Heavy Flavor Hadronization and Hadron Chemistry in Heavy-ion Collisions

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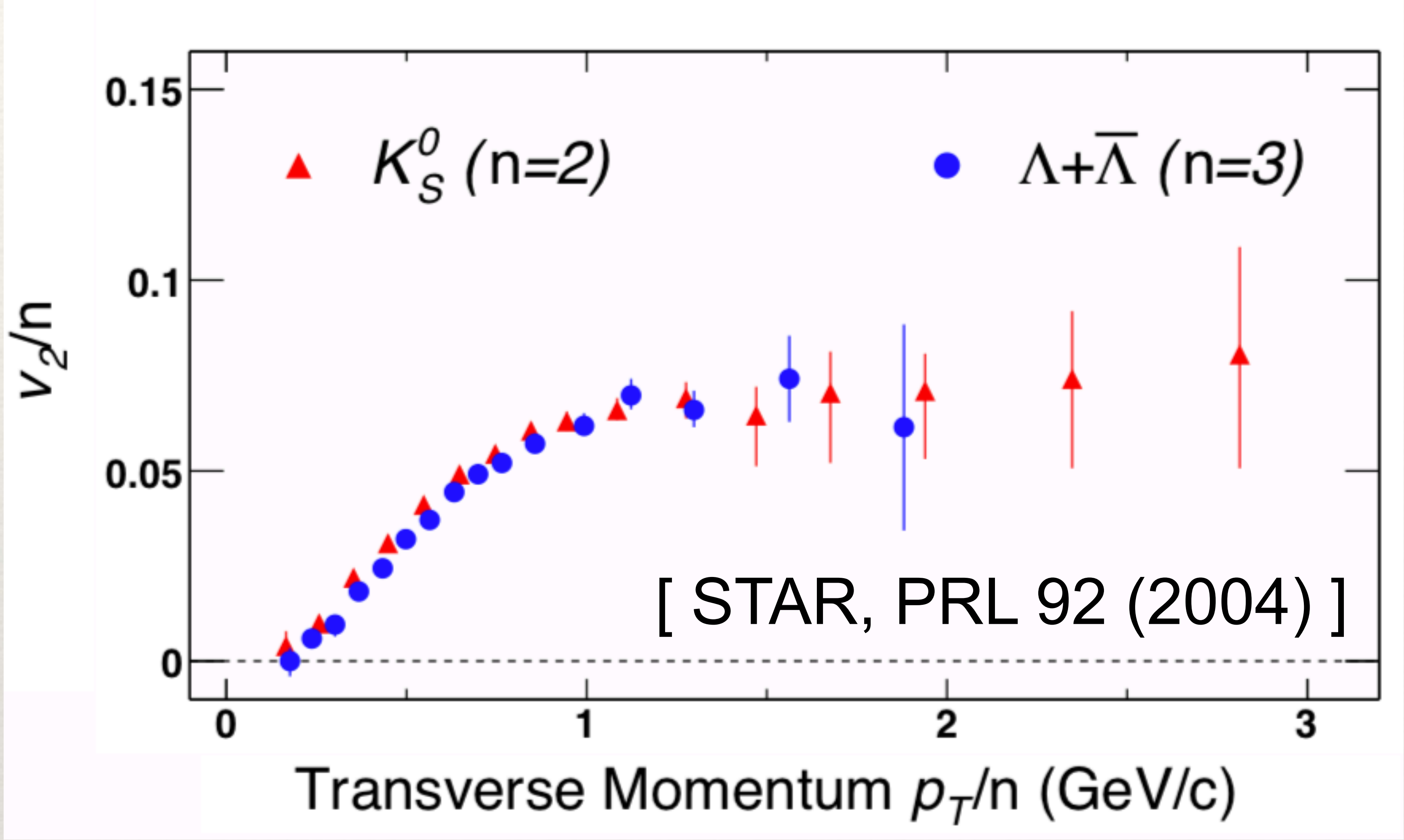
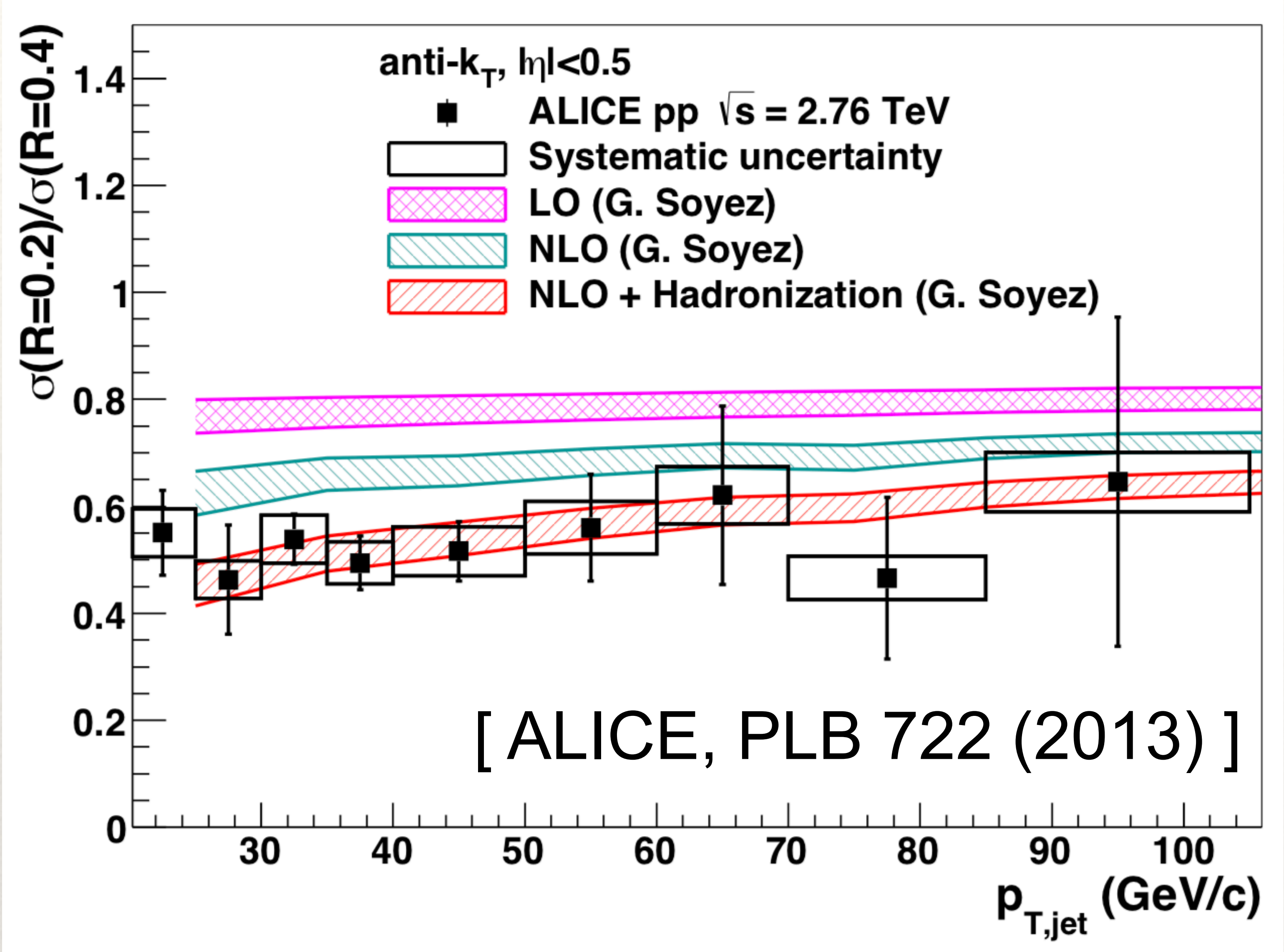
Hadronization is an important but difficult topic

Soft: NCQ scaling of hadron v_2



- Coalescence of quarks into hadron
- Quark degree of freedom inside the hot nuclear matter in heavy-ion collisions

