

# **Heavy hadrons from large to small collision systems with a coalescence plus fragmentation approach**

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di CATANIA



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IN COLLABORATION WITH:

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Heavy-Flavor Transport in QCD Matter

26-30 April 2021, ECT\* (online)

# Outline

- Hadronization:
  - ◆ Fragmentation
  - ◆ Coalescence model
- Heavy Quarks in AA collisions:
  - ◆  $\Lambda_c$  and D mesons spectra for RHIC and LHC
  - ◆  $\Lambda_c/D^0$  ratio
- Heavy Quarks in small systems:
  - ◆  $\Lambda_c/D^0$  (p-p @ 5.02 TeV)
  - ◆  $\Sigma_c/D^0, \Xi_c/D^0$  (p-p @ 13 TeV)
- Conclusions

# Relativistic Boltzmann eq. at finite $\eta/s$

## Bulk evolution

$$p^\mu \partial_\mu f_q(x, p) + m(x) \partial_\mu^x m(x) \partial_p^\mu f_q(x, p) = C[f_q, f_g]$$

$$p^\mu \partial_\mu f_g(x, p) + m(x) \partial_\mu^x m(x) \partial_p^\mu f_g(x, p) = C[f_q, f_g]$$

free-streaming

field interaction  
 $\varepsilon - 3p \neq 0$

collision term  
gauged to some  $\eta/s \neq 0$

Equivalent to  
viscous hydro  
 $\eta/s \approx 0.1$

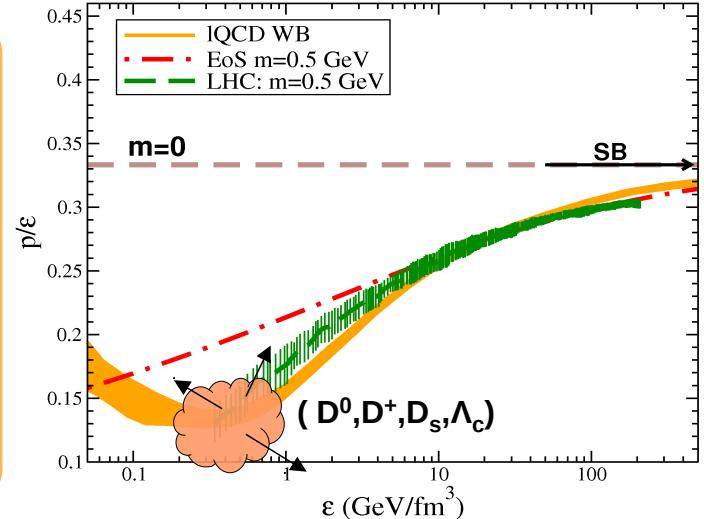
## Heavy quark evolution

$$p^\mu \partial_\mu f_Q(x, p) = C[f_q, f_g, f_Q]$$

$$\begin{aligned} C[f_q, f_g, f_Q] &= \frac{1}{2E_1} \int \frac{d^3 p_2}{2E_2 (2\pi)^3} \int \frac{d^3 p_1'}{2E_1' (2\pi)^3} \\ &\times [f_Q(p_1') f_{q,g}(p_2') - f_Q(p_1) f_{q,g}(p_2)] \\ &\times |M_{(q,g) \rightarrow Q}(p_1 p_2 \rightarrow p_1' p_2')| \\ &\times (2\pi)^4 \delta^4(p_1 + p_2 - p_1' - p_2') \end{aligned}$$

M scattering matrix by QPM model fit to IQCD thermodynamics

S. Plumari et al., J.Phys.Conf.Ser. 981 012017 (2018).



# $\Lambda_c/D^0$ ratio in elementary collisions

$$\frac{dN_h}{d^2 p_h} = \sum_f \int dz \frac{dN_f}{d^2 p_f} D_{f \rightarrow h}(z)$$

*Fragmentation function*

The distribution function is evaluated at the Fixed-Order plus Next-to-Leading-Log (FONLL)

M. Cacciari, P. Nason, R. Vogt, PRL 95 (2005) 122001

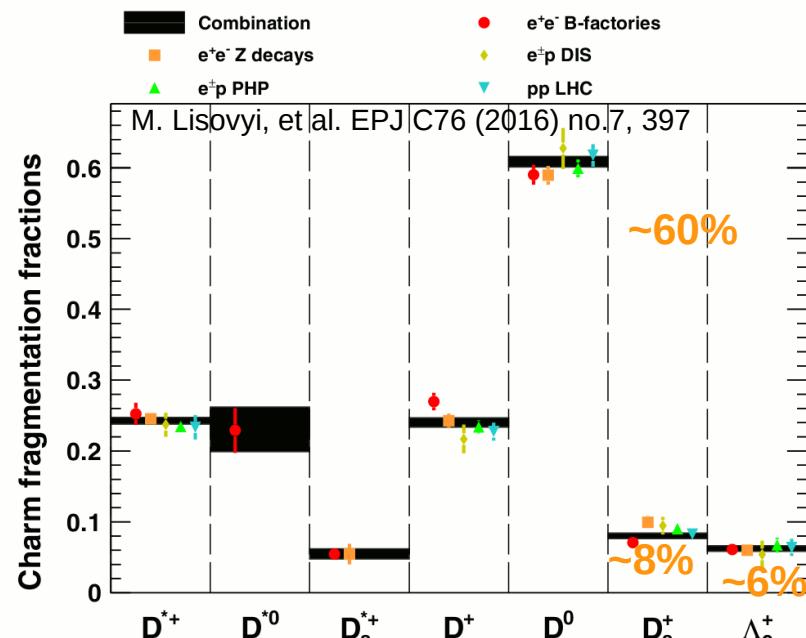
We use the Peterson fragmentation function

C. Peterson, D. Schalatter, I. Schmitt, P.M. Zerwas PRD 27 (1983) 105

$$D_{f \rightarrow h}(z) \propto \frac{1}{z \left[ 1 - \frac{1}{z} - \frac{\epsilon}{1-z} \right]^2}$$

Recent update He-Rapp, PLB795(2019):

Increase  $\approx 2$  due to added  $\Lambda_c$  resonance not present in PDG, but predicted by RQM [assumed BR with  $\Lambda_c$  dominance]



## \* Fragmentation functions

$$\left( \frac{\Lambda_c^+}{D^0} \right)_{e^+ e^-} \approx 0.1 \quad \left( \frac{D_s^+}{D^0} \right)_{e^+ e^-} \approx 0.13$$

## \* Thermal models about 2 times larger

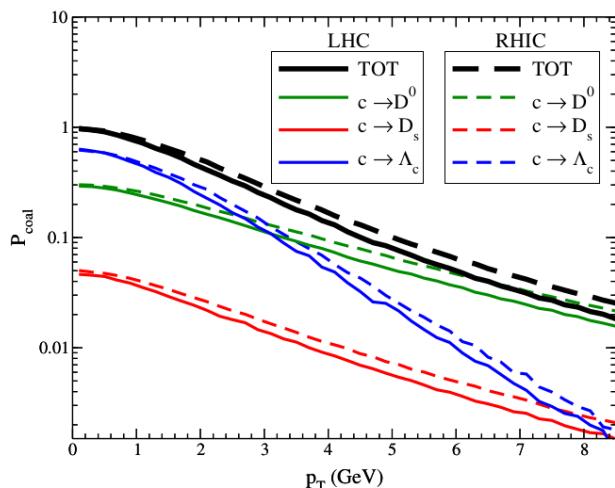
A. Andronic et al., Phys. Lett. B571, 36 (2003)  
I. Kuznetsova, J. Rafelski, EPJ C51, 113 (2007)

$$\left( \frac{\Lambda_c^+}{D^0} \right)_{p p} \approx 0.25 - 0.30$$

# Heavy flavour Hadronization: Coalescence

$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^n p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i) f_W(x_1, \dots, x_n; p_1, \dots, p_n) \delta(p_T - \sum_i p_{iT})$$

charm distribution function at mid-rapidity from parton simulations solving Boltzmann transport eq. that give good description of both  $R_{AA}$  and  $v_2(p_T)$  from RHIC to LHC energies.



