Novel experimental measurements of heavy flavor resonances and its applications

Jing Wang (MIT)

Workshop on Advancing the Understanding of Non-Perturbative QCD Using Energy Flows
20 September 2022

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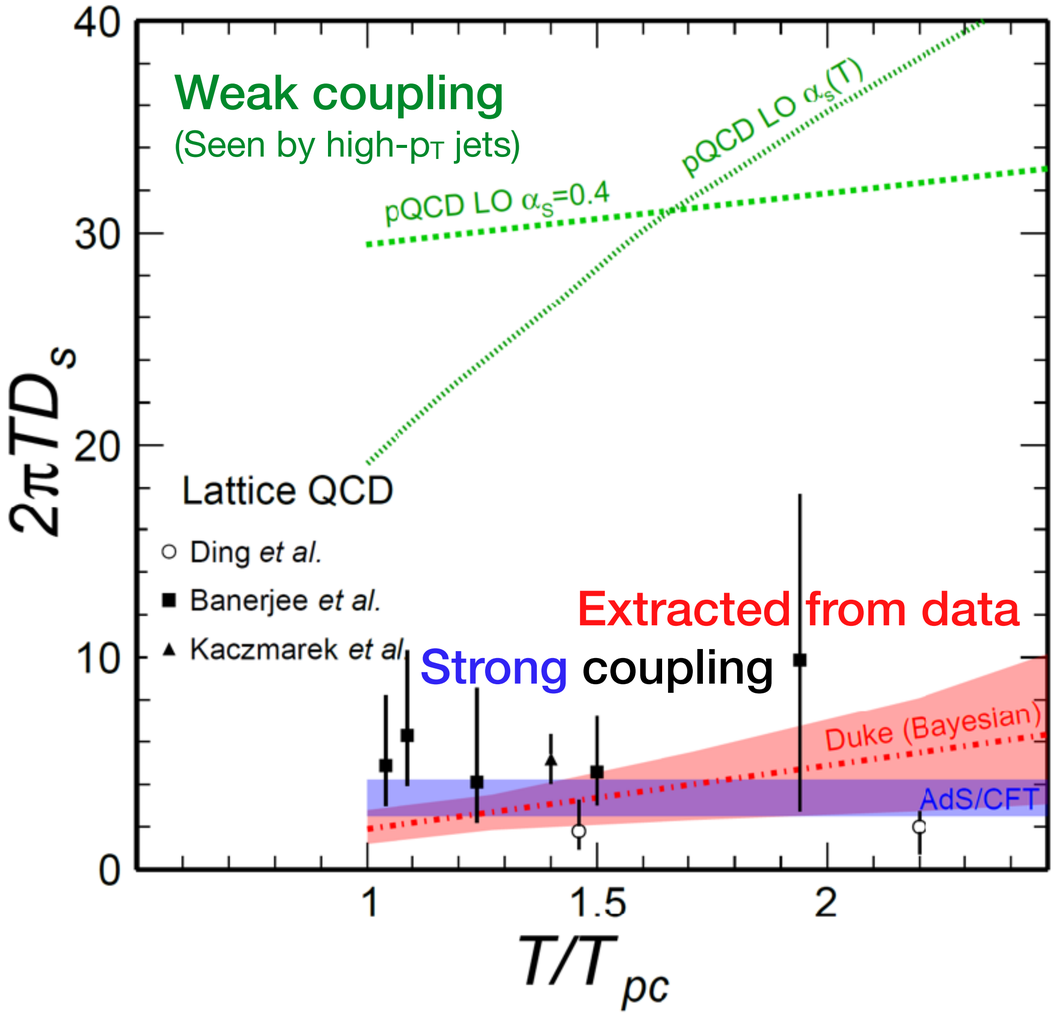
QGP in The Eyes of Heavy Quarks

Heavy quarks: unique low p_T hard probes

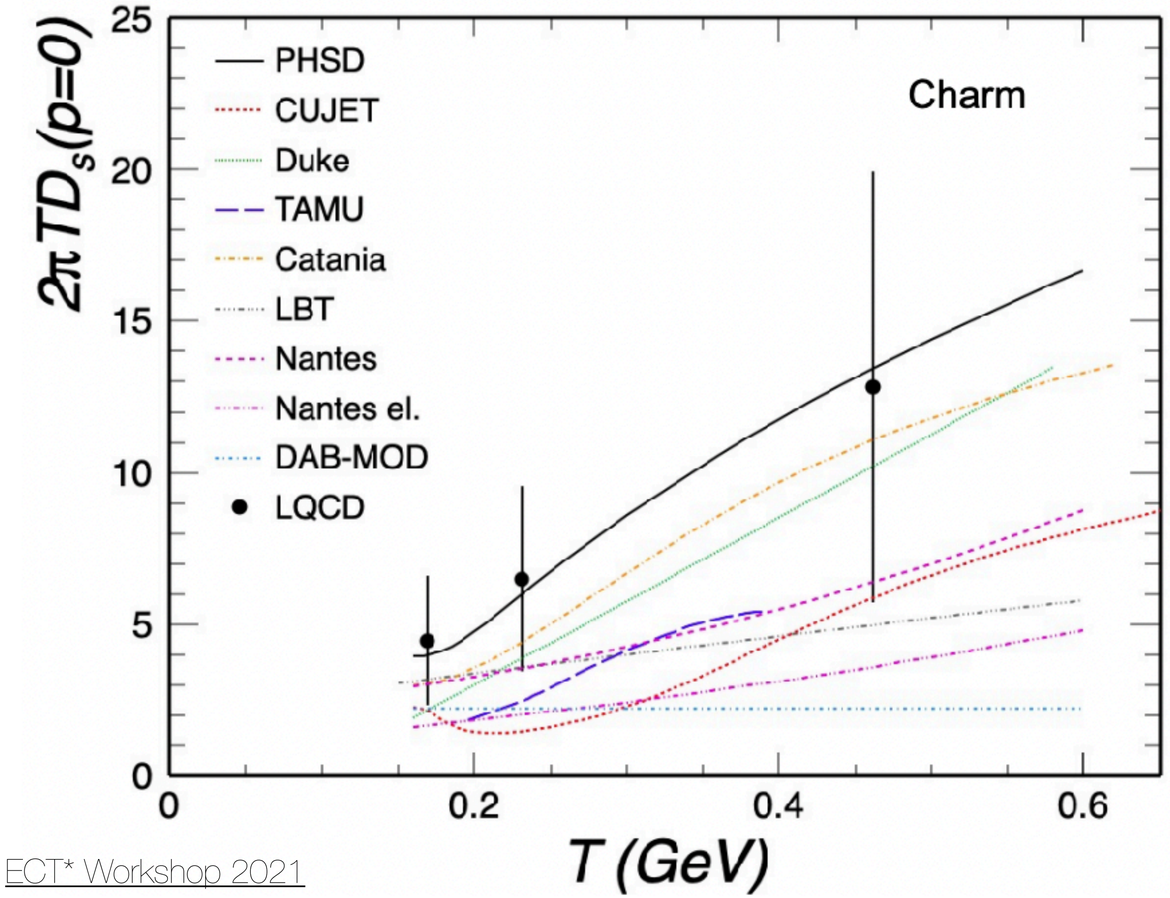
- Characterized by well-defined transport coefficients
  - Diffusion at low p_T
    - Brownian motion ➜ Fokker Planck equation
    - *Diffusion coefficient* D_s

- Data agrees with strong coupling
  - Sensitive to long-range forces probing non-perturbative QCD



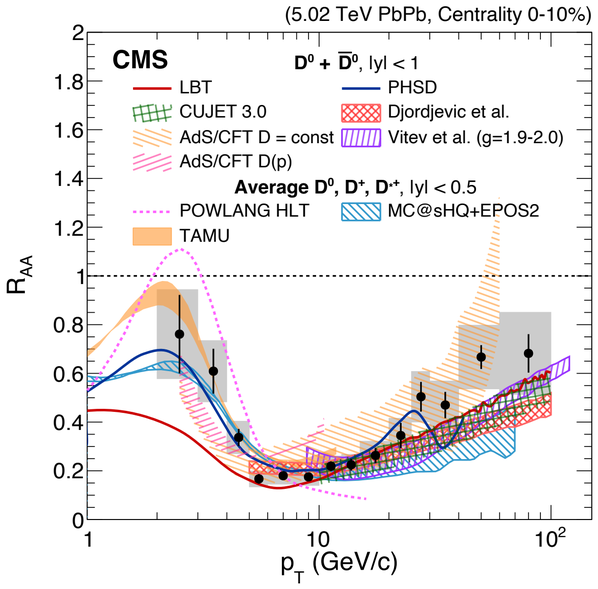
Diffusion Coefficient of Heavy Quarks

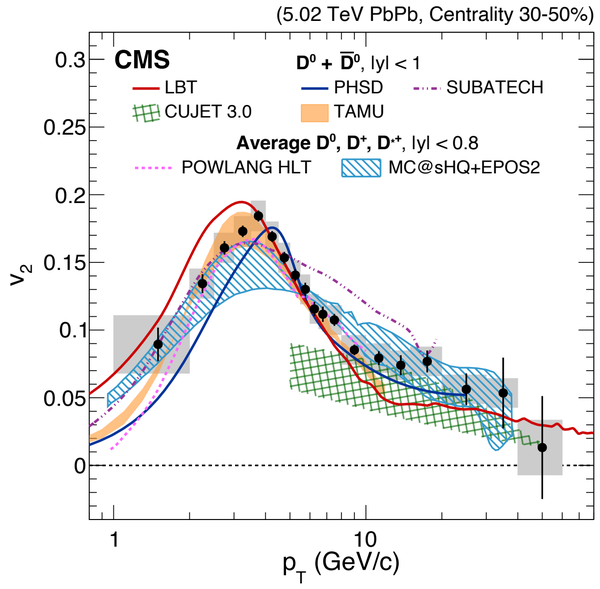
- Current (2021 April) best estimation of D_s to match experimental results
- Spreading coefficient estimation from various theoretical models
- Is it because of poor data precision?

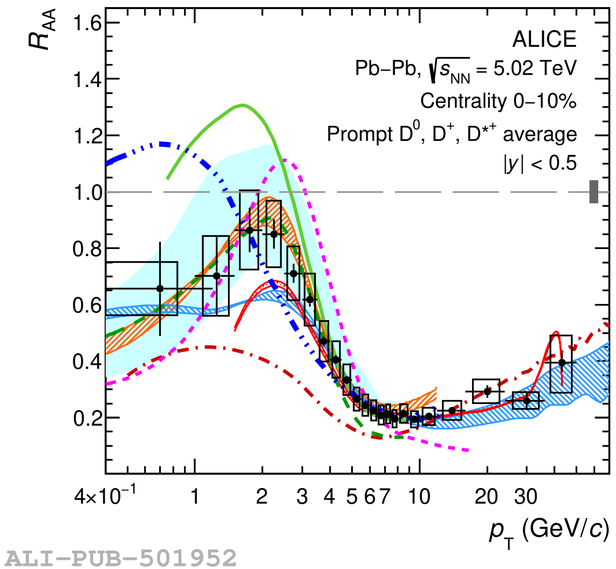


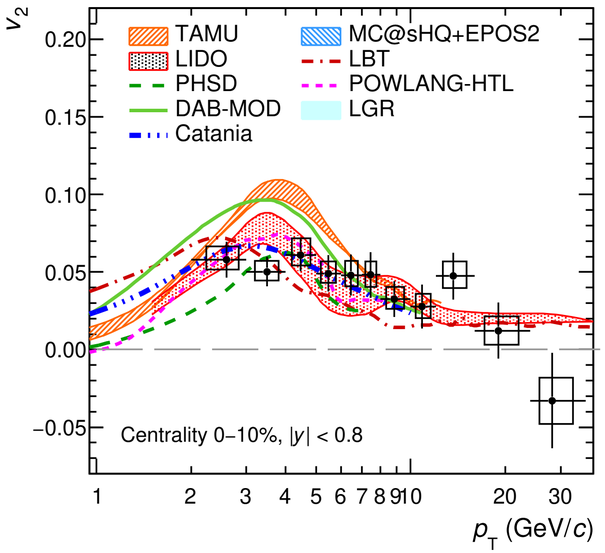
ECT* Workshop 2021

Classic Observables: R_{AA} and v_2









ALI-PUB-501952

- Similar R_{AA}, v_2 calculations with very different underlying mechanisms and components in these models
- Uncertainties in theoretical calculations
- Not (only) because of limited data precision

PLB 816 (2021) 136253
PLB 813 (2021) 136054
PLB 782 (2018) 474
JHEP 01 (2022) 174

Theoretical Model Calculation

	Ingredients
Initial production	Hard scattering spectra
	nPDF
Bulk evolution simulation	Initial condition
	Hydro vs. kinetic, viscosity, EoS
	Parameters (e.g. T_c, τ_0)
HQ-medium interaction *Characterized by transport coefficients*	α_s, Debye mass m_D, n_f, M_Q, K factor
	Thermal parton mass
	Inclusion of inelastic interactions (Collitional vs. radiative Eloss)
	Boltzmann vs. Langevin eq.
Hadron phase	Hadronization
	Rescatterings

- Flexibility in nearly all ingredients

➡ Constraining each ingredient
  - Necessary for precise D_s extraction
  - Requires new observables in addition to traditional R_{AA} and v_2

Impact and Constraint of Each Ingredient

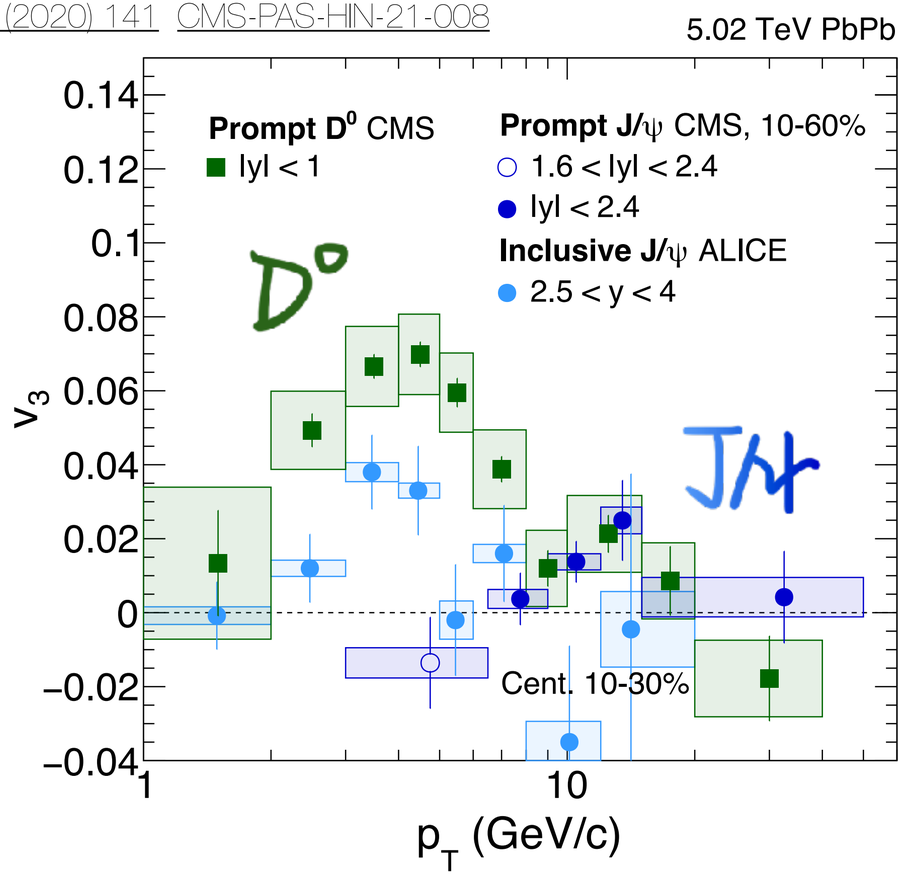
	Ingredients	Impact	Experimental Constraints
Initial production	Hard scattering spectra	Small	High precision measurements in pp
	nPDF	Medium	Common set, production in pA
Bulk evolution simulation	Initial condition		
	Hydro vs. kinetic, viscosity, EoS		
	Parameters (e.g. T_c, τ_0)		
HQ-medium interaction *Characterized by transport coefficients*	α_s, Debye mass m_D, n_f, M_Q, K factor		
	Thermal parton mass		
	Inclusion of inelastic interactions (Collitional vs. radiative Eloss)		
	Boltzmann vs. Langevin eq.		
Hadron phase	Hadronization		
	Rescatterings		

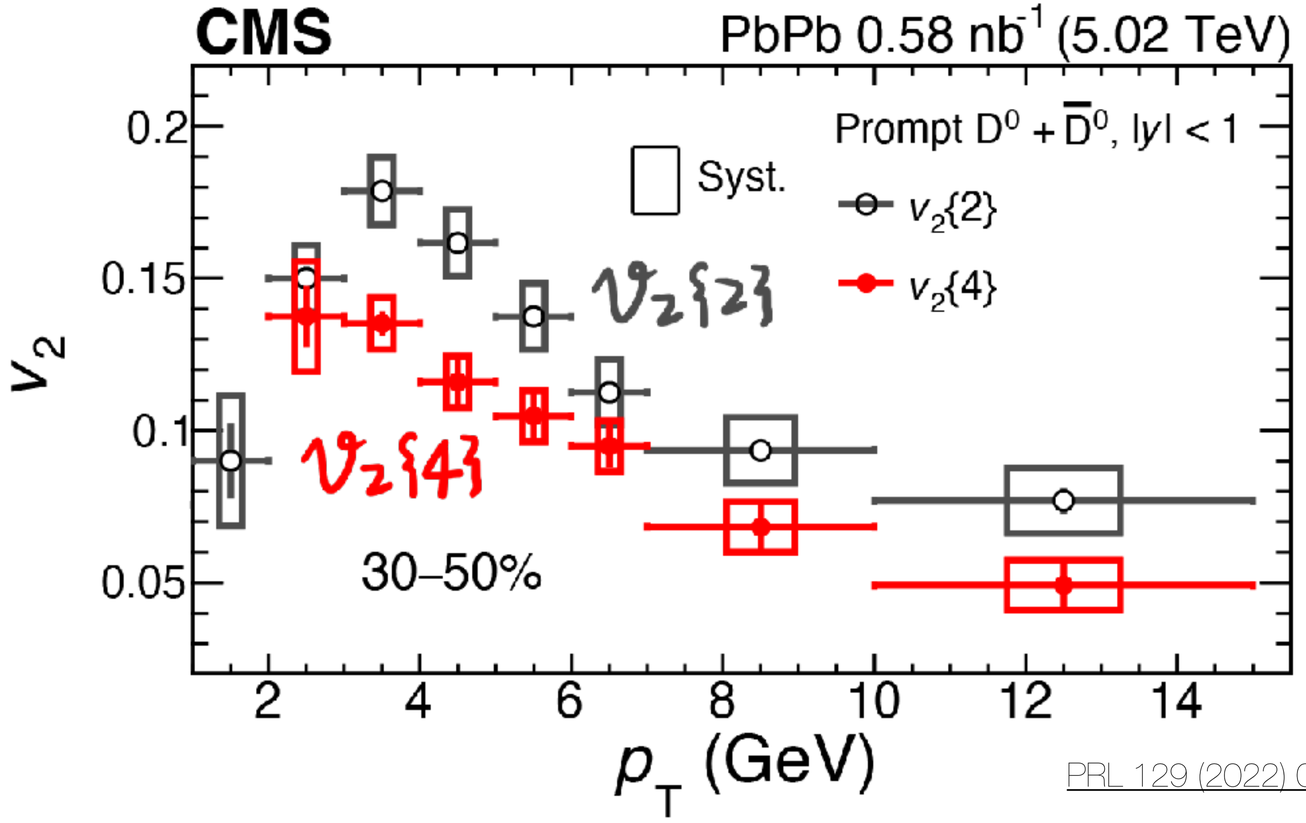
- Initial condition
  - Initial energy distribution + its fluctuations
  - Initial tilt of matter
  - With or without initial transverse flow

