Open charm in heavy-ion collisions

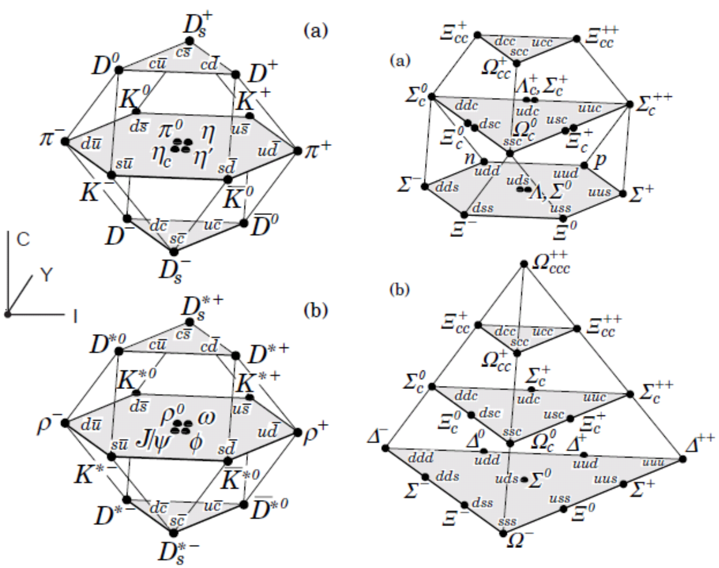
A Heavy-Ion Seminar talk by Szymon Harabasz

TECHNISCHE UNIVERSITÄT DARMSTADT

Outline:

- Charmed hadrons
- Why charm physics?
- How to do charm physics
- Open questions on open charm:
    - D mesons R_{AA} at low p_T at RHIC
    - D mesons R_{AA} compared to pions
    - D mesons R_{AA} compared to beauty
    - v_2 of D mesons

Charmed hadrons



Particle	J^P	Quark Content	Mass (GeV/c^2)	cτ
D^0	0^-	$c\bar{u}$	1.86	124 μm
$D^\pm$	0^-	$c\bar{d}$ / $\bar{c}d$	1.87	317 μm
D^{*0}	1^-	$c\bar{u}$	2.01	94 fm
$D^{*\pm}$	1^-	$c\bar{d}$ / $\bar{c}d$	2.01	1500 fm
$D_s^\pm$	0^-	$c\bar{s}$ / $\bar{c}s$	1.97	140 μm
Λ_c^+	$½^+$	udc	2.29	62 μm
J/Ψ	1^-	$c\bar{c}$	3.10	(Γ=92.9 keV)
Ψ’	1^-	$c\bar{c}$	3.69	(Γ`~300 keV)

Reminder (mainly for the speaker):

$Q=I_3+½Y$

Relatively large mass of c-quark leads to breaking of SU(4) flavor symmetry and to mass differences between multiplets‘ components.

Why is charm physics charming?

Mass of about 1.3 GeV is larger than:

- Λ_{QCD} (about 0.2 GeV)
- QCD phase transition temperature (of the order of ~0.15 GeV)
- Typical temperatures at early stages of HIC
  (about 0.3-0.4 at RHIC maximum energies)

→ **produced mainly in initial N-N hard-scattering interactions**

→ **production described by pQCD**

→ at the same time it is small enough to make charmed hadrons sensitive to reinteractions in medium and c-quarks to reinteractions in QGP

Why is charm physics charming?

TECHNISCHE UNIVERSITÄT DARMSTADT

c-quarks are produced early in the collision (~ $1/2m_c \rightarrow t_c$=0.08 fm)

Charmed hadrons are produced late, at time scale comparable to the lifetime of QGP τ_{QGP} ~ 5 fm/c (top RHIC energies)

Time scales for quark production and hadronization are separated $\rightarrow$ "Factorization"

Why is charm physics charming?

They preserve the identity (cannot be created/destroyed)

→ **are propagated through the medium during its evolution**

$$\sigma_{c\bar{c}} = 1/2 \; [\sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \cdots]$$

Medium modifications may affect redistribution of charm among hadrons, but not the total production cross section

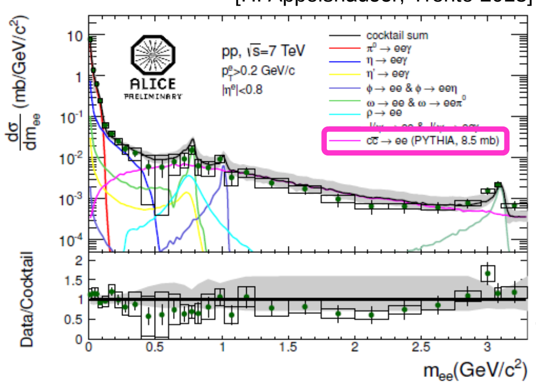
It is inconsistent with the charm conservation to reduce all charmed hadron masses in the medium
→ It would increase cross section

Moreover…

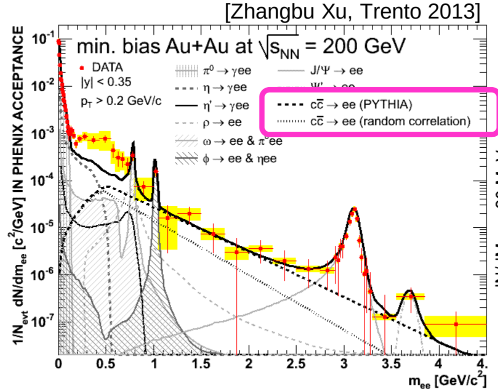
Significant part of low-mass dileptons continuum (!!!)

Total charm rate is a reference for J/ψ

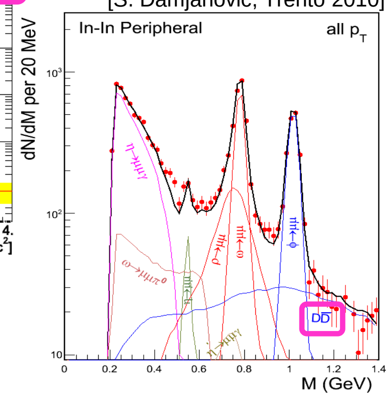
[H. Appelshäuser, Trento 2013]



[Zhangbu Xu, Trento 2013]



[S. Damjanovic, Trento 2010]



CBM
NICA
STAR BES
…

Deconfinement phase transition at high net baryon densitiy

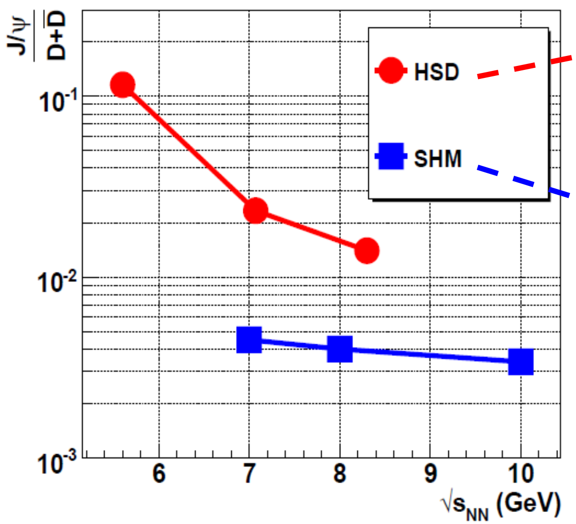
How are the produced charm quarks propagating in the dense phase, quark like or (pre-) hadron like?

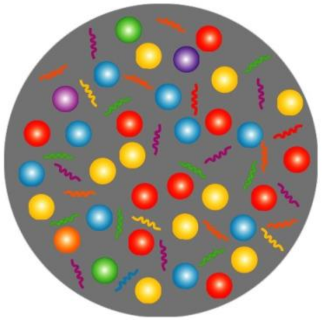
- Hidden over open charm as indicator (J/ψ, ψ', D^0, $D^{\pm}$)
- Charmed baryons important for a complete picture (Λ_c, Ξ_c)
- Are there indicators for collectivity?

$NN \rightarrow D \not\subset_c N$

$NN \rightarrow DD\ NN$

$NN \rightarrow J/\psi\ NN$





[HSD: O. Linnyk et al., Int.J.Mod.Phys.E17, 1367 (2008)]
[SHM: A. Andronic et al., Phys. Lett. B 659 (2008) 149]

Statistical hadronization predictions for open and hidden charm at low energies

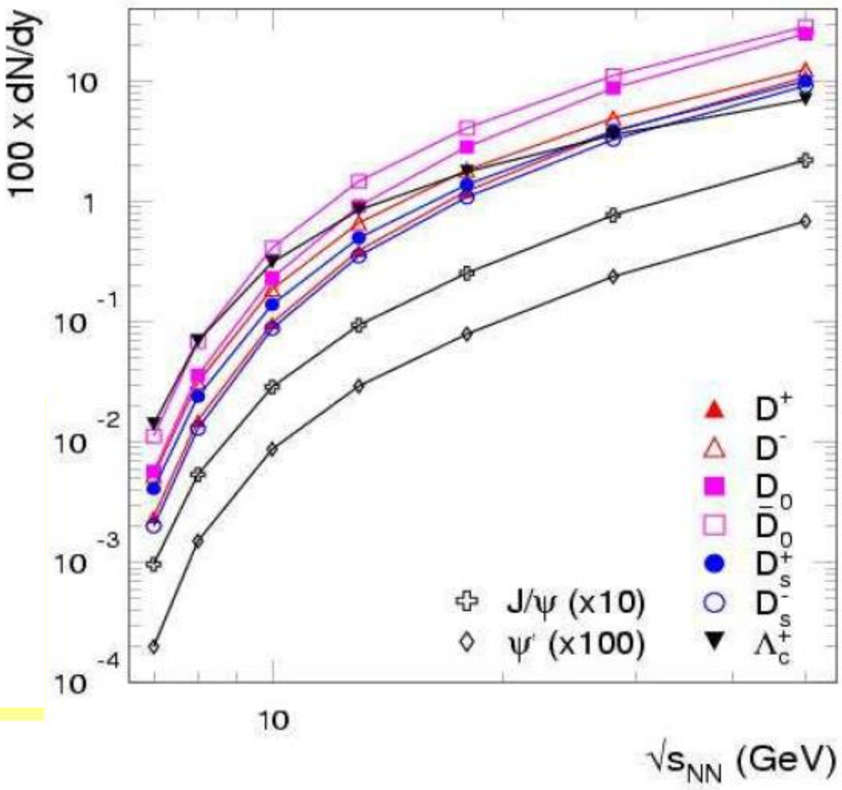
TECHNISCHE UNIVERSITÄT DARMSTADT

Model predictions without medium modifications

Vacuum masses

Charmed baryons play an important role

It is crucial to measure them at SIS300 energies (CBM)



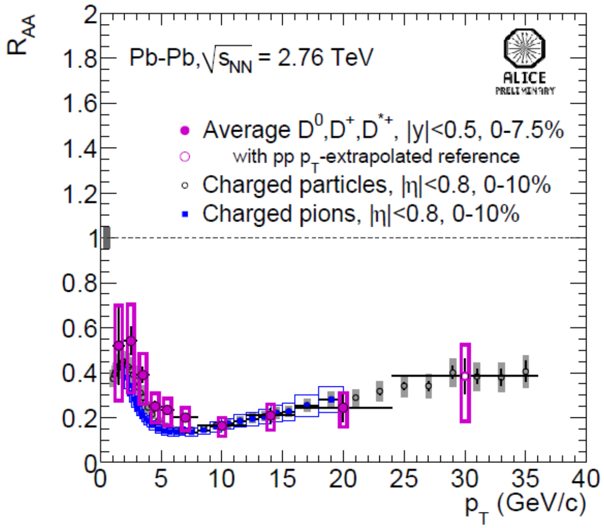
[PBM, Bad Honnef, 2008]

What to look at

Nuclear modification factor:

$$R_{AA} = \frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle\, dN_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

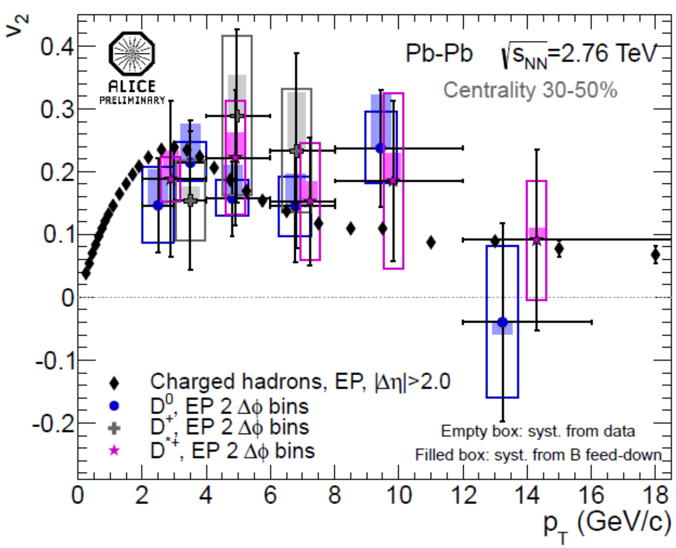
gives us an information (although no trivial correspondence) about energy loss of a heavy quark



Elliptic flow coefficient:

$$v_2 = \langle \cos(2\phi) \rangle$$

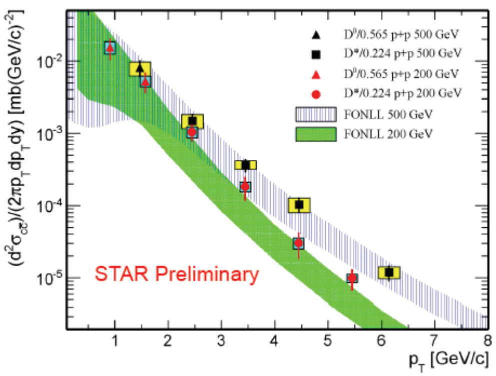
Large values can appear only if thermalization of the medium is rapid enough (initial free streaming reduces spatial anisotropy and ability to convert it to momentum anisotropy)



Reference – pp? pA?