- The width parameters  $\sigma$  in  $f_W(\dots)$  fixed by the root-mean-square charge radius as predicted by quark models

C.-W. Hwang, EPJ C23, 585 (2002).  
C. Albertus et al., NPA 740, 333 (2004)

$$\langle r^2 \rangle_{D^+} = 0.184 \text{ fm}^2 \quad \langle r^2 \rangle_{D_s^+} = 0.124 \text{ fm}^2 \quad \langle r^2 \rangle_{\Lambda_c^+} = 0.152 \text{ fm}^2$$

- Normalization in  $f_W(\dots)$  fixed by requiring that  $P_{coal}=1$  for  $p=0$

- The charm not “coalesces” undergo fragmentation: charm number conserved at each  $p_T$
- Is the same approach employed to predict  $\Lambda/K$

# Heavy flavour (charm): Resonance decay

In our calculations we take into account main hadronic channels, including the ground states and the first excited states for D and  $\Lambda_c$

## MESONS

$D^+$  ( $I=1/2, J=0$ )

$D^0$  ( $I=1/2, J=0$ )

$D_s^+$  ( $I=0, J=0$ )

## Resonances

$D^{*+}$  ( $I=1/2, J=1$ )  $\rightarrow D^0 \pi^+$  B.R. 68%

$D^{*+}$  ( $I=1/2, J=1$ )  $\rightarrow D^+ X$  B.R. 32%

$D^{*0}$  ( $I=1/2, J=1$ )  $\rightarrow D^0 \pi^0$  B.R. 62%

$D^{*0}$  ( $I=1/2, J=1$ )  $\rightarrow D^0 \gamma$  B.R. 38%

$D_s^{*+}$  ( $I=0, J=1$ )  $\rightarrow D_s^+ X$  B.R. 100%

$D_{s0}^{*+}$  ( $I=0, J=0$ )  $\rightarrow D_s^+ X$  B.R. 100%

## Statistical factor

$$\frac{[(2J+1)(2I+1)]_{H^*}}{[(2J+1)(2I+1)]_H} \left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-(E_{H^*}-E_H)/T}$$

## BARYONS

$\Lambda_c^+$  ( $I=0, J=1/2$ )

## Resonances

$\Lambda_c^+(2595)$  ( $I=0, J=1/2$ )  $\rightarrow \Lambda_c^+$  B.R. 100%

$\Lambda_c^+(2625)$  ( $I=0, J=3/2$ )  $\rightarrow \Lambda_c^+$  B.R. 100%

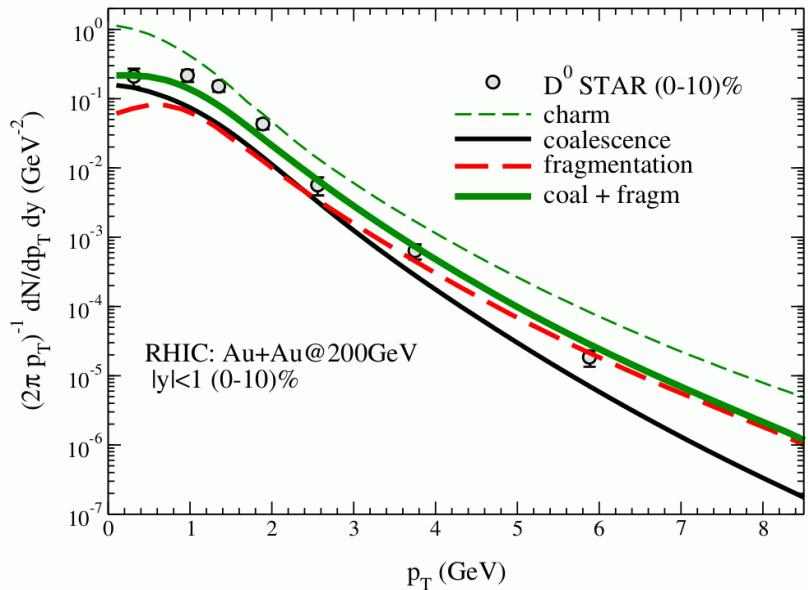
$\Sigma_c^+(2455)$  ( $I=1, J=1/2$ )  $\rightarrow \Lambda_c^+ \pi$  B.R. 100%

$\Sigma_c^+(2520)$  ( $I=1, J=3/2$ )  $\rightarrow \Lambda_c^+ \pi$  B.R. 100%

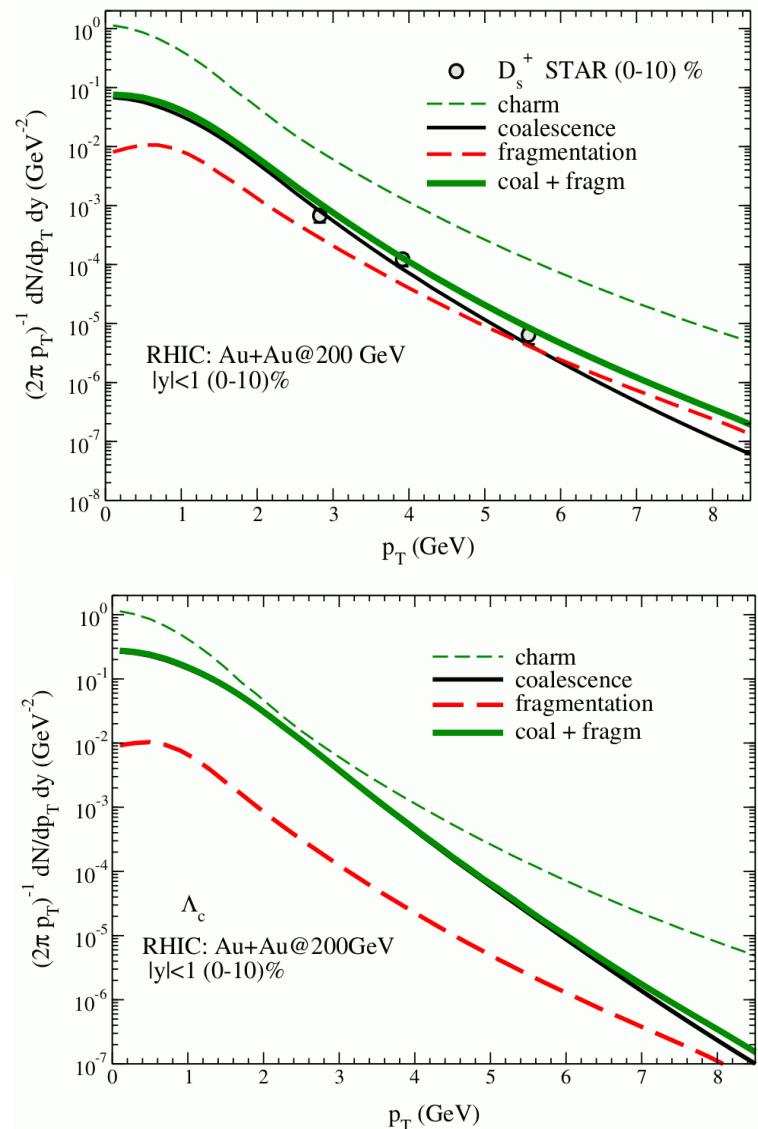
# RHIC: results

Data from STAR Coll., arXiv:1704.04364 [nucl-ex].

Data from STAR Coll. PRL **113** (2014) no.14, 142301



S. Plumari, et al., Eur. Phys. J. **C78** no. 4, (2018) 348



# RHIC: Baryon/meson

S. Plumari, et al., Eur. Phys. J. **C78** no. 4, (2018) 348

## Coalescence

Following: L.W.Chen, C.M. Ko, W. Liu, M. Nielsen, PRC 76, 014906 (2007). K.-J. Sun, L.-W. Chen, PRC 95, 044905 (2017).

For hypersurface of proper time  $\tau$  and non relativistic limit:

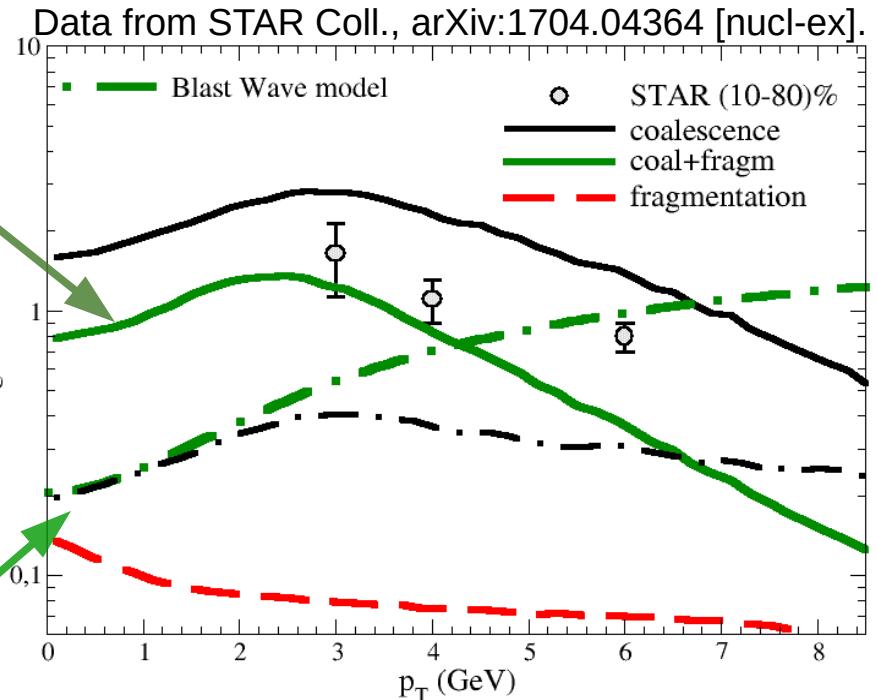
$$\text{for } p_T \ll m \quad \frac{\Lambda_c^+}{D^0} \propto \frac{g_\Lambda}{g_D} \left( \frac{m_T^\Lambda}{m_T^D} \right) e^{-(m^\Lambda - m^D)/T_C} \tau \mu_2$$

$$\mu_2 = \frac{m_3(m_1 + m_2)}{m_1 + m_2 + m_3} \quad \text{Is the reduced mass of the baryon}$$

## Blast Wave model:

$$\frac{\Lambda_c^+}{D^0} = \frac{g_\Lambda}{g_D} \frac{m_T^\Lambda}{m_T^D} \frac{K_1(m_T^\Lambda/T_C)}{K_1(m_T^D/T_C)}$$

$$\text{for } p_T \ll m \quad \approx \frac{g_\Lambda}{g_D} \left( \frac{m_T^\Lambda}{m_T^D} \right)^{1/2} e^{-(m^\Lambda - m^D)/T_C} \approx 0.17$$