Constrain Initial Condition: Fluctuations

PLB 816 (2021) 136253

JHEP 10 (2020) 141 CMS-PAS-HIN-21-008

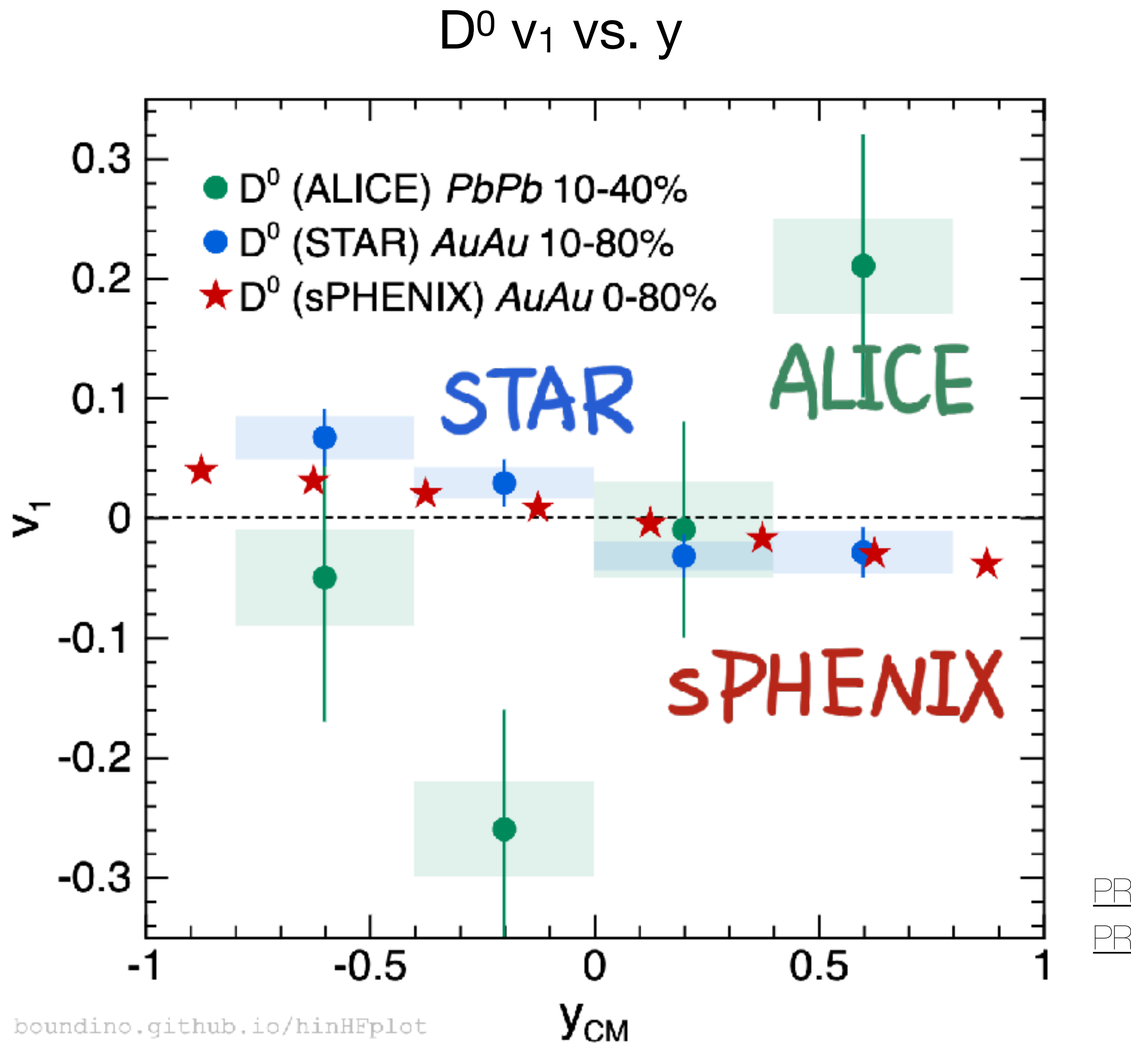




PRL 129 (2022) 022001

- Probe fluctuations via high-order v_n and multiple-particle correlation $v_2\{4\}$ measurements
  - Indirect constraints ➜ depends on other ingredients of models

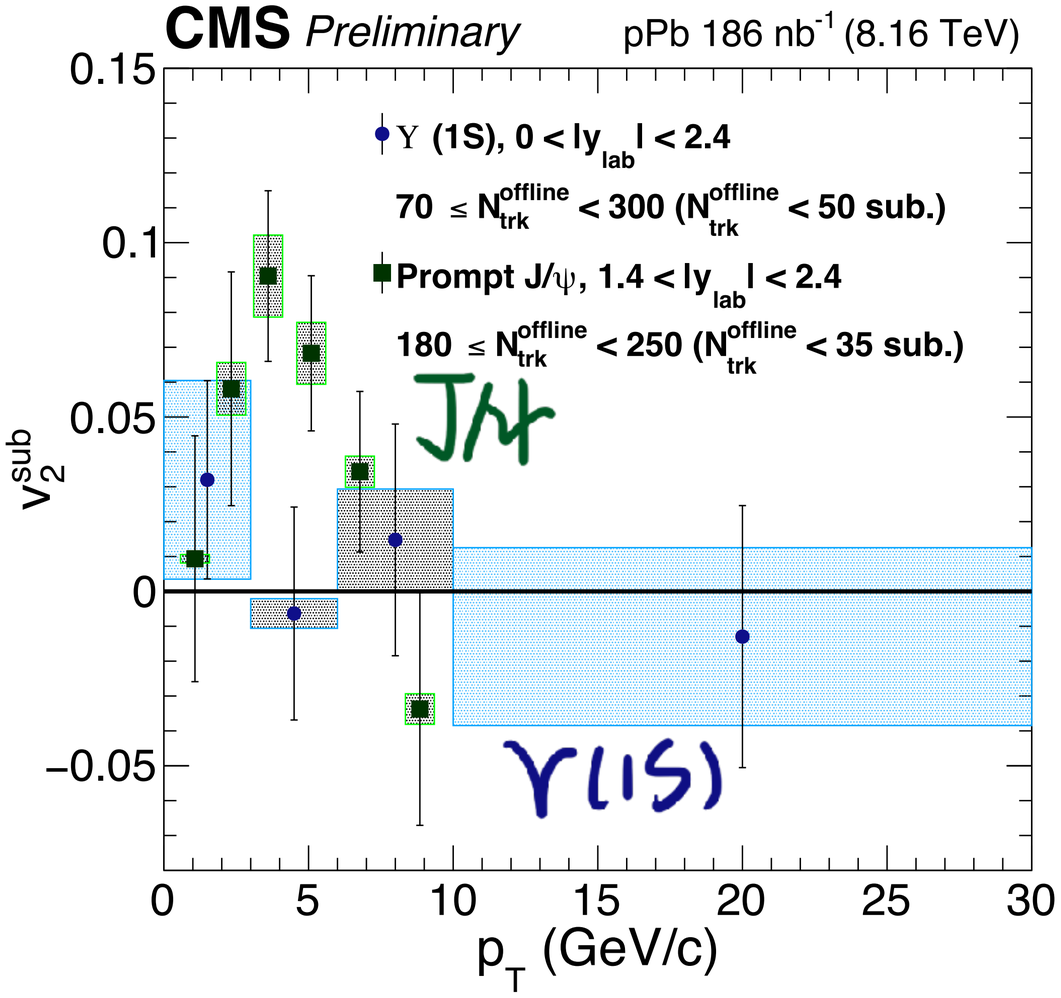
Constrain Initial Condition: Tilt



- Heavy quarks produced earlier
  - Larger Δv_1 signal sensitive to initial EM field and tilt
- Opposite slope of Δv_1 in ALICE and STAR?
  - High precision of sPHENIX and next run of LHC may draw the conclusion

PRL 125 (2020) 022301
PRL 123 (2019) 162301

Constrain Initial Condition: Initial Correlation

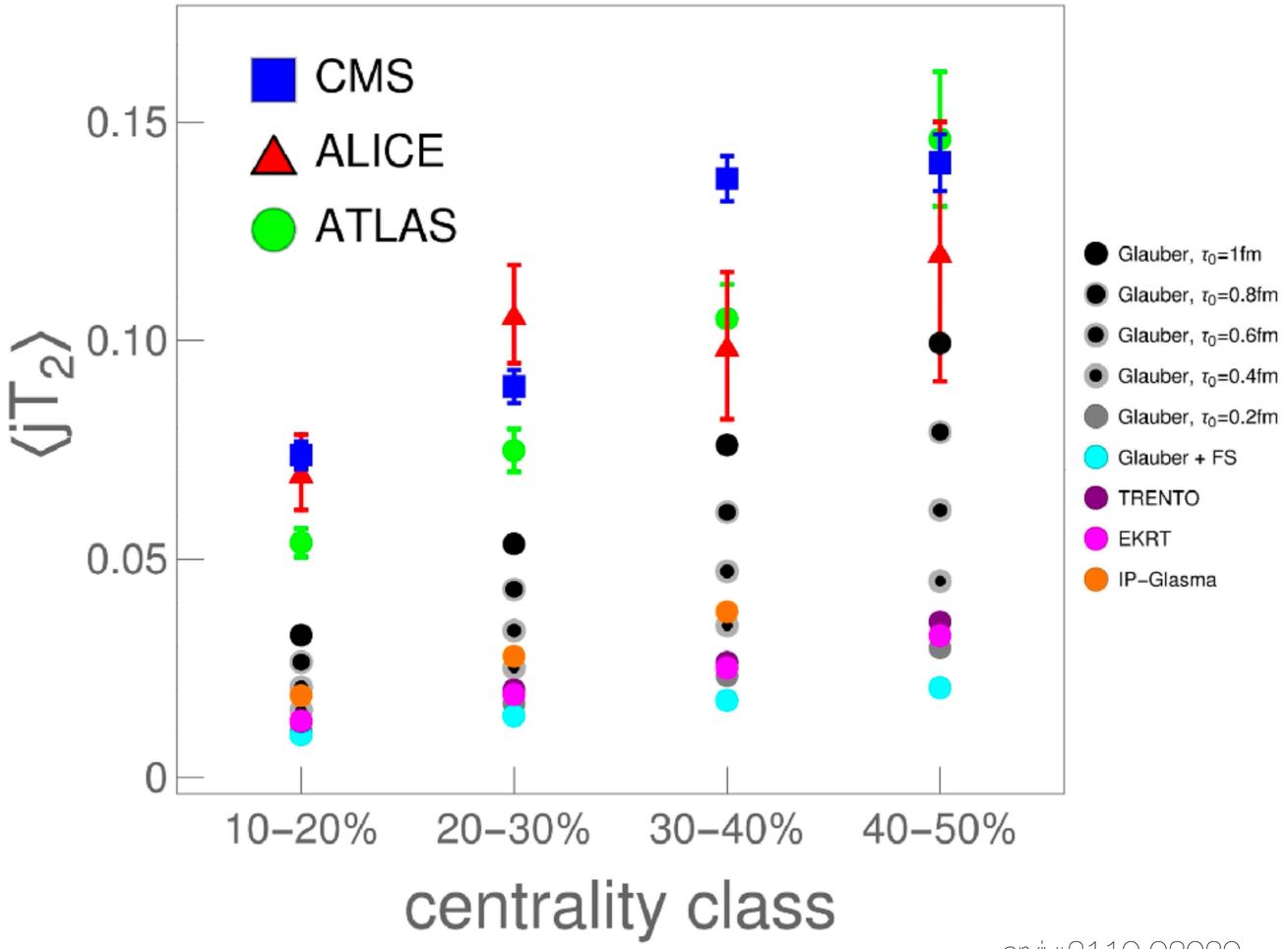


- Is there initial transverse flow?
  - Supposed to be constrained in small systems
  - However, final state effects may be convoluted
  - CGC predicts similar J/ψ and Υ(1S) v_2 in pPb
    ← not supported by data

CMS-PAS-HIN-21-001
PRD 102 (2020) 034010

Constrain Medium Expansion

- Mainly constrained by light flavor observables
- Maybe new observable, e.g.
  - $v_2/(1\text{-}R_{AA})$ (~ $\langle jT_2 \rangle$) is expected to saturate at high p_T and be sensitive to medium simulation
  - Provide test in HF sector



arxiv:2110.02029

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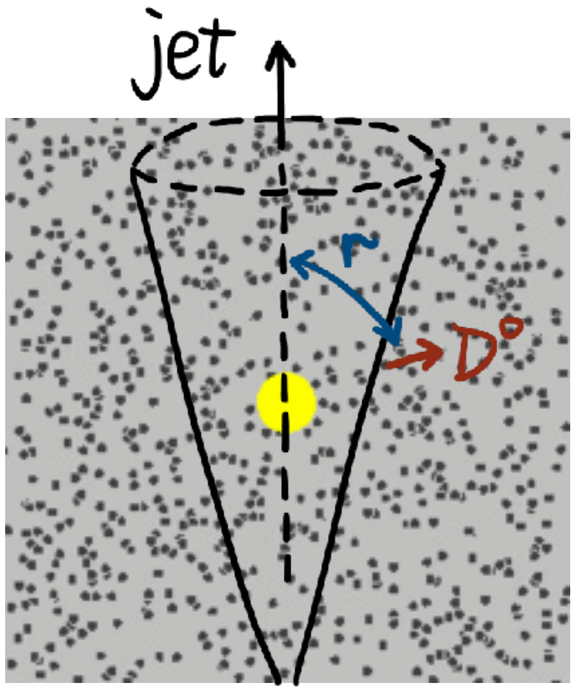
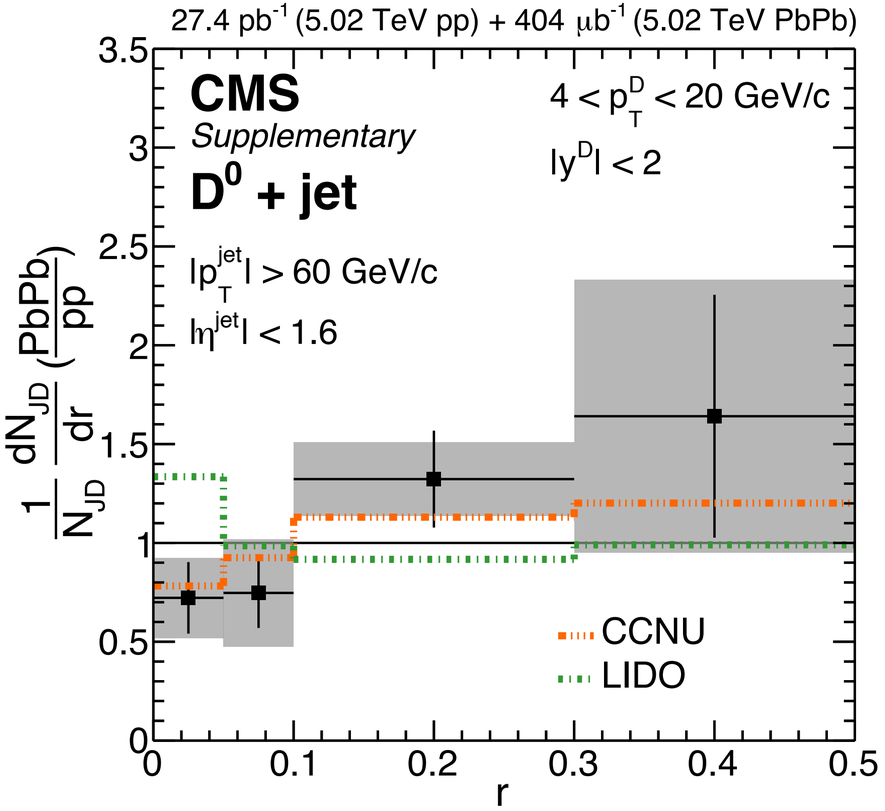
Bulk evolution simulation	Initial condition	Medium	High order v_n, multi-particle correlation, v_1
	Hydro vs. kinetic, viscosity, EoS	Medium	Soft probes, High p_T R_{AA} and v_2
	Parameters (e.g. T_c, τ_0)	Small	
HQ-medium interaction *Characterized by transport coefficients*	α_s, Debye mass m_D, n_f, M_Q, K factor		
	Thermal parton mass		
	Inclusion of inelastic interactions (Collitional vs. radiative Eloss)		
	Boltzmann vs. Langevin eq.		
Hadron phase	Hadronization		
	Rescatterings		

- The way how HQ-medium interaction is implemented affects the coefficient extraction

Constrain Thermal Parton Mass (1/2)

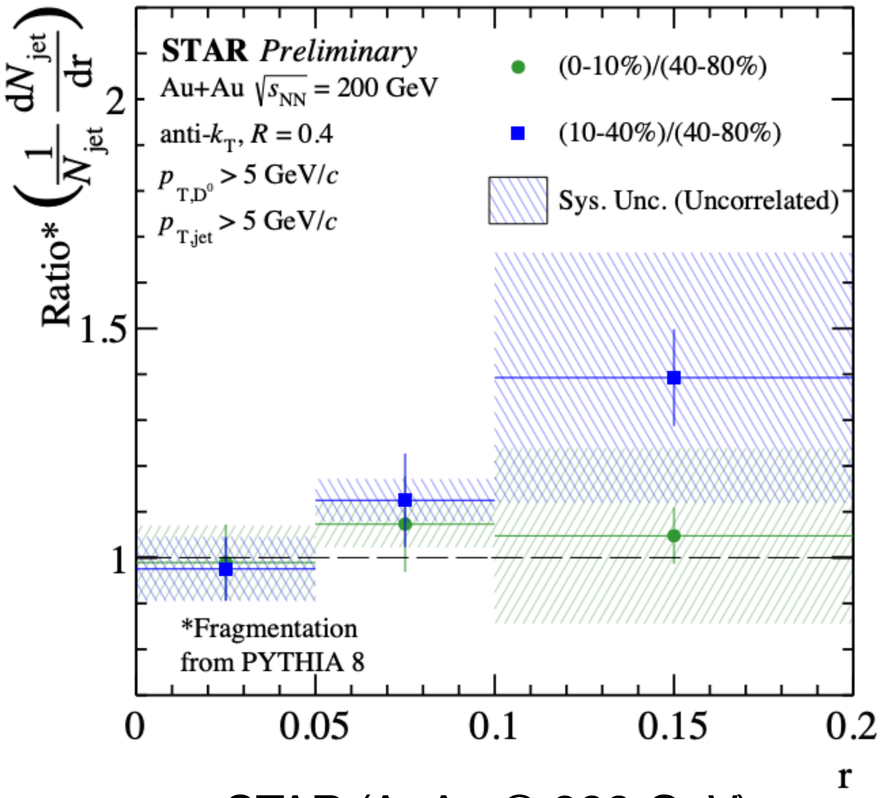
- Observables sensitive to thermal parton mass
  - Angular correlations between D-jet, D-h, D-$\bar{D}$, D-γ
    - Reflect angular distribution of HQ-parton scattering





