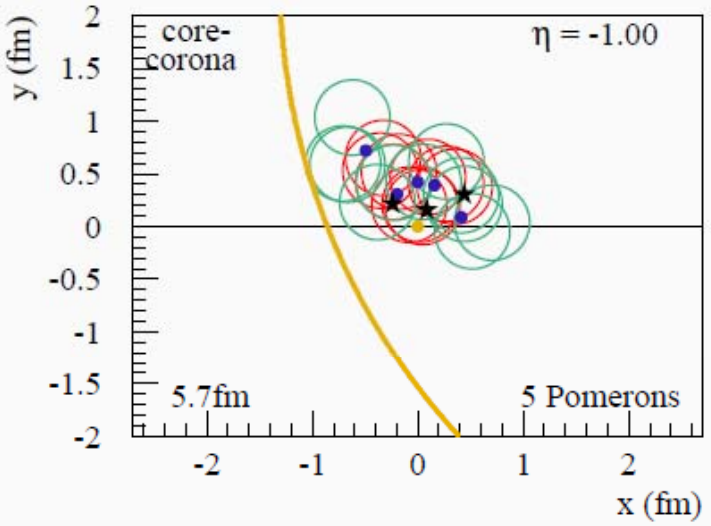
EPOS model - core-corona approach

- at τ_0 fluid (core) and escaping hadrons (incl. jet hadrons) (corona)
- criterion based on momentum and density of string segments
- assuming fast equilibration for core $\Rightarrow$ initial $T^{\mu\nu}$ of the fluid
- fluctuating initial conditions
  $\rightarrow$ one random event
  ($30-50\%$ central,
  $\sqrt{s} = 2.76$ TeV, Pb+Pb)



EPOS model - core-corona approach

- at τ_0 fluid (core) and escaping hadrons (incl. jet hadrons) (corona)
- criterion based on momentum and density of string segments
- assuming fast equilibration for core $\Rightarrow$ initial $T^{\mu\nu}$ of the fluid
- fluctuating initial conditions $\rightarrow$ one random event ($30-50\%$ central, $\sqrt{s} = 2.76$ TeV, Pb+Pb)



- core-corona separation: $\rightarrow$ one random event

($b = 5.7$ fm, pPb, positions of the projectile nucleon (yellow dot), the Pb surface (yellow line), the hit target nucleons (stars), Pomerons (blue dots), as well as the core (red circles) and the corona (green circles) string segments.

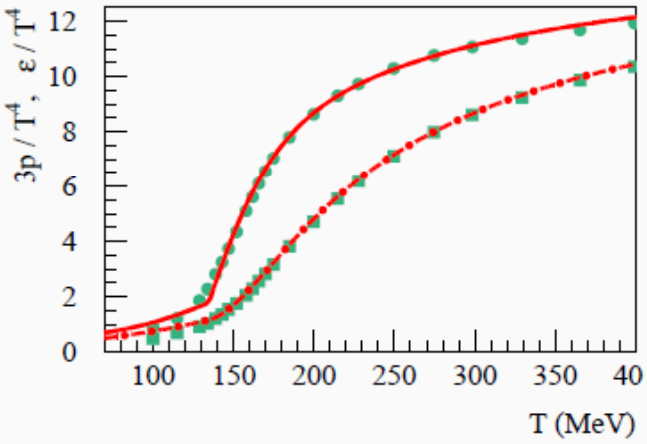
EPOS model - (viscous) fluid dynamical evolution

uses the $3+1$ dimensional (viscous with $\eta/s = 0.08$) fluid dynamical code by Iu. Karpenko, vHLLE Comput.Phys.Commun. 185 (2014)

initial mapping:

$$T^{\mu\nu}(x) = \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x - x_i)$$

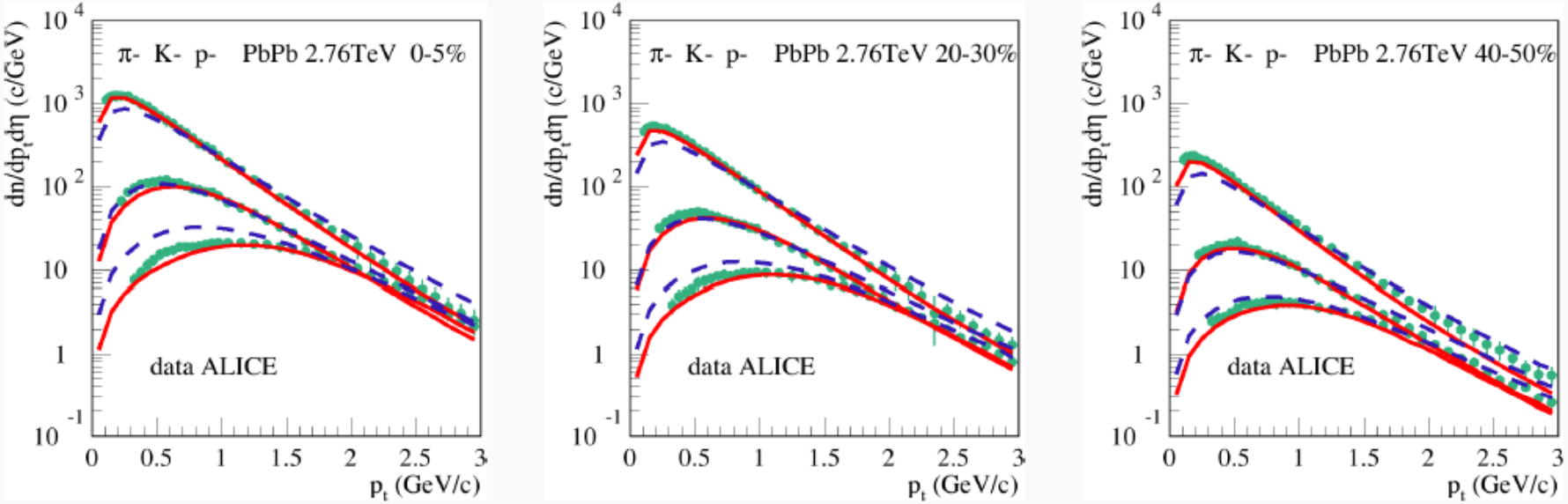
- solves second-order viscous fluid dynamical equations
- provides space-time evolution of energy density and fluid velocities



parametrization of the lattice equation of state WB collab., JHEP 1011 (2010)

EPOS model - freeze-out and hadronic afterburner

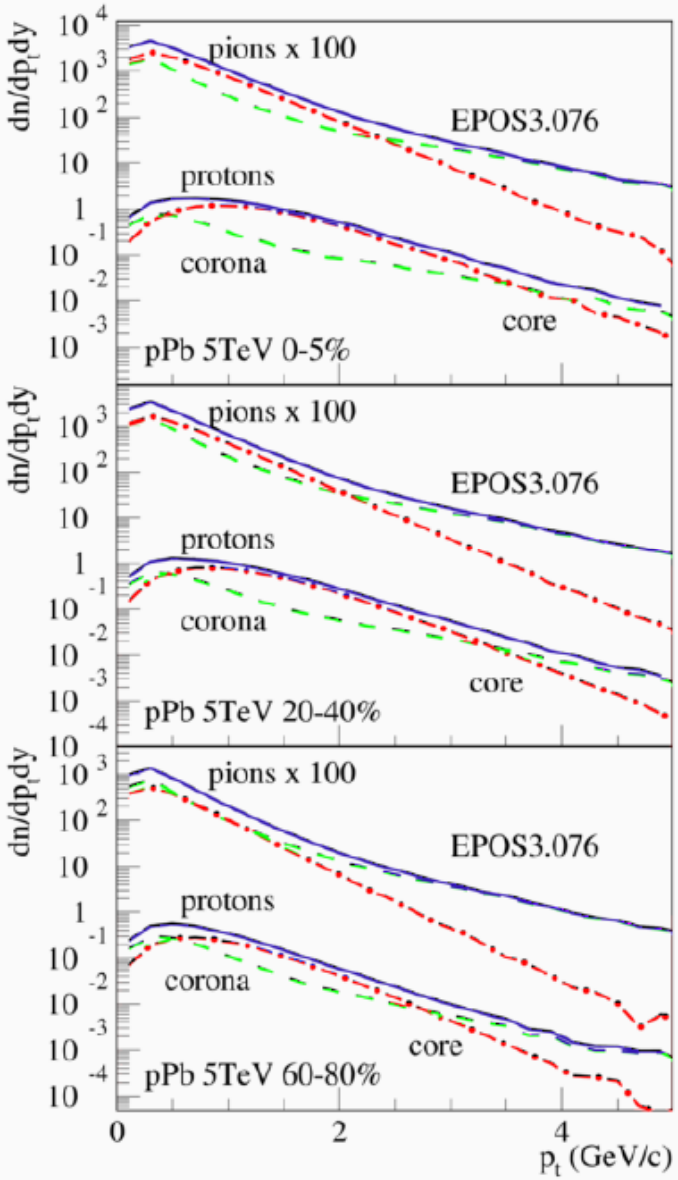
transverse momentum distributions (π, K, p) for different centralities (EPOS2)



green: ALICE data blue: without hadronic cascade red: full calculations

- particlization on hypersurface of constant energy density/temperature $T_H = 166$ MeV, Cooper-Fry procedure.
  (but space-time evolution of fluid dynamical fields is available until $T \sim 130$ MeV)
- subsequent hadronic final state interactions via UrQMD.