# RHIC: Baryon/meson

S. Plumari, et al., Eur. Phys. J. **C78** no. 4, (2018) 348

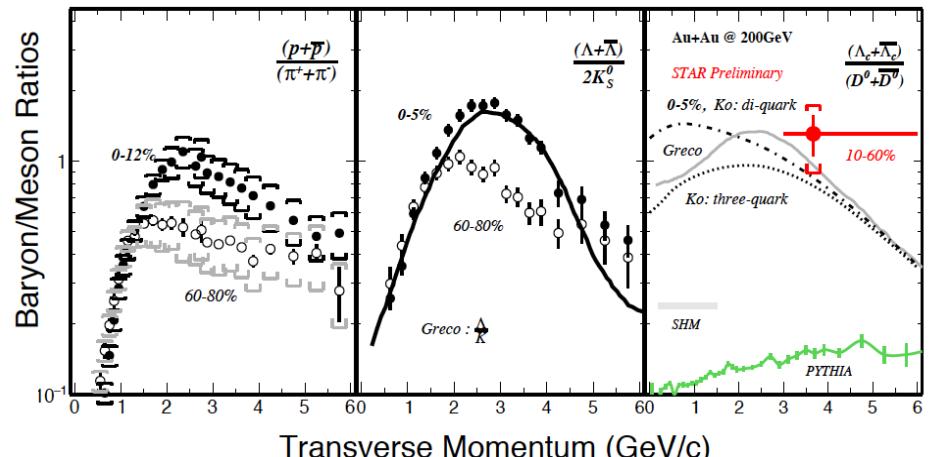
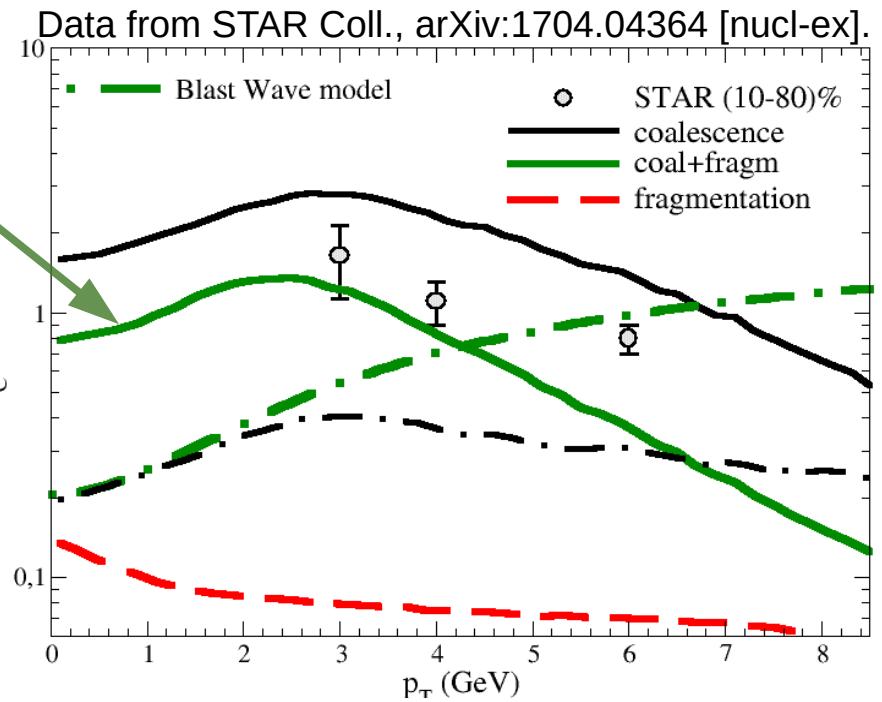
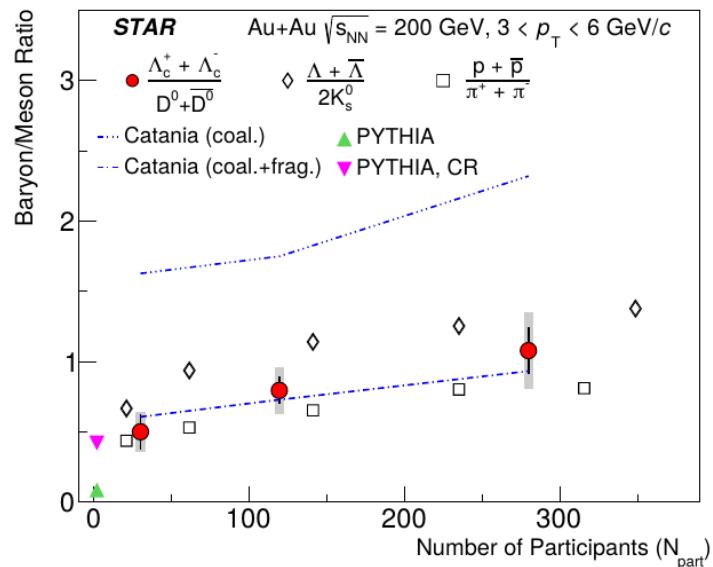
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$$\text{for } p_T \ll m \quad \frac{\Lambda_c^+}{D^0} \propto \frac{g_\Lambda}{g_D} \left( \frac{m_T^\Lambda}{m_T^D} \right) e^{-(m^\Lambda - m^D)/T_c} \quad \tau \mu_2$$

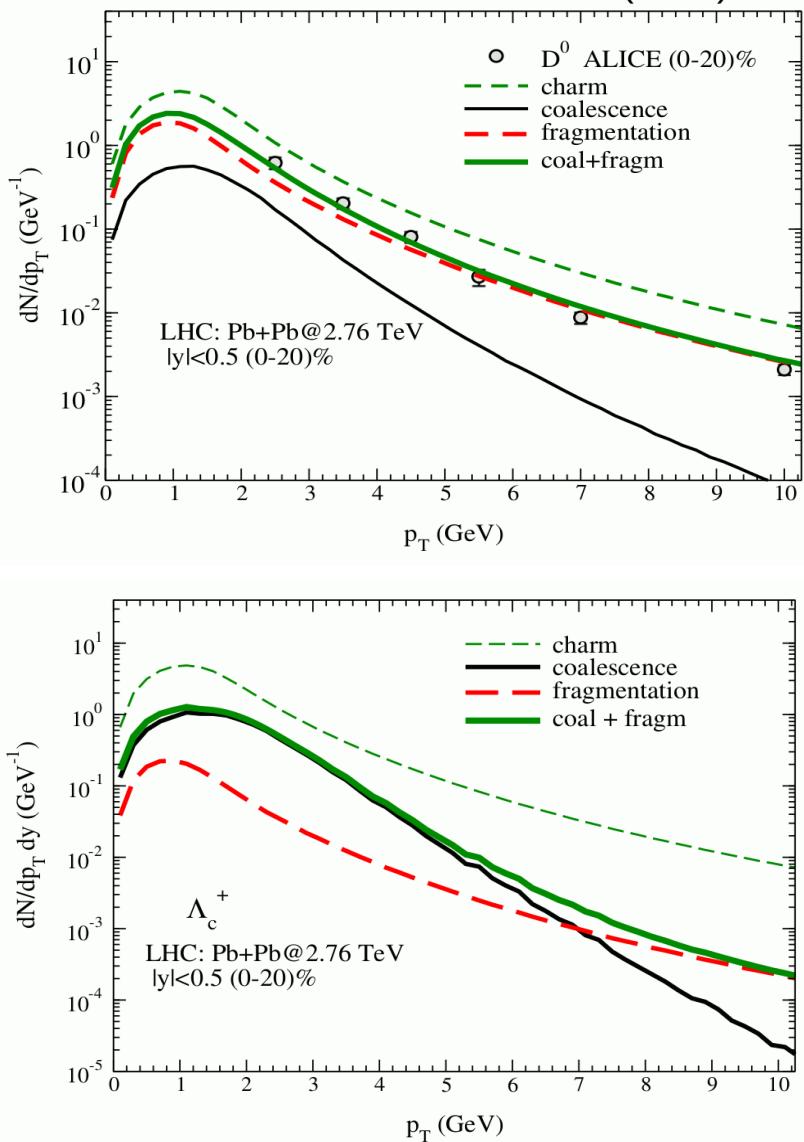
$$\mu_2 = \frac{m_3(m_1 + m_2)}{m_1 + m_2 + m_3} \quad \text{Is the reduced mass of the baryon}$$