PRL 125 (2020) 102001

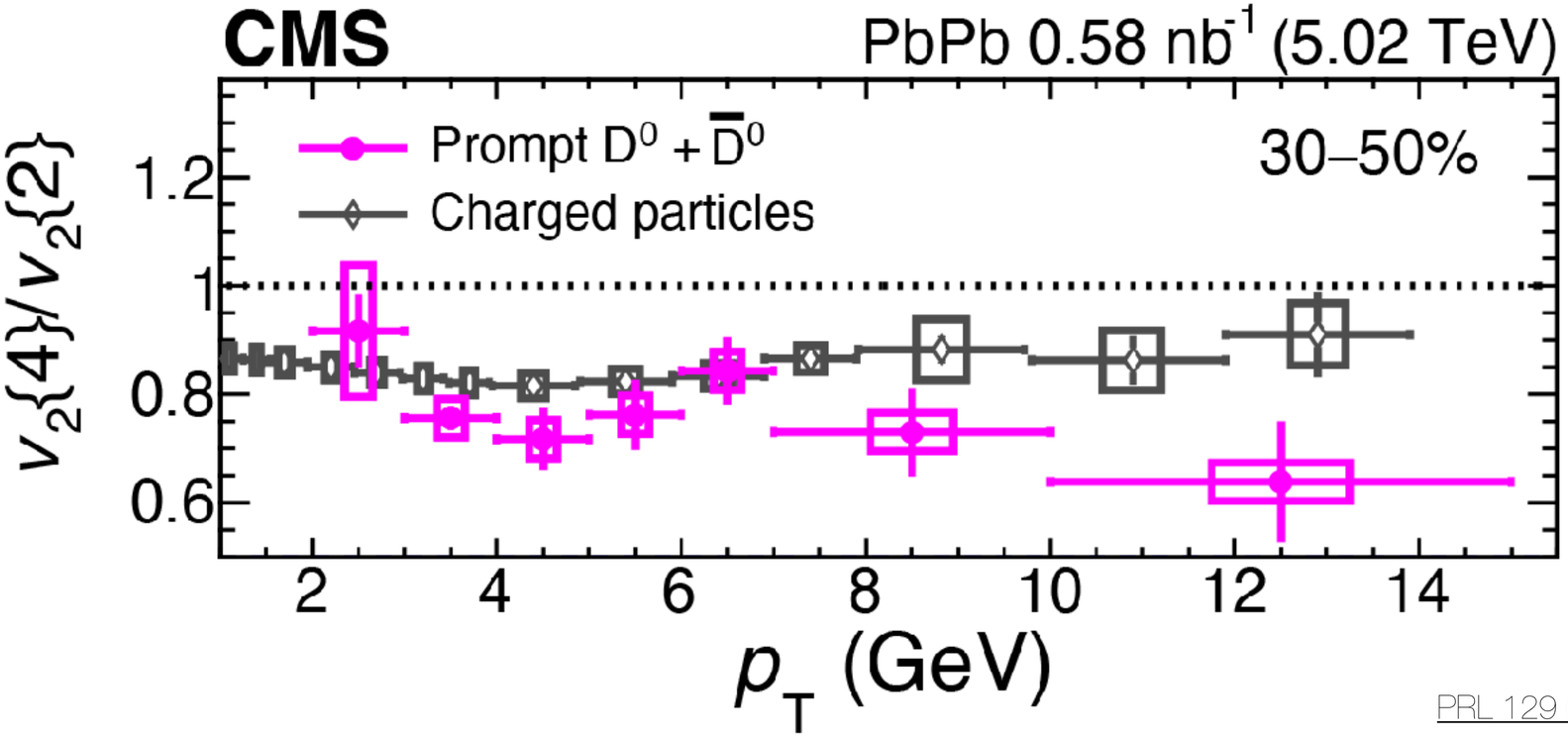
CMS (PbPb @ 5 TeV)



STAR (AuAu @ 200 GeV)

Constrain Thermal Parton Mass (2/2)

- Observables sensitive to thermal parton mass
  - Energy loss fluctuation
    - Flow fluctuation ($v_2\{4\}/v_2\{2\}$) of D^0 to probe fluctuations of energy loss
    - Different from light flavors for which only initial geometry fluctuations dominate



PRL 129 (2022) 022001

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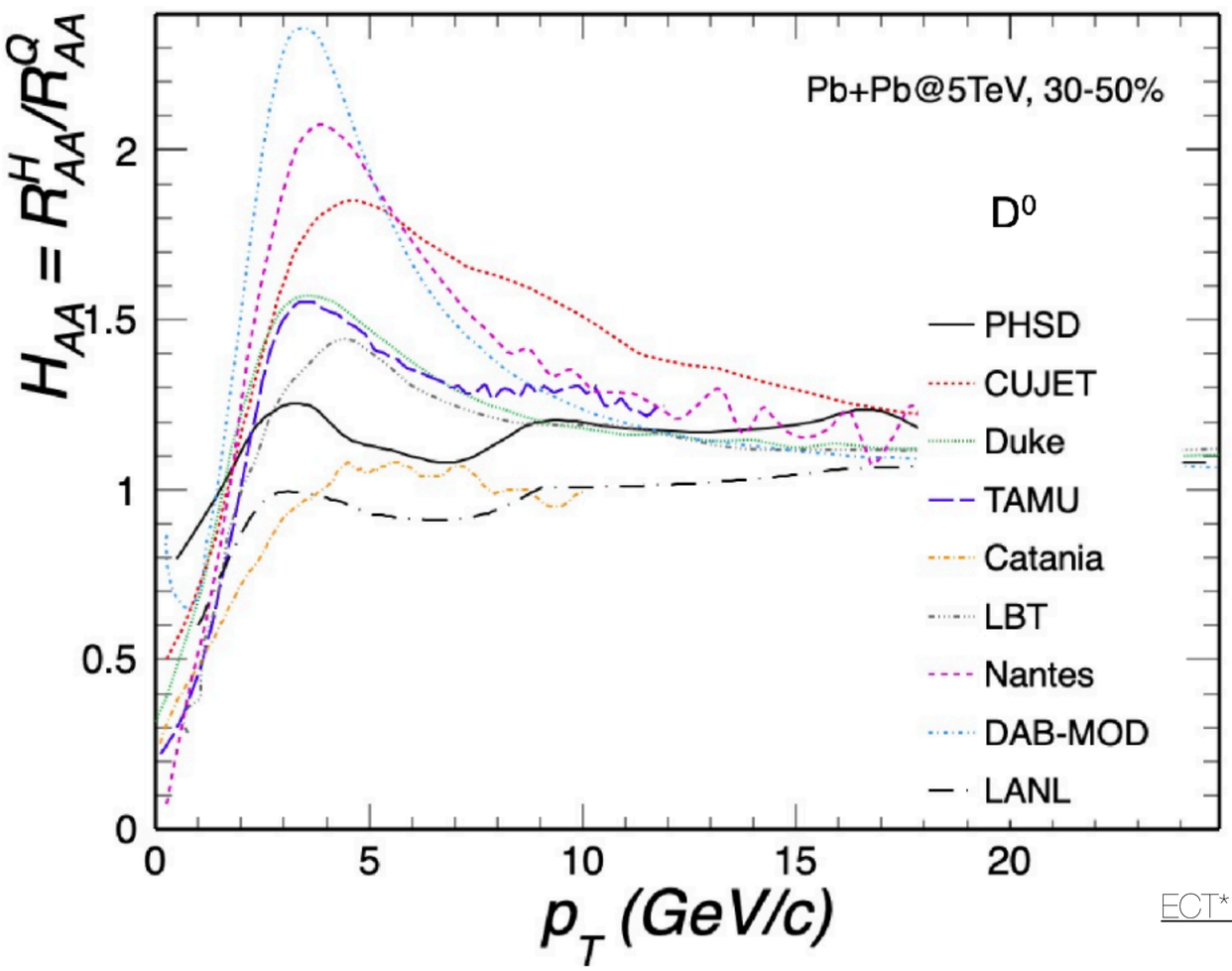
	Parameters (e.g. T_c, τ_0)	Small	
HQ-medium interaction *Characterized by transport coefficients*	α_s, Debye mass m_D, n_f, M_Q, K factor		
	Thermal parton mass	Large	D-h/jet/$\bar{D}$/γ angular correlation, energy loss fluctuation Full p_T range, full flavor dependence
	Inclusion of inelastic interactions (Collitional vs. radiative Eloss)	Large	
	Boltzmann vs. Langevin eq.	Small	Beauty not sensitive
Hadron phase	Hadronization		
	Rescatterings		

Impact and Constraint of Hadronization

D meson R_{AA} / c-quark R_{AA}



- Largest uncertainty from hadronization
- Constrained by strangeness, baryon and exotica measurements
- Also look for observables not sensitive to hadronization
  - e.g. low p_T heavy flavor jets

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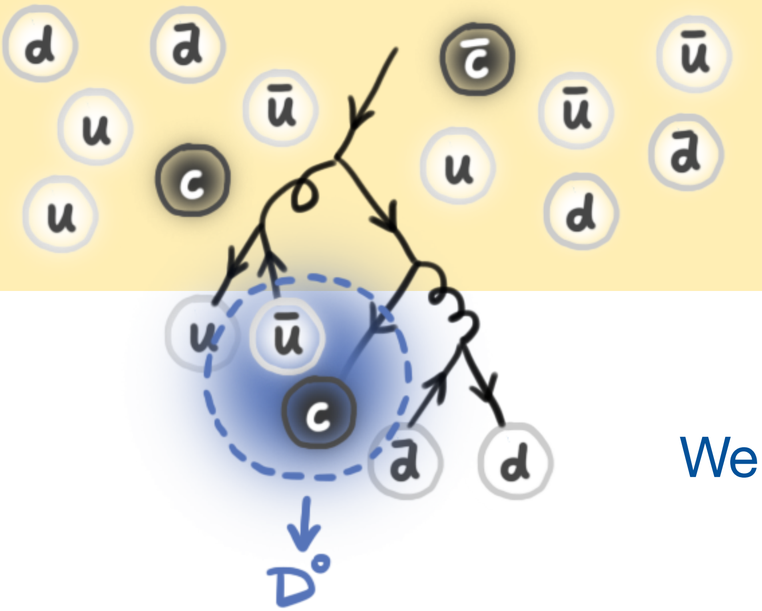
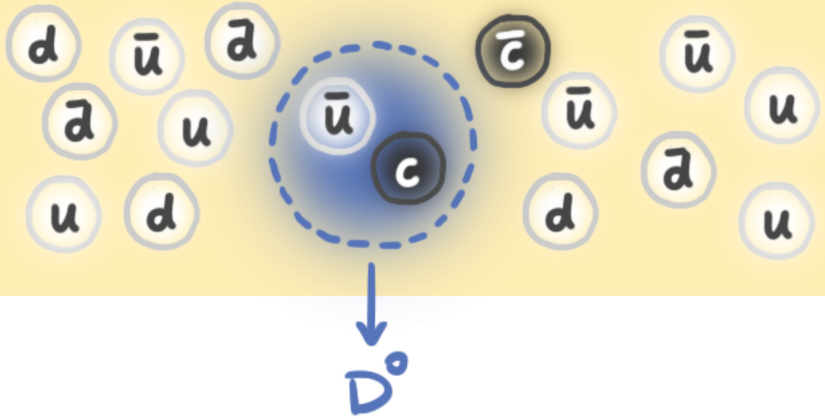
In-medium Hadronization

QGP

Fragmentation
(High-p_T)



Coalescence
(Low-p_T)



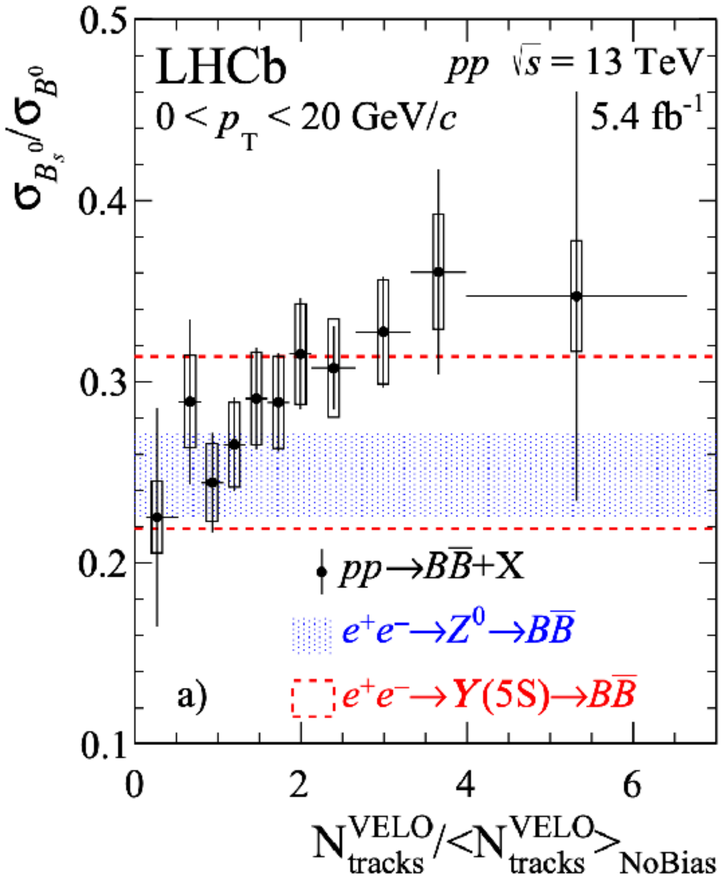
- Universality of fragmentation

We are not sure about:

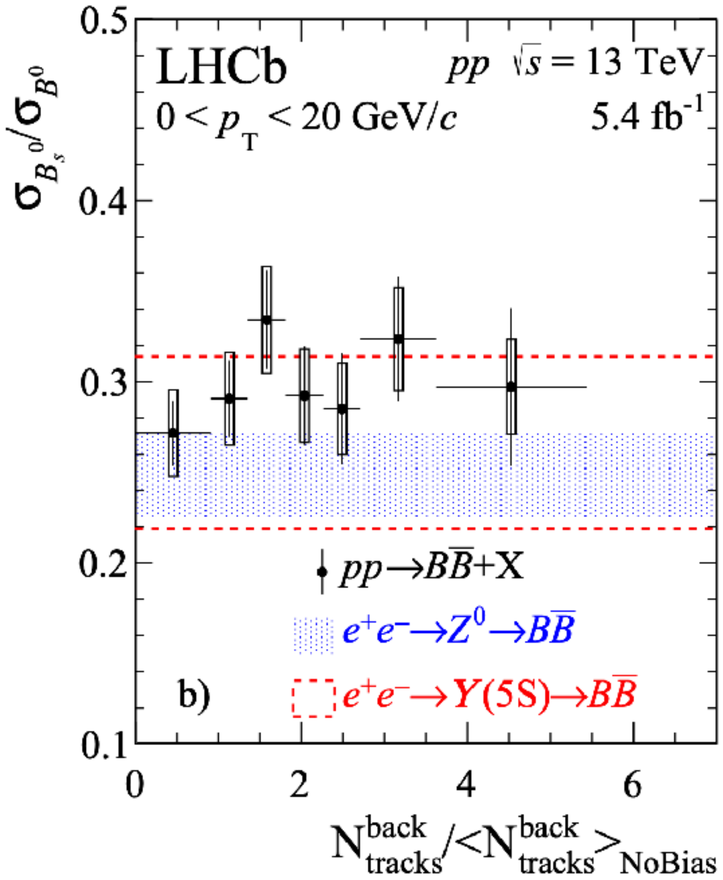
- Instantaneous assumption
  ➜ Instantaneous coalescence model (ICM)
  ➜ Resonance recombination model (RRM)
- Parameters (thermal quark m_q, width parameter, global normalization, …)

Strange-HF Mesons in pp Collisions

B_s/B^0: Multiplicity counted on both sides

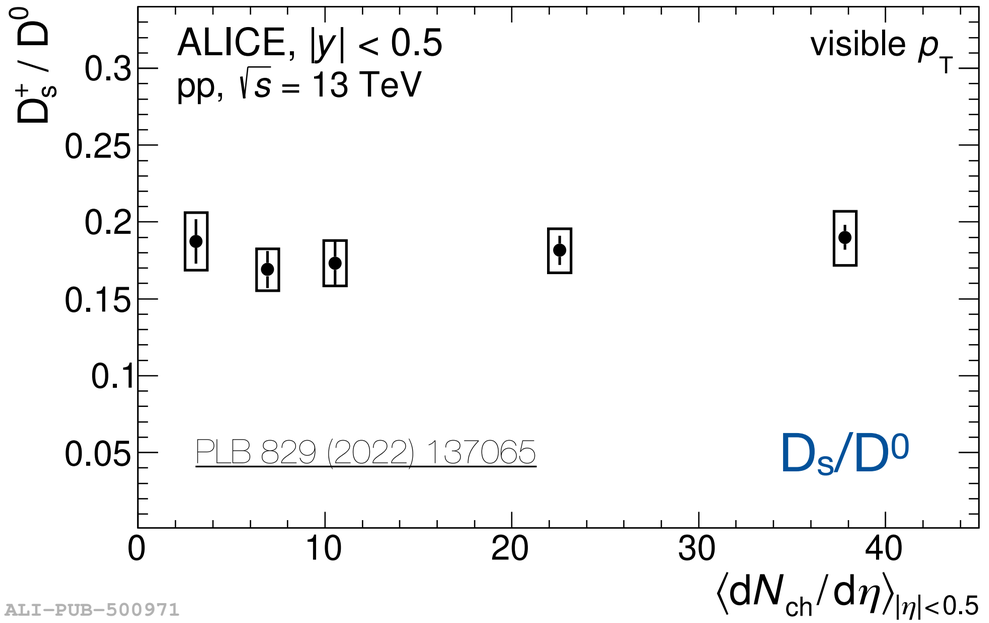


B_s/B^0: Multiplicity counted only on back side



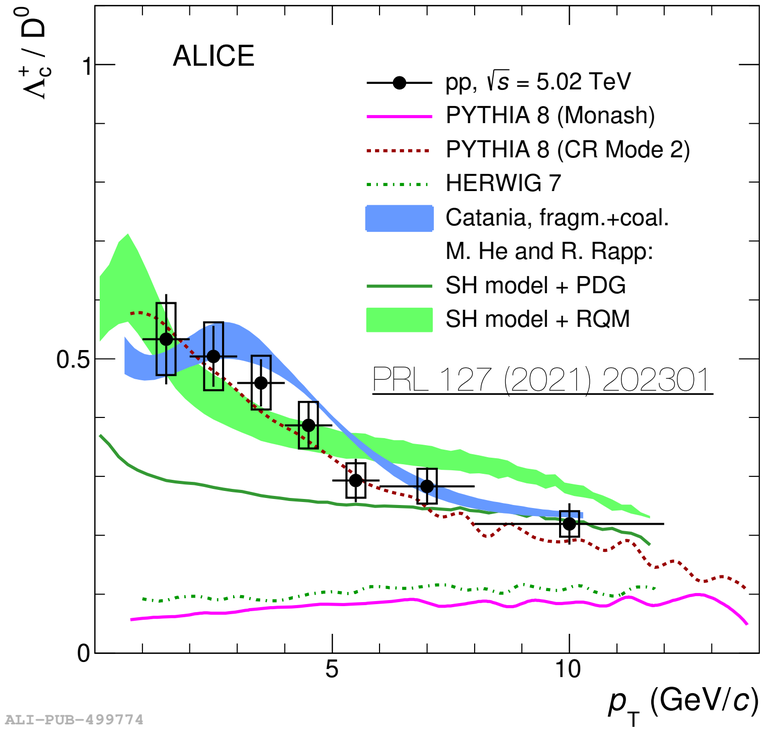
arXiv:2204.13042

- Increased B_s/B^0 vs. multiplicity
  - But not observed in D_s/D^0?
- The dependence disappears when multiplicity is counted in back side
  - Imply it can only feel the local color environment?



