Quark-Gluon Plasma Characterisation with Heavy Flavour Probes (HYBRID)

Heavy Quark Statistical Hadronization in High-energy pp Collisions

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High-energy pp: Charm Statistical Hadronization

- Basic idea: charm statistical coalescence hadronization likely in the (light)quark-rich environment

  ➔ relative chemical equilibrium (according to statistical weights) achieved between different charm-hadron species, with charm-baryon spectrum augmented by RQM/lattice

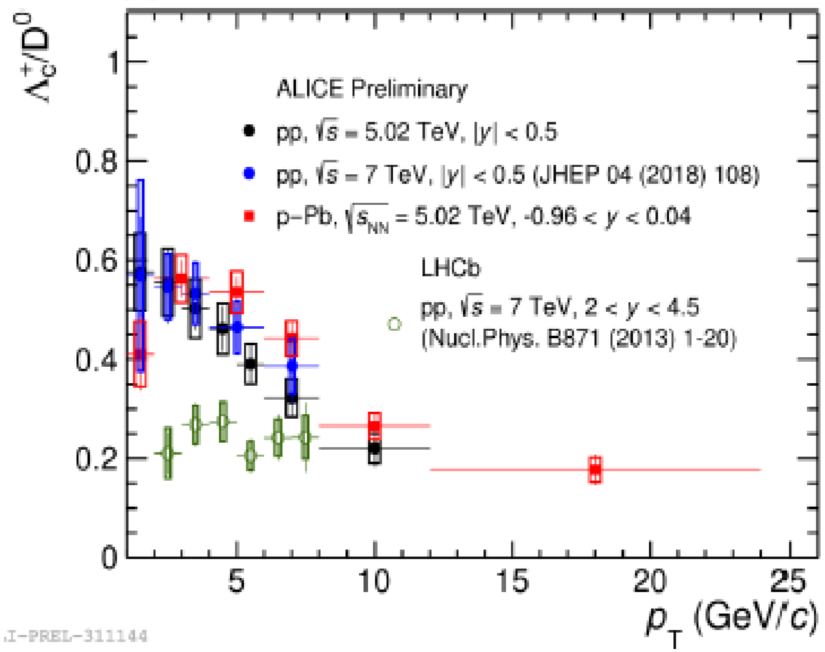
- Implementations:
  - Grand-canonical-ensemble SHM: mini.bias pp, quantum charges conserved on average
  - Canonical-ensemble SHM: low-multiplicity pp, quantum charges conserved strictly
  - Generalization to the bottom-hadron sector: preliminary results

Part I

Λ_c^+/D^0 in mini.bias pp collisions: grand-canonical SHM

M. He & R. Rapp, PLB795(2019)117-121

Large Λ_c^+/D^0 in pp collisions



- Conventional fragmentation models consistent with e^+e^-: Λ_c^+/D^0 ~0.1-0.15 Lisovyi'16, Maciula'18, Kniehl'20

- SHM with PDG only charm-hadrons (in particular baryons) Λ_c^+/D^0 ~0.22 A. Andronic + P.B.-M.

- PYTHIA8: color-reconnection ➔ enhancing baryon production

Augmented (grand-canonical) 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

- Grand-canonical SHM density T_H=170 MeV $n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2(\frac{m_i}{T_H})$

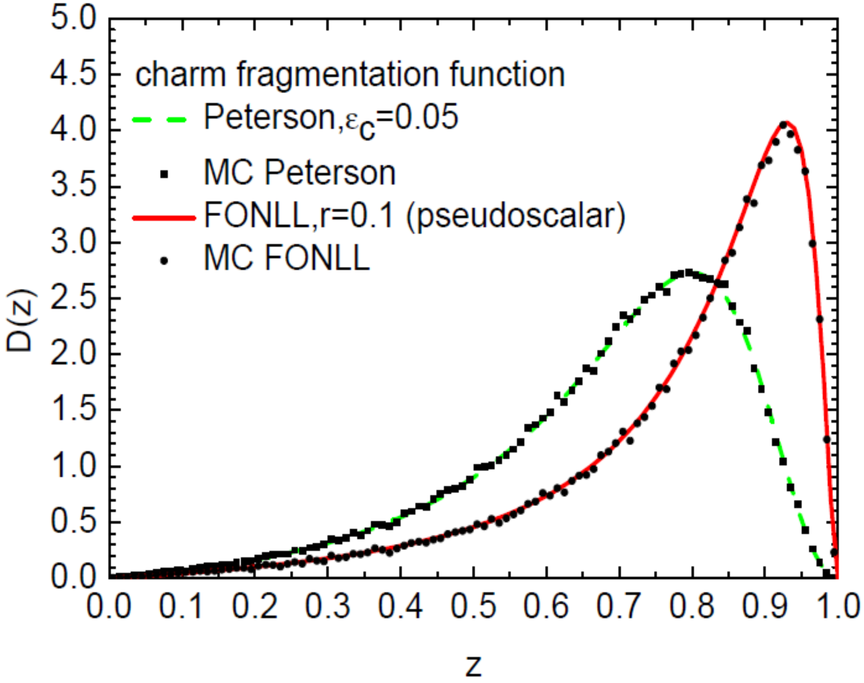
n_i $(\cdot 10^{-4}\ \mathrm{fm}^{-3})$	D^0	D^+	D^{*+}	D_s^+	Λ_c^+	$\Xi_c^{+,0}$	Ω_c^0
PDG(170)	1.161	0.5098	0.5010	0.3165	0.3310	0.0874	0.0064
RQM(170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144

