中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA

Probing heavy flavor hadronization with hadron chemistry in Heavy-ion Collisions

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Outline

- Introduction of heavy flavor hadronization
- Theoretical framework of heavy quark energy loss and hadronization
- Heavy flavor hadron chemistry
- Systematic analysis of model uncertainties
- Summary

References:

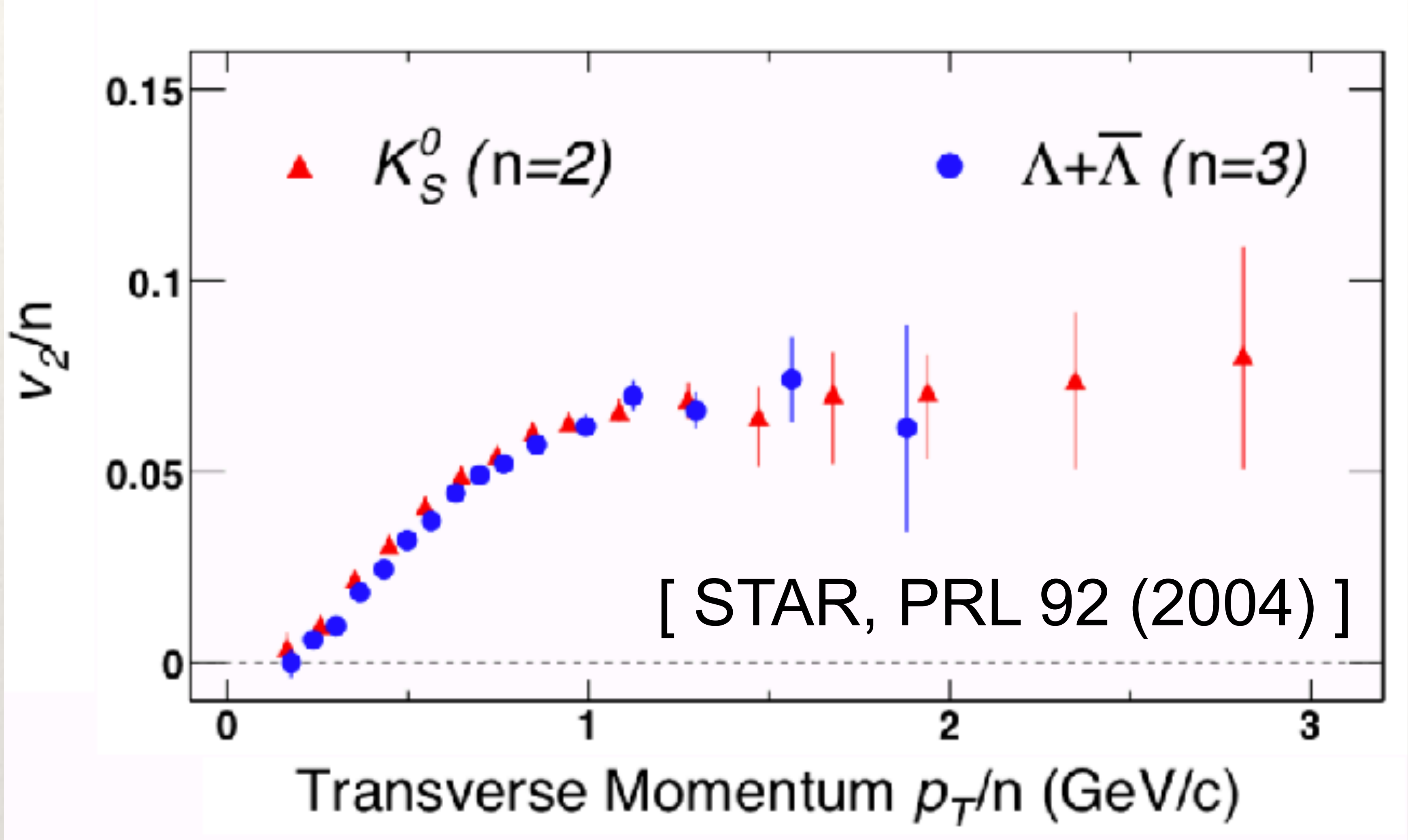
Heavy quark energy loss: Phys. Rev. C 92 (2015) 2, 024907, arXiv:1505.01413

Improved hadronization model: Phys. Lett. B 807 (2020) 135561, arXiv:1911.00456

Model uncertainties: Chin. Phys. C 44 (2020) 11, 114101, arXiv:2005.03330

Hadronization is an important but difficult topic

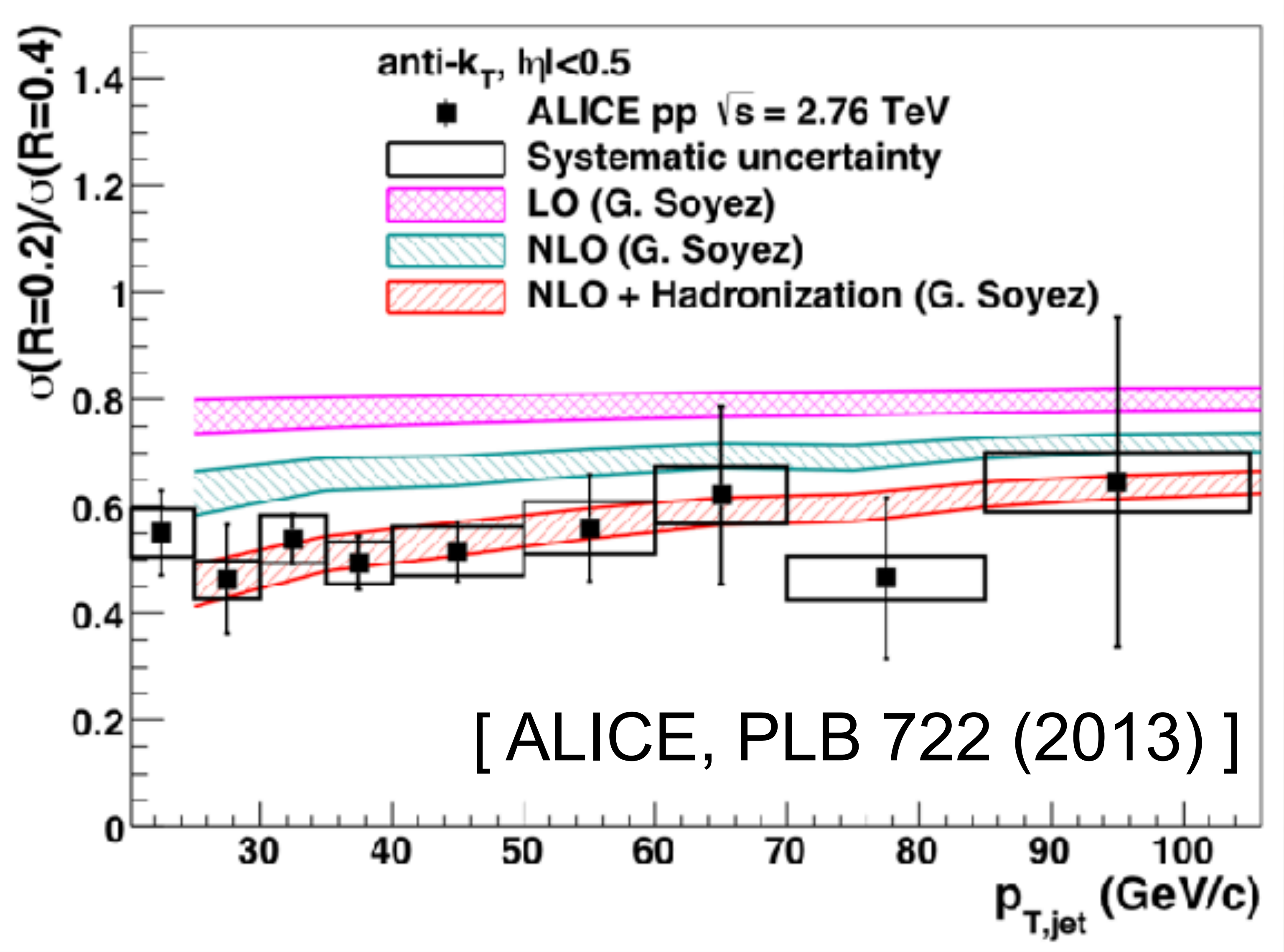
Soft: NCQ scaling of hadron v_2



[STAR, PRL 92 (2004)]

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

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

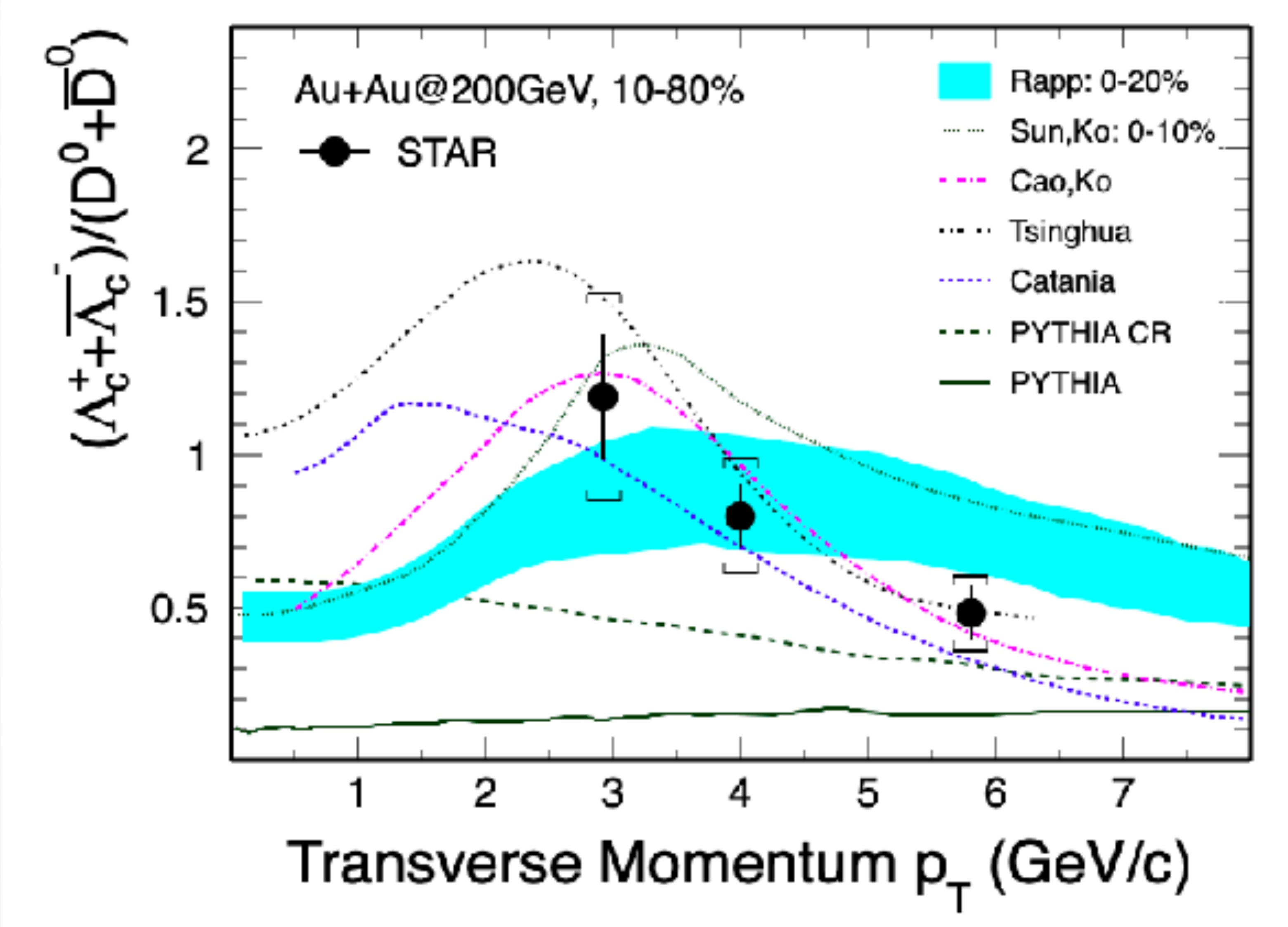


[ALICE, PLB 722 (2013)]

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

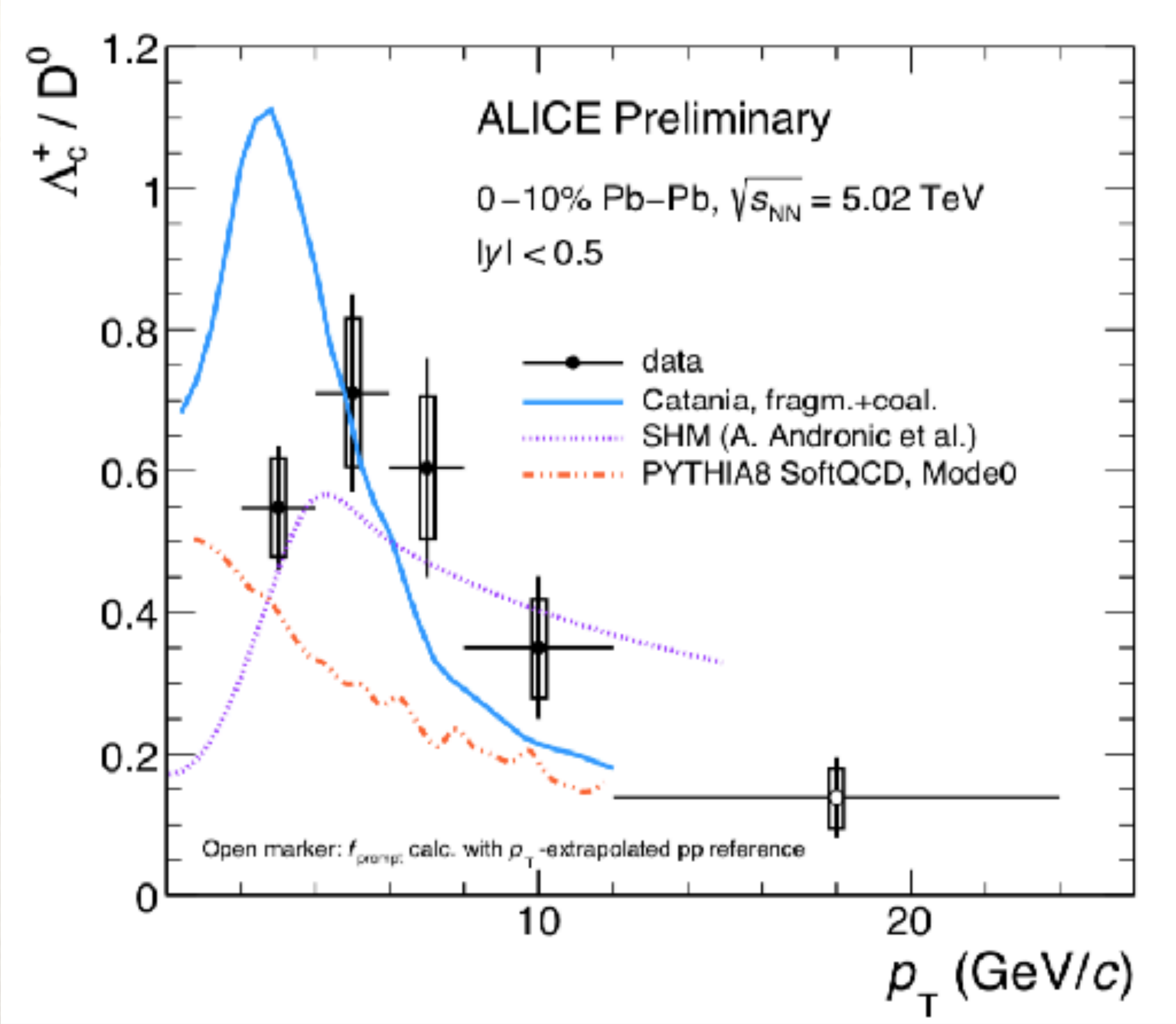
Charmed hadron chemistry

RHIC



[STAR, PRL 124 (2020)]

