

Charm-Hadron Production in pp & AA Collisions

Min He

Nanjing University of Sci. & Tech., Nanjing, China

**Based on recent work done in collaboration with
Ralf Rapp of Texas A&M University**

Contents

1. Introduction

- Heavy quark probes & charm hadronization

2. Charm-hadron production in pp

- SHM augmented with RQM, vs PDG
- Charm-baryon enhancement

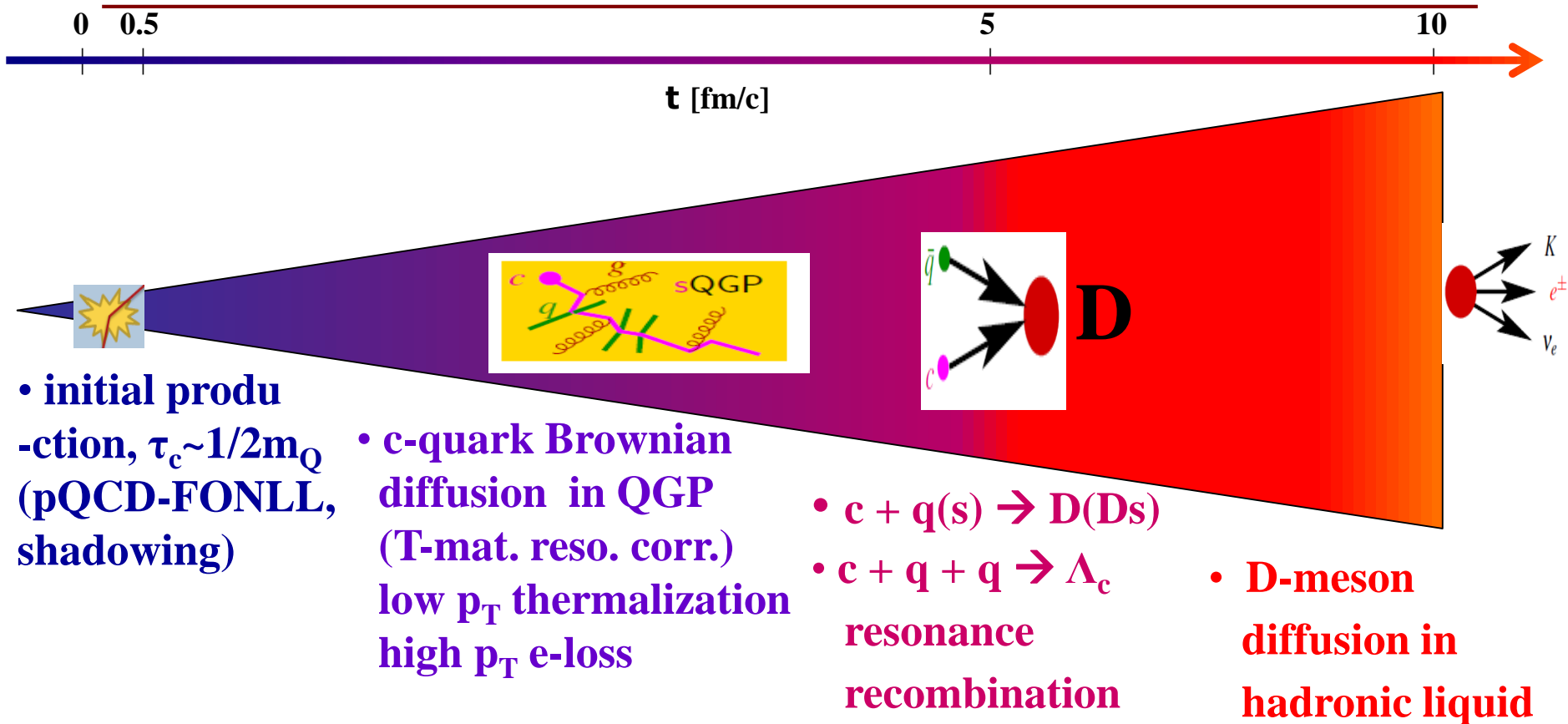
3. Charm-hadron production in AA

- 2- & 3-body RRM, equilibrium mapping
- Space-momentum correlations
- Event-by-event implementations of hydro-Langevin-RRM
- RQM augmented baryons

4. Results

- Collectivity pattern: R_{AA}, v_2
- p_T -dependent charm hadro-chemistry: $D_s^+/D^0, \Lambda_c^+/D^0$

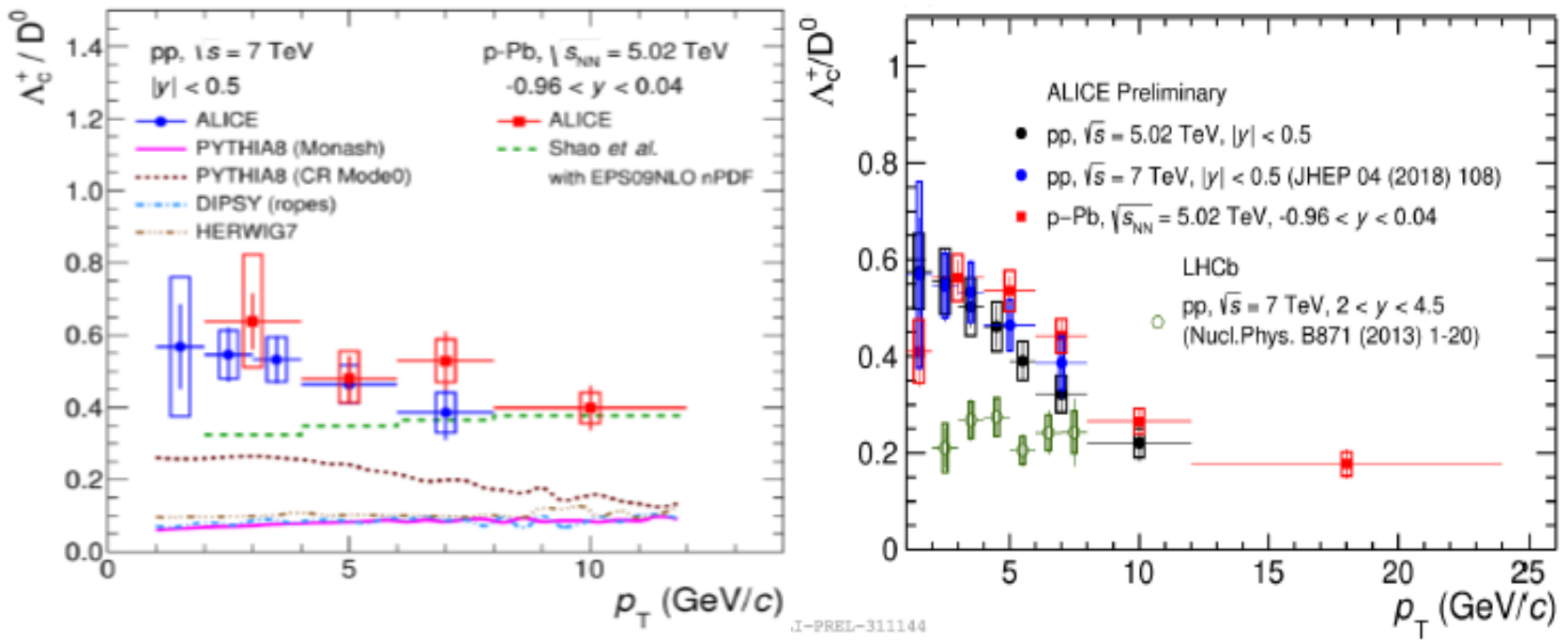
Heavy flavor transport in hot QCD matter



- **Calibrated & tagged probes preserving memory of interaction history**
- **Trans. coeffi. $\mathcal{D}_s(2\pi T)$: coupling strength \rightarrow probe in-medium QCD force**

Charm-hadron production in pp collisions

- ❑ Enhanced Λ_c^+/D^0 w.r.t. pQCD based MC event generators
- ❑ Already a puzzle in pp? → **statistical coalescence (SHM) in a quark-rich environment?!**



- ❑ Standard SHM (with PDG only spectra) $\Lambda_c^+/D^0 \sim 0.22$ too small **P. B.-M.**
- ❑ Tension between ALICE (mid-rapidity) vs LHCb (forward-rapidity)?

