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解に向けた理論・実験共同研究会
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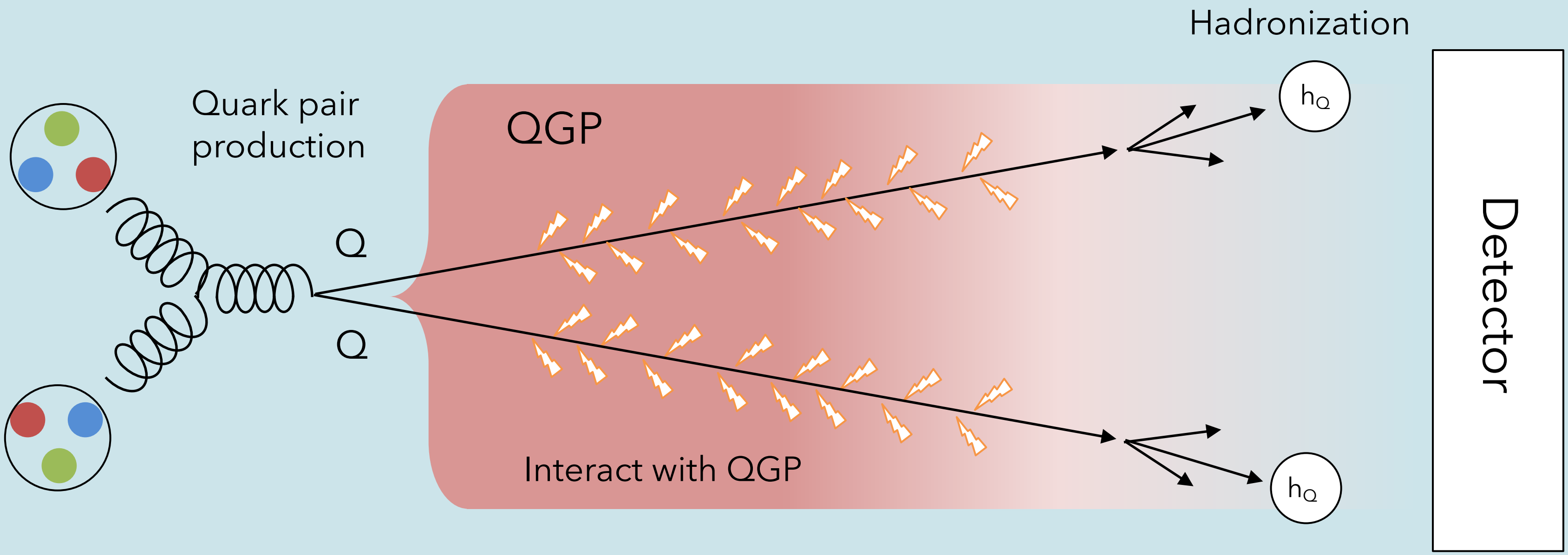
Open heavy flavor

What is heavy flavor (HF)?

- Heavy flavor (charm & beauty)
  - Mass: m_c (~1.3 GeV/c^2), m_b (~4.5 GeV/c^2) >> Λ_{QCD} (~0.2 GeV)
- Produced initial hard scattering processes
  - Accurate interpretation by pQCD
- Short formation time
  - $\tau \sim 1/2m_q \sim 0.07$ fm/c < QGP (0.1 – 1 fm/c)
- Long life time
  - D^0: $\tau c \sim$ 120μm, Λ^+_c: $\tau c \sim$ 60μm
  - B^0: $\tau c \sim$500μm , Λ^0_b: $\tau c \sim$ 440μm

Key features of using HF to investigate QGP properties

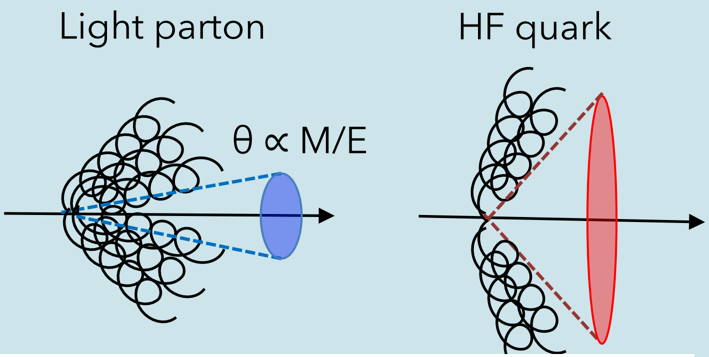
- Ideal probe for a tomography of QGP
  - Produced at only initial stage of collisions
  - Conservation of the number of HF quark



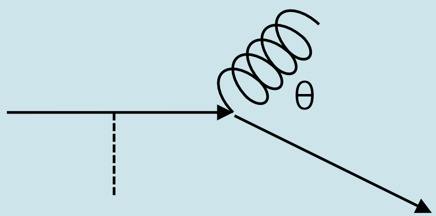
HF is one of the cleanest probe!

Energy loss

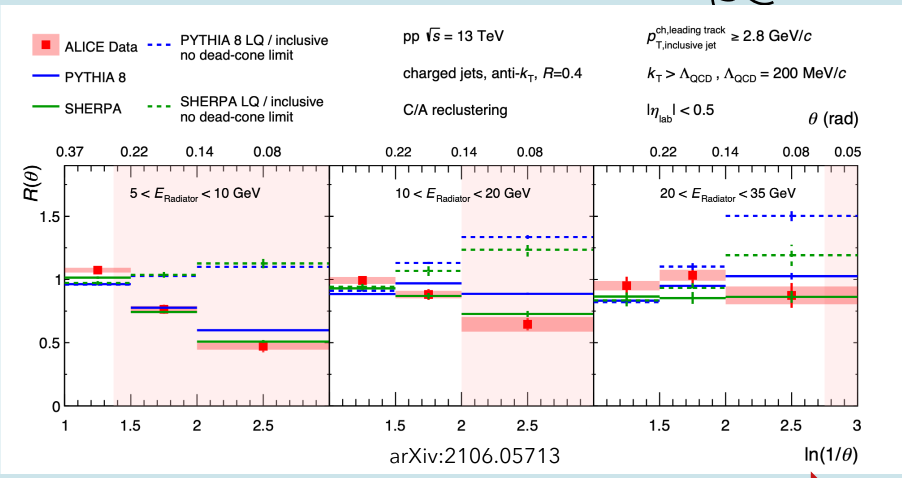
- Passing partons lose their energy via elastic scattering and gluon radiation
  - Depending on
    - Color charge (Casimir factor)
    - Quark mass (Dead cone effect)
    - Path length in medium
  - $\Delta E_{loss}(g) > \Delta E_{loss}(u,d,s) > \Delta E_{loss}(c) > \Delta E_{loss}(b)$



Radiative energy loss

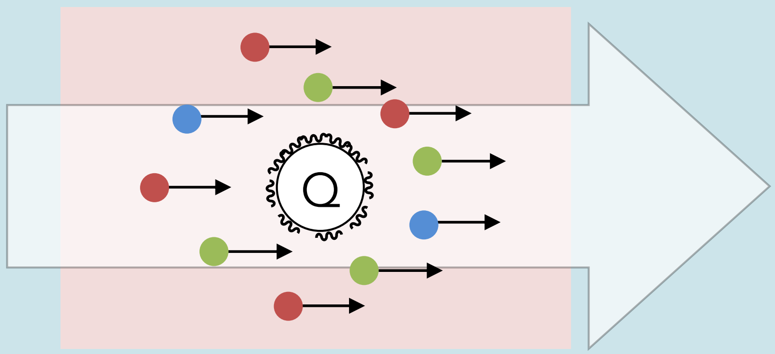


Gluon radiation
Gluon emission angle $\theta \propto M/E$
Sensitive to transport coefficient: $q=\mu^2/\lambda$

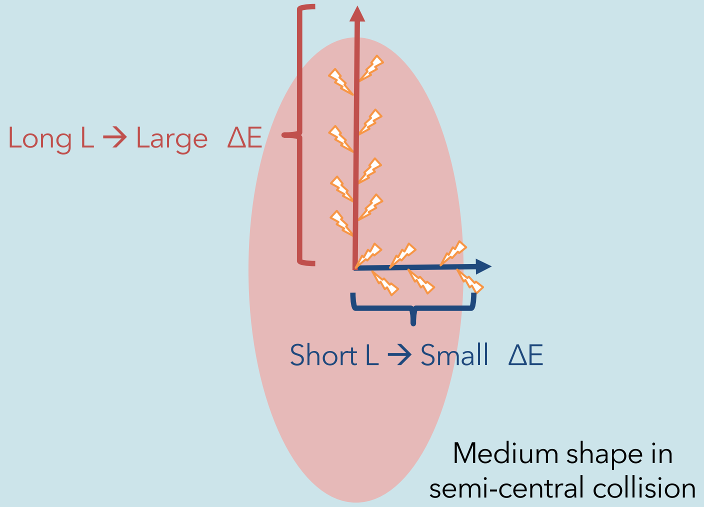


Azimuthal anisotropy

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



Drift in the moving medium

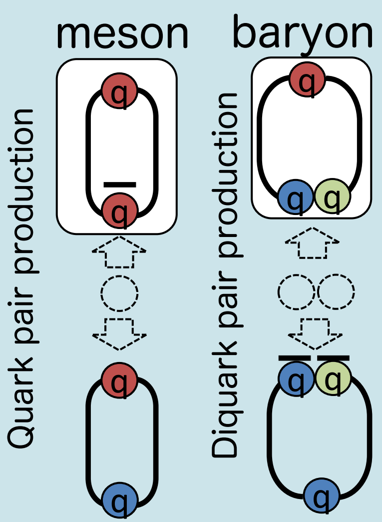


Energy loss depends on L

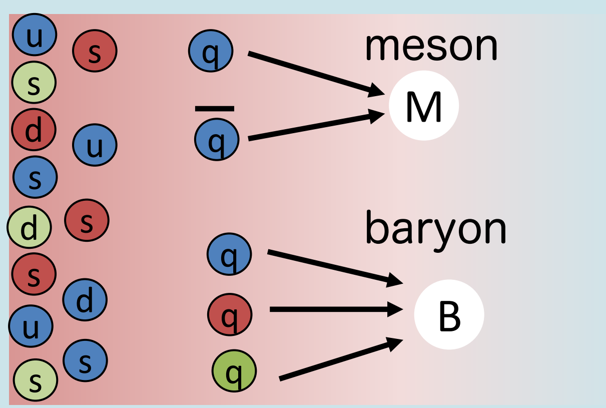
Coalescence

- 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:π ~ 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 ~ 1 : 1 : 0.3 : 10^{-11}