Particle production - corona vs. fluid



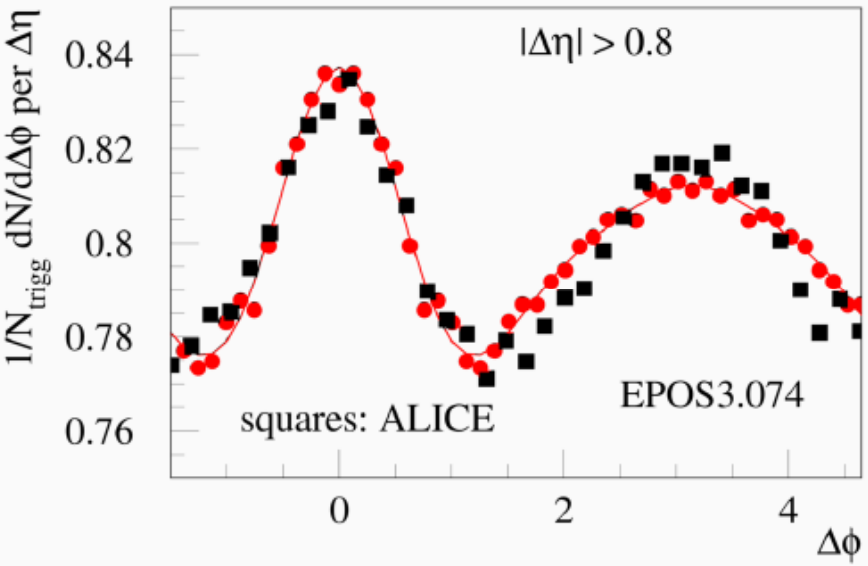
in pPb collisions

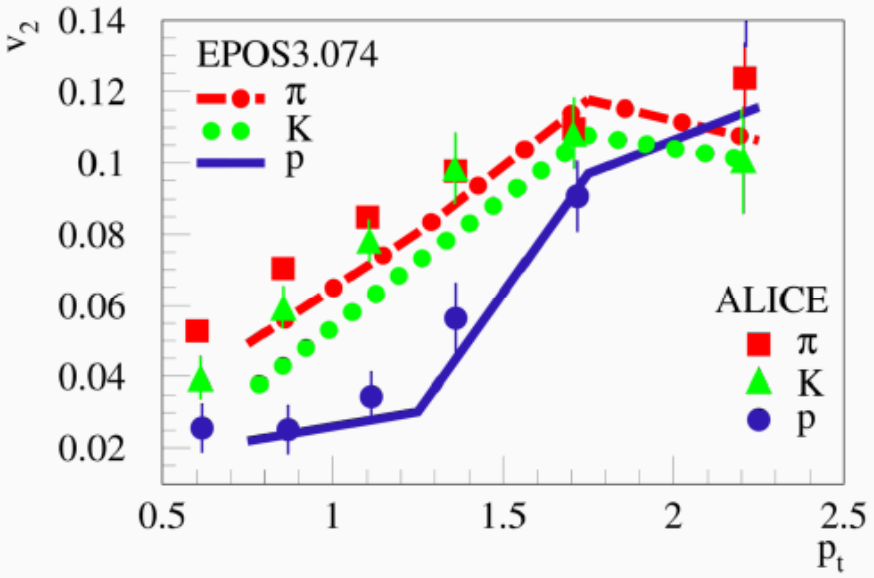
total

core - dominant at low/intermediate p_T

corona - dominant at high-p_T

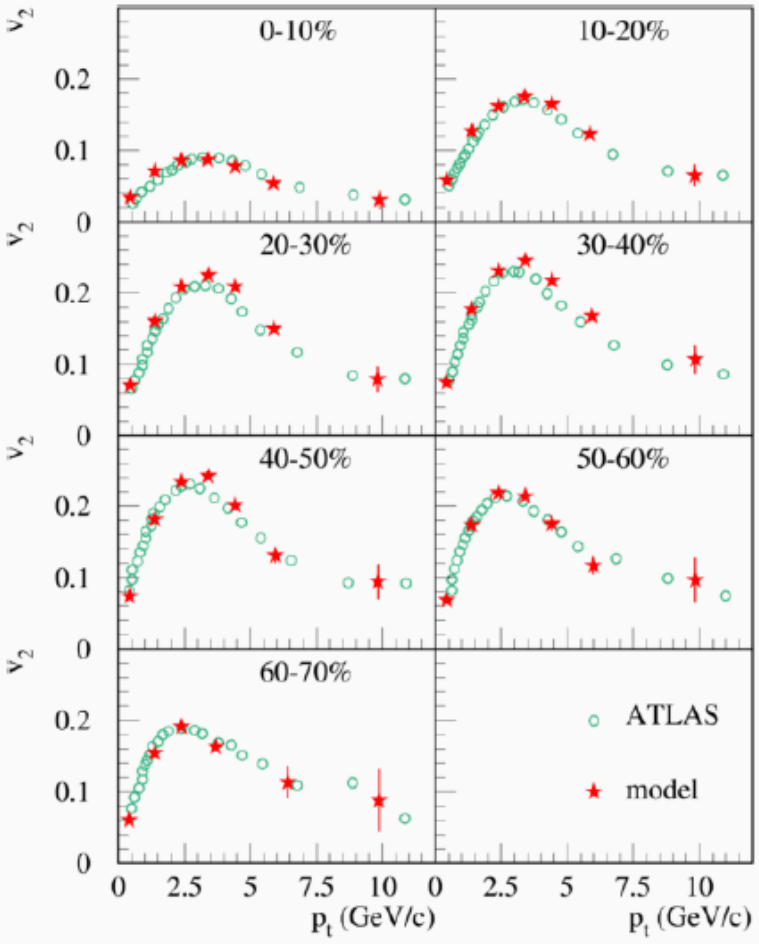
Flow in pPb collisions





mass splitting for v_2 as in PbPb collisions!

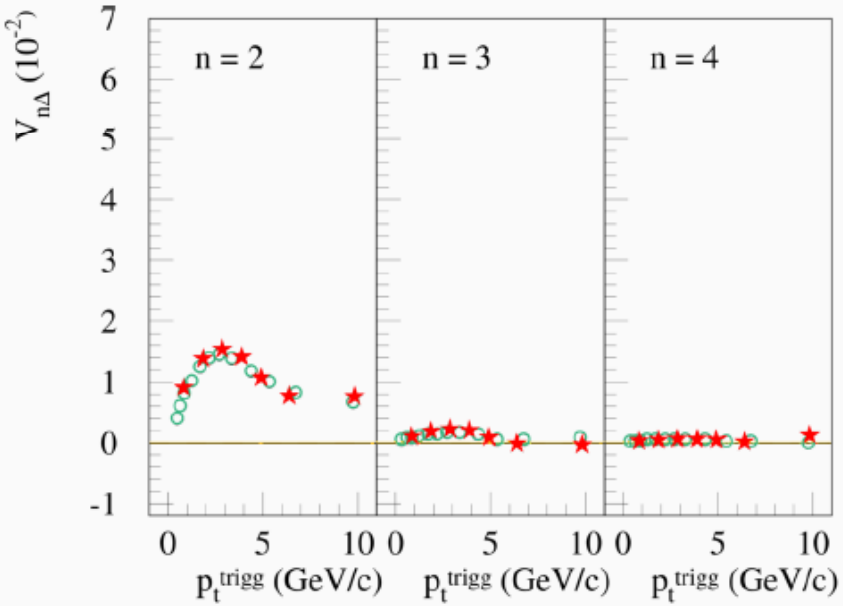
Flow in PbPb collisions



(EPOS2)

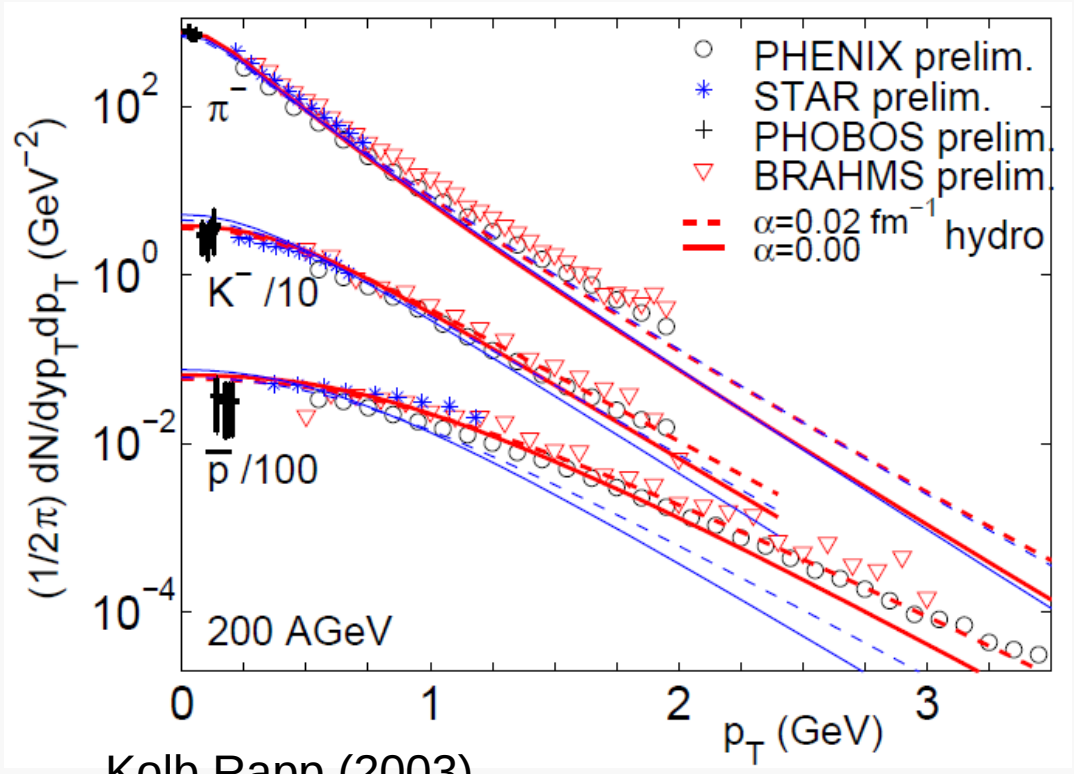
left: v_2 with respect to opposite hemisphere sub-event plane

below: v_n from di-hadron correlations, semi-peripheral collisions, data from ALICE, $p_{T,\mathrm{assoc}} = 0.25 - 0.5$ GeV/c



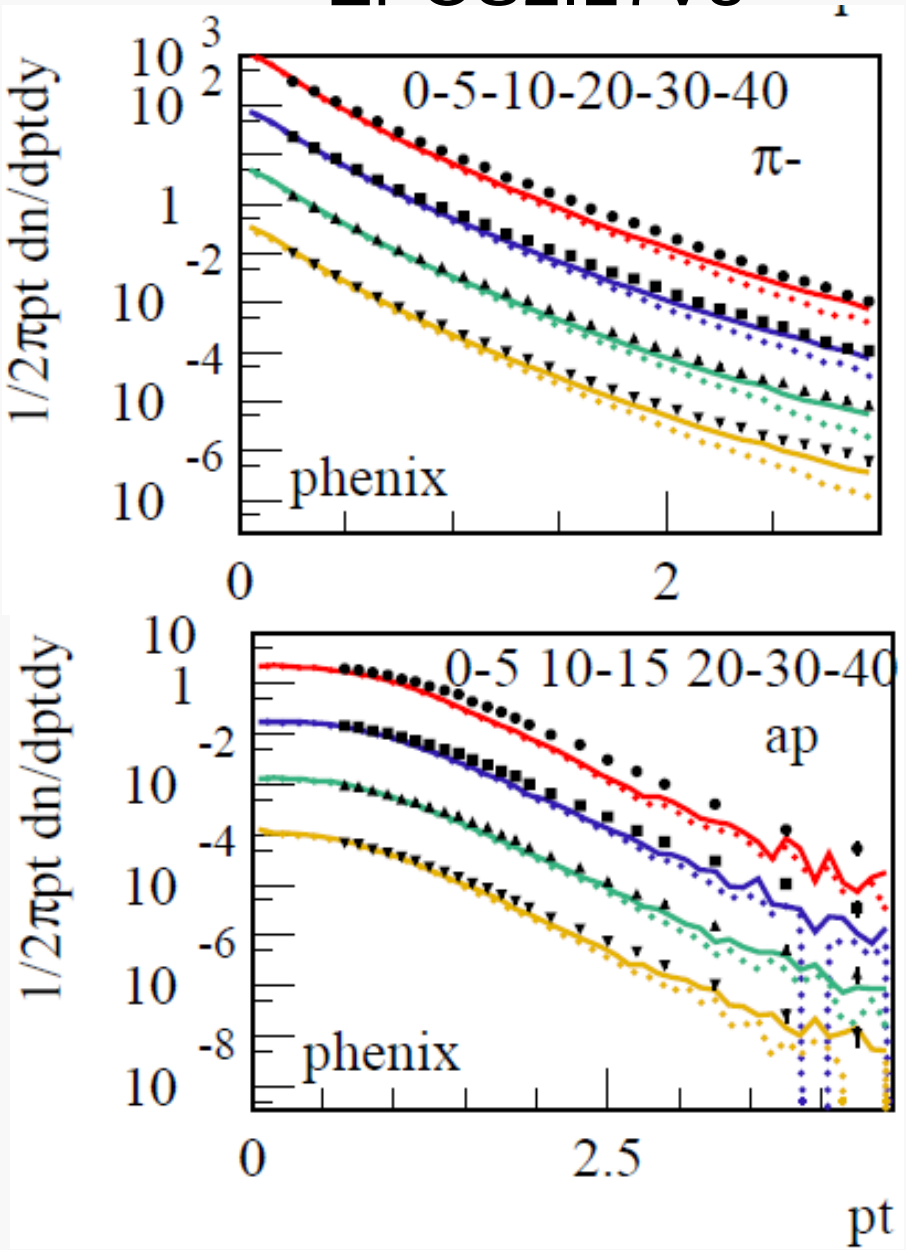
Epos model – Freeze out and hadronic afterburner

Kolb-Heinz



Kolb Rapp (2003)

EPOS2.17V3

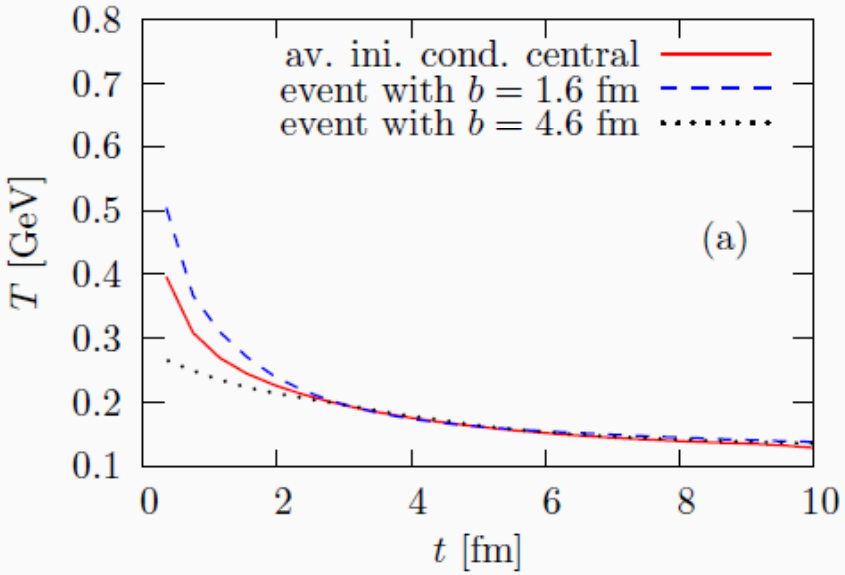


better agreement if
initial flow (vr=tanh(0.02 r))

