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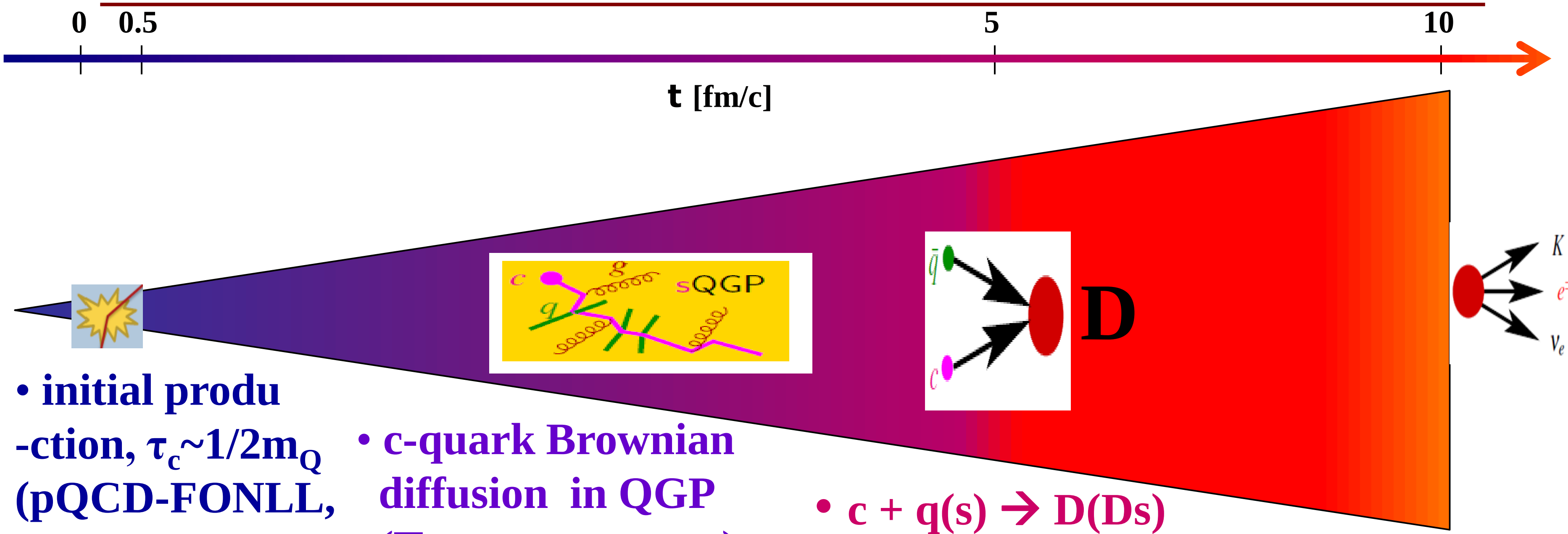
- Collectivity pattern: R_{AA}, v_2
- p_T-dependent charm hadro-chemistry: D_s^+/D^0, Λ_c^+/D^0

Heavy flavor transport in hot QCD matter



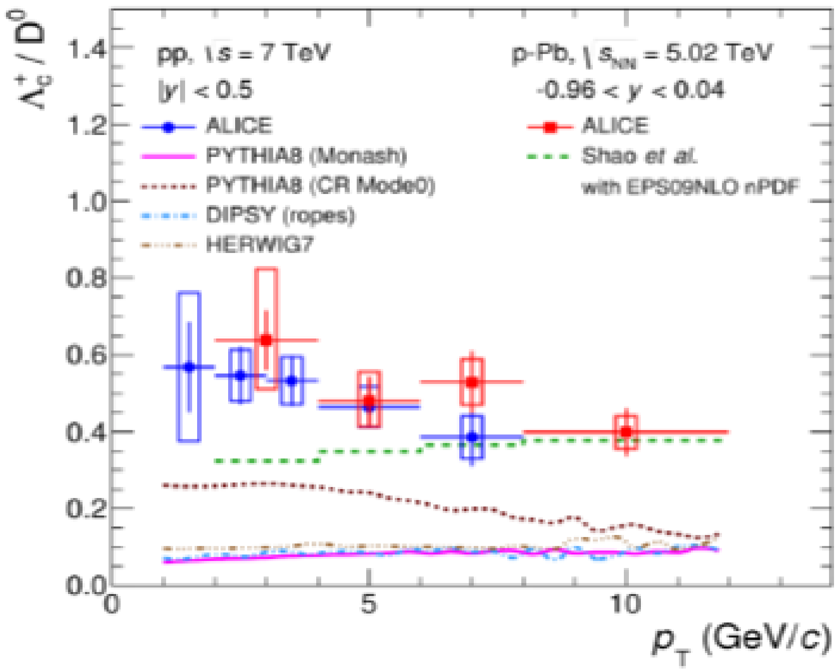
- initial produ -ction, $\tau_c \sim 1/2m_Q$ (pQCD-FONLL, shadowing)
- c-quark Brownian diffusion in QGP (T-mat. reso. corr.) low p_T thermalization high p_T e-loss
- c + q(s) → D(Ds)
- c + q + q → Λ_c resonance recombination
- D-meson diffusion in hadronic liquid

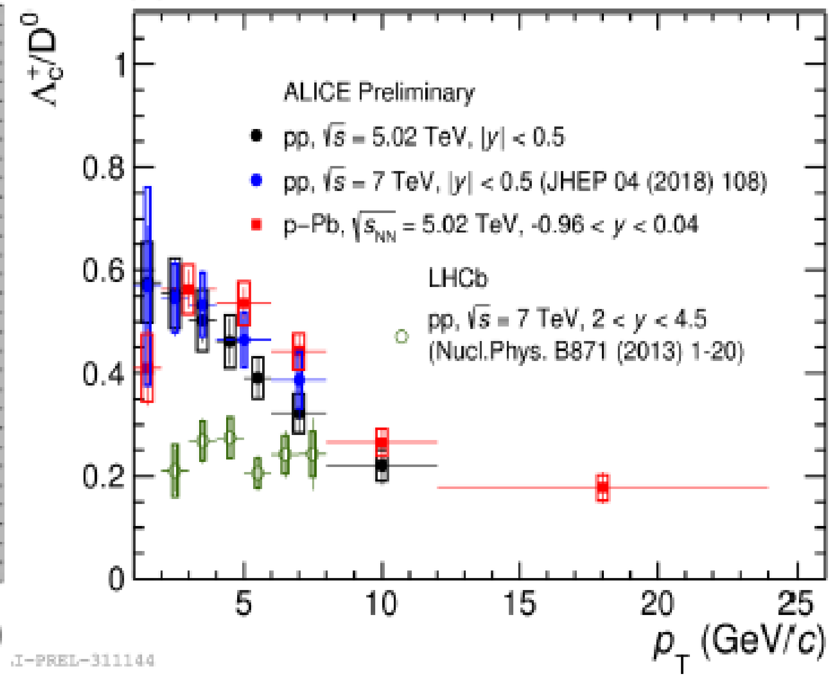
➢ **Calibrated & tagged probes preserving memory of interaction history**

