Charm-Hadron Production in pp & AA Collisions

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

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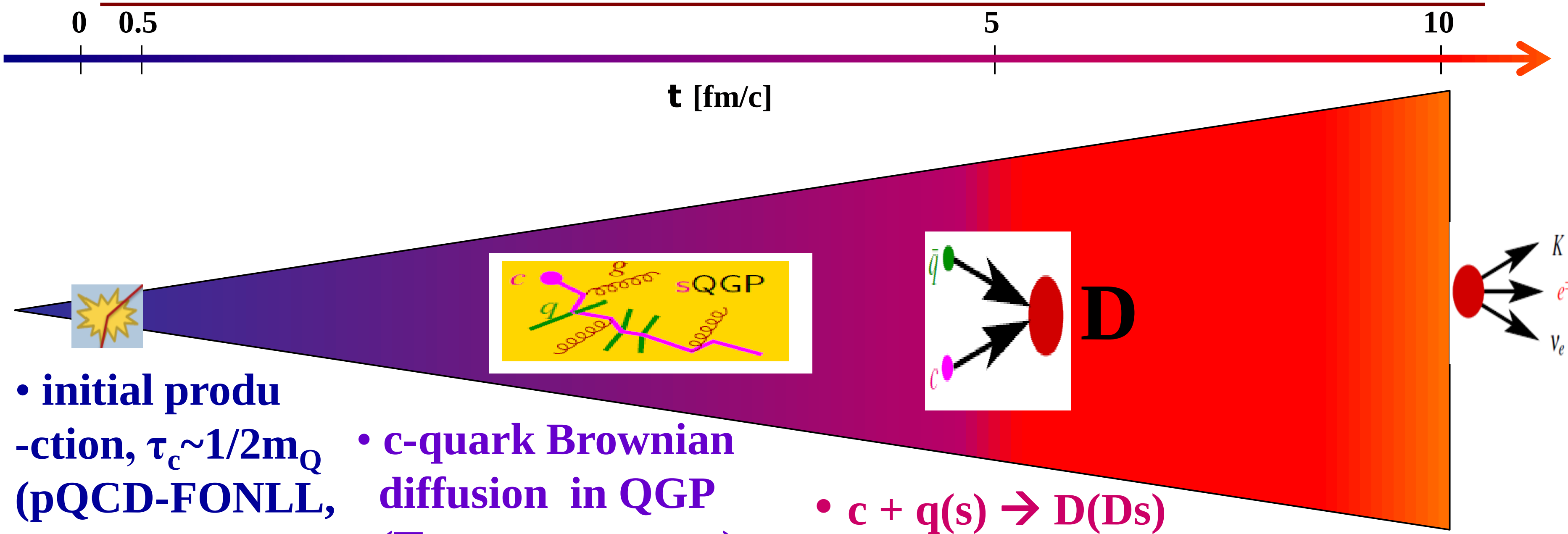
Heavy flavor transport in hot QCD matter



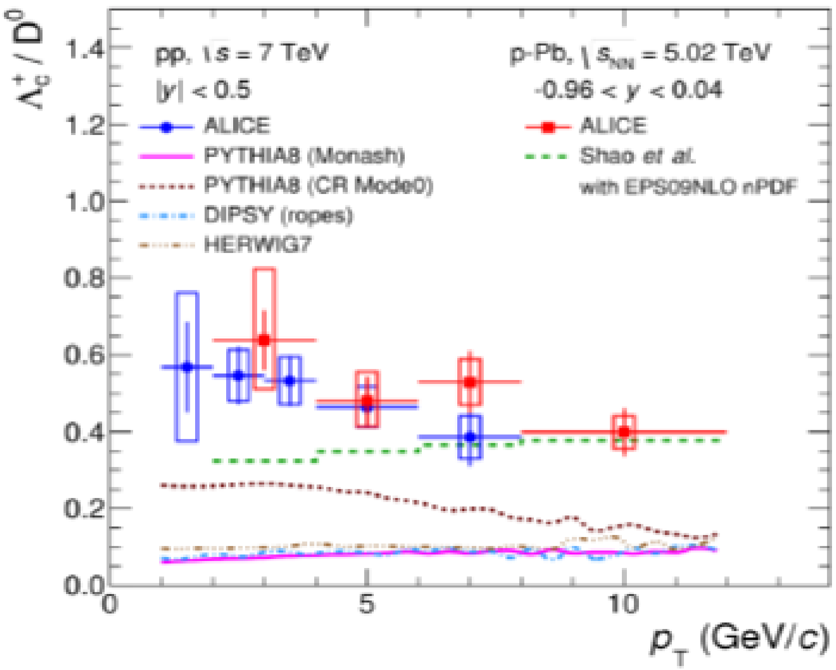
- initial produ -ction, $\tau_c \sim 1/2m_Q$ (pQCD-FONLL, shadowing)
- c-quark Brownian diffusion in QGP (T-mat. reso. corr.) low p_T thermalization high p_T e-loss
- c + q(s) → D(Ds)
- c + q + q → Λ_c resonance recombination
- D-meson diffusion in hadronic liquid

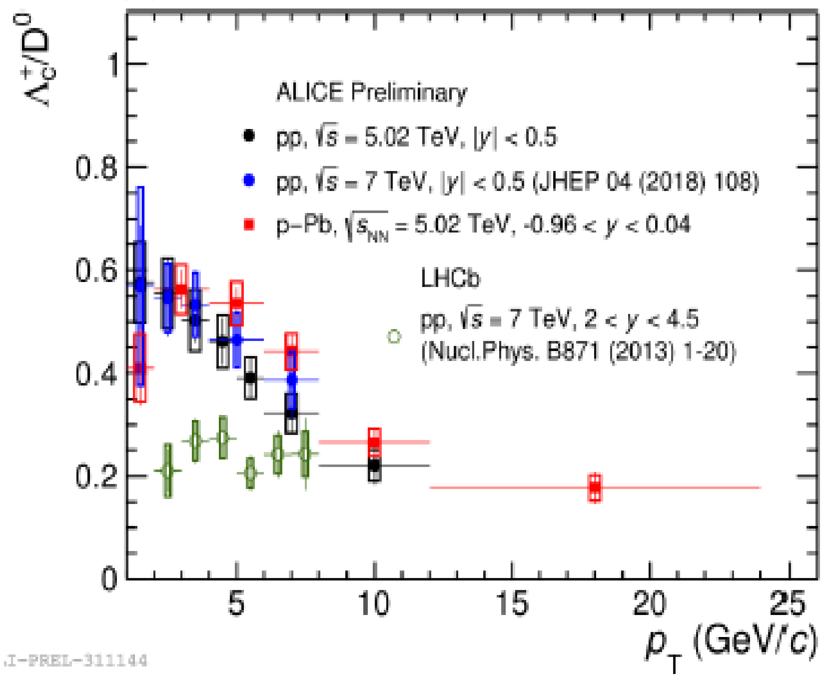
➢ **Calibrated & tagged probes preserving memory of interaction history**

➢ **Trans. coeffi. $\mathcal{D}_s(2\pi T)$: coupling strength → 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) Λ_c^+/D^0 ~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
PDG(170)	1.161	0.5098	0.5010	0.3165	0.3310	0.0874	0.0064
RQM(170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144