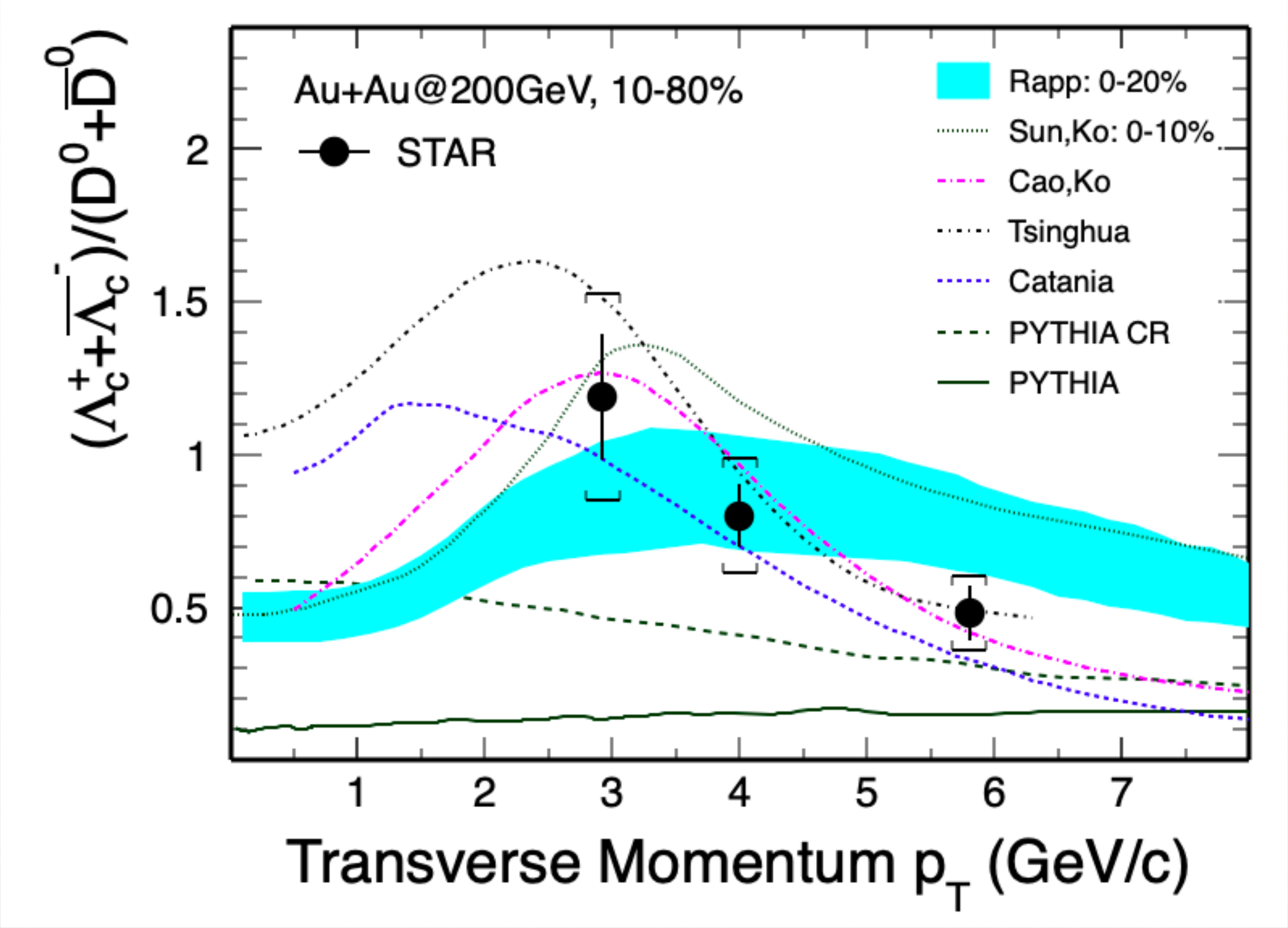
Hard: cone size dependence of $\sigma(\mathrm{jet})$



- Similar contributions from hadronization and NLO effects
- No state-of-the-art hadronization model for hard probes yet

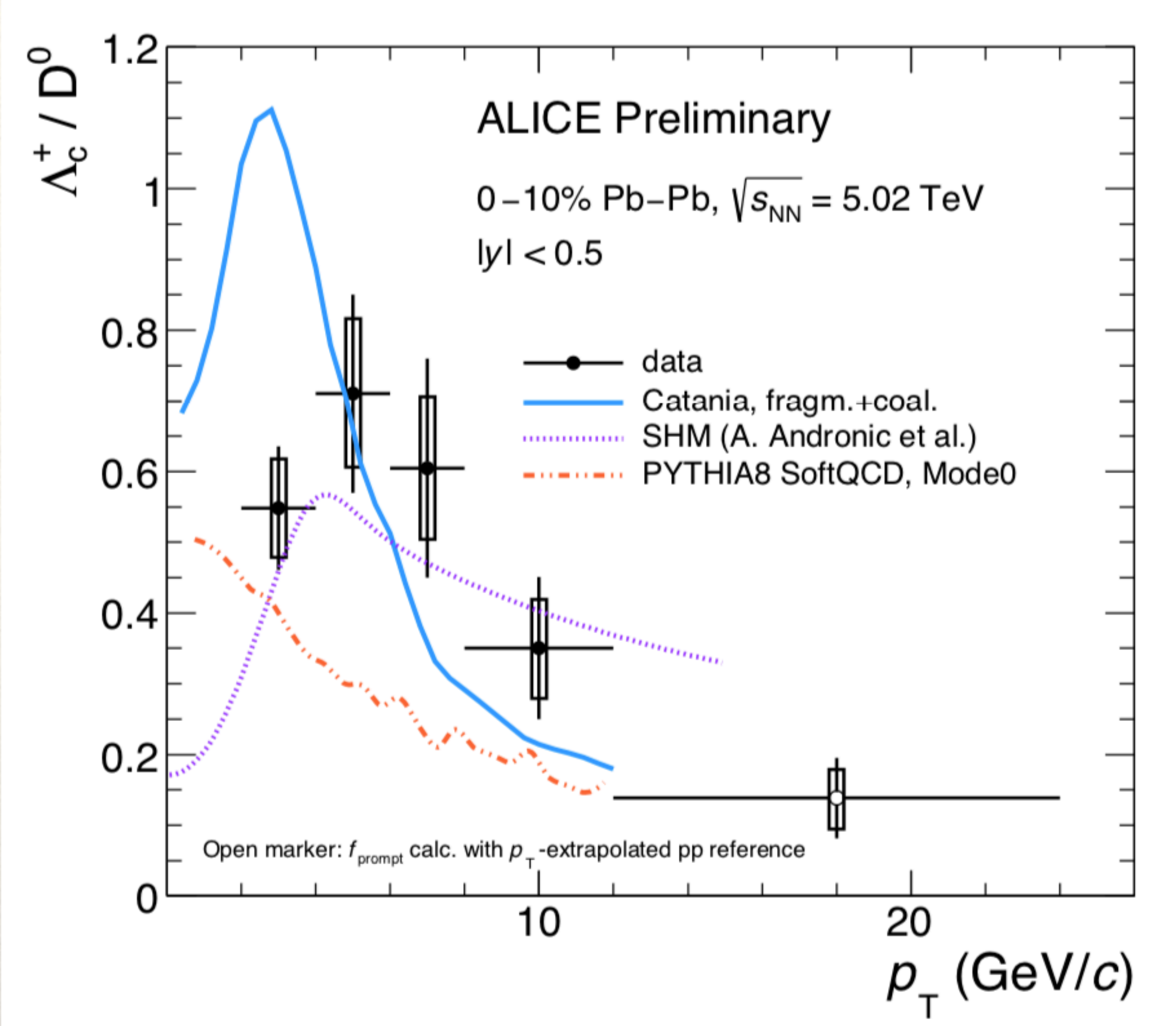
Charmed hadron chemistry

RHIC



[STAR, PRL 124 (2020)]

LHC



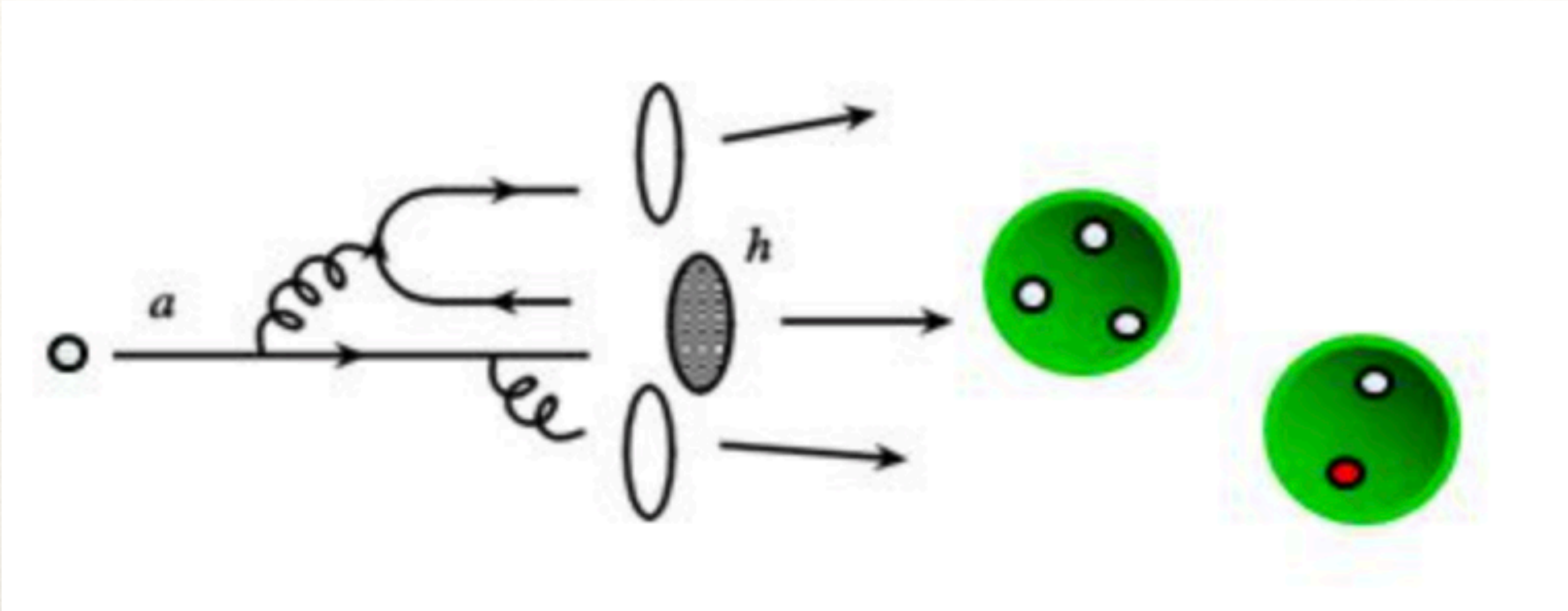
[ALICE, arXiv:1910.11738]

