

Heavy Quark Statistical Hadronization in High-energy pp Collisions

Min He

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

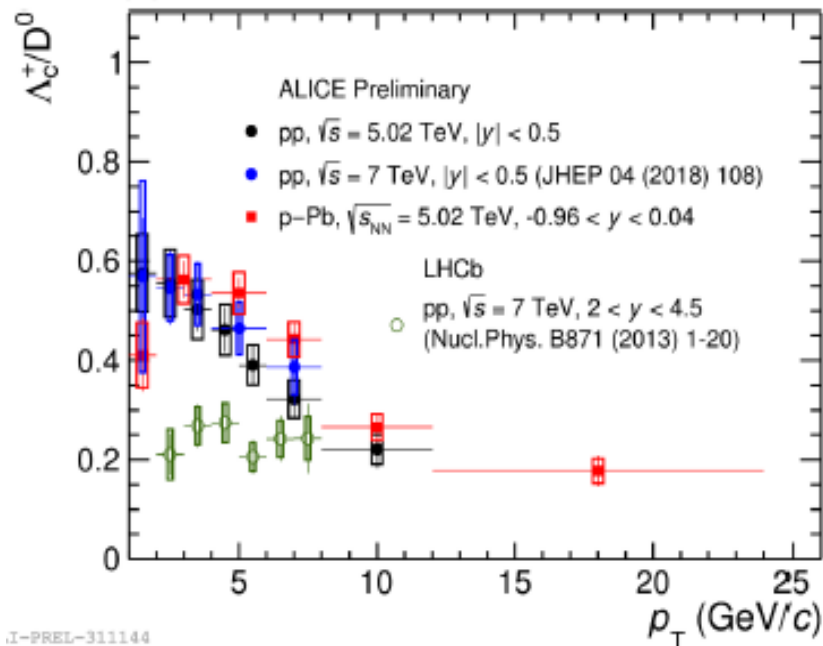
High-energy pp: Charm Statistical Hadronization

- 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

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^- :
 $\Lambda_c^+/\text{D}^0 \sim 0.1-0.15$ Lisovyi'16, Maciula'18, Kniehl'20
- SHM with PDG only charm-hadrons (in particular baryons)
 $\Lambda_c^+/\text{D}^0 \sim 0.22$ A. Andronic + P.B.-M.
- PYTHIA8: color-reconnection \rightarrow 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
$$n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2\left(\frac{m_i}{T_H}\right)$$

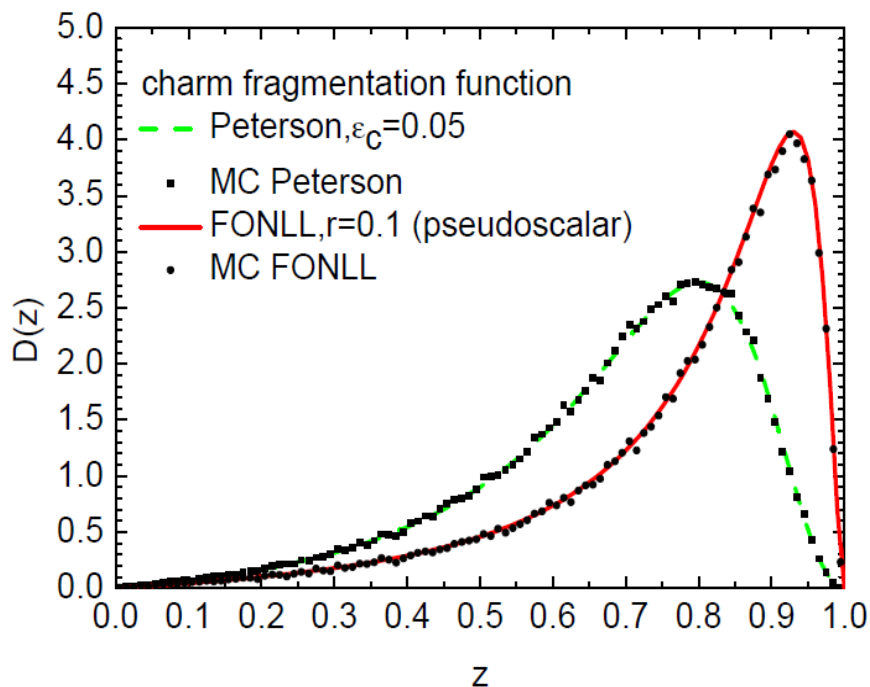
$n_i (\cdot 10^{-4} \text{ fm}^{-3})$	D^0	D^+	D^{*+}	D_s^+	Λ_c^+	$\Xi_c^{+,0}$	Ω_c^0
<u>PDG(170)</u>	1.161	0.5098	0.5010	0.3165	<u>0.3310</u>	0.0874	0.0064
<u>RQM(170)</u>	1.161	0.5098	0.5010	0.3165	<u>0.6613</u>	0.1173	0.0144

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>

- 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. $\gamma_s=0.6$ & charm fugacity $\gamma_c=1$