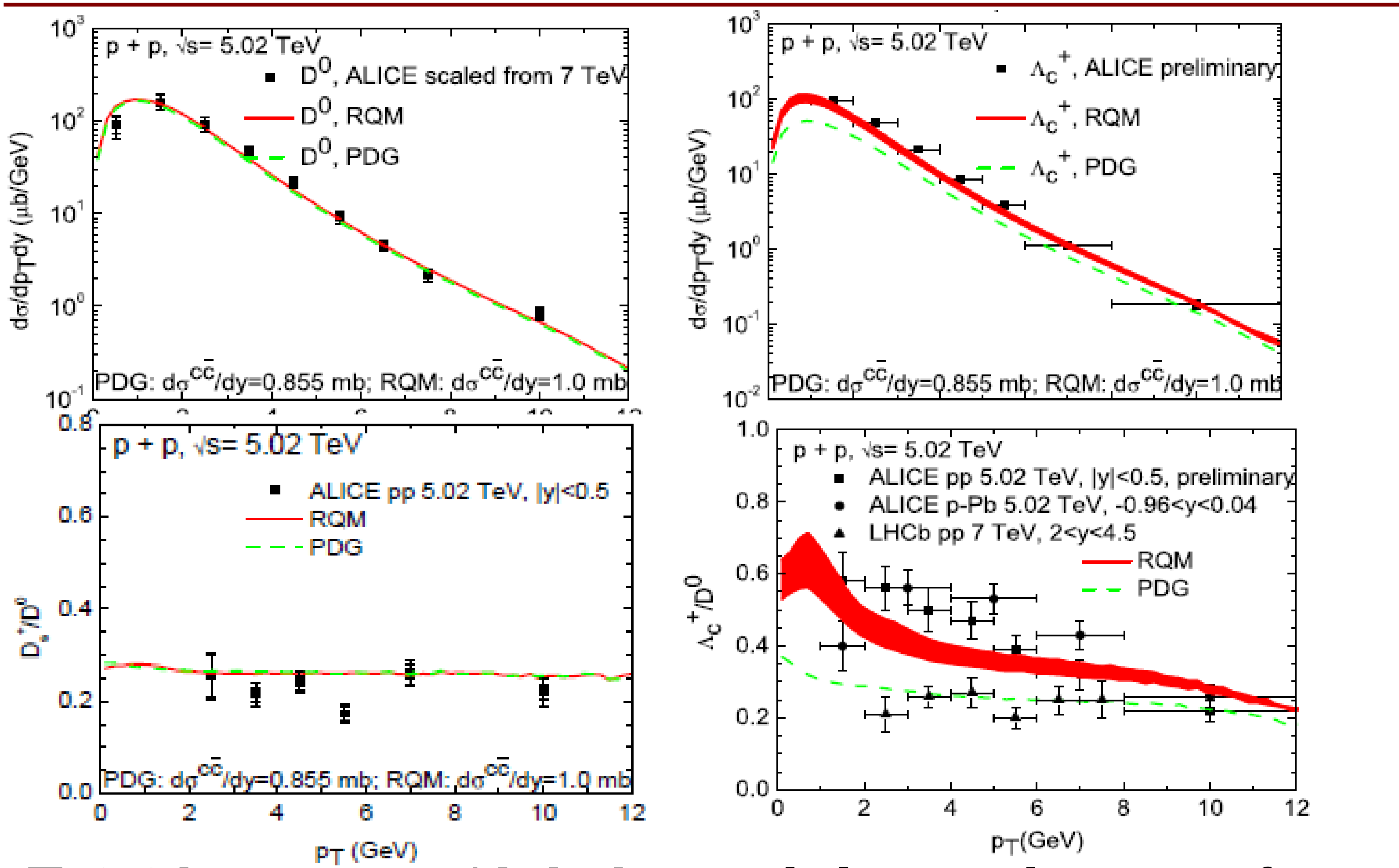
- **Strong feeddowns of excited states all included: BR=100% to Λ_C^+ for all Λ_C & Σ_C even above DN (2805 MeV) threshold**
  -- Strangeness supp. γ_s=0.6

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

➔ **FONLL fragmentation of charm quarks into all kinds of charm-hadrons**
relative weight: according to the SHM thermal densities

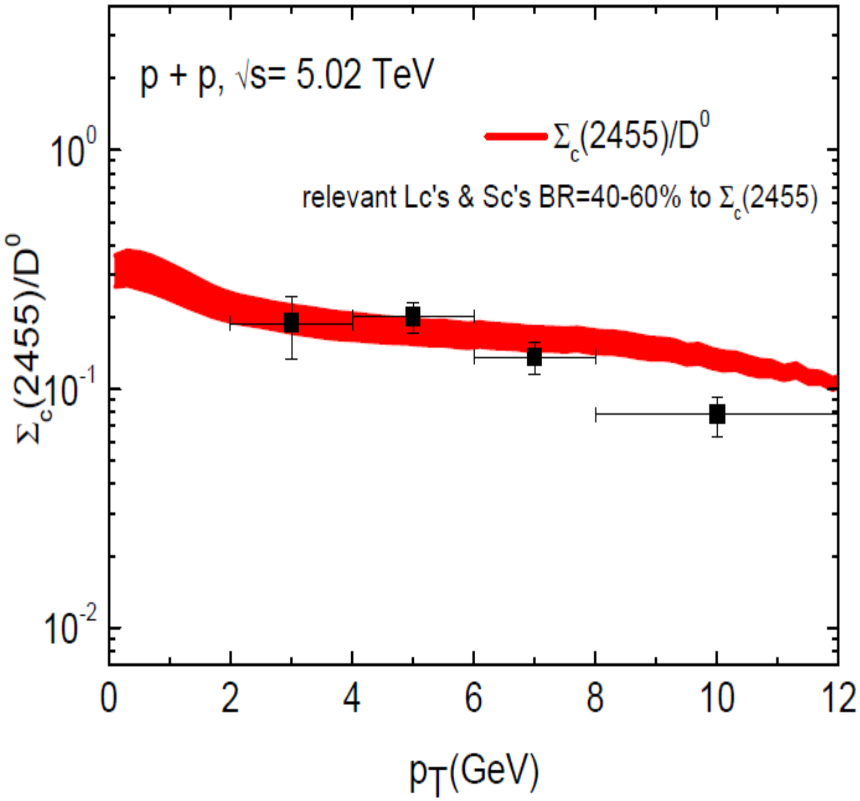
& Decay simulations of all excited states to ground state D^0 , D^+, D_s^+, Λ_C^+, Ξ_C & Ω_C

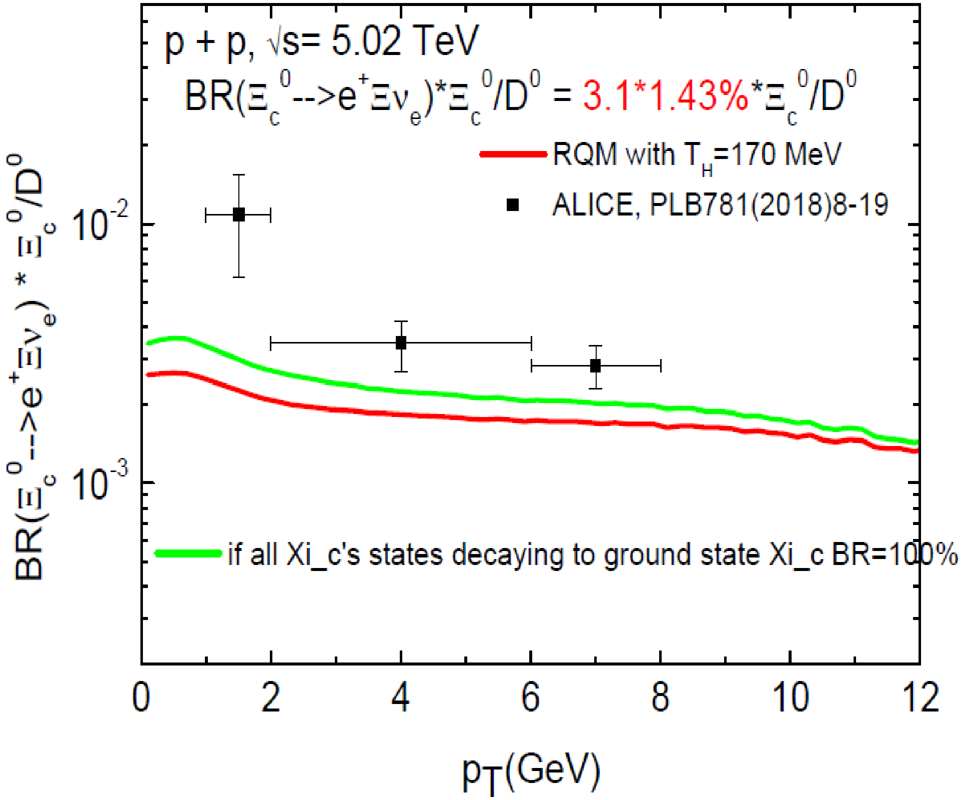
Results: pp 5.02 TeV collisions



- ☐ **Λ_C^+ favors RQM with dσ/dy=1.0 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**

Results: more B/M ratios





- **$\Sigma_c(2455)/D^0$ can also be accounted for within uncertainties**
- **But Ξ_c^0/D^0 is much underestimated, although twice PYTHIA8(CR ~ 0.001)**

