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TAMU Modelling of Charm Quark Hadronization

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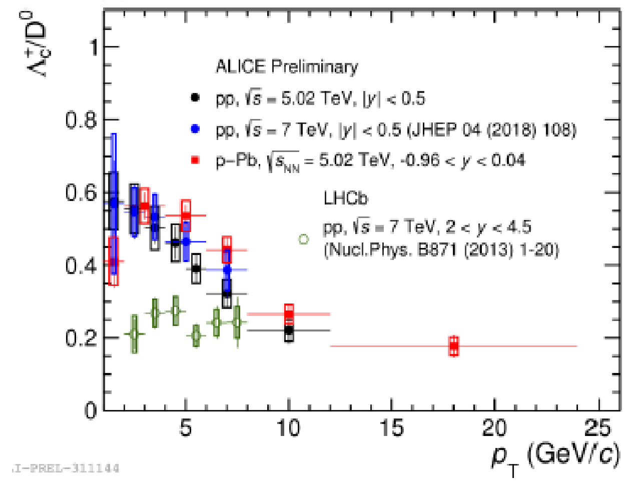
Baseline: charm hadronization in pp collisions

- Postulate: *relative* chemical equilibrium is reached among different charm-hadron species
  ➔ a gauge of charm hadronization in both pp & AA collisions

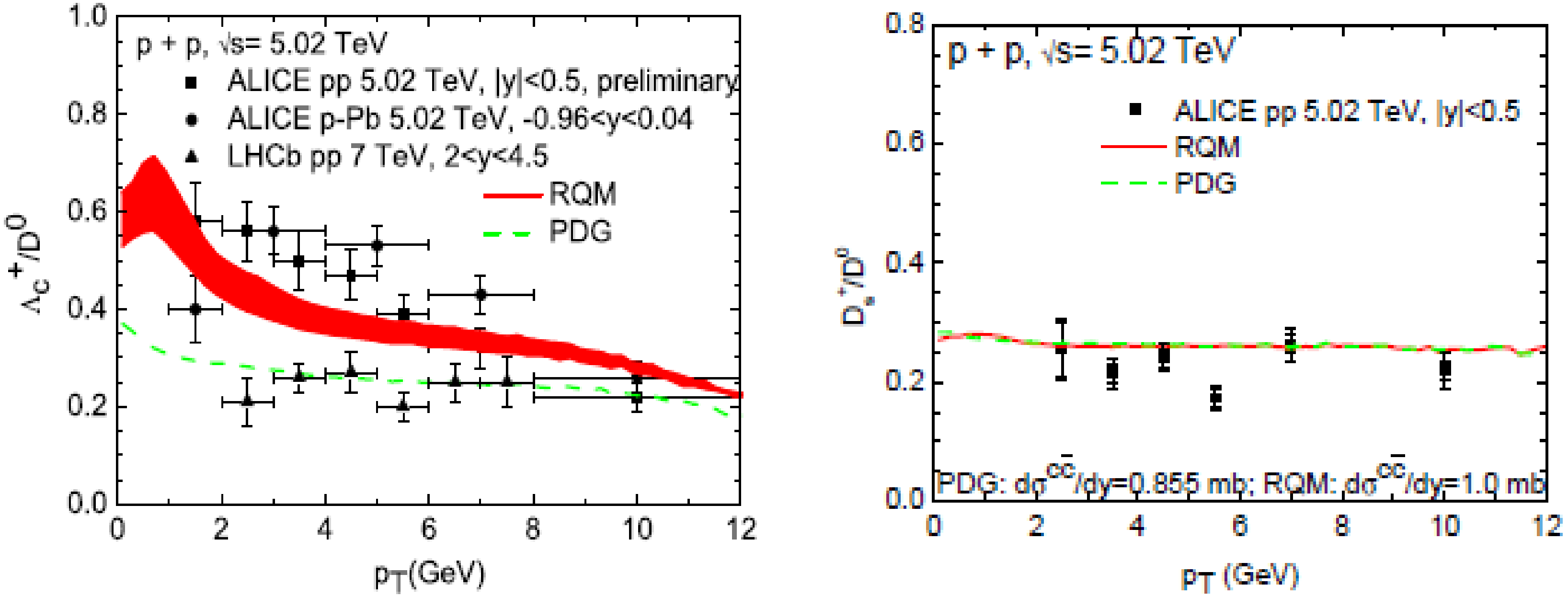
- Statistical hadronization T_H=170 MeV $n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2(\frac{m_i}{T_H})$ γ_s=0.6