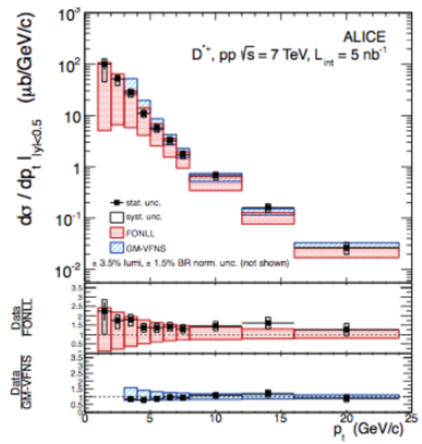
TECHNISCHE UNIVERSITÄT DARMSTADT

pp @ 200, 500 GeV



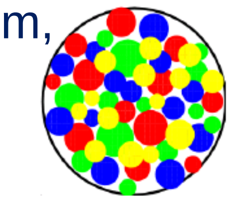
[STAR, PRD 86 (2012) 72013 (200 GeV)]
[J. Bielcik, Moriond2013]

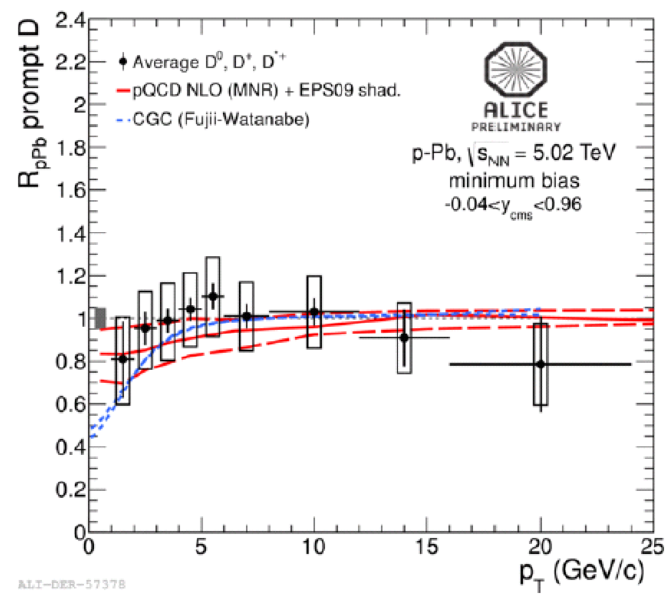
pp @ 7 TeV



[ALICE, JHEP01 (2012) 128]

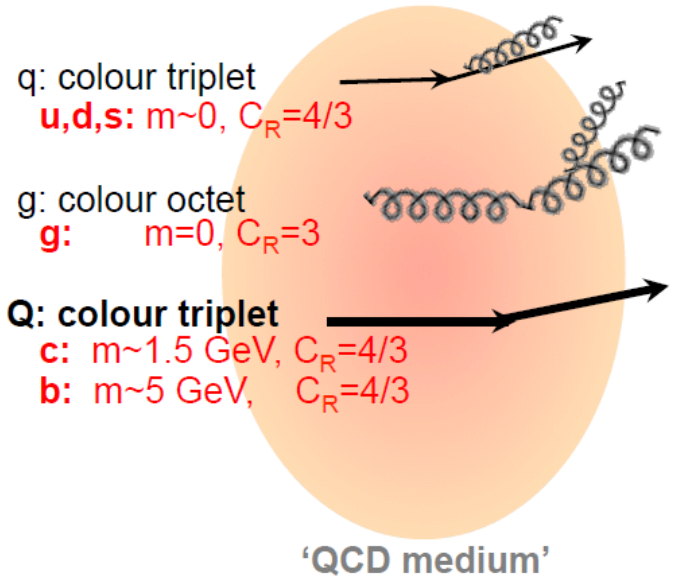
What if observed suppression comes not from hot QCD medium, but from parton PDFs shadowing/saturiation/reduction in initial state?





→ Charm production in pp
is reasonably described by pQCD

Why is charm physics charming?



Parton energy loss:
→ gluon radiation
→ collsions with gluons
Depends on:
→ color charge
→ mass of particle

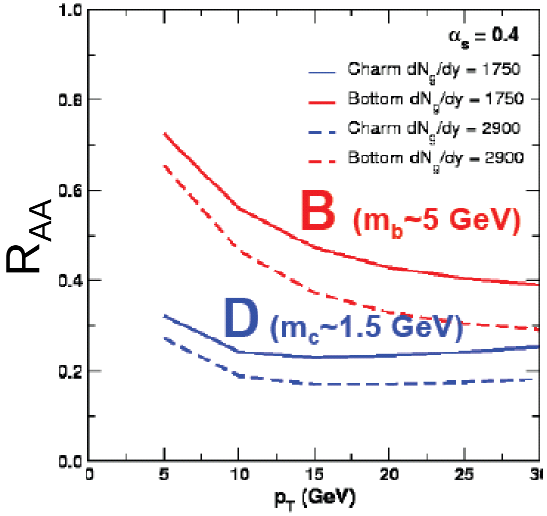
$$\Delta E_g > \Delta E_c > \Delta E_b$$

Forward emission suppressed in the forward "dead cone„ $\Theta < \Theta_0 = \frac{m_c}{E}$:

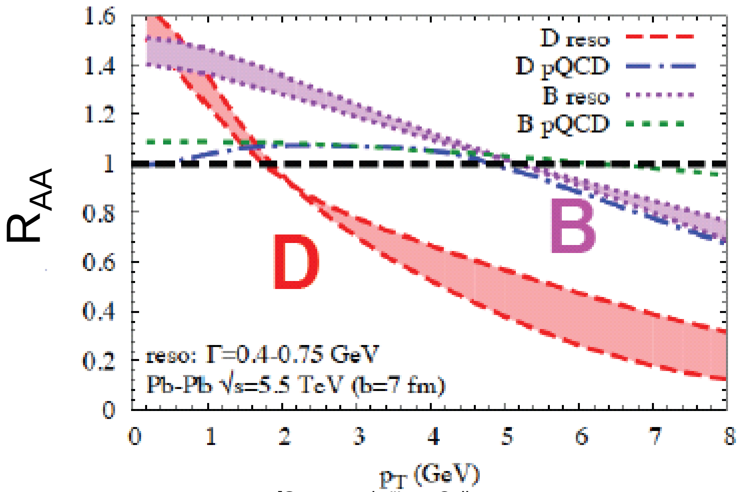
$$\propto \frac{1}{\left[\Theta^2 + \left(m_Q/E_Q\right)^2\right]^2}$$

Also colissional energy loss depends on $1/m_Q$

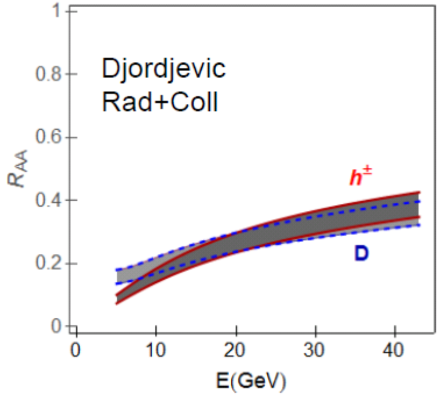
Predictions for energy loss



[Wicks, Gyulassy, "Last Call for LHC Predictions" Workshop 2007]



[Greco *et al.*, "Last Call for LHC Predictions" Workshop 2007]

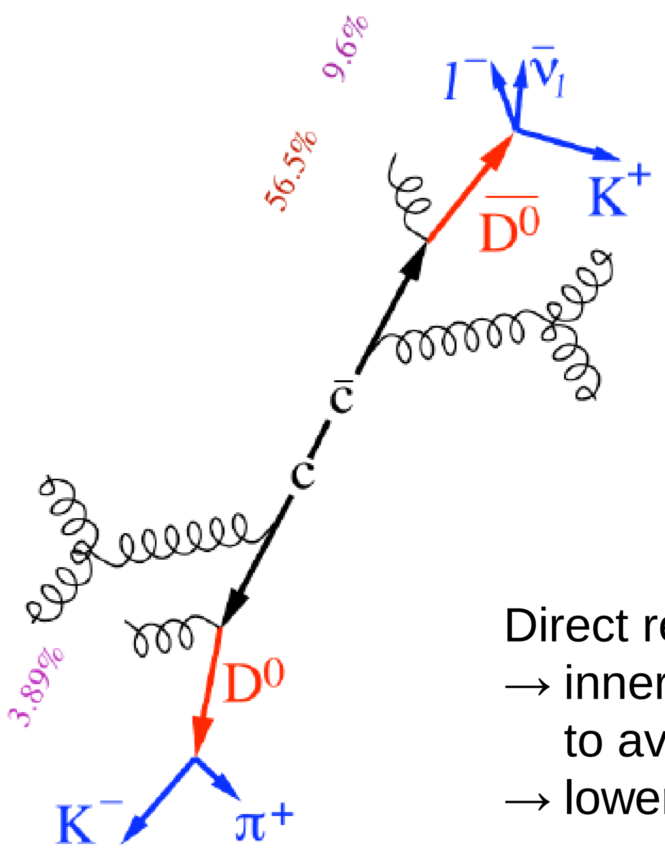


→ Pions (at LHC below 10-15 GeV) originate mainly from gluons

→ Gluons fragmentation and their softer p_T spectrum counterbalances larger energy loss

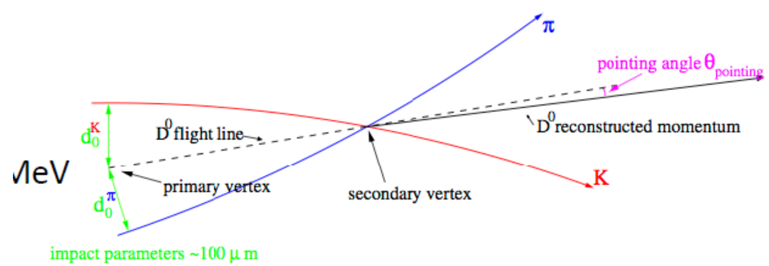
→ **Be careful when interpreting R_{AA}!!!**

How to measure open charm



[D. Kikola, from D. Tlusty]

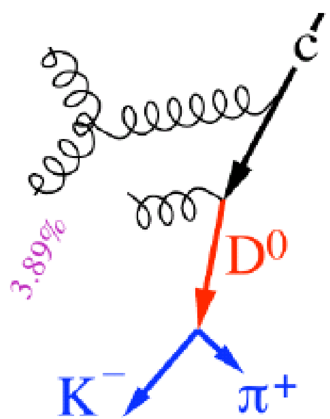
Semi-leptonic decays
(non-photonic electrons)
→ cannot disentangle c from b
→ higher branching ratio