- Heavy quarks: early production in collisions, interact with QGP with flavor conservation
- Ideal probe of the in-medium hadronization mechanism of hard partons
- Few precise model descriptions of data, puzzling smaller Λ_c/D^0 at LHC than at RHIC
- Goal of this work: develop a comprehensive hadronization model and understand the heavy flavor hadron chemistry (arXiv:1911.00456)

Two major hadronization mechanisms

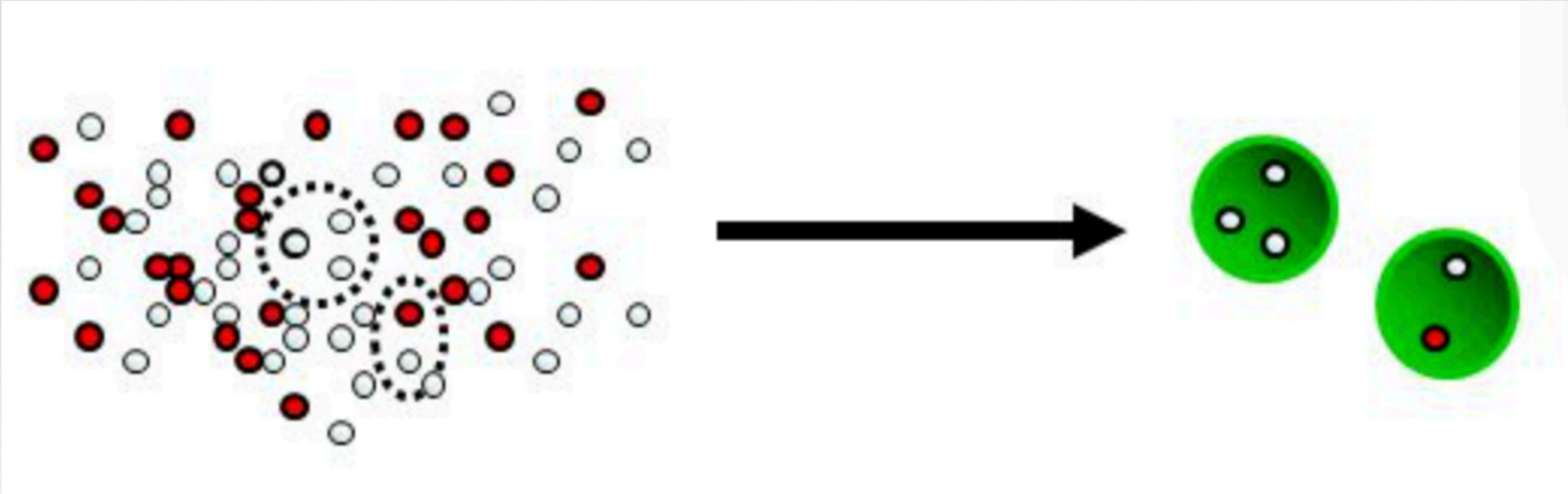
Fragmentation:

High momentum heavy quarks are more likely to fragment into hadrons
[Peterson, FONLL, Pythia, etc.]



***Coalescence* (*recombination*)**:

Low momentum heavy quarks are more likely to combine with thermal partons into hadrons



Oh, Ko, Lee and Yasui, PRC 79 (2019)
Plumari, Minissale, Das, Coci and Greco, EPJC 98 (2018)
Cho, Sun, Ko, Lee and Oh, PRC 101 (2020)
SC, Sun, Li, Liu, Xing, Qin and Ko, arXiv:1911.00456

Coalescence model

- Sudden approximation: $|q, g\rangle \to |h\rangle$ as T drops across T_c
- Probability for quarks to combine into hadrons: Wigner function (wave function overlap)
- Example: 2-body system for meson formation

$$W(\vec{r}, \overrightarrow{k}) \equiv |\langle M | q_1, q_2 \rangle|^2 = g_M \int d^3 r' e^{-i\vec{k}\cdot\vec{r}'} \phi_M(\vec{r} + \vec{r}'/2) \phi_M^*(\vec{r} - \vec{r}'/2)$$

g_M: ratio of spin-color degeneracy between meson and quark states

ϕ_M: meson wavefunction (S.H.O. approximation with a frequency parameter ω)

$\vec{r} = \vec{r}'_1 - \vec{r}'_2 \qquad \overrightarrow{k} = \dfrac{1}{E'_1 + E'_2}(E'_2 \overrightarrow{p}'_1 - E'_1 \overrightarrow{p}'_2)$ (r' and p' defined in the meson rest frame)

- Momentum space Wigner function (after averaging over position space) for s and p wave ϕ_M:

$W_s = g_M \dfrac{(2\sqrt{\pi}\sigma)^3}{V} e^{-\sigma^2 k^2} \qquad W_p = g_M \dfrac{(2\sqrt{\pi}\sigma)^3}{V} \dfrac{2}{3} \sigma^2 k^2 e^{-\sigma^2 k^2}$ ($\sigma = 1/\sqrt{\mu\omega}$, μ: reduced mass)

Coalescence model

- Hadron spectrum from coalescence

$$f_M(\vec{p}'_M) = \int d^3p_1 d^3p_2 f_1(\vec{p}_1) f_2(\vec{p}_2) W(\vec{p}_1, \vec{p}_2) \delta(\vec{p}'_M - \vec{p}_1 - \vec{p}_2)$$

$f_i(\vec{p}_i)$: distribution of constituent quarks

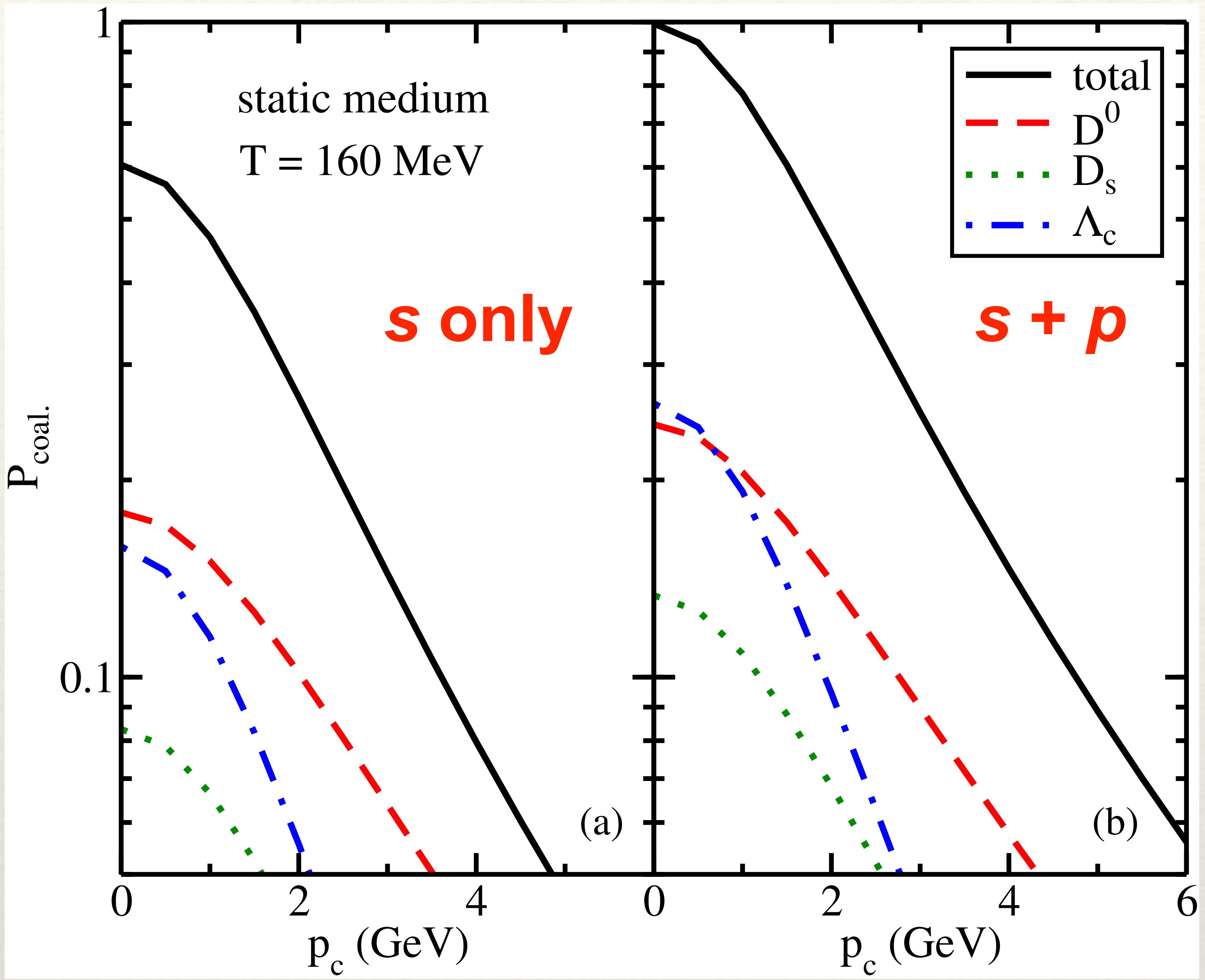
Light quarks: thermal distribution in the local rest frame of the QGP (gluons are converted to light quark pairs by $gg \to q\bar{q}$)

Heavy quarks: from a Langevin-hydrodynamics simulation (discuss later)

- Straightforward to extend to a 3-body system for baryon formation
- Coalescence probability for a single charm quark with a given p_c into a particular hadron species

$$P_{\rm coal}(p_c) = \int d^3p'_M f_M(\vec{p}'_M) \quad \text{with} \quad f_c(\vec{p}) = \delta(\vec{p} - \vec{p}_c)$$