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

- Here, 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 & charm fugacity γ_c=1

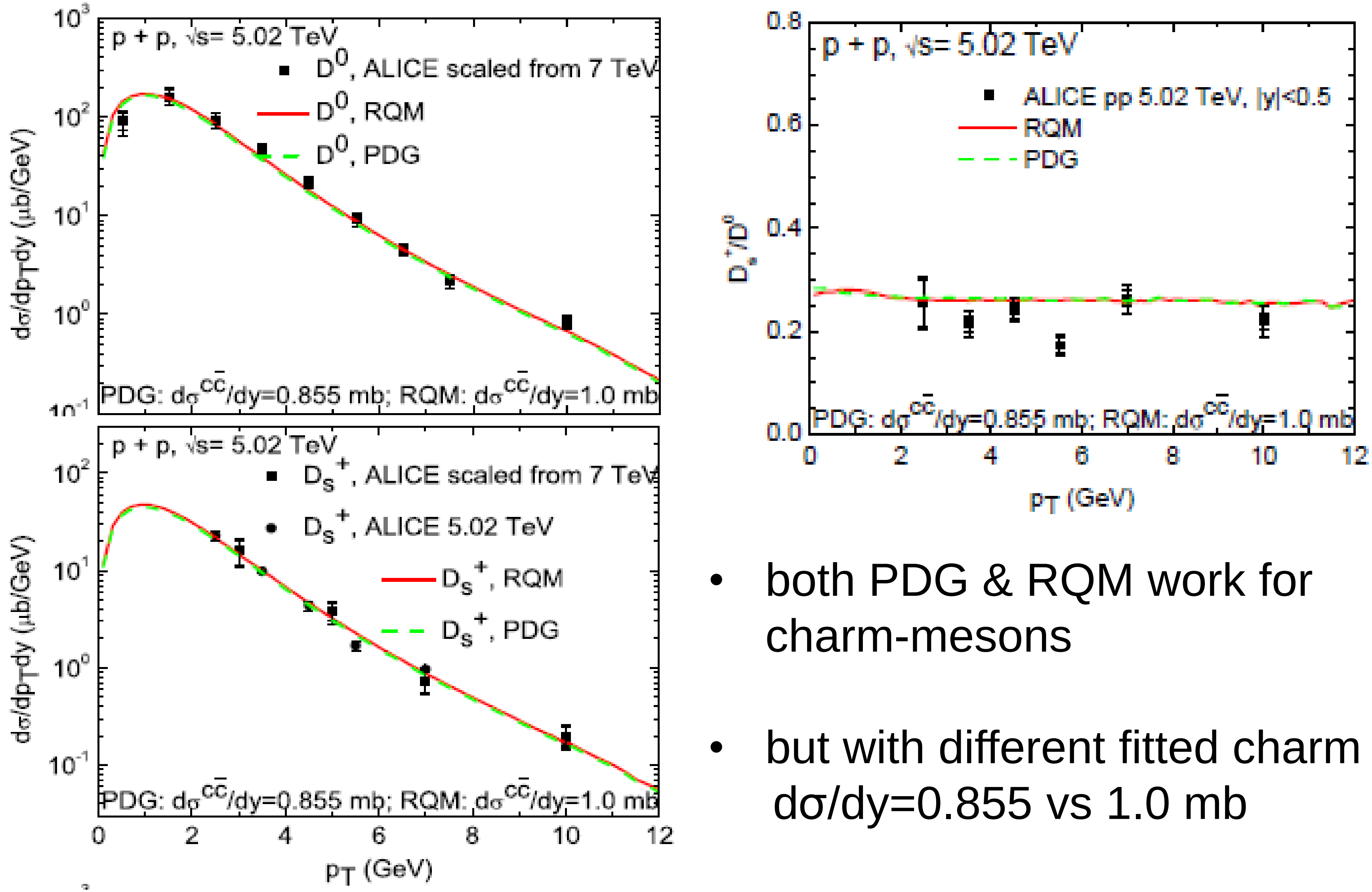
Fragmentation & decay simulations

- FONLL fragmentation of charm quarks into all kinds of charm-hadrons: relative weight <-->SHM thermal densities