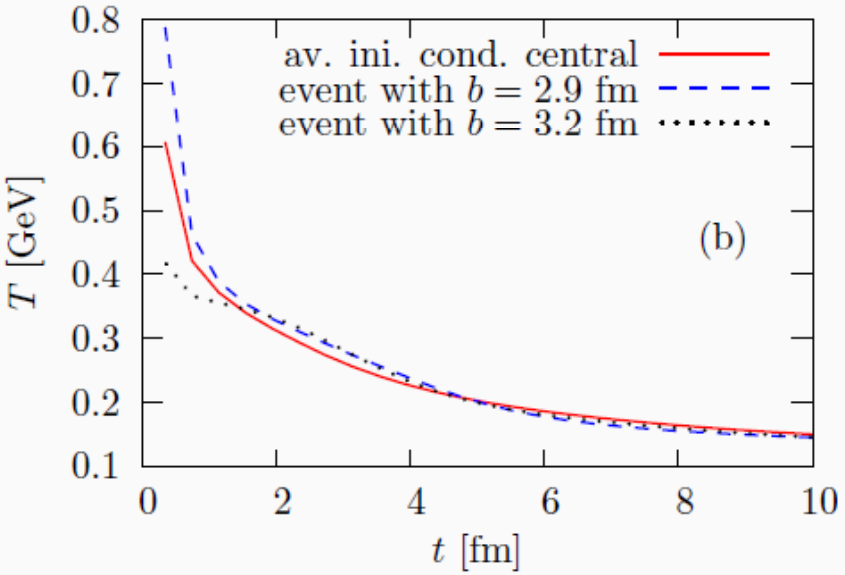
Temperature profiles

A comparison of the temperature evolution in the middle of the fireball ($x = y = \eta = 0$):

RHIC, $\sqrt{s} = 200$ GeV



LHC, $\sqrt{s} = 2.76$ TeV

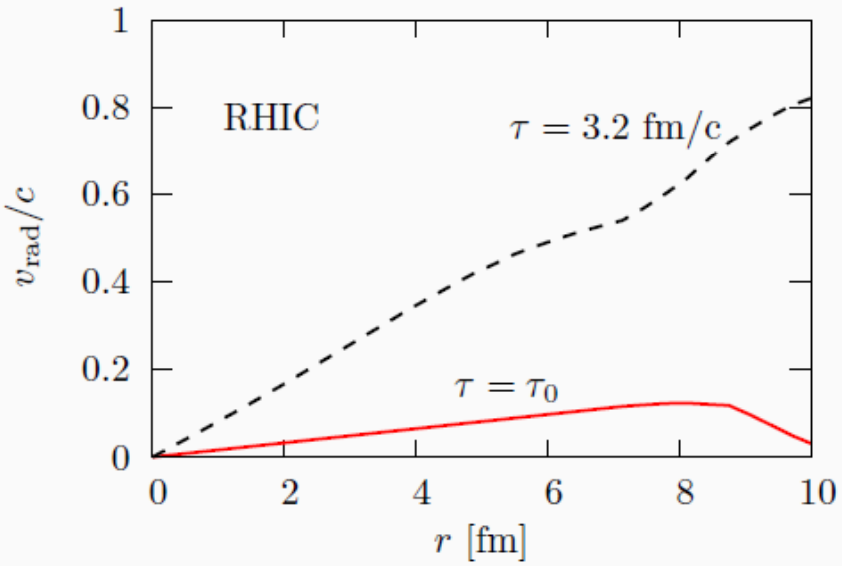


(EPOS2)

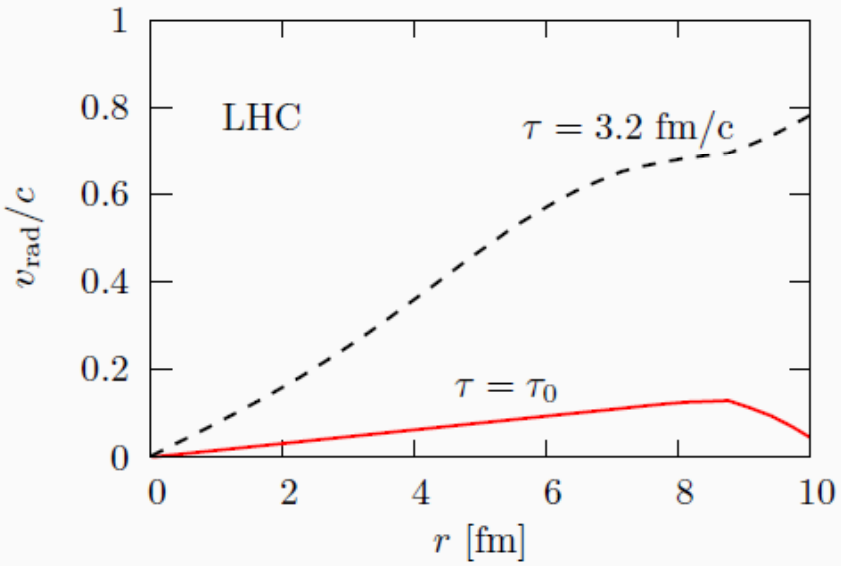
Velocity profiles

A comparison of the radial velocities as a function of the radius in central collisions:

RHIC, $\sqrt{s} = 200$ GeV

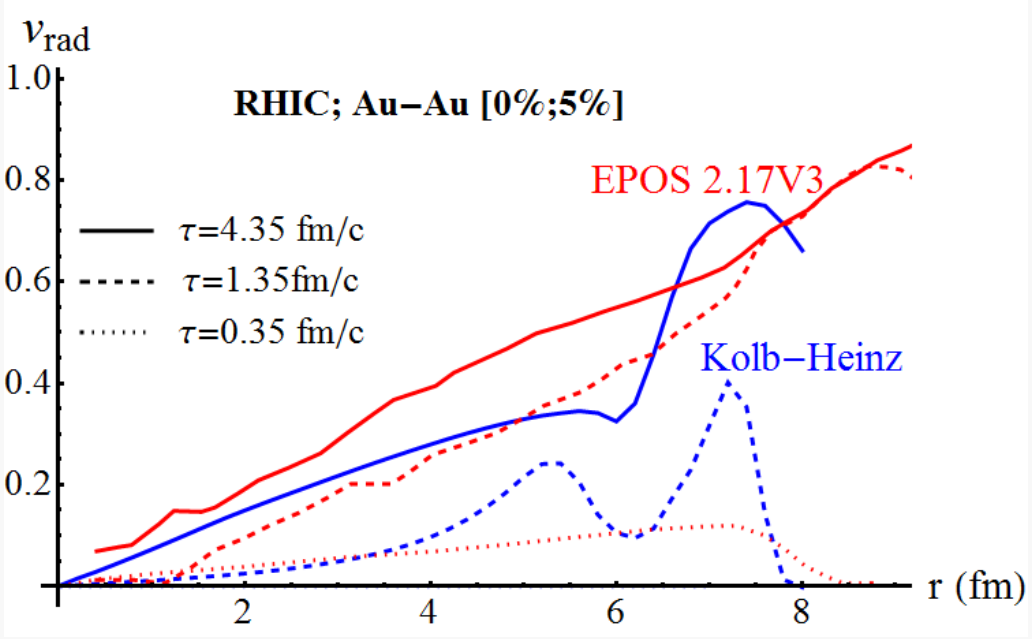


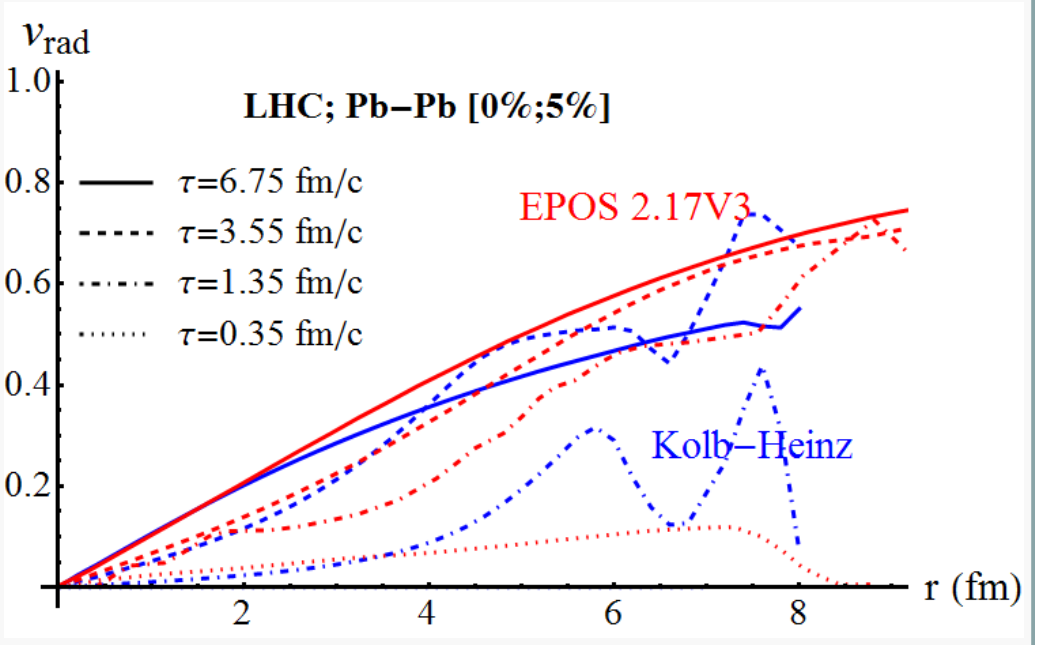
LHC, $\sqrt{s} = 2.76$ TeV



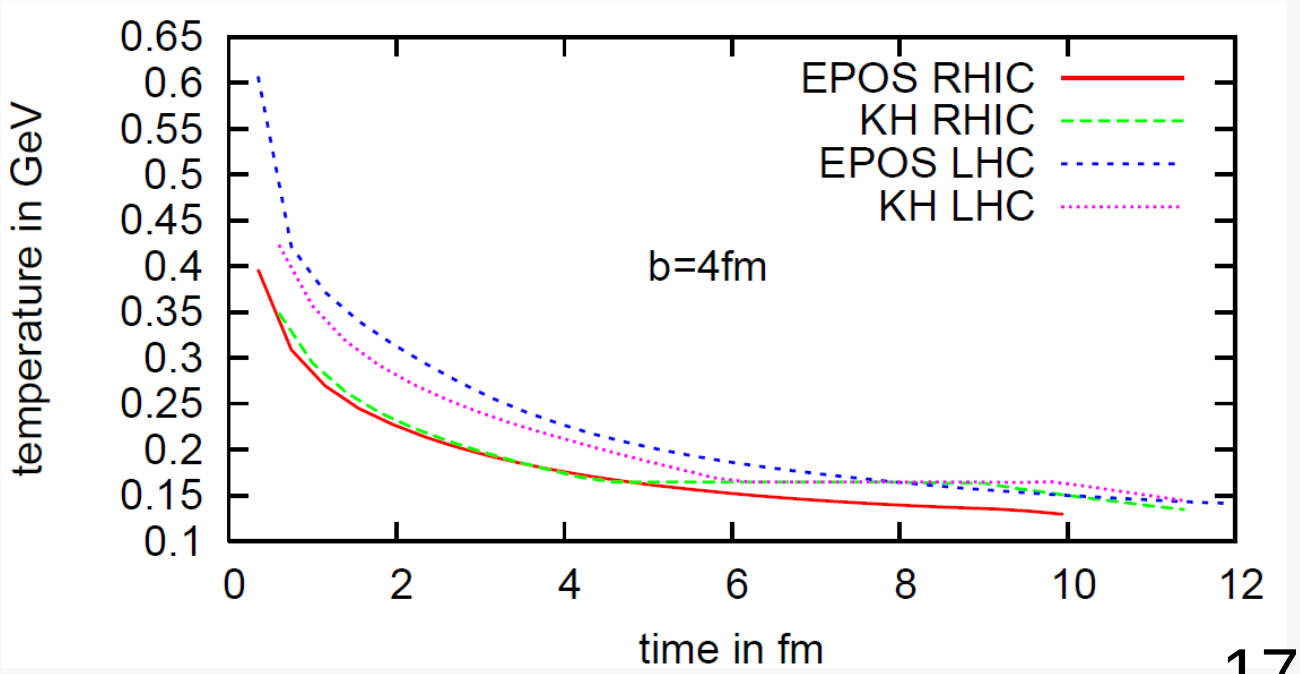
(EPOS2 - includes preequilibrium flow)

