Report of EMMI-RRTF on Open Heavy Flavor

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EMMI Heavy Flavor Task Force

- Purpose: scrutinize modelling components between models, to quantify how the uncertainties impact the extraction of $\mathcal{D}s(2\pi\mathcal{T})$

- Two onsite meetings convened at GSI in Jul. & Dec. 2016

- Key questions/problems addressed:

  - Comparison of conceptual underpinnings between models
  - Comparison of bulk medium evolution models & impact
  - Comparison and impact of HQ hadronizataion/coalescence
  - Comparison of transport coefficients: T- & p- dependence
  - Boltzmann vs Langevin as simulation tools

- Summary published: Nucl. Phys. A979 (2018) 21-86

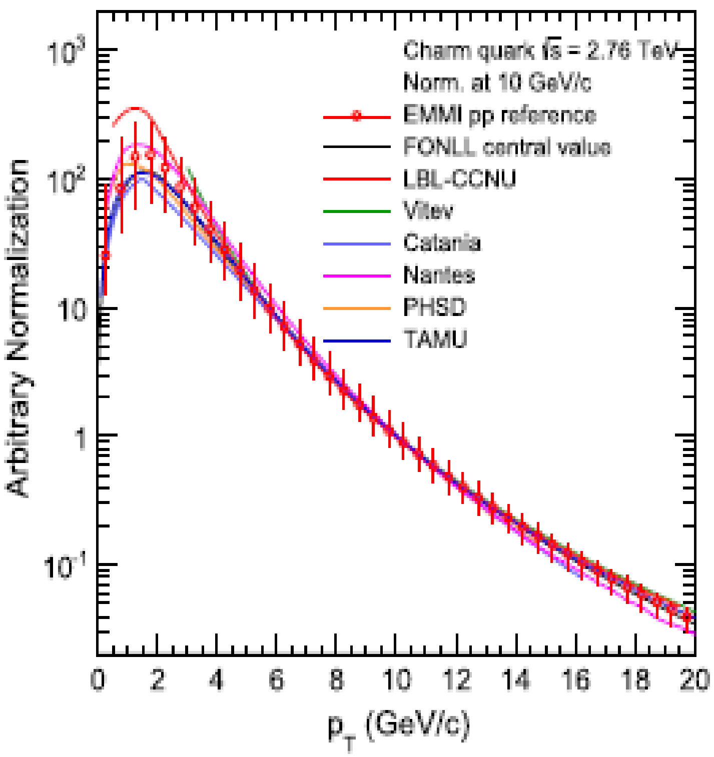
Outline

- Initial charm quark spectrum & shadowing
- Bulk evolution models
- Modelling of hadronization: coalescence vs fragmentation
- Transport coefficient: p- & T-dependence
- Simulation tool: Boltzmann vs Langevin

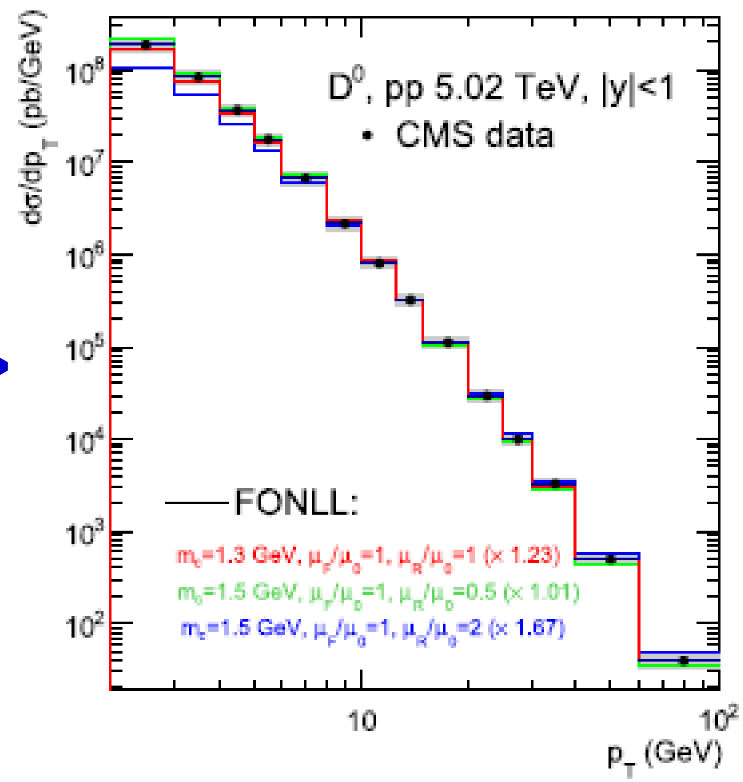
➔ I will go through comparisons of these components between different models; and discuss the conceptual underpinnings of each model when appropriate

Initial spectra: pp baseline

- Baseline charm quark p_t spectrum: model usage vs FONLL
- Baseline D^0 p_T spectrum: FONLL/BCFY fragmentation



FONLL FF



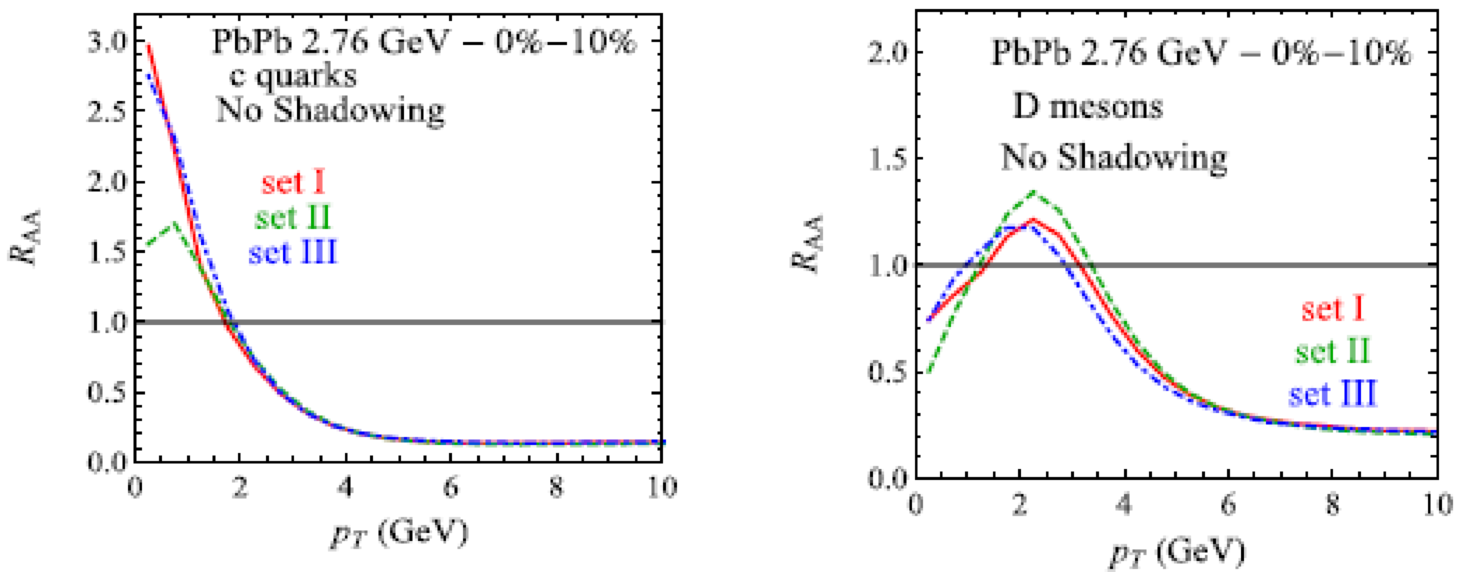
--- FONLL FF: $D_{c\rightarrow D}(r, z)$, e.g. r=0.1 for m_c=1.5 GeV

Initial spectra: pp baseline uncertainties

- Uncertainties in FONLL: m_c, factorization/renormalization scales
  - set I: $m_c = 1.3$ GeV, $\mu_F/\mu_0 = 1$, $\mu_R/\mu_0 = 1$, scaled by 1.33
  - set II: $m_c = 1.5$ GeV, $\mu_F/\mu_0 = 1$, $\mu_R/\mu_0 = 0.5$, scaled by 0.93
  - set III: $m_c = 1.5$ GeV, $\mu_F/\mu_0 = 1$, $\mu_R/\mu_0 = 2$, scaled by 2.21

--- HQ transverse mass $\mu_0 = \sqrt{m_Q^2 + p_t^2}$.