Charm Baryons in pp Collisions (1/2)

	Λ_c^+ (udc)
Monash	✘
CR-BLC	✔
Catania	✔
QCM	✔
SHM + RQM	✔



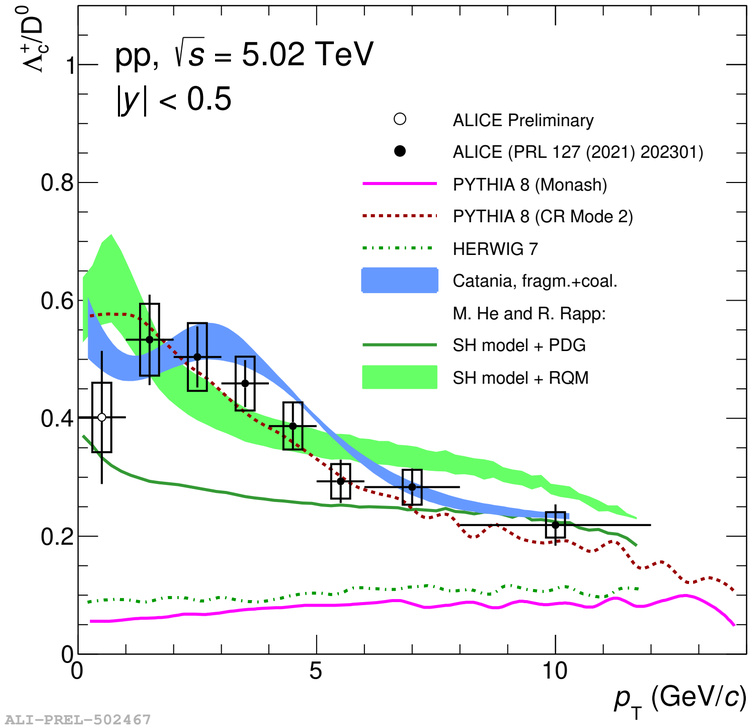
- Modification (wrt e^+e^-) happens in pp
- Several efforts to describe the enhancement
  - Color reconnection
  - Recombination in pp as well
  - Additional excited baryons than PDG

Charm Baryons in pp Collisions (2/2)

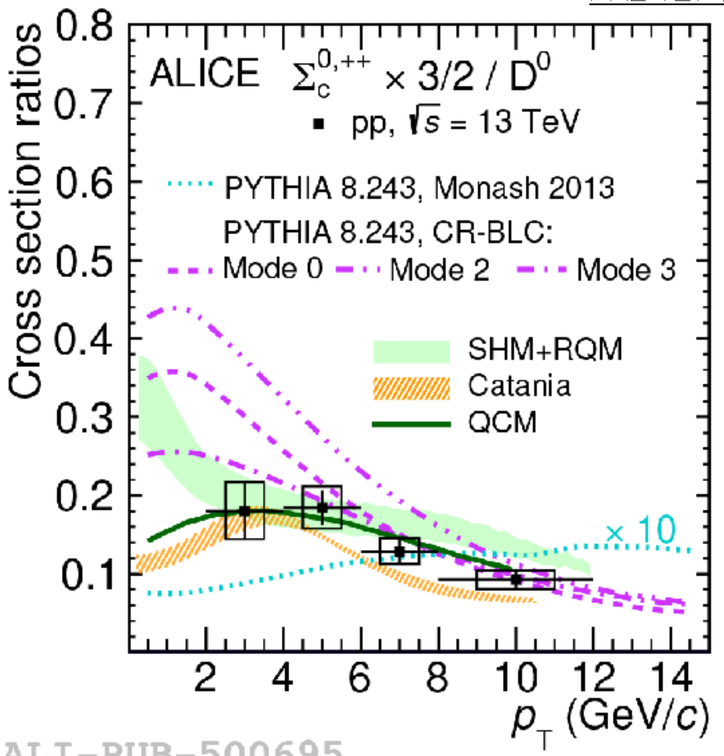
X/D^0	Λ_c^+ (udc) (p_T > 1 GeV)	Λ_c^+ (udc) (p_T < 1 GeV)	Σ_c (uuc/ddc)	Ξ_c^0 (dsc)
Monash	✘	✘	✘	✘
CR-BLC	✔	◥	◥	✘
Catania	✔	◥	◥	◥
QCM	✔	-	✔	✘
SHM + RQM	✔	◥	✔	✘

* Collected by L. Vermunt

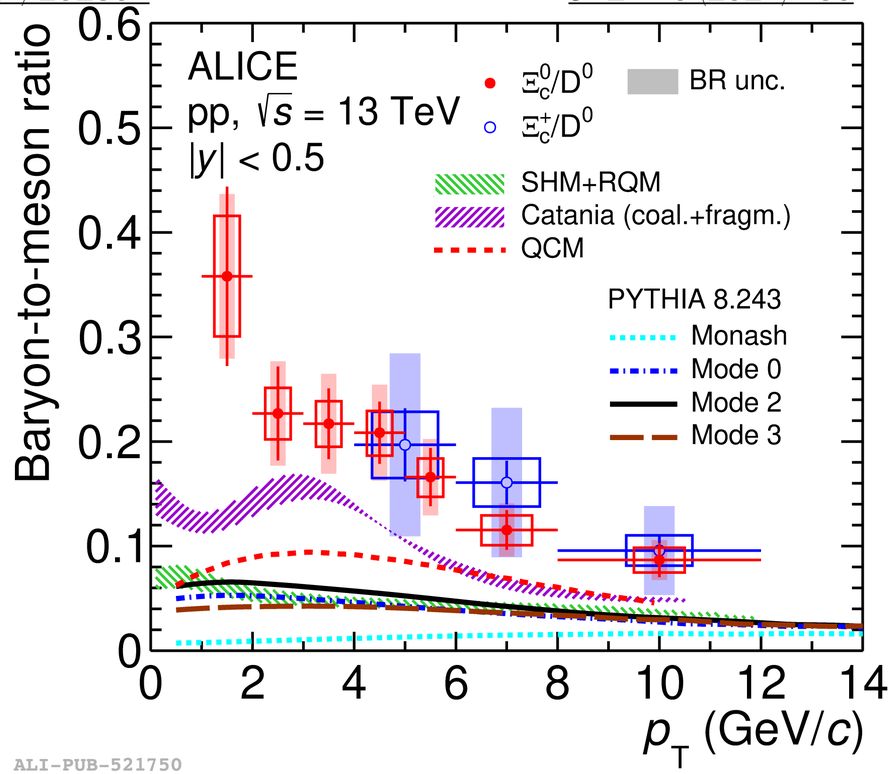
- Any additional constraint from different kinematic ranges, particle species etc. matters



PRL 127 (2021) 202301

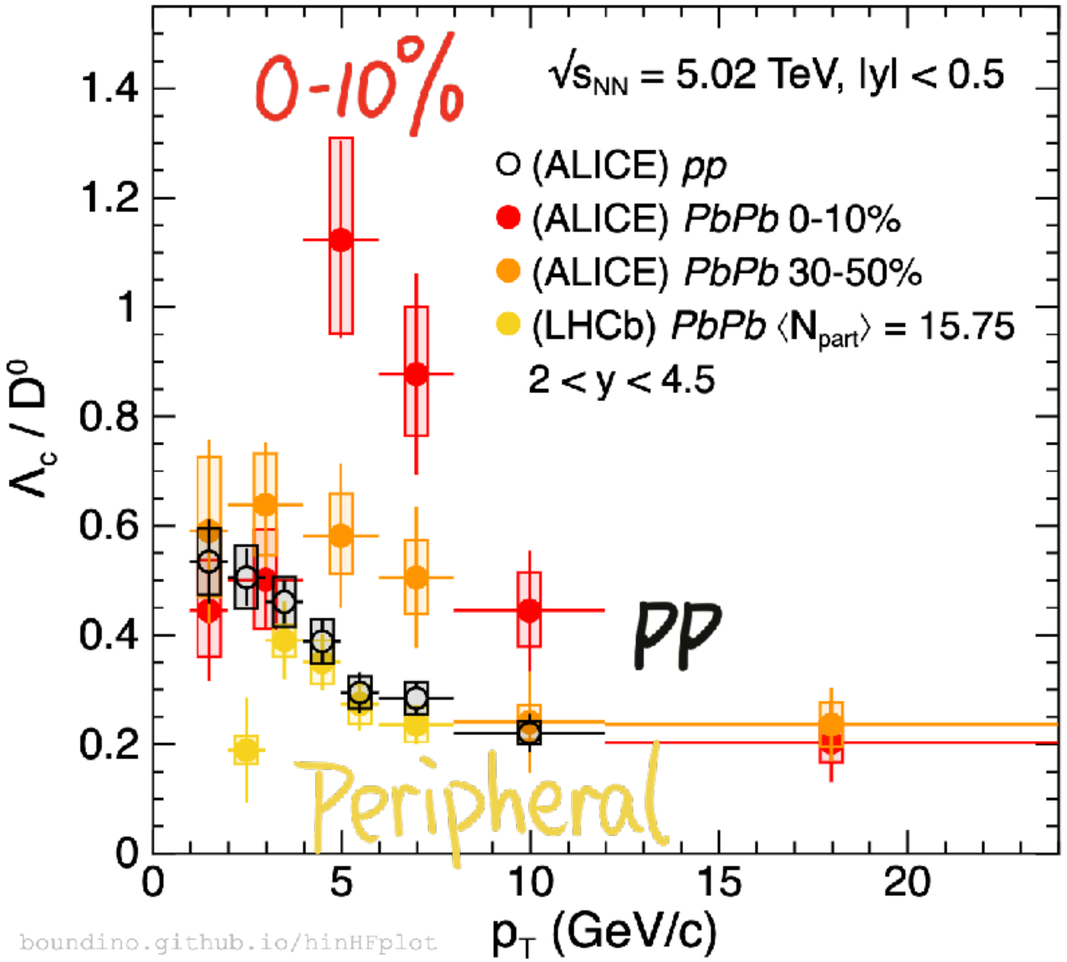


JHEP 10 (2021) 159



Charm Baryons in AA Collisions

Λ_c/D^0 in PbPb

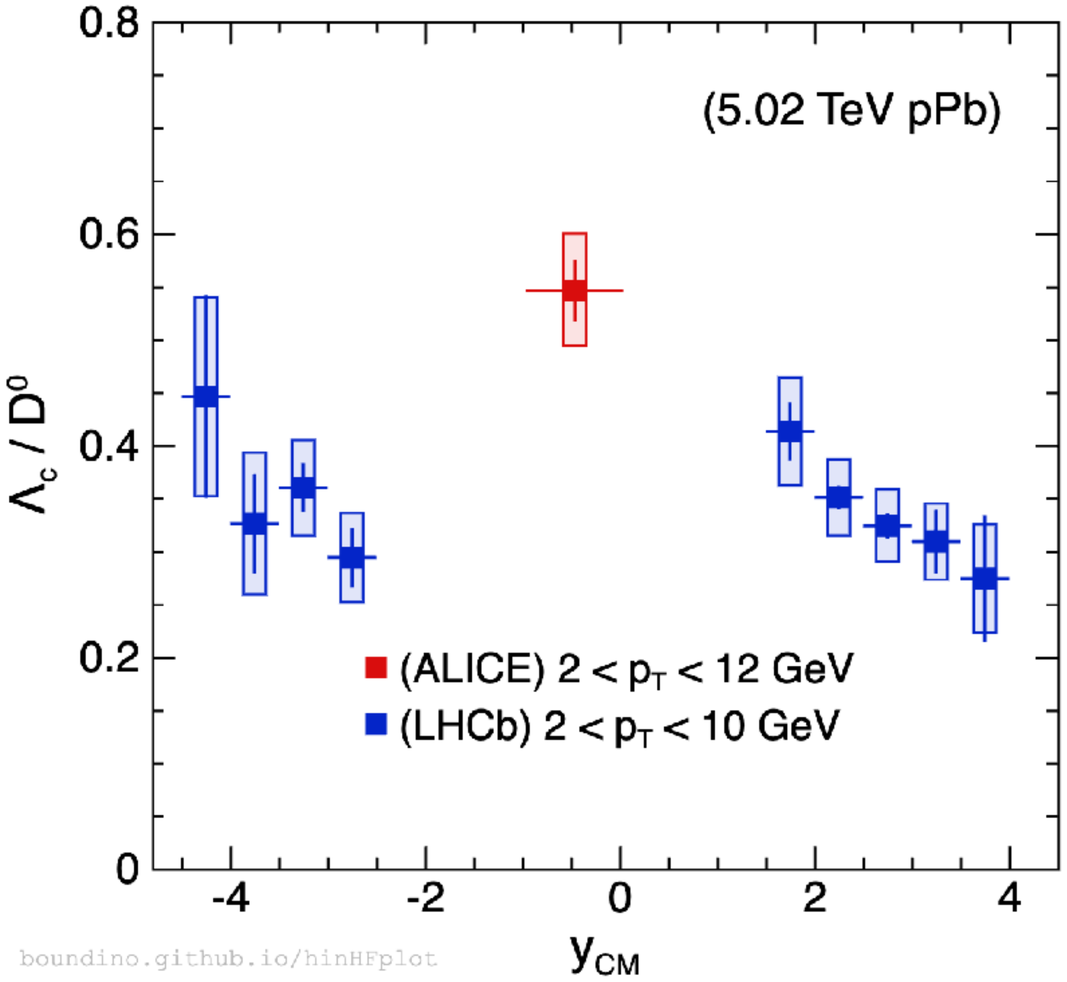


- Enhanced production of charmed baryons in PbPb
- Hint of lower ratio in very peripheral events than pp
  - Note: different rapidity range
    ➜ What's the role of rapidity?

arXiv:2112.08156
LHCB-PAPER-2021-046

Charm Baryons in pA Collisions

Λ_c/D^0 in pPb



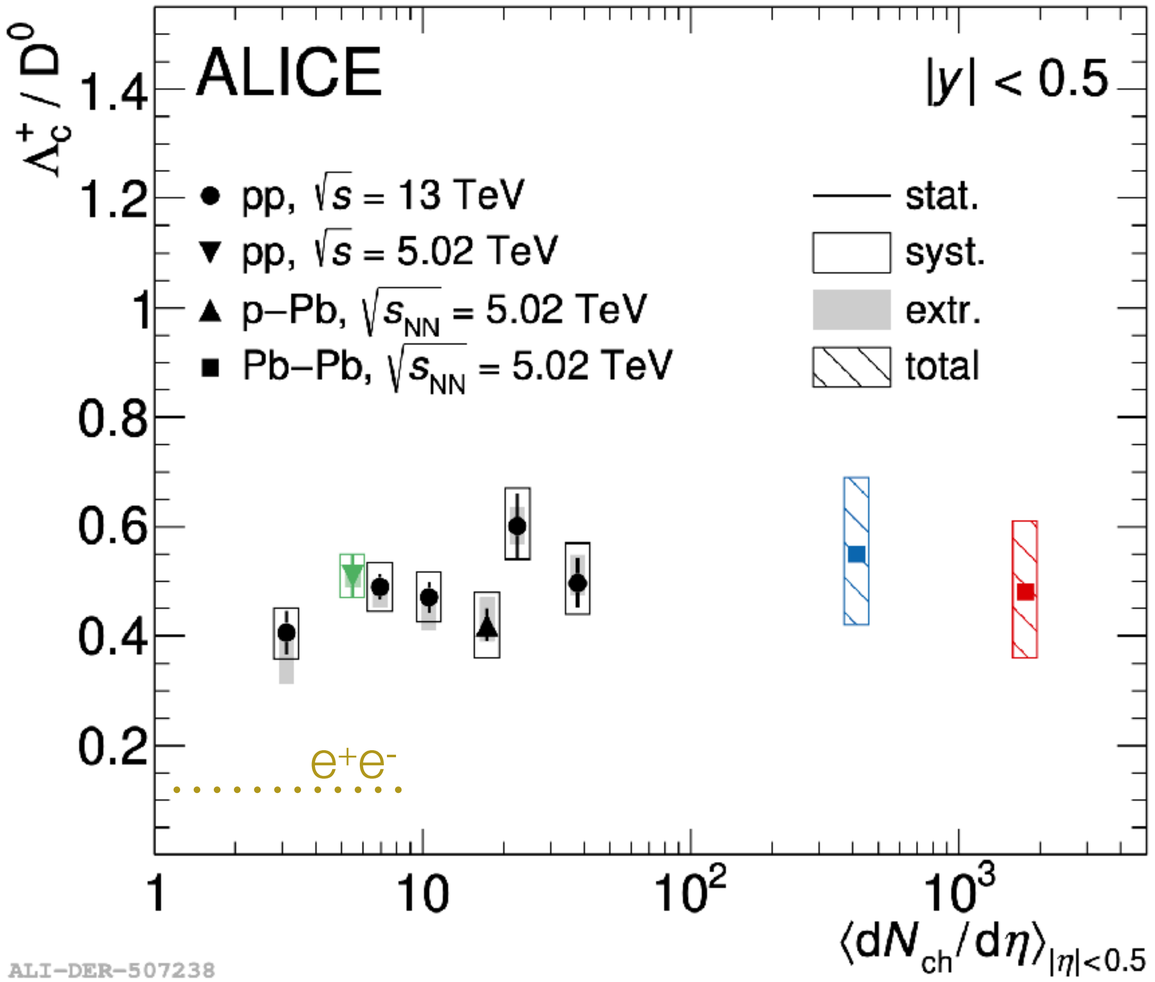
- Hint of larger Λ_c/D^0 at mid-rapidity than both forward and backward in pPb
  - Cannot be explained by nPDF and comovers

PRC 104 (2021) 054905

JHEP 02 (2019) 102

Charm Baryons Over Collision Systems

p_T-integrated Λ_c/D^0



- p_T integrated ratio is independent of collision system, centrality, multiplicity and energy
  - Redistribution instead of enhancement
- But indeed larger than e^+e^-
  - What is the essential difference between e^+e^- and pp/pPb/PbPb?
  - What about eA collisions?
  - Where is the onset of saturation?

