

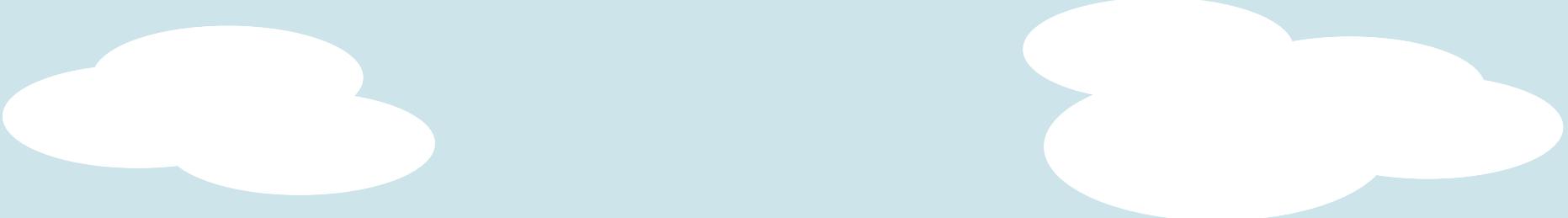


Heavy quark and quarkonia

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重イオン衝突におけるダイナミクス・時空発展の統合的理理解に向けた理論・実験共同研究会

2021/09/24



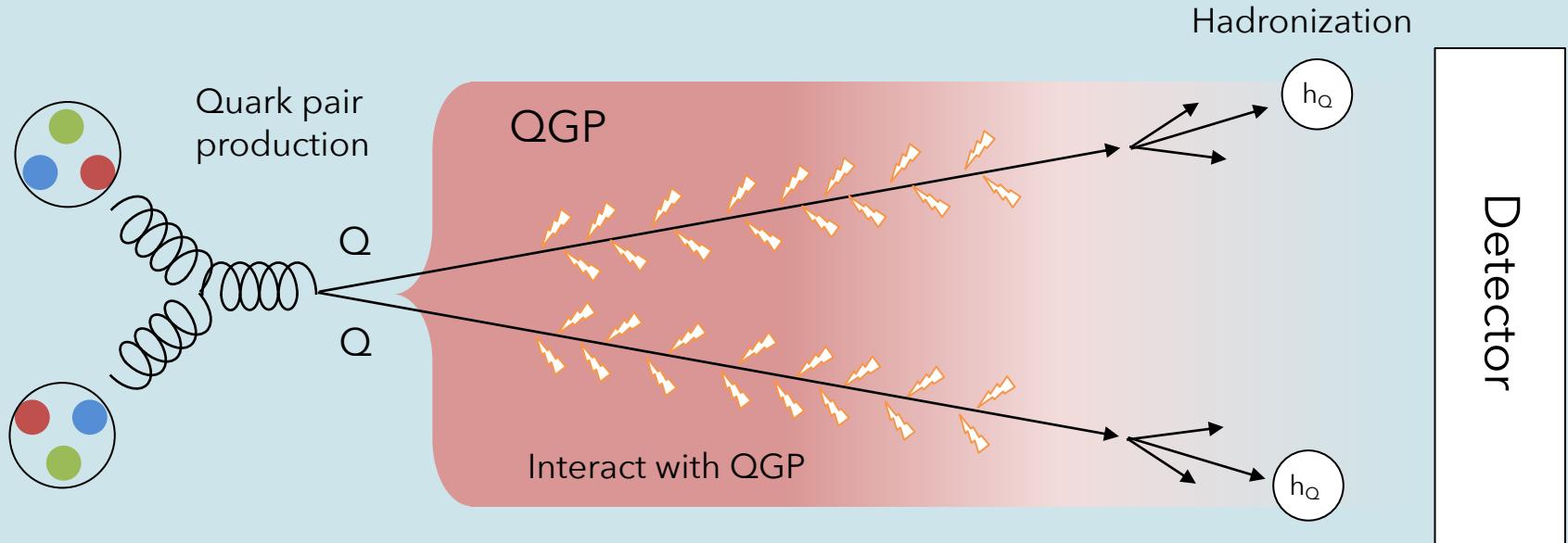
Open heavy flavor

What is heavy flavor (HF)?

- Heavy flavor (charm & beauty)
 - Mass: $m_c (\sim 1.3 \text{ GeV}/c^2)$, $m_b (\sim 4.5 \text{ GeV}/c^2) \gg \Lambda_{\text{QCD}} (\sim 0.2 \text{ GeV})$
- Produced initial hard scattering processes
 - Accurate interpretation by pQCD
- Short formation time
 - $\tau \sim 1/2m_q \sim 0.07 \text{ fm}/c < \text{QGP} (0.1 - 1 \text{ fm}/c)$
- Long life time
 - $D^0: \tau c \sim 120 \mu\text{m}$, $\Lambda_c^+: \tau c \sim 60 \mu\text{m}$
 - $B^0: \tau c \sim 500 \mu\text{m}$, $\Lambda_b^0: \tau c \sim 440 \mu\text{m}$

Key features of using HF to investigate QGP properties

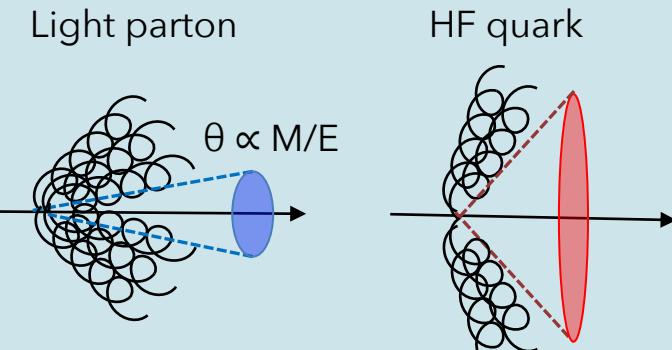
- Ideal probe for a tomography of QGP
 - Produced at only initial stage of collisions
 - Conservation of the number of HF quark



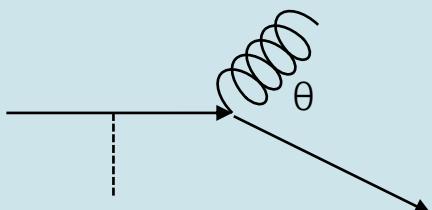
HF is one of the cleanest probe!

Energy loss

- Passing partons lose their energy via elastic scattering and gluon radiation
 - Depending on
 - Color charge (Casimir factor)
 - Quark mass (Dead cone effect)
 - Path length in medium
 - $\Delta E_{\text{loss}}(g) > \Delta E_{\text{loss}}(u,d,s) > \Delta E_{\text{loss}}(c) > \Delta E_{\text{loss}}(b)$



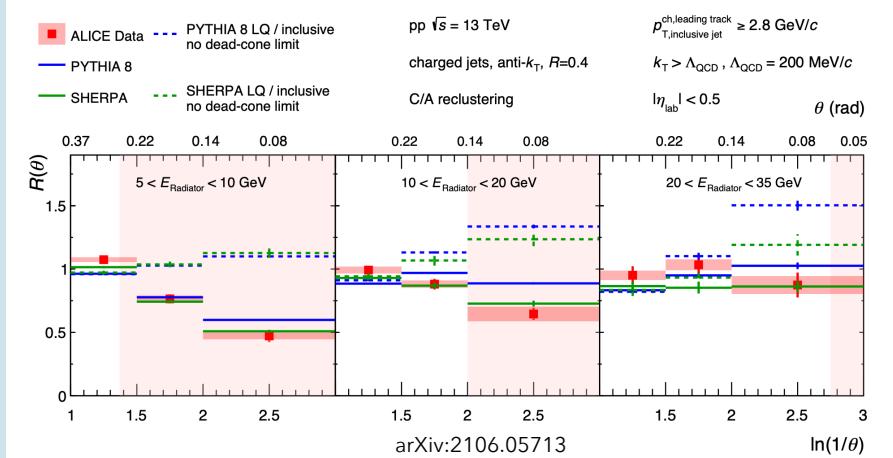
Radiative energy loss



Gluon radiation

Gluon emission angle $\theta \propto M/E$

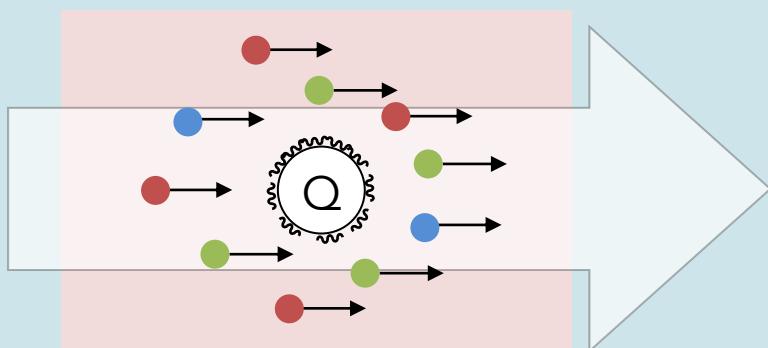
Sensitive to transport coefficient: $q = \mu^2/\lambda$



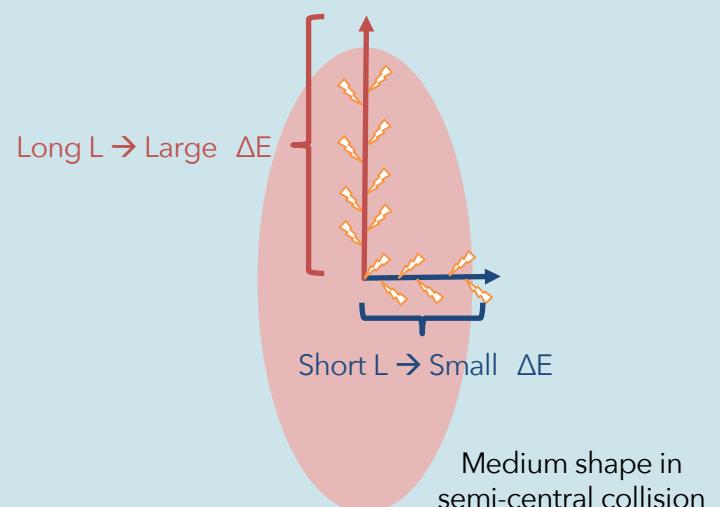
$D^0 p_T$

Azimuthal anisotropy

- Participation in medium collective motion
 - Pushed by the medium as “foreign object”
 - Sensitive to the spatial diffusion coefficient
- Path-length dependence of energy loss
 - Much energy loss with passing long distance in medium



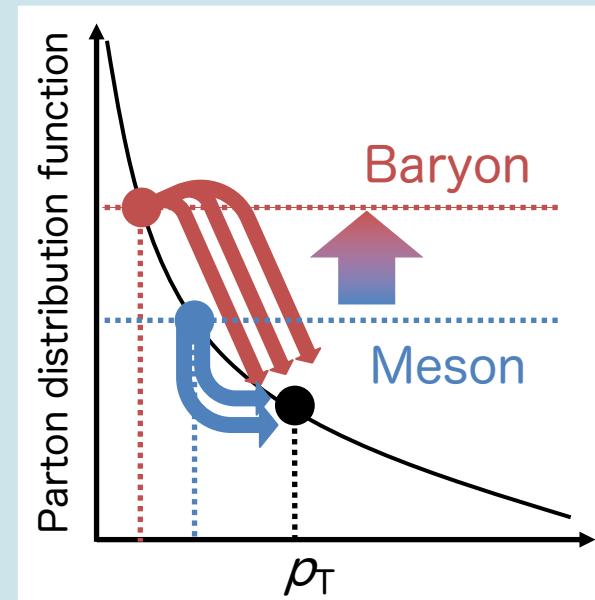
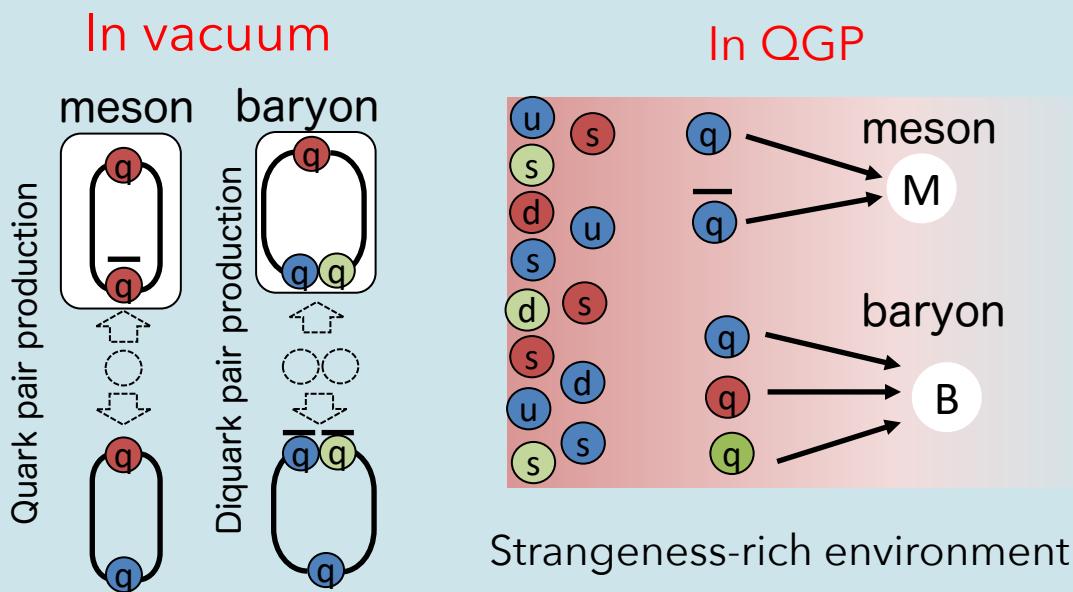
Drift in the moving medium