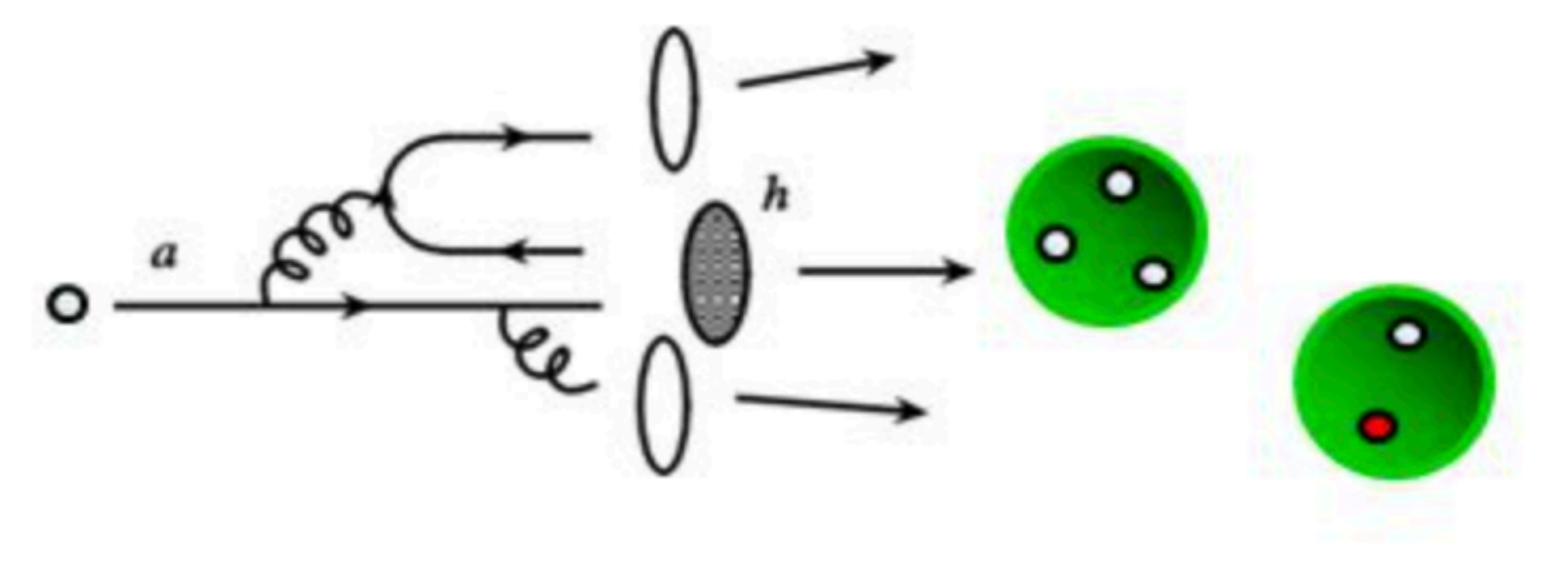
LHC



[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

Two major hadronization mechanisms

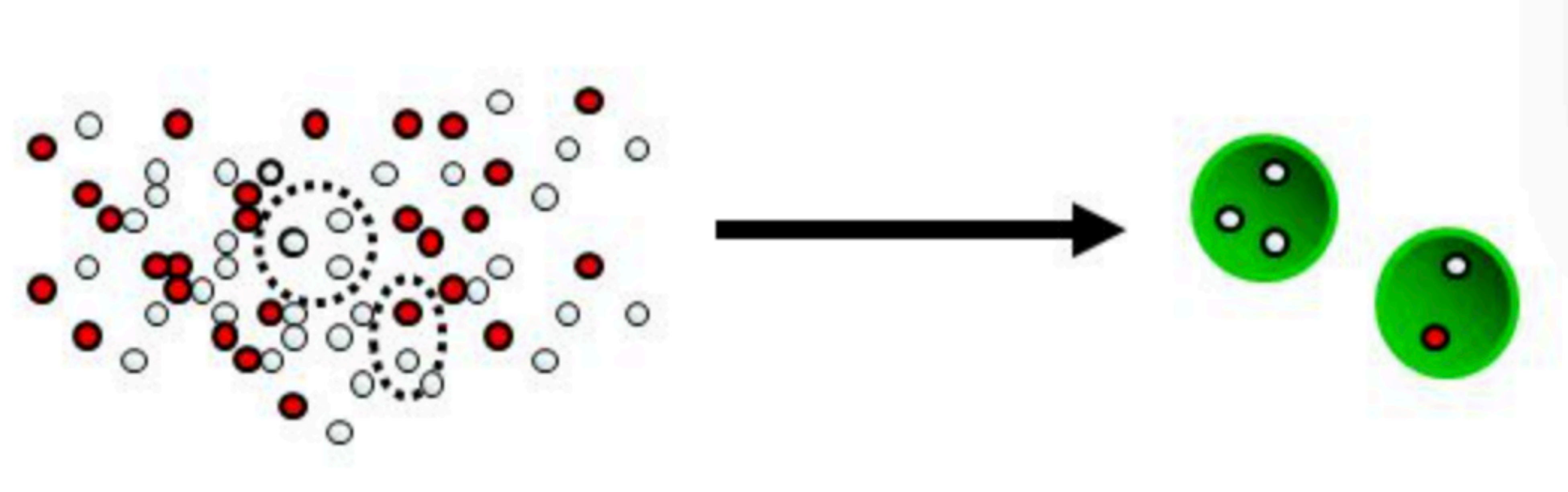


***Fragmentation*:**

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 (2009)
Plumari, Minissale, Das, Coci and Greco, EPJC 98 (2018)
Cho, Sun, Ko, Lee and Oh, PRC 101 (2020)
Cao, Sun, Li, Liu, Xing, Qin and Ko, PLB 807 (2020)

Coalescence models

- Simplified models: equal-velocity coalescence [Shao et. al., e.g. EPJC 78 (2018)]

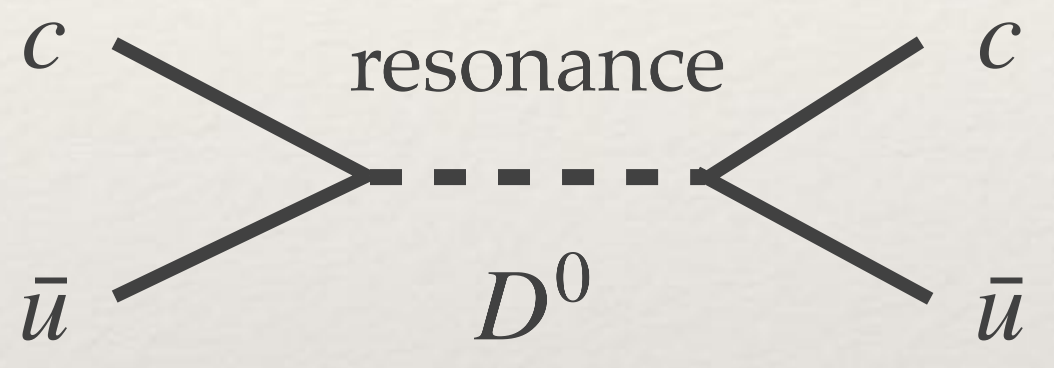
  coalescence between neighboring particles [AMPT, e.g. PRC 101 (2020)]

- Resonance recombination: coalescence probability ~ resonant scattering rate

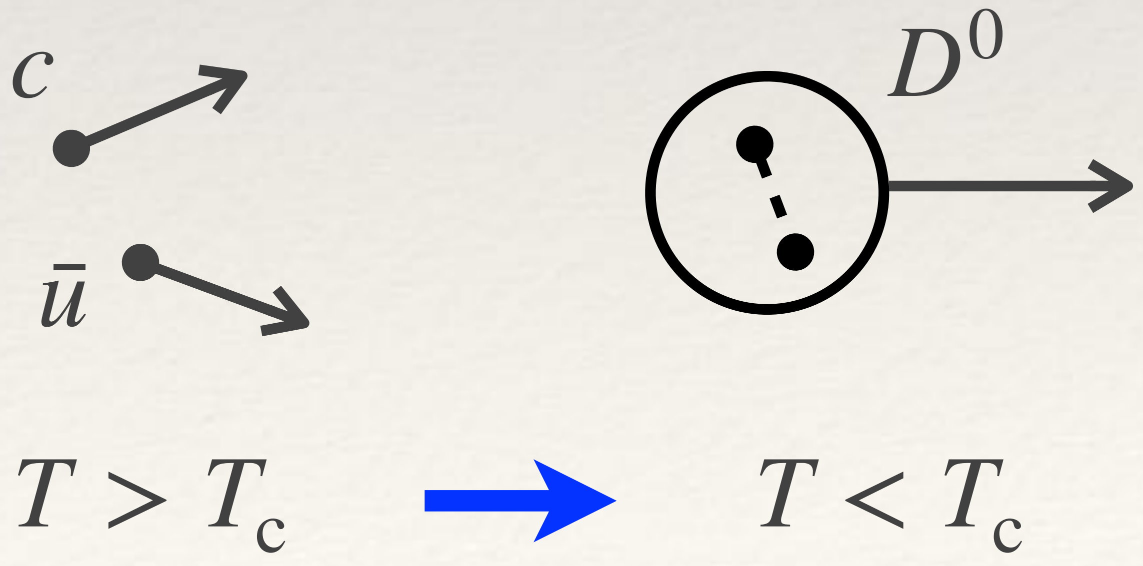
  [He et. al., e.g. PRC 86 (2012), PRL 124 (2020)]

  $P_{\rm coal}(p) = \Delta\tau_{\rm res}\Gamma_Q^{\rm res}(p)$

  $\Delta\tau_{\rm res}$: time window; $\Gamma_Q^{\rm res}(p) = n_q\langle\sigma_{qQ}^{\rm res}v_{\rm rel}\rangle$: formation rate



- Instantaneous coalescence: coalescence probability ~ wavefunction overlap
  - Sudden approximation: $|q, g\rangle \rightarrow |h\rangle$ as T drops across T_c
  - Probability: wave function projection $W_M \equiv |\langle M|q_1, q_2\rangle|^2$
  - Encodes information of microscopic hadron structures



Coalescence model

- Example: 2-body system for meson formation

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

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)

$\vec{r} = \vec{r}'_1 - \vec{r}'_2 \qquad \vec{k} = \frac{1}{E'_1 + E'_2}(E'_2 \vec{p}'_1 - E'_1 \vec{p}'_2)$ (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:

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

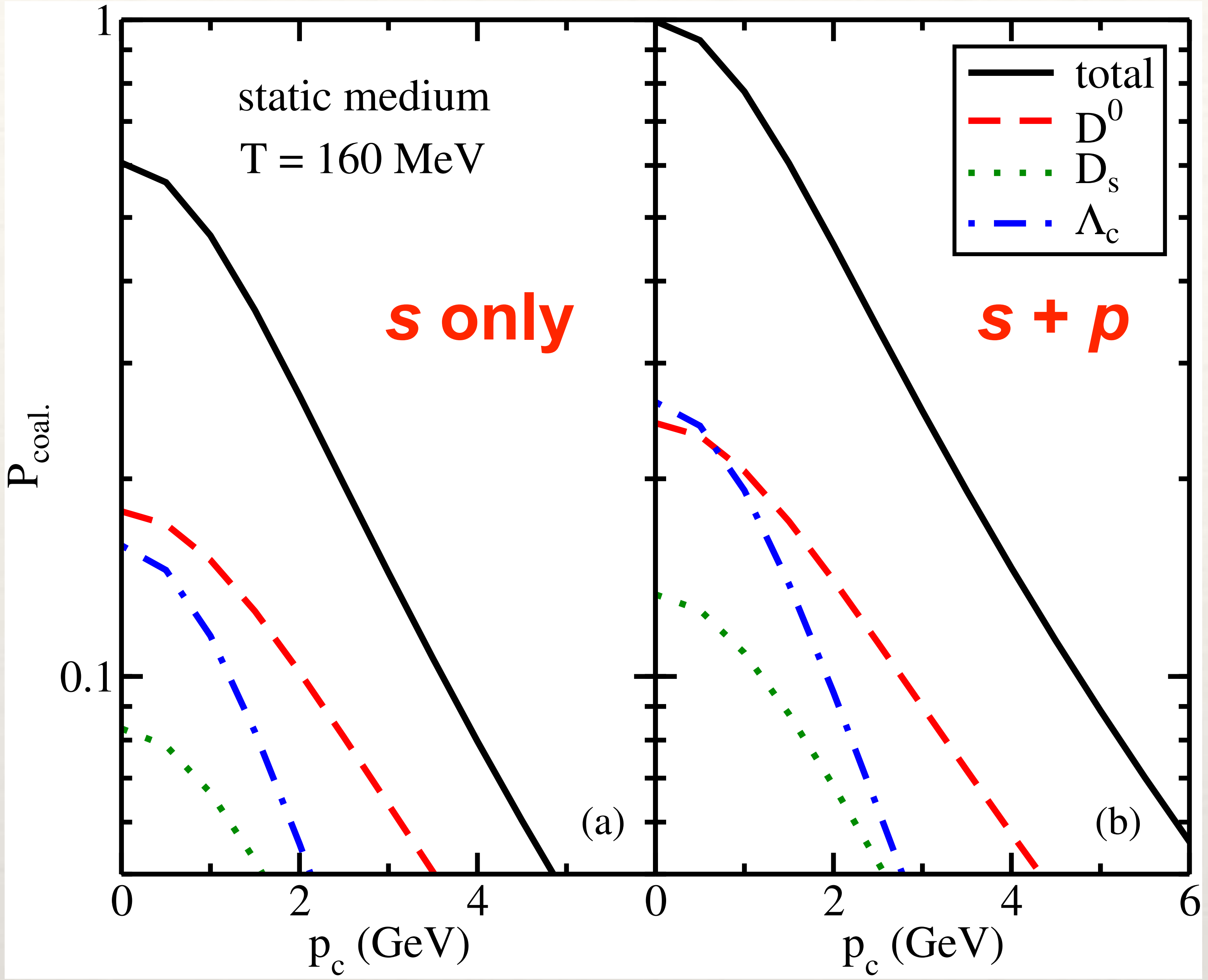
Light quarks: thermal distribution in the local rest frame of the QGP (gluons are converted to light quark pairs by $gg \to q\bar{q}$)

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

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

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

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

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

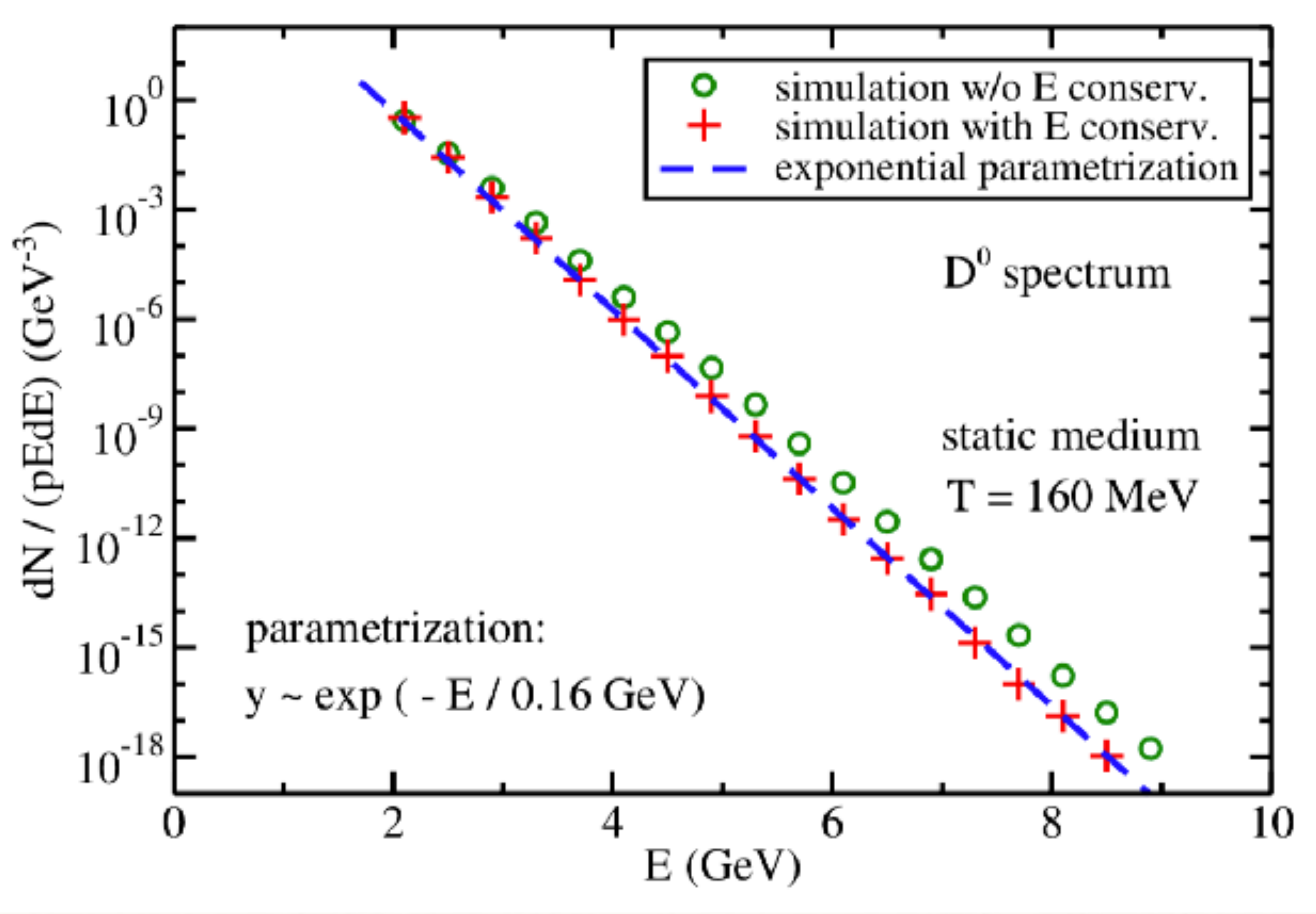
- Cover nearly all charmed hadrons in PDG
- Enhance the total $P_{\rm coal}$
- Allow normalizing $P_{\rm coal}(p_c = 0) = 1$ with a proper $\omega = 0.24$ GeV, abandoning arbitrary normalization factors in literature
- Predict larger in-medium hadron size ($r_{D^0} = \sqrt{3/(2\mu\omega)} = 0.97$ fm) than in vacuum (0.83 fm), consistent with relativistic potential model prediction (Shi, Zhao, Zhuang, CPC 44 (2020) 8, 084101)
- 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 $(E_M, \vec{p}_M) + (E_\pi, \vec{p}_\pi)$