X. Dong and V. Greco., Prog.Part.Nucl. Phys. (2018)

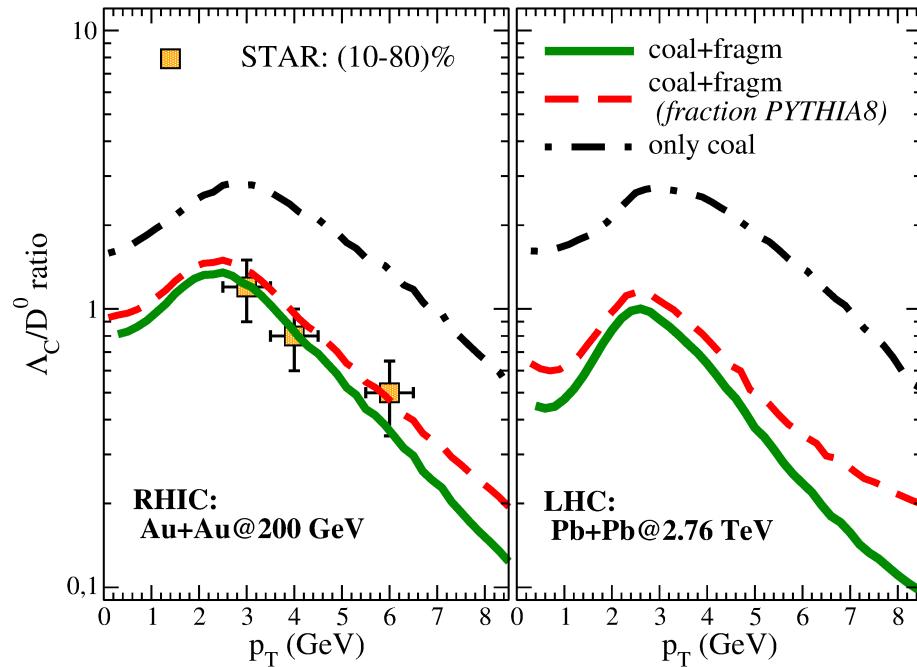
# LHC: results

Data from ALICE Coll. JHEP 1209 (2012) 112



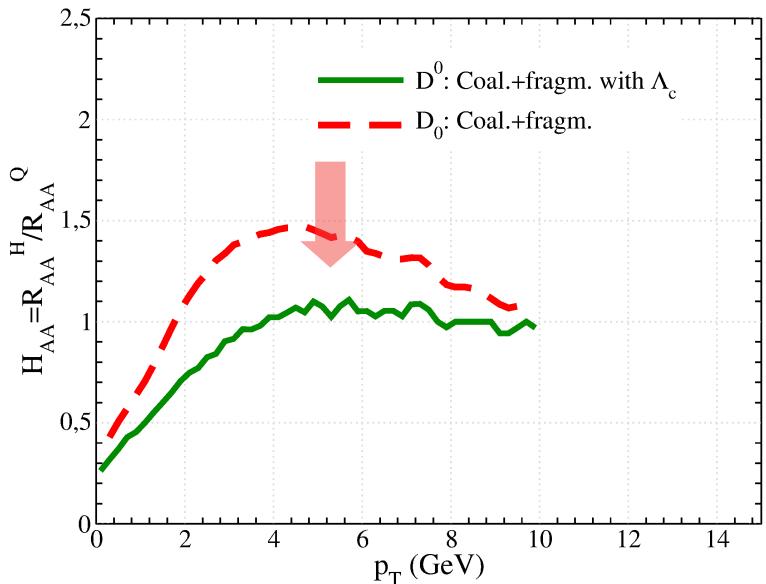
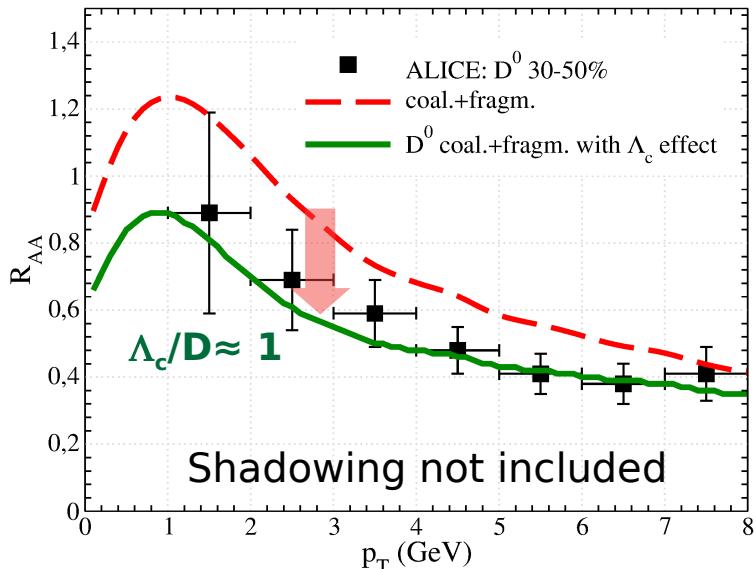
wave function widths  $\sigma_p$  of baryon and mesons  
kept the same at RHIC and LHC!

STAR coll. arXiv:1910.14628



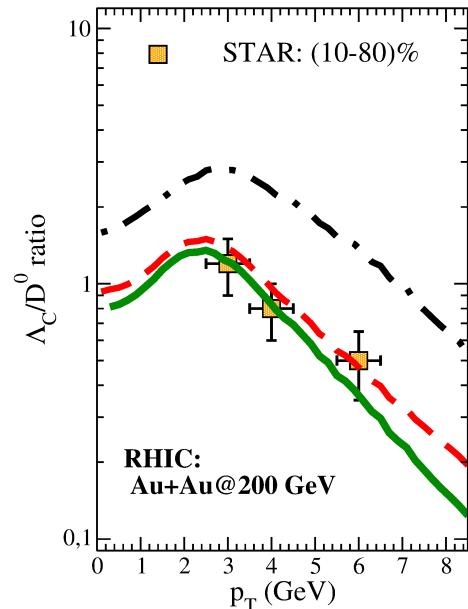
The  $\Lambda_c/D^0$  ratio is smaller at LHC energies:  
fragmentation play a role at intermediate  $p_T$

# Impact of large $\Lambda_c$ production on $R_{AA}(p_T)$

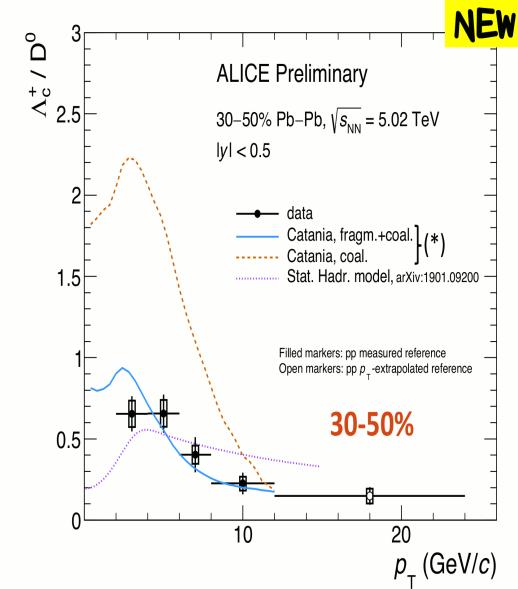


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ALICE coll. Zampolli SQM2019

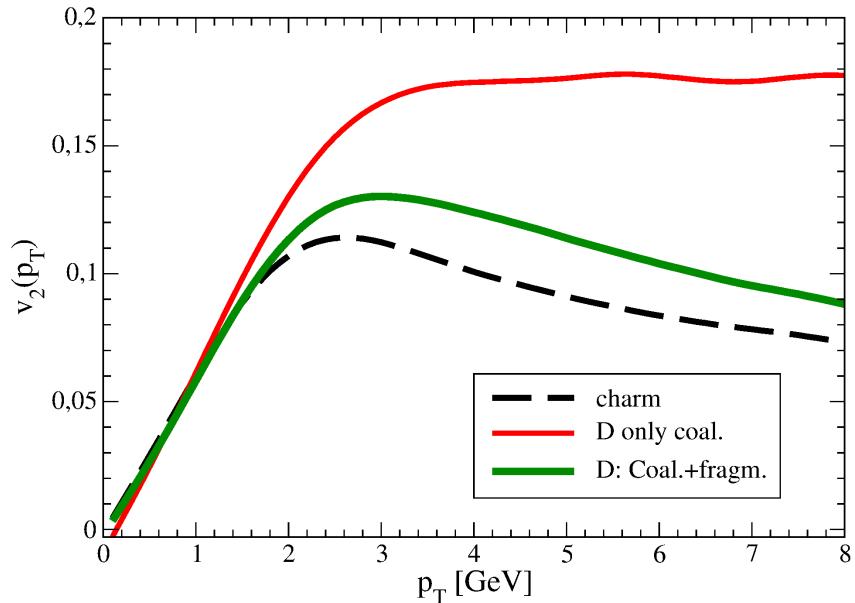
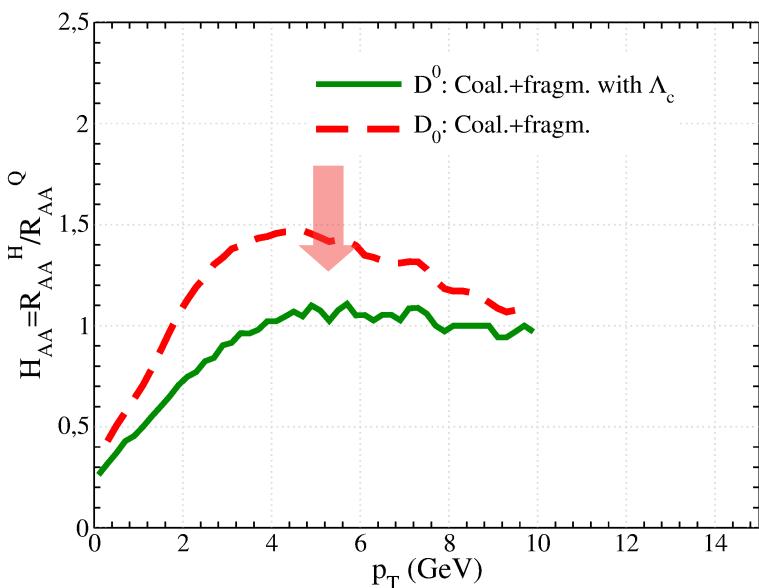
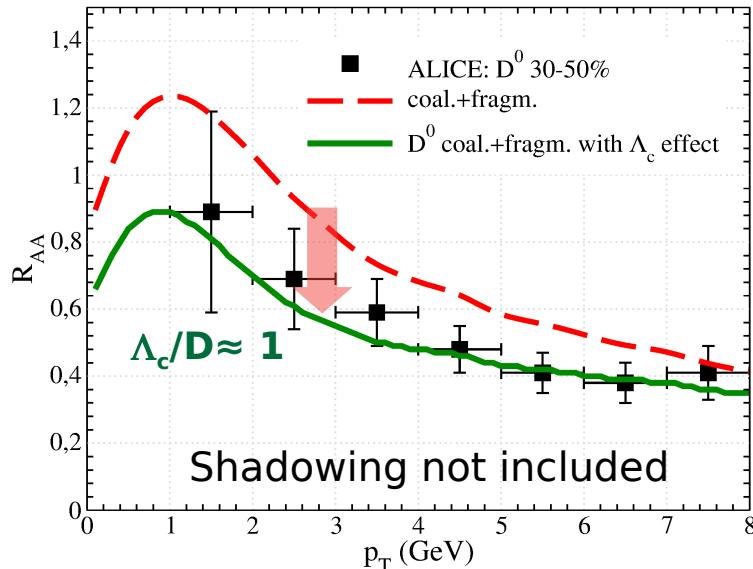