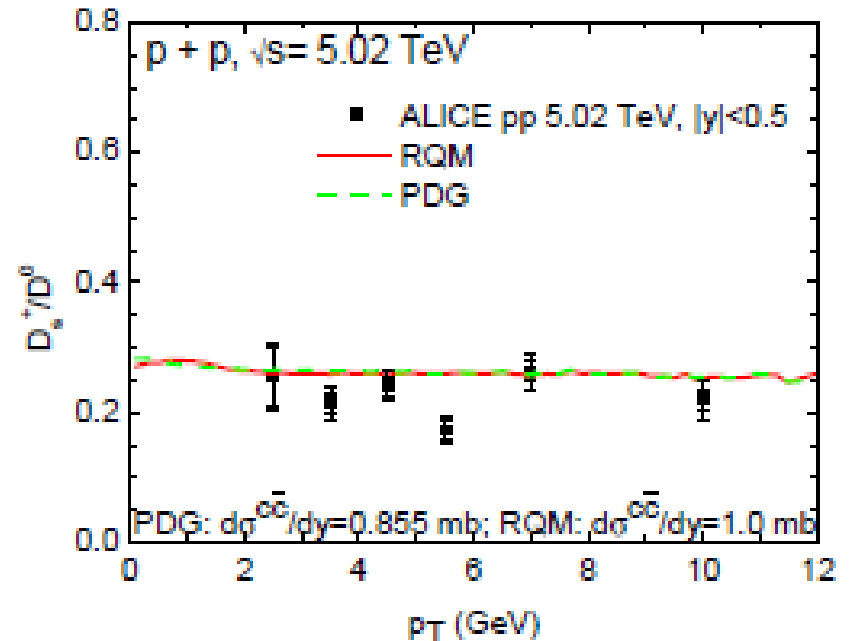
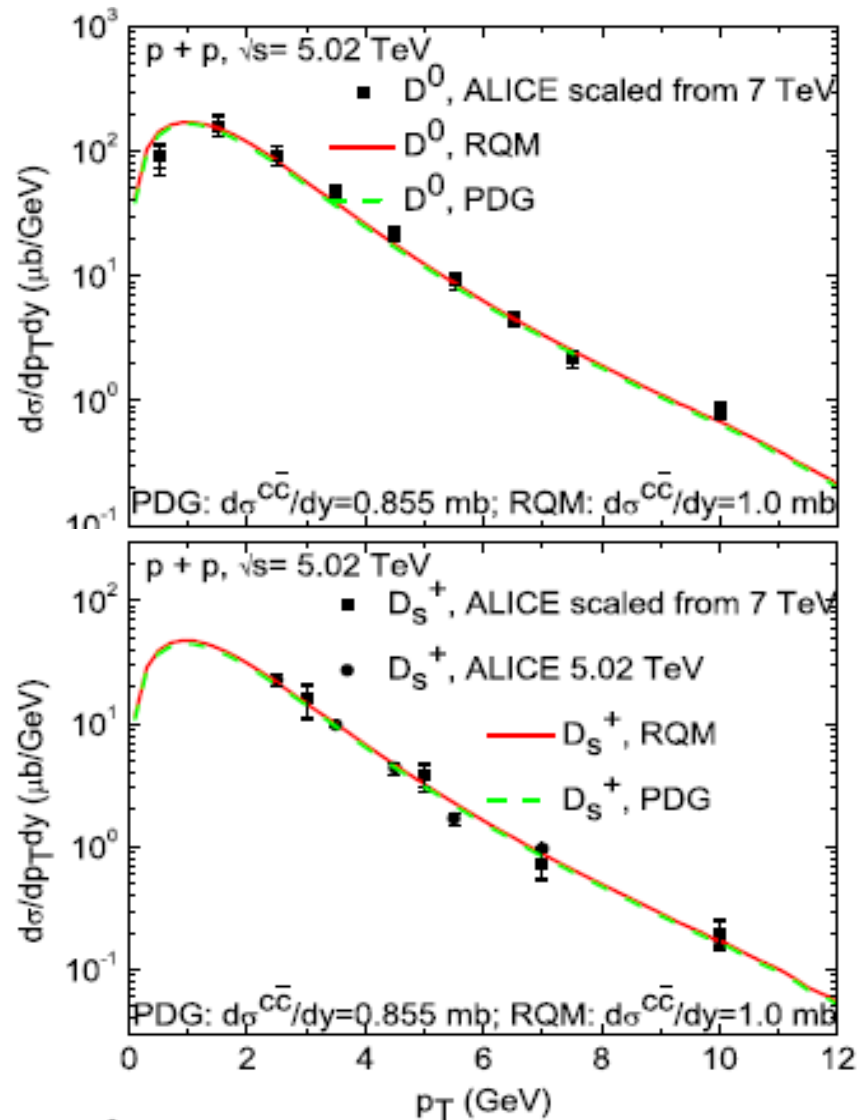
Fragmentation & decay simulations

- FONLL fragmentation of charm quarks into **all** kinds of charm-hadrons: **relative weight** \leftrightarrow SHM thermal densities