Energy loss depends on L

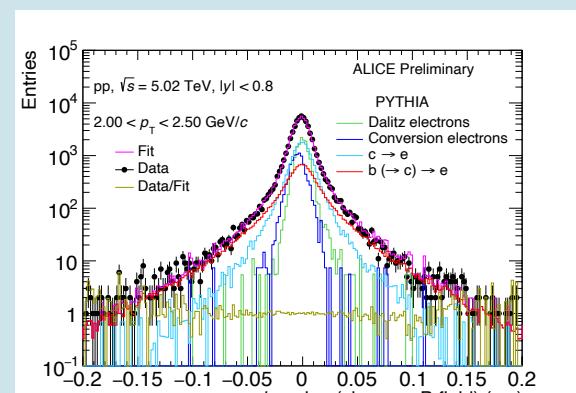
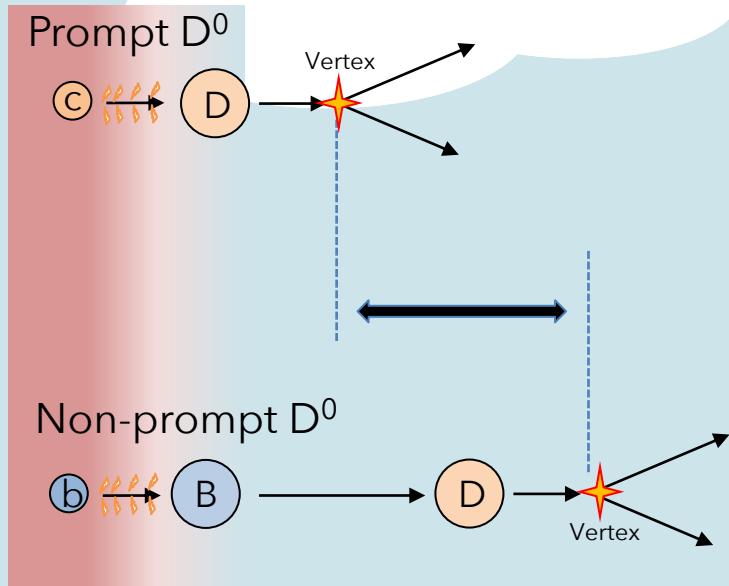
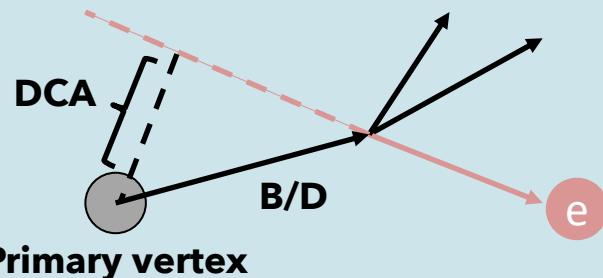
Coalescence

- Enhancement of baryon/meson ratio w.r.t to pp collisions
 - In vacuum, two quark pairs should be produced at the same time to make a baryon
 - $p:\pi \sim 0.2:1$
- Enhancement of strangeness hadron w.r.t non-strangeness hadron
 - Quark pair production probability depends on quark mass
 - $uu : dd : ss : cc \sim 1 : 1 : 0.3 : 10^{-11}$



How to measure HFs?

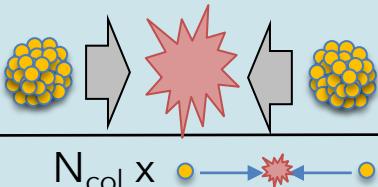
- Full reconstruction
 - $D^0 \rightarrow K^- \pi^+$ (BR: 3.95%)
 - $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ (BR: 0.1%)
- Partial decay product measurement
 - Hadron decay channel
 - $B^+ \rightarrow J/\psi K^+$
 - Semi-leptonic decay channel
 - $D^0 \rightarrow e^+ X$ (BR: 6.49%)
 - $B^+ \rightarrow e^+ X$ (BR: 10.99%)
 - $B^+ \rightarrow D^0 X$ (BR: 79%)



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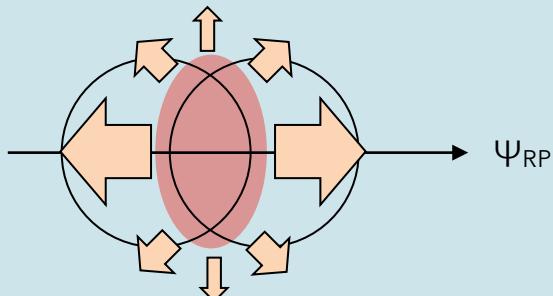
Main observation

- Nuclear modification factor (R_{AA}):
 - Comparison of particle production in PbPb collisions with that in pp scaled by the number of collisions (N_{col})

$$R_{AA} = \frac{\text{Number of particles in PbPb}}{N_{\text{col}} \times \text{Number of particles in pp}}$$


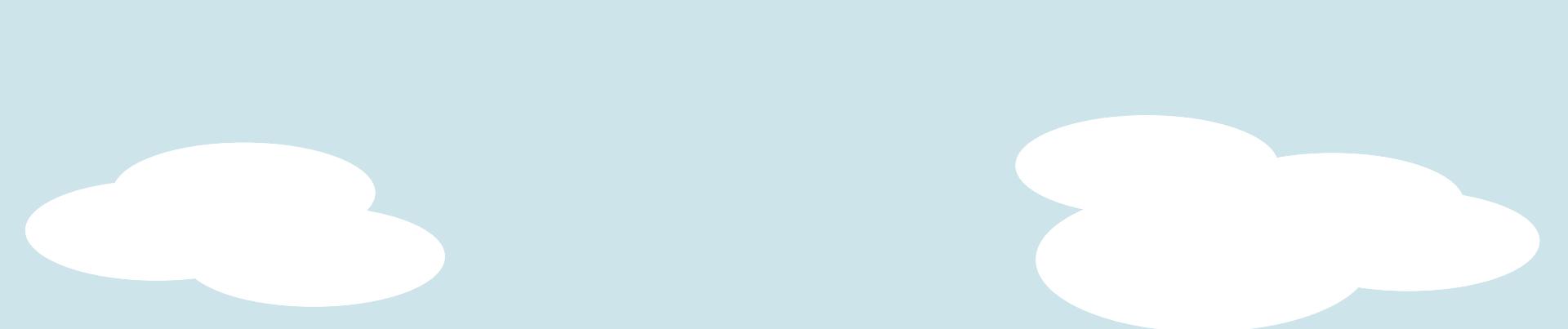
If no medium effects are present $\rightarrow R_{AA} \sim 1$
If medium effects are present $\rightarrow R_{AA} \neq 1$

- Elliptic flow (v_2):
 - Study azimuthal distribution of produced particle with respect to the reaction plane (Ψ_{RP})



$$N(\phi) \propto 1 + 2 \sum v_n \cos\{n(\phi - \Psi_{RP})\}$$

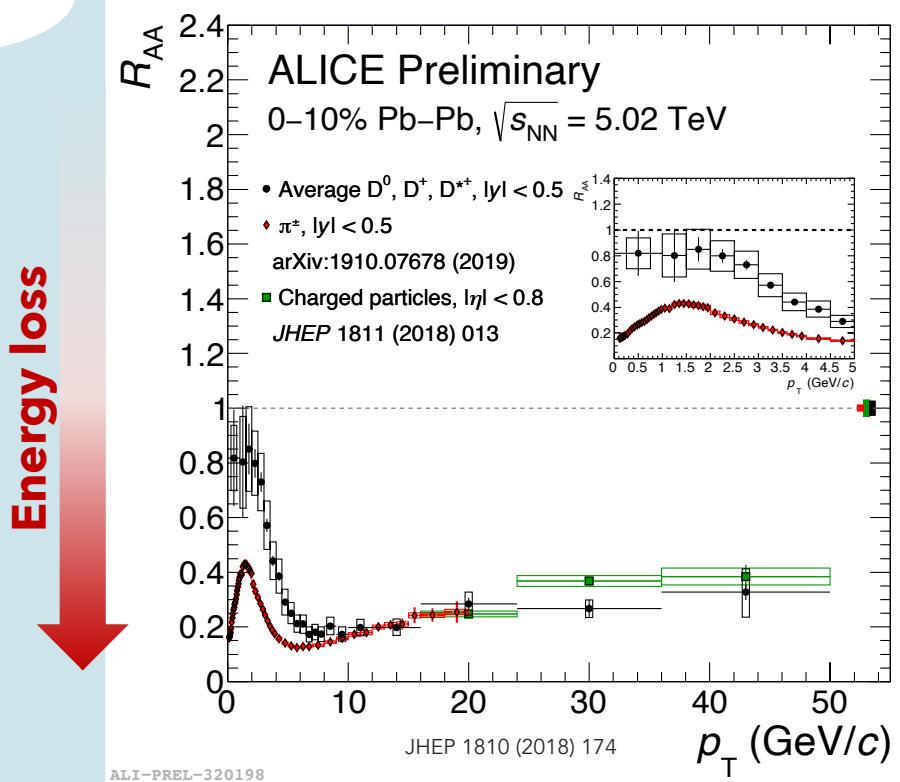
If the collectivity effects are present $\rightarrow v_2 > 0$ (low- p_T)
If the path-length effects are present $\rightarrow v_2 > 0$ (high- p_T)



Latest results

Nuclear modification factor R_{AA}

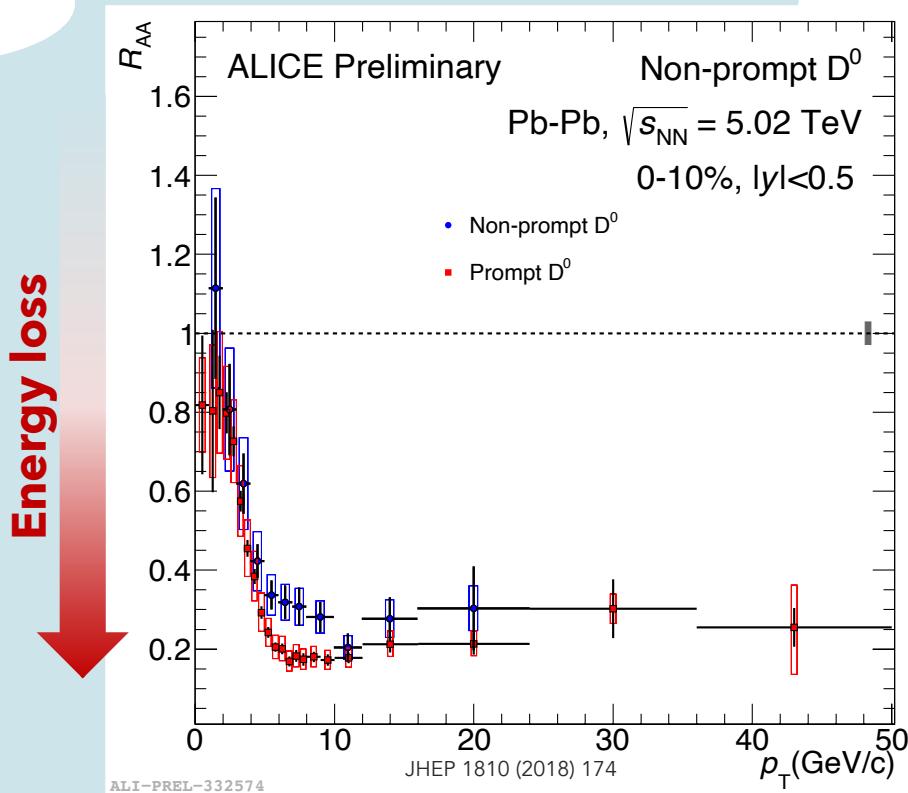
Light v.s. Charm



- At low- p_T (< 10 GeV/c): $\Delta E_{\text{loss}}(\text{light}) > \Delta E_{\text{loss}}(\text{c})$
 - Indicating smaller energy loss in charm hadron
- At high- p_T (> 10 GeV/c): $\Delta E_{\text{loss}}(\text{light}) \sim \Delta E_{\text{loss}}(\text{c})$
 - Indicating the same energy loss mechanism in light and charm hadron

