Hadronisation Mechanism

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PIANO NAZIONALE DI RIPRESA E RESILIENZA

Focus of this presentation

✧ **Focus on heavy flavor hadronization:**

- Surprises!?: Λ_C/D^0~ 0.5-1 not only in AA but even in pp, strong enhancement wrt e^+e^-

➢ **Studying charm dynamics and production:**

Coalescence+Fragm.: Coal-Catania, RR-TAMU(AA), PHSD-Frankfurt, CCNU-Duke, Coal-TAMU-CCNU, QCM, EPOS4HQ-Nantes

String Fragm./Reconn.: PYTHIA (LC→ CR), POWLANG-HERWIG… AGANTYR

Statistical Hadronization Model: SHM-Heidelberg (AA), SHM-TAMU(pp)]

→ Overview Similarities/Differences and some open questions

- quite a multiple Hazardous self-imposed Task!!

A lot of material and discussion in Altmann, Dubla, Greco, Rossi & Skands, arXiv:2405.19137

[1 week ago]

Relevance of HF Hadronization

✧ **Hadronization is very relevant:**

- **in itself:** how hadron are produced? Is it a universal process in e^+e^-, e^-p, pp, pA and AA?

- **HQ transport properties** --> estimate $2\pi TD_s(T)$ vs LQCD: both $R_{AA}(p_T)$ & $v_n(p_T)$ affected

- **QGP droplets:** infer properties of medium created in pp and/or pA

- **Polarization:** underlying the interpretation for light hadrons, open HF and quarkonia., $\rho_{00}^{coal} = \frac{1-P_q P_{\bar{q}}}{3+P_q P_{\bar{q}}}$, $\rho_{00}^{frag} \cong \frac{1+0.5\,P_q^2}{3-0.5P_q^2}$

[Xu-Guang Huang, previous talk]

- **ALICE 3:** predictions for multi-charm production PbPb vs KrKr vs ArAr

[Plumari, Tue 4, 9:10]

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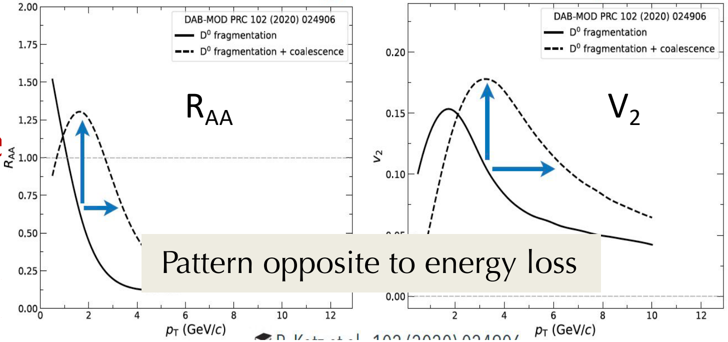

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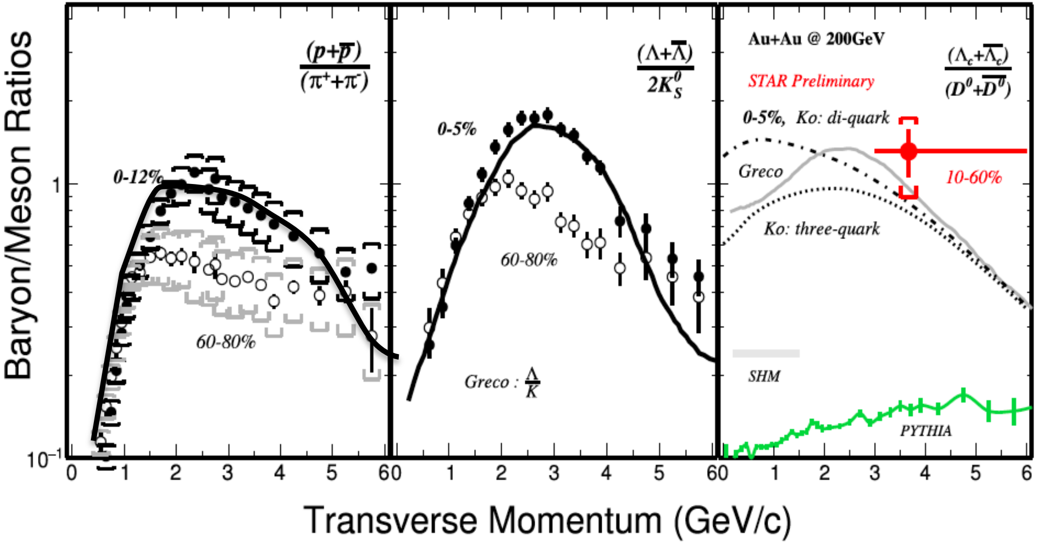
Hadronization in the light and strange sector



Dong-Greco, Prog.Part.Nucl.Phys. 104(2019)

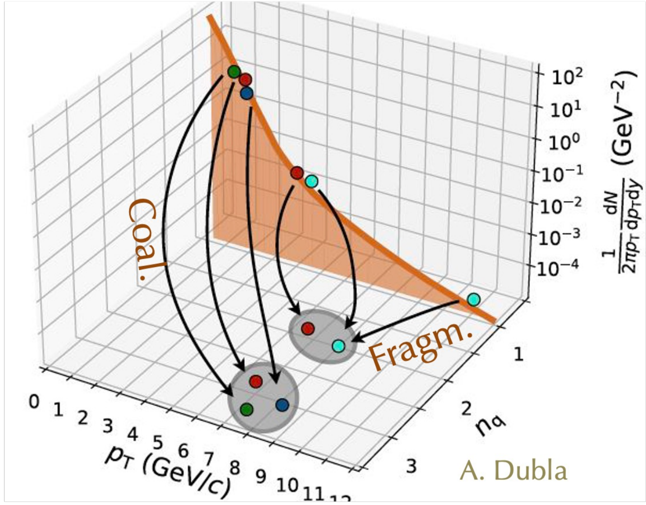
- ❖ Yields ratios ok in SHM-Heidelberg: π,p,K,Λ,…
- ❖ I[0] prediction of Ko PRC(2009) of a very large Λ_c/D^0 even at low p_T >> SHM[PDG] >> e^+e^- (~ PYTHIA)

In 2002-2004 large p/π, Λ/K at intermediate p_T:

→ development of coalescence + fragm. in AA collisions
$f_M \approx f_q \otimes f_{\bar{q}} \otimes \Phi_M$ [G-Ko-Levai & Fries-Muller-Nonaka-Bass PRL90(03)]

→ v_2 quark number scaling (~ also for ϕ…)

→ HF $\mathbf{m_{b,c} >> \Lambda_{QCD}, T}$: not created at hadronization
+ close to energy conservation with constituents quarks



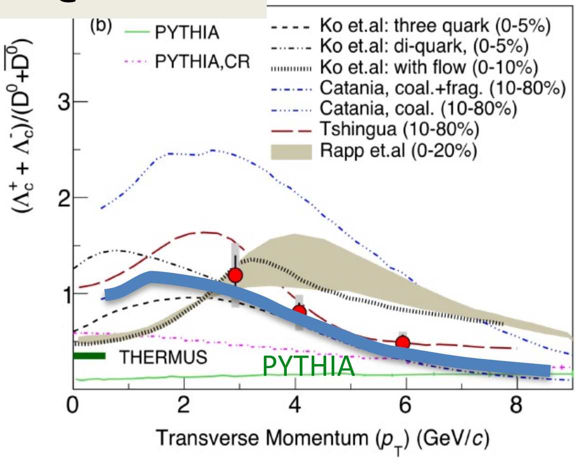
HF Baryon enhancement

✧ Heavy Flavor hadronization coal.+fragm. applied to pp and AA:

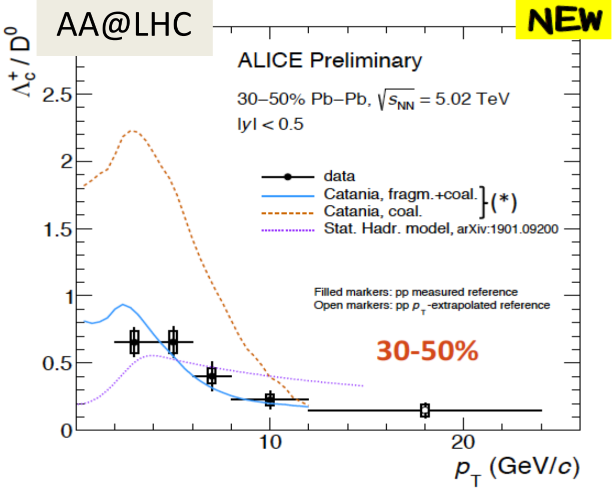
- in **AA**: a peak in $\Lambda_c/D^0 \approx O(1)$ (STAR and ALICE) predicted by Coal.+Fragm.

- but even **pp**: $\Lambda_c/D^0 \approx 0.6$, $\Xi_c/D^0 \approx 0.25$ ALICE data

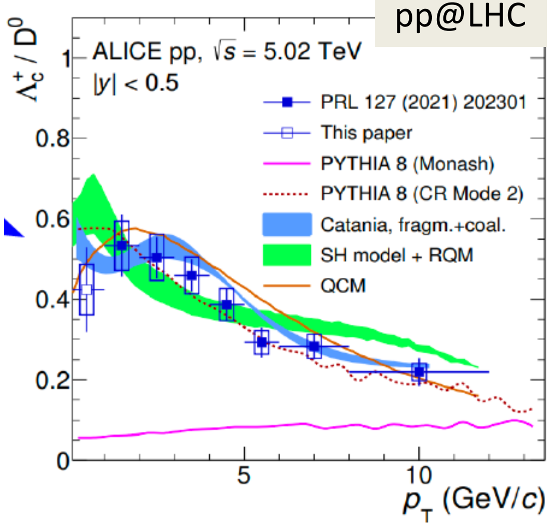
AA@RHIC-STAR



AA@LHC



pp@LHC



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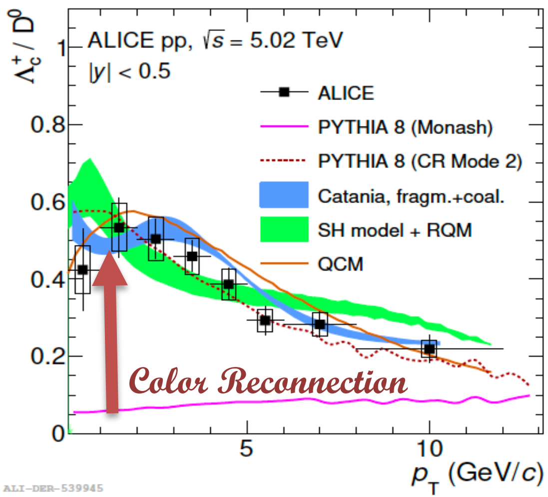
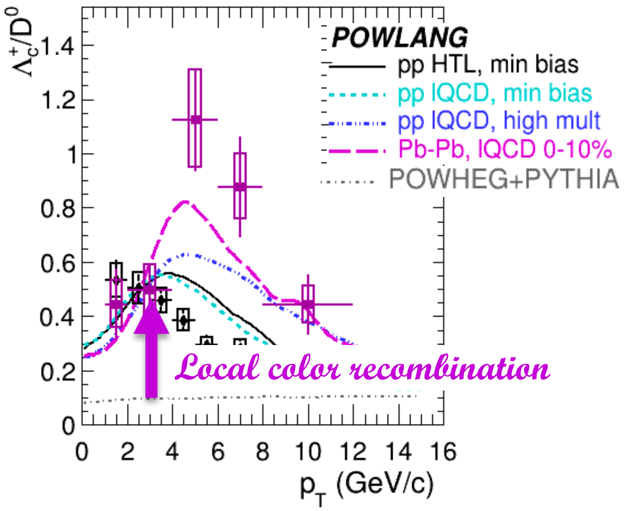
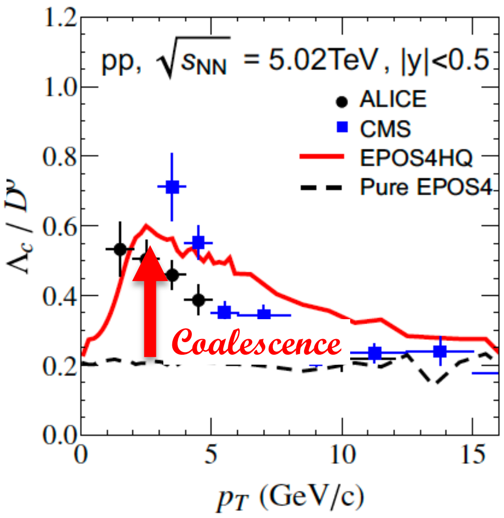
HF Baryon enhancement impact

➢ **HF hadronization have stimulated developments**:

- PYHTIA beyond Leading Color (LC)→ Color Reconnection (CR) in pp
- Coalescence+Fragmentation approach applied to pp
- Local color recombination: POWLANG in AA and in pp
- Inclusion of HF Coalescence+ Fragmentation in EPOS (pp &AA)







See also: Fionda 3 Mon [11:05], J. Cho, 4 Tue [09:30]

Let’s fix some points starting from the Catania model…

Basic fearures of Catania coal.+fragm. in AA

Statistical factor colour-spin-isospin

Parton Distribution function

Coalescence function ~ Hadron Wigner function

$$\frac{dN_{Hadron}}{d^2p_T} = g_H \int \prod_{i=1}^{N_q} p_i \cdot d\sigma_i \frac{d^3p_i}{(2\pi)^3} f_q(x_i, p_i) \mathbb{C}_H(x_1, \ldots, x_n; p_1, \ldots, p_n) \delta\left(p_T - \sum_i p_{iT}\right)$$

For **u,d,s** Thermal+flow ($p_T < 2.5$ GeV)

$$f_q(p) \sim \frac{dN_{q,\bar{q}}}{d^2p_T} \sim exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T \mp \mu_q)}{T}\right)$$

Same fireball of the predictions for p/π, Λ/K, p/ϕ and their v_n QNS scaling at RHIC and LHC [Greco-Ko-Levai, PRL(2003)]

Volume ~ V(SHMc), Andronic et al., PLB 797 (2019)

+ quenched minijets for u,d,s ($p_T > 2.5$ GeV)

For Charm $f_c(x,p)$ in **AA** from the studies of R_{AA} and v_2 of **D-meson** to determine the Space Diffusion coeff.: simulations solving Relativistic Boltzmann transport eq.