Velocity profiles (bis)





EPOS2 hotter and more explosive than Kolb-Heinz

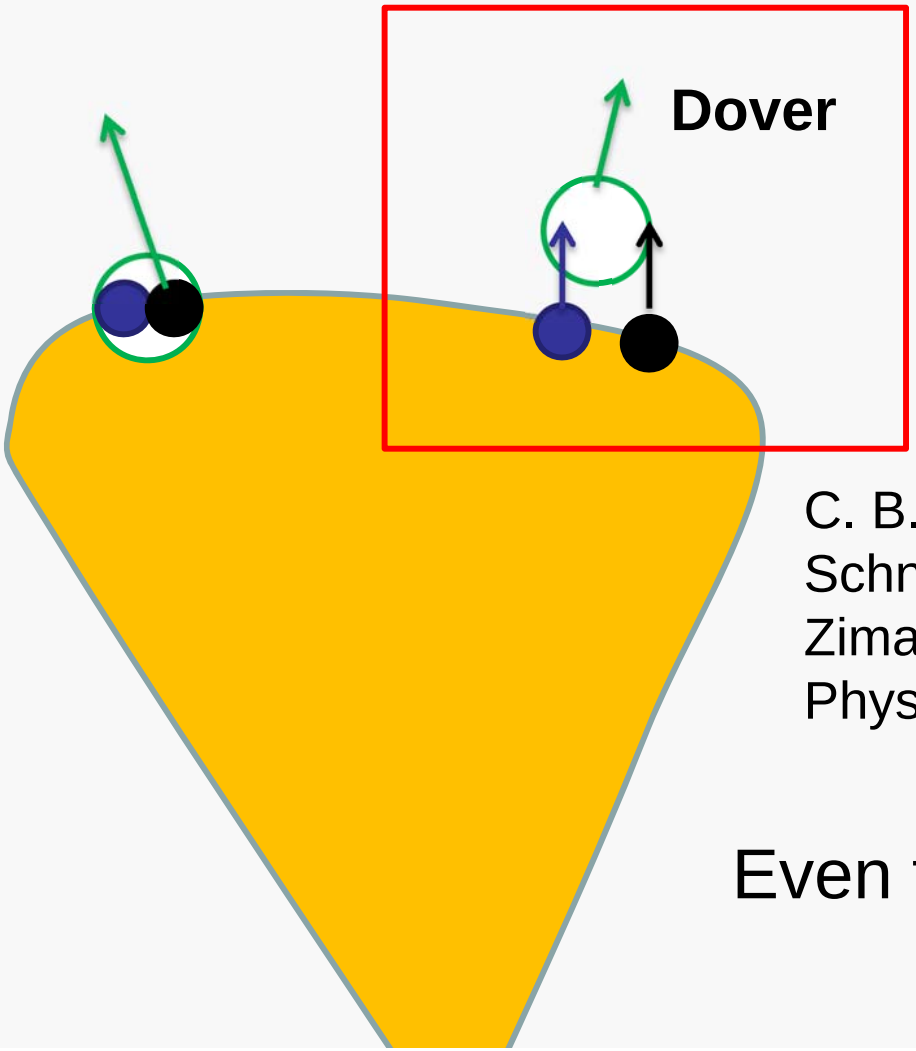


Hadronization

- Coalescence (Main ref.: PHYSICAL REVIEW C **79**, 044906 (2009))
- Global hadronization algorithm

2 physical pictures for coalescence

Lin et Molnar (03) et de Fries, Müller, Nonaka and Bass (03)



2->1

C. B. Dover, U. W. Heinz, E. Schnedermann, and J. Zimanyi,
Phys. Rev. C **44**, 1636 (1991).

Even for 2->1, several ways

$$N_{\Phi=D,B} = \int p_Q \cdot d\sigma_1 p_q \cdot d\sigma_2 \frac{d^3 p_Q}{(2\pi\hbar)^3 E_Q} \frac{d^3 p_q}{(2\pi\hbar)^3 E_q}$$

A delta distribution → $\times f_Q(x_Q, p_Q) f_q(x_q, p_q) f_\Phi(x_Q, x_q; p_Q, p_q)$

Dover vs Gossiaux (spatial)

Dover

Coall. Prob:= D_{sp} x D_p

$$C(x_1,x_2;p_1,p_2)=\alpha_{1,2}^{C}\exp\left[\frac{(x_1-x_2)^2}{2R_C^2}\right]\times\exp\left[\frac{(p_1-p_2)^2-(m_1-m_2)^2}{2P_C^2}\right], \quad (2.14)$$

Particles far away can coalesce !!!

Gaussian space (Gossiaux)

$$f_\Phi(x_Q,x_q;p_Q,p_q)=\exp\left(-\frac{\|\vec{x}_{q,\mathrm{ref\,Q}}\|^2}{2R_c^2}\right)\times\tilde{f}_\Phi(p_Q,p_q)$$

$$=\exp\left(\frac{\Delta x^2-(\Delta x\cdot u_Q)^2}{2R_c^2}\right)\times\tilde{f}_\Phi(p_Q,p_q)$$

2.2.1 (Dover)

2.2.2 (Gossiaux)

$$N_\Phi(x_Q;p_Q)=g_q\int_{p_q\cdot\hat{d\sigma}(x_Q)>0}\frac{d^3p_q}{E_q}\,p_q\cdot\hat{d\sigma}(x_Q)\,e^{-\frac{u_{\mathrm{cell}}(x_Q)\cdot p_q}{T}}\left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3\tilde{f}_\Phi(p_Q,p_q) \quad (29)$$

$$N_\Phi(x_Q;p_Q)=g_q\int_{p_q\cdot\hat{d\sigma}(x_Q)>0}\frac{d^3p_q}{E_q}\,\frac{p_q\cdot\hat{d\sigma}(x_Q)}{u_Q\cdot\hat{d\sigma}(x_Q)}\,e^{-\frac{u_{\mathrm{cell}}(x_Q)\cdot p_q}{T}}\left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3\tilde{f}_\Phi(p_Q,p_q) \quad (48)$$

The only difference

Dover vs Gaussian (momentum)

I. Gaussian p (2.3.1)

$$\tilde{f}_\Phi(\vec{p}_Q,\vec{p}_q) = \exp\left(-\frac{\|\vec{q}\|^2}{2\Lambda_{\rm cm}^2}\right) = \exp\left(-\frac{\|\vec{p}_{q,{\rm ref}\,Q}\|^2}{2m_q^2\alpha_g^2}\right) \quad (58)$$

$$\Lambda_{\rm cm} = \frac{m_q m_Q}{m_q+m_Q}\,\alpha_g \quad (57)$$

Then (also using normalisation)

$$N_\Phi(x_Q;p_Q) = g_q \int_{p_q\cdot\hat{d\sigma}(x_Q)>0} \frac{d^3p_q}{E_q}\, p_q\cdot d\sigma(x_Q)\, e^{-\frac{u_{\rm cell}(x_Q)\cdot p_q}{T}} \left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 \tilde{f}_\Phi(p_Q,p_q) \quad (29/48)$$

$$\underbrace{\left(\frac{\sqrt{2\pi}(m_q+m_Q)}{m_Q m_q \alpha_g}\right)^3}_{c_g} \exp\left(-\frac{\|\vec{p}_{q,{\rm ref}\,Q}\|^2}{2m_q^2\alpha_g^2}\right)$$

with $\|\vec{p}_{q,{\rm ref}\,Q}\|^2 = m_q^2\left[(u_Q\cdot u_q)^2-1\right]$

Dover (x) -Gaussian (p)

$$N_\Phi(x_Q;p_Q) = \tilde{c}_g g_q \int_{u_q\cdot\hat{d\sigma}(x_Q)>0} \frac{d^3u_q}{u_0}\, u_q\cdot\hat{d\sigma}(x_Q)\, e^{-\left(\frac{m_q}{T}u_{\rm cell}(x_Q)\cdot u_q + \frac{(u_Q\cdot u_q)^2-1}{2\alpha_g^2}\right)} \quad (60)$$

with $\tilde{c}_g = \left(\frac{(m_q+m_Q)}{\sqrt{2\pi}m_Q\alpha_g}\right)^3$

Gossiaux (x) - Gaussian (p): $u_q\cdot\hat{d\sigma}(x_Q) \to \frac{u_q\cdot\hat{d\sigma}(x_Q)}{u_Q\cdot\hat{d\sigma}(x_Q)}$

Dover vs Gaussian (momentum)

II Dover (2.3.2)

$$\tilde{f}_\Phi(p_Q, p_q) = \exp\left(-\left(\frac{m_Q m_q}{(m_q + m_Q)\Lambda_d}\right)^2 (u_q \cdot u_Q - 1)\right) \quad \text{with} \quad \Lambda_d = \frac{m_q m_Q}{mq + m_Q}\alpha_d$$

(63)

Then (also using normalisation) $\left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 = \left(\frac{m_Q + m_q}{m_Q m_q}\right)^3 \times \frac{1}{4\pi\alpha_d^2 K_2\left(\frac{1}{\alpha_d^2}\right) e^{\frac{1}{\alpha_d 2}}}$

$$N_\Phi(x_Q; p_Q) = g_q \int_{p_q \cdot d\hat{\sigma}(x_Q) > 0} \frac{d^3 p_q}{E_q}\, p_q \cdot d\hat{\sigma}(x_Q)\, e^{-\frac{u_{\text{cell}}(x_Q)\cdot p_q}{T}} \left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 \tilde{f}_\Phi(p_Q, p_q)$$

(29/48)

Dover (x) - Dover (p)

$$N_\Phi(x_Q; p_Q) = \tilde{c}_d g_q \int_{u_q \cdot d\hat{\sigma}(x_Q) > 0} \frac{d^3 u_q}{u_0}\, u_q \cdot d\hat{\sigma}(x_Q)\, e^{-\left(\frac{m_q}{T} u_{\text{cell}}(x_Q) + \frac{u_Q}{\alpha_d^2}\right)\cdot u_q} \quad (73)$$

with $\tilde{c}_g = \left(\frac{m_Q + m_q}{m_Q}\right)^3 \times \frac{1}{4\pi\alpha_d^2 K_2\left(\frac{1}{\alpha_d^2}\right)}$

$$u_q \cdot d\hat{\sigma}(x_Q) \to \frac{u_q \cdot d\hat{\sigma}(x_Q)}{u_Q \cdot d\hat{\sigma}(x_Q)}$$