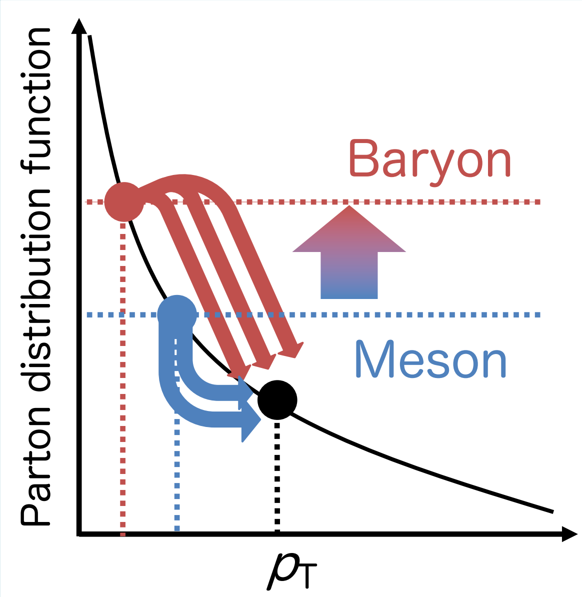
In vacuum



In QGP



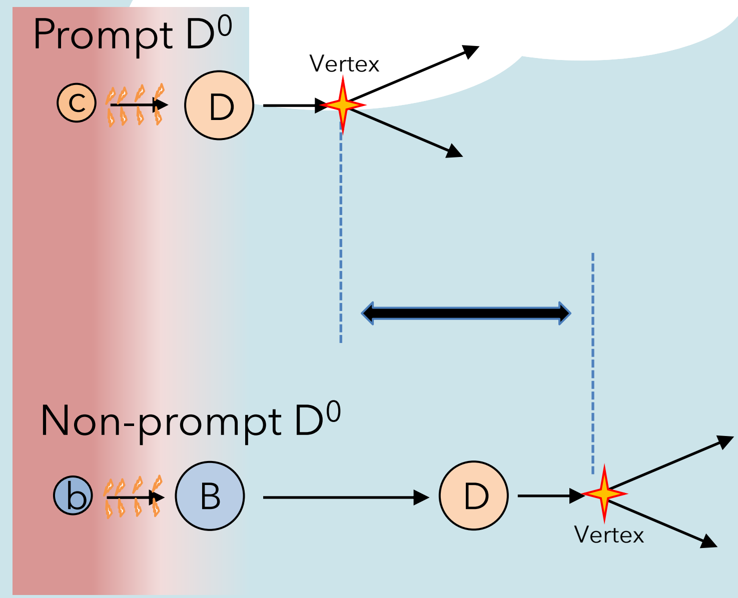
Strangeness-rich environment

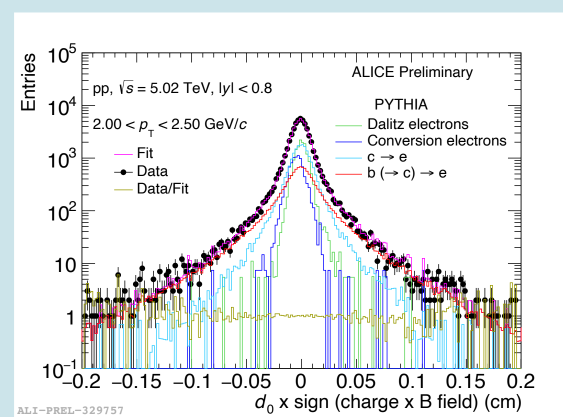


How to measure HFs?

- 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/ψ** 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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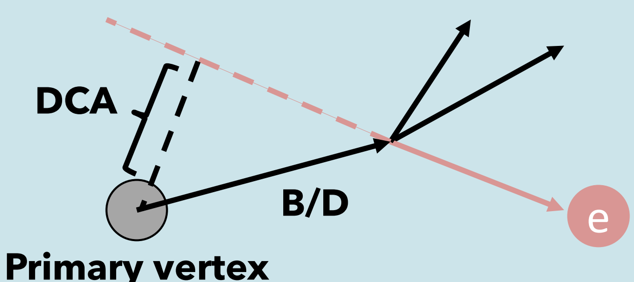
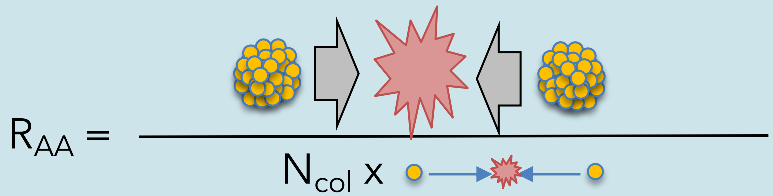


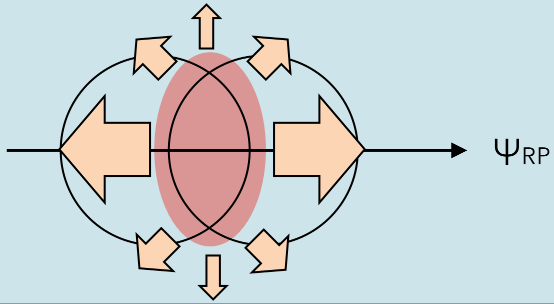
Main observation

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



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

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

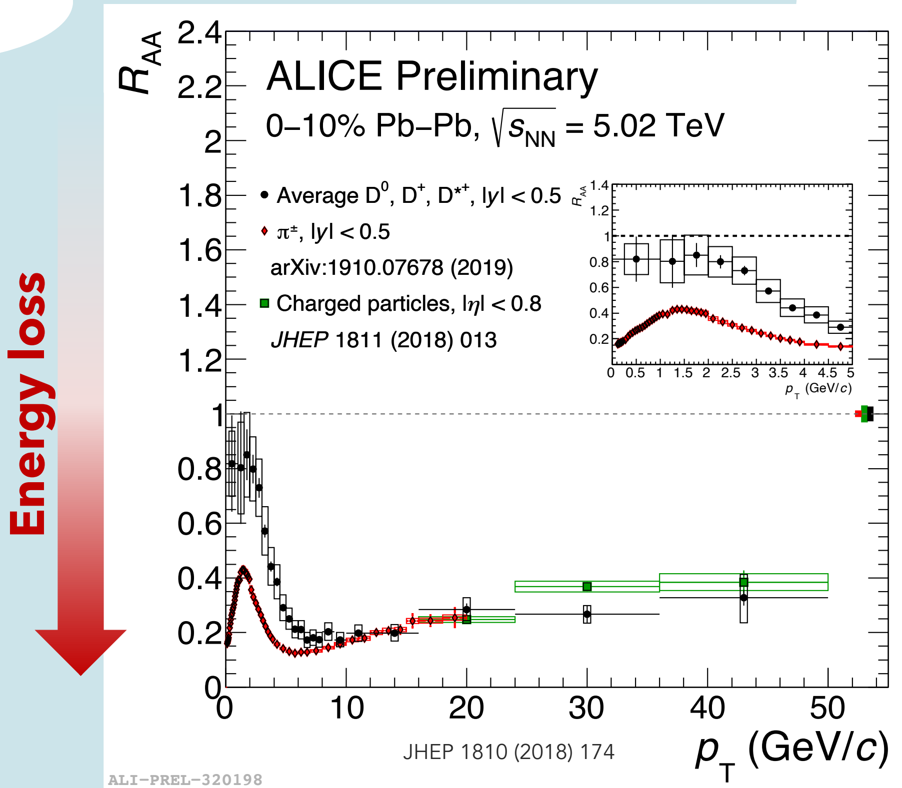


$$N(\varphi) \propto 1+2\sum v_n \cos\{n(\varphi - \psi_{RP})\}$$

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

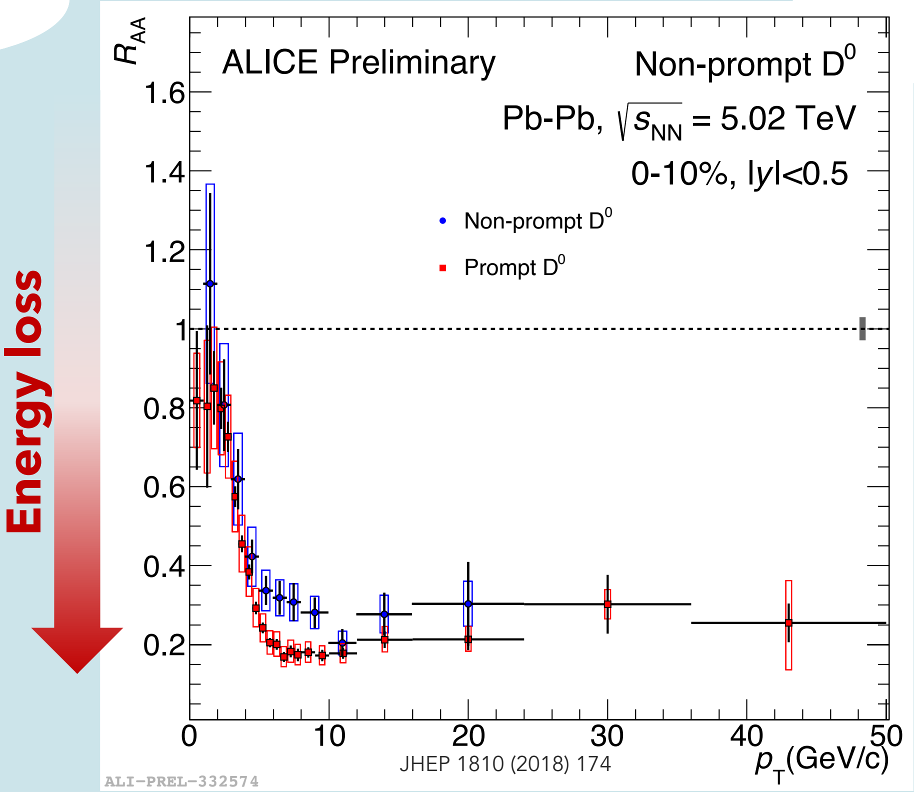
Latest results

Nuclear modification factor R_{AA}
Light v.s. Charm



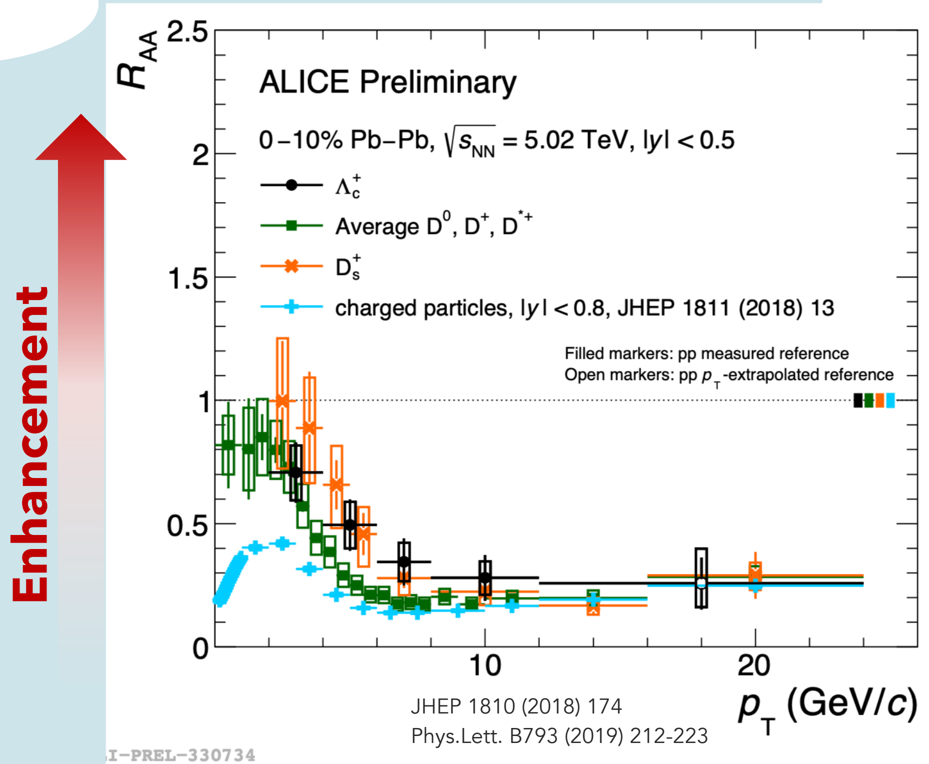
- At low-p_T (<10 GeV/$_c$): ΔE_{loss}(light) > ΔE_{loss}(c)
  - Indicating smaller energy loss in charm hadron
- At high-p_T (>10 GeV/$_c$): ΔE_{loss}(light) ~ ΔE_{loss}(c)
  - Indicating the same energy loss mechanism in light and charm hadron

