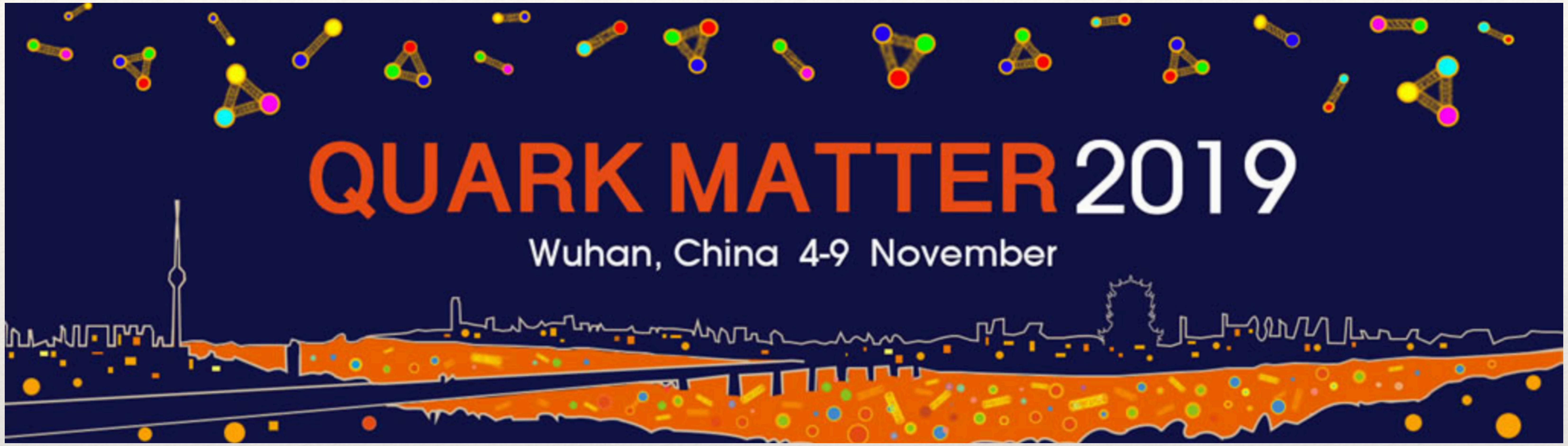
Heavy Quark Transport: a Theoretical Overview



Shanshan Cao

Wayne State University, Texas A&M University

Outline

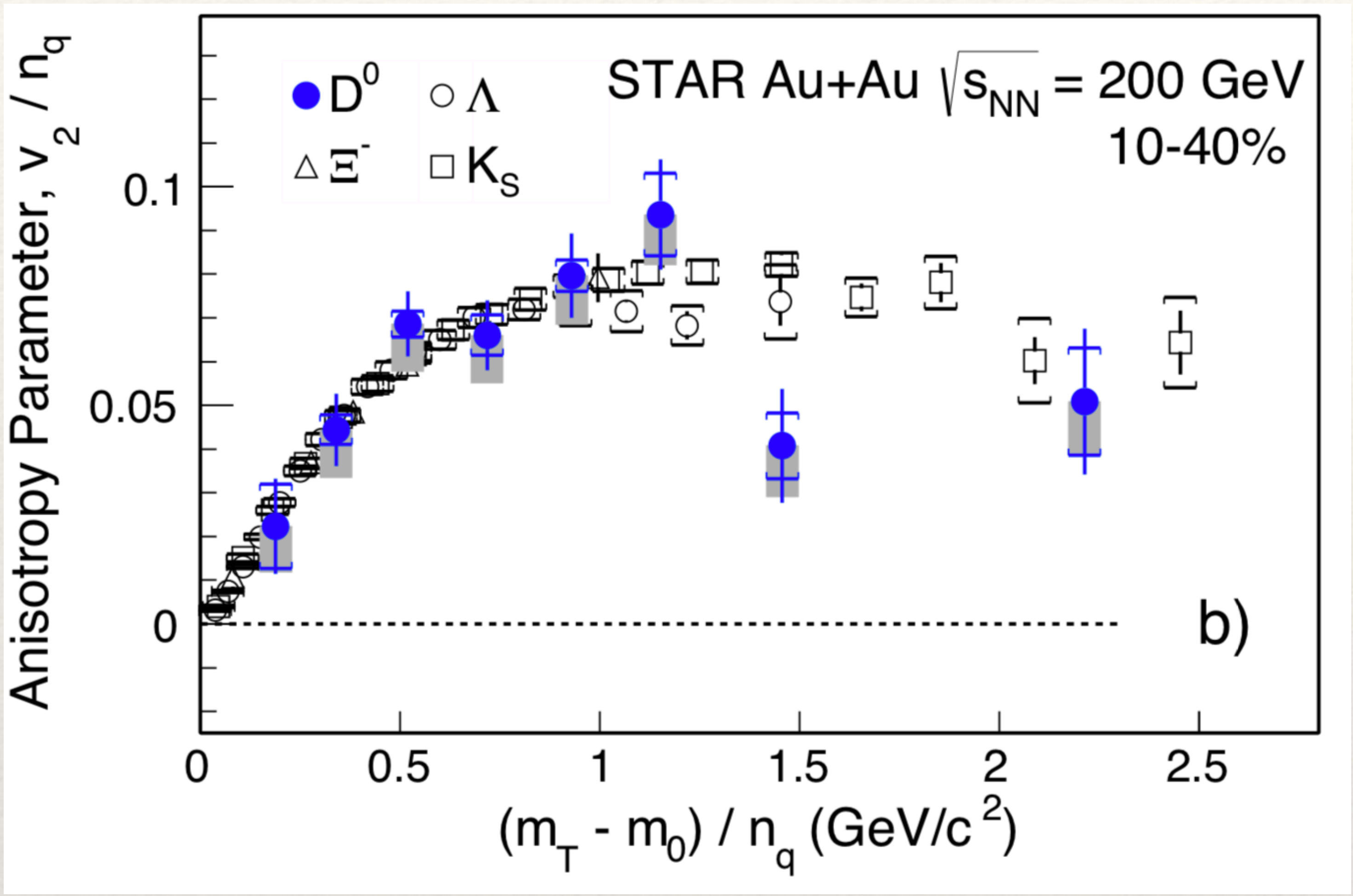
- **Overview of heavy quark theories/models at different momentum scales**
  - Jet energy loss at high p_T
  - Hadronization at medium to low p_T
  - Color potential interaction at low p_T

- **Multi-scale approaches for heavy quark energy loss**

- **Future challenges and prospects**
  - Constraining model uncertainties
  - Probing medium properties
  - From single hadrons to heavy flavor jets

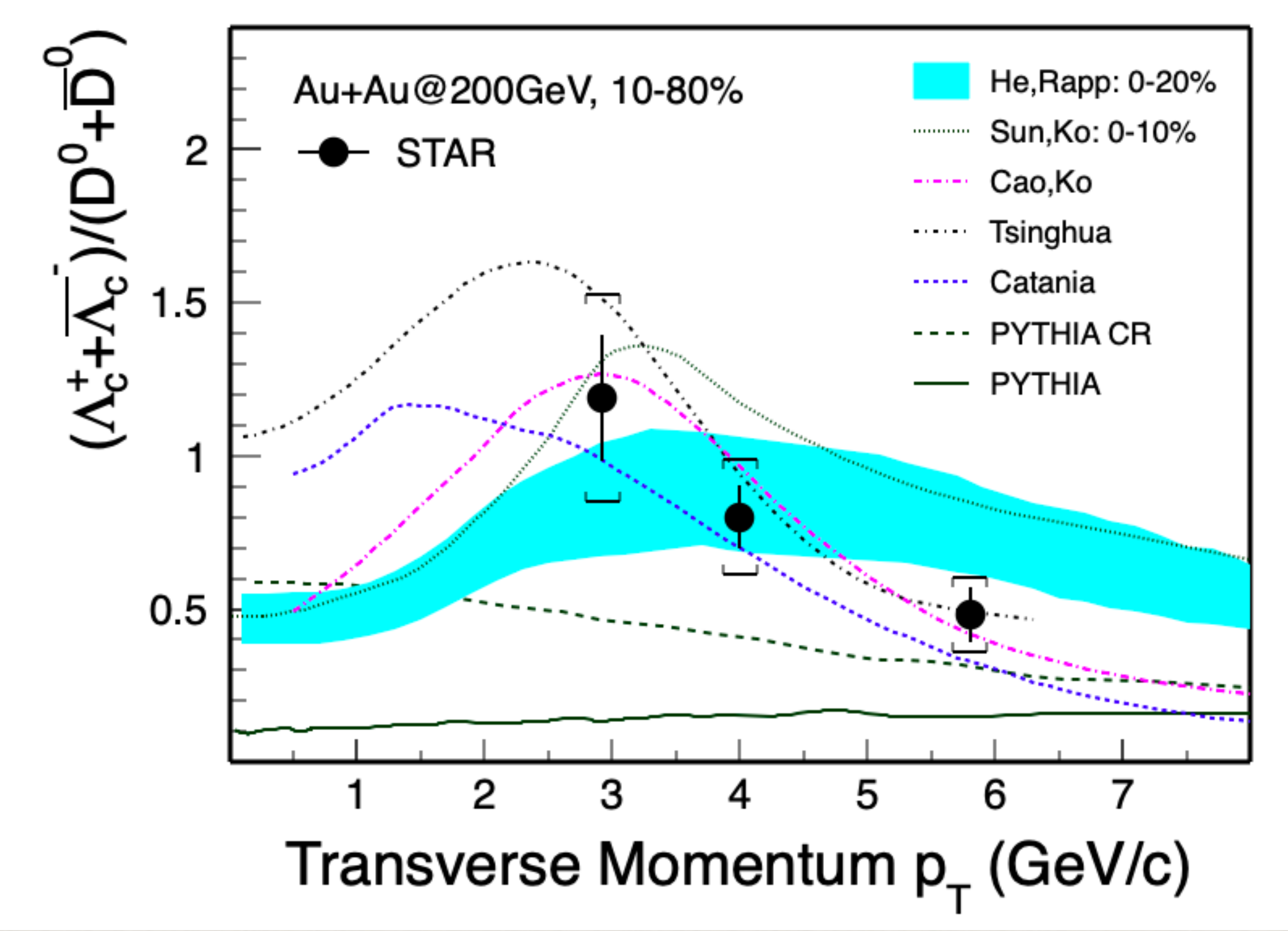
Heavy quark physics at different scales

low p_T



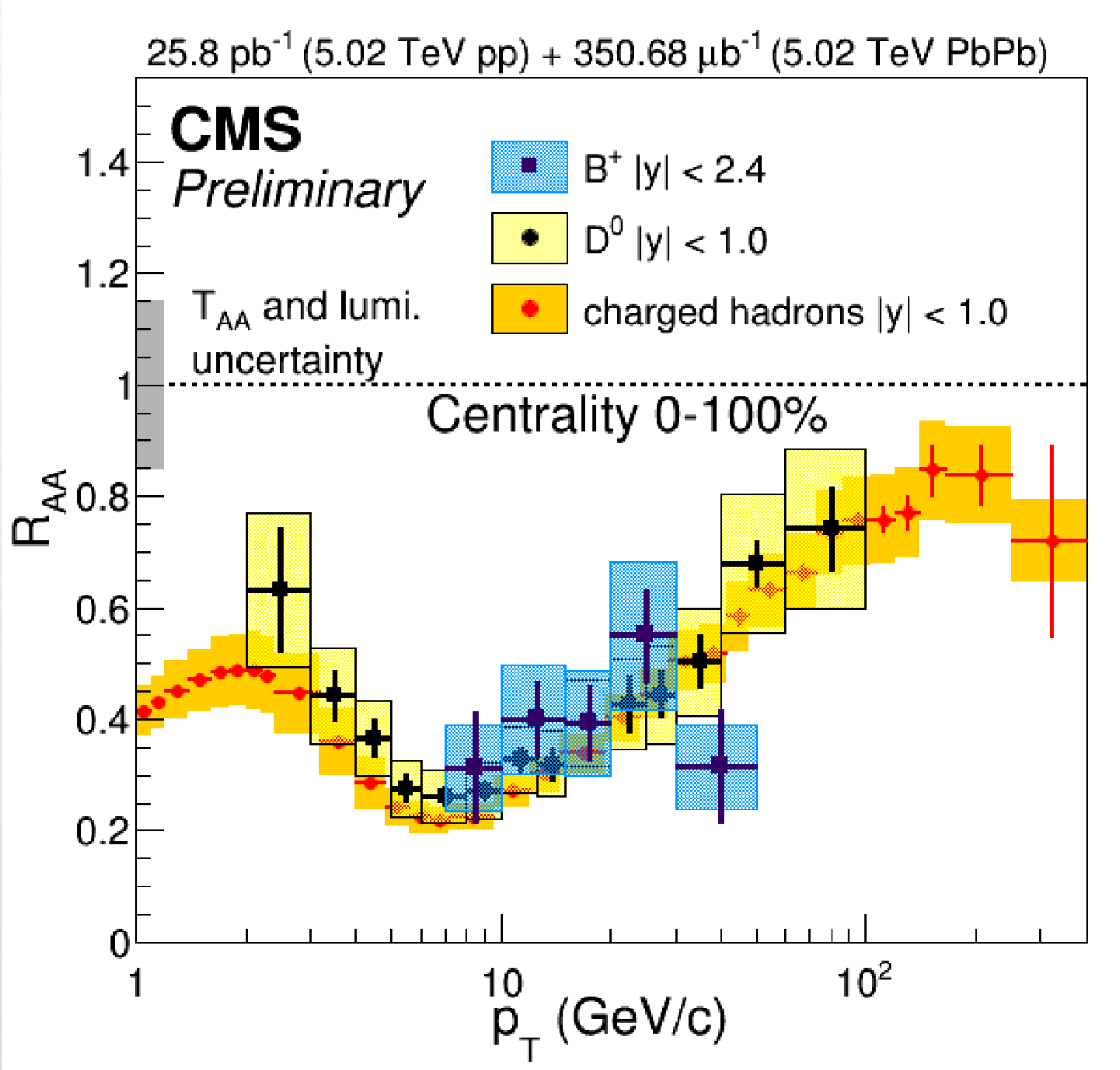
- Study the thermalization process of heavy quarks
- Constrain the color potential of HQ-medium interaction

medium p_T



- Study the hadronization process of heavy quarks
- Constrain the in-medium hadron wave-function

high p_T



- Study the energy loss process of heavy quarks
- Constrain the flavor hierarchy of parton energy loss

High p_T HQ's — collisional and radiative energy loss

Boltzmann transport

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\mathrm{el}} + \mathscr{C}_a^{\mathrm{inel}})$$

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Elastic energy loss ($ab \to cd$)

$$\mathscr{C}_a^{\mathrm{el}} = \sum_{b,c,d} \int \prod_{i=b,c,d} \frac{d[p_i]}{2E_a} (\gamma_d f_c f_d - \gamma_b f_a f_b) \cdot (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab \to cd} \right|^2$$

$2 \to 2$ scattering matrices

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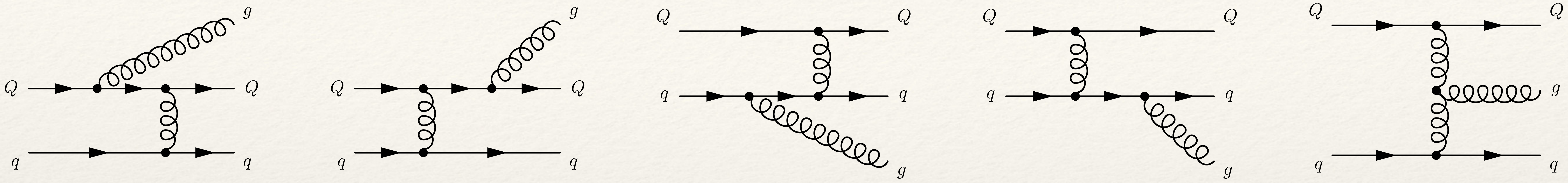
$2 \to 2$ scattering matrices

loss term: **scattering rate**
(for Monte-Carlo simulation)

$$\Gamma_a^{\mathrm{el}}(\mathbf{p}_a, T) = \sum_{b,c,d} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} d[p_i] f_b \cdot (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab\to cd} \right|^2$$

Inelastic energy loss

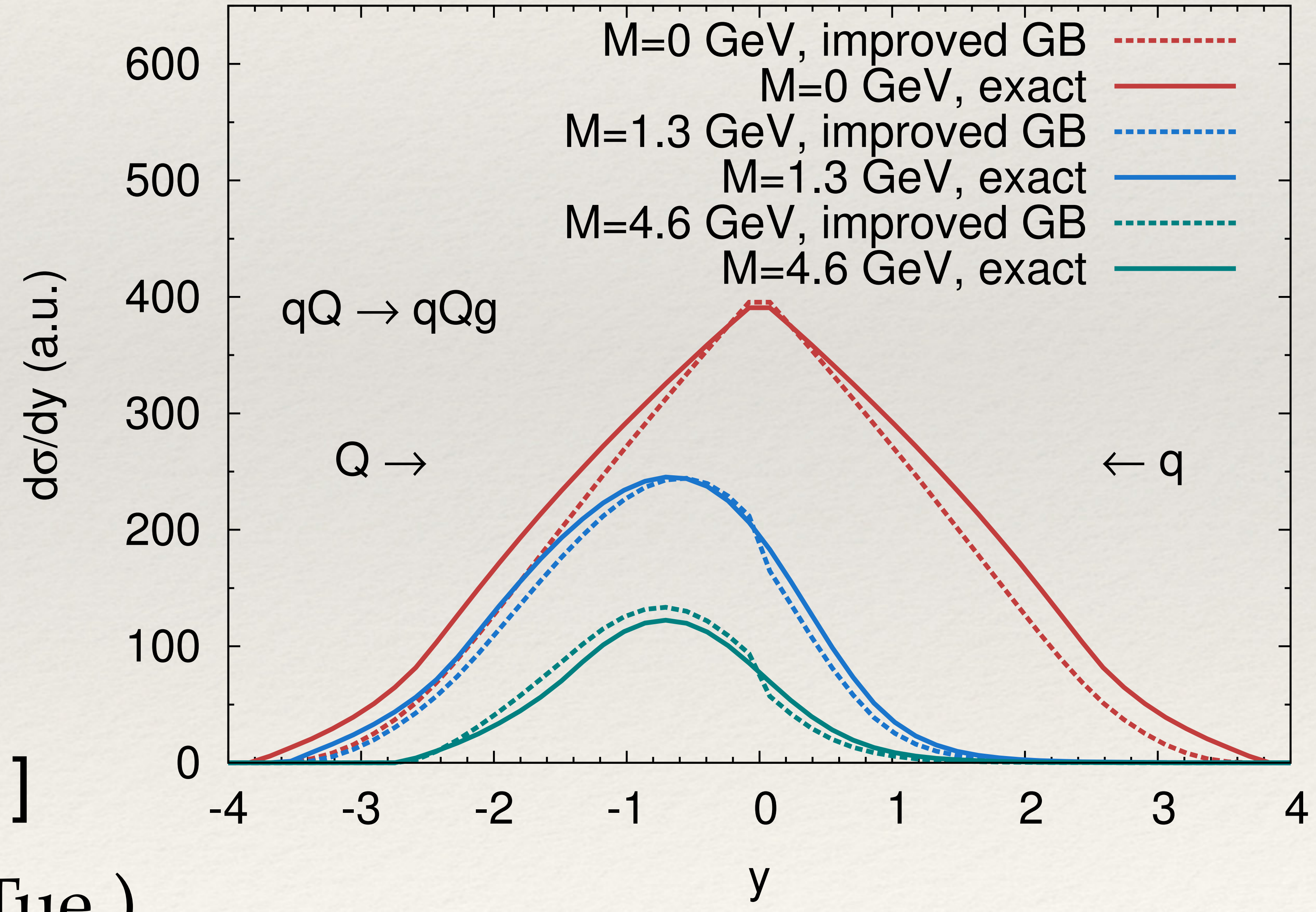
- $2 \rightarrow 3$ **scattering with a quasi-particle**



- Calculate LO diagrams [Kunszt et al., PRD21 (1980)]
- Gunion-Bertsch Approximation derived at high energy limit [Gossiaux et al., JPG 37 (2010); Fochler et al., PRD 88 (2013)]

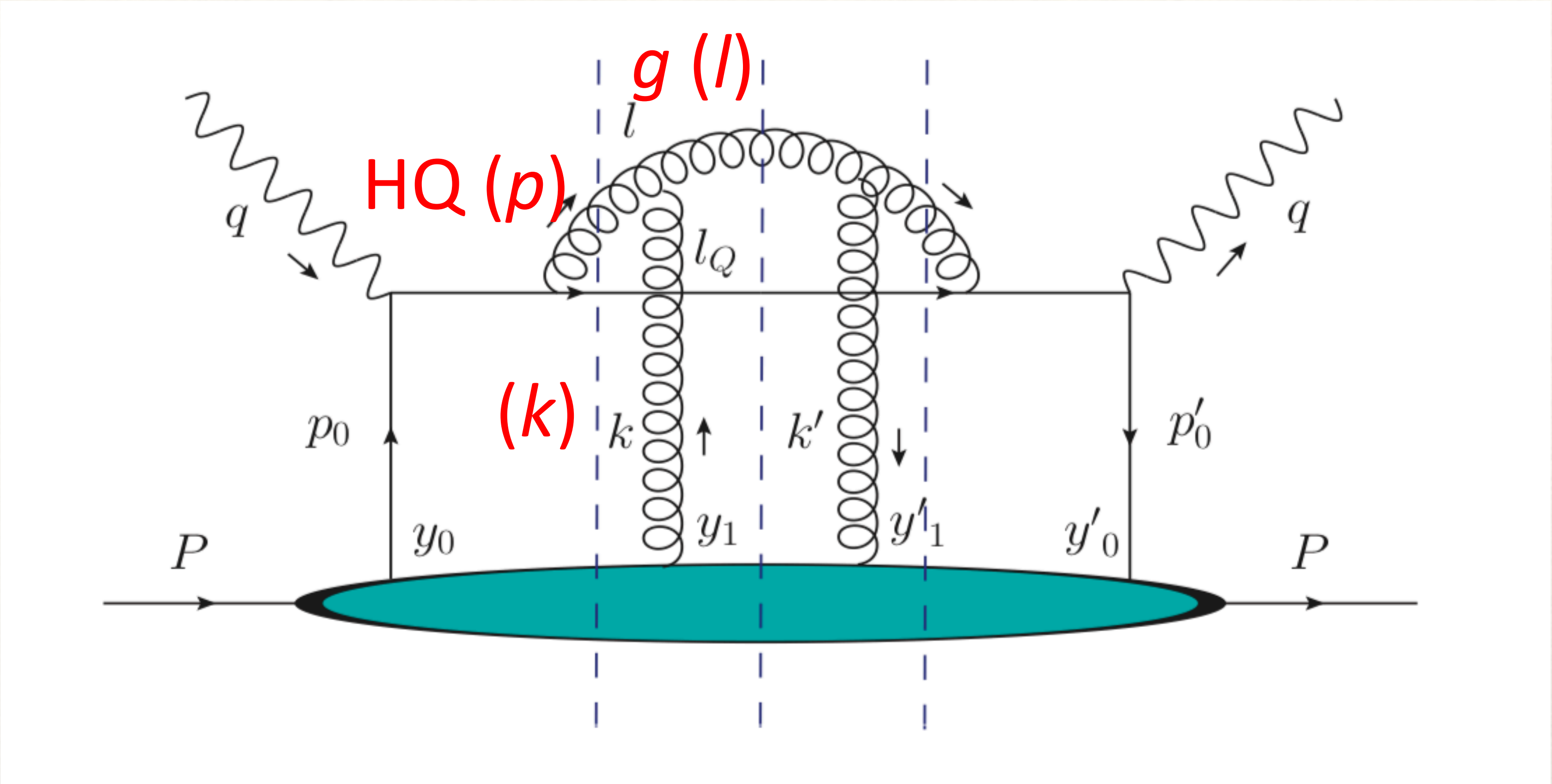
$$\left|\overline{\mathcal{M}}_{qQ\to qQg}\right|^2 = 12g^2(1-\bar{x})^2\left|\overline{\mathcal{M}}_0^{qQ}\right|^2\left[\frac{\vec{k}_\perp}{k_\perp^2+x^2M^2}+\frac{\vec{q}_\perp-\vec{k}_\perp}{(\vec{q}_\perp-\vec{k}_\perp)^2+x^2M^2}\right]^2$$

- Application: Frankfurt (BAMPS) [Uphoff et al., JPG 42 (2015)]
  Nantes (EPOSHQ) [Gossiaux et al., JPG 37 (2010)]
  Duke (Lido) [Ke et al, PRC 98 (2018)] ❖ Ke's talk (Tue.)



Inelastic energy loss

- **Inelastic scattering with a general medium**



[Majumder PRD 85 (2012); Zhang, Wang and Wang, PRL 93 (2004)]

- **Higher-twist**: collinear expansion
  ($\langle k_\perp^2 \rangle \ll l_\perp^2 \ll Q^2$)

$$\frac{d\Gamma_a^{\rm inel}}{dzdl_\perp^2} = \frac{dN_g}{dzdl_\perp^2dt} = \frac{6\alpha_s P(z) l_\perp^4 \hat{q}}{\pi(l_\perp^2 + z^2M^2)^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

- Medium information absorbed in $\hat{q} \equiv d\langle p_\perp^2 \rangle / dt$

Inelastic energy loss

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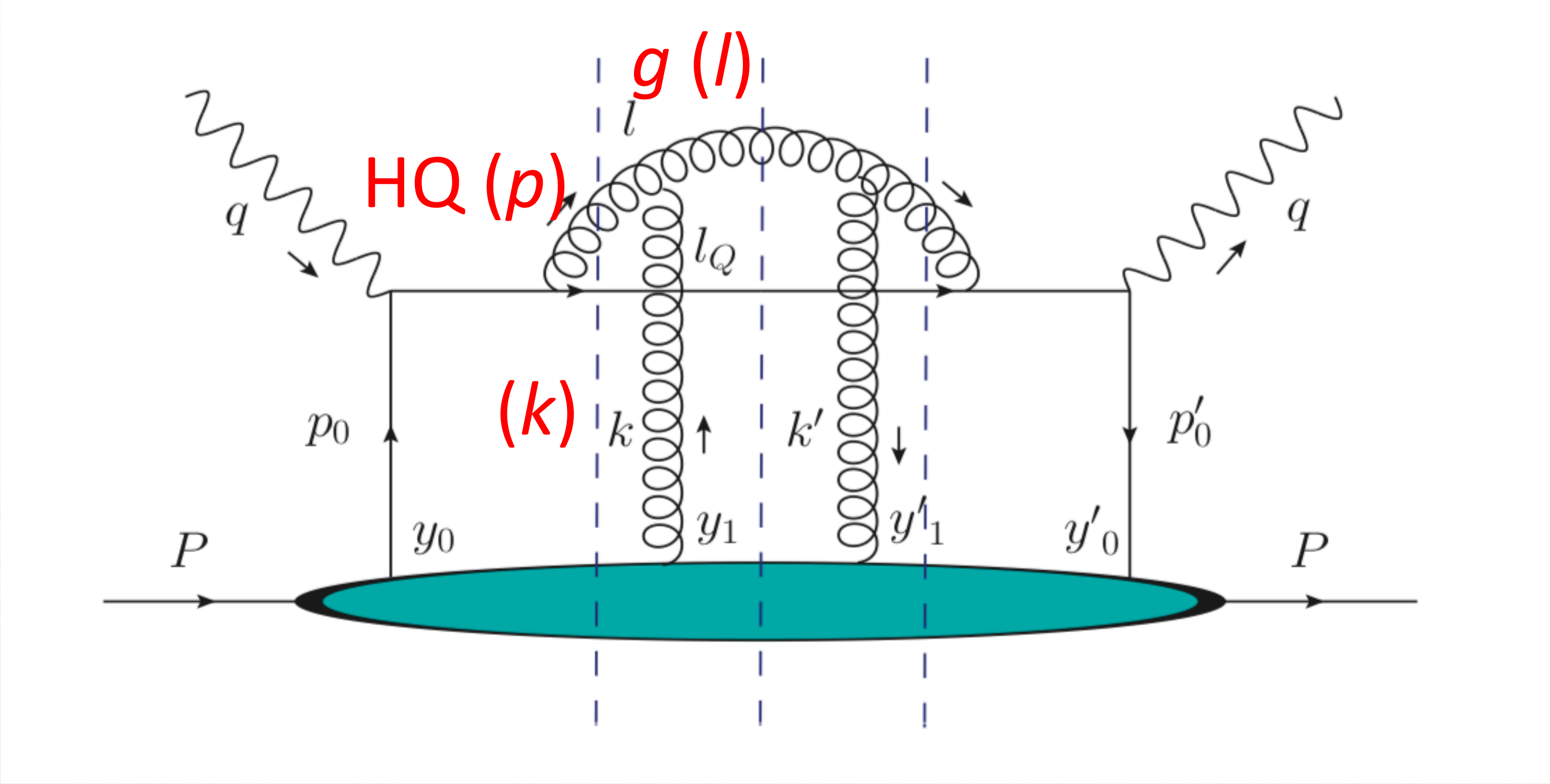

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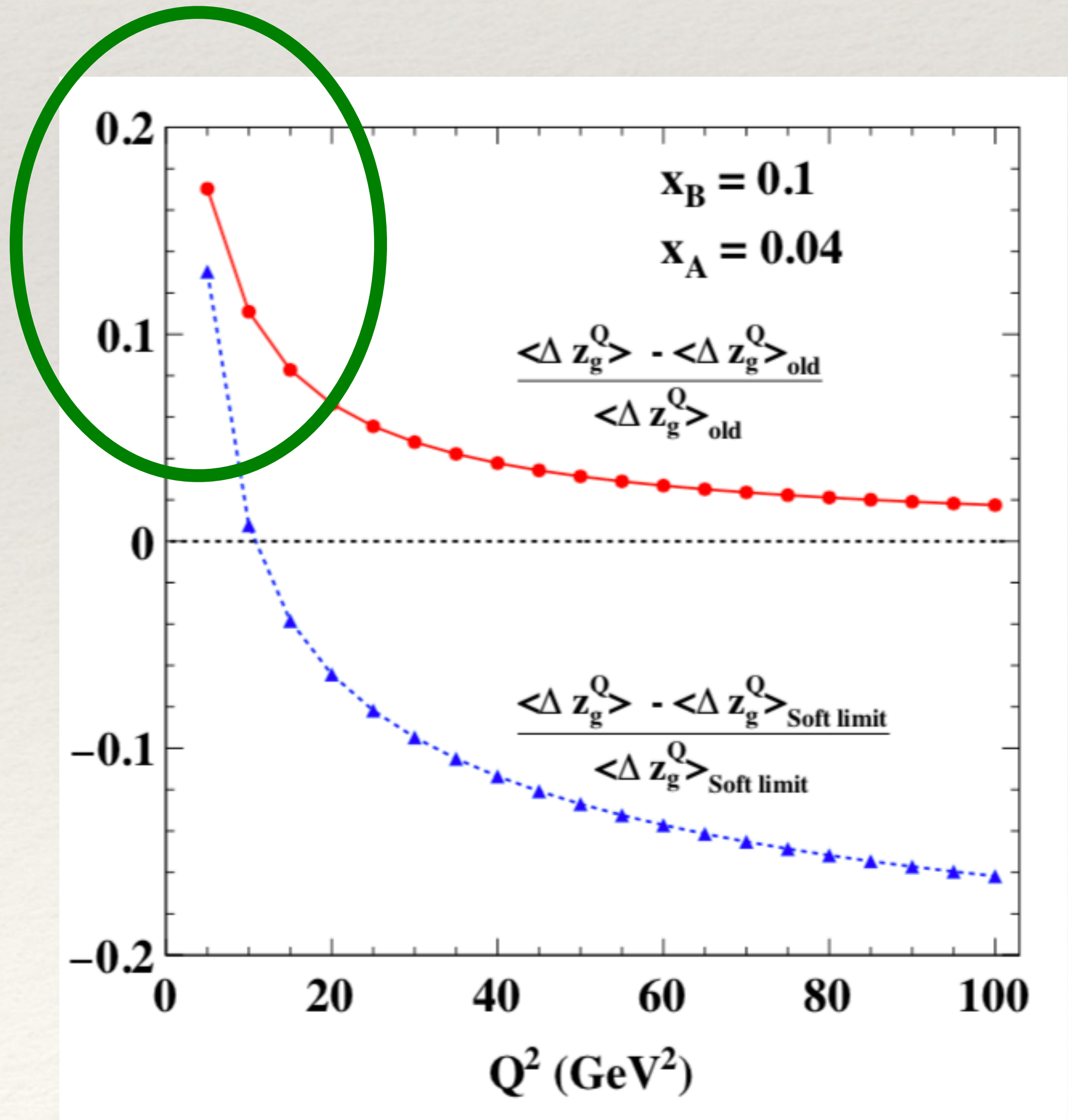
- **Recent developments in higher-twist:**
- Ensuring gauge invariance – larger HQ energy loss at low Q²
[Du, He, Wang, Xing and Zong, PRD 98 (2018)]
- Going beyond the collinear and soft approximation => relate the gluon spectrum to the differential elastic scattering rate [Zhang, Hou and Qin, PRC 100 (2019)]



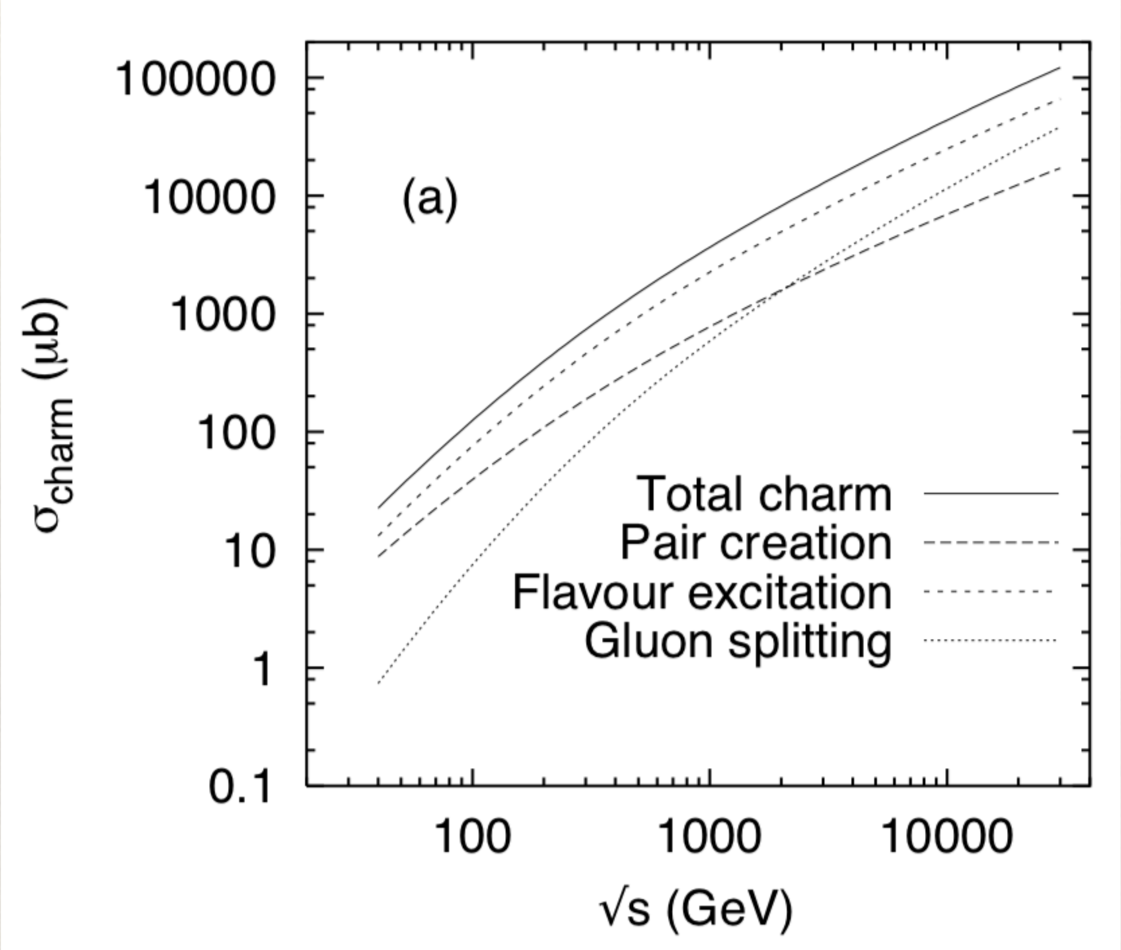
Flavor hierarchy of jet quenching

Clean perturbative framework is sufficient for describing the flavor hierarchy at high p_T (> 8 GeV)

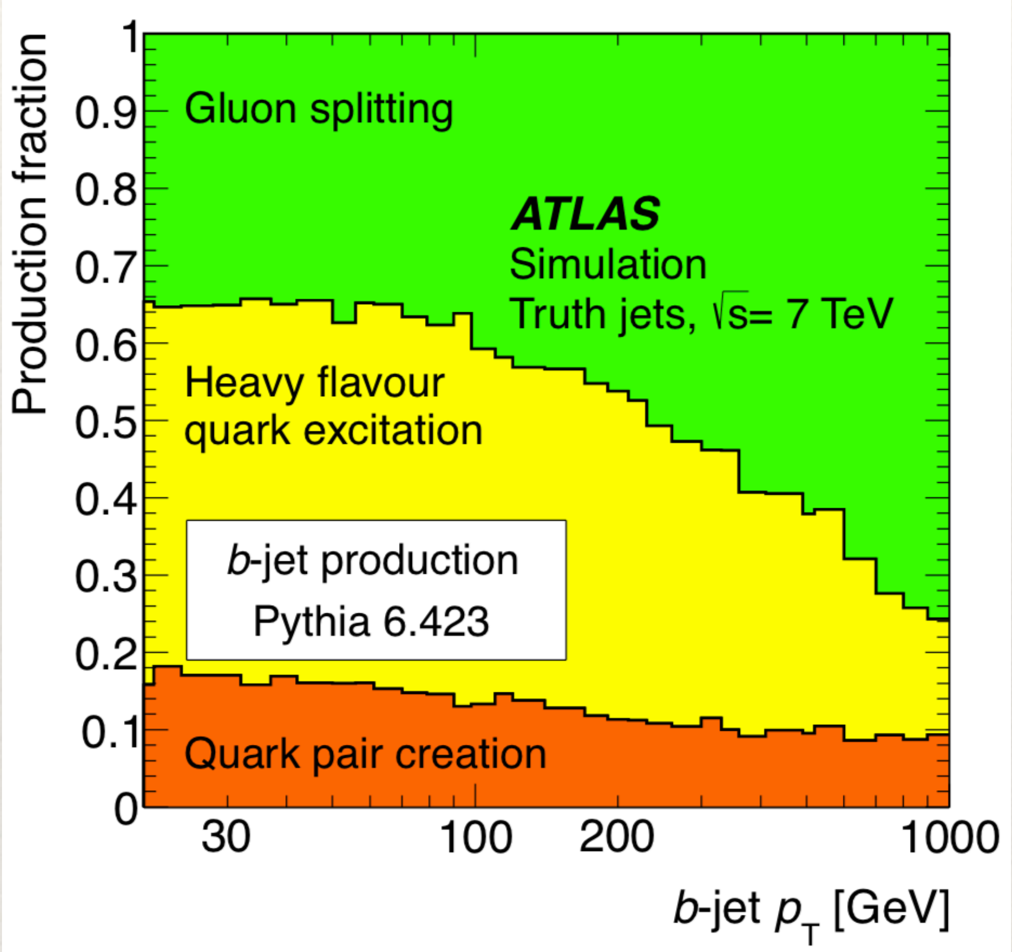
[Xing, Cao, Qin and Xing, arXiv: 1906.00413]

❖ Xing's talk (Tue.)