Coalescence probability



- Include both *s* and *p*-wave states in a full 3-D calculation

  e.g. D^0 $(c\bar{u})$ meson formation with $S = 0, 1$

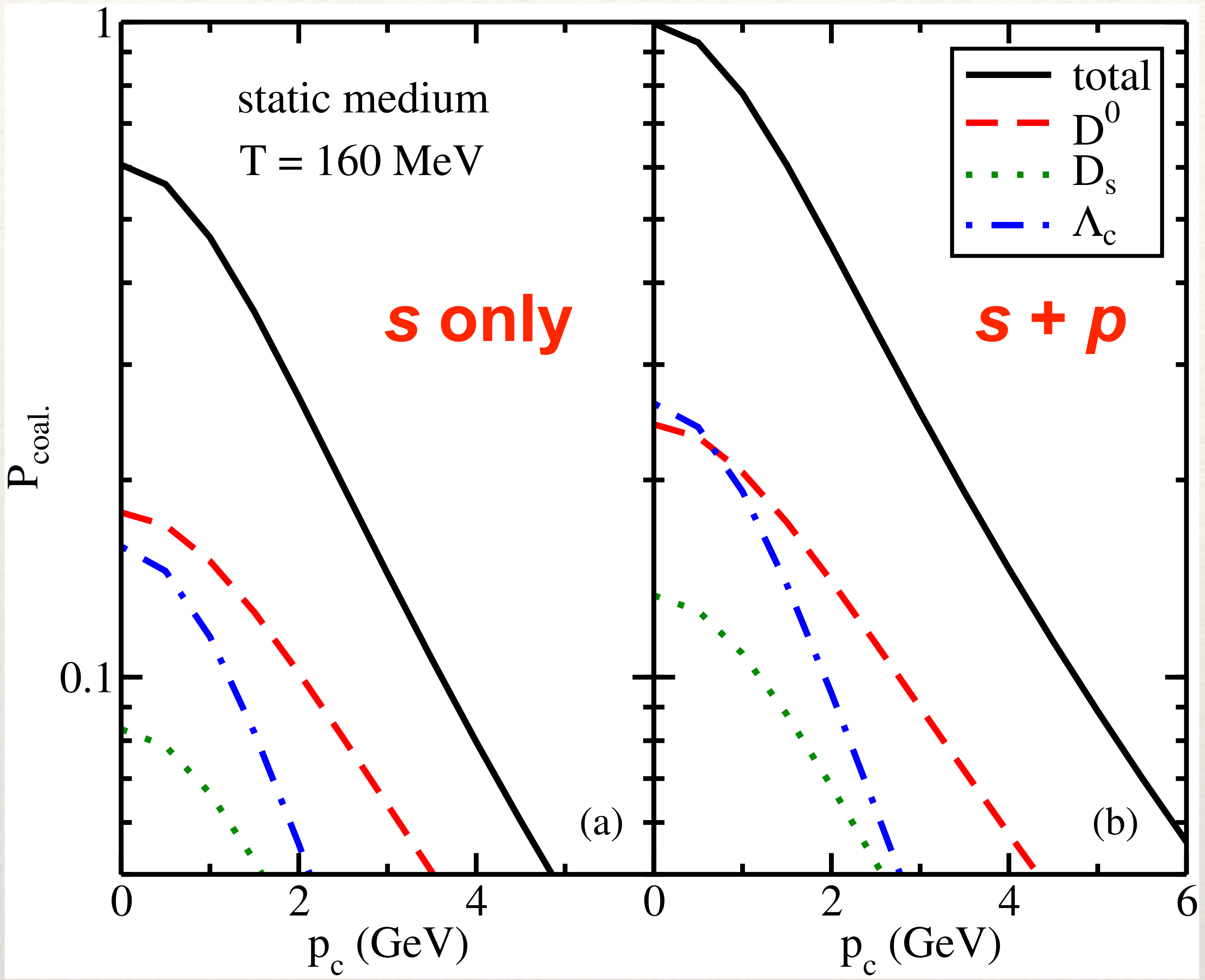
  s wave $(L = 0)$: $S = 0 \rightarrow J = 0\ (D^0)$; $S = 1 \rightarrow J = 1\ (D^{*0})$

  p wave $(L = 1)$: $S = 0 \rightarrow J = 1\ (D_1^0)$;

  $S = 1 \rightarrow J = 0\ (D_0^{*0}),\ J = 1\ (D_1^{*0}),\ J = 2\ (D_2^{*0})$

- Cover nearly all charmed hadrons in PDG
- Enhance the total $P_{\rm coal}$

Coalescence probability



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- Cover nearly all charmed hadrons in PDG
- Enhance the total P_{coal}

- Allow normalizing $P_{\mathrm{coal}}(p_c = 0) = 1$ with a proper $\omega = 0.24$ GeV, abandoning arbitrary normalization factors in literature
- Predict larger in-medium hadron size ($r_{D^0} = \sqrt{3/(2\mu\omega)} = 0.97$ fm) than in vacuum (0.83 fm), consistent with relativistic potential model prediction (Shi, Zhao, Zhuang, arXiv:1905.10627)
- Coalescence-fragmentation model: use Pythia to fragment heavy quarks that do not coalesce

Energy conservation and thermal limit

- Recall: $f_M(\vec{p}'_M) = \int d^3p_1 d^3p_2 f_1(\vec{p}_1) f_2(\vec{p}_2) W(\vec{p}_1, \vec{p}_2) \delta(\vec{p}'_M - \vec{p}_1 - \vec{p}_2)$

- Energy is not conserved if $\vec{p}'_M$ is directly put on-shell with the hadron mass

- 3-*p* → 4-*p* conservation: coalesce to an off-shell *c*-hadron $(E'_M, \vec{p}'_M)$ and then decay it to an on-shell *c*-hadron with a pion $(E_M, \vec{p}_M) + (E_\pi, \vec{p}_\pi)$

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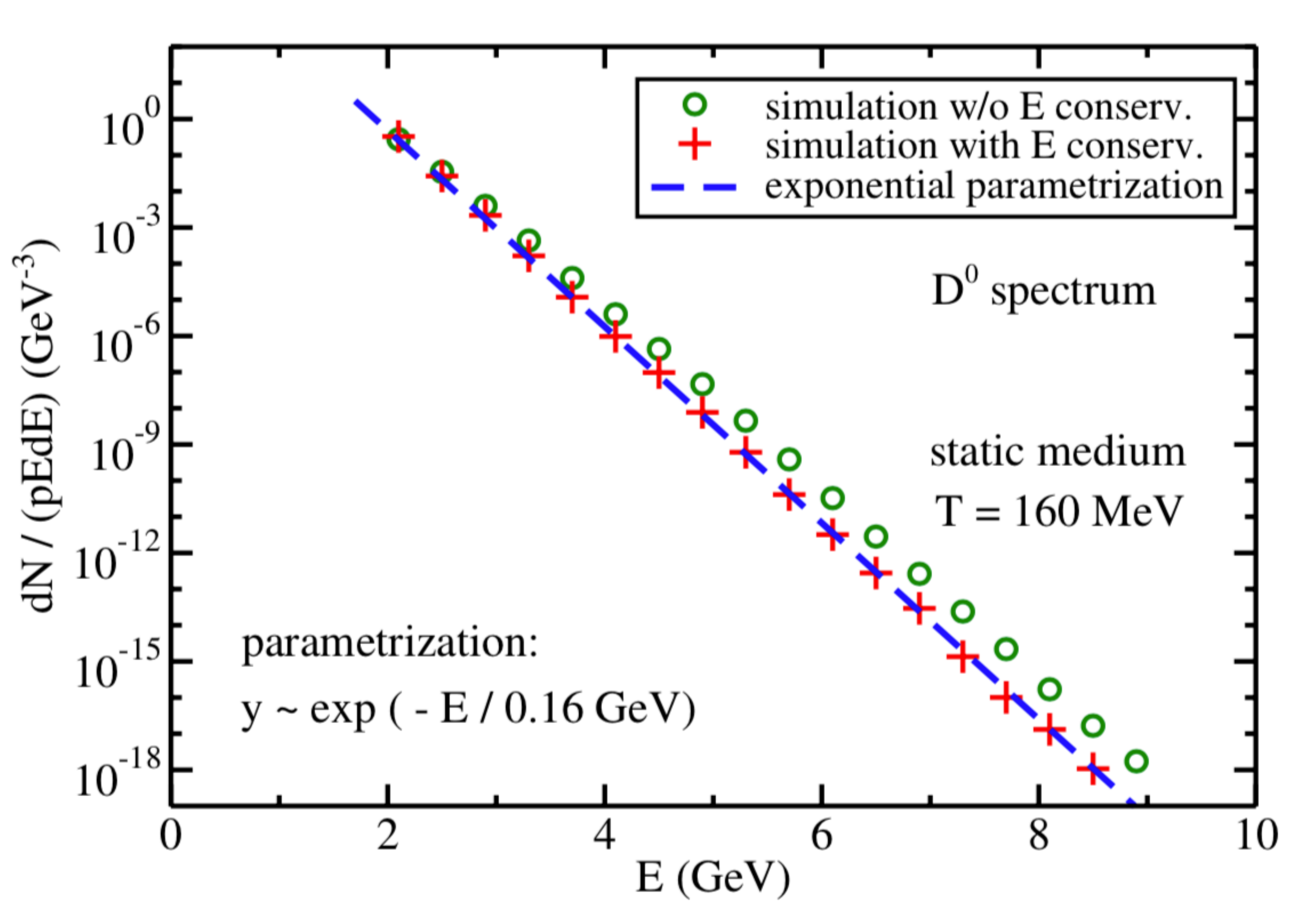