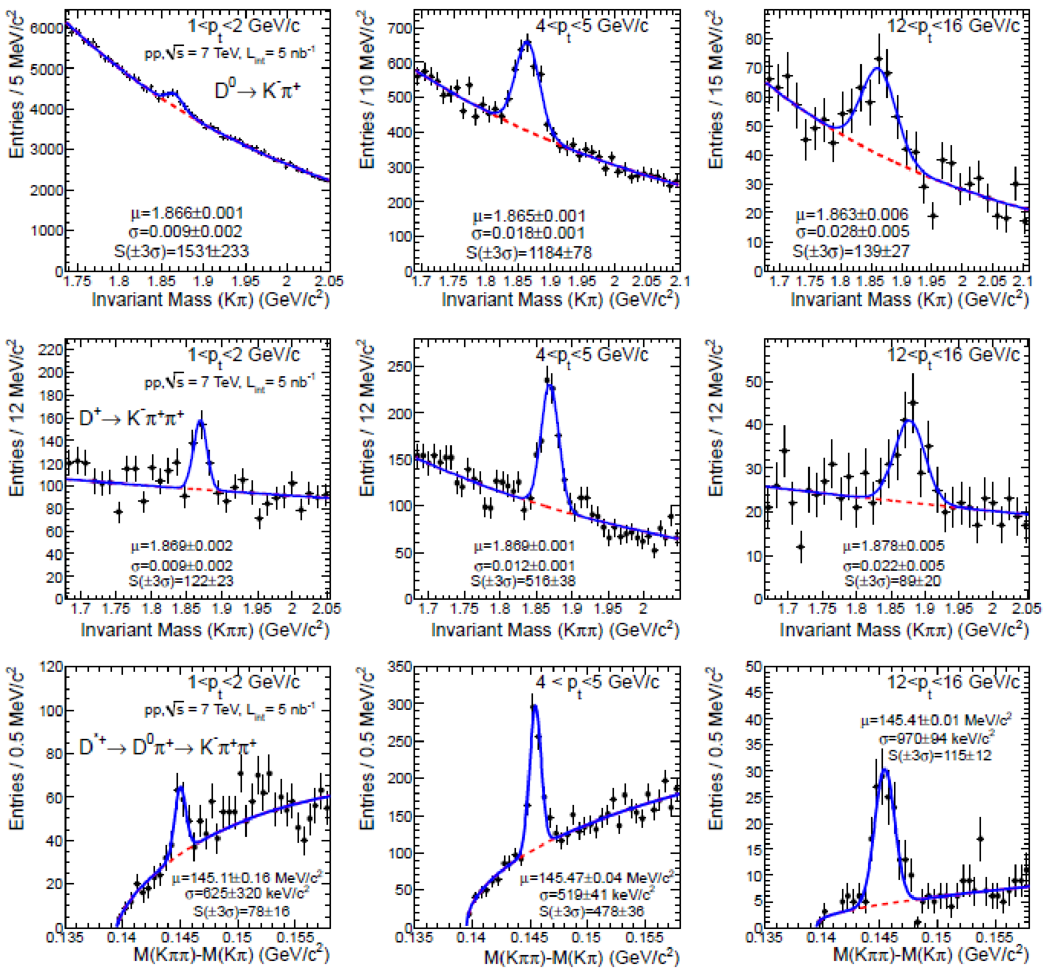


Direct reconstruction
→ inner tracker needed
to avoid "wrong" pairs
→ lower branching ratio

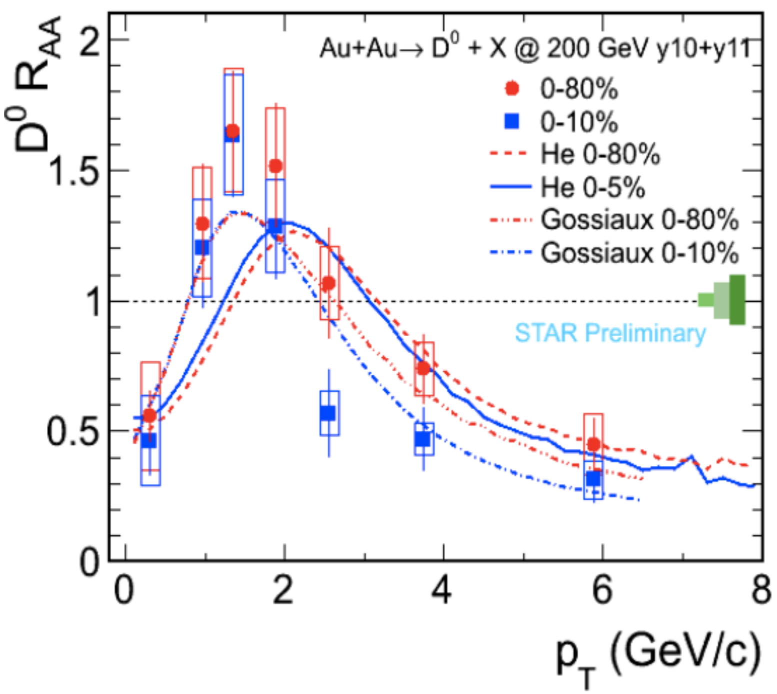
How to measure open charm

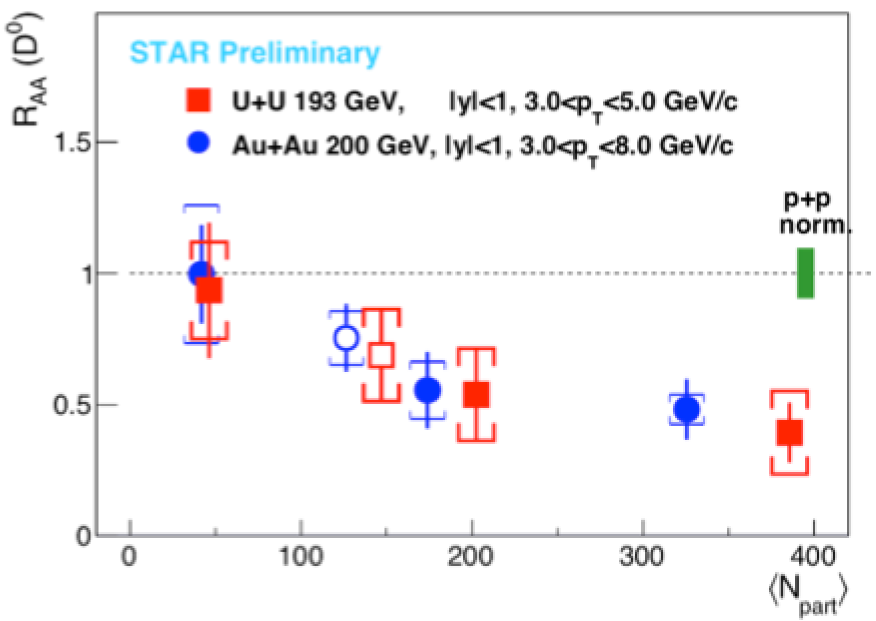
[arXiv:1111.1553]





D mesons R_{AA} at RHIC





Suppression at high p_T
Enhancement at low p_T:
coalescence? radial flow?

(no secondary vertex reconstruction, but huge statistics ~800M events)

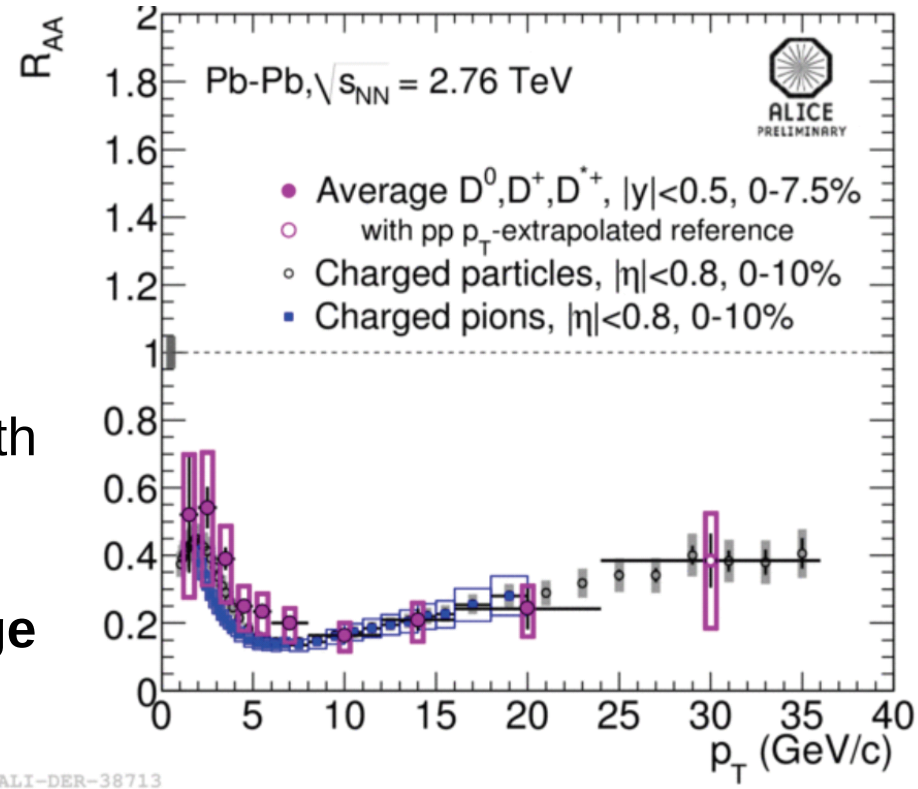
D mesons R_{AA} at LHC

– Below 2 GeV/c no direct comparison to pions (they do not scale with N_{coll}, R_{AA} definition does not apply)

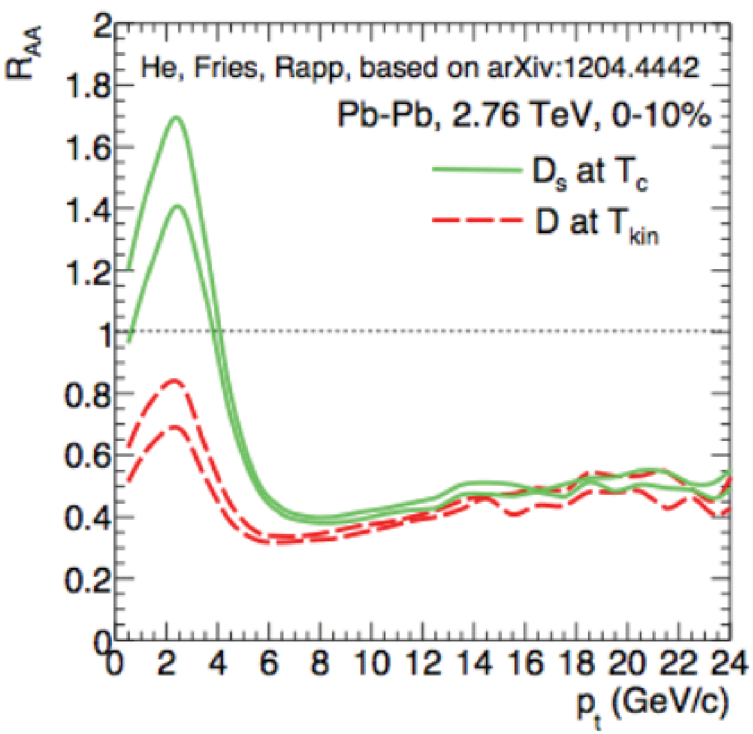
– 2-5 GeV/c – D seems to be above π

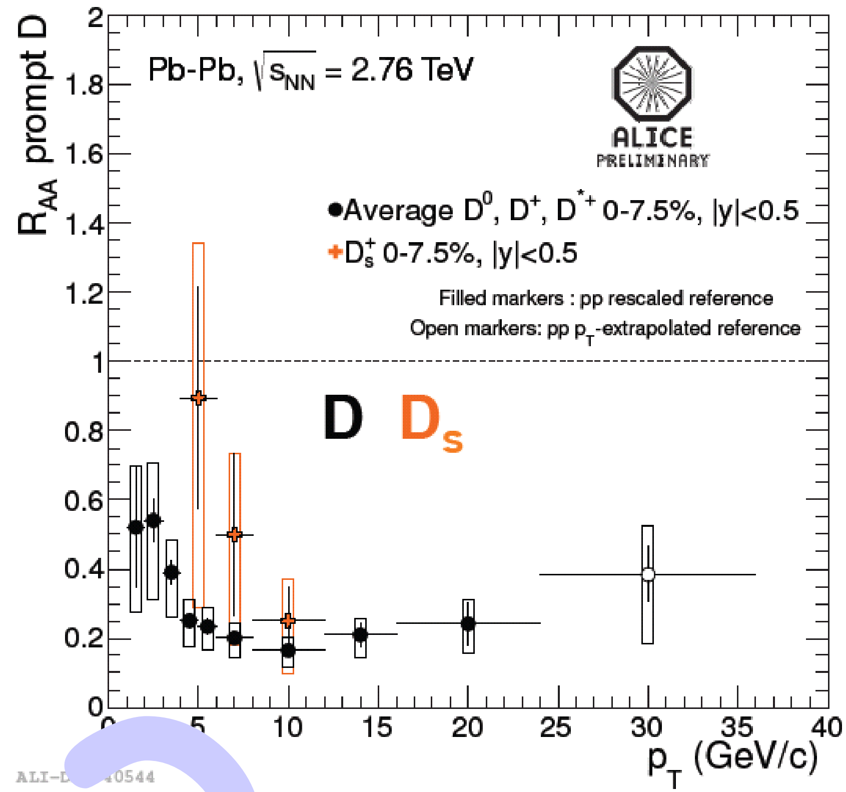
– Above 5-6 GeV/c – D comparable with pions