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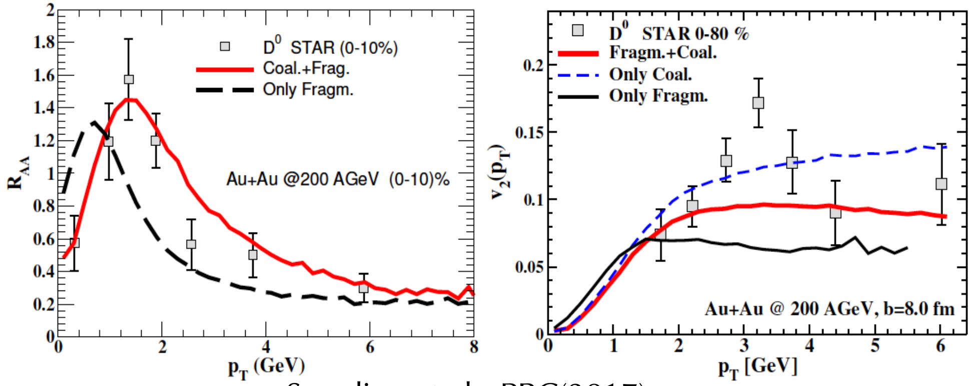

Scardina et al., PRC(2017)

Coalescence approach in phase space

Statistical factor colour-spin-isospin

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Coalescence function <-> Wigner function

$$\mathbb{C}_H(\ldots) = C^{N_q-1} f_H\left(x_1 .. x_{N_q}, ;\ p_1 \ldots p_{N_q}\right)$$

Wigner function **width σ_r** fixed by root-mean-square charge radius from **relativistic quark model**

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

Wigner function f_H <-> Wave function φ_M

$\varphi_M(\boldsymbol{r})$ *meson wave function*: gaussian

$$f_H(x_i, ;\ p_i) = \prod_{i=1}^{N_q-1} 8 \exp\left(-\frac{x_{r,i}^2}{\sigma_{r,i}^2} - p_{r,i}^2 \sigma_{r,i}^2\right)$$

Meson $N_q=2$, baryon $N_q=3$

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Meson N_q=2 , baryon N_q=3

- Employing <r^2> from RQM there are **no free parameters**! Even if modification of <r^2> can be envisaged at T=155 MeV
- Resonances (D^*, Λ_c, Σ_c …) yields rescaled according to SHM (thermal suppresion)

Coalescence + fragmentation in phase space

Statistical factor colour-spin-isospin

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  $P_{coal}(p \to 0)=1$ not in standard coalescence ….
  affects quadratically baryon production, has a quite physical motivation

- ✧ The charm not "coalescencing" undergo fragmentation:

$$\frac{dN_{had}}{d^2p_T\,dy} = \sum \int dz \frac{dN_{fragm}}{d^2p_T\,dy} \frac{D_{had/c}(z,Q^2)}{z^2}$$

Peterson or Kartvelishvili et al.

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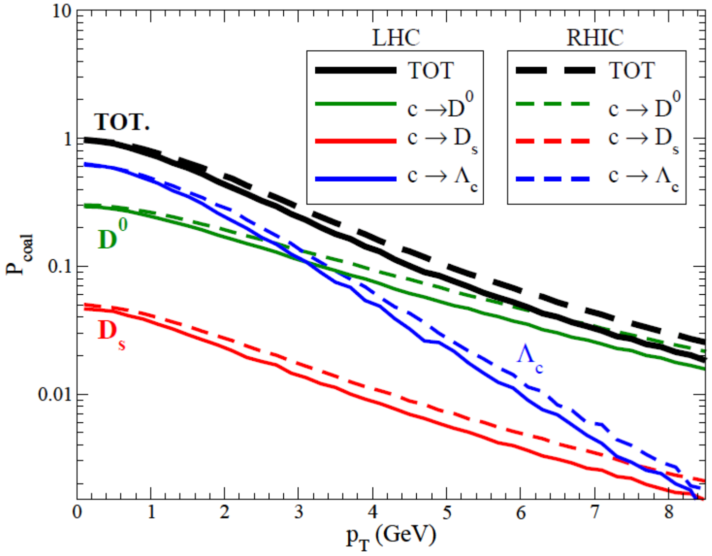
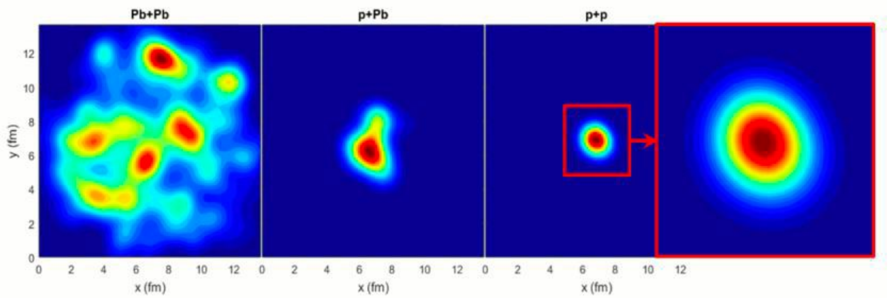


S. Plumari, V. Minissale et al., EPJ **C78**(2018) 348

Coalescence in pp?

Daring to assume a small fireball according **viscous hydro** applied to pp as in AA, but **size,time, flow given by hydro for pp**



R. D. Weller, P. Romatschke,PLB 774 (2017) 351-356

p+p @ 5 TeV

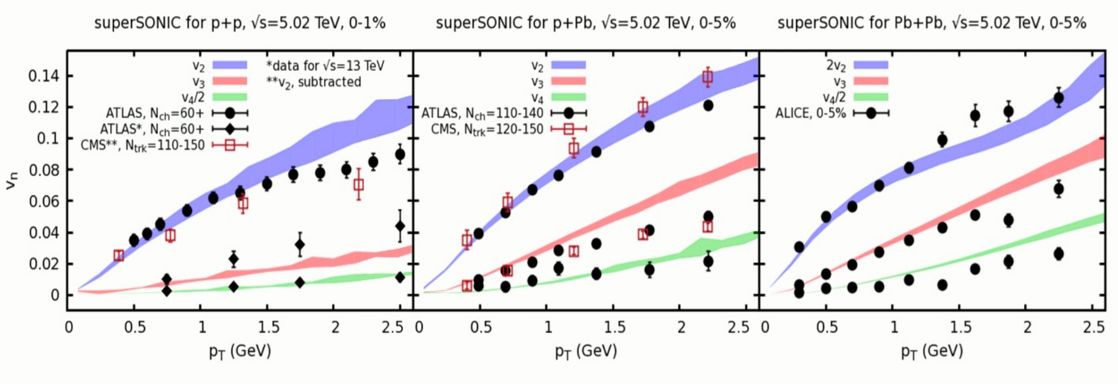
- t_{pp}=1.7 fm/c
- β_0=0.4
- R=2.5 fm
- V~30 fm³

+ $f_c(p)$ from FONNL distribution

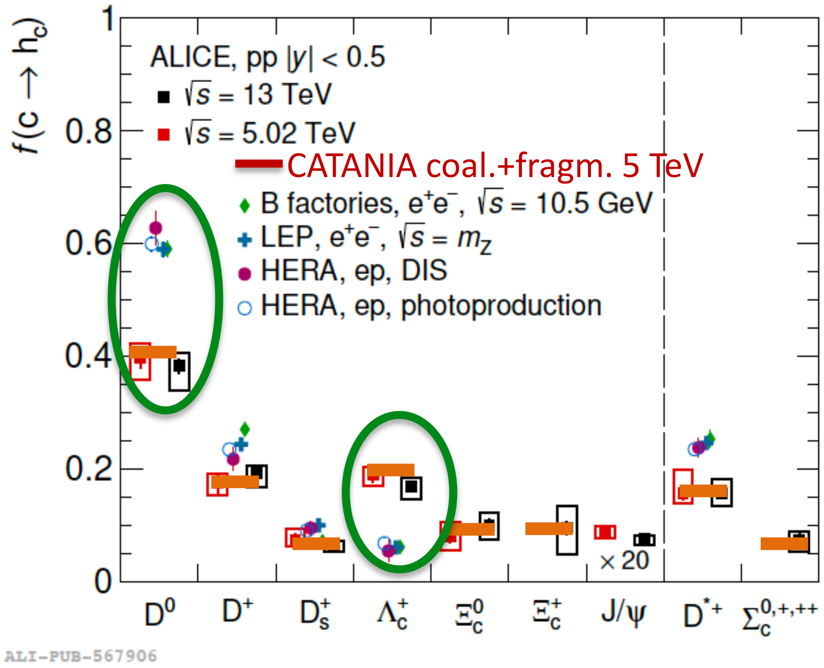
$$f_q(p) \sim \frac{dN_{q,\bar{q}}}{d^2p_T} \sim exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T \mp \mu_q)}{T}\right)$$

\+ same Wigner function widths $\sigma_{r,i}$ of hadrons in AA

$$f_H(x_i,; p_i) = \prod_{i=1}^{N_q-1} 8\exp\left(-\frac{x_{r,i}^2}{\sigma_{r,i}^2} - p_{r,i}^2\sigma_{r,i}^2\right)$$



“Fragmentation” Fractions in pp Catania Coalescence

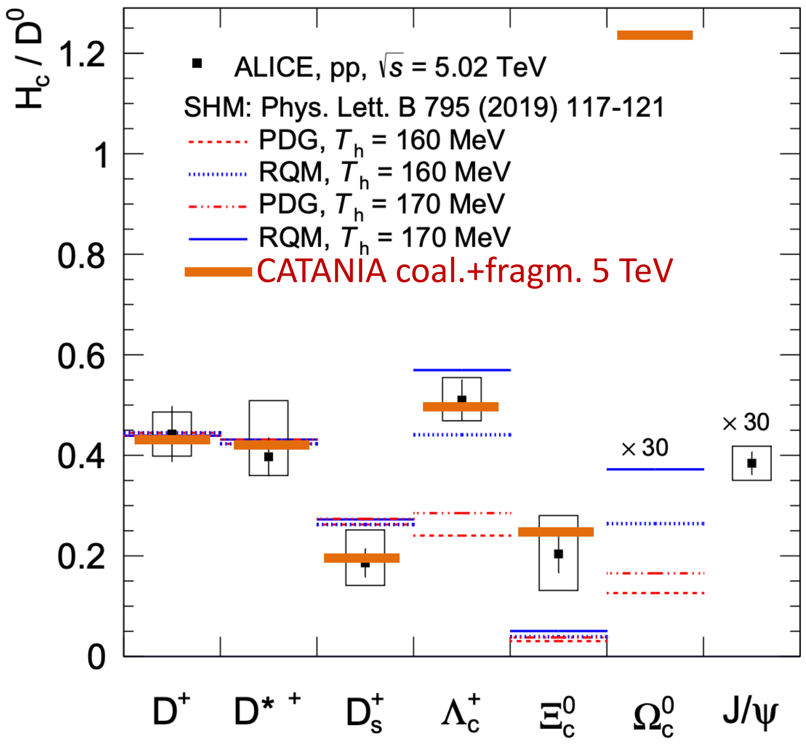


- Evidence of different “Fragmentation” Fractions in pp at LHC wrt e^+e^-(e^-p) collisions.

- Catania Coal+Fragm. very close to pp FF

- SHM+RQM baryon resonances would have a similar agreement (T~160-170 MeV)… except for Ξ_c

Ratio to D^0 in pp



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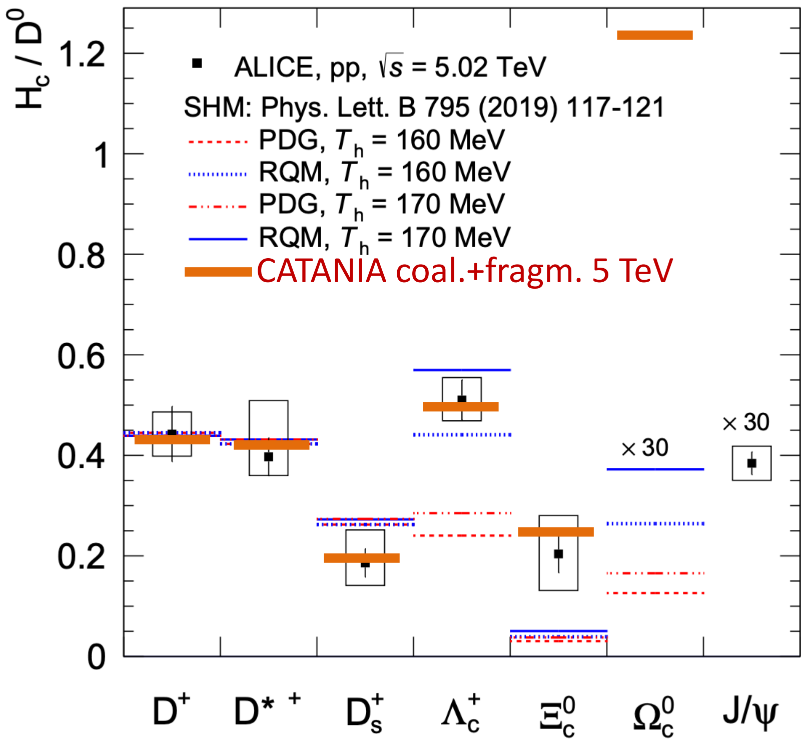
  … except for Ξ_c, Ω_c

Similar for AA with SHM_C[Andronic et al., *JHEP* 07 (2021)]

Fractions to D^0 in pp Catania Coalescence



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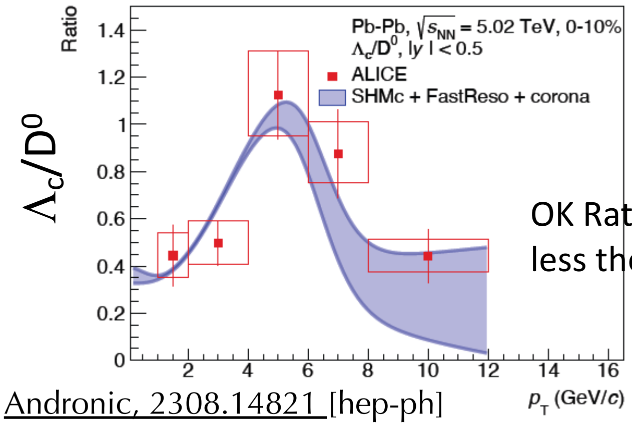
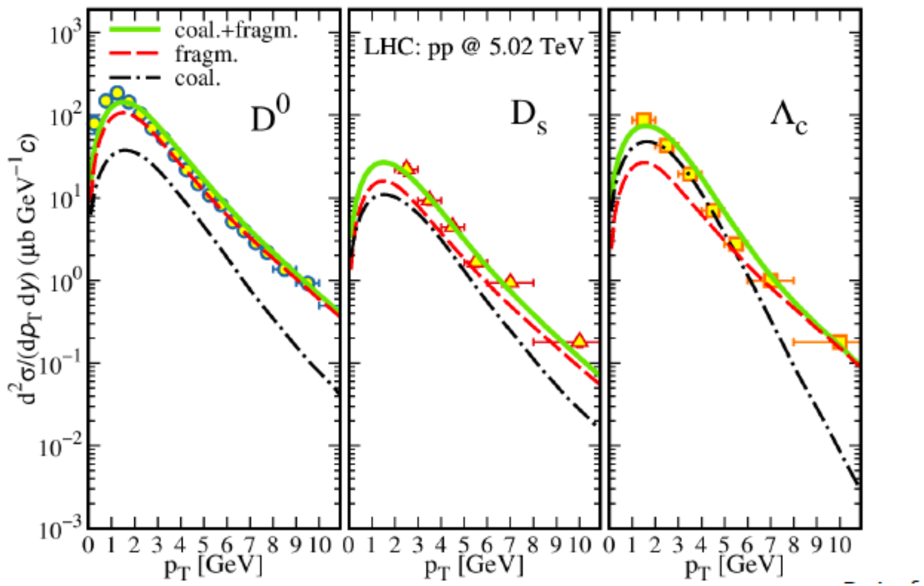
Coupling SHMc-RQM in AA to visco hydro