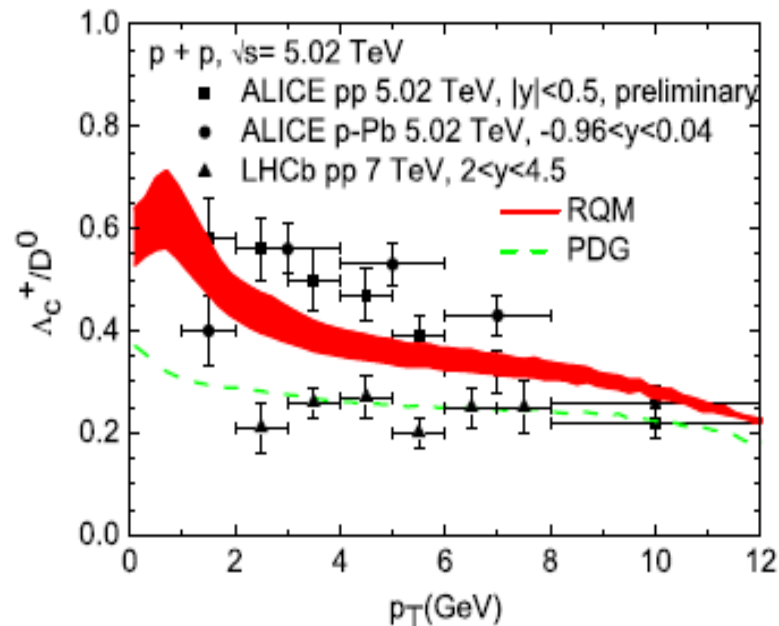
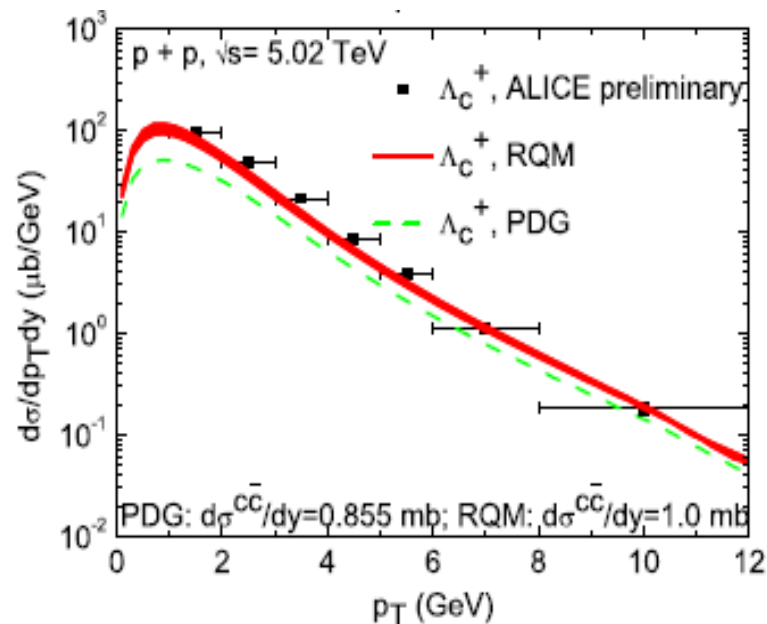
- Decay simulations of **all** excited states to ground states D^0 , D^+ , D_s^+ , Λ_C^+ , Ξ_C & Ω_C

Results: charm-mesons



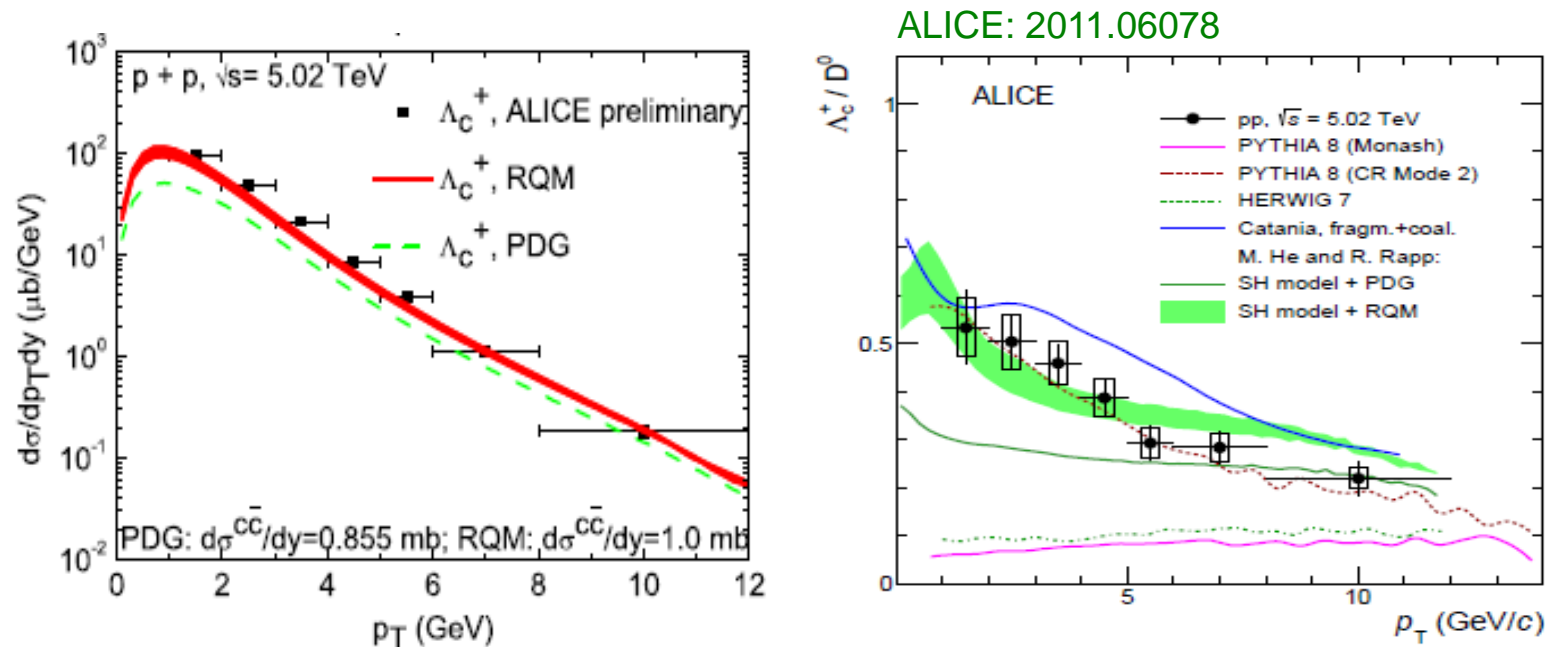
- both PDG & RQM work for charm-mesons
- but with different fitted charm $d\sigma/dy = 0.855$ vs 1.0 mb

