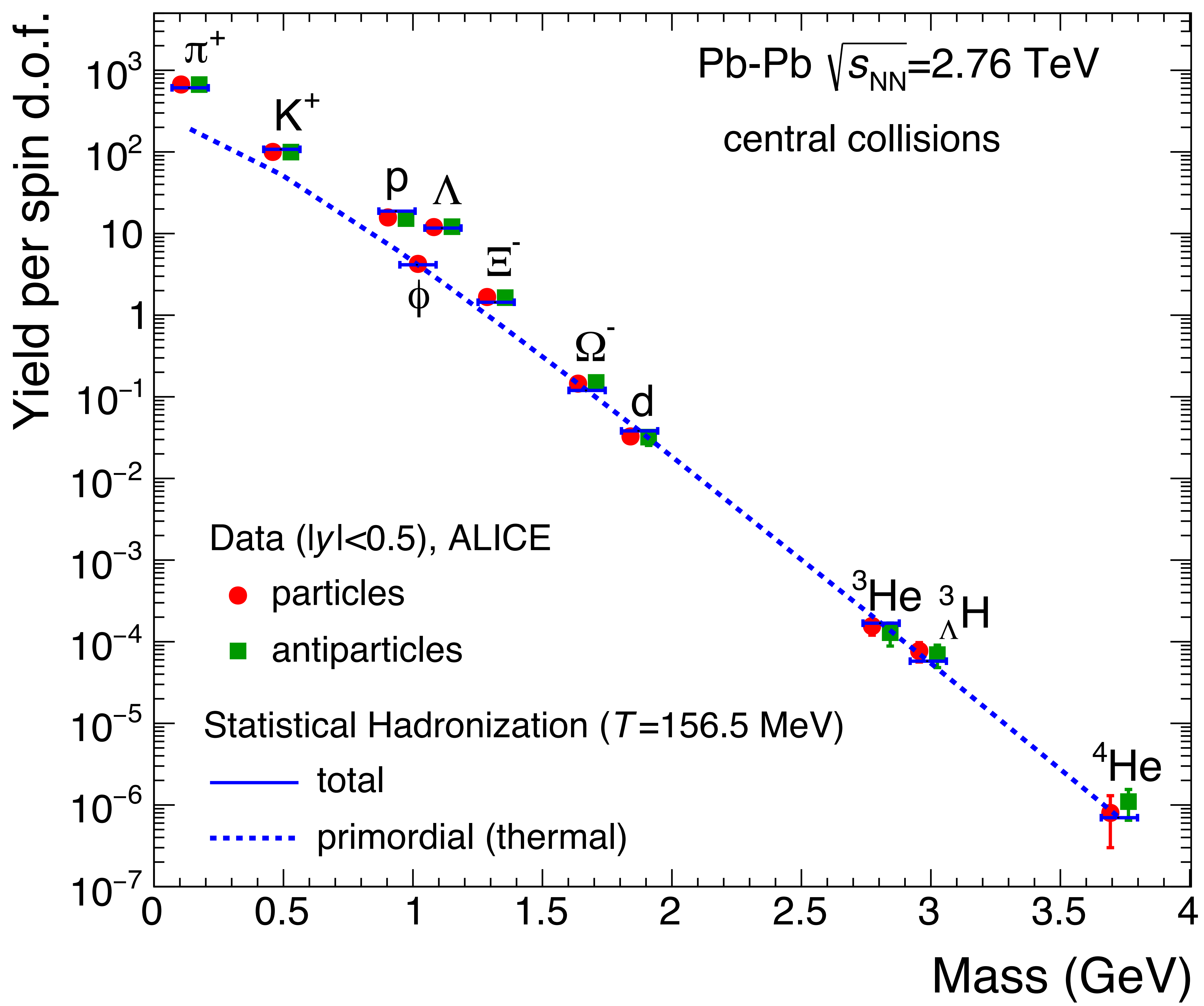
The multiple-charm hierarchy in the statistical hadronization model

Anton Andronic, Peter Braun-Munzinger, Markus K. Kohler, Aleksas Mazeliauskas,
Krzysztof Redlich, Johanna Stachel, V. V., J. High Energ. Phys. 2021, 35 (2021)

All predictions shown in this talk are available on the arXiv page as supplementary material

Statistical Hadronization Model

Very good description of (light-flavour) particle yields over multiple orders of magnitude
⇒ Few model paramteters: volume, temperature, baryonic chemical potential



A. Andronic *et al*, Phys Lett B797 (2019) 134836

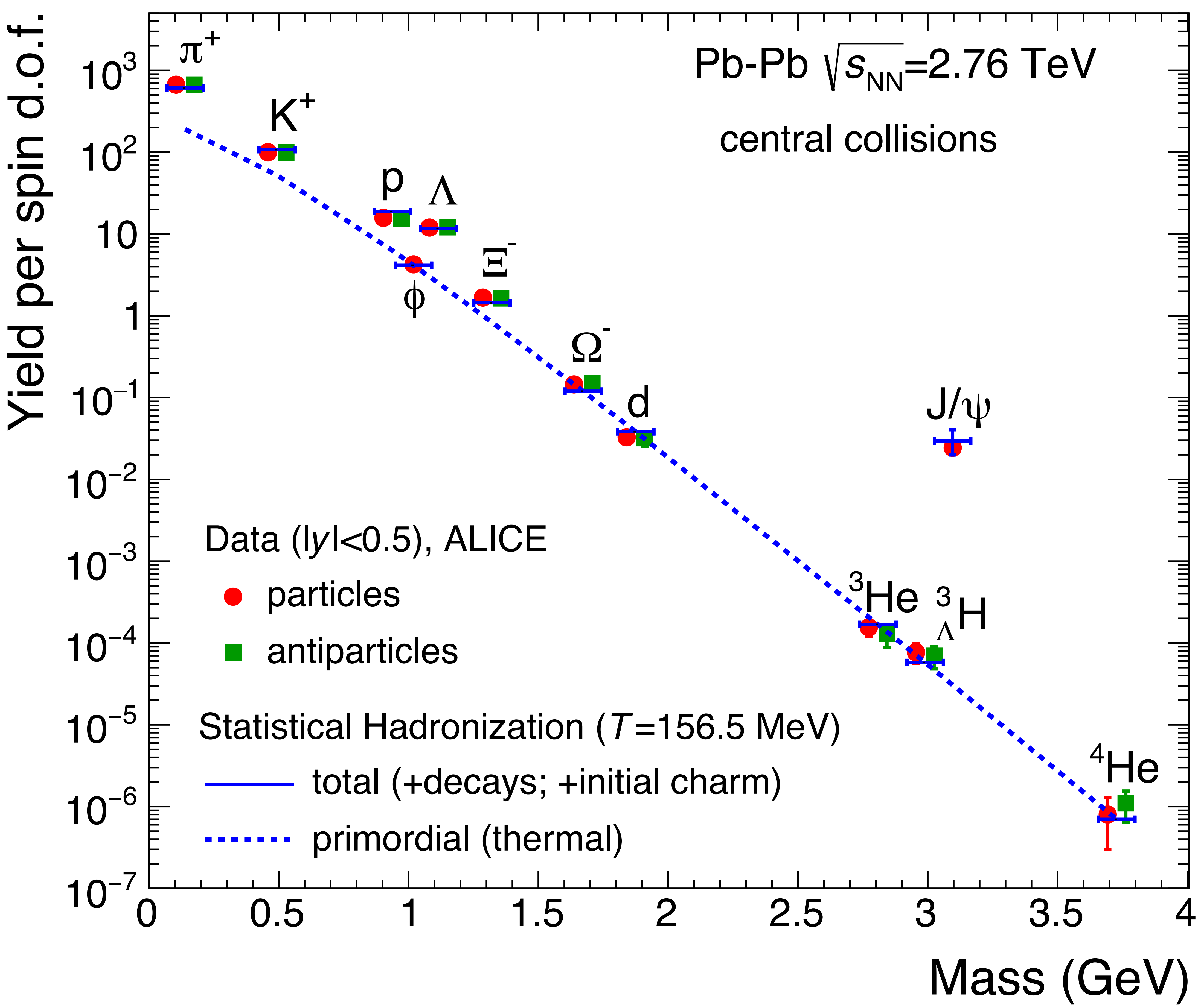
Statistical Hadronization Model

Very good description of (light-flavour) particle yields over multiple orders of magnitude
⇒ Few model paramteters: volume, temperature, baryonic chemical potential

Statistical Hadronization Model for charm

- Charm quark mass >> $T_{pc} \approx 156\ \mathrm{MeV}$, thermal production strongly suppressed

⇒ c quarks predominantly produced in initial hard scatterings
⇒ J/ψ yield 900 times larger w.r.t. thermal!