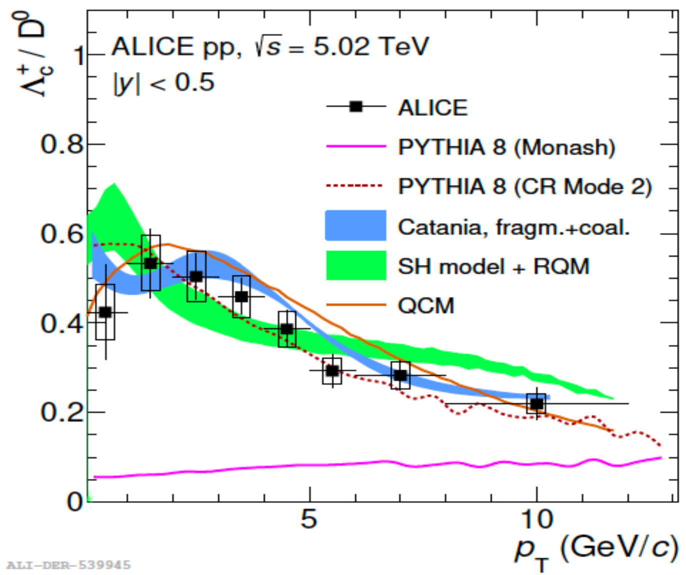


OK Ratio
less the p_T sectrum

Andronic, 2308.14821 [hep-ph]

Coalescence in pp baryon/meson vs p_T

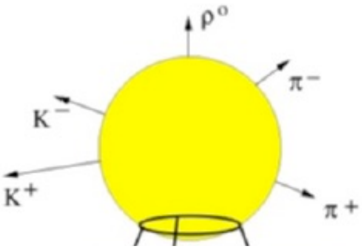


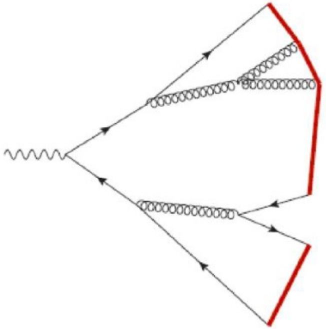


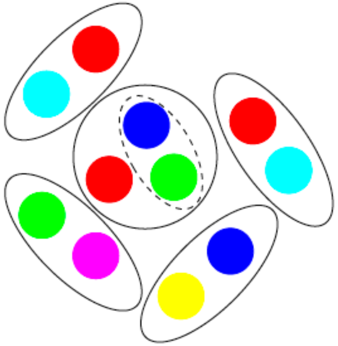
Minissale et al., PLB821(2021)

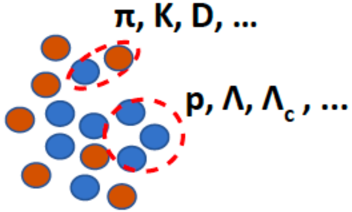
- Coalescence does not affect significantly D^0, but is dominant for baryons Λ_c and Ξ_c
- More abundant the coalescence contribution for B even in pp, Minissale et al., 2405.19244

Let's go through the different approaches to HF Hadronization









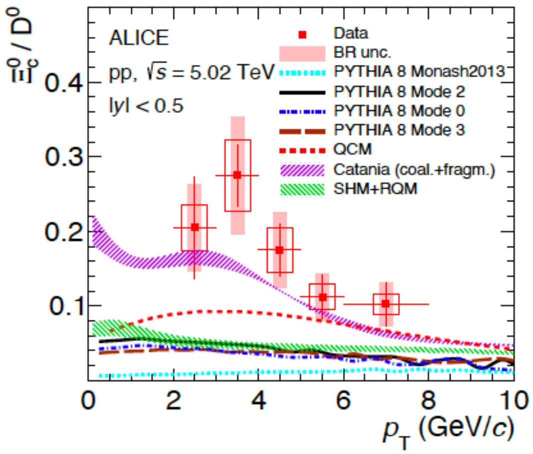
SHM+RQM (TAMU for pp)

M. He, R. Rapp, PLB795(2019) [charm]
M. He, R. Rapp, PRL131(2023) [bottom]

$$n_i \cong g_i \frac{T_H m_i^2}{2\pi^2} K_2\left(\frac{m_i}{T_H}\right) \quad i = D^0, D^+, D^{*+}, D_s, \Lambda_c, \Sigma_c, \Xi_c, \ldots$$

Needs additional set of
c-baryon state according to RQM(*) (and ~LQCD)

- Very good Λ_c/D^0 vs data [*T_H=170 MeV, flavor hierarchy?!*]
- RQM Resonances not yet seen in e^+e^-, e^-p
- For the yield assumes a thermal distribution, but for comparing data vs p_T a fragmentation function is exploited
- Other ratios like Ξ_c/D^0 still lack yields
- Extended to bottom in pp: an explanation of Λ_b/B^0 evolution from e^+e^- to pp →Canonical Suppression
  [but assuming V_{corr} values and a linear evolution with N_{tracks}]



(*)-Increased set of baryons for the Λ_c production:
PDG: $5\Lambda_c$, $3\Sigma_c$, $8\ \Xi_c$, $2\ \Omega_c$
RQM: $18\ \Lambda_c$, $42\ \Sigma_c$, $62\ \Xi_c$, $34\ \Omega_c$

Effective thermal yield

$$g_{\Lambda_c}^{RQM} \sim 2 g_{\Lambda_c}^{PDG}$$

SHM+RQM (TAMU for pp)

M. He, R. Rapp, PLB795(2019) [charm]
M. He, R. Rapp, PRL131(2023) [bottom]

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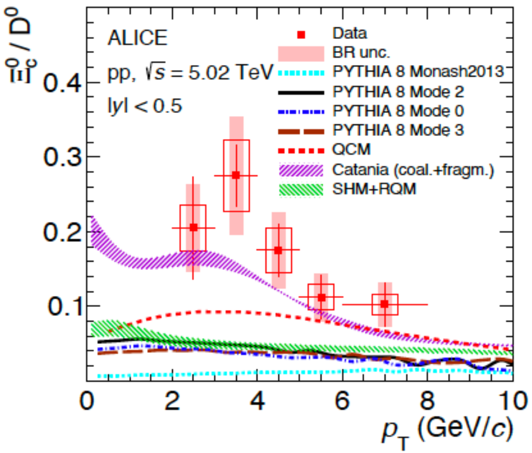
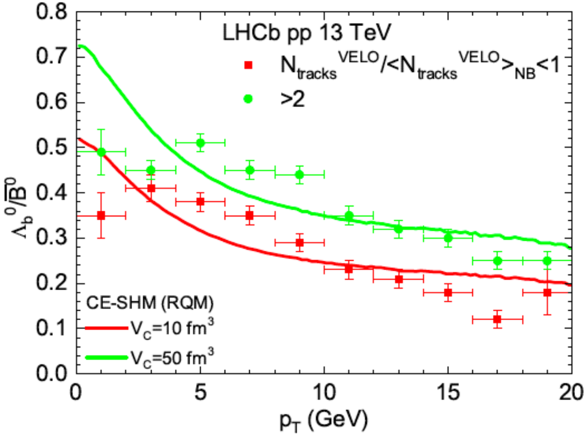




(*)-Increased set of baryons for the Λ_c production:
PDG: $5\Lambda_c$, $3\Sigma_c$, $8\ \Xi_c$, $2\ \Omega_c$
RQM: $18\ \Lambda_c$, $42\ \Sigma_c$, $62\ \Xi_c$, $34\ \Omega_c$

Effective thermal yield

$$g_{\Lambda_c}^{RQM} \sim 2 g_{\Lambda_c}^{PDG}$$

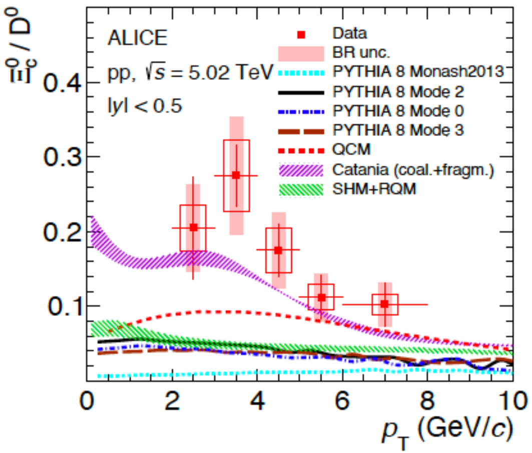
SHM+RQM (TAMU for pp)

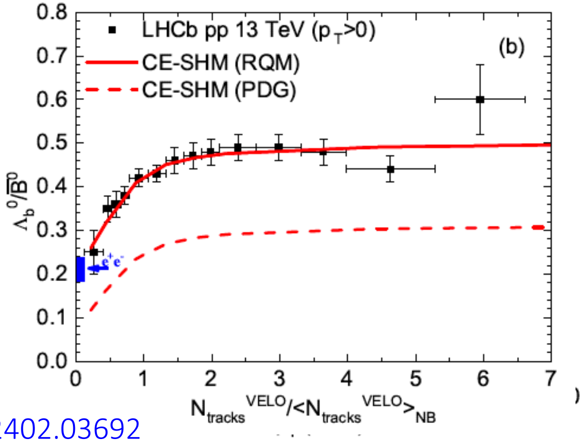
M. He, R. Rapp, PLB795(2019) [charm]
M. He, R. Rapp, PRL131(2023) [bottom]

$$n_i \cong g_i \frac{T_H m_i^2}{2\pi^2} K_2\left(\frac{m_i}{T_H}\right) \quad i = D^0, D^+, D^{*+}, D_s, \Lambda_c, \Sigma_c, \Xi_c, ...$$

Needs additional set of
c-baryon state according to RQM(*) (and ~LQCD)

- Very good Λ_c/D^0 vs data [*T_H=170 MeV, flavor hierarchy?!*]
- RQM Resonances not yet seen in e^+e^-, e^-p
- For the yield assumes a thermal distribution, but for comparing data vs p_T a fragmentation function is exploited
- Other ratios like Ξ_c/D^0 still lack yields
- Extended to bottom in pp: an explanation of Λ_b/B^0 evolution from e^+e^- to pp →Canonical Suppression
  [but assuming V_{corr} values and a linear evolution with N_{tracks}]





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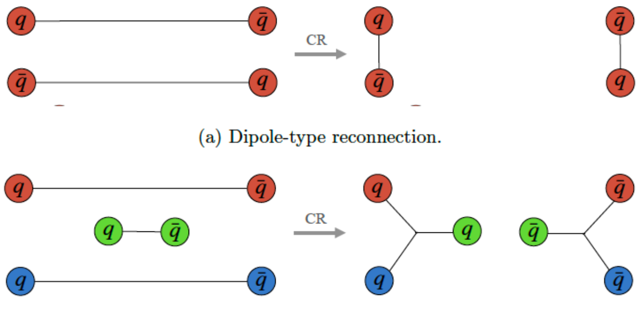
Dai- He, 2402.03692

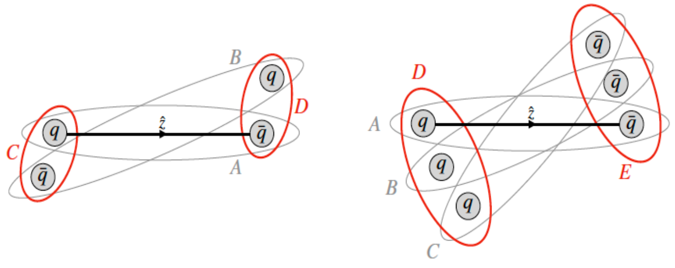
PYTHIA Color Reconnection

Altmann et al., arXiv 2405.19137



(a) Dipole-type reconnection.

(b) Junction reconnection.



(a) Mesonic reconnection.

(b) Baryonic reconnection.

Leading Color ($N_c \rightarrow \infty$): Prob. of Local Color neutralization → 0

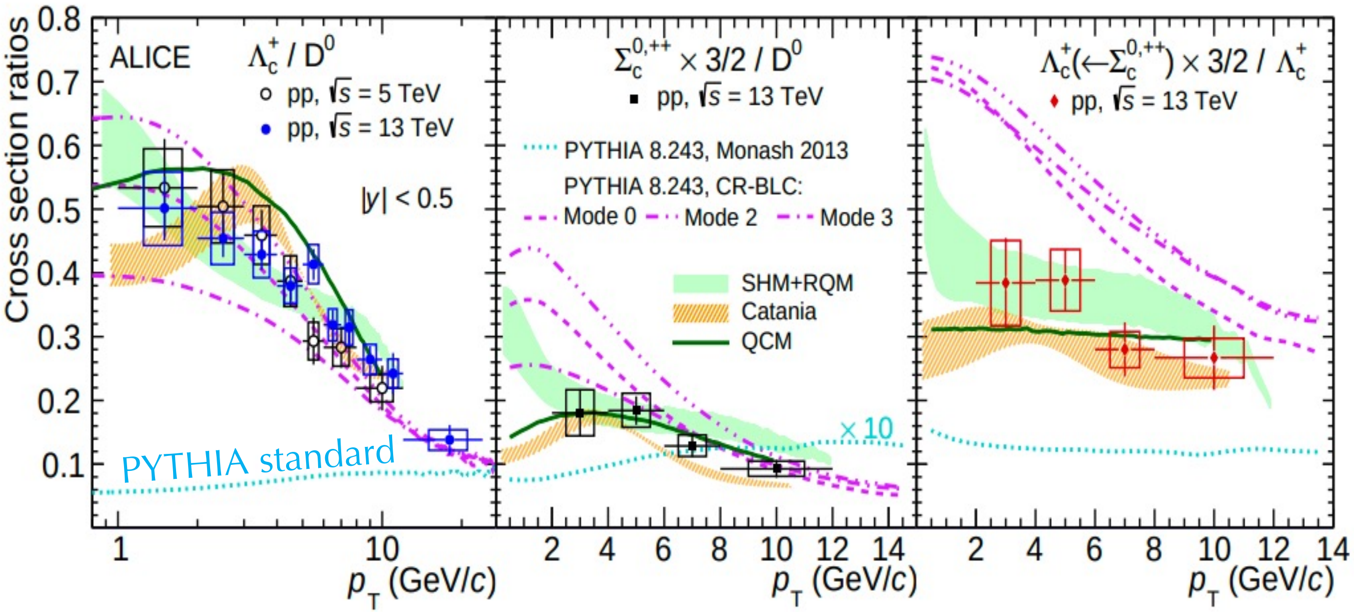
- **In LC** HF baryon only by [di-quark+HF] with **HF as string end point** [*c from string* $exp(-\pi m^2_c/k) \lesssim 10^{-11}$]
- When string color reconnection is switched-on in pp according to SU(3) counting:
  → Very large baryon Λ_c, Σ_c enhancement
  → not that relevant for D, ~ coalescence+fragmentation