NLO contribution to HQ production in Pythia simulation (gluon splitting)



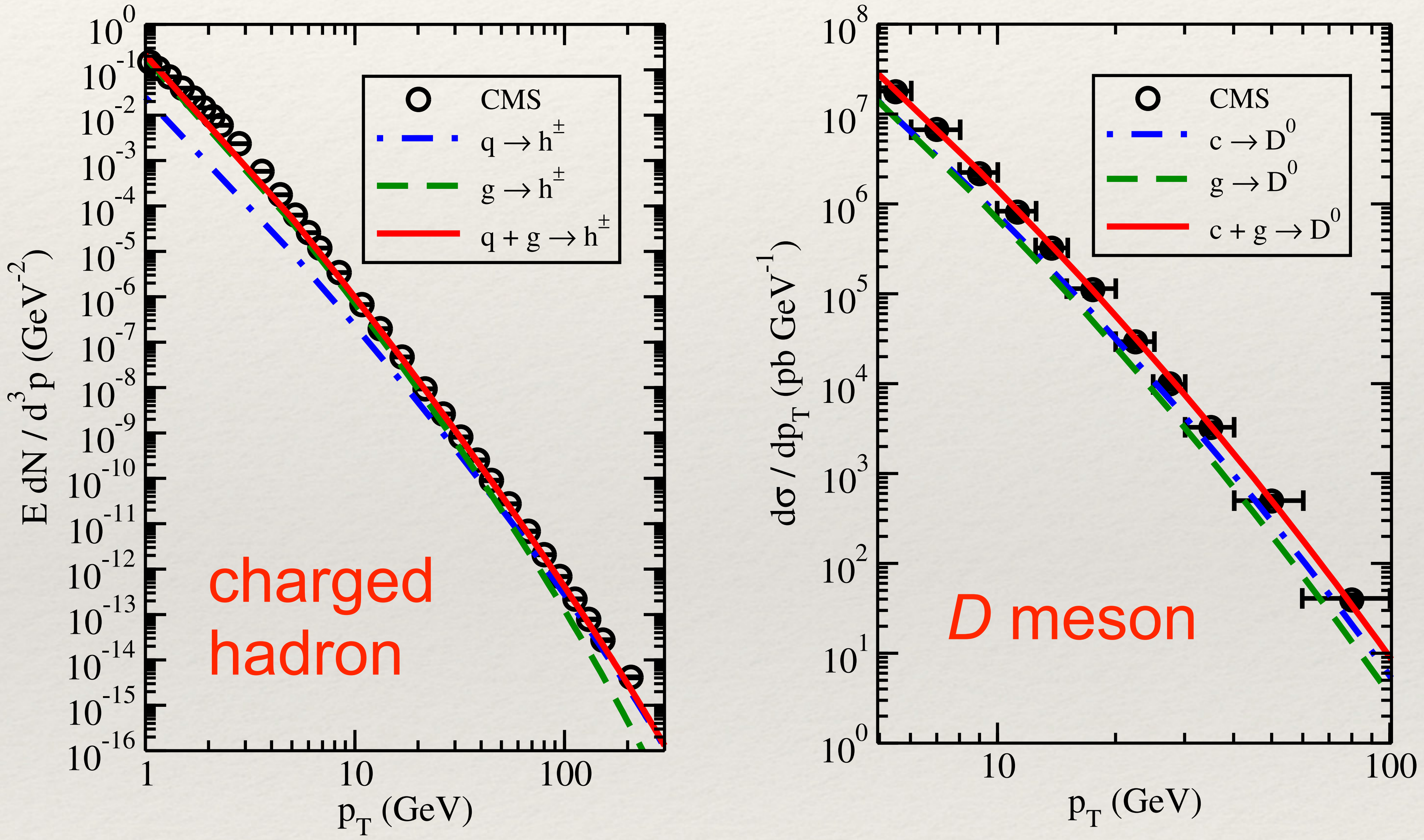
[Norrbin and Sjostrand, EPJC 17 (2000)]



[ATLAS, EPJC 73 (2013)]

- NLO contribution increases with $\sqrt{s}$
- NLO contribution increases with *b*-jet p_T

Light vs. heavy hadron spectra within NLO production + fragmentation framework



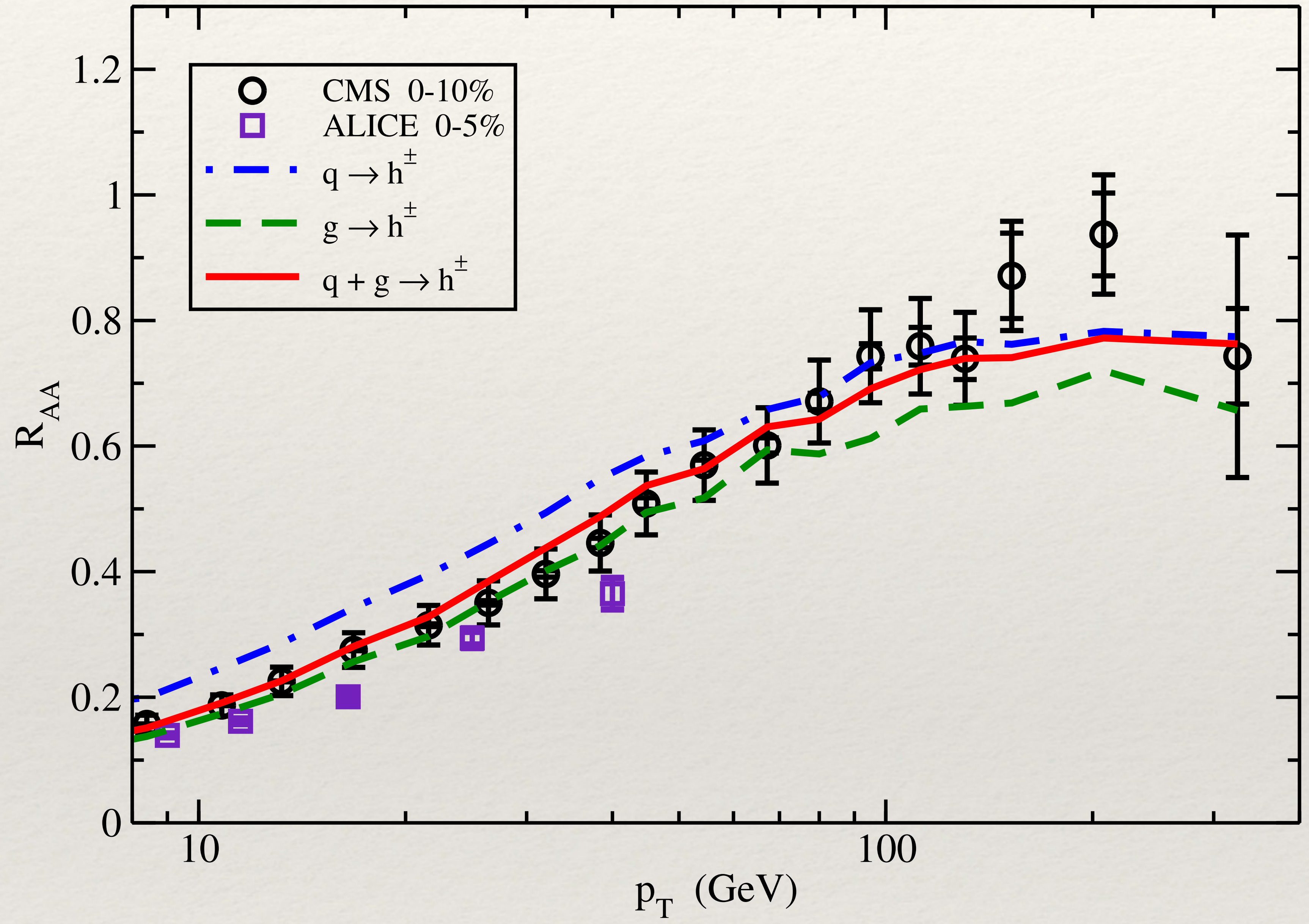
Gluon fragmentation

- dominates $h^{\pm}$ production up to 50 GeV
- contributes to over 40% *D* up to 100 GeV

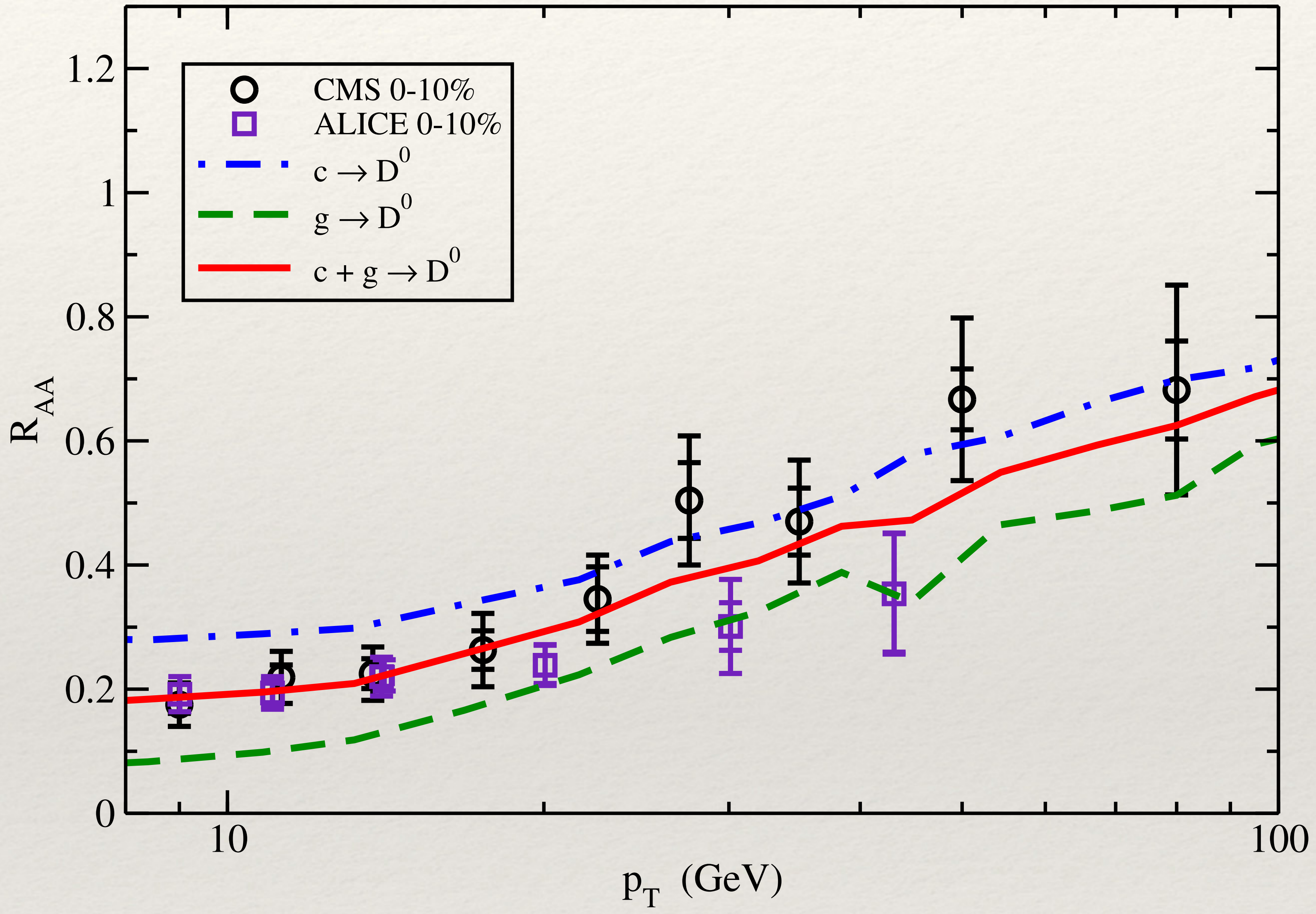
Flavor hierarchy of jet quenching

NLO initial production and fragmentation + Boltzmann transport (elastic and inelastic energy loss) + hydrodynamic medium for QGP

charged hadron



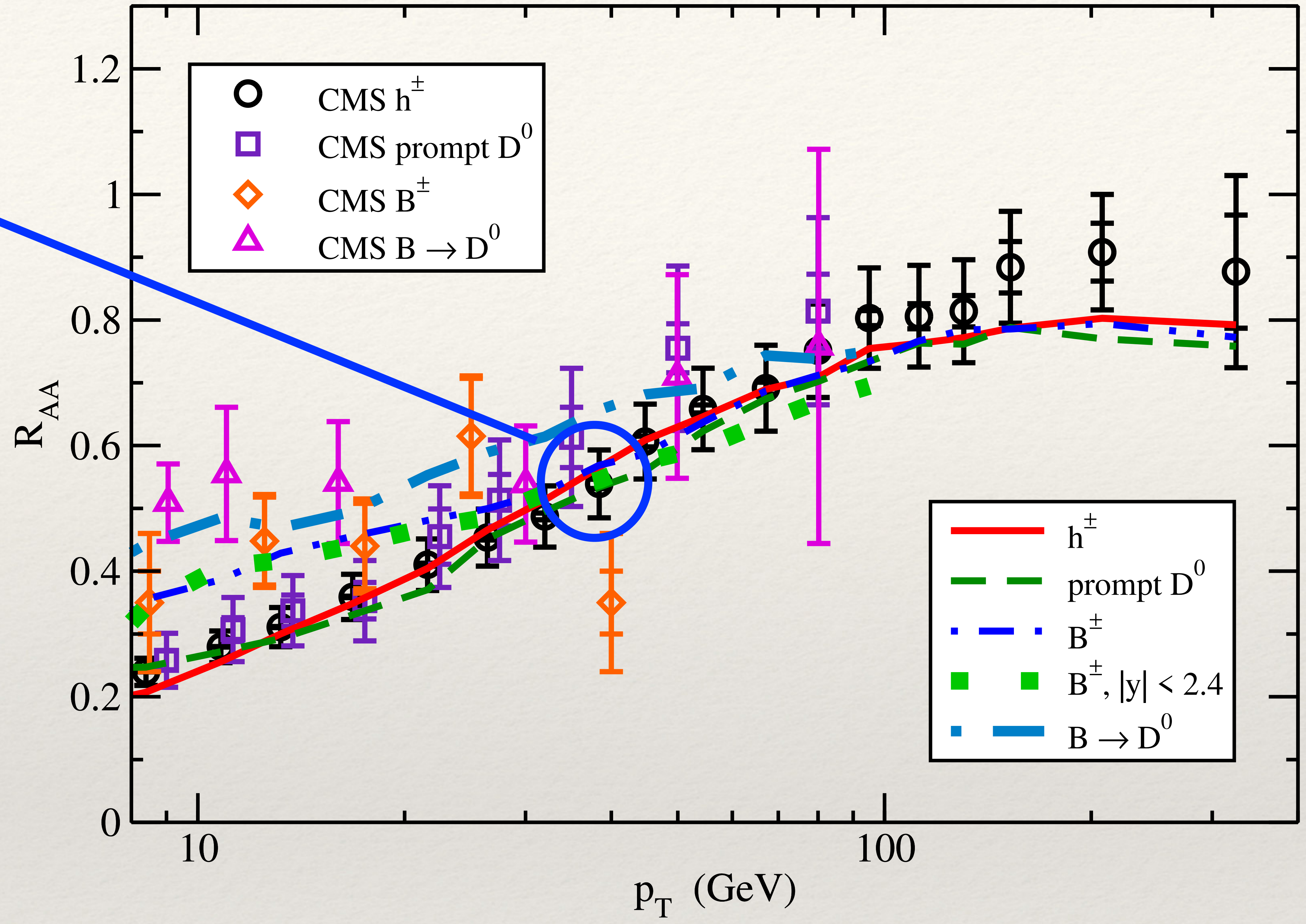
D meson



- *g*-initiated *h* & *D* R_{AA} < *q*-initiated *h* & *D* R_{AA} => **$\Delta E_g > \Delta E_q > \Delta E_c$ holds**
- Although R_{AA} (*c*->*D*) > R_{AA} (*q*->*h*), R_{AA} (*g*->*D*) < R_{AA} (*g*->*h*) due to different fragmentation functions => **R_{AA} (*h*) ≈ R_{AA} (*D*)**

Flavor hierarchy of jet quenching

Merging of *D* and *B* R_{AA} at p_T ~ 40 GeV



❖ Xing's talk (Tue.)

[Xing, Cao, Qin and Xing, arXiv: 1906.00413]

- A simultaneous description of charged hadron, *D* meson, *B* meson, *B*-decay *D* meson R_{AA}'s starting from p_T ~ 8 GeV
- Predict R_{AA} separation between *B* and *h* / *D* below 40 GeV, but similar values above – **wait for confirmation from future precision measurement**

Medium to low p_T HQ's — hadronization

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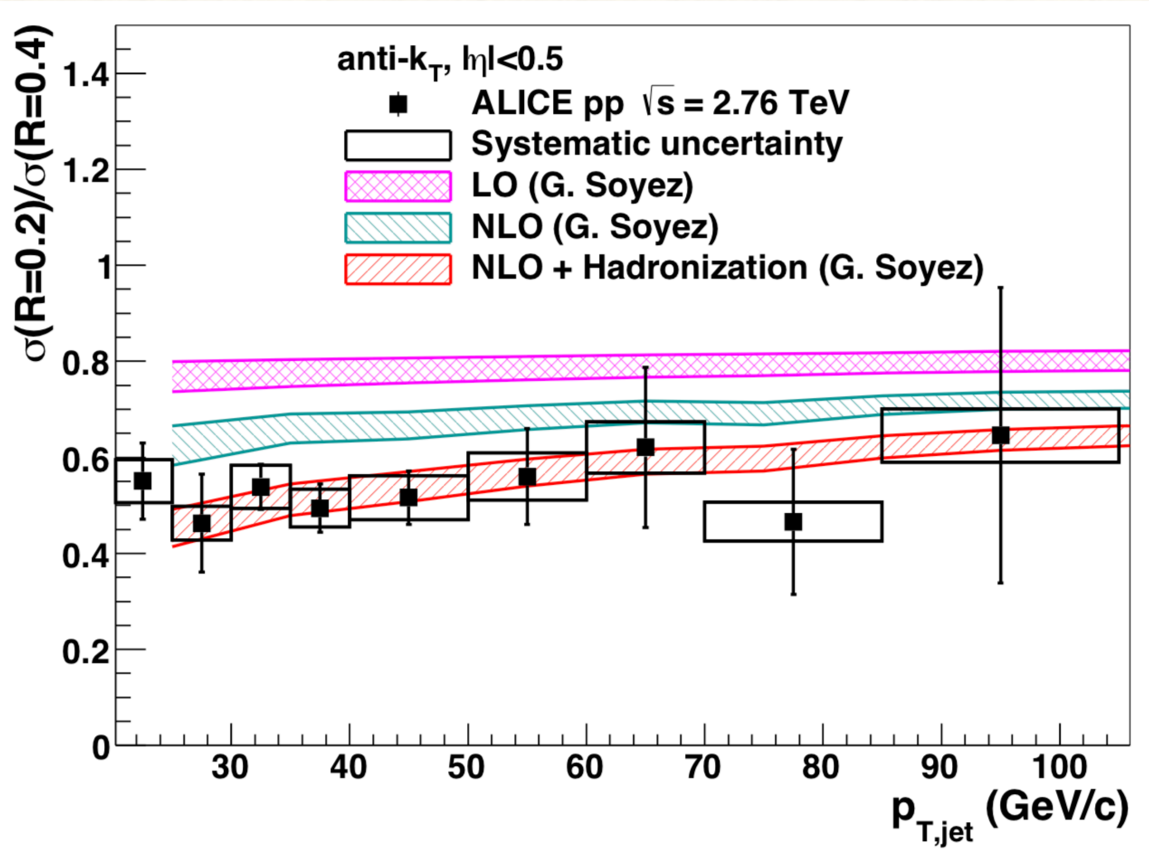
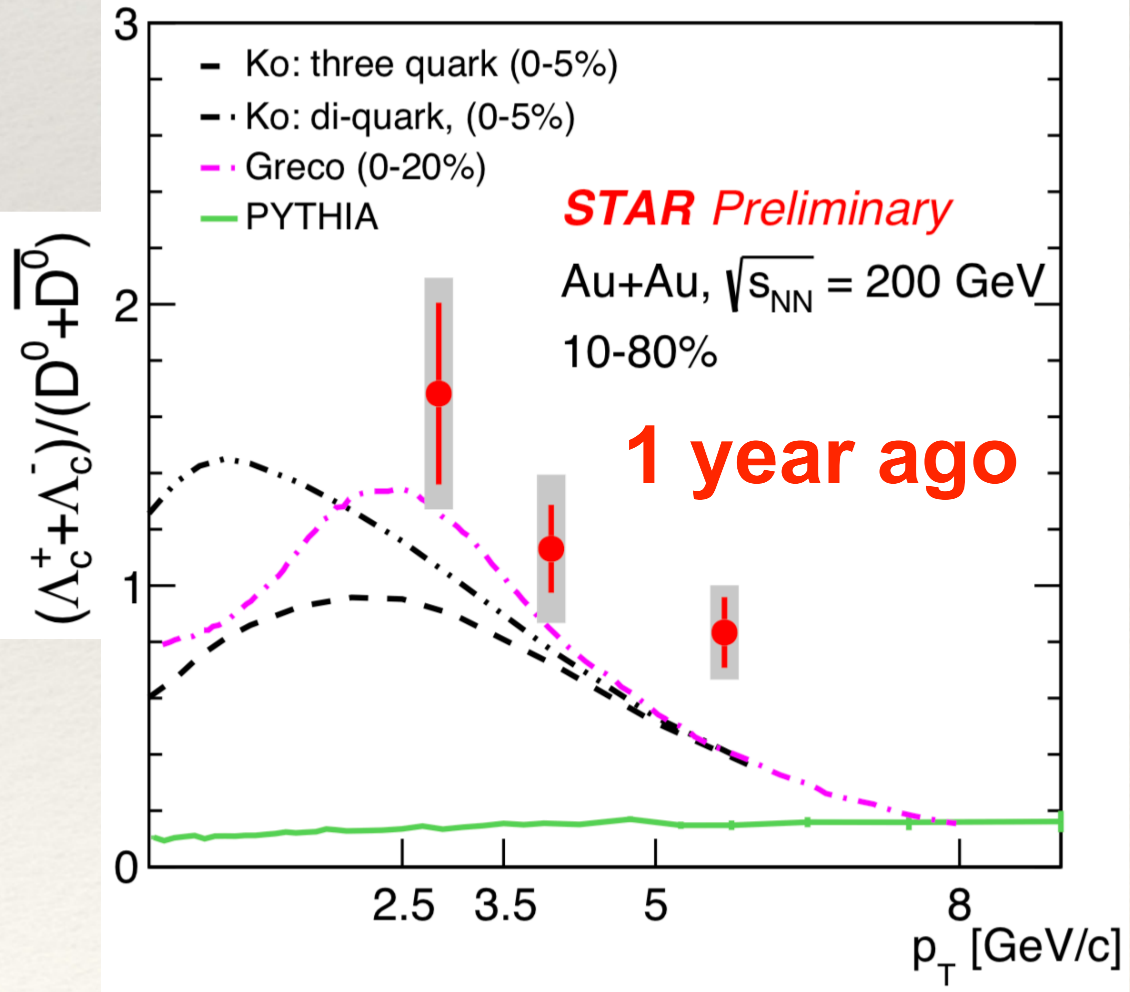
Importance of hadronization



[ALICE, PLB 722 (2013)]



1 year ago

[STAR, QM 2018]

Soft hadrons:

NCQ scaling of v_2

Jets:

equal importance as the NLO effects

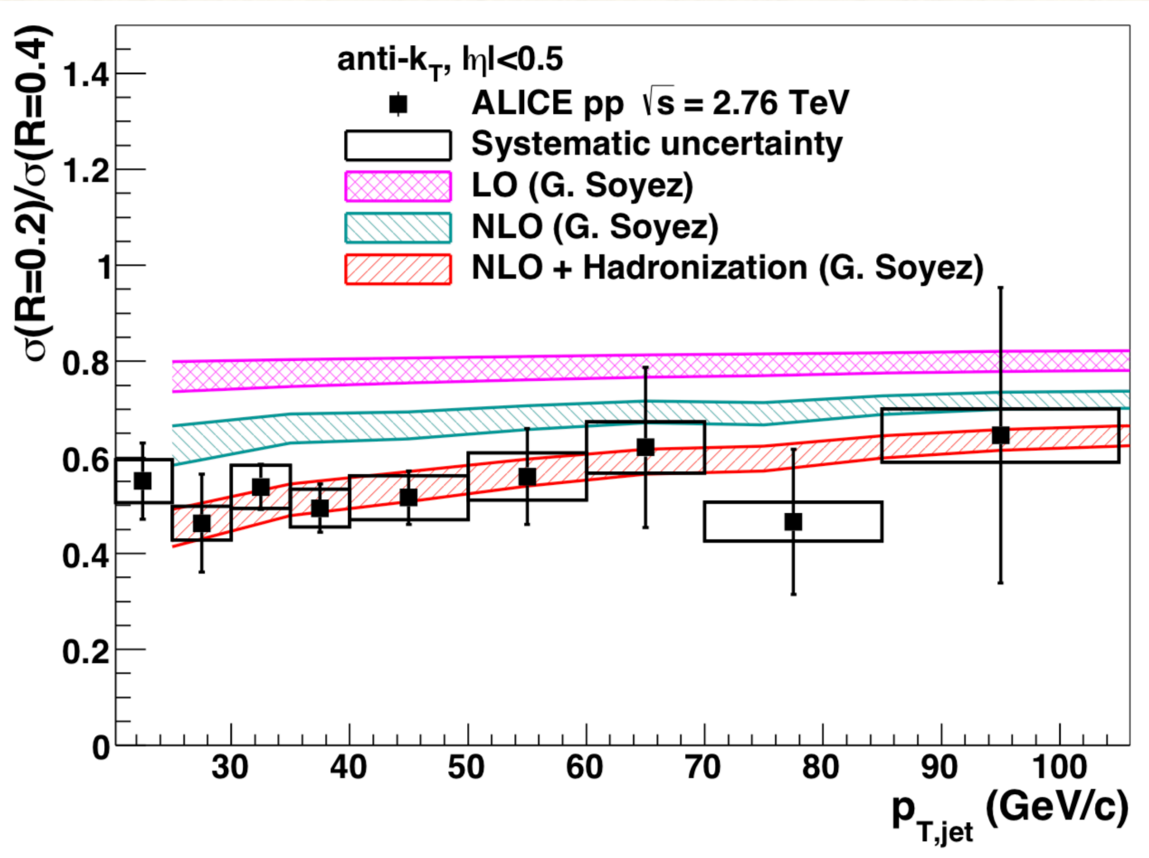
Heavy quarks:

hadron chemistry

Insufficient efforts on this topic until 1 year ago

Medium to low p_T HQ's — hadronization

Importance of hadronization



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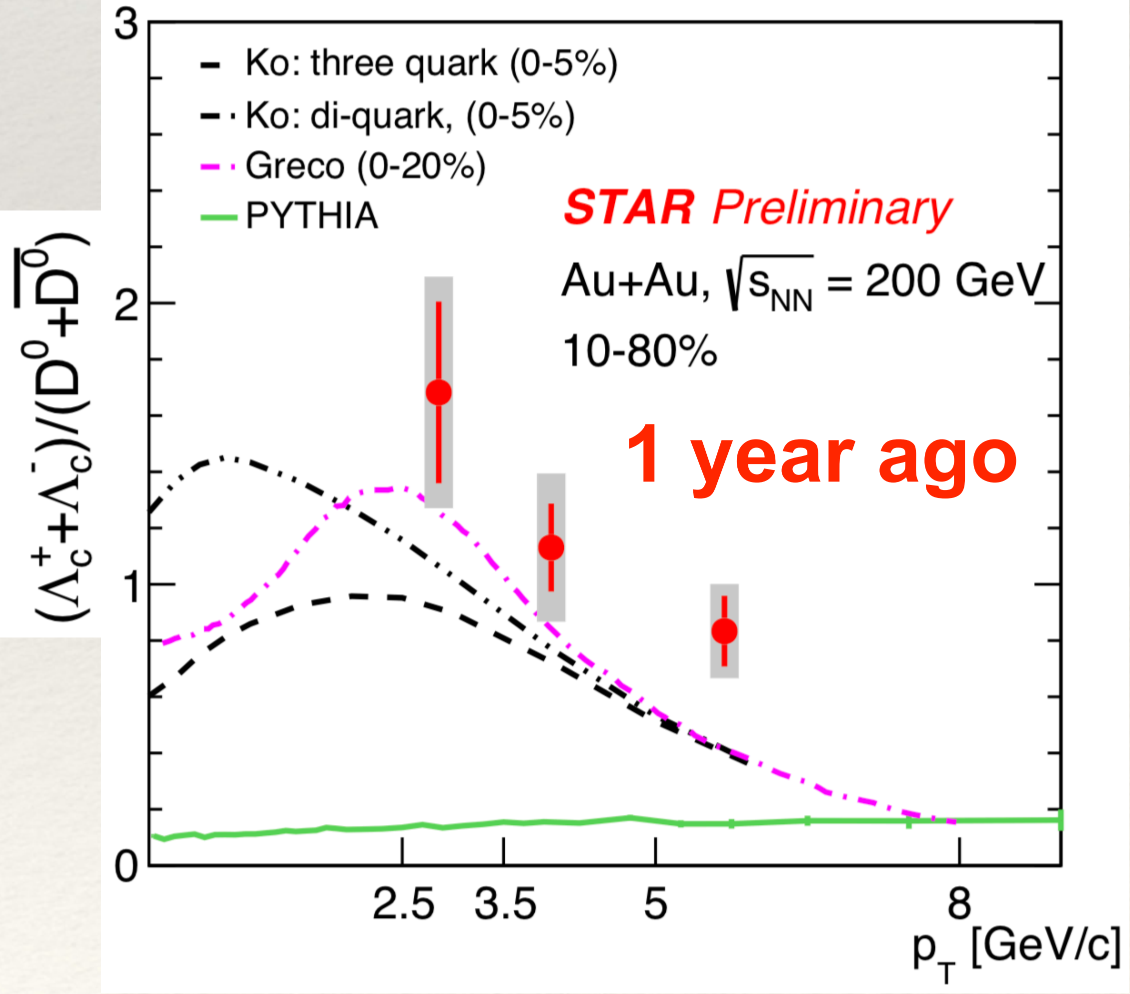

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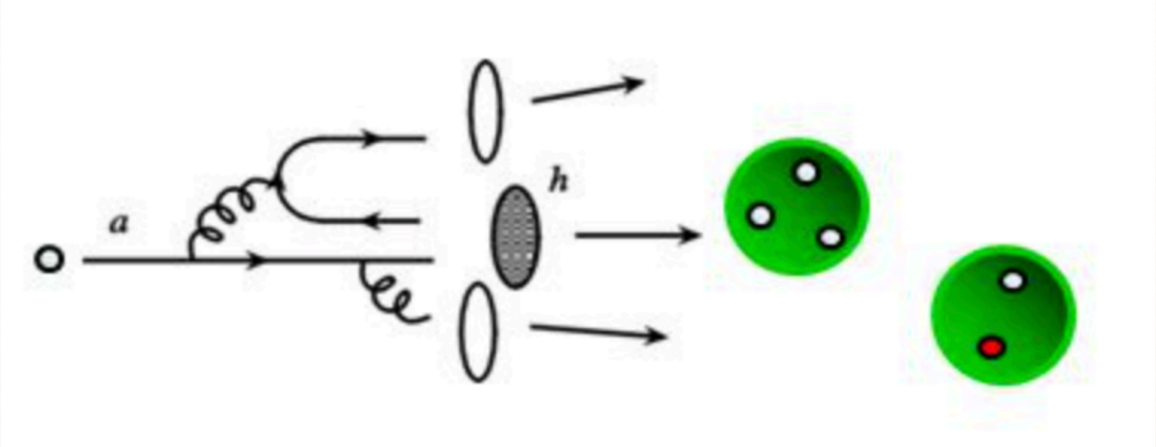
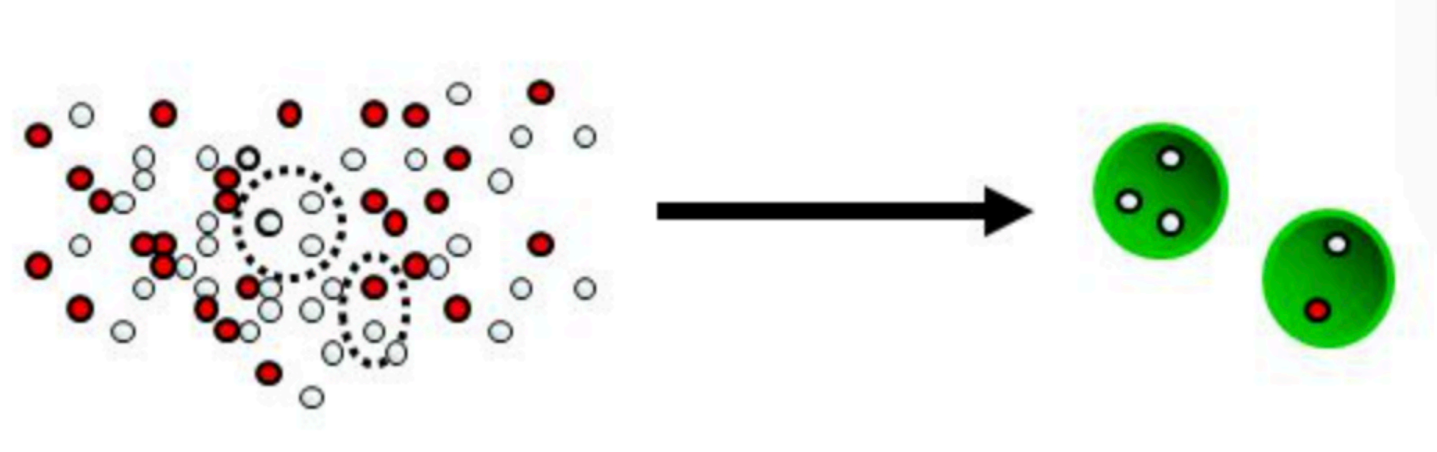
Hadronization mechanisms



Fragmentation:
High p partons fragment into hadrons
[Peterson, FONNL, Pythia, etc.]