Gossiaux (x) - Dover(p) **(our favorite)**

Calibration: section 2.4

Assuming u_{cell} oriented along $d\sigma$

4 combinations

$$N_{\Phi,D,G}(x_Q u_{\rm cell}\cdot u_Q) = \tilde{c}_g g_q \int \frac{d^3u_q}{u^0} u_q\cdot u_{\rm cell}\, e^{-\left(\frac{m_q}{T}u_q\cdot u_{\rm cell}+\frac{(u_Q\cdot u_q)^2-1}{2\alpha_g^2}\right)} \quad (75)$$

$$N_{\Phi,D,D}(x_Q; u_{\rm cell}\cdot u_Q) = \tilde{c}_d g_q \int \frac{d^3u_q}{u^0} u_q\cdot u_{\rm cell}\, e^{-\left(\frac{m_q}{T}u_{\rm cell}+\frac{u_Q}{\alpha_d^2}\right)\cdot u_q}. \quad (76)$$

space momentum

$$N_{\Phi,Gx,G}(x_Q; u_{\rm cell}\cdot u_Q) = \tilde{c}_g g_q \int \frac{d^3u_q}{u^0}\frac{u_q\cdot u_{\rm cell}}{u_Q\cdot u_{\rm cell}} e^{-\left(\frac{m_q}{T}u_q\cdot u_{\rm cell}+\frac{(u_Q\cdot u_q)^2-1}{2\alpha_g^2}\right)} \quad (77)$$

$$N_{\Phi,Gx,D}(x_Q; u_{\rm cell}\cdot u_Q) = \tilde{c}_d g_q \int \frac{d^3u_q}{u^0}\frac{u_q\cdot u_{\rm cell}}{u_Q\cdot u_{\rm cell}} e^{-\left(\frac{m_q}{T}u_{\rm cell}+\frac{u_Q}{\alpha_d^2}\right)\cdot u_q} \quad (78)$$

One needs to fix the parameters (mq and Λ_{xxx} / $\alpha_{d/g}$)

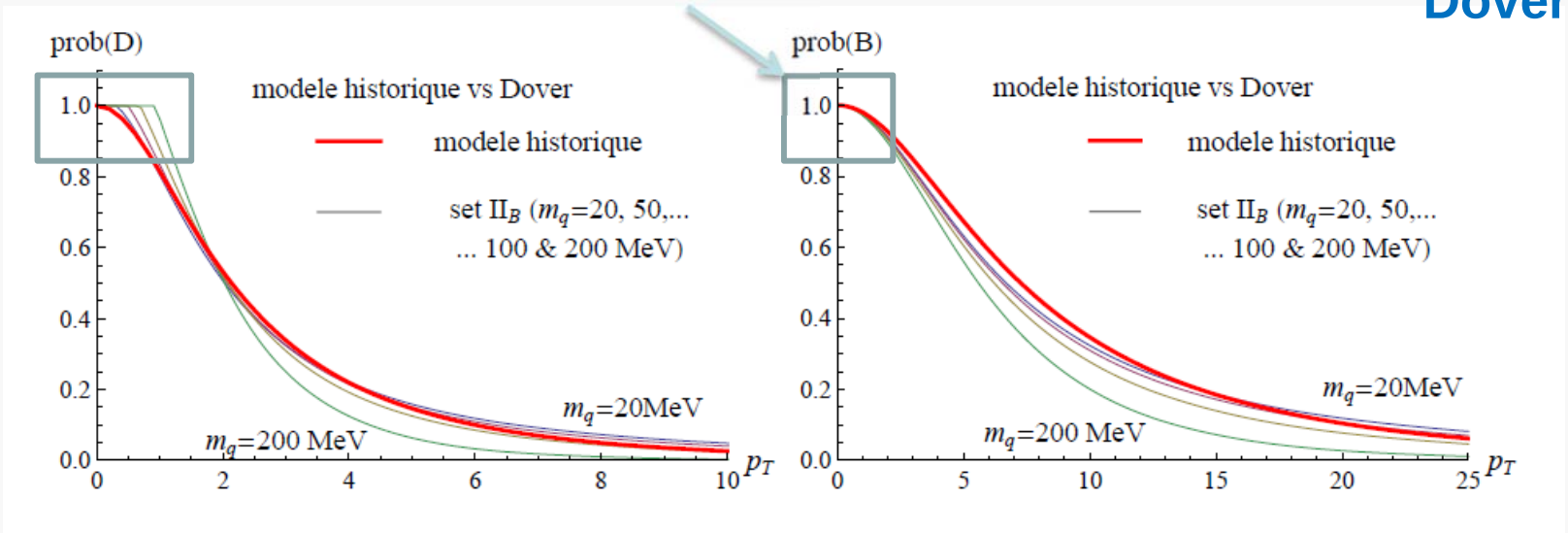
Calibration: section 2.4.5 (& 2.4.3)

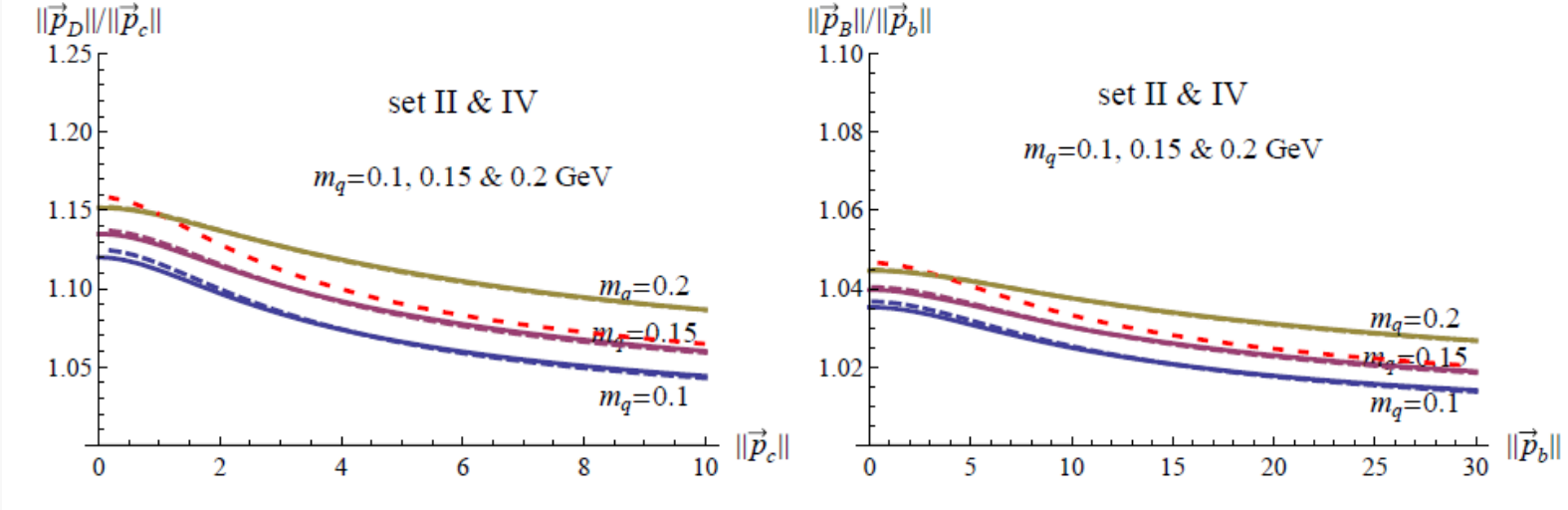
Assuming: u_{cell} oriented along $d\sigma$ and general p_Q

And Gossiaux spatial

Parameters tuned such that prob b->B is = 1 through coalescence

Dover p (set II)





$$m_q \approx 100 \text{ MeV} \quad \text{et} \quad \alpha_d = 0.876 \ (\text{set } II_{\text{b}}\text{bis})$$

Optimal wrt hist. model

General (section 2.5) **Assuming: $u_q \cdot d\sigma > 0$ (space-like surface)**

Dover spacial

$$N_{\Phi,D,D}(x_Q;p_Q) = \left(\frac{m_Q+m_q}{m_Q}\right)^3 \frac{m_q g_q}{\alpha_d^2 T K_2\left(\frac{1}{\alpha_d^2}\right)} \times (u_{\text{cell}} + \mu\, u_Q)\cdot \hat{d\sigma} \times \frac{K_2(D)}{D^2}$$

with $$D = \frac{m_q}{T} \times \sqrt{1 + 2\mu u_{\text{cell}}\cdot u_Q + \mu^2} \quad \text{et} \quad \mu = \frac{T}{m_q \alpha_d^2}$$

Gossiaux spatial

$$N_{\Phi,Gx,D}(x_Q;p_Q) = \left(\frac{m_Q+m_q}{m_Q}\right)^3 \frac{m_q g_q}{\alpha_d^2 T K_2\left(\frac{1}{\alpha_d^2}\right)} \times \left(\mu + \frac{u_{\text{cell}}\cdot \hat{d\sigma}}{u_Q \cdot \hat{d\sigma}}\right) \times \frac{K_2(D)}{D^2}$$

After normalization

Depends on 3 invariant quantities

$$\text{prob}_\Phi(x_Q;p_Q) = \max\left(ff \times \text{prob}_\Phi(x_Q;p_Q,\hat{d\sigma}=u_{\text{cell}}),1\right)$$

$$\text{prob}_\Phi(x_Q;p_Q,\hat{d\sigma}=u_{\text{cell}}) = \left(\mu + \frac{1}{u_Q\cdot u_{\text{cell}}}\right)\left(\frac{m_Q+m_q}{m_Q}\right)^3 \frac{m_q g_q}{T}\frac{K_2(D)/D^2}{K_2\left(\frac{1}{\alpha_d^2}\right)/\frac{1}{\alpha_d^2}}$$

Fig 2 of PRC79

$$ff = \frac{\mu + \frac{u_{\text{cell}}\cdot\hat{d\sigma}}{u_Q\cdot\hat{d\sigma}}}{\mu + \frac{1}{u_Q\cdot u_{\text{cell}}}}$$

Flux factor

Caviats

1) m_q probably too small

2) Coalescence -> « average » D meson (chemistry not taken into account)

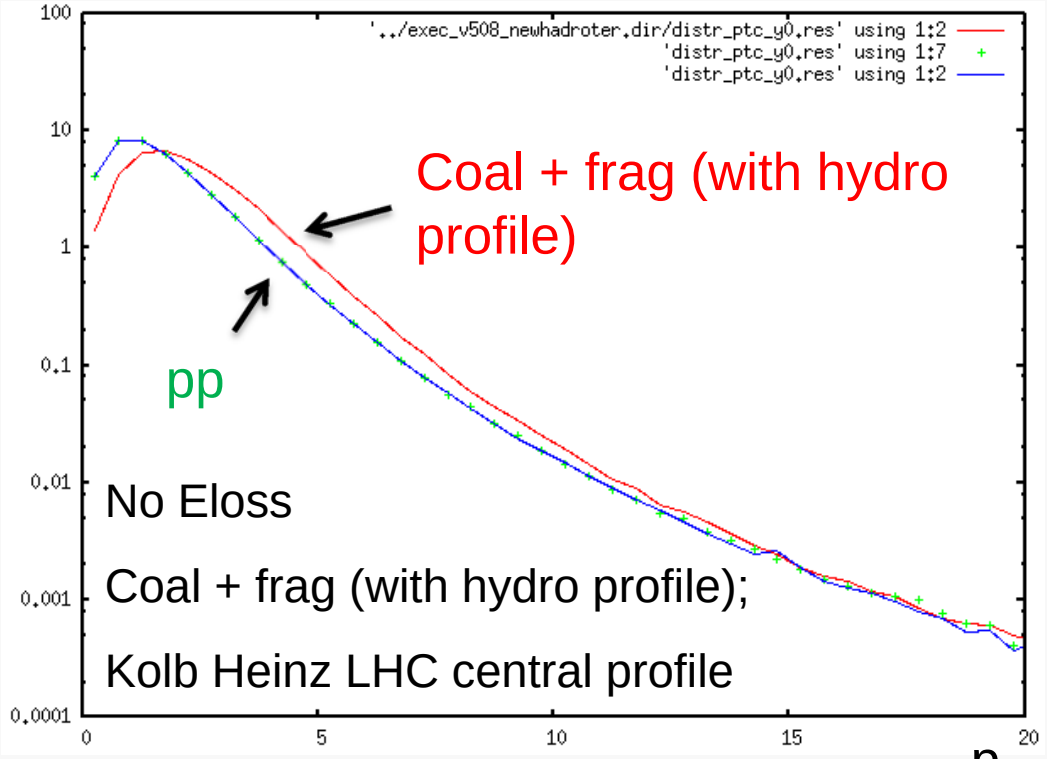
Hadronization algorithm

1) For pp: use p_T-frag ($y_D=y_c$ and $\mathbf{p}_{TD}=z\ \mathbf{p}_{Tc}$)

2) For pA or AA:
   1) Perform criteria in the fluid cell rest frame
   2) When fragmentation is chosen perform the same fragmentation as in pp, staying in the lab frame