A. Andronic *et al*, Phys Lett B797 (2019) 134836

P. Braun-Munzinger and J. Stachel, Phys. Lett. B 490 (2000) 196–202
L. Grandchamp, R. Rapp, Phys. Lett. B 523 (2001) 60-66
Mark I. Gorenstein *et al*, J. Phys. G 28 (2002) 2151-2167
A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Phys. Lett. B 571 (2003) 36–44
F. Becattini, Phys. Rev. Lett. 95 (2005) 022301
A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nucl. Phys. A 789 (2007) 334–356
A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Phys. Lett. B 659 (2008) 149–155

SHMc: **S**tatistical **H**adronization **M**odel for **c**harm

- Charm quarks survive and *thermalize* in the QGP

  ⇒ Treat charm as "impurities" with yields driven by x-section

  ⇒ Leads to fugacity g_c in the balance equation

Charm balance equation:

$$N_{c\bar{c}} = \underbrace{\frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{\mathrm{th}}}_{\text{(Single) open charm}} + \underbrace{g_c^2 V \sum_{h^j_{hc}} n_j^{\mathrm{th}}}_{\text{Hidden charm}} + \underbrace{\frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\mathrm{th}}}_{\text{(Double) open charm}}$$

SHMc: **S**tatistical **H**adronization **M**odel for **c**harm

- Charm quarks survive and *thermalize* in the QGP
  ⇒ Treat charm as "impurities" with yields driven by x-section
  ⇒ Leads to fugacity g_c in the balance equation

Charm balance equation:

$$N_{c\bar{c}} = \frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{\mathrm{th}} + g_c^2 V \sum_{h^j_{hc}} n_j^{\mathrm{th}} + \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\mathrm{th}}$$

⇒ Volume obtained from SHM fits in light-flavour sector

SHMc: **S**tatistical **H**adronization **M**odel for **c**harm

- Charm quarks survive and *thermalize* in the QGP
  - ⇒ Treat charm as "impurities" with yields driven by x-section
  - ⇒ Leads to fugacity g_c in the balance equation

Charm balance equation:

$$N_{c\bar{c}} = \frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{th} + g_c^2 V \sum_{h^j_{hc}} n_j^{th} + \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{th}$$

⇒ Volume obtained from SHM fits in light-flavour sector

⇒ Thermal densities n_X^{th} given by T_{CF}, μ_B

SHMc: **S**tatistical **H**adronization **M**odel for **c**harm

- Charm quarks survive and *thermalize* in the QGP
  - ⇒ Treat charm as "impurities" with yields driven by x-section
  - ⇒ Leads to fugacity g_c in the balance equation

Charm balance equation:

$$N_{c\bar{c}} = \frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{\mathrm{th}} + g_c^2 V \sum_{h^j_{hc}} n_j^{\mathrm{th}} + \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\mathrm{th}}$$

⇒ Volume obtained from SHM fits in light-flavour sector

⇒ Thermal densities n_X^{th} given by T_{CF}, μ_B

⇒ N_{cc} from cross section measurements in pp + p-Pb

⇒ Can calculate g_c

SHMc: **S**tatistical **H**adronization **M**odel for **c**harm

- Charm quarks survive and *thermalize* in the QGP
  - ⇒ Treat charm as "impurities" with yields driven by x-section
  - ⇒ Leads to fugacity g_c in the balance equation

Charm balance equation:

$$N_{c\bar{c}} = \frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{\mathrm{th}} + g_c^2 V \sum_{h^j_{hc}} n_j^{\mathrm{th}} + \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\mathrm{th}}$$

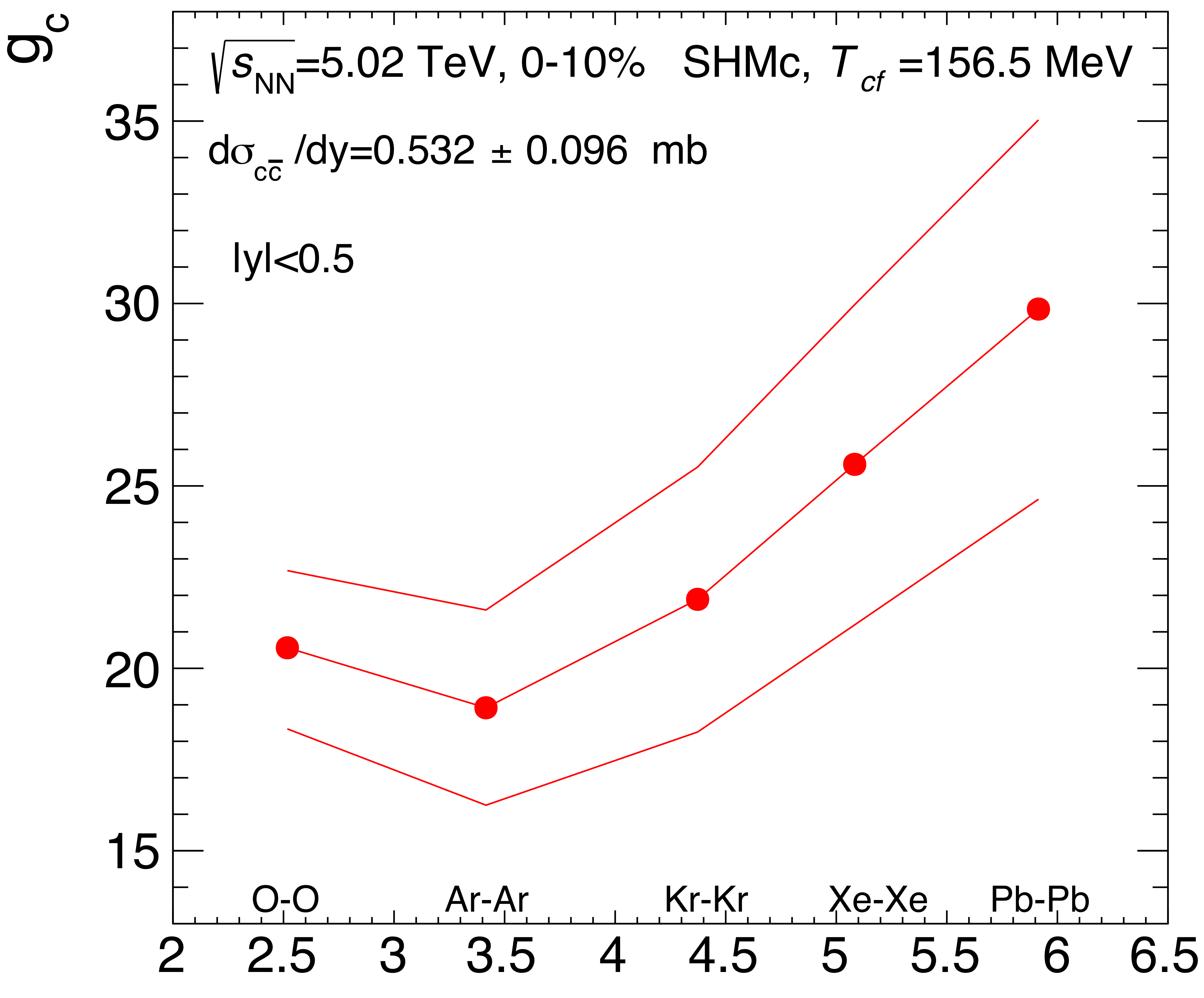
⇒ Volume obtained from SHM fits in light-flavour sector

⇒ Thermal densities n_X^{th} given by T_{CF}, μ_B

⇒ N_{cc} from cross section measurements in pp + p-Pb

⇒ Can calculate g_c

⇒ In central Pb—Pb collisions at the LHC and at mid rapidity, $g_c \approx 30$



JHEP 07 (2021), 035

⇒ Enhancement of single-charmed hadrons by a factor 30 and for double-charmed hadrons by a factor 900!

Constructing transverse momentum spectra

Using Core-Corona picture

Core:

⇒ Bulk particle production in a thermalised and deconfined medium

⇨ All charm quarks produced in the core are thermalised ⇨ 100% opacity

⇒ Hydrodynamical expansion of the system modifies particle spectra

Constructing transverse momentum spectra

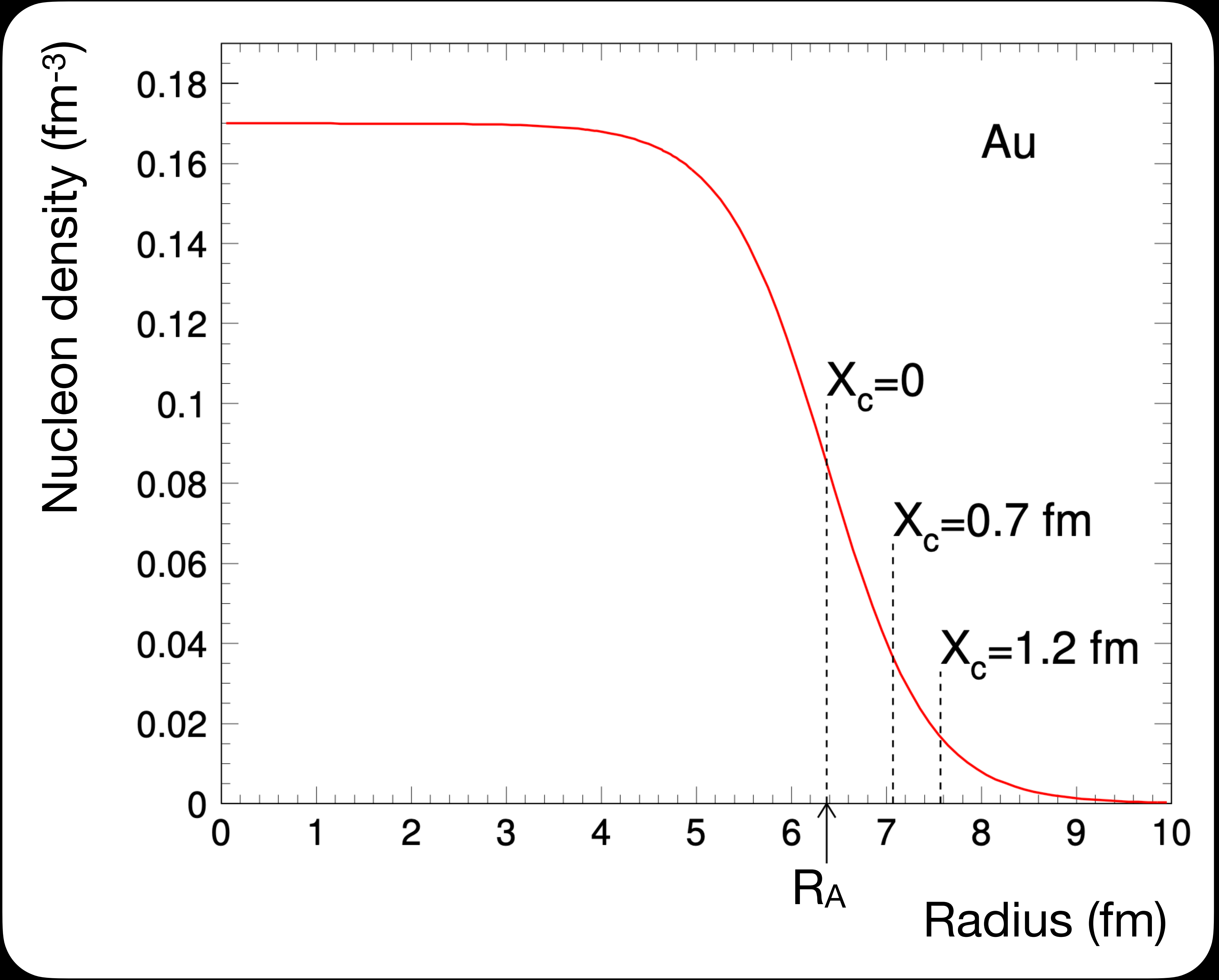
Using Core-Corona picture

Core:

⇒ Bulk particle production in a thermalised and deconfined medium

⇨ All charm quarks produced in the core are thermalised ⇨ 100% opacity

⇒ Hydrodynamical expansion of the system modifies particle spectra



Corona:

⇒ Perturbative "pp-like" scatterings between nucleons in the corona of colliding nuclei

⇒ Estimated using cross section measurements in pp collisions

⇒ $\langle T_{AA} \rangle$ from Glauber, 10% of central Pb—Pb density

⇒ Power-like scaling at larger p_T, not described by hydro

⇒ For simplicity, here parametrise pp cross section as

$$Cp_T \left[1 + (p_T/p_0)^2\right]^{-n}$$

Constructing transverse momentum spectra for the core

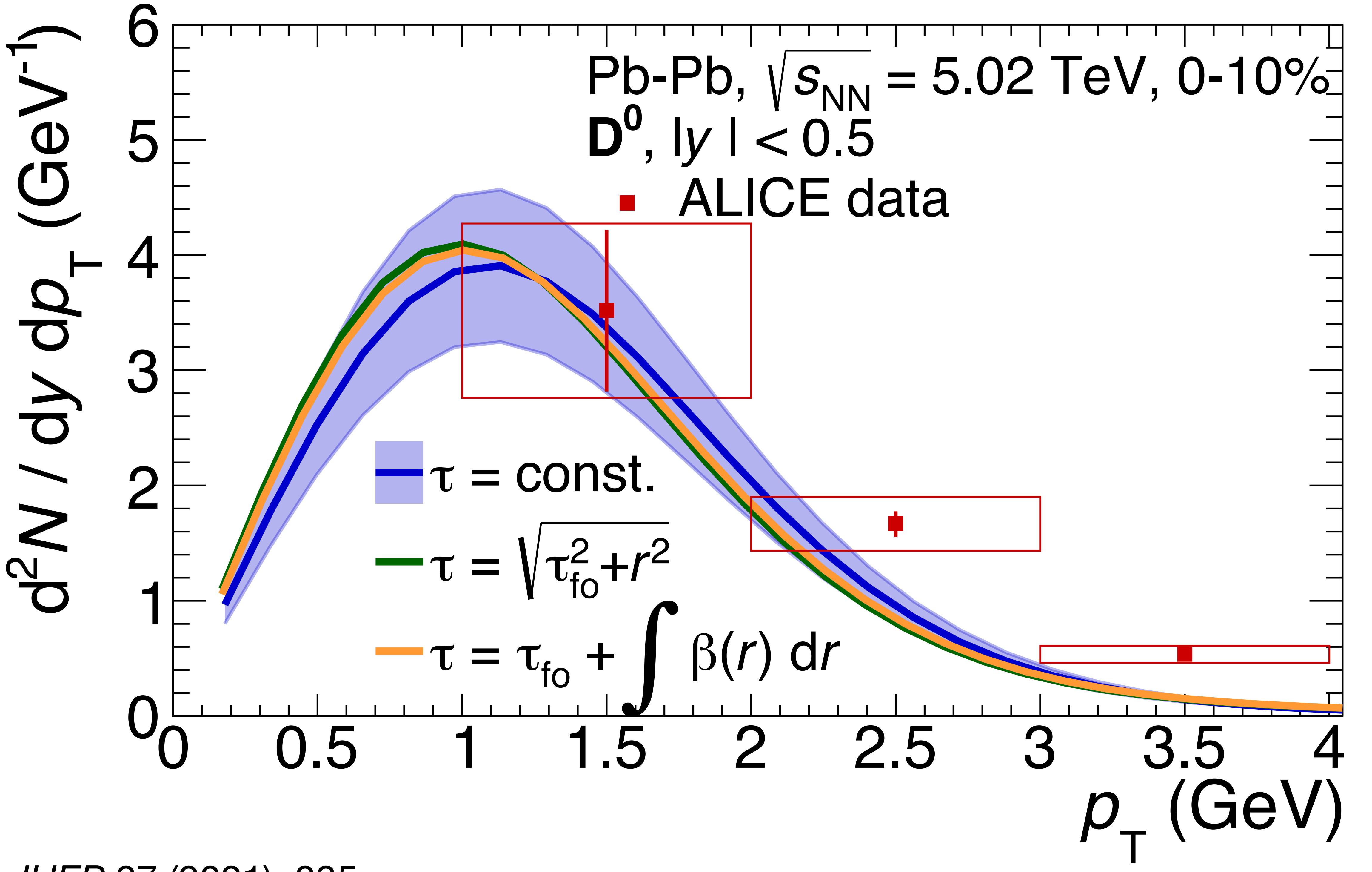
Particle spectra for the core computed using blast wave prescription

- Cooper-Frye freeze-out reduced to a one-dim. integral along τ-r plane
- Volume and temperature from SHM fits in light sector
- Freeze-out kernels $K_1^{\mathrm{eq}}, K_2^{\mathrm{eq}}$ calculated with FastReso code

  ⇒ Already includes feed-down from 72 2-body and 10 3-body decay channels of charmed hadrons!

$$\frac{\mathrm{d}^2 N}{2\pi p_\mathrm{T} dp_\mathrm{T} dy} = \frac{2J+1}{(2\pi)^3}\int \mathrm{d}\sigma_\mu p^\mu f(p)$$

$$= \frac{2J+1}{(2\pi)^3}\int_0^{r_{\max}} \mathrm{d}r\tau(r)r\left[K_1^{\mathrm{eq}}\left(p_\mathrm{T}, u^r\right) - \frac{\partial\tau}{\partial r}K_2^{\mathrm{eq}}\left(p_\mathrm{T}, u^r\right)\right]$$



JHEP 07 (2021), 035

A. Mazeliauskas, S. Floerchinger, E. Grossi, and D. Teaney, Eur. Phys. J. C 79 no. 3, (2019) 284
A. Mazeliauskas and V. Vislavicius, Phys. Rev. C 101 no. 1, (2020) 014910

Constructing transverse momentum spectra for the core

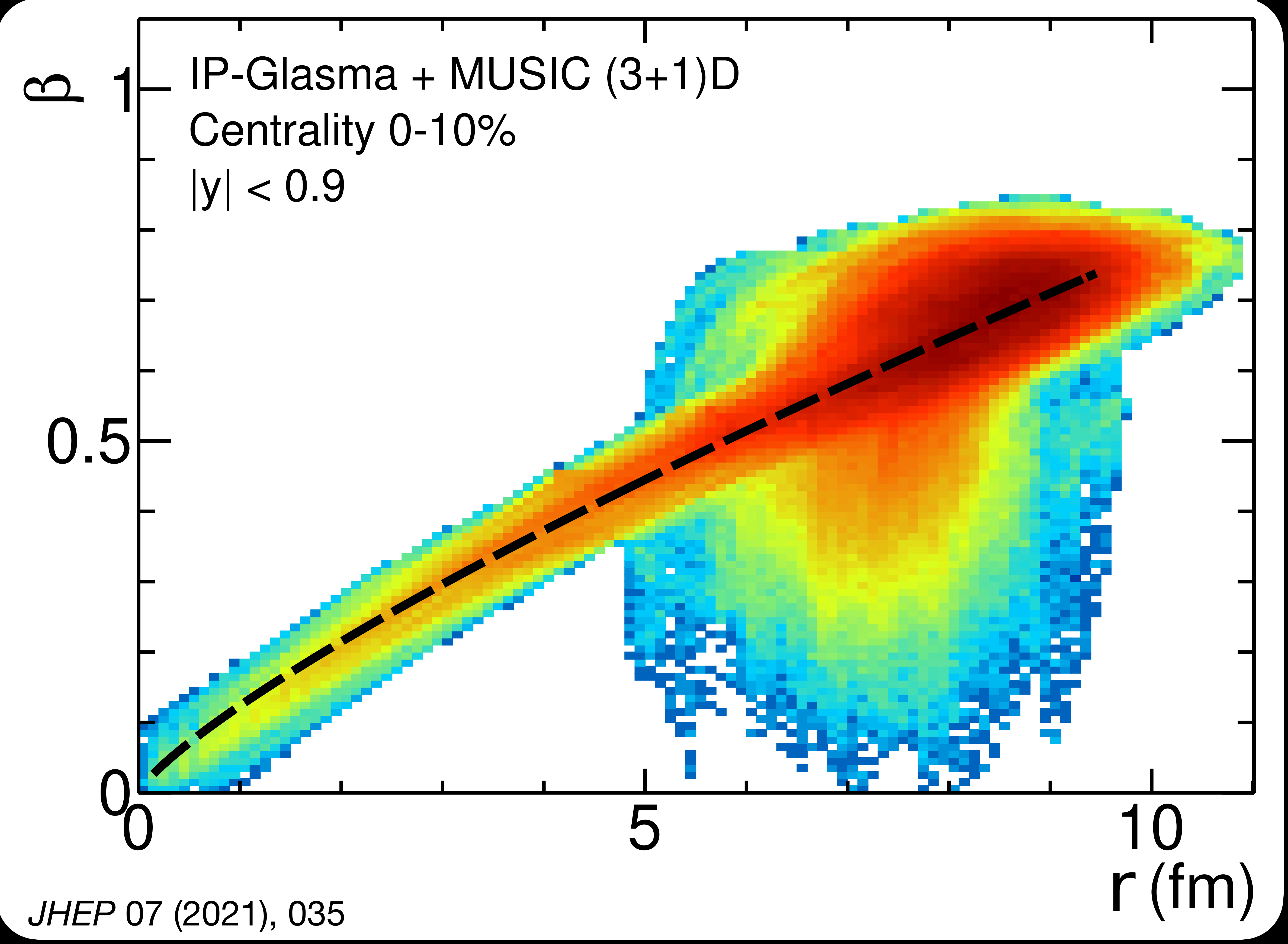
Particle spectra for the core computed using blast wave prescription