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

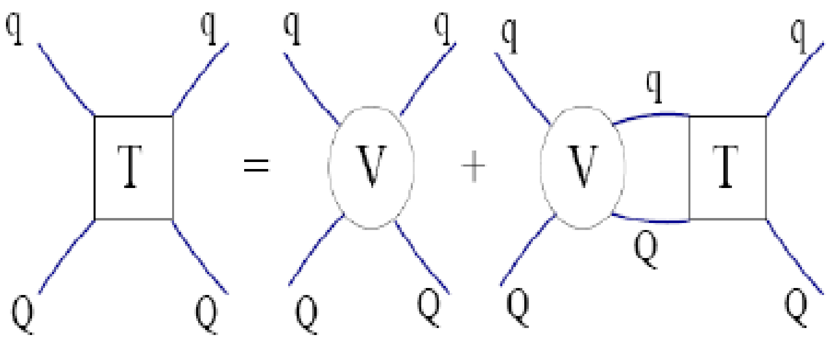
Charm in QGP: transport coeffi. & diffusion

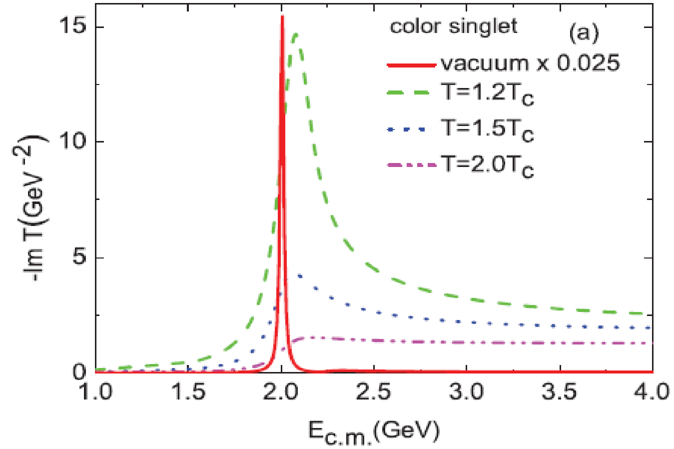
Langevin + hydro simulation down to Tc=170 MeV
fluid rest frame updates → boost to lab frame

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

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

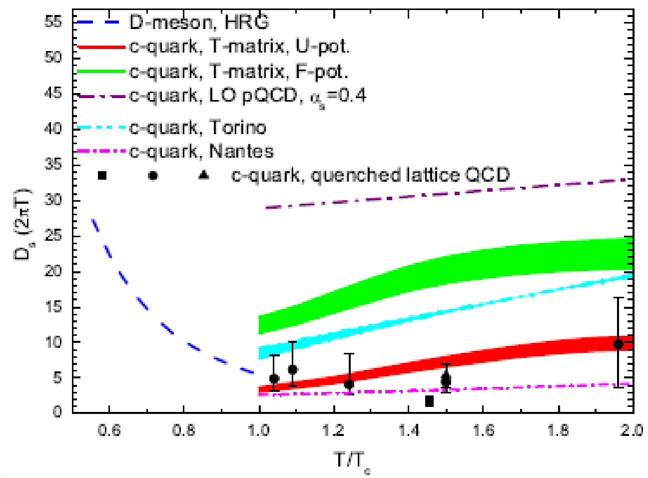
- Lattice-contrained Q-q/g T-matrix





- mesonic resonant correlations & resonant scattering beyond pQCD

- p- and T-dependent transport with $\mathcal{D}_s(2\pi T) \sim 2\text{-}4$ near T_{pc}
  ➔ strong coupling



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 $c\bar{q} \longrightarrow D$ as the T-matrix resonant interaction between c-qbar strengthens towards T_c**

- **Derived from Boltzmann eq.** **Ravagli & Rapp 2007**

$$f_M(\vec{x},\vec{p}) = \frac{\gamma_M(p)}{\Gamma_M}\int \frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2)\, \sigma_M(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

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

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

$$f_B(\vec{x},\vec{p}) = \frac{E_B(\vec{p})}{\Gamma_B m_B}\int \frac{d^3p_1 d^3p_2 d^3p_3}{(2\pi)^6}\frac{E_d(\vec{p}_{12})}{\Gamma_d m_d} f_1(\vec{x},\vec{p}_1) f_2(\vec{x},\vec{p}_2) f_3(\vec{x},\vec{p}_3)$$

$$\times\, \sigma_{12}(s_{12}) v^{12}_{\rm rel}(\vec{p}_1,\vec{p}_2)\sigma_B(s_{d3}) v^{d3}_{\rm rel}(\vec{p}_{12},\vec{p}_3)|_{\vec{p}_{12}=\vec{p}_1+\vec{p}_2}\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2-\vec{p}_3)$$

➔ **3 quark distributions: 2 light thermal + Langevin c-quark**

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

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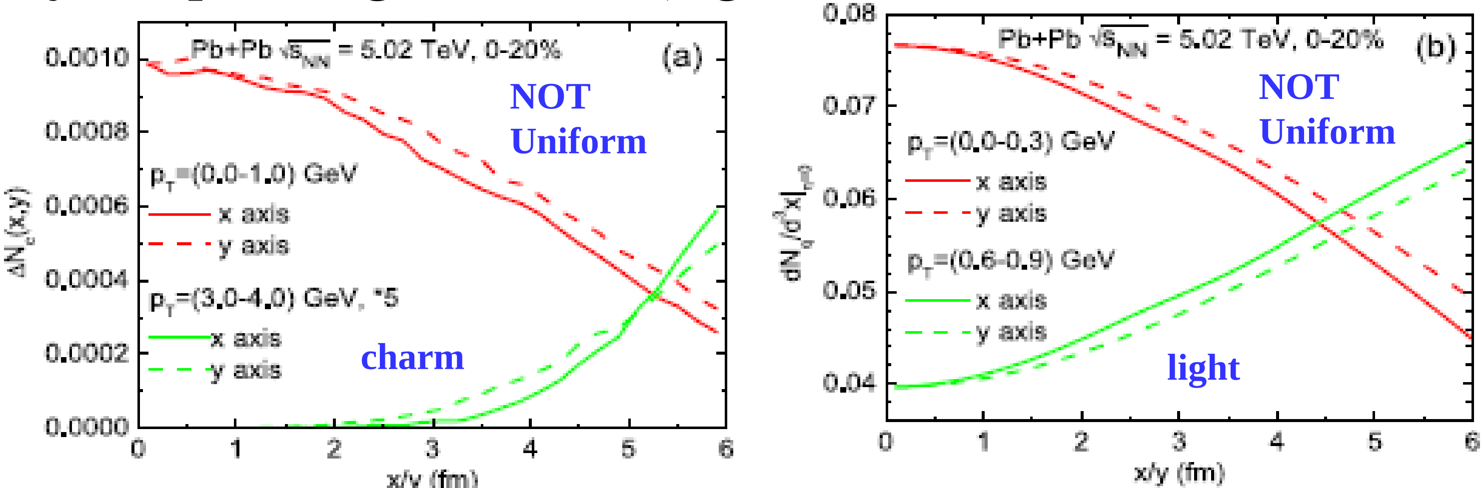
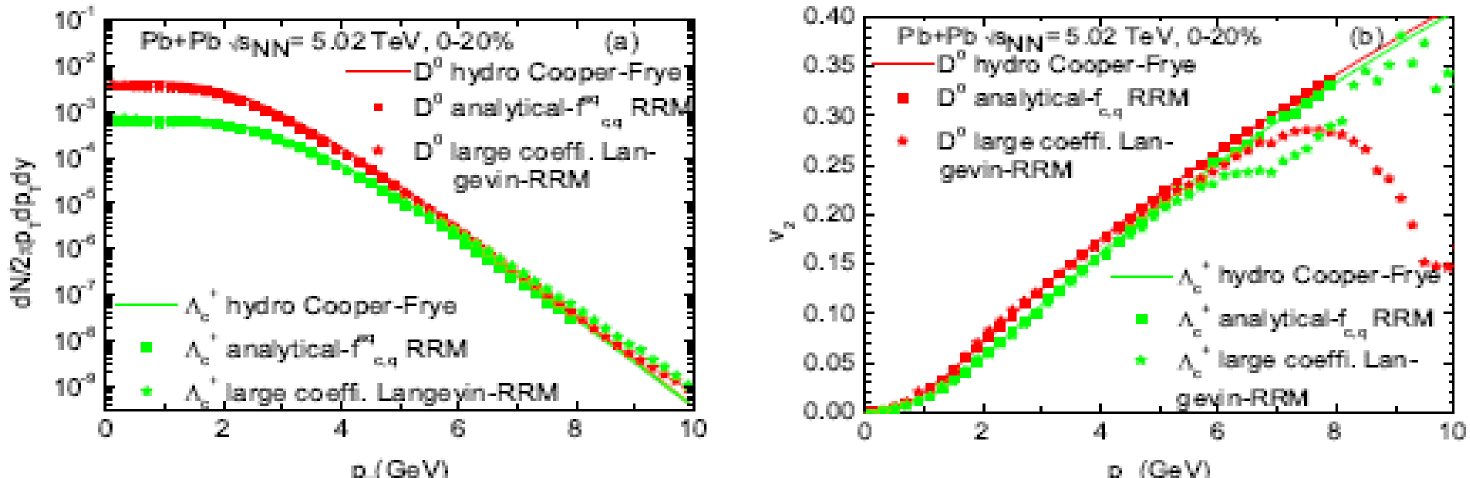
Space-momentum correlations (SMCs)