- 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 [Cao, Qin and Bass, PRC 88 (2013)]

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

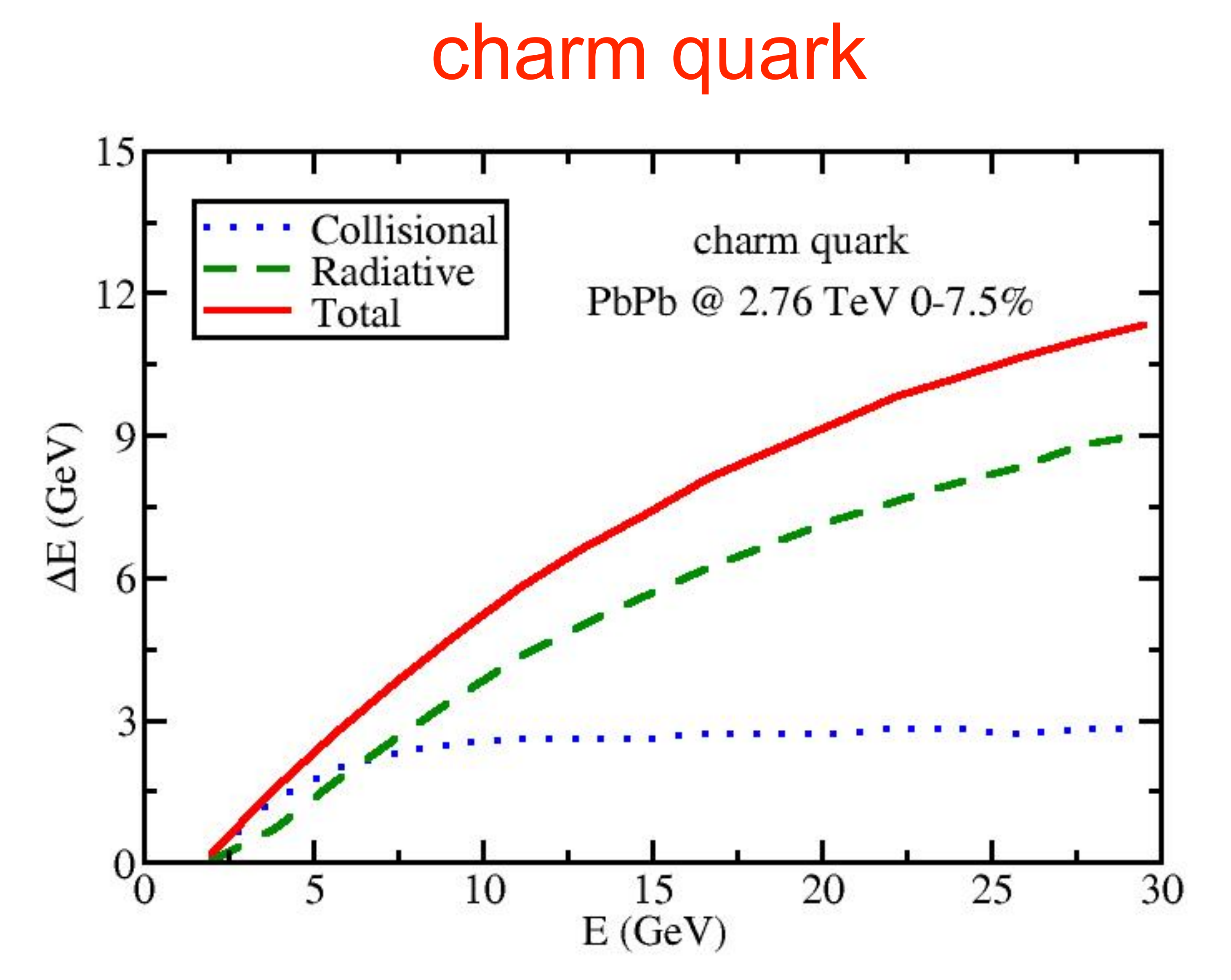
  The medium-induced gluon momentum $\overrightarrow{p}_g$ follows the spectra from the higher-twist formalism

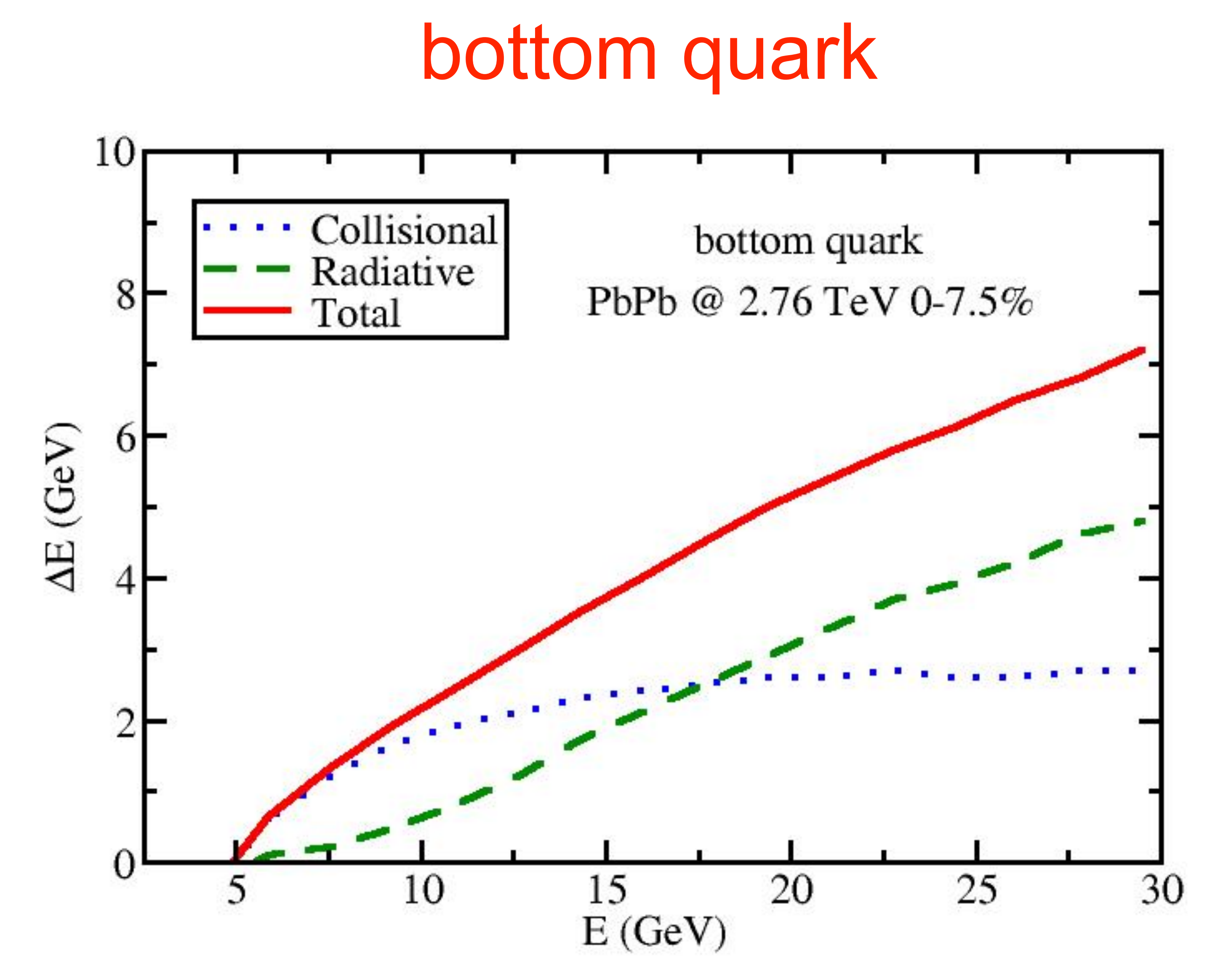
  Hydrodynamics: VISHNEW [Qiu, Shen, Heinz, PLB 707 (2012)]

- **Hadronization**: Coalescence-Fragmentation at the $T_\mathrm{c} = 160\ \mathrm{MeV}$ hypersurface

- Model parameter: heavy quark diffusion coefficient $D_\mathrm{s}(2\pi T)$ — 3.5 at RHIC and 4 at LHC

Heavy quark energy loss: collisional *vs.* radiative

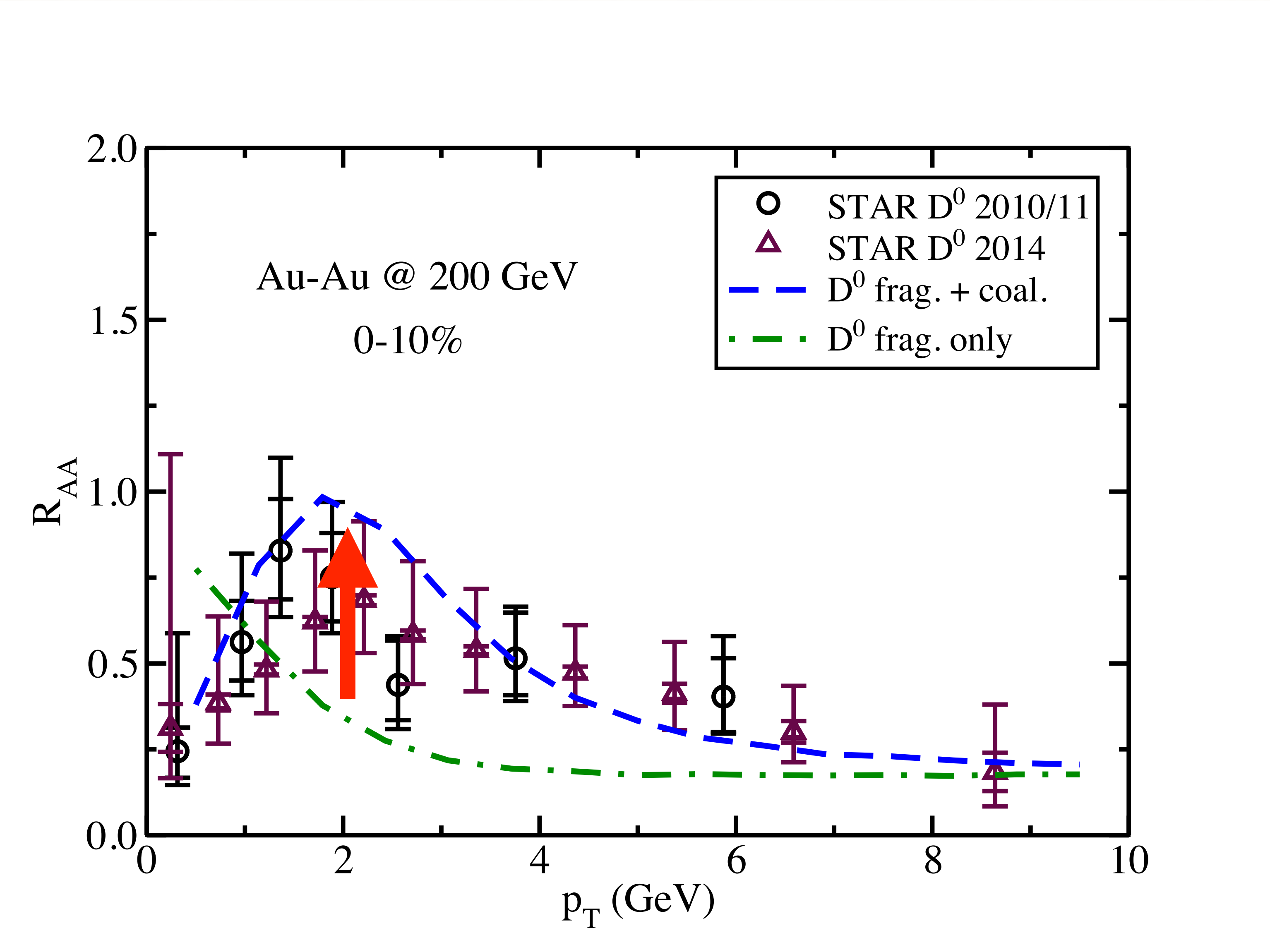




- Collisional energy loss dominates at low energy, radiative dominates at high energy
- Crossing point: 7 GeV for charm quark, 18 GeV for bottom quark
- Collisional energy loss alone may be sufficient for describing low p_T data at RHIC, but insufficient for LHC