Coalescence (***recombination***):
Low p partons combine with thermal partons into hadrons

Coalescence models

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

  coalescence between neighboring particles [AMPT, e.g. arXiv:1909.07191]

- Resonance recombination: coalescence probability ~ resonant scattering rate

  $P_{\rm coal}(p) = \Delta\tau_{\rm res}\Gamma_Q^{\rm res}(p)$ [He et. al., e.g. PRC 86 (2012), arXiv:1905.09216]

  ❖ He's talk (Tue.)

  $\Delta\tau_{\rm res}$: the time window for resonant state

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

- Instantaneous coalescence: coalescence probability ~ wavefunction overlap

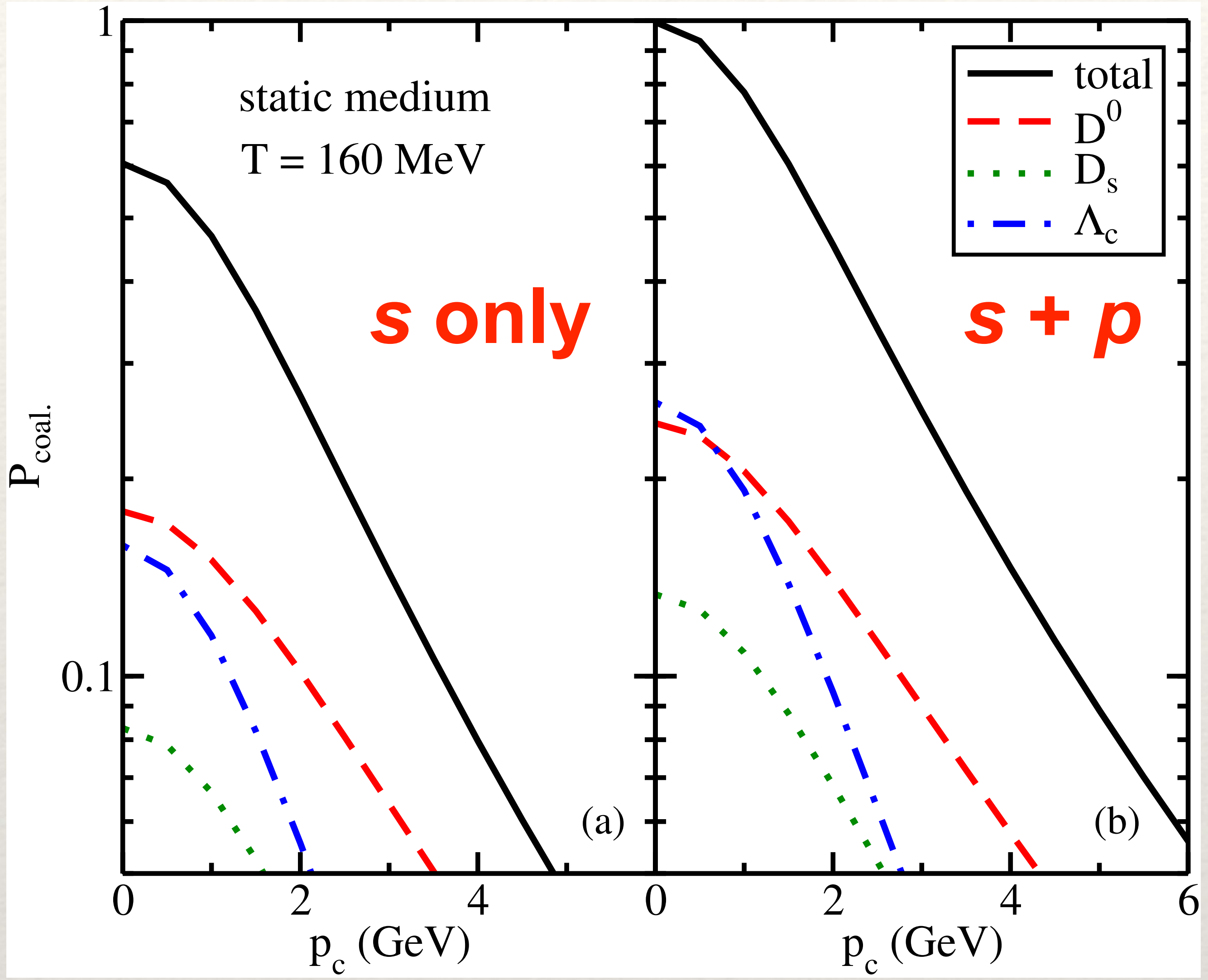
  Probability: Wigner function $f_M^W \equiv |\langle M|q_1, q_2\rangle|^2$ (for meson)

  - Encodes information of microscopic hadron structures
  - Wide application: Duke, LBL, Catania, Nantes, PHSD, Ko, Li, Zhuang, etc.

Progress in the coalescence model

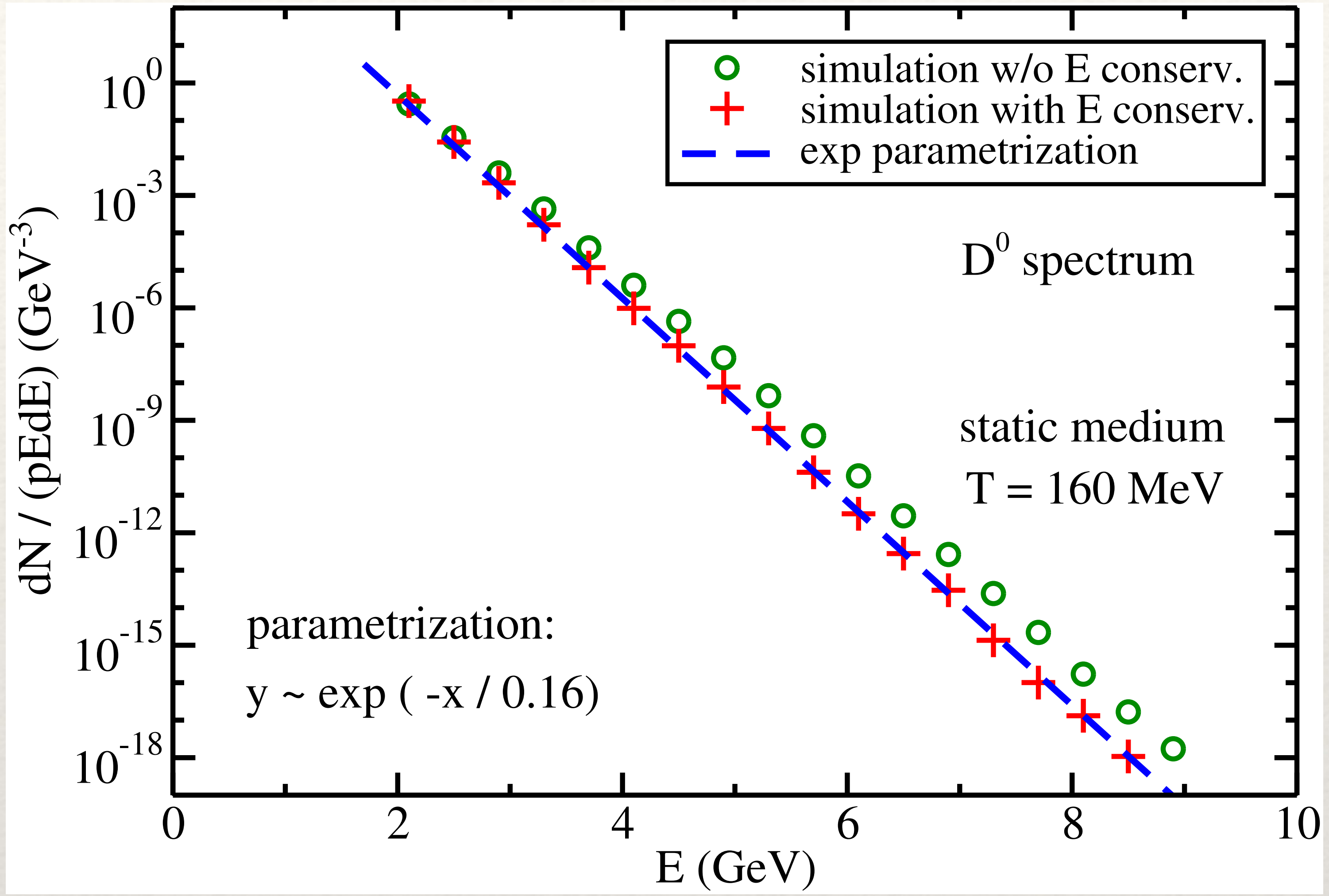
[Cao, Sun, Liu, Xing, Qin and Ko, arXiv:1911.00456]

Including both *s* and *p*-wave states



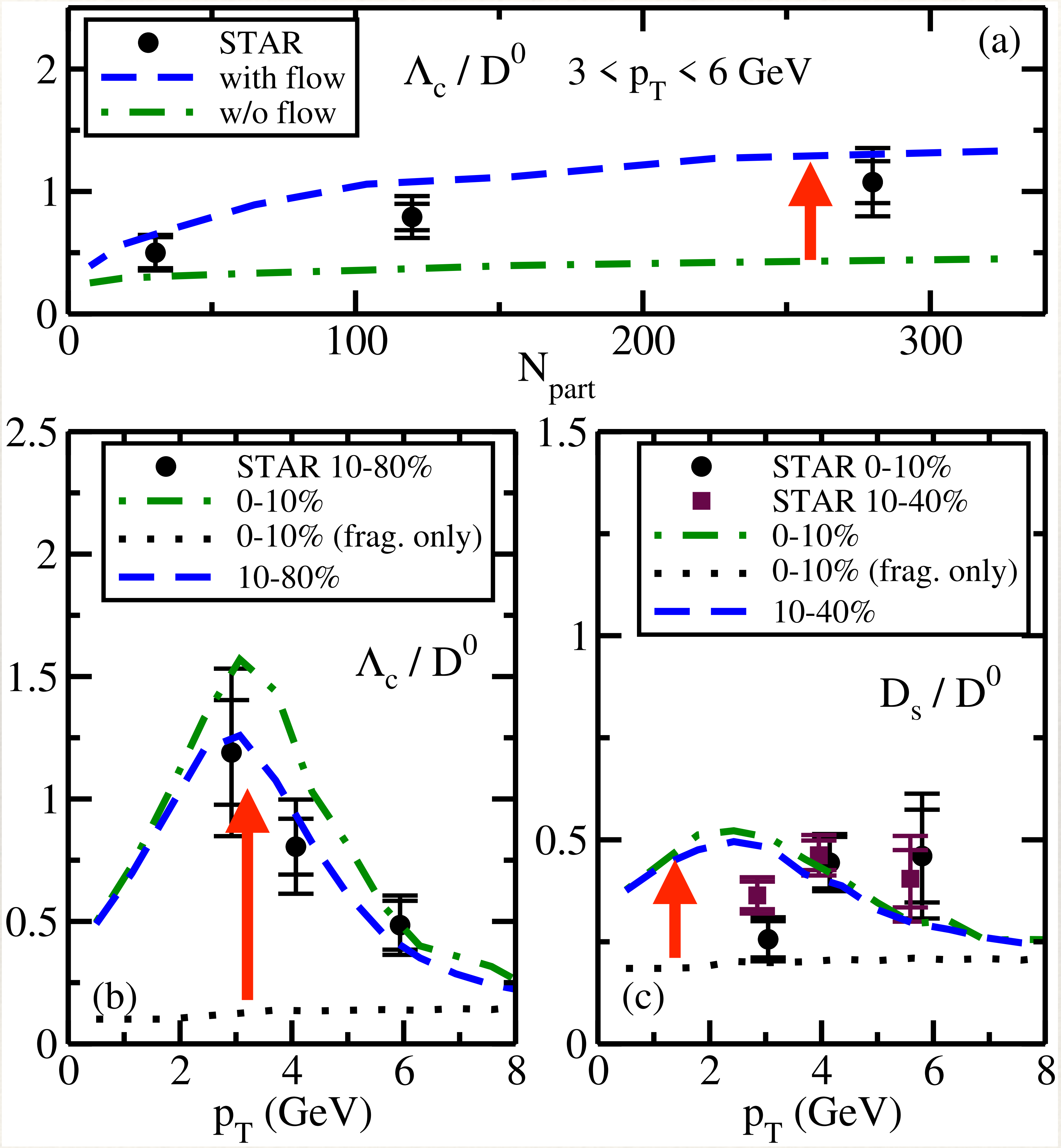
- Enhances the total $P_{\rm coal}$
- Includes nearly all *c*-hadrons in PDG
- Allows normalizing $P_{\rm coal}(p_c = 0)$ with proper in-medium hadron sizes ($r_{D^0} = 0.97$ fm)
- Enhances the Λ_c/D^0 ratio

Energy conservation and thermal limit



- 3-*p* → 4-*p* conservation by coalescing to off-shell excited states and then decay to on-shell ground states
- Guarantees boost invariance
- Guarantees the thermal limit of *c*-hadrons: thermal *c* + thermal *q* → thermal D^0

Charmed hadron chemistry



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effects of the QGP flow

effects of coalescence

- Stronger QGP flow boost on heavier hadrons => increases the Λ_c/D^0 ratio
- Coalescence increases Λ_c/D^0 and D_s/D^0 ratios compared to fragmentation
- Prediction — larger hadron (D^0) size in medium (0.97 fm) than in vacuum (0.83 fm) — waits for confirmation by hadronic model calculations

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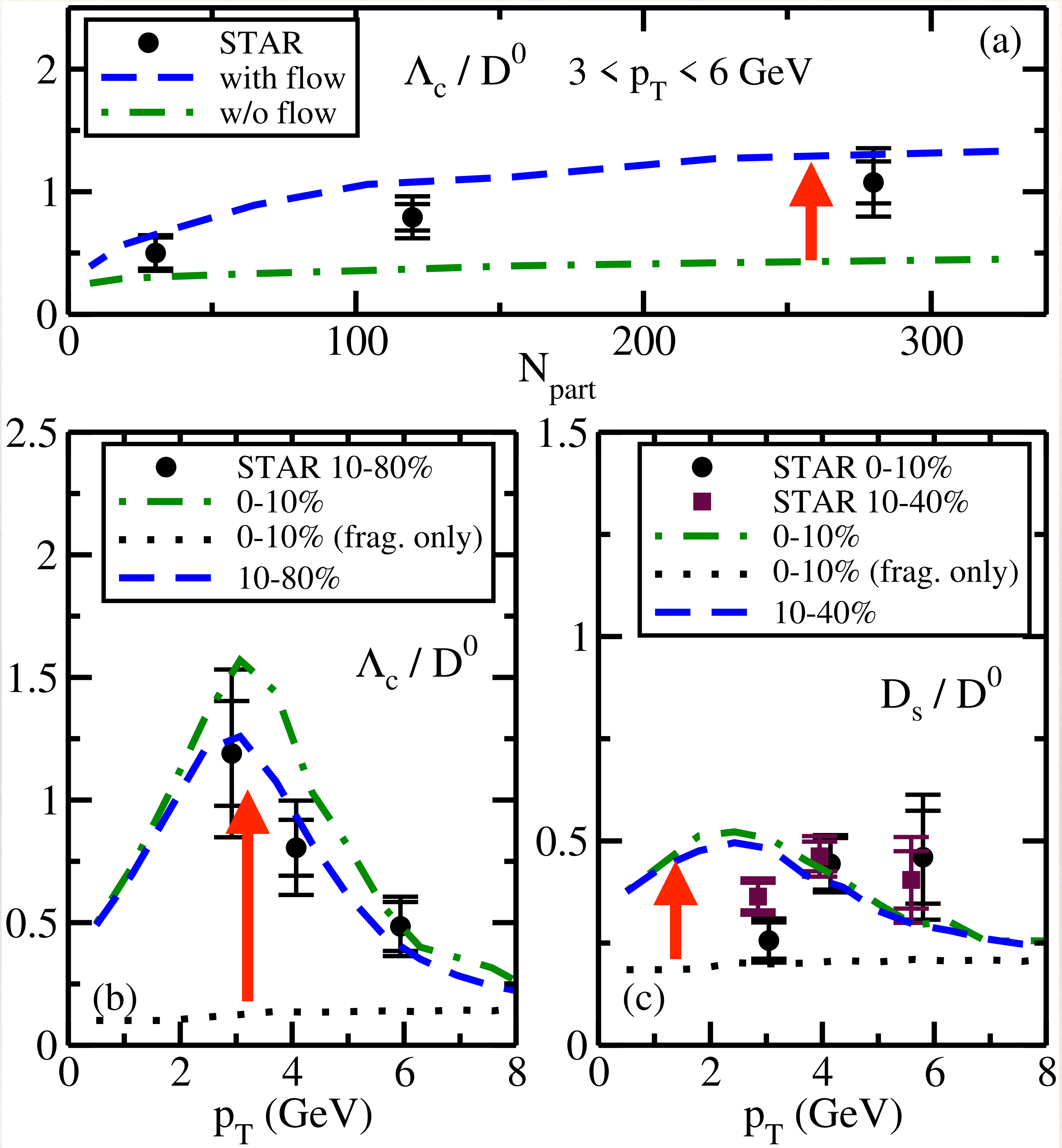

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- Other effects:

  Resonance decays beyond PDG ❖ He's talk (Tue.)

  Sequential coalescence of *c*-hadrons at different temperatures ❖ Zhao's talk (Tue.)
- **Significant improvements in both theory and experiment over the past year!**

Low p_T HQ's — color potential interaction

- Suppression of radiative energy loss due to the "dead cone effect"
- Heavy quark diffusion, **diffusion coefficient** κ or D_s as important input into transport models

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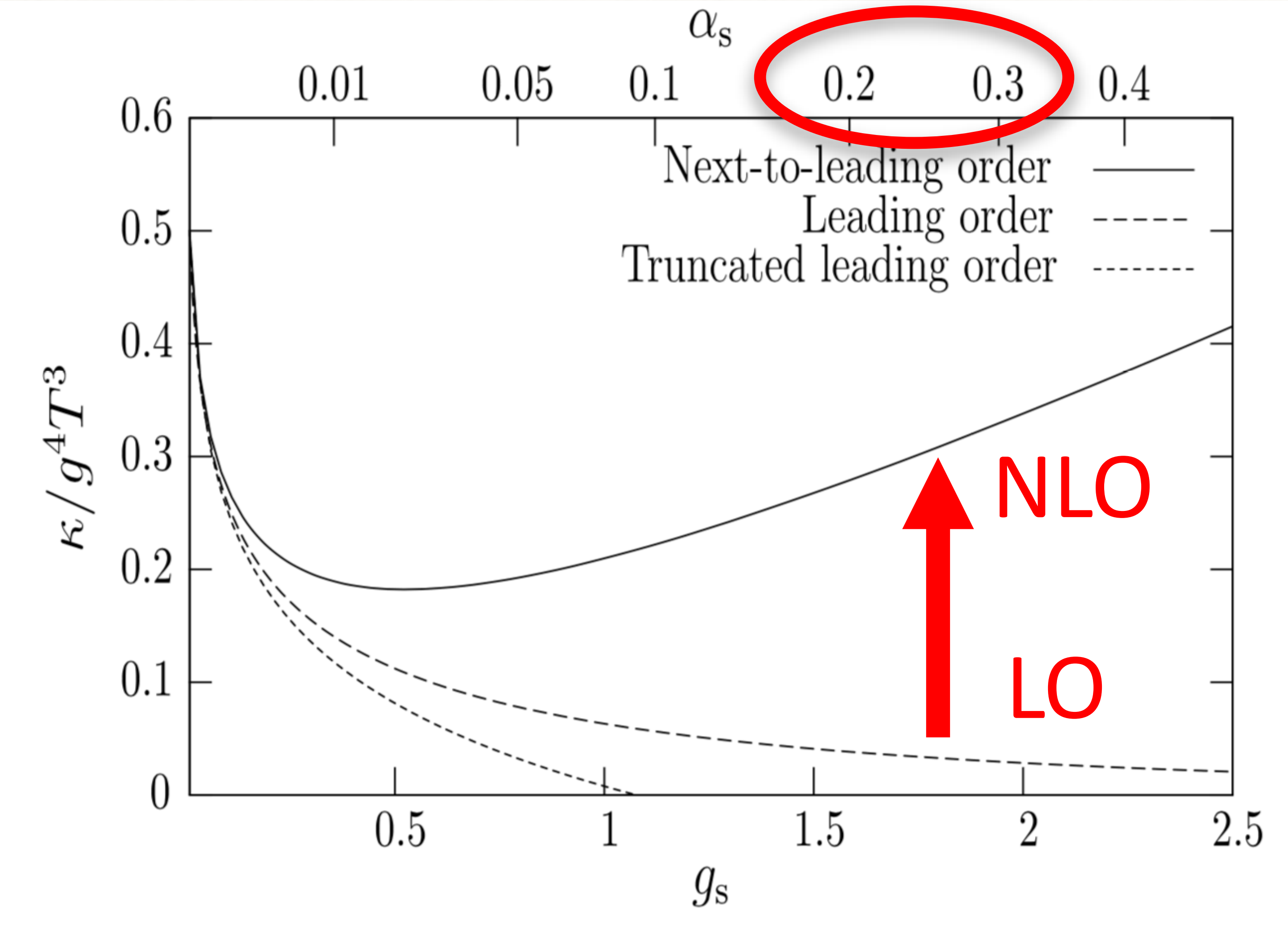
Perturbation calculation fails at low p_{T}



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- NLO: Caron-Huot and Moore, JHEP 02 (2008)
- A factor of over 5 increase at NLO

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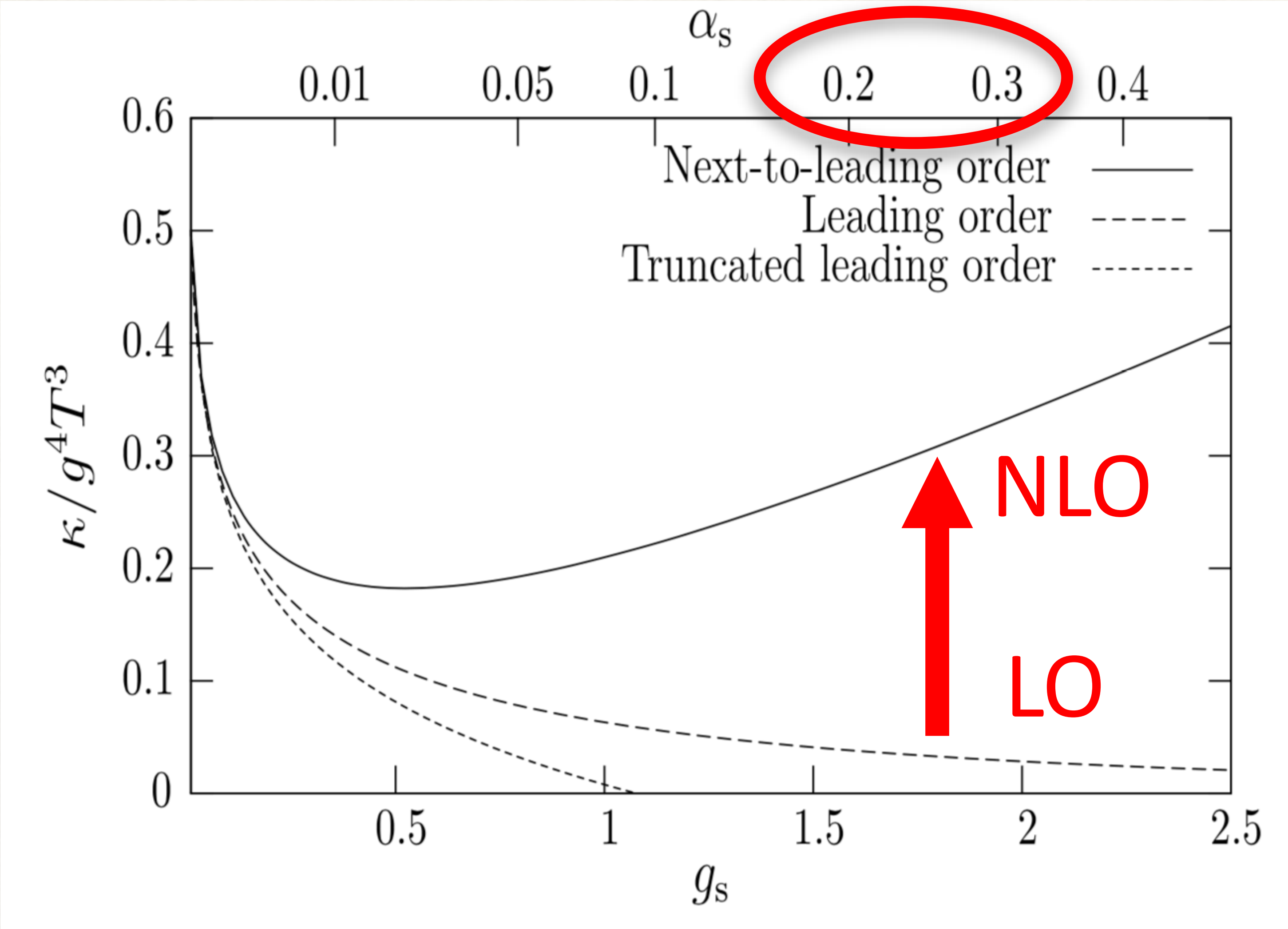

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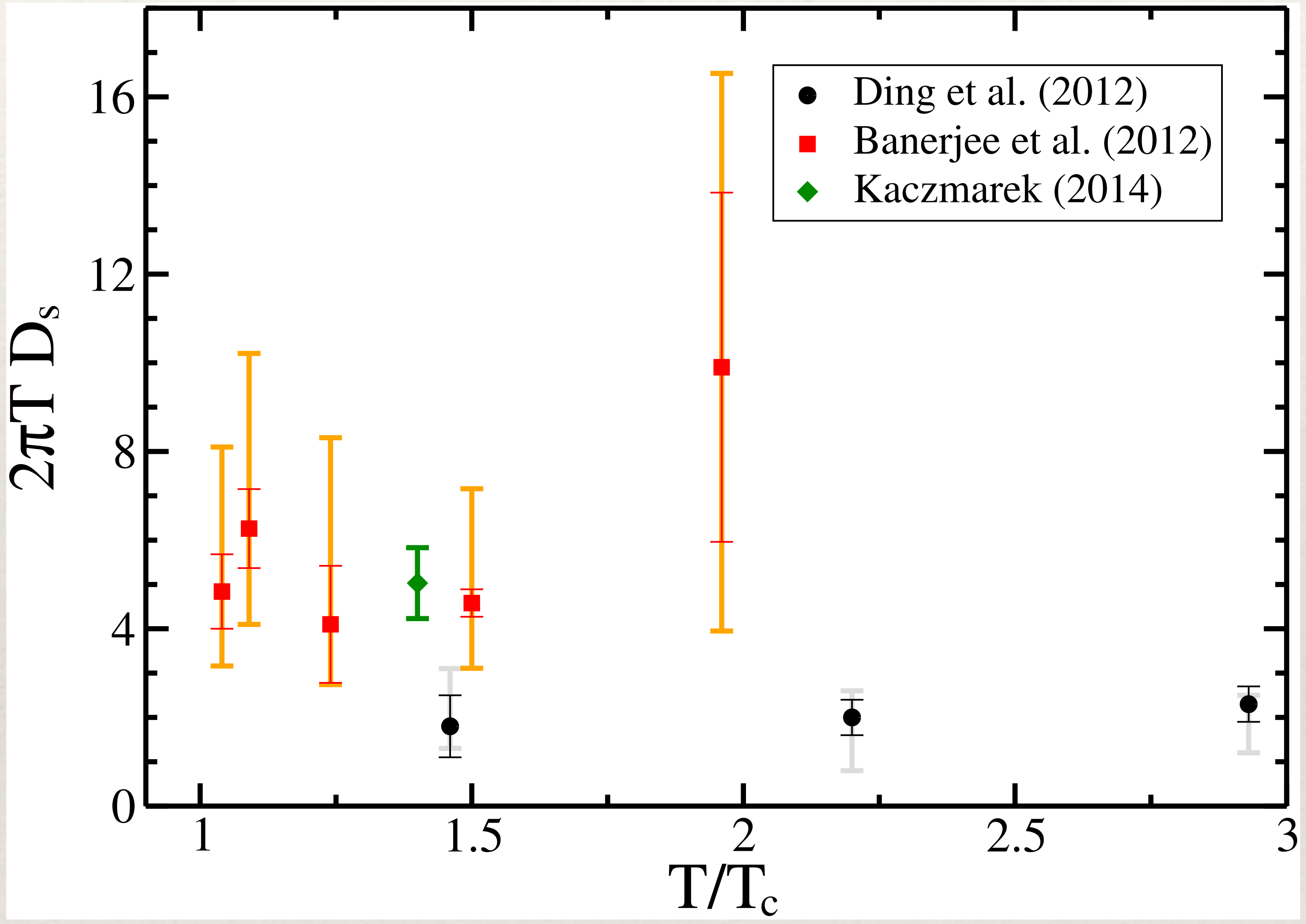
Inputs from lattice calculations



- No results for finite momentum HQ yet
- Progress: 1st continuum extrapolated results of vector correlators for J/ψ and Υ => c vs. b diffusion coefficient

❖ Kaczmarek's talk (Tue.)

❖ Ding's talk (Mon.)

Non-perturbative method driven by lattice

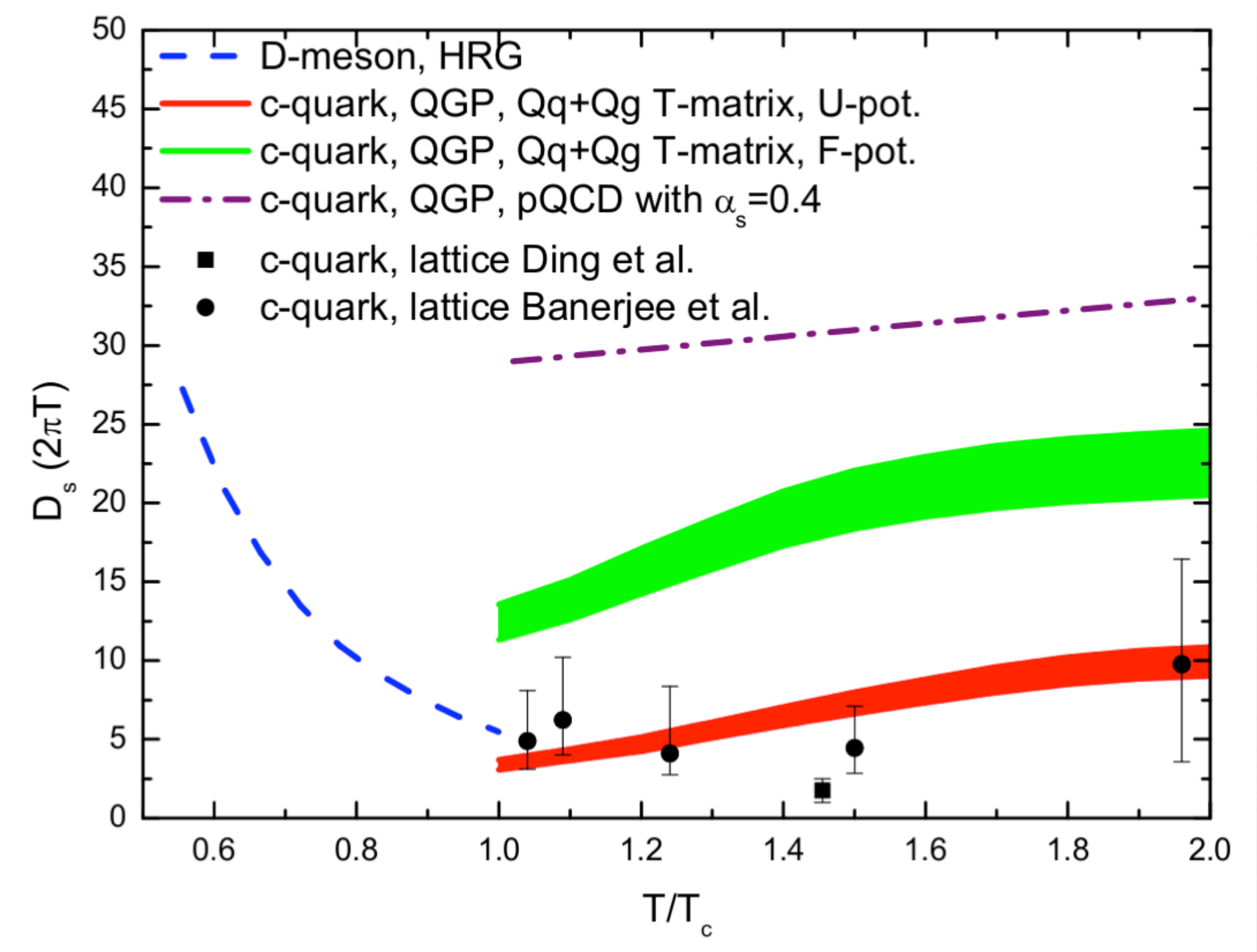
Resonant scattering (*T*-matrix) approach (TAMU)

[Hees et al., PRC 73 (2006), PRL 100 (2008); He et al., PRC 86 (2012)]