Charm-hadron production: pp SHM

- PDG: 5 Λ_C (I=0), 3 Σ_C (I=1), 8 Ξ_C (I=1/2), 2 Ω_C (I=0) → **missing baryons?!**
RQM: 18 extra Λ_C , 42 extra Σ_C , 62 extra Ξ_C , 34 extra Ω_C up to 3.5 GeV
 → supported by lattice [PRD 84 \(2011\) 014025](#); [PoS LAT. 2014 \(2015\) 084](#); [PLB 737 \(2014\) 210](#)

- Statistical Hadronization Model (SHM): $T_H=170$ MeV $n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2(\frac{m_i}{T_H})$

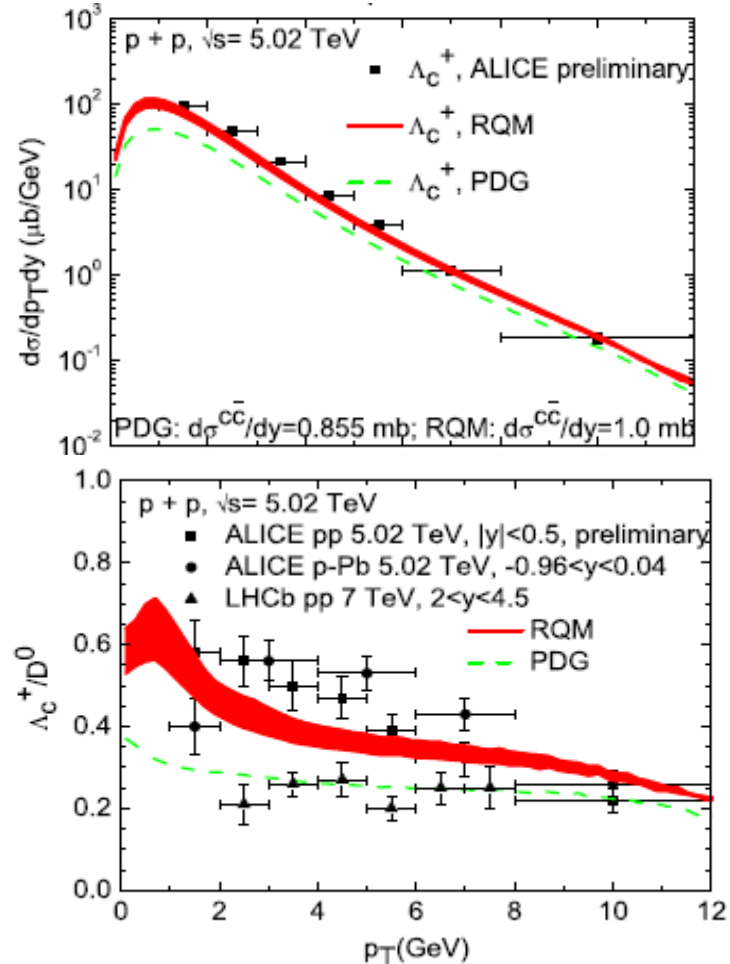
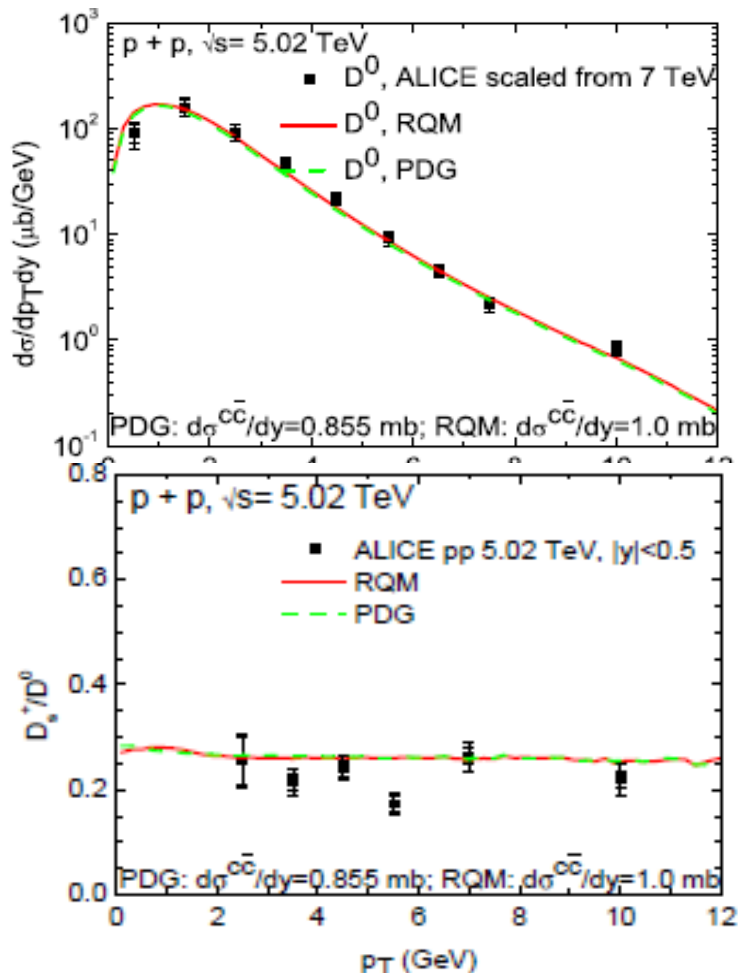
n_i ($\cdot 10^{-4}$ fm $^{-3}$)	D^0	D^+	D^{++}	D_s^+	Λ_c^+	$\Xi_c^{+,0}$	Ω_c^0
<u>PDG(170)</u>	1.161	0.5098	0.5010	0.3165	<u>0.3310</u>	0.0874	0.0064
<u>RQM(170)</u>	1.161	0.5098	0.5010	0.3165	<u>0.6613</u>	0.1173	0.0144

- Strong feeddowns of excited states all included: BR=100% to Λ_C^+ for all Λ_C & Σ_C even above DN (2805 MeV) threshold
 -- Strangeness supp. $\gamma_s=0.6$

r_i	D^+/D^0	D^{++}/D^0	D_s^+/D^0	Λ_c^+/D^0
<u>PDG(170)</u>	0.4391	0.4315	<u>0.2736</u>	<u>0.2851</u>
<u>RQM(170)</u>	0.4391	0.4315	<u>0.2726</u>	<u>0.5696</u>

- FONLL fragmentation of charm quarks into all kinds of charm-hadrons
relative weight: according to the SHM thermal densities
 & Decay simulations of all excited states to ground state D^0 , D^+ , D_s^+ , Λ_C^+ , Ξ_C & Ω_C

Results: pp 5.02 TeV collisions



- \square Λ_c^+ favors RQM with $d\sigma/dy = 1.0 \text{ mb}$: low p_T enhancement from feeddowns of RQM augmented baryons **uncertainty band: BR=50%-100% to ground state Λ_c^+ for Λ_c 's & Σ_c 's above DN (2805 MeV) threshold**

Charm-hadron production in AA collisions

- **Charm quark diffusion in QGP: T-matrix & Langevin**
- **Hadronization: 2- & 3-body RRM**
- **Space-momentum correlations (SMCs)**
- **Analysis: role of SMCs & RQM augmented baryons**
- **Results & observables**

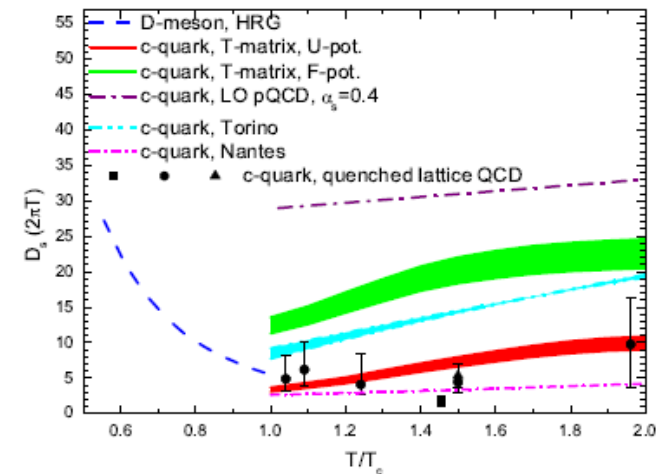
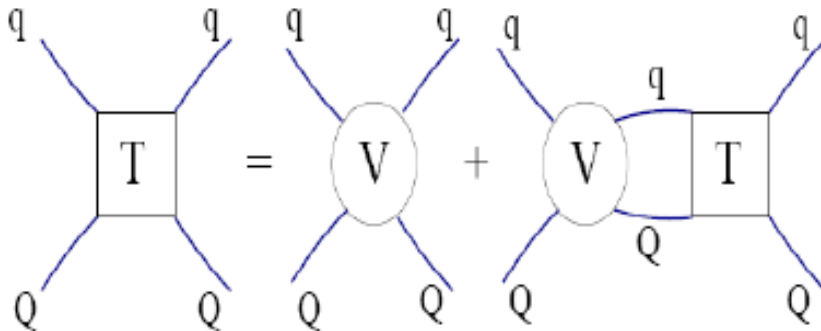
Charm in QGP: transport coeffi. & diffusion