PDG: 5 Λ_C (I=0), 3 Σ_C (I=1), 8 Ξ_C (I=1/2), 2 Ω_C (I=0) to be augmented by
RQM: 18 extra Λ_C, 42 extra Σ_C, 62 extra Ξ_C, 34 extra Ω_C up to 3.5 GeV **Ebert et al. '11**



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

Charm hadrochemistry in pp



- SHM thermal densities as weights to do fragmentation of charm quarks into all charm-hadron species, and then excited states decayed into ground state charm-hadrons

- Λ_C^+ favors RQM with $d\sigma^{ccbar}/dy$=1.0 mb: low p_T enhancement from feeddowns of RQM augmented baryons

➔ All RQM augmented charm-hadrons will be also used in AA

Resonance Recombination Model (RRM)

- Hadronization = Resonance formation $c\bar{q} \longrightarrow D$

  → consistent with T-matrix resonant correlations strengthening towards T_c

- Realized by Boltzmann equation **Ravagli & Rapp,2007**

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

$$\beta(\vec{x},\vec{p}) = \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2) \times \sigma(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

gain term

Breit-Wigner

$$\sigma(s) = g_\sigma \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s-m^2)+(\Gamma m)^2}$$

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

- Energy conservation + detailed balance

  equilibrium mapping between quark & meson distributions

Generalization to 3-body RRM

- The 1st step: $q_1(p_1)$ + $q_2(p_2)$ → diquark (p_{12})

$$f_d(\vec{x},\vec{p}_{12}) = \frac{E_d(\vec{p}_{12})}{\Gamma_d m_d}\int \frac{d^3p_1 d^3p_2}{(2\pi)^3} f_1(\vec{x},\vec{p}_1) f_2(\vec{x},\vec{p}_2)\sigma_{12}(s_{12}) v_{\rm rel}^{12}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}_{12}-\vec{p}_1-\vec{p}_2)$$

- The 2nd step: diquark (p_{12}) + $q_3(p_3)$ → baryon (p)
  - light diquark correlations in charm-baryons **Ebert et al. '11**

quark content	diquark type	mass (MeV)	wave func.	charm-baryon
[u,d]	Scalar	710	$\bar{\mathbf{3}}_{\rm color}\bar{\mathbf{3}}_{\rm flavor}\mathbf{0}^+_{\rm spin}$	Λ_c: c[ud]
{u,d}	Axial-vector	909	$\bar{\mathbf{3}}_{\rm color}\mathbf{6}_{\rm flavor}\mathbf{1}^+_{\rm spin}$	Σ_c: c{ud}

$$f_B(\vec{x},\vec{p}) = \frac{E_B(\vec{p})}{\Gamma_B m_B}\int \frac{d^3p_{12} d^3p_3}{(2\pi)^3} f_d(\vec{x},\vec{p}_{12}) f_3(\vec{x},\vec{p}_3)\sigma_B(s_{d3}) v_{\rm rel}^{d3}(\vec{p}_{12},\vec{p}_3)\delta^3(\vec{p}-\vec{p}_{12}-\vec{p}_3)$$