- Assume two body (*qQ*) interaction with *V*
- Solve *T*-matrix and extract D_s

$$A_Q(p) \sim |T|^2, \quad D_s = T/(MA_Q)$$

- Enhanced energy loss than in pQCD



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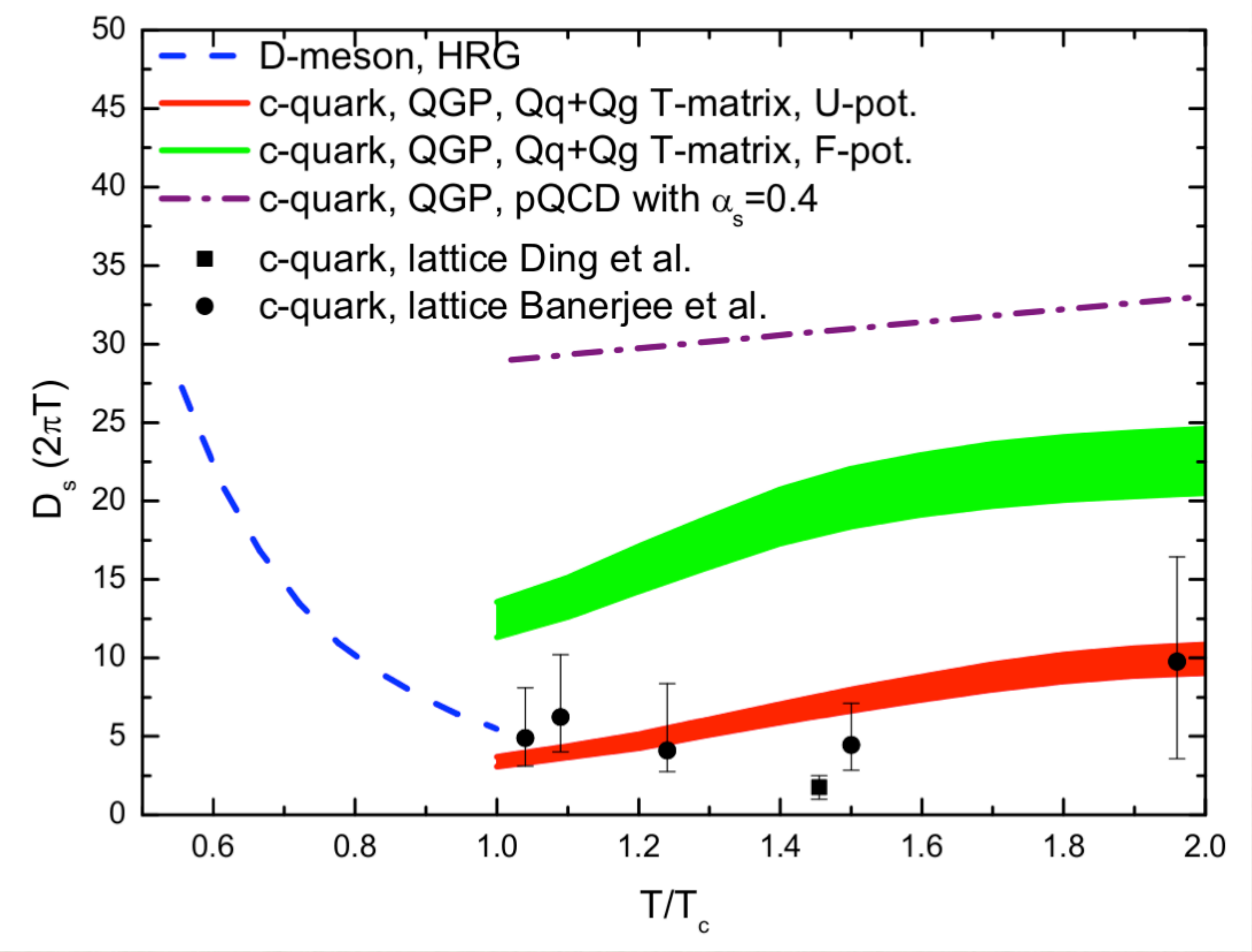
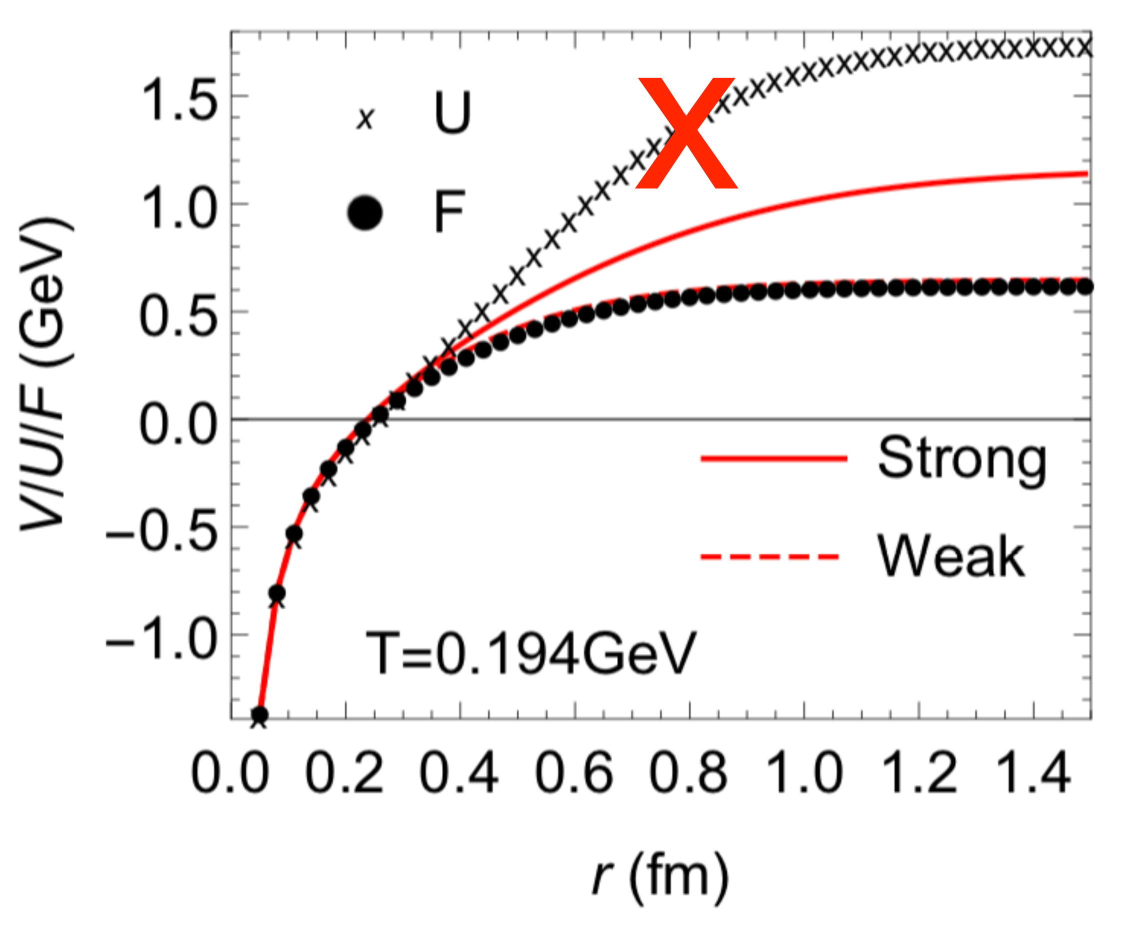
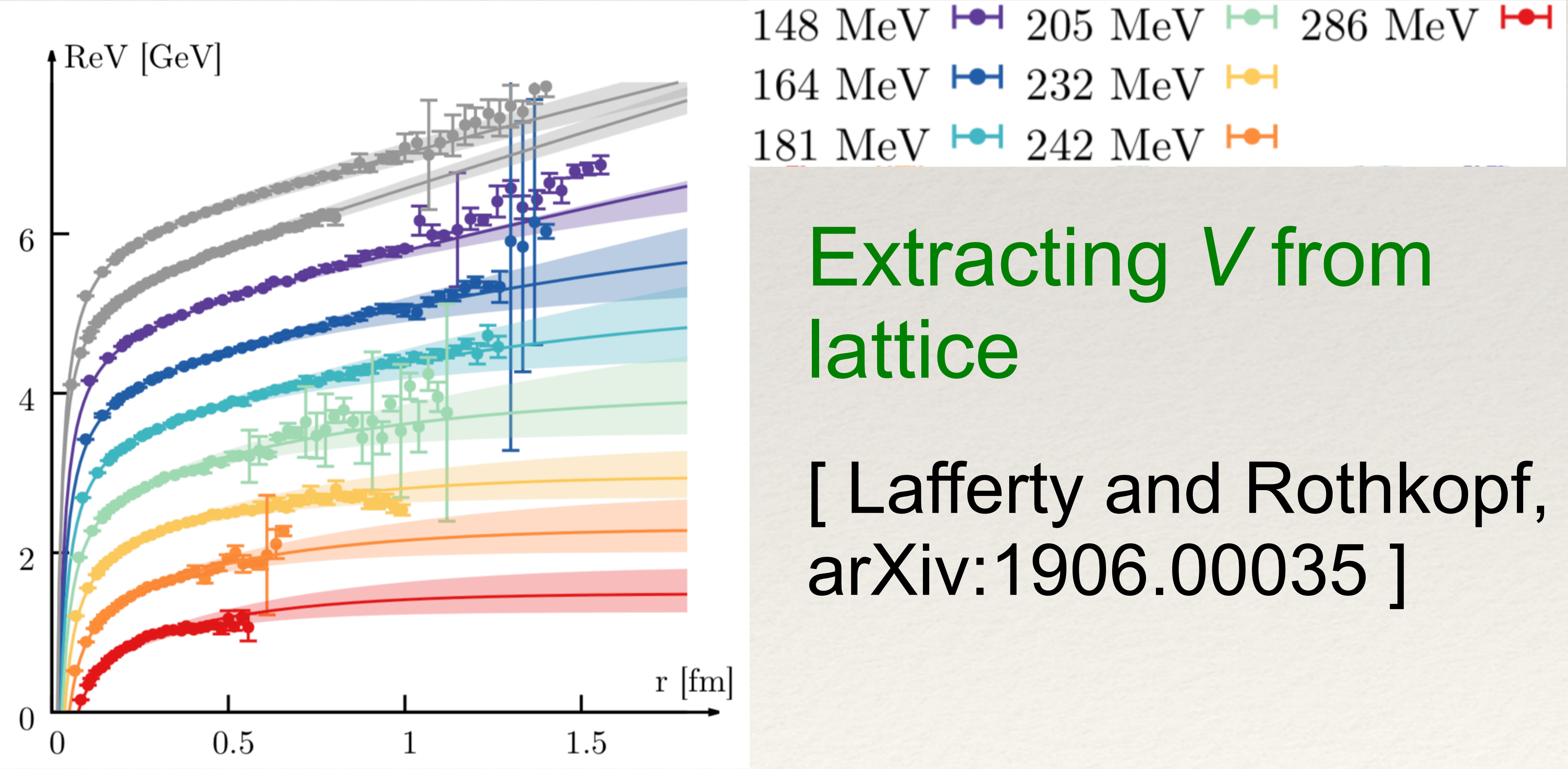


From *U*, *F* to the real potential *V*



Solving *V* self-consistently in the *T*-matrix framework

[Liu, He and Rapp, PRC 97 (2018)]



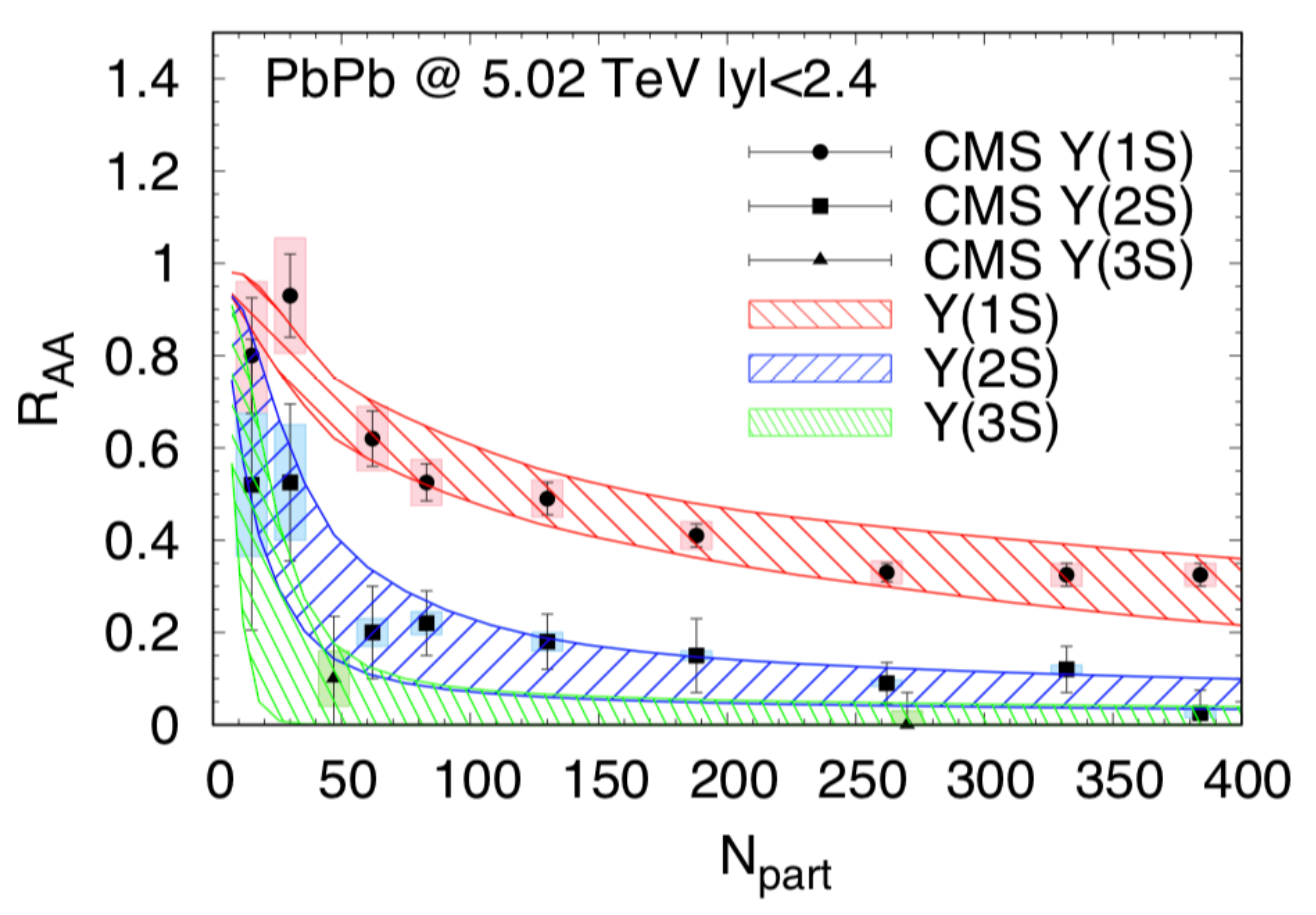
Extracting *V* from lattice

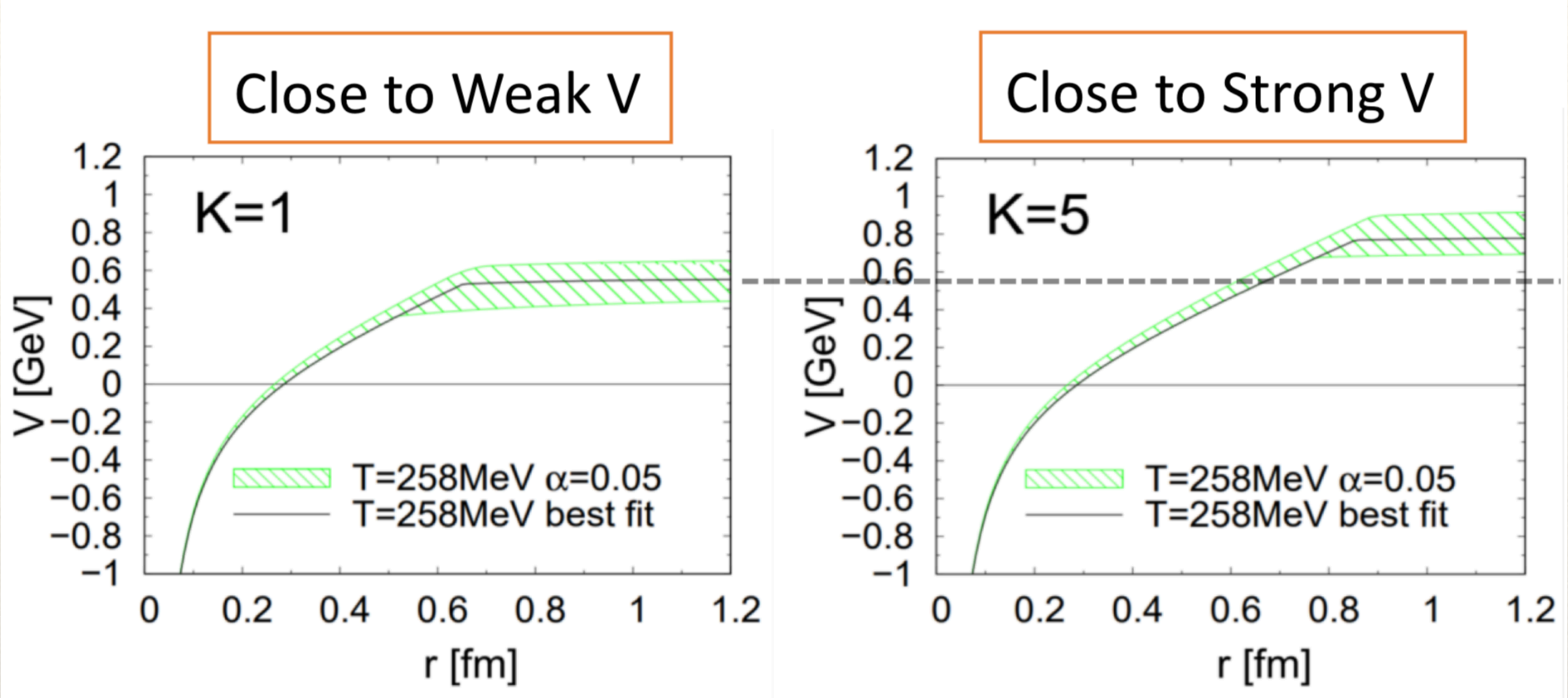
[Lafferty and Rothkopf, arXiv:1906.00035]

Solution is not unique!

Constraining color potential with HQ phenomenology

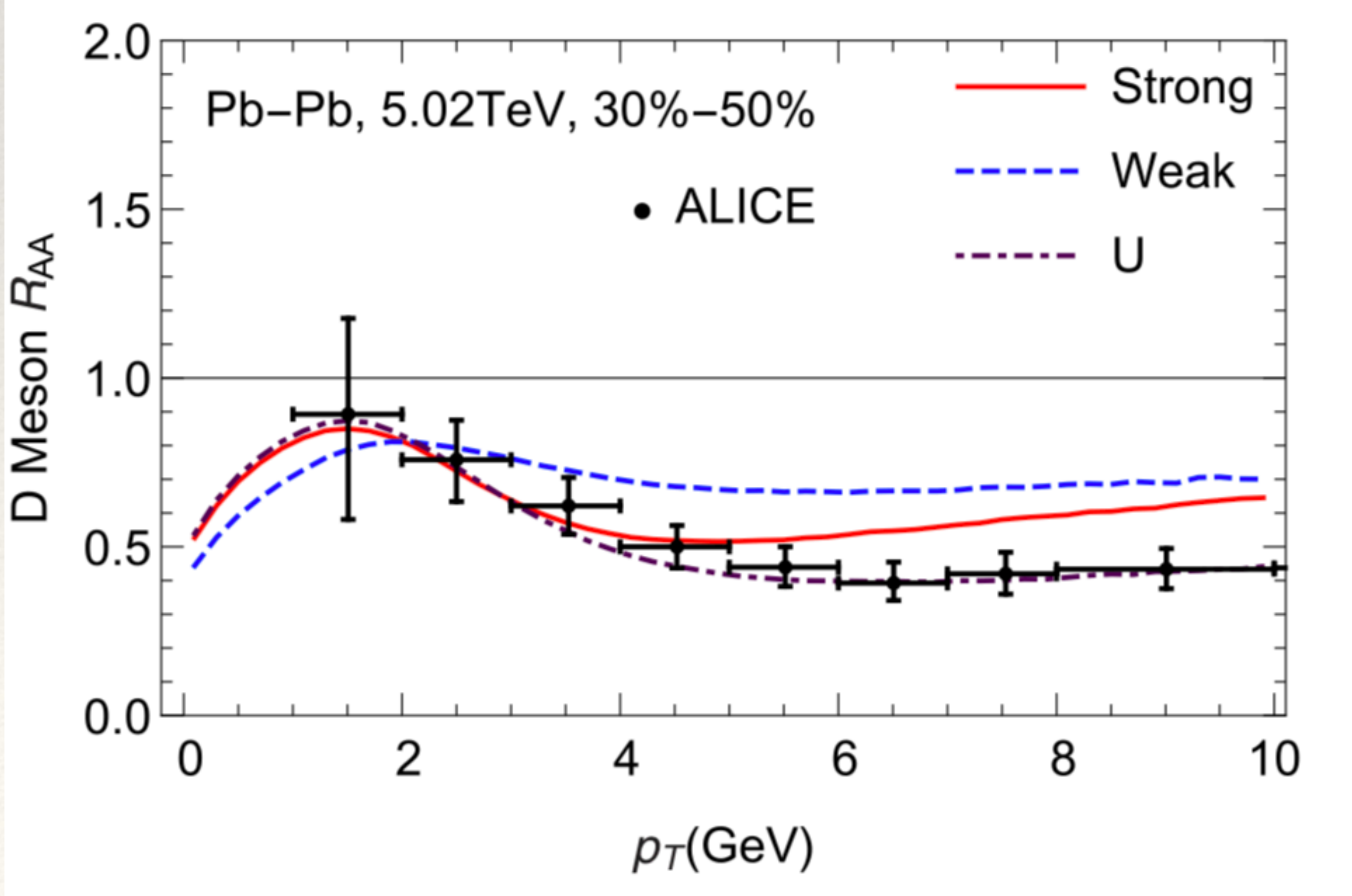
Quarkonium [Du, Liu and Rapp, Phys. Lett. B796 (2019)]

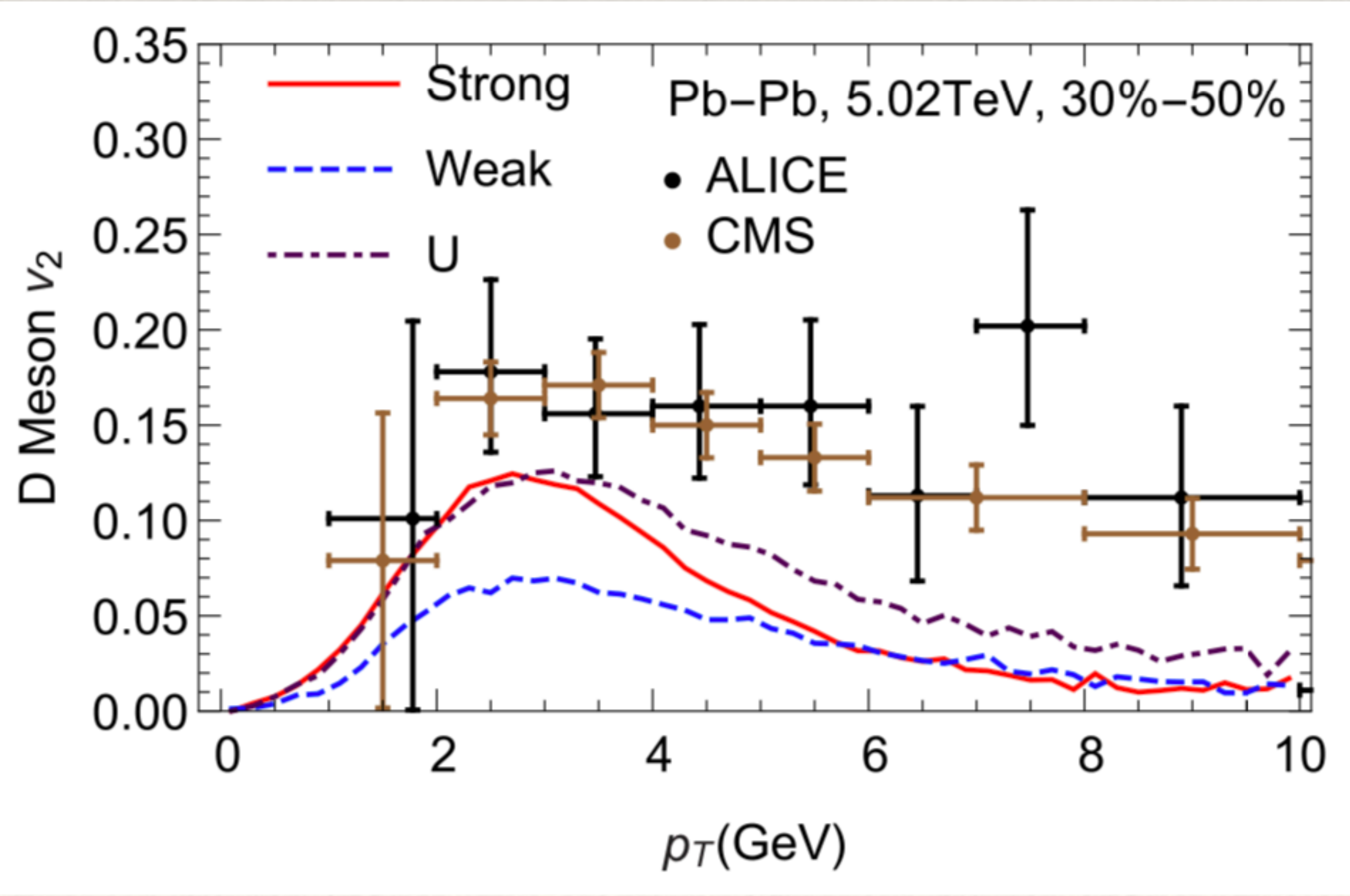




- Weak and strong solutions from T-matrix describe data equally well (depending on the model parameter K)
- Not conclusive

Open heavy meson [Liu, He and Rapp, PRC 97 (2018)]





- D meson R_{AA} and v_2 prefer the strong V solution from the T-matrix calculation
- Necessary to use open and hidden heavy flavor together to constrain the color potential

Multi-scale approaches for HQ energy loss

A complete description of HQ evolution requires multi-scale approaches.

Example 1: DGLAP + transport evolution [Cao, Majumder, Qin and Shen, PLB 793 (2019)]

Scale 1 ($Q \gg M_{\rm HM}$): HQ fragmentation function (FF) is treated with the DGLAP equation

- Input 1: medium-modified splitting function (higher-twist)

$$P(y, Q^2) = P_{\rm vac}(y) + P_{\rm med}(y, Q^2)$$

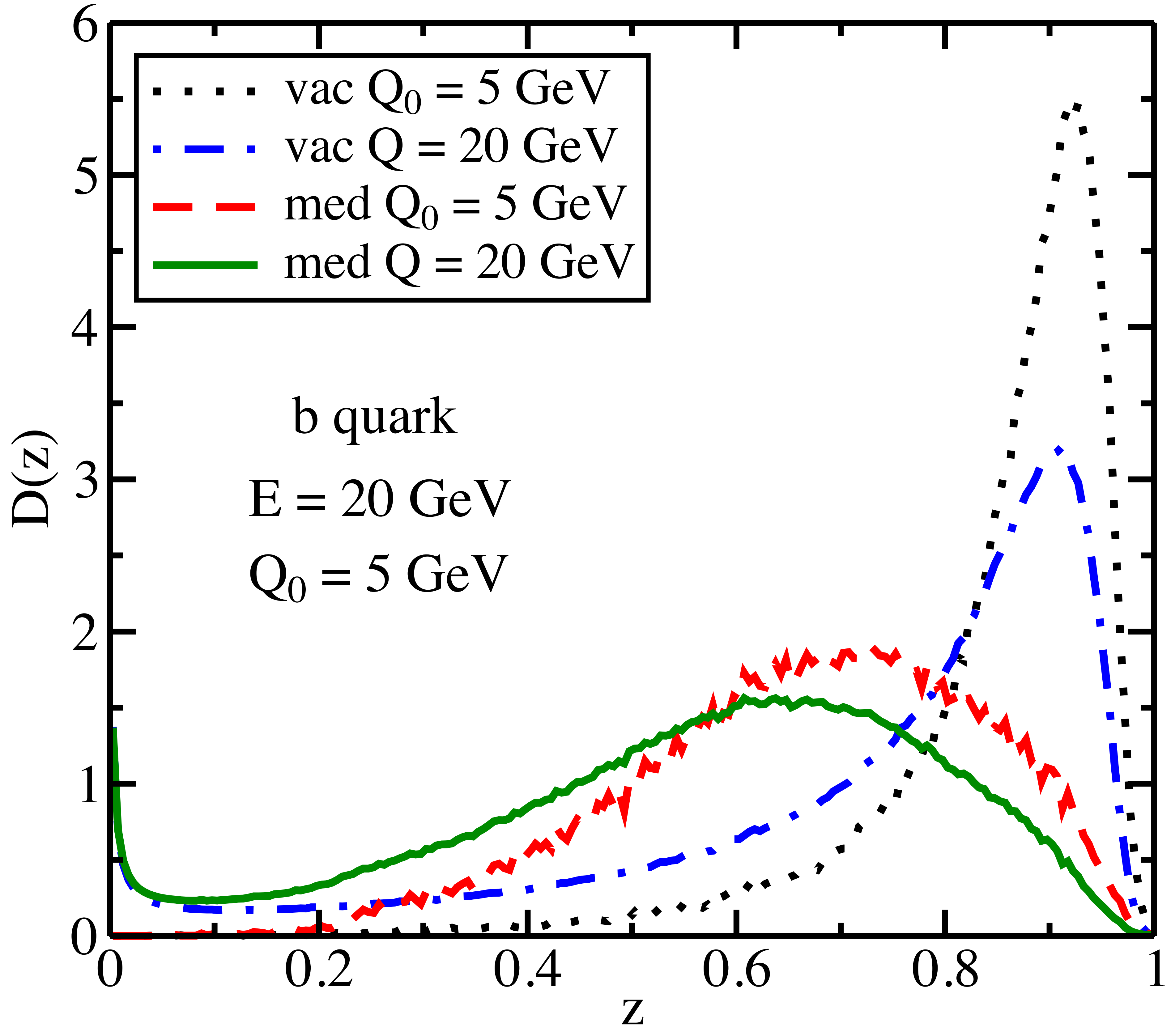
- Input 2: FF at a low scale $D(z, E, Q_0^2)$

Extracted from transport model (in scale 2) — medium modified FF at $Q_0 \sim M_{\rm HM}$

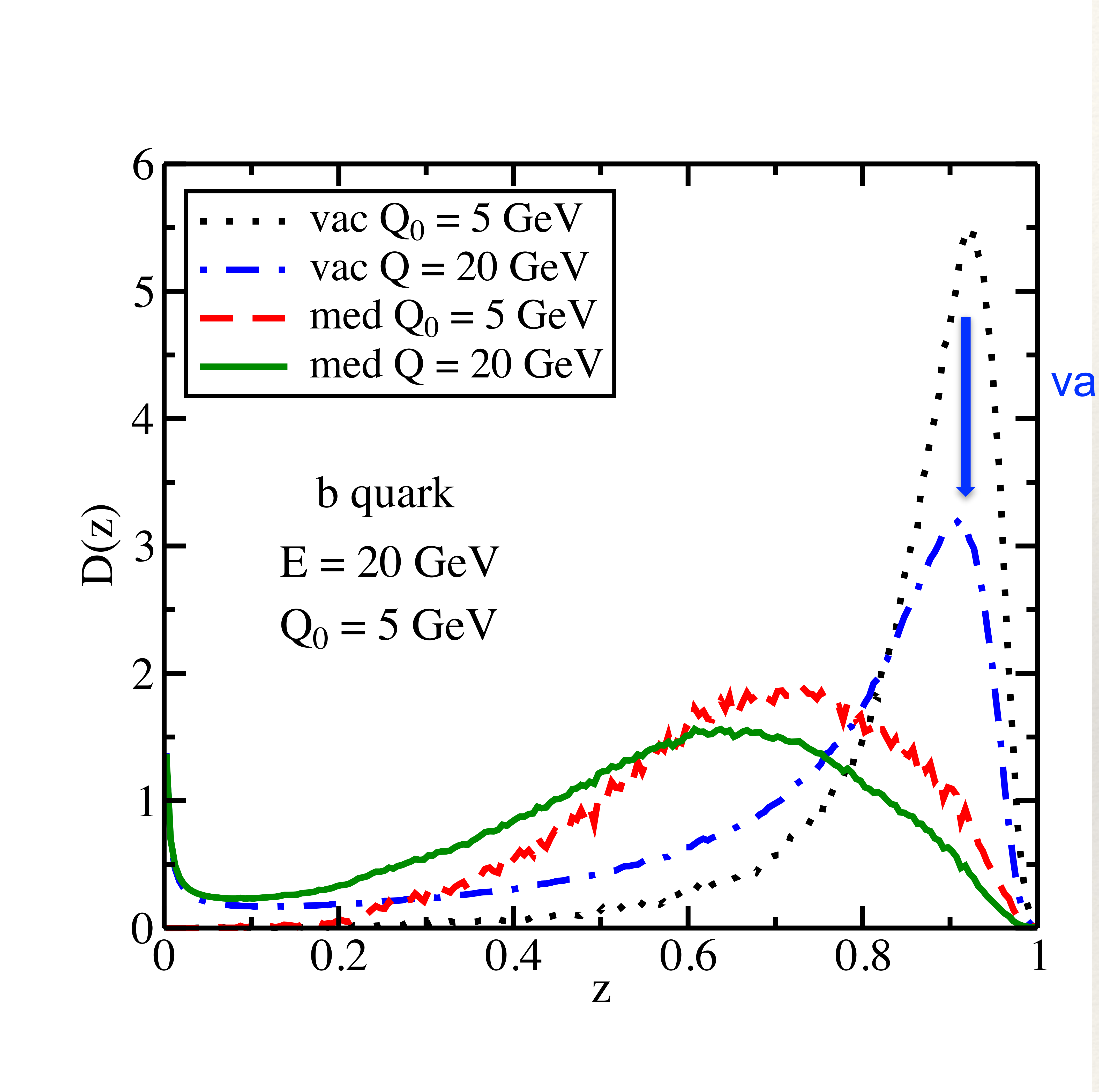
Scale 2 ($Q \sim M_{\rm HM}$): Transport model with the rate equation (elastic + inelastic)

$$\Gamma^{\rm inel}(t) = \int dy \int dl_\perp^2 \frac{dN}{dy dl_\perp^2 dt}$$ (page 6)

Multi-scale evolution of the *b*-quark fragmentation function



Multi-scale evolution of the *b*-quark fragmentation function



vac DGLAP

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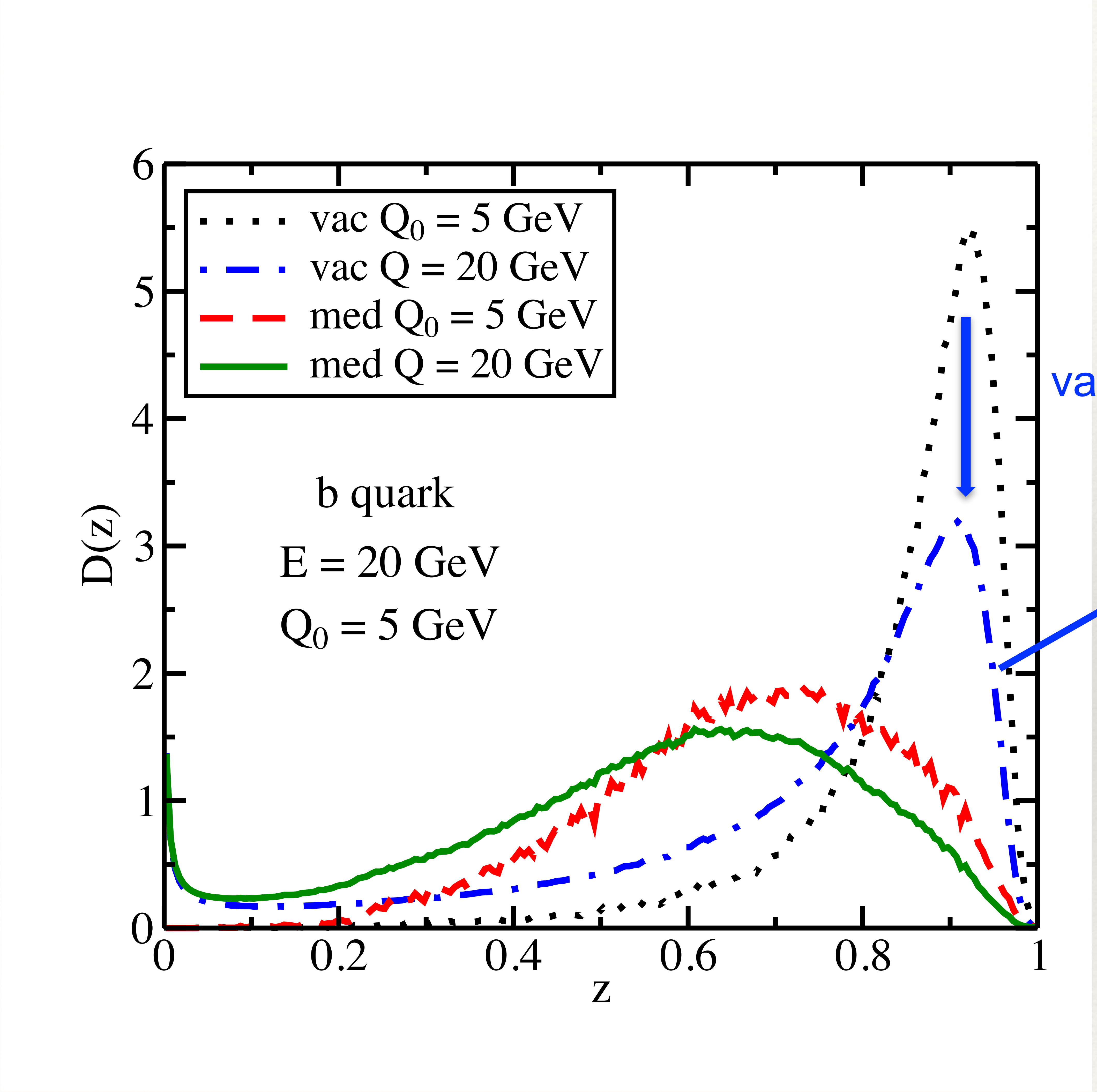
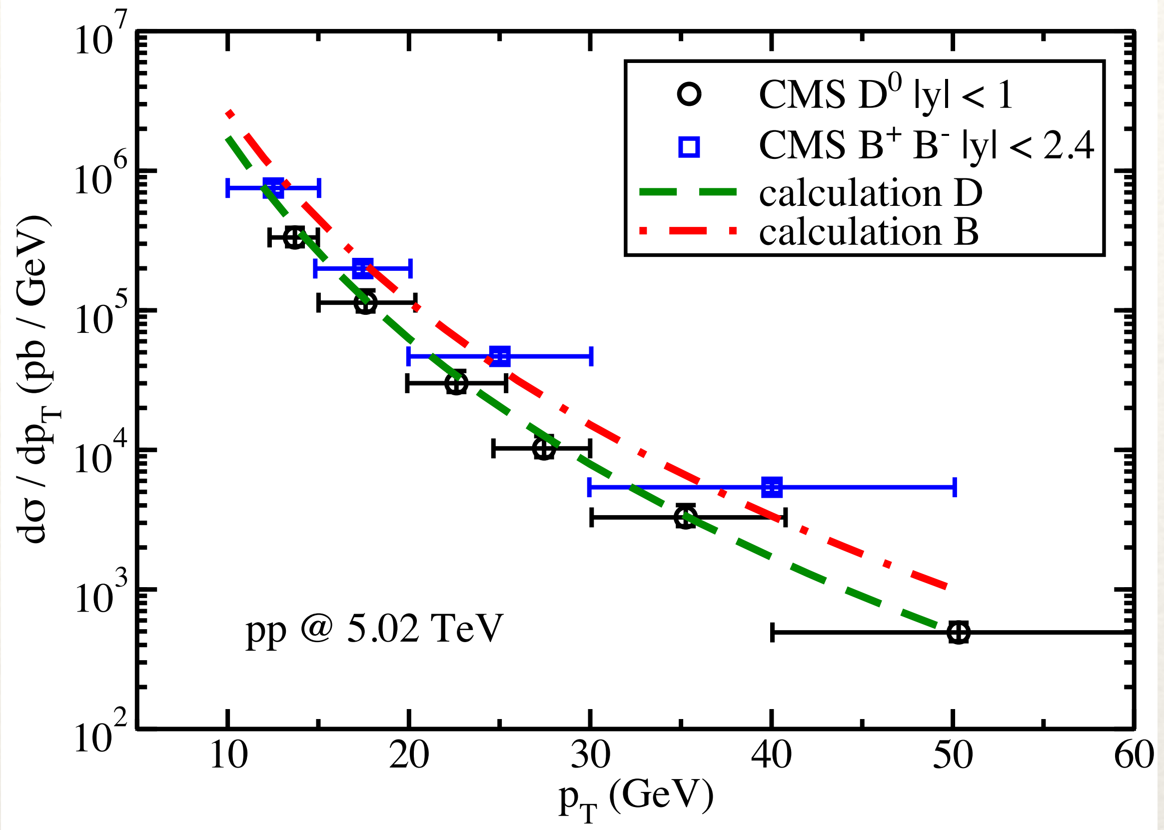