✓ Not indipendent strings - **Local reconnection → string energy minimization →** smaller invariant mass and breaking of long y correlation

✓ Not so different qualitatevely wrt Coalescence and POWLANG Local color recombination

Going deeper into Λ_c enhancement

Altmann et al., arXiv 2405.19137



- Catania-coal & SHM-RQM/QCM natural good description of Σ_c/D^0 and $\Lambda_c \leftarrow \Sigma_c$
- PYTHIA-CR too many $\Sigma_c \rightarrow \Lambda_c/D^0$

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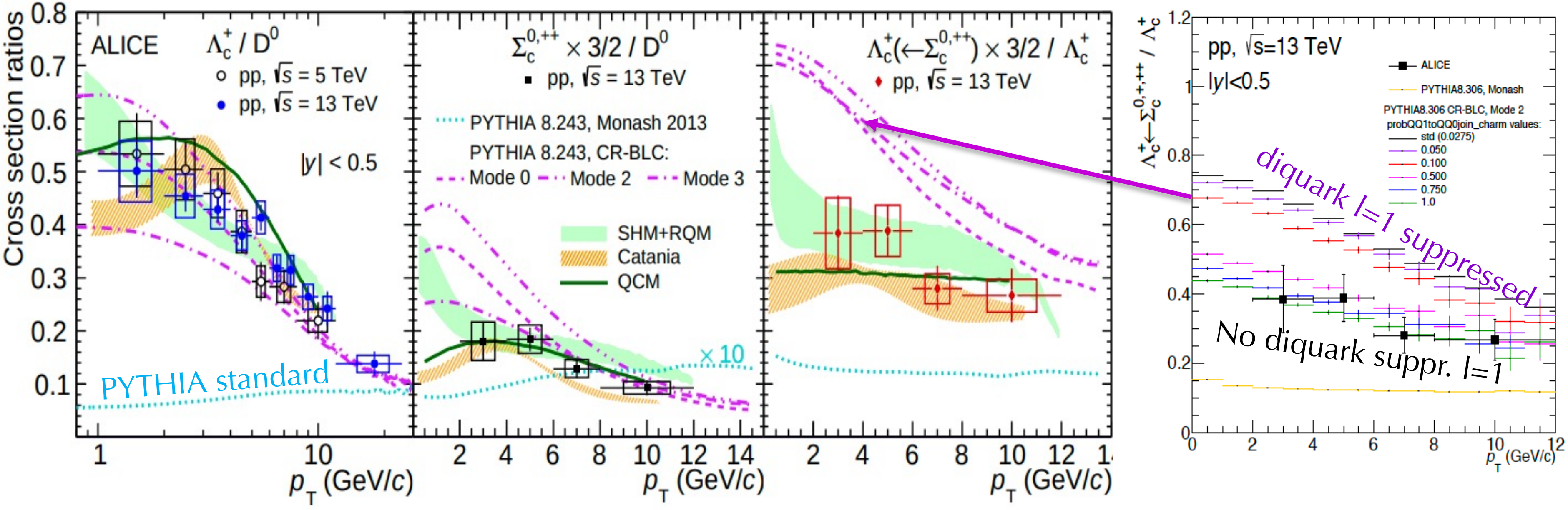
Altmann et al., arXiv 2405.19137

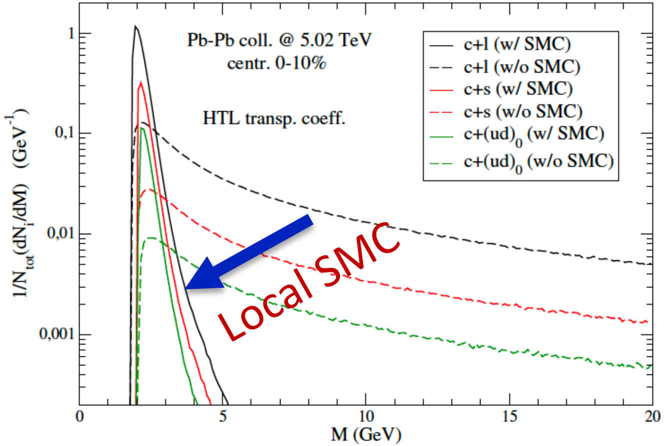


- Catania-coal & SHM-RQM/QCM natural good description of Σ_c/D^0 and $\Lambda_c \leftarrow \Sigma_c$
- PYTHIA-CR too many $\Sigma_c \rightarrow \Lambda_c/D^0$; associated to a suppression of junction **diquark *I=1*** *(set ~* e^+e^- for string di-quark). *Removing it → Agreeement to data of $\Lambda_c \leftarrow \Sigma_c$*

It goes in the direction of simply recombine according to SU(3) ~ simple colaescence

POWLANG Local Color Neutralization

A. Beraudo et al., EPJC82(2022) [AA]
A. Beraudo et al., PRD109(2024) [pp]



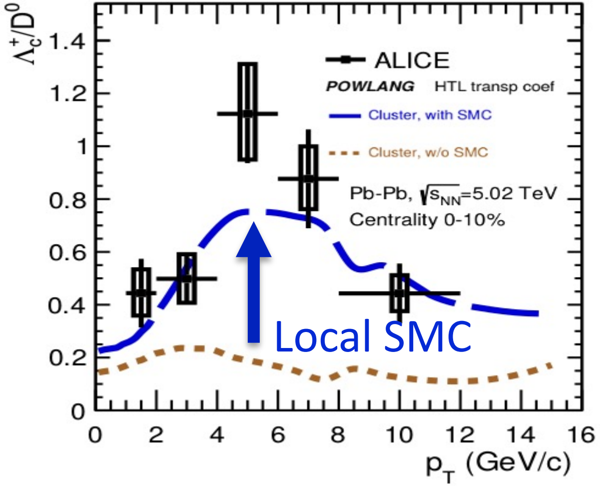
Charm recombine ***locally*** with quarks & diquarks assumed thermally distributed + radial flow :

$$n_l \cong g_s g_I \frac{T_H m_l^2}{2\pi^2} K_2\left(\frac{m_l}{T_H}\right) \qquad l = q, \bar{q}, s, \bar{q}, (ud)_0, (sq)_0, (sq)_1, \ldots$$

Narrow invariant M distribution → Space Momentum Corr. :

If $\mathcal{M} > \mathcal{M}_H$ 2-body decay into g.s charm hadrons

If $\mathcal{M} > \mathcal{M}_{max}$=4 GeV string fragmentation (~PYTHIA/HERWIG)



Dense medium (pp &AA) →**local** color statistical neutralization, qualitatevely similar to PYTHIA with local CR → smaller $\mathcal{M}$

- ***again*** ~ Coalescence & Resonance Recombination(TAMU)

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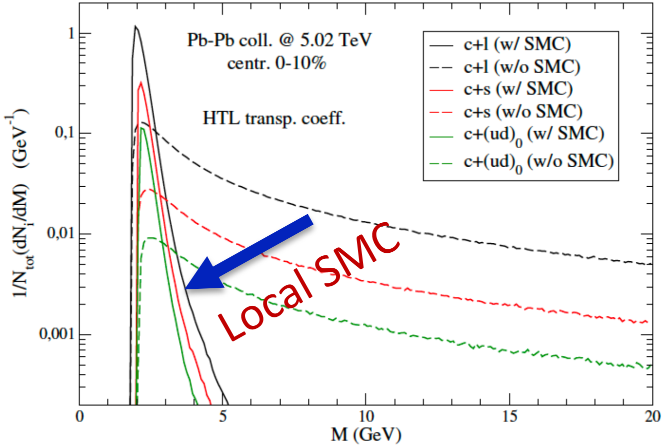

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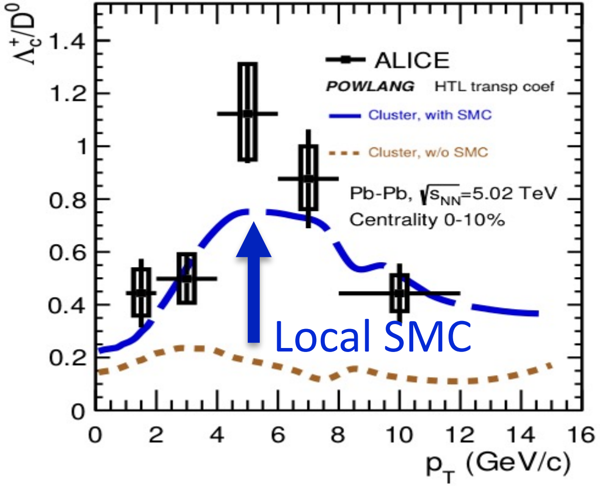

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- again ~ Coalescence & Resonance Recombination(TAMU)

Specific of the approach:

- Existence of thermal flowing diquarks
- Very strong impact on $v_2(p_T)$ from c→ D, Λ_c (all recomb.)
- Large D_s^+ production already in pp

Resonance Recombination (TAMU for AA)

M. He, R. Rapp, PRL124 (2020)

$$\frac{dN_M}{d^2p_T dy} = \int \frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi^3)} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2) \frac{\sigma_M(s)}{M\Gamma} v_{rel}(\vec{p}_1,\vec{p}_2) \delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

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

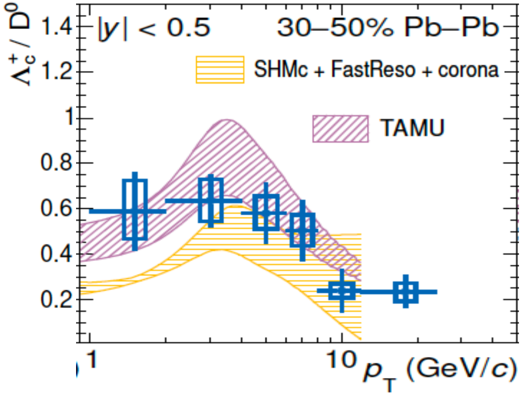
Coalescence $f_M \approx f_q \otimes f_{\bar{q}} \otimes \Phi_M \cdot \delta(\vec{p}_M - \vec{p}_q - \vec{p}_{\bar{q}})$

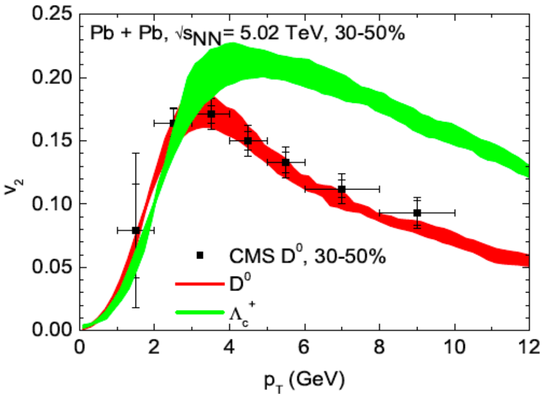
Recomb. according **not to a w.f. but to a Breit-Wigner** cross section (still a closeness in phase space costrained byΓ_{M-B} ~ 100-300 MeV):

→ Assumed a set of additional RQMc-baryons(*)[*as in SHM*]

→ Similar effects to coalescence on R_{AA} and v_2 of D & Λ_c because $f_M \approx f_q \otimes f_{\bar{q}}$, $f_B \approx f_q \otimes f_q \otimes f_q$ → quark v_2 enhanced with n_q (QNS)

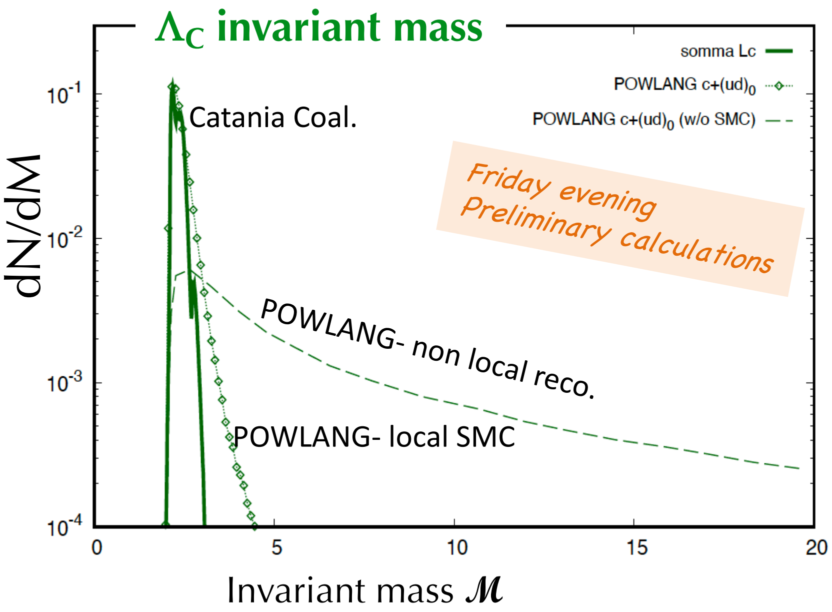
→ Again is a local phase-space recombination with strong Space-Momentum-Correlation→ small $\mathcal{M}$ objects

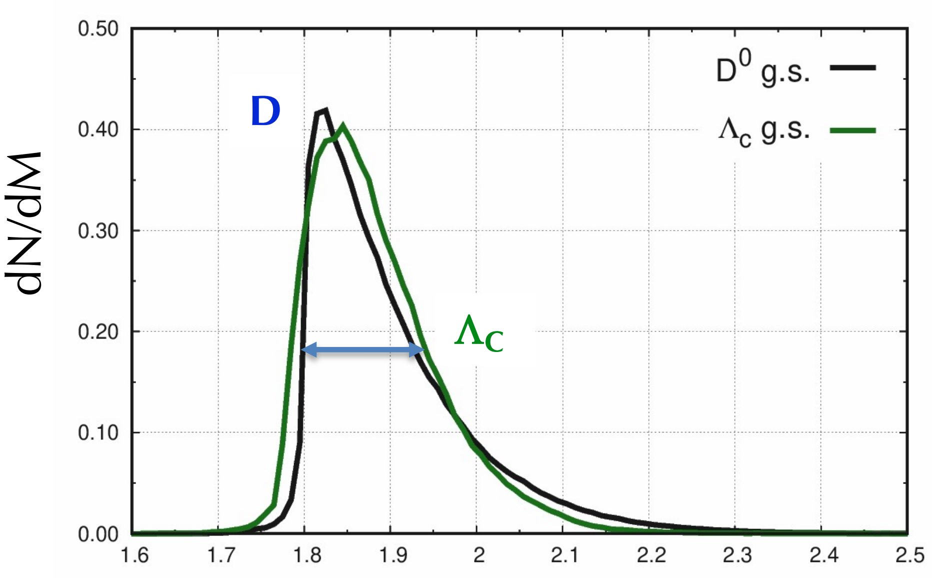




(*) $g_{\Lambda_c}^{RQM} \sim 2\, g_{\Lambda_c}^{PDG}$

Coalescence and invariant mass distribution





- POWLANG local recombination → small $\mathcal{M}$ ~ coalescence [*non local → large $\mathcal{M}$ → small Λ_c/D*]

- Coalescence invariant mass objects with $\Gamma \sim \sqrt{m_q T} \sim 0.15 - 0.20\ GeV$

- RR-TAMU Breit-Wigner resonance with $\Gamma_{M-B} \sim 0.1 - 0.3$ GeV (like T-matrix in medium resonances)

Many Coalescence[+Fragmentations] model:

Catania, Coal-TAMU(KO), Ko-Cao, CCNU-Duke,

[QCM], PHSD, RRM-TAMU, Nantes-EPOS4HQ,…

Many, different and in contradiction?