The  $\Lambda_c/D^0$  ratio is smaller at LHC energies:  
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S. Plumari, et al., Eur. Phys. J. C78 no. 4, (2018) 348

- ◊ The impact will be even larger for B meson  $\Lambda_b/B$

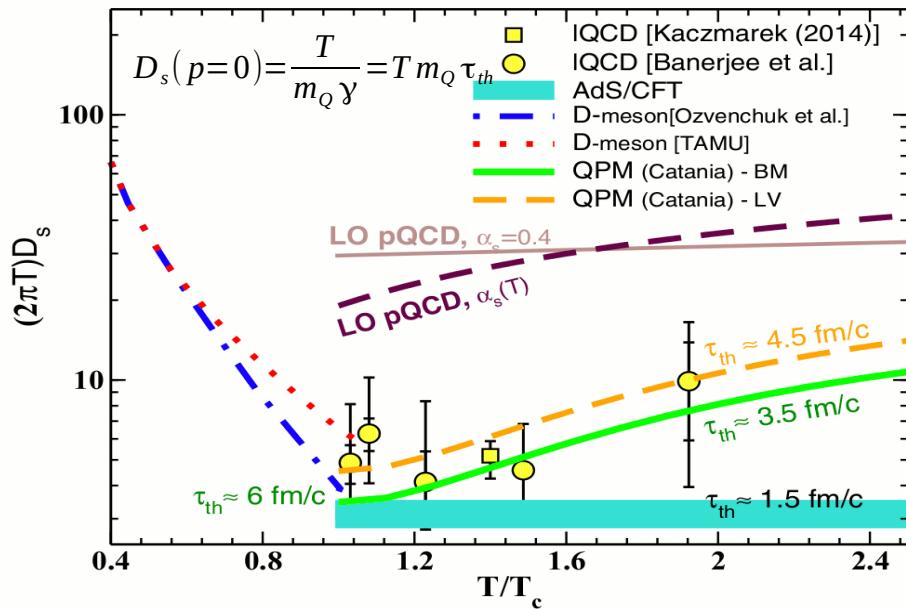
# Impact of hadronization on $R_{AA}(p_T)$ and $v_2(p_T)$



In (30-50)% the  $v_2(p_T)$  due to only coalescence increase a factor 2 compared to the  $v_2(p_T)$  charm.

# LHC: results

See talk S. K. Das (Tuesday 15:50)

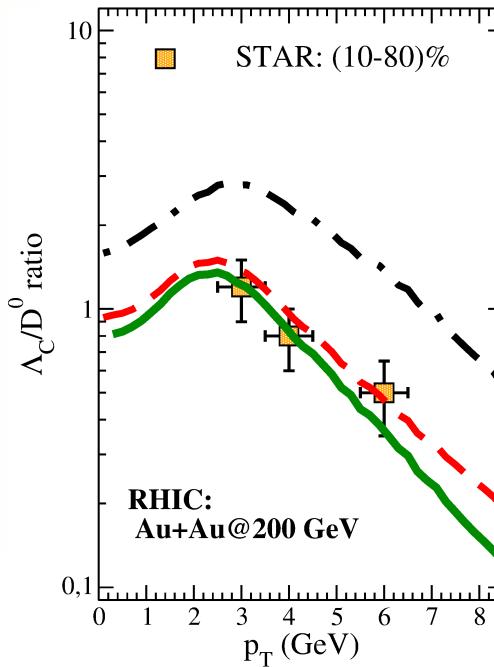


- Not a model fit to IQCD data! but the result from spectra or  $R_{AA}(p_T)$  &  $v_2(p_T)$
- With the same coalescence plus fragmentation model we describe the  $\Lambda_c/D^0$

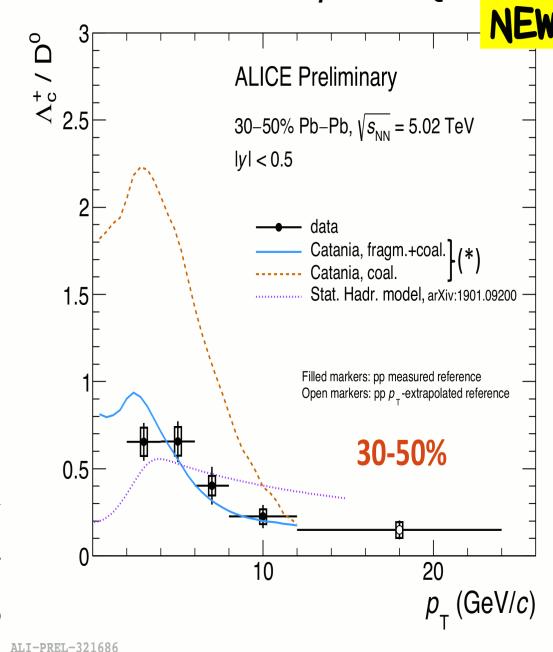
F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco,  
PRC96 (2017) no.4, 044905.

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STAR coll. arXiv:1910.14628



ALICE coll. Zampolli SQM2019

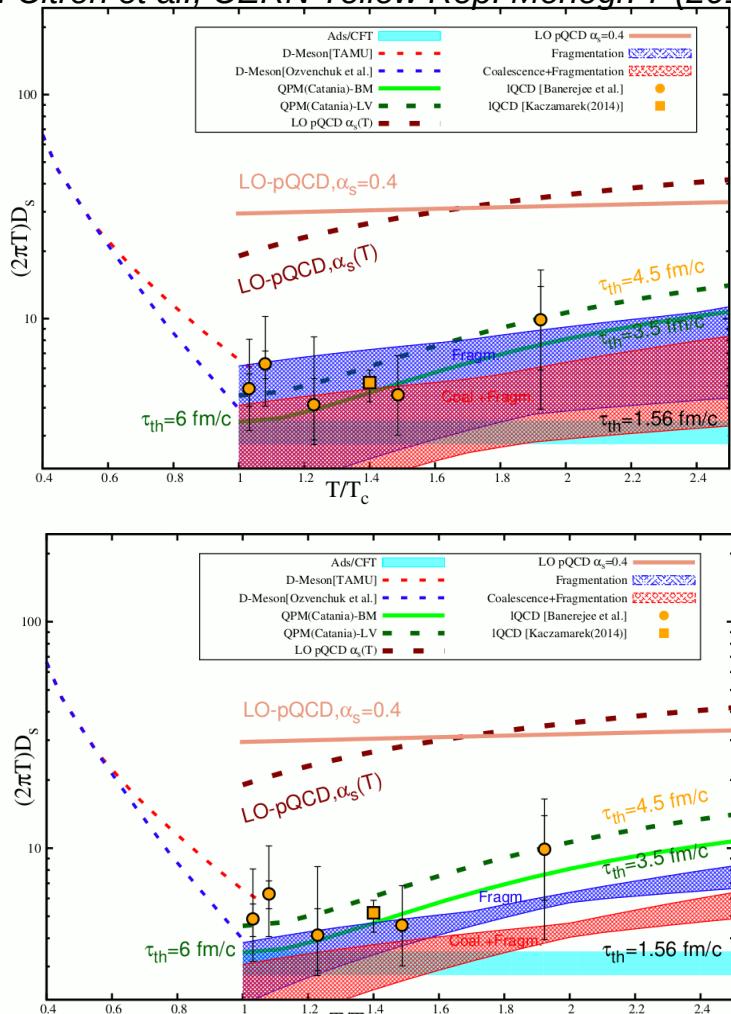


The  $\Lambda_c/D^0$  ratio is smaller at LHC energies:  
fragmentation play a role at intermediate  $p_T$