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

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

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

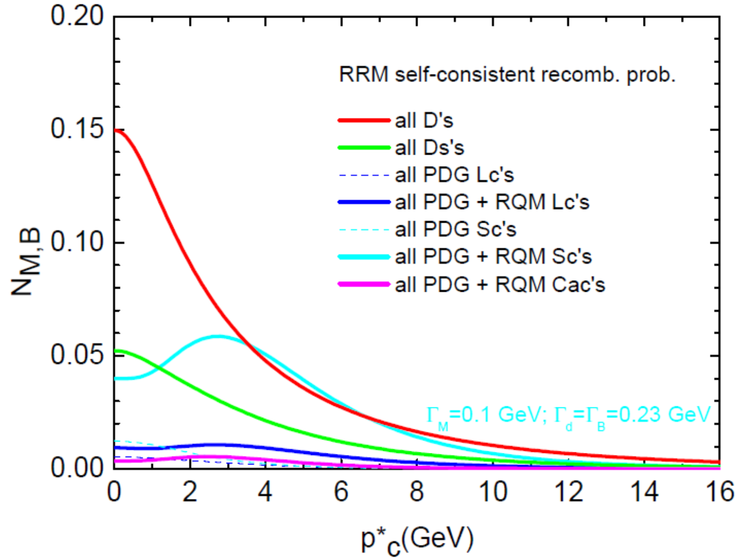
Charm quark recombination probability

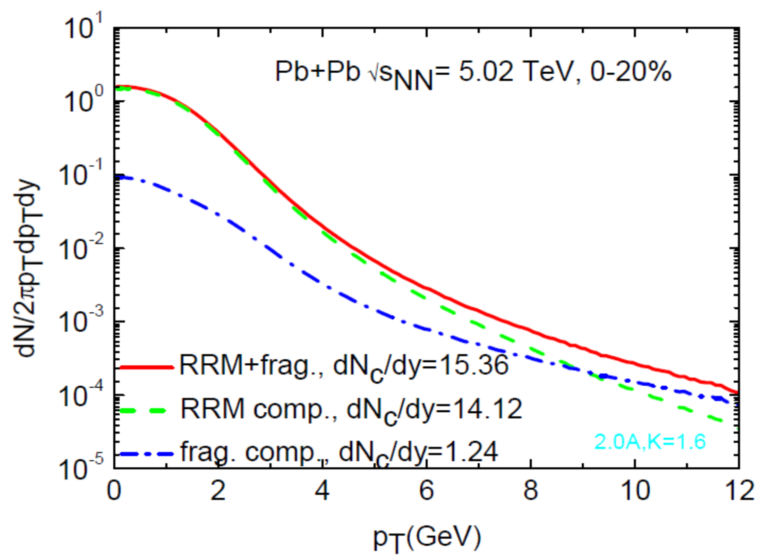
- No. of mesons/baryons formed from a single c-quark of rest frame p_c^*

$$N_M(p_c^*) = \int \frac{d^3\vec{p}_1^*}{(2\pi)^3} g_q e^{-E(\vec{p}_1^*)/T_{\rm pc}} \frac{E_M(\vec{p}^*)}{m_M\Gamma_M}\sigma(s)v_{\rm rel},$$

$$N_B(p_c^*) = \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} g_1 e^{-E(\vec{p}_1)/T_c} g_2 e^{-E(\vec{p}_2)/T_c} \frac{E_d(\vec{p}_{12})}{m_d\Gamma_d}\sigma(s_{12})v_{\rm rel}^{12}(\vec{p}_1,\vec{p}_2)\frac{E_B(\vec{p})}{m_B\Gamma_B}\sigma(s_{d3})v_{rel}^{d3}(\vec{p}_{12},\vec{p}_{30}),$$

- Renormalizing $N_M(p_c^*)$ and $N_B(p_c^*)$ by a common factor ~4 for all charmed mesons/baryons such that $\sum_M P_{{\rm coal},M}(p_c^*=0) + \sum_B P_{{\rm coal},B}(p_c^*=0) = 1$





➔ charm conservation consistently built in, in an (e-by-e) way without spoiling the relative chemical equilibrium realized by RRM

Space-momentum correlations: light-q

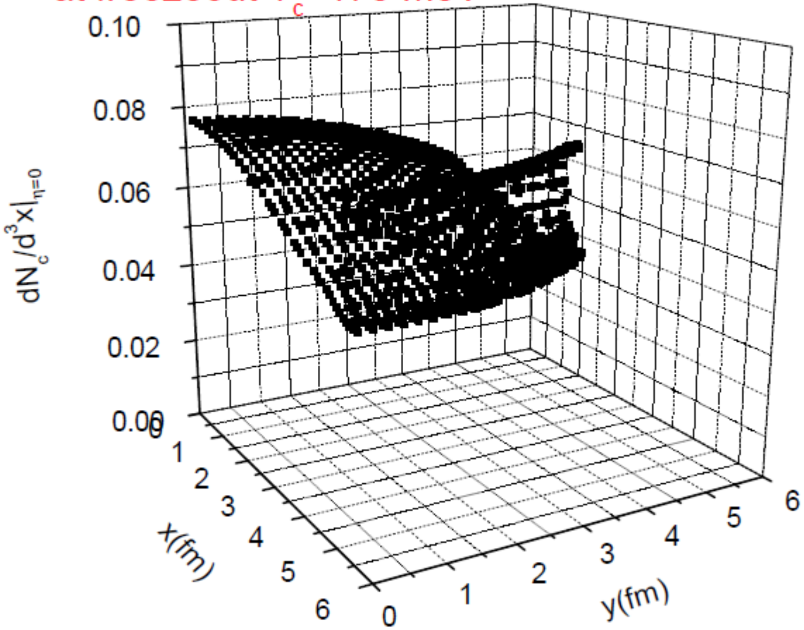
- hydro: a manifestation of SMCs

$$f_q^{eq}(\vec{x},\vec{p}) = g_q e^{-p\cdot u(x)/T(x)} = g_q e^{-\gamma_T(x)[m_T\cosh(y-\eta)-\vec{p}_T\cdot\vec{v}_T(x)]/T(x)}$$