Langevin + hydro simulation down to $T_c=170$ MeV
fluid rest frame updates \rightarrow boost to lab frame

$$dx_j = \frac{p_j}{E} dt,$$

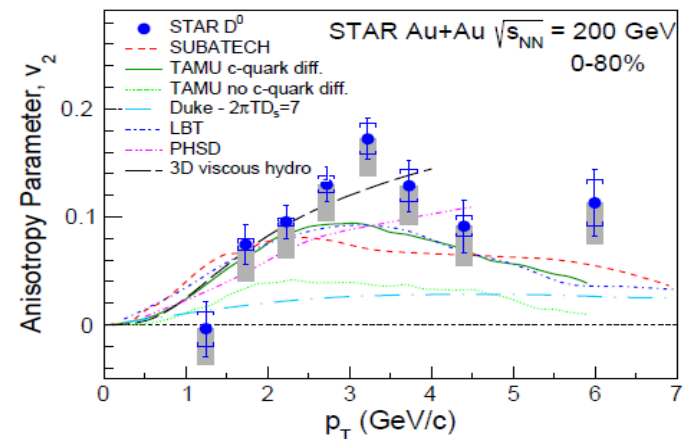
$$dp_j = -\Gamma(p)p_j dt + \sqrt{2dt D(|p + \xi d p|)} \rho_j.$$

□ Lattice-constrained Q-q/g T-matrix



□ p- and T-dependent transport with $D_s(2\pi T) \sim 2-4$ near T_{pc}

□ Observed large D-meson v_2 --- strong coupling of charm with QGP near T_{pc} He, Fries, Rapp



Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- Hadronization: 2- & 3-body RRM
- Space-momentum correlations (SMCs)
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables

Resonance Recombination Model (RRM)

□ **Hadronization = Resonance formation** $c\bar{q} \rightarrow D$ as the T-matrix resonant interaction between c-qbar strengthens towards T_c

□ **Realized by Boltzmann eq.** Ravagli & Rapp 2007

$$p^\mu \partial_\mu f_M(t, \vec{x}, \vec{p}) = -m\Gamma f_M(t, \vec{x}, \vec{p}) + p^0 \beta(\vec{x}, \vec{p}).$$

→ conserving 4-mom. + recovering both kinetic & chemical equil. limit

□ **Generalized to 3-body** Λ_c taking advantage of light diquark correlations

$$f_B(\vec{x}, \vec{p}) = \frac{E_B(\vec{p})}{\Gamma_B m_B} \int \frac{d^3 p_1 d^3 p_2 d^3 p_3}{(2\pi)^6} \frac{E_d(\vec{p}_{12})}{\Gamma_d m_d} f_1(\vec{x}, \vec{p}_1) f_2(\vec{x}, \vec{p}_2) f_3(\vec{x}, \vec{p}_3) \\ \times \sigma_{12}(s_{12}) v_{\text{rel}}^{12}(\vec{p}_1, \vec{p}_2) \sigma_B(s_{d3}) v_{\text{rel}}^{d3}(\vec{p}_{12}, \vec{p}_3) |_{\vec{p}_{12}=\vec{p}_1+\vec{p}_2} \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)$$

→ 3 quark distributions: 2 light thermal + Langevin c-quark

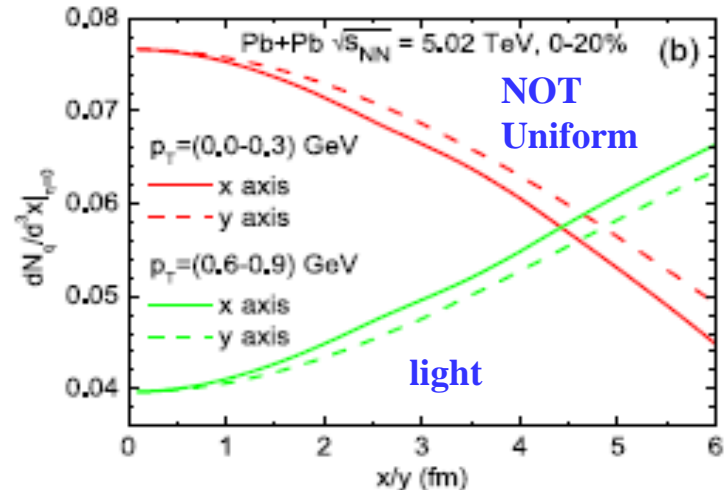
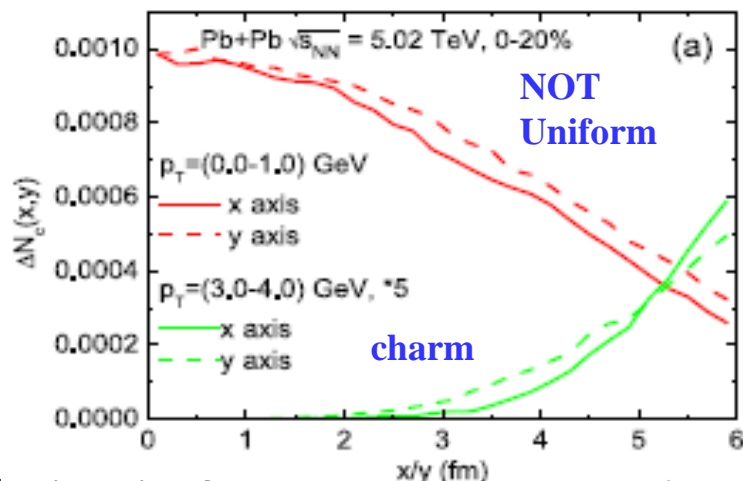
□ **Charm-meson/baryon RRM implemented on hydro Cooper-Frye hadronization hypersurface at $T_H=170$ MeV**

Charm-hadron production in AA collisions

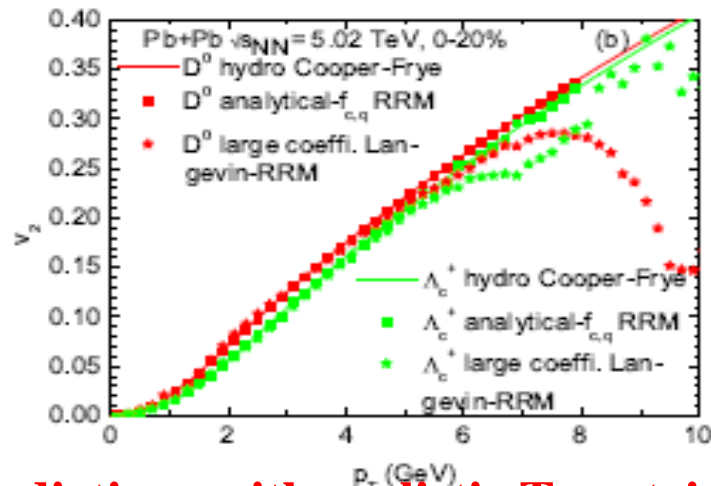
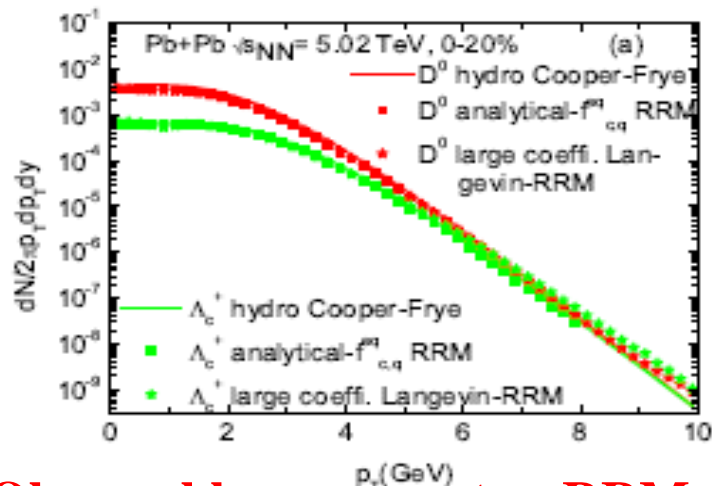
- Charm quark diffusion in QGP: T-matrix & Langevin
- Hadronization: 2- & 3-body RRM
- Space-momentum correlations (SMCs)
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables

Space-momentum correlations (SMCs)

□ hydro- q & Langevin- c : low (high) p_T more populated in center (outer)