→ **Is this compatible with color charge dependence?**



D mesons R_{AA} at LHC

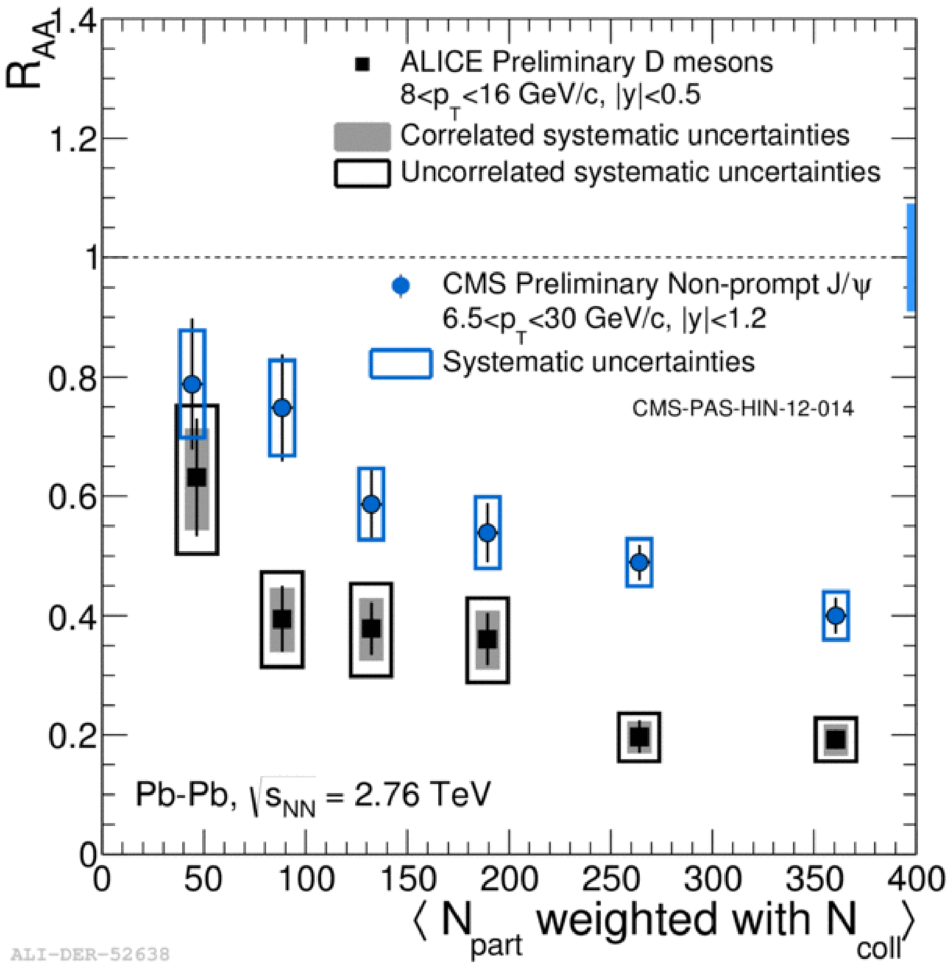




Low-p_T D_s enhancement expected if c-quarks do coalesce
Data look intriguing, although not conclusive

D and B mesons R_{AA} at LHC

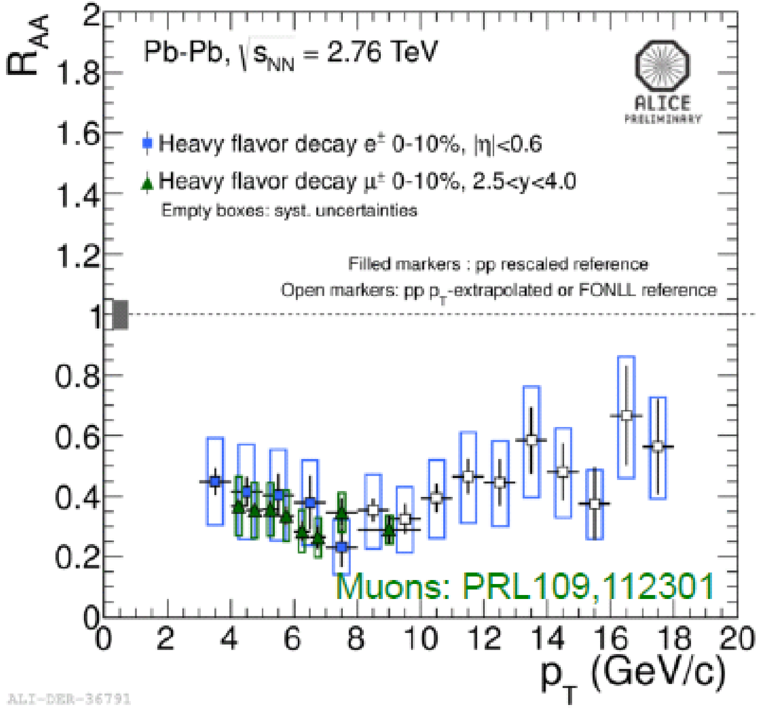
TECHNISCHE UNIVERSITÄT DARMSTADT

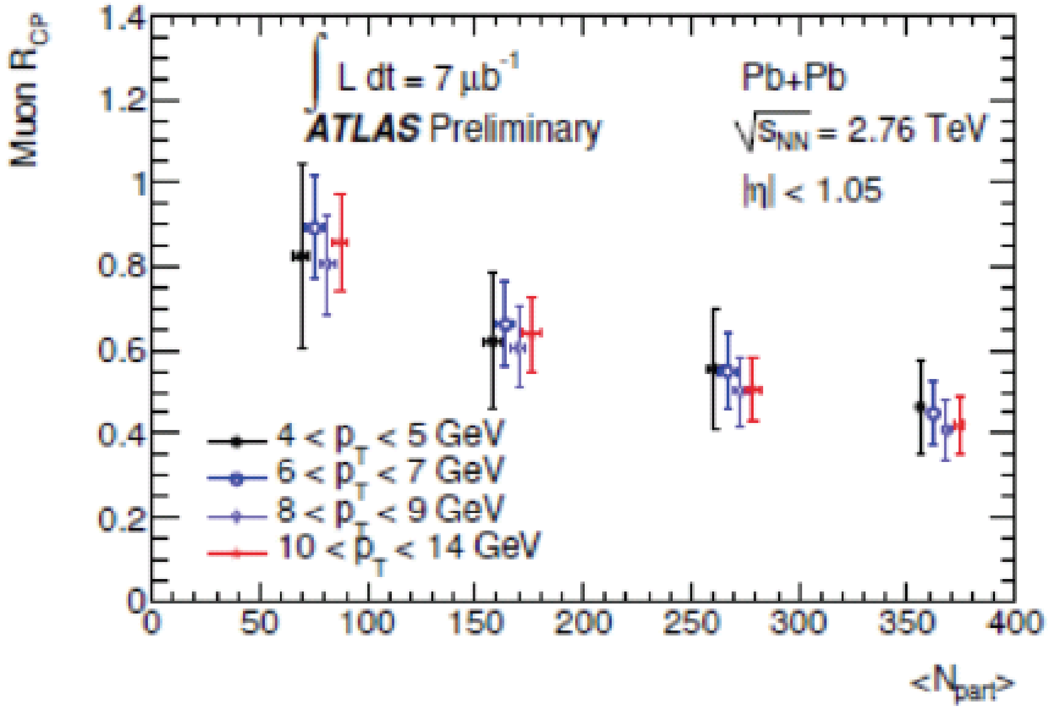


Mass dependence of energy loss?

Non-photonic R_{AA} at LHC

ATLAS-CONF-2012-081

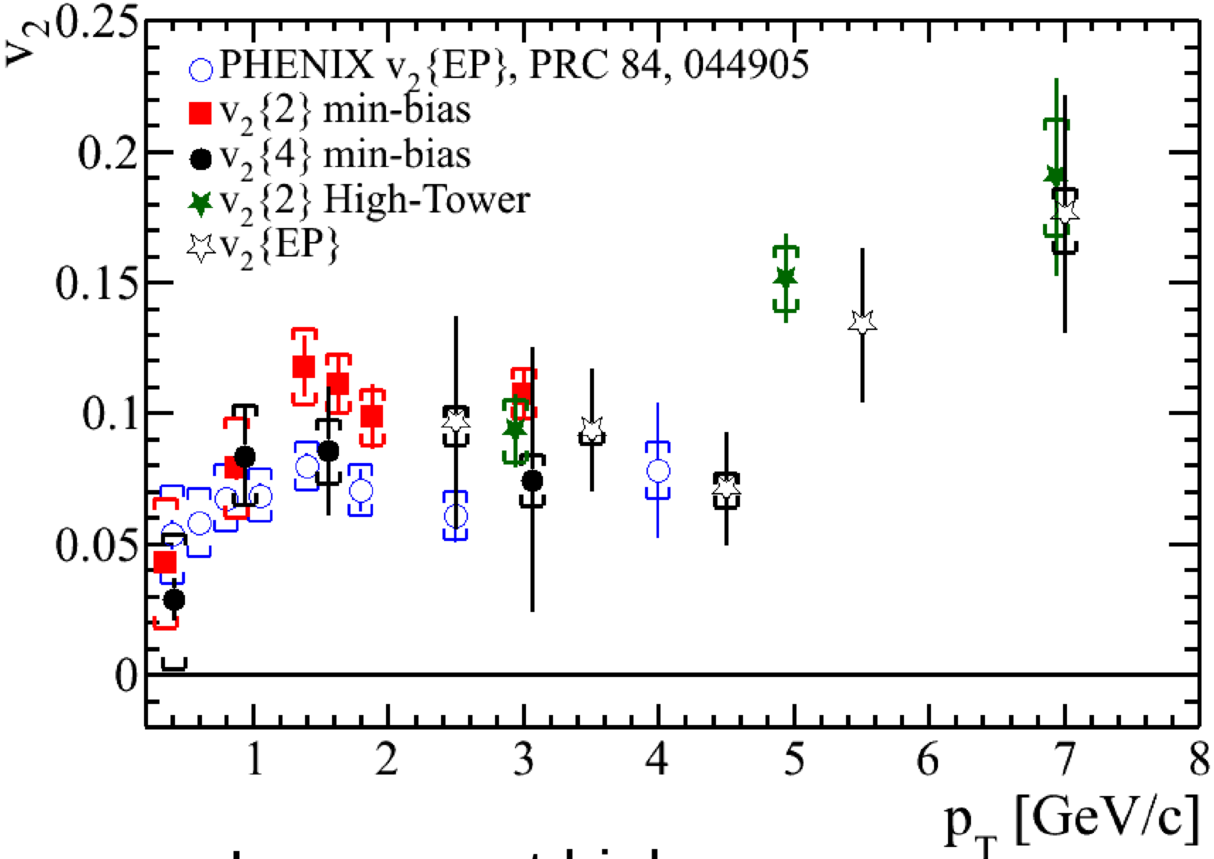




$(p_T^{hadron} \approx 2p_T^{lepton})$

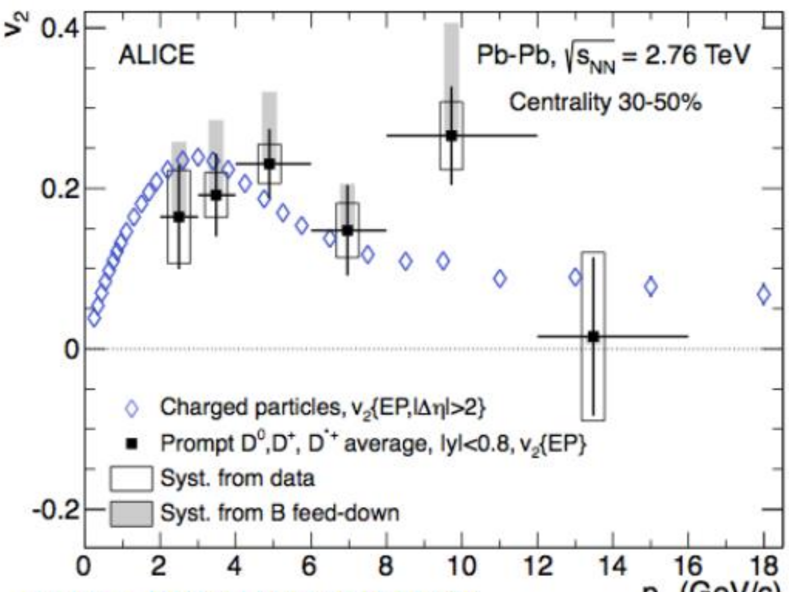
Clear centrality dependence
Central and forward rapidity comparable
No p_T dependence