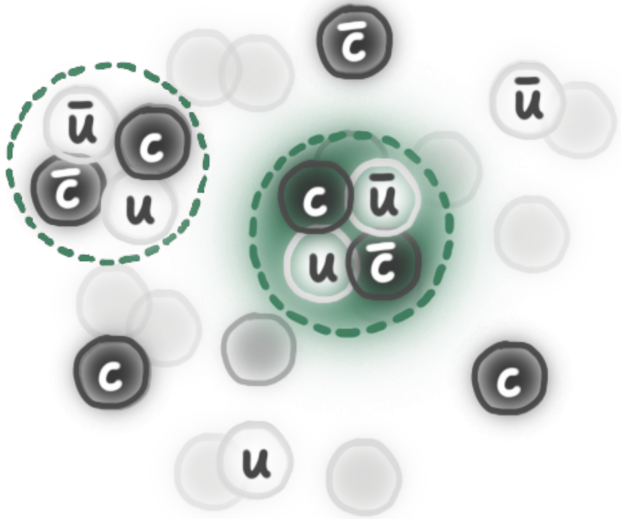
arXiv:2207.07590

One More Quark Than Baryons: X(3872)

- Coalescence with particles in HIC ➜ Enhance X(3872)

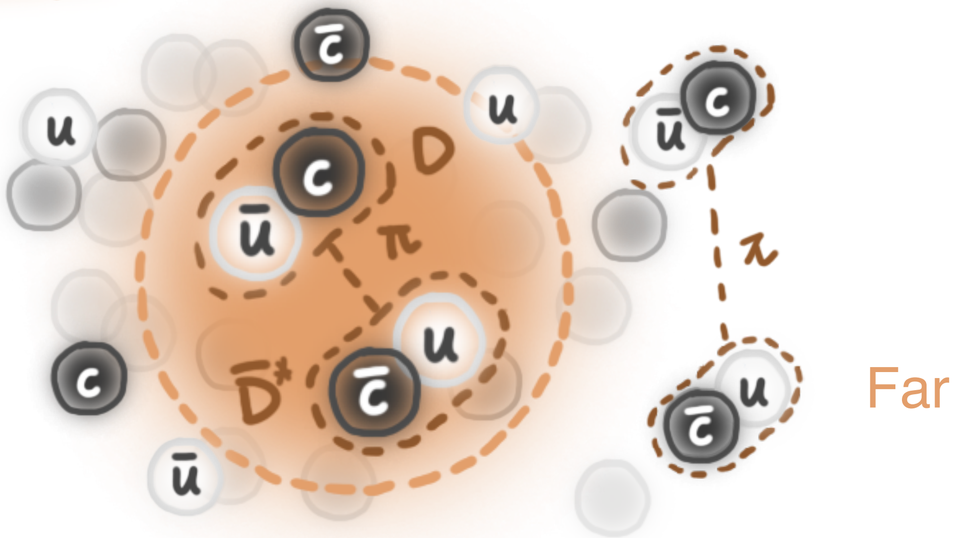
Tetraquark

Tightly bound
Small radius



Hadron molecule

Loosely bound
Large radius



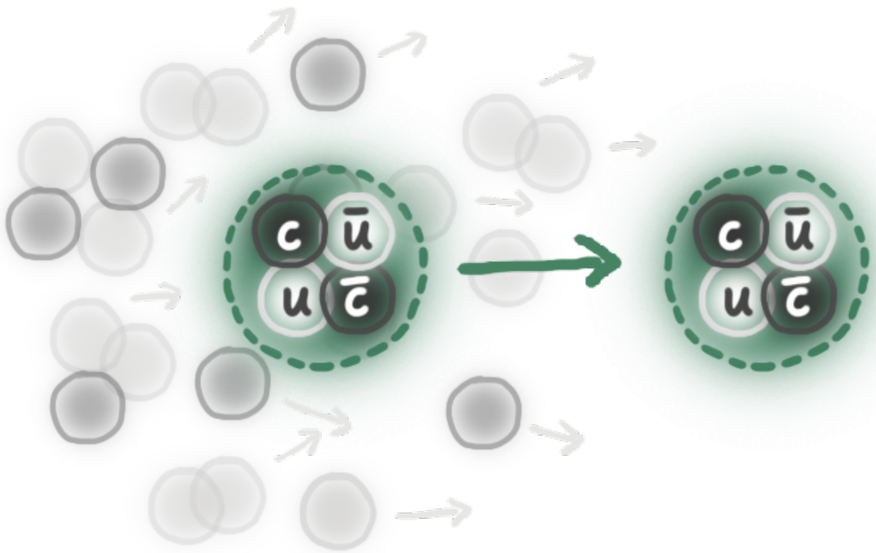
Coalescence probability depends on X(3872) inner structure

Exotic Hadron: X(3872) in HIC

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with particles in HIC ➜ Enhance X(3872)

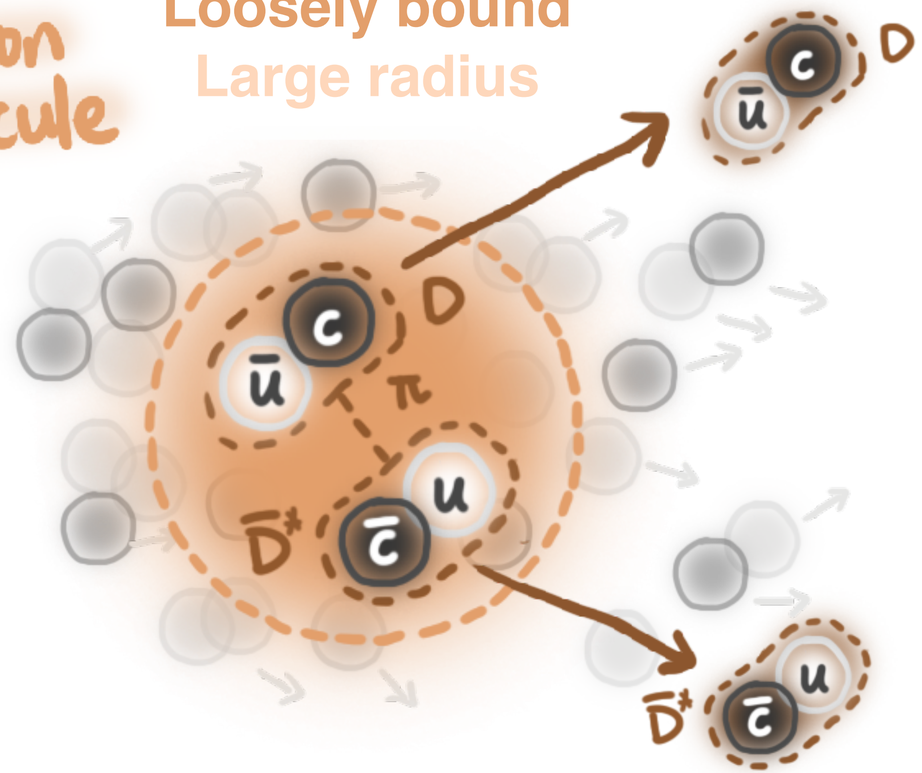
Tetraquark

Tightly bound
Small radius



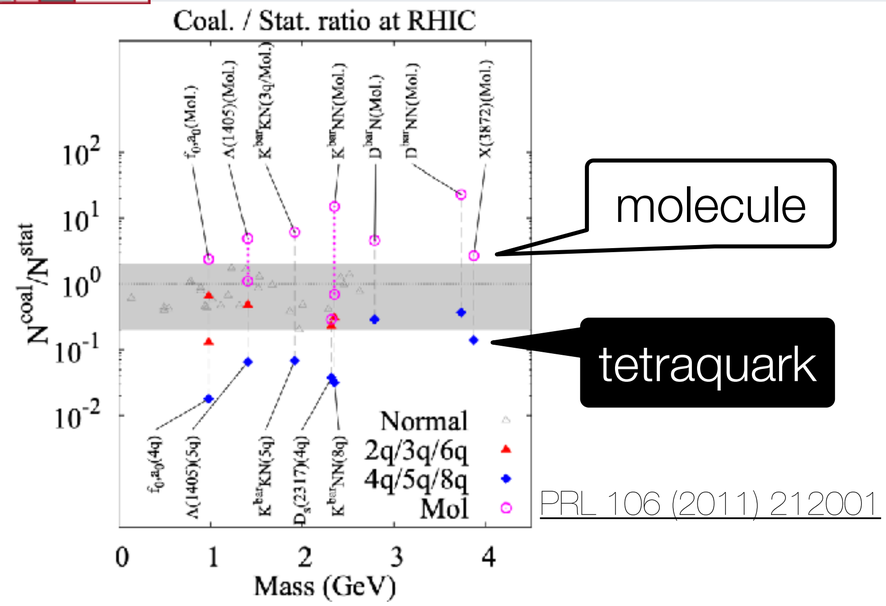
Hadron molecule

Loosely bound
Large radius

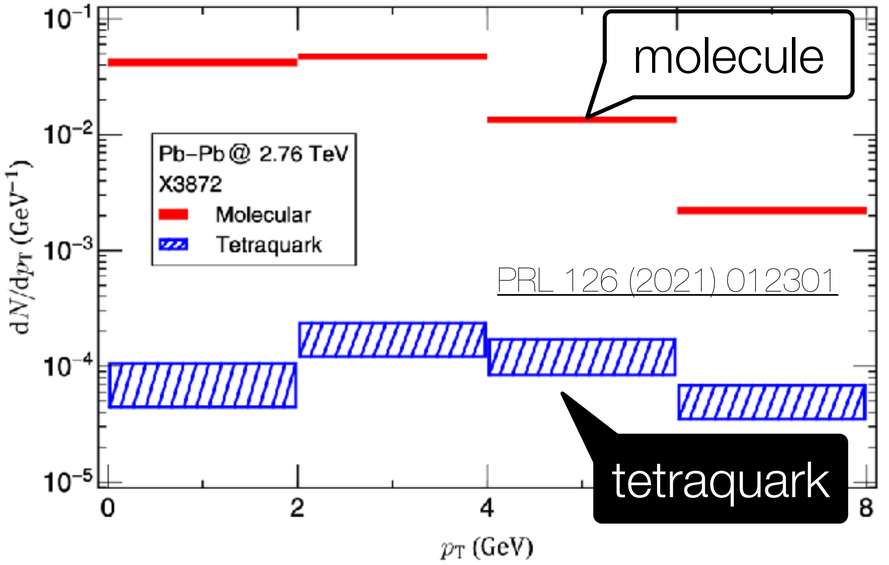


Dissociation probability depends on X(3872) inner structure

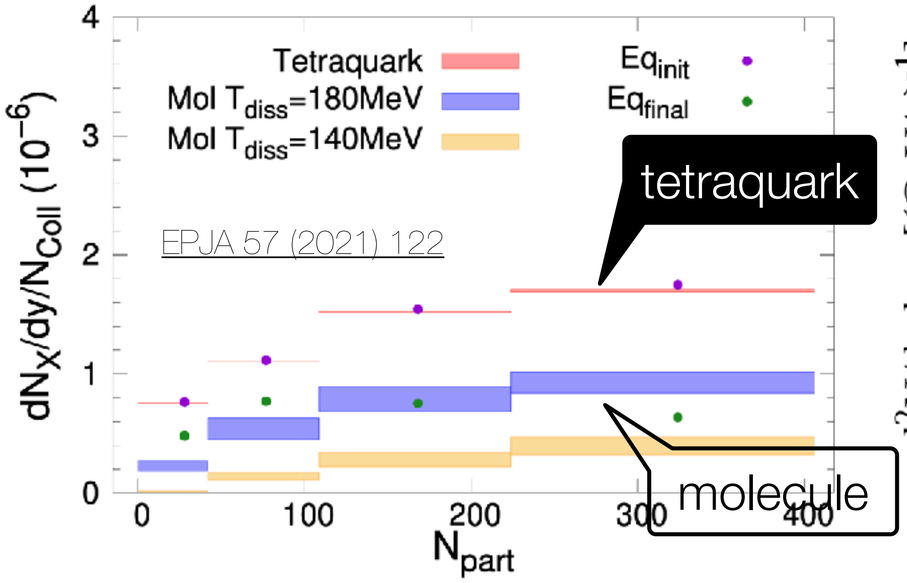
Exotic Hadron: X(3872)



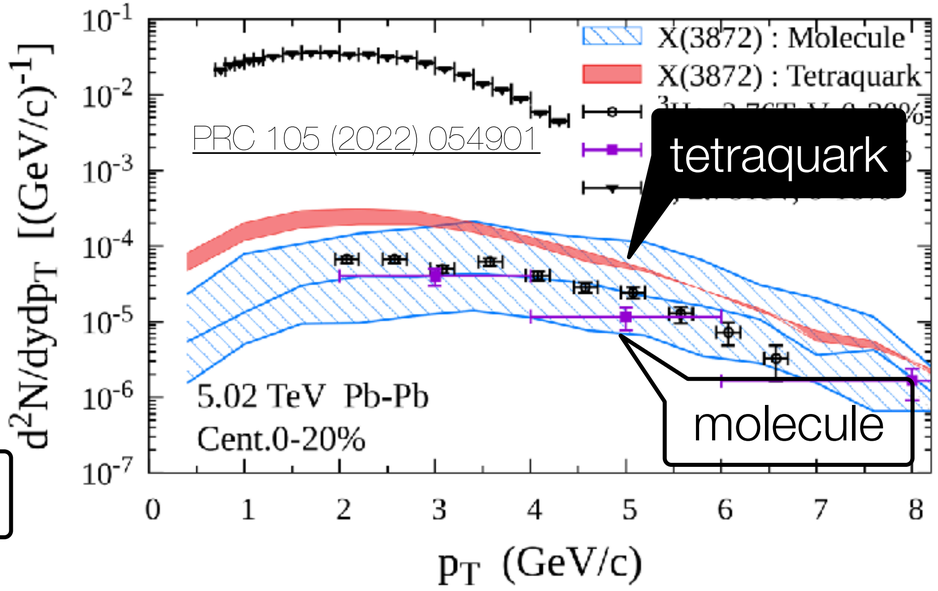
PRL 106 (2011) 212001



PRL 126 (2021) 012301



EPJA 57 (2021) 122



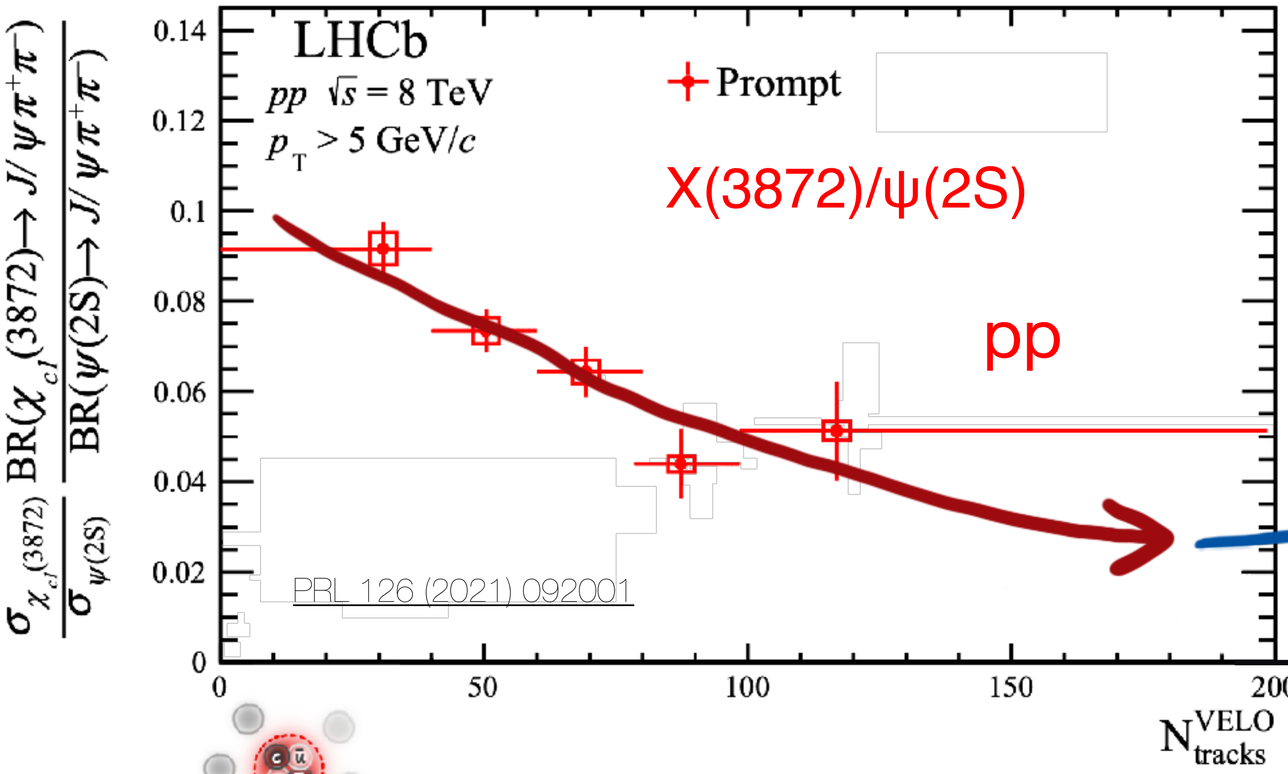
PRC 105 (2022) 054901

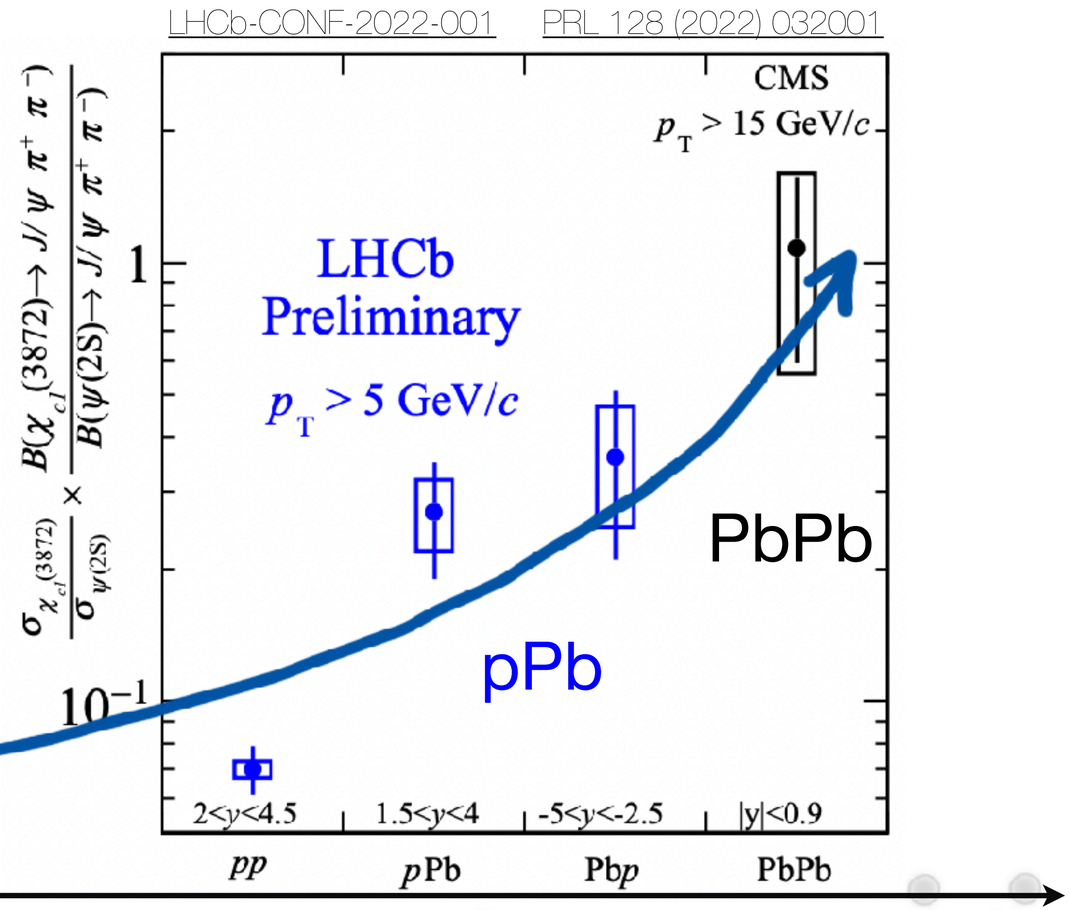
- Divergence in theoretical calculations
- Different recombination and dissociation implementation

* Collected by J. Zhao

X(3872) Production Over Collision Systems

- X(3872)/ψ(2S) decreases wrt multiplicity in pp, but has hint of enhancement in pPb and PbPb
  - Remove contribution of ψ(2S) ➜ differential
  - What about eA, pAu and AuAu?





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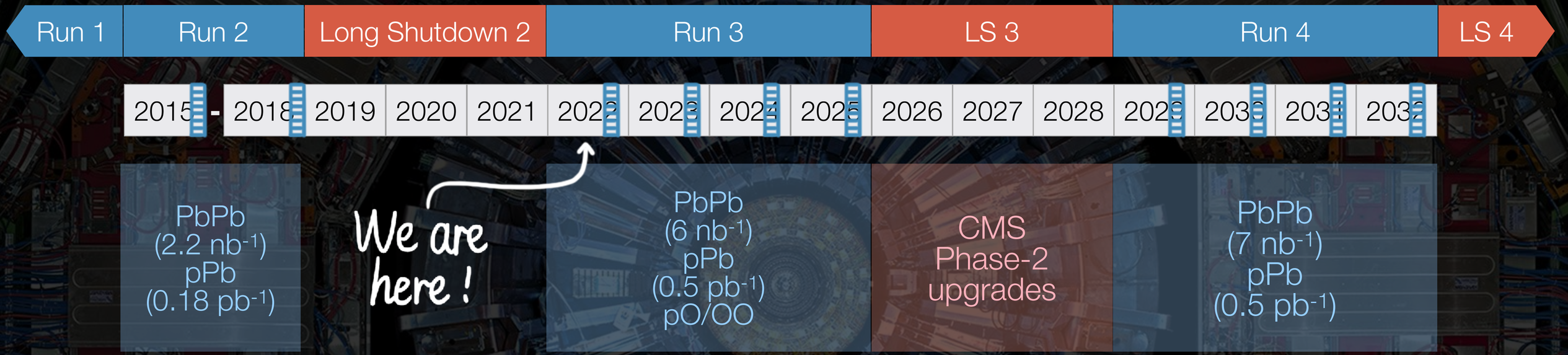
	Parameters (e.g. T_c, τ_0)	Small	
HQ-medium interaction *Characterized by transport coefficients*	α_s, Debye mass m_D, n_f, M_Q, K factor		
	Thermal parton mass	Large	D-h/jet/$\bar{D}$/γ angular correlation, energy loss fluctuation Full p_T range, full flavor dependence
	Inclusion of inelastic interactions (Collitional vs. radiative Eloss)	Large	
	Boltzmann vs. Langevin eq.	Small	Beauty not sensitive
Hadron phase	Hadronization	Large	Strange, baryons, exotica, low-p_T HF jets
	Rescatterings	Small	Femtoscopy


Isabelle
Thanks for your attention!