S. Plumari, et al., Eur. Phys. J. C78 no. 4, (2018) 348

# Impact of large $\Lambda_c$ production on $R_{AA}(p_T)$

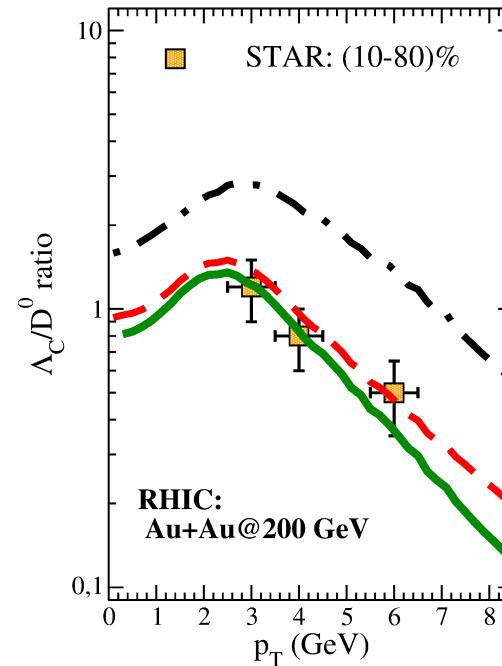
Z. Citron et al., CERN Yellow Rep. Monogr. 7 (2019) 1159



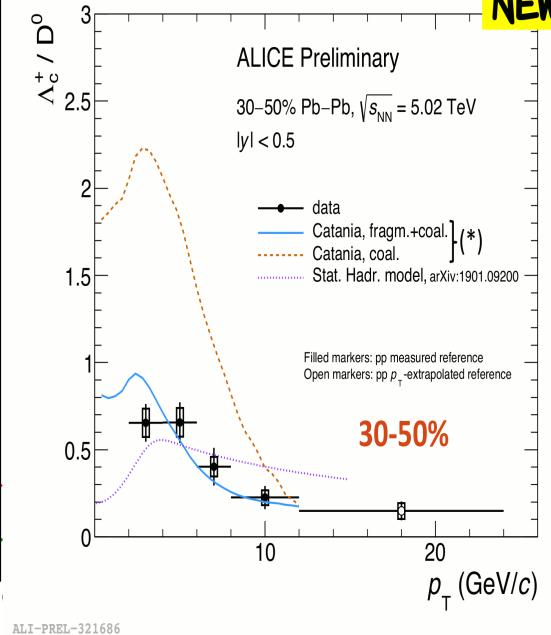
Different hadronization models can affect the extraction of the charm quark diffusion coefficient

wave function widths  $\sigma_p$  of baryon and mesons kept the same at RHIC and LHC!

STAR coll. arXiv:1910.14628



ALICE coll. Zampolli SQM2019



The  $\Lambda_c/D^0$  ratio is smaller at LHC energies: fragmentation play a role at intermediate  $p_T$

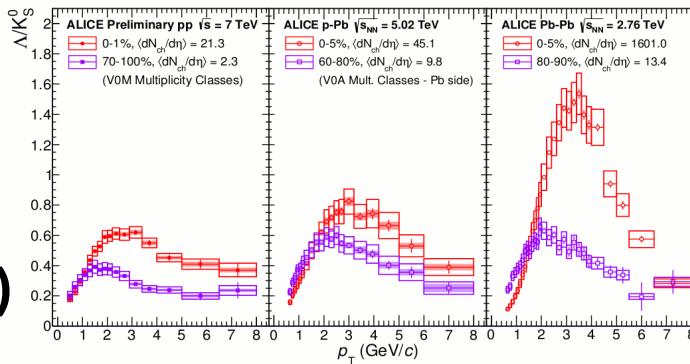
S. Plumari, et al., Eur. Phys. J. C78 no. 4, (2018) 348

# Small systems

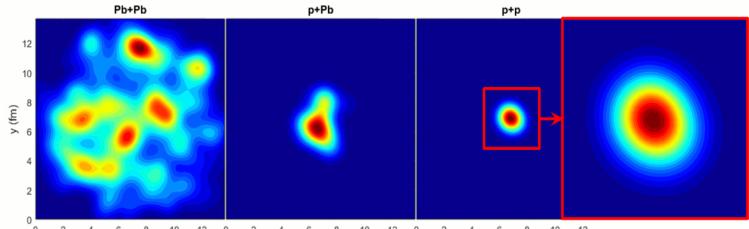
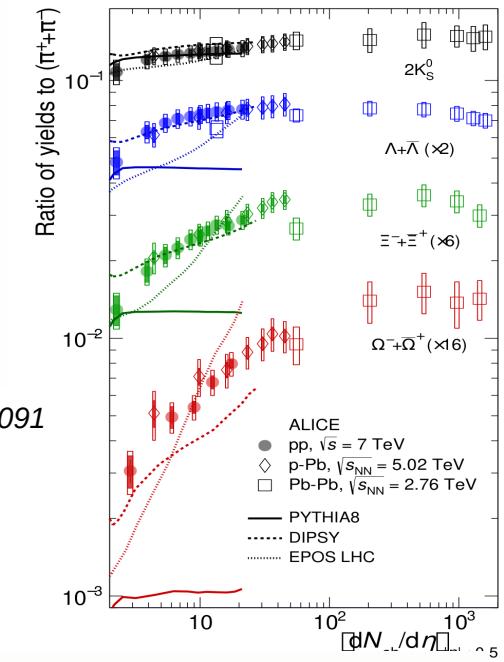
ALICE coll. *Nature Phys.* 13 (2017) 535

## Traditional view:

- QGP in Pb+Pb
- no QGP in p+p (“baseline”)

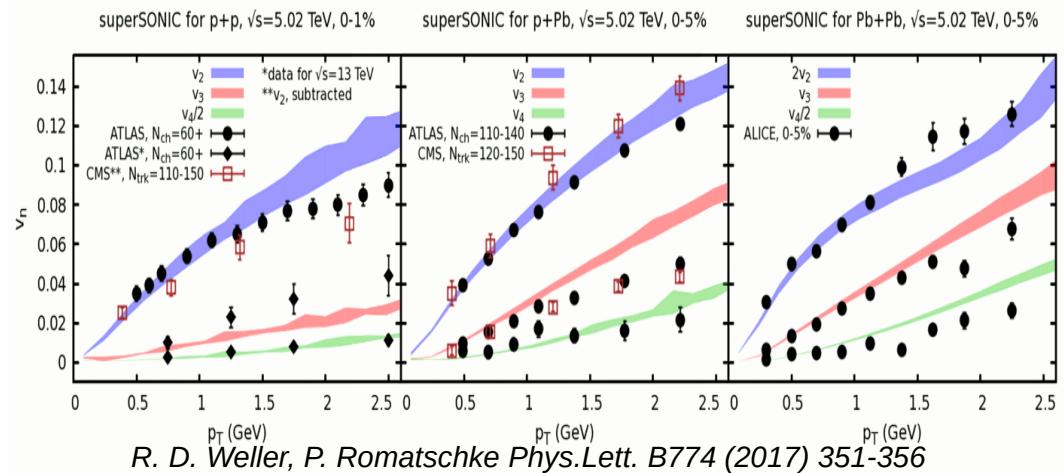


ALICE Coll., *PRL* 111 (2013) 222301  
 ALICE Coll., *J. Phys.: Conf. Ser.* 509 (2014) 012091  
 ALICE Coll. *NPA* 956 (2016) 777-780.



## Objections to applying hydro in pp

- Too few particles, cannot be collective
- System not in equilibrium



R. D. Weller, P. Romatschke *Phys.Lett.* B774 (2017) 351-356

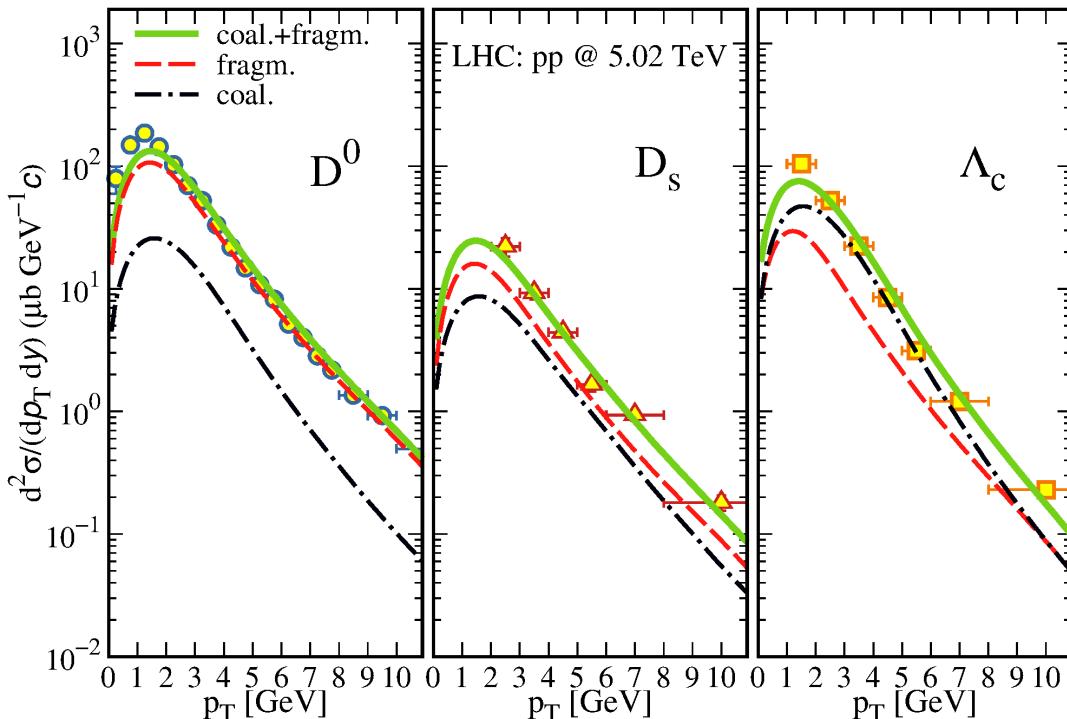
# Small systems: Coalescence in pp?