Results: charm-baryons



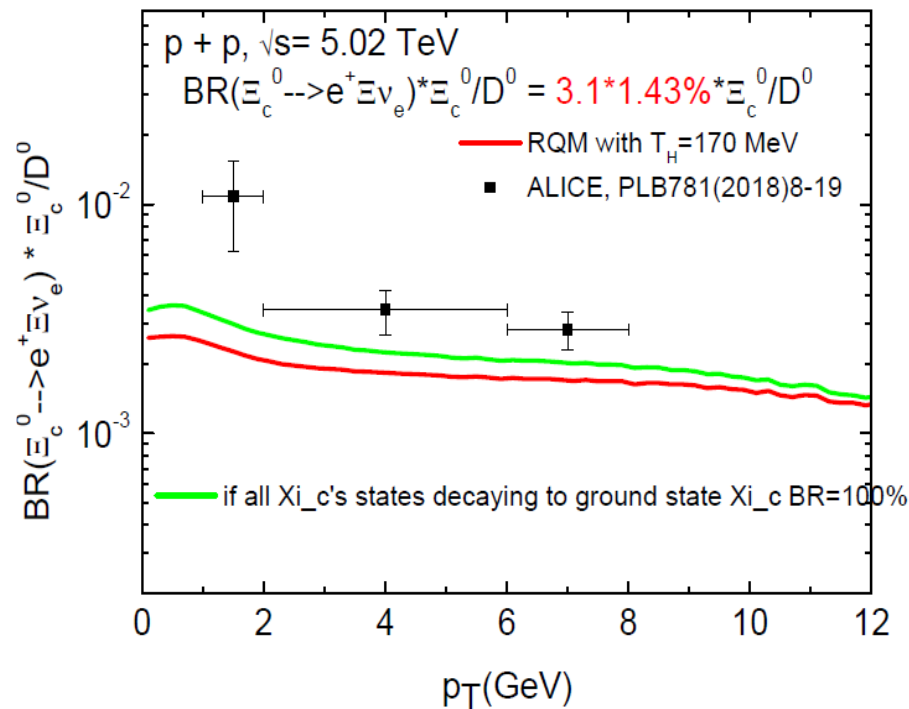
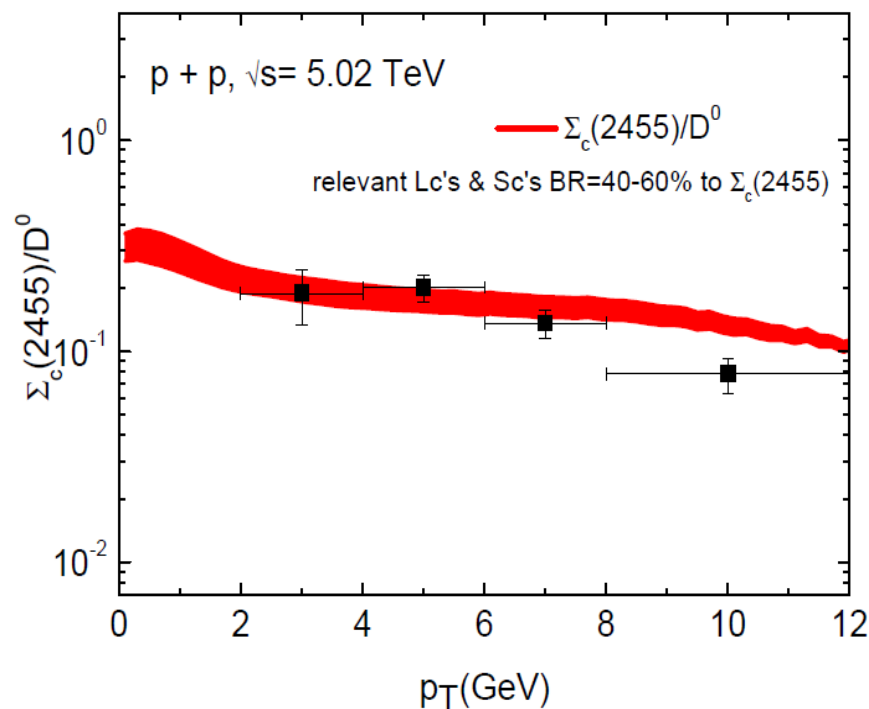
- Λ_C^+ favors RQM with $d\sigma/dy=1.0 \text{ mb}$: **low p_T enhancement** from feeddowns of RQM augmented baryons
- uncertainty band: BR=50%-100% to ground state Λ_C^+ for Λ_C 's & Σ_C 's above DN (2805 MeV) threshold

Results: charm-baryons



- 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

Results: charm-baryons (cont.)