Many colescence models? Many & different?

Coal-Catania, Ko-TAMU, Ko-Cao-LBT → good Λ_c/D^0 with PDG states

SHM-TAMU and RR (pp&AA), SHM_c needs to add baryon states according to RQM, **who is right?**

Not orthoghonal approaches: one can include additional RQM baryon states in Coal.→

this modifies the coeff. enforcing $P_{coal}(p_T \rightarrow 0)=1$ in *Catania or Ko-Cao-LBT*

The two should tend to compensate… but to be done!

Many colescence models? Many & different?

Gossiaux, 4 Tue [9:30]

Coal-Catania, Ko-TAMU, Ko-Cao-LBT → good Λ_c/D^0 with PDG states

TAMU-SHM/RR (pp&AA) needs to add baryon states according to RQM, **who is right?**

Not orthoghonal approaches: one can include additional baryon states in Coal.→
this modifies the coeff. enforcing $P_{coal}(p_T \rightarrow 0)=1$ in *Catania or Ko-Cao-LBT*
The two should tend to compensate… but to be done!

Implicitely done now with EPOS4HQ!

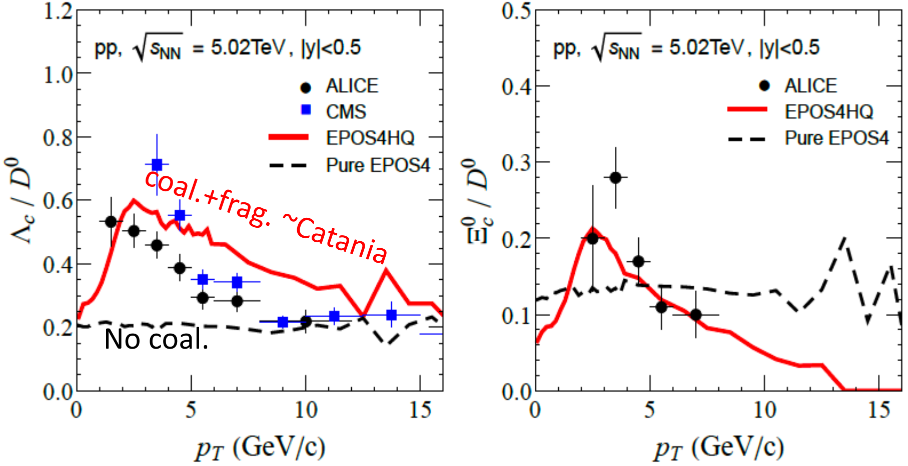
To describe HF spectra & ratios needs Coalescence in phase space ~Catania

Only difference wrt Catania:

- Assume RQM states like in SHM

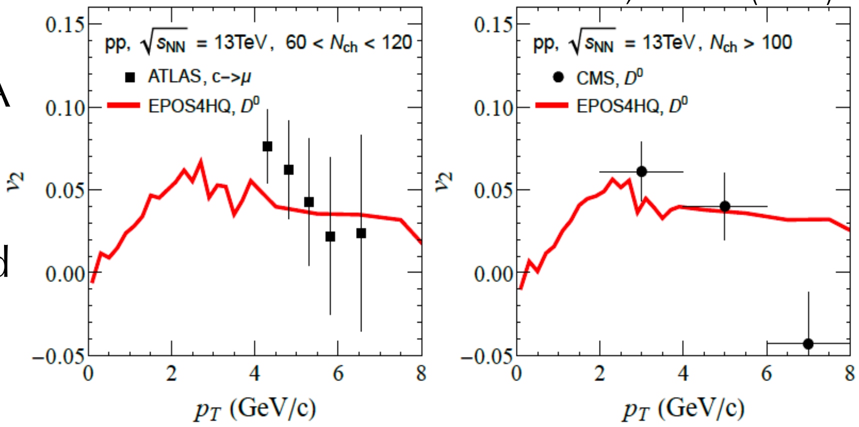
* II only difference: m_q=0.1 GeV → longer p_T tail
[m_q~0.3 GeV in Catania, Cao-Ko, Duke, PHSD]

J.Zhao et al., PRD109 (2024)



HF coalescence in EPOS4HQ

J.Zhao et al., PRD109 (2024)



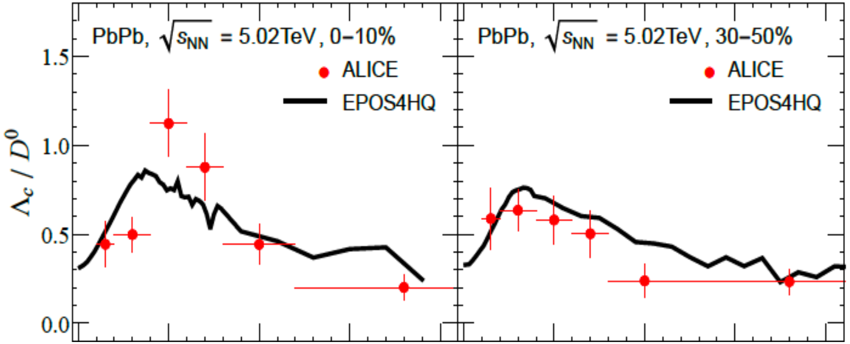
- ➢ <u>Advantages of implementing coal. in EPOS4</u>:
- \- Full dynamical realistic dynamics from ep, pp to AA
- \- **Able to predict also a sizeable elliptic flows**
  → more solid costraints to hadronization
  and the properties of the pp QCD matter created

  → $v_2(\Lambda_c)/v_2(D^0)$ would give more insight into coal.

- ➢ Would PYHTIA-CR predict finite v_2 of D, Λ_c in pp? String shoving?

Extension to AA and bottom,

J. Zhao et al. arXiv:2401.11275



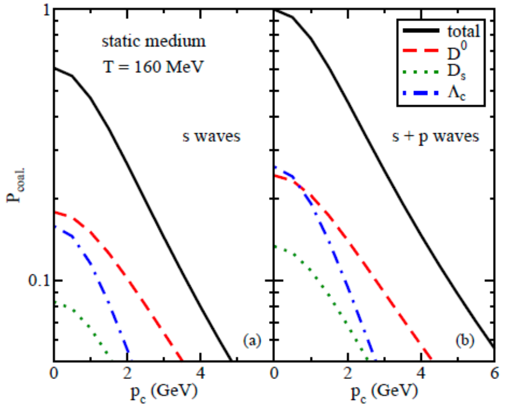
Coalescence Ko-Cao(LBT) vs Catania

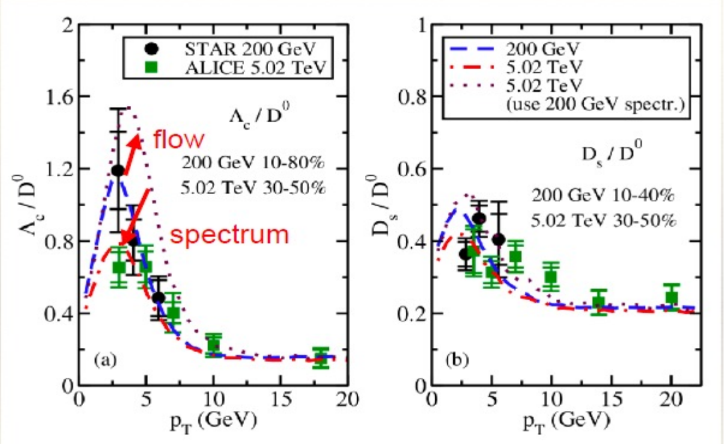
S. Cao, et al. et C. Ko, PLB 807 (2020)

As already mentioned wrt to Ko-Cao both enforce $P_{coal}(p_T \rightarrow 0)=1$ [but with a different procedure]

- A difference Ko-Cao(LBT) wrt to Catania, EPOS4HQ,QCM: for Resonances with *l=1* it is considered the proper Wigner transform from harm.osc. wave function:

$$W_P(p_r) = g_h \frac{(2\sqrt{\pi}\sigma)^3}{V} \frac{2}{3}\sigma^2 p_r^{\,2} e^{-\sigma^2 p_r^{\,2}}$$ for l=1 but integrated over r





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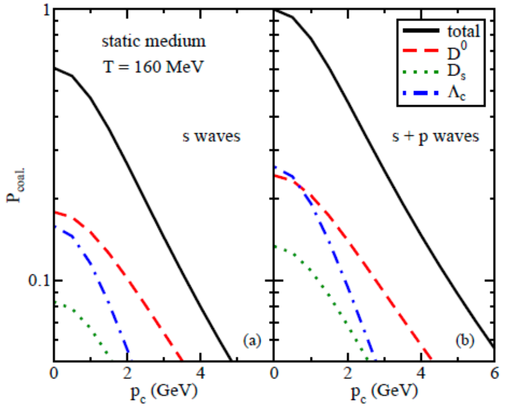
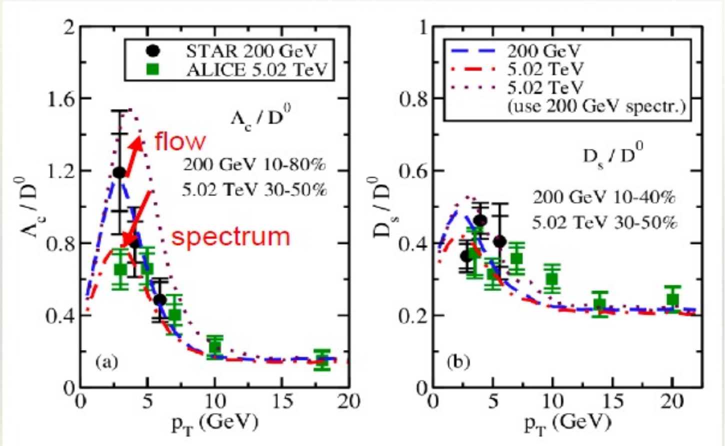


- It should be studied how this compares to resonances according a thermal suppression *[Catania, RR &SHM TAMU, QCM, EPOS4HQ,…]*

- **Phase-space coalescence with *l=0,1*** Wigner functions are being developed also **for quarkonia** in both pp and AA [*Frankfurt-Nantes with PHSD medium*]

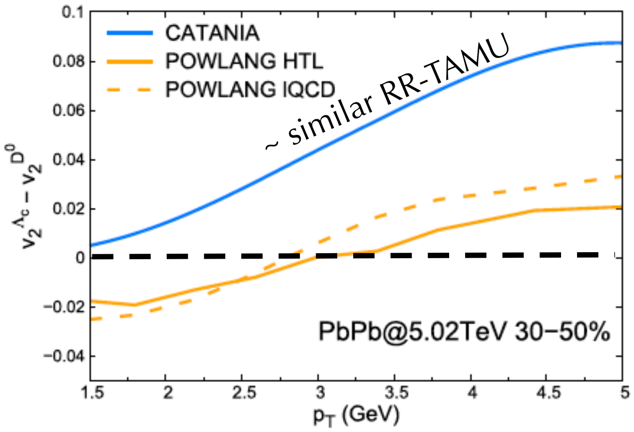
[Song, Tue 4,14:00]
[Zhao, this afternoon]



Impact of diquark?

QCD challenges from pp to AA, EPJC 84(2024)

- Coal. Approaches (*Catania, LBT, EPOS4HQ… RR-TAMU*)
  ➔ **$v_2(\Lambda_c)> v_2(D^0)$** at p_T> 2 GeV
  because Λ_c gets flow from 2 light quarks, D^0 from 1+fragm.
- POWLANG assume diquark hydrodynamical flow and
  Λ_c=(qq)+c -> $v_2(\Lambda_c)$~$v_2(D^0)$ at intermediate p_T



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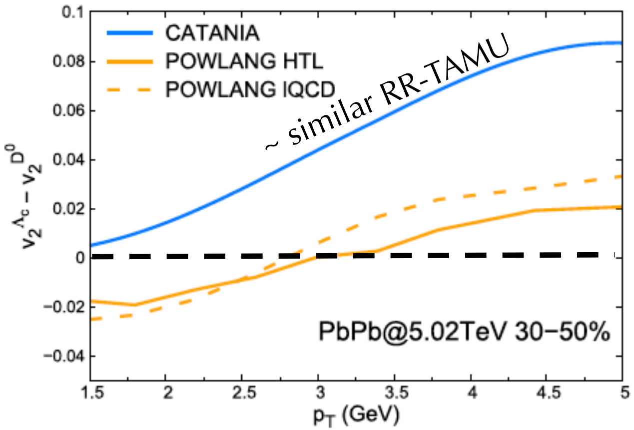
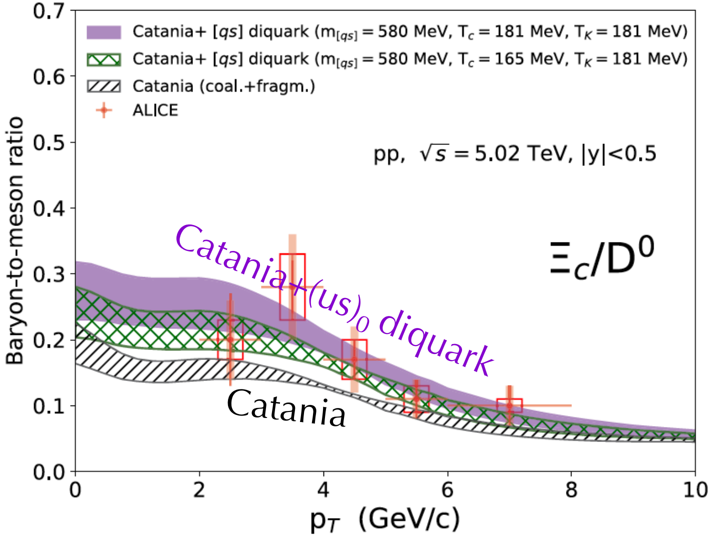


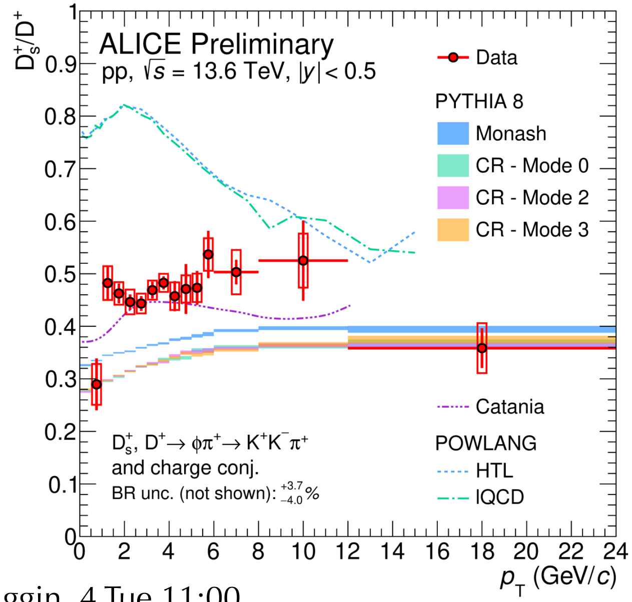


- ❑ Quark model gives $(us)_0$ large binding energy →small mass.
  If V(r,T) potential at finite T with large m_D ~ LQCD
  Assumption:
  - Again $(us)_0$ thermal yield flowing with the medium