- Impact on observables after in-medium transport

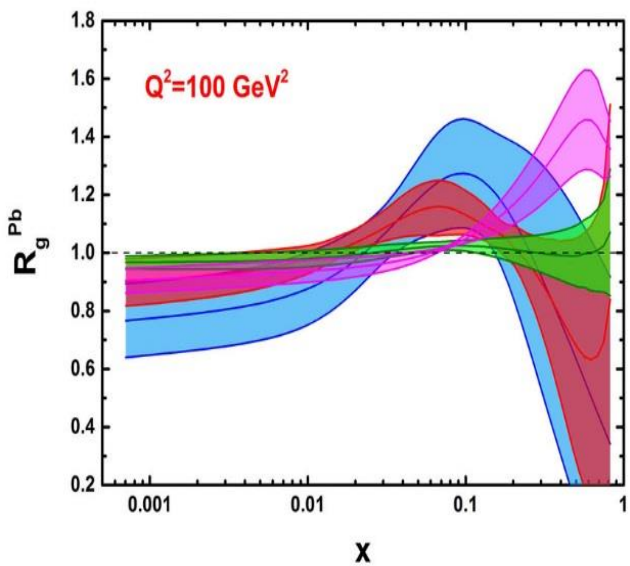


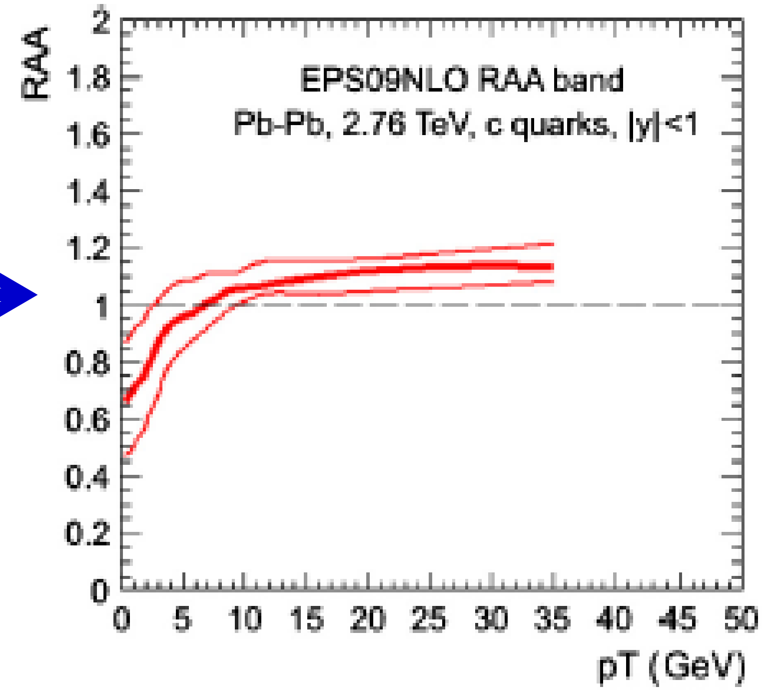
--- Sensitivities at low p_t (lesser after hadronization): to adopt common pp baseline

Initial spectra: shadowing on top of pp baseline

- Major CNM at LHC energies: nuclear shadowing on charm

$$R_i^A(x, Q^2) = f_i^A(x, Q^2)/f_i^p(x, Q^2)$$





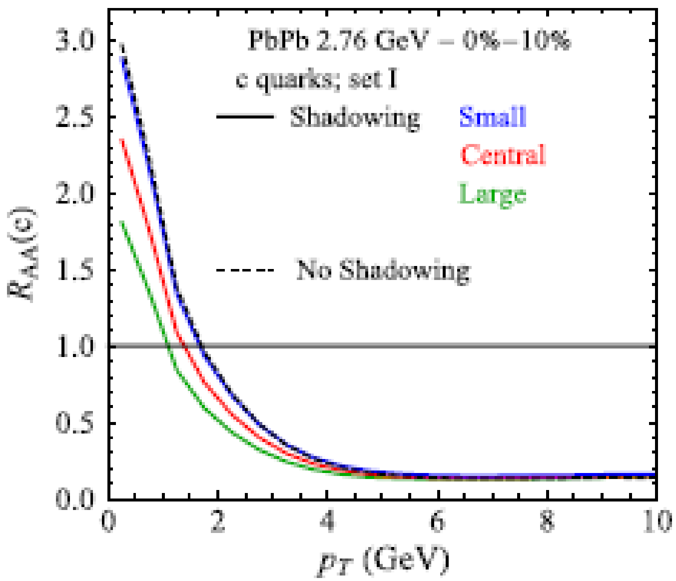
- EPS09 shadowing function $R_{AA}(p_t)$ employed for comparison

--- small → central → large shadowing
--- central: ~80% integrated yields left, i.e. ~20% depletion

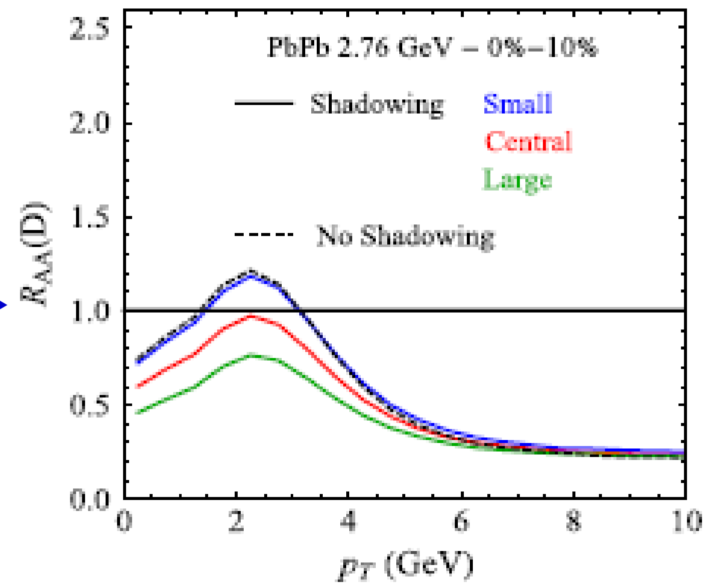
Initial spectra: shadowing effect

- Initial/input charm quark spectrum for transport
  --- $R_{AA}(p_t)$ x FONLL pp $d\sigma/dp_t$

- Charm shadowing impact on observables after transport



c→D



--- +- 25% variations around central at low p_T
--- Uncertainty in shadowing dominates over FONLL intrinsic uncertainties

Bulk evolution models: gross features

- $u_\mu(\tau,x,y,\eta)$ & $T(\tau,x,y,\eta)$: linking HQ interaction & spectral evolution
- Hydro models
  - ideal: UrQMD, TAMU, Nantes VS viscous: LBL-CCNU, Duke, CUJET, POWLANG
  - EoS: all lattice-QCD fitted
  - τ_0=0.3-0.6 fm/c
  - hadronization temperature (end of QGP): T_c=160-170 MeV (POWLANG 155 MeV)
- Full transport models: Catania (quasiparticle) VS PHSD (offshell)