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{2J+1}{(2\pi)^3}\int d\sigma_\mu p^\mu f(p)$$

$$= \frac{2J+1}{(2\pi)^3}\int_0^{r_{max}} dr\tau(r)r\left[K_1^{eq}\left(p_T,u^r\right) - \frac{\partial\tau}{\partial r}K_2^{eq}\left(p_T,u^r\right)\right]$$

- Cooper-Frye freeze-out reduced to a one-dim. integral along τ-r plane
- Volume and temperature from SHM fits in light sector
- Freeze-out kernels K_1^{eq}, K_2^{eq} calculated with FastReso code
  ⇒ Already includes feed-down from 72 2-body and 10 3-body decay channels of charmed hadrons!
- Radial expansion from (3+1)D viscous hydro code:
  $\beta = \beta_{max}\left(r/r_{max}\right)^n$

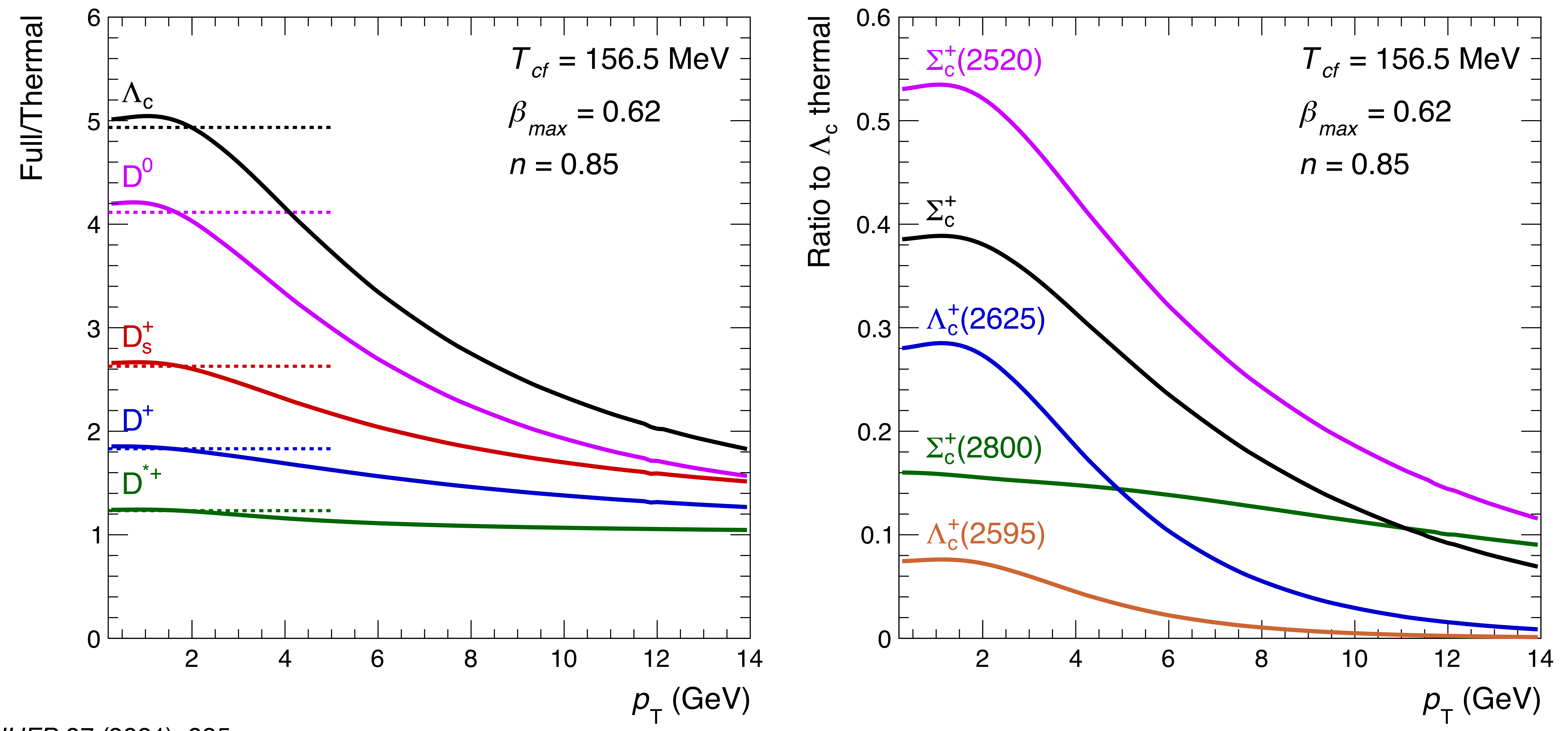
- No new parameters in the model, only external input from hydro and measurements



A. Mazeliauskas, S. Floerchinger, E. Grossi, and D. Teaney, Eur. Phys. J. C 79 no. 3, (2019) 284
A. Mazeliauskas and V. Vislavicius, Phys. Rev. C 101 no. 1, (2020) 014910
B. Schenke, S. Jeon, and C. Gale, Phys. Rev. C82 (2010) 014903
B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. 108 (2012) 252301

SHMc predictions: thermal vs. full

- Full treatment of decay kinematics for resonance decays (before: thermal spectra times feed-down correction)
- Decay products populate mostly low pT region, can be as large as 5 times the thermal yield!
- ... but core dominates only up to 3-4 GeV