Nuclear modification factor R_{AA}
Charm v.s. Beauty



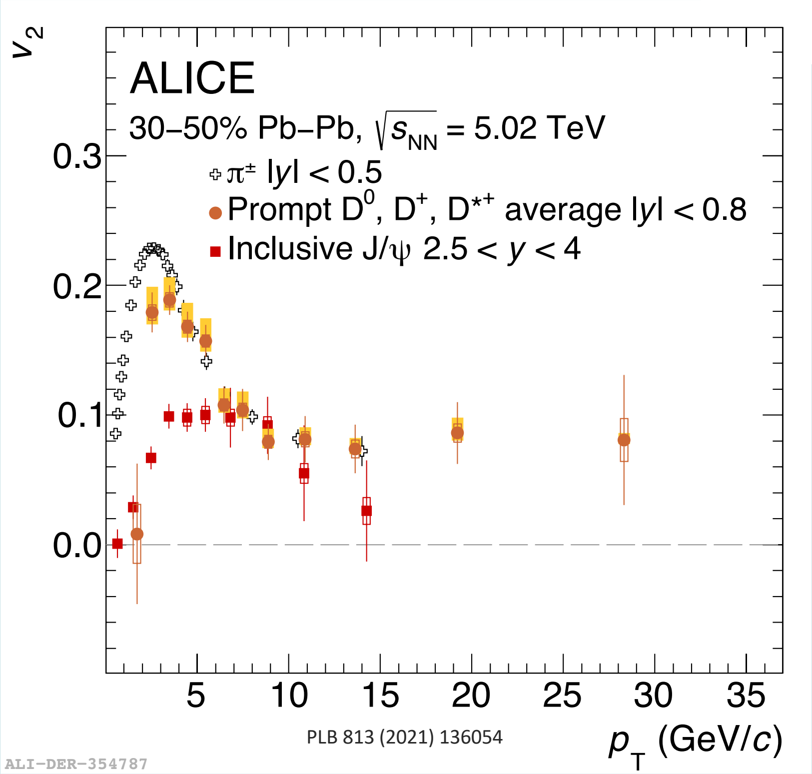
- All p_T (<20 GeV/c): $\Delta E_{loss}(c) > \Delta E_{loss}(b)$
  - Indicating smaller energy loss in beauty hadron

Nuclear modification factor R_{AA}
Meson v.s. Baryon
Charm with Strangeness v.s. Charm



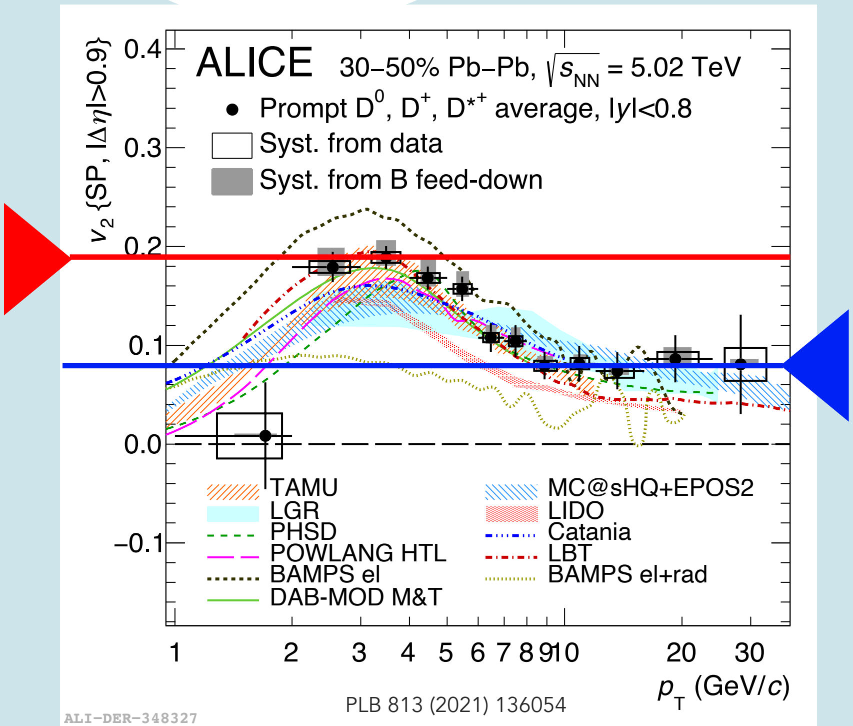
- At low-p_T (<10 GeV/$_c$): **Baryon > Meson**, **D_s > D(non-strangeness)**
  - Indicating coalescence contribution
- At high-p_T (>10 GeV/$_c$): **Baryon = Meson**, **D_s = D(non-strangeness)**
  - Indicating the same production mechanism

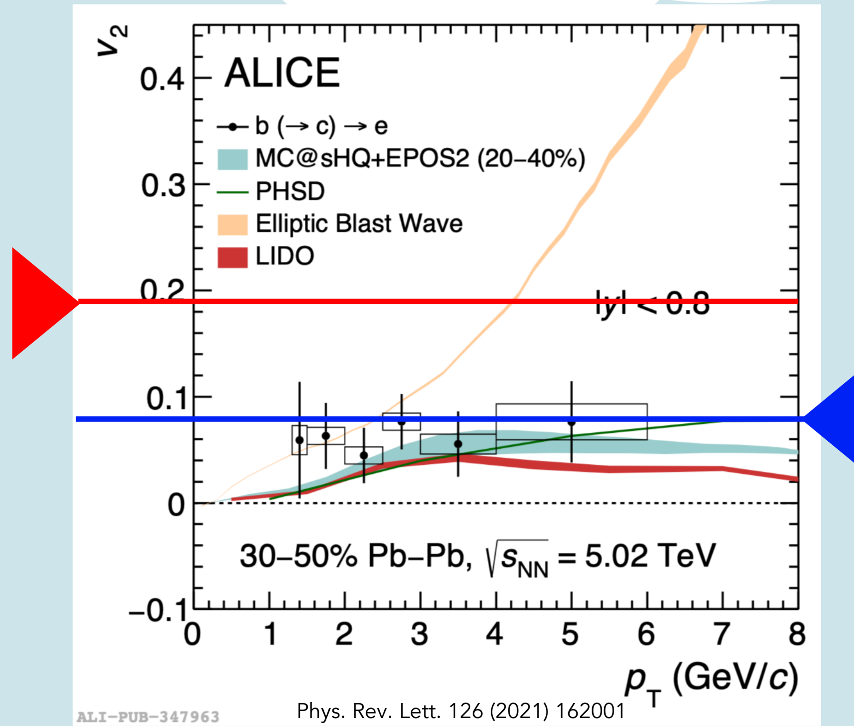
Elliptic flow (v2) Light v.s. Charm



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

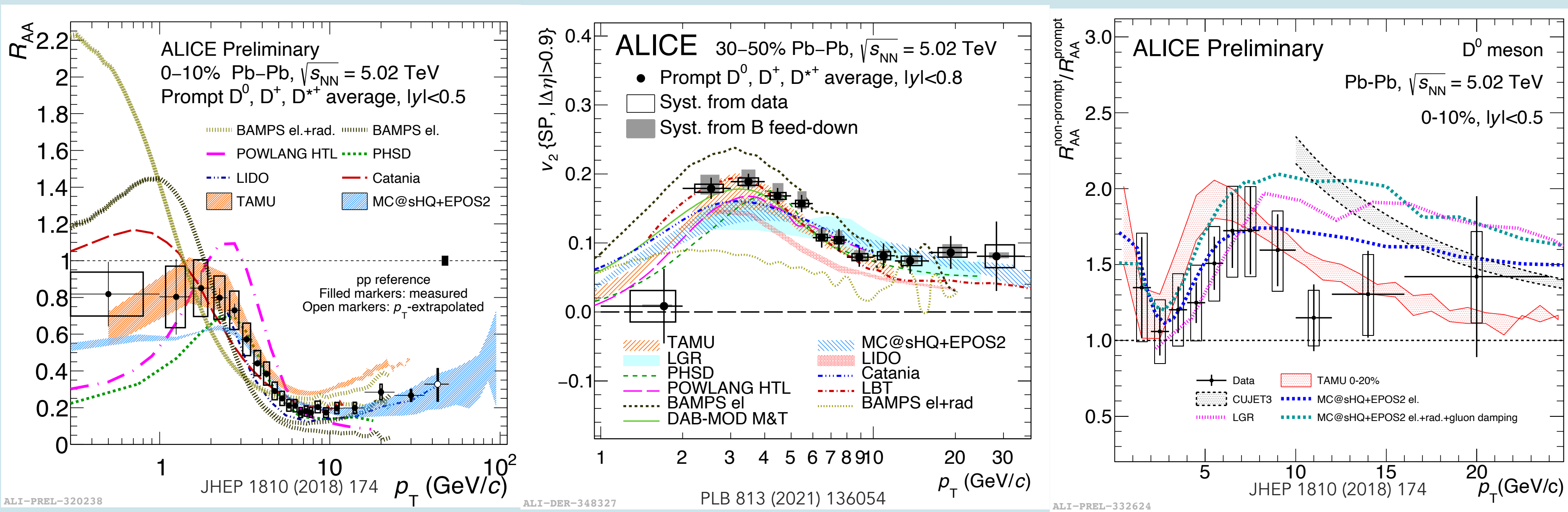
Elliptic flow (v2)
Charm v.s. Beauty





- 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 = 3.096GeV/c^2
    - Ψ(2S): M = 3.686GeV/c^2
  - Bottomonium (bbbar state)
    - Υ(1S): 9.46 GeV/c^2
    - Υ(2S): 10.023 GeV/c^2
    - Υ(3S): 10.3552 GeV/c^2

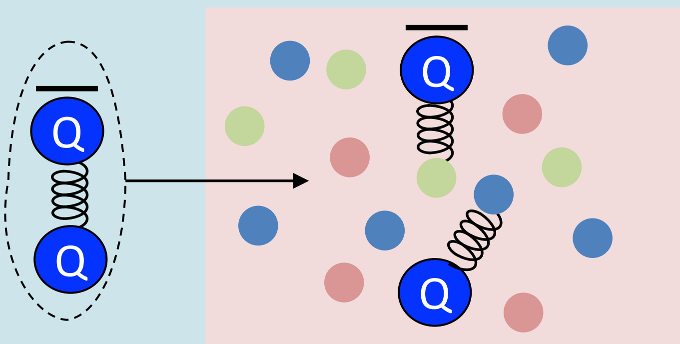
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