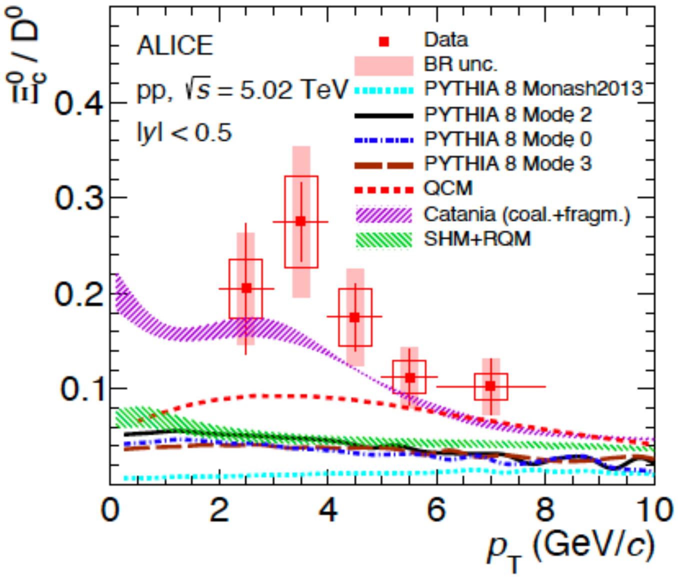
* More precise data needed to draw any conclusion

H. Yun, S.H. Lee et al., PLB 851(2024)

Strangeness in pp for HF sector



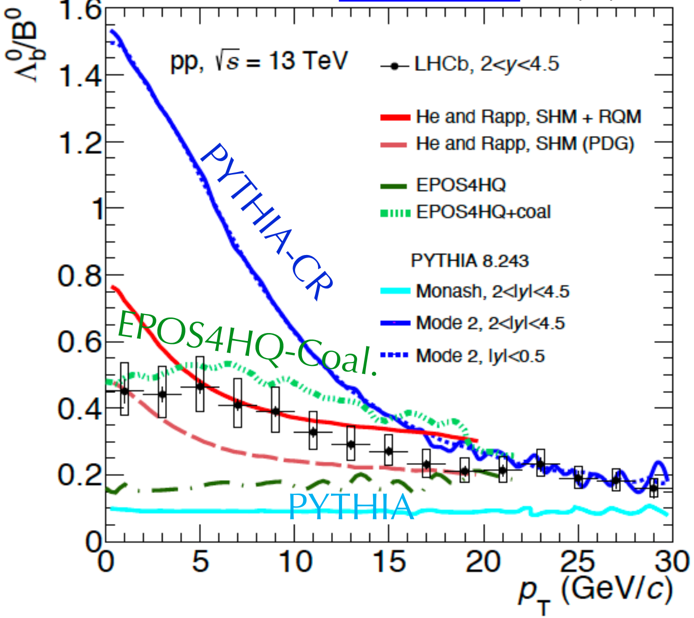
ALICE - Faggin, 4 Tue 11:00



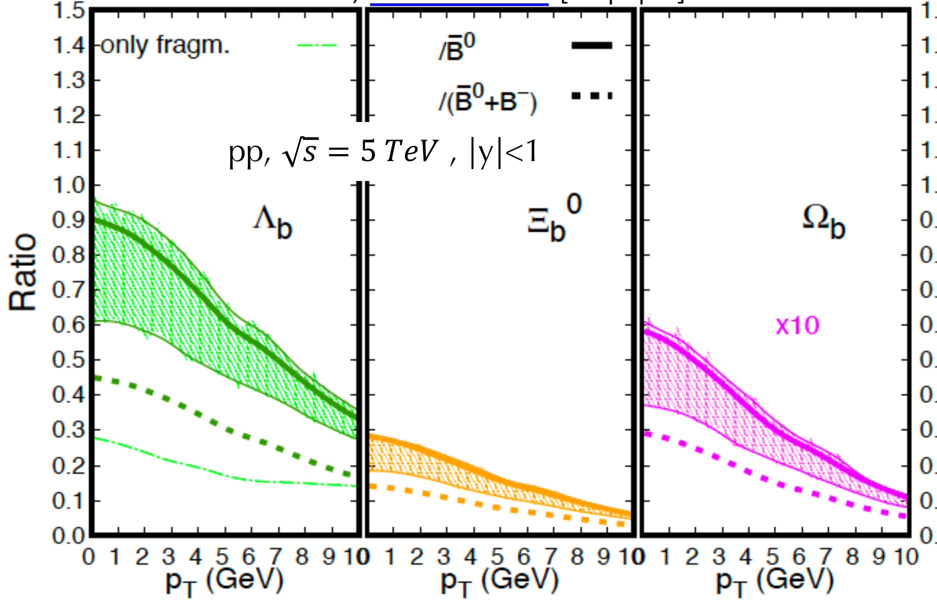
- Catania Coalesc.+Frag. quite ok, but it is large the fragmentation contribution
- POWLANG/LCN too high, but the approach has only recombination also for mesons
- PYTHIA-CR seems to have a lack of strangeness [see also Ξ_c]

Early results and predictions for Bottom in pp

Altmann et al., 2405.19137 [hep-ph]



V. Minissale et al., 2405.19244 [hep-ph]



Plumari, Tue 4-[9:10]

- Again Need CR in PYTHIA→ seems too strong at forward (no rapidity dependence)
- EPOS4HQ**+coal** close to data (rapidity dependence?). At y=0 Catania results
- SHM +RQM about close, less the p_T shape (Frag.-Function)
- Coal./Fragm. ratio in pp larger for B than D

Common features, some open question and next

Emerging from **Coalescence** a common framework for HF hadronization from pp to AA.

Other approaches (*PYTHIA-CR, POWLANG-LCN,RR-TAMU…)* point anyway to:

- In **medium local recombination** → small (reduced) invariant mass widths
- Large evolution from e^+e^-(e^- p) to pp (@TeV), while reshuffling in p_T from pp to AA
- Several imply resonances (or diquark) yields and/or yields close to thermal equilibrium (SHM)

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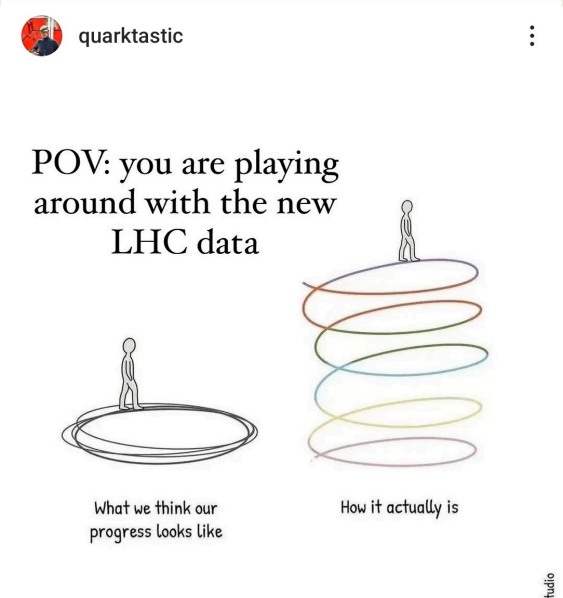
A suggestion from Instagram….



Common features, some open question and next

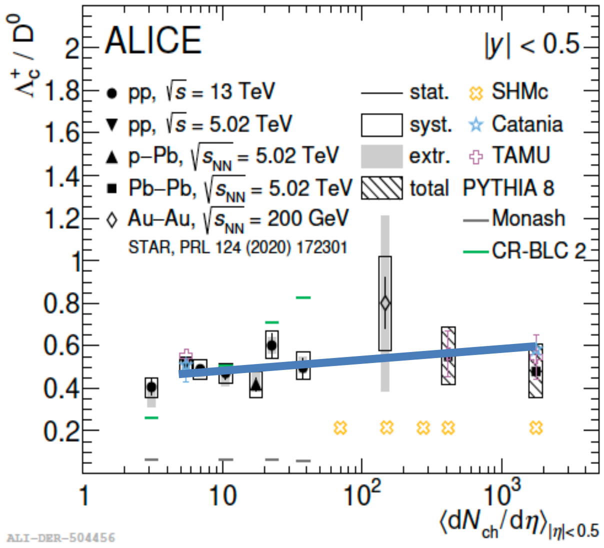
- **Assessment of open issues** and several microscopic mechanism/ "details"(?):
  - Rapidity evolution of baryon/meson [most work at y~0]
  - Extension to bottom + reduced data error bars, will show similar agreement?
  - Coal./Fragm. dominance of coal. in Λ_c? → a probe large $v_{2D}/v_{2\Lambda C}$ vs p_T
  - di-quark role in Ξ_c/D^0 ? need smaller error at low p_T
  - hydro flowing diquarks? ← $v_2(\Lambda_c) - v_2(D)$ at intermediat p_T
  - strength SpaceMomentumCorrelation, PDG/RQM resonances …

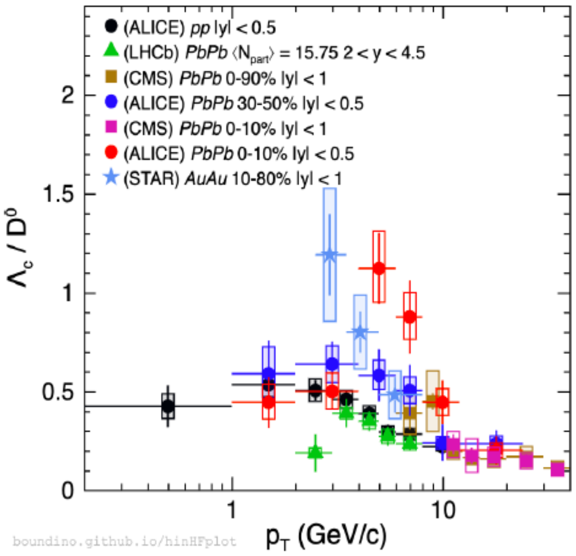
- **Multicharm baryon** production (ALICE3): Ω_{ccc} yield large sensitivity to charm kinetic equilibration and its wave function width [$\sigma_r^2 < (2\mu T)^{-1}$]

Plumari, Tue 4 [9:10]

Back-up

Strong system size/multiplicity dependence





Main change is from e^+e^- and e^-p to pp (TeV)

- Once coalescence sets in Baryon/Meson yields ratio expected to have a **weak dependence** on the yield: because very similar local density or T_H.

  Effects: - small size (corona) → baryon are more suppressed when $V_{fireball} \sim V_H$

  - High-multiplicity → more radial flow (SMC) → mainly reshuffle in p_T (peak shift)

- On this would agree Catania Coal, EPOS4HQ, POWLANG [*HQ biased towards hot spots in pp]*, LBT, RR-TAMU … to be scrutinized/modified in PYTHIA (strong multiplicity dependence→ new version)

Coalescence approach: impact of widths

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

In non-relativistic approx. for Gaussian w.f. + therm. distr + no flow

$$f_M(x_1,x_2;p_1,p_2) = A_W \exp\left(-\frac{x_{r1}^2}{\sigma_r^2} - p_{r1}^2\sigma_r^2\right)$$

$$N_M \sim \frac{\sigma_r^2}{\sigma_r^2 + (2\mu T)^{-1}}$$

$\sigma_r^2 >> (2\mu T)^{-1}$ large width or large T → sensitivity off

$m_q \approx 0.2\ m_c \approx\ 2T \approx 1.6\ fm^{-1}$

Meson	$\langle r^2\rangle_{ch}$	σ_{p1}	σ_{p2}
$D^+ = [c\bar{d}]$	0.184	0.282	—
$D_s^+ = [\bar{s}c]$	0.083	0.404	—
Baryon	$\langle r^2\rangle_{ch}$	σ_{p1}	σ_{p2}
$\Lambda_c^+ = [udc]$	0.15	0.251	0.424
$\Xi_c^+ = [usc]$	0.2	0.242	0.406
$\Omega_c^0 = [ssc]$	-0.12	0.337	0.53

D^+: $\sigma_r^2 \approx (0.7)^2 \approx 0.5\ fm^2$ and $(2\mu T)^{-1} \sim 0.46\ fm^2$

$\sigma_r \to \infty$ yield increase a factor of 2

increasing <r²> by a factor 2 → 30% more

Ω_c : $\sigma_{r1}^2 \approx (0.58)^2 \approx 0.34\ fm^2$ $\sigma_{r2}^2 \approx (0.35)^2 \approx 0.12\ fm^2$

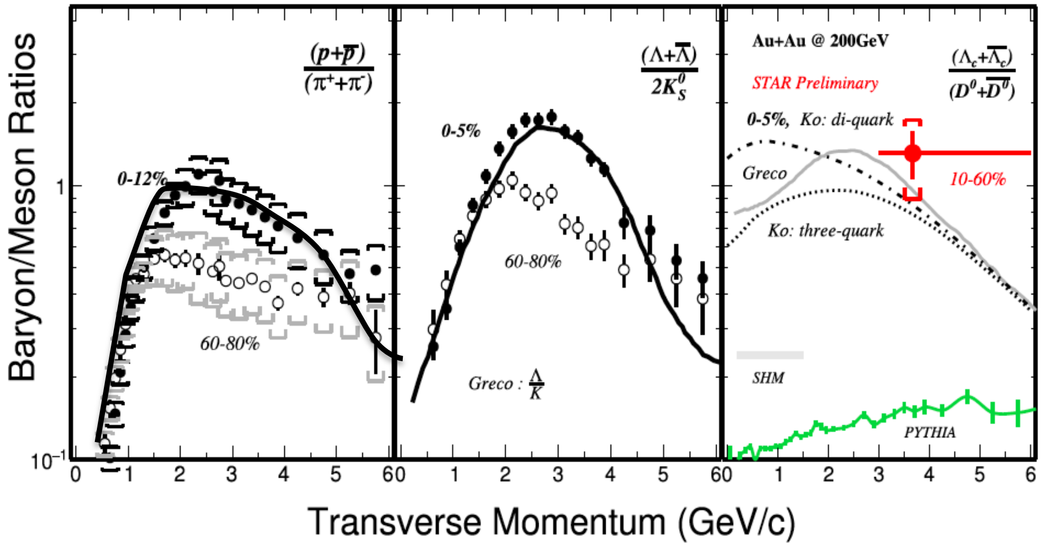
$(2\mu_{ss}T)^{-1} \approx 0.6\ fm^2$ $(2\mu_{(ss)c}T)^{-1} \approx 0.22\ fm^2$

