HF2022: Heavy Flavours from small to large systems, Institut Pascal, 3-21/10/2022,

Comparison of Heavy quark Hadronization Mechanisms in heavy ion collisions

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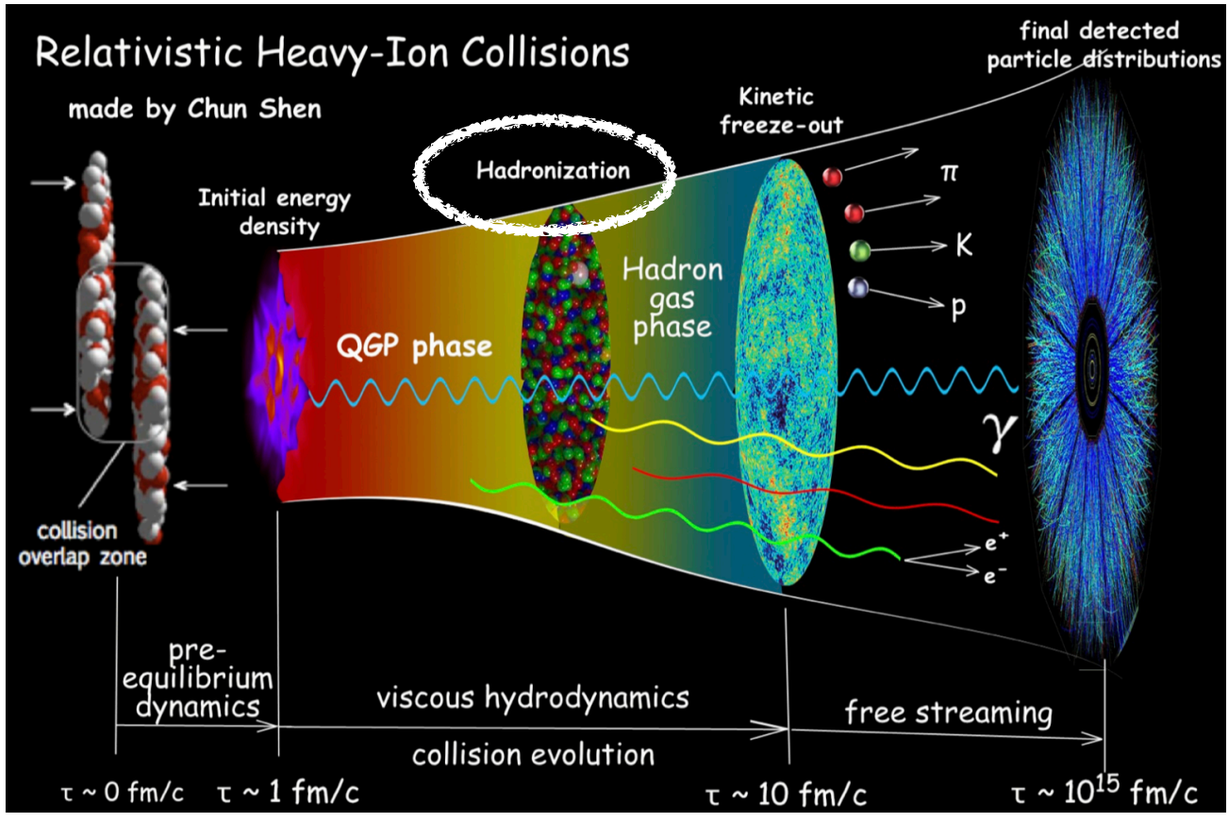
10/10/2022

Relativistic heavy ion collisions

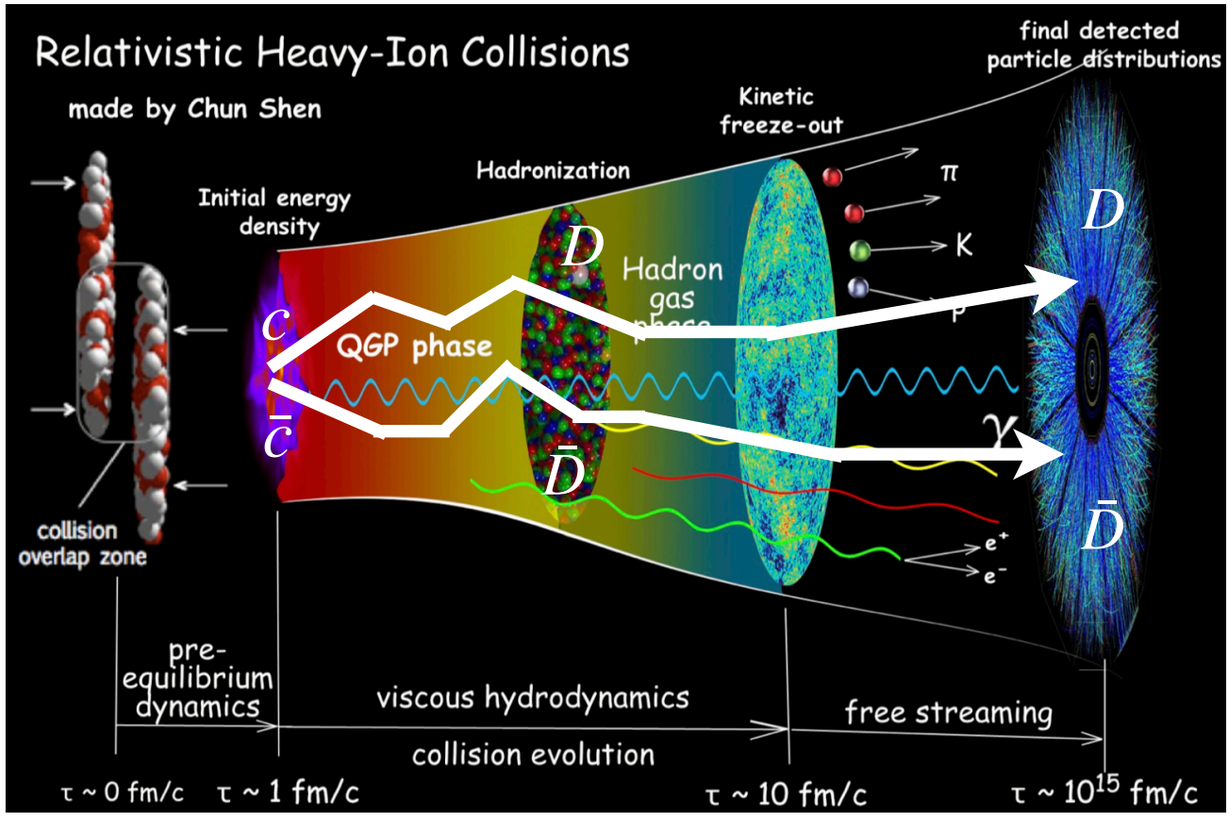


A deconfined QCD matter — quark-gluon plasma (QGP) has been created!

Hadronization: the freedom changed from quarks/gluons to hadrons

Hadronization is a non-perturbative process!

Relativistic heavy ion collisions



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Hadronization is a non-perturbative process!

Why heavy flavor ?

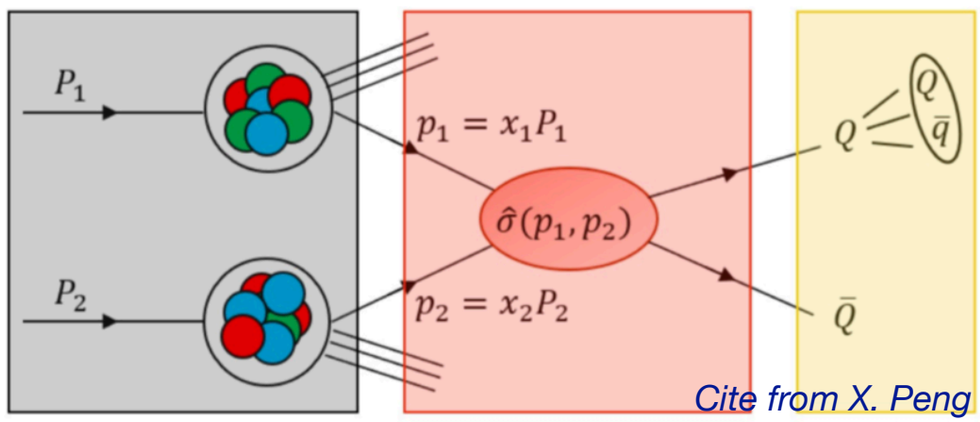
1. *Mc, Mb >> Λ_{QCD}, produced by hard scattering and described by pQCD.*
2. *Number is conserved during the evolution.*
3. *Evolution (energy loss) in the QGP is well studied.*
4. *Hadronization probability can be manageable based on heavy flavor effective theory.*
5. *Few excited states compared to light hadrons.*
6. *The Direct and Feed-down contributions can be well separated in experiments.*

Hadronization mechanism in vacuum

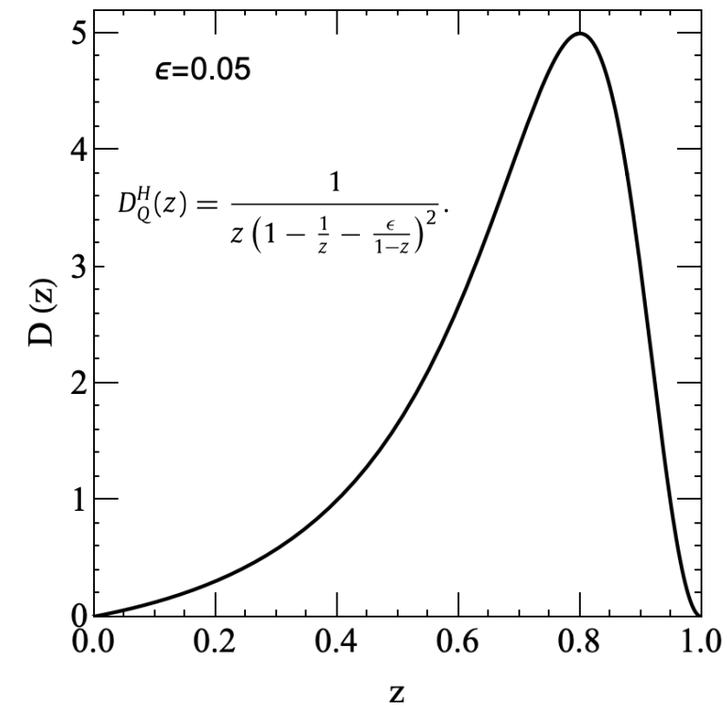
- *Fragmentation*:

$$\frac{d\sigma^{H_c}}{dp_T}(\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_T^{c}}(x_1,x_2,\mu_F,\mu_R) \otimes D_{c\to H_c}(z = p_{H_c}/p_c,\mu_F)$$