Nuclear modification factor R_{AA}

Charm v.s. Beauty

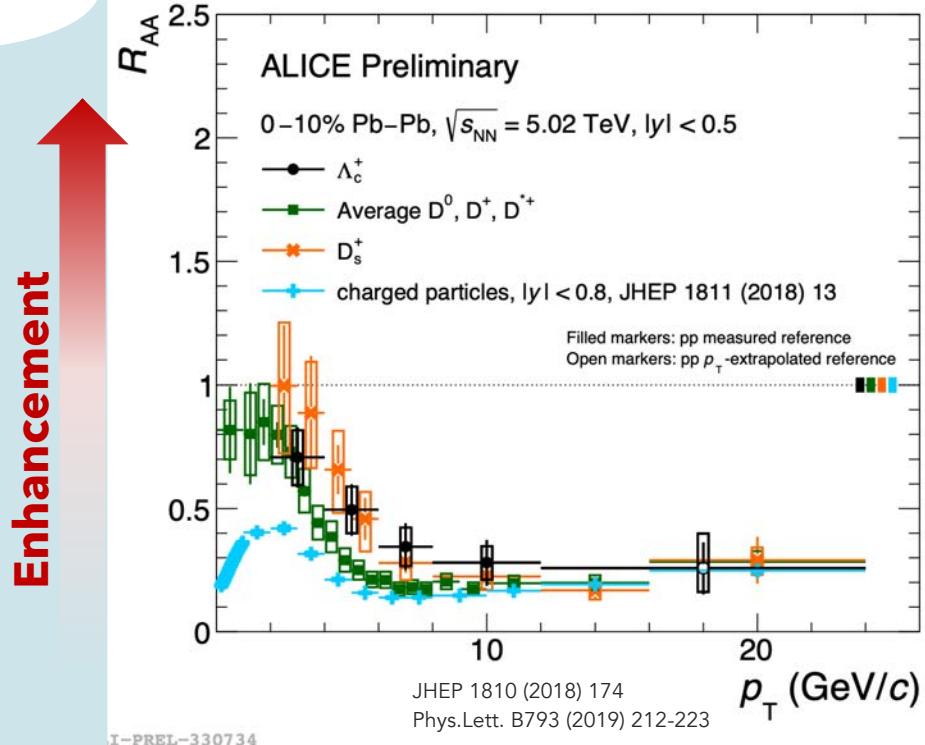


- All p_T (< 20 GeV/c): $\Delta E_{\text{loss}}(c) > \Delta E_{\text{loss}}(b)$
 - Indicating smaller energy loss in beauty hadron

Nuclear modification factor R_{AA}

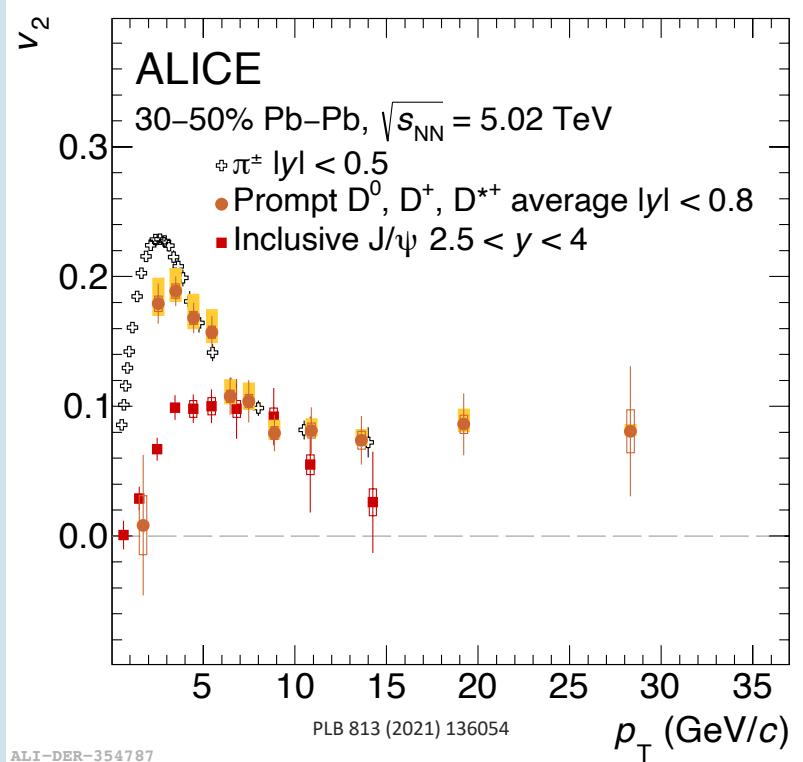
Meson v.s. Baryon

Charm with Strangeness v.s. Charm



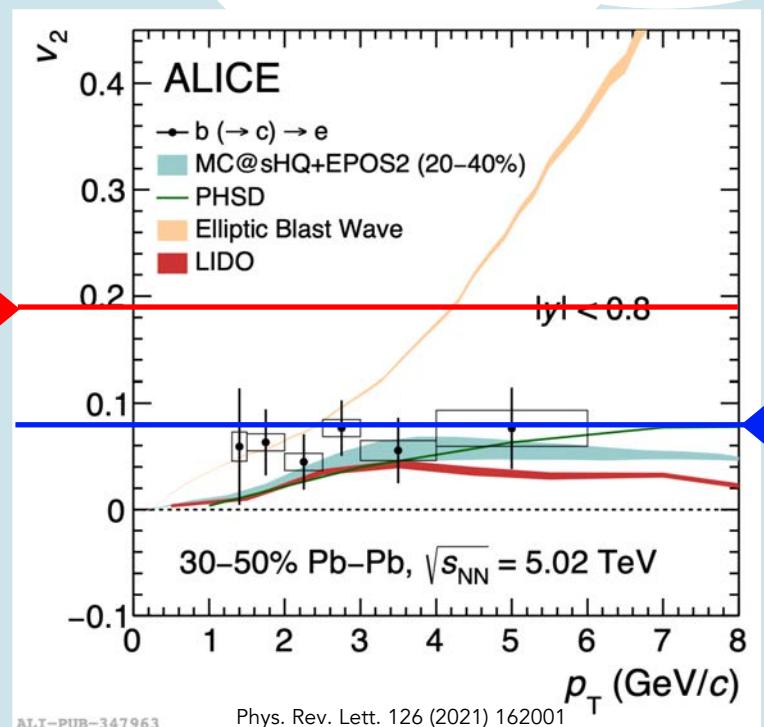
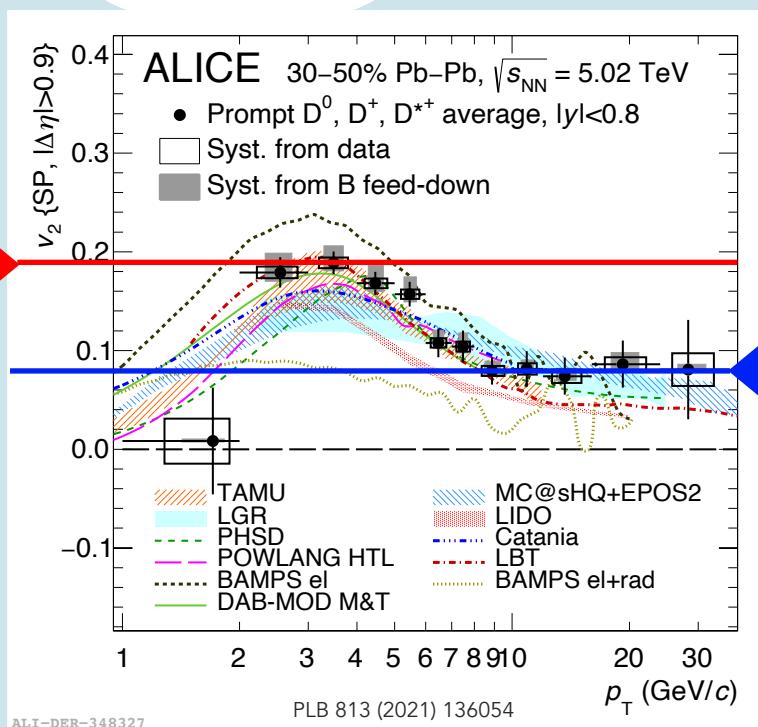
- At low- p_T (<10 GeV/c): **Baryon > Meson, $D_s >$ D(non-strangeness)**
 - Indicating coalescence contribution
- At high- p_T (>10 GeV/c): **Baryon = Meson, $D_s =$ D(non-strangeness)**
 - Indicating the same production mechanism

Elliptic flow (v_2) Light v.s. Charm



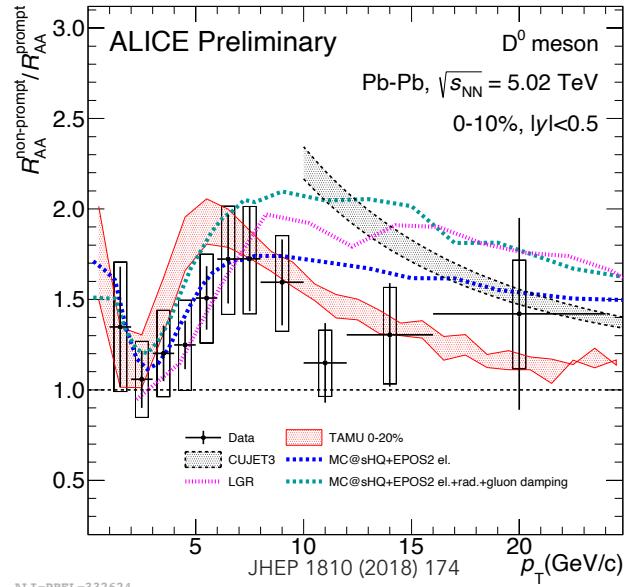
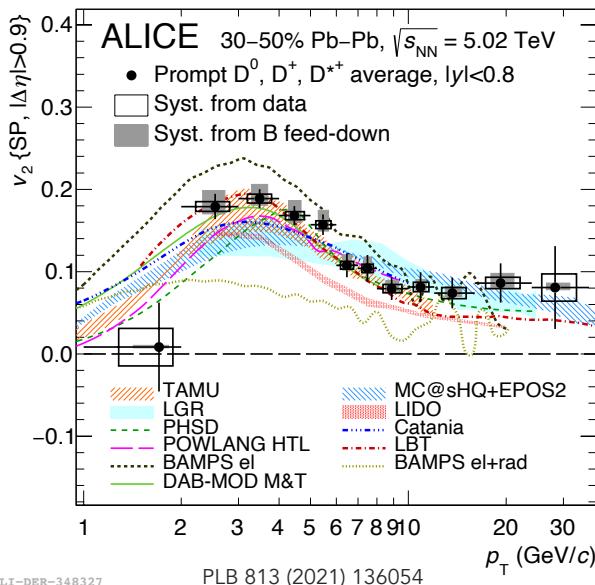
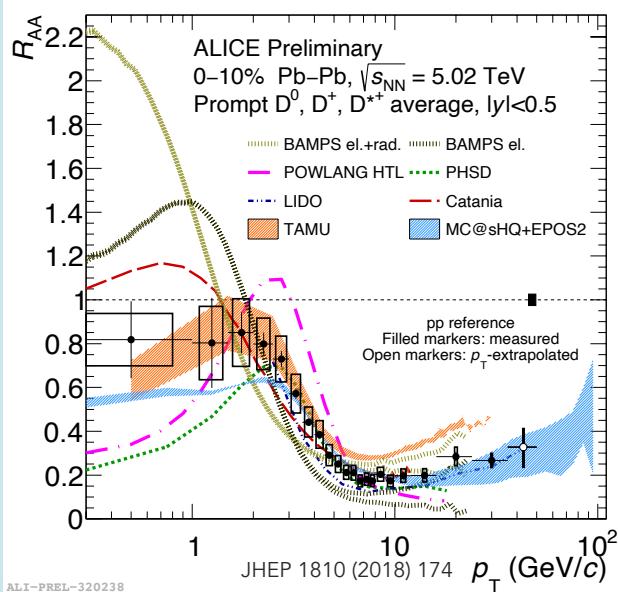
- Almost the same v_2 as light hadron
 - Contribution from thermalized charm?
- Flattened and compatible with light hadron at high- p_T (> 7 GeV/c)
 - Energy loss path-length dependence?

Elliptic flow (v_2) Charm v.s. Beauty



- Positive beauty v_2 !
 - Different shape from the other particle (no significant p_T dependence)
- Beauty v_2 compatible with charm v_2 at high- p_T
 - Energy loss path-length dependence?