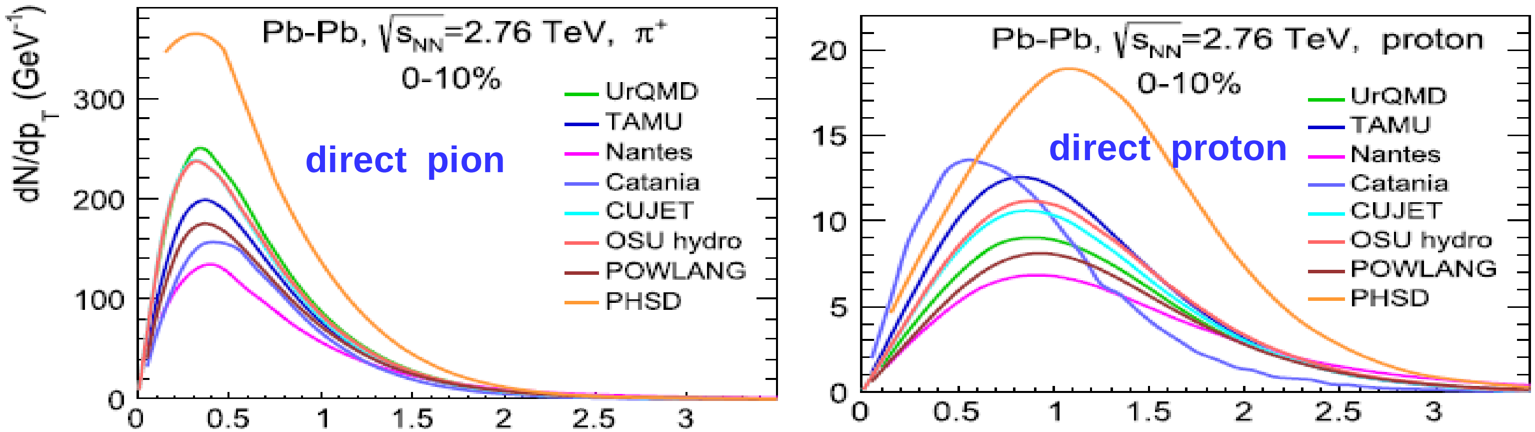
Model	dN_{π^+}/dy $(dS/d\eta)$		dN_p/dy	
inclusive π's, p's	0–10%	30–50%	0–10%	30–50%
UrQMD	495	152	34	11
TAMU	682 (12400)	170 (3080)	58	15
Nantes	478	129	38	10
Catania	(14000)	(3700)		
LBL-CCNU/Duke	653 (12600)	160 (3080)		
CUJET	610 (10820)	142 (2610)	45	11
POWLANG	(9100)	(1450)		
PHSD	722	148	31	6
exp.	670±68	163±15	31±4	8±1

--- discrepancies between models

--- due to different entropy input

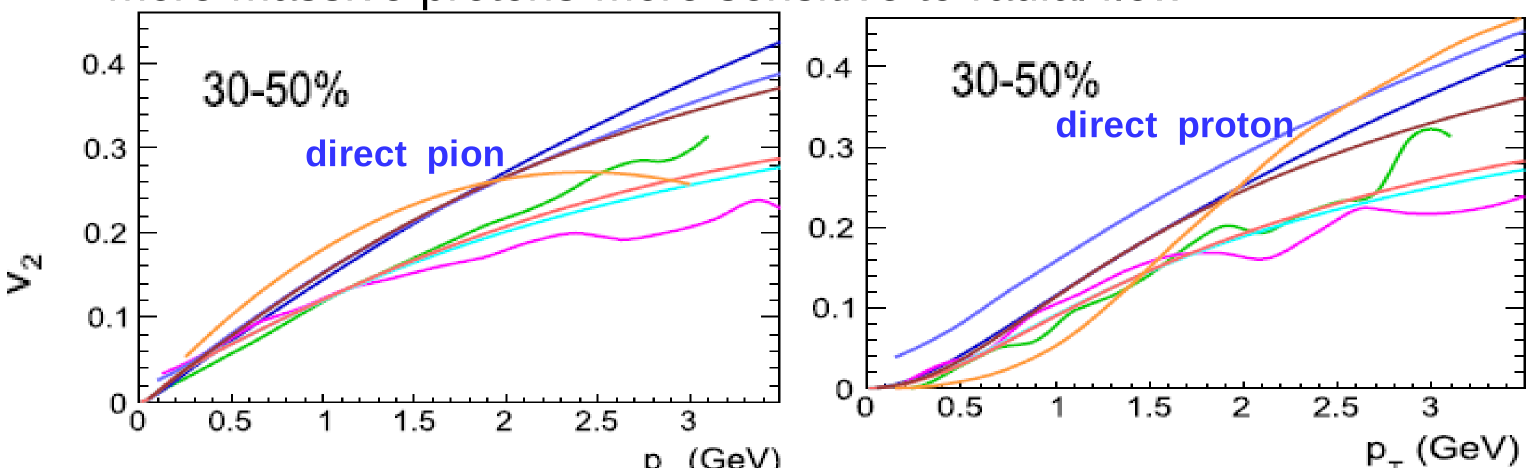
➔ **to be resolved!**

Bulk evolution models: flows at Tc



--- agreement within ~20% in magnitude & peak structure for most hydro models

--- more massive protons more sensitive to radial flow



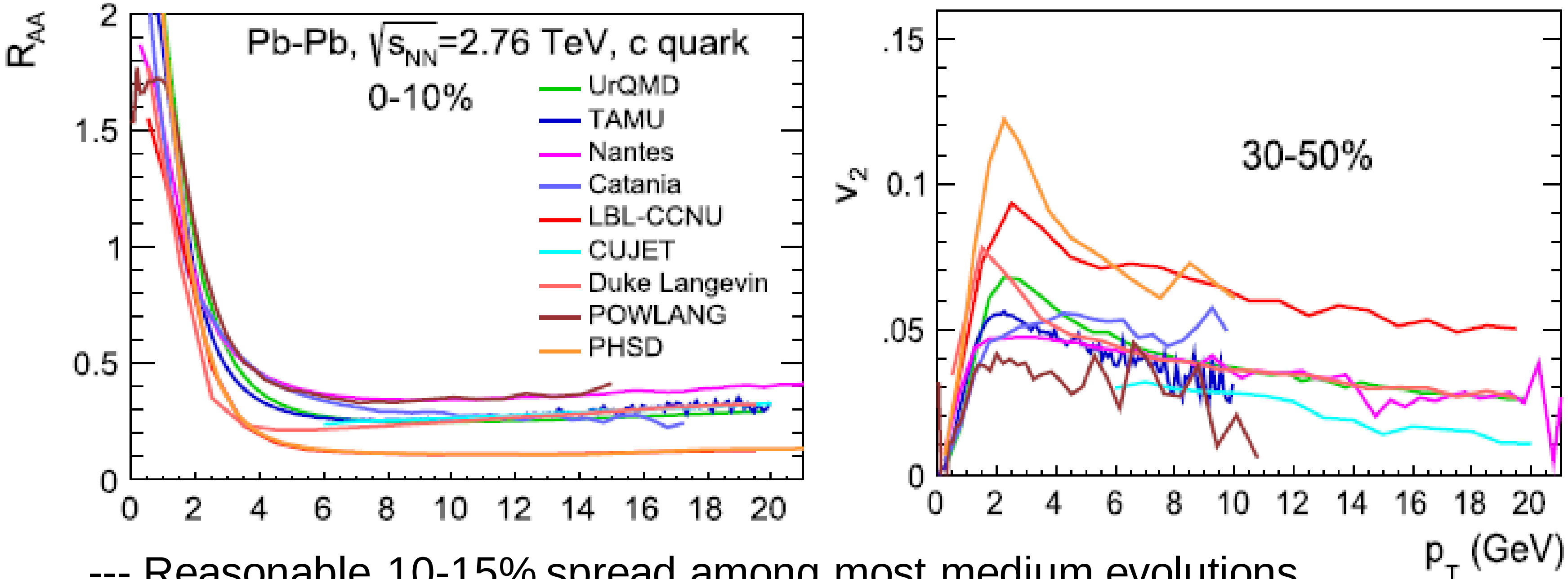
--- v_2 reasonably collimated for p_T<2 GeV