Back up

Thanks for your attention!

The Road: Past, Present and Future

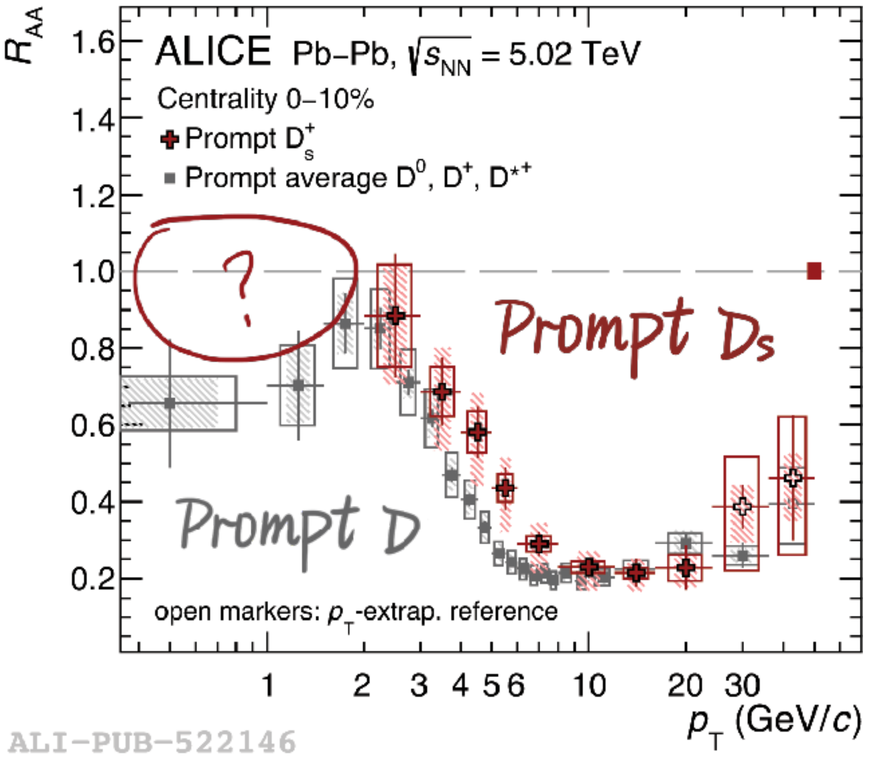


- Great success of CMS heavy-ion project in Run 2
- Run 3 is around the corner

Strange/Charm- HF Mesons in AA

PLB 827 (2022) 136986

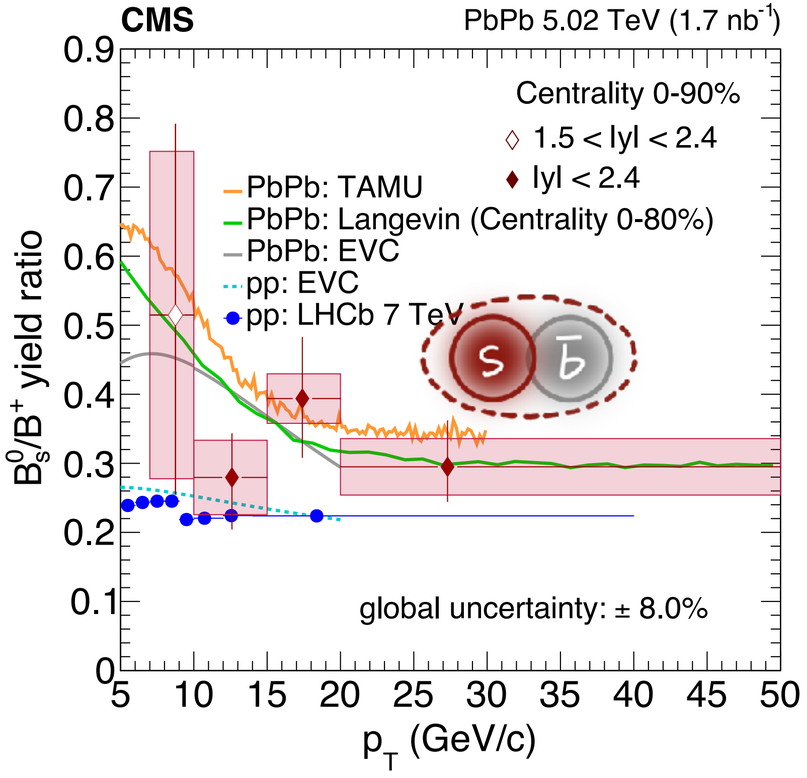
D_s R_{AA}



- Indication of larger D_s R_{AA} (2.3σ)
- What about happen at lower p_T?

PLB 829 (2022) 137062

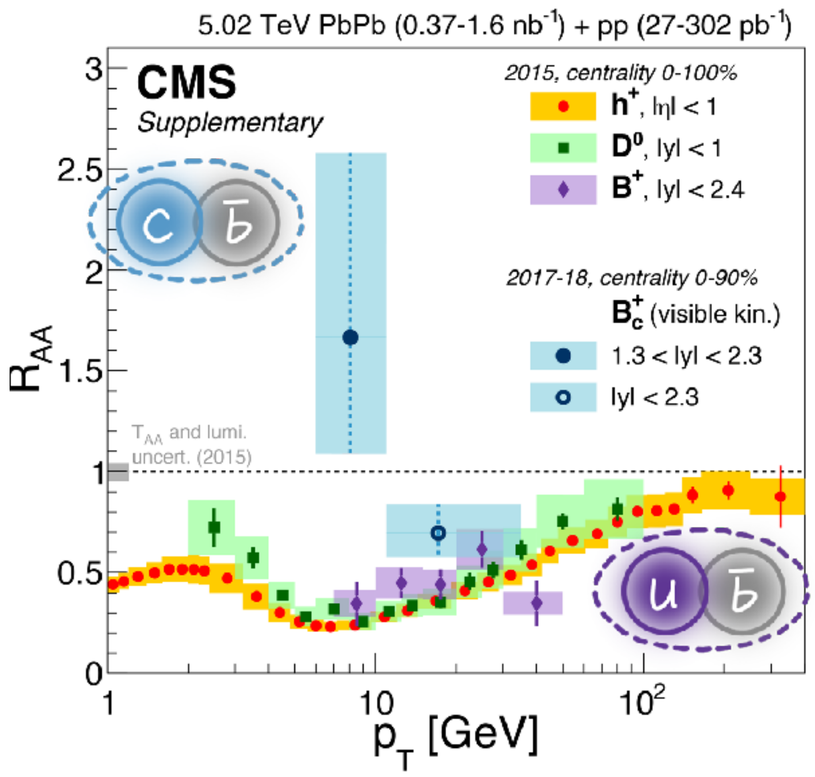
B_s/B^+ ratio



- Statistically compatible b/w PbPb and pp

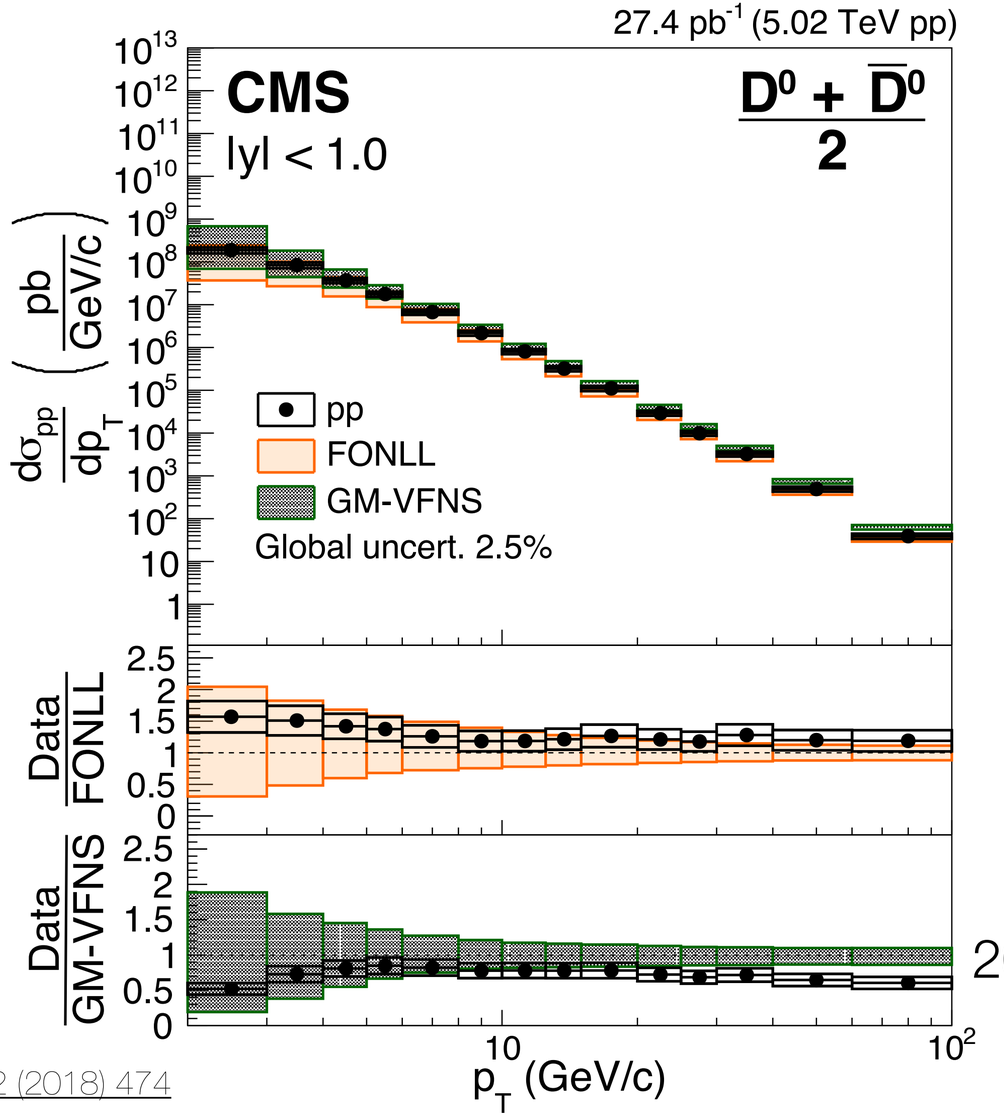
PRL 128 (2022) 252301

B_c R_{AA}



- Hint of larger B_c R_{AA} than B^+ R_{AA} at low p_T

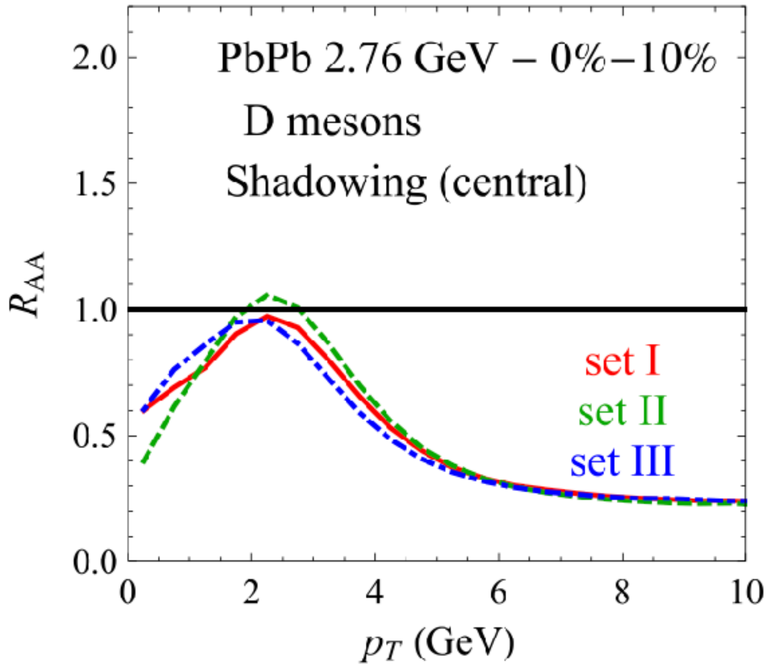
Impact and Constraint of Initial Production



2015 data

PLB 782 (2018) 474

- All models use FONLL initial spectra
- Uncertainties are fragmentation, renormalization scales and quark mass
- Constrained by measurements in pp
  - Systematic neck bottle: tracking efficiency



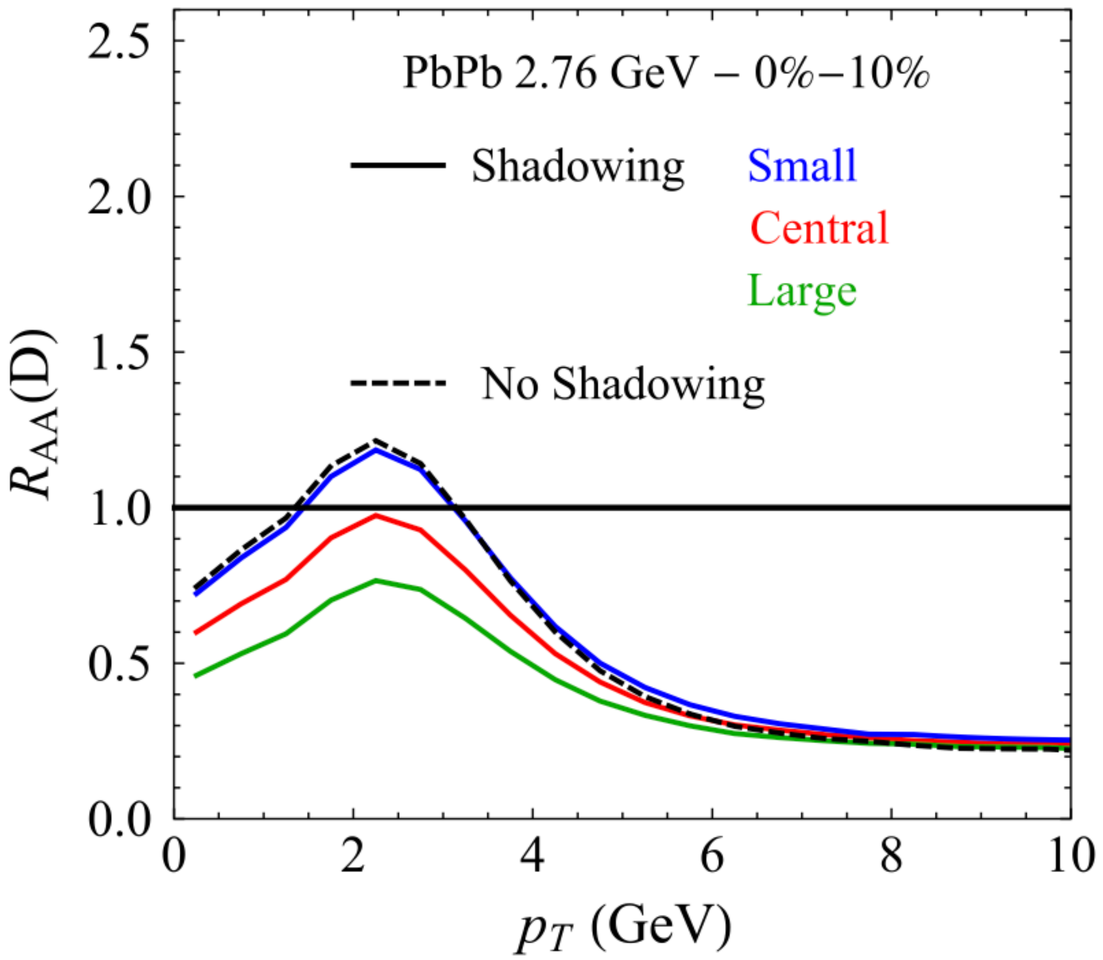
Vary FONLL parameters

NPA 979 (2018) 21

- Impact of initial production is small

Impact and Constraint of nPDF

Only vary CNM effect



- Stronger effect than hard scattering spectra
- Only affect low p_T
- Can be unified in theoretical models
- Common efforts of constraints (e.g. pA measurements)

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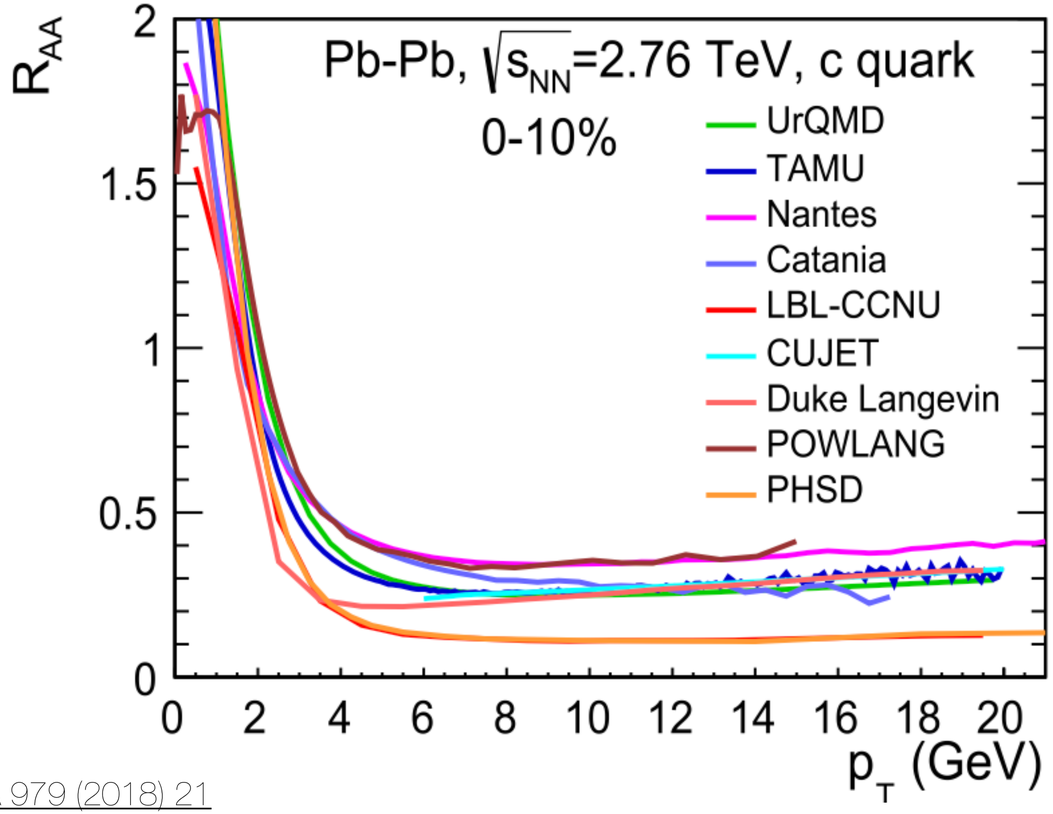
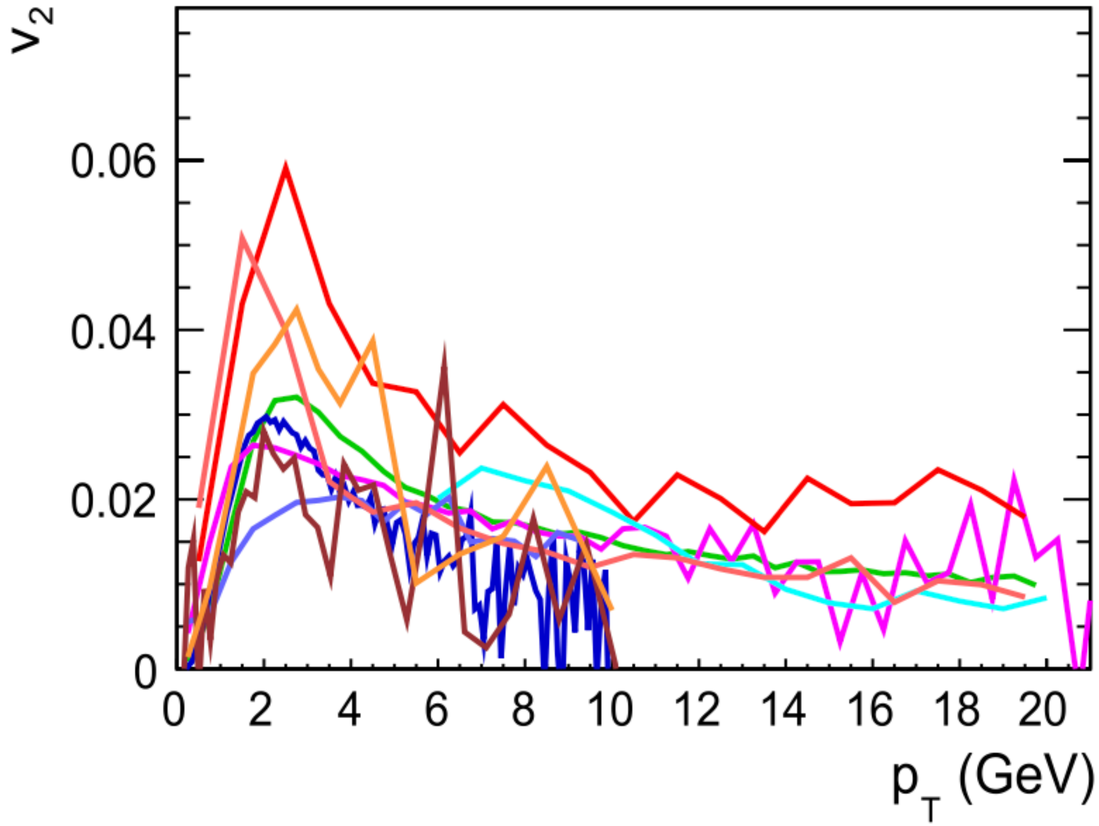
Impact of Bulk Evolution