Common consensus of possible presence of QGP in smaller system.

What if:

- Assuming QGP formation also in pp?
- What coalescence+fragmentation predicts in this case?

Data taken from: ALICE coll. EPJ C79 (2019) no.5, 388  
ALICE coll. Meninno Hard Probes 2018



If we assume in  $p+p$  @ 5 TeV a medium similar to the one simulated in hydro:

◆ Thermal Distribution ( $p_T < 2$  GeV)

$$\frac{dN_q}{d^2r_T d^2p_T} = \frac{g_g \tau m_T}{(2\pi)^3} \exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T)}{T}\right)$$

$$\text{◆ Collective flow } \beta_T = \beta_0 \frac{r}{R}$$

◆ Fireball radius+radial flow constraints  $dN_{ch}/dy$  and  $dE_T/dy$

◆ Minijet Distribution ( $p_T > 2$  GeV)  
NO QUENCHING

## $p+p$ @ 5 TeV

- $t_{pp} = 1.7$  fm/c
- $\beta_0 = 0.4$
- $R = 2.5$  fm
- $V \sim 30$  fm $^3$

wave function widths  $\sigma_p$  of baryon and mesons kept the same at RHIC and LHC!

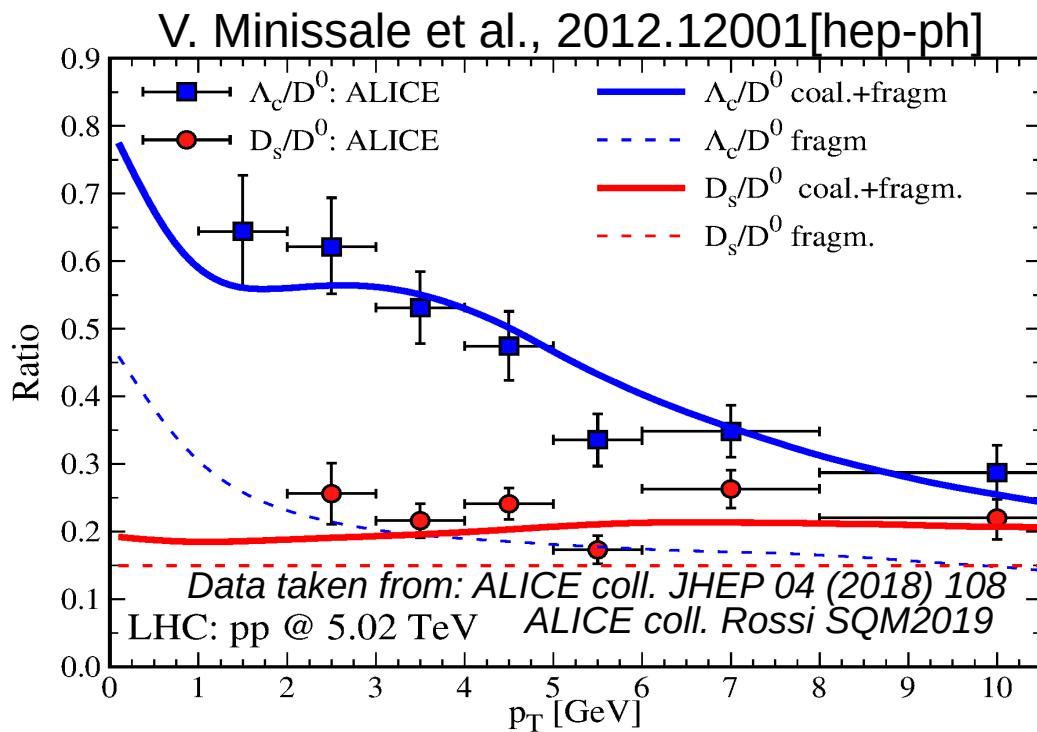
V. Minissale et al.,  
2012.12001[hep-ph]

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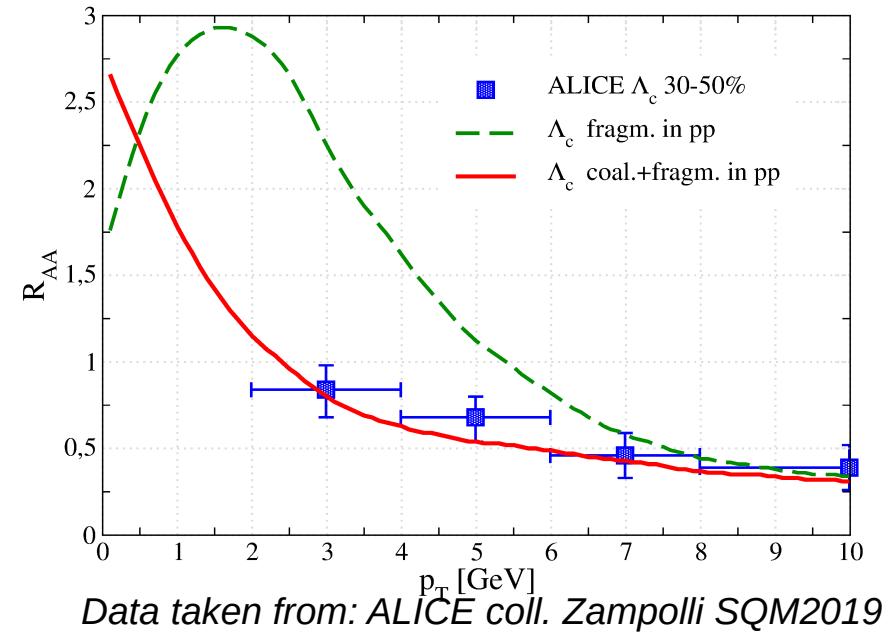
What if:

- Assuming QGP formation also in pp?
- What coalescence+fragmentation predicts in this case?



Big effect in AA collisions on  $R_{AA}$  of  $\Lambda_c \rightarrow$  different behaviour especially at low momenta.

Data seem to favour model where both coalescence and fragmentation are present in pp



# Heavy flavour (charm): Resonance decay

## Ground States

- $\Xi_c^+$  ( $I=1/2, J=1/2$ ) (usc)  $m=2467$  MeV
- $\Xi_c^0$  ( $I=1/2, J=1/2$ ) (dsc)  $m=2470$  MeV

## Resonances

- $\Xi'_c +$  (2578) ( $I=1/2, J=1/2$ )  $\rightarrow \Xi_c^+ \gamma$ ; B.R. 100
- $\Xi'_c 0$  (2579) ( $I=1/2, J=1/2$ )  $\rightarrow \Xi_c^0 \gamma$ ; B.R. 100%
- $\Xi_c^+$  (2645) ( $I=1/2, J=3/2$ )  $\rightarrow \Xi_c^+ \pi^-$ ,  $\Xi_c^0 \pi^+$ ; B.R. 100%
- $\Xi_c^+$  (2790) ( $I=1/2, J=1/2$ )  $\rightarrow \Xi'_c \pi$ ; B.R. 100%
- $\Xi_c^+$  (2815) ( $I=1/2, J=3/2$ )  $\rightarrow \Xi'_c \pi$ ,  $\Xi_c(2645) \pi$