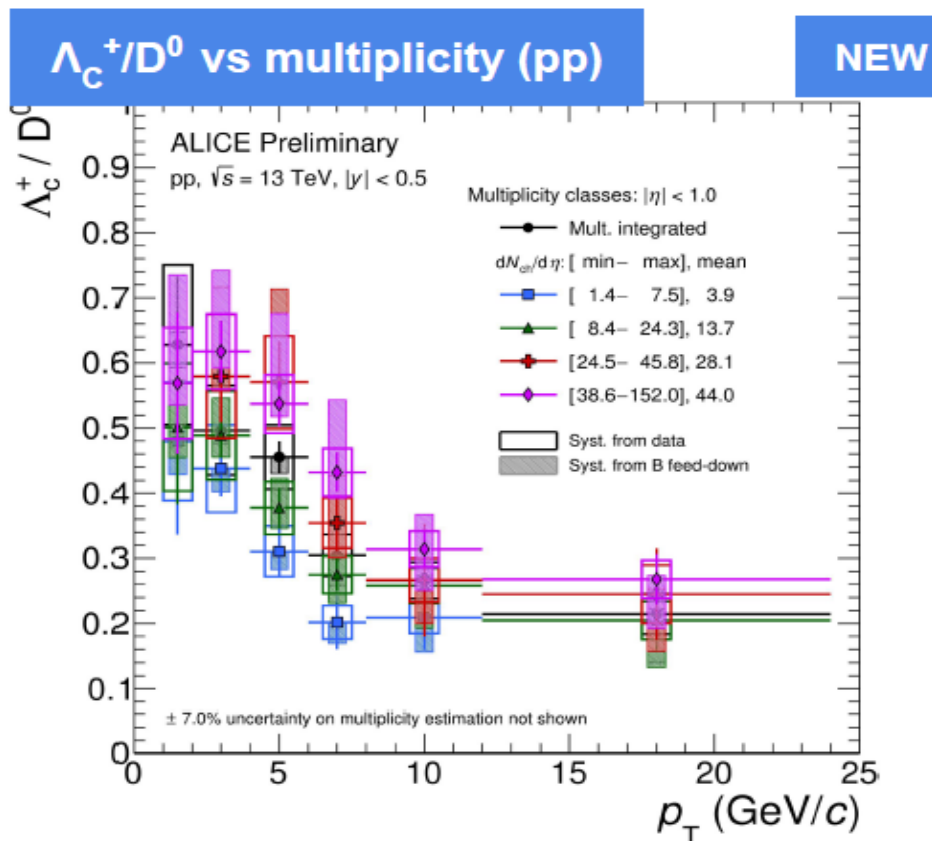


- $\Sigma_c(2455)/D^0$ can also be accounted for within uncertainties
- But Ξ_c^0/D^0 much underestimated, although already twice as large as PYTHIA8(CR) ~ 0.001

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

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

$\Lambda_c^+/\text{D}^0 : \text{d}N_{\text{ch}}/\text{d}\eta$ dependence



- Significant enhancement with increasing charged-particle multiplicity
- Might be straightforwardly consistent with statistical coalescence:
 $\Lambda_c^+ \sim cqq$, $\text{D}^0 \sim cq \Rightarrow \Lambda_c^+/\text{D}^0 \sim q \sim \text{d}n_{\text{ch}}/\text{d}\eta$

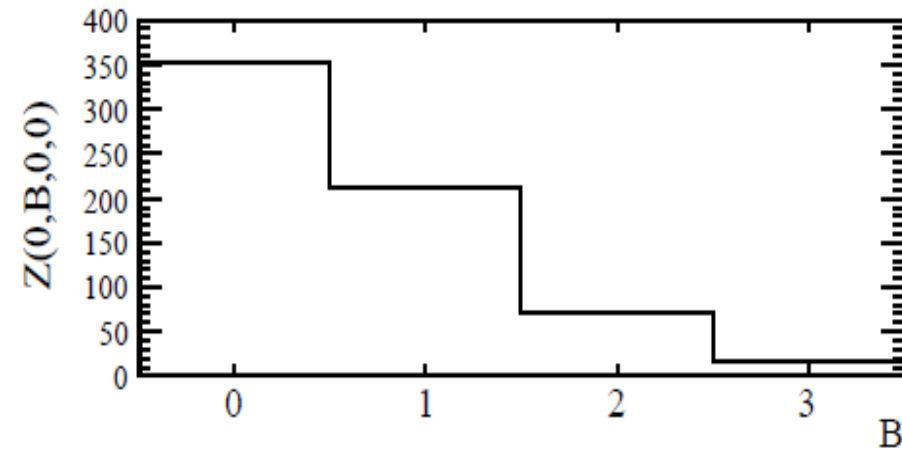
Canonical-ensemble SHM

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

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

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

- 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	$V=10 \text{ fm}^3$	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) $T_H = 170 \text{ MeV}$, $\gamma_s = 0.6$, $\gamma_c = 15$

- Column** at given V : CF progressively smaller for hadrons containing more charges (S, B, BS, BSS)
- Row**: CF increases with volume, tending to the **same** 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

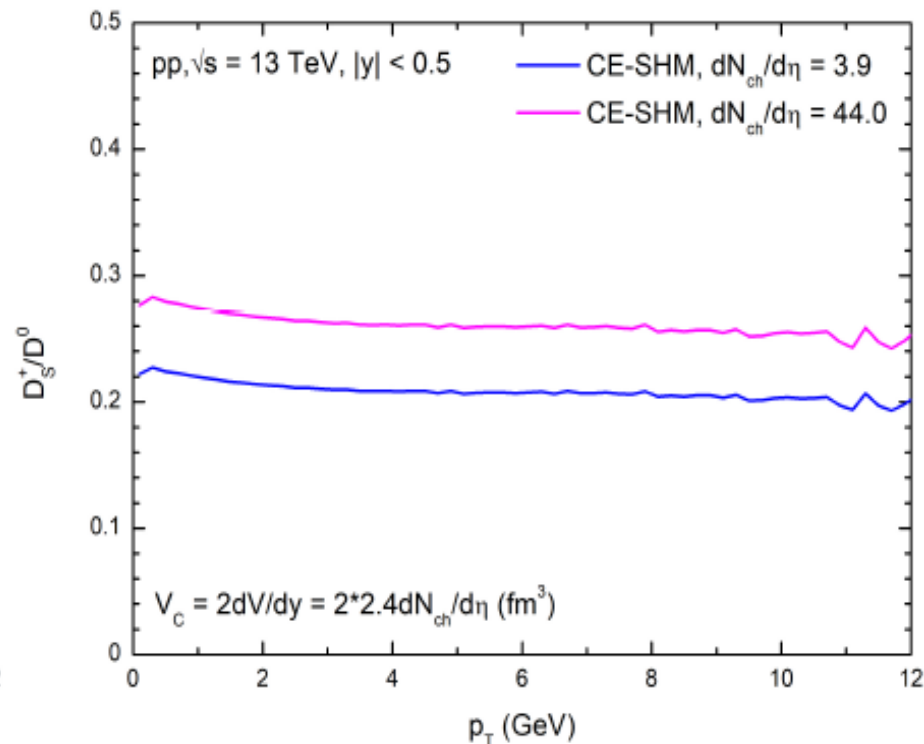
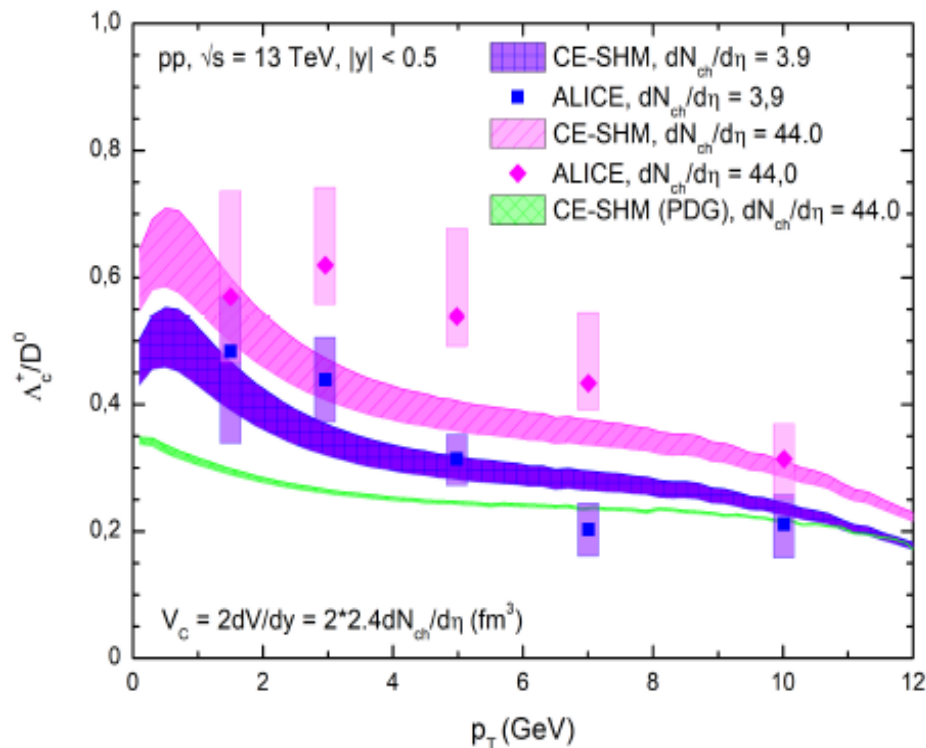
n_j ($\cdot 10^{-4} \text{fm}^{-3}$)	V=10 fm ³	20	50	100	200	GCE
D^0	0.445553	1.148287	3.310131	6.495330	10.934662	17.420949
D^+	0.194705	0.503847	1.453016	2.851351	4.800262	7.647869
D_s^+	0.075040	0.252484	0.847910	1.720531	2.939551	4.747914
Λ_c^+ (BR50%)	0.126963	0.439135	1.497132	3.045487	5.207572	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 fm³