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

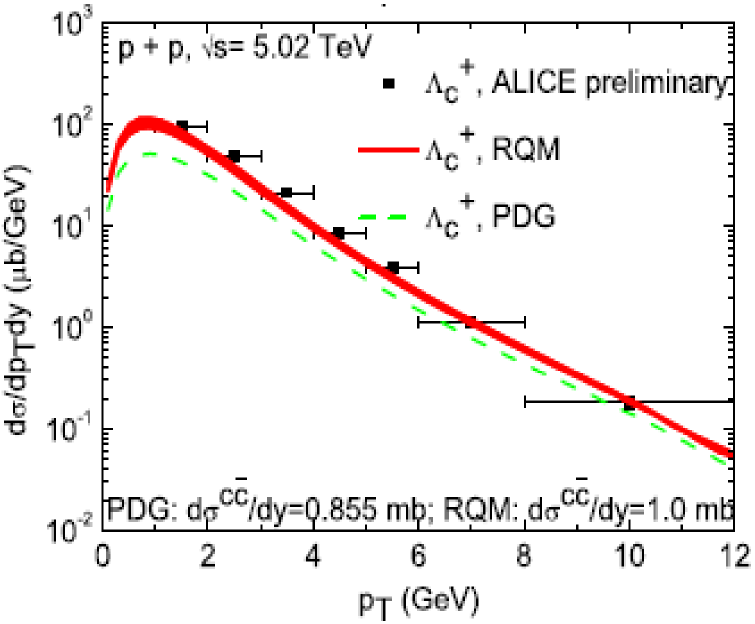
Results: charm-mesons



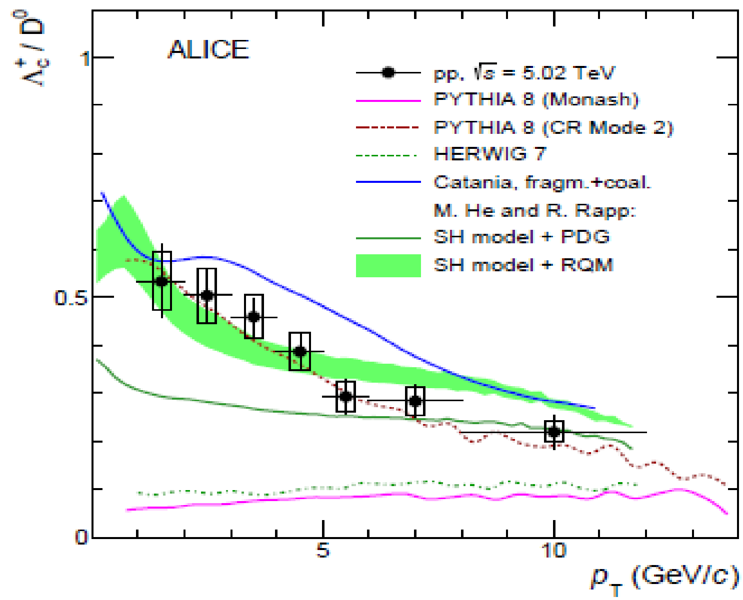
- both PDG & RQM work for charm-mesons

- but with different fitted charm $d\sigma/dy$=0.855 vs 1.0 mb

Results: charm-baryons



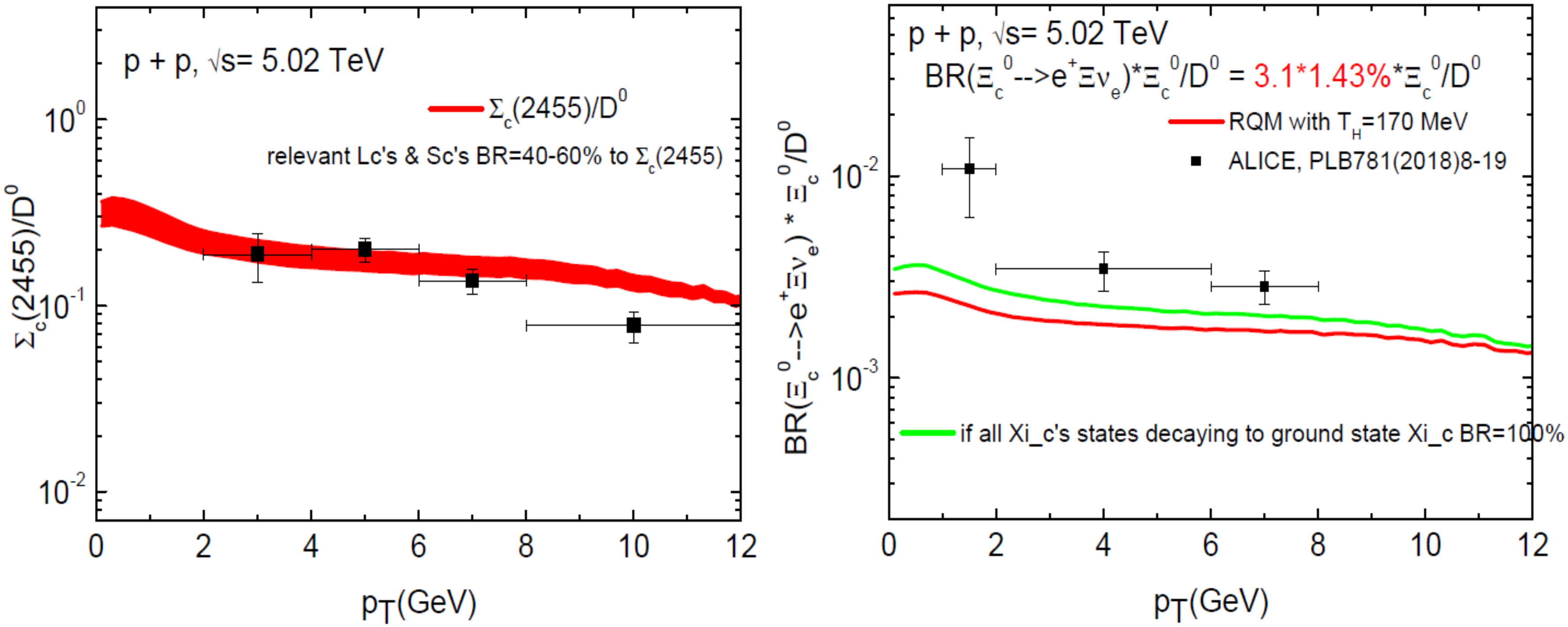
ALICE: 2011.06078



- 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: charm-baryons (cont.)