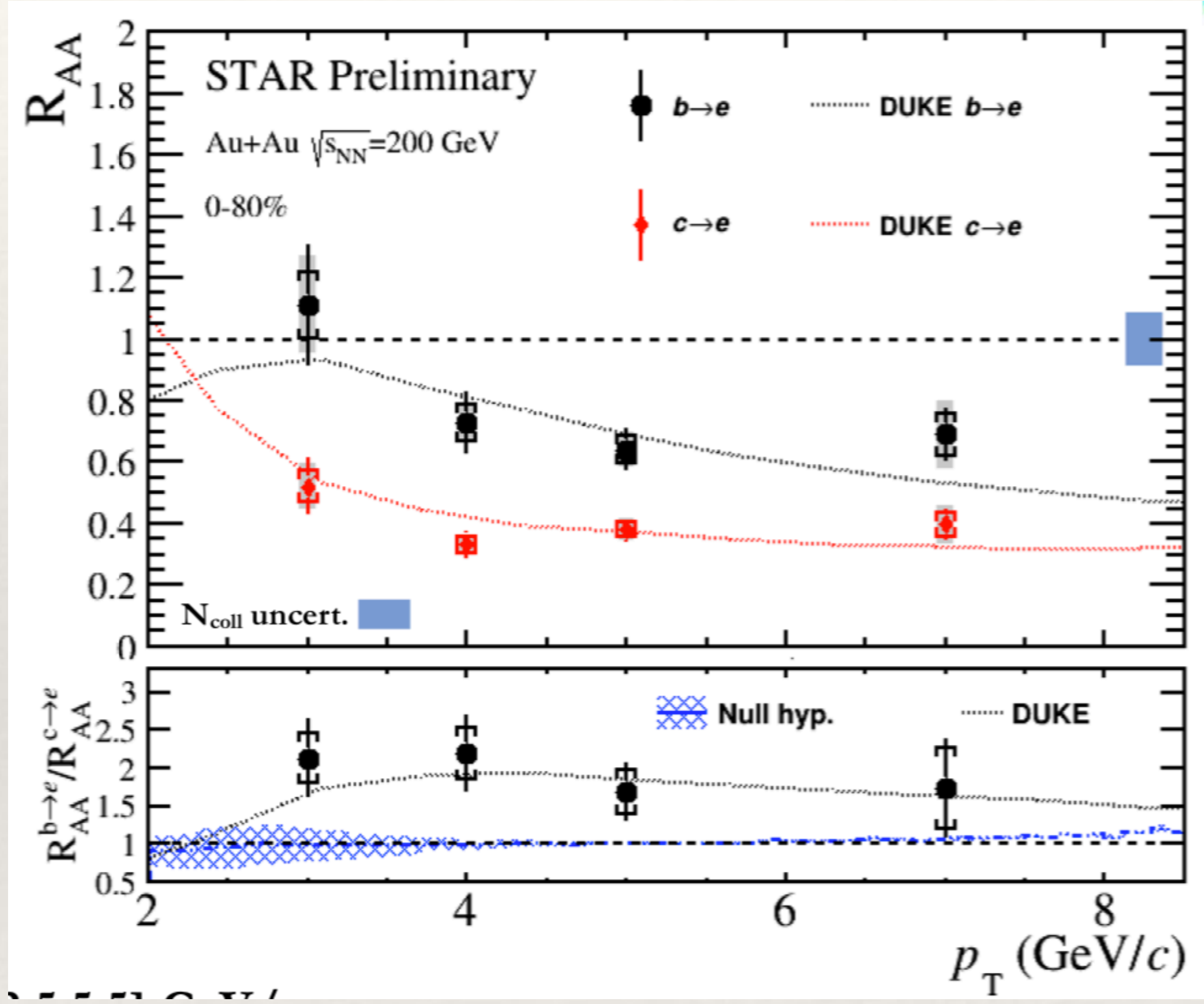
Examples of heavy flavor R_{AA} and v_2

D meson R_{AA}

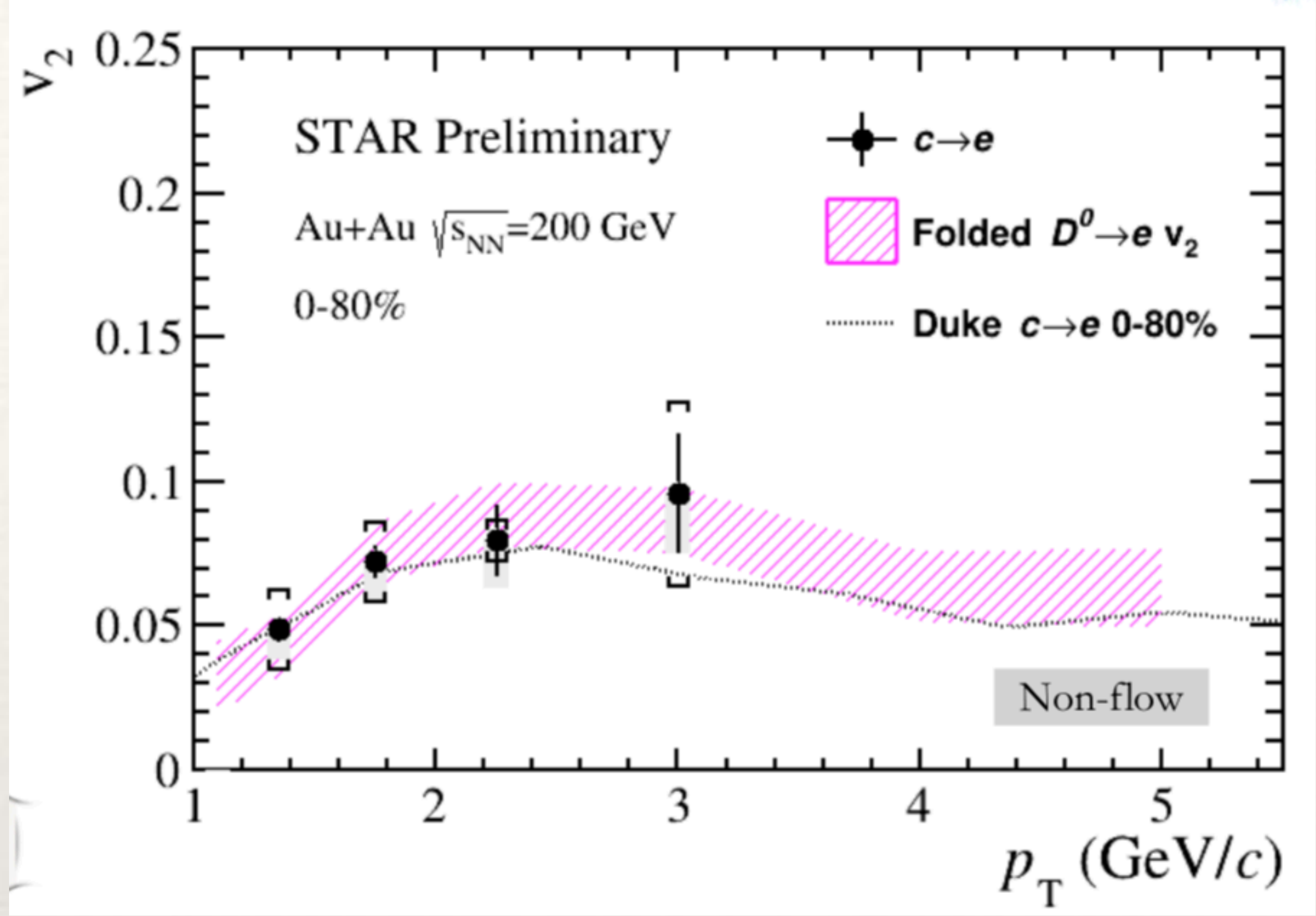


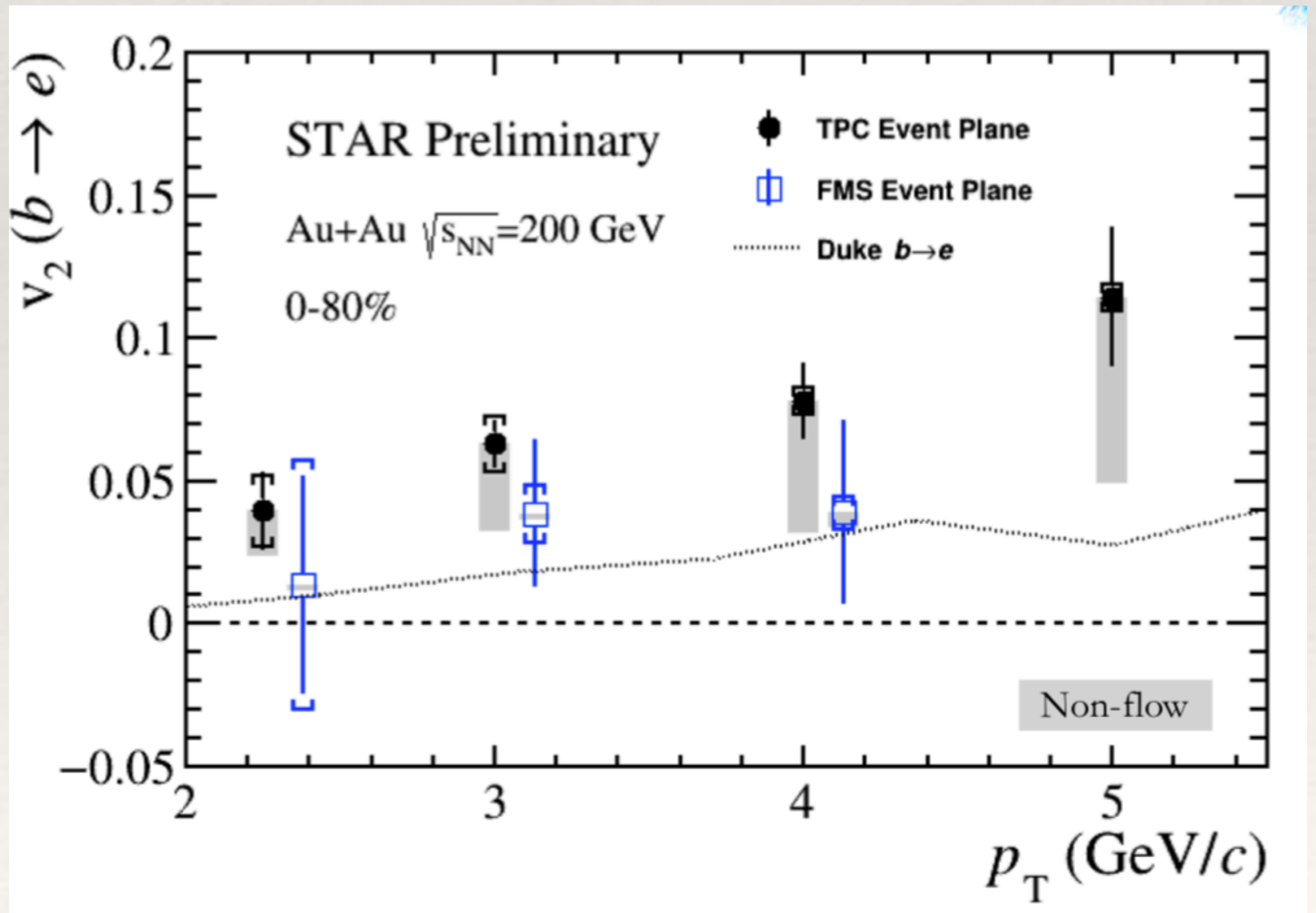
- Coalescence enhances the D^0 R_{AA} at medium p_T, generates its bump structure

c and b decay electron R_{AA} and v_2

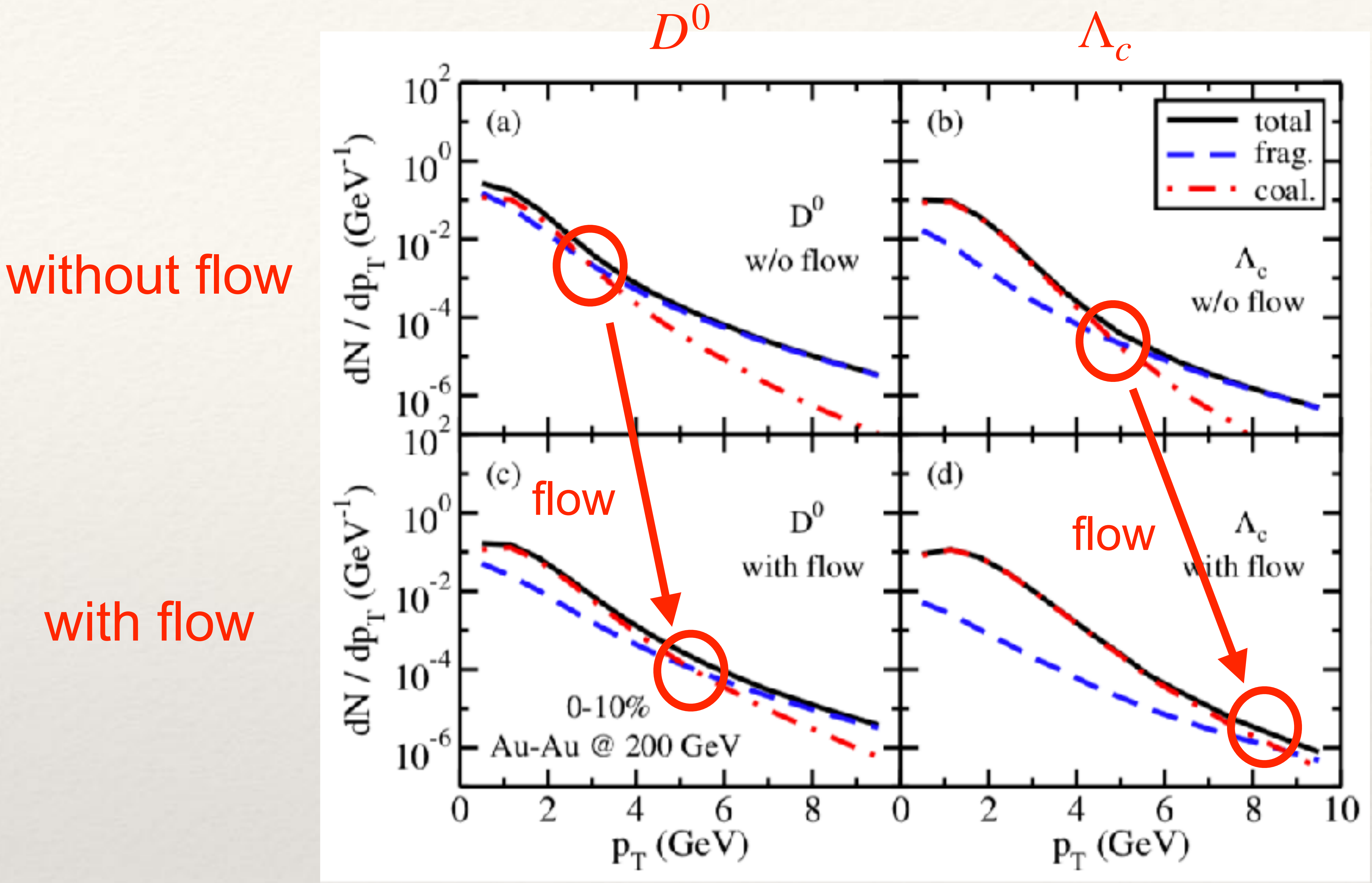


(taken from STAR presentation at QM2019 by M. Kelsey)