Parton distribution functions (PDFs) | Hard scattering cross section (pQCD) | Fragmentation function (hadronisation)



Cite from X. Peng



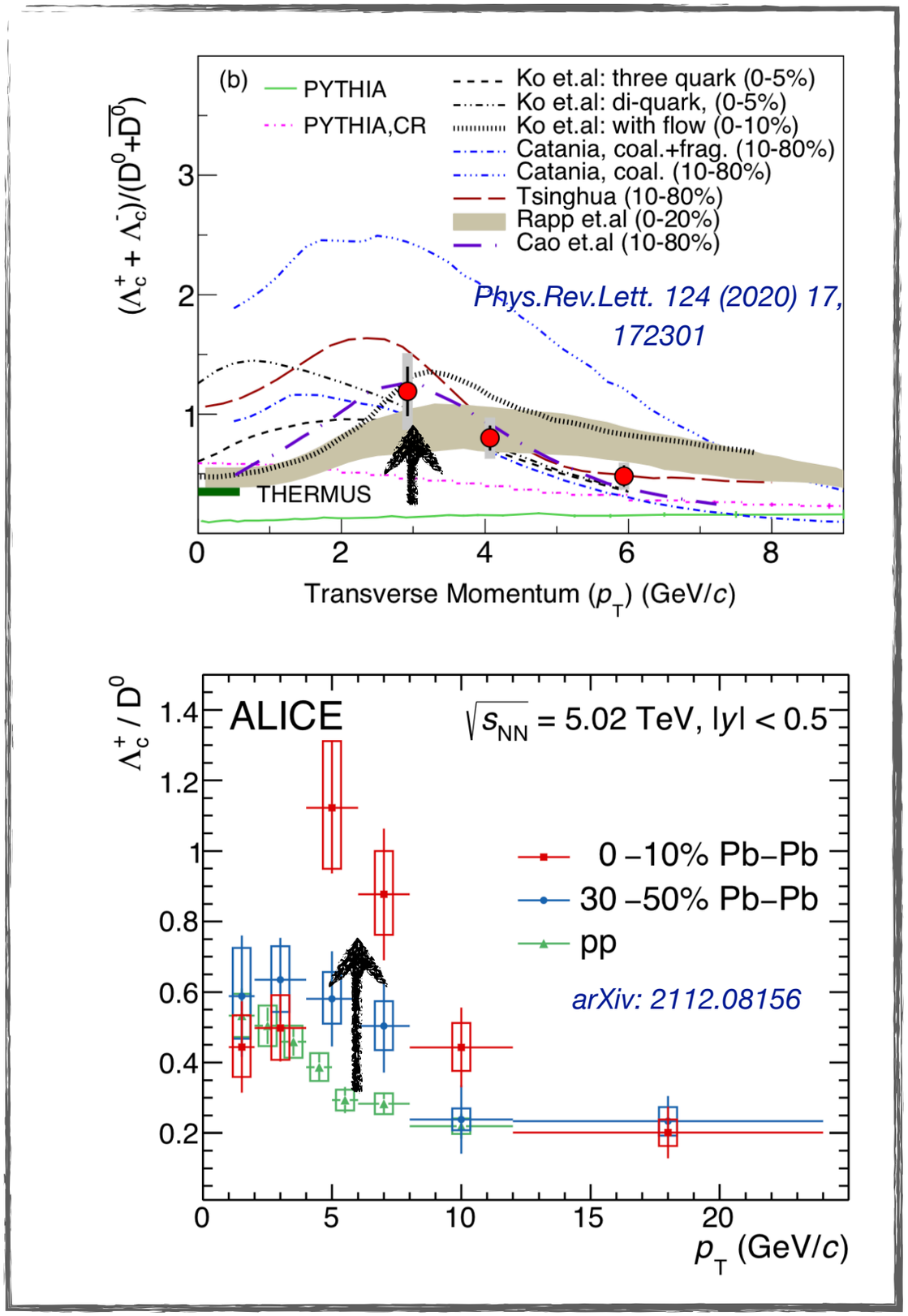
Fragmentation functions can be determined by experimental datas (e^+e^-, pp,…)

Hadronization in the hot QCD medium shows a huge difference compared to the vacuum case.

Open a new window to study the hadronization mechanism!

Hadronization mechanism in hot medium

- *Enhancement Baryon / Meson Ratio*



Hadronization mechanism in hot medium

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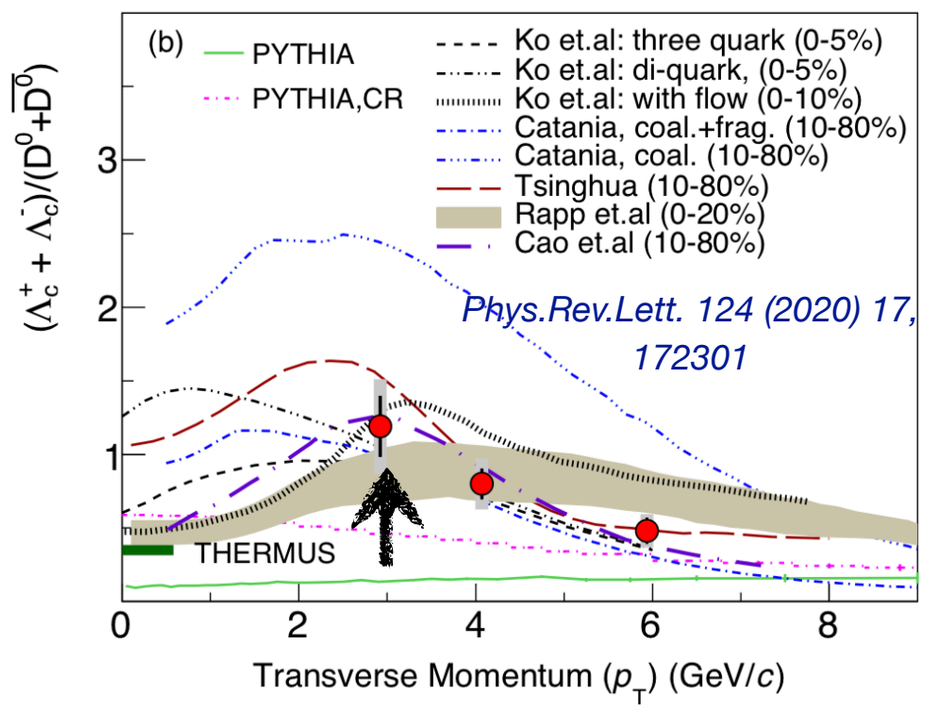
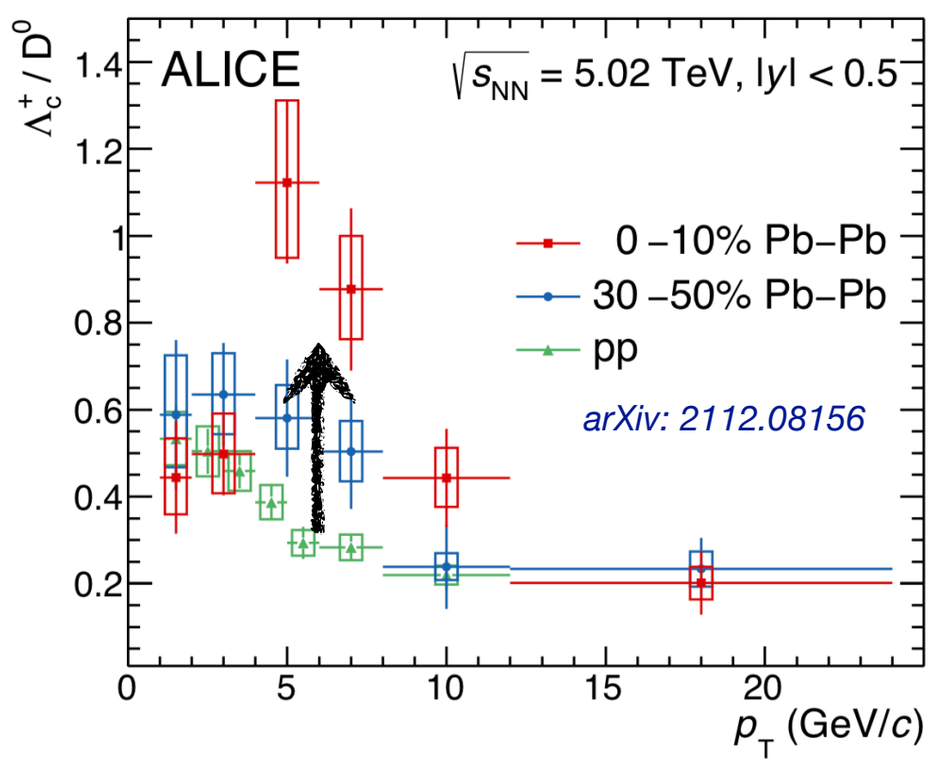
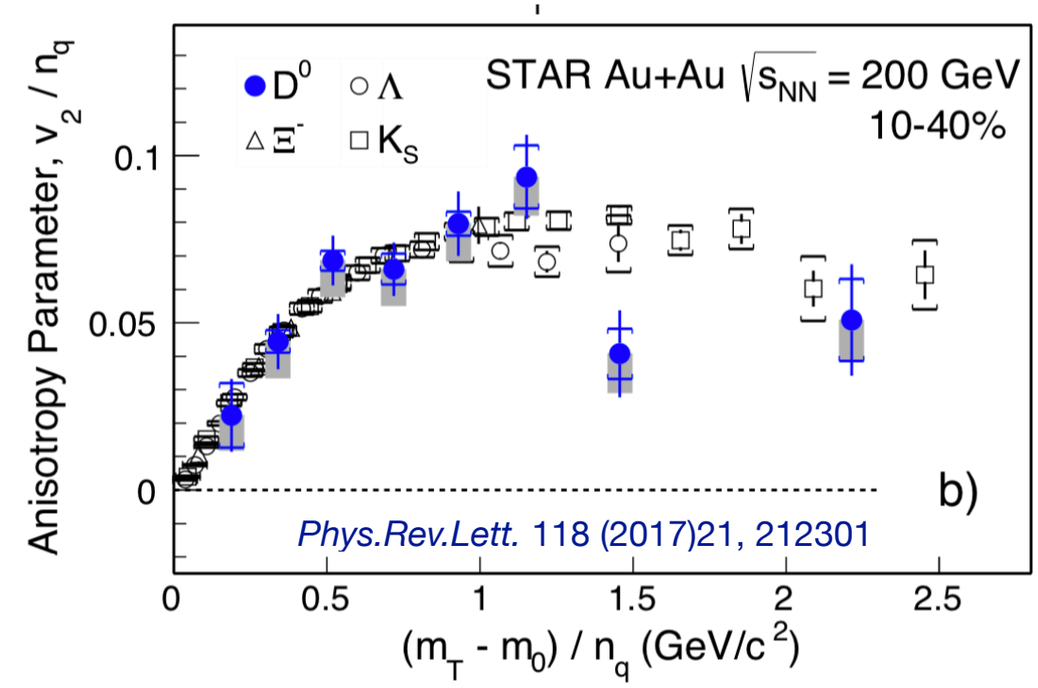
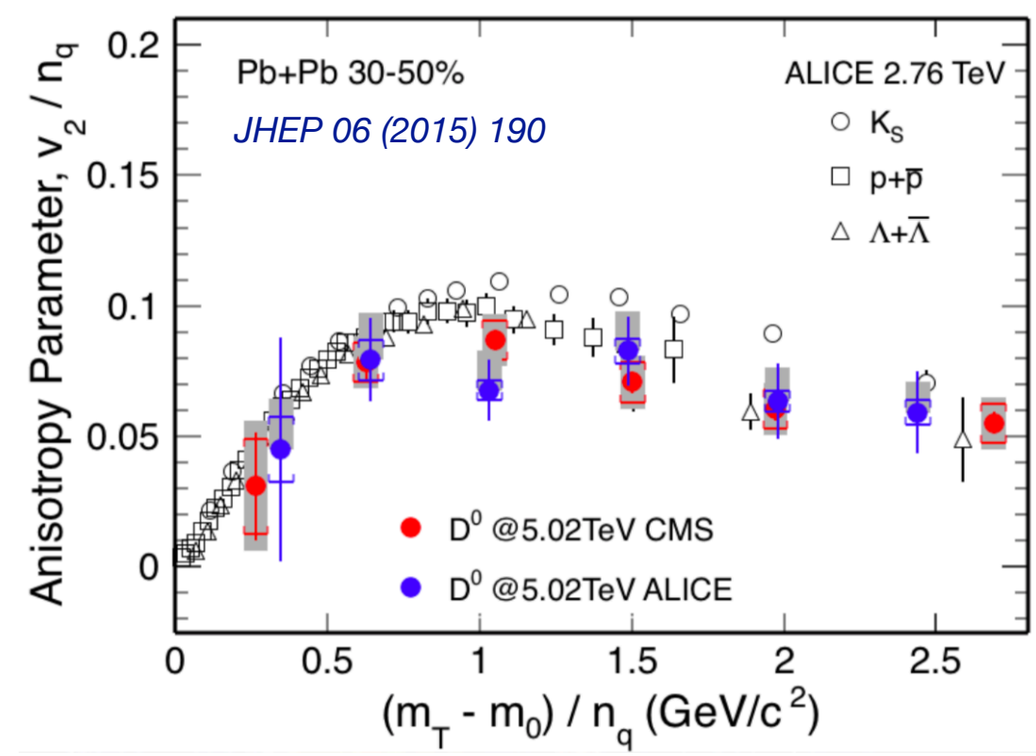