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.

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

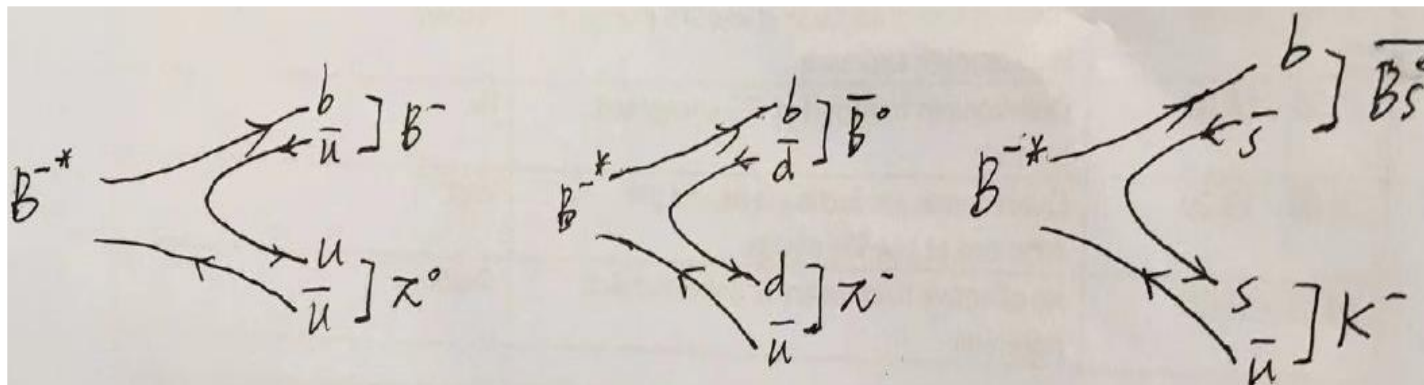
n_i ($\cdot 10^{-12} \text{ fm}^{-3}$)	B^-	\bar{B}^0	\bar{B}_s^0	Λ_b^0	Ξ_b^{0-}	Ω_b^-
PDG(170MeV)	<u>1.0094</u>	1.0089	<u>0.29308</u>	<u>0.31590</u>	<u>0.10097</u>	0.0023406
RQM(170MeV)	<u>1.2045</u>	1.2041	<u>0.32513</u>	<u>0.61702</u>	<u>0.19548</u>	0.0063204

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

- Strangeness supp. $\gamma_s=0.6$ & bottom fugacity $\gamma_b=1$
- Feeddowns to ground states: BR's systematics ---