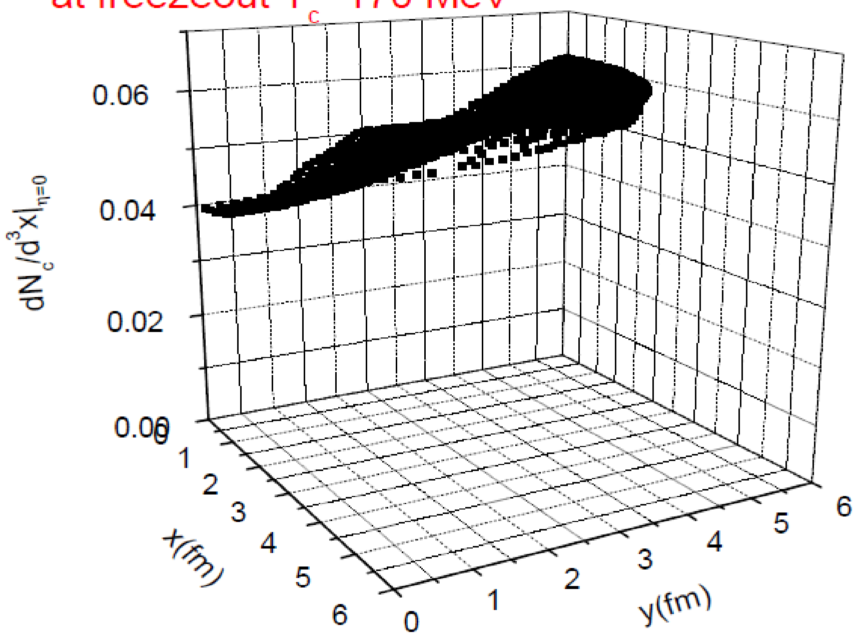
longitudinal boost invariance: y- η　　transverse SMCs pT▪vT

- hydro-q: low (high) p_T more concentrated in center (boundary)