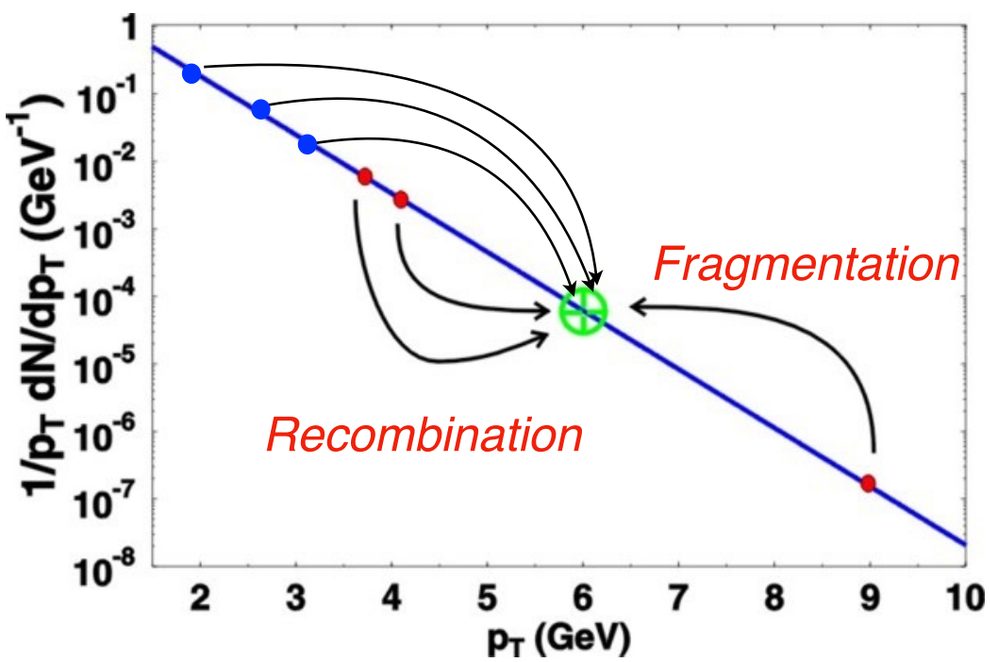
- *Quark Number Scaling of Elliptic flow*





Hadronization mechanism in hot medium

- *Recombination (eg. Coalescence)*:



R. Fries, V. Greco, P. Sorensen. Anna. Rev. Null. Part. Sci 58(2008)177.

$$N_M = \sum_{ab} \int \frac{d^3P}{(2\pi)^3} \langle M;\mathbf{P}| \hat{\rho}_{ab} |M;\mathbf{P}\rangle$$

R. Fries, B. Muller, C. Nonaka and S. Bass. Phys. Rev. C68, 044902(2004).

For mesons

$$\frac{dN}{d^2P_T d\eta} = C \int \frac{P^\mu d\sigma_\mu}{(2\pi)^3} \int \frac{d^4r d^4q}{(2\pi)^3} F(x_1,p_1,x_2,p_2) W(r,q)$$

- *The hadronization hypersurface is determined by hydrodynamics.*
- *Quark distribution functions:*

$$F(x_1,p_1,x_2,p_2) = f_c(x_1,p_1) f_q(x_2,p_2)$$

- *The Wigner function can self-consistently be determined by the wavefunction. (advantage of heavy flavor).*

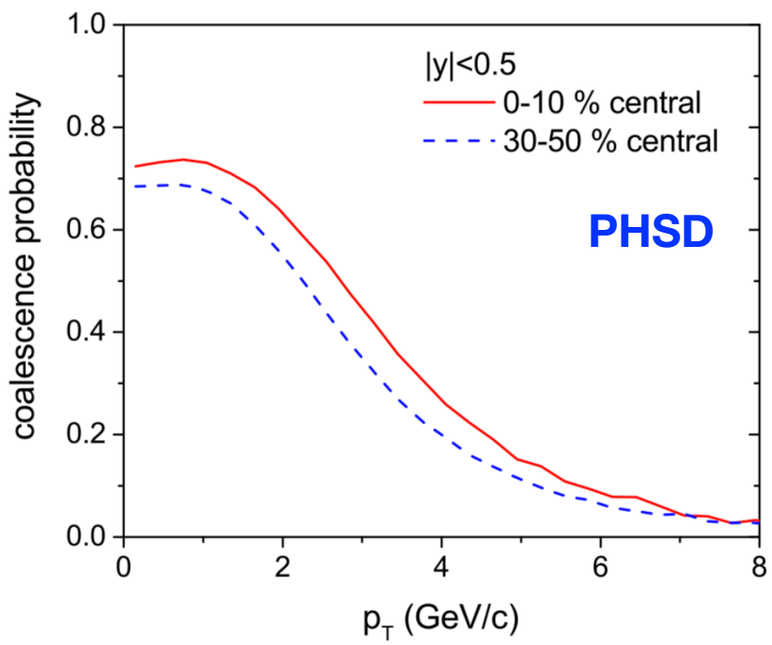
$$W(r,p) = \int d^4y e^{-ipy} \psi(r+\frac{y}{2})\psi(r-\frac{y}{2})$$

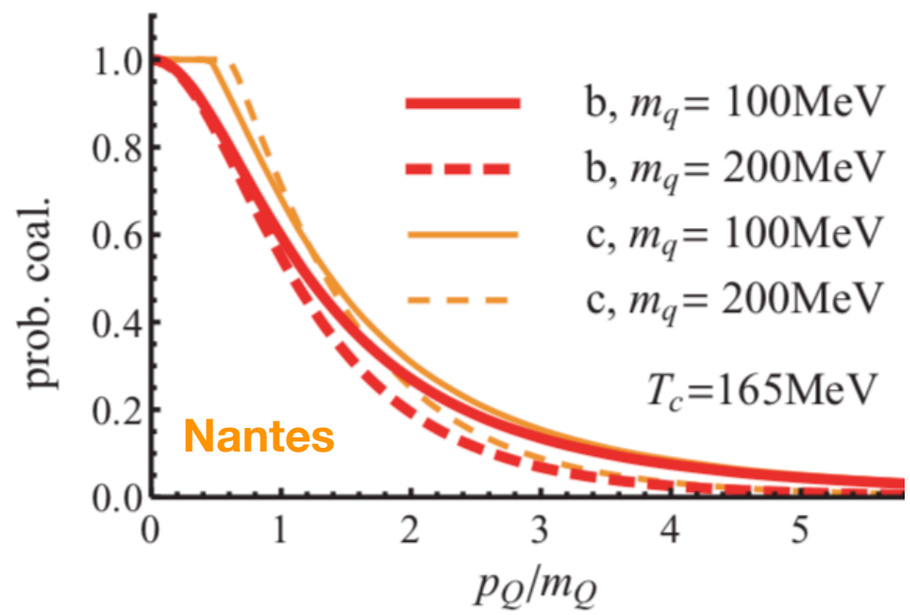
- *Enhancement Baryon / Meson Ratio*
- *Quark Number Scaling of Elliptic flow*

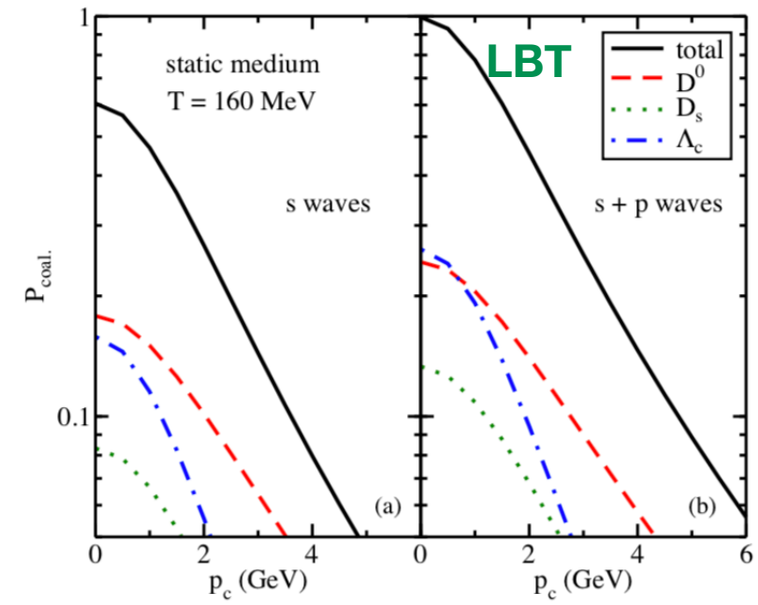
Statistics play an important role in the hadronization mechanism in hot medium!