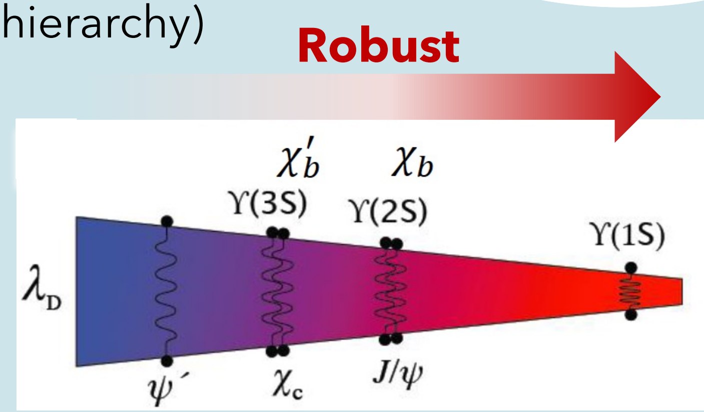
($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

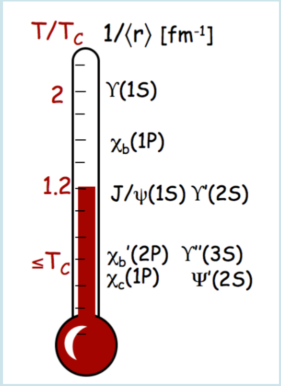
- About 1 % heavy quark pairs form quarkonium
  - Open heavy quark meson: ~90%
  - Open heavy quark baryon: ~9%

Melting v.s. regeneragtion

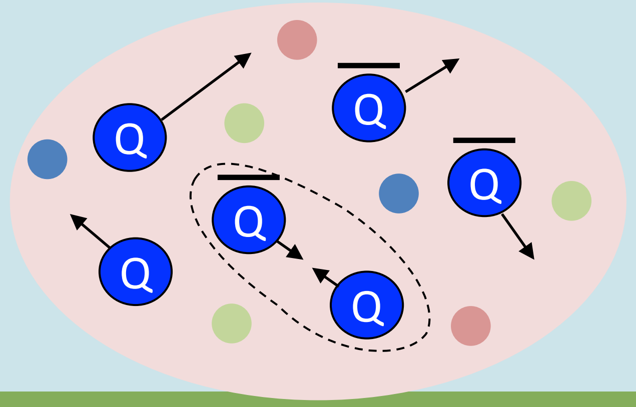
- Quarkonium melting caused by Debye screening
  - Depends on hadron radius (hierarchy)

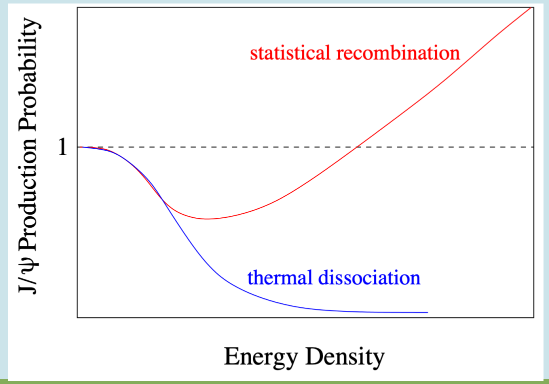






- Quarkonium regeneration
  - ~30 ccbar pairs in a collision (0-5%:PbPB@5.02TeV)

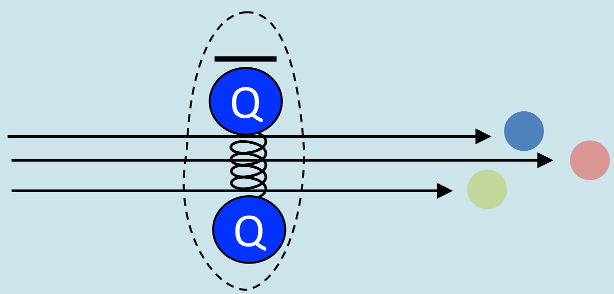


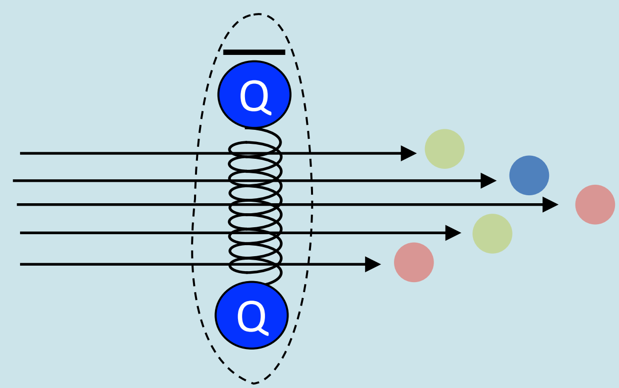


Comover interaction

- Quarkonium is produced in initial stage of collisions
  - Hadronization at very early formation time
    - $\tau_{\psi(2S)} \sim 0.35$ fm/c
  - Dense condition even in small collision system
    - **Possible to see the effect in small collision system (w/o QGP)**

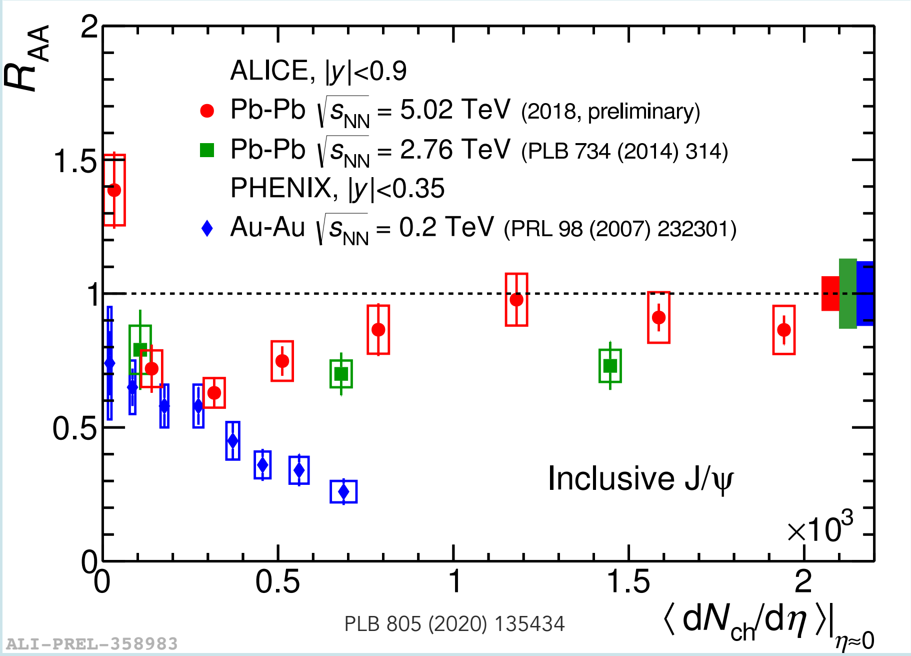
- Break-up quarkonium with passing soft particles
  - Depending on the radius
  - Sequential break-up in J/ψ, ψ(2S), Υ(1S) , Υ(2S) , Υ(3S)…





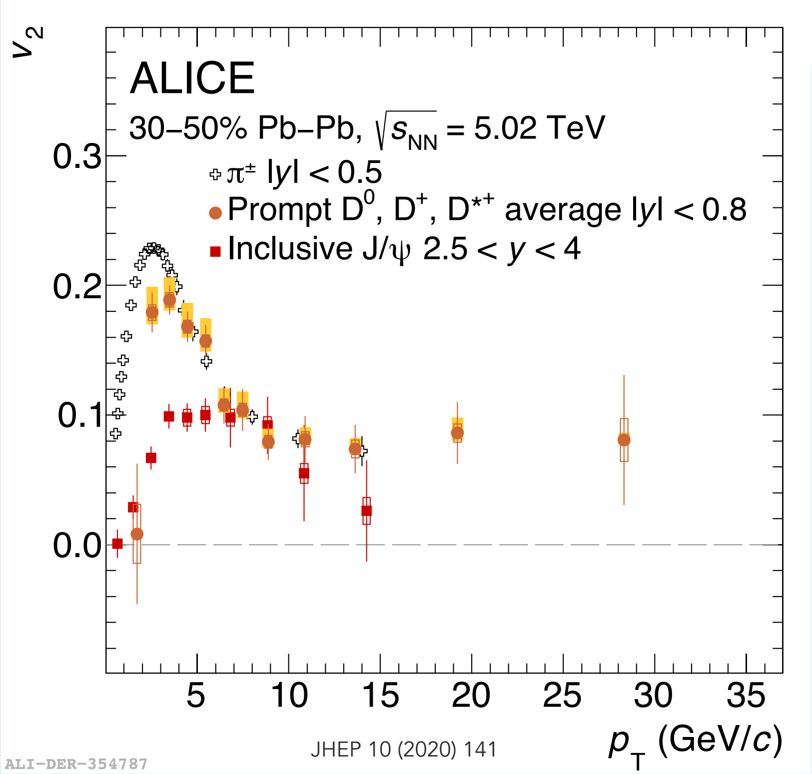
Latest results

Nuclear modification factor R_{AA} Melting v.s. regeneration



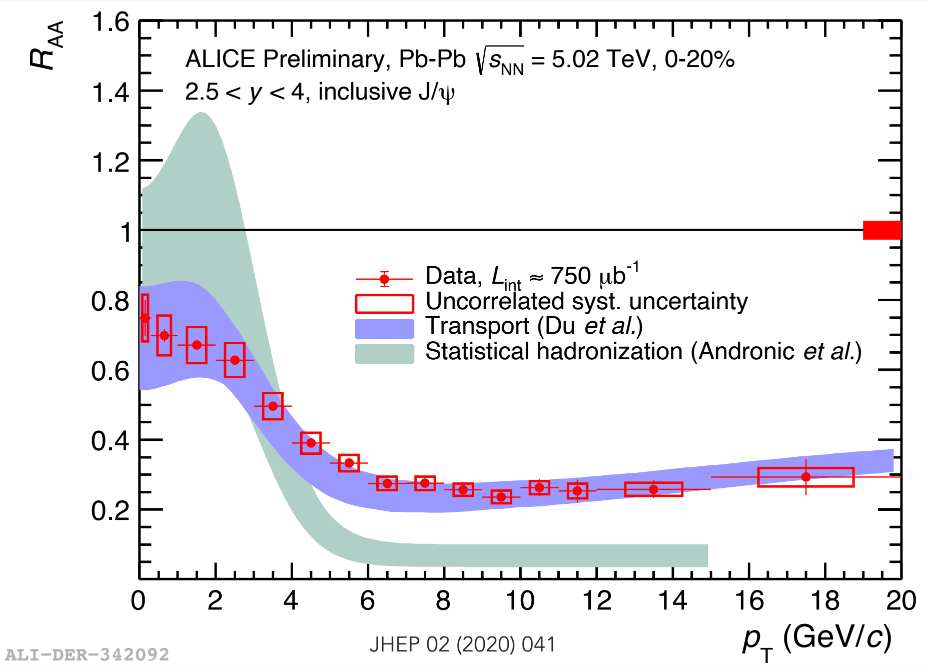
- Obvious energy dependence of R_{AA}(5.02 TeV) > R_{AA}(2.76 TeV) > R_{AA}(0.2 TeV)
- Regeneration > melting @ LHC!