D mesons v_2 at RHIC (STAR)

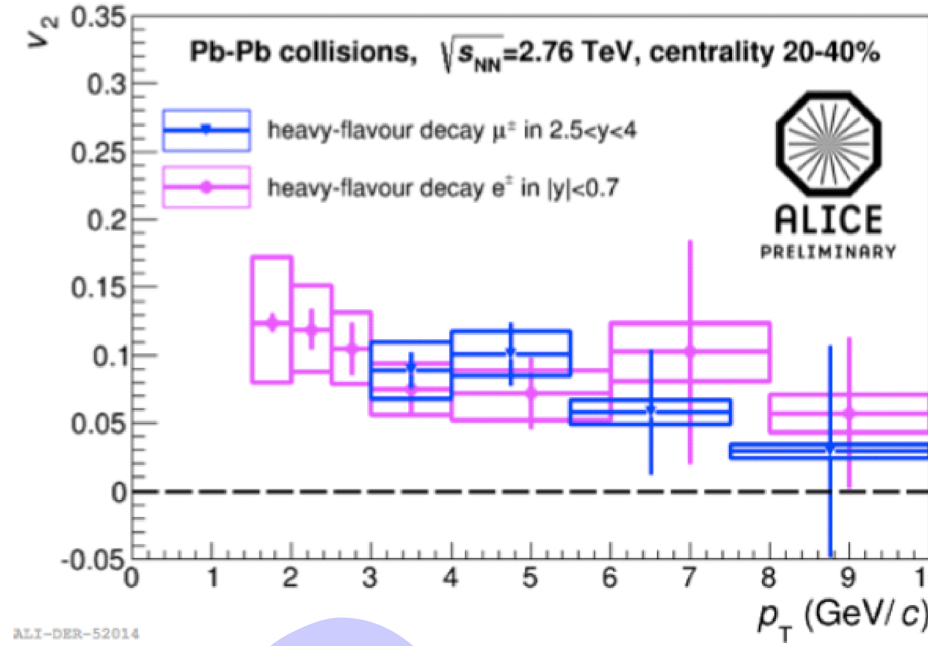


Increase at high p_T

D mesons v_2 at LHC



ALICE, PRL111(2013)102301

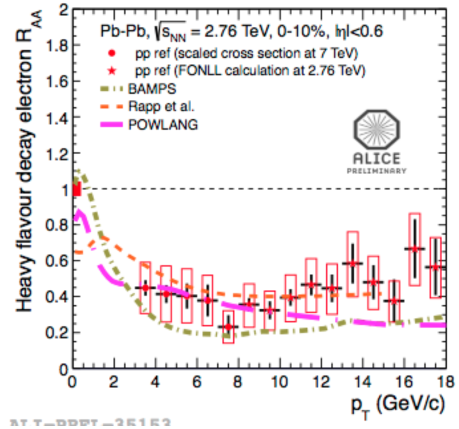


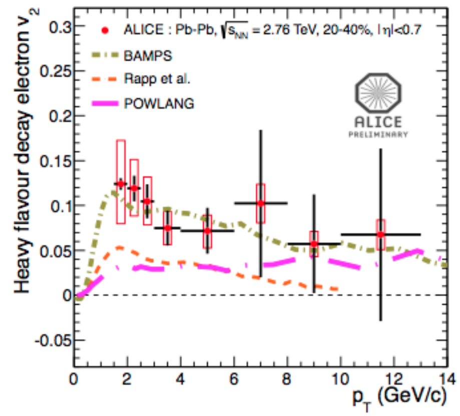
Not clear what is the origin of v_2. Coalescence? c-quark flow?
Need more data

Models for LHC energies

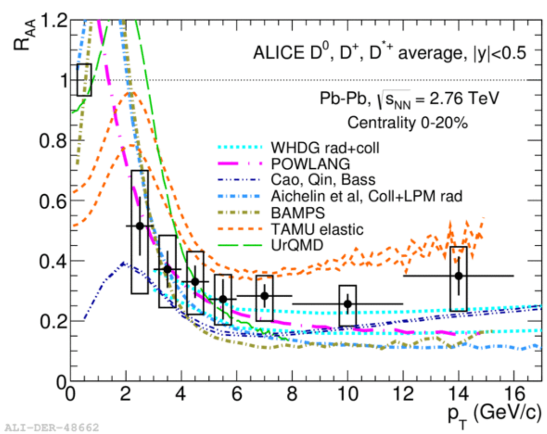
TECHNISCHE UNIVERSITÄT DARMSTADT

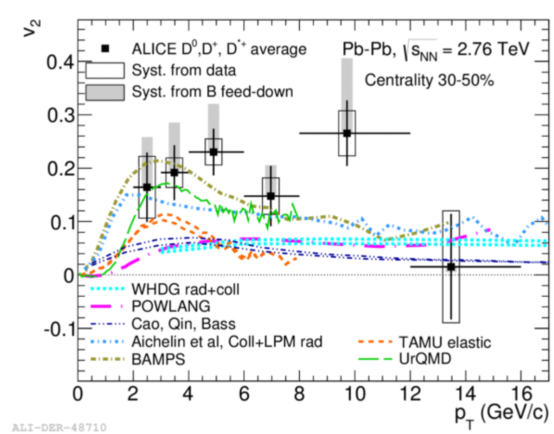
Heavy Flavor decay electrons:





D mesons reconstructed directly

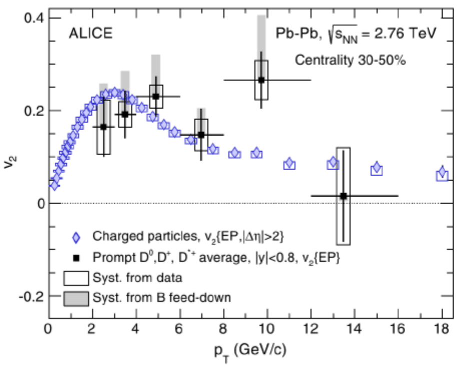


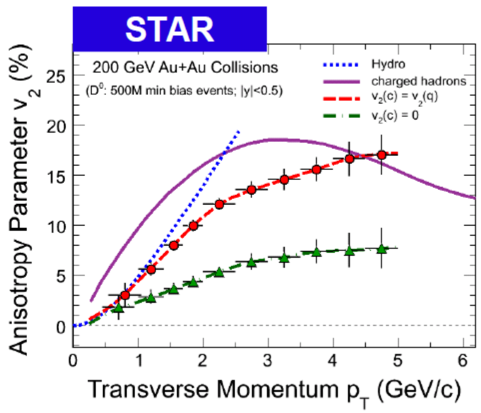


?

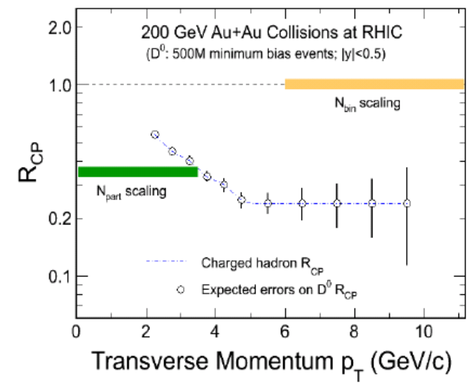
Instead of Summary – Outlook

Heavy Flavor Tracker at **STAR**





D meson R_{CP}



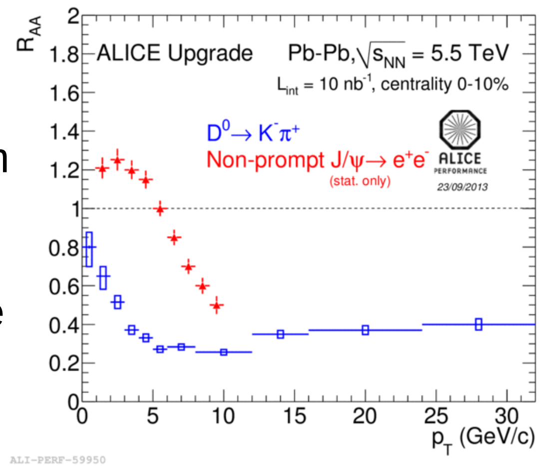
Vertex Tracker at **PHENIX**

Major upgrade of **ALICE**

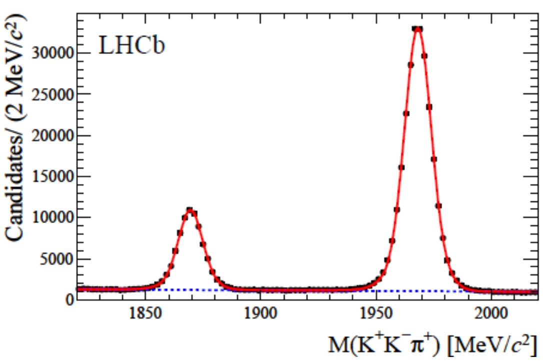
- New Inner Tracking System
- New TPC readout
- Upgraded DAQ/HLT/Offline

SHINE...

CBM...



LHCb?



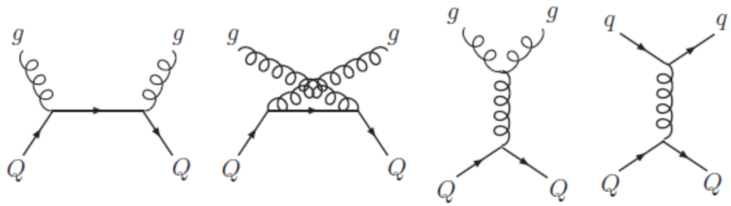
TECHNISCHE UNIVERSITÄT DARMSTADT

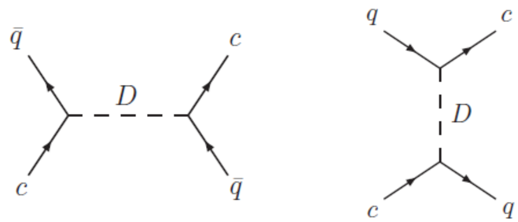
THANK YOU FOR YOUR ATTENTION

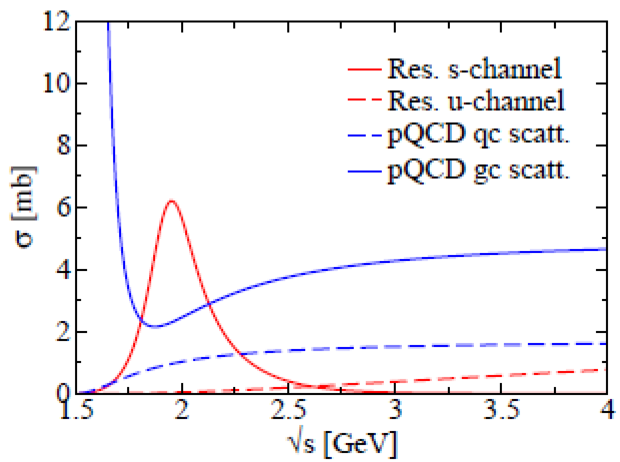
BACKUP SLIDES

Heavy quark interactions in medium

Perturbative QCD vs. resonance model

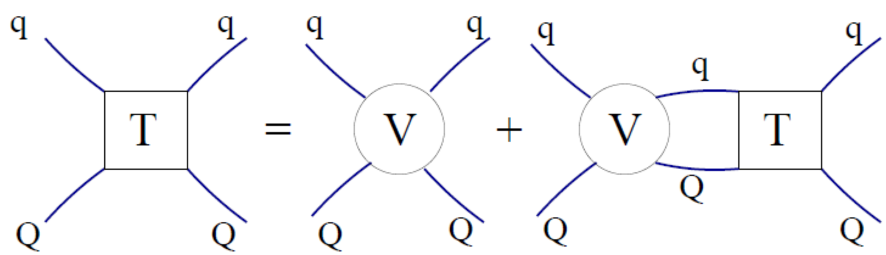




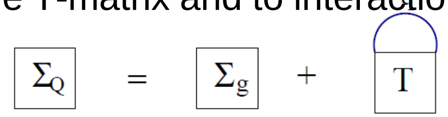


- pQCD expexted to be dominated by a forward emission, from resonance model the angular distribution is more isotropic, which makes it more efficient in thermalizing heavy quarks.