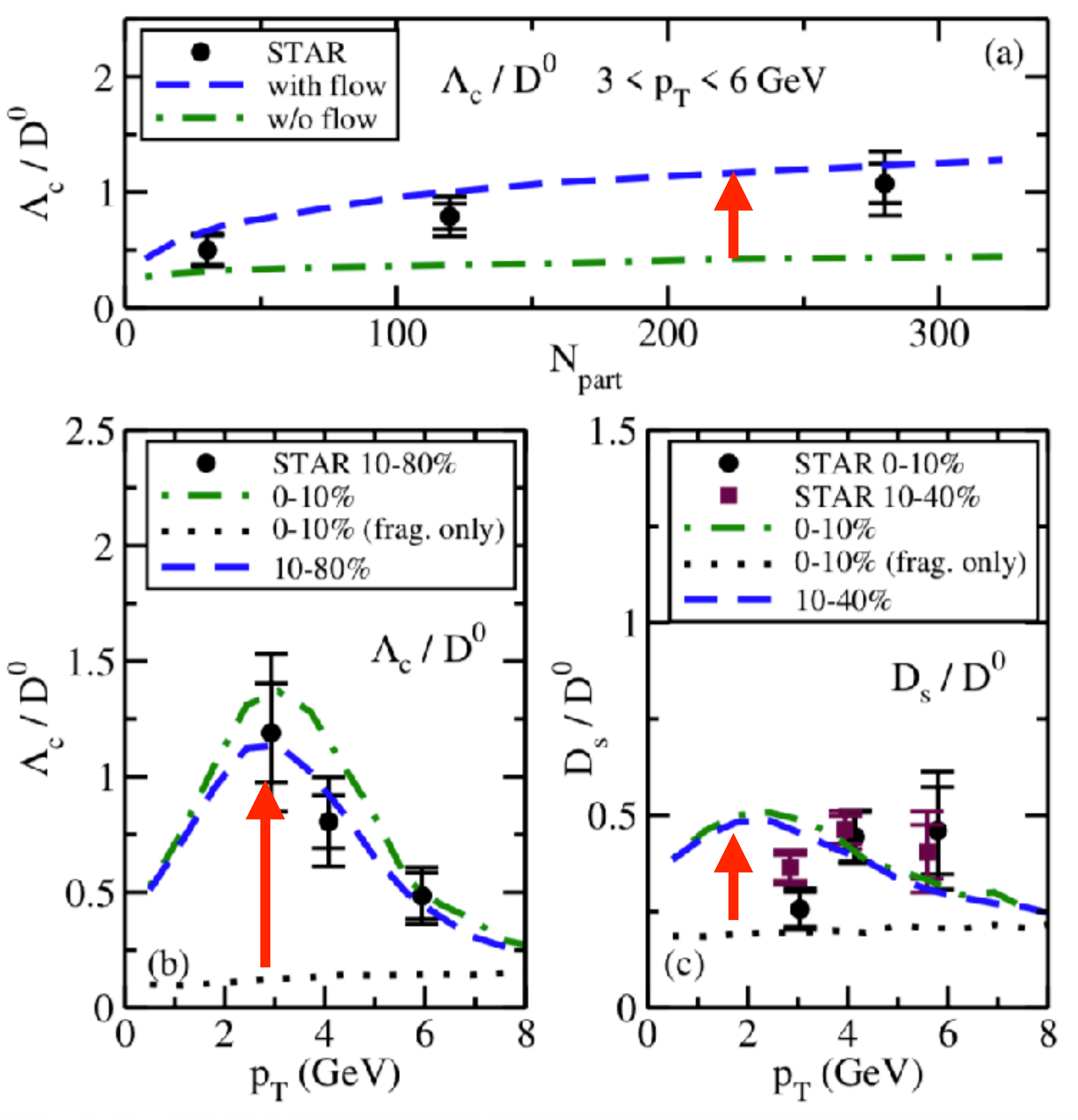


Charmed hadron spectra: QGP flow effect



- 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



effects of the QGP flow

effects of coalescence

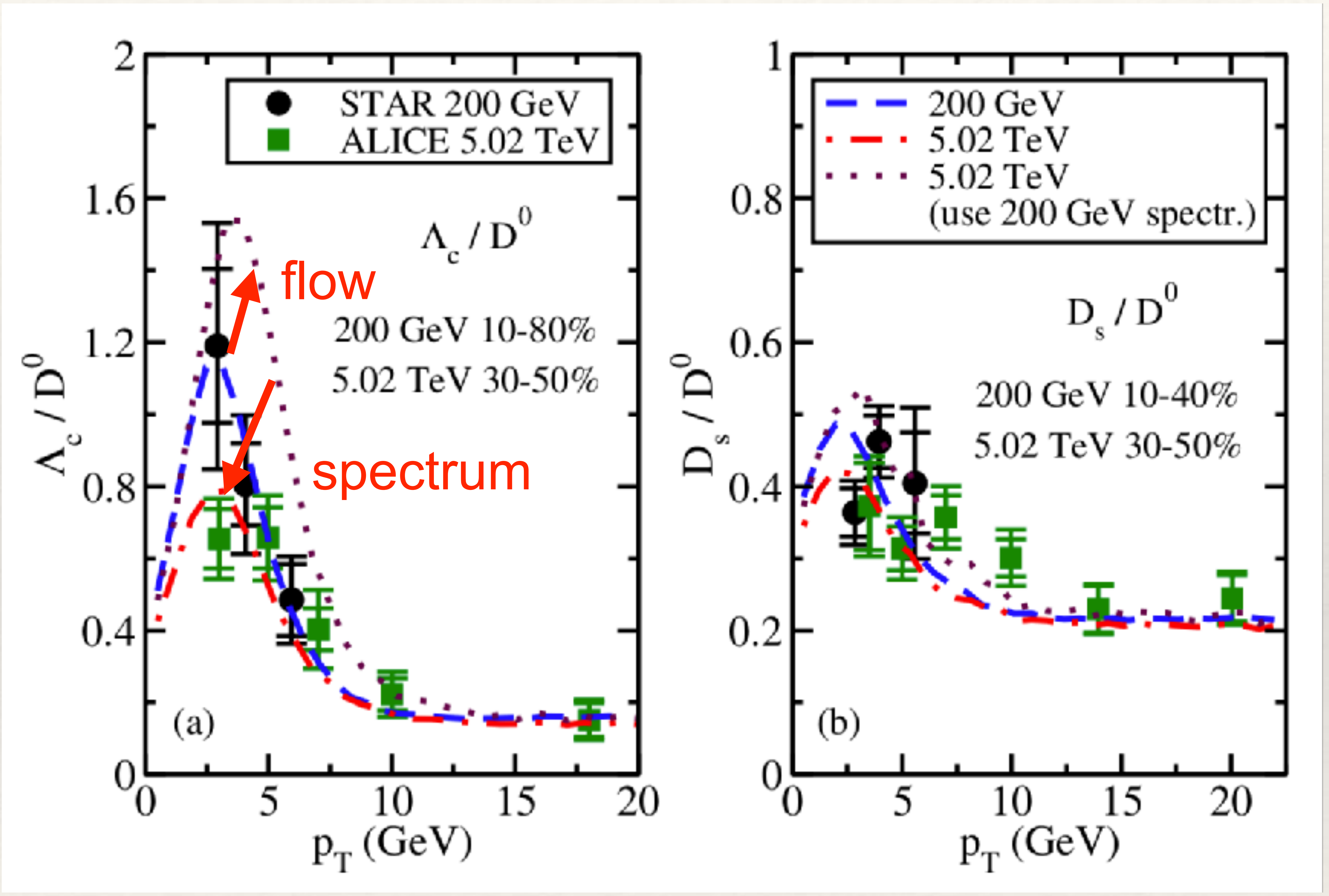
- (a) Stronger QGP flow boost on heavier hadrons => increasing Λ_c/D^0 with N_{part}

- (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

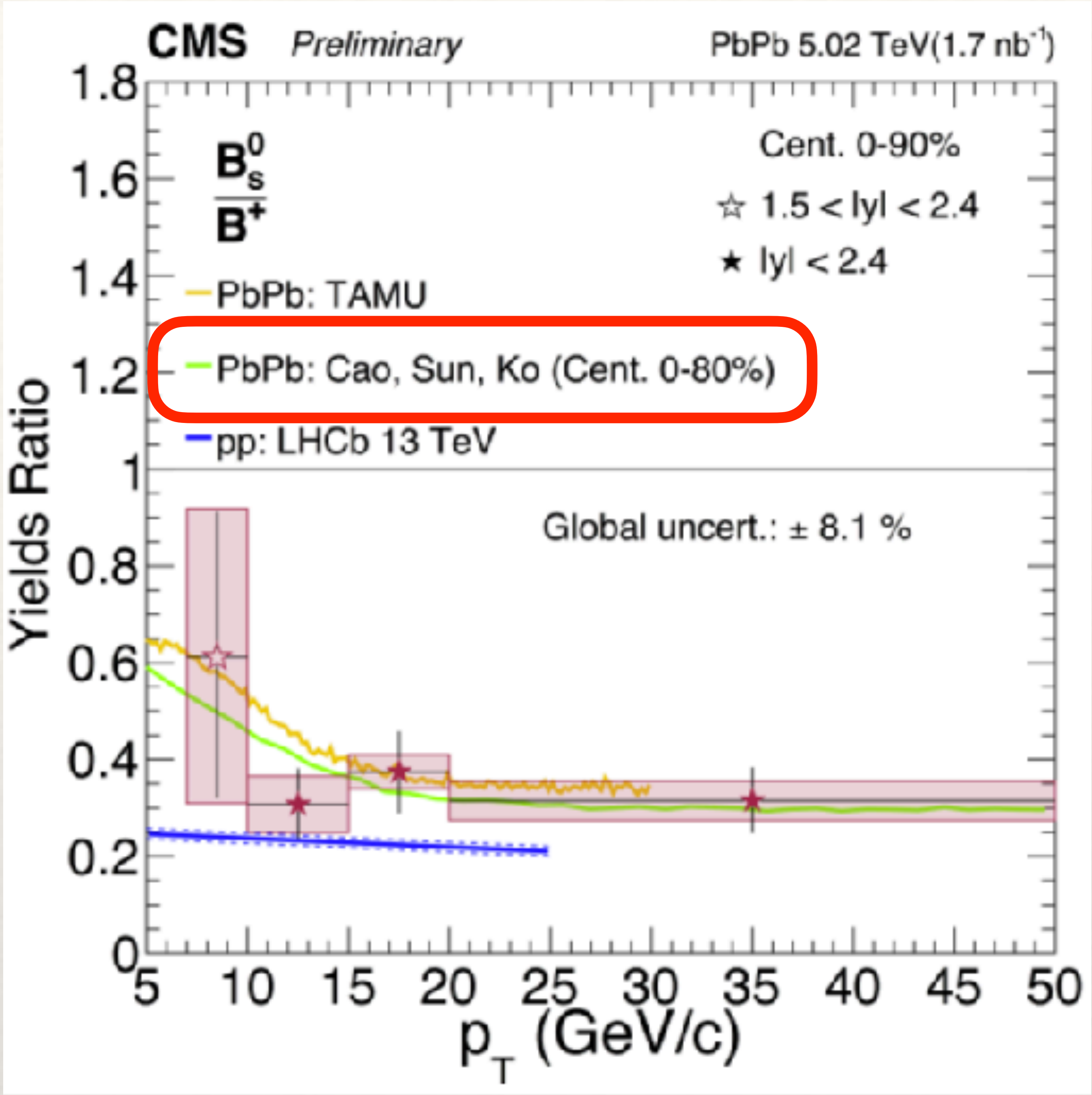
RHIC vs. LHC

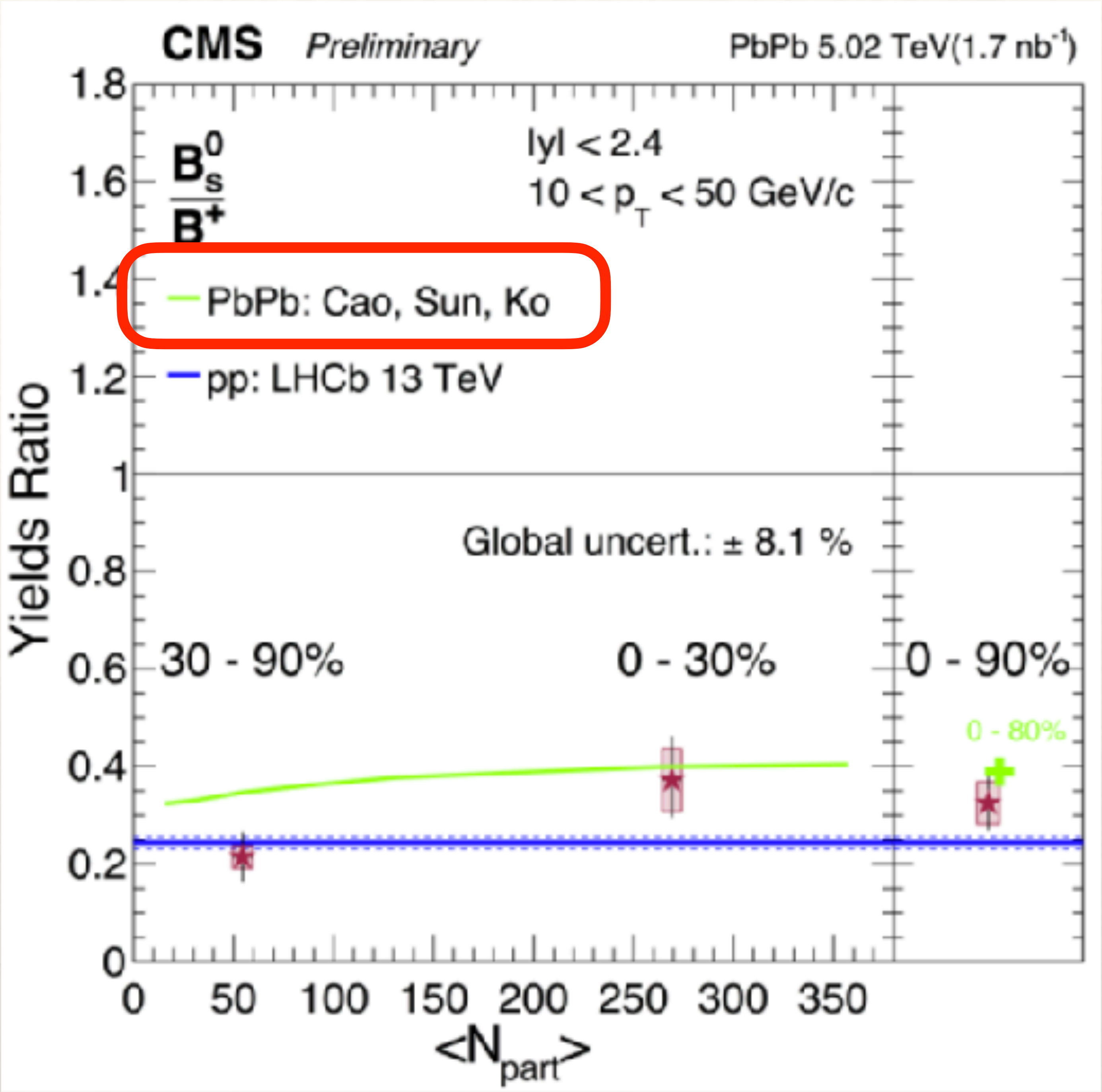
Λ_c/D^0 D_s/D^0



- 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: $\omega_c = 0.24\ \mathrm{GeV}\ \rightarrow\ \omega_b = 0.14\ \mathrm{GeV}$ so that $P_{\mathrm{coal}}(p_b = 0) = 1$ for *b* quarks

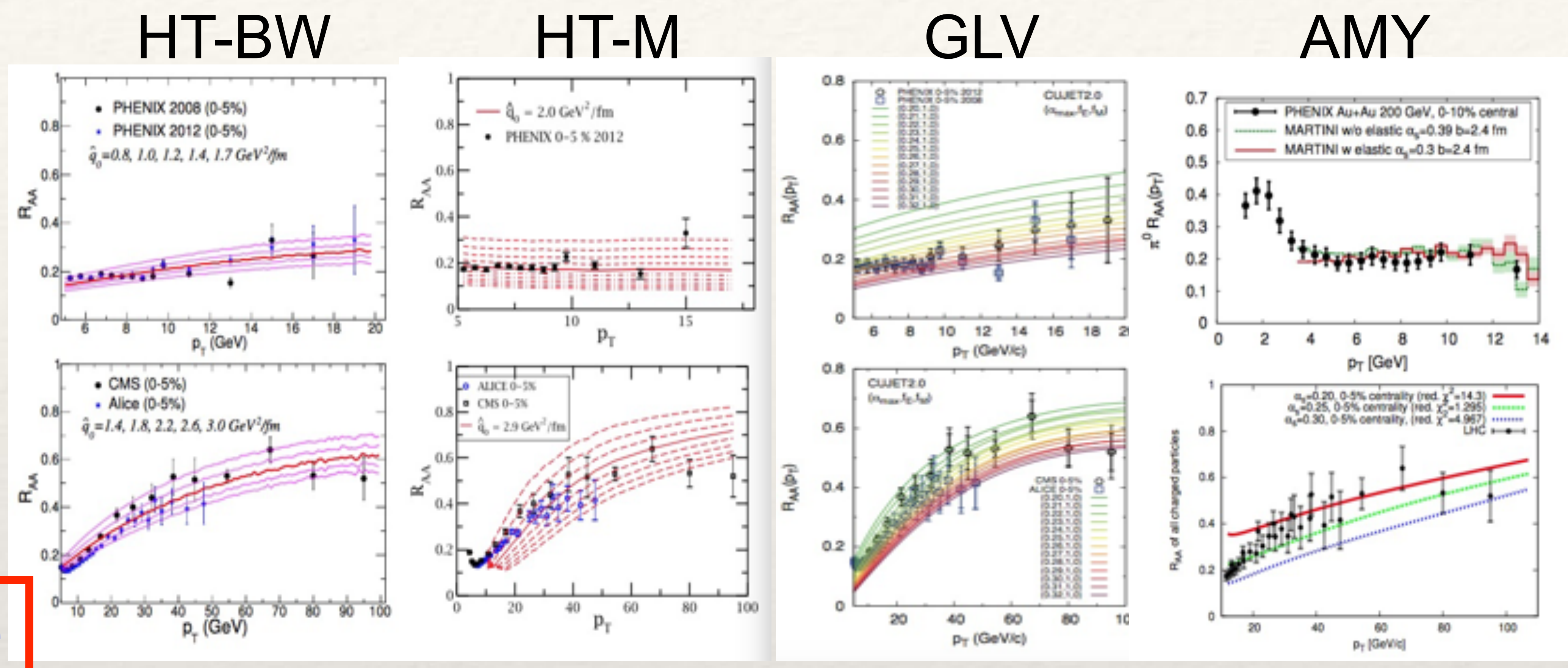
Constraining model uncertainties

Transport coefficients: *A* (longitudinal momentum loss), $\hat{q}$ (transverse momentum broadening)