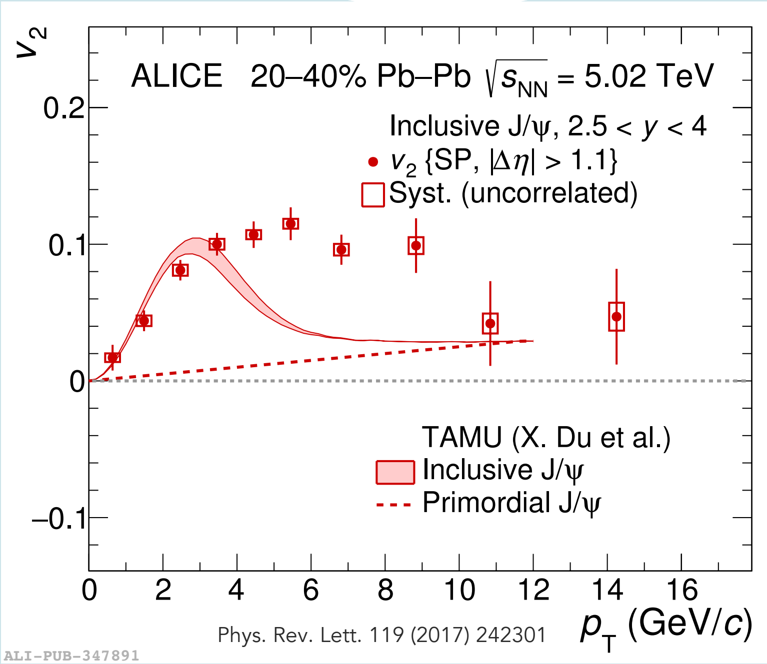
Elliptic flow (v2)
Light v.s. Open-charm v.s. Hidden Charm



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

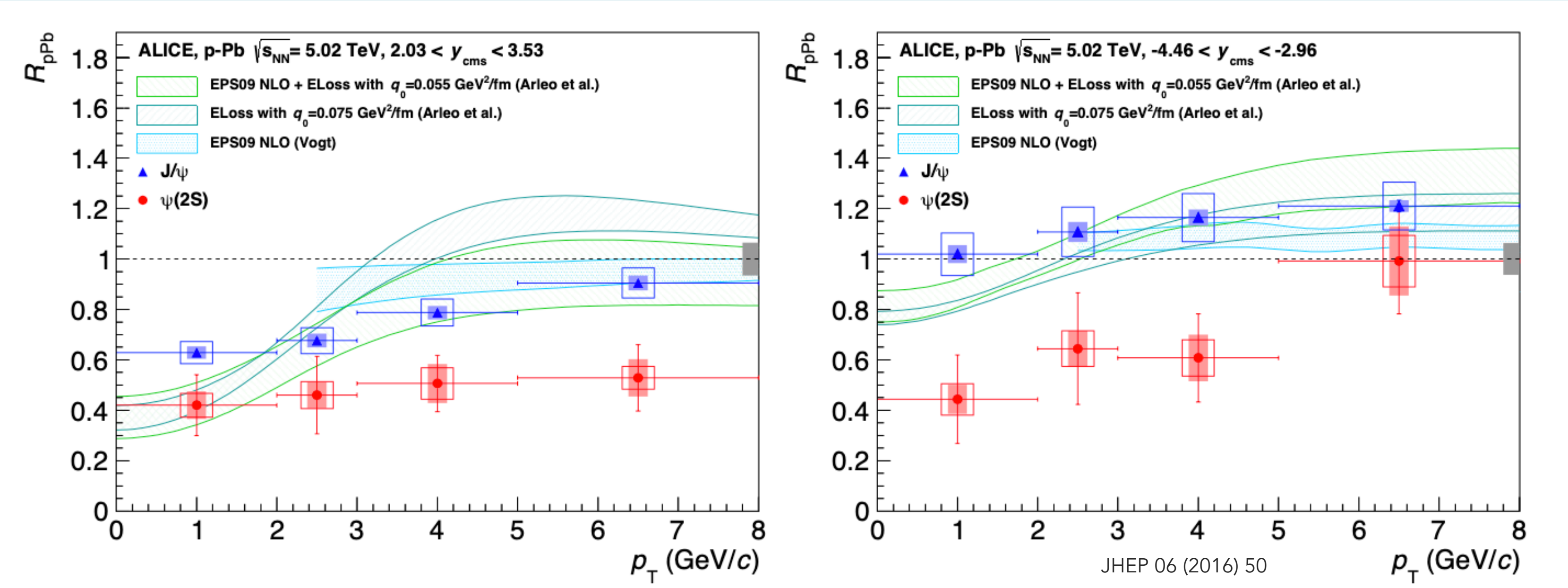
Comparison with theory





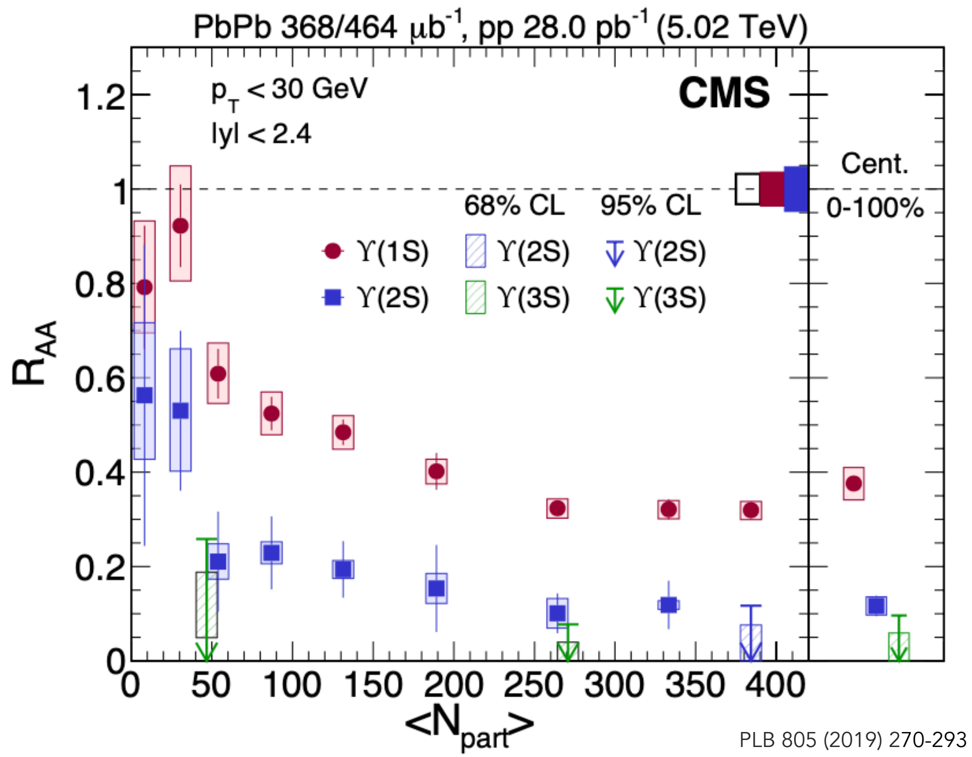
- Well description of R_{AA} with transport model including primordial, melting, and regeneration with thermalized charm
- Good agreement with v_2 for $p_T < 4$ GeV/c, but large deviation from data for $4 < p_T < 10$ GeV/c

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 ψ(2S)
- Need to be considered the interaction to discuss sequential melting

Bottomonium
Sequential suppression



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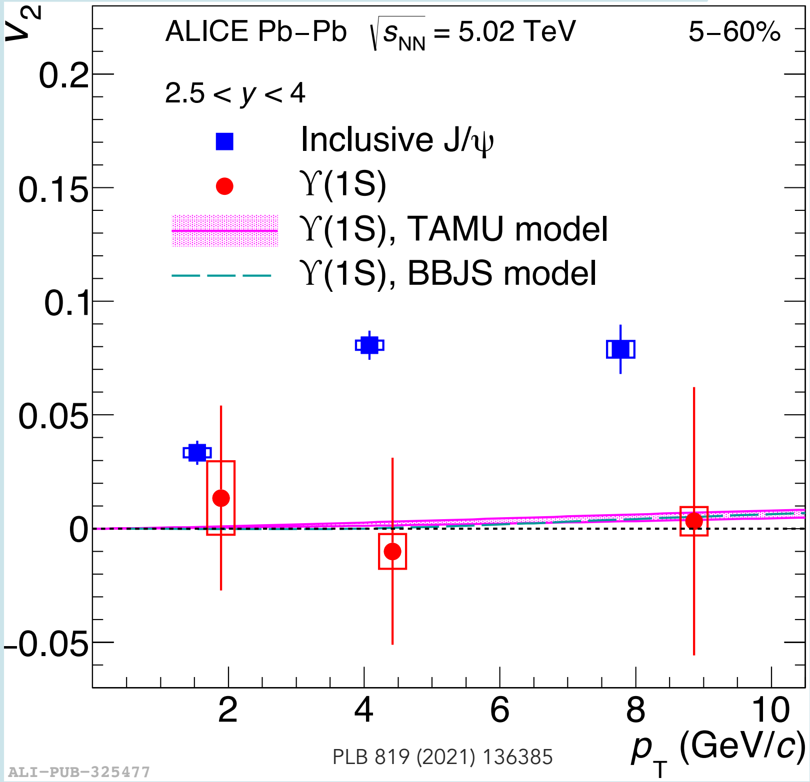
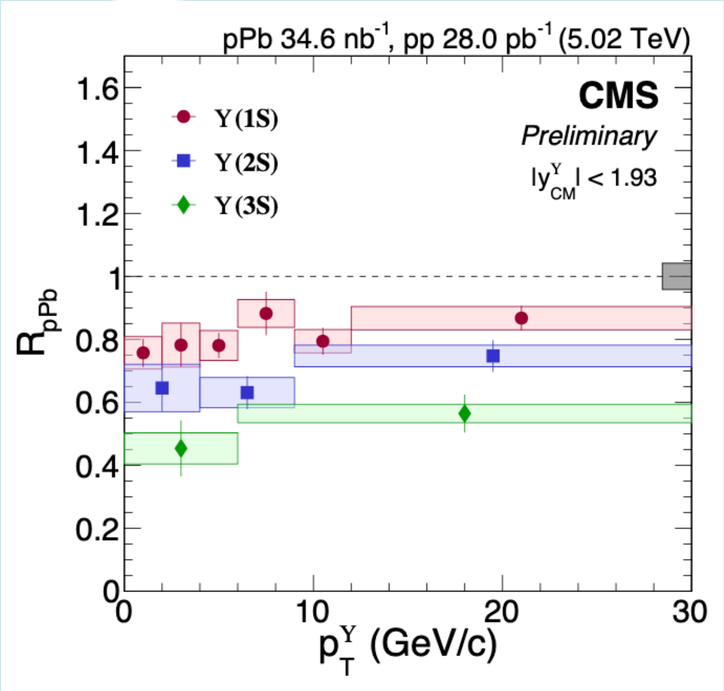
- Sequential suppression for Y family
  - R_{AA}(Y(1S)) > R_{AA}(Y(2S)) > R_{AA}(Y(3S))