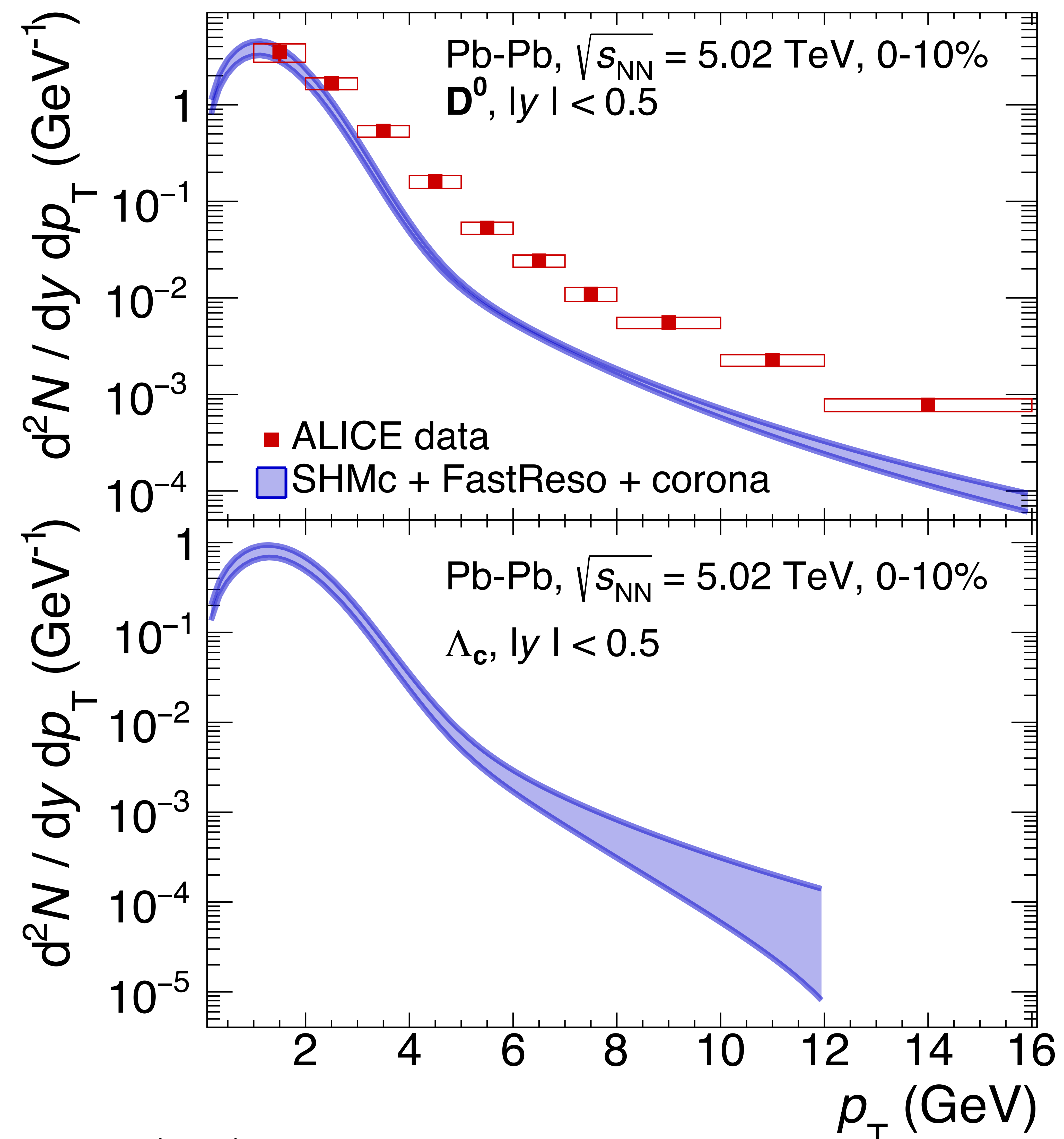
JHEP 07 (2021), 035

SHMc predictions: transverse momentum spectra

- D^0: good agreement with the data for core, underpredicts the high-p_T tail
  ⇒ Bulk of the yields is below 3 GeV
- No new parameters in the model, only external input!
- Dominant model uncertainties: g_c for core,

  pp parametrisation for corona

- Λ_C: measured spectra coming soon, our predictions are available as supplementary material on arXiv (also for other species!)

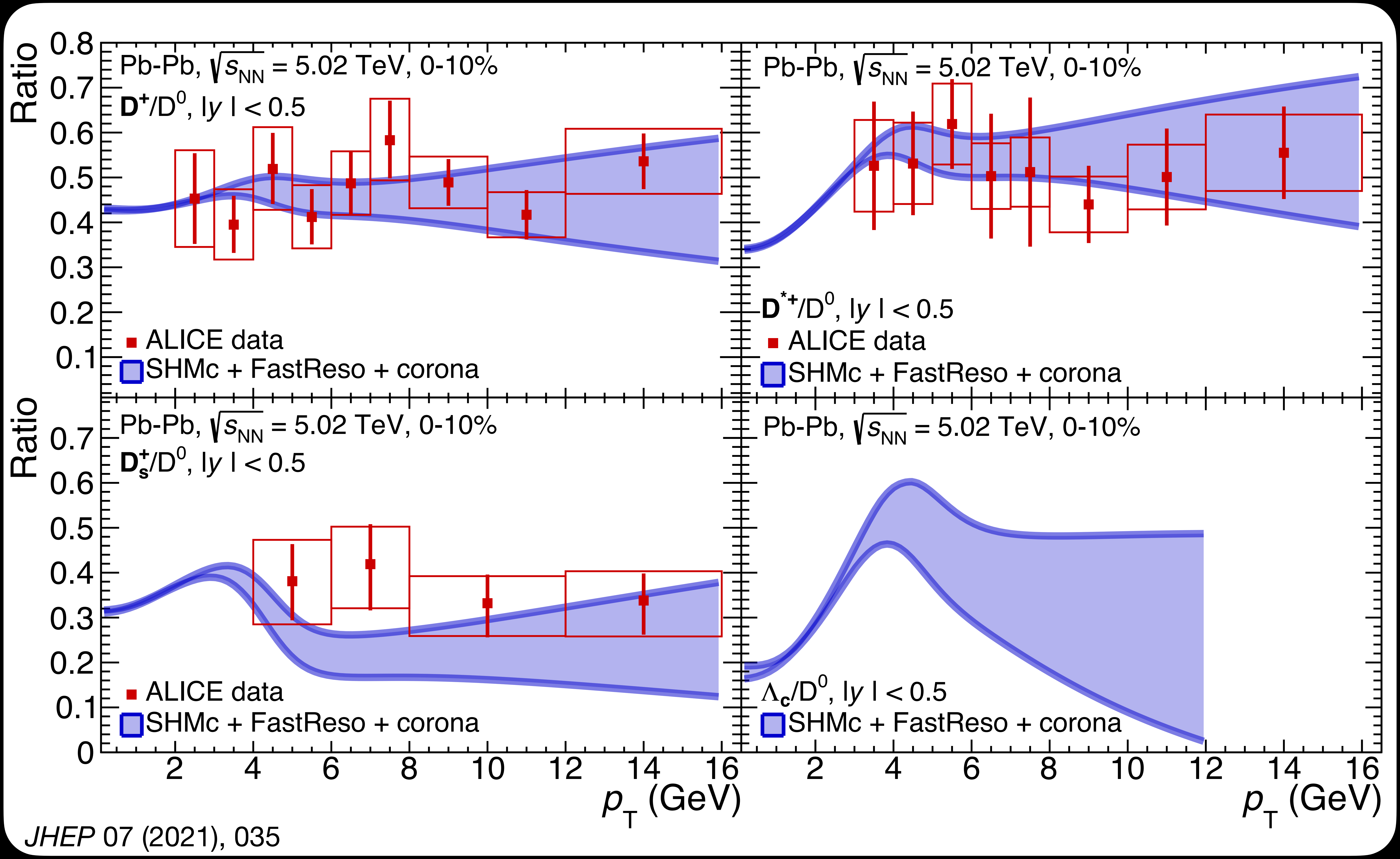


JHEP 07 (2021), 035

Pb—Pb data:
ALICE Collaboration, JHEP 10 (2018) 174
pp data for corona:
ALICE Collaboration, arXiv:2011.06079 [nucl-ex]
ALICE Collaboration, Eur. Phys. J. C 79 no. 5, (2019) 388
ALICE Collaboration, arXiv:2102.13601 [nucl-ex]

SHMc predictions: particle ratios

- Very good agreement between model and the data for all particle species!
- No free parameters!
- Peak-like structure for Λ_C: hydro → jets
- g_c eliminated, model width dominated by the measurement
- Looking forward to measurements down to low p_T values



Pb—Pb data:
ALICE Collaboration, JHEP 10 (2018) 174
pp data for corona:
ALICE Collaboration, arXiv:2011.06079 [nucl-ex]
ALICE Collaboration, Eur. Phys. J. C 79 no. 5, (2019) 388
ALICE Collaboration, arXiv:2102.13601 [nucl-ex]

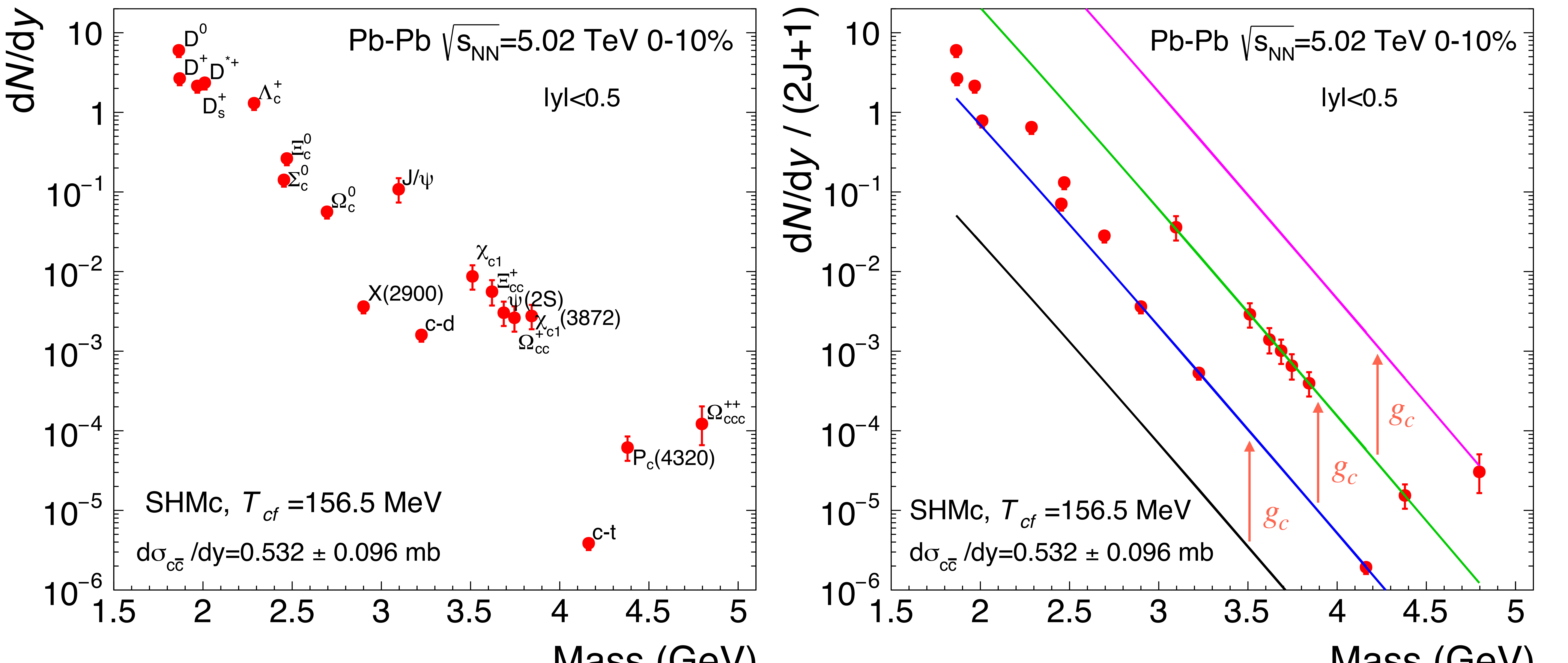
SHMc predictions: integrated particle yields

Can compute yields for any (multi-)charmed hadrons, including Ω_{ccc} and more speculative states, e.g. c-deuteron

⇒ For Pb—Pb collisions at LHC and mid rapidity, $g_c \approx 30 \Longrightarrow$ Ω_{ccc} enhanced by a factor of $\sim 2.7 \cdot 10^4$

⇒ Measurements of Ω_{ccc} possible in the future runs of LHC?