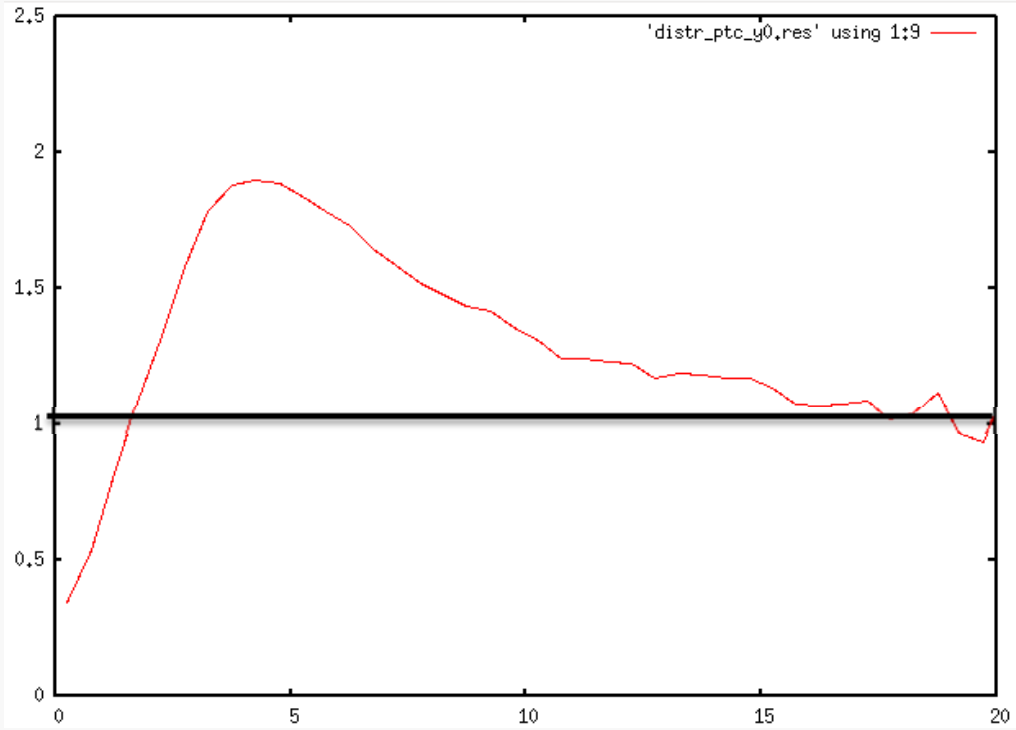
This allows to preserve the rapidity invariance as well as Q (ratio) =1 if no Eloss (and no shadowing)…(NOT SO TRIVIAL !!!) Then looking for the coal + frag case:

dN_D/dp_T



p_T

$Q_D(p_T)$



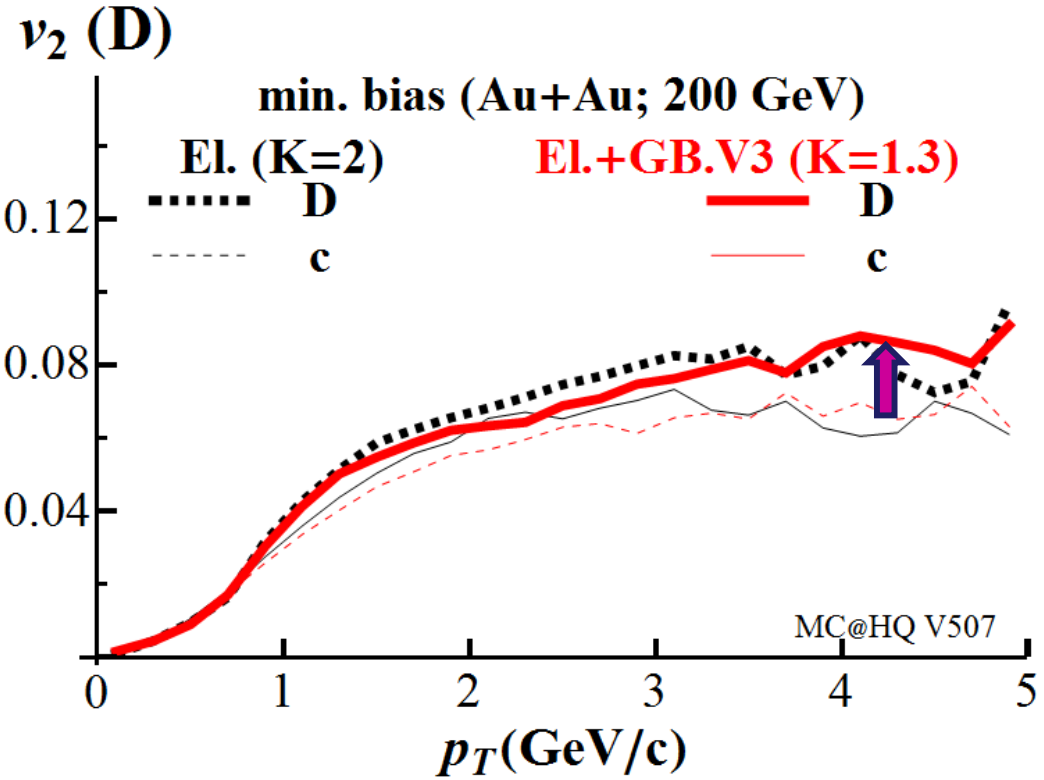
p_T

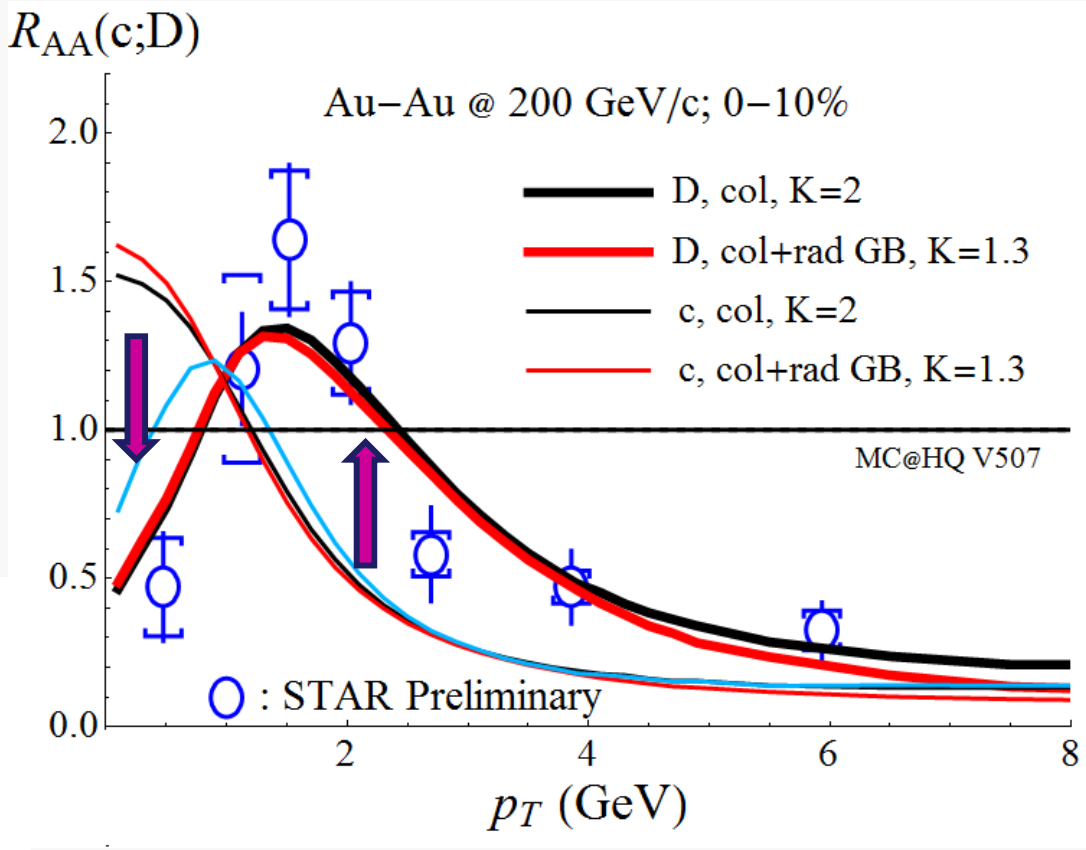
While boost invariance is preserved as well for boost invariant QGP (checked but not shown)

some effects on HQ evolution

Basic observables (RHIC)

Kolb Heinz hydro

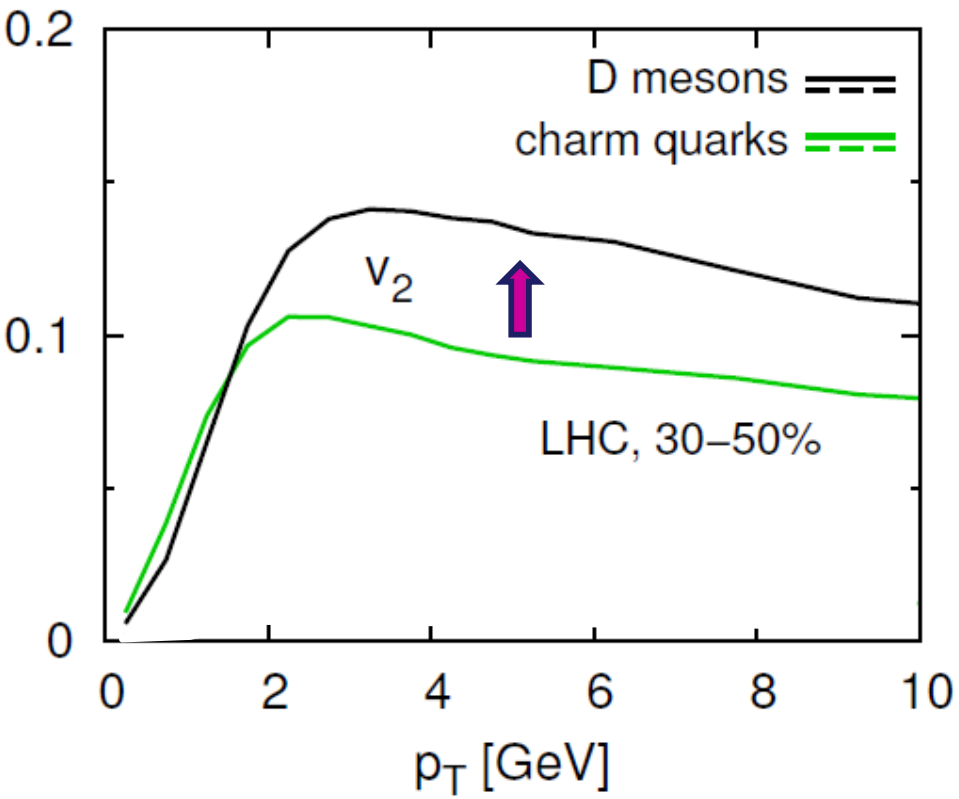


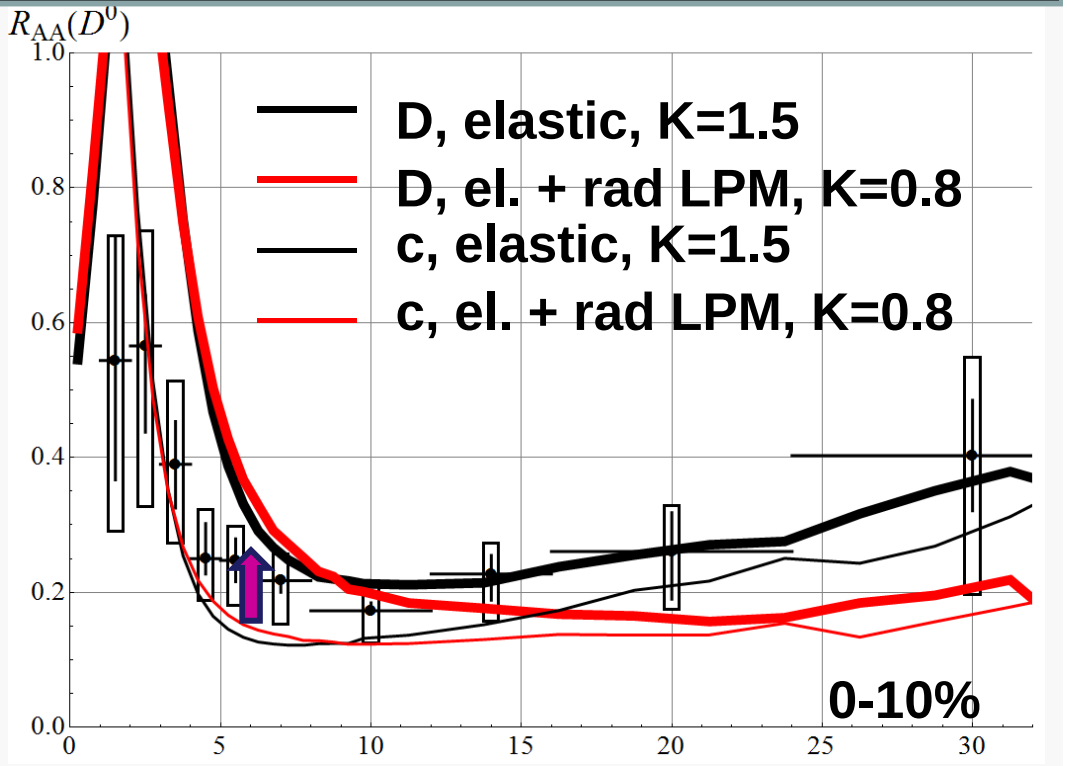


Large effects from coalescence (especially in the R_{AA})… to be studied in a more systematic way