➢ *Snapshot ➔ <v_T>(τ) & <ε_P>(τ): better measure of evolution*

Bulk evolution models: impact on observables

- c-quark simulation with common 5*pQCD transport coefficient (Langevin) or cross sections (Boltzmann) m_c=1.5 GeV

$$\mathcal{M}_t \propto \frac{\alpha_s}{t - m_D^2} \quad \alpha_s = 0.4 \quad m_D = m_{\mathrm{th}} = gT \longrightarrow \mathcal{D}_s(2\pi T) \simeq 6$$ at T~300 MeV

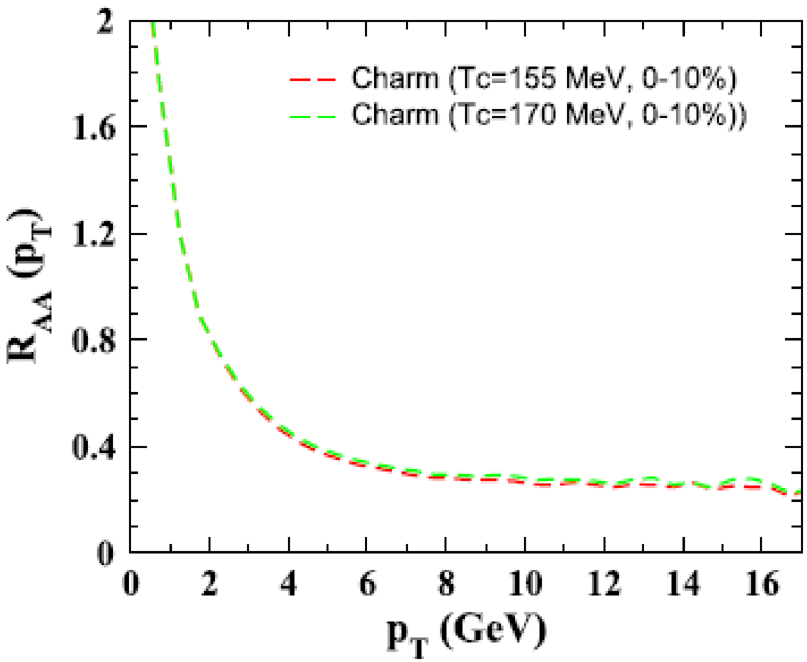


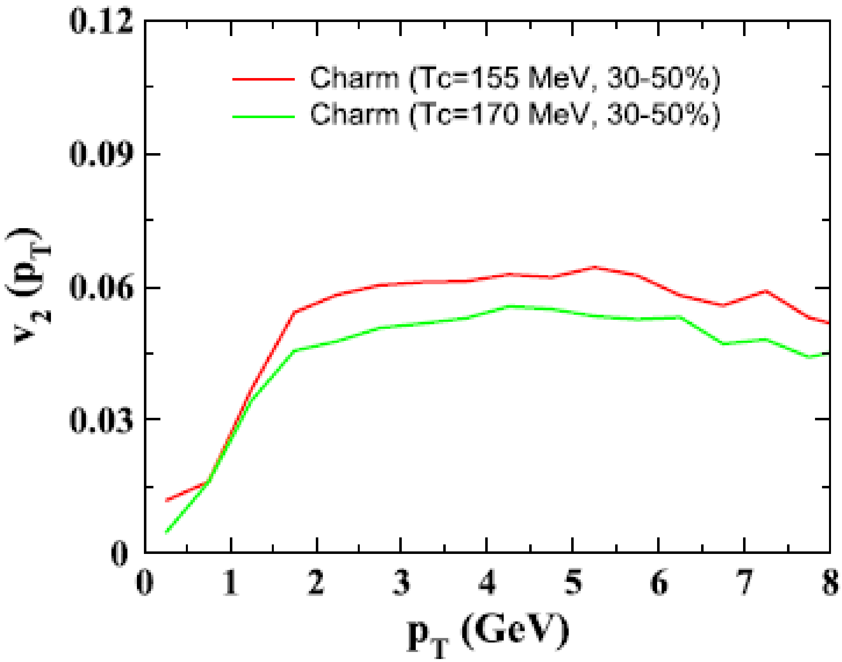
--- Reasonable 10-15% spread among most medium evolutions

--- Except for LBL-CCNU (& PHSD): much smaller R_{AA} and larger v_2 than its counterpart Duke, probably due to the use of massless thermal partons

Bulk evolution models: impact of different Tc

- Catania group with 5*pQCD comparing T_c=155 vs 170 MeV





--- charm quark R_{AA} little affected, v_2 significantly enhanced

--- Suppression most effective in early state with high density

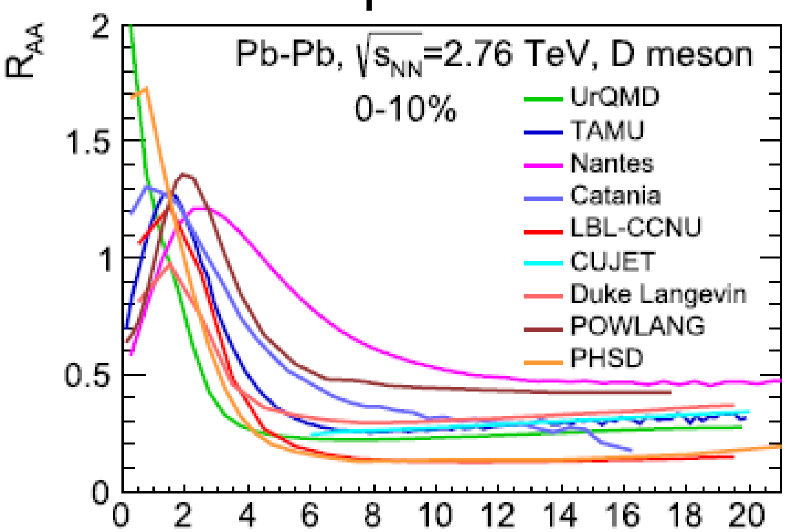
--- transfer of v_2 to charm quark most effective around T_c when the bulk v_2 is already mostly built up + strong coupling of HQ with medium around T_c

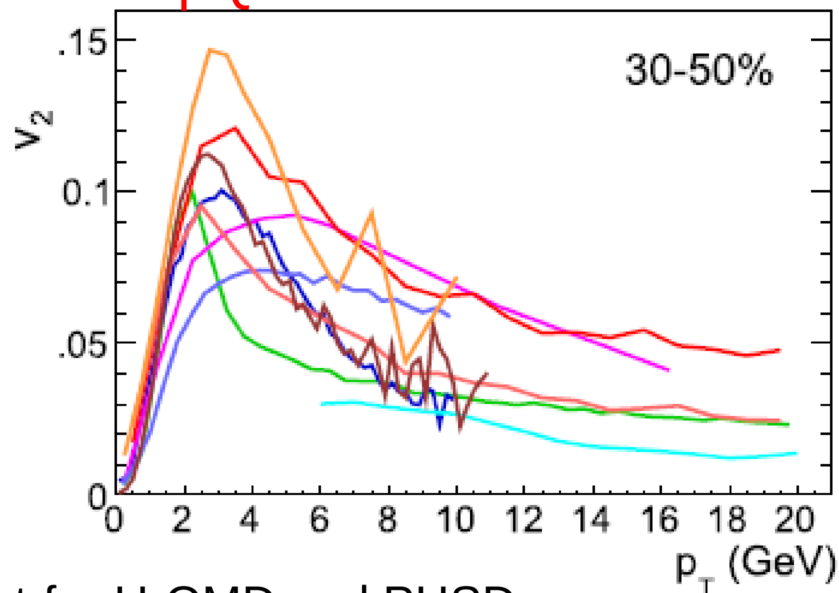
Hadronization: coal.+frag.