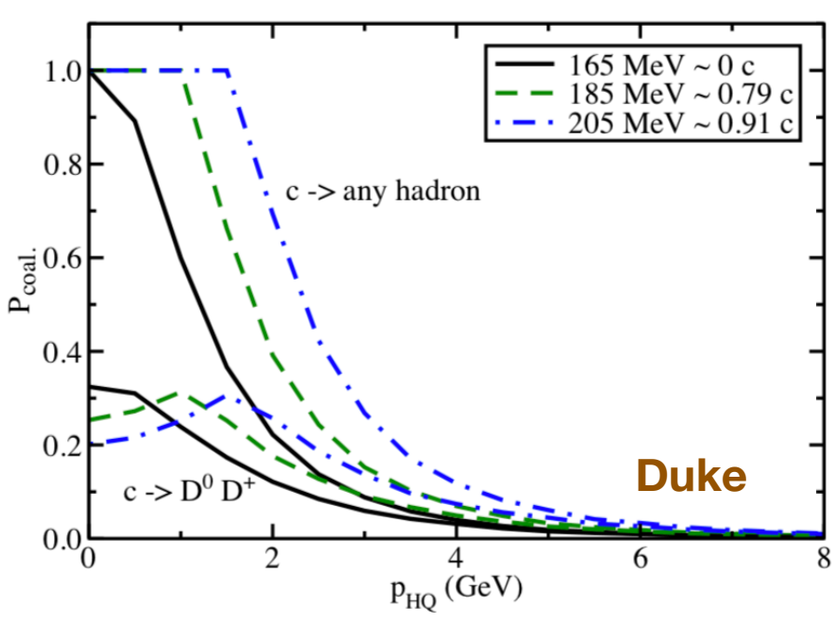
Hadronization mechanism in hot medium

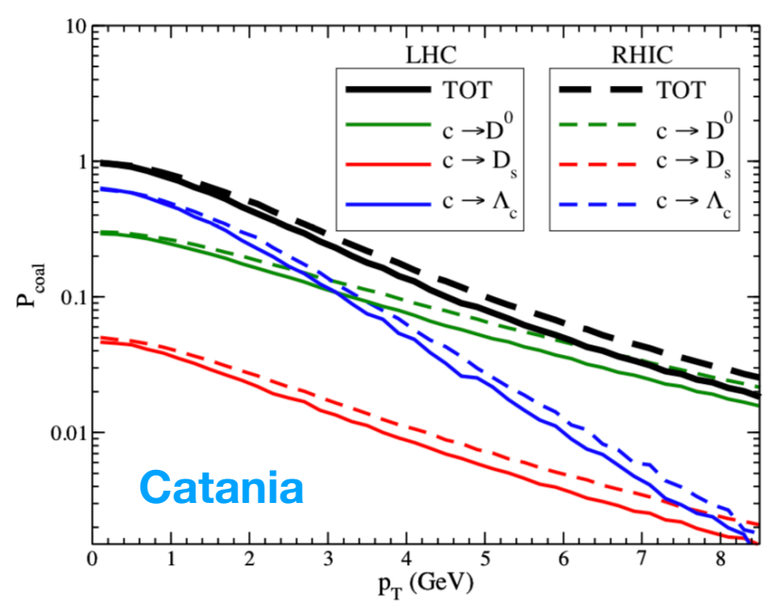
- *Recombination + Fragmentation*:











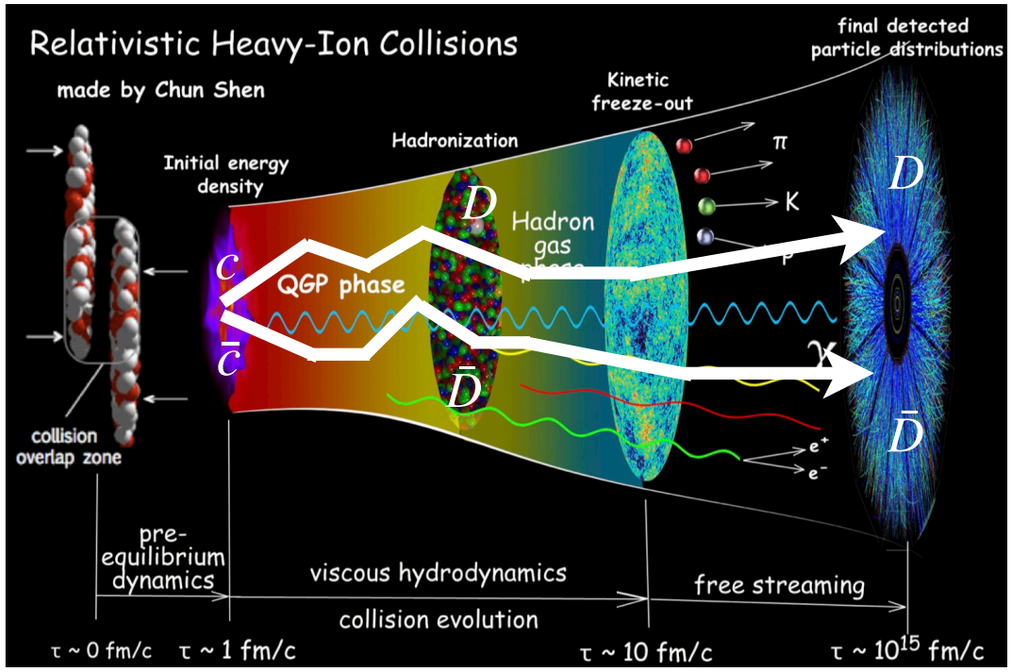
$$P_{frag.}(p_T) = 1 - P_{coal.}(p_T)$$

Low pT heavy flavor hadronize via the recombination, while high pT through the fragmentation!
Each model can give a nice explanation of the experimental data!

Model comparison for hadronization

Key elements in each model:

- *Initial charm distribution.*
- *Energy loss in the QGP medium.*
- *Bulk evolution.*
- *Hadronization mechanism (direct and feed-down).*
- *Evolution in the hadronic phase.*



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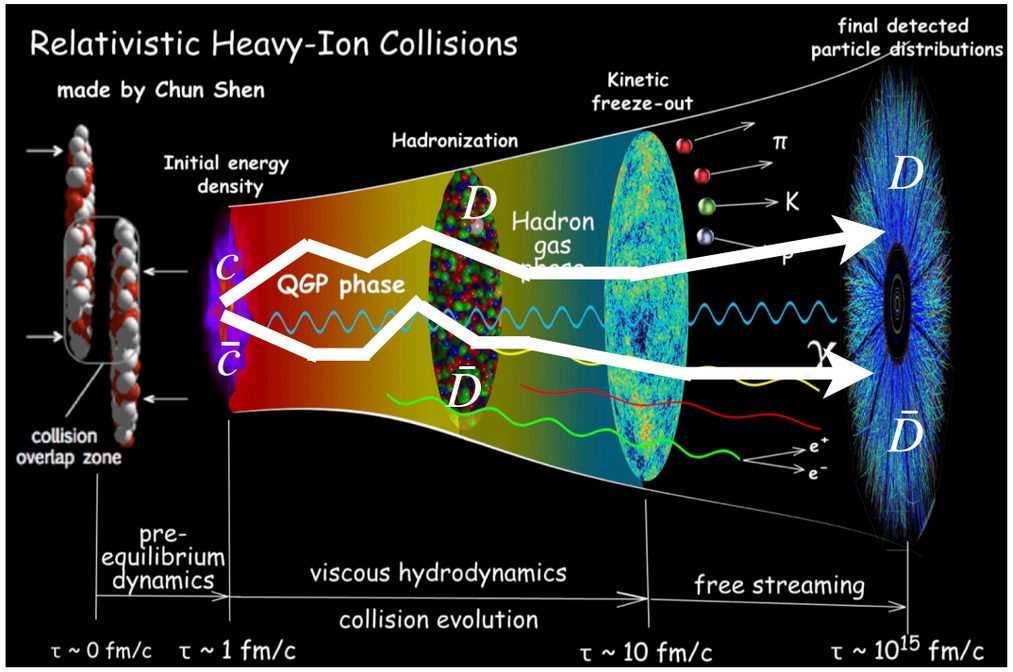


"Systematic studies of the parameter dependence in the various hadronization models should be carried out for a simplistic blast-wave-type fireball model at a given hadronization temperature, in connection with a common charm-quark distribution function as transported through the QGP hadronization" —*J. Aichelin*

Catania, Duke, LBT, Nantes, PHSD, TAMU, Turin, Vitev group

Fix the freeze-out hypersurface and charm distribution at freeze-out hypersurface.