➢ **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

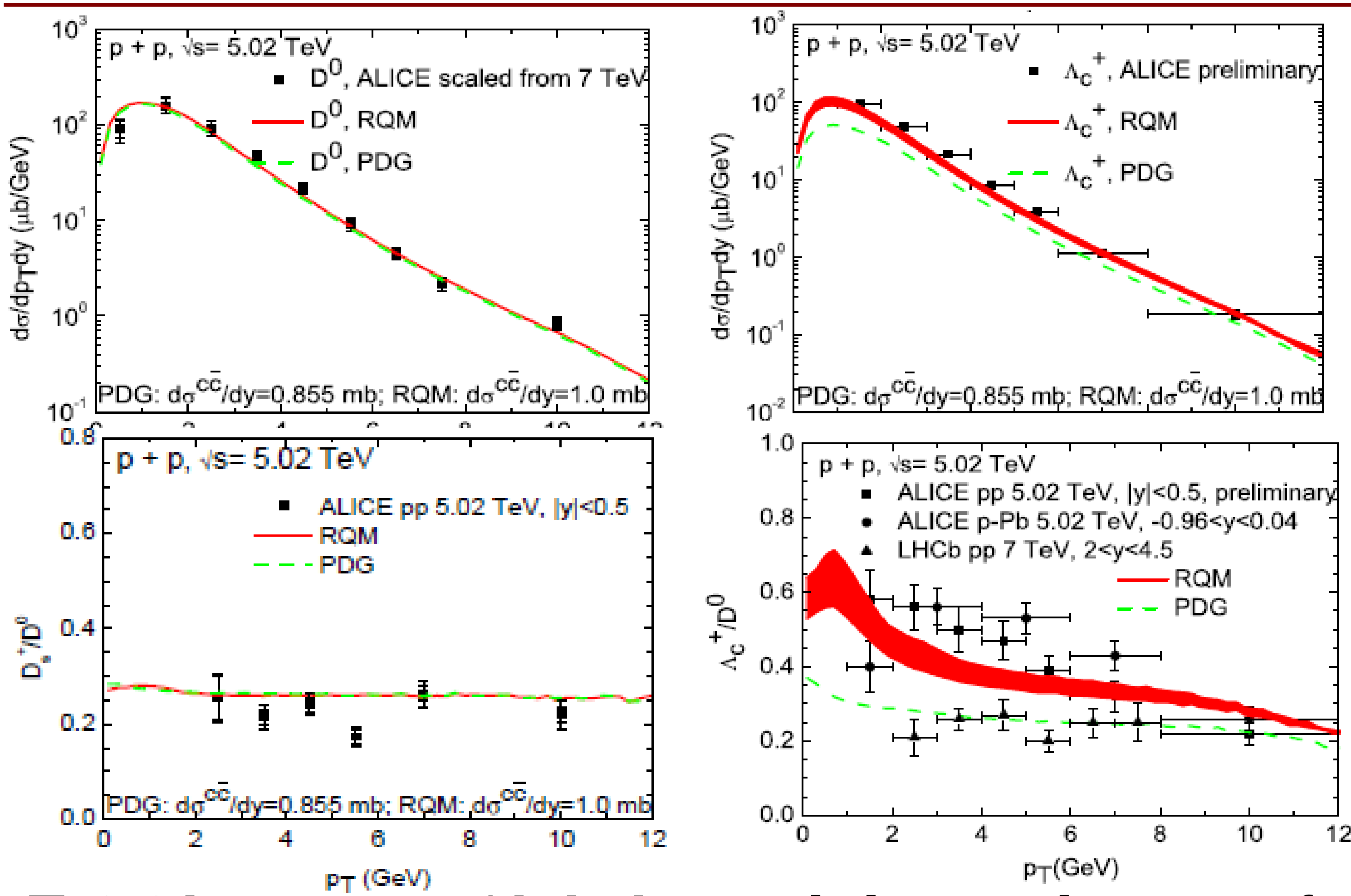
- **Strong feeddowns of excited states all included: BR=100% to Λ_C^+ for all Λ_C & Σ_C even above DN (2805 MeV) threshold**
  -- Strangeness supp. γ_s=0.6

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 $d\sigma/dy$=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

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

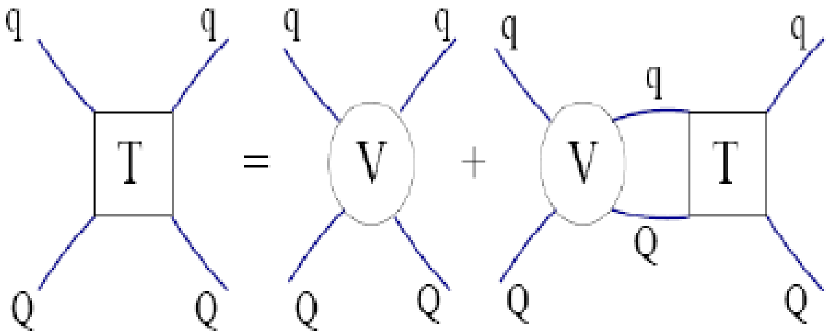
Charm in QGP: transport coeffi. & diffusion

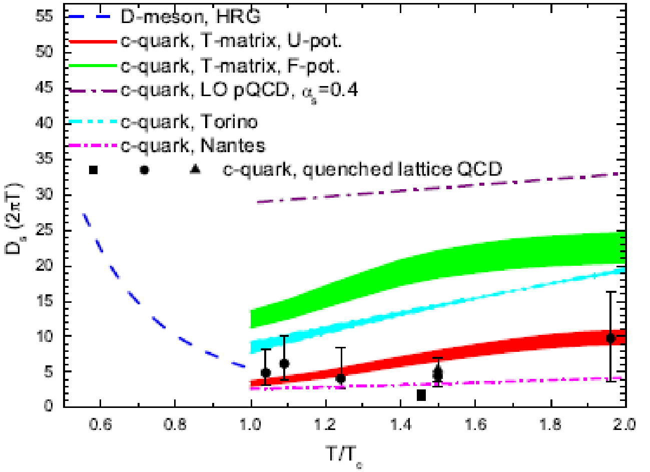
Langevin + hydro simulation down to Tc=170 MeV
fluid rest frame updates → boost to lab frame

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

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

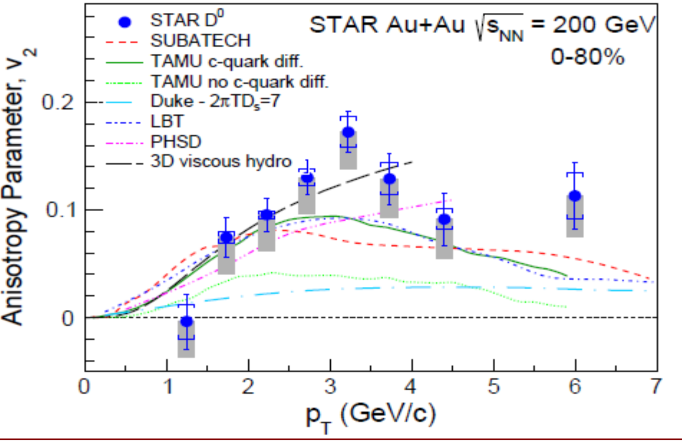
- Lattice-contrained Q-q/g T-matrix





- p- and T-dependent transport with $\mathcal{D}_s(2\pi T)$ ~ 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 $c\bar{q} \longrightarrow D$ 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