- ☐ **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

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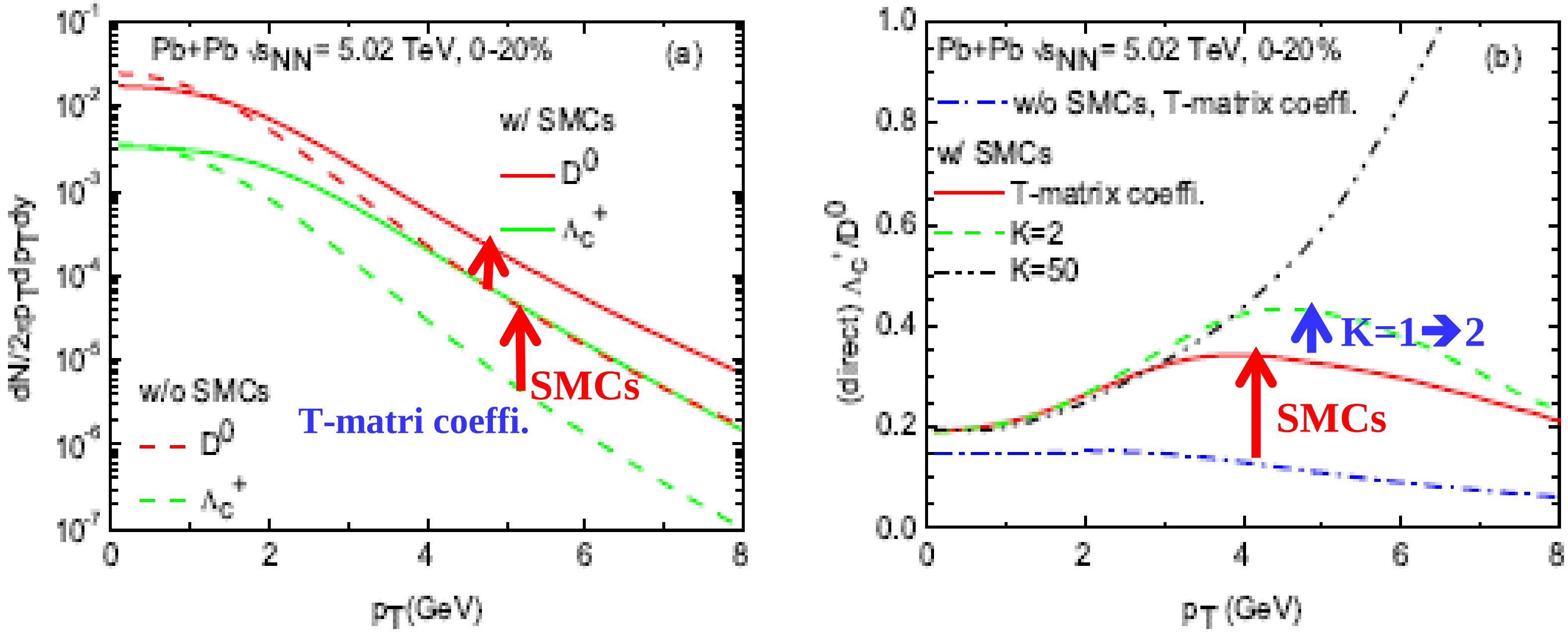
Direct D^0 & Λ_c^+ production via RRM

- Including **SMCs** makes the spectra **harder** & enhances the ratio Λ_c^+/D_0

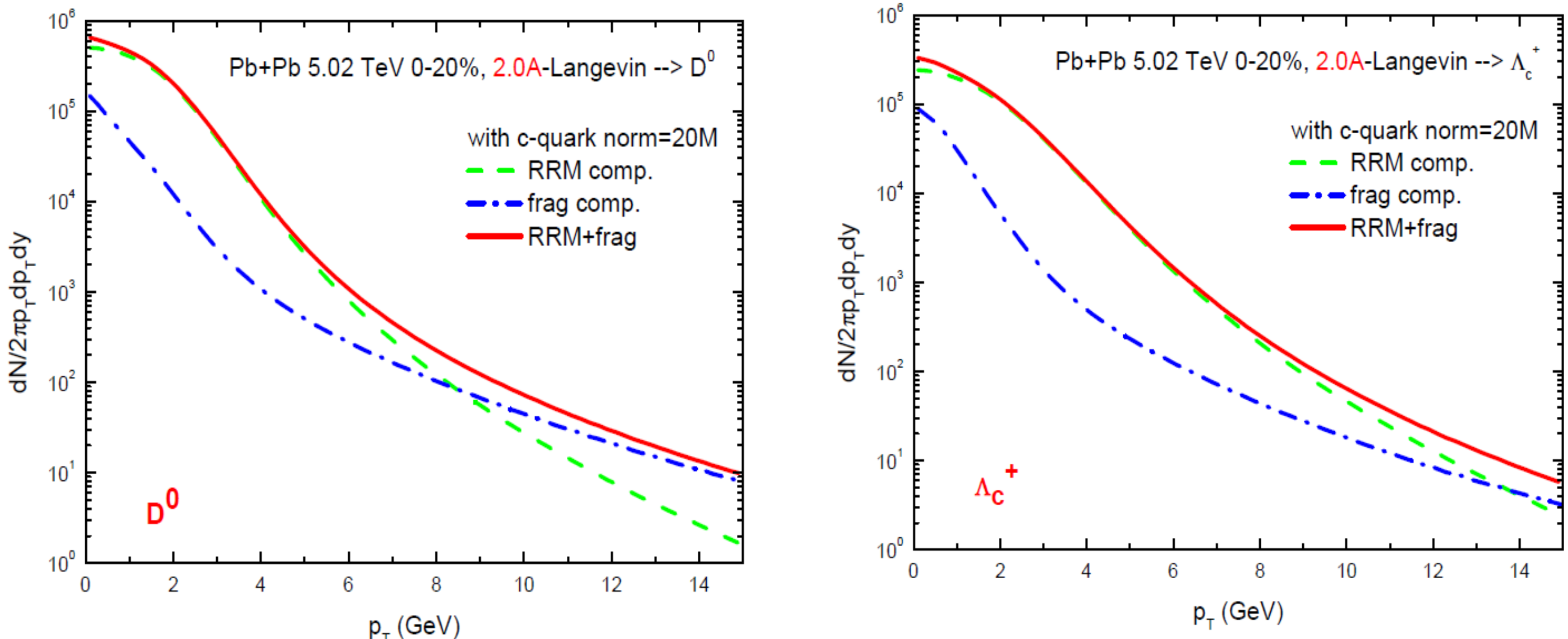


- Fast-moving c-quarks [p_T~ 3-4 GeV] moving to outer part of fireball find higher-density of harder [p_T~ 0.6-0.9 GeV] light quarks for recombination

- An effect entering **squared** for the recombination production of Λ_c^+
  ➔ **larger enhancement for Λ_c^+ ➔ Λ_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 ~8.5 (13) GeV for D^0 (Λ_C^+)**