- Guarantee boost invariance
- Respect the thermal equilibrium limit of *c*-hadrons: thermal *c* + thermal *q* → thermal D^0
- Sudden approximation $|q, g\rangle \rightarrow |h\rangle$ (no inverse process) does not require the chemical equilibrium

Heavy quark evolution in heavy-ion collisions

- **Initial production**: MC-Glauber for *x* space, FONLL with CT14NLO (+EPPS16) for *p* space
- **Interaction with QGP**: Langevin-hydrodynamics model [SC, Qin and Bass, PRC 88 (2013)]

Langevin: $\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g$, with gluon radiation $\vec{f}_g = -\frac{d\vec{p}_g}{dt}$

The medium-induced gluon momentum $\vec{p}_g$ follows the spectra from the higher-twist formalism

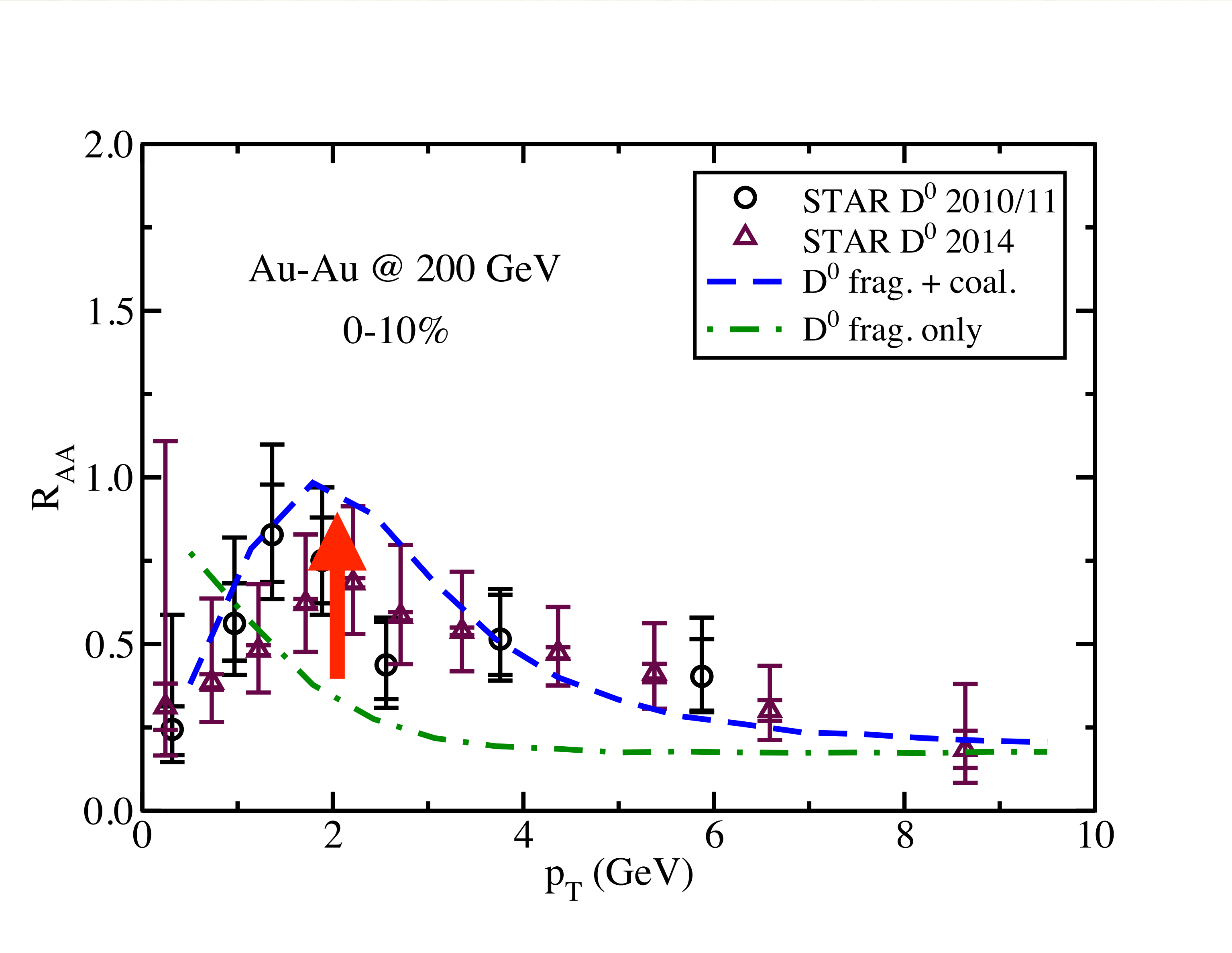
Hydrodynamics: VISHNEW [Qiu, Shen, Heinz, PLB 707 (2012)]

- **Hadronization**: Coalescence-Fragmentation at the $T_c = 160$ MeV hypersurface

- Model parameter: heavy quark diffusion coefficient $D_s(2\pi T)$ — 3.5 at RHIC and 4 at LHC