Strong decay systematics: BR's estimation

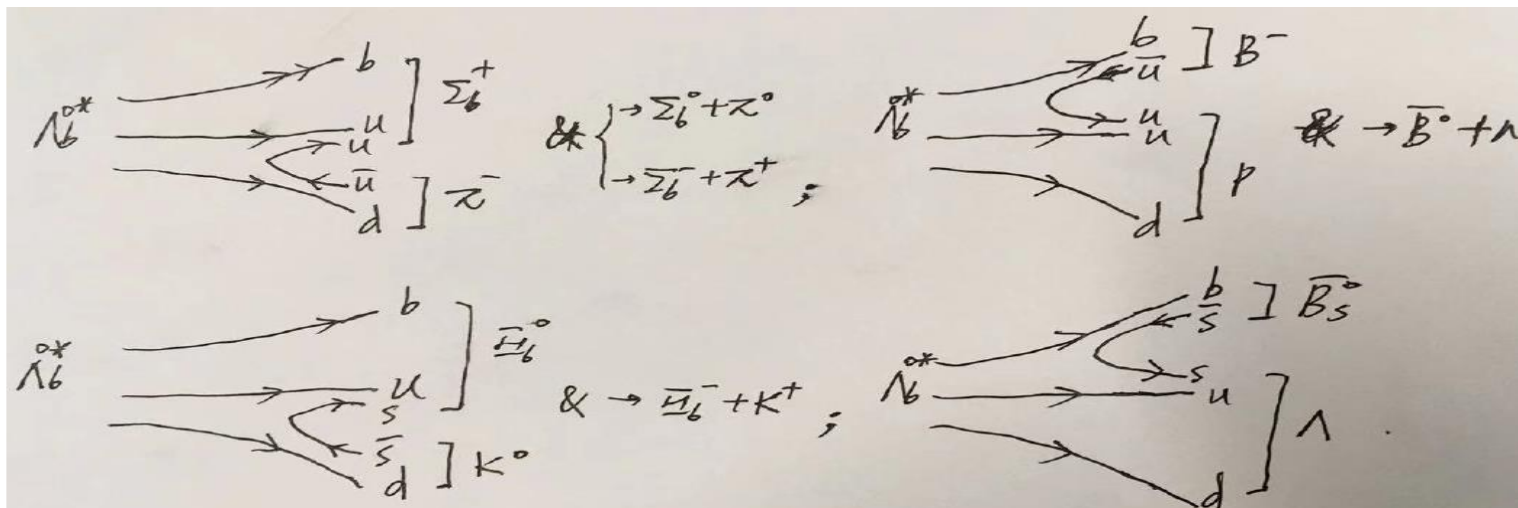
- Counting all possible diagrams once above the threshold



- Probability of producing a q - q bar pair $\propto \exp(-2m/T_H)$
 - ➔ $\exp(-2m_q/T_H) : \exp(-2m_s/T_H) = 1 : 1/3$ [$m_q \sim 8$, $m_s \sim 100$ MeV]
 - ➔ diagrams involving s - s bar counted as $1/3$
- E.g. $\text{BR}(B^{*-} \rightarrow B^- + \pi^0) = 1/(1+1+1/3) = 43\%$
 $\text{BR}(B^{*-} \rightarrow \bar{B}^0 + \pi^-) = 1/(1+1+1/3) = 43\%$
 $\text{BR}(B^{*-} \rightarrow \bar{B}_s^0 + \pi^0) = 1/3/(1+1+1/3) = 14\%$

Strong decay systematics: BR's estimation

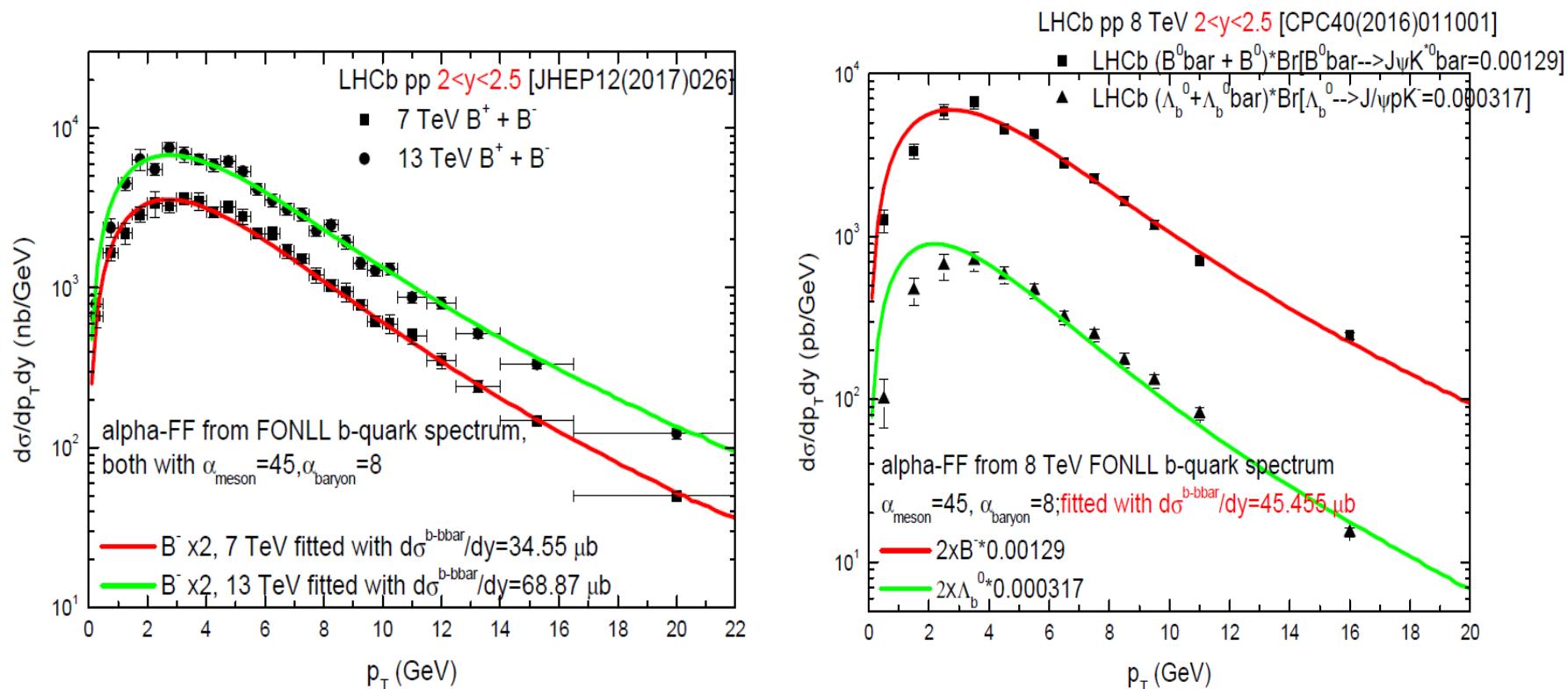
- Counting all possible diagrams once above the mass threshold