hydro light quarks p_T=0.0-0.3 GeV, at freezeout T_c=170 MeV

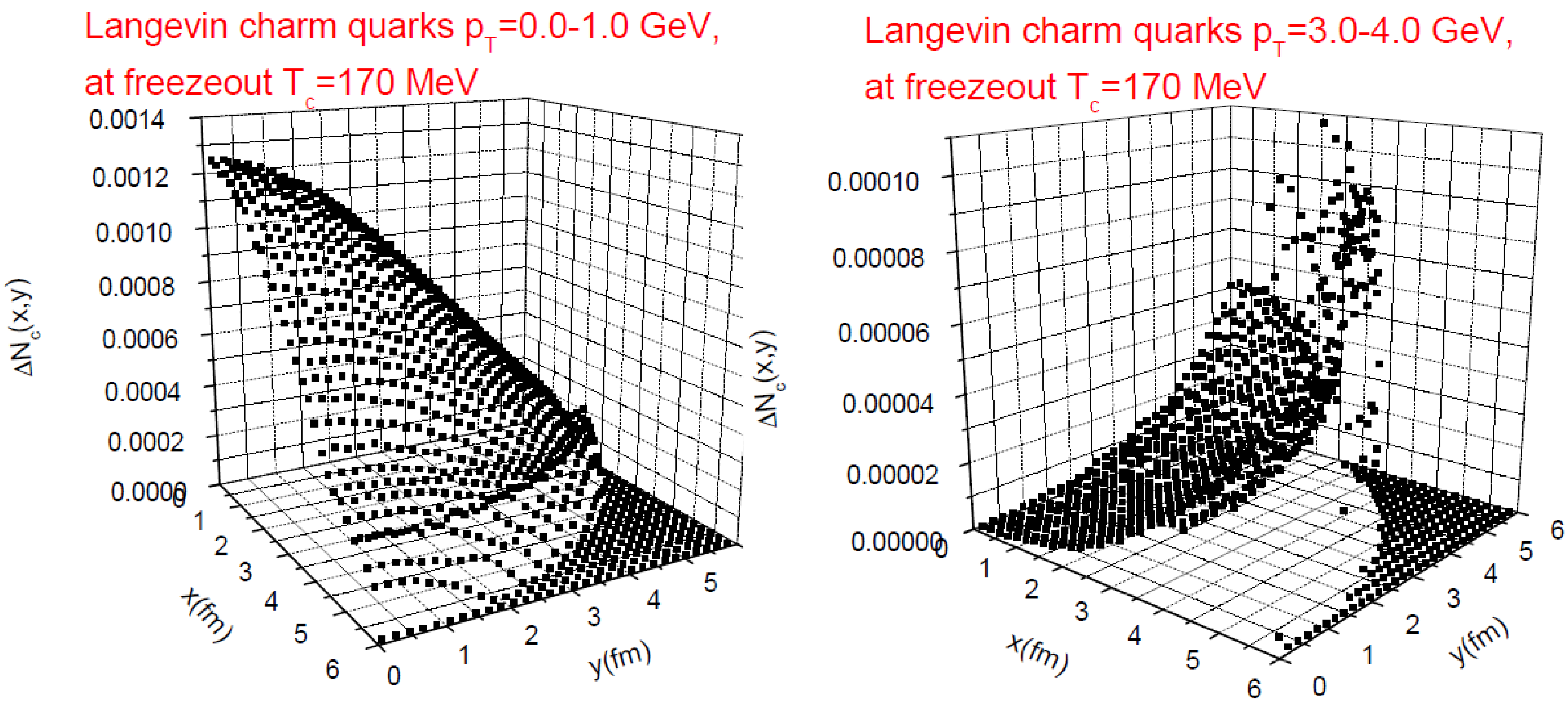


hydro light quarks p_T=0.6-0.9 GeV, at freezeout T_c=170 MeV



SMCs: Langevin charm quarks

- Langevin-c: low (high) p_T more populated in central (outer)



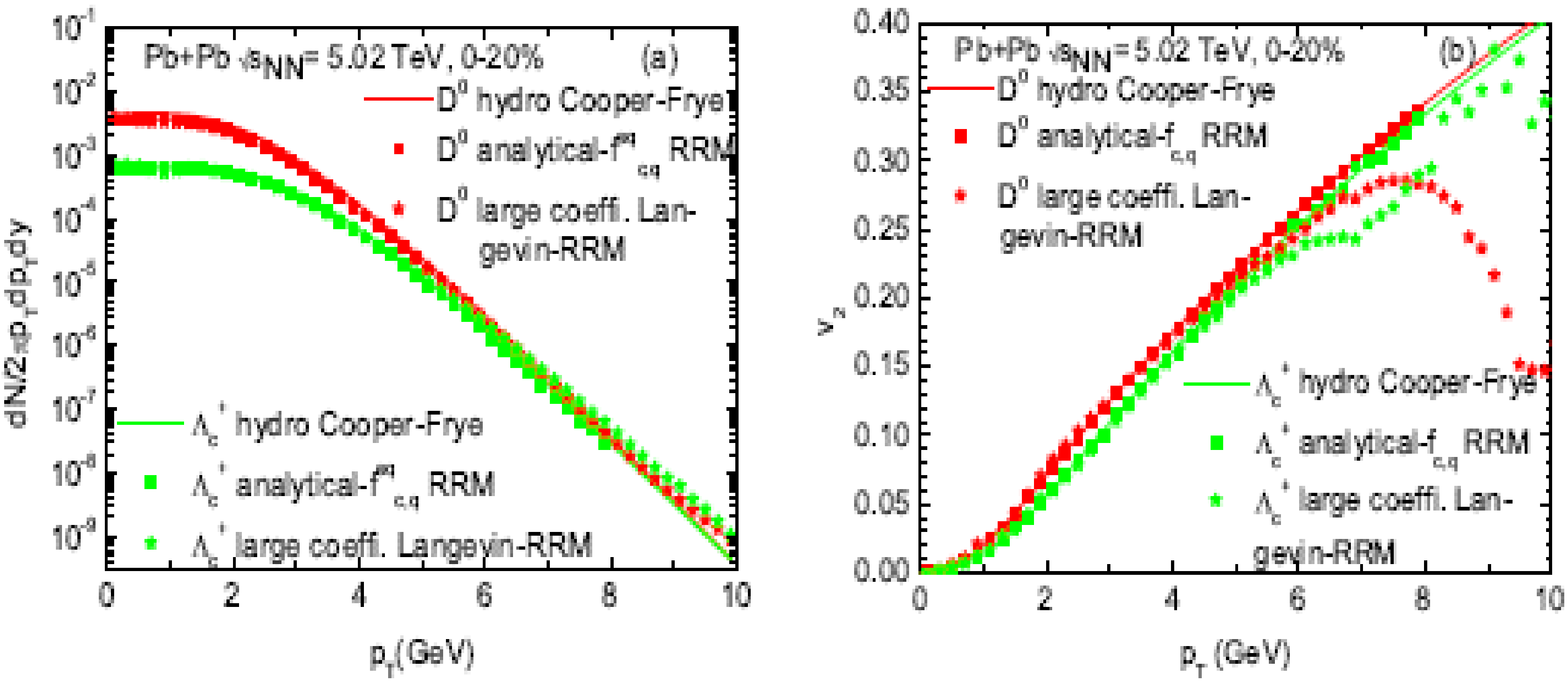
- SMCs usually neglected in ICMs: uniformly distributed independent of p_T