□ kinetic & chem. equil. mapping with large trans. coeff. SMCs incorporated



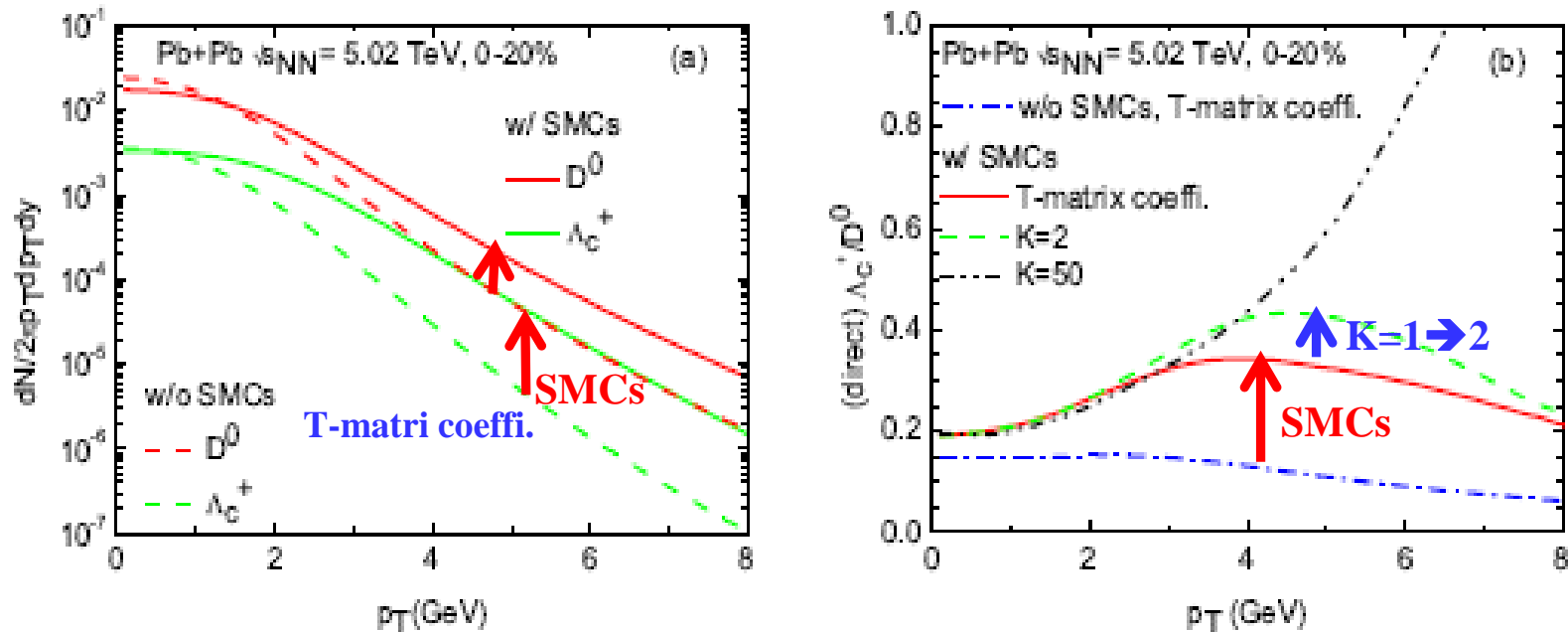
→ Observables come out as RRM predictions with realistic T-matrix coeffi.

Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- Hadronization: 2- & 3-body RRM
- Space-momentum correlations (SMCs)
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables

Direct D^0 & Λ_c^+ production via RRM

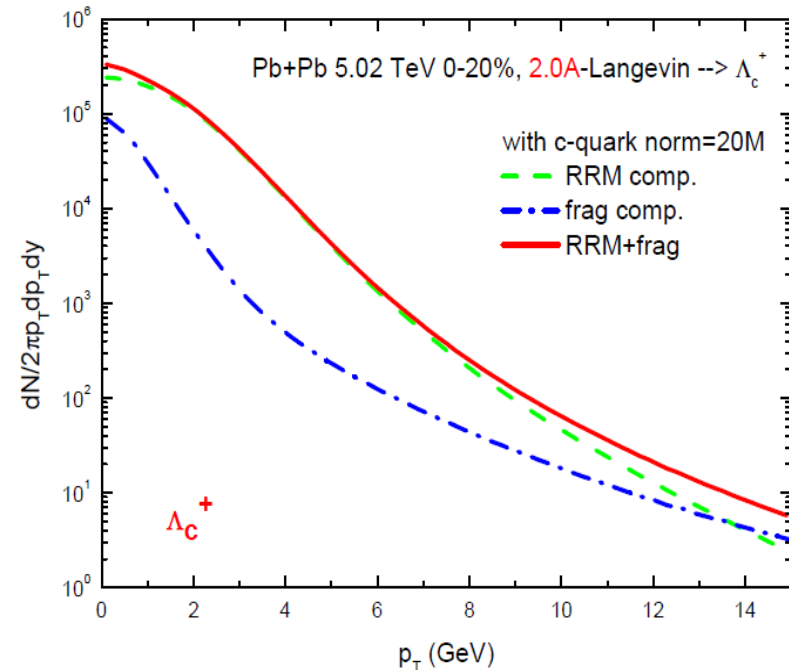
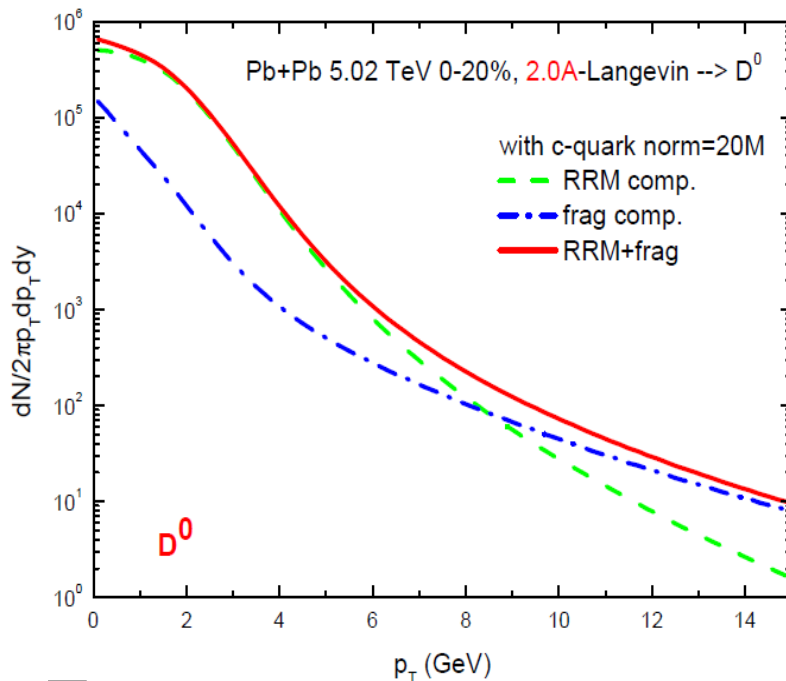
- Including **SMCs** makes the spectra **harder** & enhances the ratio Λ_c^+/D^0



- Fast-moving c-quarks [$p_T \sim 3-4$ GeV] moving to outer part of fireball find higher-density of harder [$p_T \sim 0.6-0.9$ GeV] light quarks for recombination
- An effect entering **squared** for the recombination production of Λ_c^+
 \rightarrow larger enhancement for $\Lambda_c^+ \rightarrow \Lambda_c^+/D^0$ ratio enhanced!

Recombinant vs fragmenting spectra

- **Hydro-Langevin-RRM(+fragmentation):** for all charm-mesons/baryons
 → higher states decay into ground state D^0 , D^+ , D_s^+ , Λ_C^+



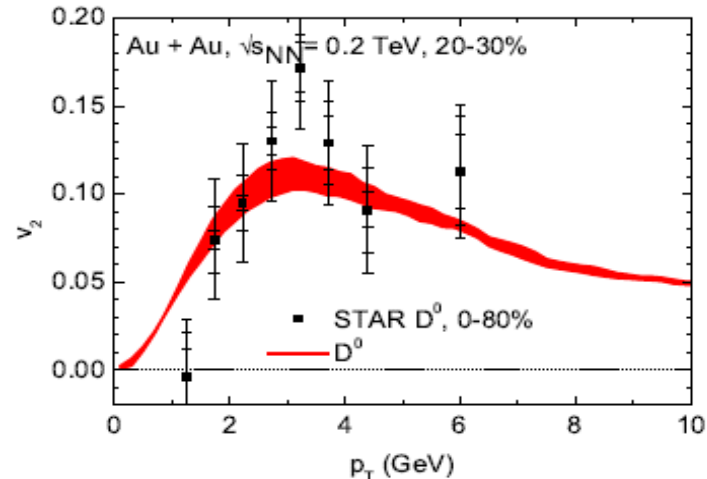
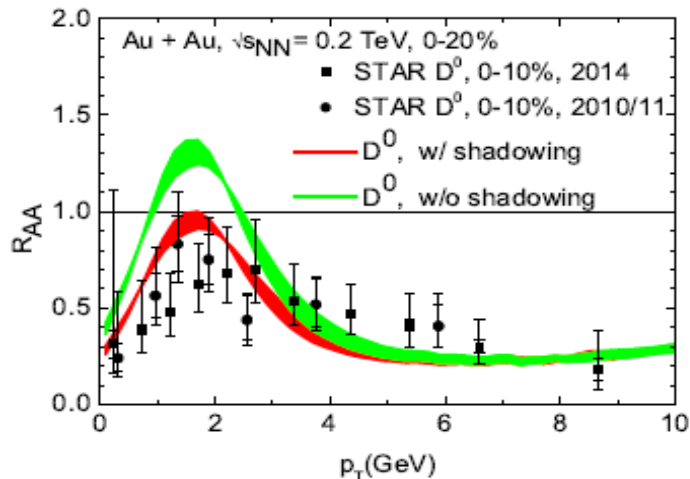
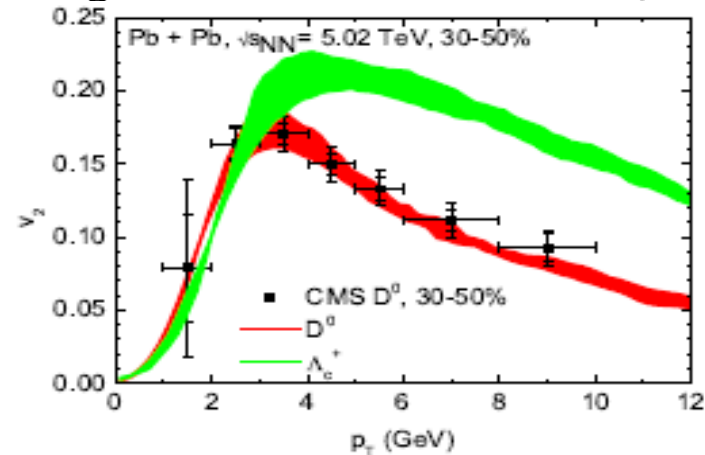
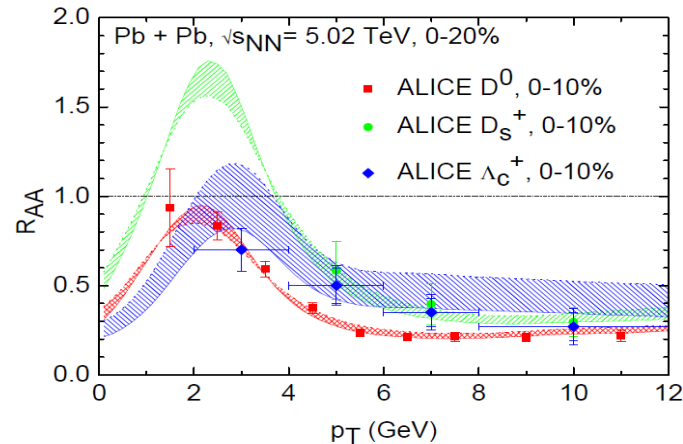
- **SMCs extend the recombination reach toward (much) higher p_T ;**
RQM augmented higher baryon states' RRM spectra even harder (also thanks to SMCs) → RRM & frag. cross at $p_T \sim 8.5$ (13) GeV for D^0 (Λ_C^+)
- **Helpful for large total v_2 (weighted between RRM vs frag. components)**

Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- Hadronization: 2- & 3-body RRM
- Space-momentum correlations (SMCs)
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables

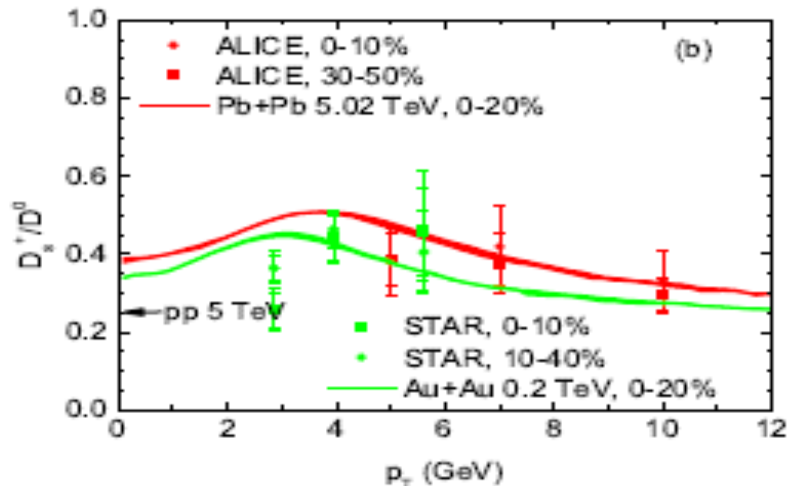
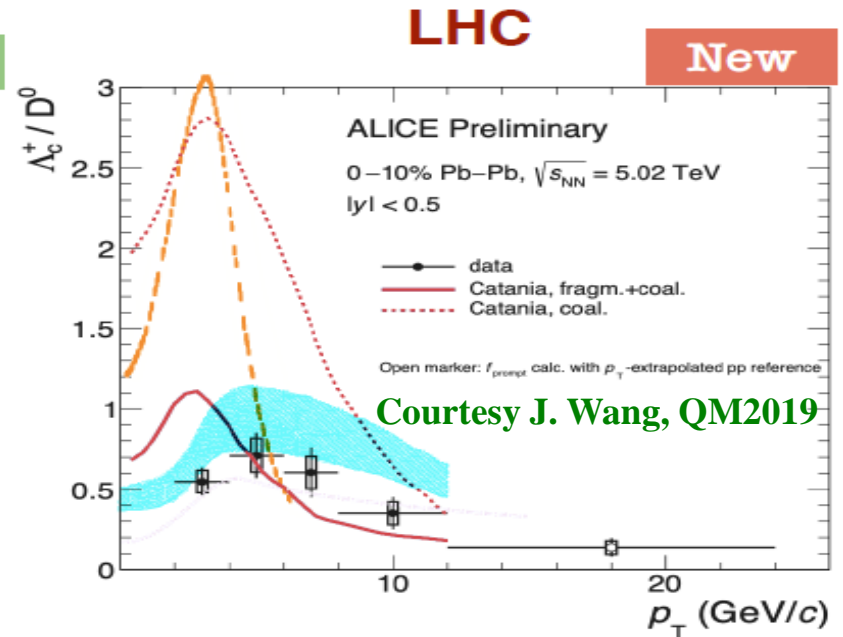
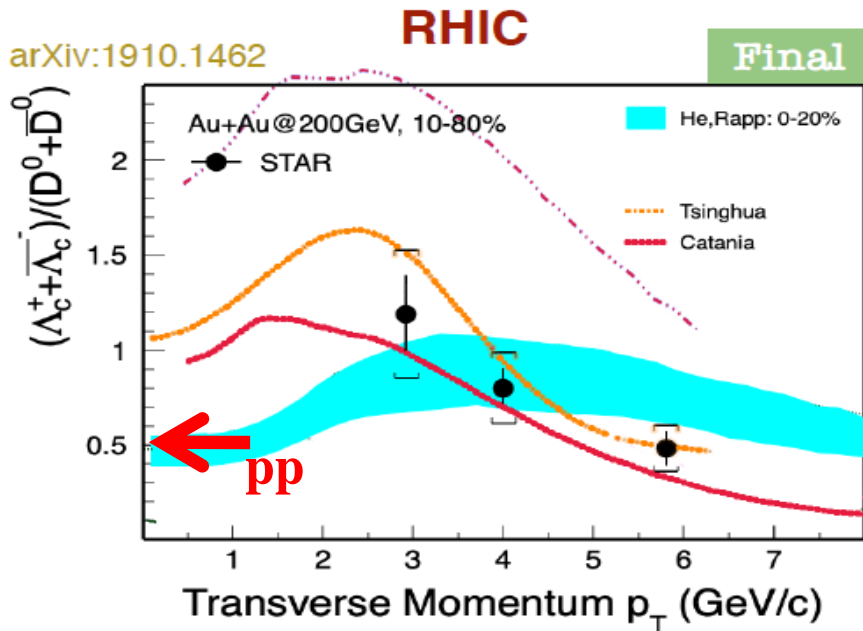
D^0 , D_s^+ & Λ_c^+ suppression & elliptic flow

□ Final total D^0 , D_s^+ & Λ_c^+ , including feeddowns from all RQM baryons



□ T-matrix coefficient * K-factor (=1.6), to compensate for radiative e-loss;
uncertainty: **BR=50-100%** to Λ_c^+ for Λ_c^+ 's & Σ_c^+ 's above DN (2805 MeV)

Charm-hadron ratios: Λ_c^+/D_0 & D_s^+/D_0



□ Λ_c^+/D_0 : low p_T RRM equil. limit = SHM pp; intermediate p_T enhancement from RRM with SMCs; high p_T fragmentation pp value

□ D_s^+/D_0 enhancement: recomb. of charm in a strangeness-equilibrated QGP

Summary & outlook

>> Charm-hadron production in pp collisions

- RQM augmented SHM
- Low p_T enhancement of Λ_c^+ from “missing” charm-baryons feeddowns