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

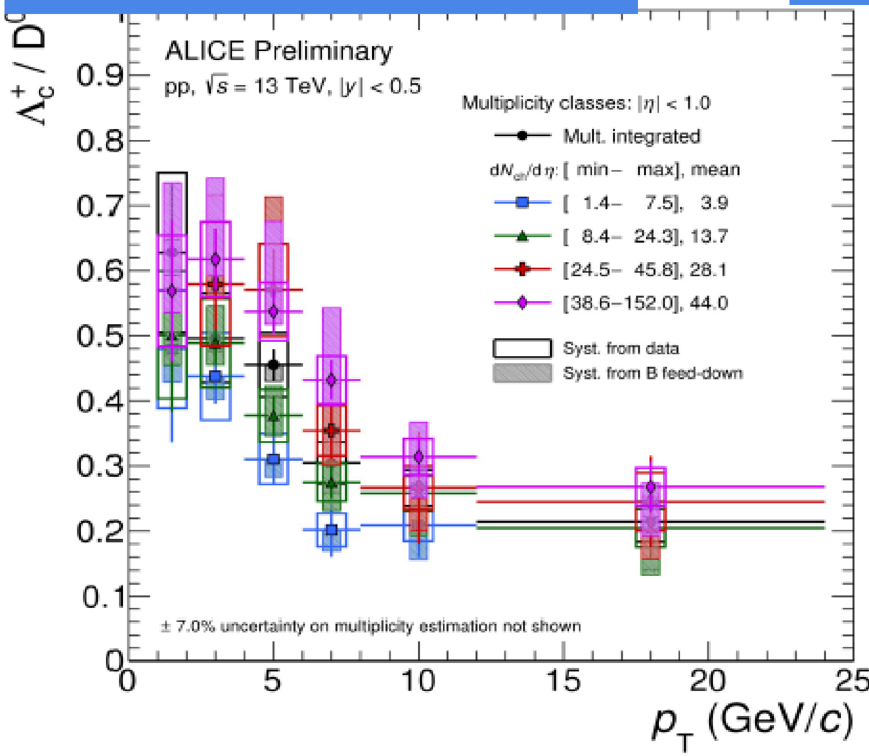
Part II

System size dependence of Λ_c^+/D^0 in pp collisions: canonical SHM

Y. Chen & M. He, PLB815 (2021)136144

Λ_c^+/D^0 : $dN_{ch}/d\eta$ dependence

Λ_c^+/D^0 vs multiplicity (pp) **NEW**



- Significant enhancement with increasing charged-particle multiplicity
- Might be straightforwardly consistent with statistical coalescence: Λ_C^+~cqq, D^0~cq ➔ Λ_C^+/D^0 ~ q ~ $dn_{ch}/d\eta$

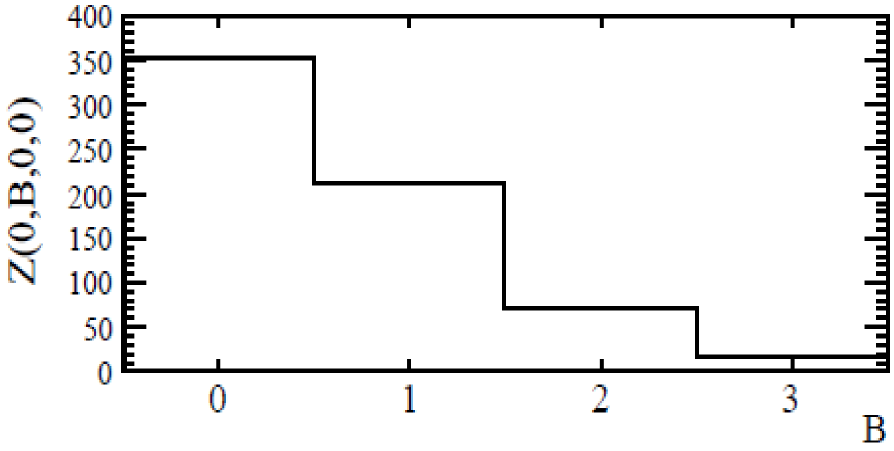
Canonical-ensemble SHM

- Canonical partition function conserving charge $\vec{Q} = (Q, B, S, C)$

$$Z(\vec{Q}) = \frac{1}{(2\pi)^4} \int_0^{2\pi} d^4\phi e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j]$$

where $z_j = (2J_j + 1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$

- Pair creation➔ energy-expensive: once a baryon created, simultaneous creation of an antibaryon is required to fulfill baryon-number conservation



- Hadron mean number

$$\langle N_j \rangle^{CE} = \langle N_j \rangle^{GCE} \frac{Z(\vec{Q} - \vec{q}_j)}{Z(\vec{Q})}$$

chemical factor characterizing canonical suppression for charged hadron with $\vec{q}_j \neq 0$

Chemical factors: canonical suppression

CF	V=10 fm^3	20	50	100	200
D^0	0.025877	0.066239	0.190294	0.373107	0.627886
D^+	0.025439	0.065891	0.190002	0.372841	0.627669
D_s^+	0.015805	0.053178	0.178586	0.362376	0.619125
Λ_c^+	0.016956	0.055485	0.182039	0.365923	0.622147
Ξ_c^{+0}	0.009884	0.042956	0.167943	0.352535	0.611073
Ω_c	0.003495	0.022604	0.130312	0.312514	0.576383
Λ_c^+/D^0	0.655254	0.837649	0.956620	0.980745	0.990860
D_s^+/D^0	0.610774	0.802820	0.938474	0.971239	0.986047

pp mid-rapidity neutral (Q,B,S,C)=(0,0,0,0)

$T_H = 170$ MeV, $\gamma_s = 0.6$, $\gamma_c = 15$

- Column at given V: CF progressively smaller for hadrons containing more charges (S, B, BS, BSS)
- Row: CF increases with volume, tending to the common residual canonical charm supp. (canonical B/S supp. diminishing)
- Relative CF: Λ_C^+/D^0 & D_s/D^0 increases with volume toward unity