$$f_{c,q}(\vec{x},\vec{p}) = (2\pi)^3 \frac{dN_{c,q}}{d^3\vec{x}d^3\vec{p}} = \frac{(2\pi)^3}{VE_{(\vec{p})}} \frac{dN_{c,q}}{p_T dp_T d\phi_q dy}$$

RRM equilibrium mapping

- Event-by-event Langevin-RRM simulation with very large trans. coeffi. & with SMCs properly incorporated

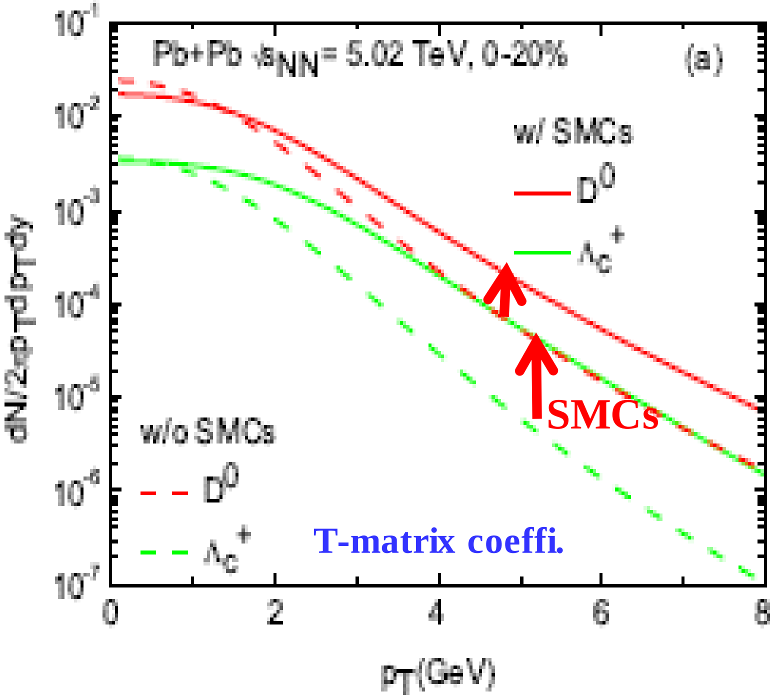
  ➔ kinetic & chemical equil. mapping

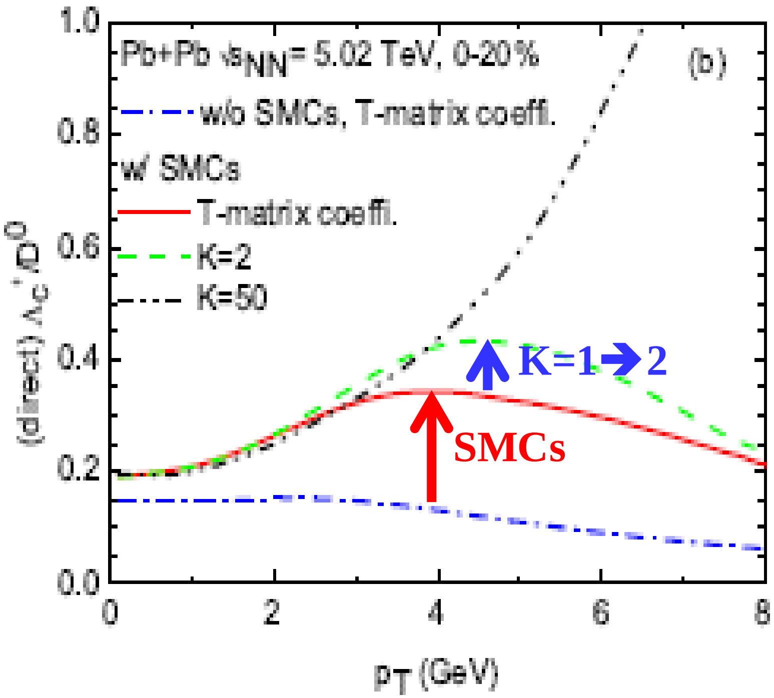


➔ Observables come out as RRM predictions with realistic T-matrix coeffi.