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

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

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

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

Charm-hadron production in AA collisions

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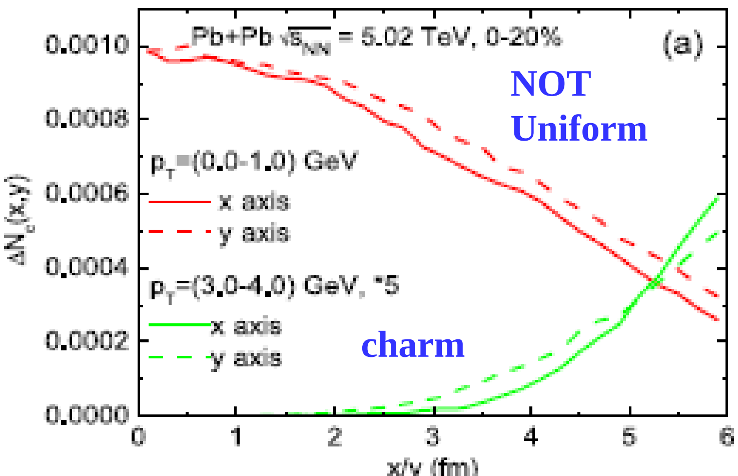
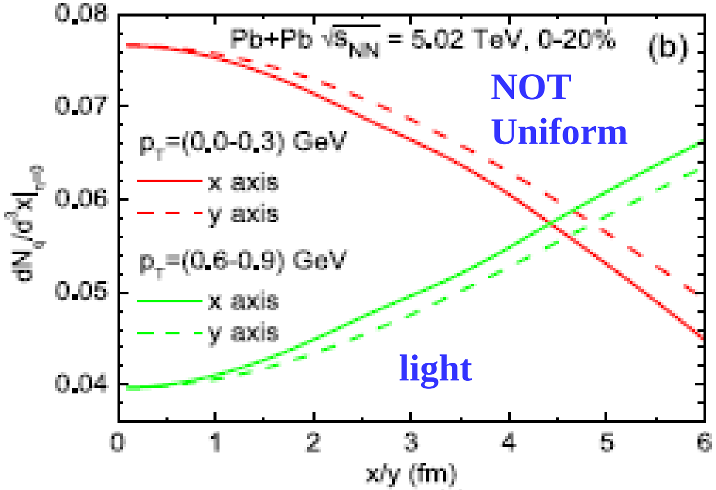
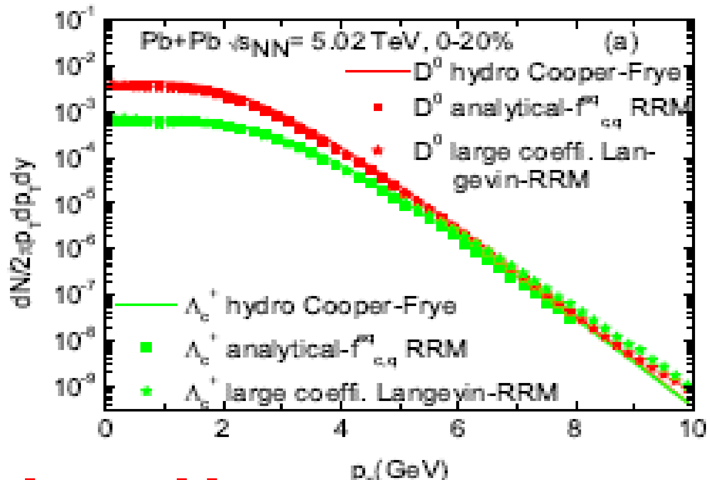
Space-momentum correlations (SMCs)

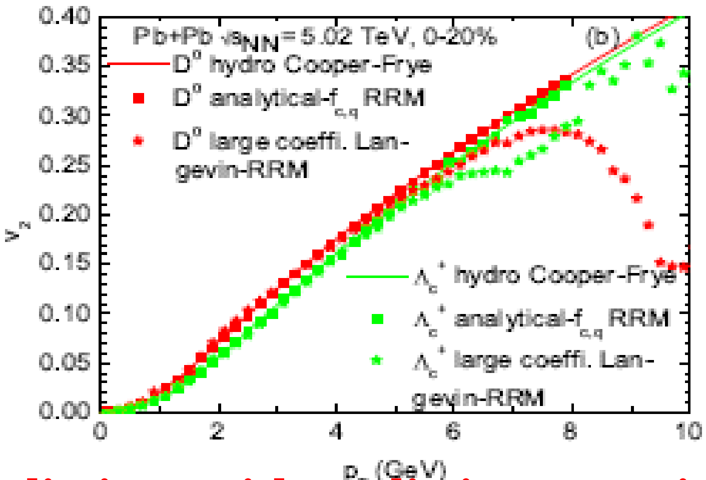
- hydro-q & Langevin-c: low (high) p_T more populated in center (outer)





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





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

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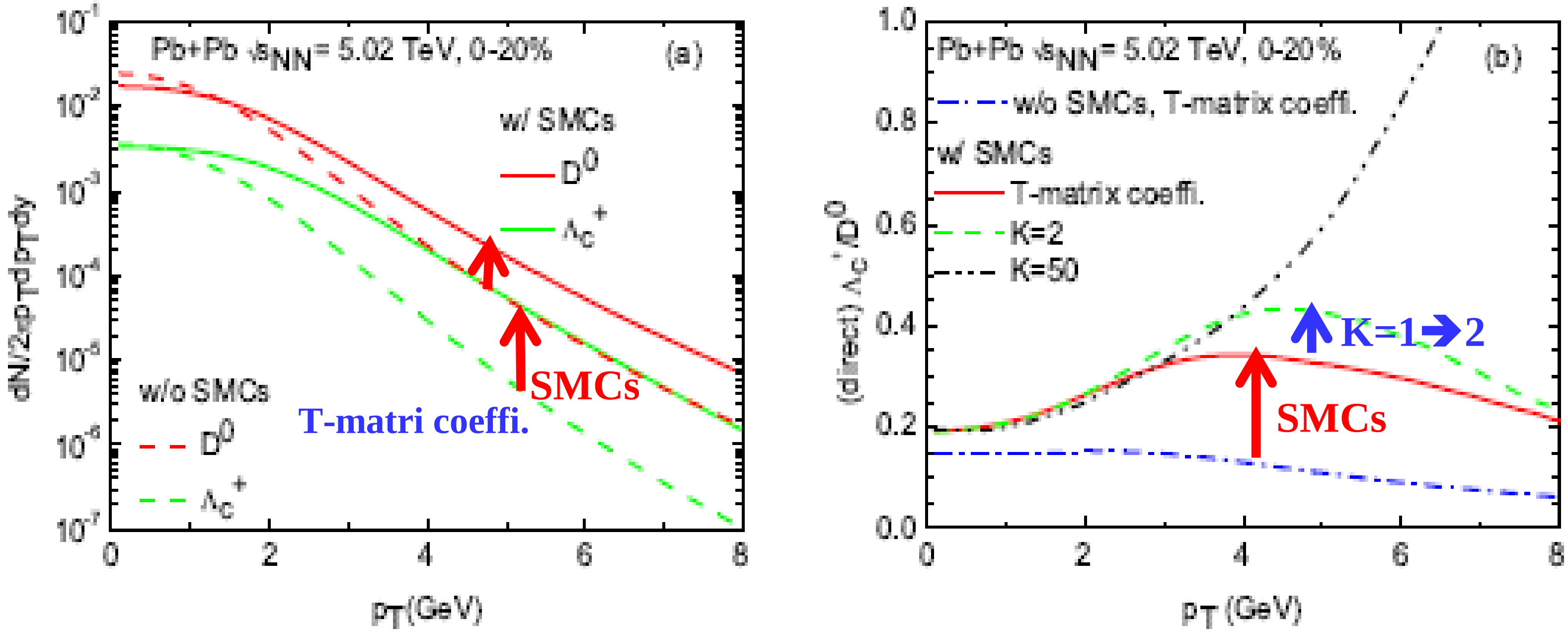
Direct D^0 & Λ_c^+ production via RRM