- *Given by the Fireball model for* $\sqrt{s_{NN}} = 2.76TeV$ *Pb+Pb with b=7fm and* T_{fo}*=180MeV.*

  H. van Hees, V. Greco, and R. Rapp, Phys. Rev. C 73, 034913 (2006)

- *Uniform distribution in the coordinate space and momentum space is given by EMMI RRTF. (so far, no space-momentum correlation)*

  Nucl. Phys. A 979 (2018) 21-86.

$$\frac{dN_c}{dp_T} \times [1 + 2v_2(p_T)\cos(2\phi)]$$

- *No hadronic interaction.*

Model comparison for hadronization

We prepared four tasks:

1. *Description of the hadronization scheme in your model*

2. *Final yield of charm hadrons with given charm distribution at hadronization hypersurface.*

   - *For pure fragmentation (assuming all c quarks proceed through fragmentation)*
   - *For pure coalescence / recombination*
   - *For your genuine hadronization model*

   For each cases, calculate the H_{AA} *of D* ($D^+ + D^0$), D_s *and* Λ_c.

$$H_{AA} = \frac{dN_D/dp_T}{dN_c/dp_T}$$

3. *Same as the second one but in p+p collisions.*

4. *Elliptic flow* v_2 *with and without the c-quark flow.*

$$\frac{dN}{d^2\mathbf{p}_T dy} = \frac{1}{\pi dp_T^2 dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\left(\phi - \Psi_n\right)\right)\right]$$

Model comparison for hadronization

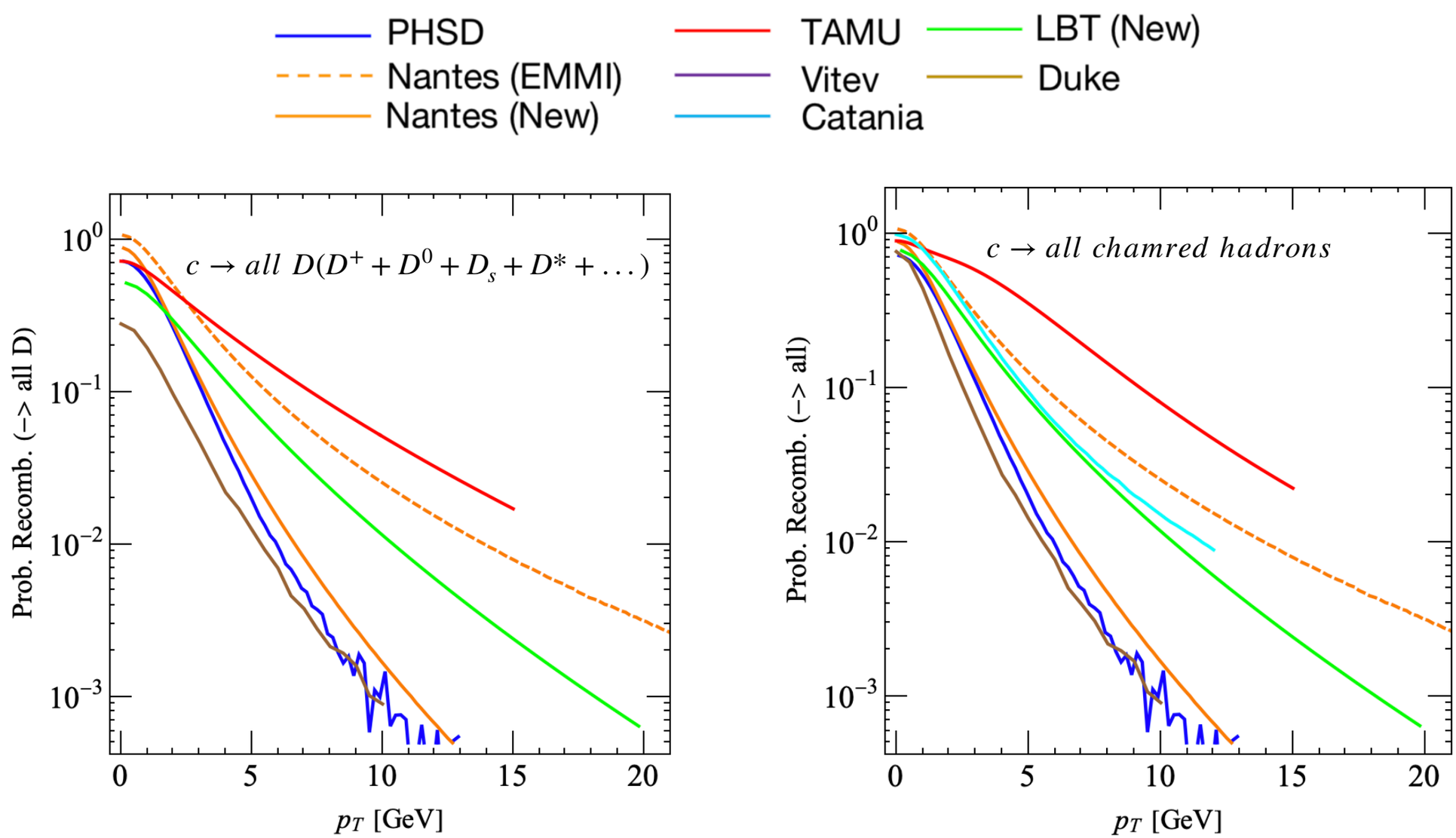
We prepared four tasks, but so far only two tasks are finished :

2. *Yield (H_{AA}) via fragmentation, recombination, and both with given c-quark distribution in HIC.*

4. *Elliptic flow v_2 with and without the c-quark flow.*

	Frag.	Recom.	Mix	$D(D^0 + D^+)$	D_s	Λ_c
Catania	✓	✓	✓	✓	✓	✓
Duke	✓	✓	✓	✓	✗	✗
LBT	✓	✗	✓	✓	✓	✓
Nantes	✓	✓	✓	✓	✗	✗
Nantes(new)	✓	✓	✓	✓	✗	✗
PHSD	✓	✓	✓	✓	✓	✗
TAMU	✓	✓	✓	✓	✓	✓
Turin	✗	✗	✓	✓	✓	✓
Vitev	✓	✗	✗	✓	✓	c-baryons

Model comparison — Recombination probability

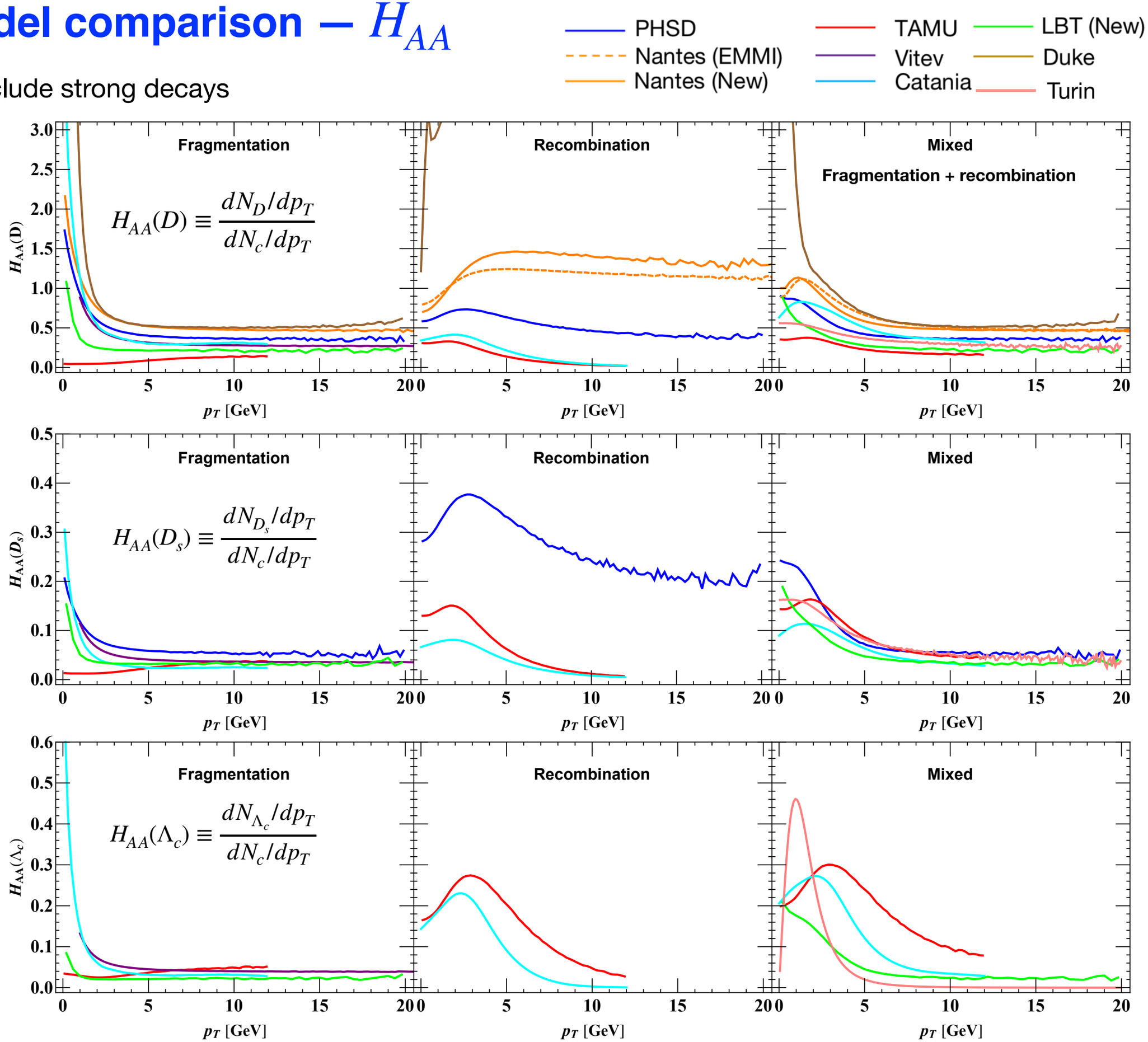


! TAMU: pT of charm quark in the local rest frame; Others in the Lab frame.