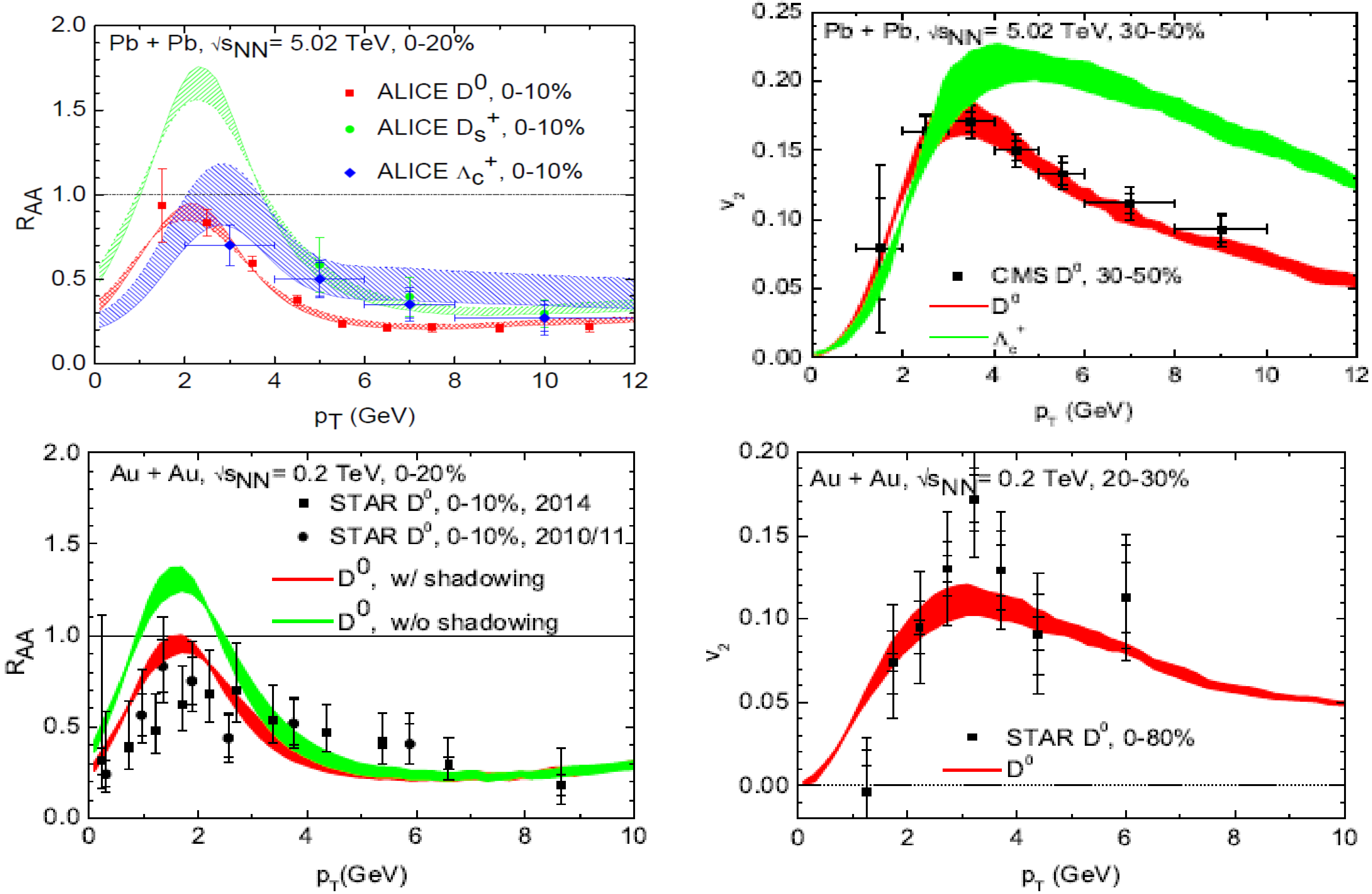
- **Helpful for large total v_2 (weighted between RRM vs frag. components)**

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

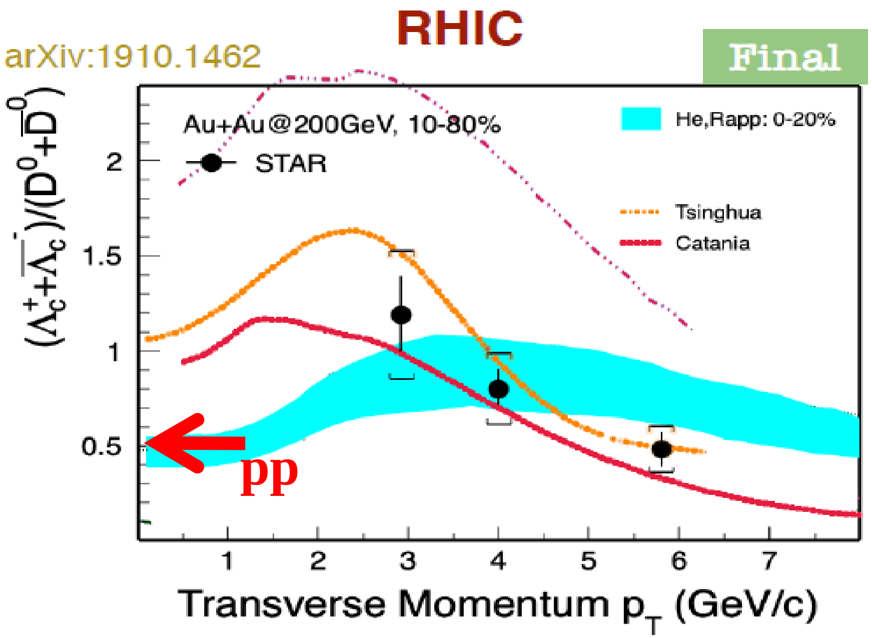
D^0, D_s^+ & Λ_c^+ suppression & elliptic flow

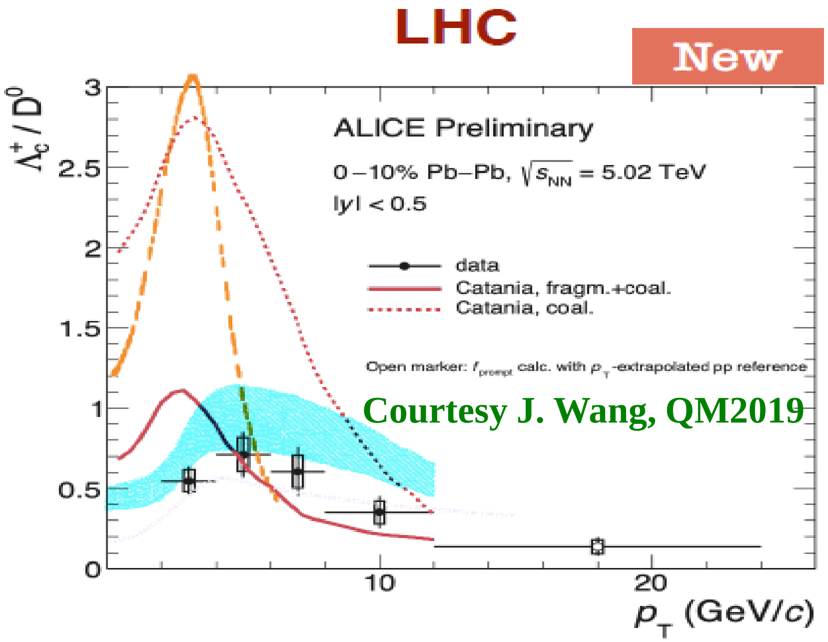
- **Final total D^0 , D_s^+ & Λ_c^+, including feeddowns from all RQM baryons**

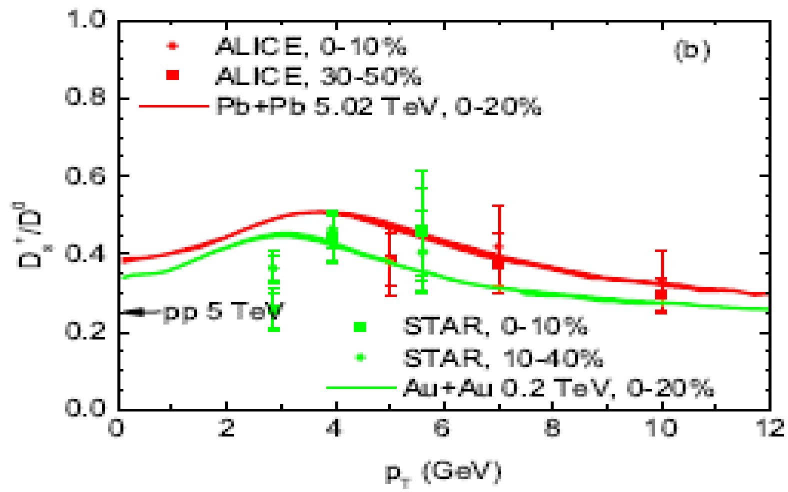


- **T-matrix coefficient*K-factor(=1.6), to compensate for radiative e-loss; uncertainty: BR=50-100% to Λ_C^+ for Λ_C's & Σ_C's above DN (2805 MeV)**