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

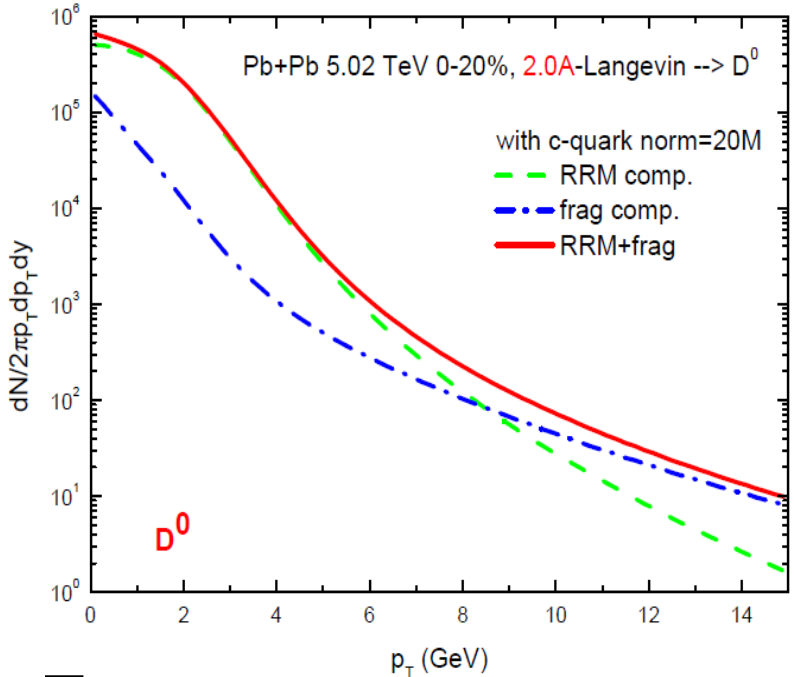


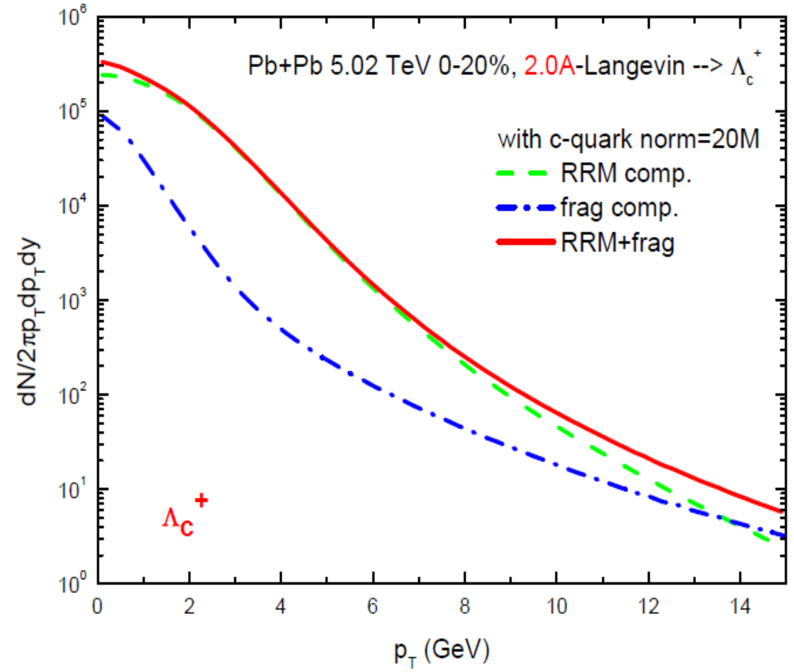
- **Fast-moving c-quarks [p_T~ 3-4 GeV] moving to outer part of fireball find higher-density of harder [p_T~ 0.6-0.9 GeV] light quarks for recombination**

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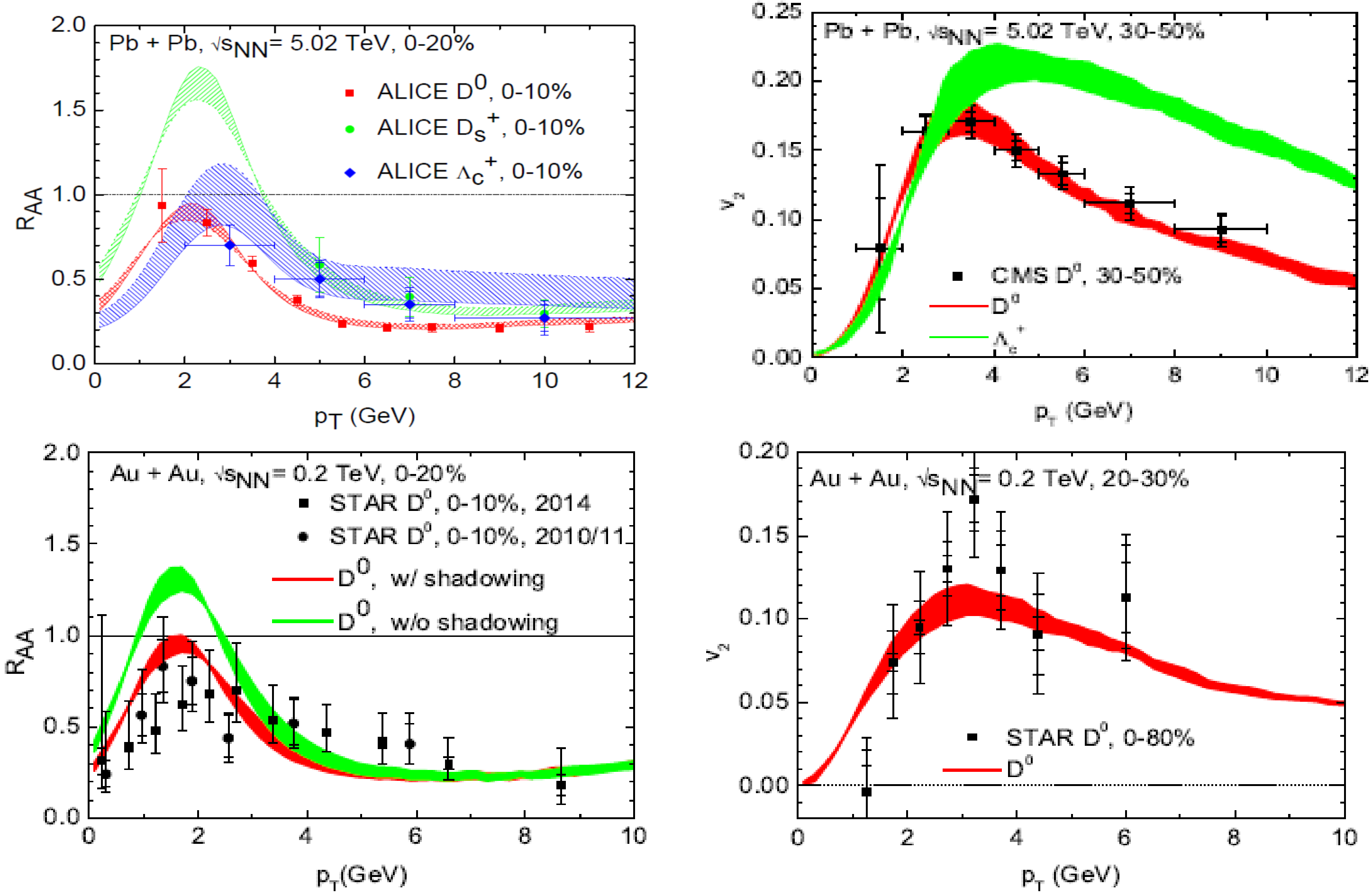
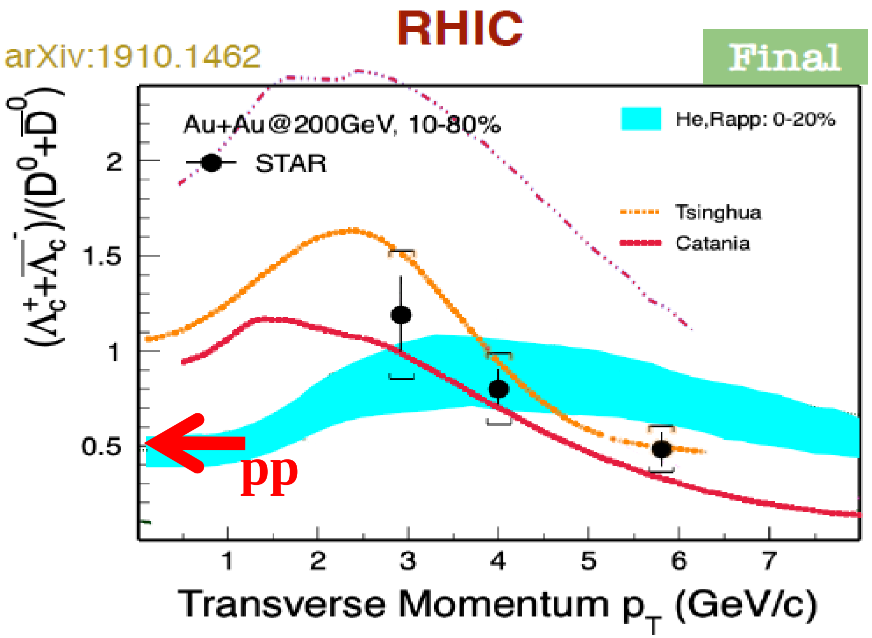
D^0, D_s^+ & Λ_c^+ suppression & elliptic flow