c quark R_{AA} & v_2 with common transport coefficients and initial production





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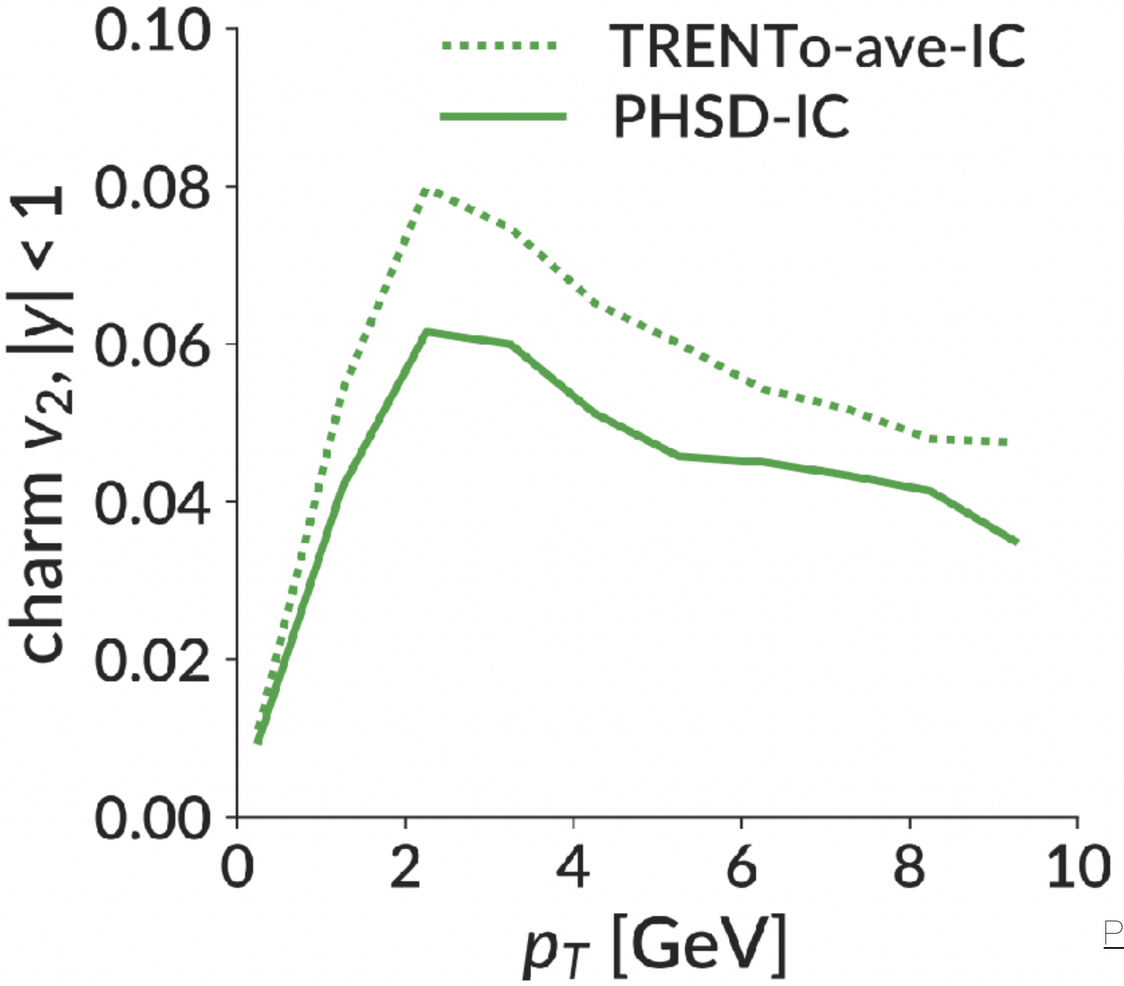
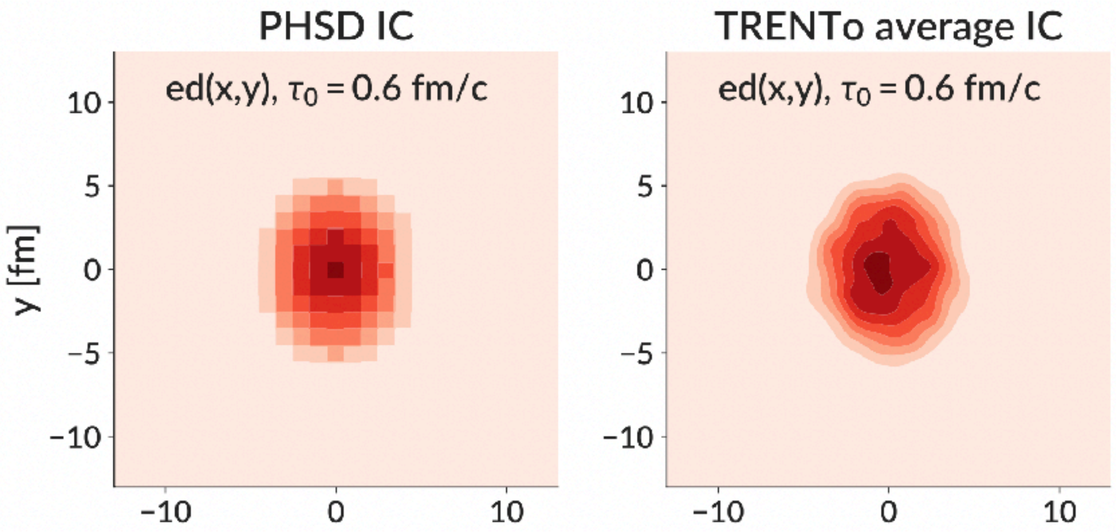
- Significant effects from different medium evolution models
- Different initial condition, medium model, parameters (T_c, τ_0)

Impact of Initial Condition

Only vary initial energy density distribution



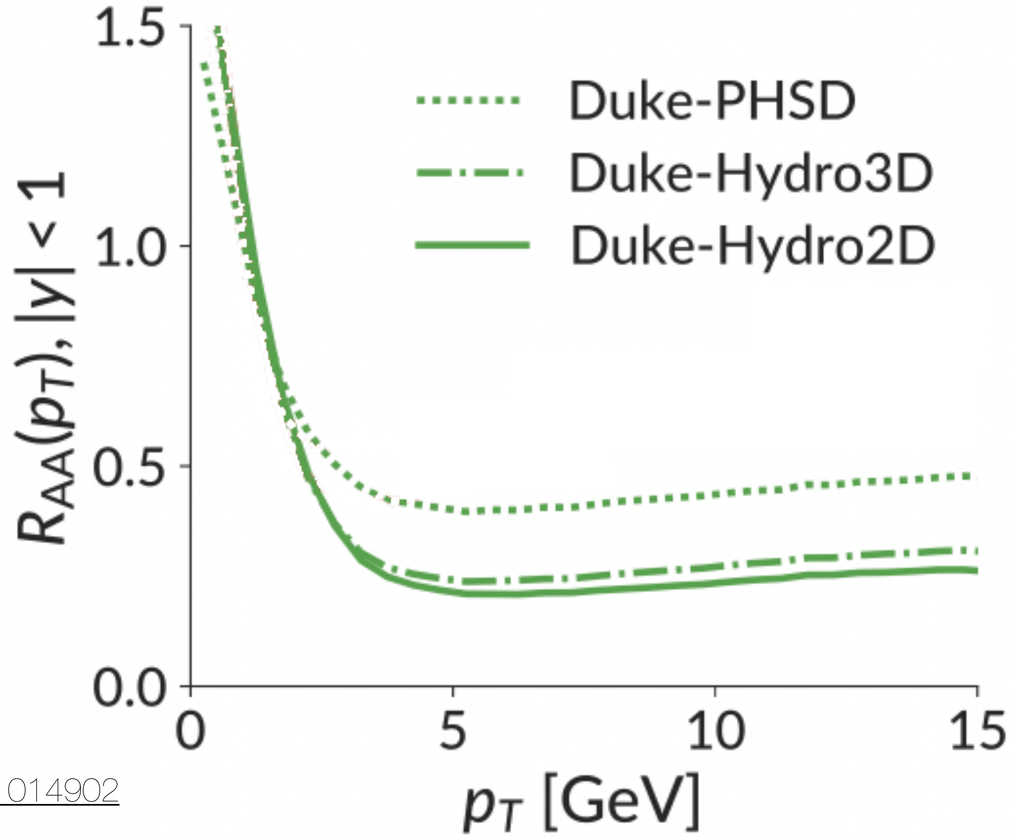
- Different initial condition treatment include
  - Initial energy density distribution
  - Energy density fluctuation
  - Initial tilt of matter
  - With or without initial transverse flow

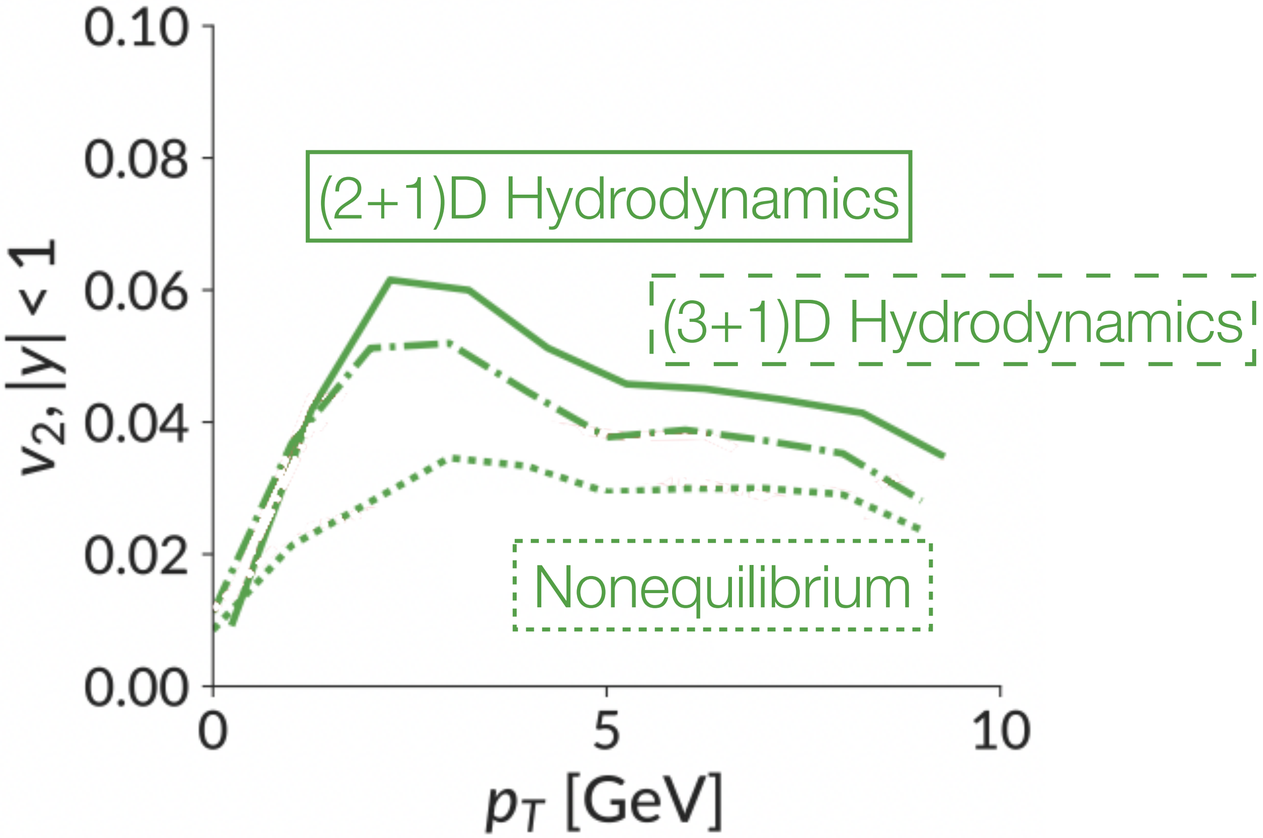


PRC 99 (2019) 014902

Impact of Medium Expansion

Only vary expanding medium



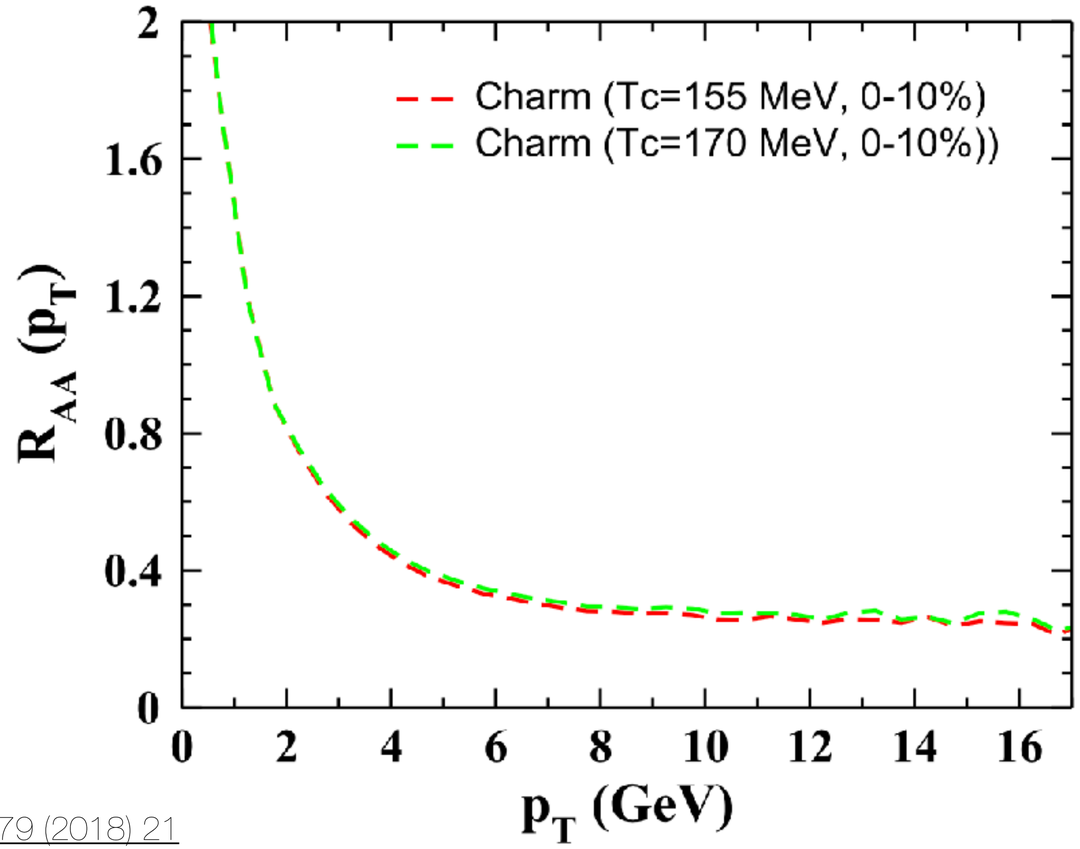


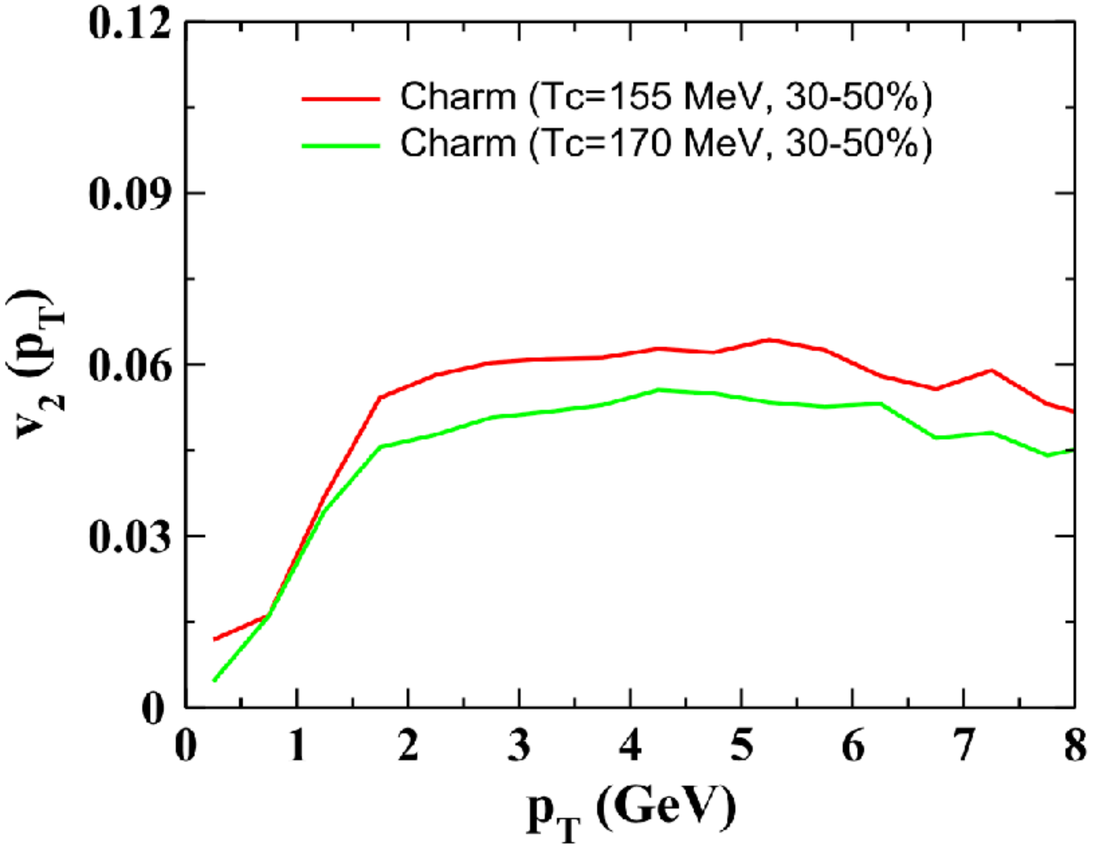
PRC 99 (2019) 014902

- With and without assumption of local thermal equilibrium
- Significantly depend on QGP medium treatment