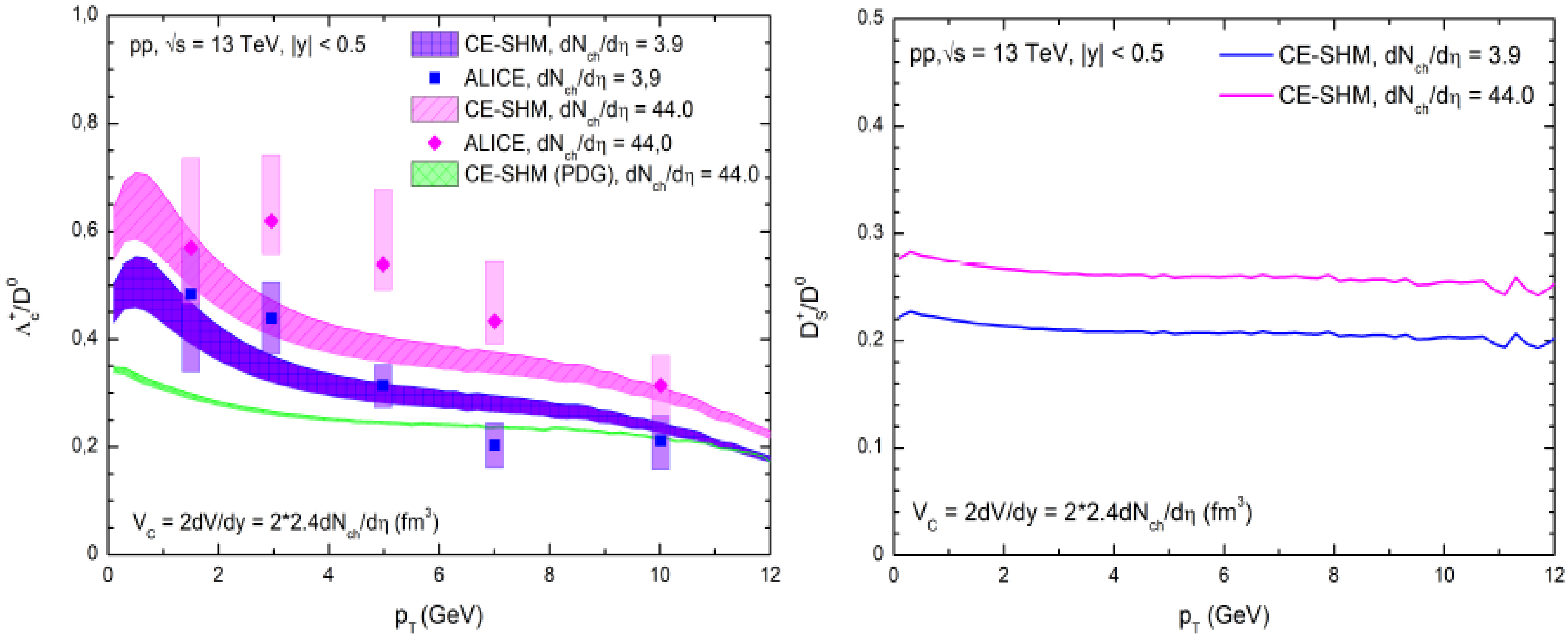
CE-SHM densities with feeddowns

n_j $(\cdot 10^{-4}\text{fm}^{-3})$	V=10 fm^3	20	50	100	200	GCE
D^0	0.445553	1.148287	3.310131	6.495330	10.934662	17.420949
D^+	0.194705	0.503847	1.453016	2.851351	4.800262	7.647869
D_s^+	0.075040	0.252484	0.847910	1.720531	2.939551	4.747914
Λ_c^+(BR50%)	0.126963	0.439135	1.497132	3.045487	5.207572	8.415360
Λ_c^+(BR100%)	0.149573	0.519555	1.776775	3.617118	6.187127	10.001702
Ξ_c^{+0}	0.016539	0.071955	0.281624	0.591389	1.025276	1.678110
Ω_c	0.000756	0.004889	0.028184	0.067592	0.124662	0.216283
Λ_c^+/D^0(BR50%)	0.284956	0.382426	0.452288	0.468873	0.476244	0.483060
Λ_c^+/D^0(BR100%)	0.335702	0.452461	0.536769	0.556880	0.565827	0.574119
D_s^+/D^0	0.168420	0.219879	0.256156	0.264887	0.268829	0.272540

pp mid-rapidity neutral (Q,B,S,C)=(0,0,0,0) $T_H = 170\,\text{MeV}$, $\gamma_s = 0.6$, $\gamma_c = 15$

- Row: density of each charm-hadron increases with volume
- Λ_C^+/D^0 & D_s/D^0: marked system-size dependence: a ~40% reduction from V=200 (~GCE-SHM) to V=10 fm^3

Fragmentation & decay: p_T-dependent ratios



- Splitting of Λ_C^+/D^0 between $dN_{ch}/d\eta$=3.9 vs 44.0 roughly reproduced, due to additional canonical baryon supp. on charm-baryons, which becomes stronger toward smaller system-size

- Similar splitting of D_s^+/D^0 by additional canonical strangeness supp.