vac DGLAP

spectra in p-p



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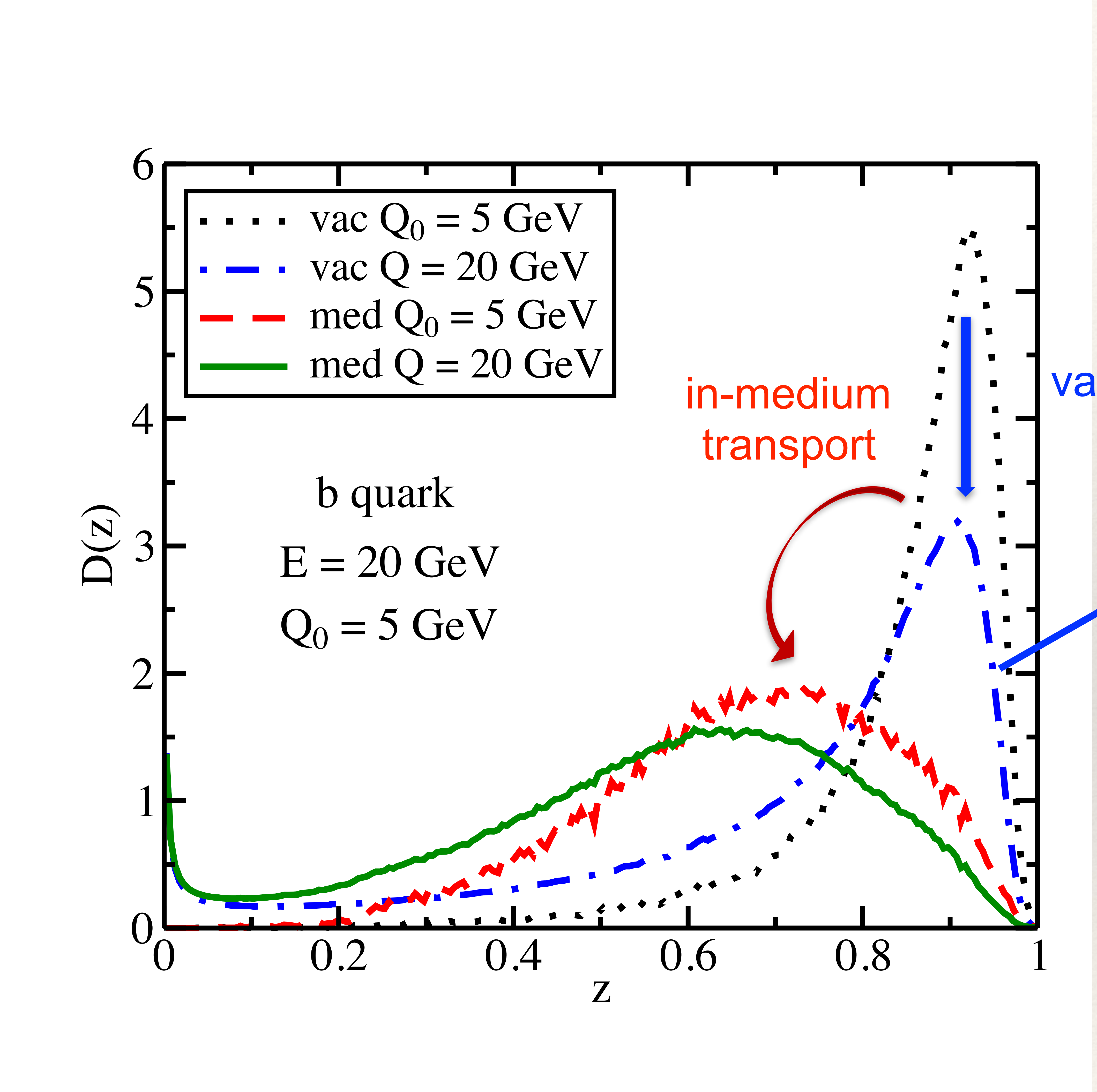
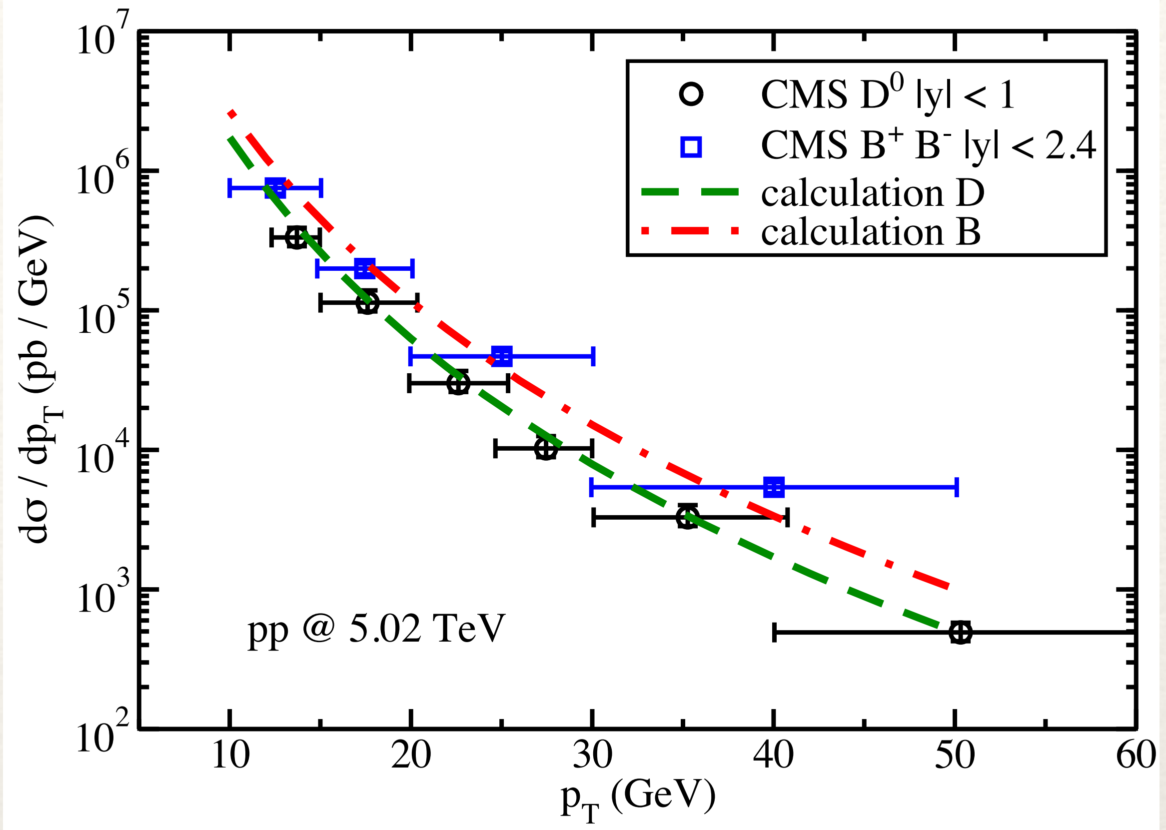


in-medium transport

vac DGLAP

spectra in p-p



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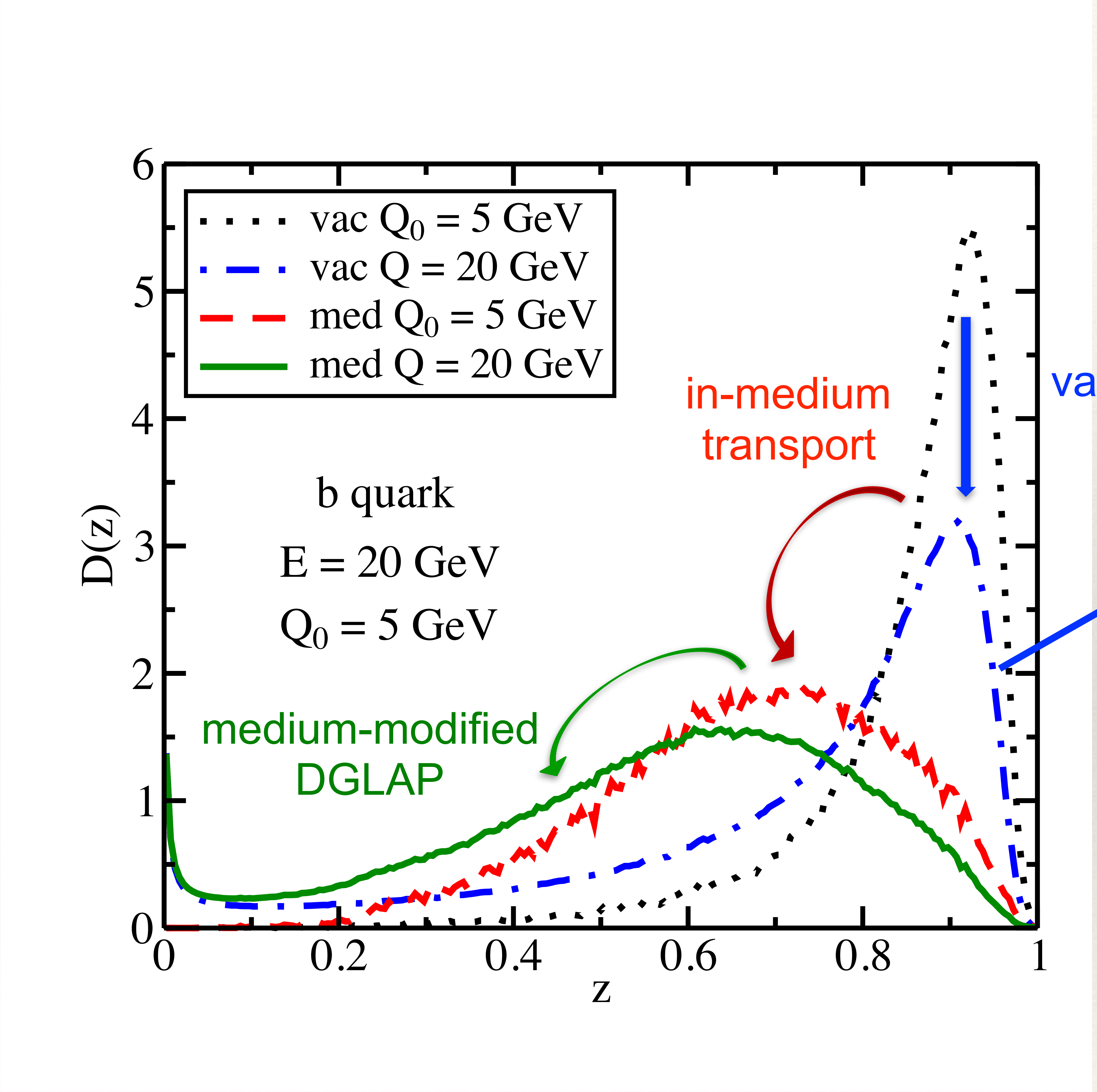
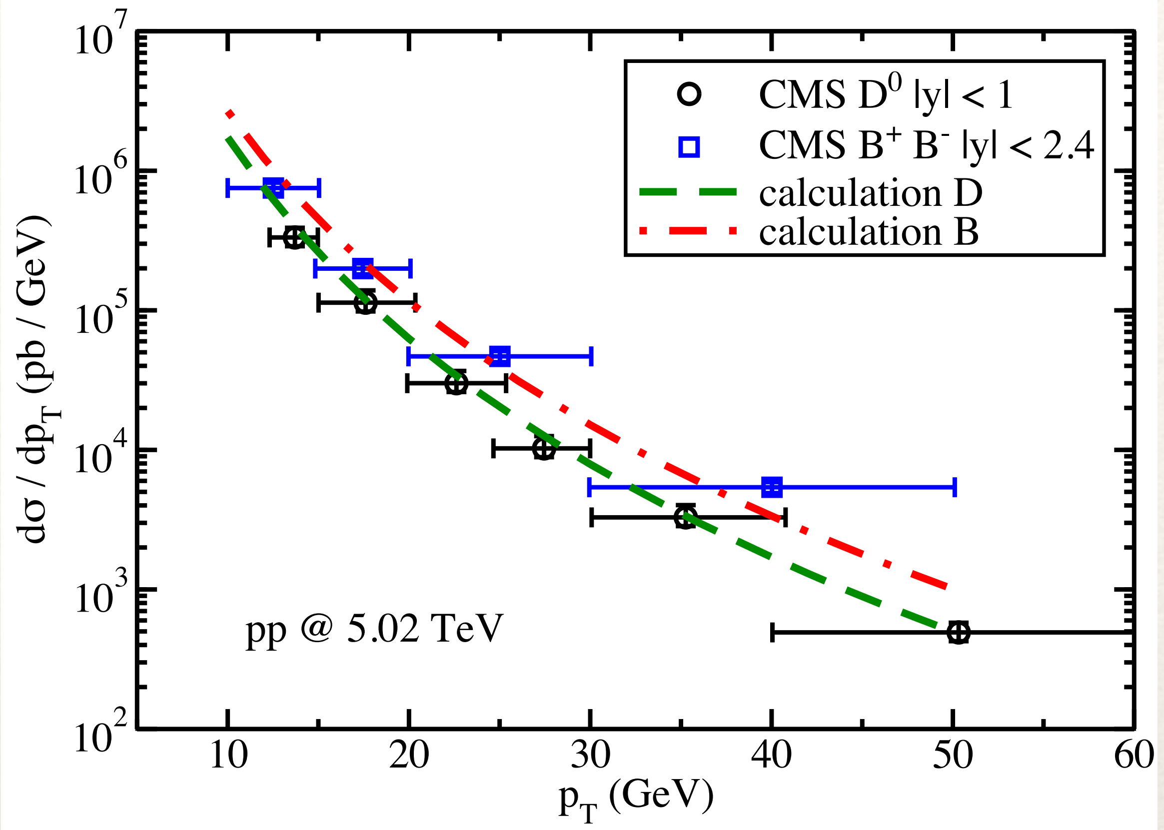


in-medium transport

medium-modified DGLAP

vac DGLAP

spectra in p-p



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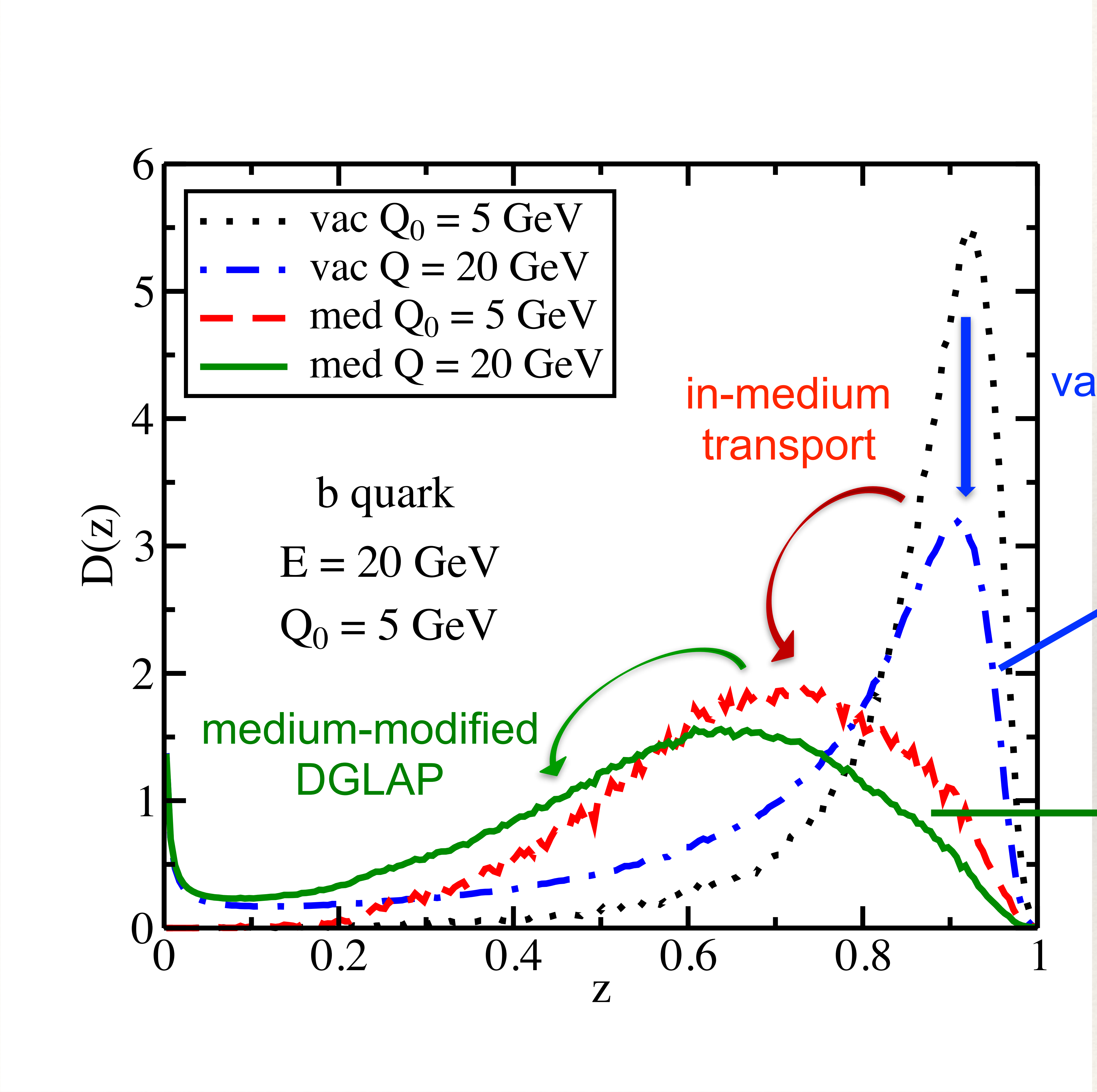

in-medium transport

vac DGLAP

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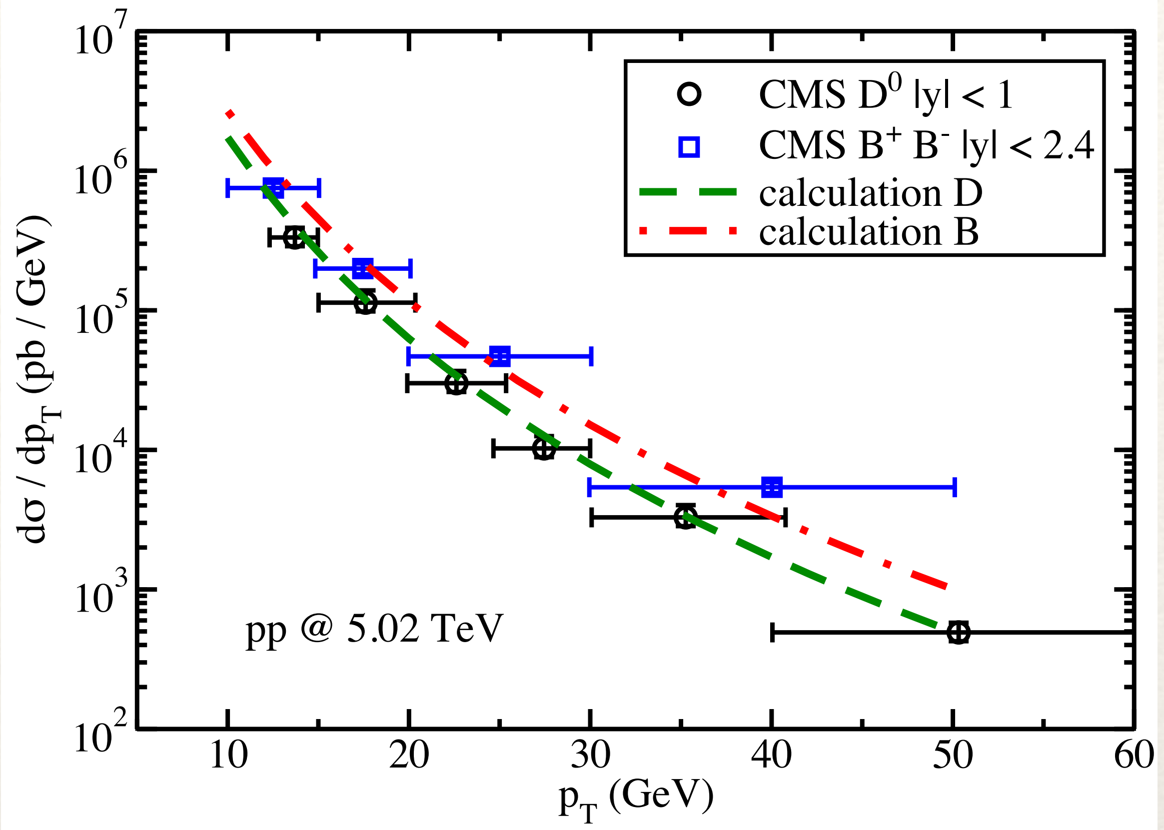
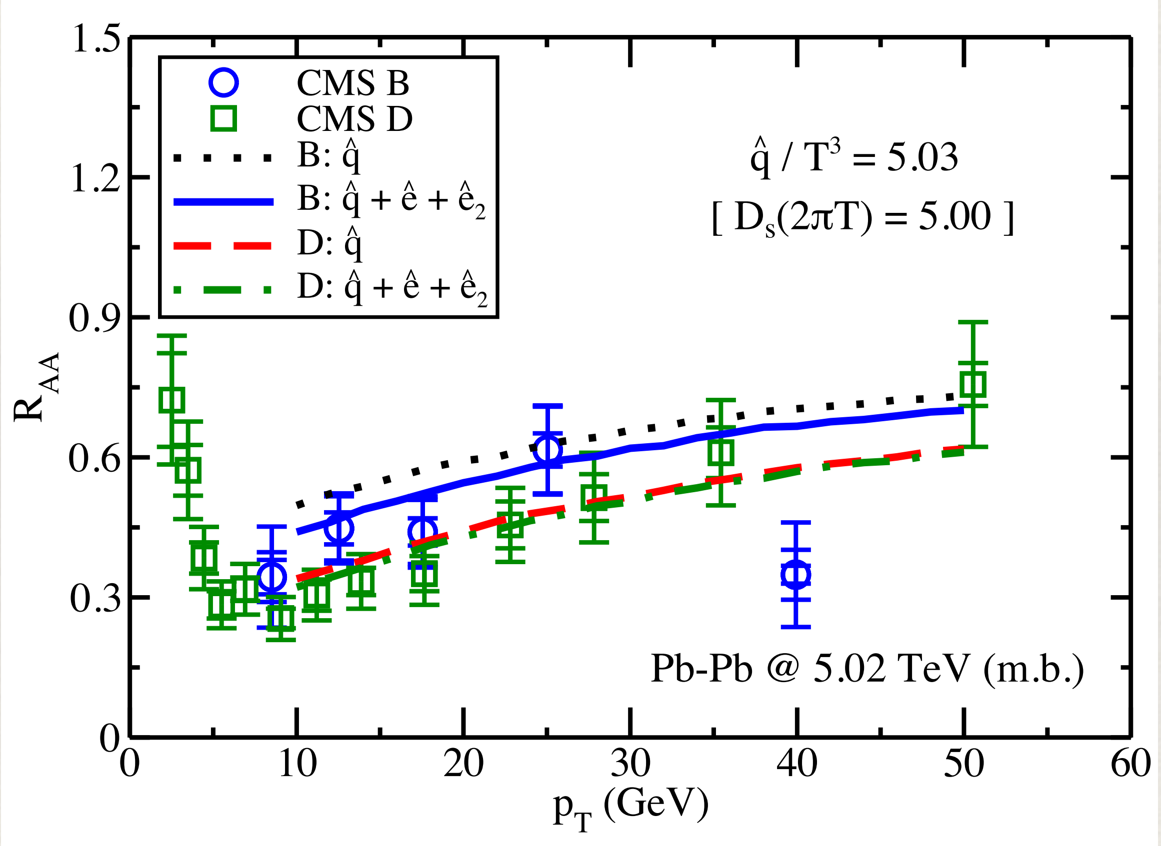
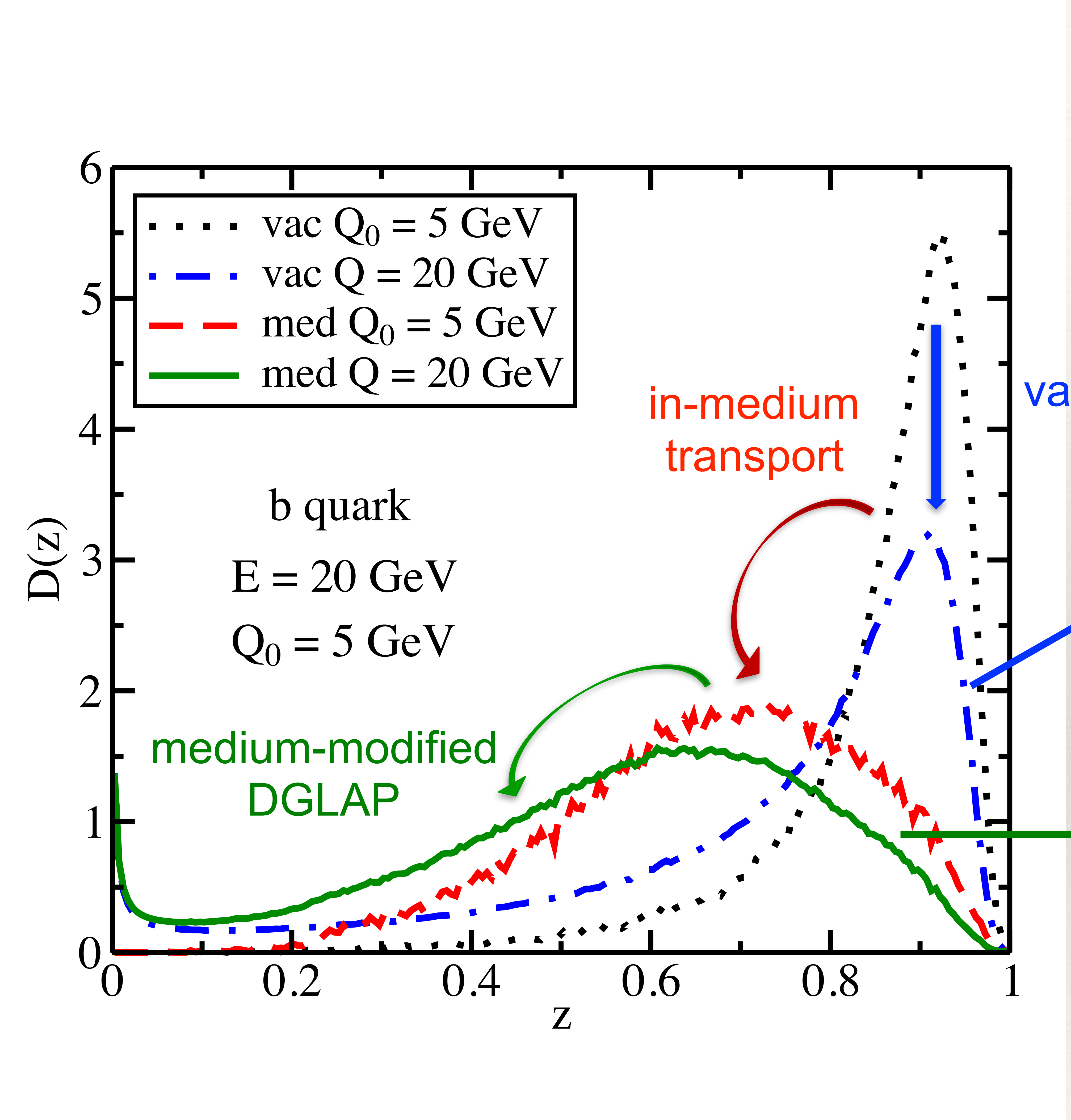
spectra in p-p



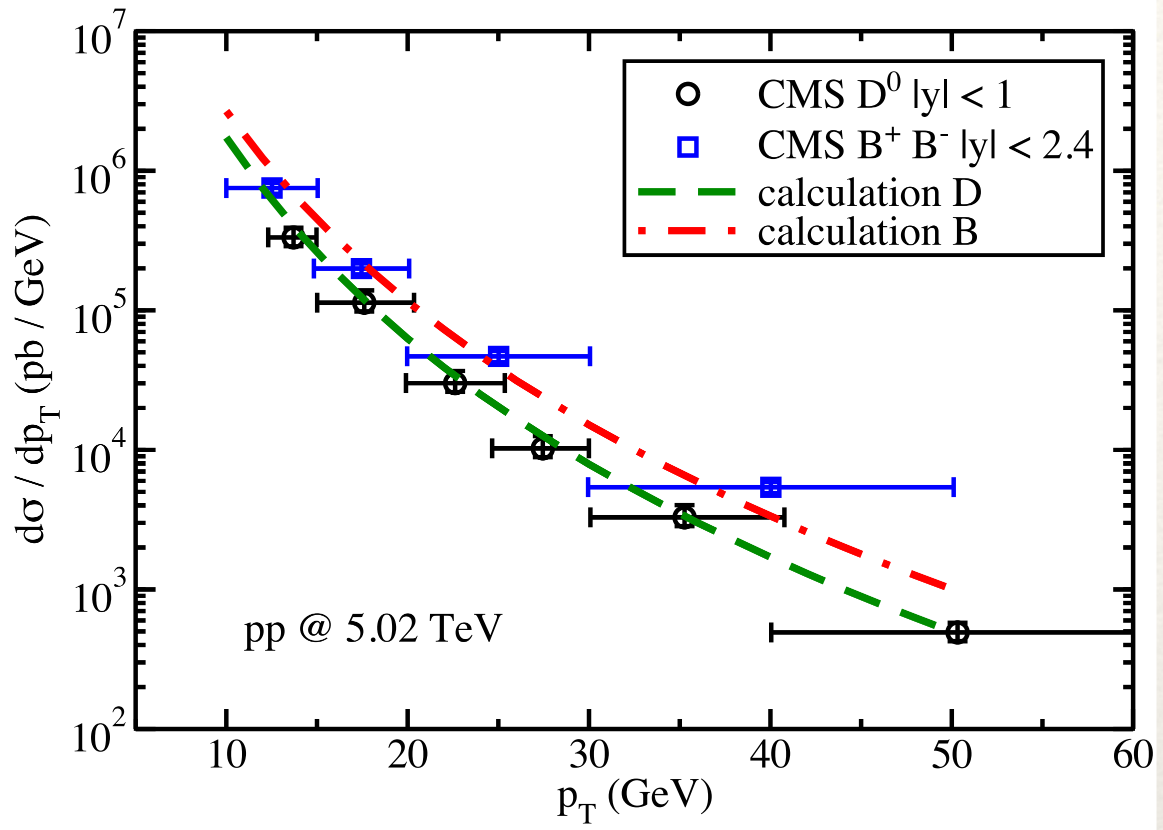
spectra in A-A, thus R_{AA}



Multi-scale evolution of the *b*-quark fragmentation function



spectra in p-p



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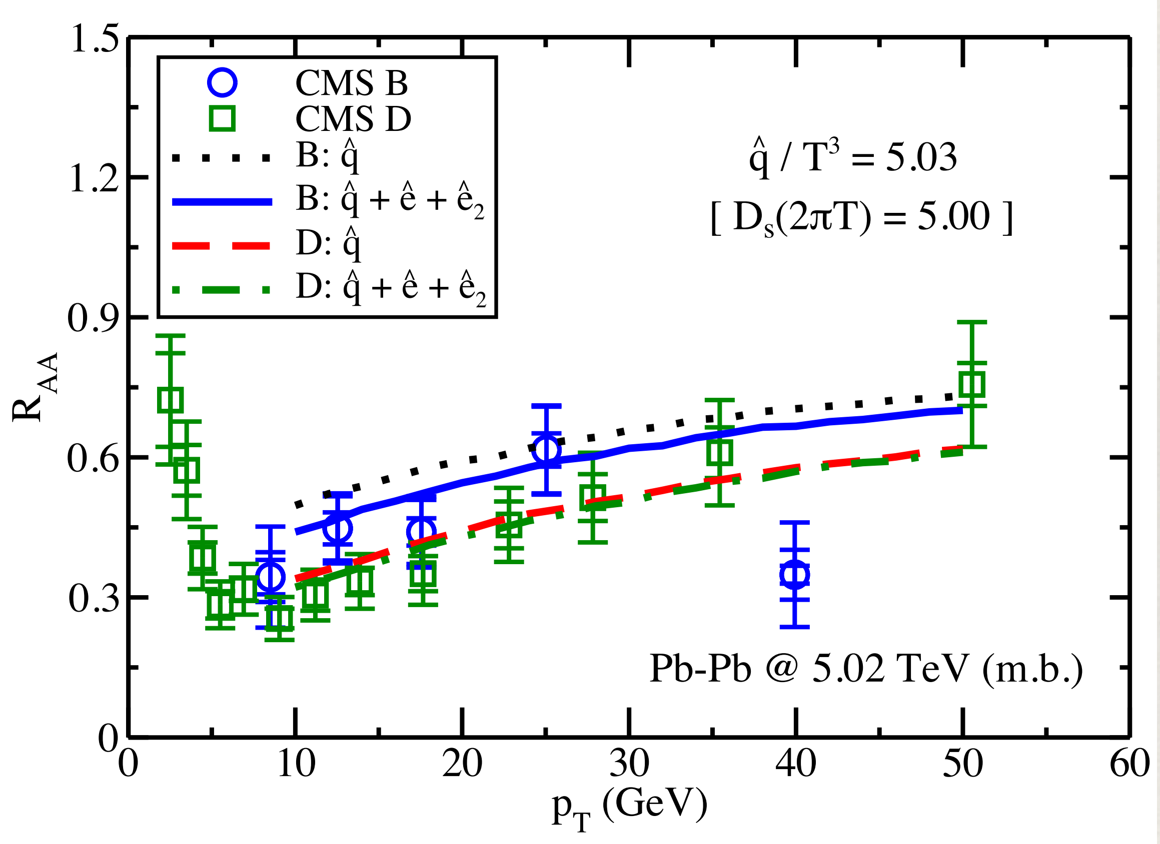


Semi-analytical calculation [Cao et. al., PLB 793 (2019)]

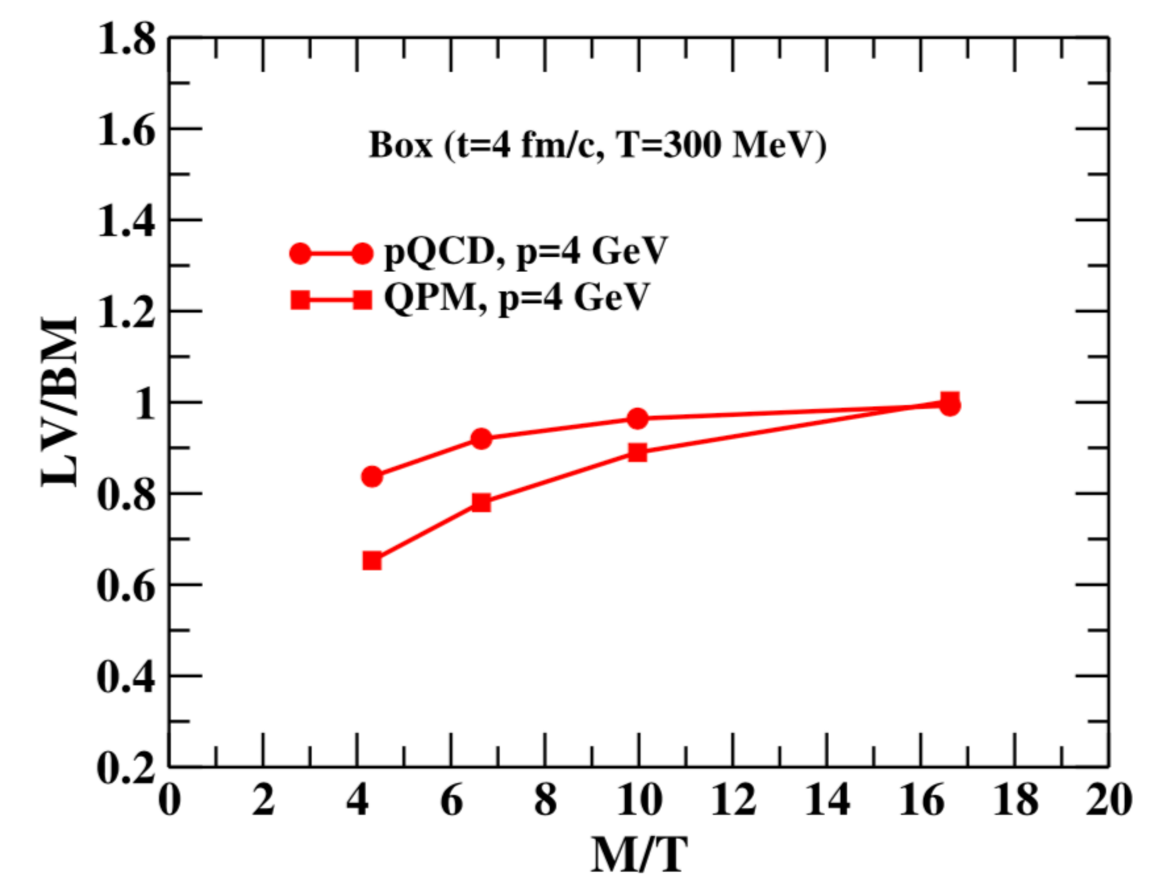
→ full Monte-Carlo simulation — JETSCAPE

❖ Vujanovic's talk (Tue.)