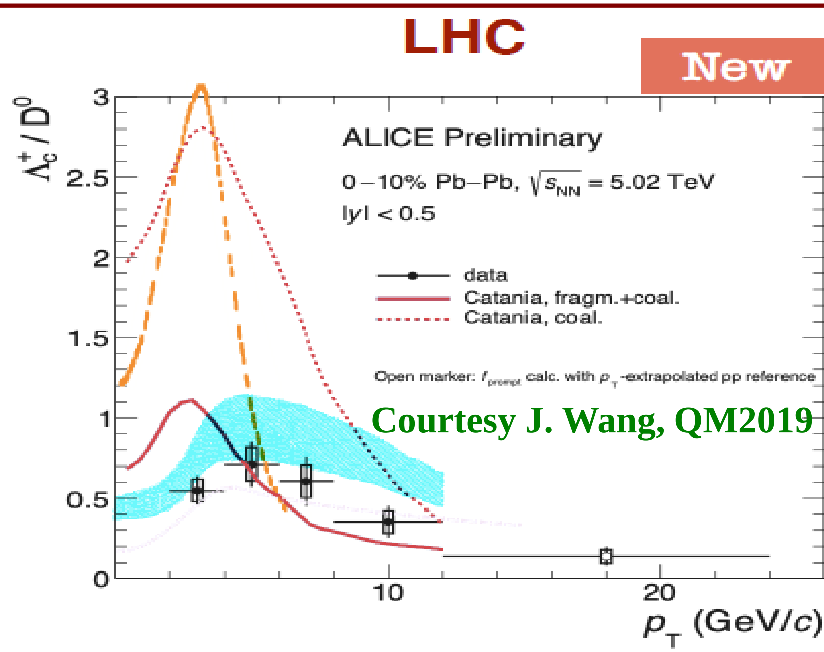
- ☐ **Final total D^0 , D_s^+ & Λ_c^+, including feeddowns from all RQM baryons**

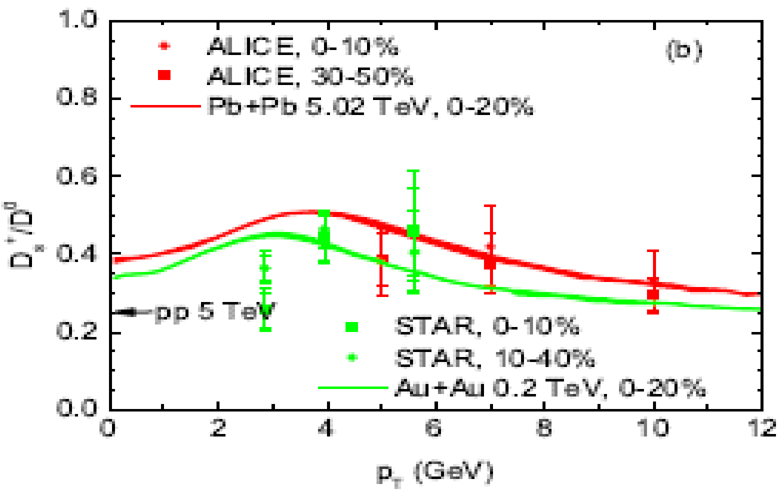


- ☐ **T-matrix coefficient*K-factor(=1.6), to compensate for radiative e-loss; uncertainty: BR=50-100% to Λ_C^+ for Λ_C's & Σ_C's above DN (2805 MeV)**

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

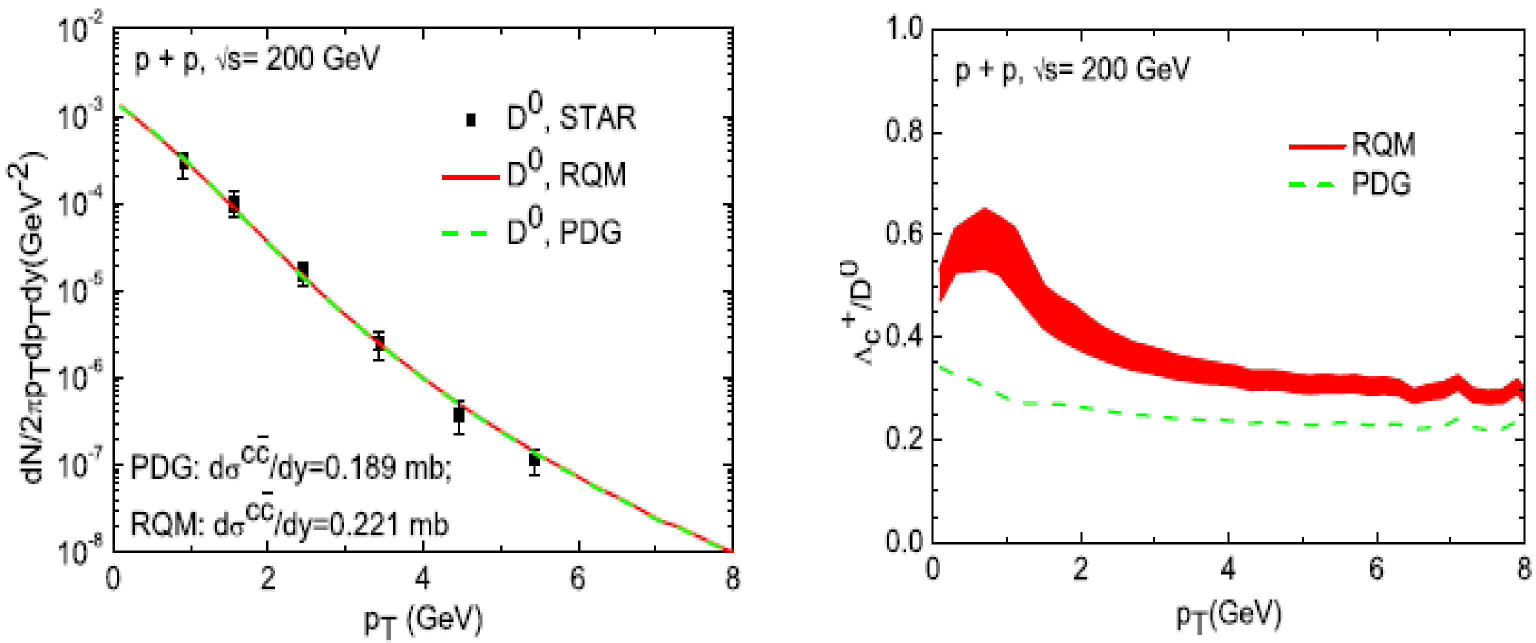
>> Charm-hadron production in AA collisions