➢ Hadronization modelling

- ICM + FF: UrQMD, Nantes, Catania, LBL-CCNU, Duke, PHSD
- RRM + FONLL-FF: TAMU
- FF only: CUJET; in-medium FF (similar to coalescence): POWLANG
- m_q=0.3-0.37 GeV in most models, except m_q=0.1 GeV in Nantes

➢ Model comparison with common 5*pQCD





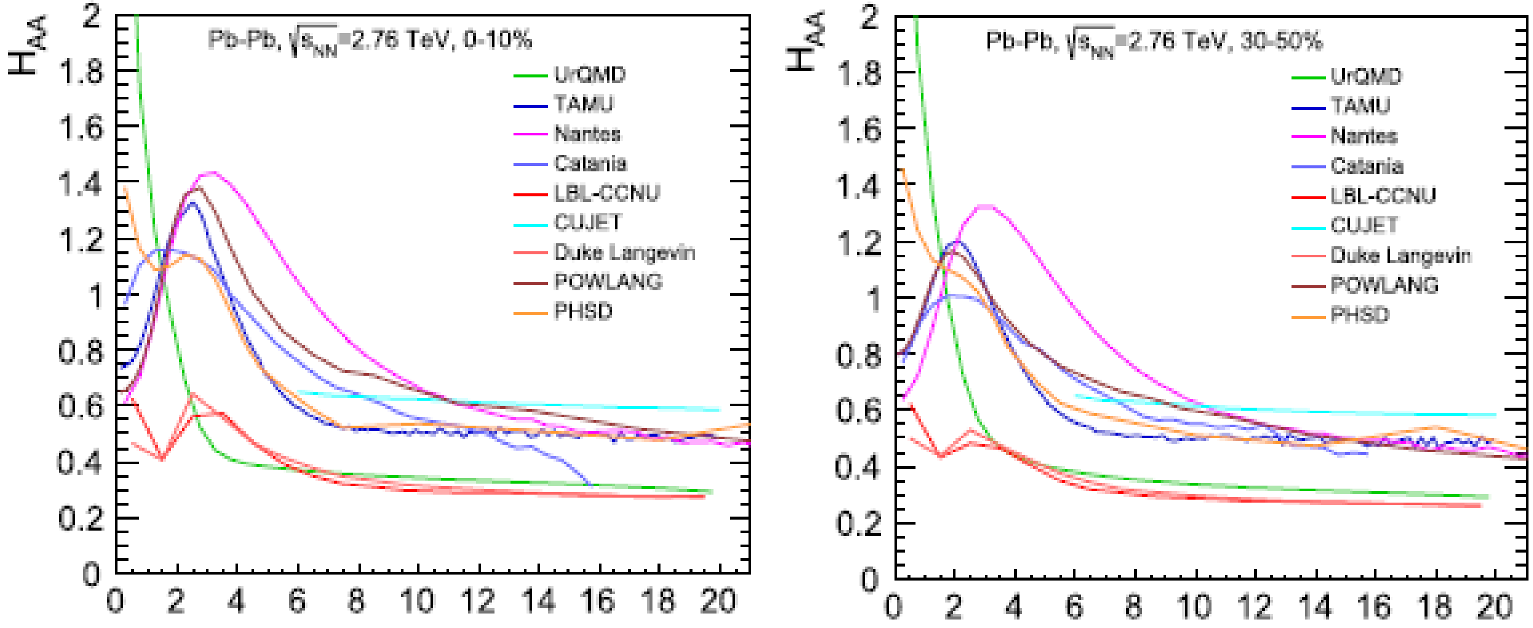
--- R_{AA}: "flow bump" emerges, except for UrQMD and PHSD;
most pronounced with Nantes, due to small m_q=0.1 GeV?

--- v_2 mostly increased by 30-40% relative to c-quark, tend to c-quark at high p_T

Hadronization direct effects: H_{AA}

- Hadronization effects directly exhibited via

$$H_{\mathrm{AA}}(p_T, p_t = p_T) = \frac{\mathrm{d}N_D/\mathrm{d}p_T}{\mathrm{d}N_c/\mathrm{d}p_t} = \frac{\mathrm{d}N_D^{\mathrm{coal}}/\mathrm{d}p_T + \mathrm{d}N_D^{\mathrm{frag}}/\mathrm{d}p_T}{\mathrm{d}N_c/\mathrm{d}p_t}$$