Multi-scale approaches for HQ energy loss

Example 2: Boltzmann (BM) + Langevin (LV) transport

- BM: scattering between **quasi-particles**
- BM + small momentum transfer (*k*) => LV
- LV deviates from BM when $k \ll p$ (or $M/T \gg 1$) is not satisfied
- LV can be extended to non-quasi-particle medium where BM does not apply



[EMMI, NPA 979 (2018)]

Neither BM nor LV alone is sufficient for HQ interaction with QGP!

Multi-scale approaches for HQ energy loss

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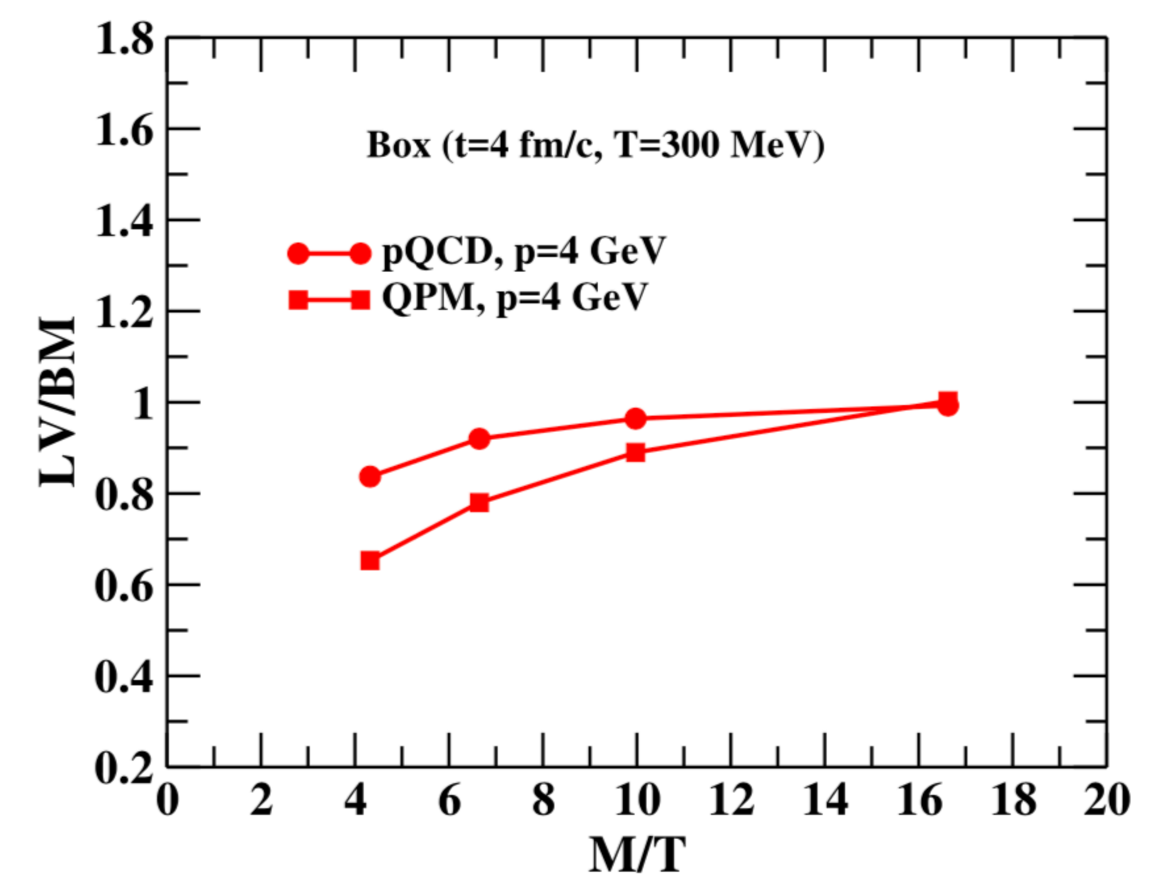
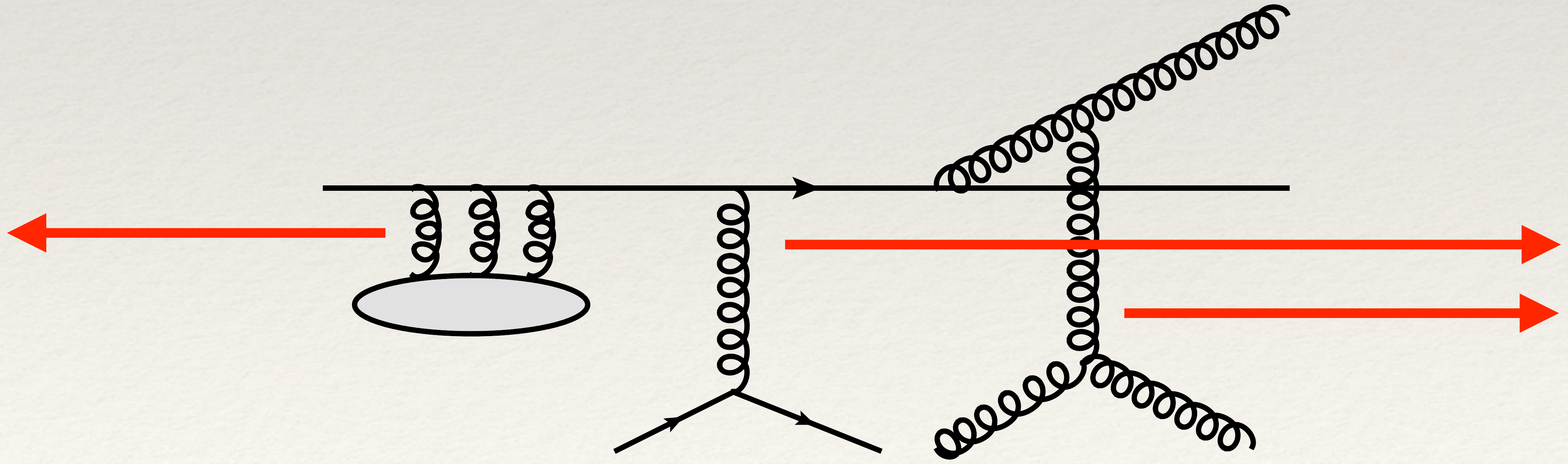


[EMMI, NPA 979 (2018)]

Neither BM nor LV alone is sufficient for HQ interaction with QGP!

Lido (Linearized Boltzmann with diffusion model) (Duke) [Ke, Xu and Bass, PRC 98 (2018)]

❖ Ke's talk (Tue.)



small k ($<k_0$)
HQ cannot "see" quasi-particles
Langevin

large k ($>k_0$)
HQ "sees" quasi-particles
Boltzmann

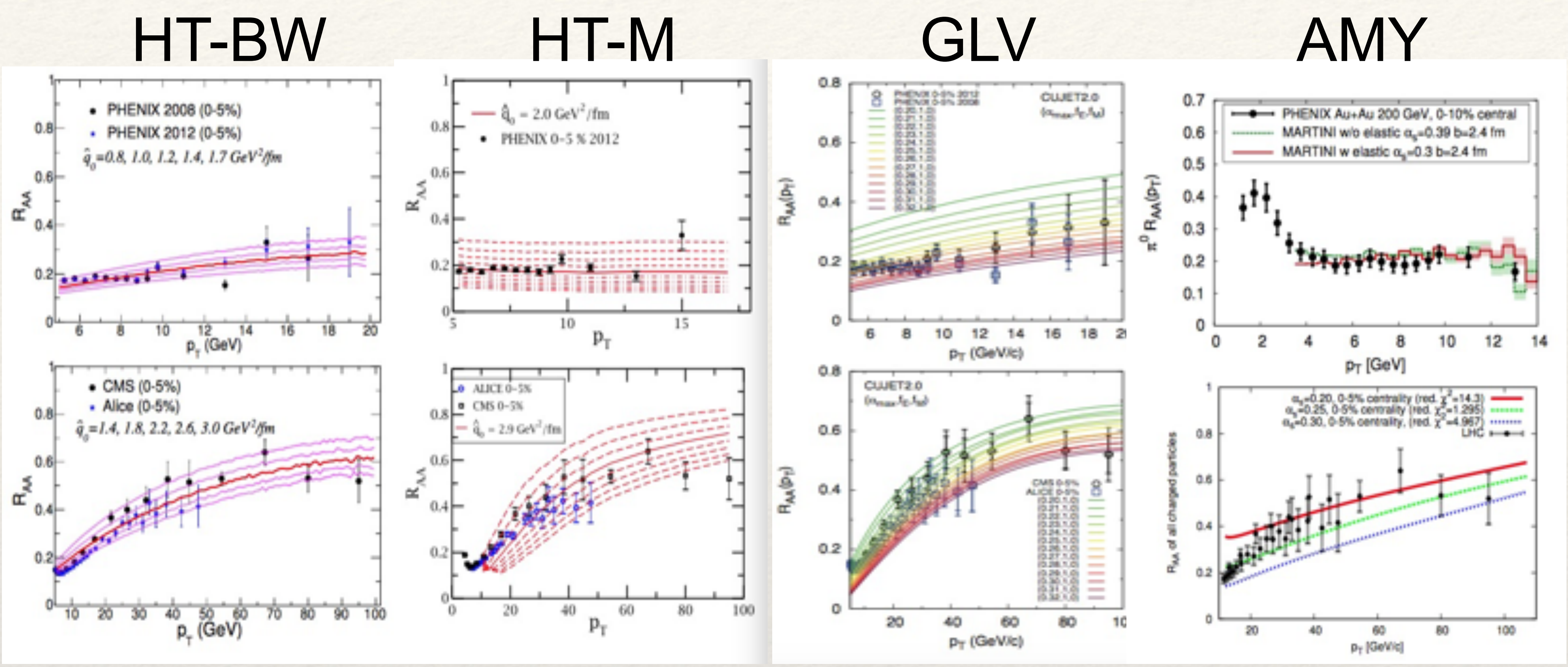
Future challenges and prospects

Constraining model uncertainties of heavy quarks

- **Uncertainties in energy loss theories**

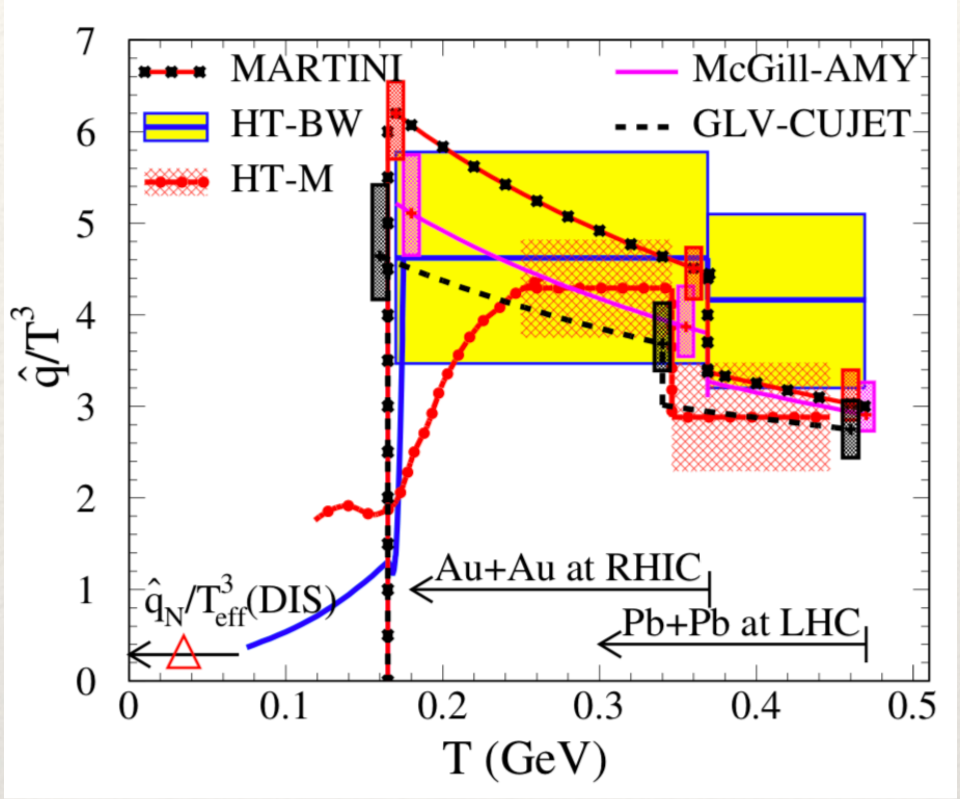
Example of high-energy jets

JET Collaboration
[PRC 90 (2014)]



uncertainty in the extracted $\hat{q}$

within a factor of 2



Future challenges and prospects

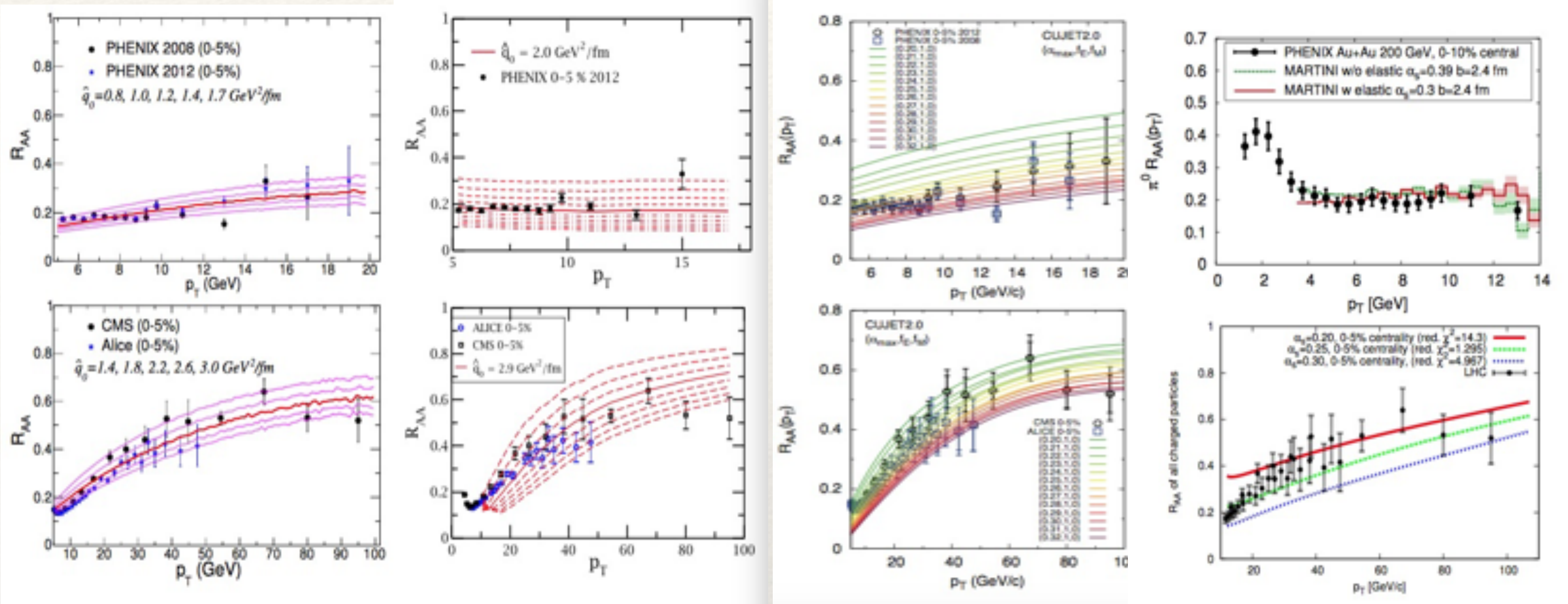
Constraining model uncertainties of heavy quarks

- **Uncertainties in energy loss theories**

Example of high-energy jets

JET Collaboration
[PRC 90 (2014)]

HT-BW HT-M GLV AMY



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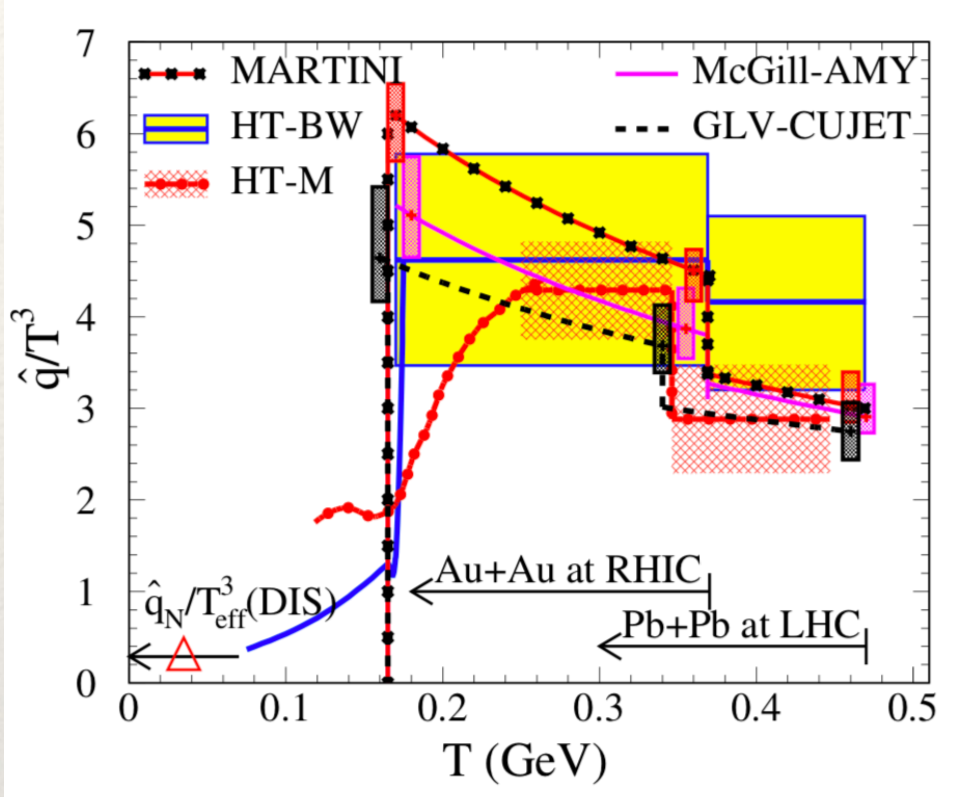
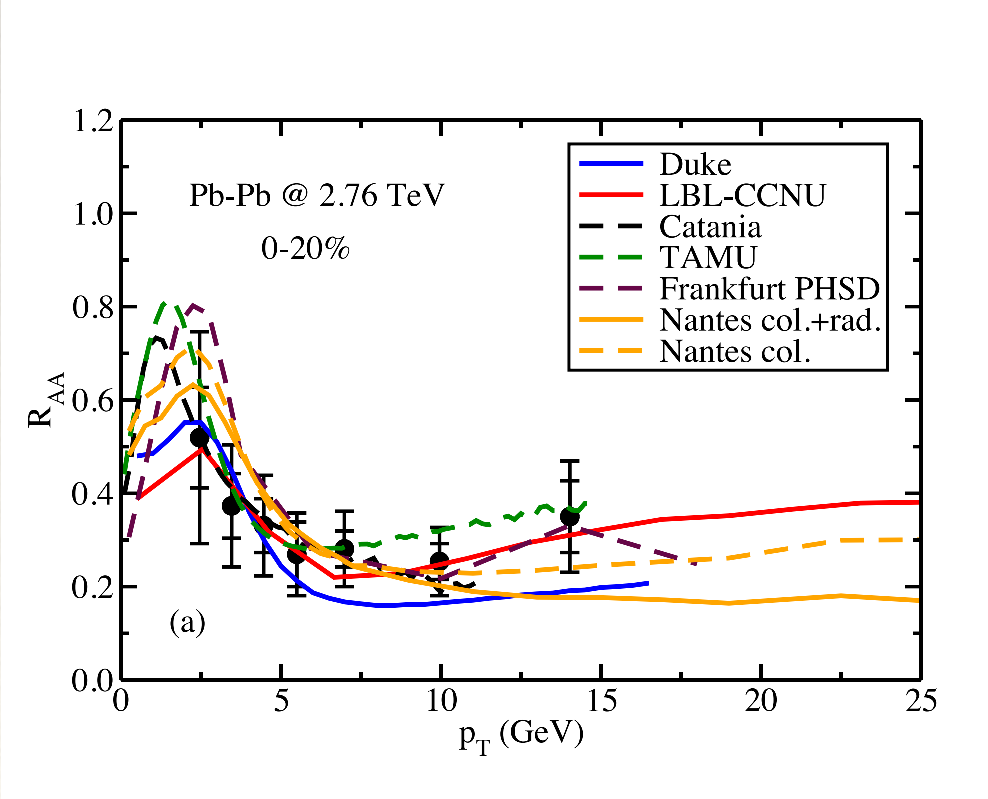
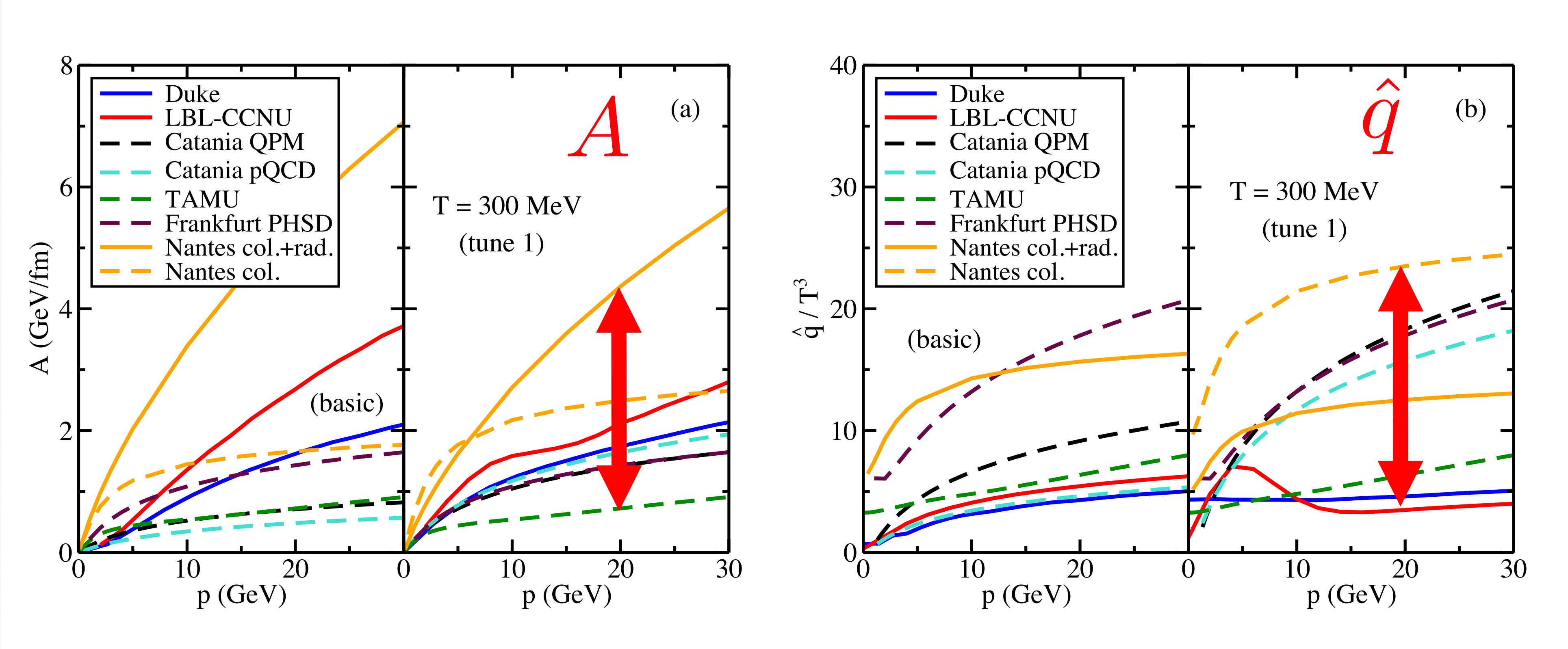


Heavy quarks



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

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



Future challenges and prospects

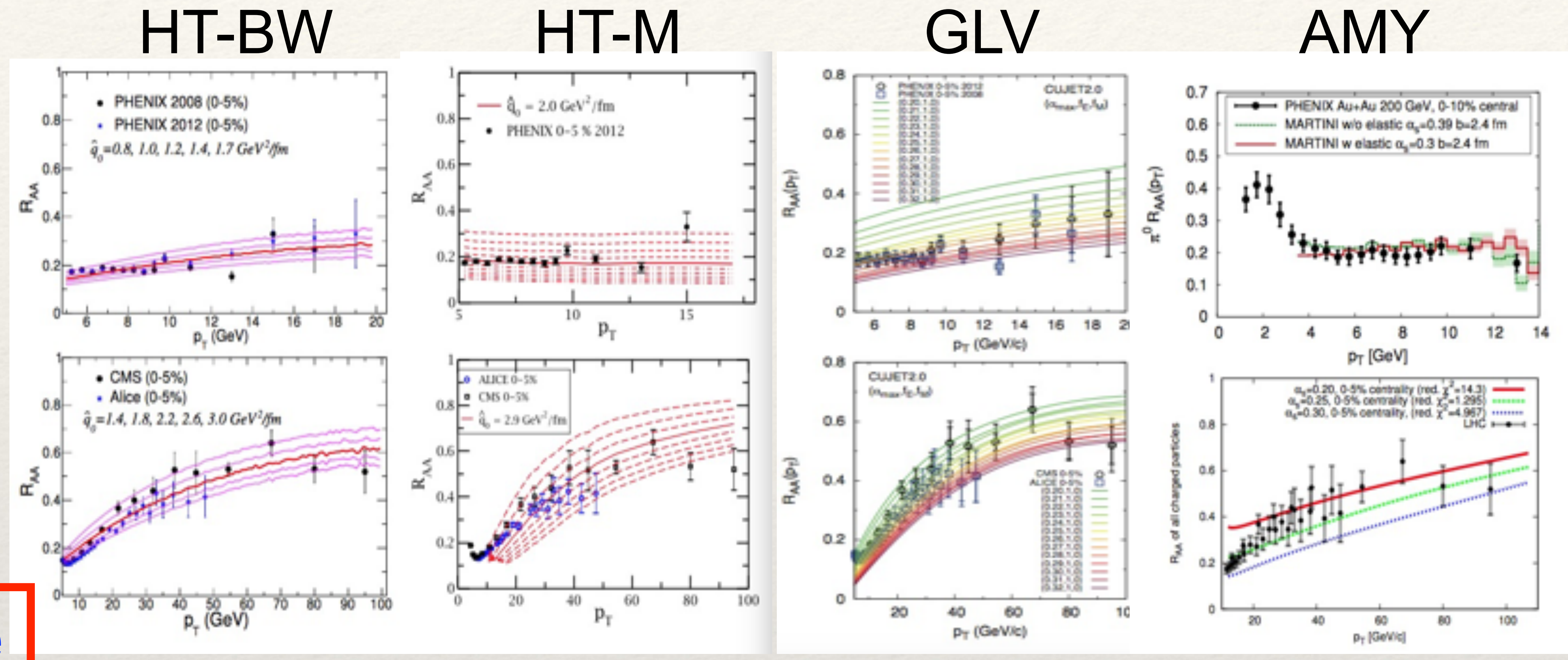
Constraining model uncertainties of heavy quarks

- **Uncertainties in energy loss theories**

Example of high-energy jets

JET Collaboration
[PRC 90 (2014)]

same hydro, simple hadronization



uncertainty in the extracted $\hat{q}$

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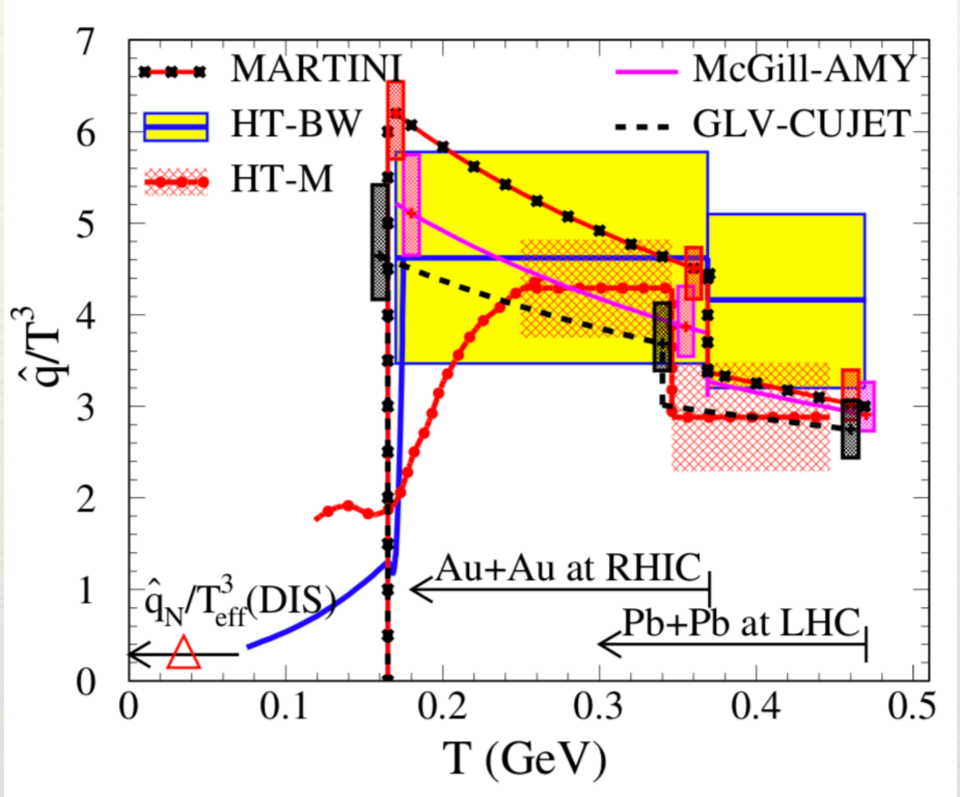
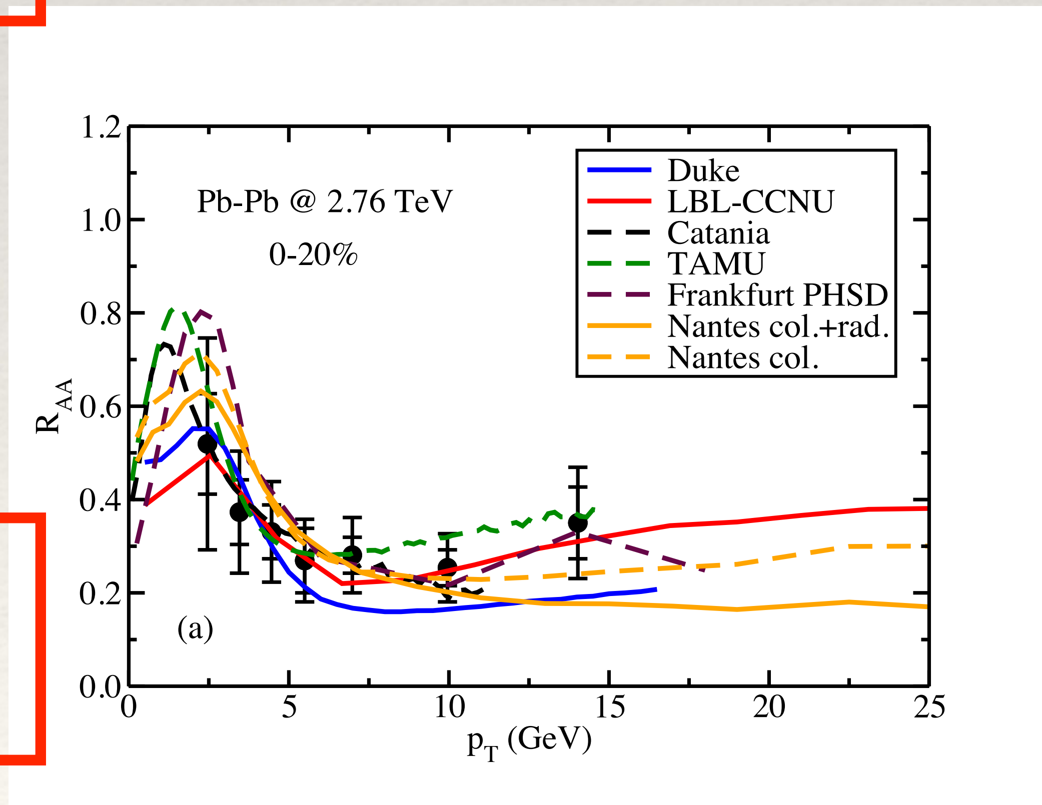