Direct D^0 & Λ_c^+ production via RRM

➢ Including SMCs makes spectra harder & enhances the Λ_c^+/D^0

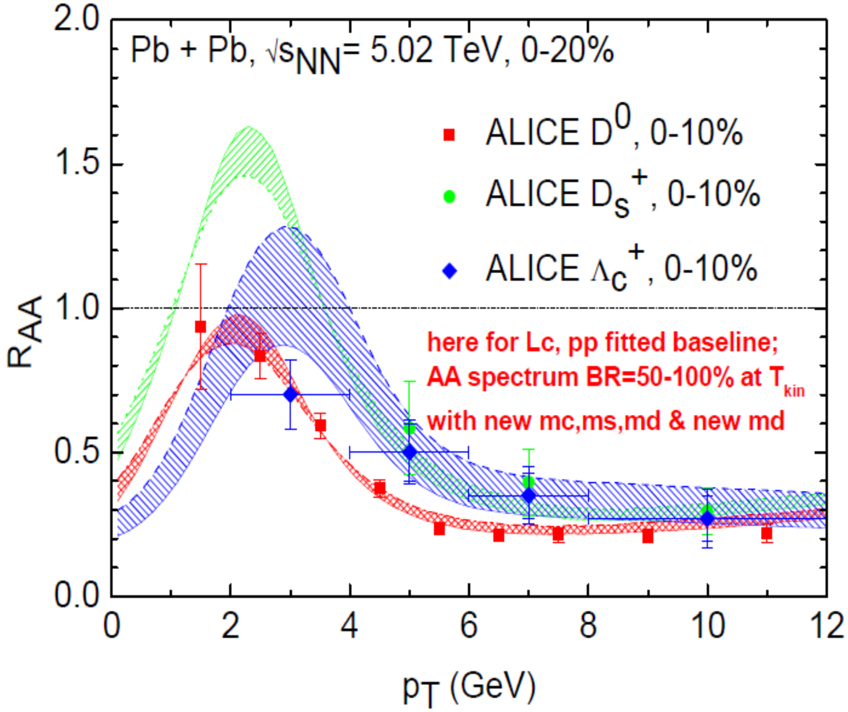


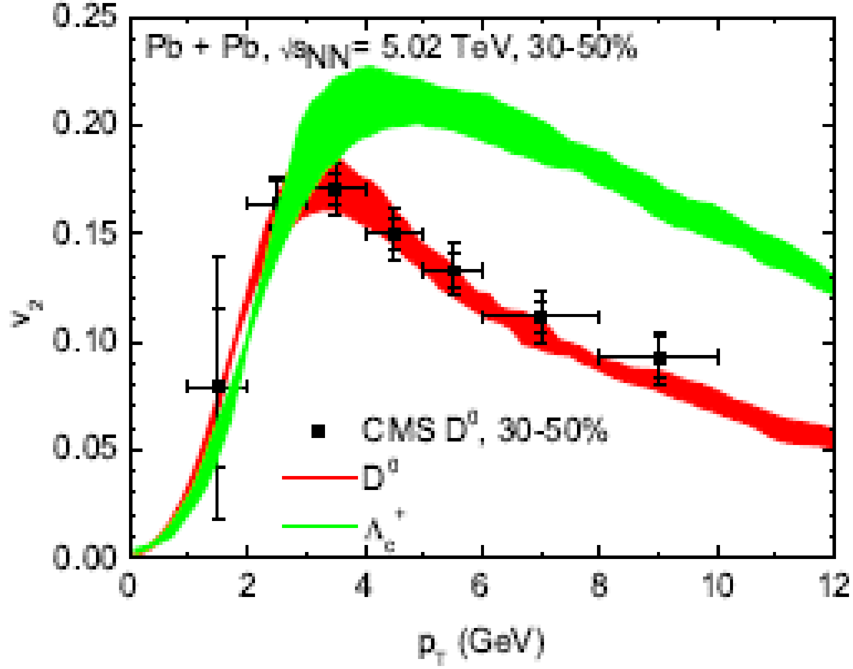


- Fast-moving c-quarks [p_T~ 3-4 GeV] moving to outer part of fireball find higher-density of harder [p_T~ 0.6-0.9 GeV] light quarks for recombination
- An effect entering squared for the recombination production of Λ_c^+ ➔ larger enhancement for Λ_c^+ ➔ Λ_c^+/D^0 ratio enhanced!