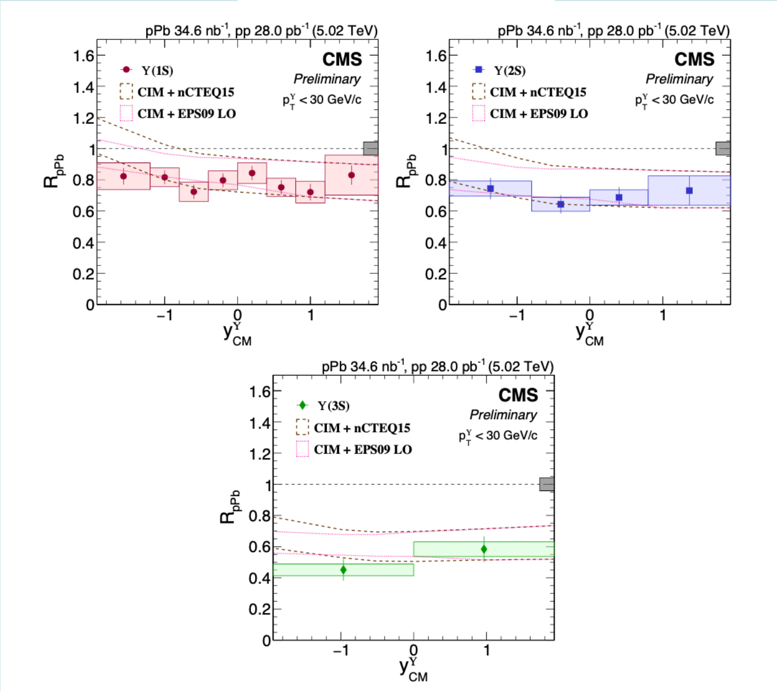
Elliptic flow of bottomonium



- Υ(1S) v_2 is significantly smaller than J/ψ
  - Υ(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)

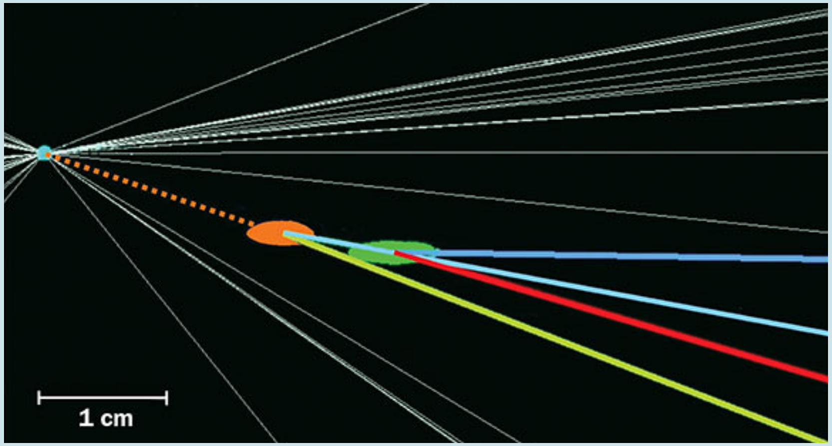
Conclusion from the experiments

- Open heavy flavor
  - Energy loss hierarchy is observed at p_T < 10 GeV/c
  - Energy loss hierarchy is disappeared at p_T > 10 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 Υ family in PbPb collisions
  - J/ψ has positive v_2, but zero consistent v_2 for Υ(1S)
  - Sequential suppression for charmonium and bottomonium in pPb collisions (possibly) due to comover interaction has been observed

What's next for HF?

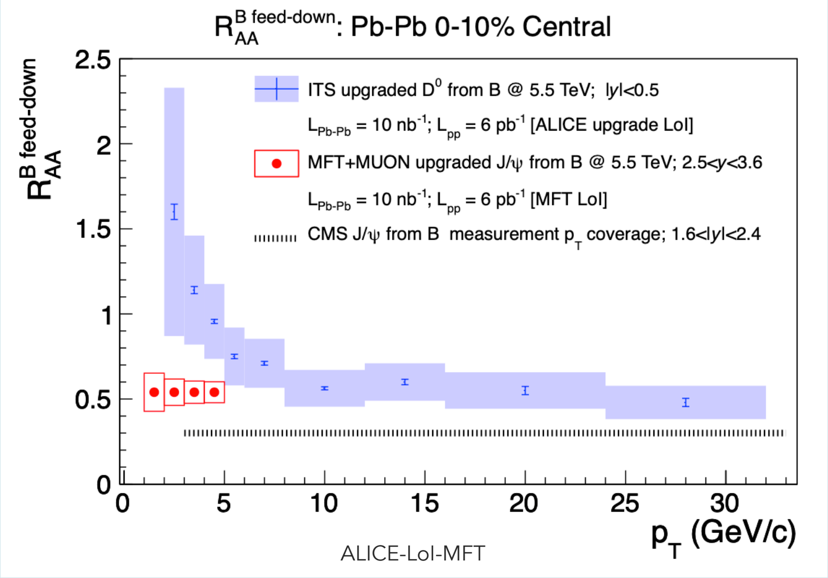
- Why don't you measure all objects at forward rapidity in PbPb collisions?
  - Large Lorentz boost at low-p_T particle
  - Longer life time for low-p_T (~10 times longer @ y~4)
    - Precise measurement of heavy flavor baryons
  - Open low-p_T muonic channel (e.g. B→J/ψK, B→ J/ψX→μμX, B→μX)

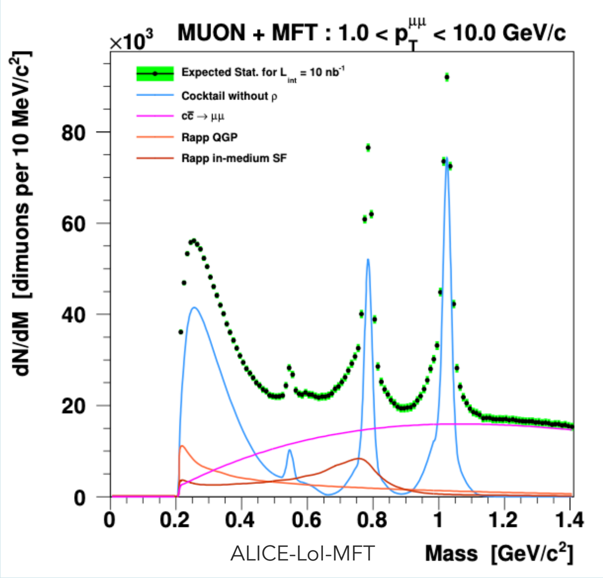


Event display of B-meson decay (orange point) from LHCb

Short-term future

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



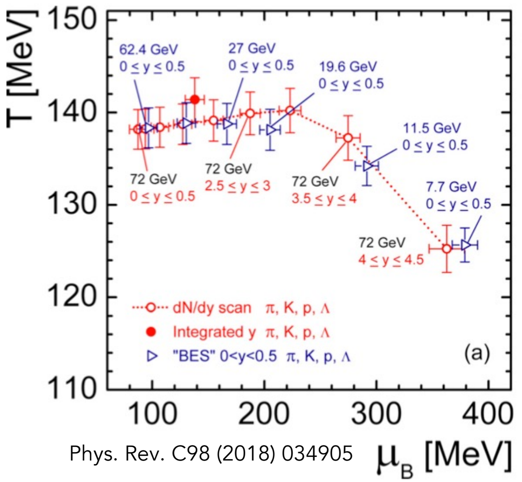


Unique idea (Long-term future)

- Fixed target experiment at LHC (AFTER@LHC)
  - Collision energy $\sqrt{s_{NN}}$ ~ 72 GeV
    - Enough energy to produce QGP
  - With high luminosity and polarized several targets