Part III

Λ_b^0/B^- in mini.bias pp collisions: grand-canonical SHM

preliminary results

Augmented (grand-canonical) SHM

- PDG: 5 B, 4 B_s, 3 Λ_b, 2 Σ_b, 4 Ξ_b, 1 Ω_b
  RQM: 25 B, 20 B_s, 30 Λ_b, 46 Σ_b, 75 Ξ_b, 42 Ω_b

Ebert et al., PRD 84 (2011) 014025

- Grand-canonical SHM density T_H=170 MeV

$$n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2\left(\frac{m_i}{T_H}\right)$$

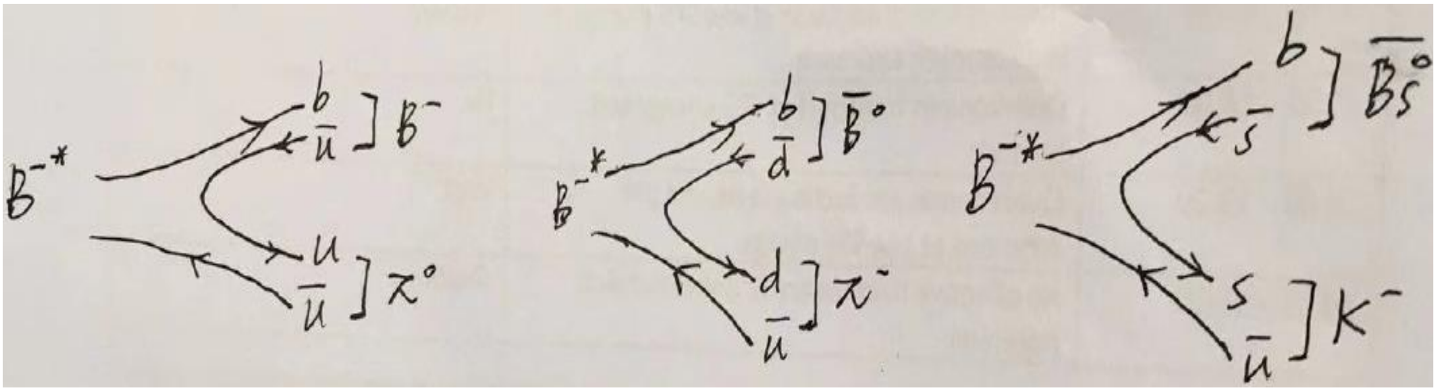
n_i $(\cdot 10^{-12}\ \mathrm{fm}^{-3})$	B^-	$\bar{B}^0$	$\bar{B}_s^0$	Λ_b^0	Ξ_b^{0-}	Ω_b^-
PDG(170MeV)	1.0094	1.0089	0.29308	0.31590	0.10097	0.0023406
RQM(170MeV)	1.2045	1.2041	0.32513	0.61702	0.19548	0.0063204

r_i	$\bar{B}^0/B^-$	$\bar{B}_s^0/B^-$	Λ_b^0/B^-	Ξ_b^{0-}/B^-
PDG(170MeV)	0.9995	0.2903	0.3129	0.10003
RQM(170MeV)	0.9996	0.2699	0.5123	0.1623

- Strangeness supp. γ_s=0.6 & bottom fugacity γ_b=1
- Feeddowns to ground states: BR's systematics ---

Strong decay systematics: BR's estimation

- Counting all possible diagrams once above the threshold

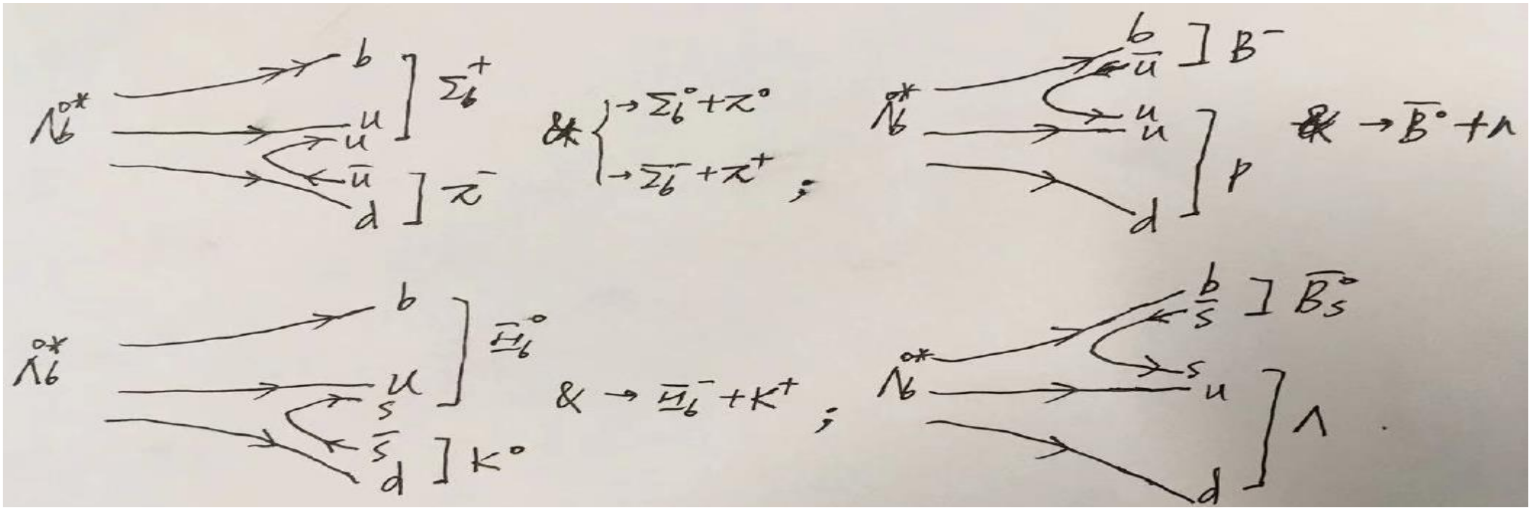


- Probability of producing a q-qbar pair ∝ $\exp(-2m/T_H)$
  ➔ $\exp(-2m_q/T_H) : \exp(-2m_s/T_H) = 1 : 1/3$ [m_q~8, m_s~100 MeV]
  ➔ diagrams involving s-sbar counted as 1/3