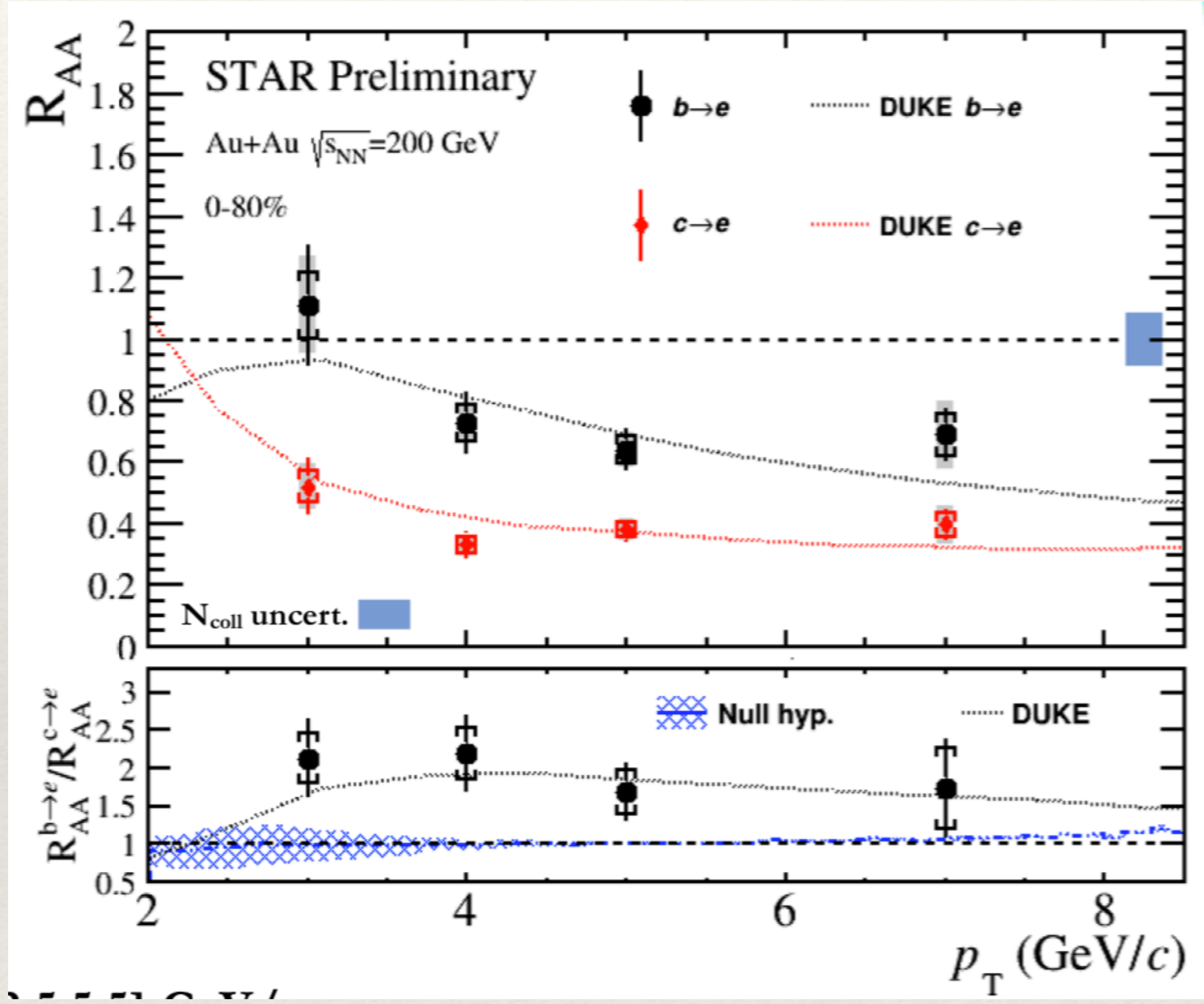
Examples of heavy flavor R_{AA} and v_2

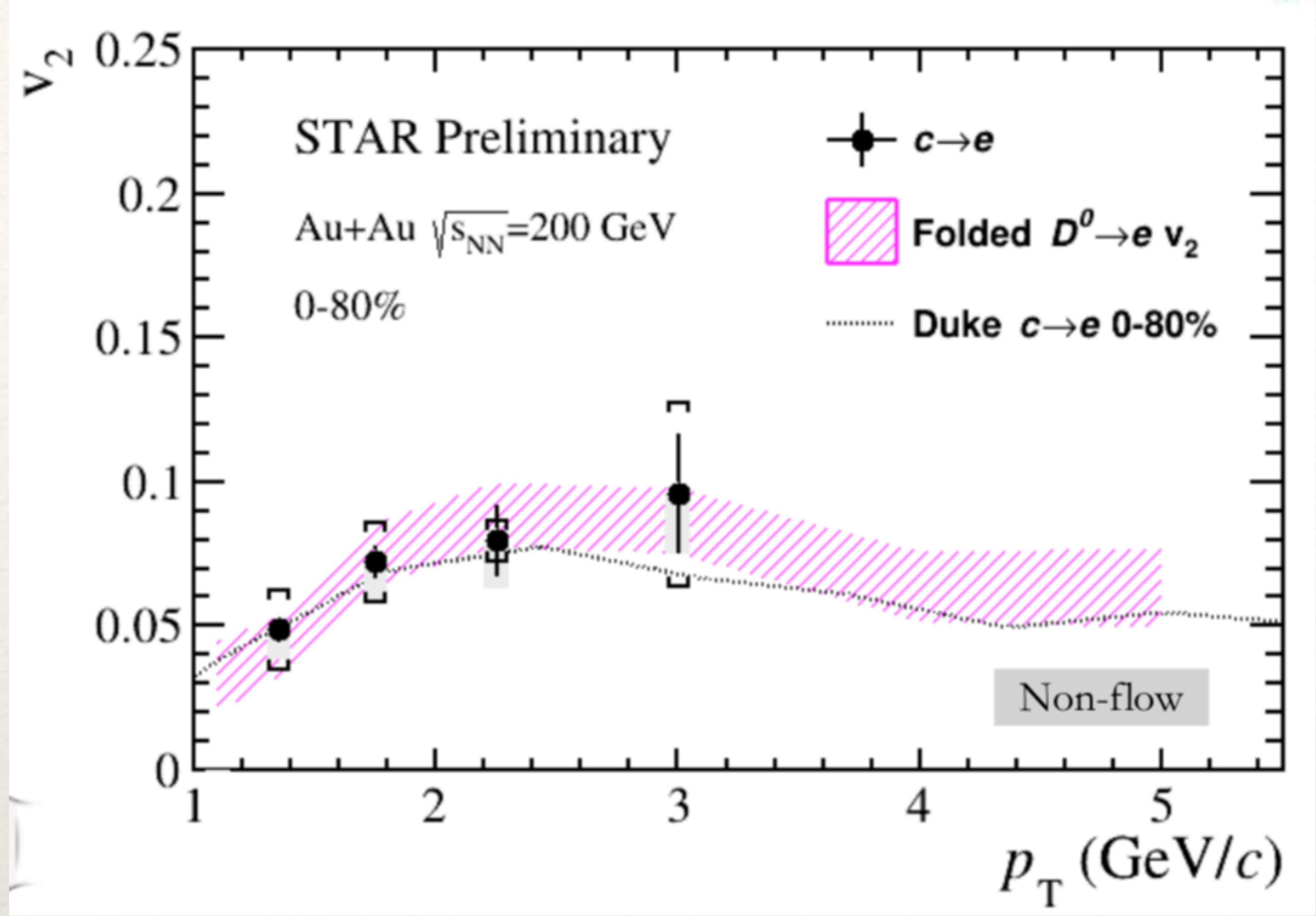
D meson R_{AA}

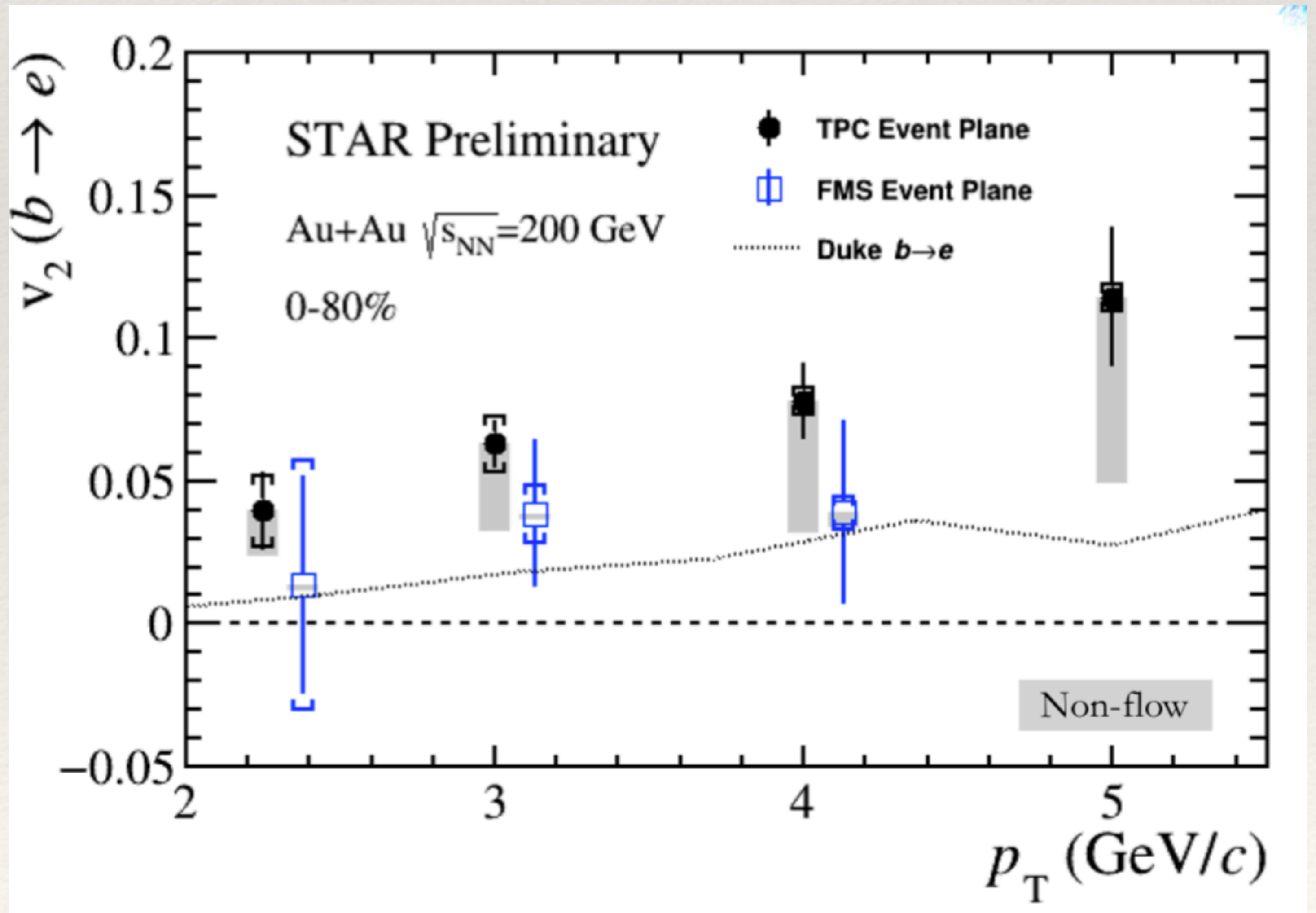


- Coalescence enhances the D^0 R_{AA} at medium p_T, generates its bump structure