⇒ Grouping for single-, double-, and triple-charmed hadrons ⇒ perfect testing grounds for deconfinement in LHC for Run 3 and beyond!



JHEP 07 (2021), 035

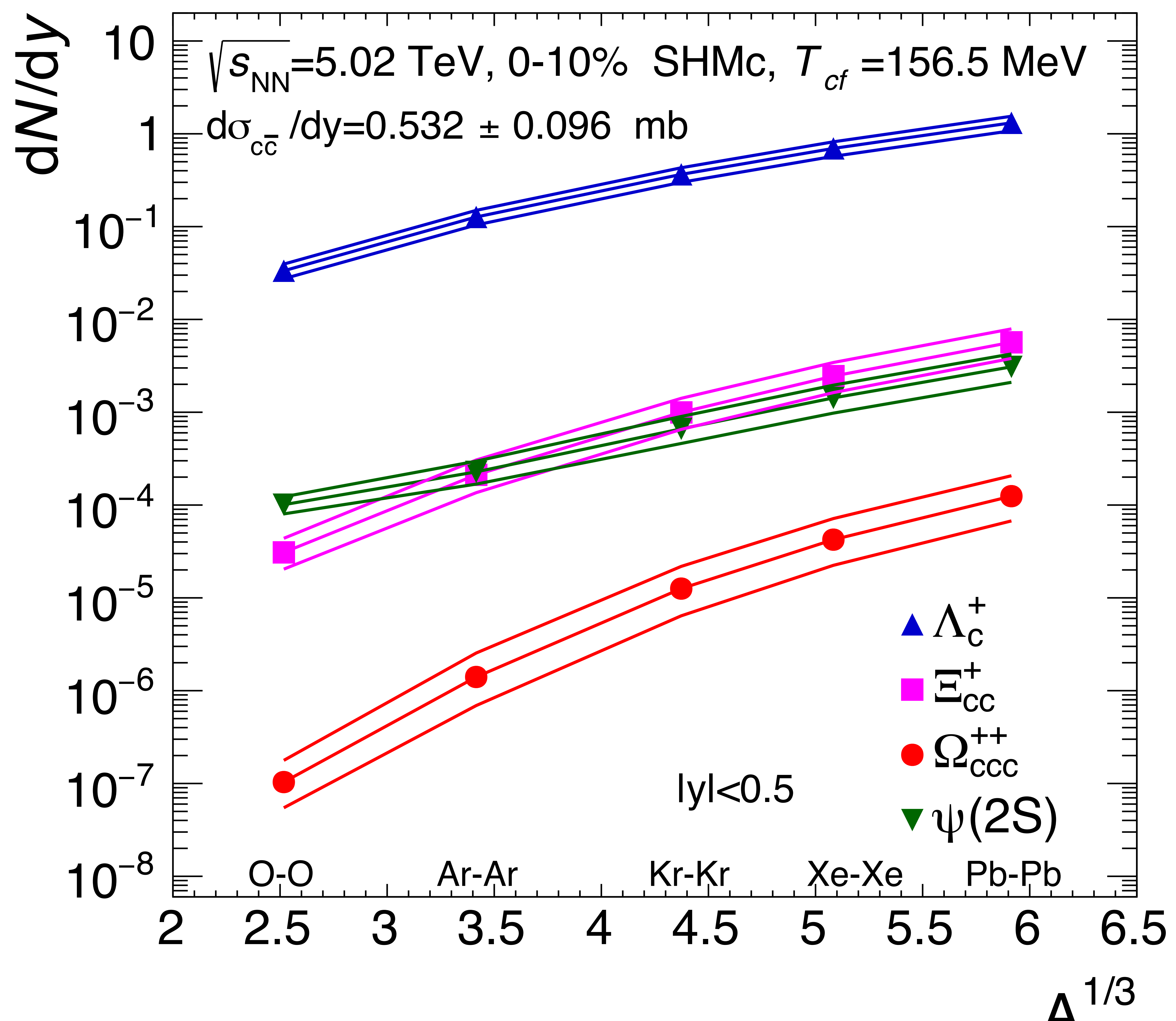
SHMc predictions: system size dependence

Canonical suppression due to small volume becomes increasingly more important in small systems:

⇒ Ω_{ccc} yield drops by ~4 orders of magnitude,

⇒ but this can be compensated by increased luminosity

	O-O	Pb-Pb
$\sigma_{\rm inel}(10\%)$ mb	140	800
$T_{\rm AA}(0-10\%)$ mb^{-1}	0.63	24.3
$\mathcal{L}(\rm cm^{-2}s^{-1})$	$4.5\cdot10^{31}$	$3.8\cdot10^{27}$
	$d\sigma_{c\bar{c}}/dy = 0.53$ mb	
$dN_{\Omega_{ccc}}/dy$	$8.38\cdot10^{-8}$	$1.25\cdot10^{-4}$
Ω_{ccc} Yield	$5.3\cdot10^{5}$	$3.80\cdot10^{5}$
	$d\sigma_{c\bar{c}}/dy = 0.63$ mb	
$dN_{\Omega_{ccc}}/dy$	$1.44\cdot10^{-7}$	$2.07\cdot10^{-4}$
Ω_{ccc} Yield	$9.2\cdot10^{5}$	$6.29\cdot10^{5}$



JHEP 07 (2021), 035

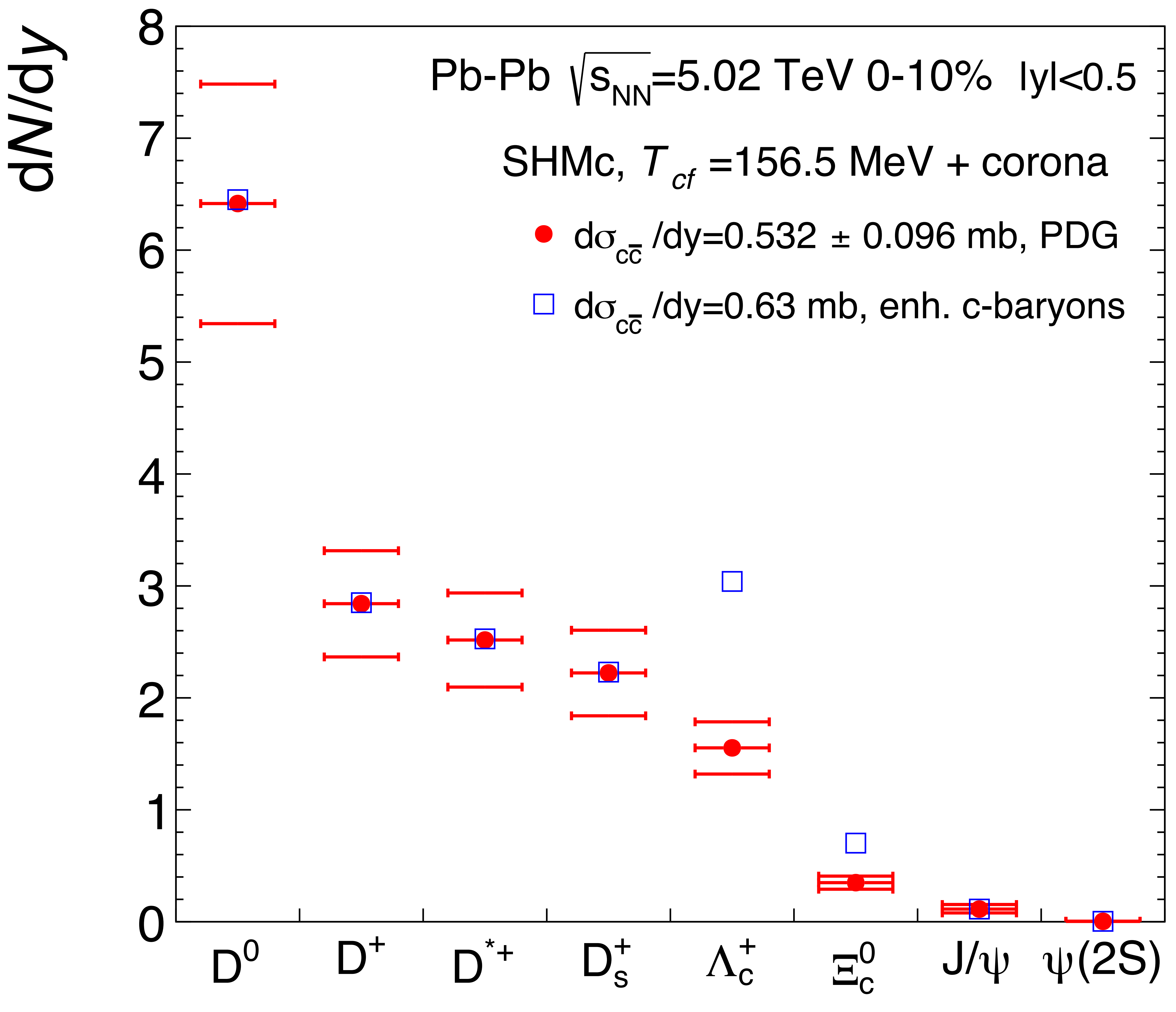
SHMc predictions: undiscovered states

- Recently, many predictions of undiscovered charmed baryon states (see eg [1])
  ⇒ Study this by *tripling* the statistical weights of all charmed baryon resonances