- ☐ 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

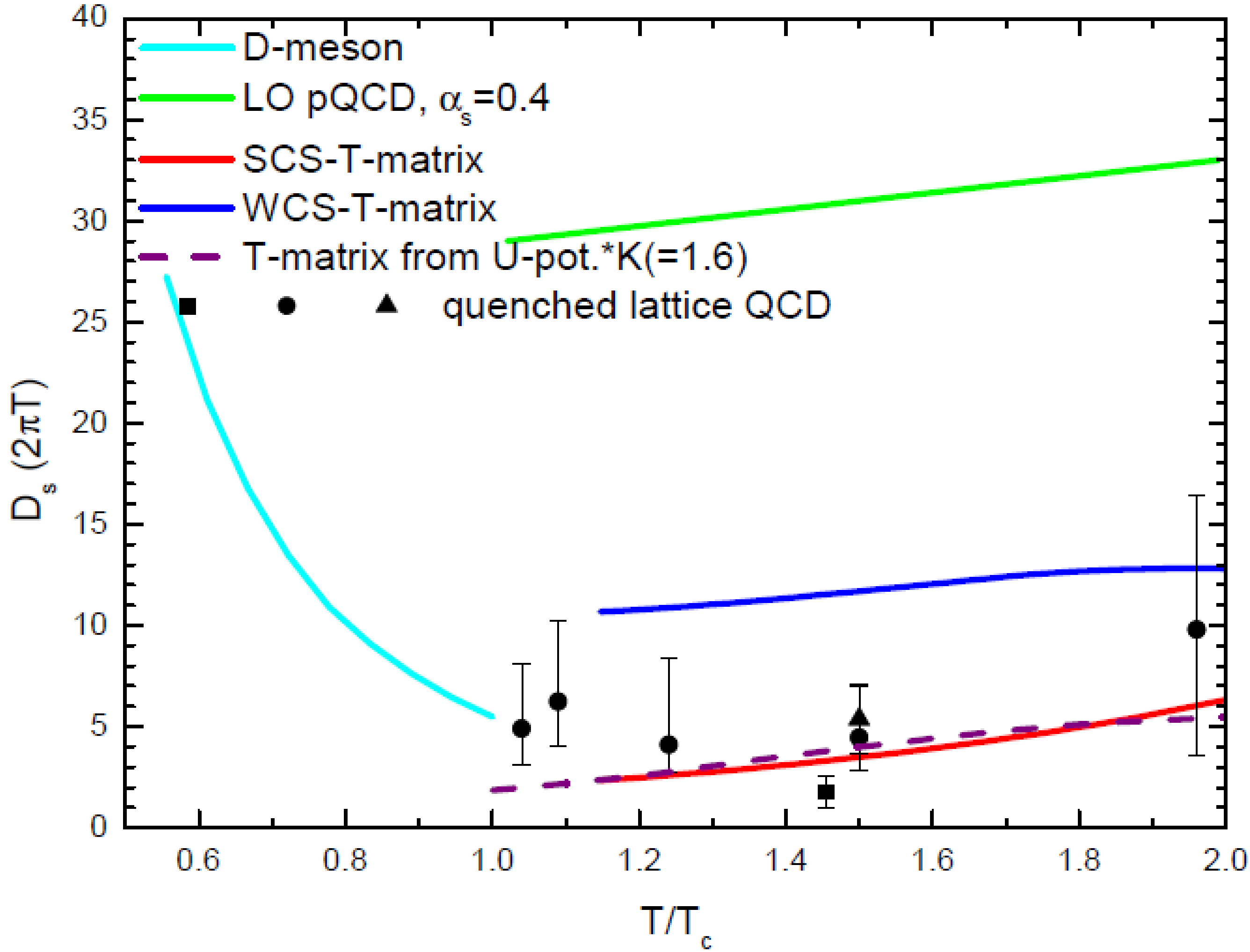
- ☐ p_T-dependent Λ_c^+/D^0 & D_s^+/D^0 enhancement emerge from hydro-Langevin-RRM(+fragmentation) simulations; data trend largely reproduced within BR's uncertainties

Back-up: pp 200 GeV collisions

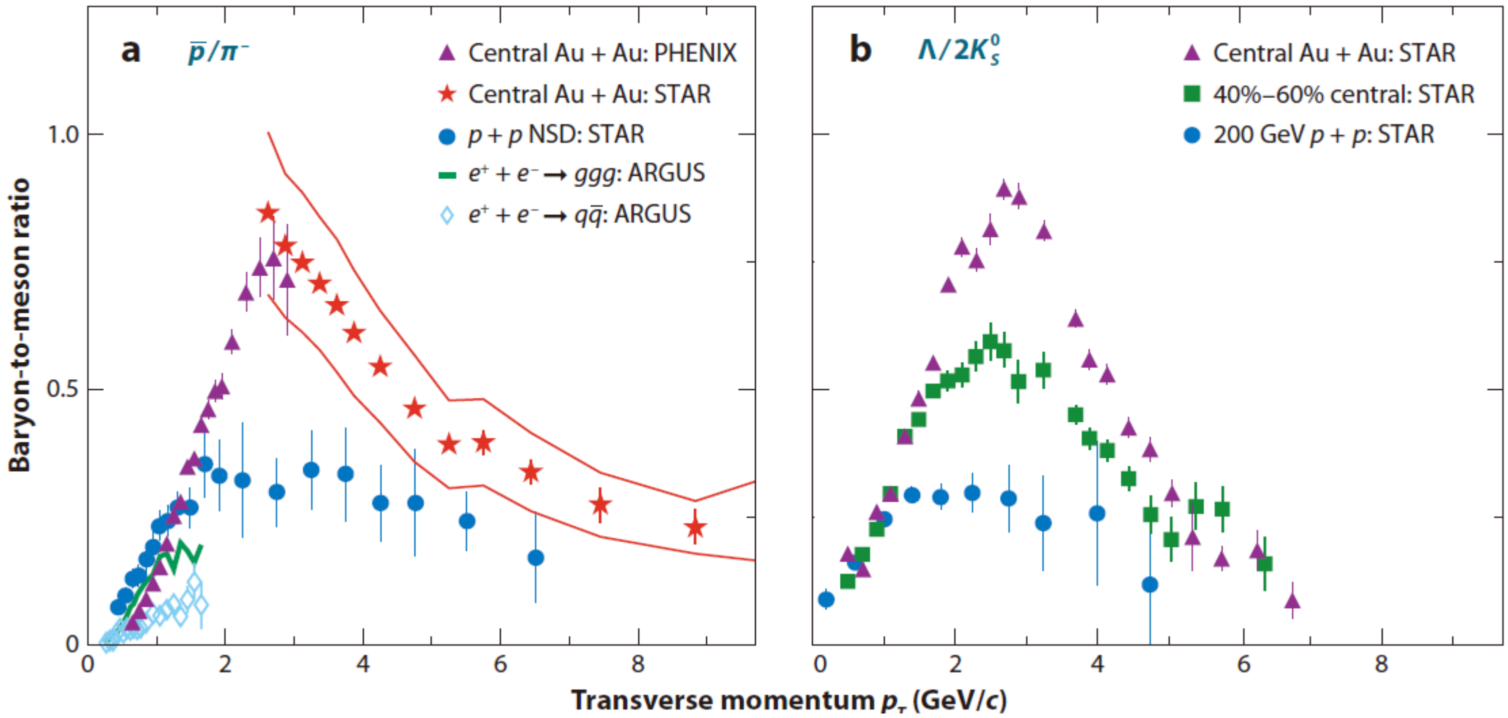


- Low pT enhancement from feeddowns of RQM augmented baryons
- Uncertainty band: BR=50-100% to Λ_C^+ for Λ_C & Σ_C above DN (2805 MeV) threshold