Example of high-energy jets

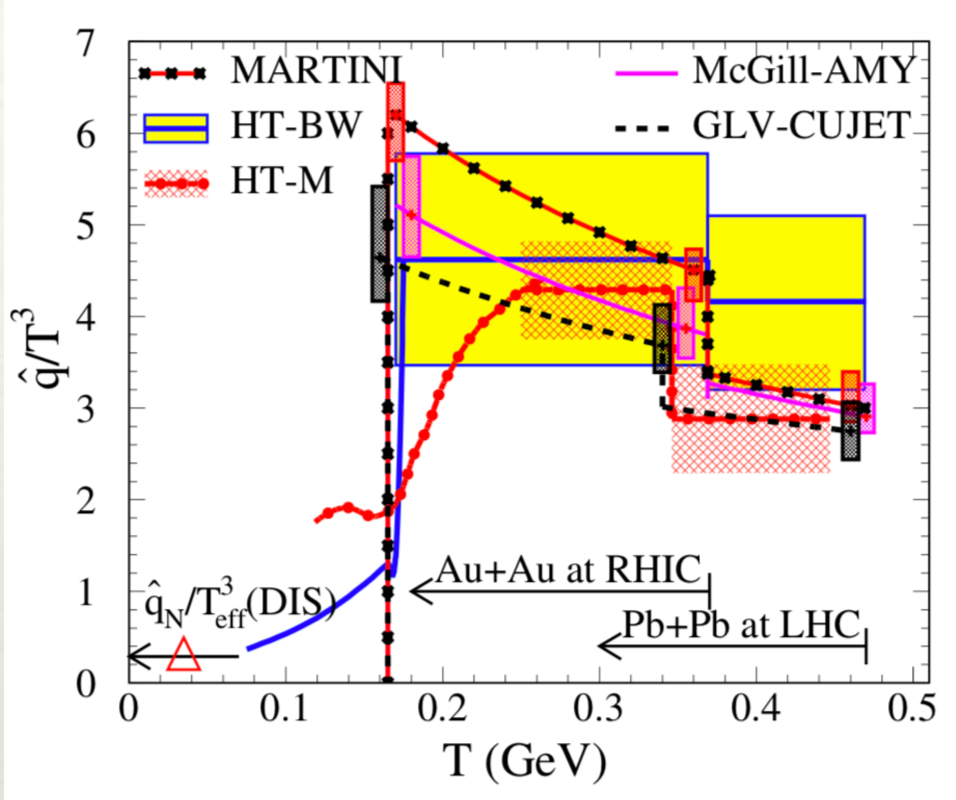
JET Collaboration
[PRC 90 (2014)]

same hydro, simple hadronization



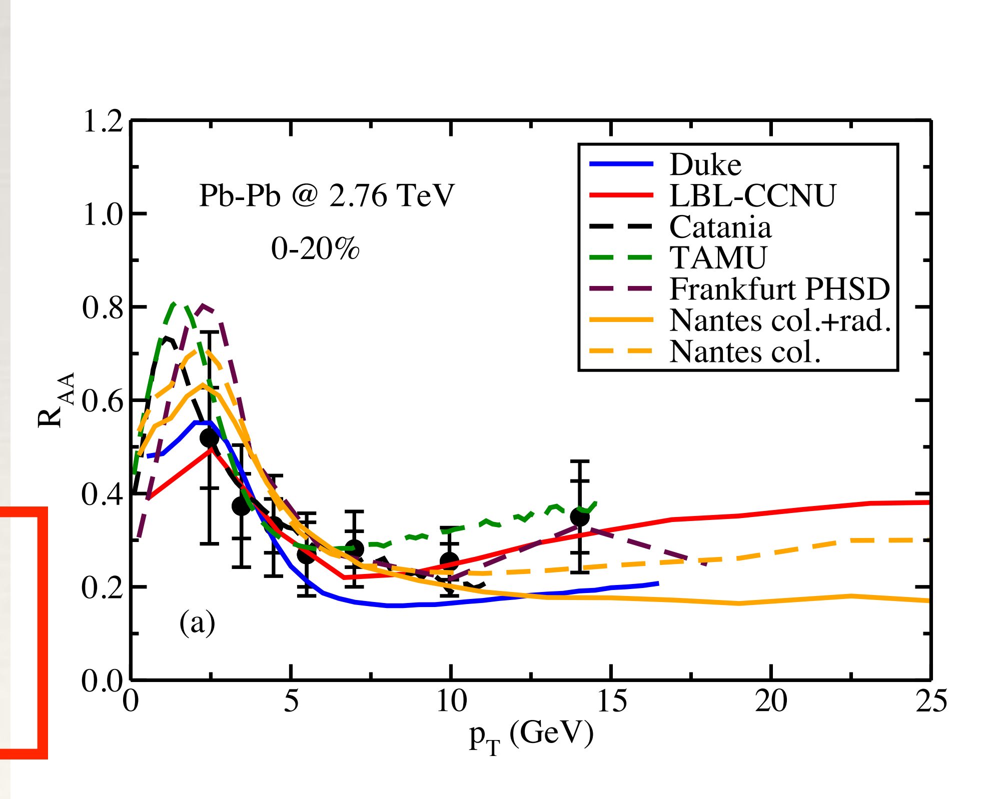
uncertainty in the extracted $\hat{q}$

within a factor of 2



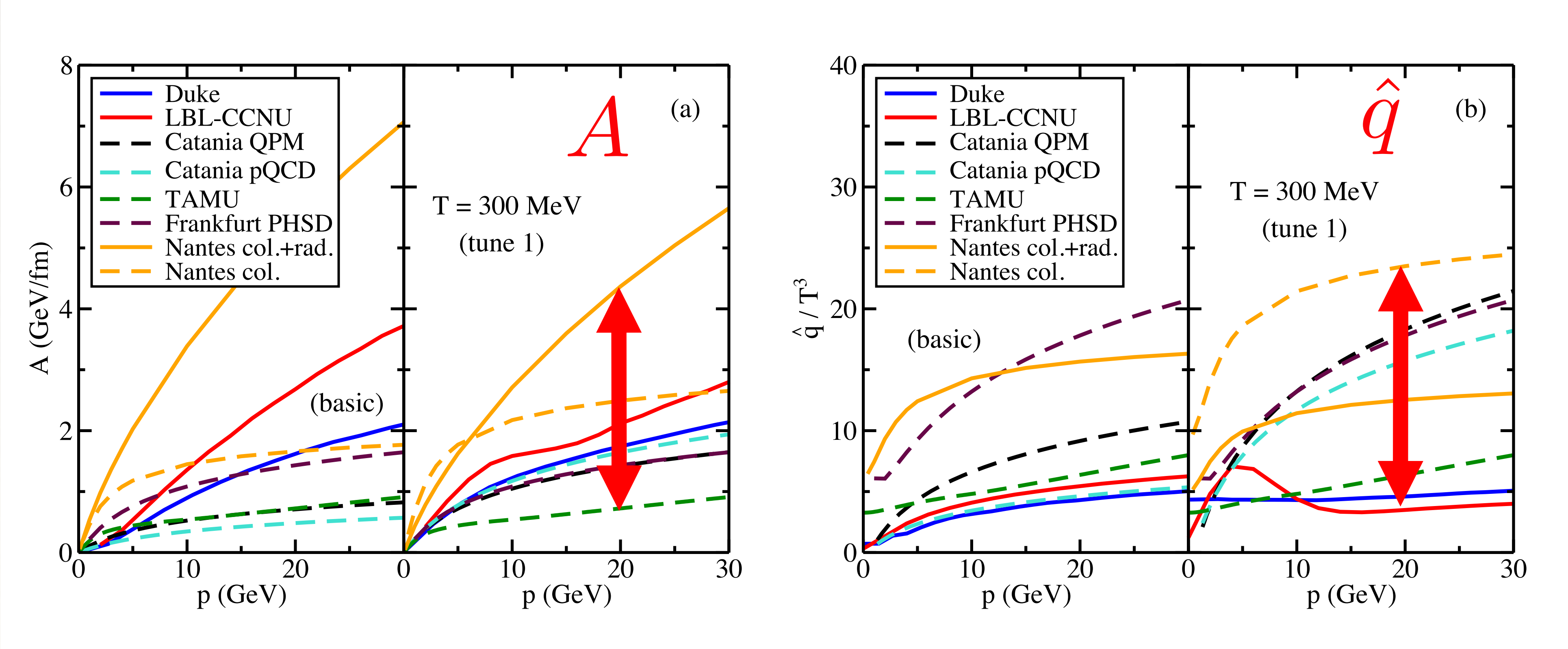
Heavy quarks

different media and hadronizations



uncertainty in the extracted *A* and $\hat{q}$

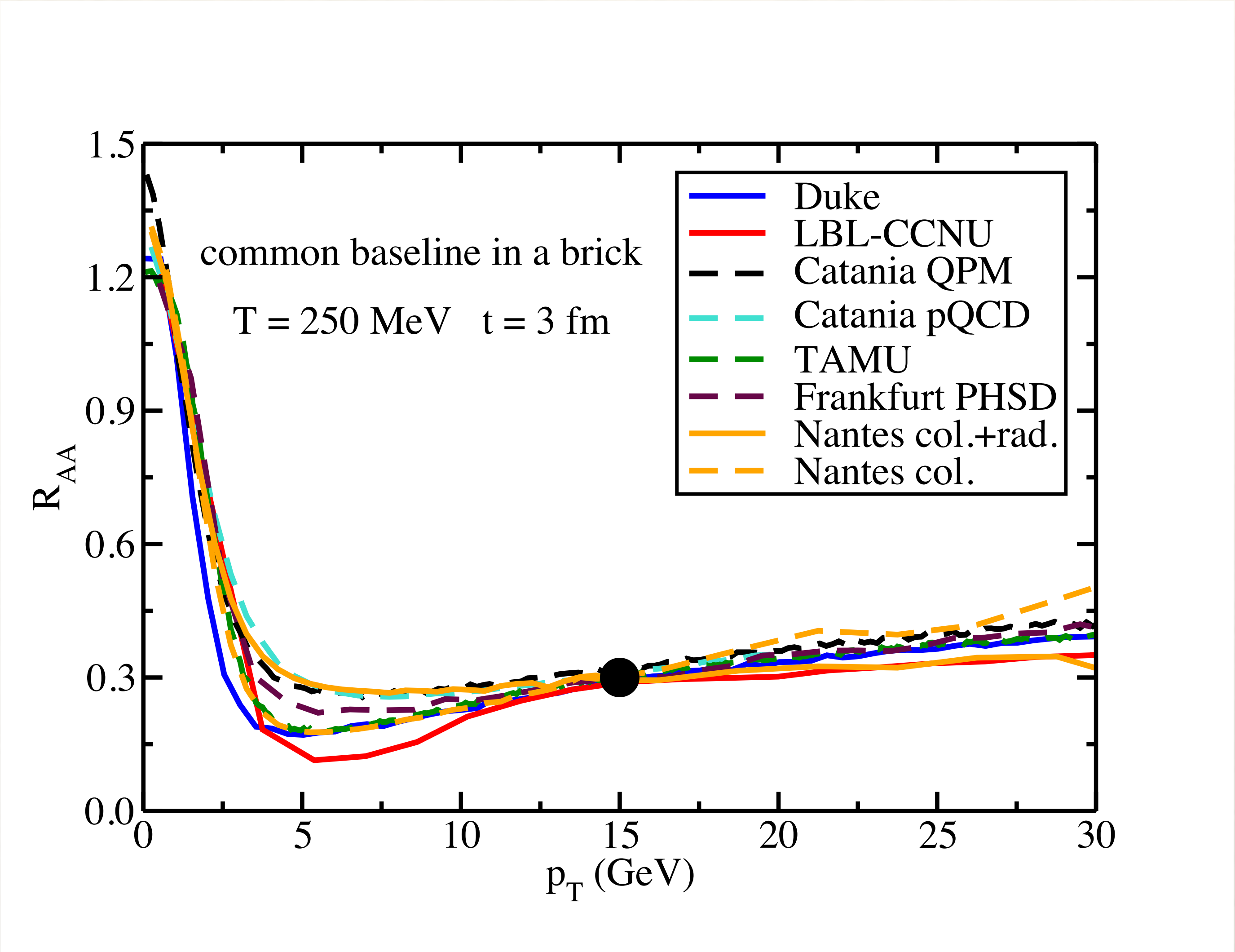
a factor of 5 (3) at high (low) momenta



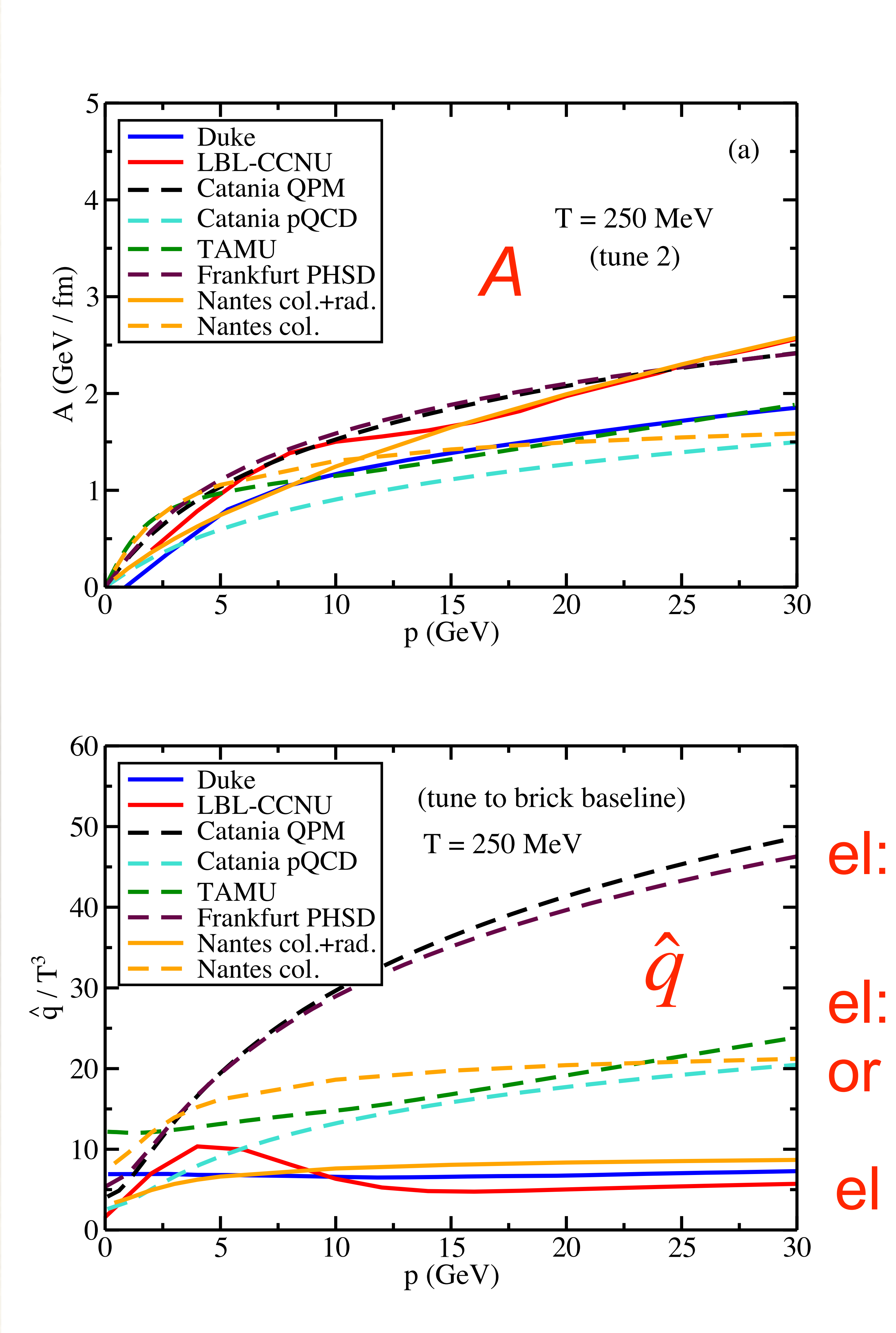
Uncertainties in heavy quark energy loss

[Cao et al., PRC 99 (2019) (initiated by the JET Collaboration)]

Common baseline:



- Same initial *c* spectrum
- Static medium *T* = 250 MeV, *L* = 3 fm
- No hadronization
- $R_{AA}(c) = 0.3$ at $p_T = 15$ GeV



el: QPM

el: pQCD or *T*-matrix

el + inel

- Uncertainties of drag (*A*) is constrained within a factor of 2
- The transverse transport coefficient ($\hat{q}$) is constrained within 3 groups
- Expect to further constrain $\hat{q}$ with heavy-heavy/light hadron correlations