⇒ Mesons affected marginally

⇒ Baryon yields ~ double

⇒ Charm production x-section increases by 18%



JHEP 07 (2021), 035

[1] M. He and R. Rapp, Phys. Lett. B 795 (2019) 117–121

Summary

- Statistical hadronization model extended to charm sector:

  ⇒ Including the full treatment of resonance decay kinematics

  ⇒ With no parameter tuning, only external input

  ⇒ Predictions for *any* charmed hadron ⇨ for LHC Run 3, 4, and ALICE3

- Equivalent treatment of open and hidden charm
- Predicted hierarchy of multi-charm states, very strong enhancement expected

  ⇒ Perfect testing grounds for deconfinement in the future LHC measurements

- All predictions here and more are available as supplementary material at

  arXiv: 2104.12754 [hep-ph]

SHMc predictions for Ω_{ccc}

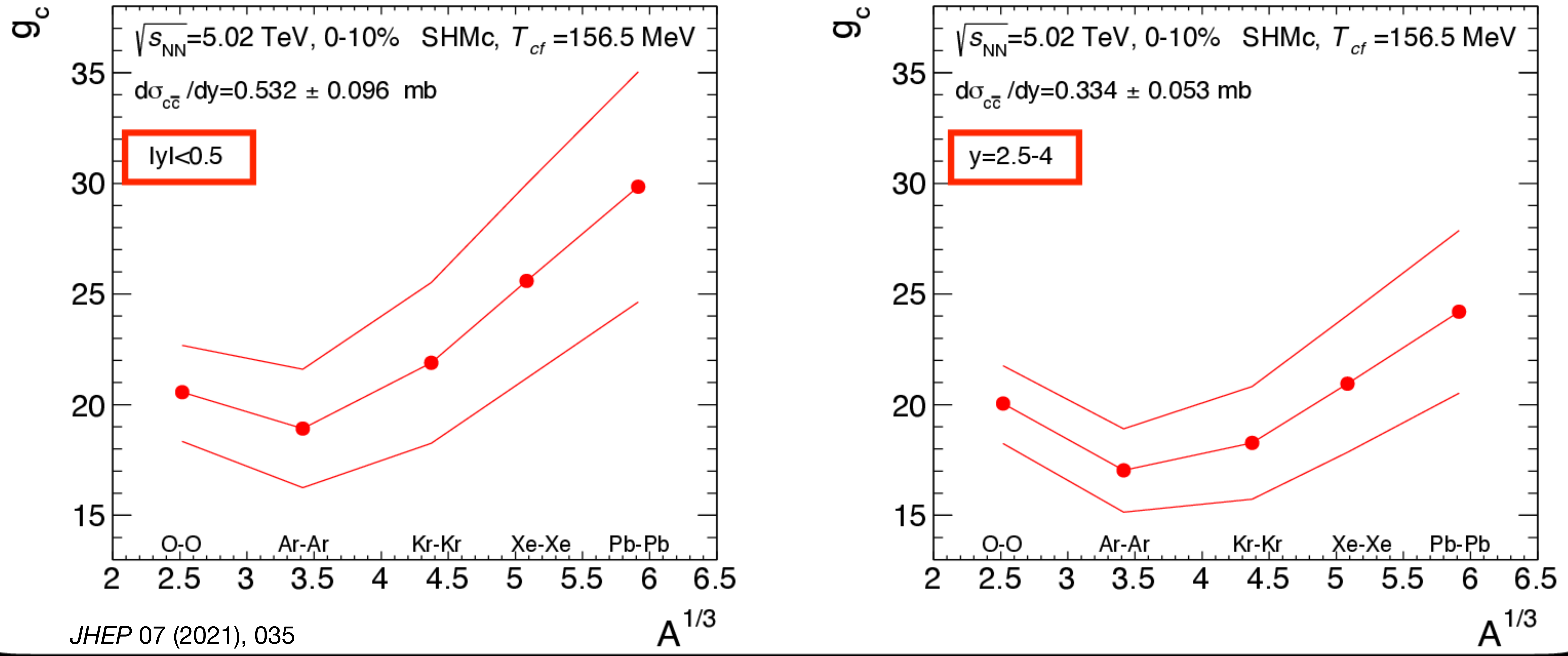
Expected yields of Ω_{ccc} in 10^6 s LHC run at $\sqrt{s_{NN}} = 5.02$ TeV for different collision systems in $\Delta y = 1$ at midrapidity

⇒ Yields in O—O comparable to those in Pb—Pb: larger luminosity, but stronger canonical suppression

	O-O	Ar-Ar	Kr-Kr	Xe-Xe	Pb-Pb
$\sigma_{\rm inel}(10\%)$ mb	140	260	420	580	800
$T_{AA}(0-10\%)$ mb^{-1}	0.63	2.36	6.80	13.0	24.3
$\mathcal{L}({\rm cm}^{-2}{\rm s}^{-1})$	$4.5\cdot10^{31}$	$2.4\cdot10^{30}$	$1.7\cdot10^{29}$	$3.0\cdot10^{28}$	$3.8\cdot10^{27}$
	$d\sigma_{c\bar{c}}/dy = 0.53$ mb				
$dN_{\Omega_{ccc}}/dy$	$8.38\cdot10^{-8}$	$1.29\cdot10^{-6}$	$1.23\cdot10^{-5}$	$4.17\cdot10^{-5}$	$1.25\cdot10^{-4}$
Ω_{ccc} Yield	$5.3\cdot10^{5}$	$8.05\cdot10^{5}$	$8.78\cdot10^{5}$	$7.26\cdot10^{5}$	$3.80\cdot10^{5}$
	$d\sigma_{c\bar{c}}/dy = 0.63$ mb				
$dN_{\Omega_{ccc}}/dy$	$1.44\cdot10^{-7}$	$2.33\cdot10^{-6}$	$2.14\cdot10^{-5}$	$7.03\cdot10^{-5}$	$2.07\cdot10^{-4}$
Ω_{ccc} Yield	$9.2\cdot10^{5}$	$1.45\cdot10^{6}$	$1.53\cdot10^{6}$	$1.22\cdot10^{6}$	$6.29\cdot10^{5}$

Charm fugacity g_c

- Obtained by numerically solving $N_{c\bar{c}} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1\left(g_c N_{oc}^{th}\right)}{I_0\left(g_c N_{oc}^{th}\right)} + g_c^2 N_{c\bar{c}}^{th}$ for ALICE (mid. rap.) and LHCb (FW)
- $g_c \propto A^{1/3}$ in large systems (grand-canonical), $\propto A^{-1/3}$ in O—O (canonical)
- In central Pb—Pb, enhancement of around 30 for single-charm, 900 for double-charm, $2.6 \cdot 10^4$ for triple charm!

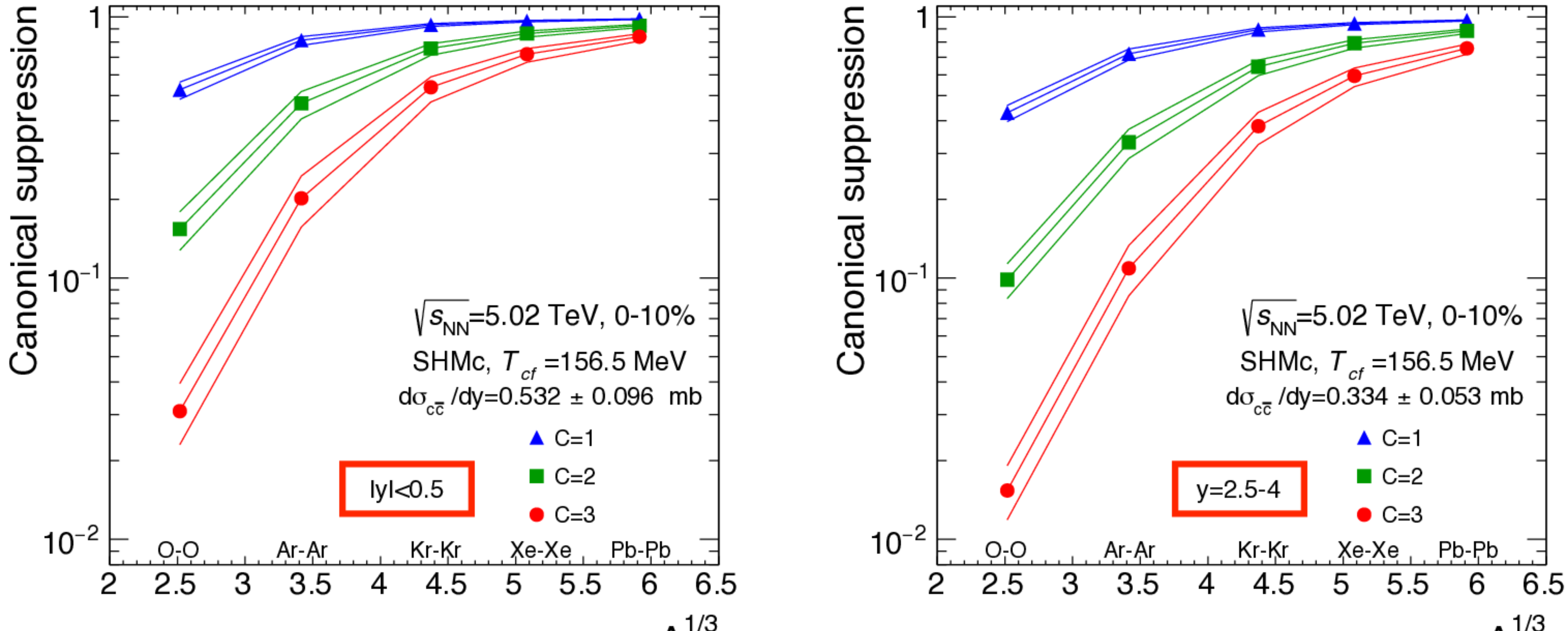


JHEP 07 (2021), 035

Canonical suppression in different collision systems

- Largest suppression for triple-charm in O—O
- In Pb—Pb, suppression for triple-charm hadrons ≈ 0.84

  ⇒ If realised in the nature, then even the heaviest (charm) hadrons could be accessible experimentally!