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



Baryon to meson ratio enhancement

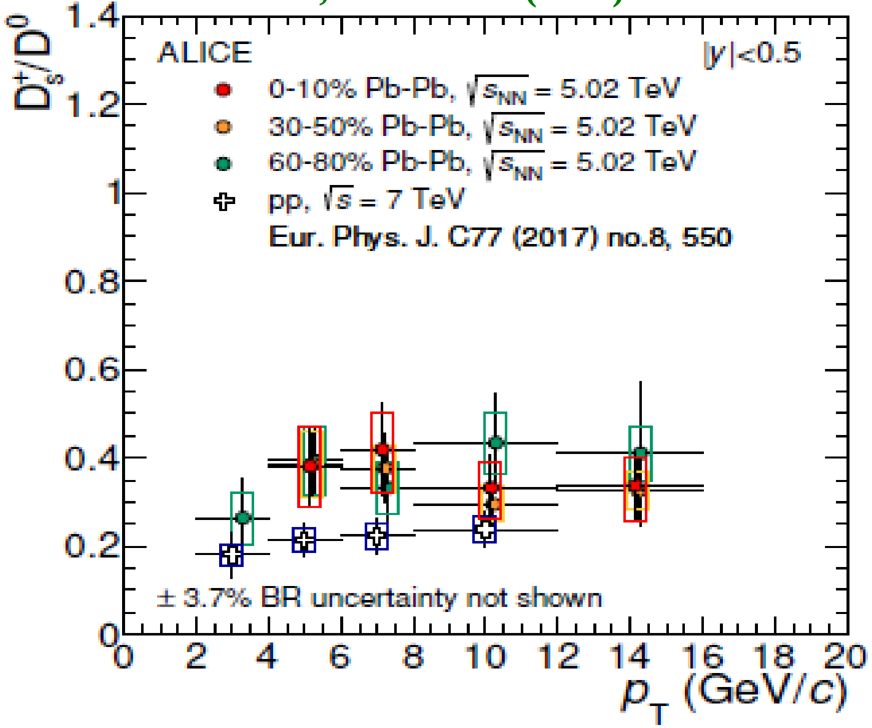


- B/M enhanced at intermediate p_T in central AA collisions
- Nicely (straightforwardly) explained by coalescence models Ko, Fries, Hwa
- A direct indication of the working of coalescence hadronization

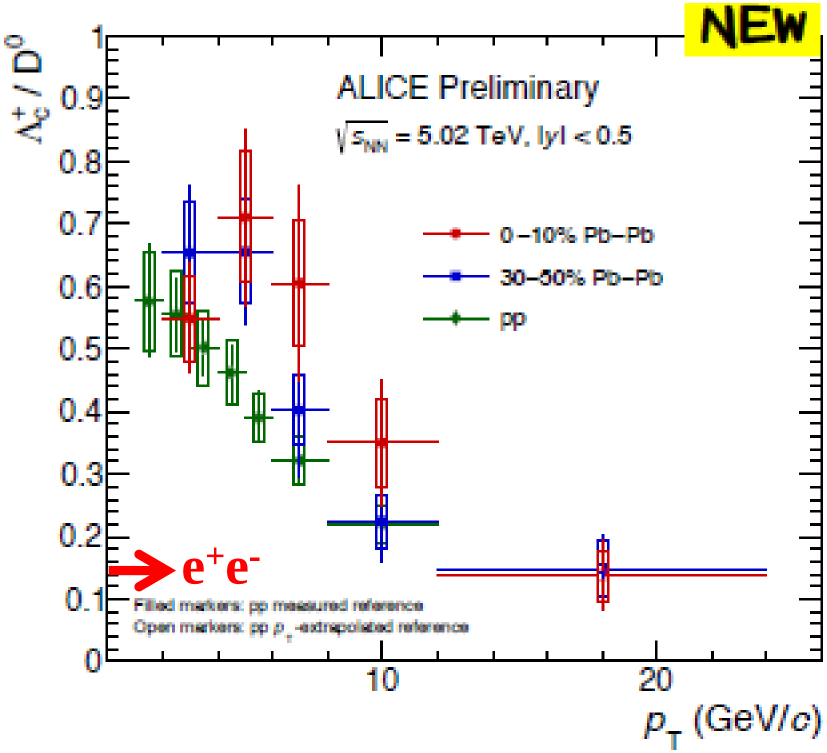
$$f_M(p_T) \sim f_q(p_T/2)*f_{qbar}(p_T/2) \quad \text{VS} \quad f_B(p_T) \sim f_q(p_T/3)*f_q(p_T/3)*f_q(p_T/3)$$

Does it carry over to the HF sector?

ALICE, JHEP 1810 (2018) 174

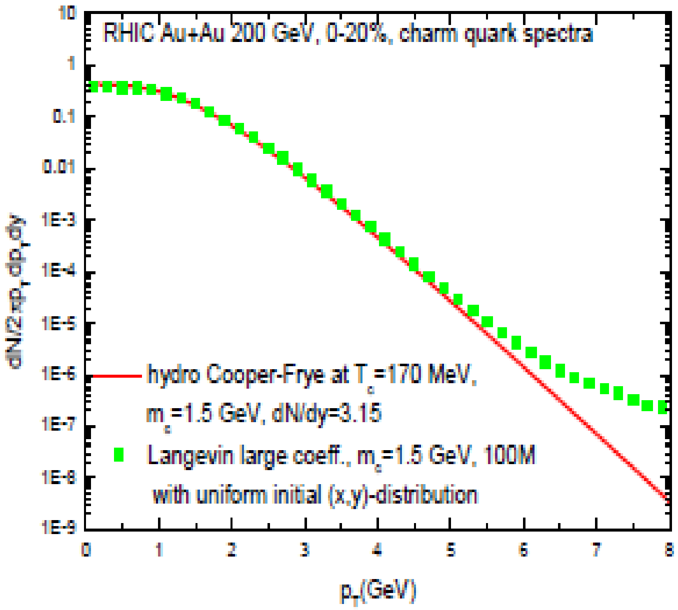


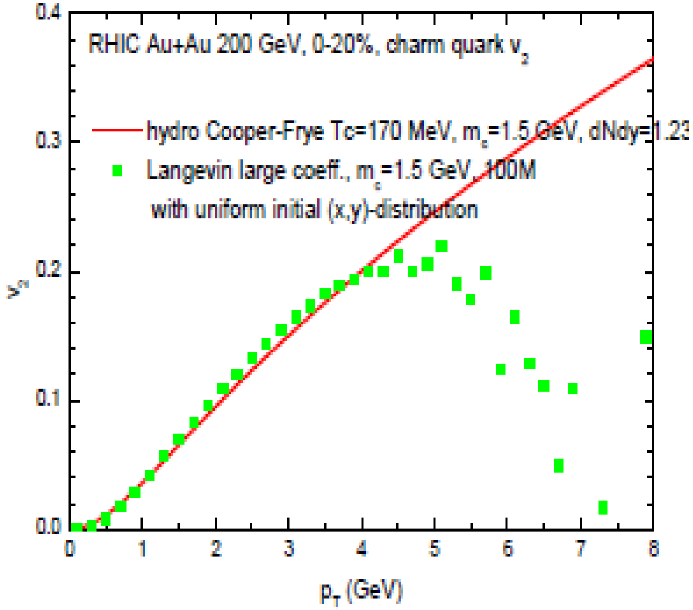
ALICE, SQM19



- 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.