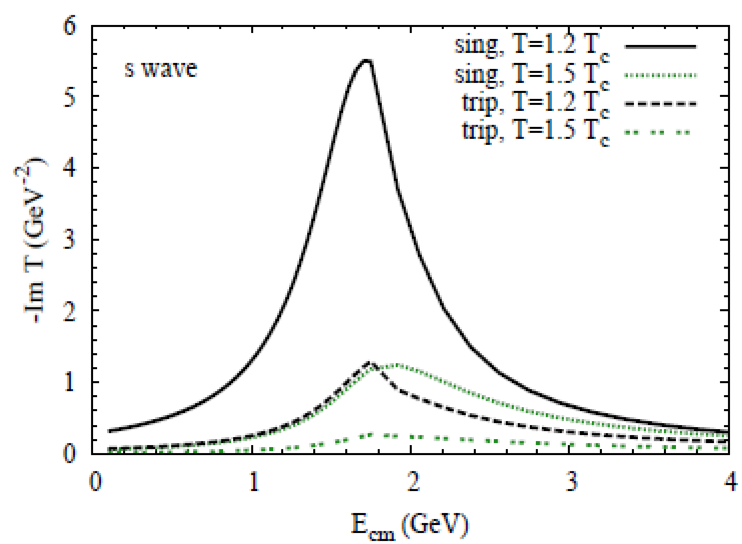
T-matrix approach



Interaction potential can be taken from lattice QCD. To the two-particle propagator enters a quark self-energy related to the T-matrix and to interactions with gluons:



- In light-quark sector this **self-consistency problem** has been solved by numerical iteration
- For heavy quarks its effect is expected to be weaker and self-energies can be approximated by constant thermal mass corrections
- Numerical calculations show dominance of attractive meson and diquark (color-antitriplet) channels and suppression of repulsive sextet and octet
  → T=V+VGV+VGVGV+…
- Resonance-like structure in the vicinity of the critical temperature



Heavy quark transport

Start from a very generic **Boltzmann** equation:

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{E} \cdot \vec{\nabla}_r - \left(\vec{\nabla}_r V\right) \cdot \vec{\nabla}_p\right) f_1(\vec{r}, \vec{p}, t) = I_{\text{coll}}(f_1)$$

Assume:

- That the mean-field term can be neglected
- That the medium is uniform

Integrate over spatial coordinate

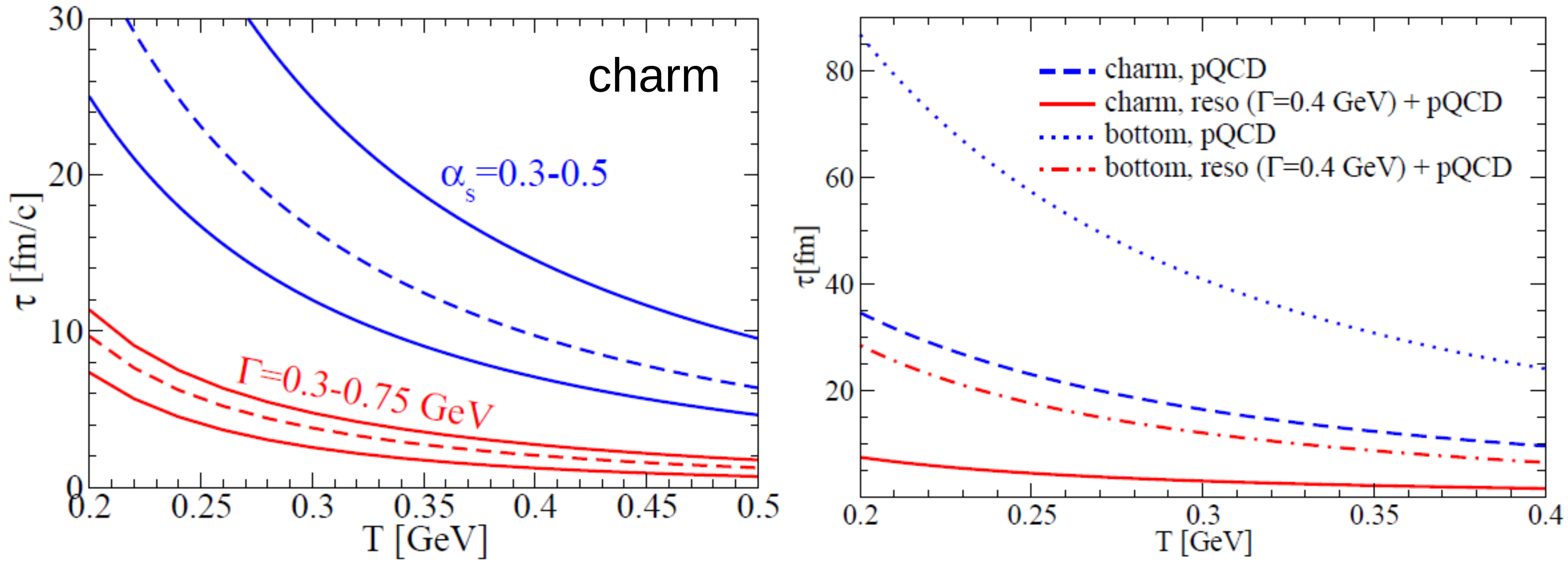
Applying to the heavy quark case, when momentum transfer *k* is much smaller that quark momentum (**Brownian motion**) one can expand collision term to the second order in k and get **Fokker-Planck** equation:

$$\frac{\partial f_Q(p,t)}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(p) + \frac{\partial}{\partial p_j} B_{ij}(p)\right] f_Q(p,t)$$

A_i describes average momentum change per unit time → friction

B_{ij} describes average momentum broadening per unit time → momentum-space diffusion

Heavy quark transport



$\tau_{thermal} = \gamma^{-1}$

Coefficient Ai involves momentum transfer k, which is small in forward pQCD emission and larger in isotropic resonance model

At high temperature thermal energy is well above the energy optimal for D-meson formation and resonance ar less efficient in c-quark scattering

Solving the Fokker-Planck equation

Langevin simulation: changes of position and momentum in small time interval δt:

$$\delta\vec{x} = \frac{\vec{p}}{\omega_p}\delta t, \qquad \delta\vec{p} = -A(t,\vec{p}+\delta\vec{p})\vec{p}\,\delta t + \delta\overrightarrow{W}(t,\vec{p}+\delta\vec{p}),$$

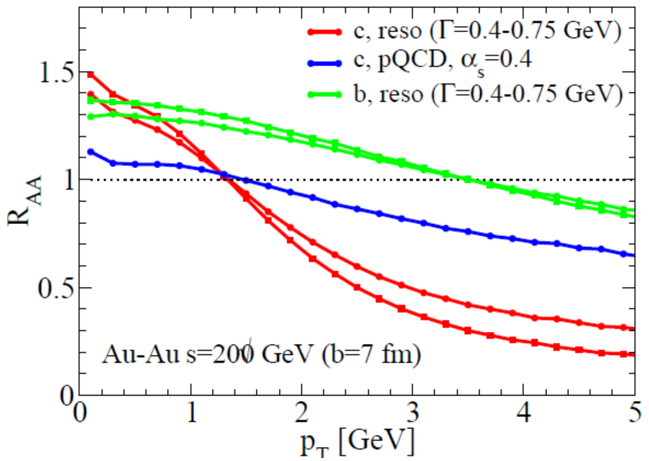
where δW is distrubited according to the Gaussian noise:

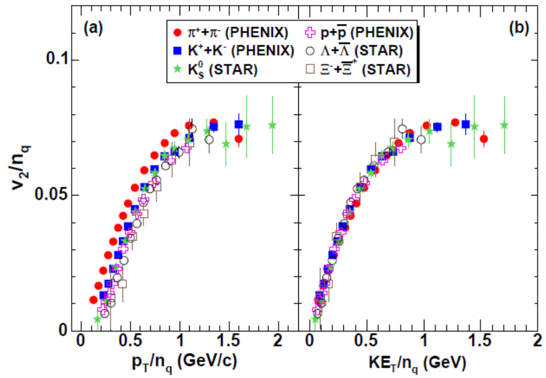
$$P\left(\delta\overrightarrow{W}\right) \propto \exp\left[-\frac{(B^{-1})_{jk}\delta W^{j}\delta W^{k}}{4\delta t}\right].$$

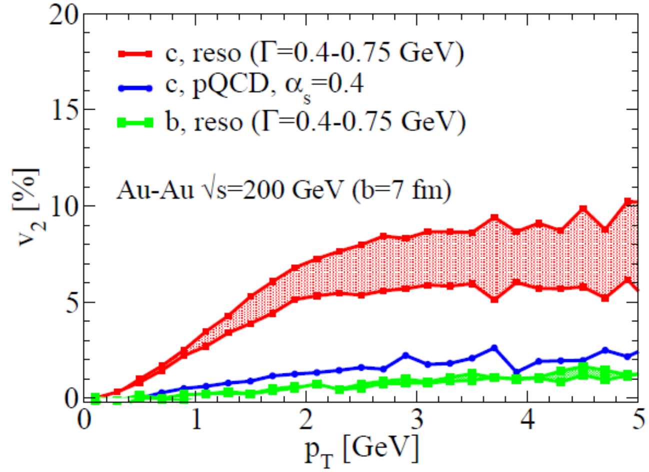
Langevin simulation

"reso" means combination of resonance interaction (restricted to light antiquark from the medium) and pQCD (dominated by thermal gluons)

With resonance interaction, plateau shape in v2 is compatible with univeral number of constituents scaling, which indicates, that c-quarks may participate in the collective expansion of the medium

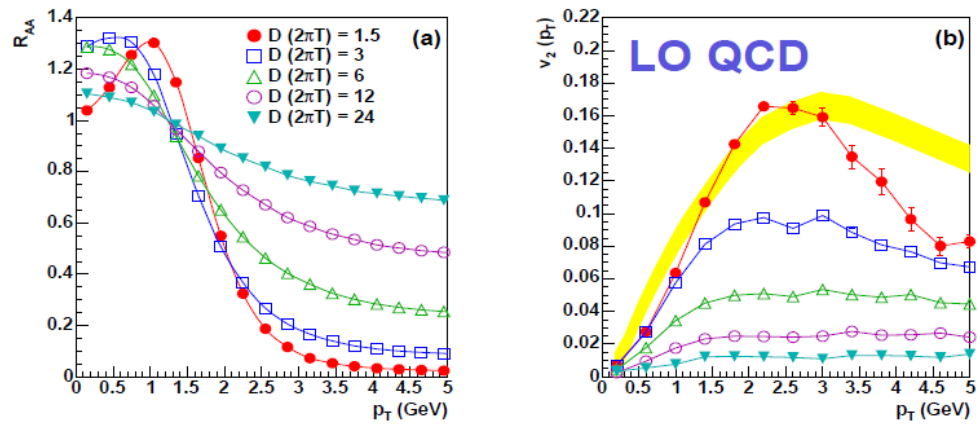




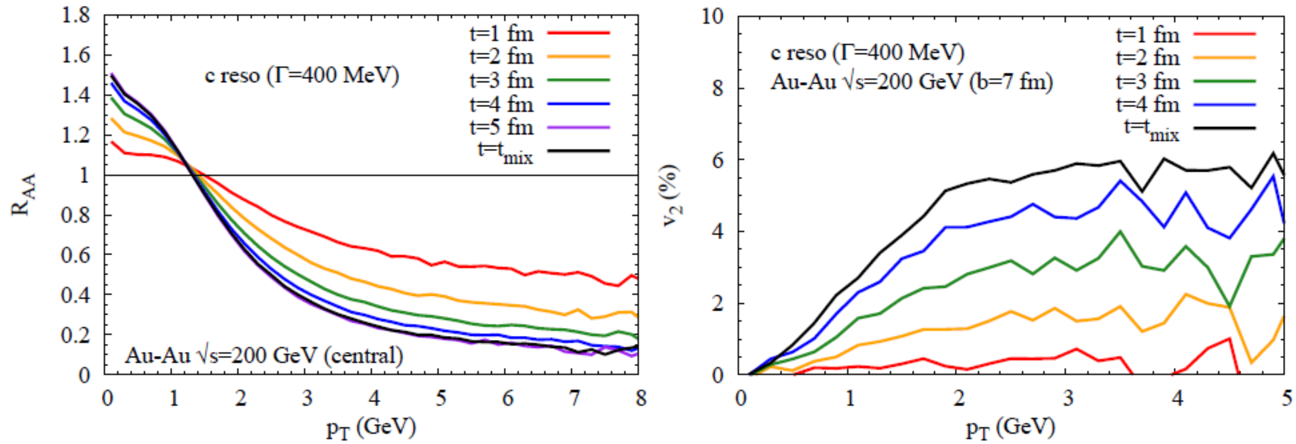


Langevin simulation

Large eliptic flow is correlated with strong suppression



… but they develop at different times



Hadronization

TECHNISCHE UNIVERSITÄT DARMSTADT

At high p_T parton production occurs at time scale of $1/p_T$ and is rather independent from hadron production with time scale of $1/\Lambda_{QCD}$