JHEP 07 (2021), 035

Constructing transverse momentum spectra for the core

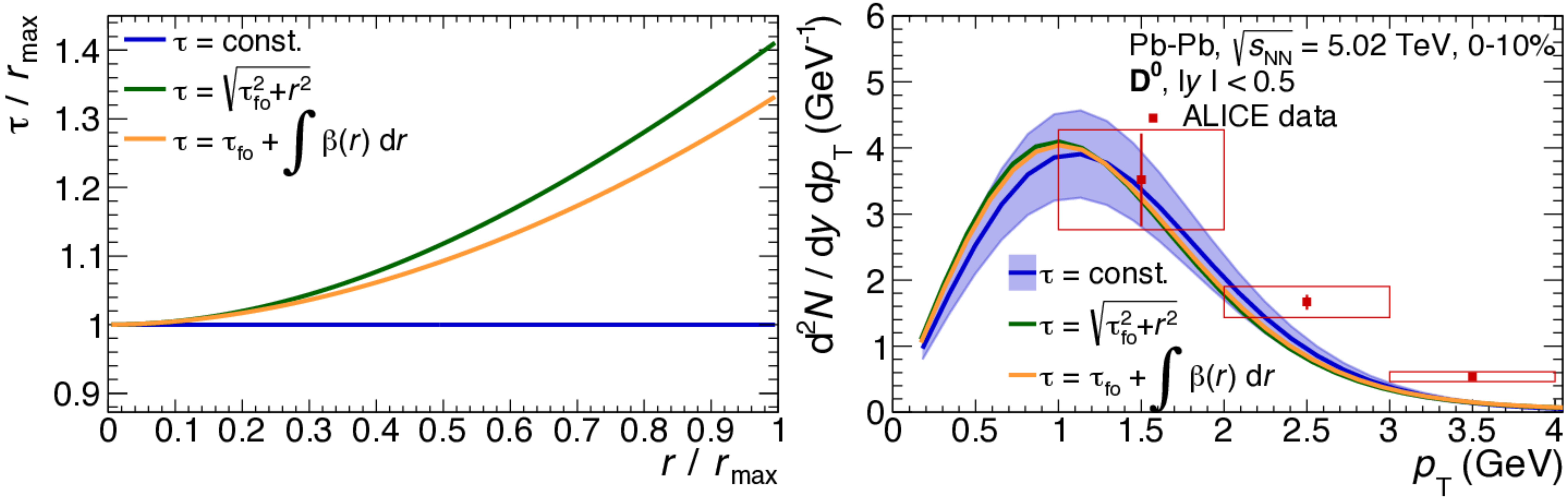
Using Core-Corona picture:

- Core yields from SHMc
- Dynamics from blast wave prescription
  ⇒ Cooper-Frye freeze-out reduced to one-dim.

  integral along $\tau - r$ plane. Dif. surfaces ⇨ sim. yields

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{2J+1}{(2\pi)^3}\int d\sigma_\mu p^\mu f(p)$$

$$= \frac{2J+1}{(2\pi)^3}\int_0^{r_{\max}} dr\tau(r)r\left[K_1^{eq}\left(p_T, u^r\right) - \frac{\partial\tau}{\partial r}K_2^{eq}\left(p_T, u^r\right)\right]$$

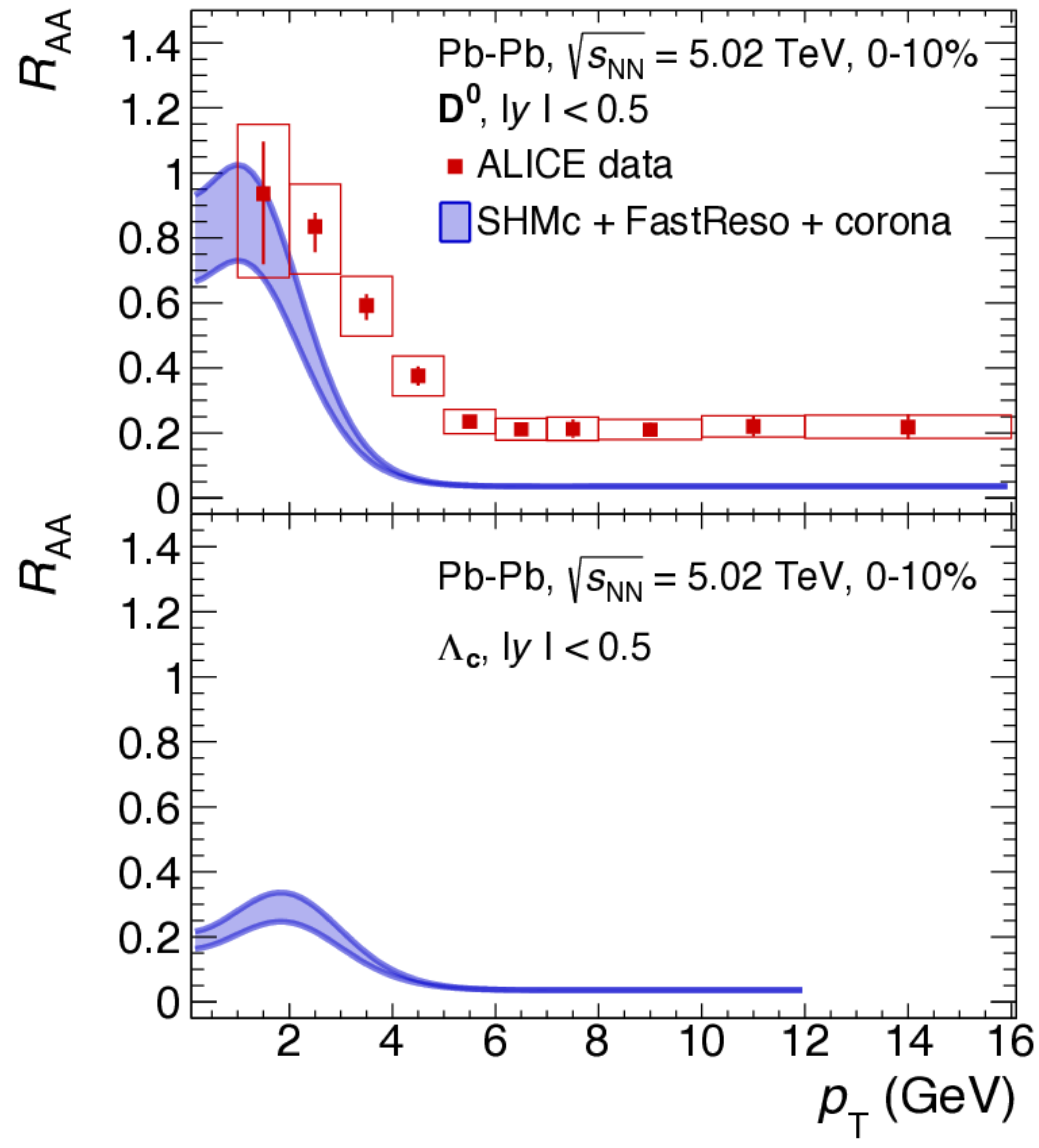


JHEP 07 (2021), 035

A. Mazeliauskas, S. Floerchinger, E. Grossi, and D. Teaney, Eur. Phys. J. C 79 no. 3, (2019) 284
A. Mazeliauskas and V. Vislavicius, Phys. Rev. C 101 no. 1, (2020) 014910

SHMc predictions: transverse momentum spectra and R_{AA}

- D^0: good agreement with the data for core, underpredicts the high-p_T tail
  ⇒ No incomplete thermalisation in the model
  ⇒ And bulk of the yields is below 3 GeV
- No new parameters in the model, only external input!
- Dominant model uncertainties: g_c for core, pp parametrisation for corona
- Λ_C: measured data preliminary so far, but our predictions are available as supplementary material on arXiv (also for other species!)
- R_{AA}: similar conclusions as for spectra



JHEP 07 (2021), 035

Pb—Pb data:
ALICE Collaboration, JHEP 10 (2018) 174
pp data for corona:
ALICE Collaboration, arXiv:2011.06079 [nucl-ex]
ALICE Collaboration, Eur. Phys. J. C 79 no. 5, (2019) 388
ALICE Collaboration, arXiv:2102.13601 [nucl-ex]