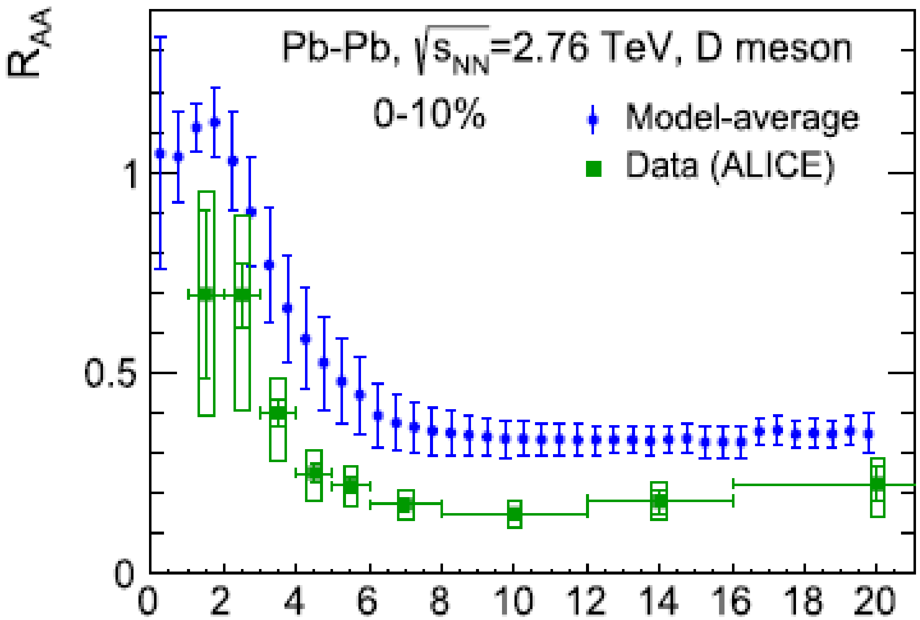


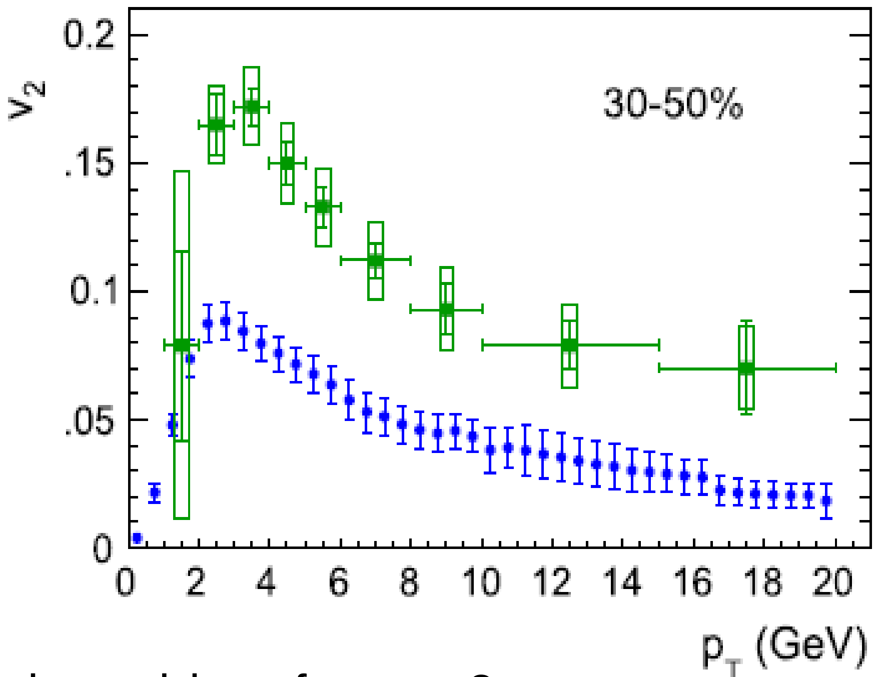
--- High p_T: only FF shift → two layers of levelling-off (lower LBL-CNU/Duke & UrQMD)

--- Low p_T: light quark p_T added to c-quark → “flow bump” (also lower LBL-CNU/Duke), more pronounced in central collisions; most marked enhancement in Nantes

Hadronization: model average VS data

➤ Model average with common 5*pQCD (excluding LBL-CCNU & PHSD):





--- High (p_T>5 GeV) suppression: overestimated by a factor ~ 2

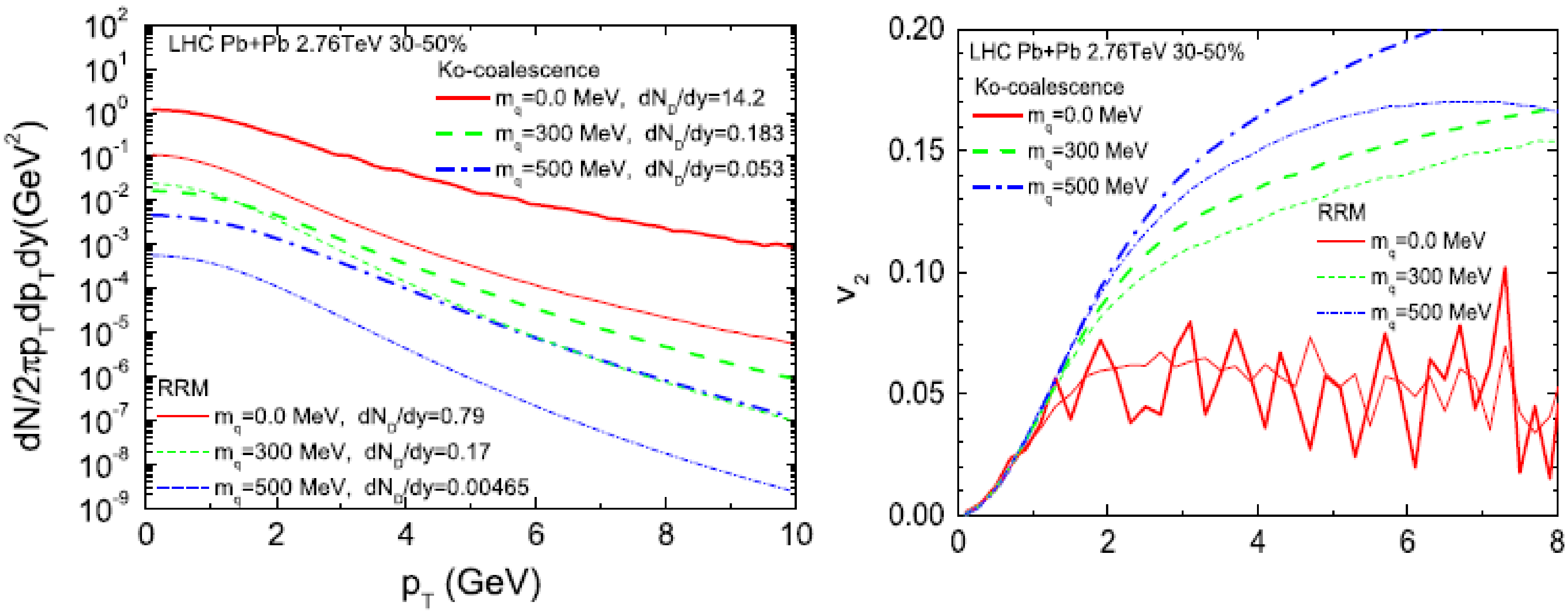
--- Low p_T v_2: as a gauge of interaction strength, underestimated by a factor ~ 2

➤ Conclusion: lack of coupling strength with 5*pQCD

➔ *Ds(2πT) must be significantly smaller than ~6 for T<=300 MeV*

Coalescence hadronization: ICM vs RRM

- ICM: Instantaneous projection q→h in 3-mom. space;
  RRM: resonant scattering within Boltzmann equation
  ➔ energy conservation + guaranteed equilibrium limit
- Comparison: 5*pQCD Langevin + hydro-q within TAMU model



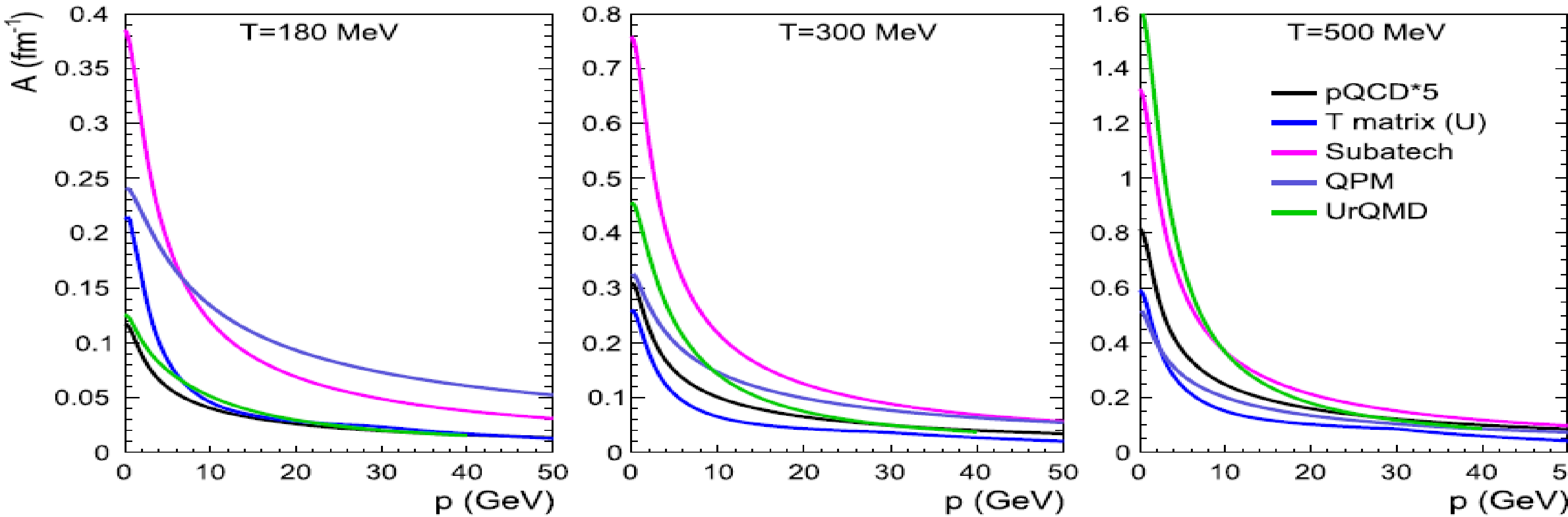
--- D-meson p_T spectrum: RRM softer than ICM when approaching thermal limit