- E.g. $BR(B^{-*} \rightarrow B^- + \pi^0) = 1/(1+1+1/3) = 43\%$
  $BR(B^{-*} \rightarrow B^0 bar + \pi^-) = 1/(1+1+1/3) = 43\%$
  $BR(B^{-*} \rightarrow B^0_s bar + \pi^0) = 1/3/(1+1+1/3) = 14\%$

Strong decay systematics: BR's estimation

- Counting all possible diagrams once above the mass threshold



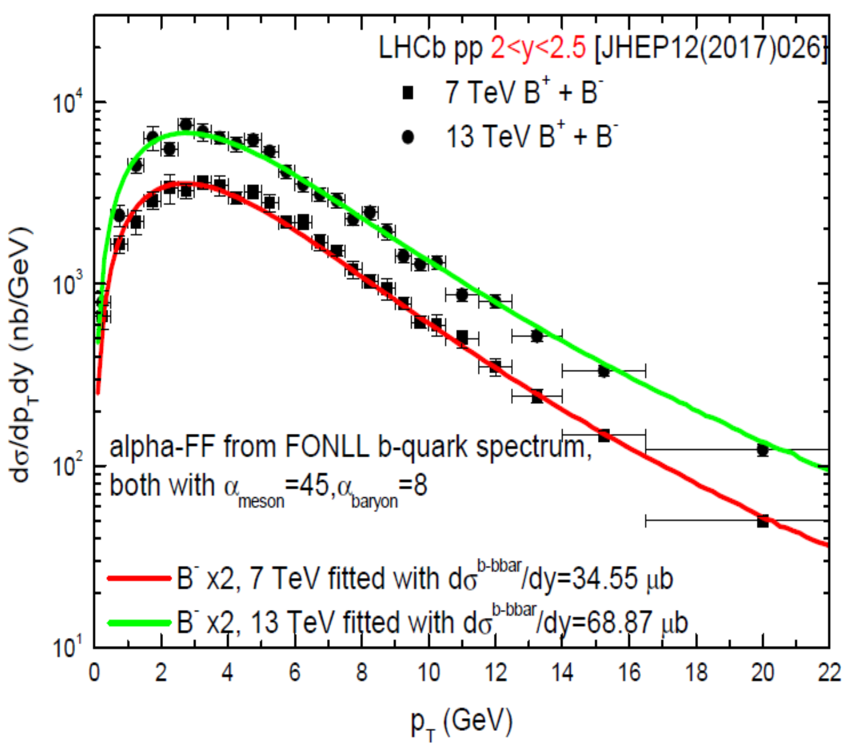
- E.g. BR($\Lambda_b^{0*} \rightarrow \Sigma_b + \pi^- \rightarrow \Lambda_b^0 + 2\pi$)=3/(3+2+2*1/3+1/3)=54%
  BR($\Lambda_b^{0*} \rightarrow B^- + p$) =1/(3+2+1/3+2*1/3)=16%
  BR($\Lambda_b^{0*} \rightarrow \Xi_b + K$) =2/3/(3+2+1/3+2*1/3)=11%
  BR($\Lambda_b^{0*} \rightarrow B^0_s$bar + Λ) =1/3/(3+2+1/3+2*1/3)=6%

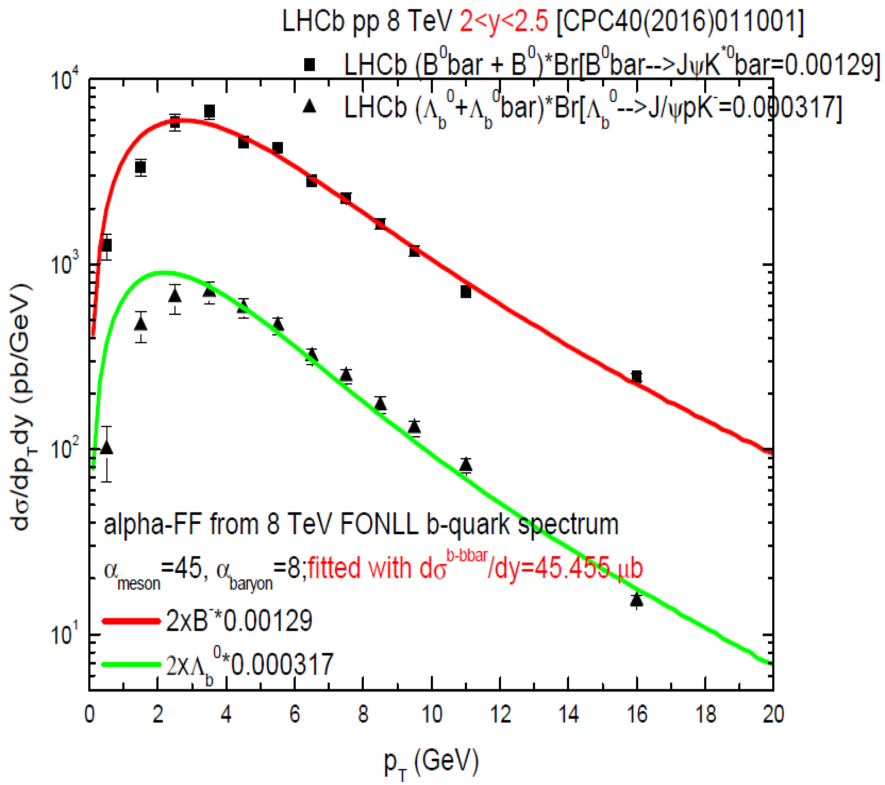
- Results comparable to (limited) results computed in $^3P_0$ model