- *Huge difference at high pT region (pT>3 GeV)*
- *Total recombination probability ~1.0 at zero pT required by all charm quarks hadronized via recombination at pT~0.*
- $P_{frag.}(p_T) = 1 - P_{coal.}(p_T)$

Model comparison — H_{AA}

Include strong decays



Model comparison — H_{AA}

What we learned:

- *Nothing but the sequence* $H_{AA}(D) > H_{AA}(D_s) > H_{AA}(\Lambda_c)$

Model comparison — H_{AA}

What we learned:

- *Nothing but the sequence* $H_{AA}(D) > H_{AA}(D_s) > H_{AA}(\Lambda_c)$

The large difference may come from the branching ratios between various charmed-hadrons

$$R = \left(\int \frac{dN_c}{dp_T} \times H_{AA} dp_T \right) \Big/ \left(\int \frac{dN_c}{dp_T} dp_T \right)$$

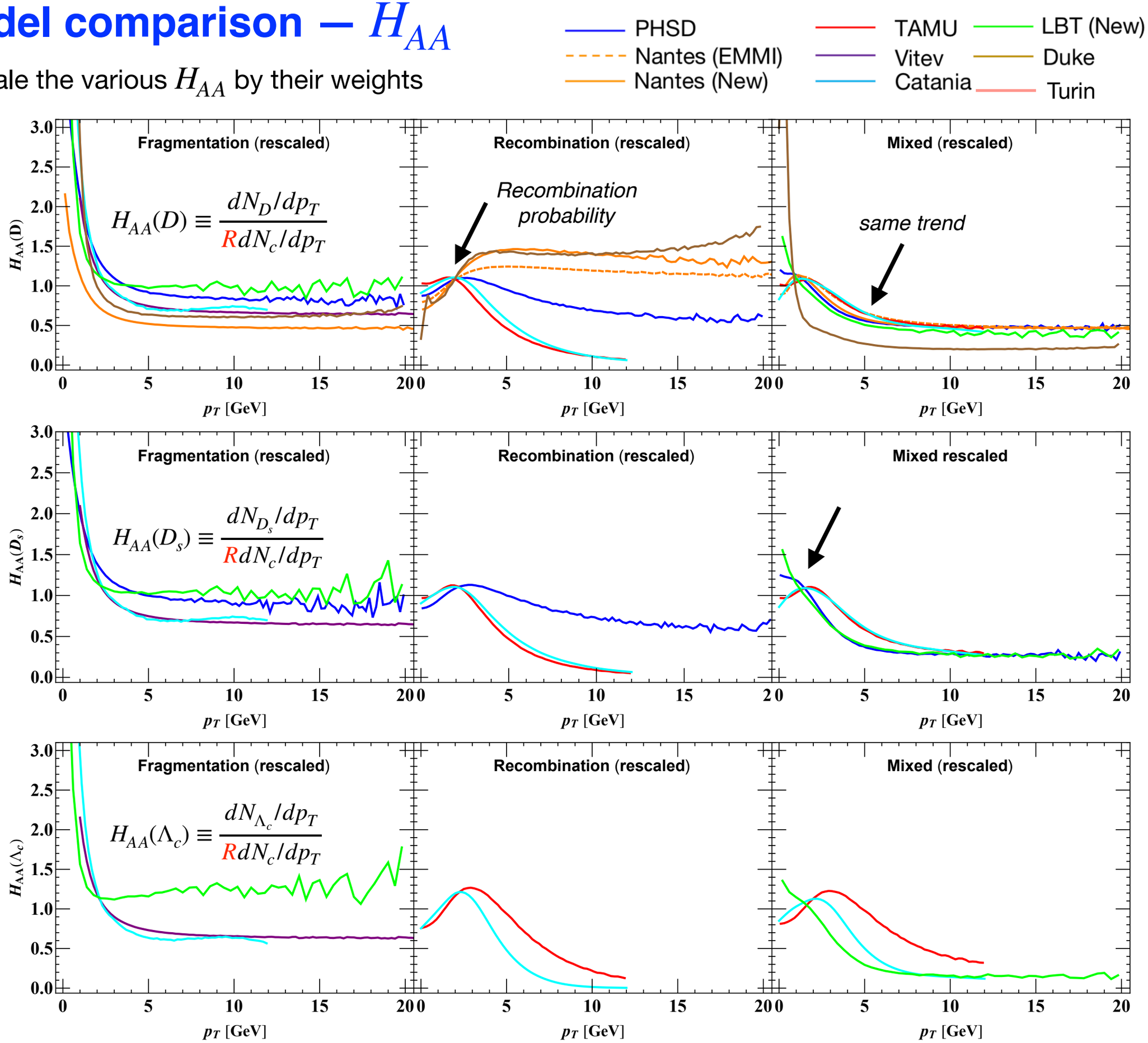
Frag.	D	D_s	Λ_c
Catania	99%	8%	13%
Duke	277%	-	-
LBT	37.8%	5.4%	3%
Nantes	100%	-	-
Nantes (new)	100%	-	-
PHSD	81%	10%	-
TAMU	5.1%	1.4%	2.9%
Vitev	42.1%	5.5%	6%

Recom.	D	D_s	Λ_c
Catania	37.5%	7.3%	19%
Duke	367%	-	-
LBT	-	-	-
Nantes	100%	-	-
Nantes (new)	100%	-	-
PHSD	67%	33%	-
TAMU	30%	13%	22%
Vitev	-	-	-

Mixed.	D	D_s	Λ_c
Catania	76.1%	10.4%	24.2%
Duke	257%	-	-
LBT	54.7%	12.1%	15.3%
Nantes	100%	-	-
Nantes (new)	100%	-	-
PHSD	75%	20%	-
TAMU	35%	15%	25%
Vitev	-	-	-