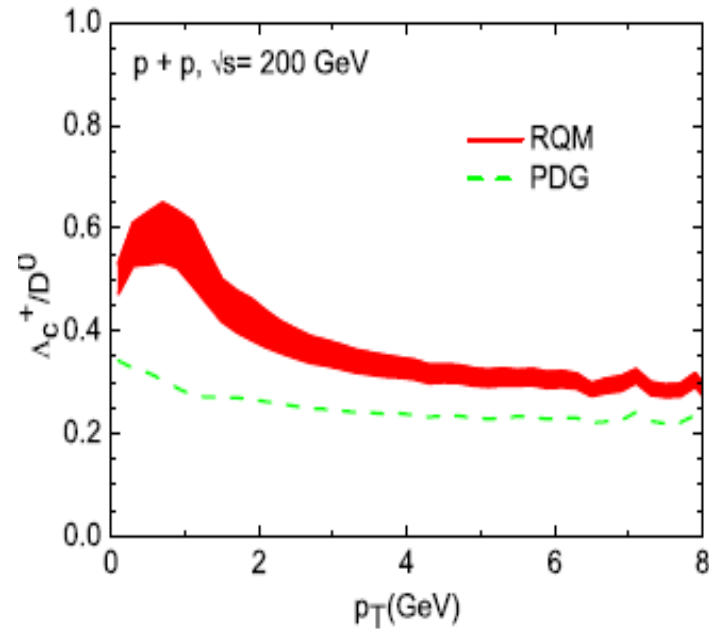
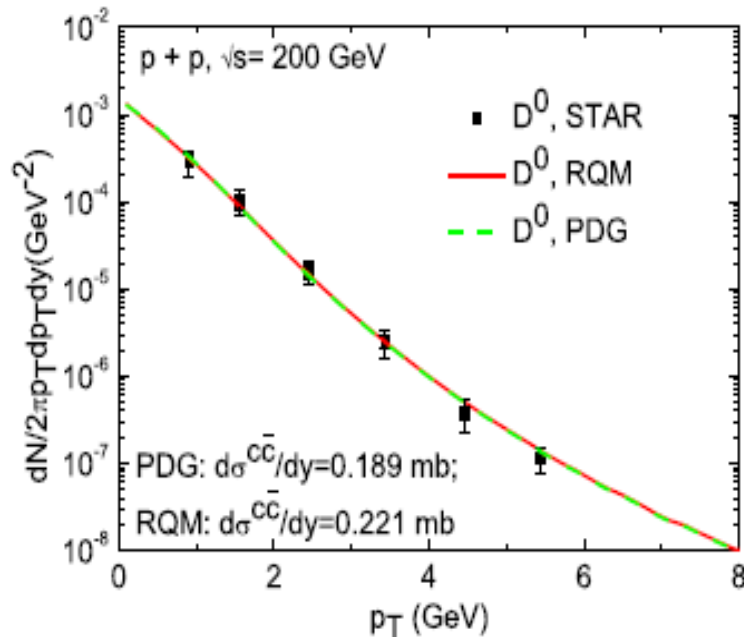
>> Charm-hadron production in AA collisions

- 3-body RRM developed, equilibrium mapping (both kinetic & chemical) ensured by 4-momentum conservation
- Genuine space-momentum correlations (SMCs) enhancing Λ_c^+/D^0 ; exact charm conservation implemented on an e-by-e basis

→ Both have been challenging within conventional instantaneous coalescence models

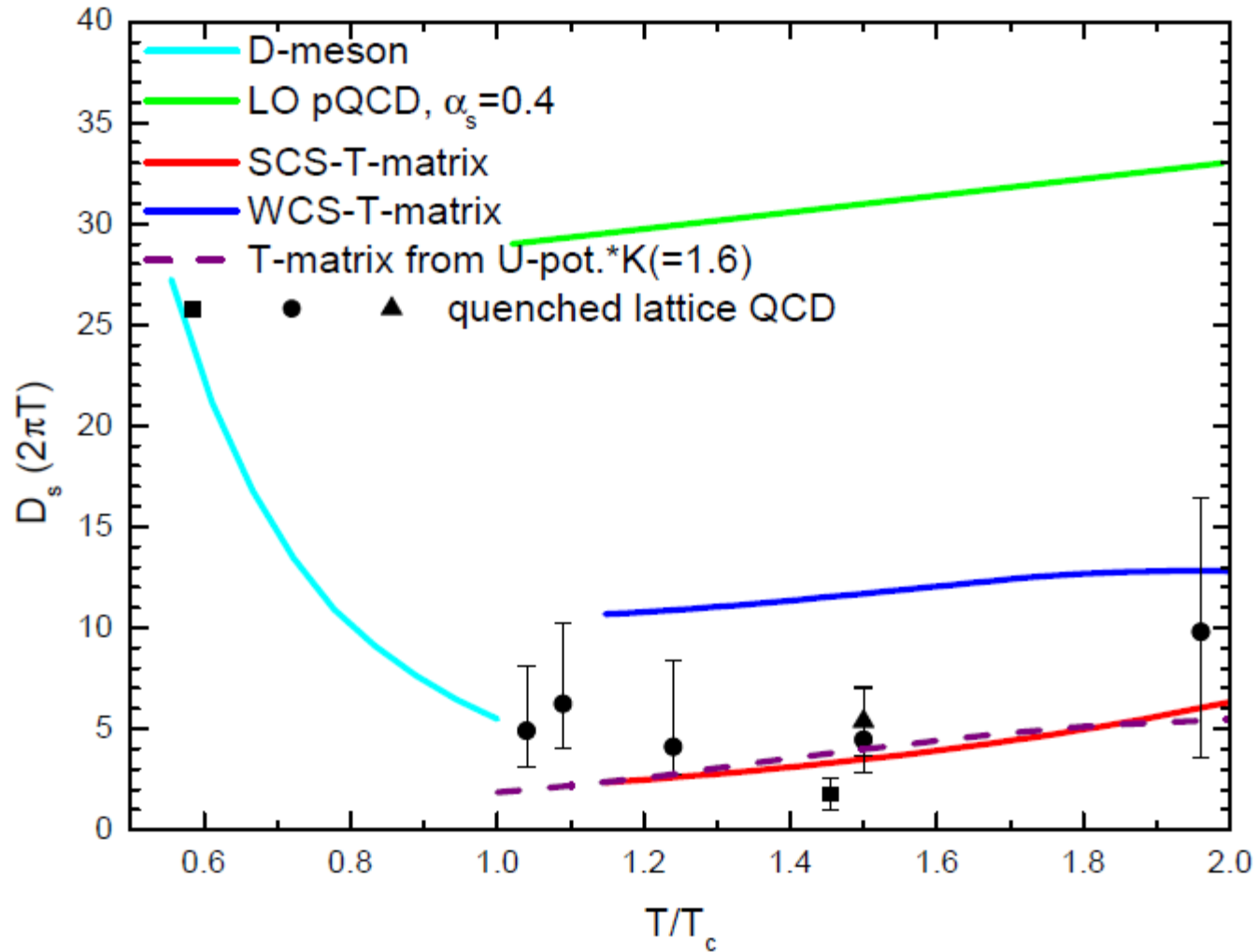
- p_T -dependent Λ_c^+/D^0 & D_s^+/D^0 enhancement emerge from hydro-Langevin-RRM(+fragmentation) simulations; data trend largely reproduced within BR's uncertainties

Back-up: pp 200 GeV collisions

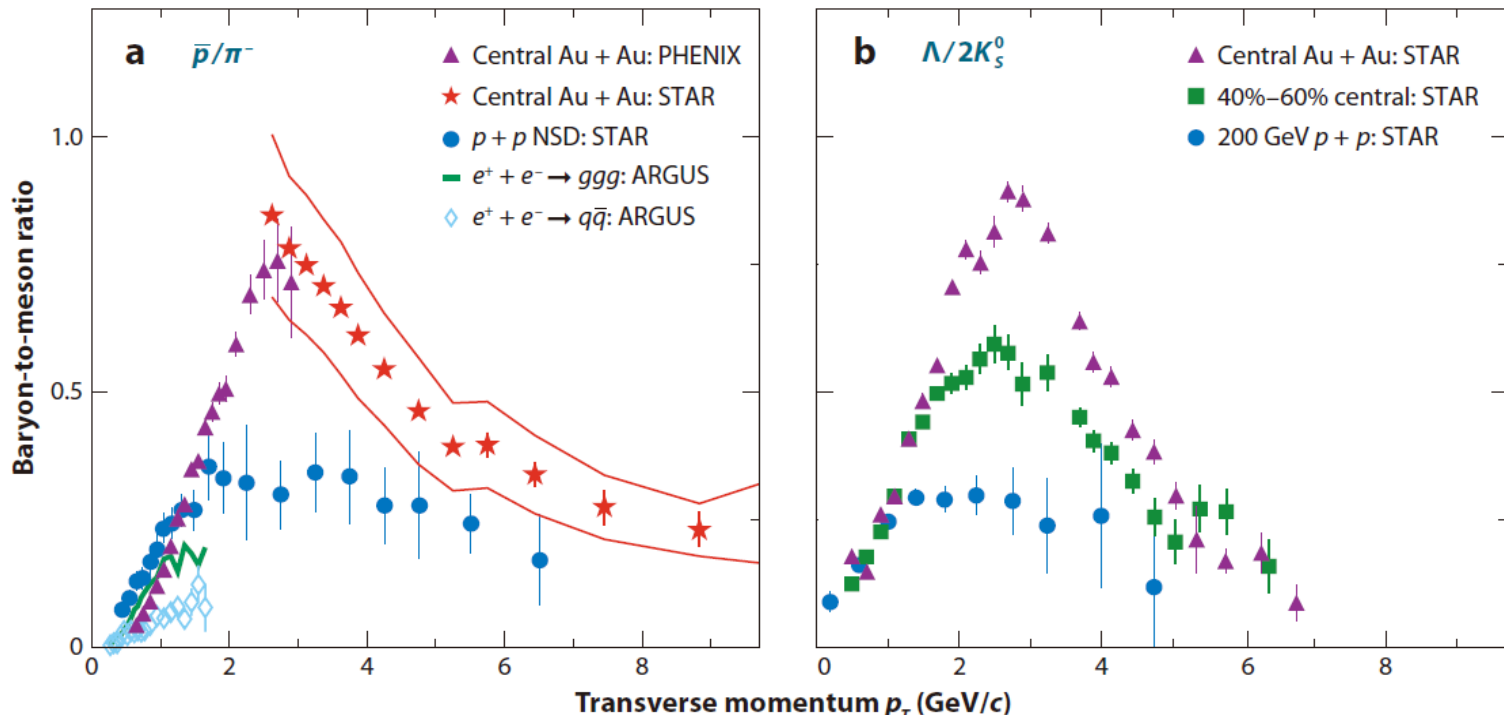


- Low p_T enhancement from feeddowns of RQM augmented baryons
- Uncertainty band: BR=50-100% to Λ_C^+ for Λ_C & Σ_C above DN (2805 MeV) threshold