Basic observables (LHC 2.76 TeV)

EPOS2





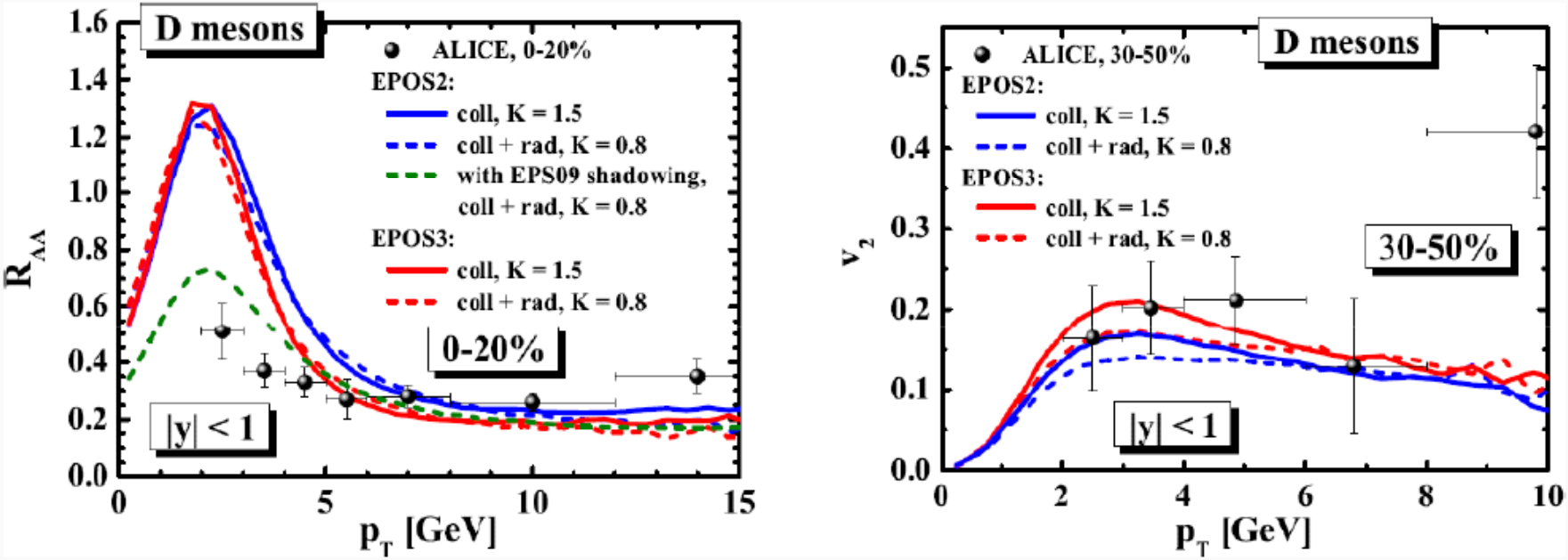
Large effects from coalescence for both observables

Comparison between EPOS2 and EPOS3

EPOS2: ideal fluid dynamics with initial smearing to flux tube size to mimick viscosity

EPOS2+shadowing

EPOS3: viscous fluid dynamics ($\eta/s = 0.08$) and individual parton saturation scales as described earlier



EPOS3 calculations by V. Ozvenchuk

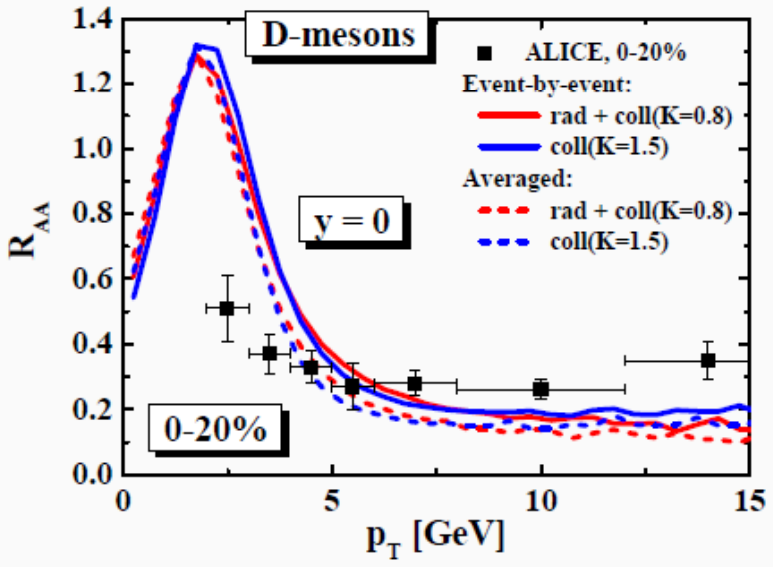
$\Rightarrow$ visible difference even in two similar approaches that both describe light hadron data VERY WELL... problematic or could be an opportunity to probe more details?!

Average vs. fluctuating IC

- consider medium with local fluctuations $\varepsilon(x) = \varepsilon_0 + \delta\varepsilon(x)$ around an averaged energy density $\langle\varepsilon(x)\rangle = \varepsilon_0$
- local energy loss: $\mathrm{d}E/\mathrm{d}x \propto T^\beta$ with $\beta \approx 1$ for collisional energy loss with running α_s to $\beta \approx 2$ for radiative LPM

- $\varepsilon \propto T^n$, with $n \approx 4$ from EoS
- $\frac{\mathrm{d}E}{\mathrm{d}x} \propto \varepsilon^\delta \quad \text{with} \quad \delta = \frac{\beta}{n} < 1$

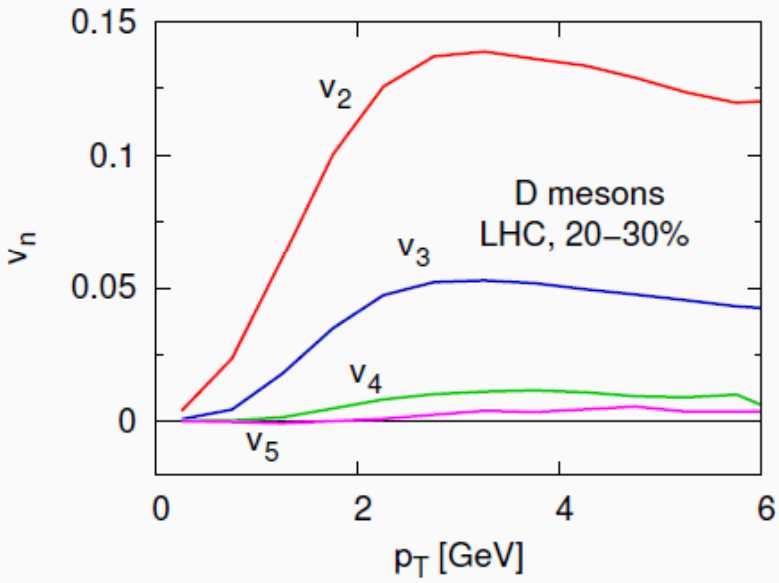
$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \frac{\mathrm{d}E(\varepsilon_0)}{\mathrm{d}x} \times \left[1 - \frac{\delta(1-\delta)}{2} \frac{\langle \delta\varepsilon^2 \rangle}{\varepsilon_0^2} + \cdots \right] .$$

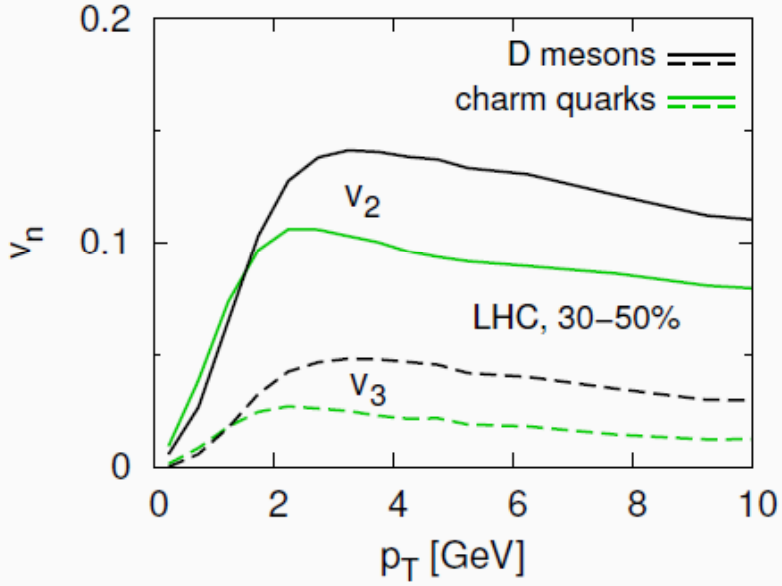


⇒ Less energy loss for event-by-event studies compared to average medium evolution!

Fluctuating IC → finite triangular flow

Fluctuating initial conditions enables us to study higher order flow harmonics for heavy quarks:





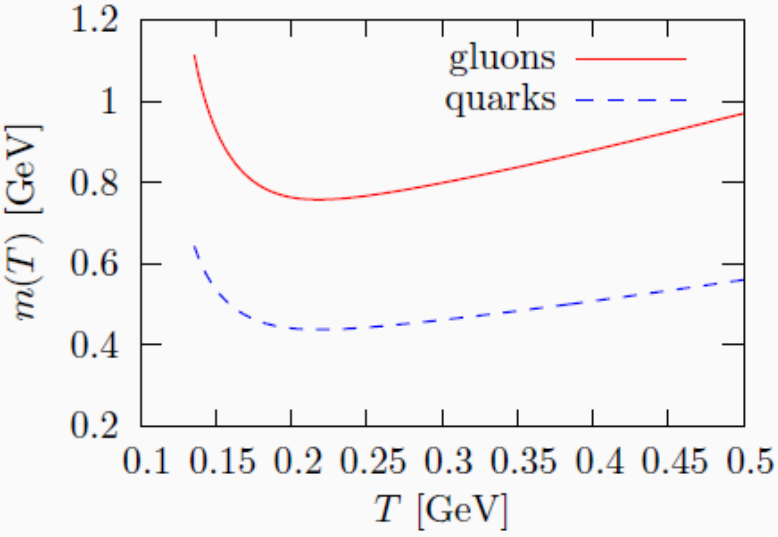
⇒ finite triangular flow for D mesons predicted! First STAR analysis under way.