Heavy quarks

different media and hadronizations



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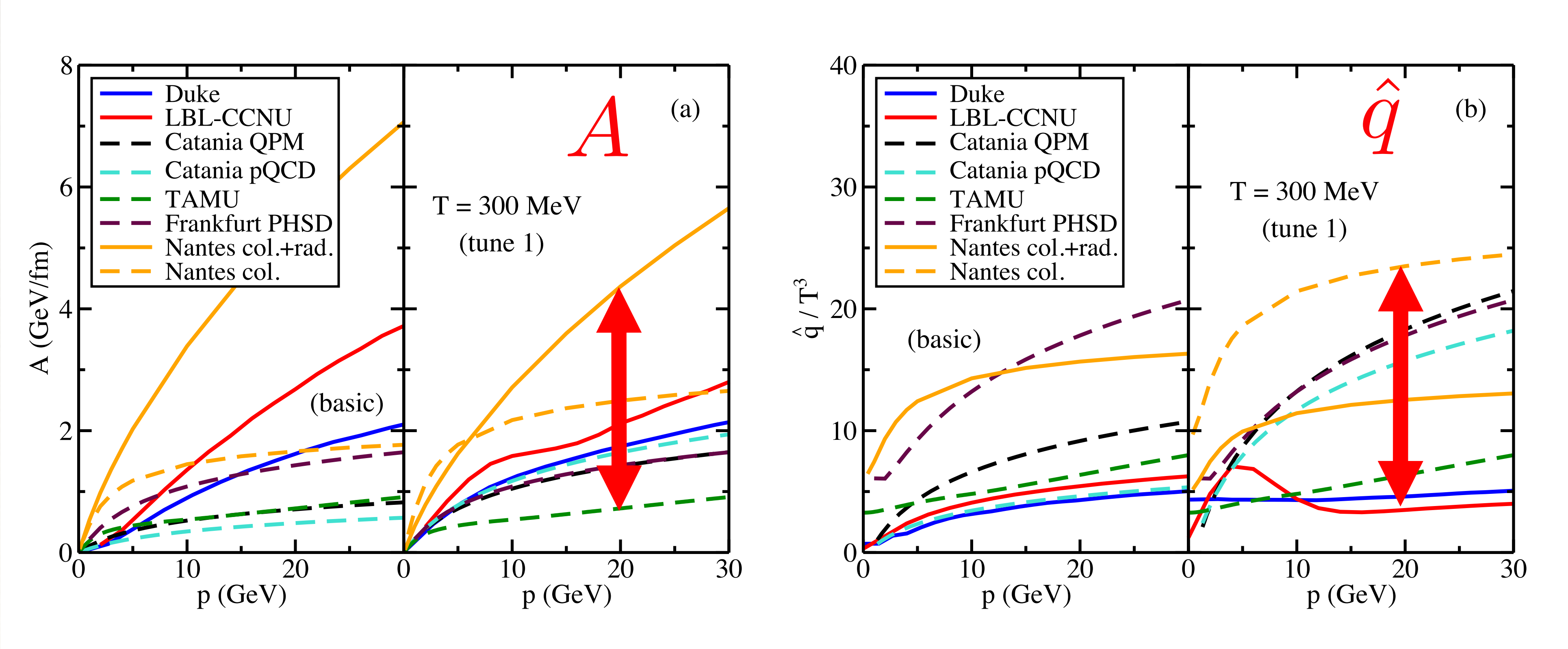
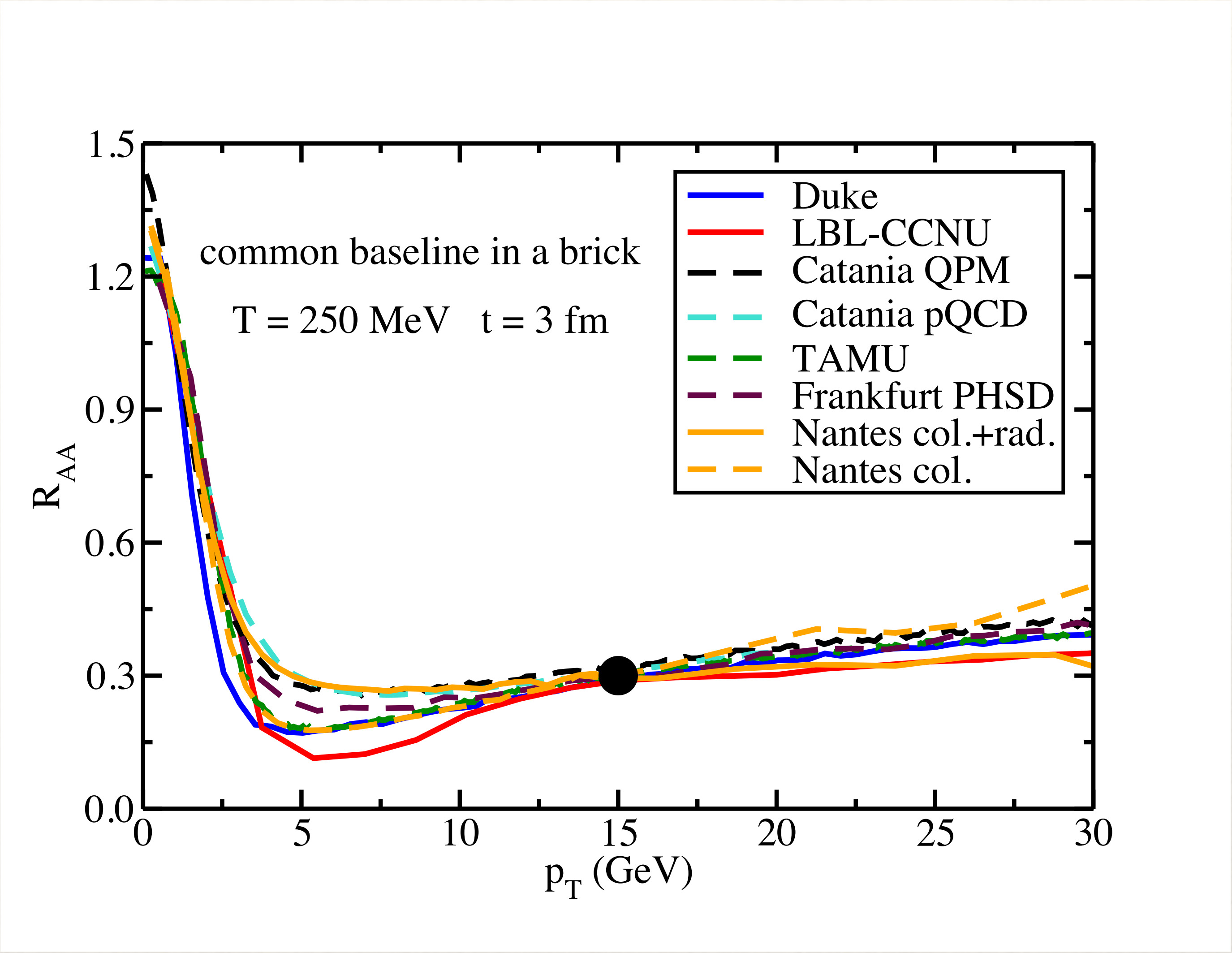


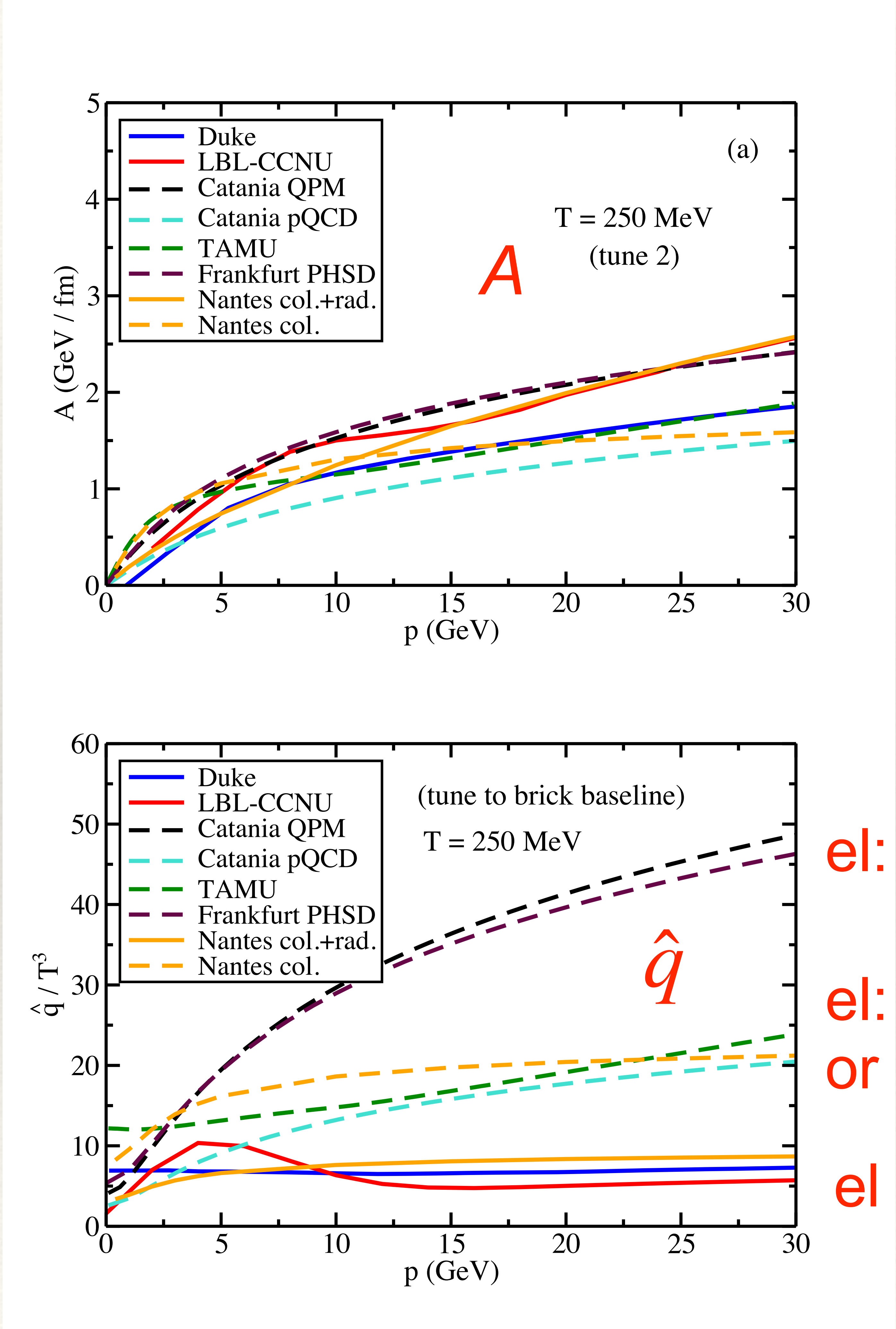
Uncertainties in heavy quark energy loss

[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

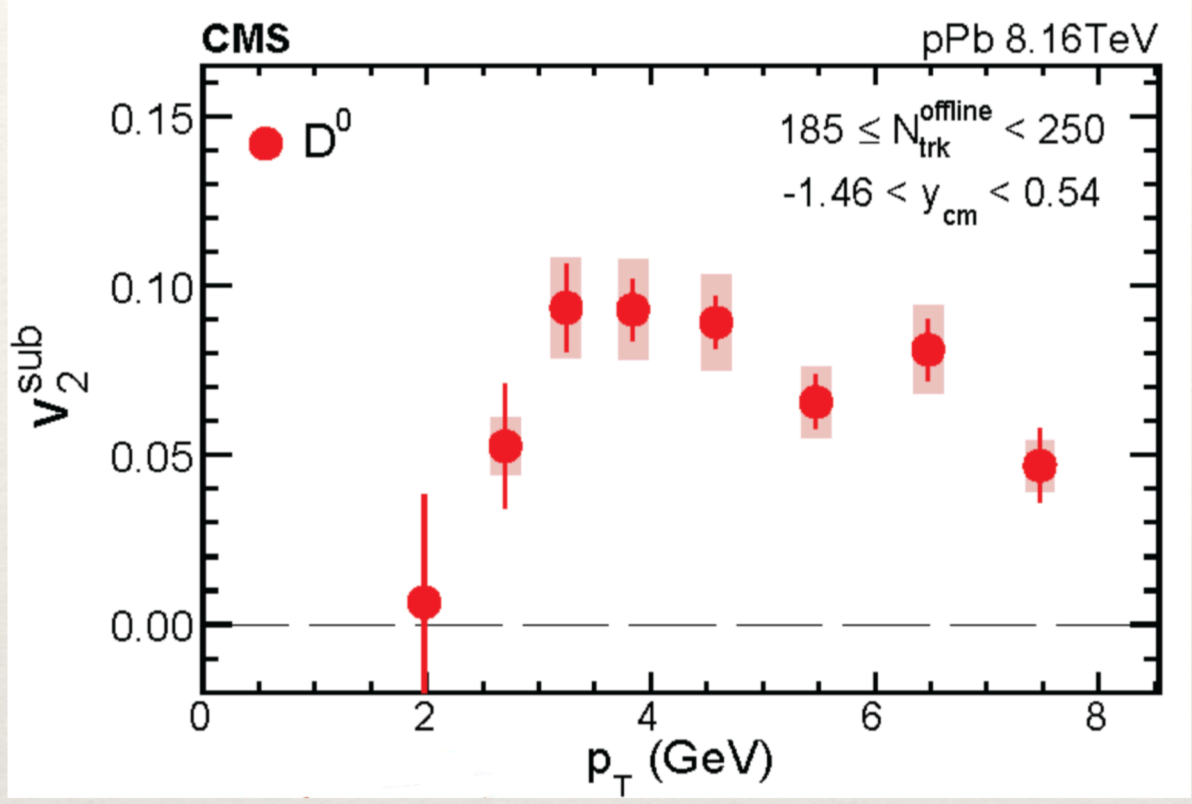
el: pQCD or T-matrix

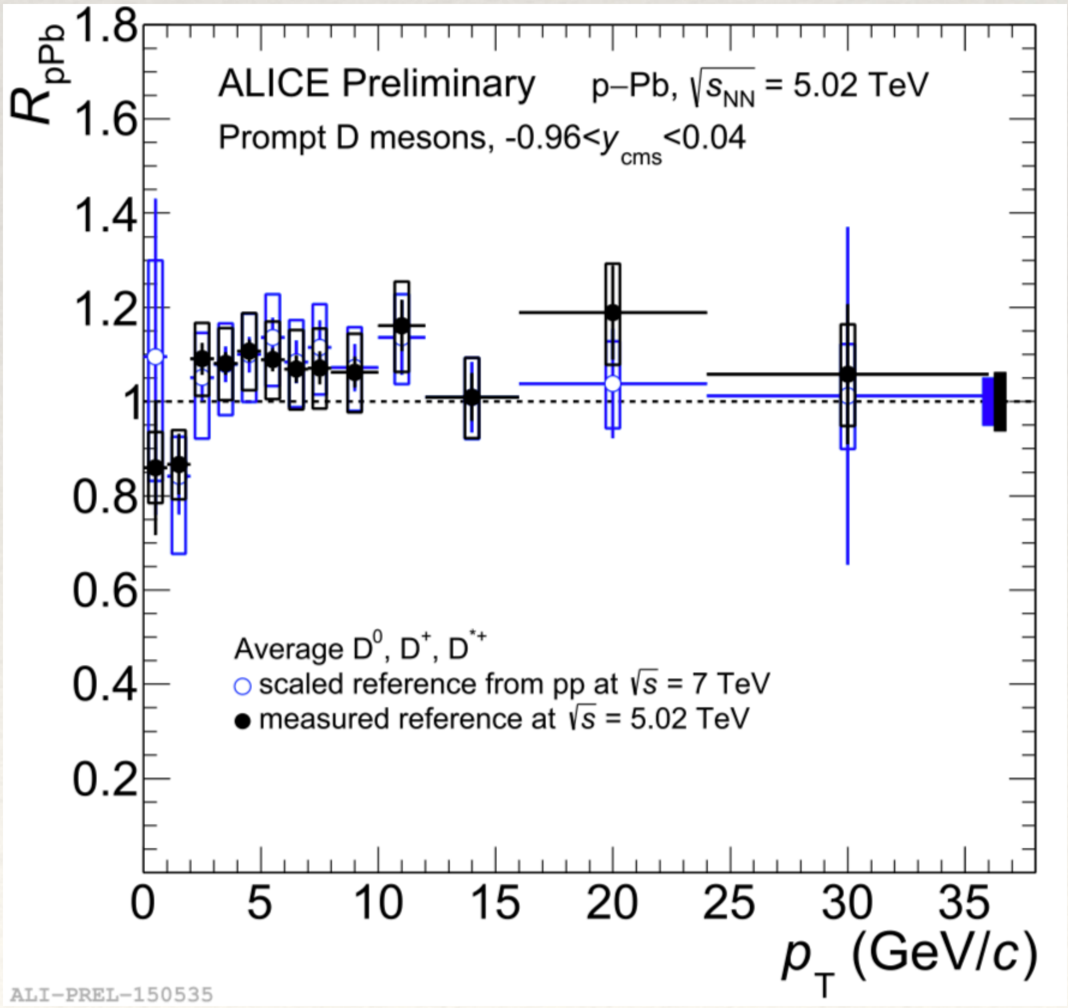
el + inel

- 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

Probing small systems and initial states

Small system (p-Pb) puzzle (1 year ago)





- Large *D* meson v_2 up to 8 GeV
- Almost no suppression
- Should not be QGP effects
- Could it be initial state effects?

Probing small systems and initial states

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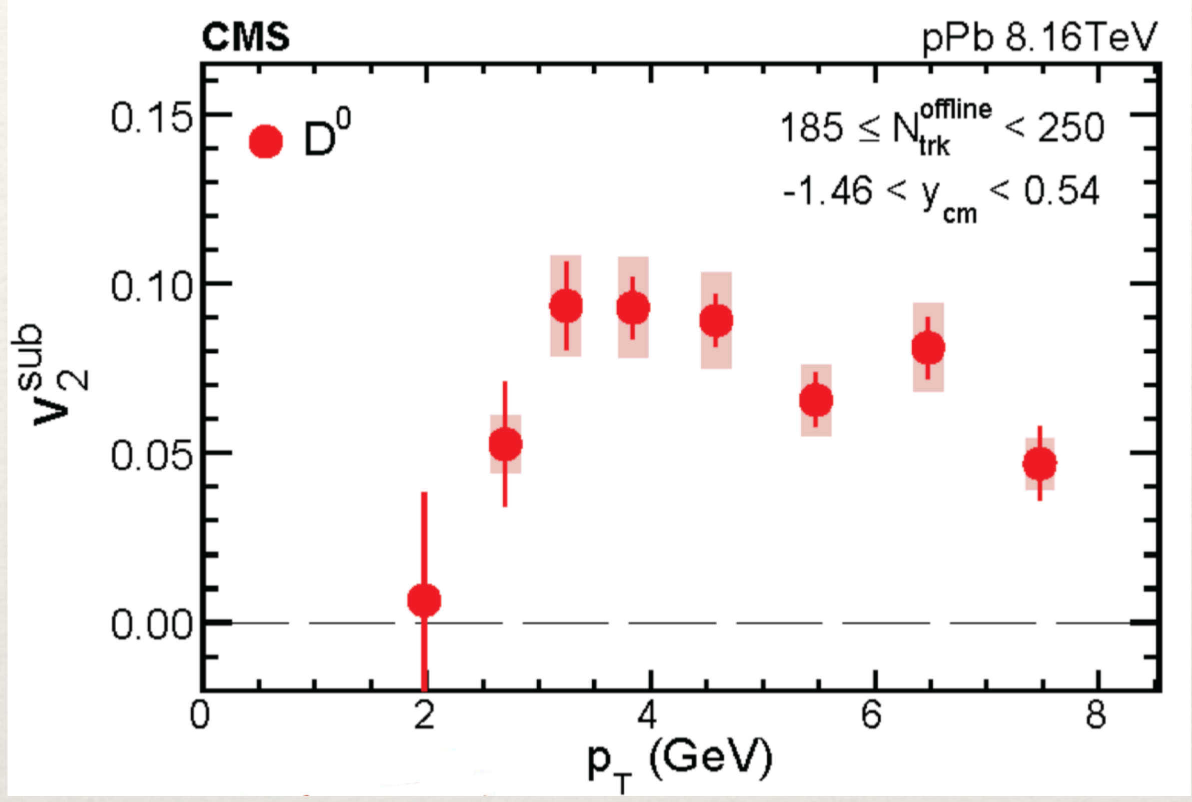

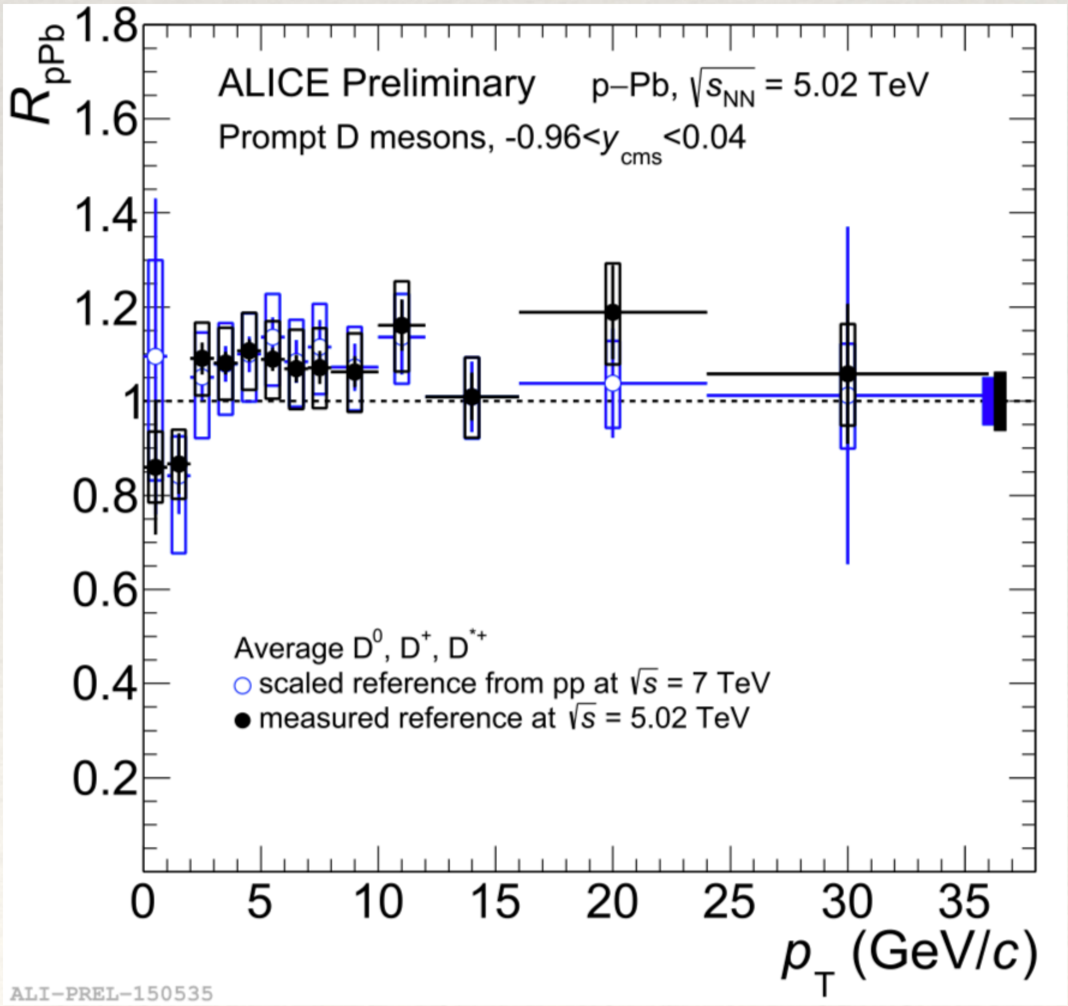

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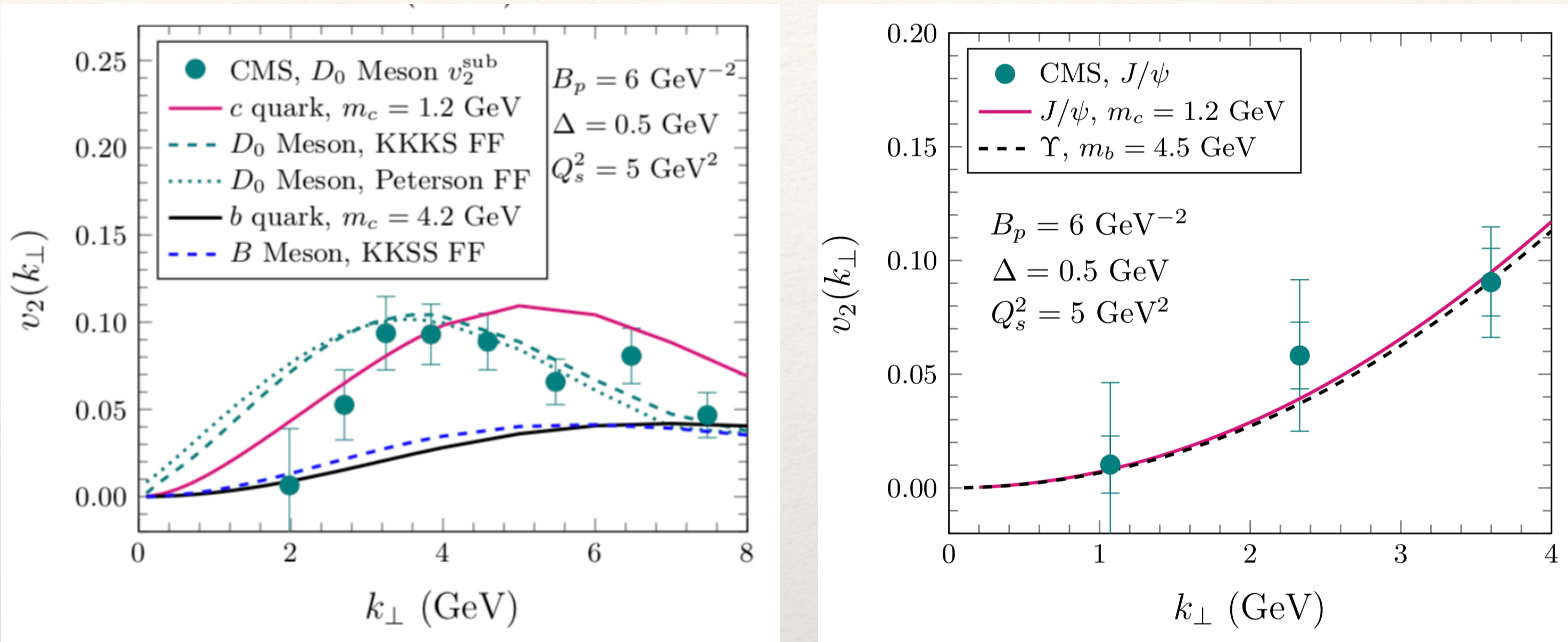
Initial state effects

❖ Zhang's talk (Tue.)



[Zhang, Marquet, Qin, Wei and Xiao, PRL 122 (2019)]

- Initial state interactions (CGC) successfully explain the large v_2 of both open charmed meson and charmonium in p-Pb collisions.
- The prediction on open *B* mesons is provided and turns out to be confirmed by new data released in this conference.

Probing cold nuclear matter (CNM)

[Ru, Kang, Wang, Xing and Zhang, arXiv:1907.11808]

❖ Xing's talk (Tue.)

Four-parameter ansatz of kinematic and scale dependence of $\hat{q}$

$$\hat{q}(x,\mu^2) = \hat{q}_0\,\alpha_s(\mu^2)\,x^{\alpha}(1-x)^{\beta}\ln^{\gamma}(\mu^2/\mu_0^2)$$

normalization

Small-x saturation

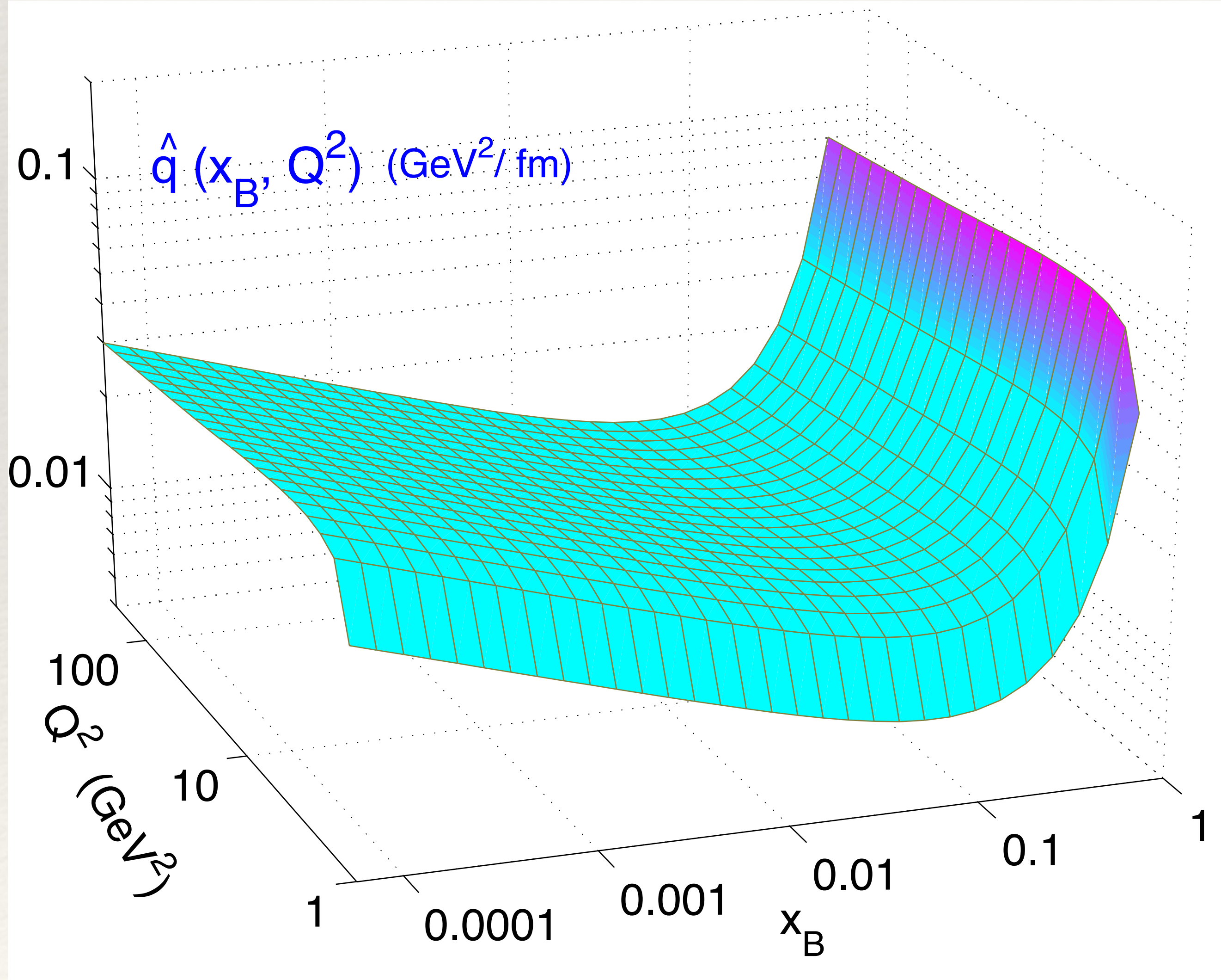
Large-x power correction

Scale dependence

Global fit to 215 data points including J/ψ and Υ

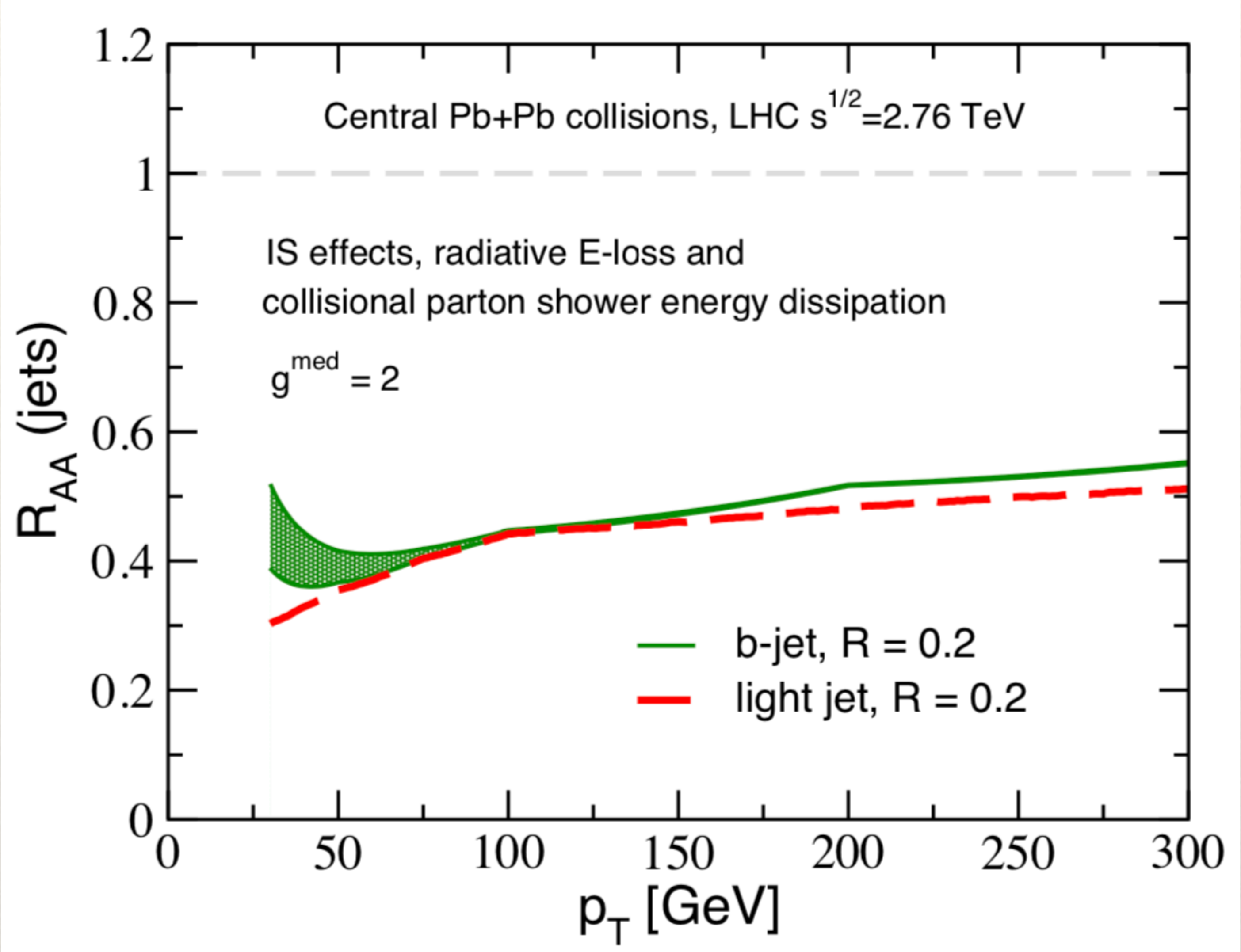
experiment	data type	data points	χ^2
HERMES [21]	SIDIS	156	189.7
FNAL-E772 [24]	DY	4	1.6
SPS-NA10 [29]	DY	5	6.5
FNAL-E772 [22, 26]	Υ	4	2.7
FNAL-E866 [23, 25]	J/ψ	4	2.4
RHIC [27]	J/ψ	10	31.0
LHC [28]	J/ψ	12	4.8
FNAL-E665 [34, 35]	DIS	20	21.5
TOTAL:		215	260.2

x_B and Q^2 dependence of $\hat{q}$ of CNM



From single heavy flavor hadrons to heavy flavor jets

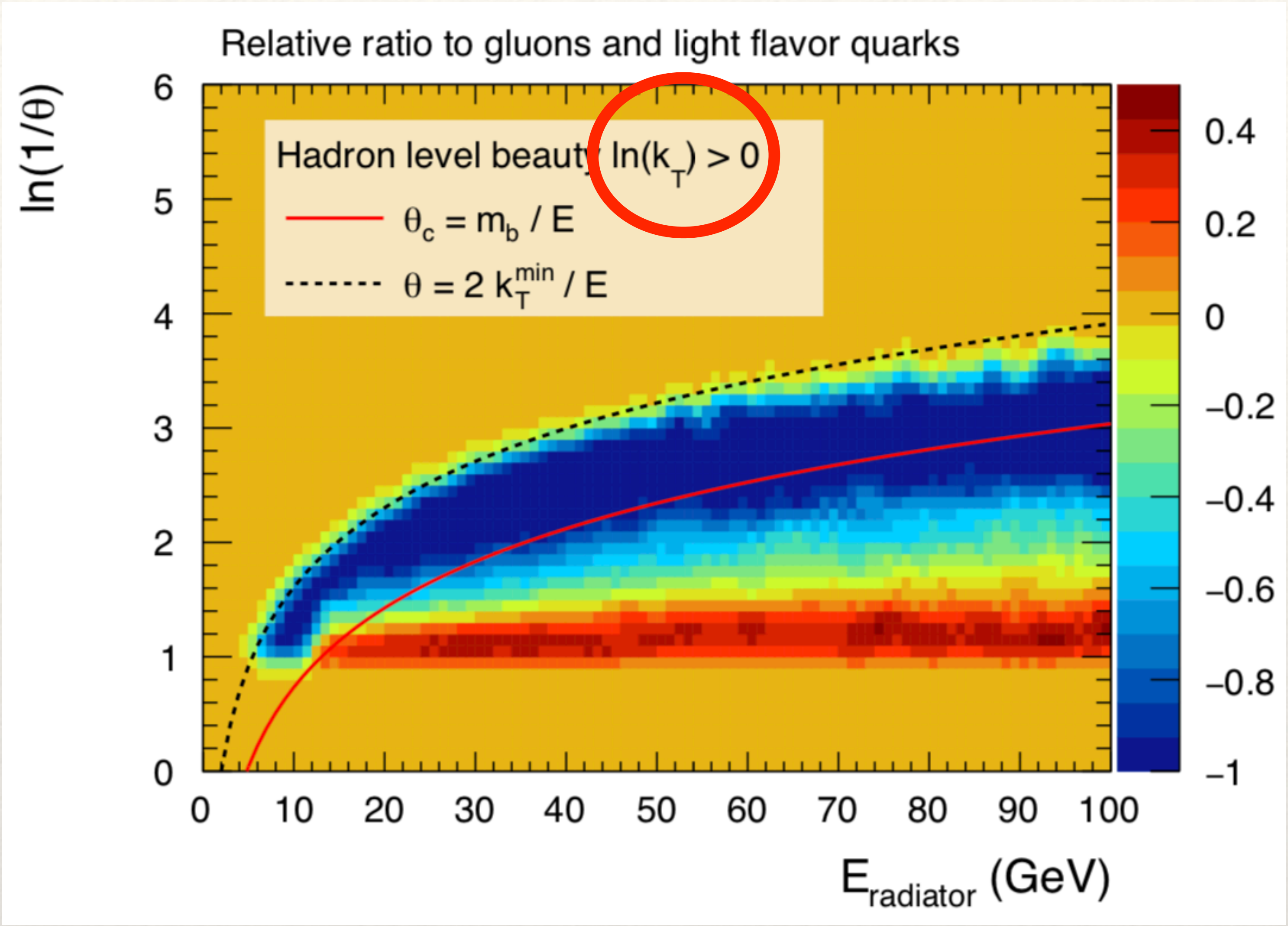
Single inclusive jet R_{AA}



[Huang, Kang and Vitev, PLB 726 (2013)]

- Gluon splitting dominates *b*-jet production
- Similar R_{AA} between heavy and light flavor jets

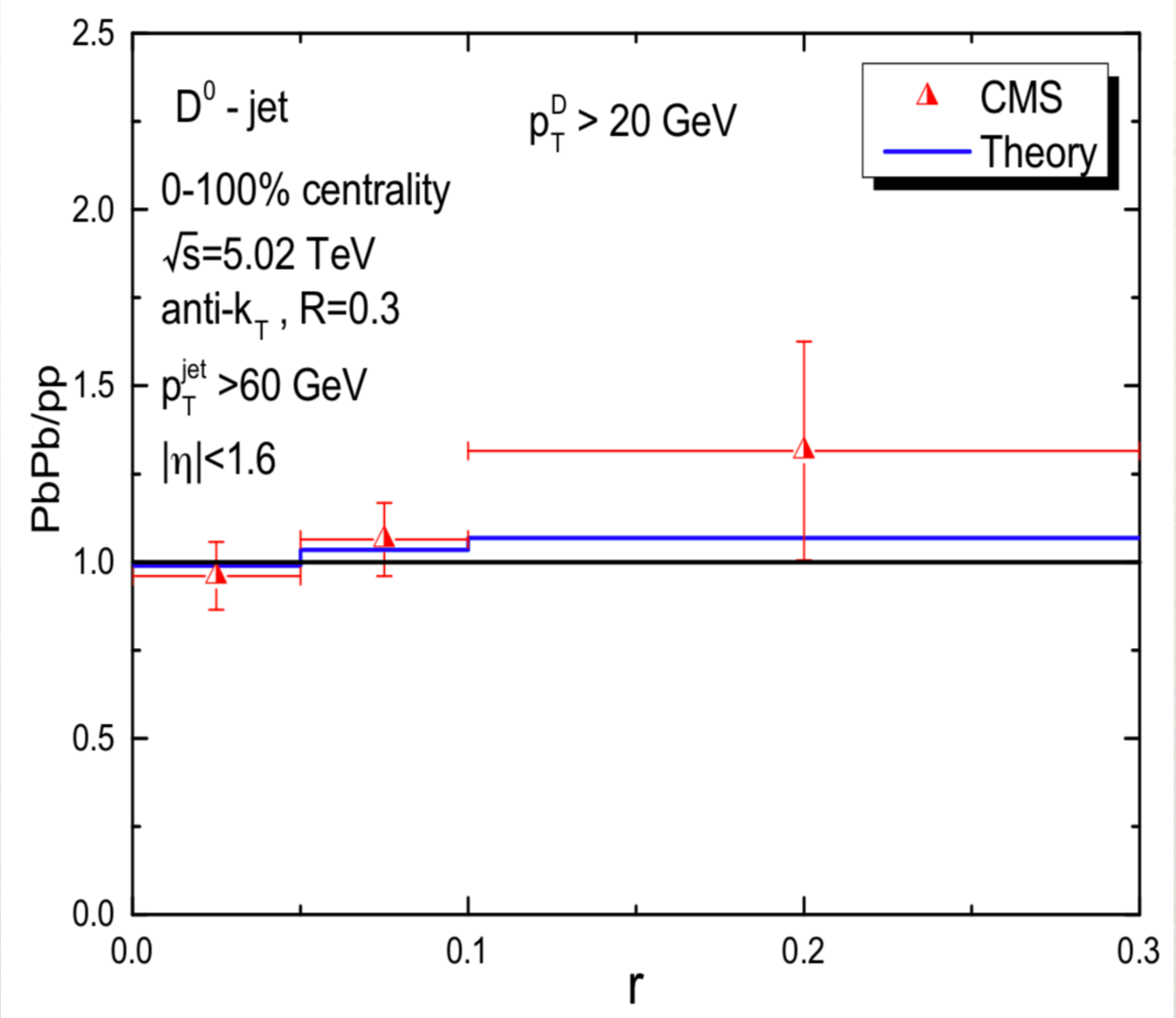
Dead cone on a Lund map



[Cunqueiro and Ploskon, PRD 99 (2019)]

- With a proper kinematic cut on the Lund map, one can directly observe the "dead cone" in heavy flavor groomed jets

Jet sub-structure



[Wang, Dai, Zhang and Wang, EPJC 79 (2019)]

❖ Wang's talk (Tue.)