Ds(2piT): K=1.6 vs updated SCS T-matrix

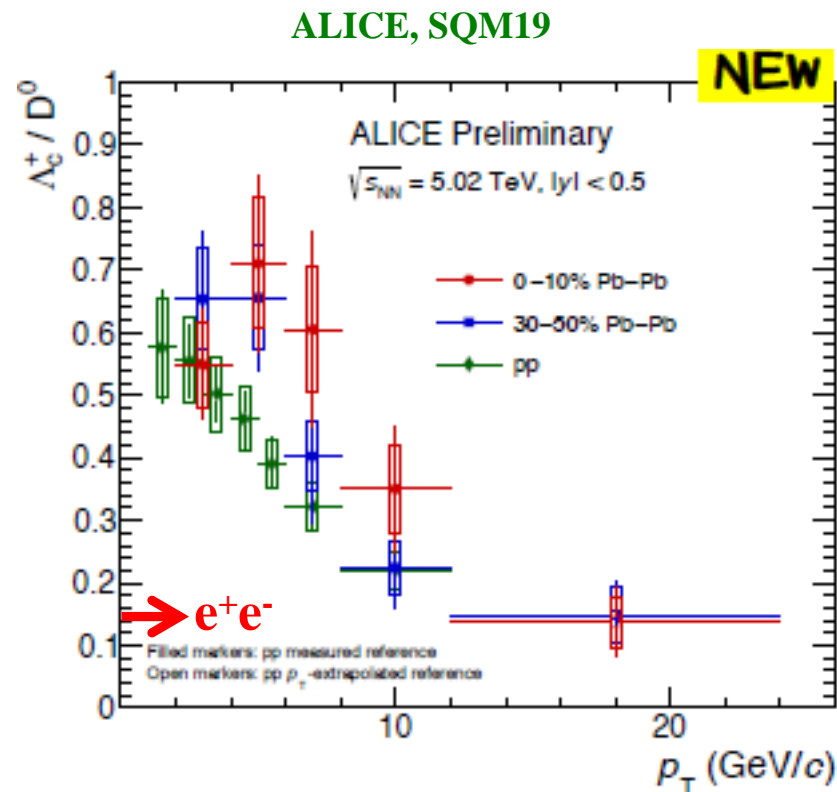
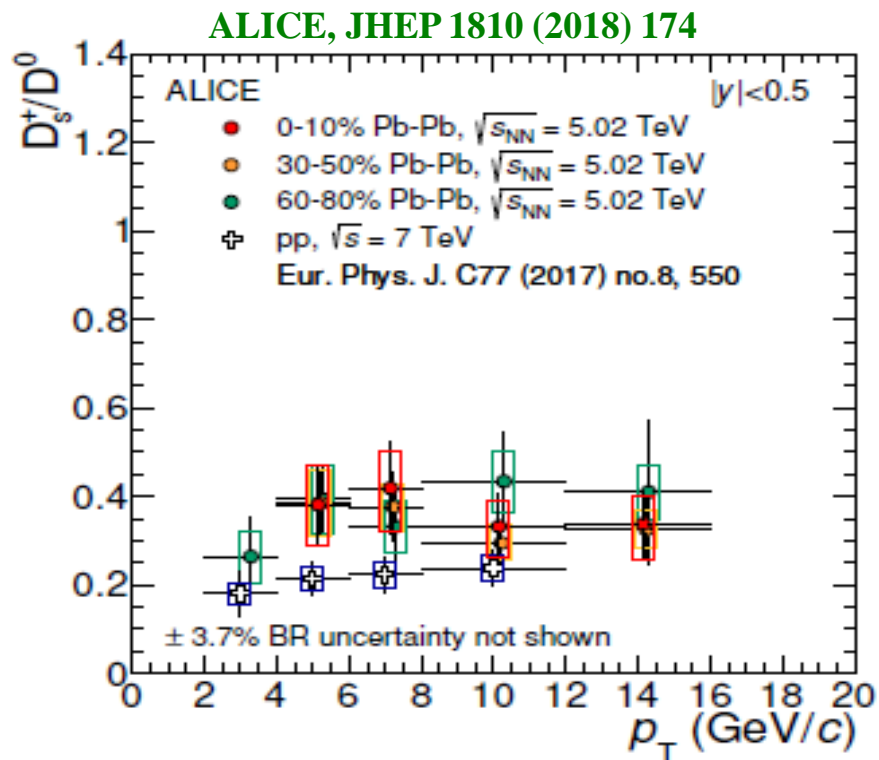


Baryon to meson ratio enhancement



- B/M enhanced at intermediate p_T in central AA collisions
 - Nicely (straightforwardly) explained by coalescence models **Ko, Fries, Hwa**
 - A direct indication of the working of coalescence hadronization
- $$f_M(p_T) \sim f_q(p_T/2) * f_{q\bar{q}}(p_T/2) \quad \text{VS} \quad f_B(p_T) \sim f_q(p_T/3) * f_q(p_T/3) * f_q(p_T/3)$$

Does it carry over to the HF sector?



- e^+e^- : **vacuum fragmentation**, costly to excite $s\bar{s}$ -pair or diquark-antidiquark pair from vacuum \rightarrow D_s and Λ_c much suppressed
- high-energy pp: **likely coalescence for Λ_c** in a quark-rich environment!
- AA: **recombination hadronization in QGP** \rightarrow modifying charm hadro-chemistry

Langevin equil. Limit with large coeffi.