Comparison with models



- There are many models, and they describe the trend well

Quarkonium

Quarkonium

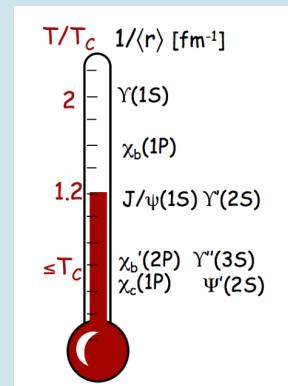
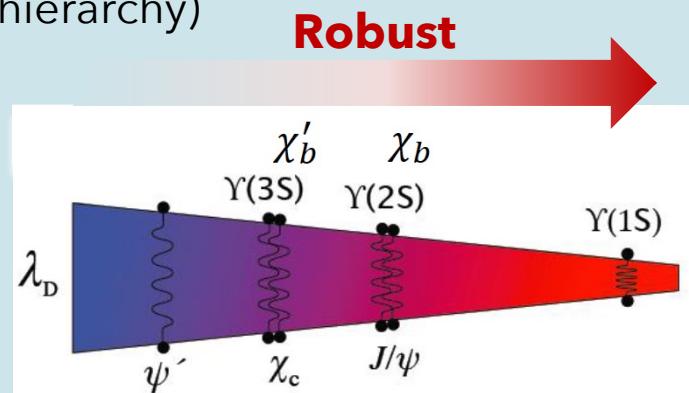
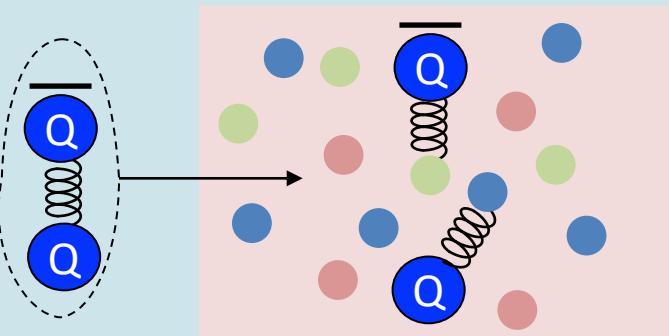
- Bound state of ccbar and bbbar
 - Charmonium (ccbar state)
 - J/ ψ : $M = 3.096 \text{ GeV}/c^2$
 - $\Psi(2S)$: $M = 3.686 \text{ GeV}/c^2$
 - Bottomonium (bbbar state)
 - $Y(1S)$: $9.46 \text{ GeV}/c^2$
 - $Y(2S)$: $10.023 \text{ GeV}/c^2$
 - $Y(3S)$: $10.3552 \text{ GeV}/c^2$
- About 1 % heavy quark pairs form quarkonium
 - Open heavy quark meson: ~90%
 - Open heavy quark baryon: ~9%

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

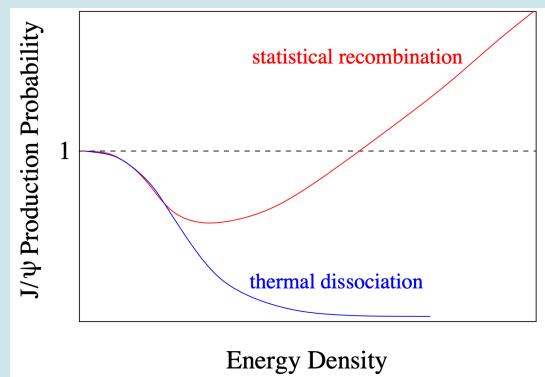
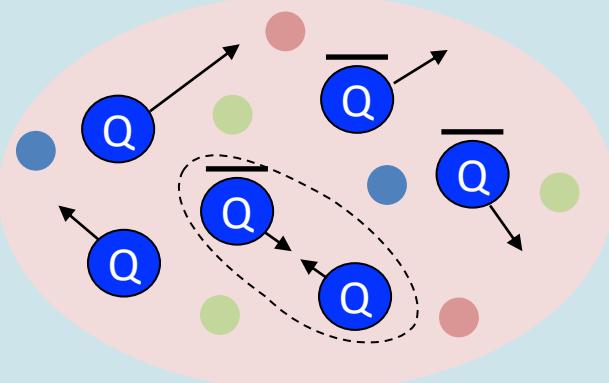
$(m_c = 1.25 \text{ GeV}, m_b = 4.65 \text{ GeV}, \sqrt{\sigma} = 0.445 \text{ GeV}, \alpha = \pi/12)$

Melting v.s. regeneration

- Quarkonium melting caused by Debye screening
 - Depends on hadron radius (hierarchy)

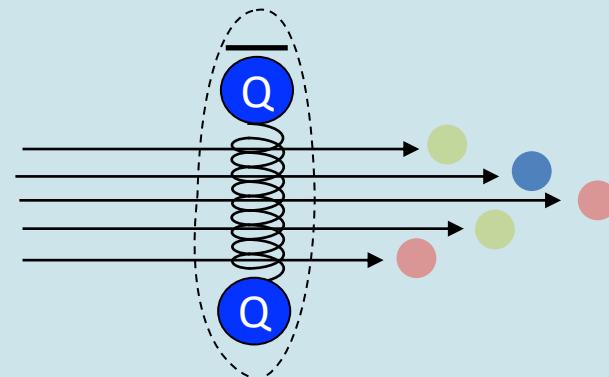
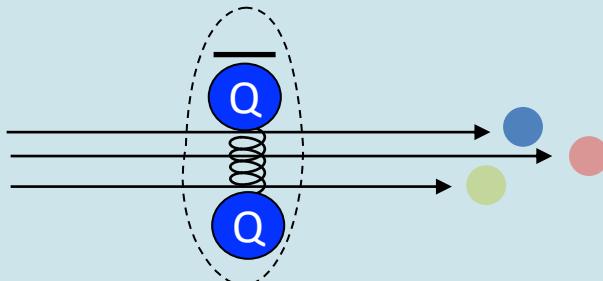


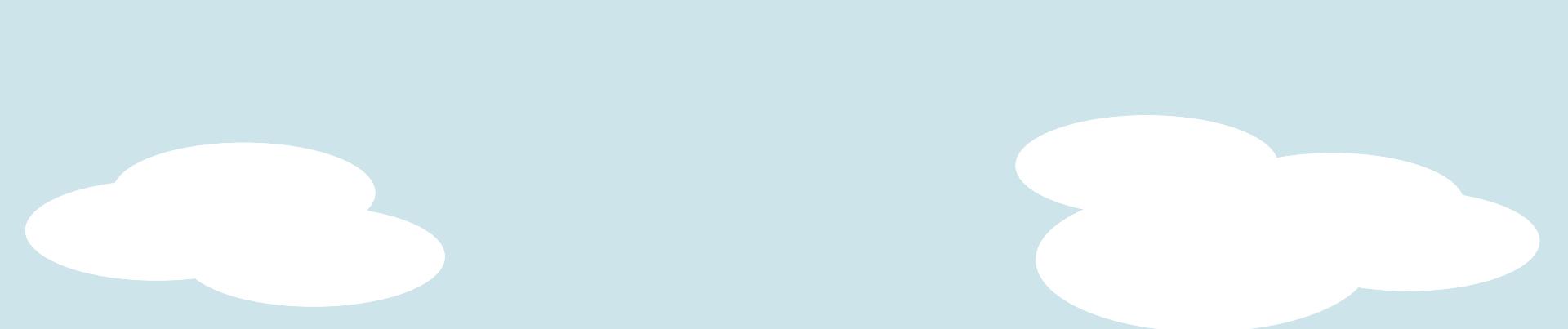
- Quarkonium regeneration
 - ~30 ccbar pairs in a collision (0-5%:PbPB@5.02TeV)



Comover interaction

- Quarkonium is produced in initial stage of collisions
 - Hadronization at very early formation time
 - $\tau_{\psi(2S)} \sim 0.35 \text{ fm/c}$
 - Dense condition even in small collision system
 - **Possible to see the effect in small collision system (w/o QGP)**
- Break-up quarkonium with passing soft particles
 - Depending on the radius
 - Sequential break-up in J/ψ , $\psi(2S)$, $Y(1S)$, $Y(2S)$, $Y(3S)$...