Uncertainties from different model components

[Li, Xing, Liu, Cao and Qin, CPC 44 (2020) 11, 114101, arXiv:2005.03330]

Uncertainties from 7 sources within the same theoretical framework

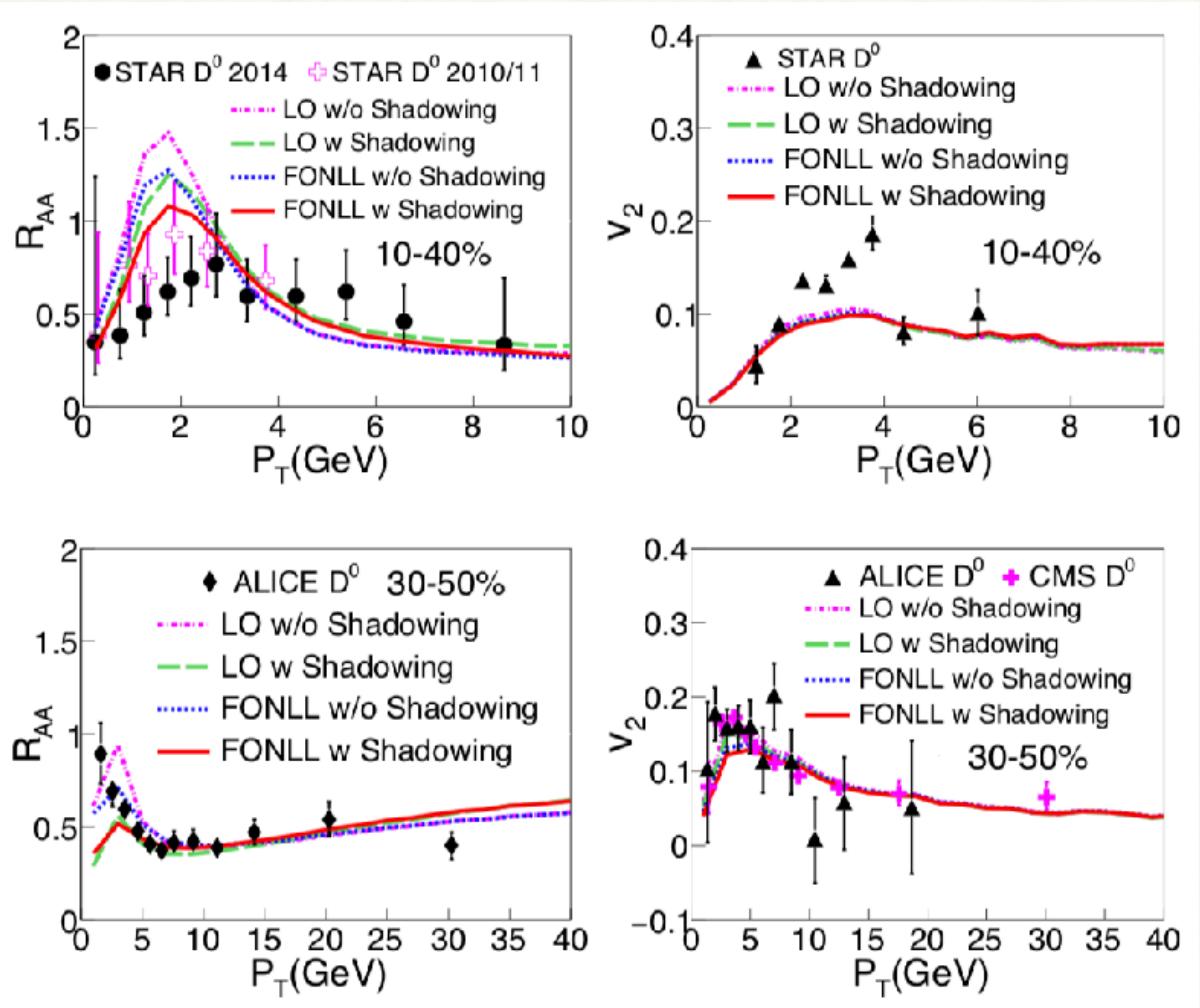
- Initial spectra of heavy quarks
- Starting time of heavy-quark-medium interaction
- Temperature evolution of the pre-equilibrium state
- Temperature dependence of heavy quark diffusion coefficient
- Energy loss mechanism: collisional vs. radiative
- Hadronization: fragmentation vs. coalescence
- QGP flow

Initial spectra of heavy quarks

R_{AA} v_2

RHIC

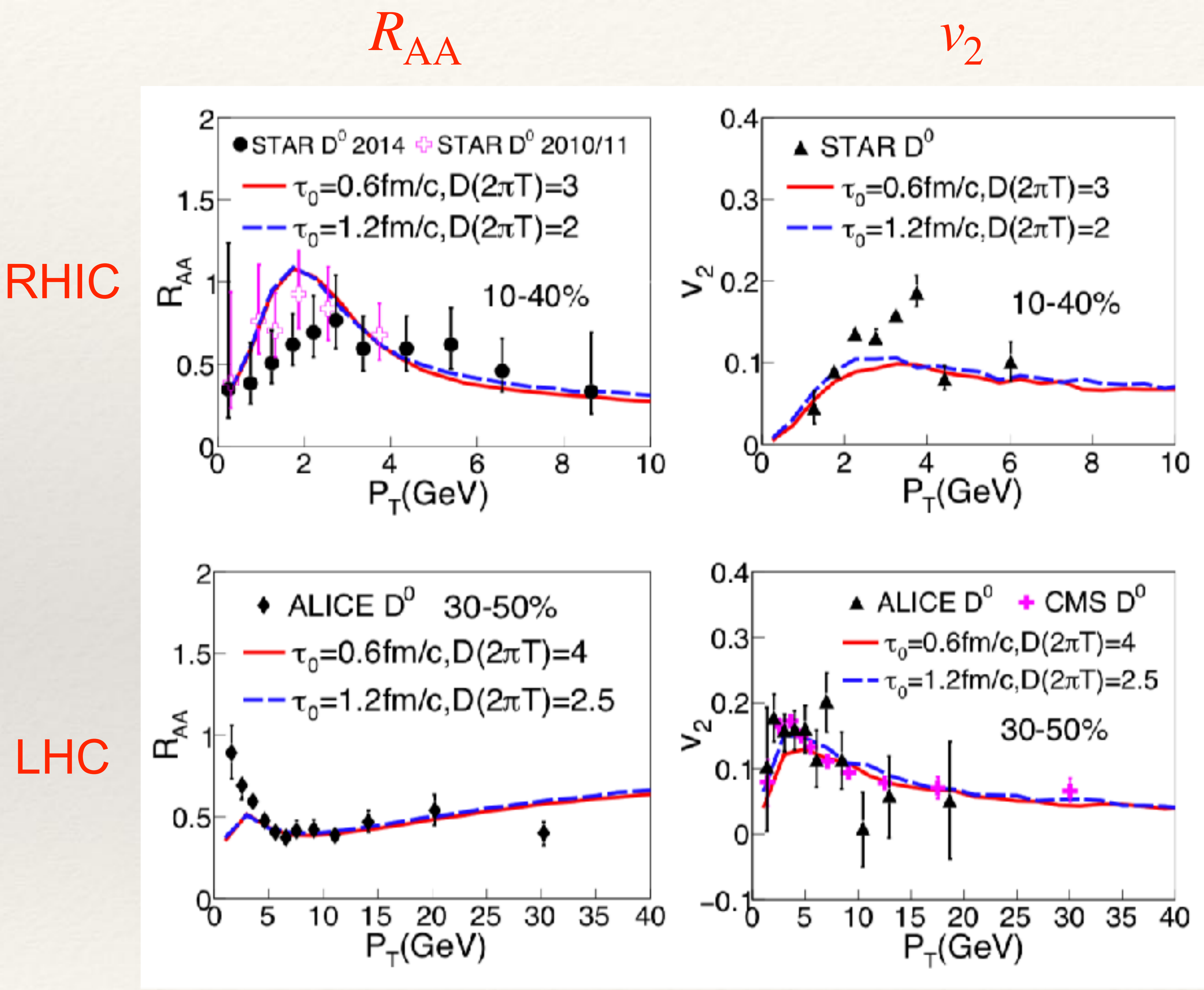
LHC



		FONLL *vs.* LO	w *vs.* wo shadowing
R_{AA}	RHIC	13% smaller	15% smaller
	LHC	25% smaller	27% smaller
v_2	RHIC	no difference	no difference
	LHC	19% smaller	no difference

- Differences only appear at low p_T (below 5 GeV)

Starting time of heavy-quark-medium interaction



- Re-adjust diffusion coefficient to fix R_{AA}

		$\tau_0 = 1.2$ fm *vs.* $\tau_0 = 0.6$ fm
v_2	RHIC	8% larger
	LHC	14% larger

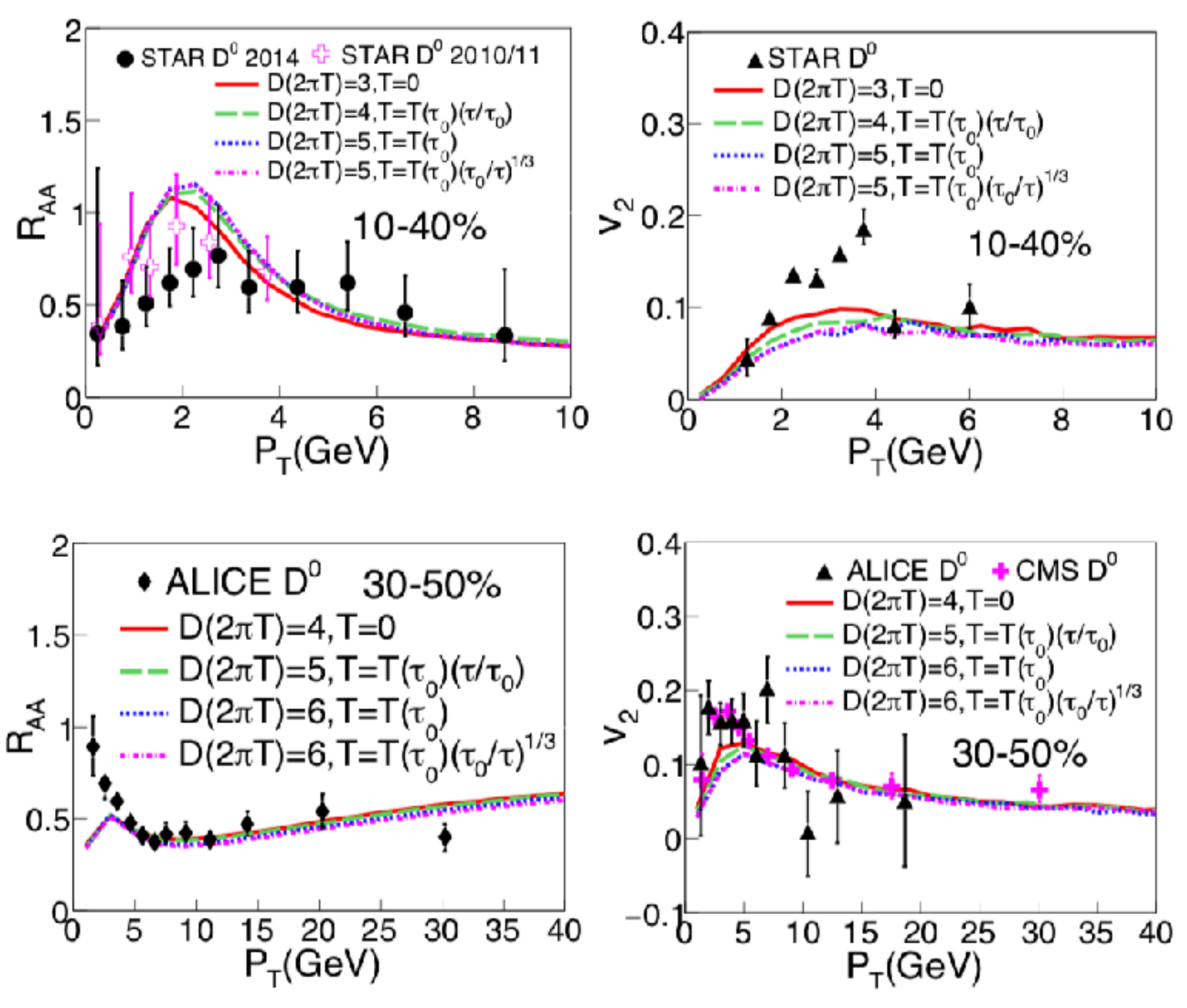
- Two sources of jet (heavy quark) v_2:
    - Asymmetric medium flow: prefer later τ_0
    - Asymmetric jet energy loss: not affected by τ_0
- Only small effect at low p_T (below 5 GeV)

Temperature evolution of the pre-equilibrium stage

R_{AA} v_2

RHIC

LHC



- Four scenarios for $T(\tau < \tau_0)$ $(\tau_0 = 0.6\ \mathrm{fm})$

  1: $T(\tau) = 0$ 2: $T(\tau) = (\tau/\tau_0)T(\tau_0)$

  3: $T(\tau) = T(\tau_0)$ 4: $T(\tau) = (\tau_0/\tau)^{1/3}T(\tau_0)$

- Re-adjust diffusion coefficient to fix R_{AA}

		Free-streaming (1) *vs.* Bjorken (4)
v_2	RHIC	39% larger
	LHC	19% larger

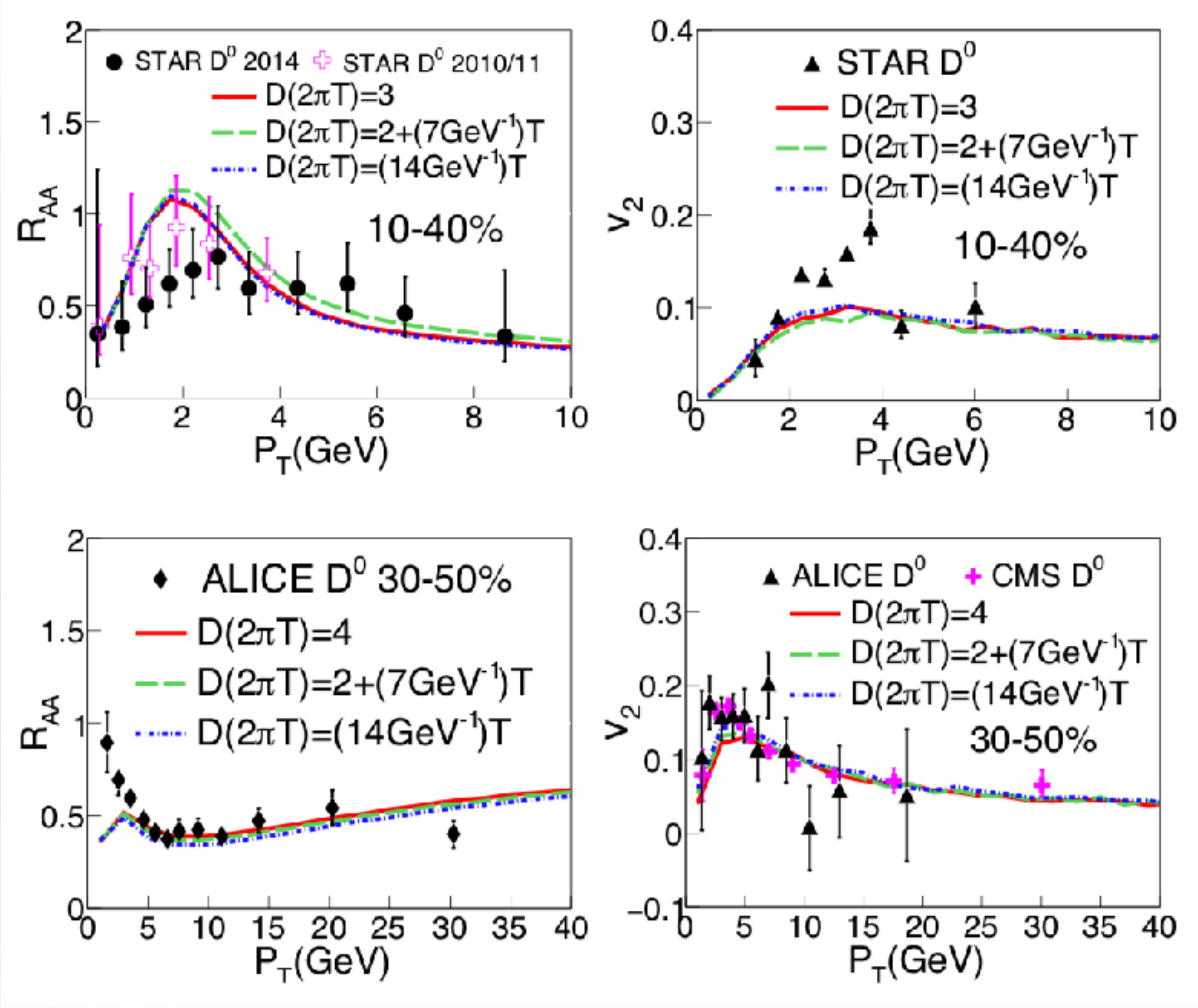
- Larger heavy quark v_2 (at $p_T < 5$ GeV) with later in-medium energy loss