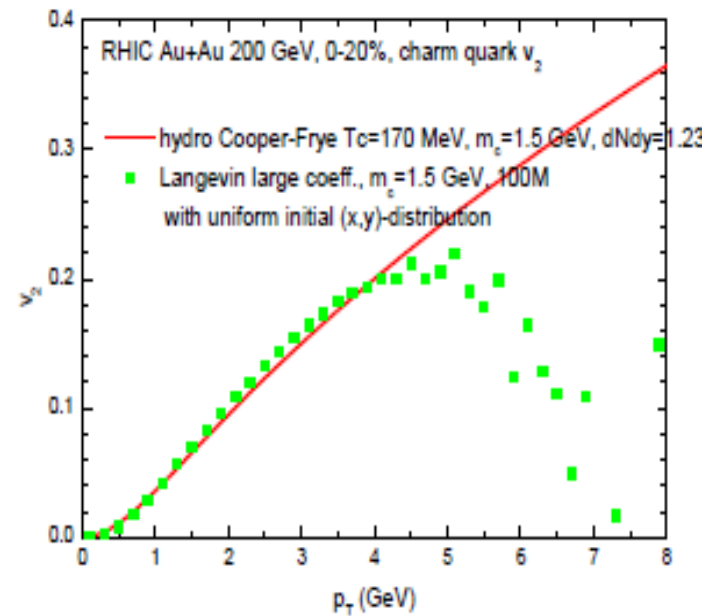
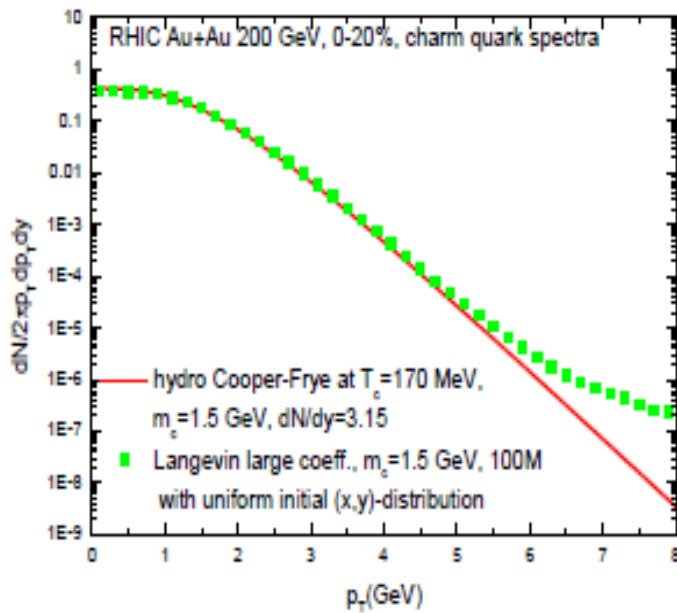
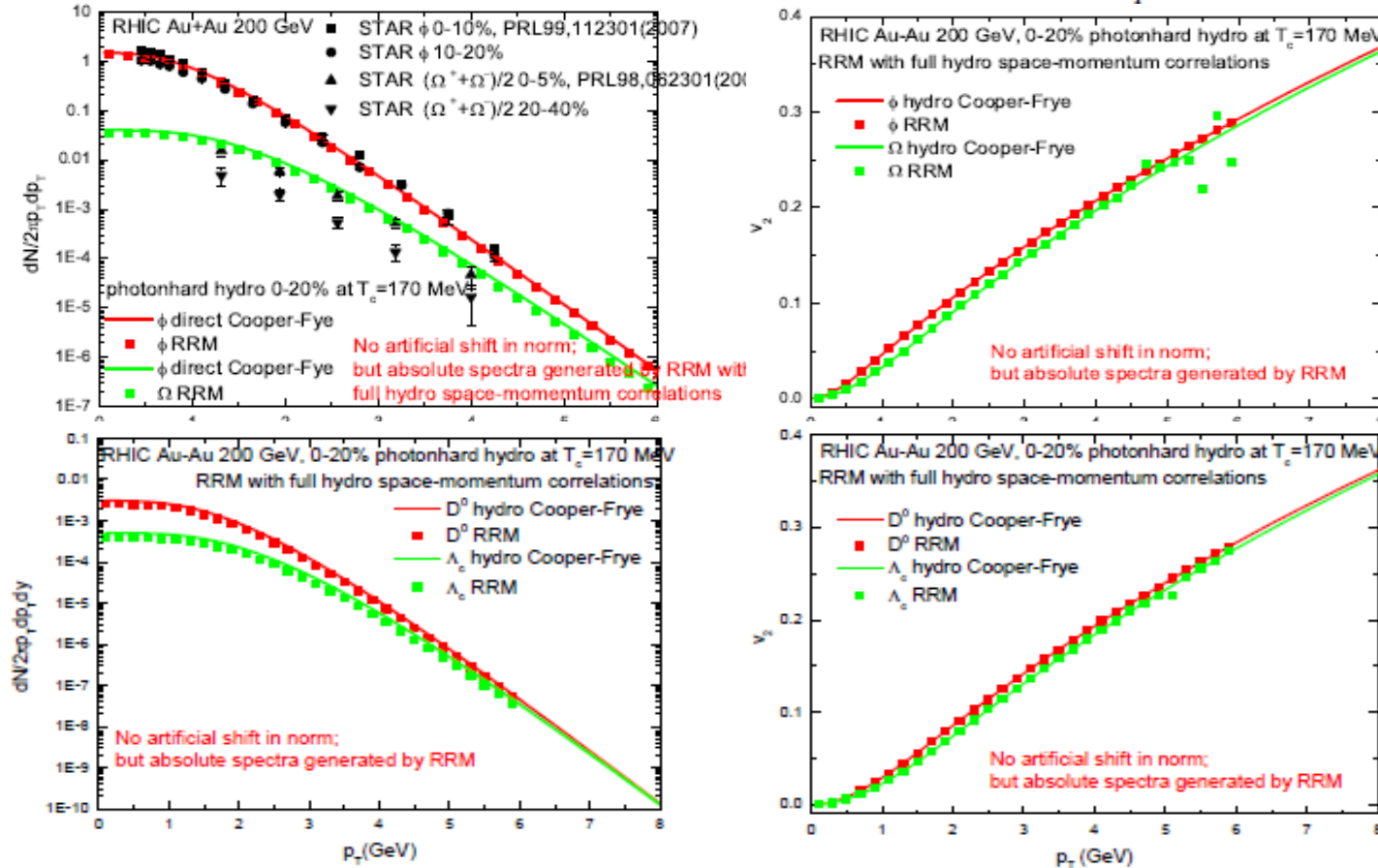


Figure 9. Langevin charm quark p_T spectra and v_2 with large coefficient.

RRM: equilibrium mapping

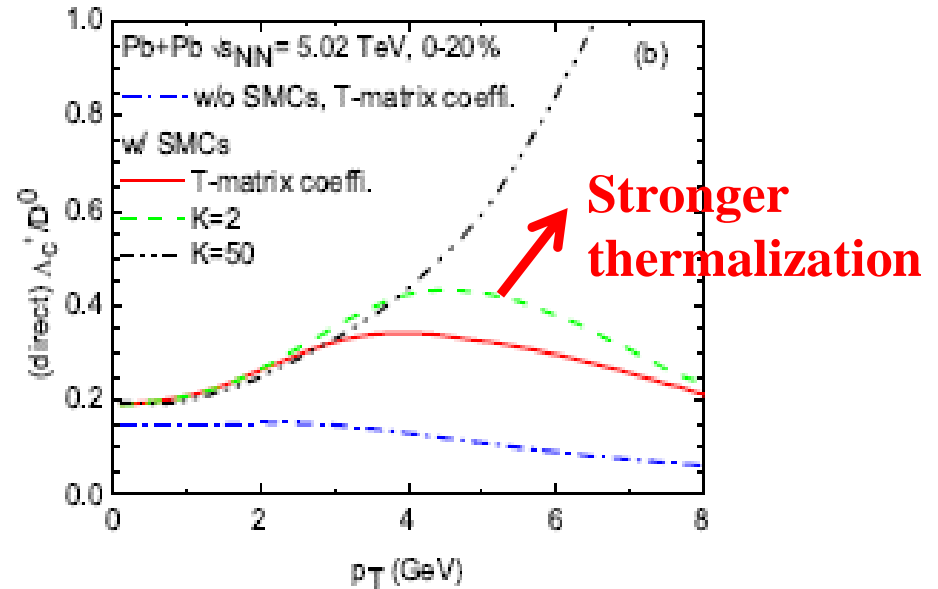
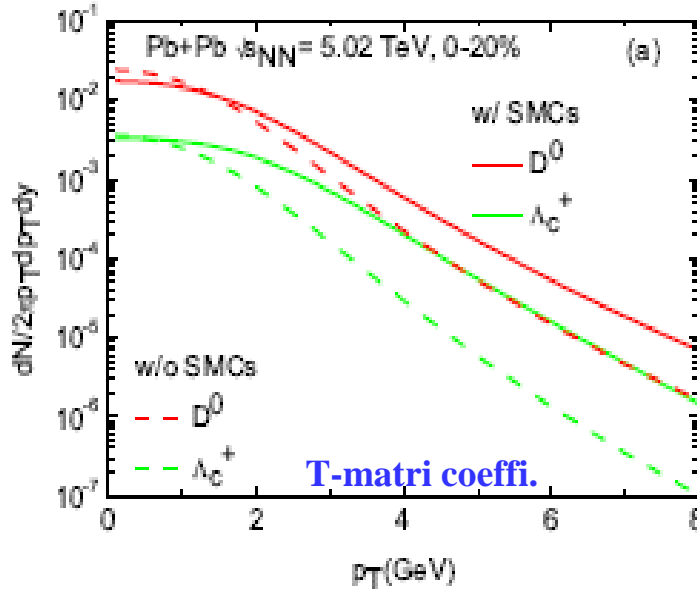
□ RRM on hydrofreezeout hypersurface at T_c with $f_q^{eq}(\vec{x}, \vec{p}) = g_q e^{-p \cdot u(x)/T(x)}$



□ Equilibrium mapping: ensured by 4-momentum conservation in RRM
 $m_q=0.3, m_s=0.4, m_c=1.5, \Gamma_M \sim 0.1$ GeV, $\Gamma_d \sim 0.2$ GeV, $\Gamma_B \sim 0.3$ GeV

Direct D^0 & Λ_c^+ production via RRM

- Including **SMCs** makes the spectra harder & enhances the ratio Λ_c^+/D^0



- Consider RRM formation of D^0 ($3.5+0.7$) & Λ_c^+ ($3.0+0.6+0.6$) of $p_T \sim 4.2$ GeV: **enhancement of density** of light- q of $p_T \sim 0.6-0.7$ GeV & c of $p_T \sim 3.0-3.5$ GeV

$$\Delta N_{D^0}(4.2) \sim \frac{\Delta N_c(3.0 - 3.5)}{V_{c,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \quad (15)$$

--- **Recombinant quark density enhanced vs w/o SMCs: $V_{\text{eff}} < V_{\text{fb}}$**

$$\Delta N_{\Lambda_c^+}(4.2) \sim \frac{\Delta N_c(3.0 - 3.5)}{V_{c,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}}$$

--- **Enhanced light- q density entering D^0 RRM only once vs twice (squared) for Λ_c^+ RRM \rightarrow the ratio Λ_c^+/D^0 enhanced!**