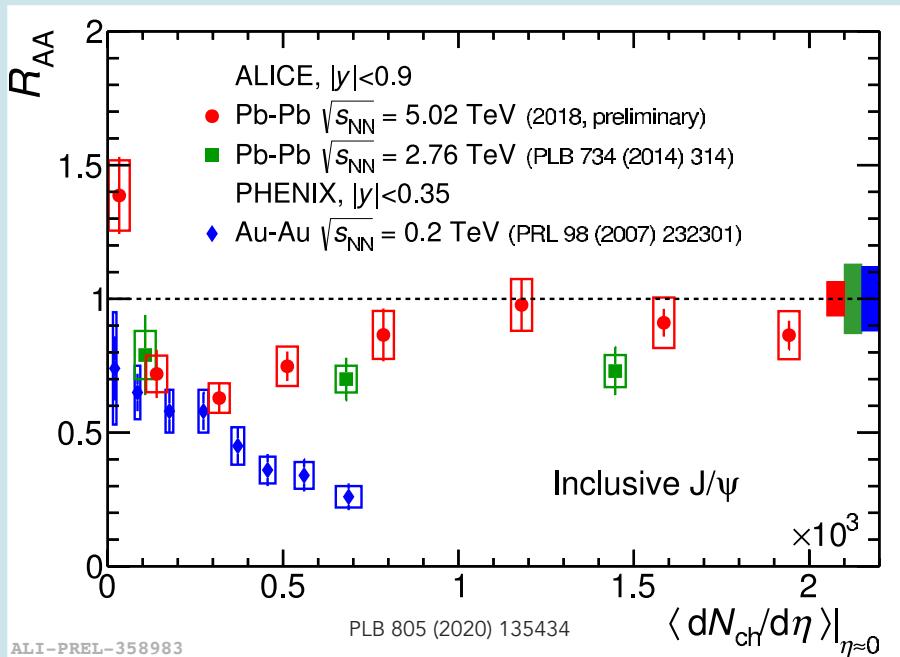




Latest results

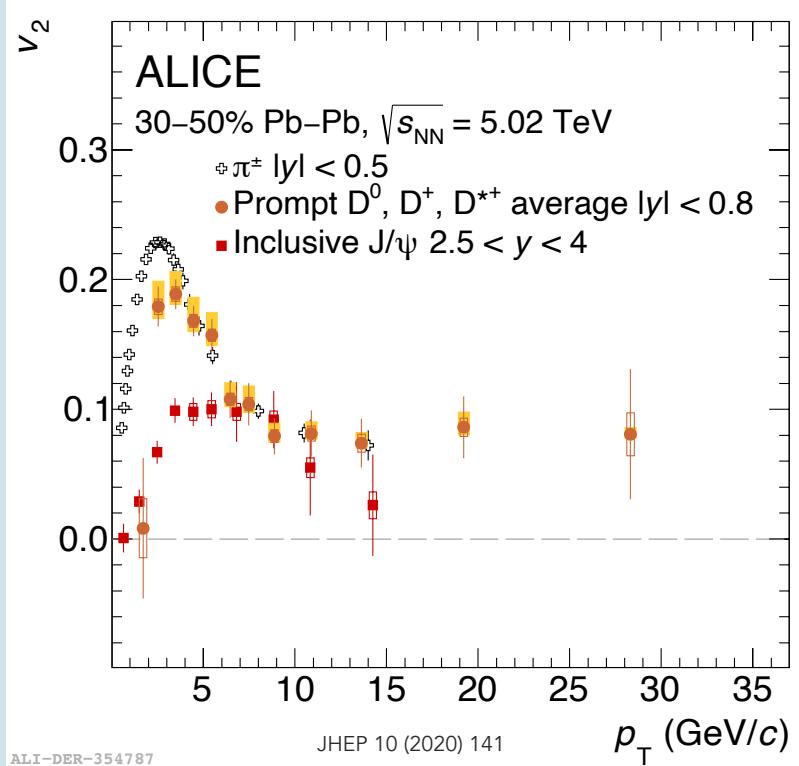
Nuclear modification factor R_{AA}

Melting v.s. regeneration



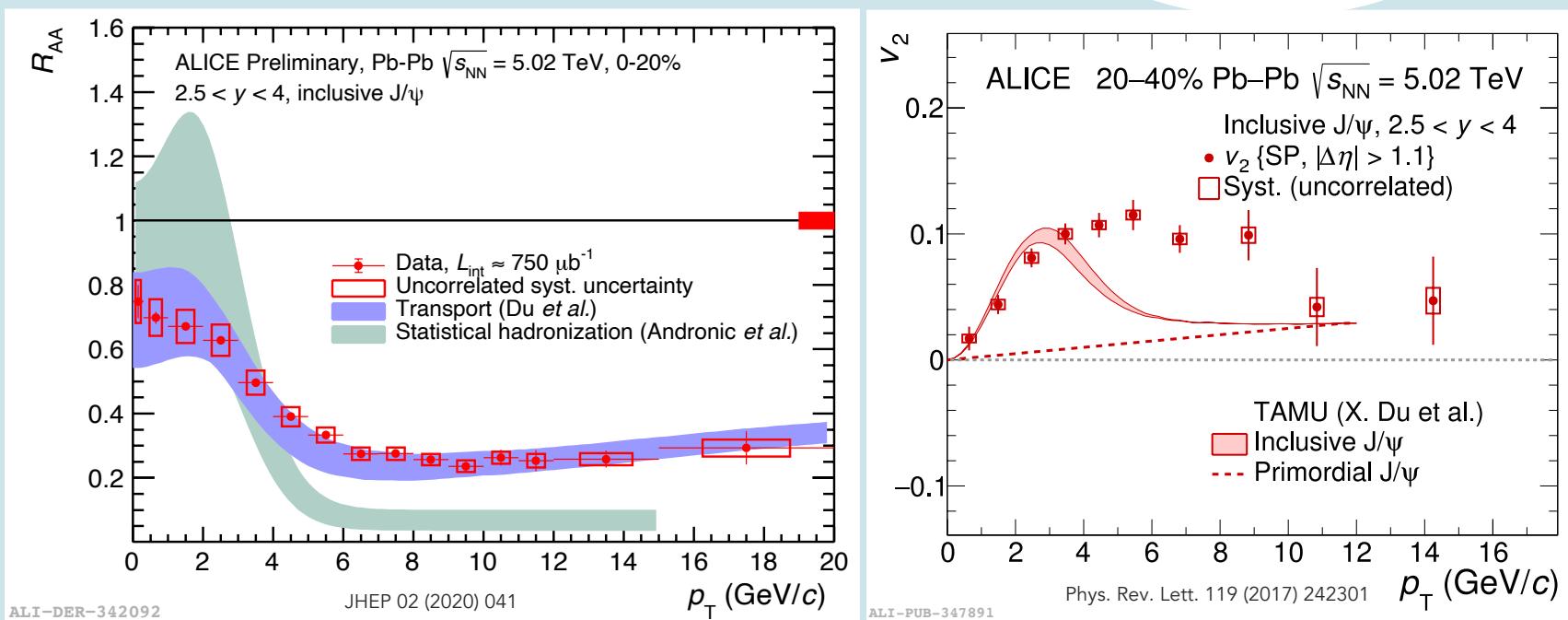
- Obvious energy dependence of $R_{AA}(5.02 \text{ TeV}) > R_{AA}(2.76 \text{ TeV}) > R_{AA}(0.2 \text{ TeV})$
- Regeneration > melting @ LHC!

Elliptic flow (v_2) Light v.s. Open-charm v.s. Hidden Charm



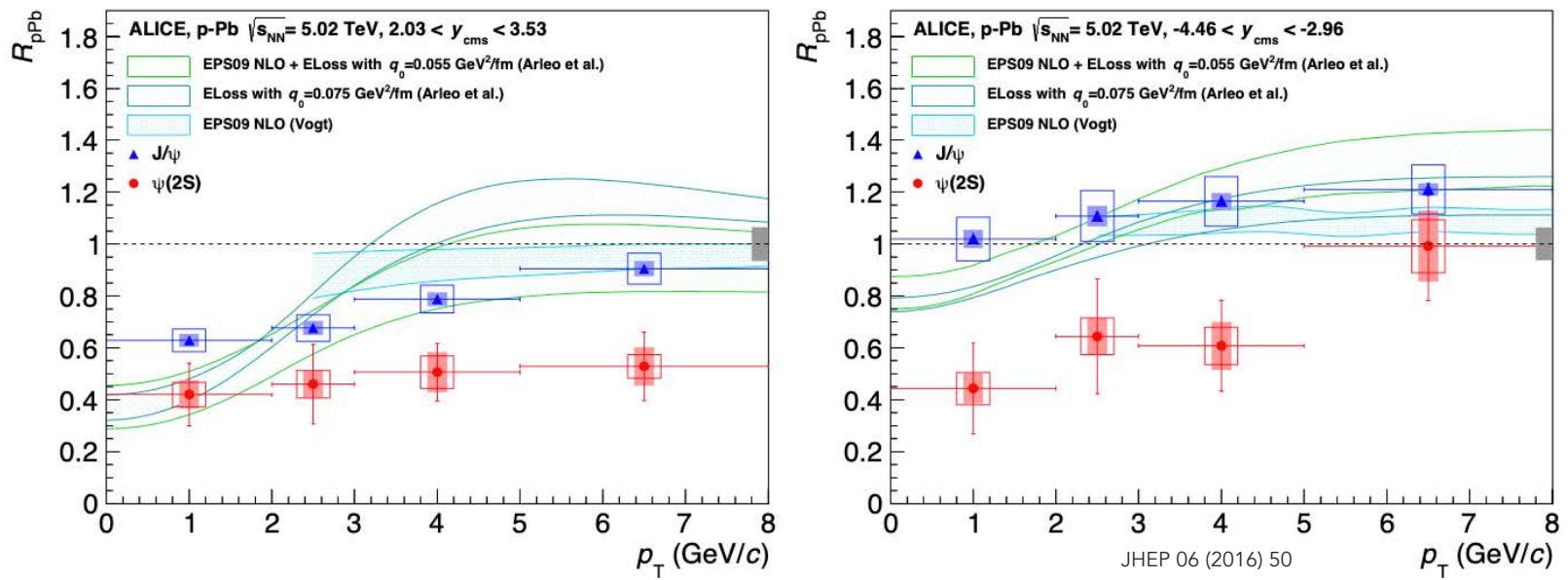
- Positive $J/\psi v_2$
 - Clear mass hierarchy with π^\pm , D , J/ψ
- Light hadron, D , $J/\psi v_2$ converge into single value at high- p_T
 - Energy loss path-length dependence?

Comparison with theory



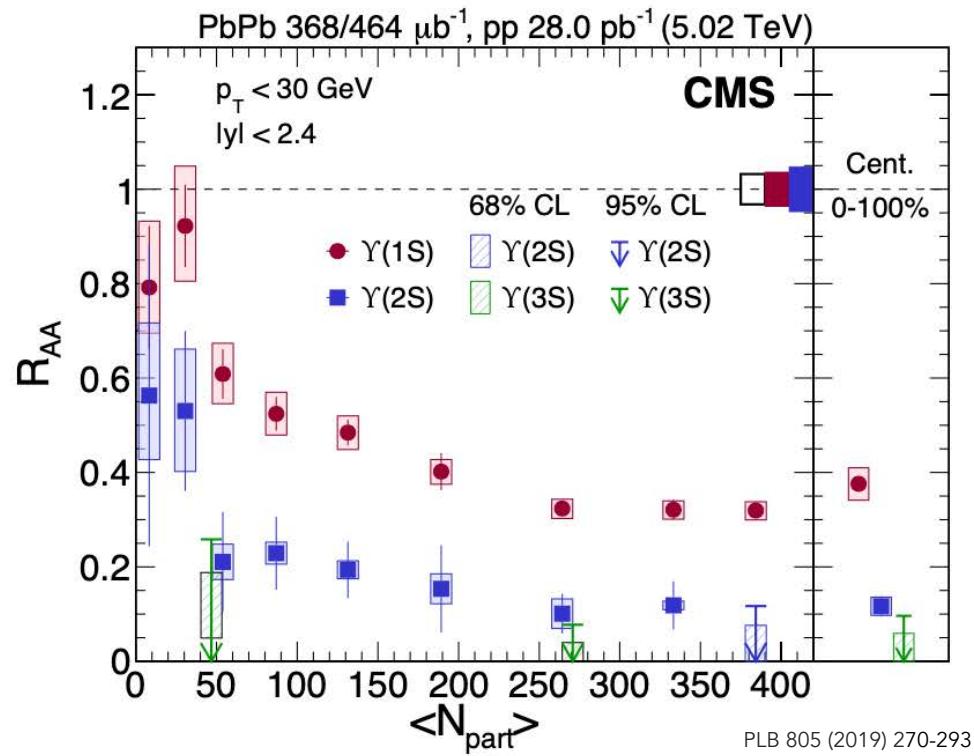
- Well description of R_{AA} with transport model including primordial, melting, and regeneration with thermalized charm
- Good agreement with v_2 for $p_T < 4$ GeV/c, but large deviation from data for $4 < p_T < 10$ GeV/c

Charmonium sequential suppression in pA collisions



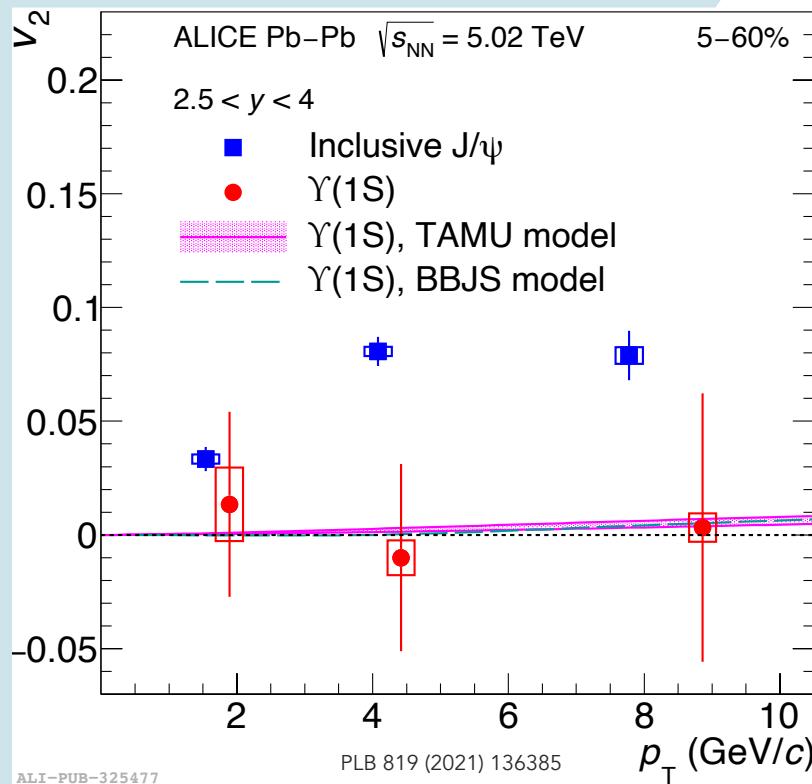
- Sequential suppression in pPb collisions!
- Not described by conventional model (ELoss in nucleus + nPDF)
 - The same suppression for J/ψ and $\psi(2S)$
- Need to be considered the interaction to discuss sequential melting

Bottomonium Sequential suppression



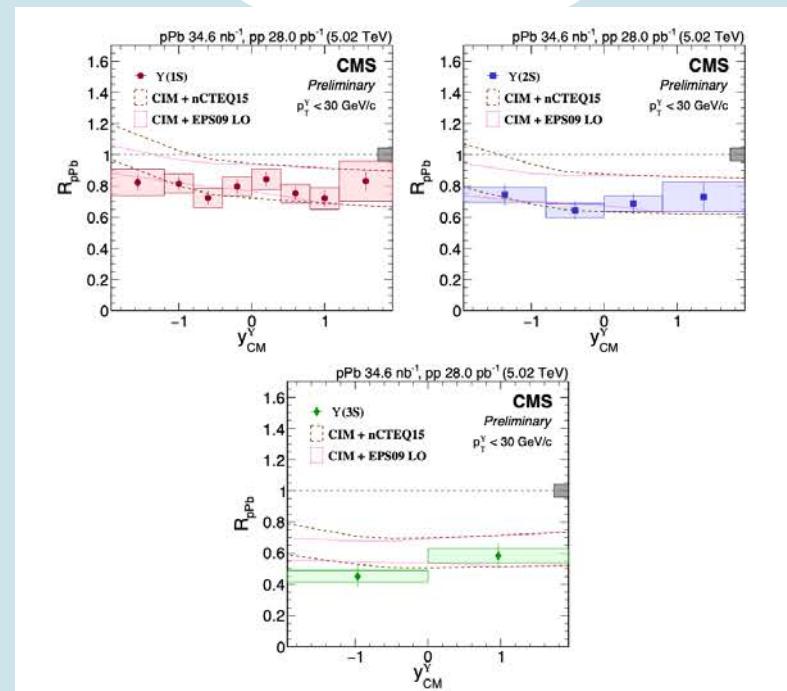
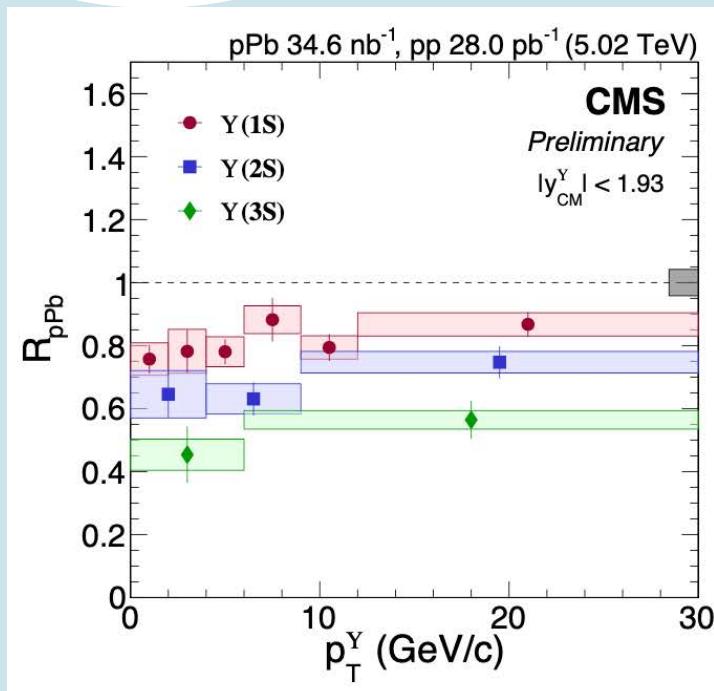
- Sequential suppression for Υ family
 - $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$