Sun et al., PRD 89(2014)054026; Mu et al., CPC 38(2014)113101

Fit of p_T-spectra & cross sections

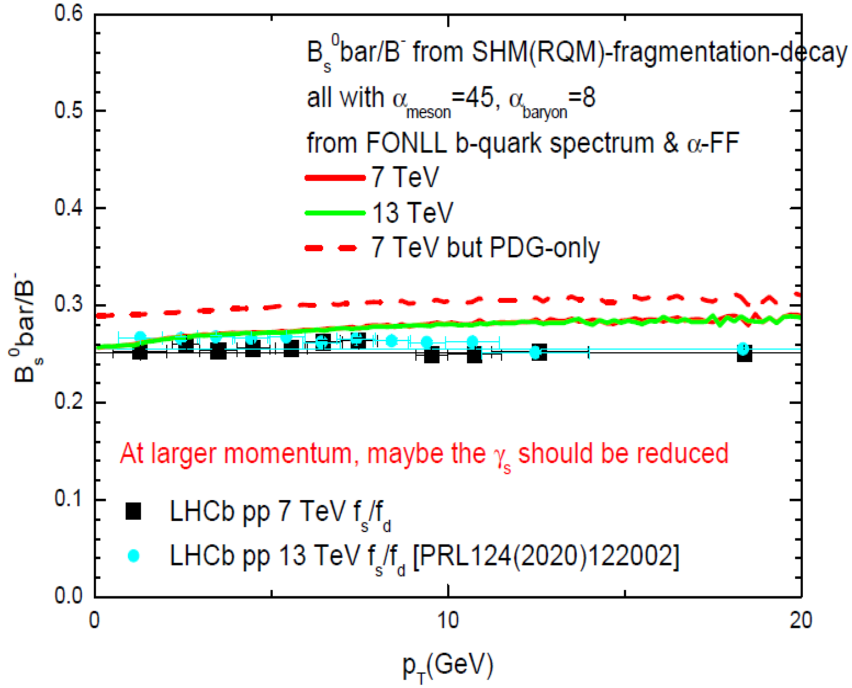
- FONLL b-quark spectrum + FF $D(z)=(\alpha+1)(\alpha+2)x^{\alpha}(1-x)$ into all states + decay simulations ➔ ground states p_T-spectra

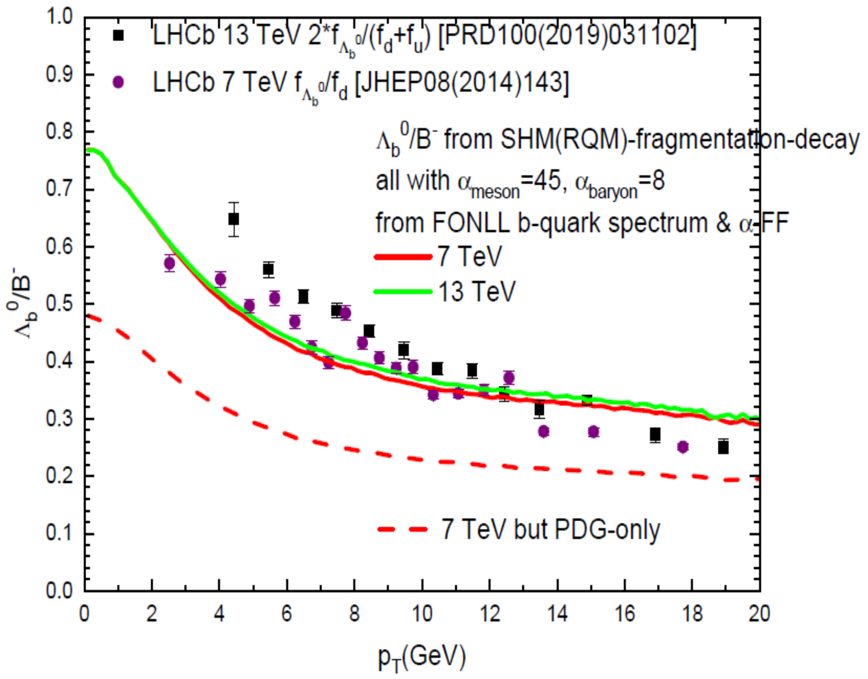




- 7 & 13 TeV data better fitted than 8 TeV (with same parameters)
- $d\sigma^{bbbar}/dy$=34.55 μb (7 TeV) & 68.87 μb (13 TeV) for 2<y<2.5

Bottom hadro-chemistry: ratios





- **B^0_sbar/B^-** & **Λ_b^0/B^-** almost unchanged from 7 to 13 TeV
- PDG-only curves far off; RQM states needed

Summary & Outlook

- High-energy pp collisions: HQs (charm & bottom) hadronization into open-HF hadrons is of statistical nature

  - "missing" HF-baryons (in particular) essential
  - p_T-dependent hadro-chemistry ratios decently described

- Baseline for study of HF production in heavy ion collisions

  - same particle spectrum to be used
  - modification of p_T-dependent hadro-chemistry