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**

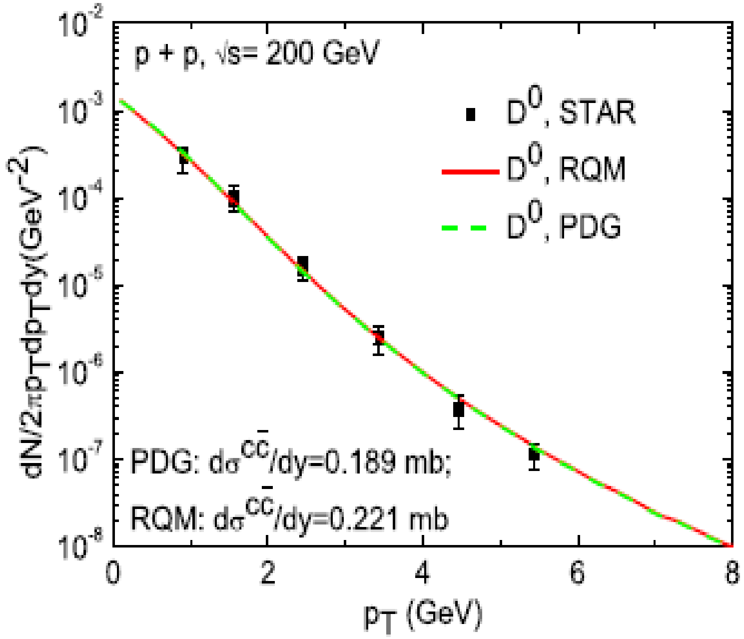
>> Charm-hadron production in AA collisions

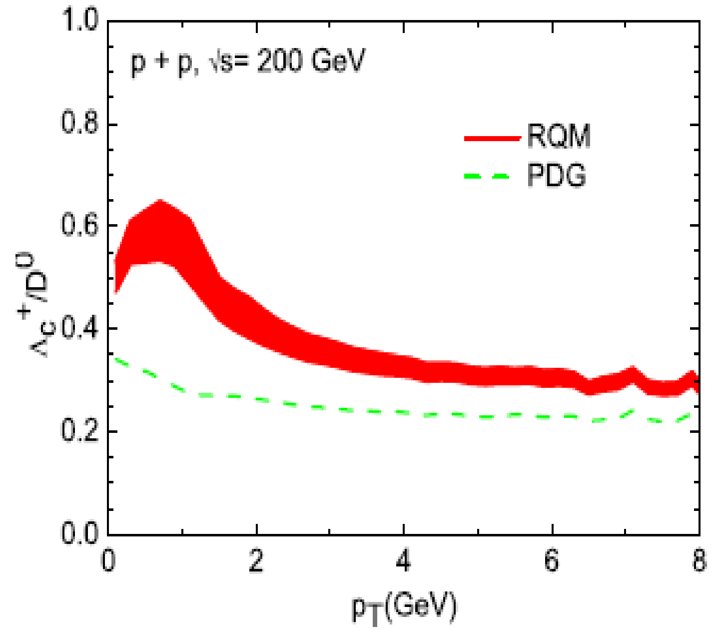
- **3-body RRM developed, equilibrium mapping (both kinetic & chemical) ensured by 4-momentum conservation**
- **Genuine space-momentum correlations (SMCs) enhancing Λ_c^+/D^0; exact charm conservation implemented on an e-by-e basis**