Impact of T_c

Vary T_c (temperature at the end of QGP evolution)





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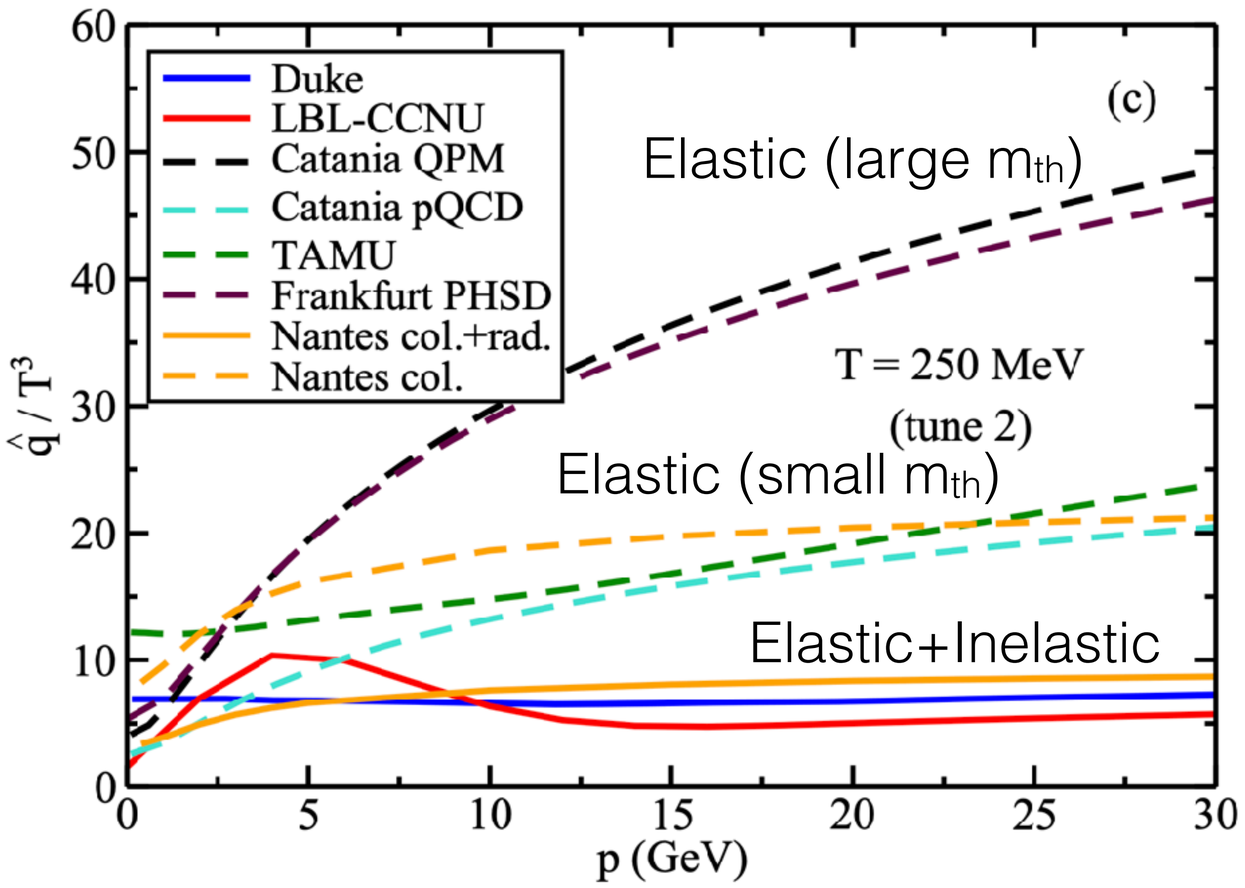
- Small effect for R_{AA} and < 20% for v_2

Impact of HQ-medium Interaction Treatment

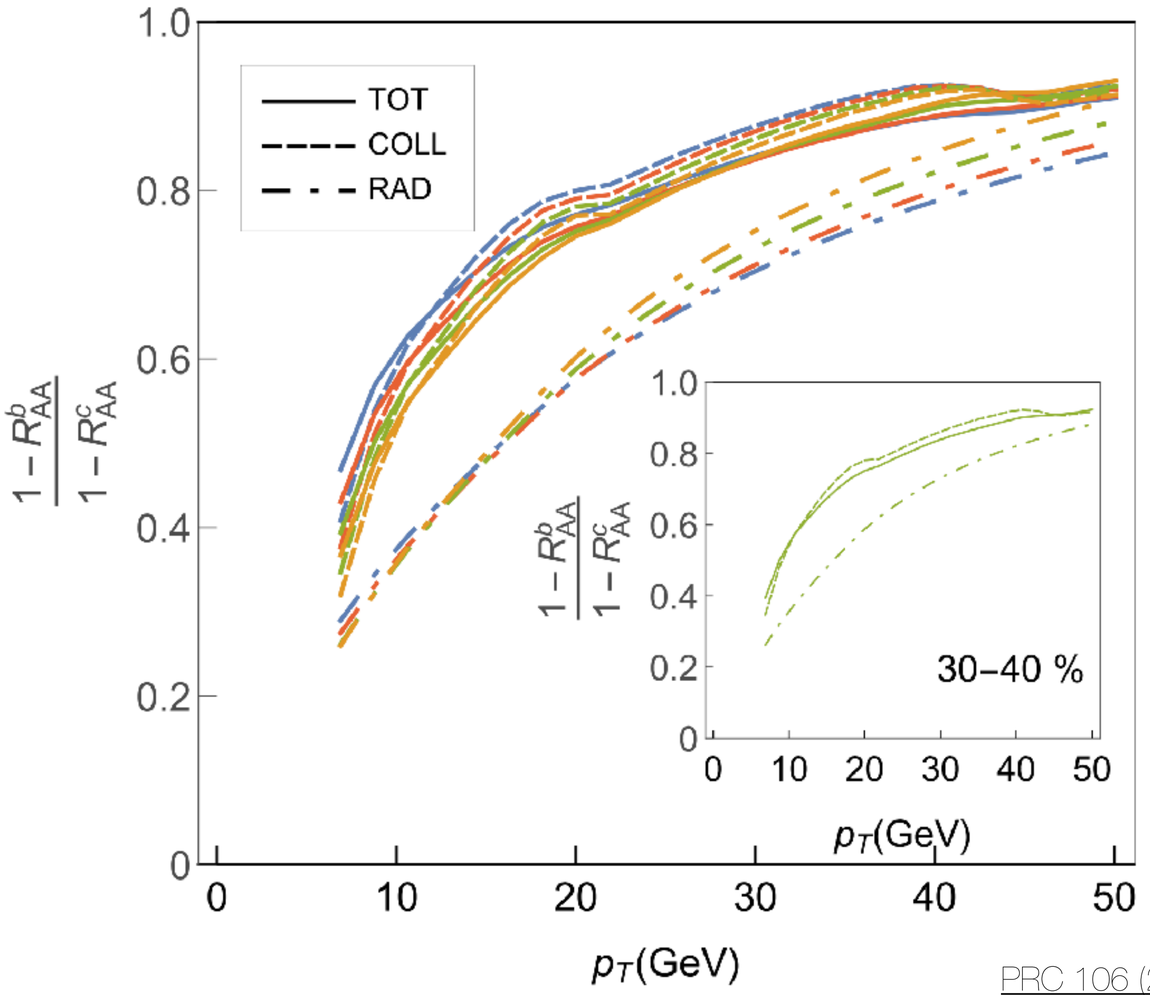
$\hat{q}$ extracted in a static brick medium, tuned to match same c-quark R_{AA}



- Large effect from inclusion of radiative energy loss and choice of thermal parton mass in medium

PRC 99 (2019) 054907

Constrain Energy Loss Mechanisms

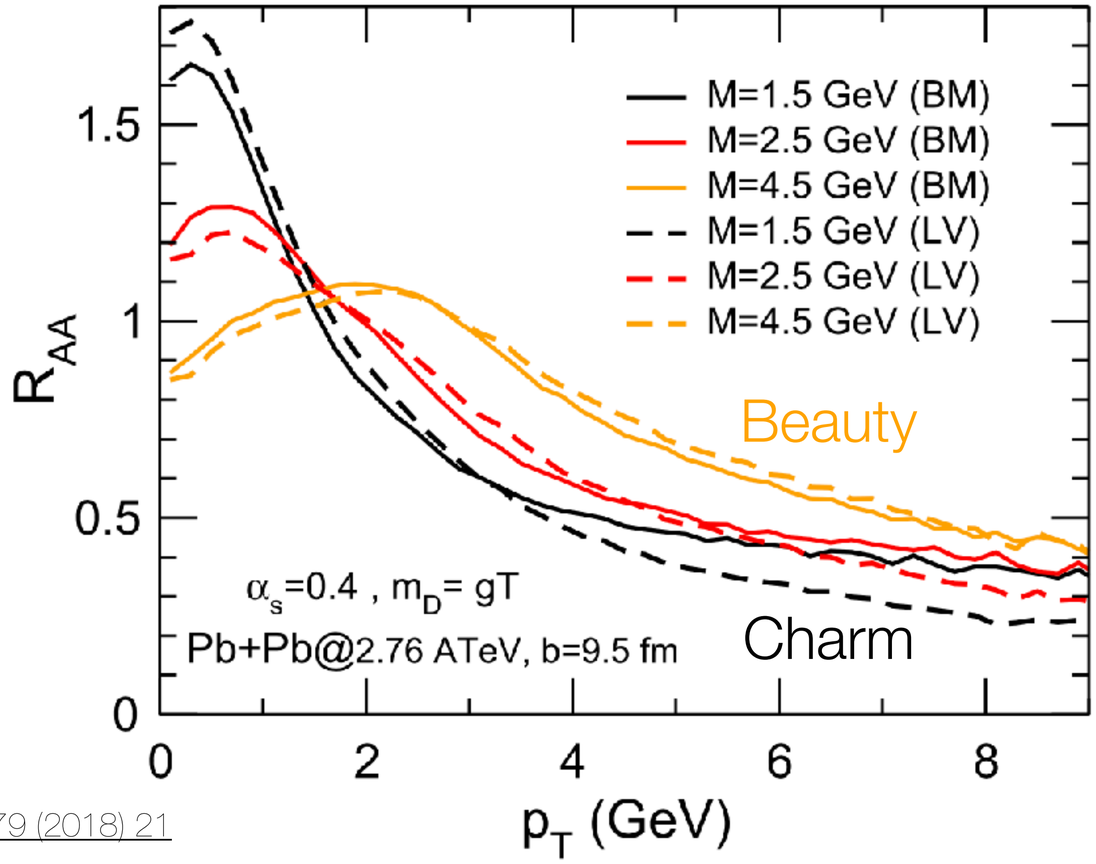


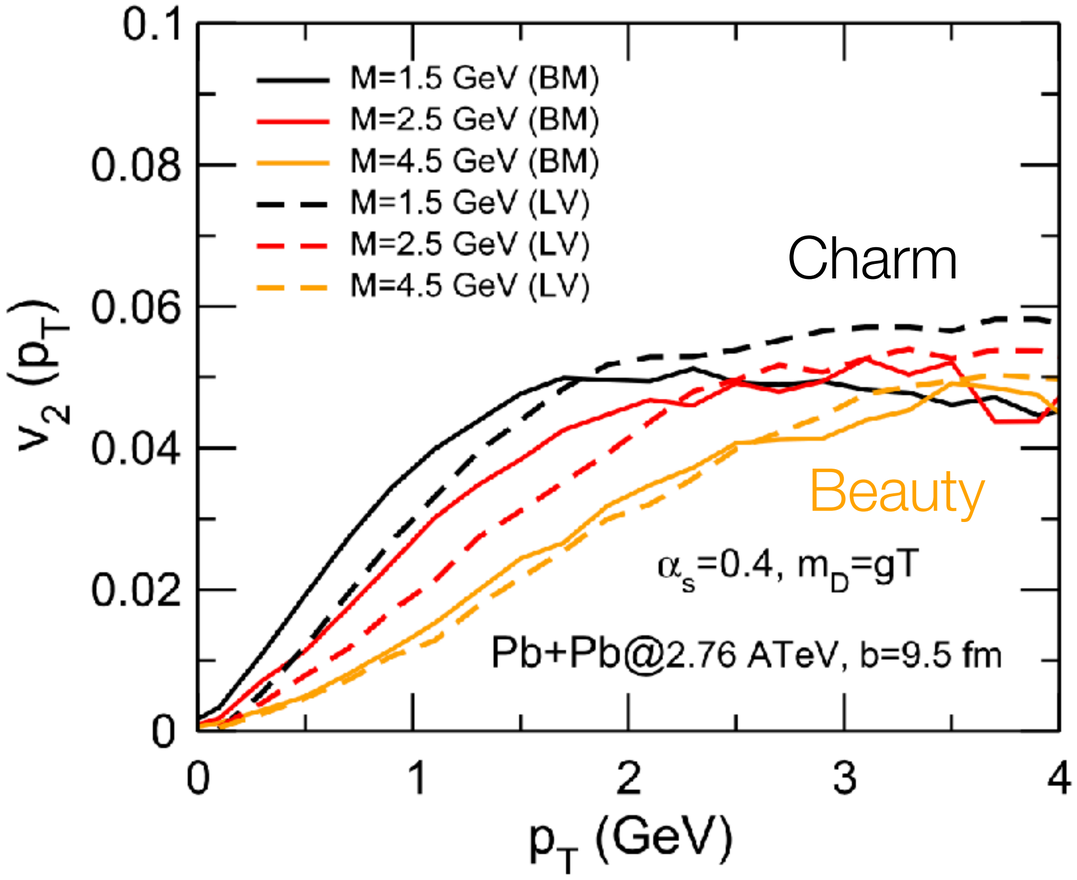
- Wide kinematic range is necessary to understand the switch of collisional and radiative energy loss
- Maybe new observables, e.g.
  - DREENA-C: $(1\text{-}R_{AA})^{b}/(1\text{-}R_{AA})^{c}$ dominantly driven by the collisional contribution

PRC 106 (2022) 014902

Impact and Constraint of LV vs. BM

Langevin vs. Boltzmann Simulation





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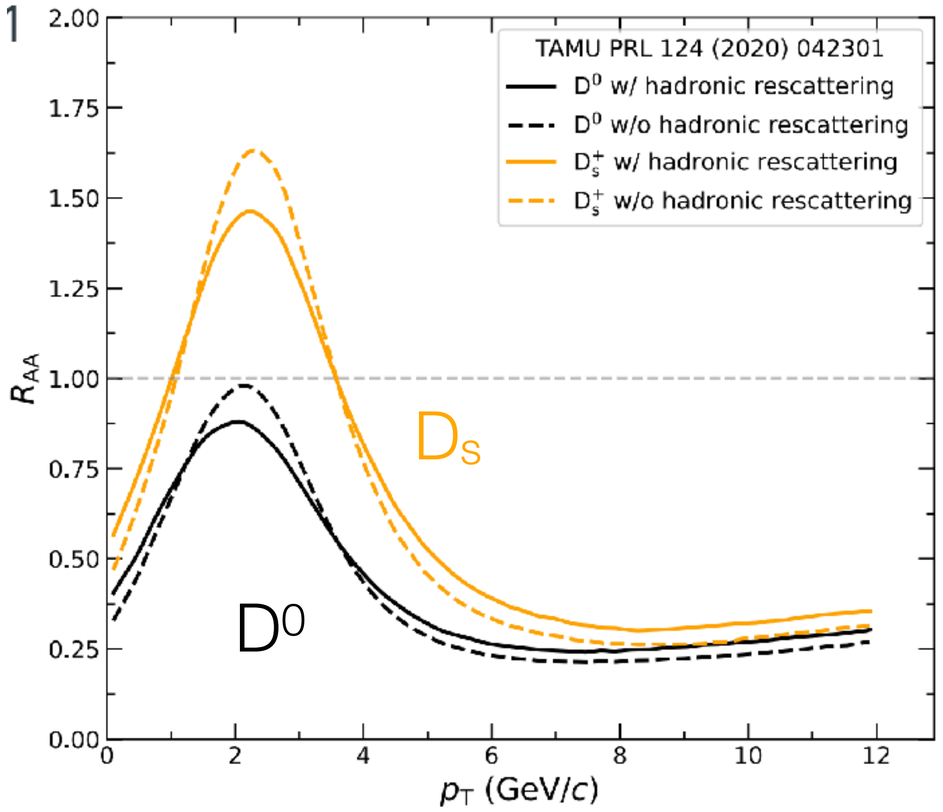
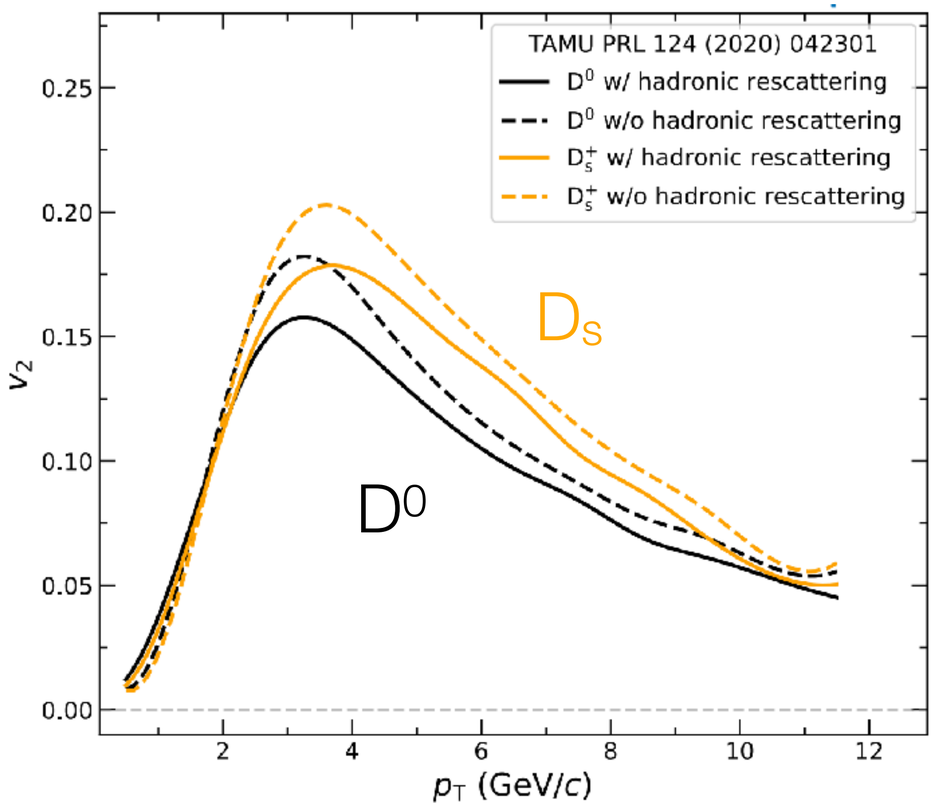
- Uncertainty from choice of LV or BM is suppressed for beauty sector

Impact and Constraint of Rescatterings

With vs. without hadronic rescatterings





- Relatively small effect from hadronic rescatterings
- Can be constrained by femtoscopy of D-h source

Strange-HF Mesons in pp Collisions