- Use the angular distribution of *D* within *D*-jets to probe effects of heavy quark diffusion

Summary

- **Overview of heavy quark theories/models**
  - pQCD is sufficient to describe flavor hierarchy of jet quenching above 8 GeV
  - Significant improvements on hadronization models over the past year
  - Constraints on color potential using open and hidden heavy-flavor observables
- **Multi-scale approaches for heavy quark energy loss**
  - DGLAP + transport
  - Boltzmann + Langevin
- **Future challenges and prospects**
  - Constraining model uncertainties via collaborative efforts
  - Probing initial state interactions and cold nuclear matter
  - Devoting more efforts on heavy flavor jets in the near future

Inelastic energy loss

Other approaches

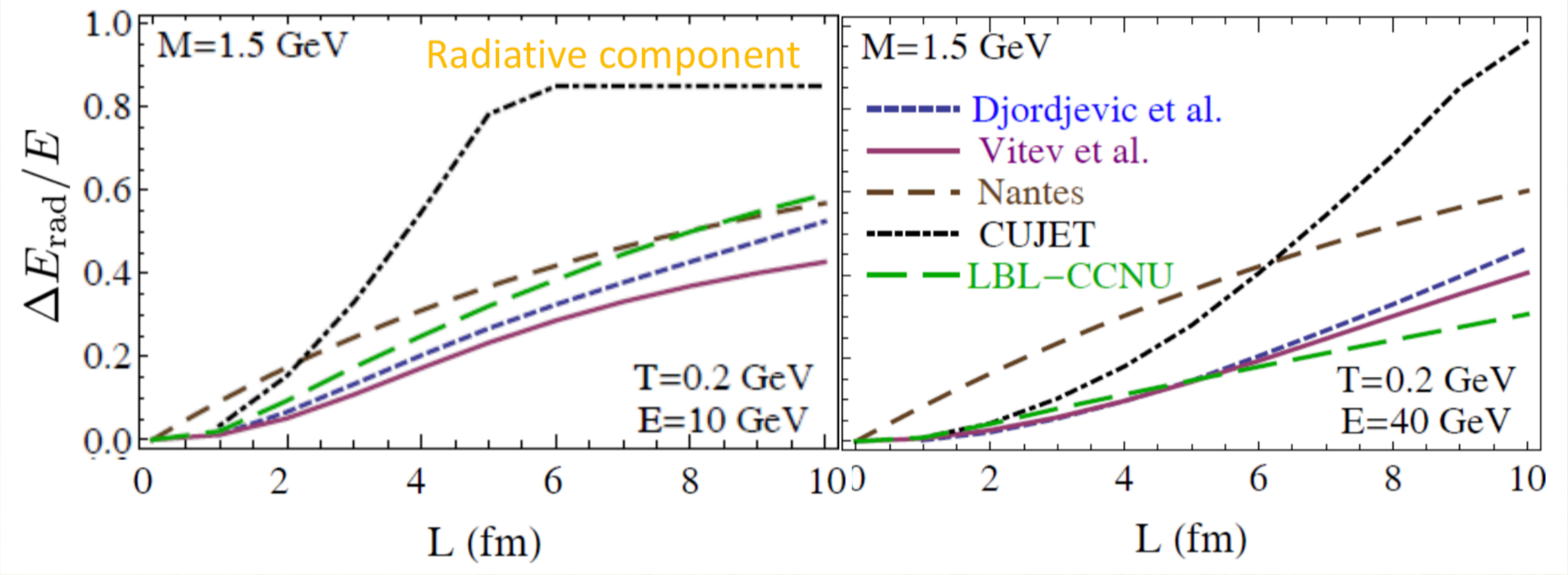
- GLV: soft approximation ($z \ll 1$)
- SCET: soft and collinear approximation
- BDMPS: **multiple scattering** induced emission with soft approximation

Inelastic energy loss

Other approaches

- GLV: soft approximation ($z \ll 1$)
- SCET: soft and collinear approximation
- BDMPS: **multiple scattering** induced emission with soft approximation

Comparison between approaches [Rapp et al., NPA 979 (2018) (EMMI-RRTF)]

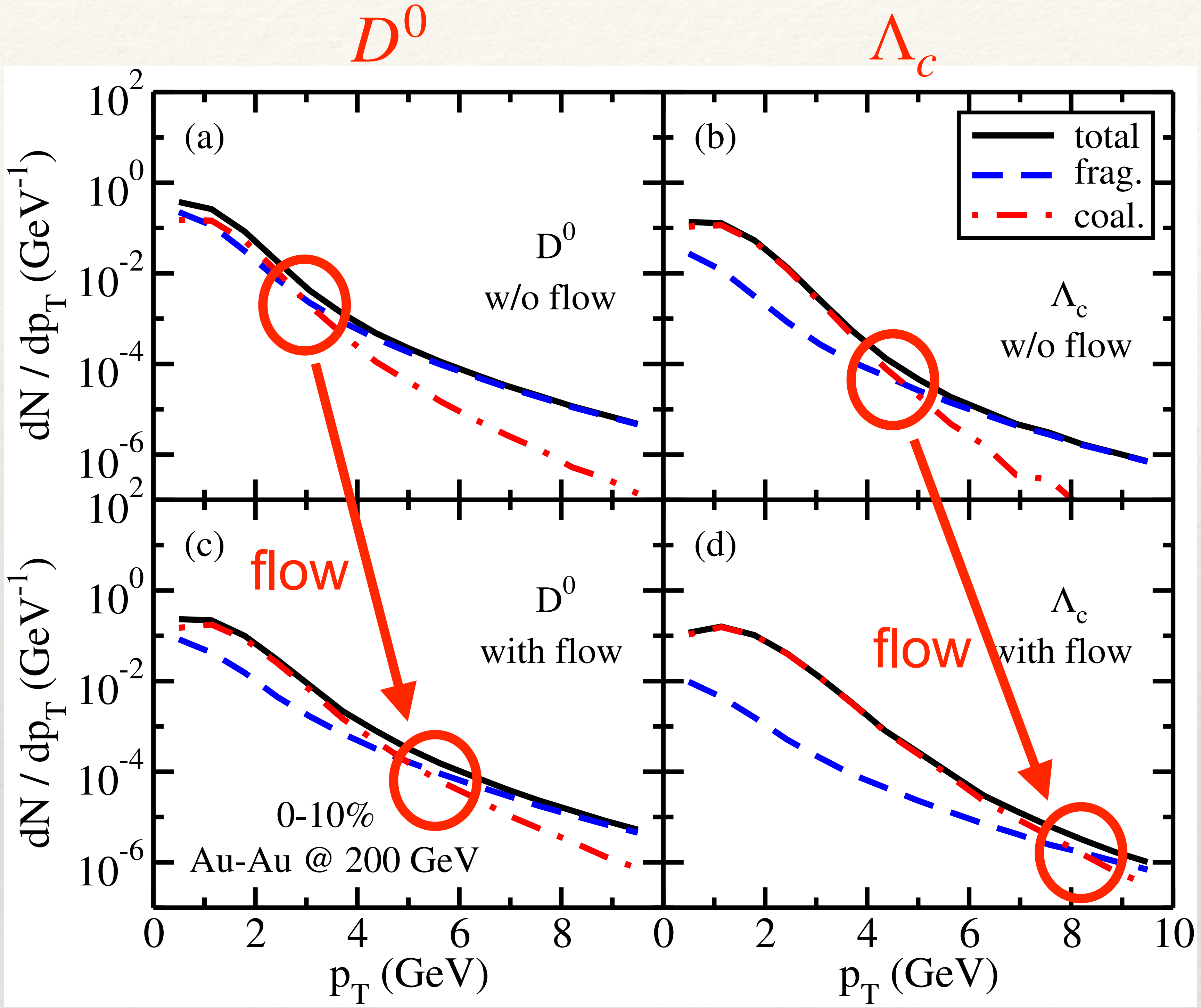


- HT, SCET and Djordjevic are consistent
- Different L-dependence with BDMPS
- Additional features with magnetic monopoles

* Djordjevic; Vitev: SCET; Nantes: GB+BDMPS; CUJET: DGLV + magnetic monopole; LBL-CCNU: HT

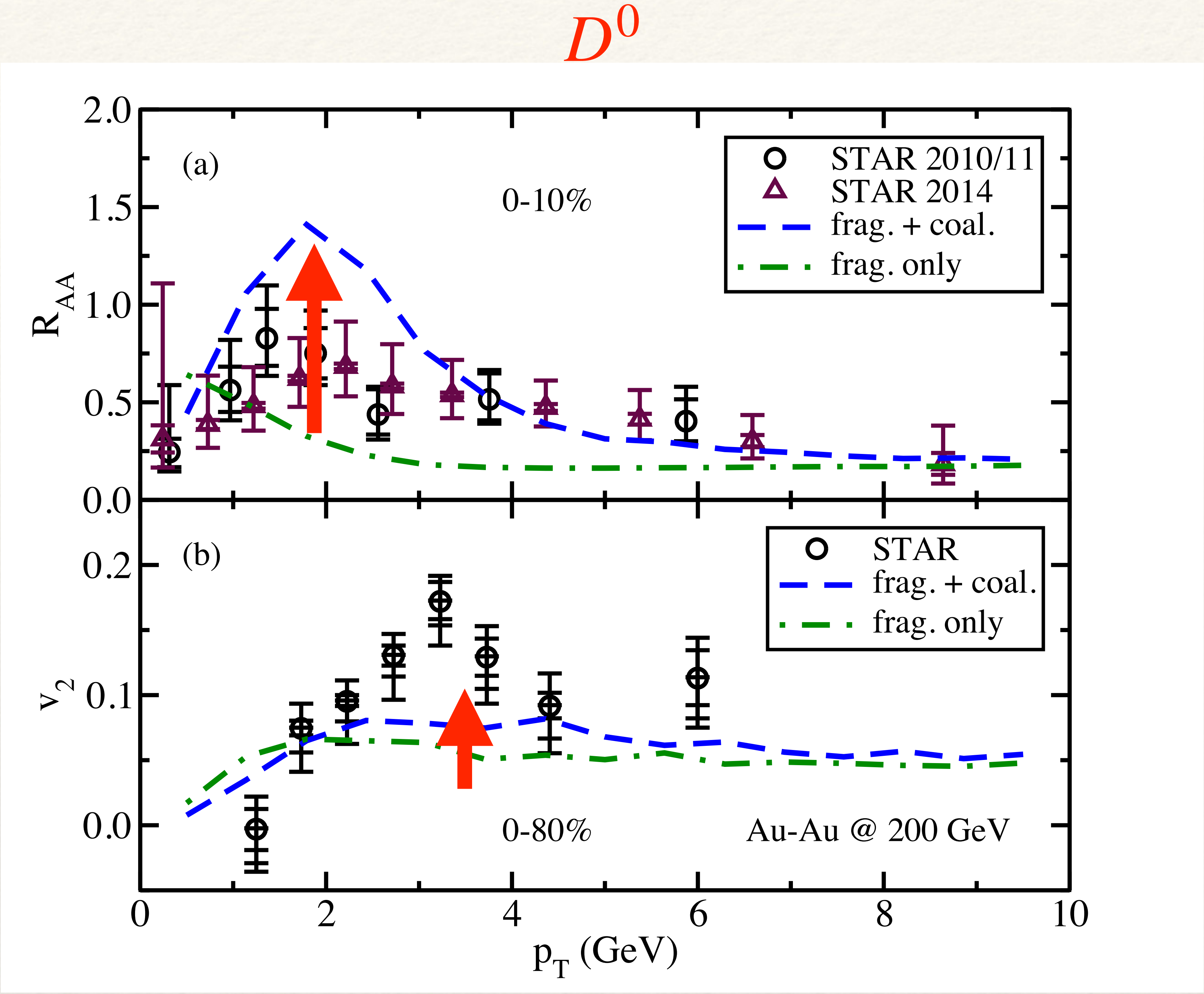
Effects of coalescence on charmed hadron spectra

Flow effects on coalescence



- Coalescence dominates Λ_c production over a wider p_T region than D^0
- The QGP radial flow significantly enhances the coalescence contribution

Effects of coalescence on R_{AA} and v_2



- Coalescence enhances the D^0 R_{AA} at medium p_T, generates its bump structure
- Coalescence increases the D^0 v_2

Multi-scale approaches for HQ energy loss

A complete description of HQ evolution requires multi-scale approaches.

Example 1: DGALP + transport evolution [Cao, Majumder, Qin and Shen, PLB 793 (2019)]

Particles in most transport models are on-shell:

$$Q^2 = p^2 - m^2 = 0$$

Quantum fluctuations allow particles to be off-shell (virtual) — $Q^2 \neq 0$

within a finite splitting time

$$\tau_f \sim \gamma \frac{1}{Q} \sim \frac{E}{Q^2}$$

Partons produced in energetic collisions usually start with high Q and then evolve back to shell after several splittings

Need a combined approach that includes medium modification at high and low Q

DGLAP + transport

Scale 1 ($Q \gg M_{\rm HM}$): HQ fragmentation function (FF) is treated with the DGLAP equation

- Input 1: medium-modified splitting function (higher-twist)

$$P(y,Q^2) = P_{\rm vac}(y) + P_{\rm med}(y,Q^2)$$

$$P_{\rm med}(y,Q^2) = \frac{P_{\rm vac}(y)}{y(1-y)Q^2}\int_{t_i}^{t_{\rm max}} dt\hat{q}(t)\left[2 - 2\cos\left(\frac{t-t_i}{\tau_f}\right)\right]$$

- Input 2: FF at a low scale $D(z,E,Q_0^2)$

Extracted from transport model (in scale 2) — medium modified FF at $Q_0 \sim M_{\rm HM}$

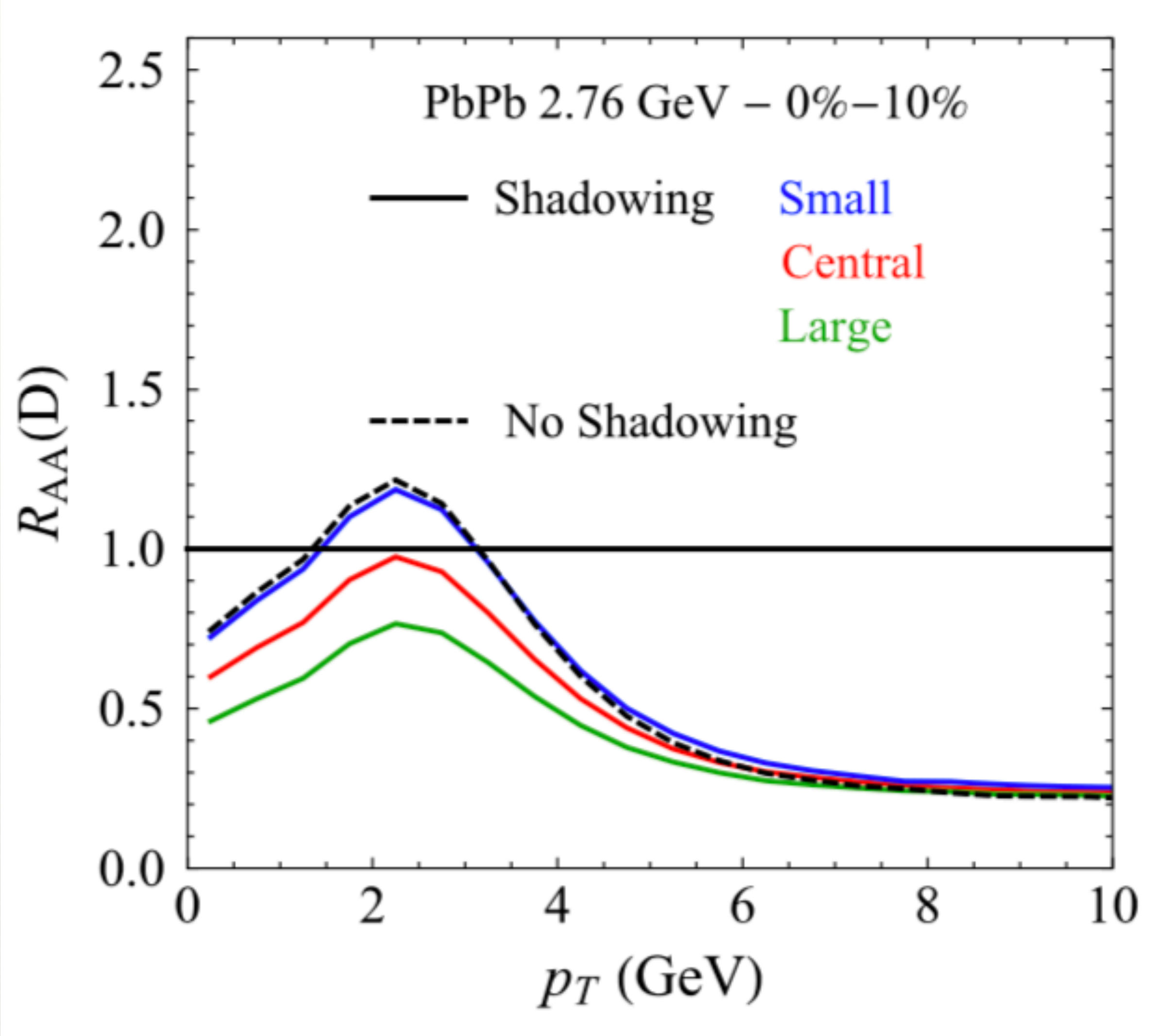
Scale 2 ($Q \sim M_{\rm HM}$): Transport model with the rate equation (elastic + inelastic)

$$\Gamma^{\rm inel}(t) = \int dy \int dl_\perp^2 \frac{dN}{dydl_\perp^2 dt}$$ (page 6)

Other model uncertainties

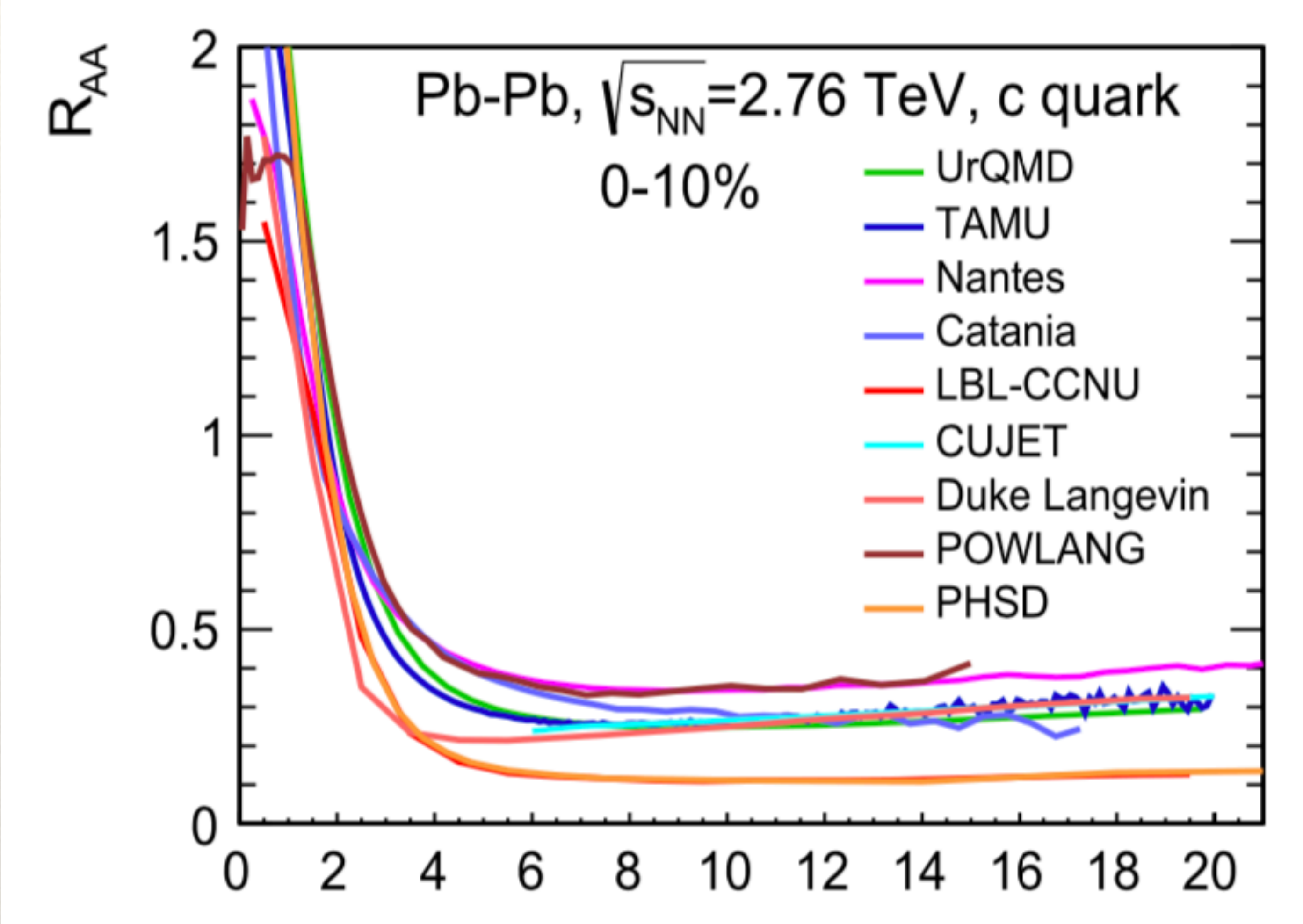
[Rapp et al., NPA (2018) (EMMI-RRTF)]

Initial spectrum



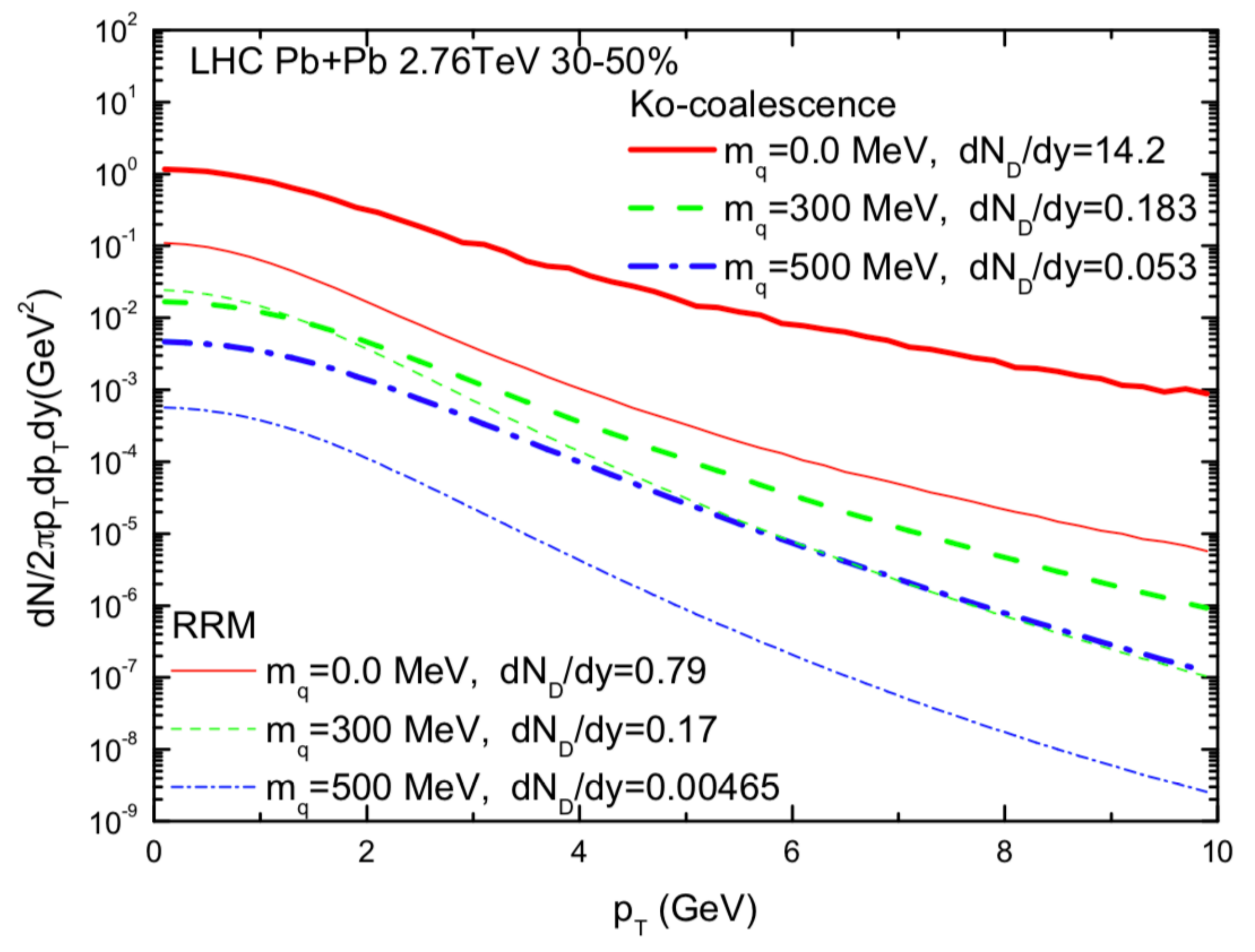
Different implementations of the nuclear shadowing introduce up to a factor of 2 uncertainty at low p_T, but negligible above 6 GeV

Medium property



Same HQ-medium interaction (5*pQCD σ) in different media yields a factor of over 2 difference in the charm quark R_{AA}

Hadronization



Resonant recombination gives smaller and softer *D* spectra than instantaneous coalescence (thermal mass dependent)

Probing nuclear matter with heavy quarks

Can heavy quarks probe the medium evolution history?

Probing nuclear matter with heavy quarks

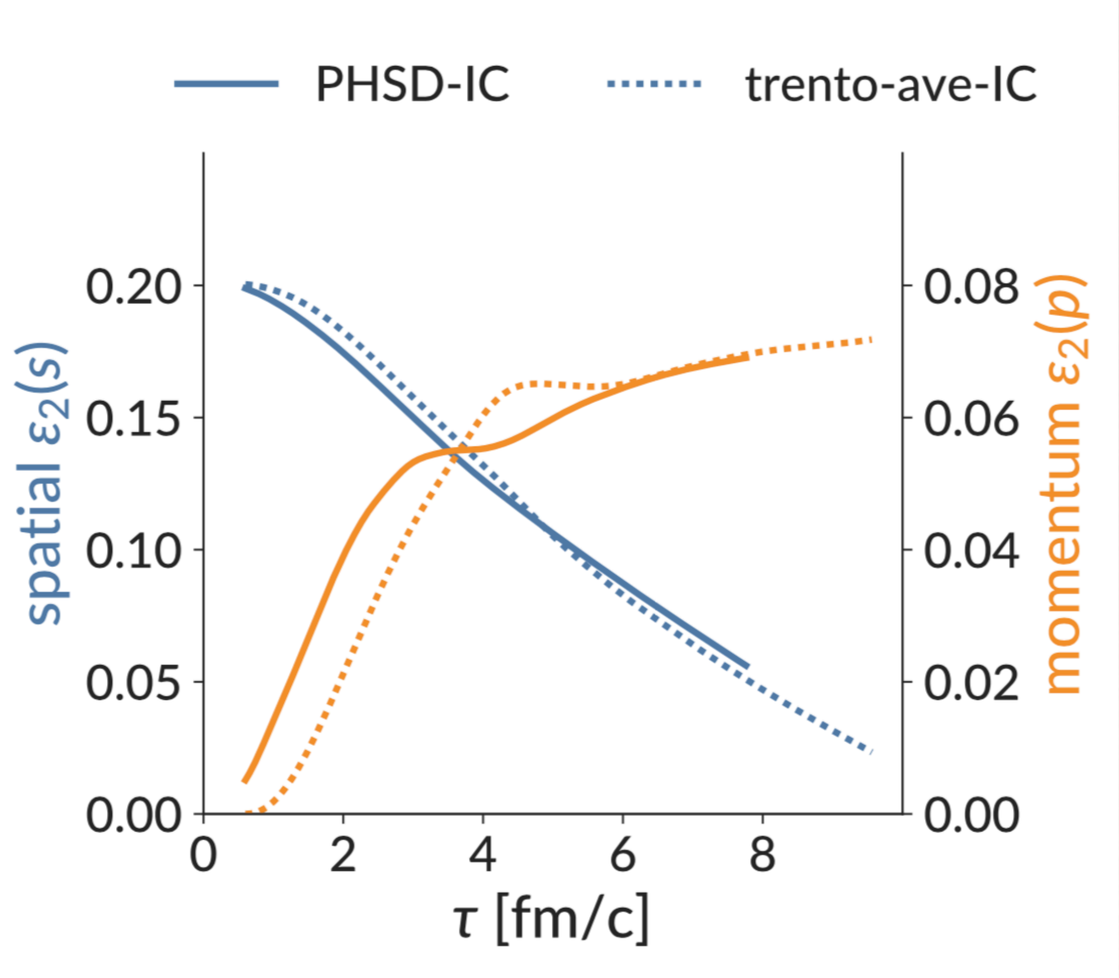
Can heavy quarks probe the medium evolution history?

Yes! [Xu et al., PRC 99 (2019) (Duke-Frankfurt)]

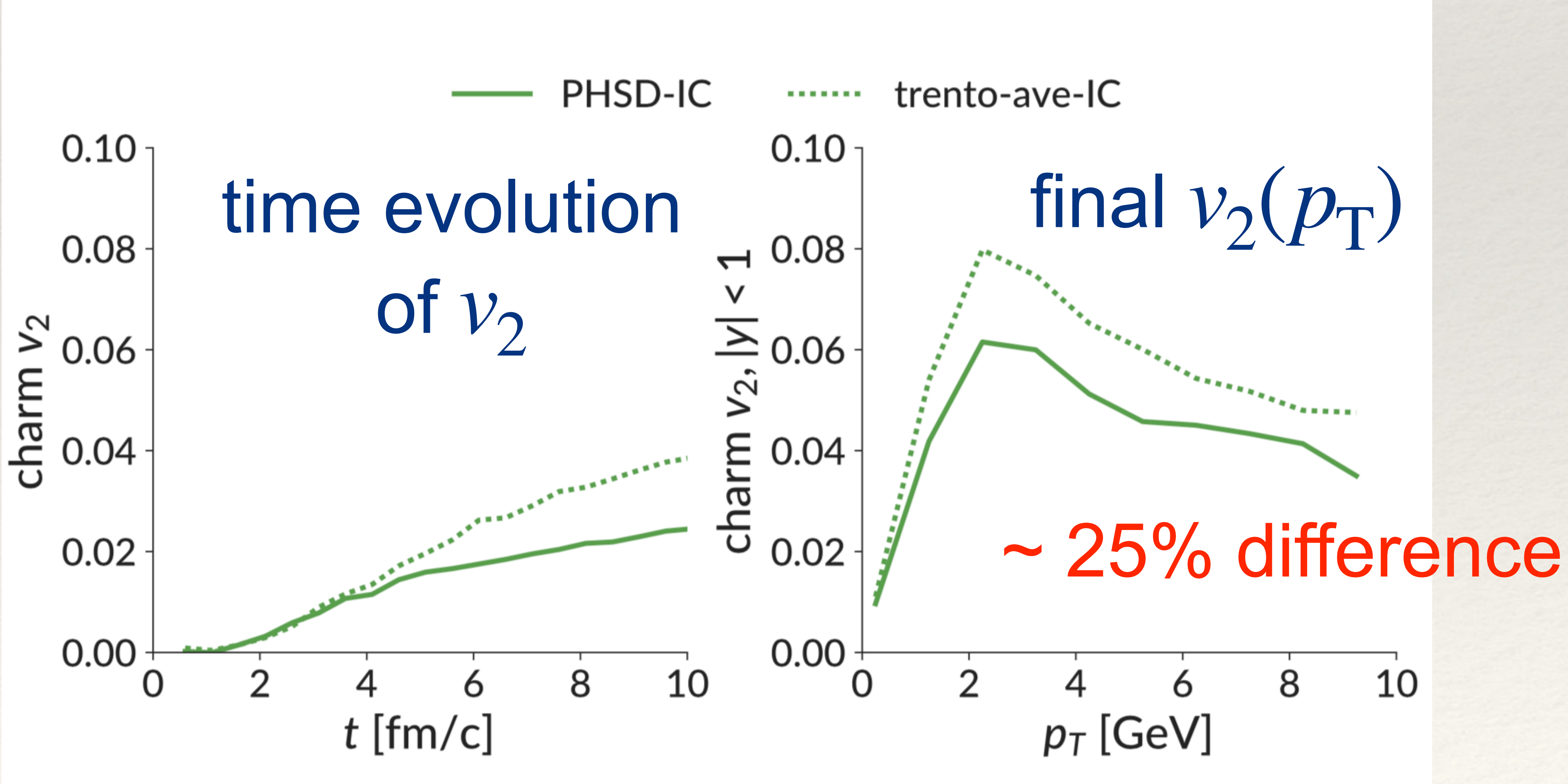
DFNCC (**Duke-Frankfurt**-Nantes-Catania-CCNU)

Different initial condition of the bulk (PHSD vs. Trento), same hydrodynamic model and heavy quark transport model

similar ϵ_2 and v_2 of the bulk



Different v_2 of charm quarks: probe different bulk histories



time evolution of v_2

final $v_2(p_T)$

~ 25% difference