  ➔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**

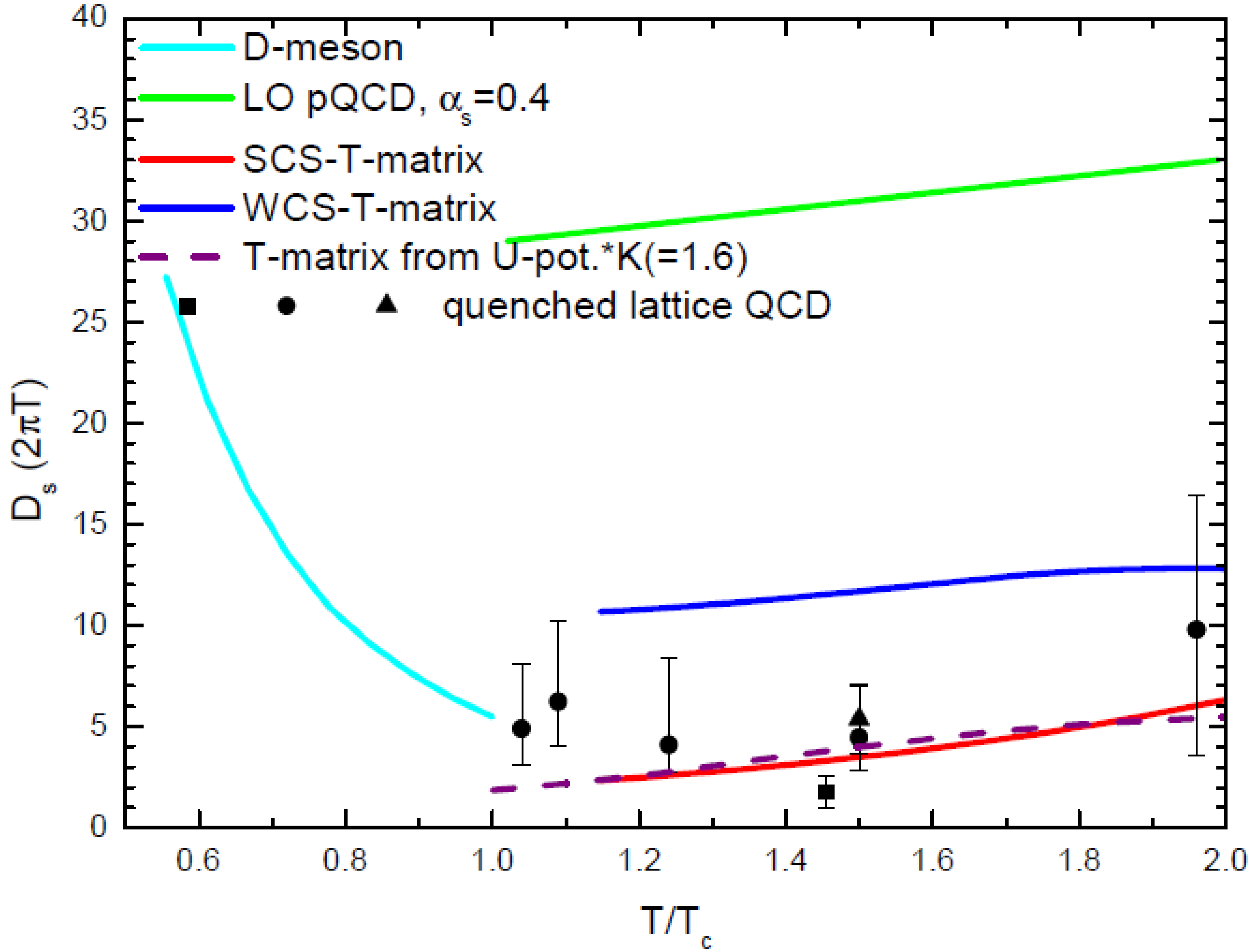
Back-up: pp 200 GeV collisions



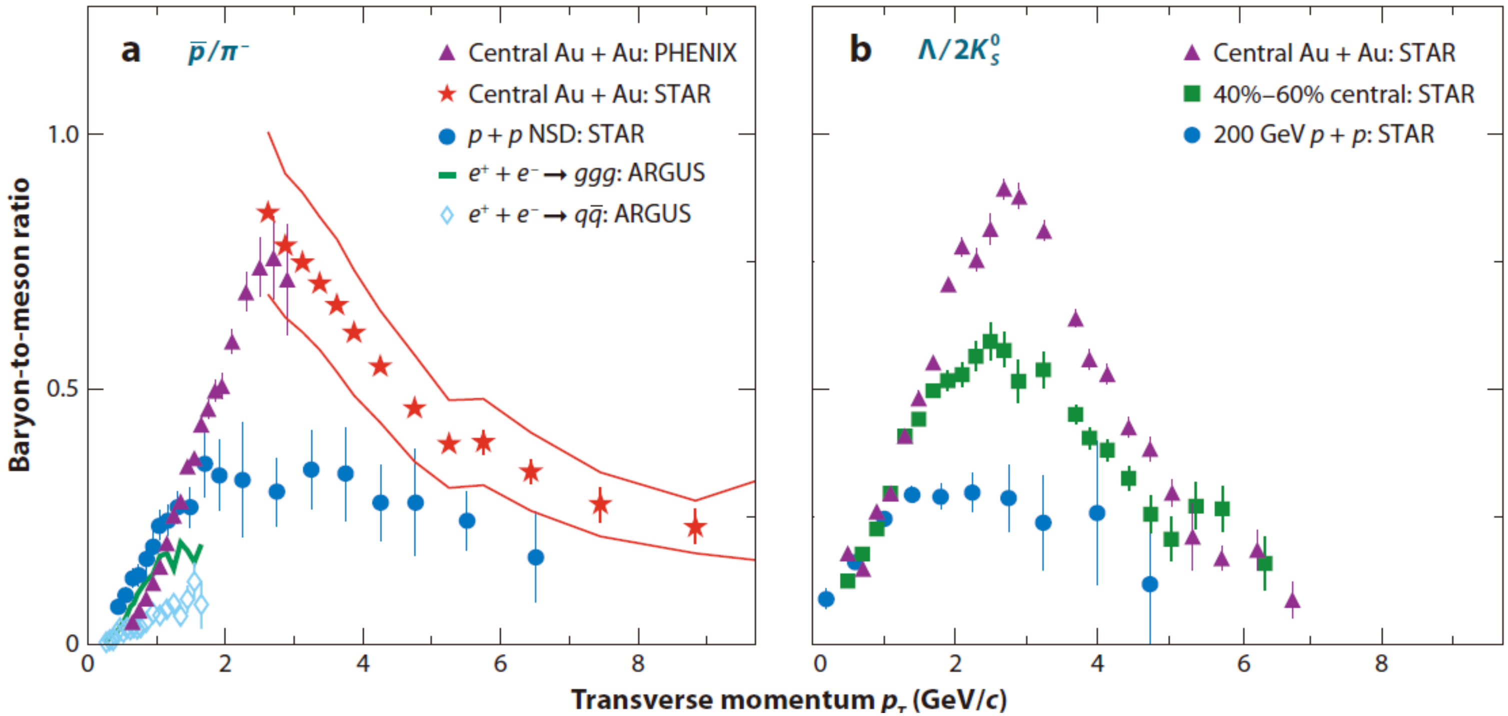


- Low pT enhancement from feeddowns of RQM augmented baryons
- Uncertainty band: BR=50-100% to Λ_C^+ for Λ_C & Σ_C above DN (2805 MeV) threshold

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



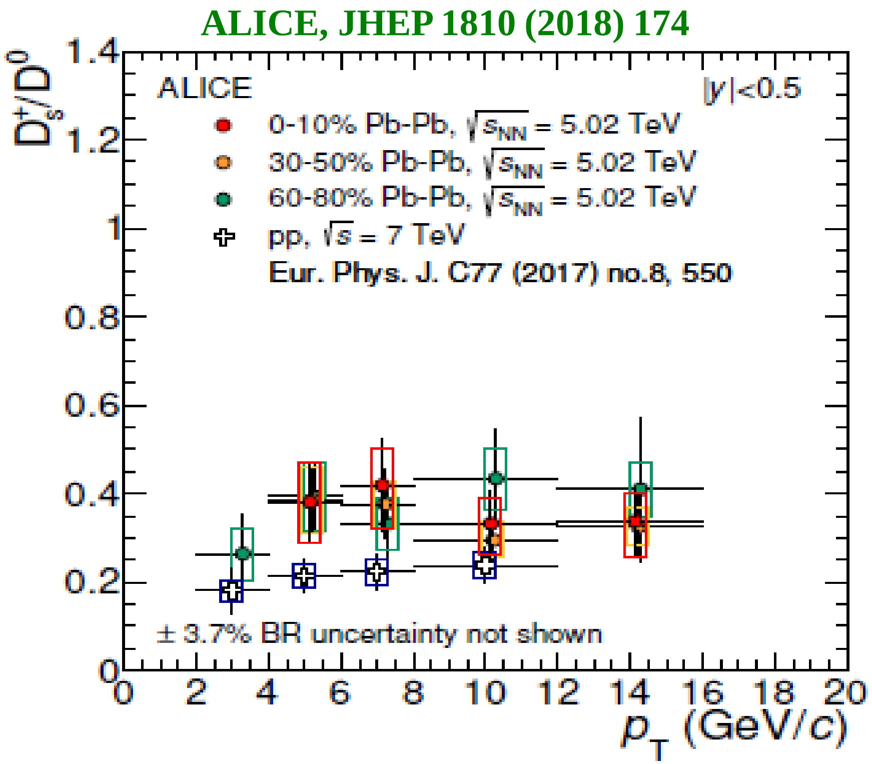
Baryon to meson ratio enhancement

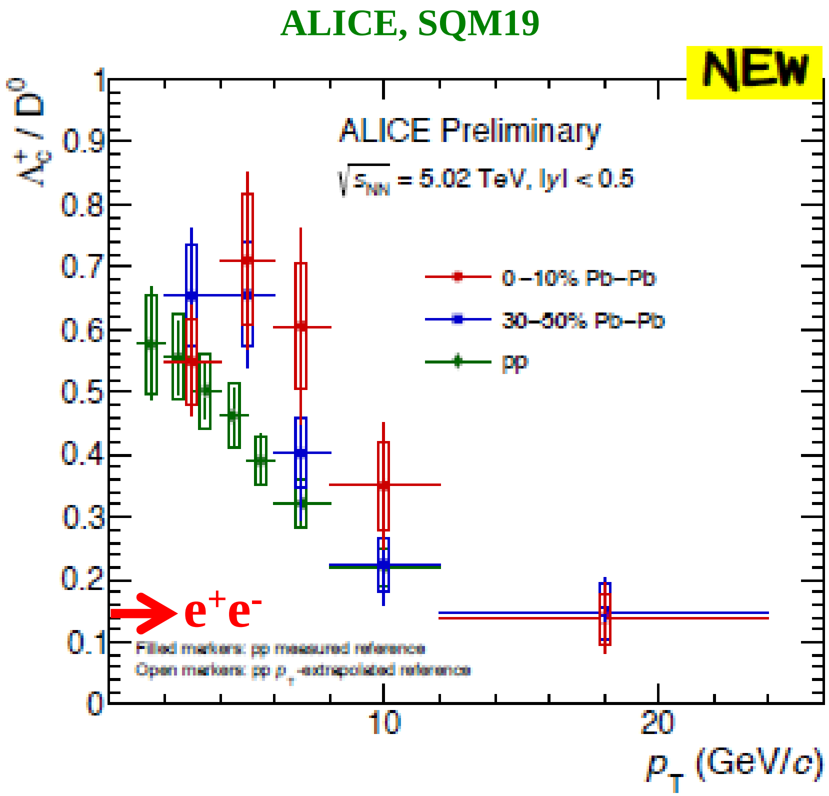


- B/M enhanced at intermediate p_T in central AA collisions
- Nicely (straightforwardly) explained by coalescence models **Ko, Fries, Hwa**
- A direct indication of the working of coalescence hadronization

$$f_M(p_T) \sim f_q(p_T/2)*f_{qbar}(p_T/2) \quad \text{VS} \quad f_B(p_T) \sim f_q(p_T/3)*f_q(p_T/3)*f_q(p_T/3)$$

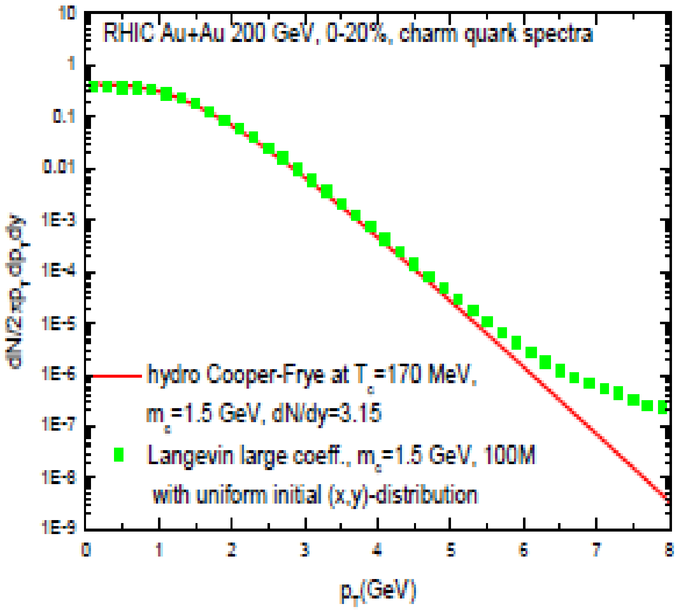
Does it carry over to the HF sector?