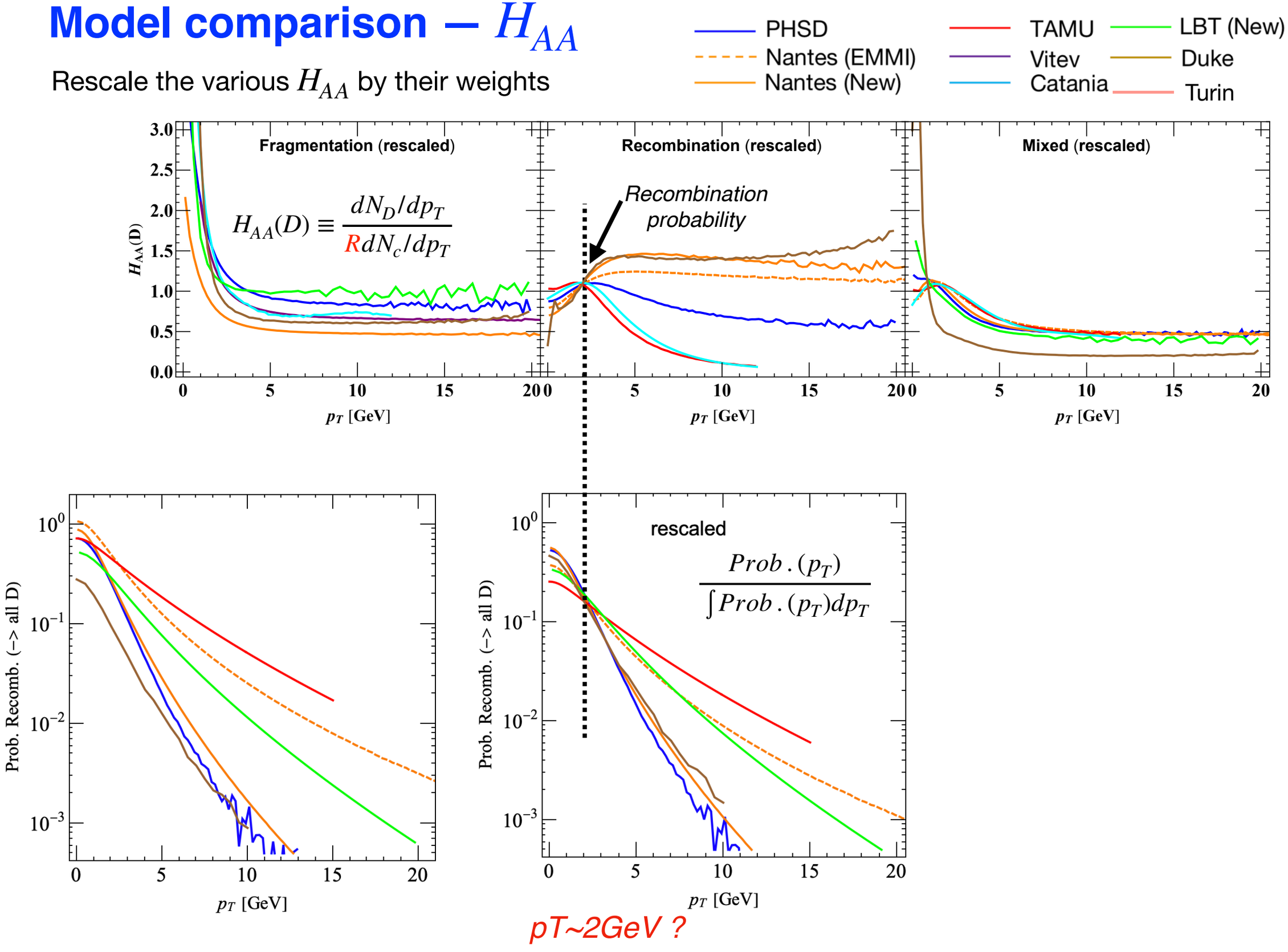
Model comparison — H_{AA}

Rescale the various H_{AA} by their weights

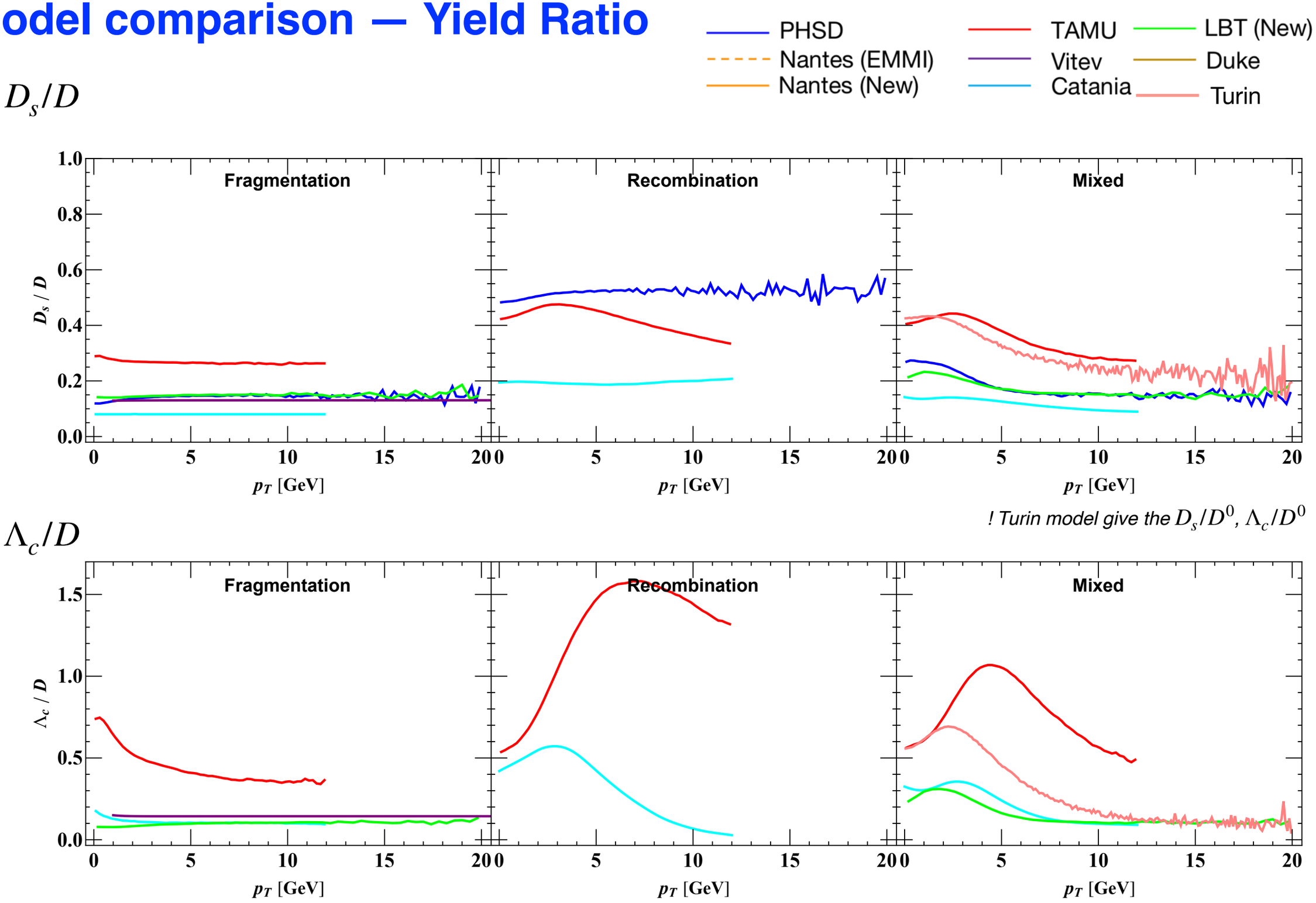


Model comparison — H_{AA}

Rescale the various H_{AA} by their weights



Model comparison — Yield Ratio



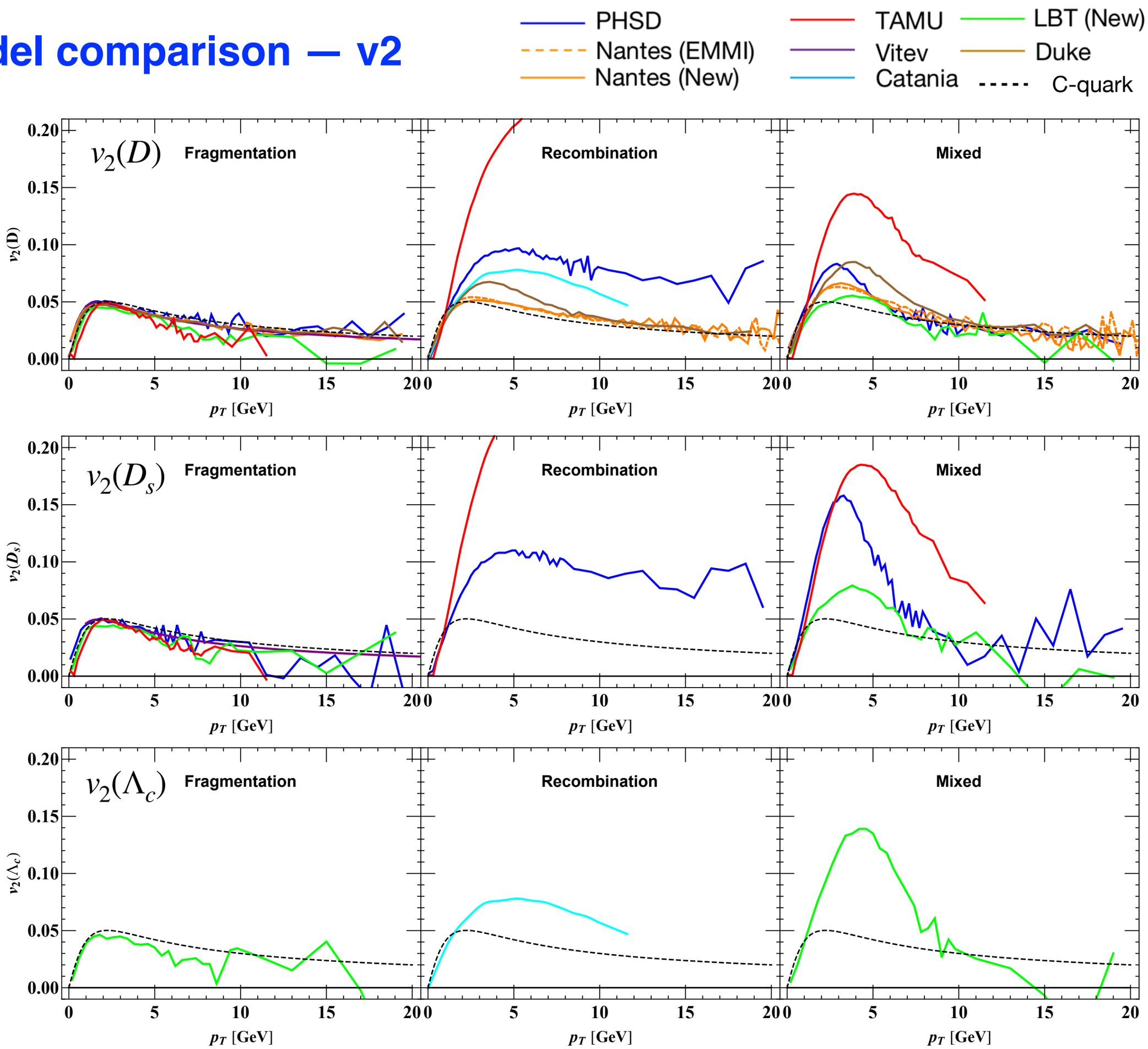
! Turin model give the D_s/D^0, Λ_c/D^0

TAMU model gives a larger Λ_c/D^0 ratio than others; may cause by "missing" baryons

Similar D_s/D, Λ_c/D ratio from fragmentation (except TAMU)

Λ_c/D ratio from recombination is much larger than fragmentation———baryon/meson enhanced

Model comparison — v2



Model comparison — v2

What we learned:

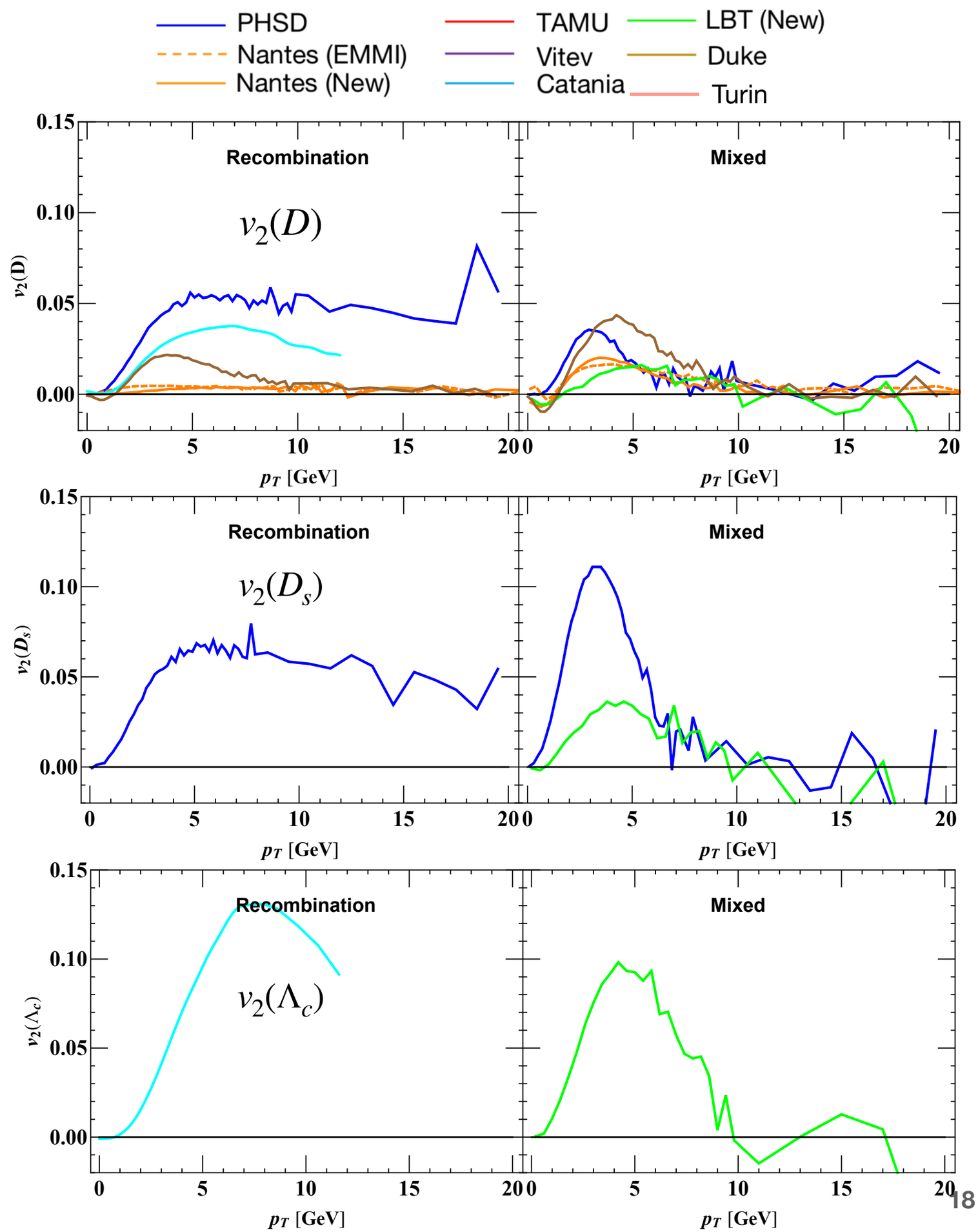
- *Charmed hadrons from the fragmentation have the same flow as the c-quark*
- *Charmed hadrons from the recombination have larger flow than the fragmentation ones and also c-quark; Light quarks make an important role in the v2 from recombination.*
- *Total v2 at low pT almost comes from recombination, while high pt region from fragmentation*
- *The existence of v2 sequence:* $v_2(\Lambda_c) > v_2(D_s) > v_2(D)$.
- *In some models, the results from mixed have a larger v2 than recombinations?*

Model comparison — v2

We take an isotropic c-quark distribution (eliminate the elliptic flow)

$$\frac{dN_c}{dp_T} \times [1 + 2v_2(p_T)\cos(2\phi)]$$

- *v2 from the fragmentation is zero. Elliptic flow fully comes from the recombined light quark/quarks.*



Summary

1. Heavy flavor is a nice probe to study the hadronization mechanism in HIC!

2. Comparing different models is very useful for further understanding the hadronization mechanism!

3. We prepared tasks for different groups with the same bulk and charm distribution functions at FO. After preliminary comparison, we can get the following messages:

- *H_{AA} of D meson seems to have the same trend after being rescaled.*
- *The yield ratio is sensitive to the number of resonances considered.*
- *The existence of v2 sequence: $v_2(\Lambda_c) > v_2(D_s) > v_2(D)$.*
- *Light quarks make an important role in the charmed hadrons v2 from recombination.*

4. What next ?

- *Finish the data collection and figure out the existed "error"*
- *Fix the light sector —(mass, distribution) ?*
- *Exclude the strong decay contribution (Direct produced D^0, D_s, Λ_c)?*
- *Find new observation to compare?*

Many thanks to : Catania, Duke, LBT, Nantes, PHSD, TAMU, Turin, Vitev group

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Thanks for your attention!