--- D-meson v_2 : RRM (allowing for isotropic cross section smearing) a bit smaller than ICM (c-q comoving momentum addition)

Transport coefficient: A(p,T)

➢ Thermalization rate: $A = \int \sum |\mathcal{M}|^2 \hat{f}(\mathbf{q})$

- Augmented pQCD-based: Nantes (running α_s + reduced screening mass)
  Catania (running α_s getting large around T_c)
- Nonperturbative: T-matrix(resume in-medium Coulomb + confining potential)
  → resonance correlations enhancing HQ coupling strength around T_c

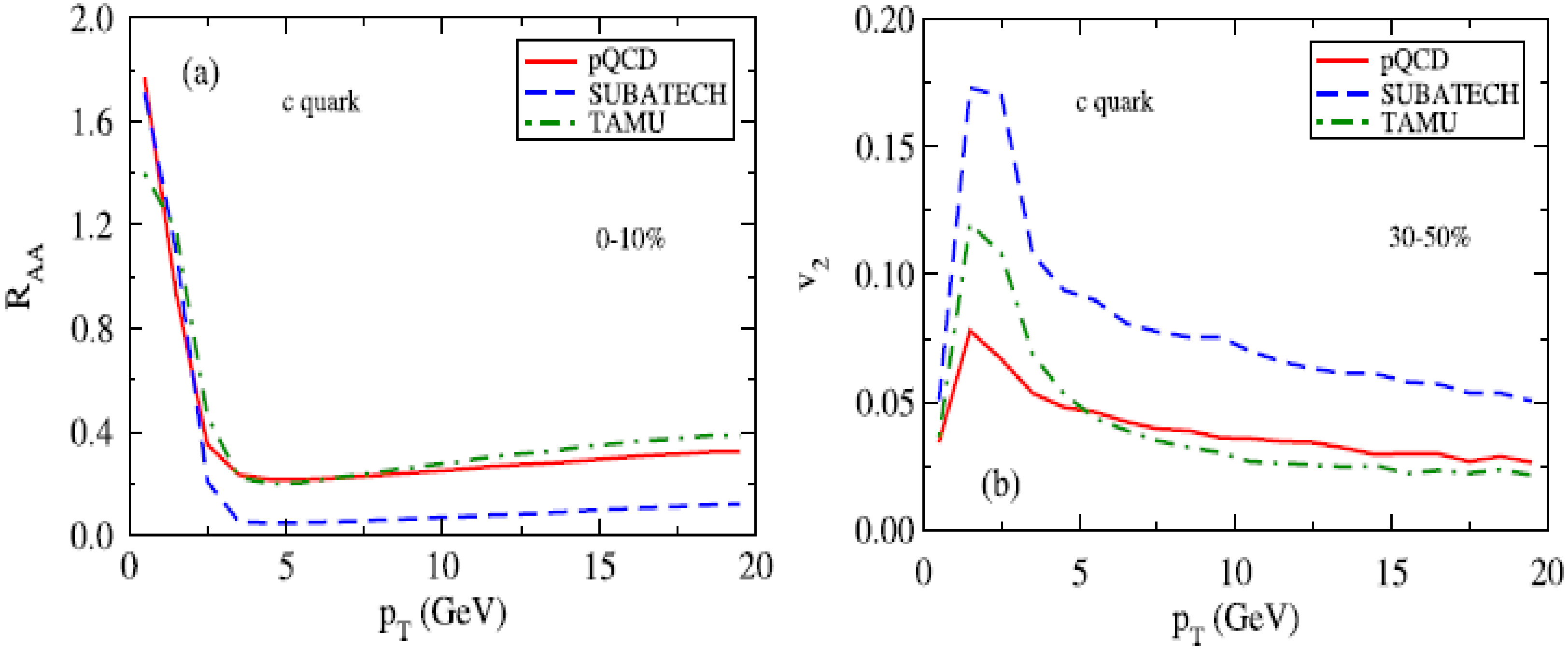


--- Low p enhancement: T-matrix resums long range remnant confining force

--- T-dependence: parton density VS reduced/screened coupling:
T-matrix ~ little change for T=200-300; 5*pQCD (fixed α_s) ~ T^2; Nantes ~ T

Different A(p,T) in common OSU hydro

- Langevin: common c-quark baseline + common hydro evolution



--- R_{AA} at high p_T: TAMU a bit less suppression due to a bit smaller A than 5*pQCD

--- v_2 at low p_T: TAMU much larger v_2 due to much large A than 5*pQCD

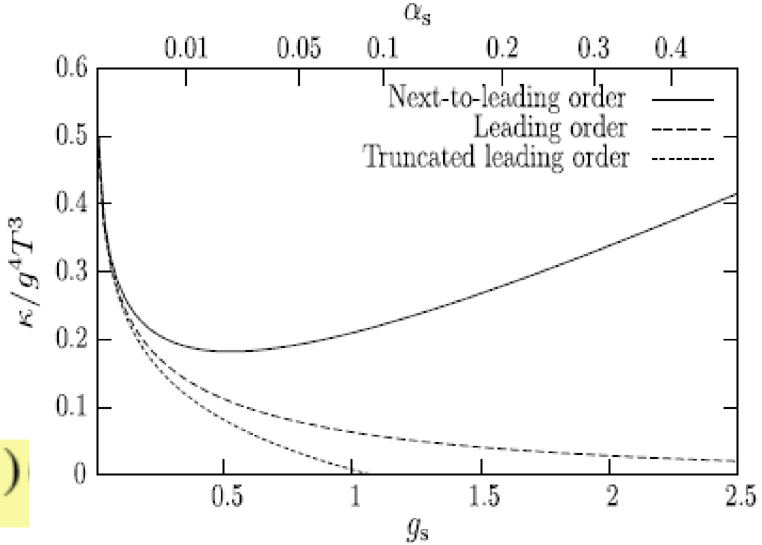
--- Nantes: much stronger suppression & larger v_2 due to much larger A

More evaluations of transport coeffi.

- NLO pQCD (G. Moore)

  --- $\kappa/T^3 = 2/(\mathcal{D}_s T)$

  --- poor convergence



- lattice QCD

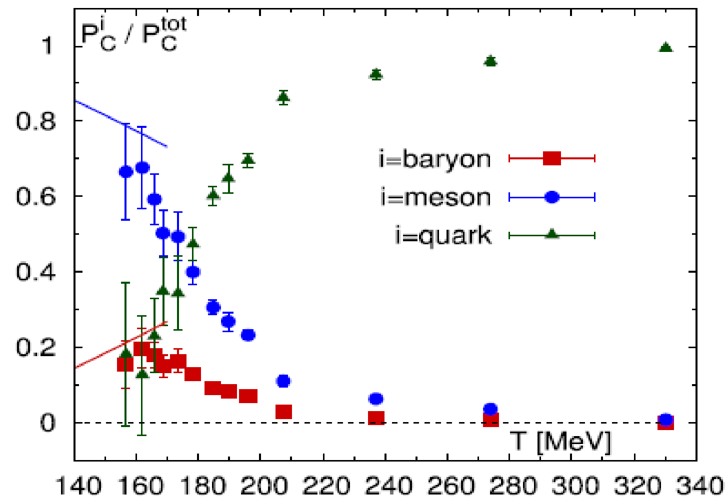
$$\mathcal{D}_s = \lim_{\omega \to 0} \sigma(\omega, \vec{p}=0)/(\omega \chi_q \pi)$$

--- $\mathcal{D}s(2\pi\mathcal{T}) \sim$ 3.7-7.0 (Banerjee et al.) VS ~1.8 (Ding et al.) at T~1.5 T_c

- lattice charm correlations (Petreczky et al.)