Fragmentation function of parton *i* into hadron *h*, $D_{h,i}(z)$, $z = p_h/p_i < 1$ for light quarks is a broad distribution centered around z=0.5

Example: Peterson fragmentation function: $D_{h,Q}(z) = \frac{N}{z\left(1-1/z-\epsilon_Q/(1-z)\right)^2}$

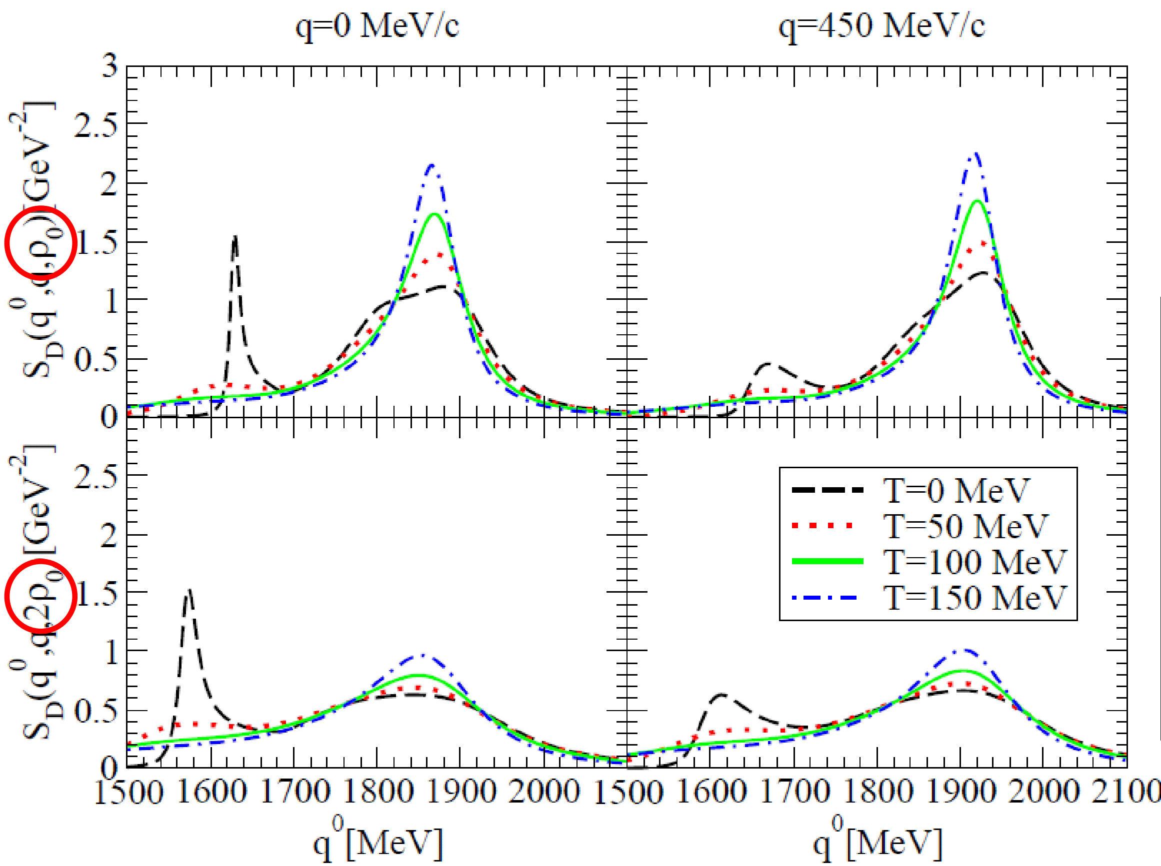
For heavy quarks it becomes peaked close to 1 and sometimes is approximated by a Dirac δ function

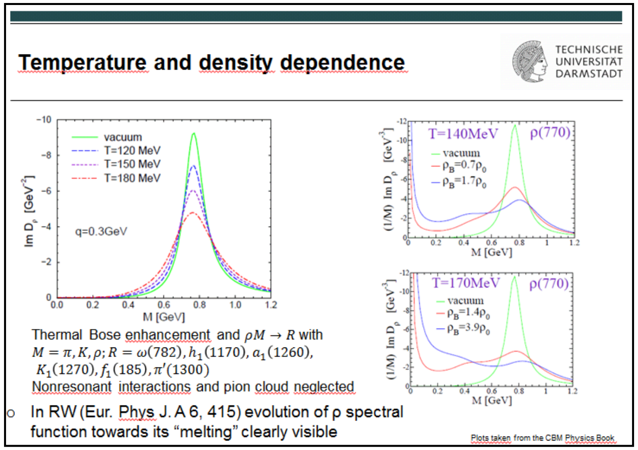
At low momenta **quark coalescence** in position and momentum space can be applied (as it explains constituent quark number scaling and large baryon-to-meson ratios)

Formation of **baryons** containing strange quarks is often **neglected**

Hadrons in medium

TECHNISCHE UNIVERSITÄT DARMSTADT

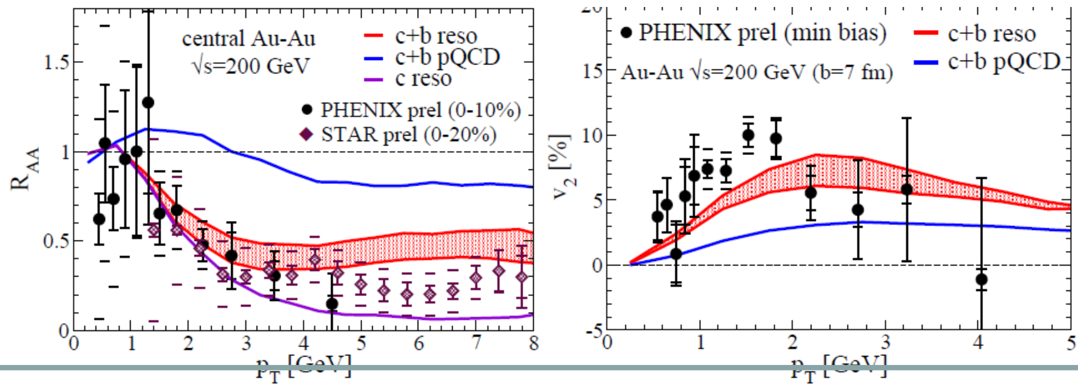


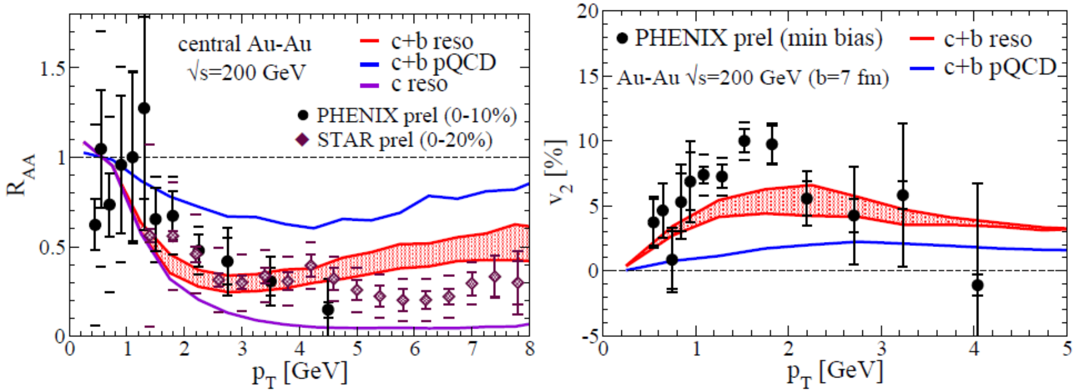


Comparison to RHIC results
(electrons from heavy-flavor decays)

Electron spectra from selimeptonic decays (e.g. D→Keν) closely follow those of D-mesons

Contributions of D and B-mesons have not been separated experimantally





Quark coalescence switched off

RHIC results from Au+Au @ 200 GeV

Strong coupling to the medium

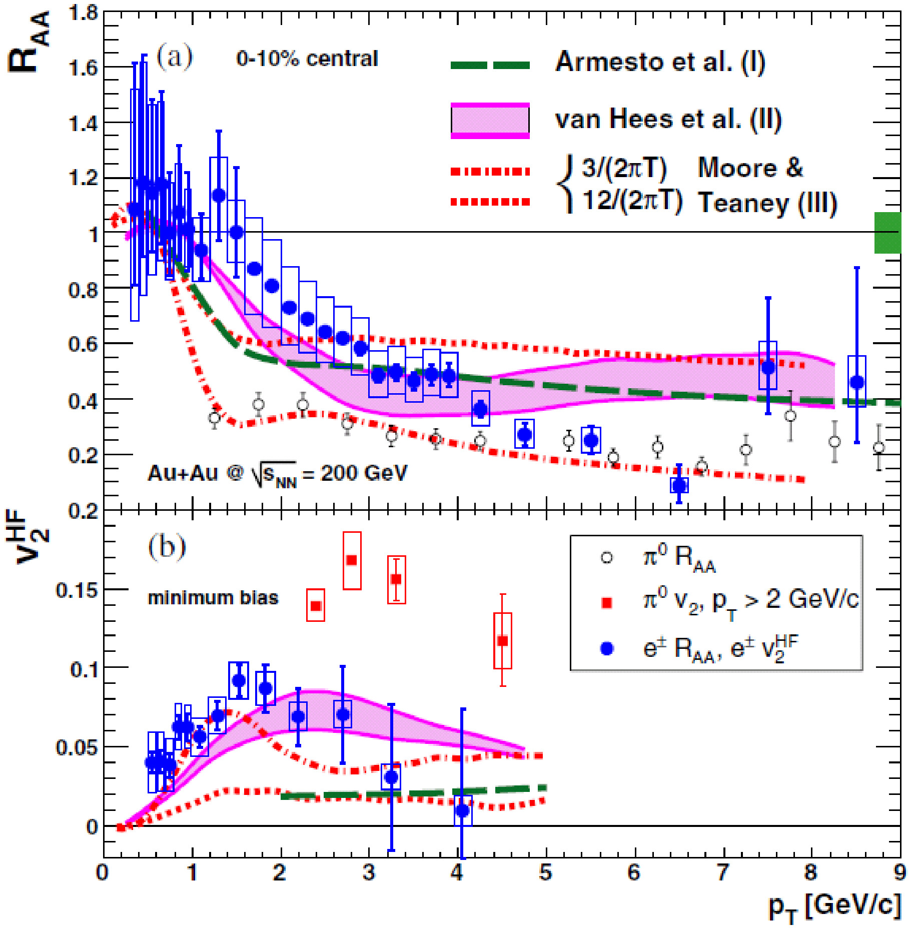
At p_T = 4 GeV R_{AA} approaches the one of π^0, however bottom quarks contribute significantly there

High v_2 indicate, that c-quark relaxation time is similar to time scale of flow development

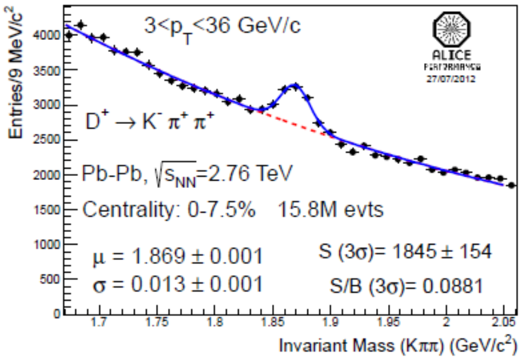
Curve I: pQCD with radiative energy loss