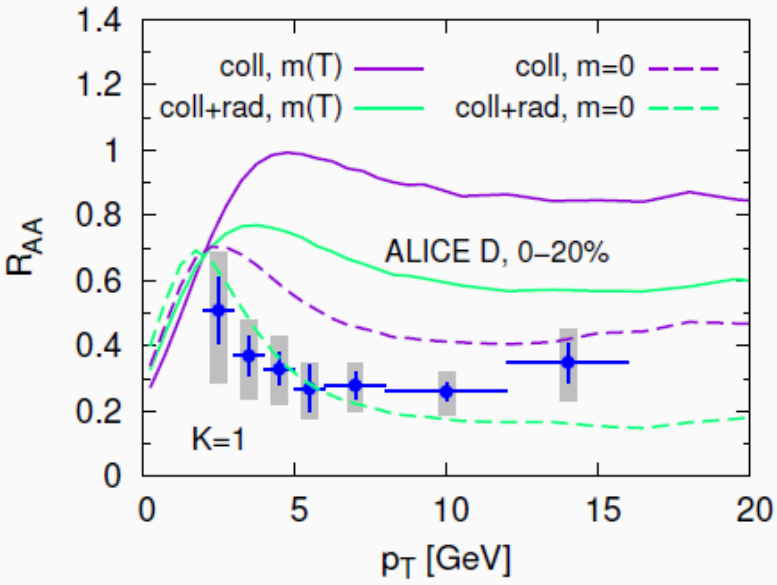
M. Nahrgang, J. Aichelin, S. Bass, P. B. Gossiaux, K. Werner, Phys.Rev. C91 (2015); J.Phys.Conf.Ser. 668 (2016)

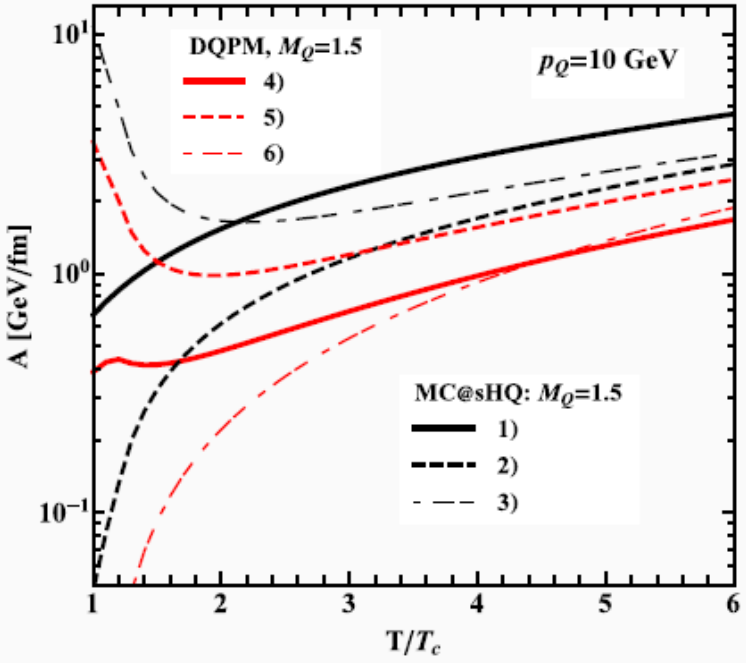
Interpretation of the EoS

scattering partner of HQ are thermal quasiparticles in the medium ⇒ nature of these quasiparticles matter!

typically, one uses either massless quasi-particles or with thermal masses from pQCD, which DOES NOT reproduce the lattice EoS!







Conclusions

The use of a realistic model for the bulk evolution is indispensable for the study of traditional (R_{AA} and v_2) and new (v_n and $\Delta\phi$ correlations) HQ observables!

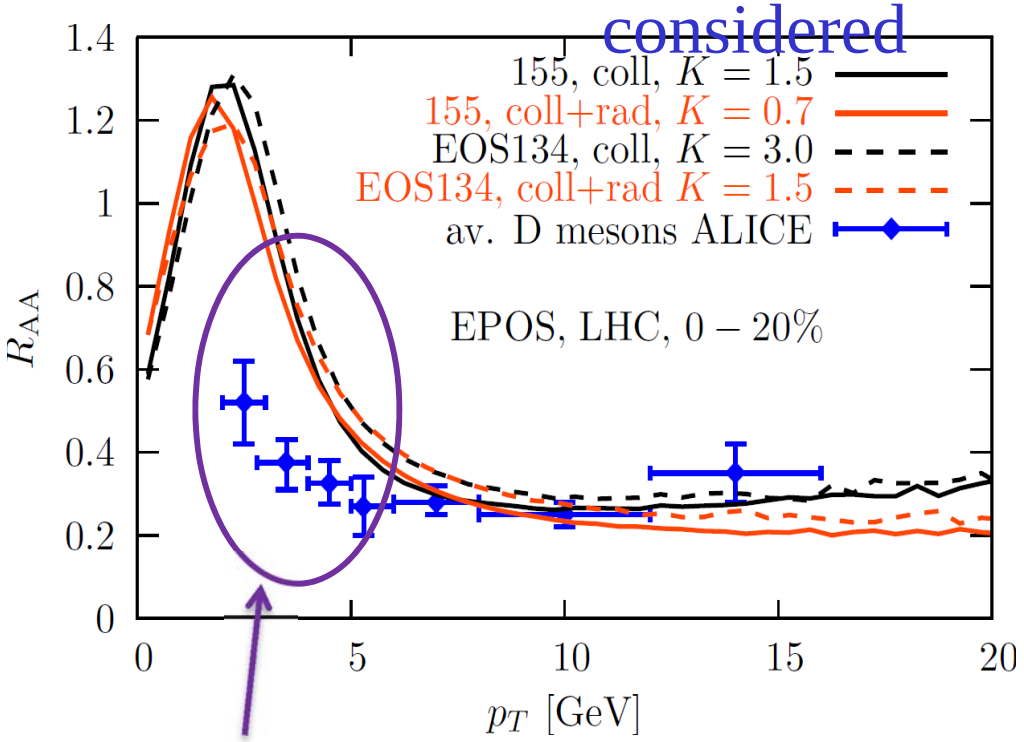
It can also serve as an opportunity to investigate more details of the QGP: initial conditions, nature of quasiparticles, etc.

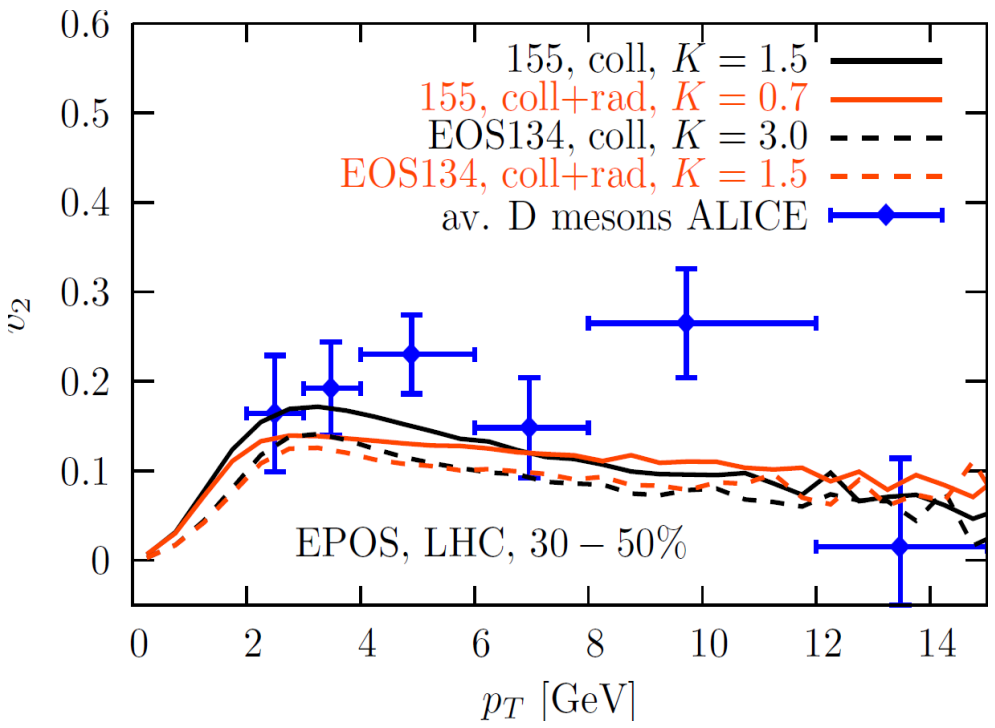
Back up

Some EPOS2+MC@sHQ results at LHC

K values fixed at p_T=10 GeV/c, x2 if reduction of dof according to EOS134 !

Still close to unity if rad + col considered





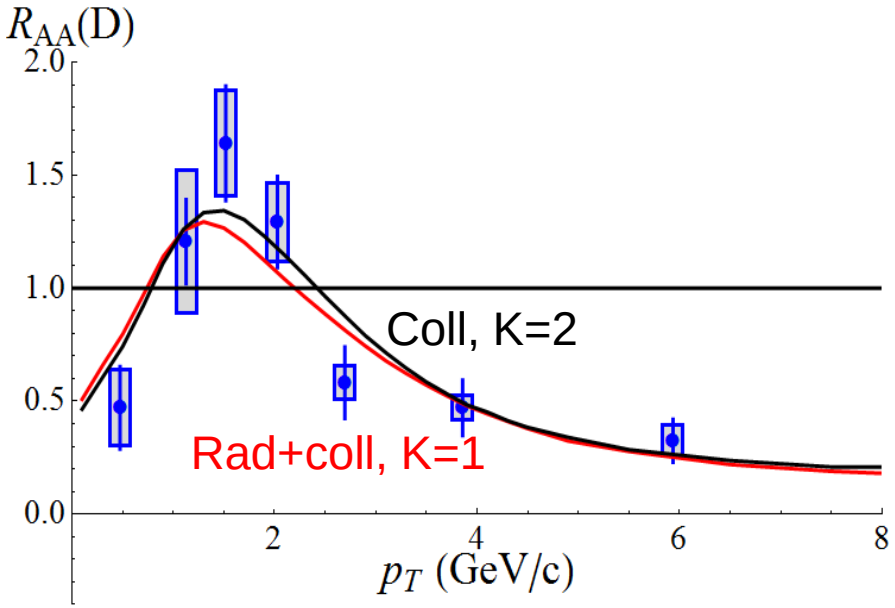
Large push from the radial flow; discrepancy unlikely to be explained by shadowing alone.

Concerns: Need to revisit the model for small p ? (Bad) consequences for v2 ?

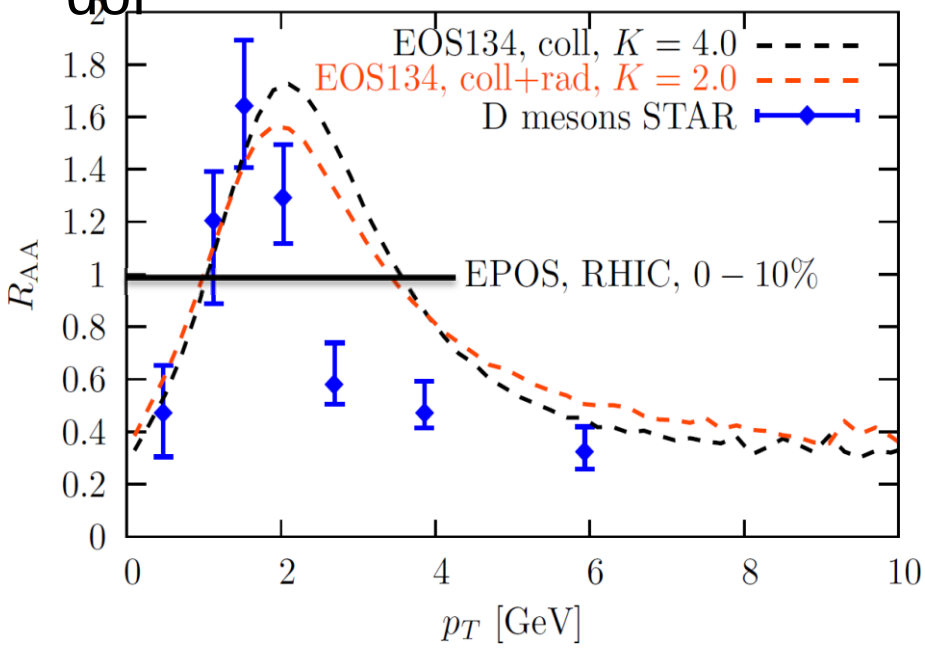
Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together

Some EPOS2+MC@sHQ results at RHIC

KH background



EPOS background + reduction of dof



Larger radial flow in EPOS

Both « cocktails » (HF energy loss + background + K factor) provide a fair agreement with the data

Data at larger pT would help a lot !

Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together