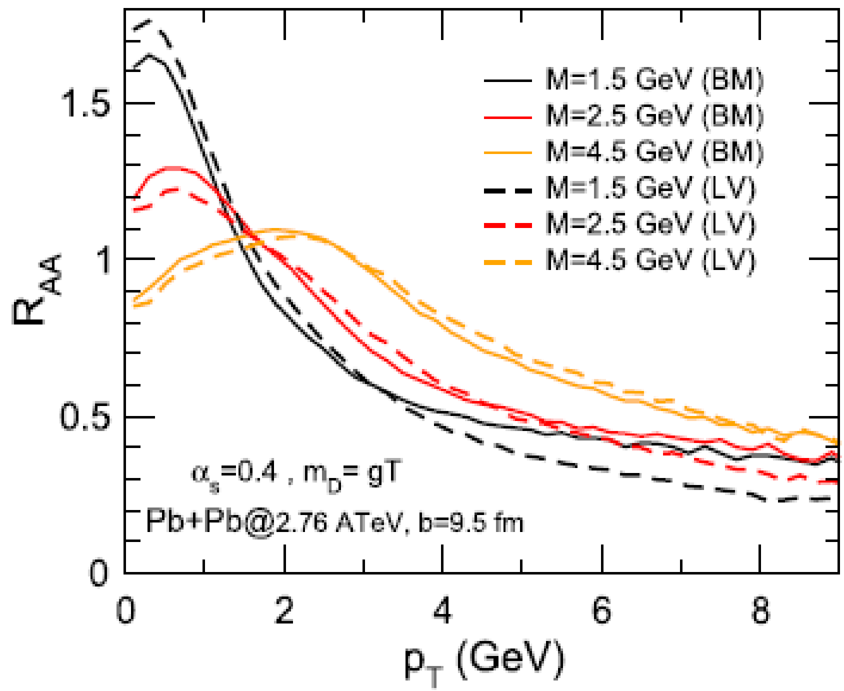
  --- partial pressures of charm quarks, mesons, baryons

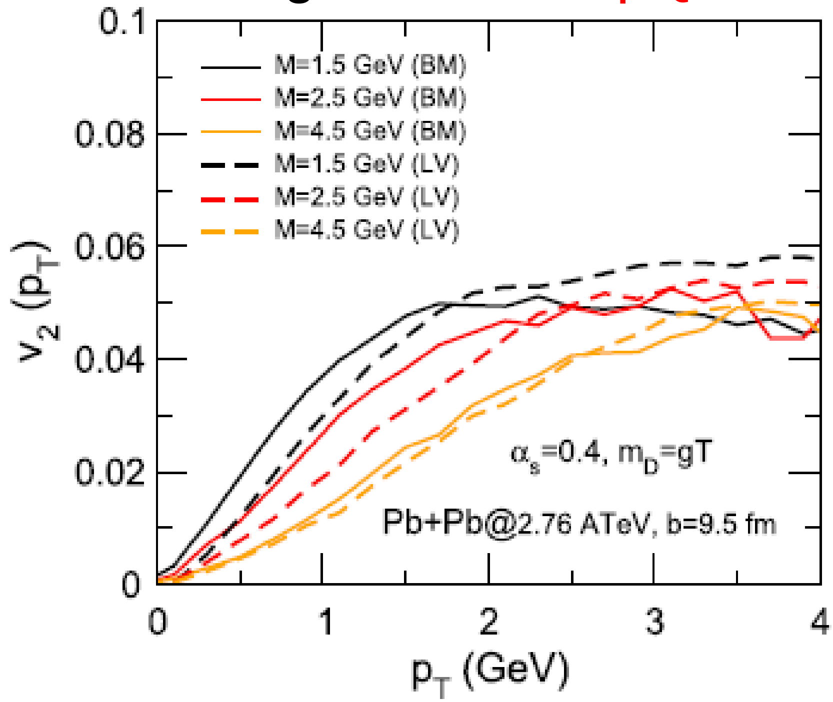
  --- hadron-like excitations persist above T_c



Implementing transport coeffi.: BM vs LV

- HQ diffusion simulation: Boltzmann vs Langevin with 5*pQCD





--- M=1.5 GeV: BM R_{AA} 25-30% larger, low p_T v_2 slightly larger than Langevin

--- BM vs LV deviations vanishing toward M=4.5 GeV;
larger toward high p_T : Gaussian distribution in Langevin e-loss less accurate

- Bottom in sQGP (no quasiparticles): LV still applicable; BM problematic

  --- Angular correlations more sensitive to BM vs LV

Summary & Findings

- EMMI-RRTF: modelling components for HF probes scrutinized & compared between models

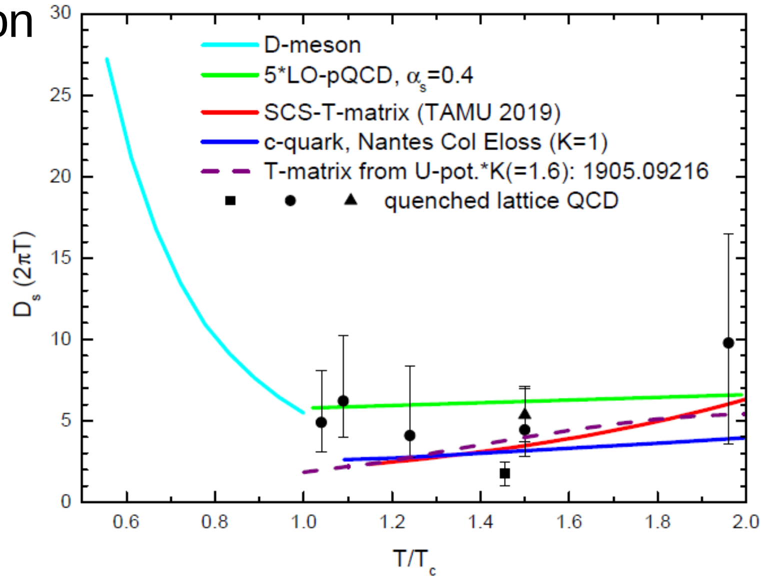
  --- baselines, shadowing, bulk evolution, transport coefficient & implementation (BM vs LV), hadronization

- Extracting transport coefficient

  --- Insufficient 5*pQCD ➔ $\mathcal{D}_s(2\pi T) \simeq 6$

  --- recent update: SCS-T-matrix vs U-pot.T-matrix*K=1.6 vs Nantes

  --- Yet p-dependence important, not reflected here



- Unravelling microscopic dynamics of QCD matter

  --- lattice constraints on computing A(p,T): F(r,T), suscepts., spectral funs. vs quasiparticles

  --- hadronization: larger discrepancy & spread between models than c-quark ➔ primary area of further improvements

Perspectives & observables suggested

- Bottom observables: cleaner probes of sQGP
- D & B v_2 peak structures: gauging interaction strength
- Precision R_{AA} and v_2: T and M dependence of tran. coeff.
- D_s & Λ_c hadronization: charm hadrochemistry and flow
- HF in jets: HF vs gluon e-loss
- Pair correlations: delineating elastic vs radiative, BM vs LV

➔ Significant progress has been made on many aspects of these issues in the past few years: to be discussed in this online workshop