$\sigma_r^2 < (2\mu T)^{-1}$ more sensitivity widths

Increasing <r²> by a factor of 2

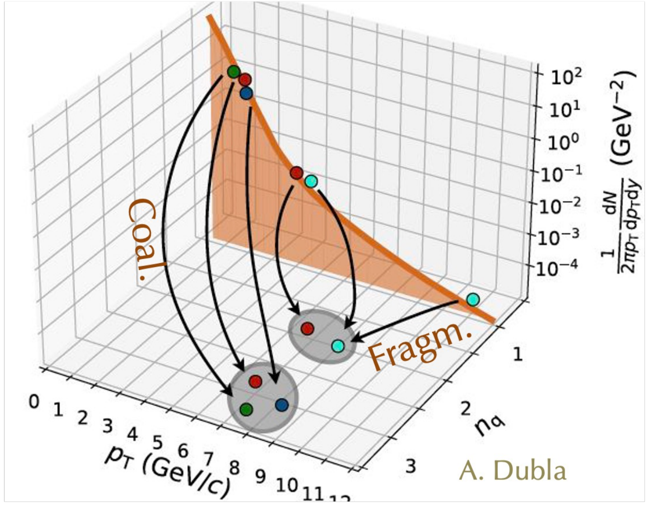
→ 2.2 more Ω_c

Hadronization in the light and strange sector



Dong-Greco, Prog.Part.Nucl.Phys. 104(2019)

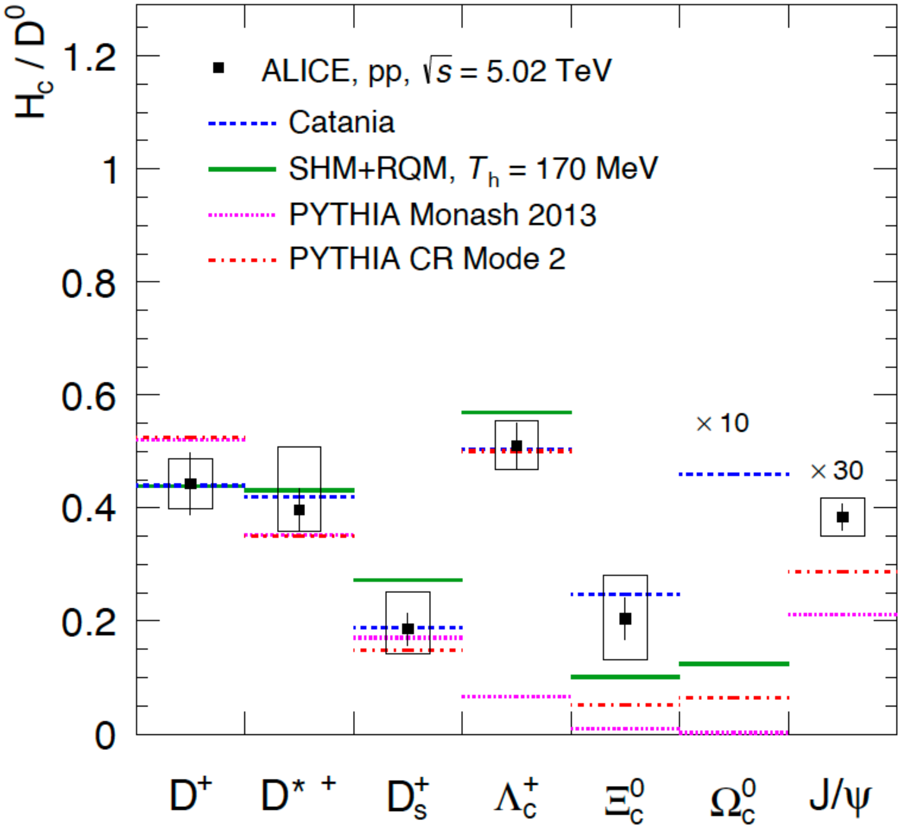
❖ Yields ratios ok in SHM-Heidelberg: π,p,K,Λ,…



<u>In 2002-2004 large p/π, Λ/K at intermediate p_T:</u>

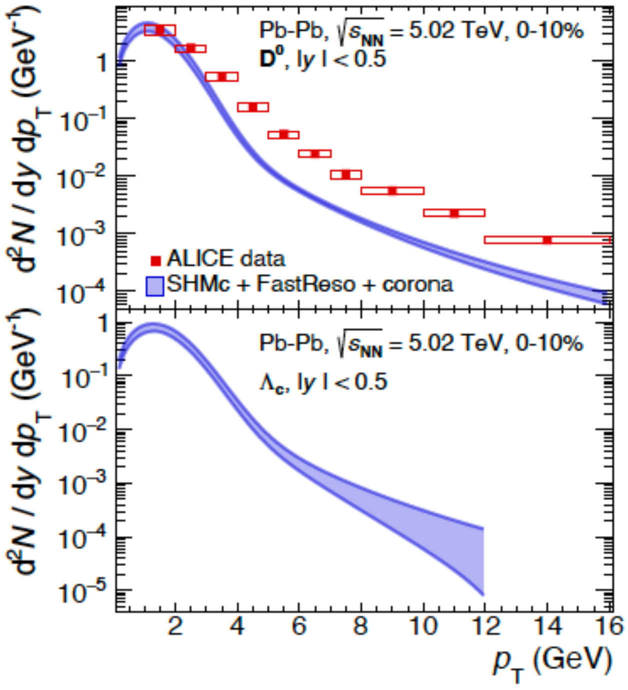
→ development of coalescence + fragm. in AA collisions
$f_M \approx f_q \otimes f_{\bar{q}} \otimes \Phi_M$ [GKL and FMNB PRL90(2003)]

→ v_2 quark number scaling (~ also for ϕ…)

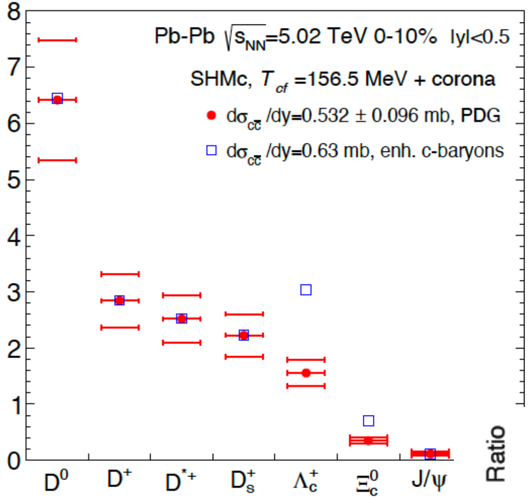


H_c / D^0
1.2
1
0.8
0.6
0.4
0.2
0
ALICE, pp, $\sqrt{s}$ = 5.02 TeV
Catania
SHM+RQM, T_h = 170 MeV
PYTHIA Monash 2013
PYTHIA CR Mode 2
× 10
× 30
D^+
D^{*+}
D_s^+
Λ_c^+
Ξ_c^0
Ω_c^0
J/ψ

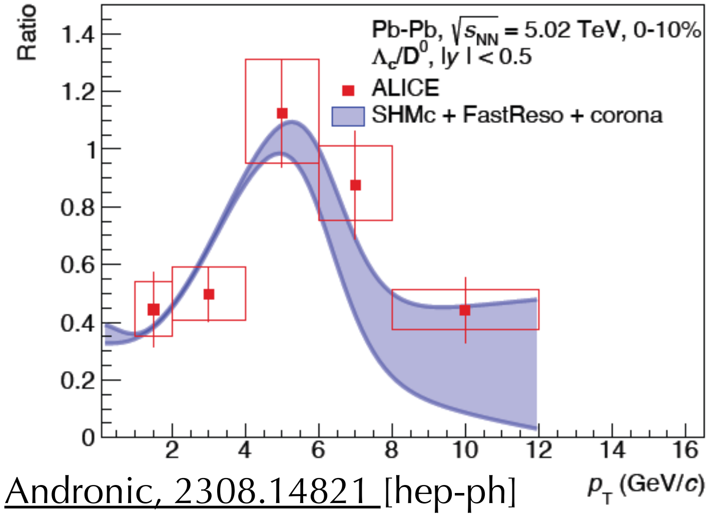
CSHMc coupled to blast-wave+ corona



A. Andronic, JHEP 07 (2021) 035

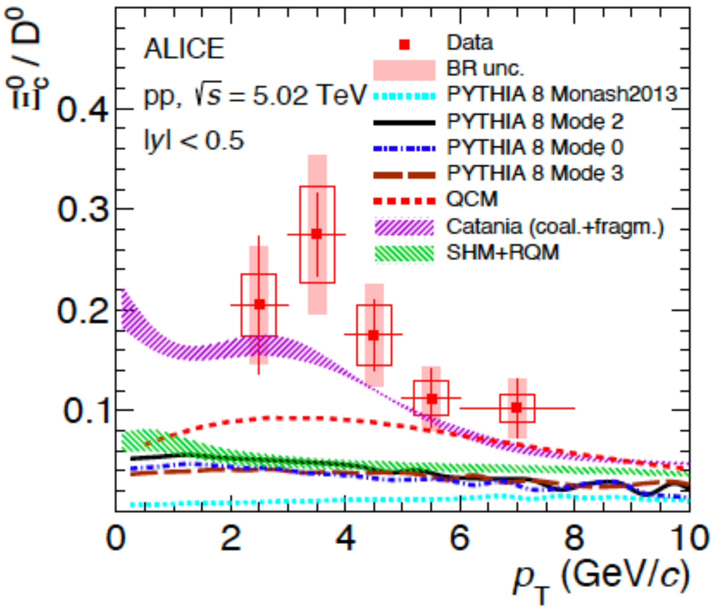


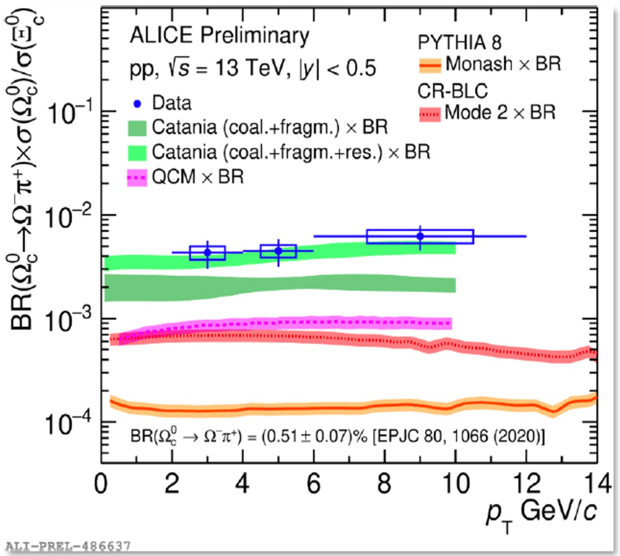
Coupling SHMc to visco hydro



Andronic, 2308.14821 [hep-ph]

HF strangeness in pp





- Catania-Coal the closest to Ξ_c/D^0 not QCM/SHM-RQM/PYTHIA –CR.
- In Ξc there could be effects of diquark [S.H. Lee]
- Also Ω_c of Catania is the closest, but large uncertainties on exicted states and BR

Multicharm production PbPb and KrKr

$\Xi_{cc}^{+,++}, \Omega_{scc}, \Omega_{ccc}$

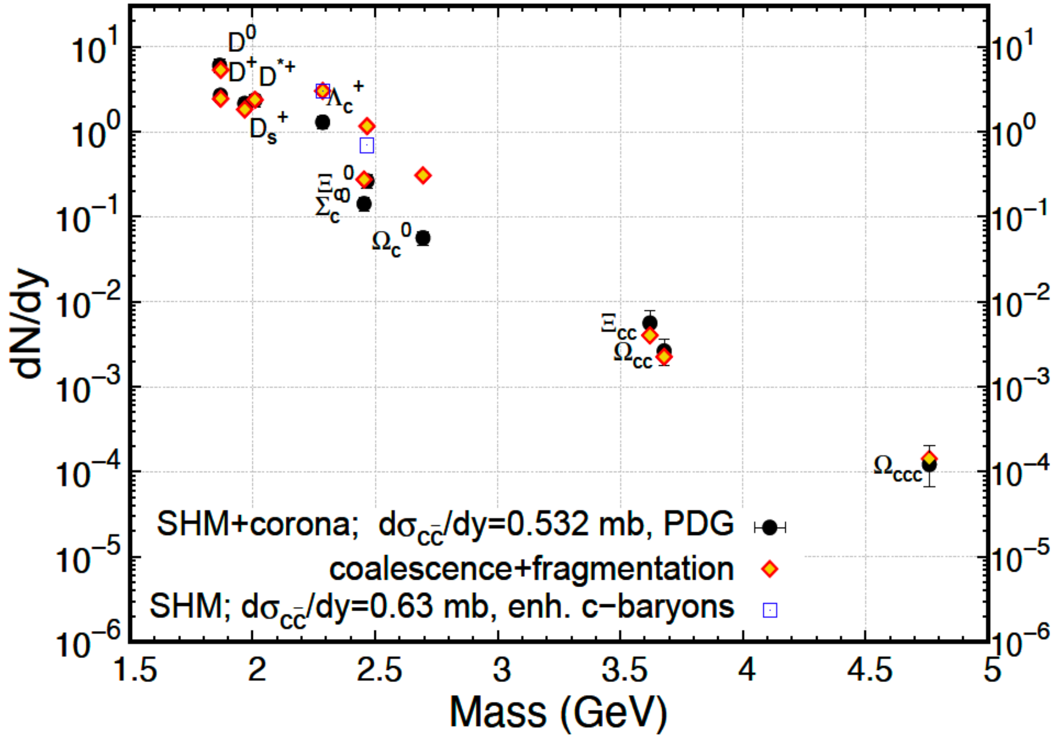
Baryon			
$\Xi_{cc}^{+,++} = dcc, ucc$	3621	$\frac{1}{2}\,(\frac{1}{2})$	
$\Omega_{scc}^{+} = scc$	3679	$0\,(\frac{1}{2})$	
$\Omega_{ccc}^{++} = ccc$	4761	$0\,(\frac{3}{2})$	
Resonances			
Ξ_{cc}^{*}	3648	$\frac{1}{2}\,(\frac{3}{2})$	$1.71 \times g.s$
Ω_{scc}^{*}	3765	$0\,(\frac{3}{2})$	$1.23 \times g.s$

like S.Cho and S.H. Lee, PRC101 (2020)
from R.A. Briceno et al., PRD 86(2012)

Strengths of the approach:

- Does not rely on distribution in equilibrium for charm
  →useful for small AA down to pp collisions and at p_T> 3-4 GeV
- Provide a p_T dependence of spectra and their ratios vs p_T

Yields in PbPb from coalescence vs SHM



Obtained starting for D from the <r^2> of the quark model, but for Λ_c we have reduce it by 20%.