Elliptic flow of bottomonium



- $\Upsilon(1S) v_2$ is significantly smaller than J/ψ
 - $\Upsilon(1S)$ is the only particle without v_2 !
 - No thermalization for beauty

Bottomonium sequential suppression in pA collisions



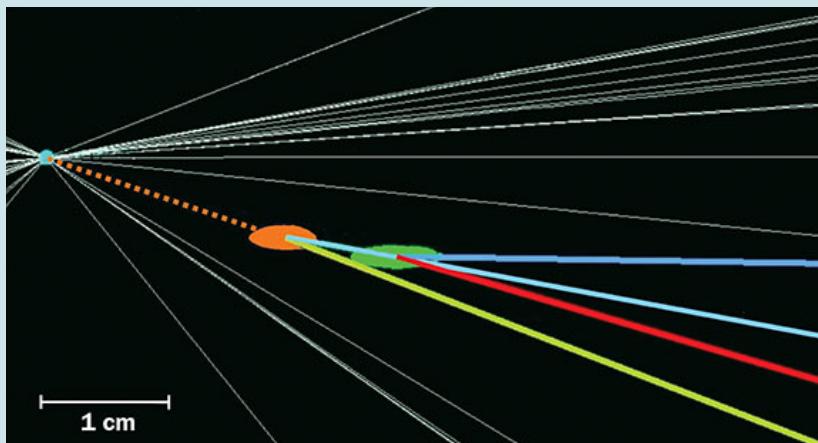
- Bottomonium sequential suppression in pPb collisions!
- Same hierarchy in comover interaction model
 - Still tension at Pb-going direction ($y < 0$)

Conclusion from the experiments

- Open heavy flavor
 - Energy loss hierarchy is observed at $p_T < 10 \text{ GeV}/c$
 - Energy loss hierarchy is disappeared at $p_T > 10 \text{ GeV}/c$
 - Charm and beauty have positive v_2 , but no p_T dependence in beauty
 - Strangeness meson and baryon is enhanced
- Quarkonium
 - Regeneration contribution is larger than melting for J/ψ at LHC
 - Sequential melting is observed for Y family in PbPb collisions
 - J/ψ has positive v_2 , but zero consistent v_2 for $Y(1S)$
 - Sequential suppression for charmonium and bottomonium in pPb collisions (possibly) due to comover interaction has been observed

What's next for HF?

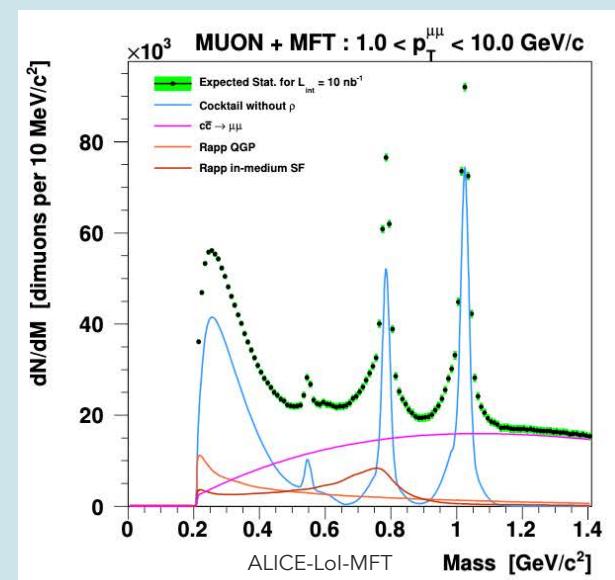
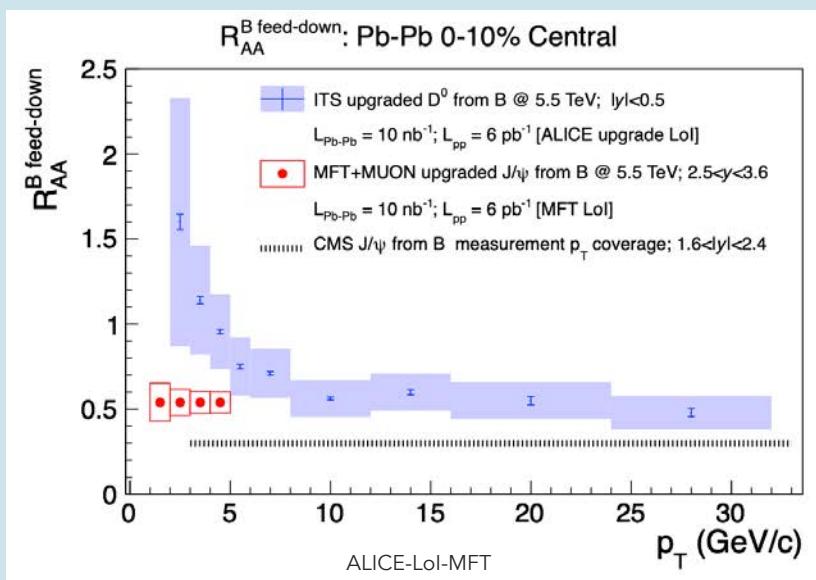
- Why don't you measure all objects at forward rapidity in PbPb collisions?
 - Large Lorentz boost at low- p_T particle
 - Longer life time for low- p_T (~ 10 times longer @ $y \sim 4$)
 - Precise measurement of heavy flavor baryons
 - Open low- p_T muonic channel (e.g. $B \rightarrow J/\psi K$, $B \rightarrow J/\psi X \rightarrow \mu\mu X$, $B \rightarrow \mu X$)



Event display of B-meson decay (orange point) from LHCb

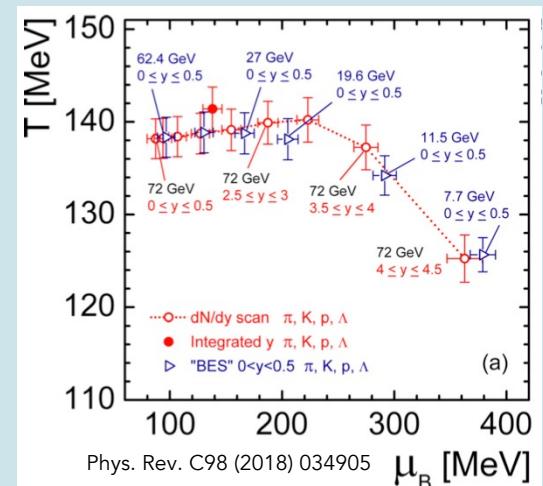
Short-term future

- ALICE experiment installs high precision Si tracker at forward rapidity
 - Access to measure muon decay point precisely

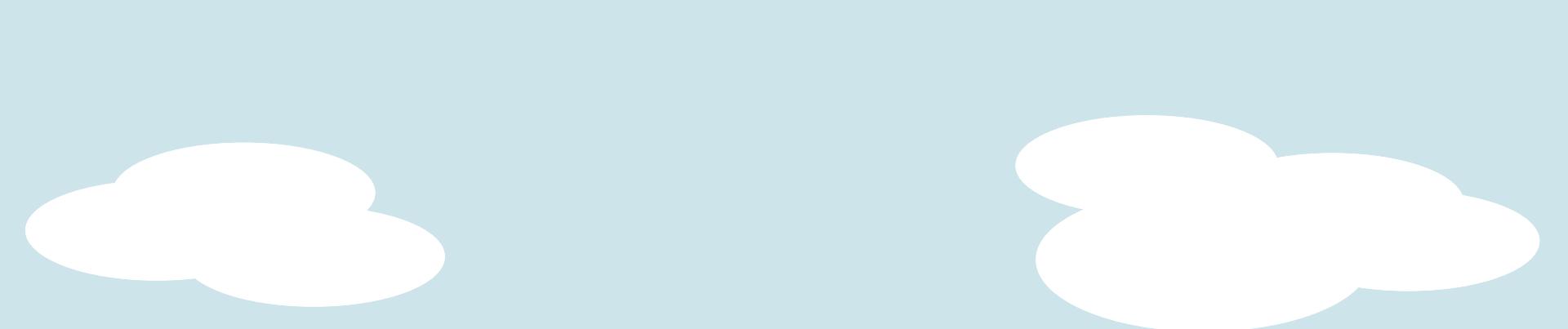


Unique idea (Long-term future)

- Fixed target experiment at LHC (AFTER@LHC)
 - Collision energy $\sqrt{s_{NN}} \sim 72$ GeV
 - Enough energy to produce QGP
 - With high luminosity and polarized several targets
- **Forward in lab-frame, but mid-rapidity in physics ($\Delta y \sim 4.3$)**
 - **Measure mid-rapidity physics with boosting!**
 - **Very good opportunity for HF measurement**
- Novel way to search QCD phase diagram
 - Baryon chemical potential depends on rapidity

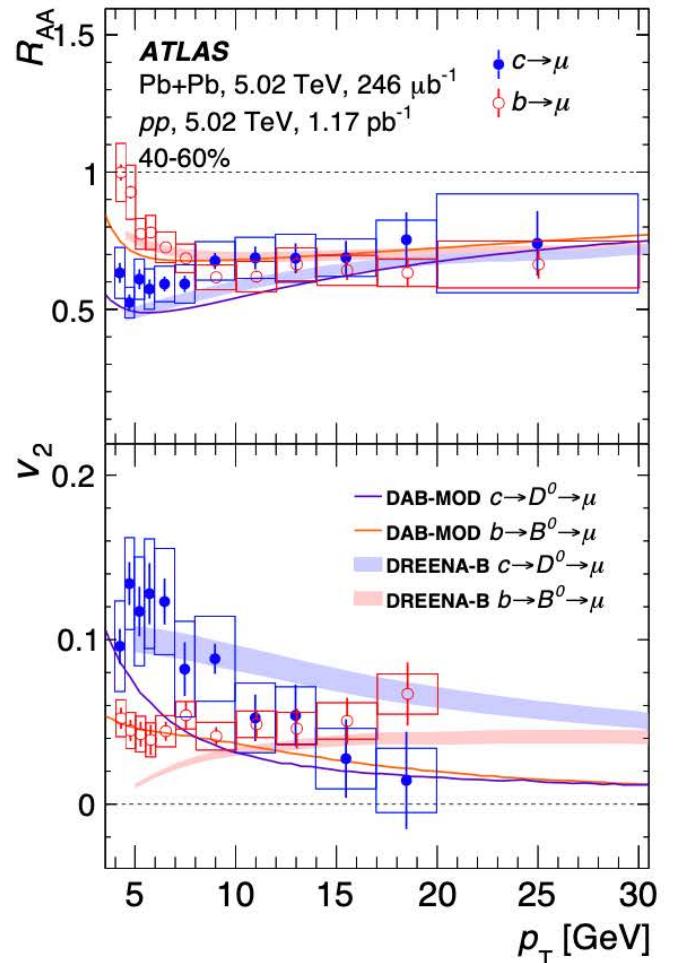
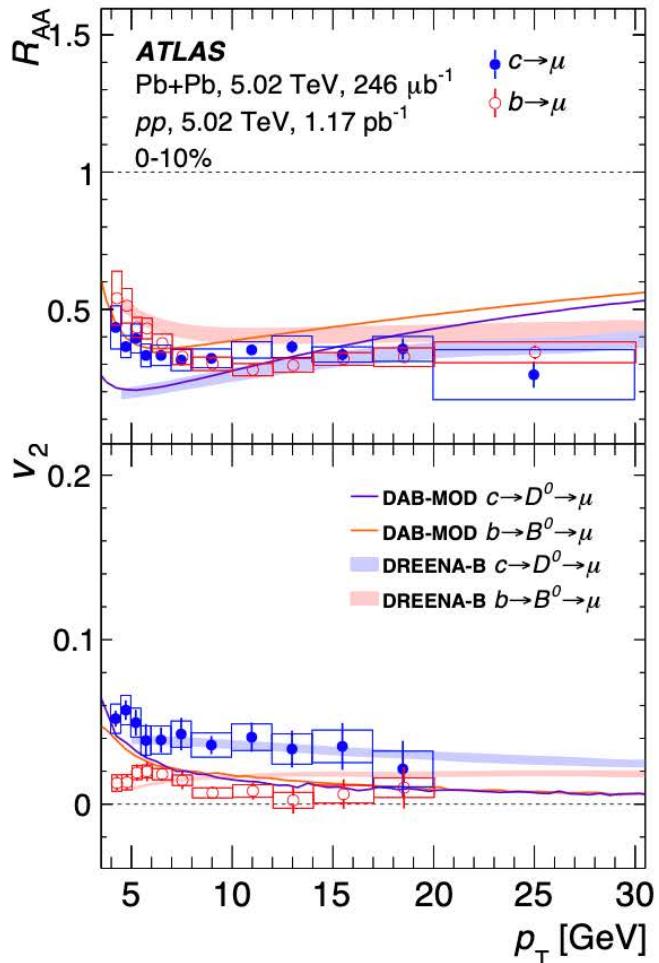