Heavy quark diffusion coefficient D_s

R_{AA} v_2

RHIC

LHC



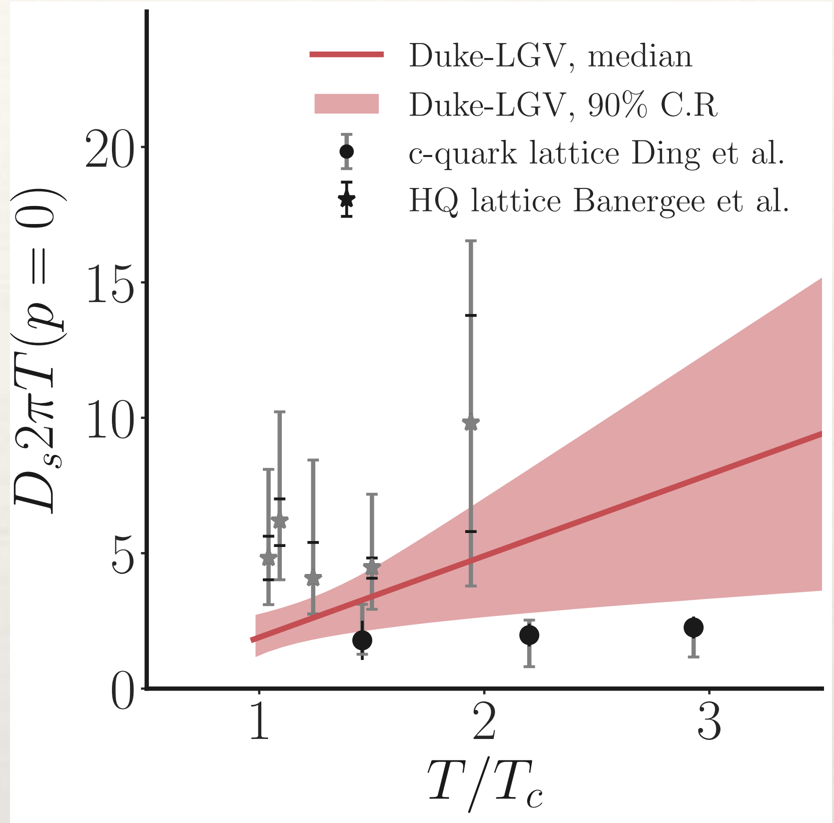
- Linear approximation

$$D_s(2\pi T) = a + bT$$

$$b = 0,\ 7 \text{ and } 14\ (\text{GeV}^{-1})$$

Adjust a to fix R_{AA}

Lattice and Bayesian extraction
[PRC 97 (2018) 014907]



		largest slope *vs*. smallest slope
v_2	RHIC	negligible difference
	LHC	12% larger

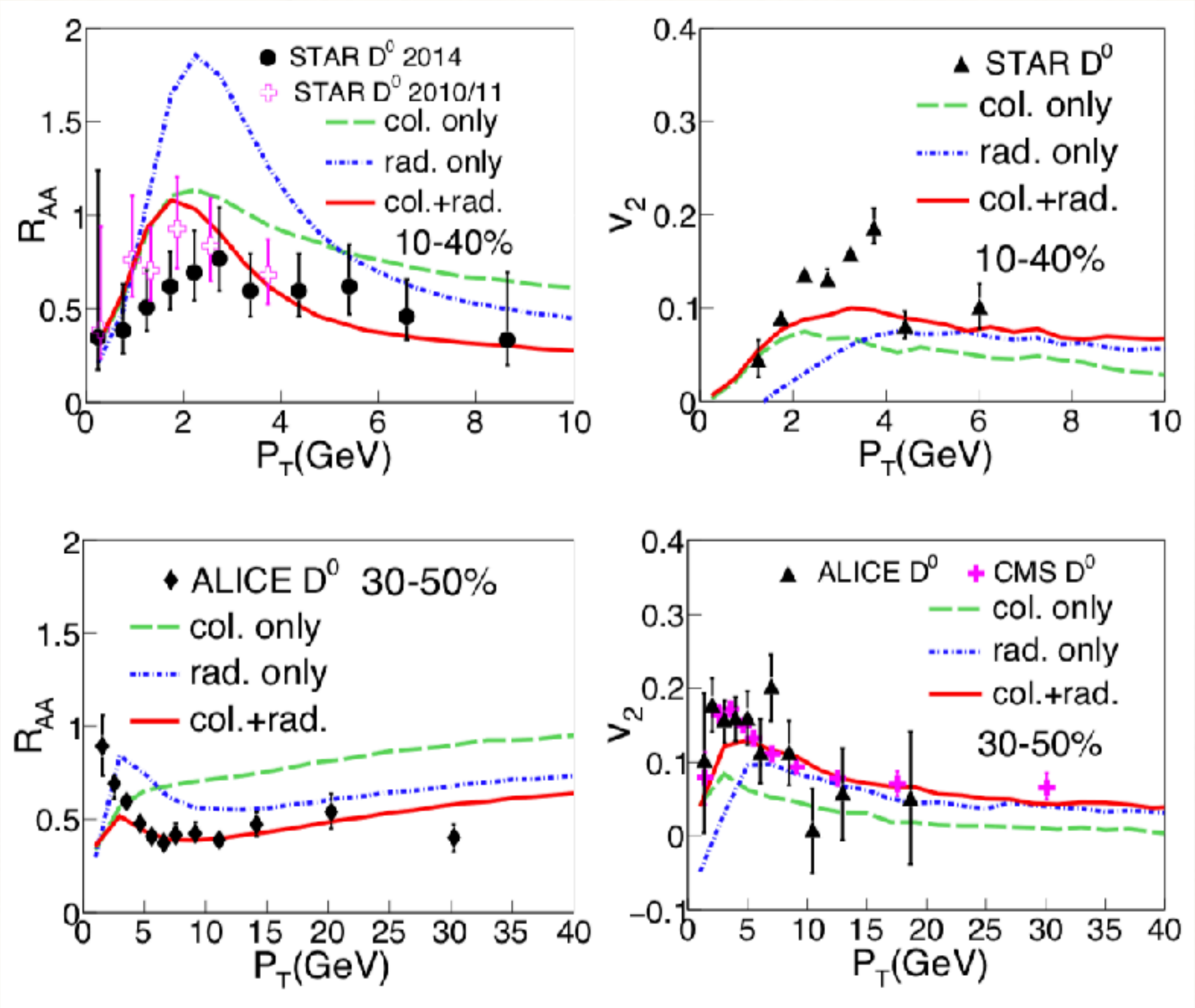
- Only small effect at low p_T (below 5 GeV)

Energy loss mechanism

R_{AA} v_2

RHIC

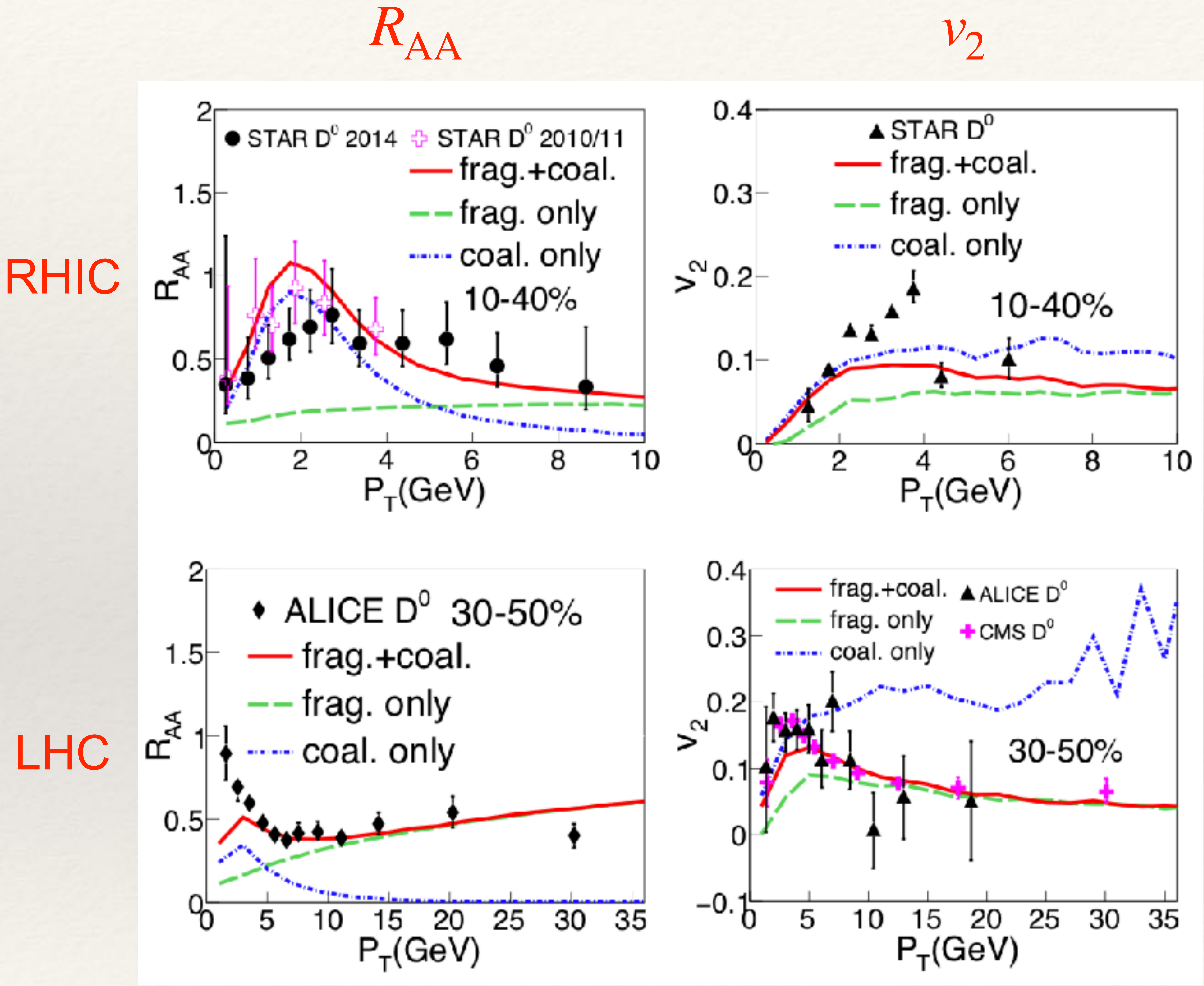
LHC



Strong effects

- Collisional energy loss dominates *D* meson spectra at low p_{T}, radiative energy loss dominates at high p_{T}
- Crossing point for R_{AA}: 5 GeV at RHIC
  7 GeV at LHC
- Collisional + radiative energy loss is necessary for describing the p_{T} dependence of R_{AA} and v_2

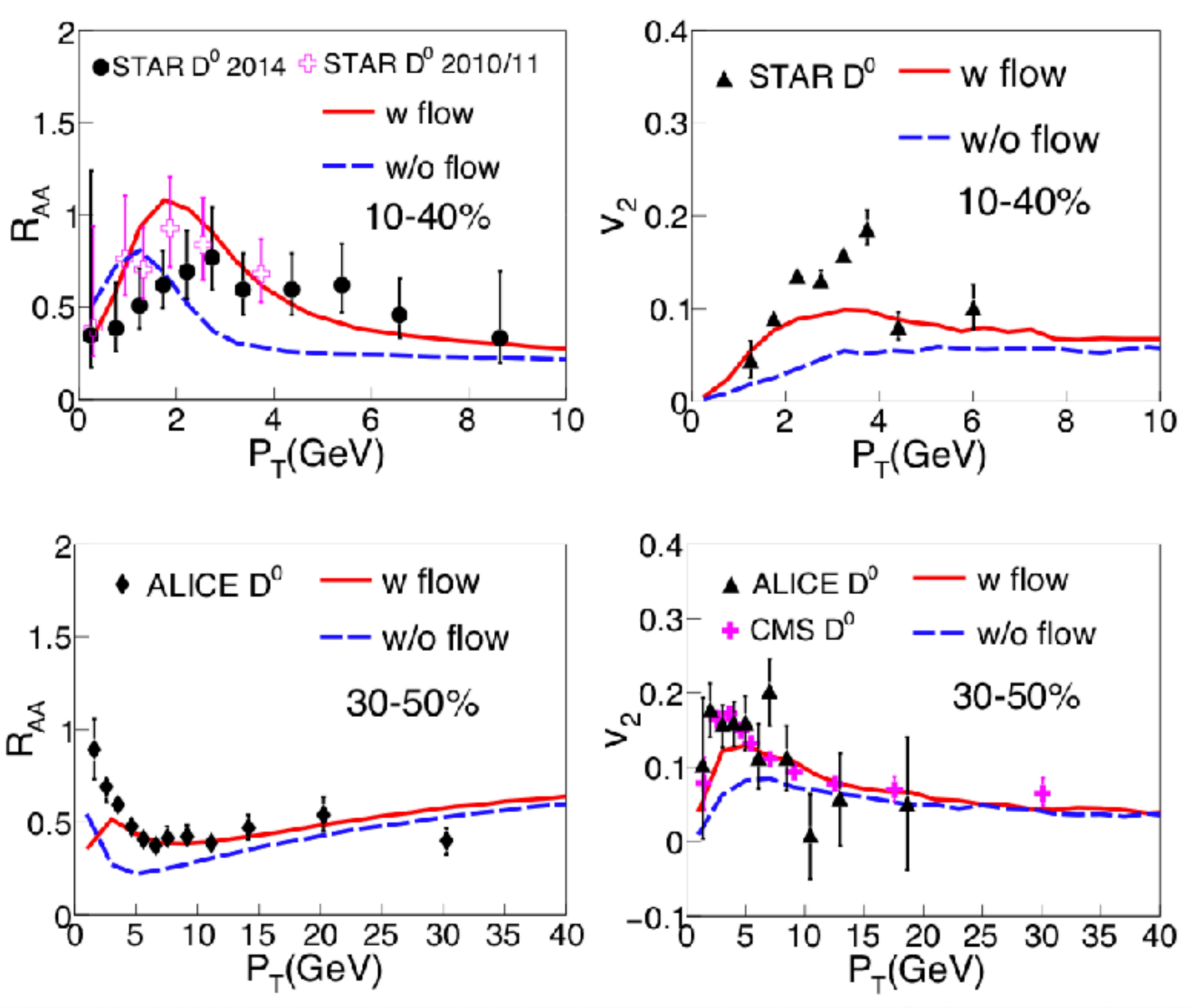
Hadronization



Strong effects

- Coalescence dominates *D* meson production at low p_T, fragmentation dominates at high p_T
- Crossing point: 5 GeV at RHIC and LHC
- Coalescence generates the bump structure of R_{AA} *vs.* p_T
- Coalescence enhances the *D* meson v_2

QGP flow



R_{AA} v_2

RHIC

LHC

Strong effects

- Recall: flow *vs*. energy loss effects on jet R_{AA} and v_2
- QGP flow accelerates low p_T charm quarks and enhances *D* meson R_{AA} up to p_T ~ 20 GeV
- QGP enhances D meson v2 up to p_T ~ 20 GeV
- High p_T *D* meson spectra are driven by charm quark energy loss, not affected by the QGP flow

Summary — hadronization

- 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

Summary — model uncertainties

- Key components: energy loss, hadronization and well-tuned QGP medium
- Quantification of other uncertainties: initial spectra, starting time of jet-medium interaction, pre-equilibrium profile of medium and *T*-dependence of diffusion coefficients — small effects

Thank you!

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