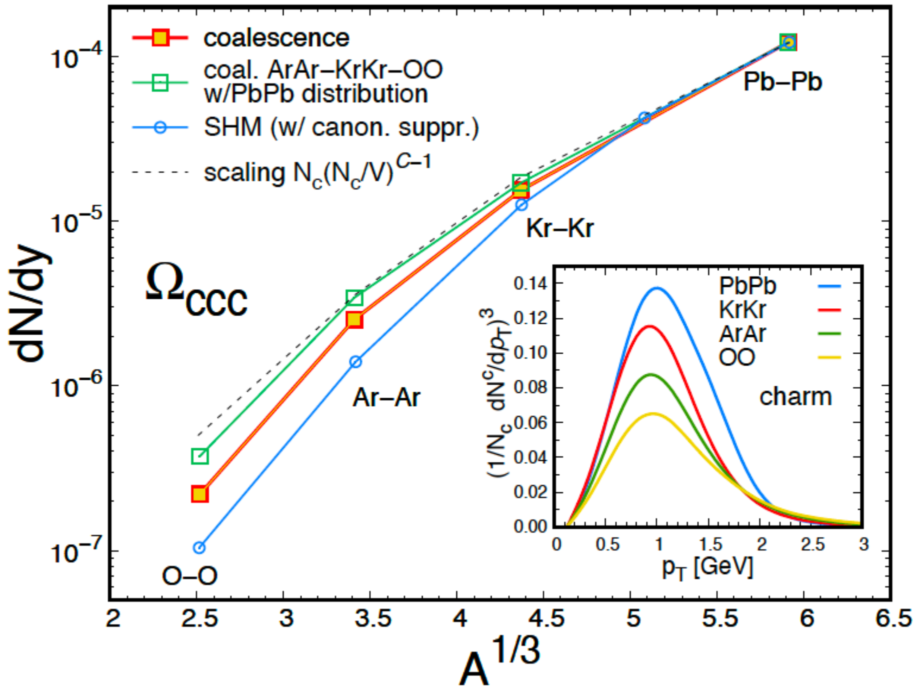
$\Sigma_c^0, \Xi_c^0, \Omega_c^0$ from quark model

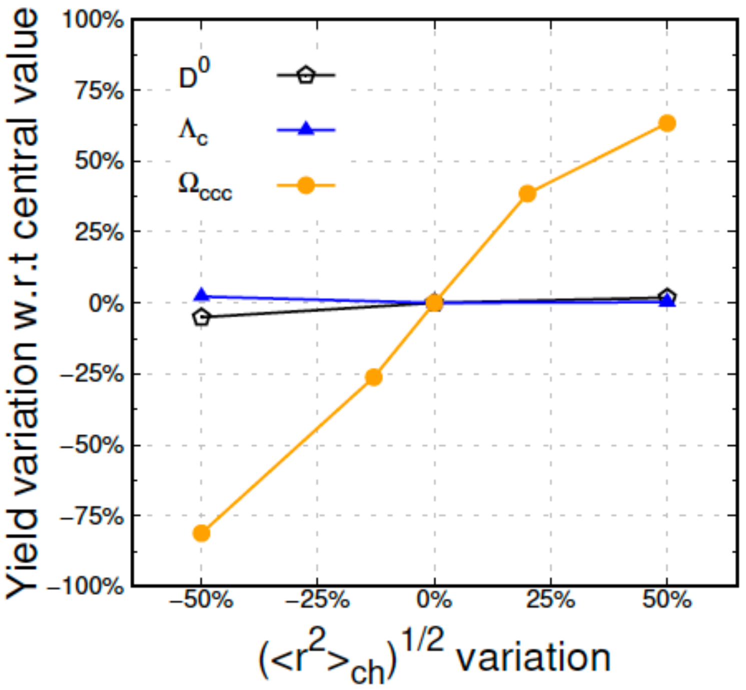
$\Xi_{cc}^{+,++}, \Omega_{cc}$ obtained rescaling the width according to the harmonic oscillator relations

$$\sigma_{ri} = 1/\sqrt{\mu_i \omega} \qquad \mu_1 = \frac{m_1 m_2}{m_1 + m_2}, \quad \mu_2 = \frac{(m_1 + m_2) m_3}{m_1 + m_2 + m_3}.$$

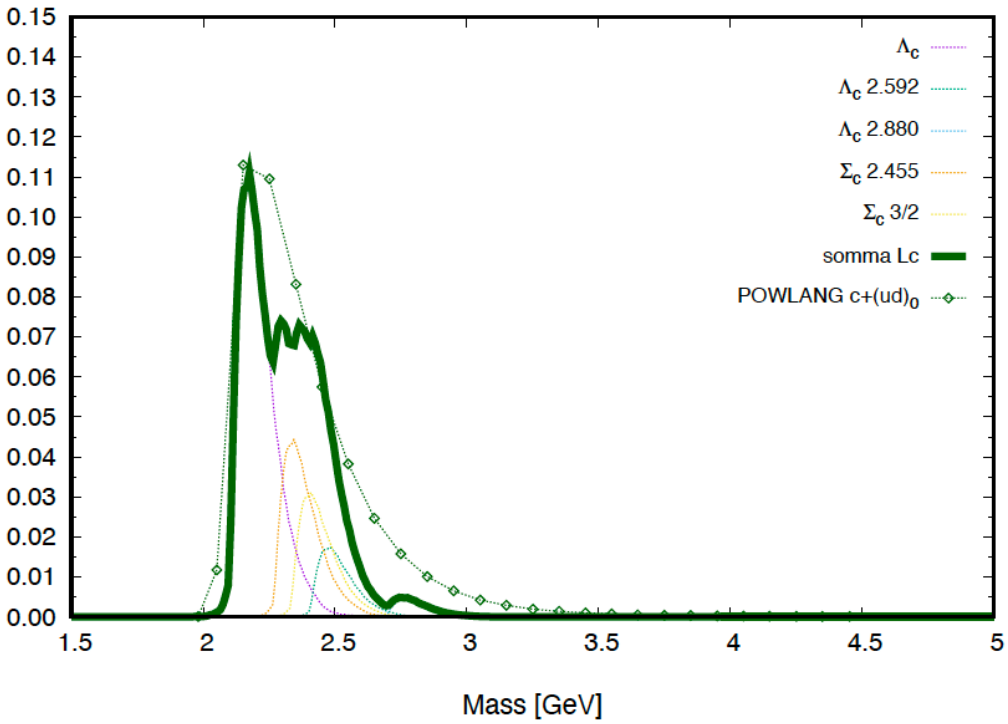
Ω_{ccc} fixing <r>=0.5 fm and $\sigma_r \cdot \sigma_p \approx 1.5$ according to Tsinghua PLB746 (2015)
[Solution of Schoedinger eq. under V(r)]

A standard harmonic oscillator scaling as for Ω_c^0 would give $\Omega_{ccc} \approx 10^{-5}$

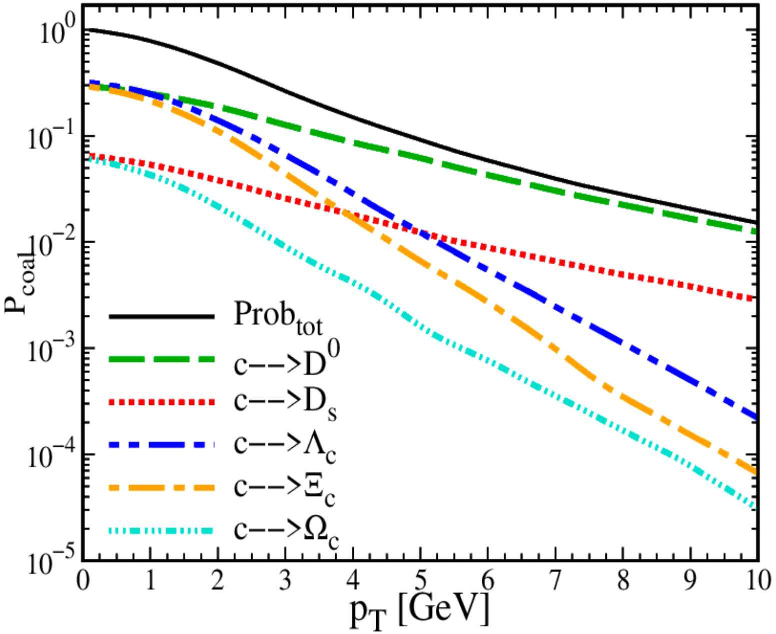




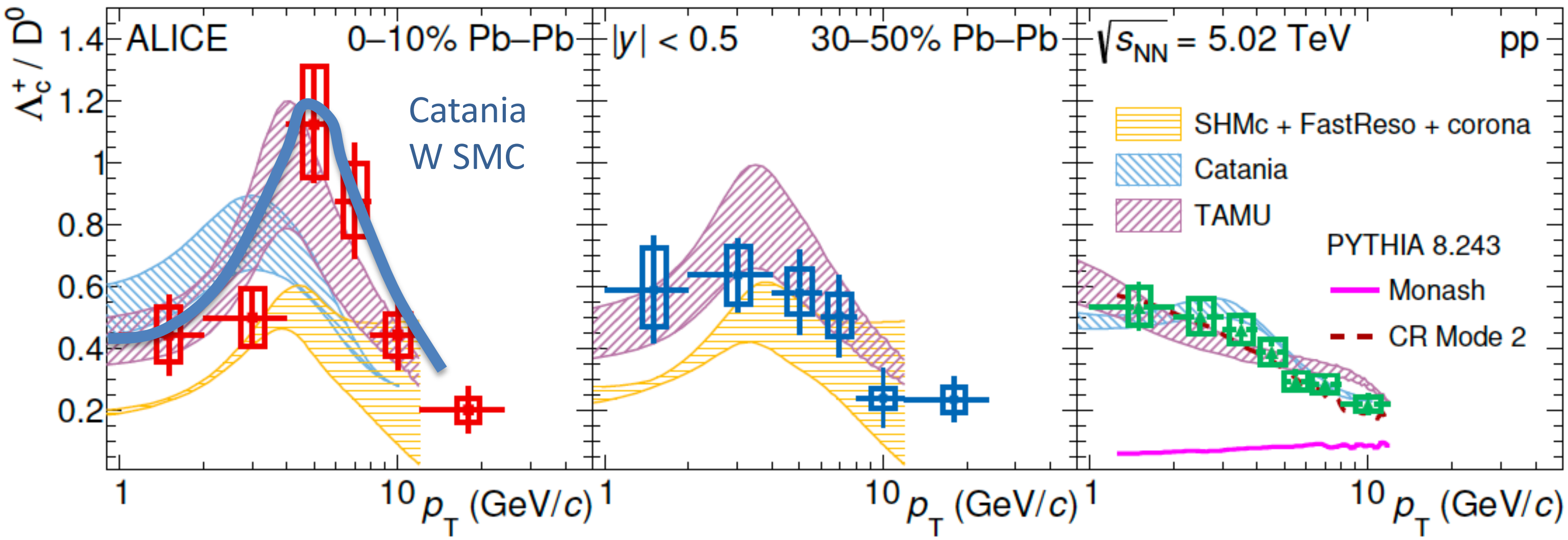
Minissale et al., EPJC(2024)



Λ_c
Λ_c 2.592
Λ_c 2.880
Σ_c 2.455
Σ_c 3/2
somma Lc
POWLANG c+(ud)$_0$
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1.5
2
2.5
3
3.5
4
4.5
5
Mass [GeV]



P_{coal}
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$Prob_{tot}$
c-->D^0
c-->D_s
c-->Λ_c
c-->Ξ_c
c-->Ω_c
0
1
2
3
4
5
6
7
8
9
10
p_T [GeV]



PRELIMINARY Catania coal.+fragm. With SMC similarly to TAMU

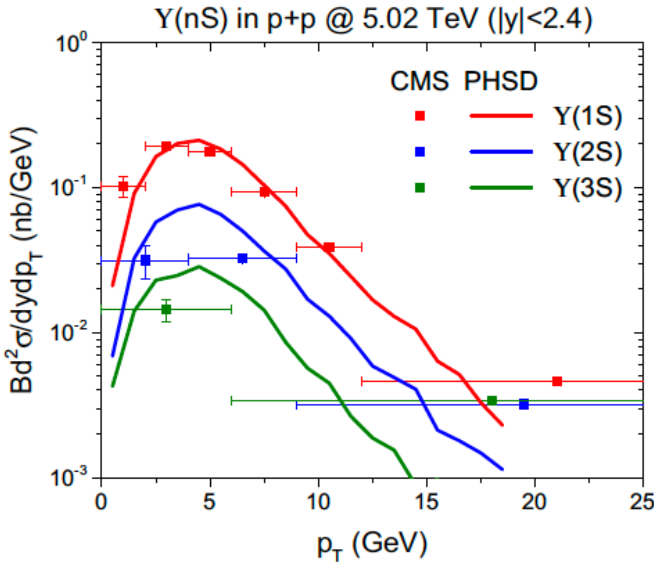
TAMU is SHM+RQM Reso in pp and RR in PbPb

SHMc suffers from baryon states in PDG

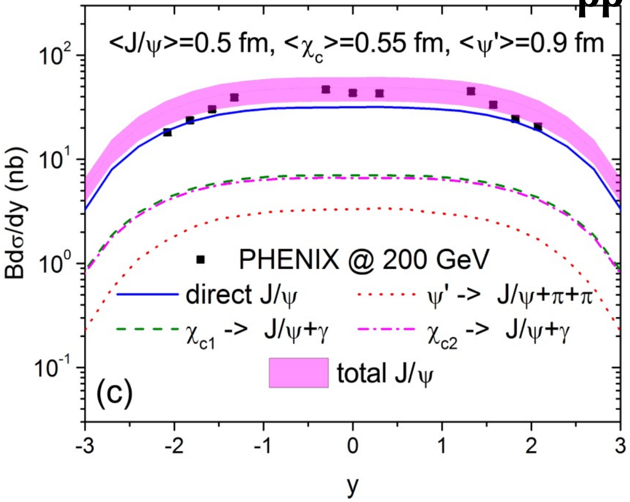
Quarkonium?

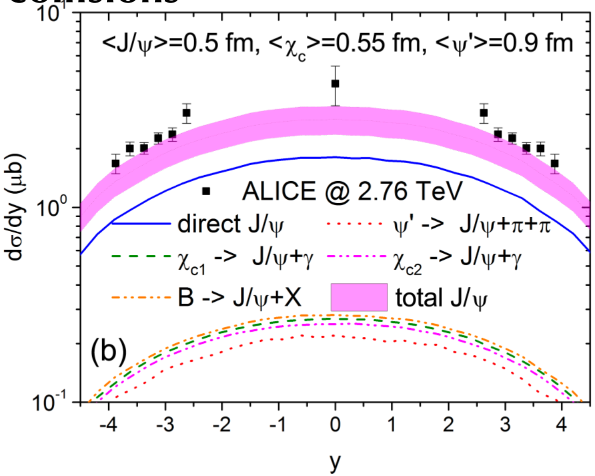
Song et al., PRC108(2023)
Song-Aichelin-Bratkovskaya,PRC96(2017)

Recombination as by decades been recognized as an hadronization mechanism in AA
Now developments with same **Wigner phase-space approach** as for open HF **both in pp and AA**



pp collisions





[Song, Tue 4,14:00]
[Zhao, this afternoon]

- Unified framework between pp and AA for the hadronization
- In AA if one neglects quarkonium suppression→ yield J/Y quite large

These development could/should couple also to those on the polarization in AA