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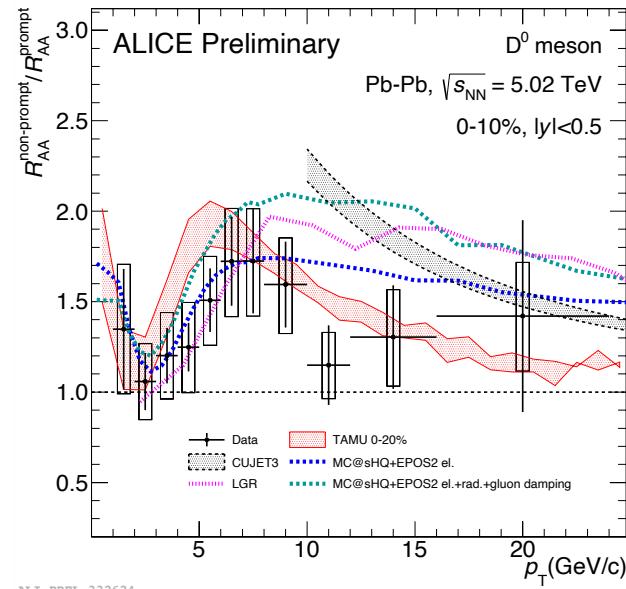
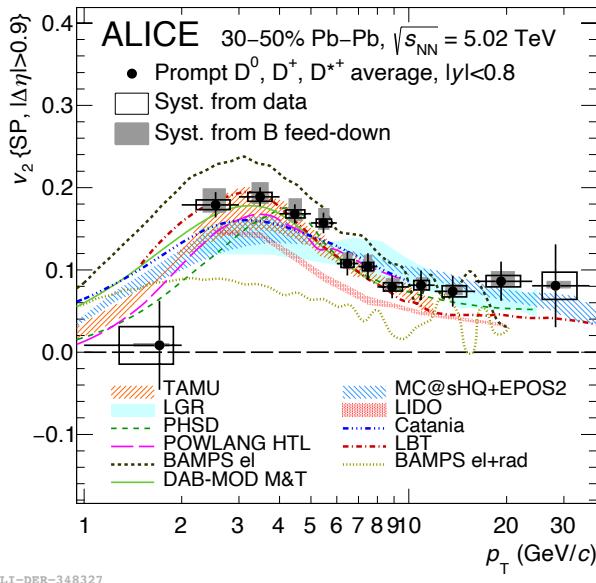
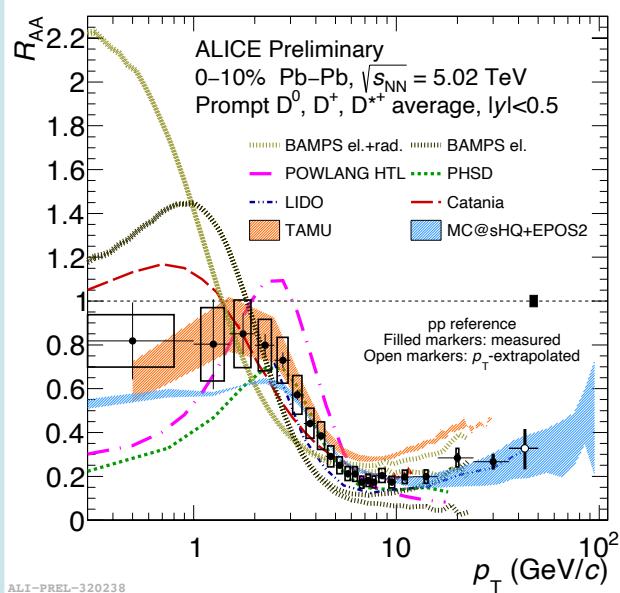


Back up

ATLAS open heavy flavor

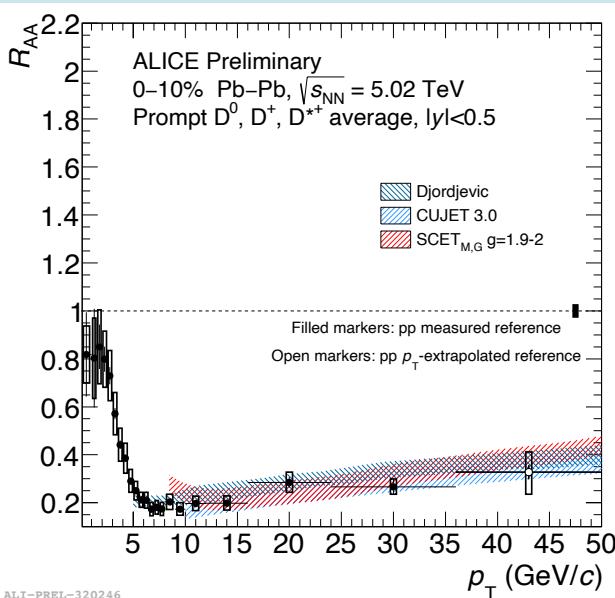
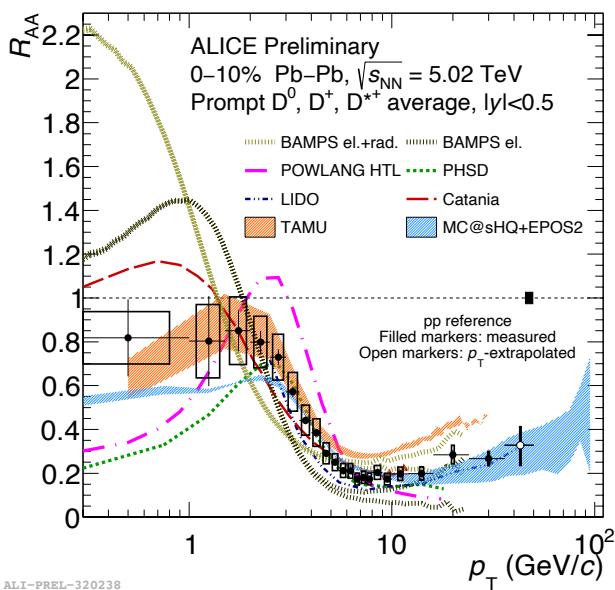


Comparison with models



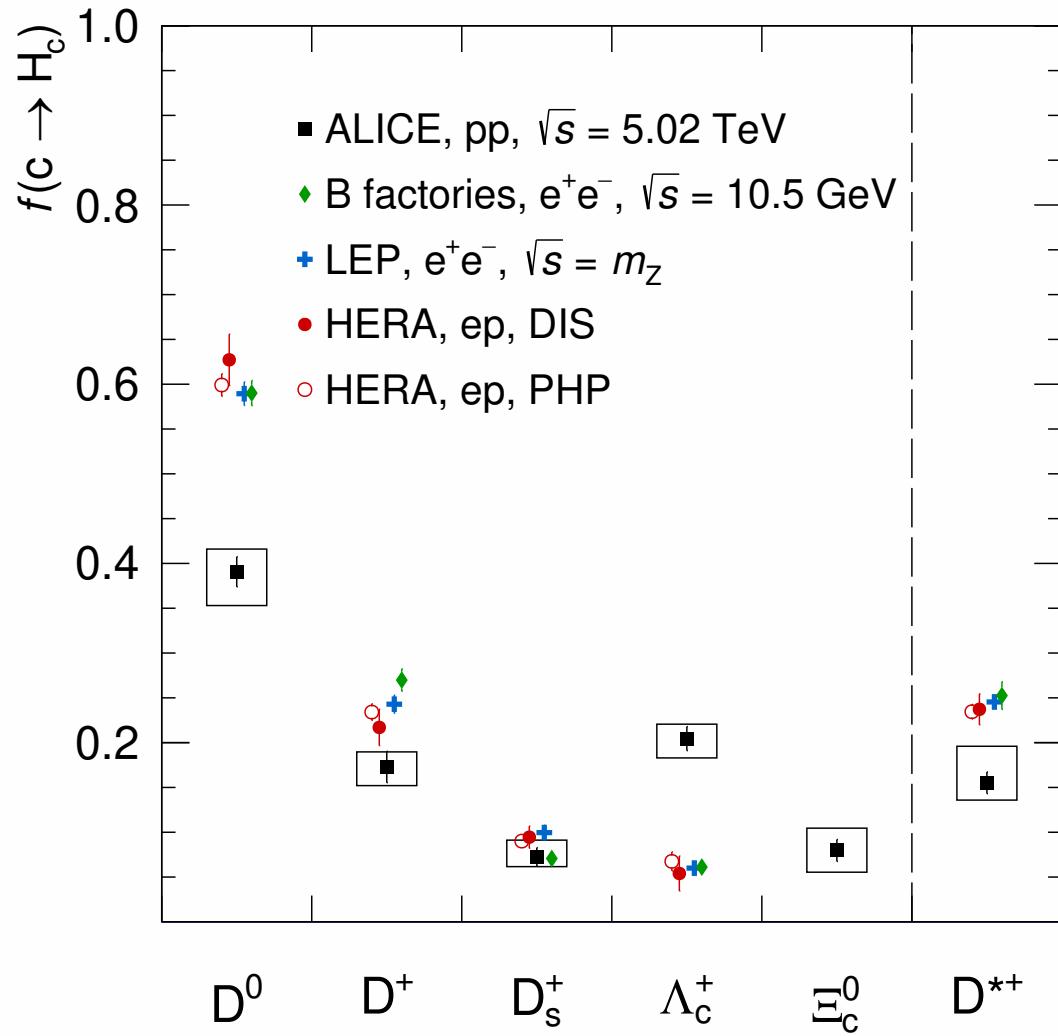
- There are many models, and they describe the trend well

$$1.5 < 2\pi D_s T_c < 7 \text{ with } T_c = 155 \text{ MeV}$$

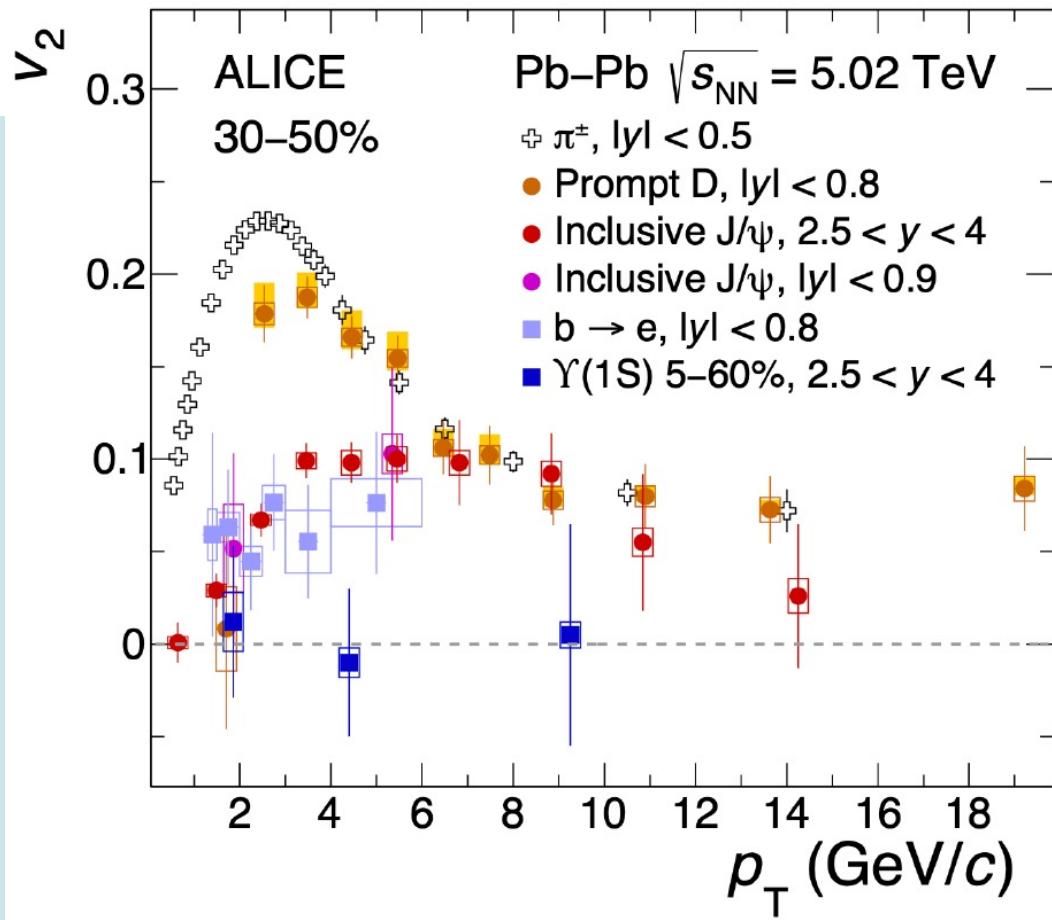


Transport Models	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
BAMPS	✓	✓	✗	✓	✗
POWLNG	✓	✗	✓	✓	✓
PHSD	✓	✗	✓	✓	✓
LIDO	✓	✓	✓	✓	✓
TAMU	✓	✗	✓	✓	✓

pQCD e-loss Models	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
Djordjevic	✓	✓	✗	✗	✓
CUJET3.0	✓	✓	✗	✗	✗
SCET	✓	✓	✗	✗	✓
MC@sHQ+EPOS	✓	✓	✓	✓	✓