- E.g. $\text{BR}(\Lambda_b^{0*} \rightarrow \Sigma_b + \pi^- \rightarrow \Lambda_b^0 + 2\pi) = 3/(3+2+2*1/3+1/3) = 54\%$
 $\text{BR}(\Lambda_b^{0*} \rightarrow B^- + p) = 1/(3+2+1/3+2*1/3) = 16\%$
 $\text{BR}(\Lambda_b^{0*} \rightarrow \Xi_b + K) = 2/3/(3+2+1/3+2*1/3) = 11\%$
 $\text{BR}(\Lambda_b^{0*} \rightarrow B^0\text{bar} + \Lambda) = 1/3/(3+2+1/3+2*1/3) = 6\%$
- Results comparable to (limited) results computed in 3P_0 model
[Sun et al., PRD 89\(2014\)054026](#); [Mu et al., CPC 38\(2014\)113101](#)

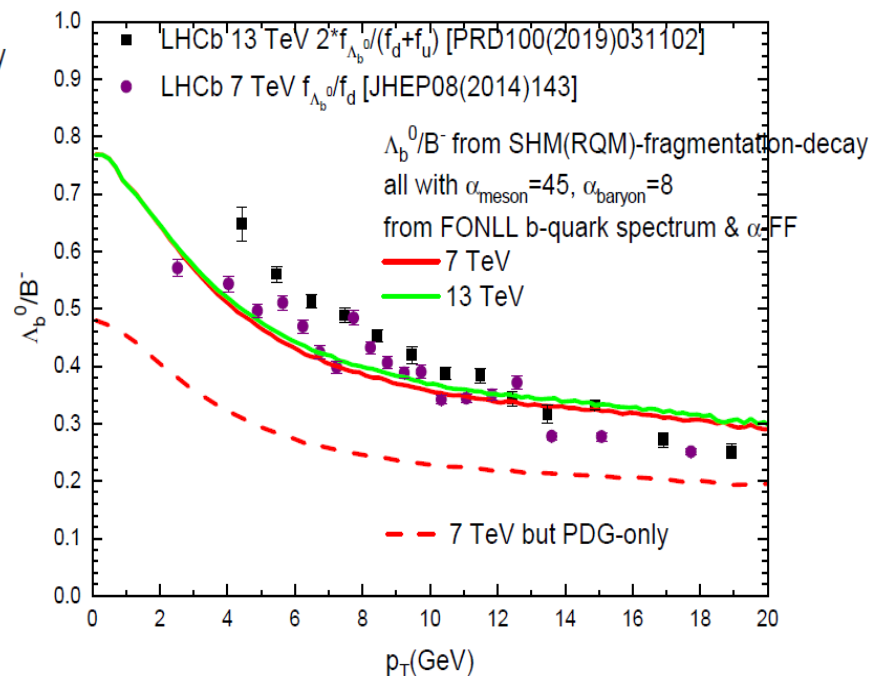
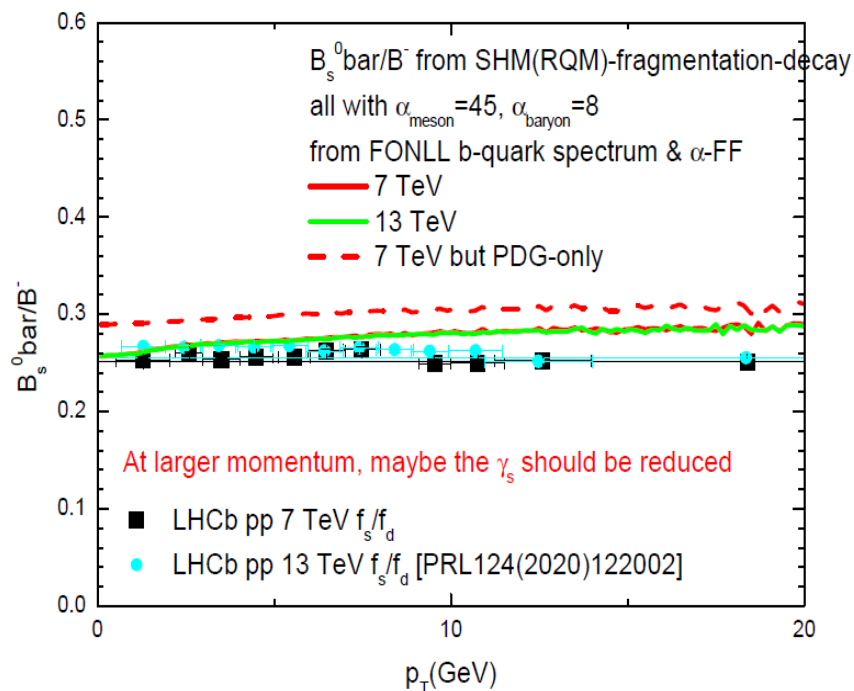
Fit of p_T -spectra & cross sections

- 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)
- $d\sigma^{b\bar{b}}/dy = 34.55 \mu\text{b}$ (7 TeV) & $68.87 \mu\text{b}$ (13 TeV) for $2 < y < 2.5$

Bottom hadro-chemistry: ratios



- $B_s^0 \text{bar}/B^-$ & 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

- Low-energy pp & AA collisions (fixed target): high- μ_B
 - high- μ_B : interesting splitting between Λ_c^+/\mathbf{D}^0 vs Λ_c^-/\mathbf{D}^0
 - high- μ_B QGP + HRG liquid: non-perturbative charm transport