- **Forward in lab-frame, but mid-rapidity in physics (Δy~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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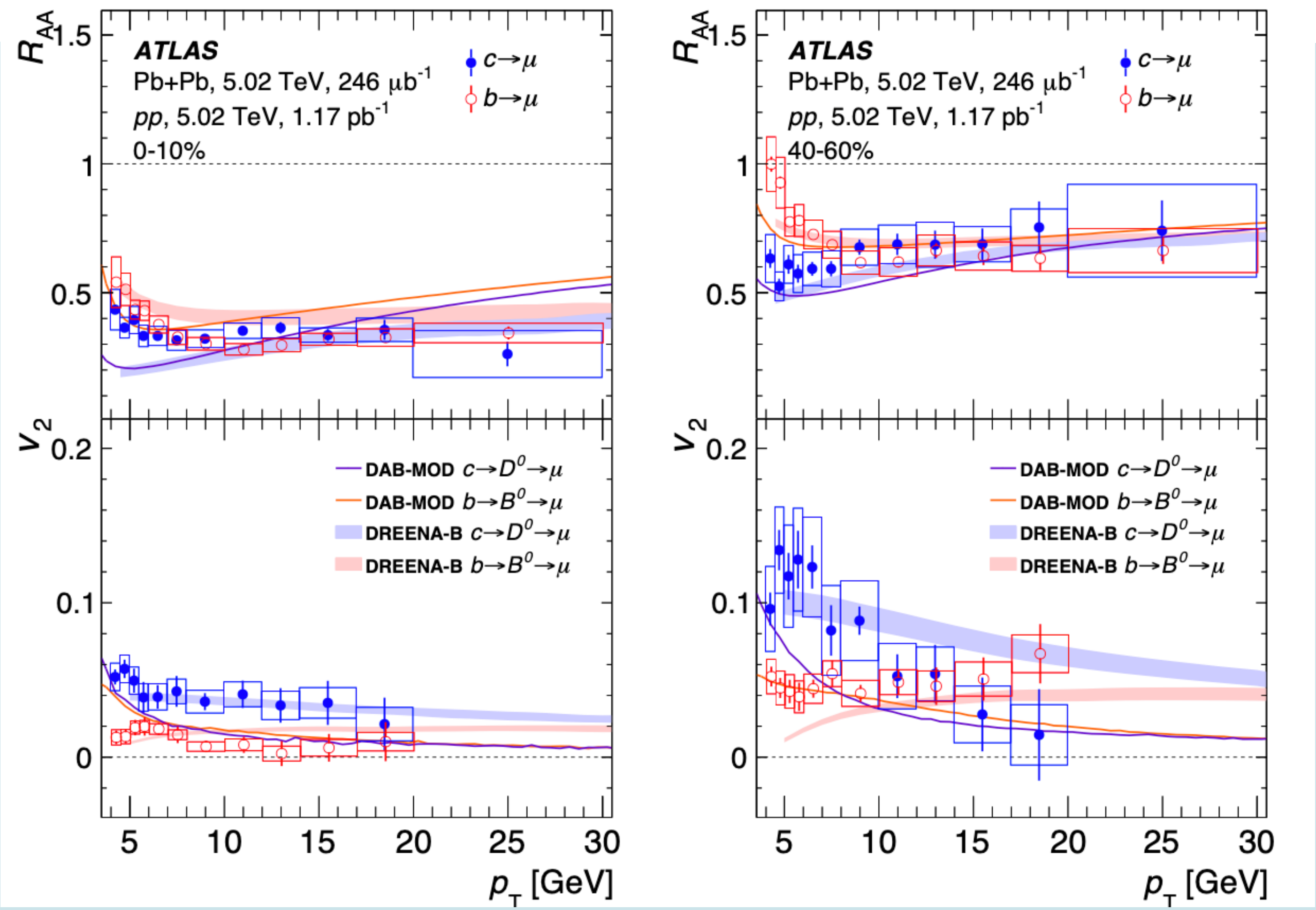
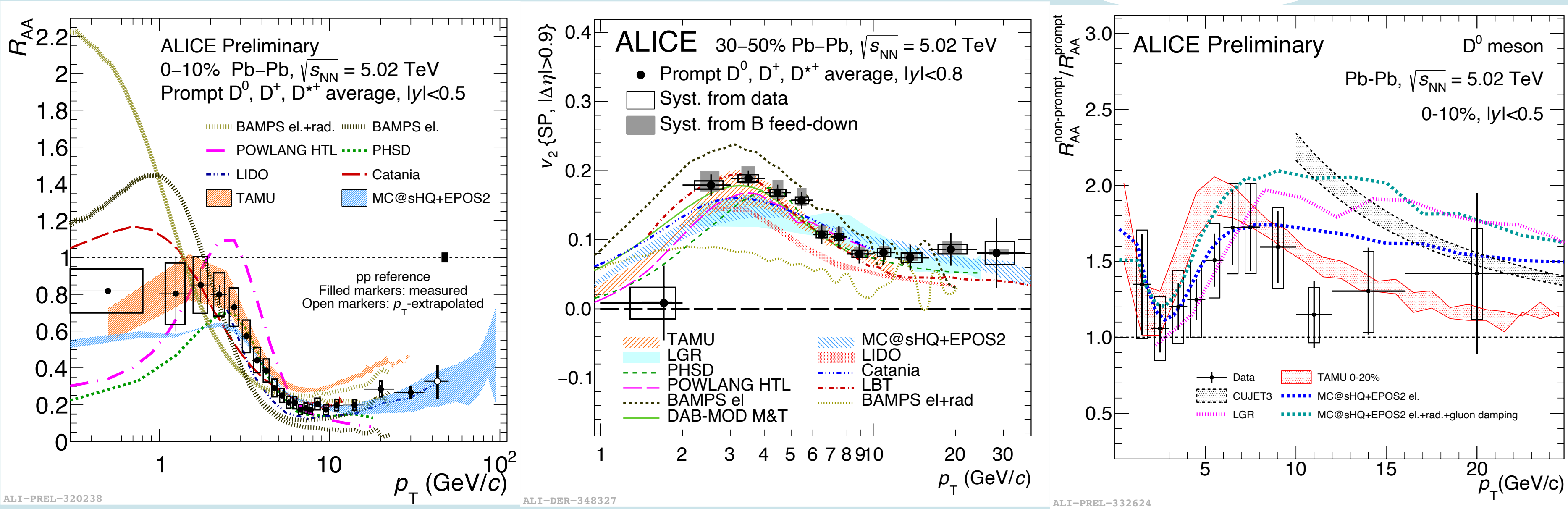
Back up

ATLAS open heavy flavor

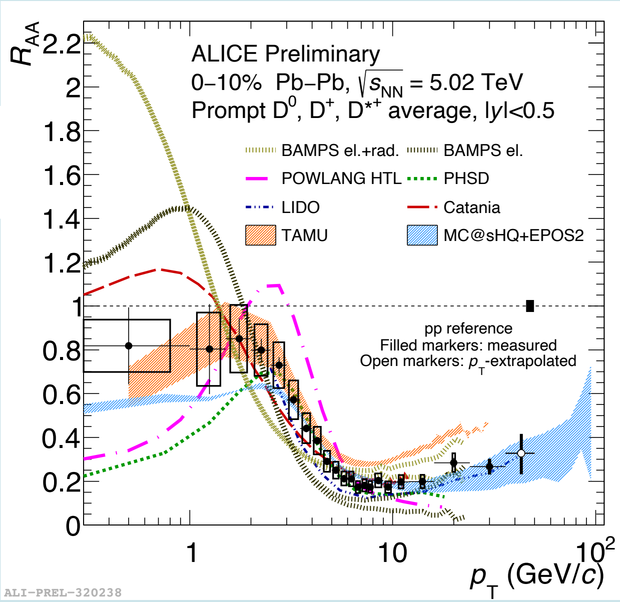


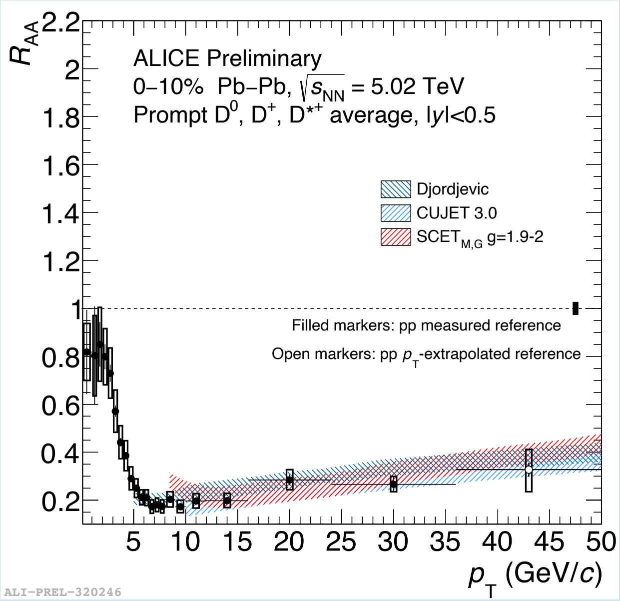
Comparison with models



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

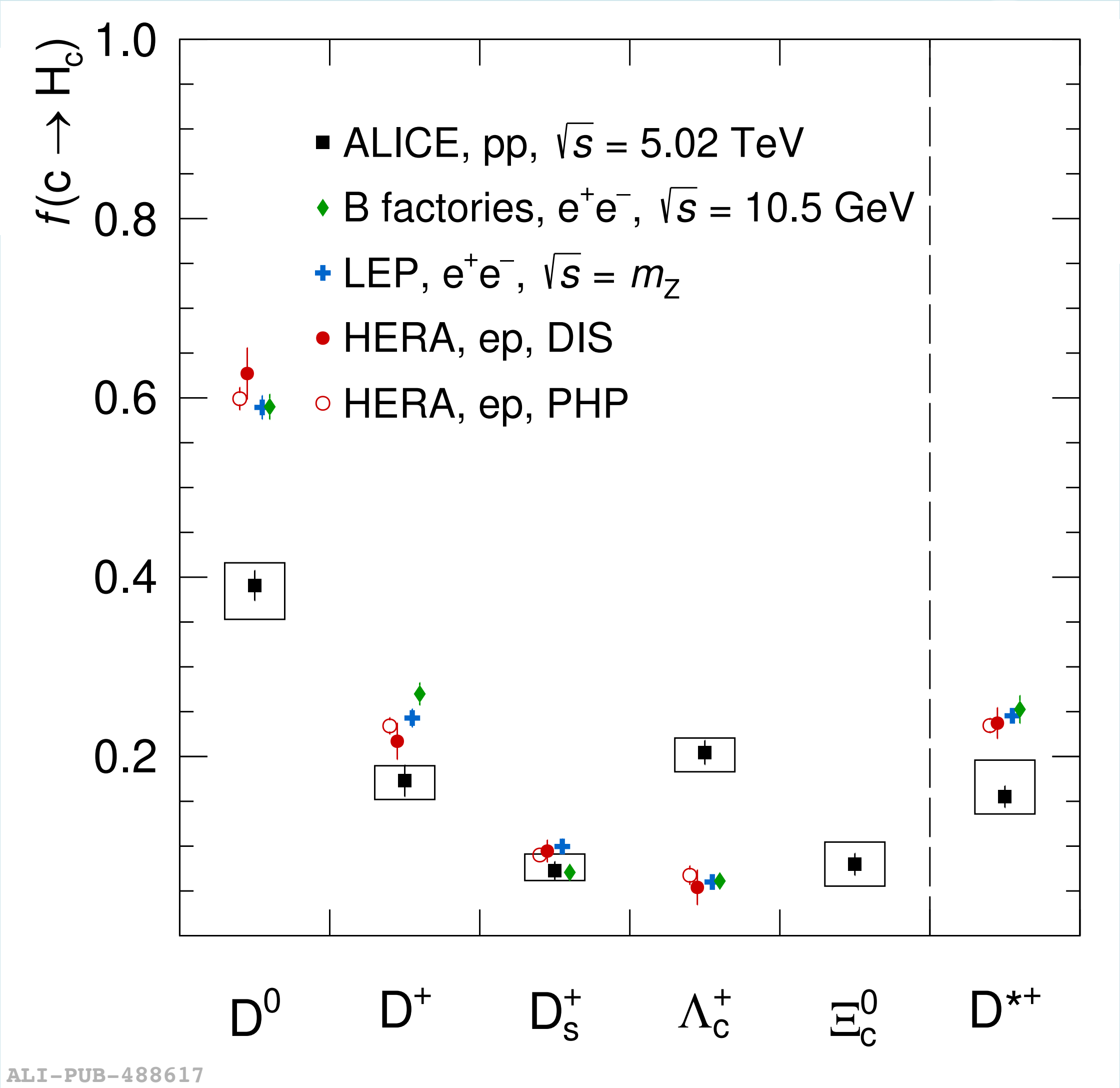
$1.5 < 2\pi D_s T_c < 7$ with T_c=155 MeV