c and *b* decay electron R_{AA} and v_2

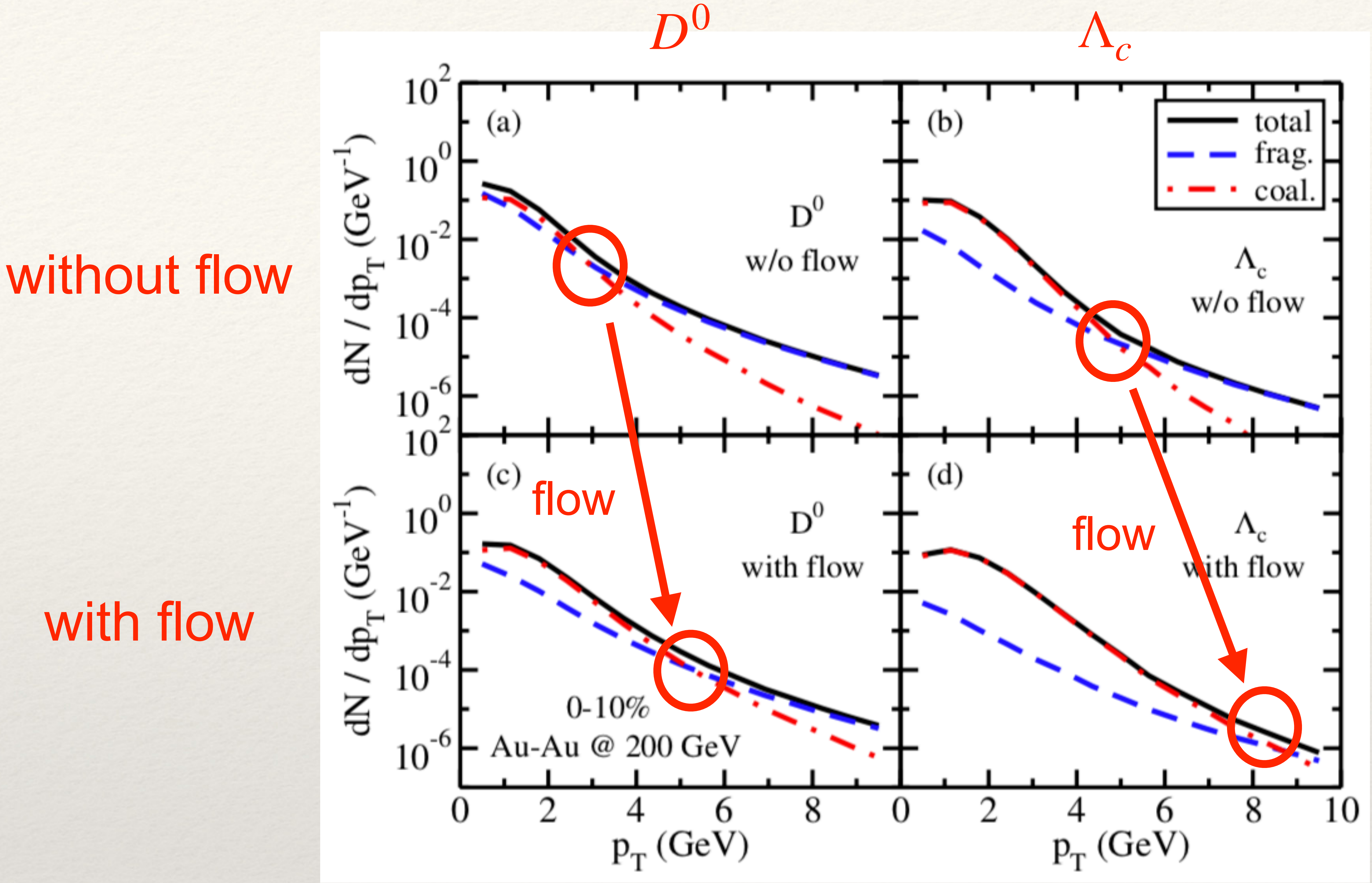






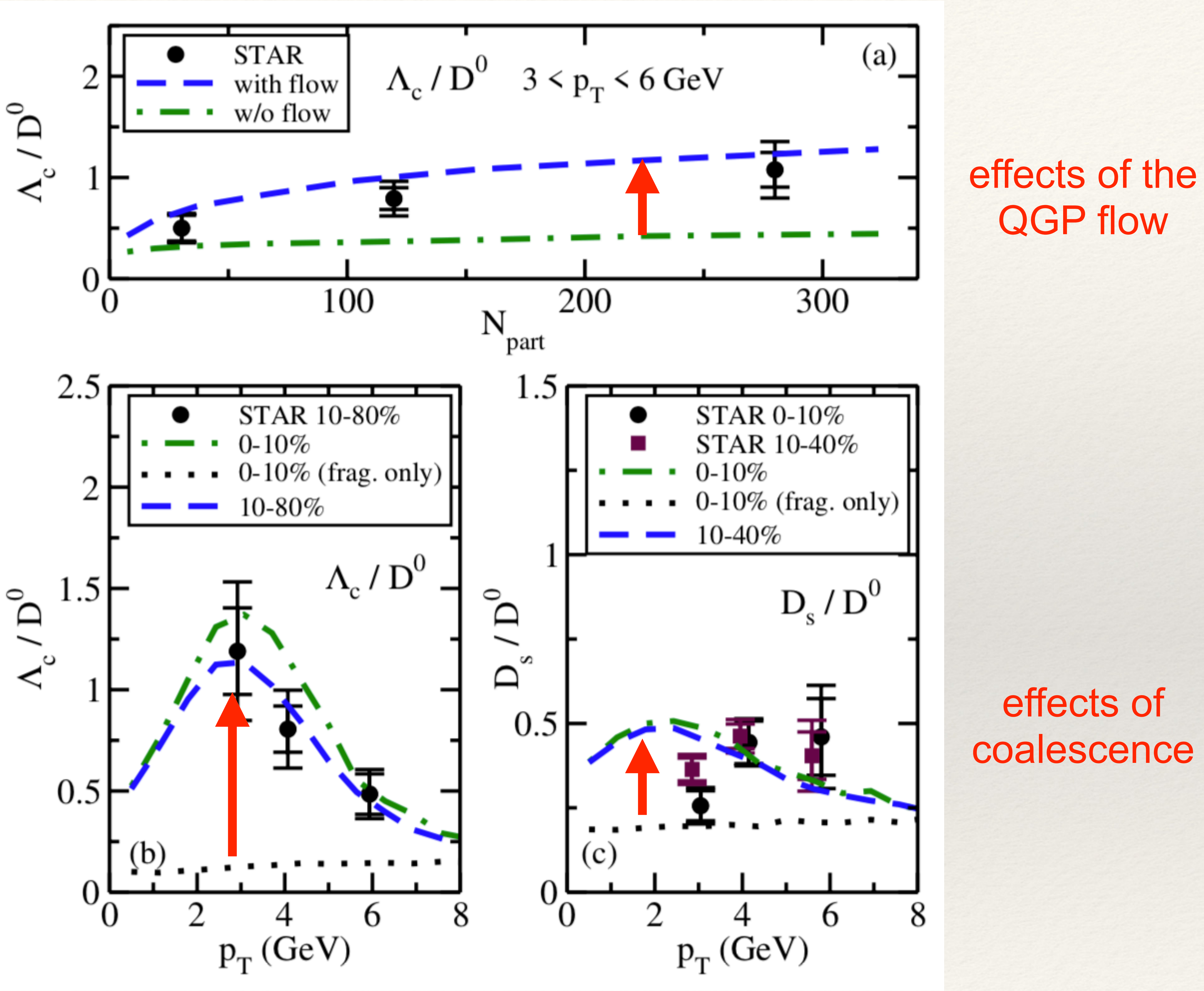
(taken from STAR presentation at QM2019 by M. Kelsey)

Charmed hadron spectra: QGP flow effect



- Coalescence dominates Λ_c production over a wider p_{T} region than D^0
- The QGP radial flow significantly enhances the coalescence contribution
- The inaccuracy of default Pythia fragmentation in pp should have minor effects on AA results, could be improved later (color reconnection [Velasquez et. al., PRL 111 (2013)], or coalescence in pp [Song, Li, Shao, EPJC 78 (2018)])

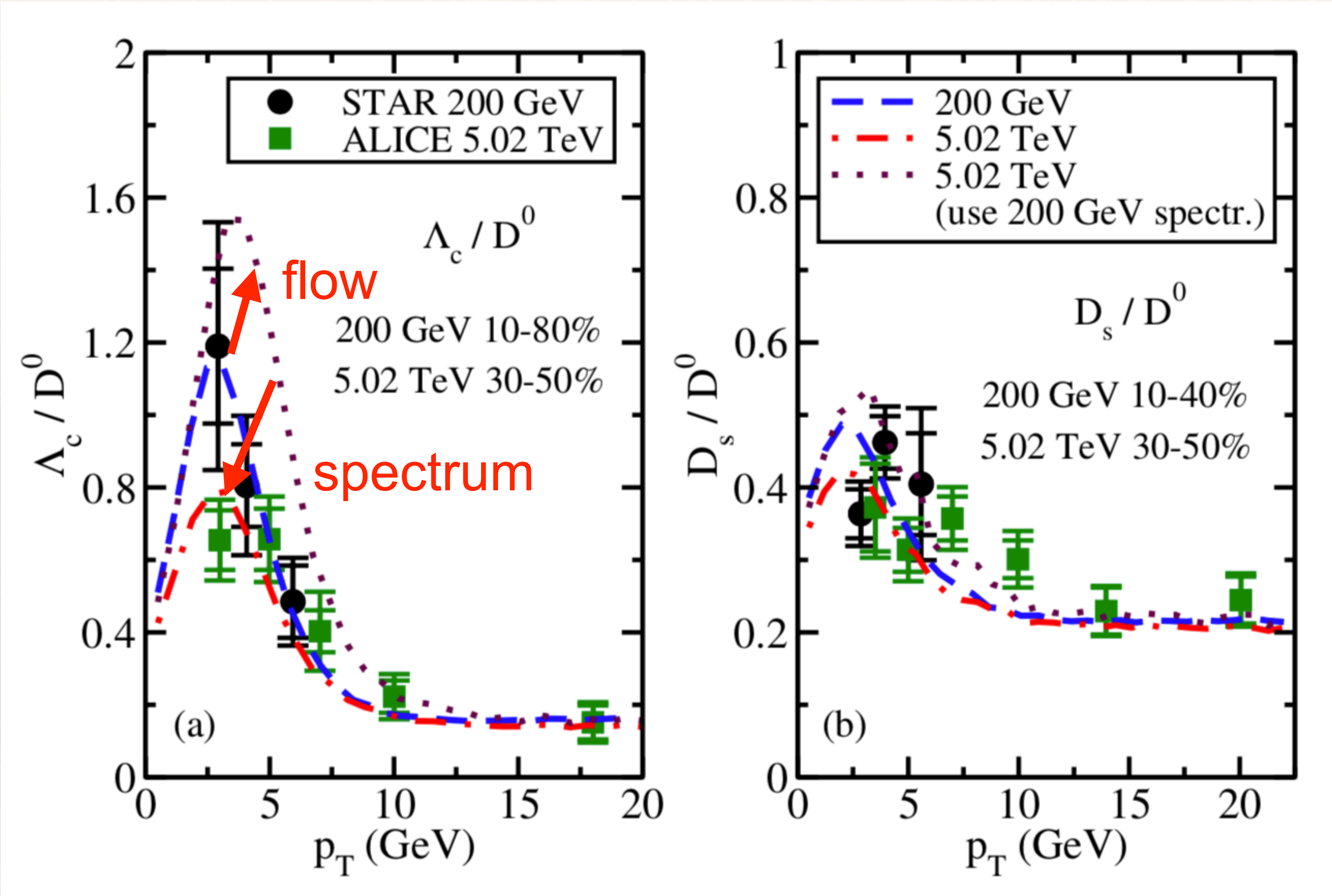
Charmed hadron chemistry at RHIC



- (a) Stronger QGP flow boost on heavier hadrons => increasing Λ_c/D^0 with N_{part}
- (b) Coalescence significantly increases Λ_c/D^0, larger value in more central collisions (stronger QGP flow)
- (c) Enhanced D_s/D^0 due to strangeness enhancement in QGP and larger D_s mass than D^0