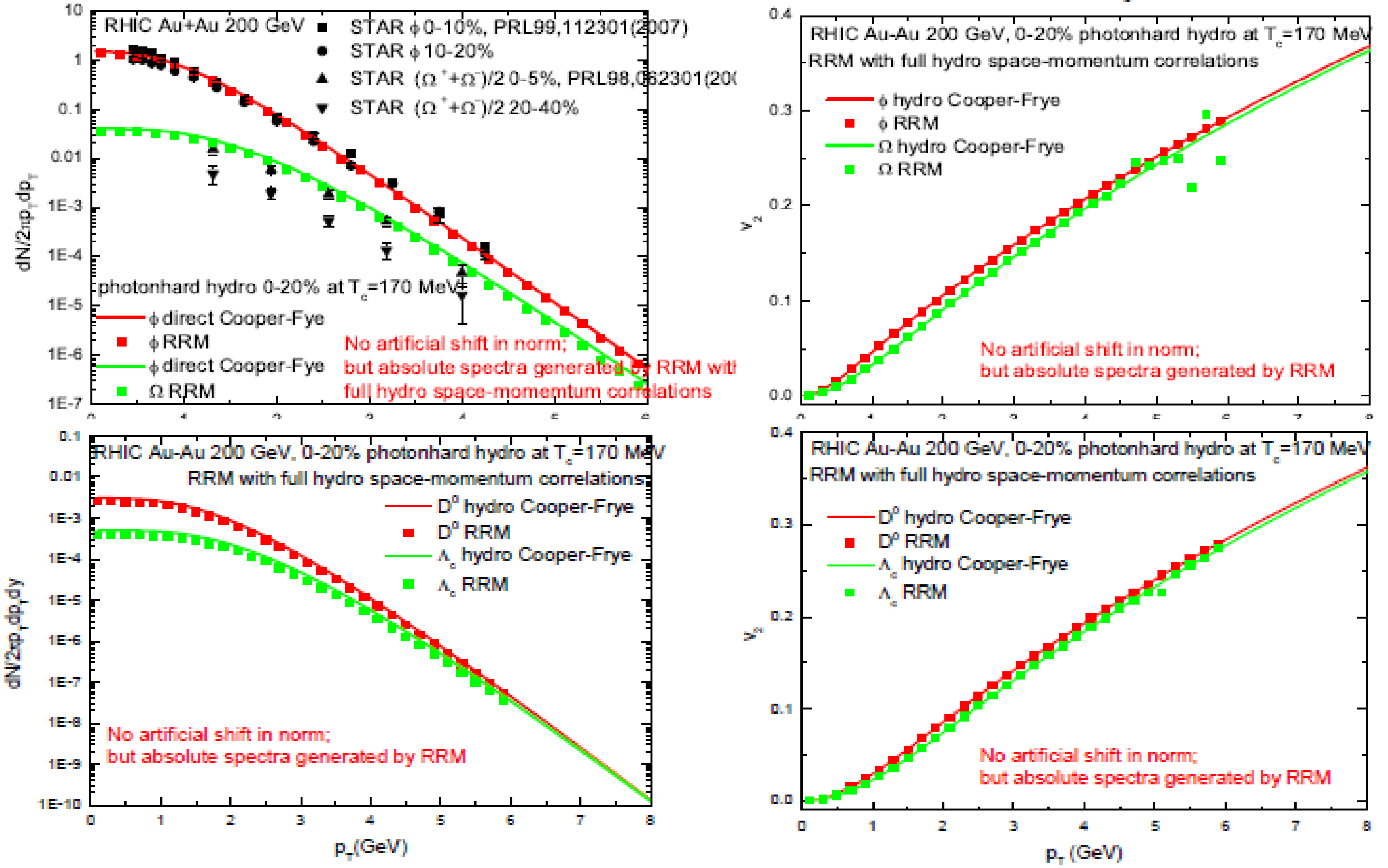




ıre 9. Langevin charm quark p_T spectra and v_2 with large coefficient.

RRM: equilibrium mapping

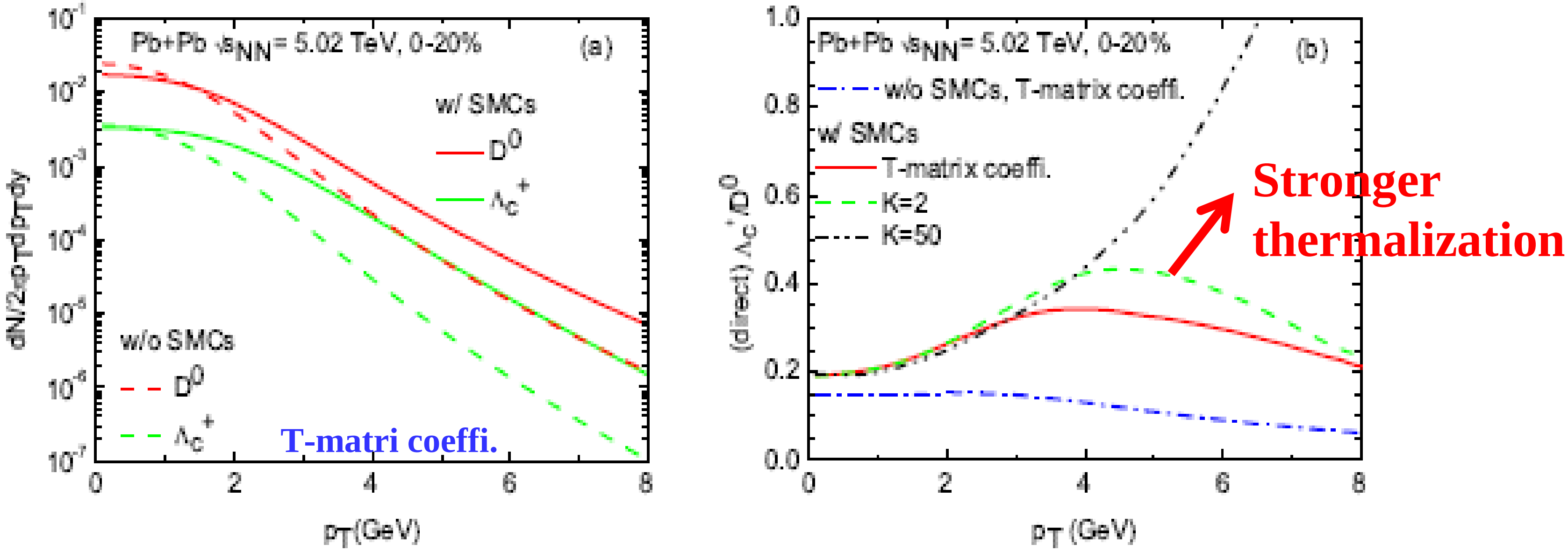
- RRM on hydrofreezeout hypersurface at T_c with $f_q^{eq}(\vec{x},\vec{p}) = g_q e^{-p\cdot u(x)/T(x)}$



- 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

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

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

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

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