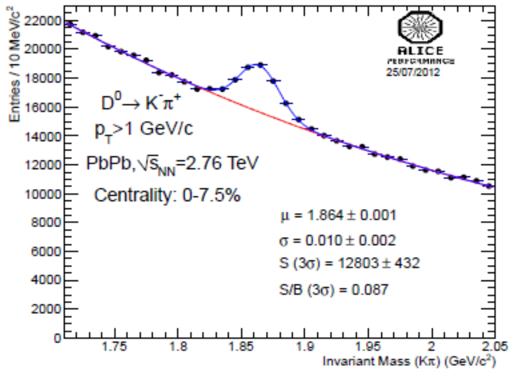
Band II: Inelastic scattering with resonances

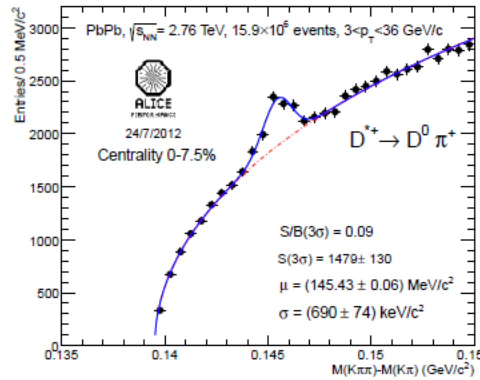
Short relaxation time and/or small diffusion coefficient are required by the data

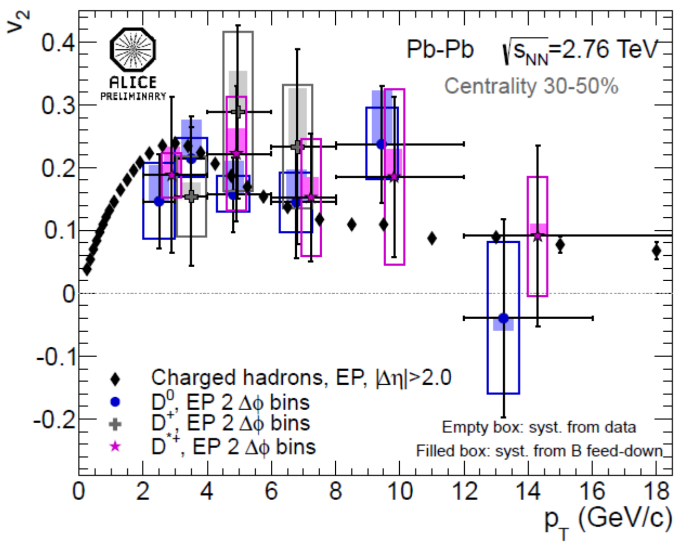


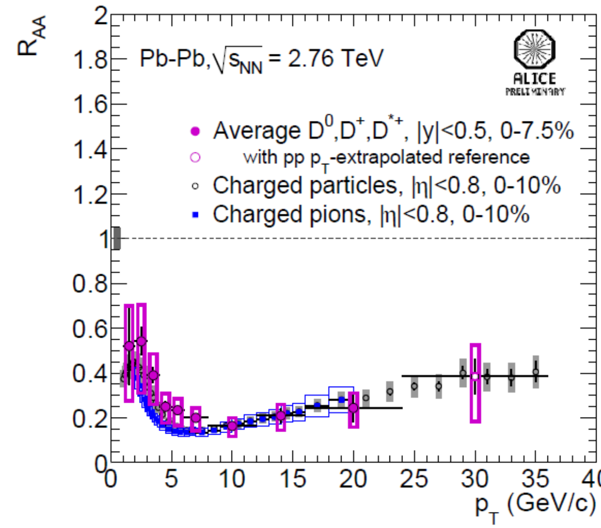
Open charm in ALICE











Boltzmann Approach to MultiParton Scattering

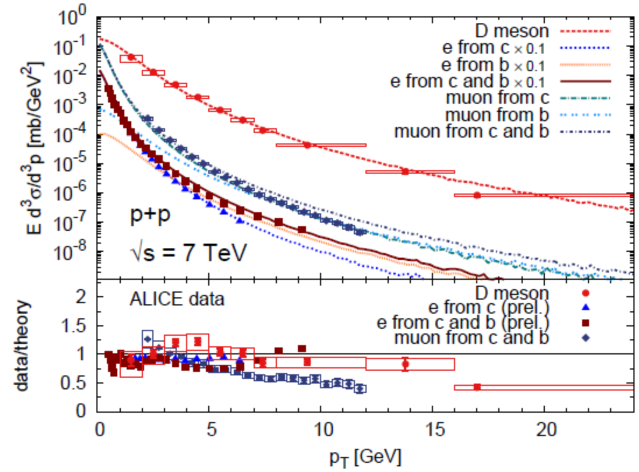
Solves Boltzmann eq.

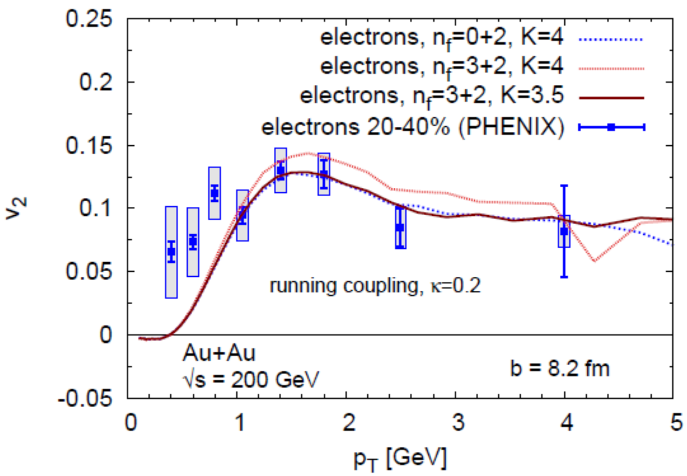
Takes scattering cross-sections from leading-order pQCD
(including Debye screening in *t* channel)

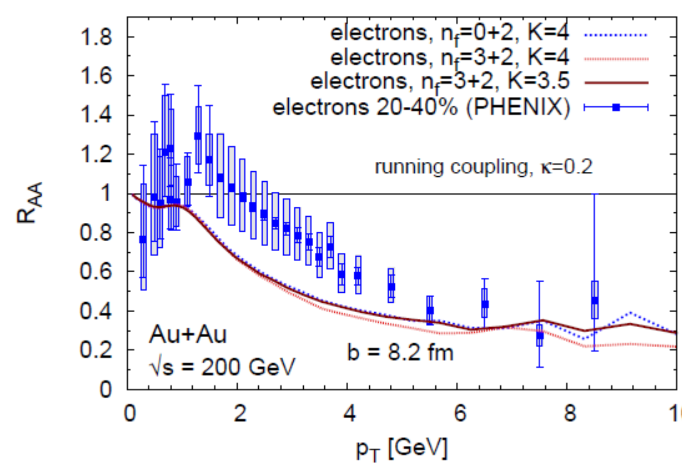
Employs running coupling constant

Uses Peterson fragmentation function

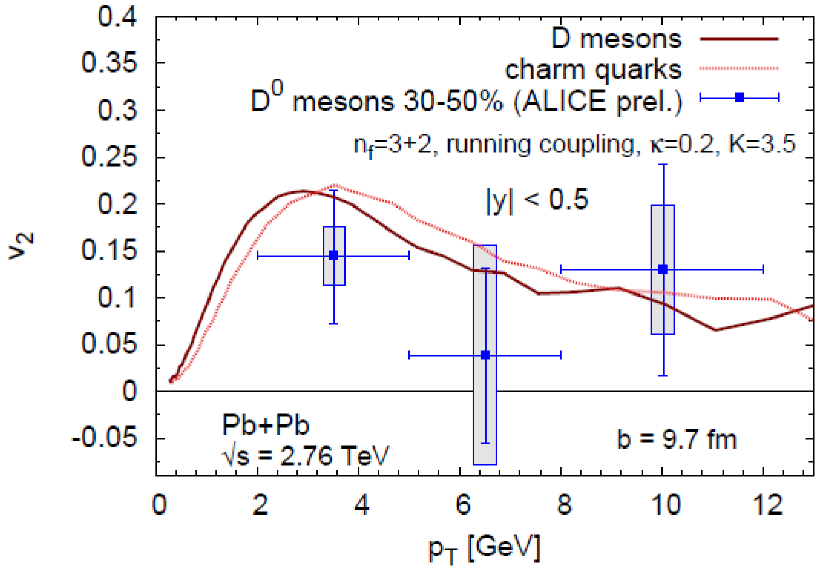
Does not include radiative processes and quantum statistics
– instead multiplies elastic cross section by a factor K

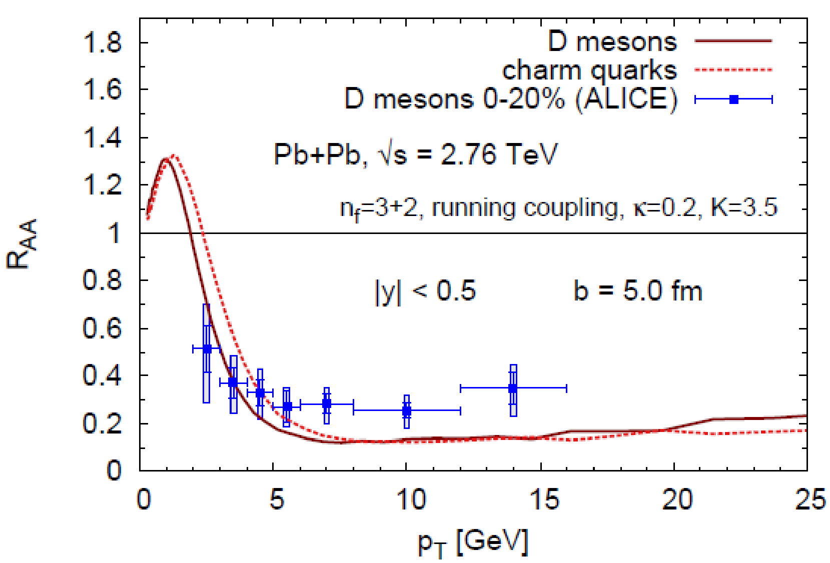






BAMPS bumps into ALICE





In future BAMPS wants to investigate radiative processes for heavy quark

A bit more on Fokker-Planck

When the medium is isotropic (particularly when it is thermalized) coefficients can be expressed as:

$$A_i(p) = \gamma(p^2)p_i, B_{ij}(p) = \left[\delta_{ij} - \frac{p_i p_j}{p^2}\right] B_0(p^2) + \frac{p_i p_j}{p^2} B_1(p^2)$$

In case of momentum independent (which is not true) coefficients it gives a simpler form of equation:

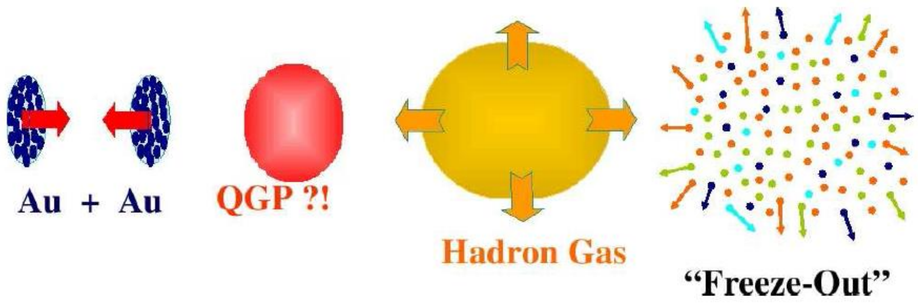
$$\frac{\partial f_Q}{\partial t} = \gamma \frac{\partial}{\partial p_i}\left(p_i f_Q\right) + D \frac{\partial}{\partial p_i} \frac{\partial}{\partial p_j} f_Q,$$

where diffusion and friction coefficients are related to the medium temperature by Einstein's formula:

$$\gamma = \frac{D}{T m_Q}.$$

This holds even for momentum-dependent coefficients in the limit of p → 0, which allows to cross-check computed coefficients with the ambient medium temperature

Fireball expansion



Expanding cylilder: $V_{FB} = z(t)\pi a(t)b(t)$

Constant total entropy, fixed to the observed hadron spectra at freeze-out

From entropy density $s(t)=S/V_{FB}(t)$, using $s_{QGP}=d_{eff}\,(4\pi^2/90)\,T^3$ one gets $T(t)$ and EoS in the hadronic phase $s_{HG}(T)$.

Initial heavy quark spectra are fixed by D-meson and $e^{\mp}$ spectra at RHIC.