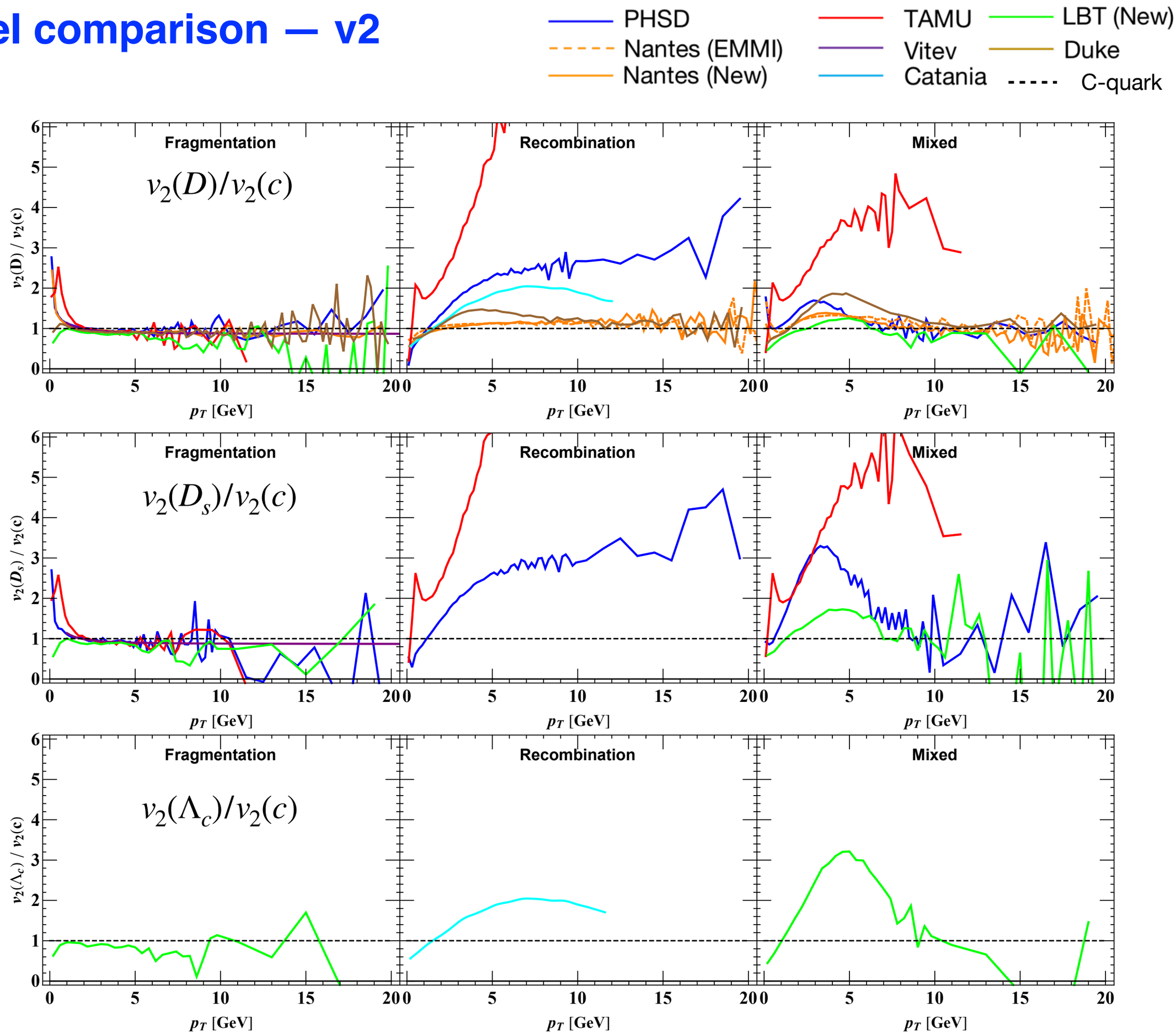
Backup

1. Recombination/Coalescence probability: Wigner function can self-consistently be determined by the wavefunction. If use Gaussian form, how to determine the width parameter? Charge radius? Probability=1 at pt=0?

2. How many charmed hadrons involved, ground state, excited states, “missing” baryons, feed-down fractions?

3. How to consider the charm conservation law?
Does there exist the hadronization sequence?

Model comparison — v2



Model comparison for hadronization

Descriptions:

	Frag.	Recom.	NOTE
Catania	Peterson	Wigner function	S-wave, D+,D0,Ds, D*+,D*0,D*s,\Lambda_c,\Sigma_c
Duke	Pythia 6.4	Wigner function	S-wave,D,D*,\Lambda_c,\Sigma_c,\Xi_c,\Omega_c
LBT	Pythia 6.4	Wigner function	S-wave,P-wave,D,Ds,D*,\Lambda_c
Nantes	Extracted from e^+e^- data	Wigner function	S-wave, D+,D0
Nantes(new)	Extracted from e^+e^- data	Wigner function	S-wave, D+,D0
PHSD	Peterson	Wigner function	S-wave, P-wave(S=1,2) D+,D0,Ds, D*+,D*0,D*s
TAMU	thermal density correlated HQET	RRM	D+,D0,Ds, D*+missing baryons
Turin	Pythia 6.4	Invariant mass	S-wave, D+,D0,Ds,\Lambda_c,\Sigma_c,\Omega_c
Vitev	HQET with energy loss	–	S-wave, D+,D0,Ds, c-baryons

Model comparison for hadronization

Fix the hot medium (freeze-out hypersurface) and charm distribution at freeze-out hypersurface.

- *Given by the Fireball model with b=7fm and T_{fo}=180MeV.*

  H. van Hees, V. Greco, and R. Rapp, Phys. Rev. C 73, 034913 (2006)

- *Uniform distribution in the coordinate space and momentum space is given by EMMI RRTF. (so far, no space-momentum correlation)*

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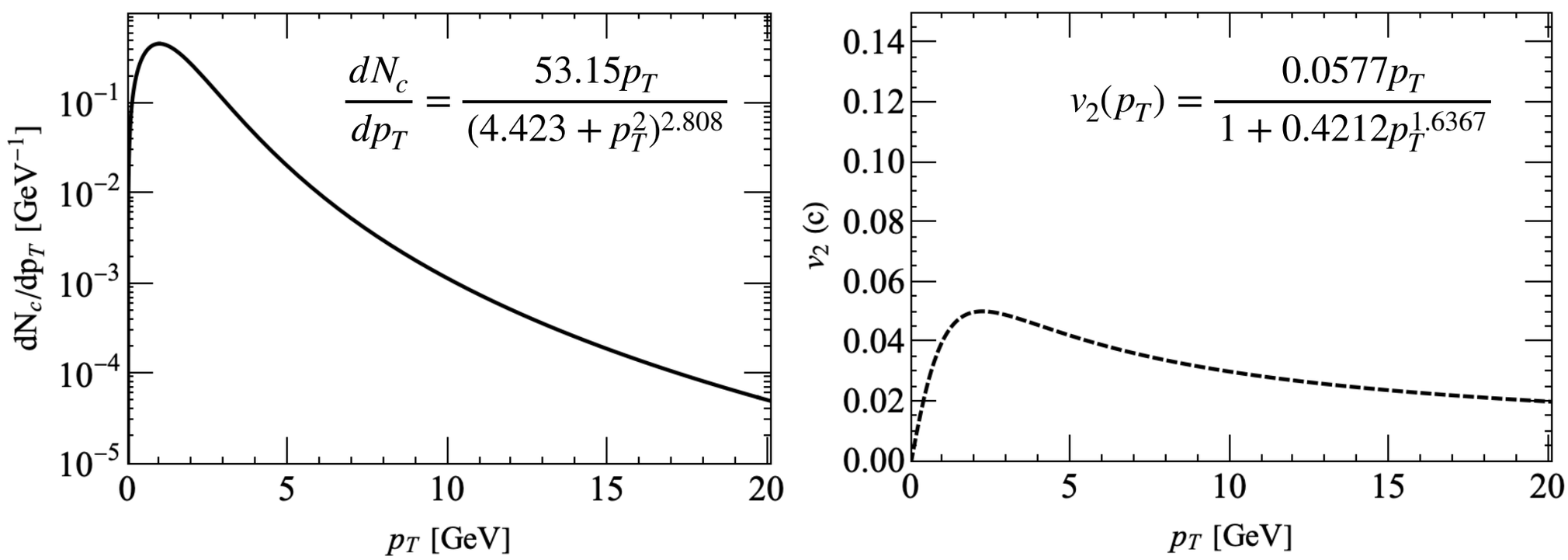

- *No hadronic interaction.*

Model comparison: understanding will go further

The Influence of bulk evolution models on heavy-quark phenomenology #1

Pol Bernard Gossiaux (SUBATECH, Nantes), Sascha Vogel (SUBATECH, Nantes), Hendrik van Hees (Giessen U.), Joerg Aichelin (SUBATECH, Nantes), Ralf Rapp (Texas A-M, Cyclotron Inst. and Texas A-M) et al. (Feb, 2011)

e-Print: 1102.1114 [hep-ph]

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