## Ground State

- $\Omega_c^0$  ( $I=0, J=1/2$ ) (ssc)  $m=2695$  MeV

## Resonances

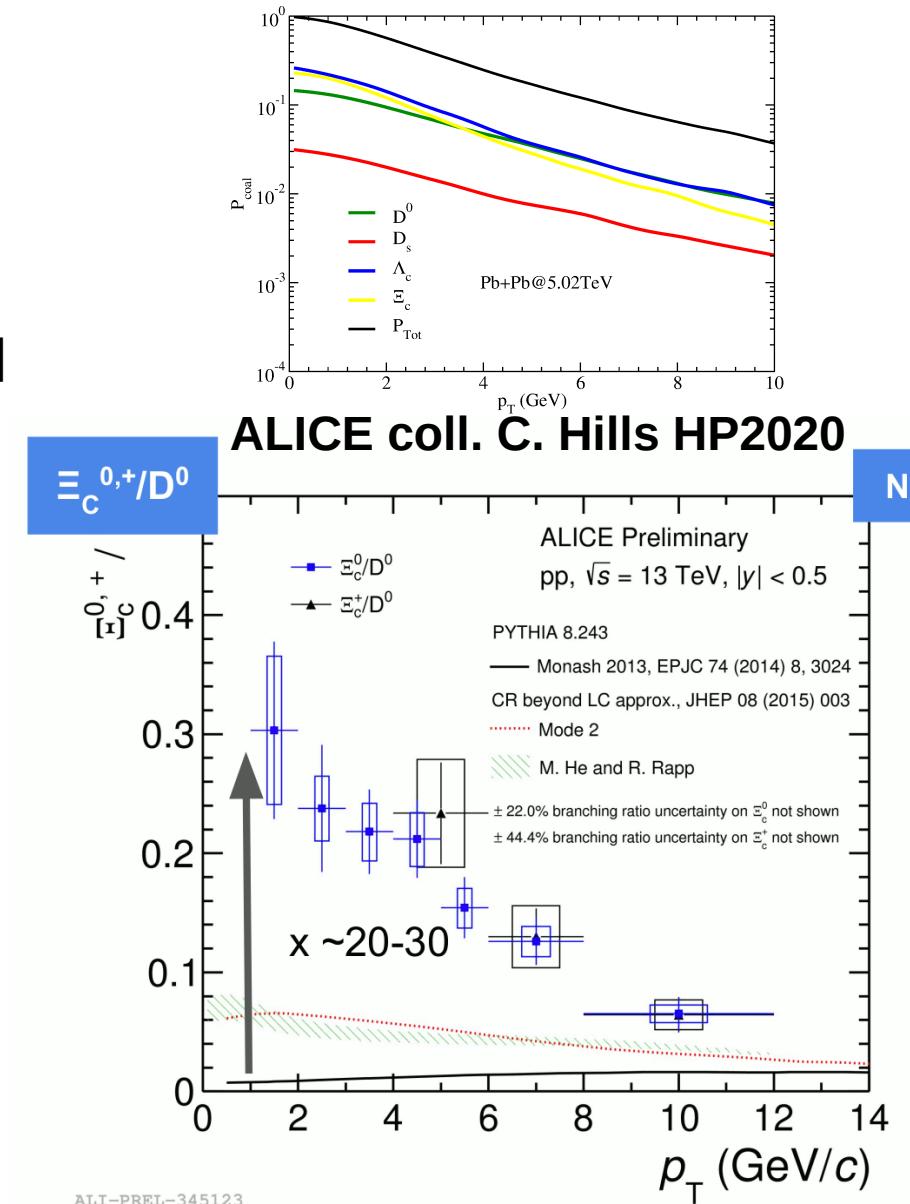
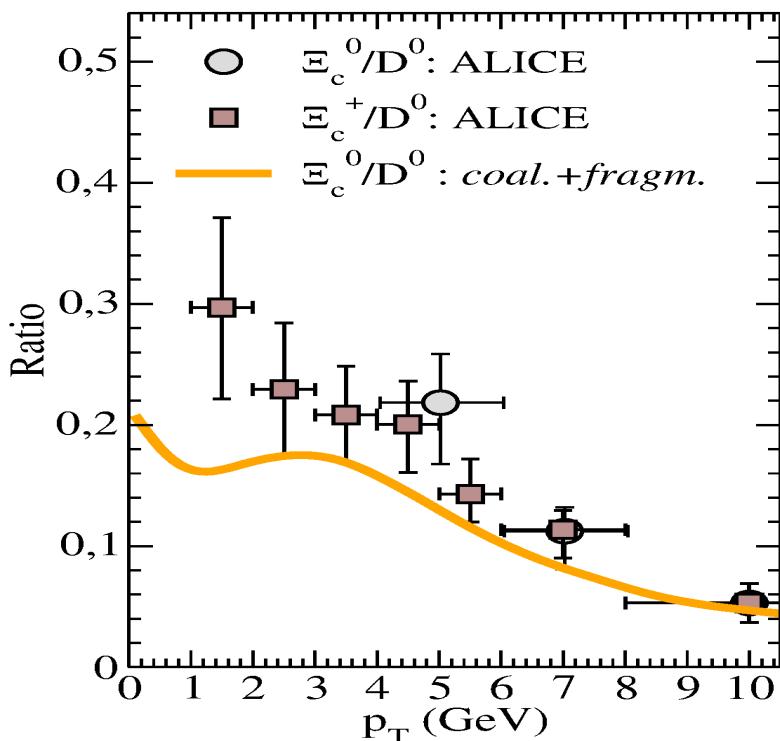
- $\Omega_c^0$  (2770) ( $I=0, J=3/2$ )  $\rightarrow \Omega_c^0 \gamma$   
B.R. 100%

In our calculations we take into account main hadronic channels, including the ground states and the first excited states

# Small systems: Coalescence in pp?

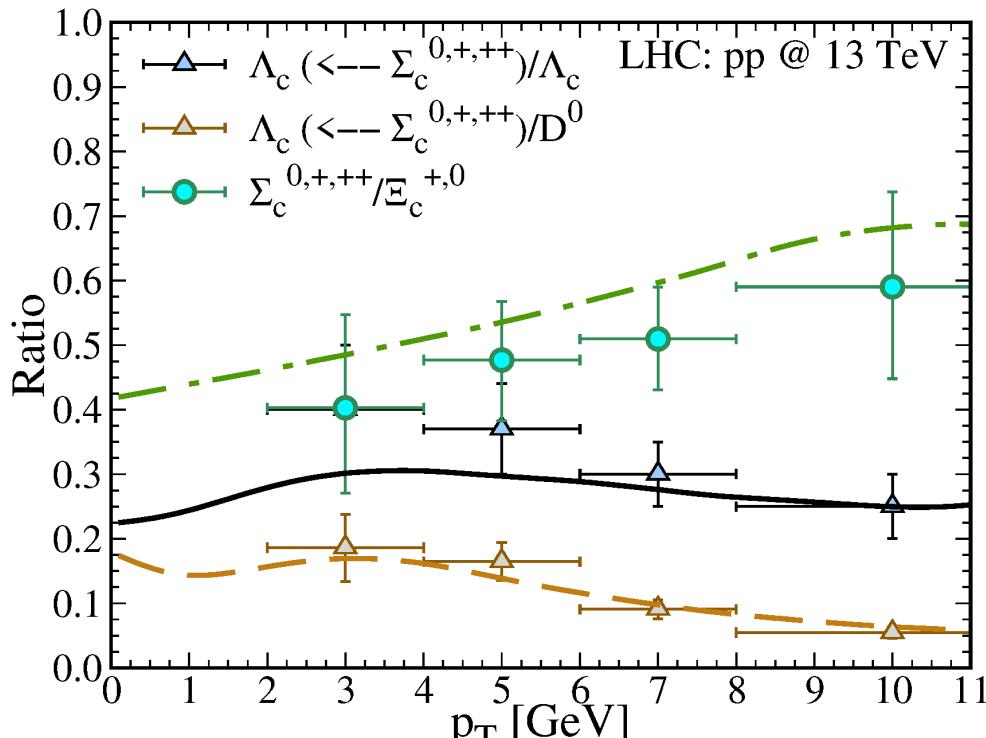
- Enhanced  $\Xi_c^0/D^0$  due to coalescence close to exp. data

V. Minissale et al., 2012.12001[hep-ph]



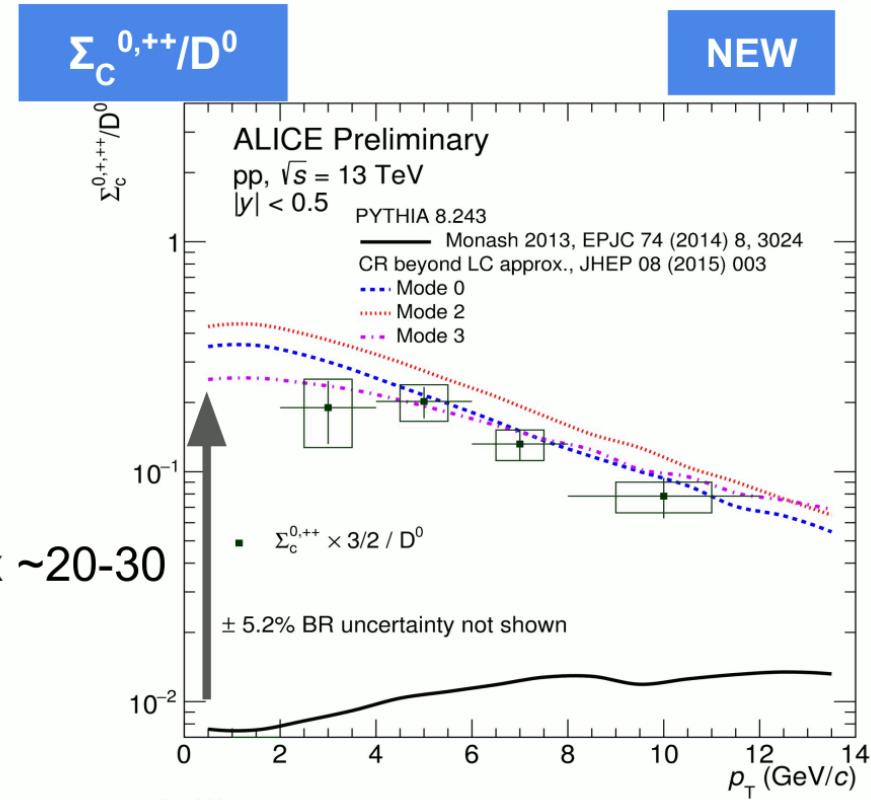
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V. Minissale et al., 2012.12001[hep-ph]



Data taken from ALICE coll. C. Hills HP2020

ALICE coll. C. Hills HP2020



# Conclusions

- Good agreement with RHIC and LHC data:

- ◆  $\Lambda_c$  production at intermediate  $p_T$  dominant role of coalescence mechanism
- ◆  $\Lambda_c/D^0 \sim 1.0$  for  $p_T \sim 3$  GeV with Coal.+fragm. Model

- In p+p assuming a medium like in hydro:

- ◆ Coal.+fragm. good description of heavy baryon/meson ratio.
- ◆ coalescence shows a mass ordering at low  $p_T$  similar to the data
- ◆ Good description of the recent data: enhancement of  $\Xi_c/D^0$  ratio due coalescence