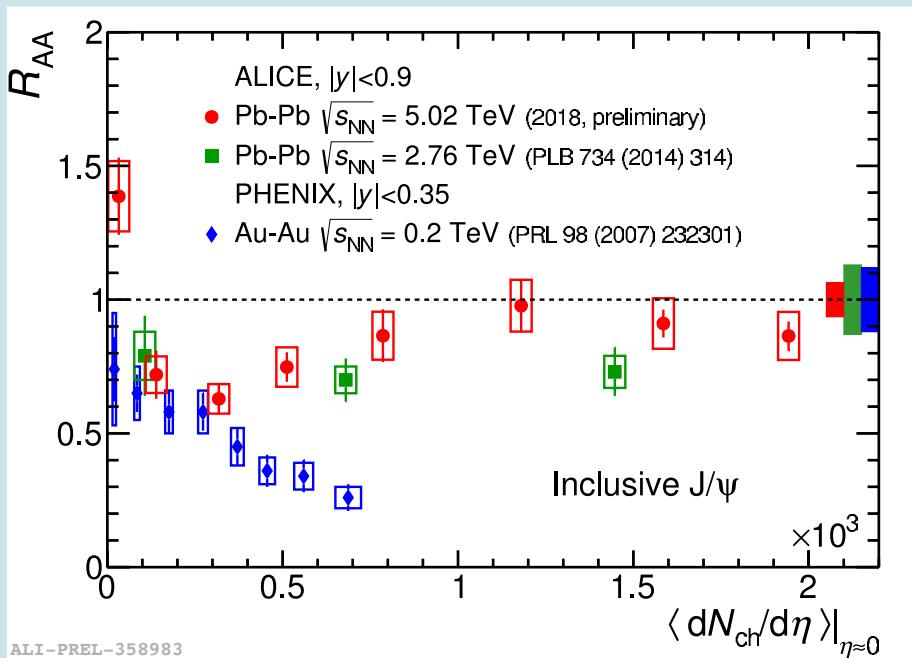
ALICE-PUB-488617



Nuclear modification factor R_{AA}

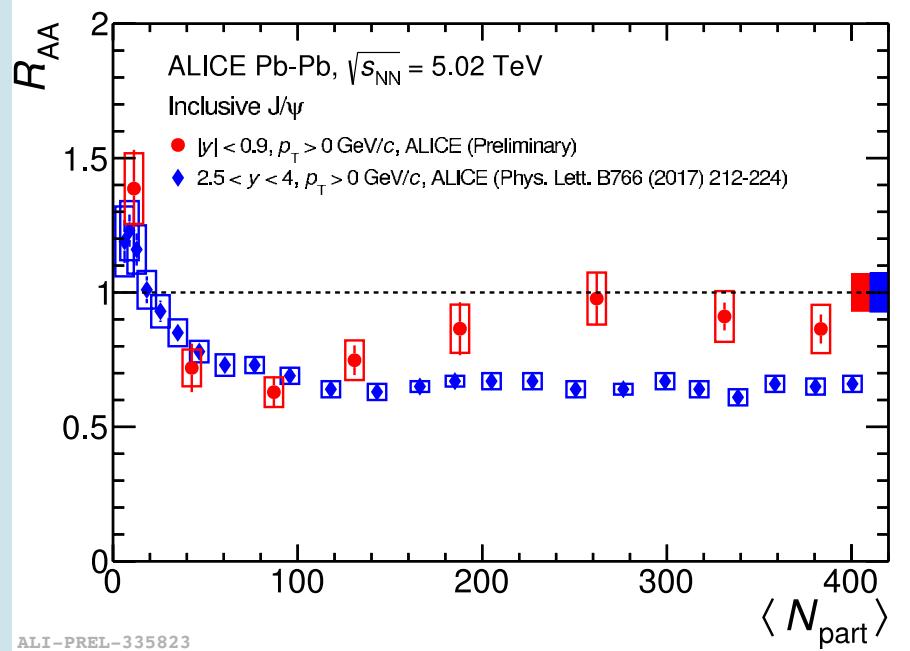
Melting v.s. regeneration

Collision energy dependence

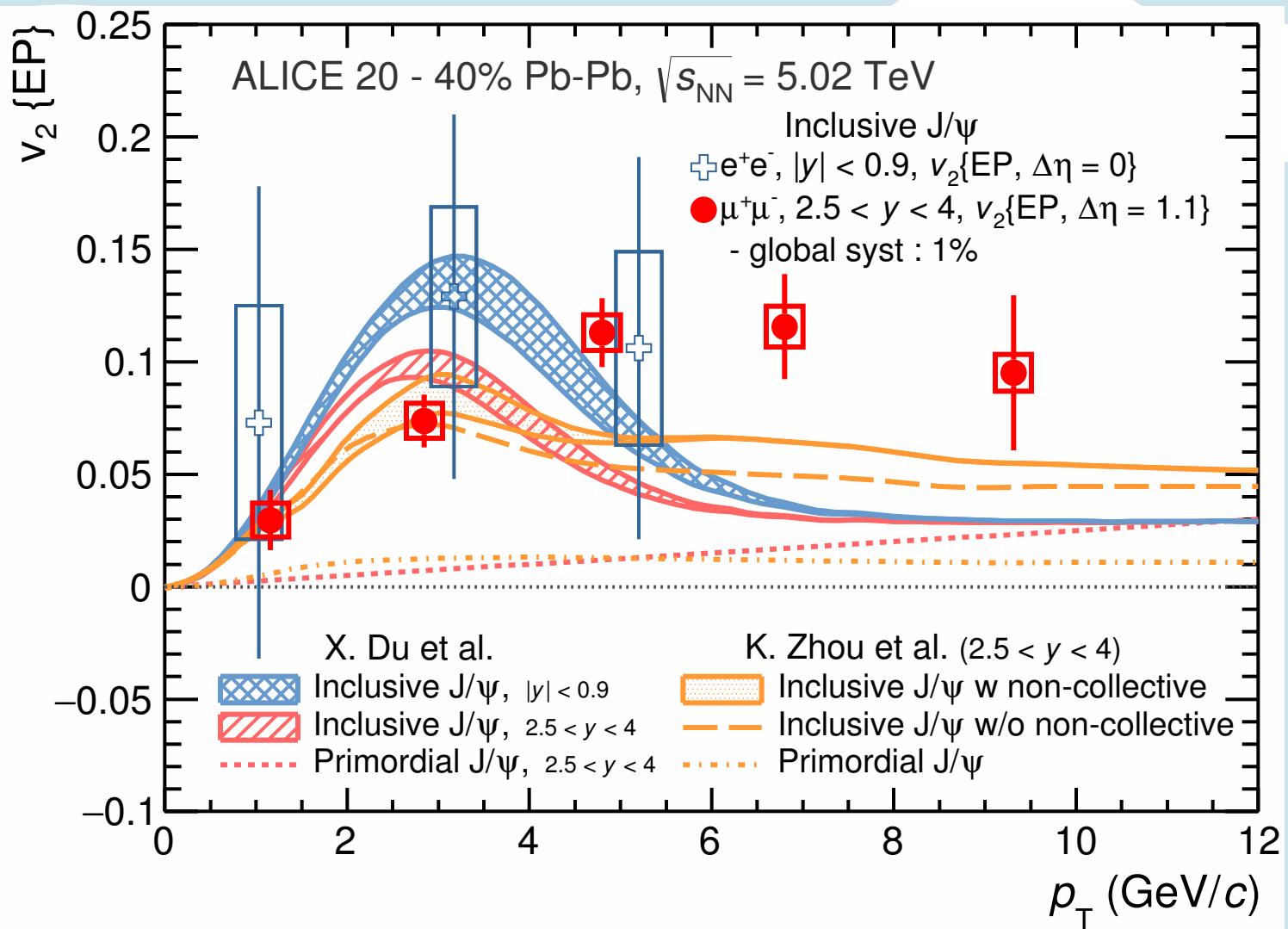


Regeneration > melting @ LHC

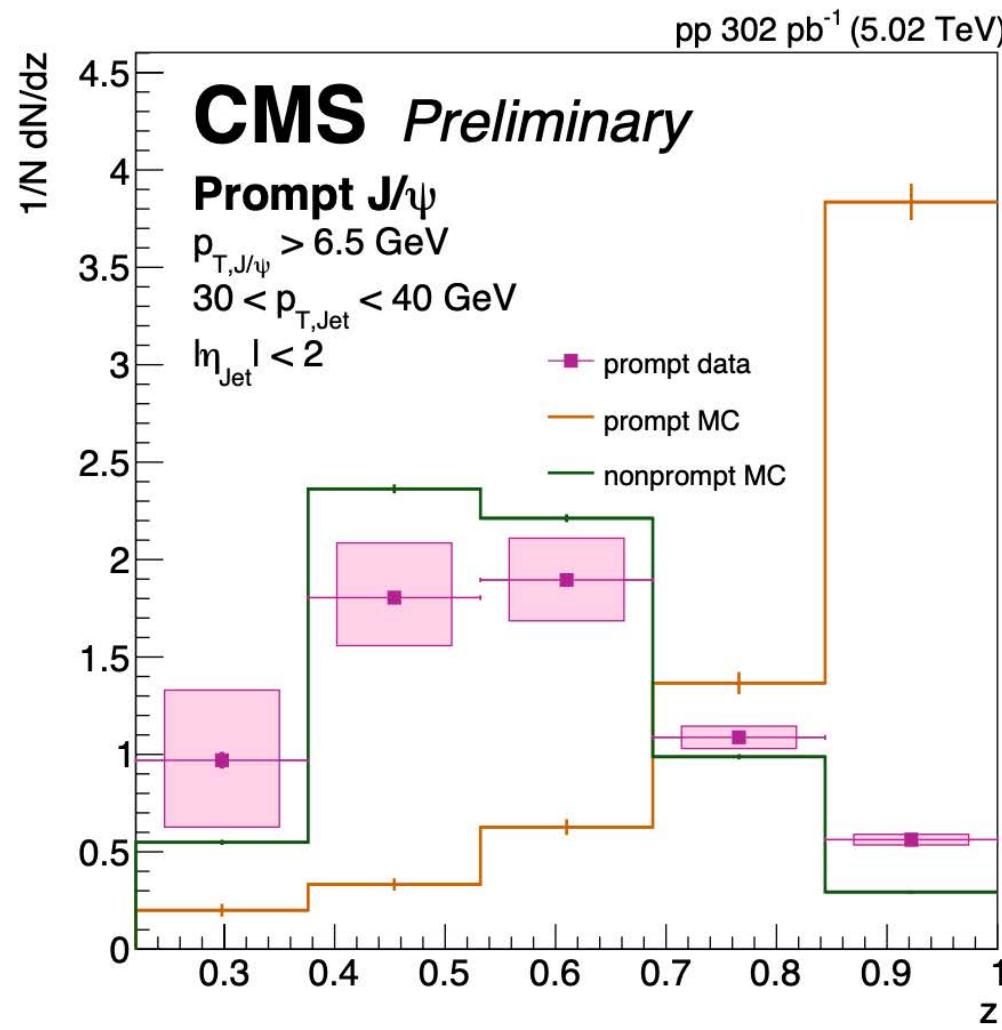
Rapidity dependence

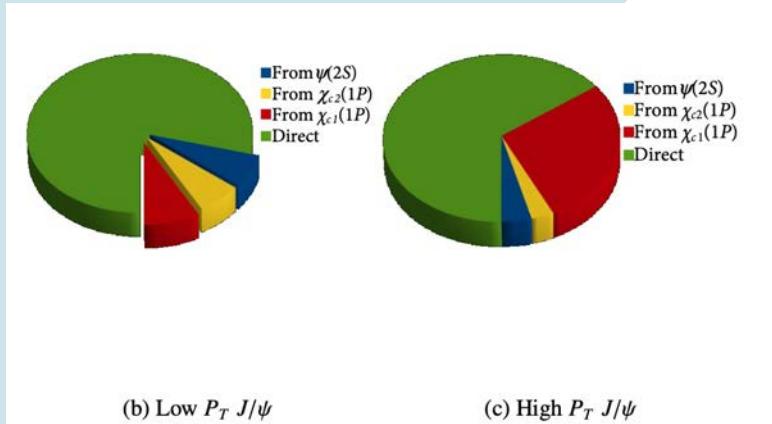


Larger energy density



Fragmentation into charmonium





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