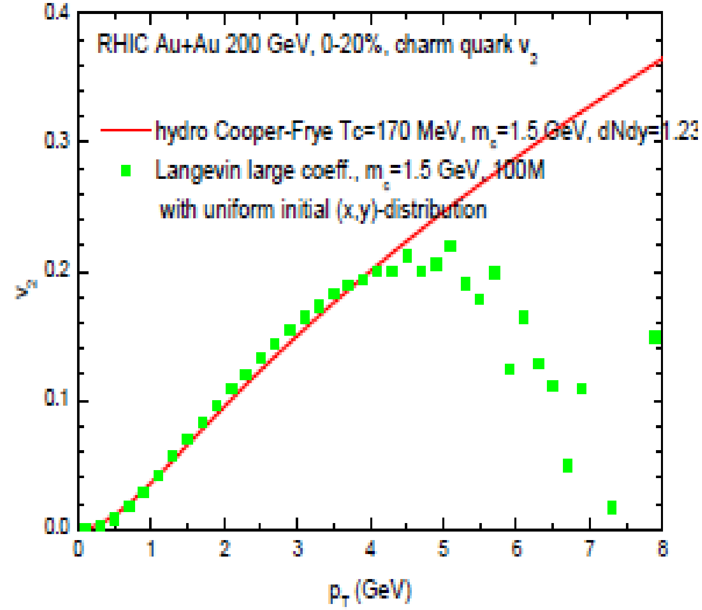




- **e^+e^- : vacuum fragmentation, costly to excite ssbar-pair or diquark-antidiquark pair from vacuum ➔ Ds and Λ_c much suppressed**
- **high-energy pp: likely coalescence for Λ_c in a quark-rich environment!**
- **AA: recombination hadronization in QGP ➔ modifying charm hadro-chemistry**

Langevin equil. Limit with large coeffi.

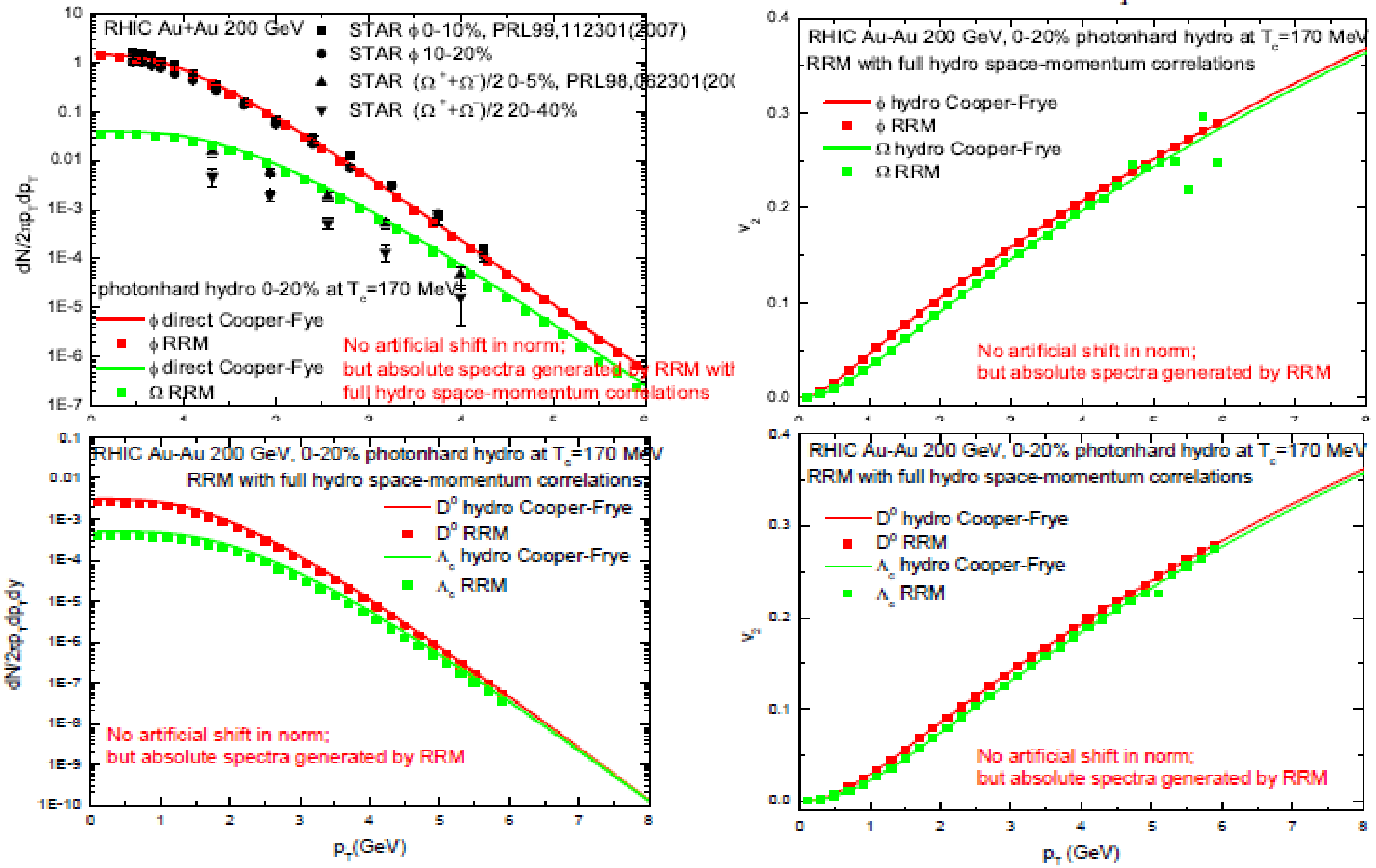




ıre 9. Langevin charm quark p_T spectra and v_2 with large coefficient.

RRM: equilibrium mapping

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

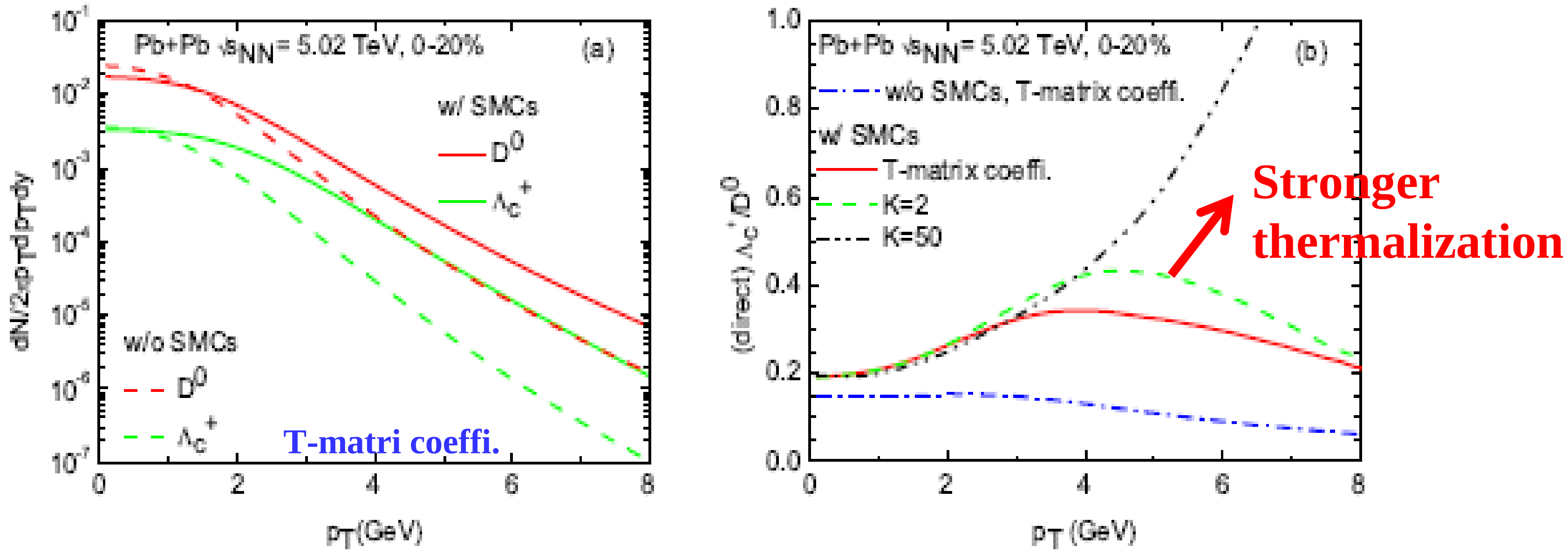


- Equilibrium mapping: ensured by 4-momentum conservation in RRM

  m_q=0.3, m_s=0.4, m_c=1.5, Γ_M~0.1 GeV, Γ_d~0.2 GeV, Γ_B~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~4.2 GeV: enhancement of density of light-q of p_T~ 0.6-0.7 GeV & c of p_T~3.0-3.5 GeV

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

--- Rencombinant quark density enhanced vs w/o SMCs: $V_{eff}<V_{fb}$

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

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