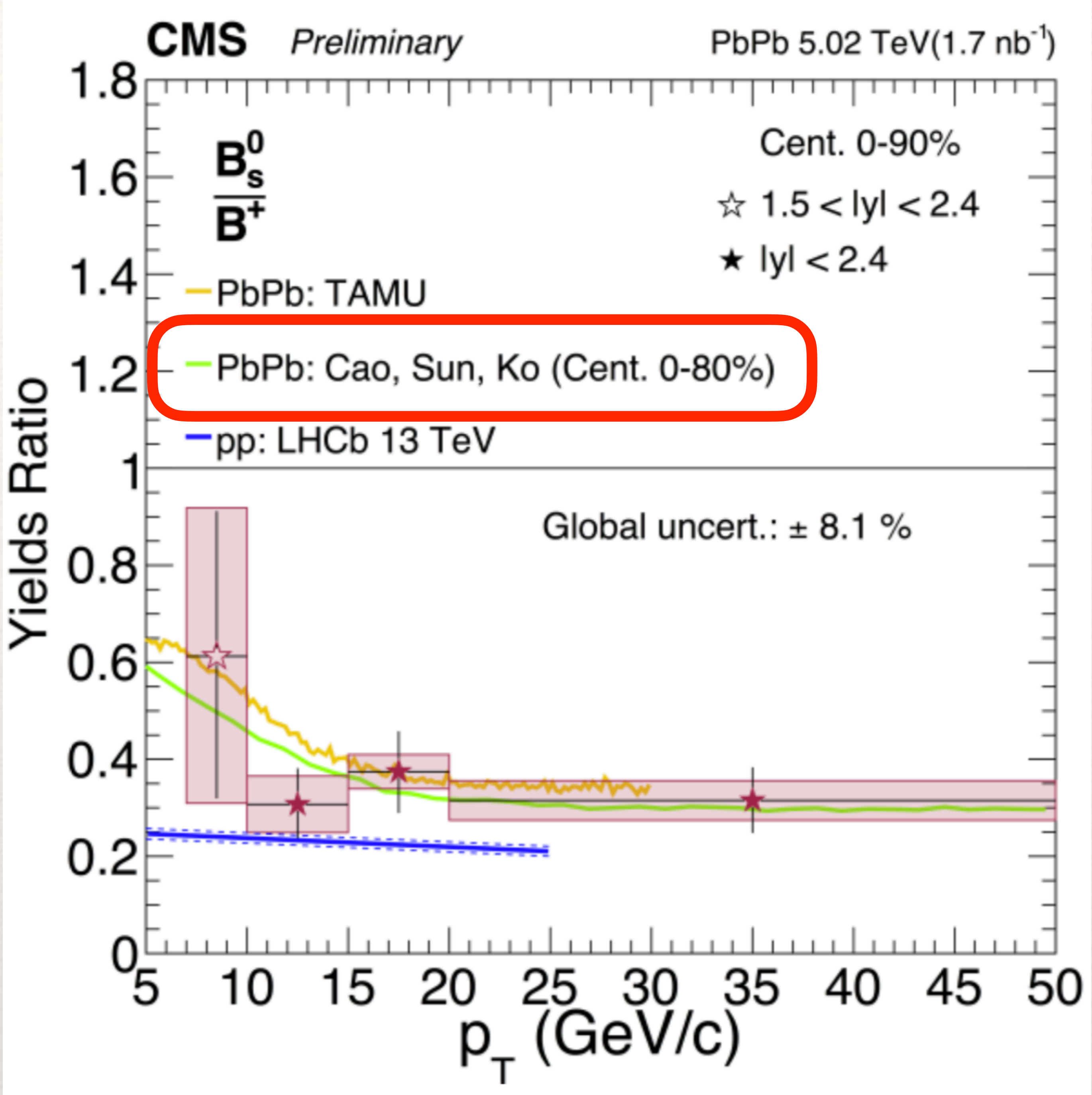
RHIC vs. LHC

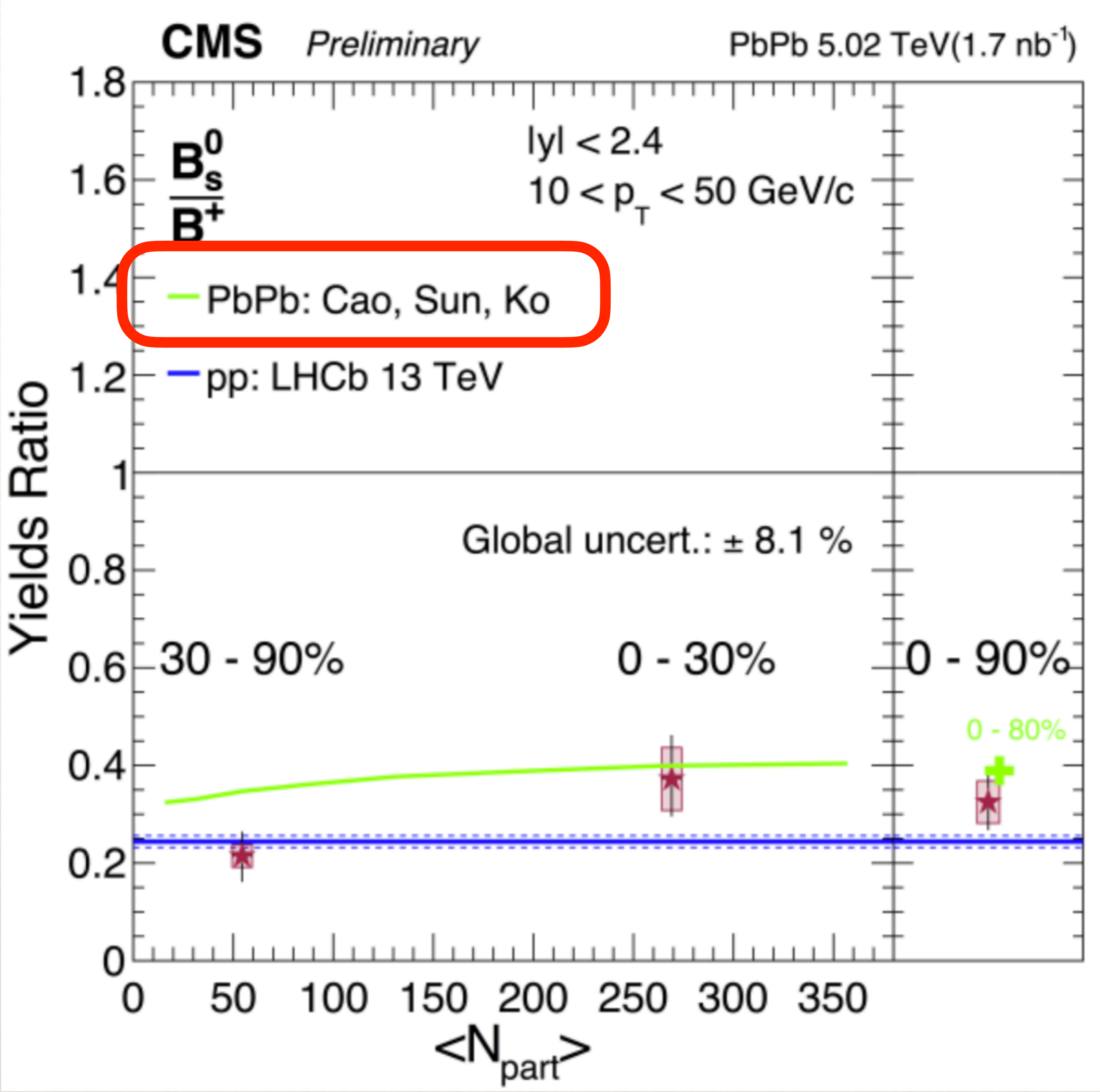
Λ_c/D^0 D_s/D^0



- IF charm quarks have the same initial spectrum at RHIC and LHC, Λ_c/D^0 would be larger at LHC than RHIC due to the flow effect
- The harder initial charm quark spectra at LHC reduces Λ_c/D^0
- Similar theoretical prediction on D_s/D^0

Prediction on beauty hadron chemistry





taken from CMS presentation at HP2020 by Z. Shi

- More constraints on the mass (velocity/momentum) dependence of hadronization models
- Assume same diffusion coefficient D_s between *c* and *b* quarks
- Only difference: $\omega_c = 0.24$ GeV $\rightarrow$ $\omega_b = 0.14$ GeV so that $P_{\rm coal}(p_b = 0) = 1$ for *b* quarks

Summary

- Developed a comprehensive hadronization model for heavy quarks
- Included a complete set of *s* and *p*-wave hadron states in coalescence, allowing to normalize the heavy quark coalescence probability at $p = 0$ with proper ω
- Introduced 4-*p* conservation to respect boost invariance and thermal equilibrium limit
- Revealed the strong QGP flow effect on the heavy flavor hadron chemistry
- Provided a good prediction on $\Lambda_c/D^0, D_s/D^0$ and B_s/B^+ at RHIC and LHC
- Found the competing effects of QGP flow and charm quark spectra yield the different observations at RHIC *vs.* LHC