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

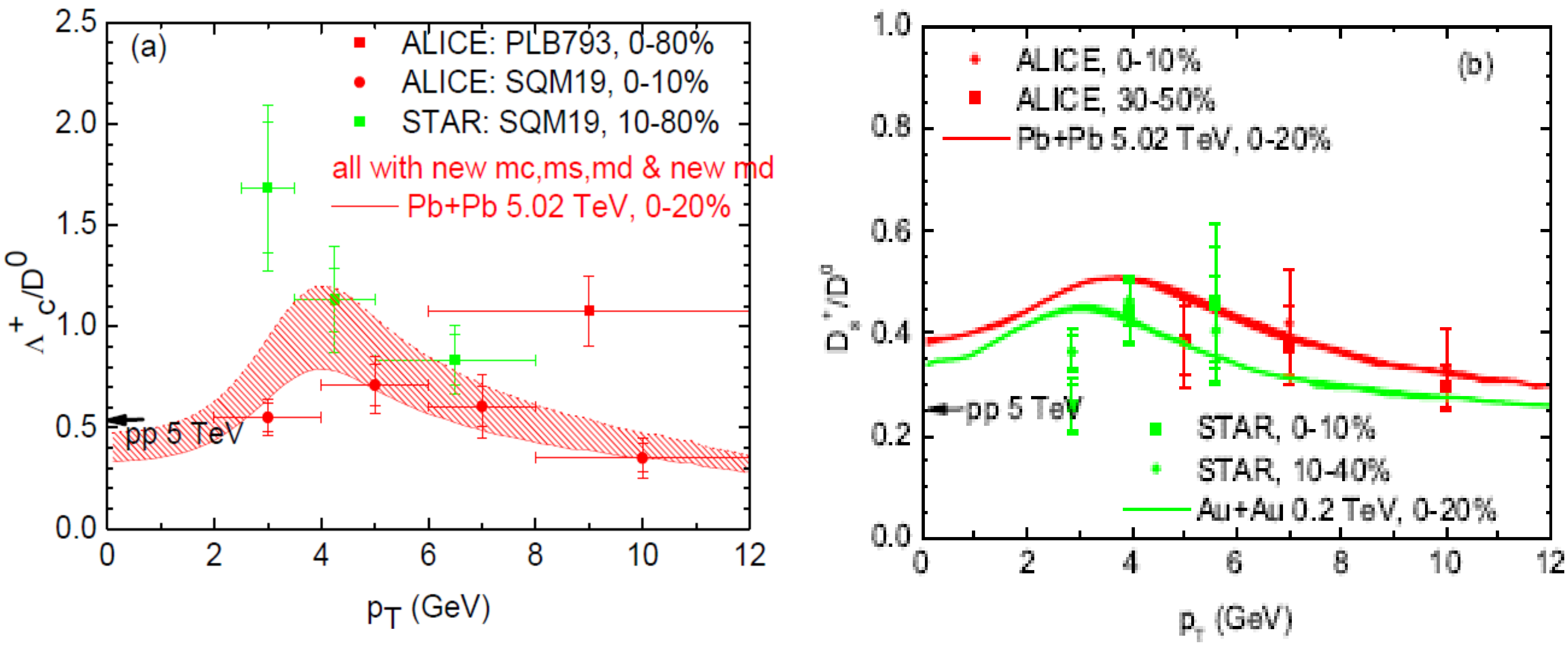
➢ Final D^0, D_s^+ & Λ_c^+, including feeddowns from all RQM baryons





- 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)
- Hadronic phase diffusion also included: seamlessly connected to hadronization (RRM+frag), increasing D-meson v_2 by ~15%

Charm-hadron ratios: Λ_c^+/D^0 & D_s^+/D^0



- Λ_c^+/D^0 : low p_T approaching RRM equil. limit = SHM pp;
  intermediate p_T enhancement from RRM with SMCs;
  high p_T fragmentation tending to pp value

- D_s^+/D^0 enhancement: recombination of charm in a strangeness-equilibrated QGP