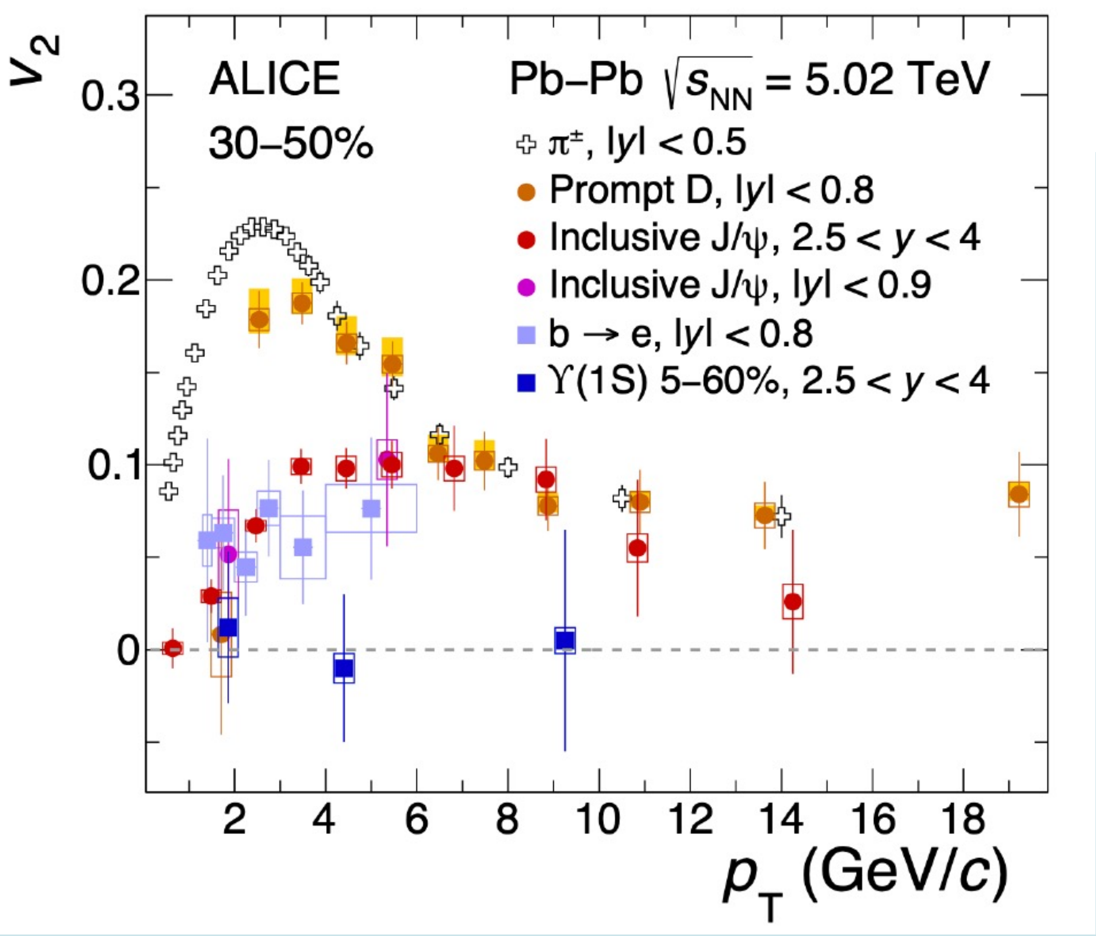


Transport Models	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
BAMPS	✓	✓	✗	✓	✗
POWLANG	✓	✗	✓	✓	✓
PHSD	✓	✗	✓	✓	✓
LIDO	✓	✓	✓	✓	✓
TAMU	✓	✗	✓	✓	✓

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

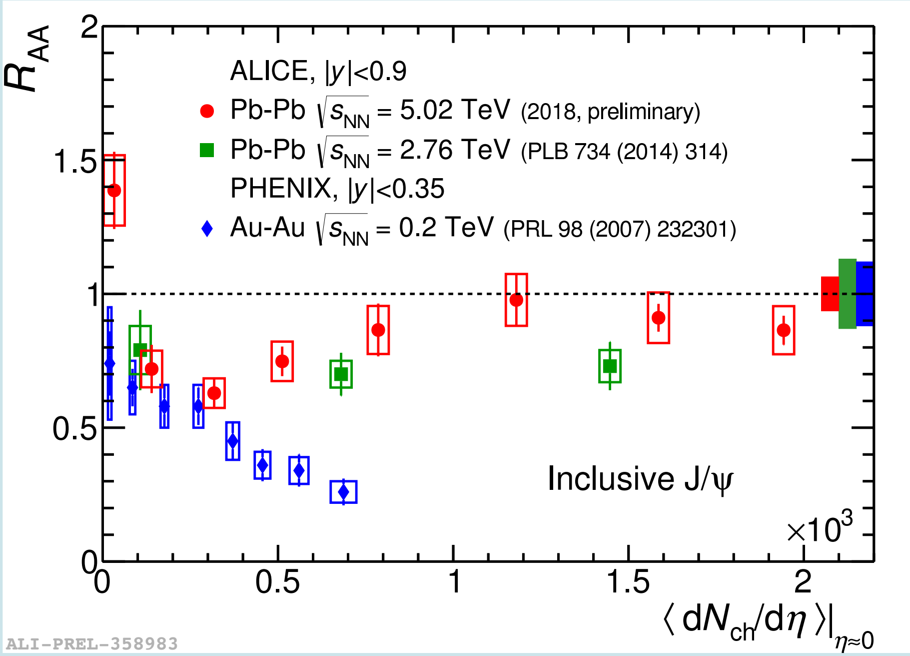


1.0
0.8
0.6
0.4
0.2
$f(c \rightarrow H_c)$
ALICE, pp, $\sqrt{s}$ = 5.02 TeV
B factories, e^+e^-, $\sqrt{s}$ = 10.5 GeV
LEP, e^+e^-, $\sqrt{s} = m_Z$
HERA, ep, DIS
HERA, ep, PHP
D^0
D^+
D_s^+
Λ_c^+
Ξ_c^0
D^{*+}
ALI-PUB-488617


ALICE
30–50%
Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
$\pi^{\pm}$, |y| < 0.5
Prompt D, |y| < 0.8
Inclusive J/ψ, 2.5 < y < 4
Inclusive J/ψ, |y| < 0.9
b → e, |y| < 0.8
ϒ(1S) 5–60%, 2.5 < y < 4
v_2
0.3
0.2
0.1
0
2
4
6
8
10
12
14
16
18
p_T (GeV/c)

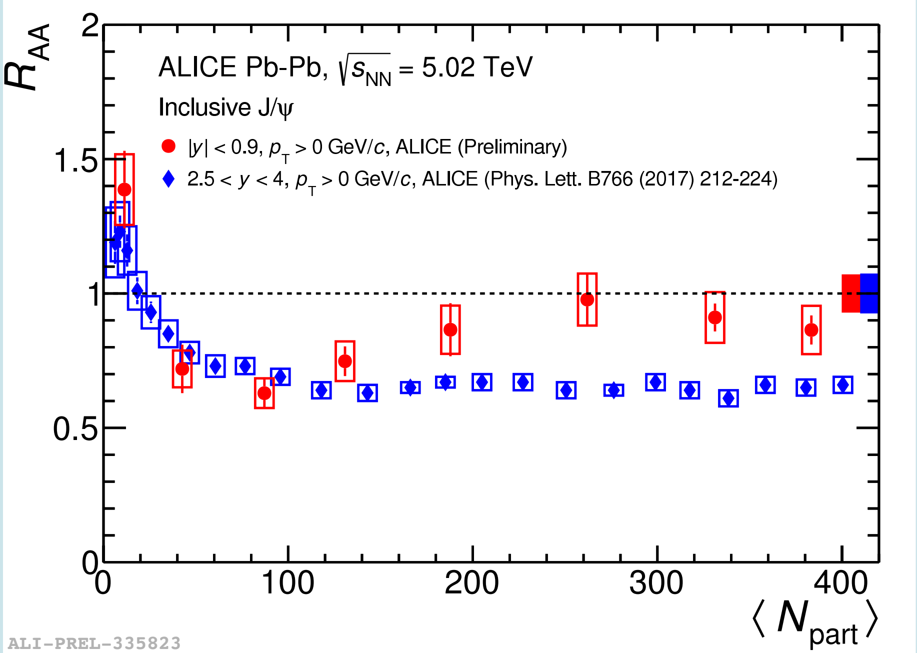
Nuclear modification factor R_{AA}
Melting v.s. regeneration

Collision energy dependence

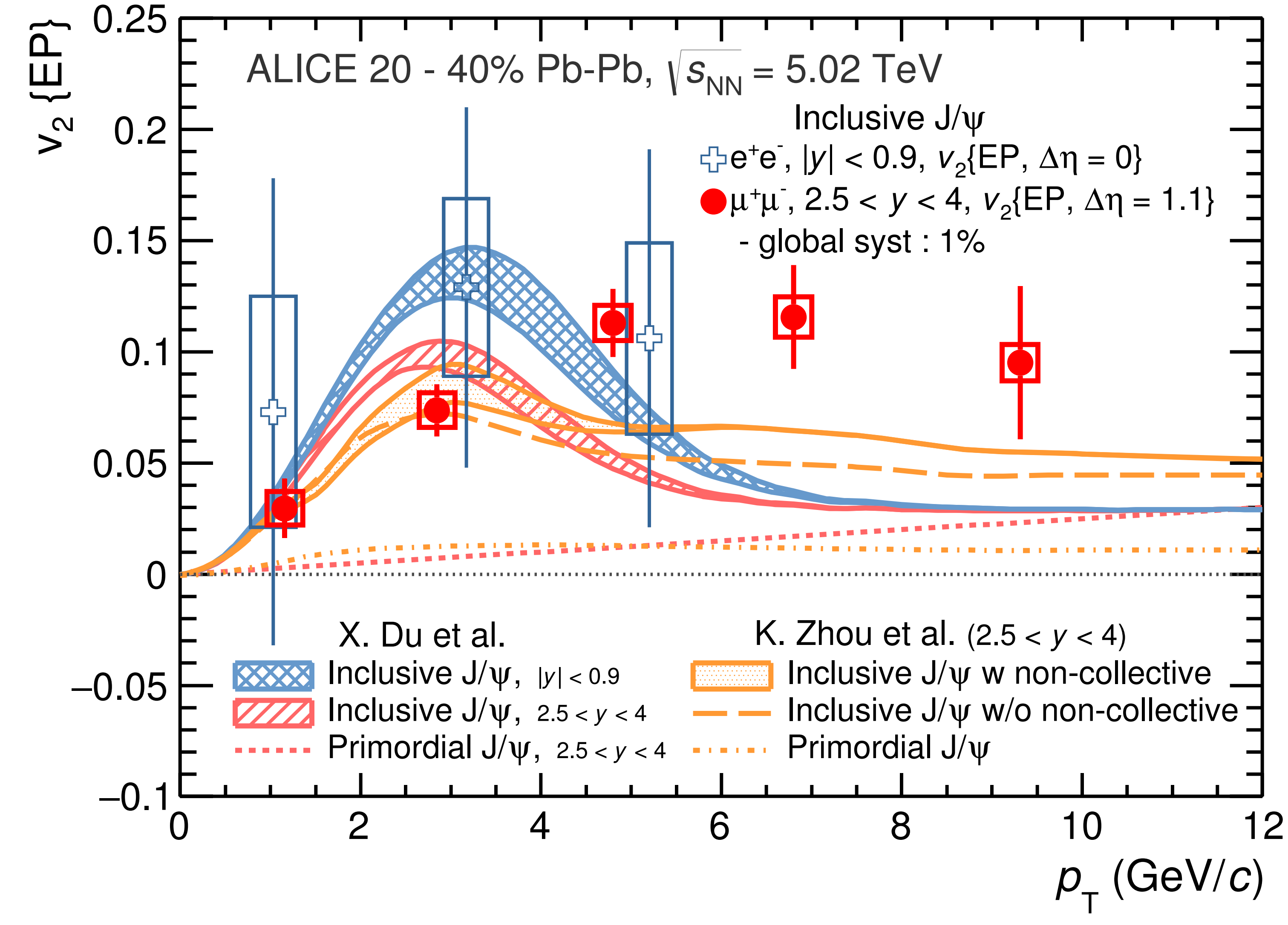


Regeneration > melting @ LHC

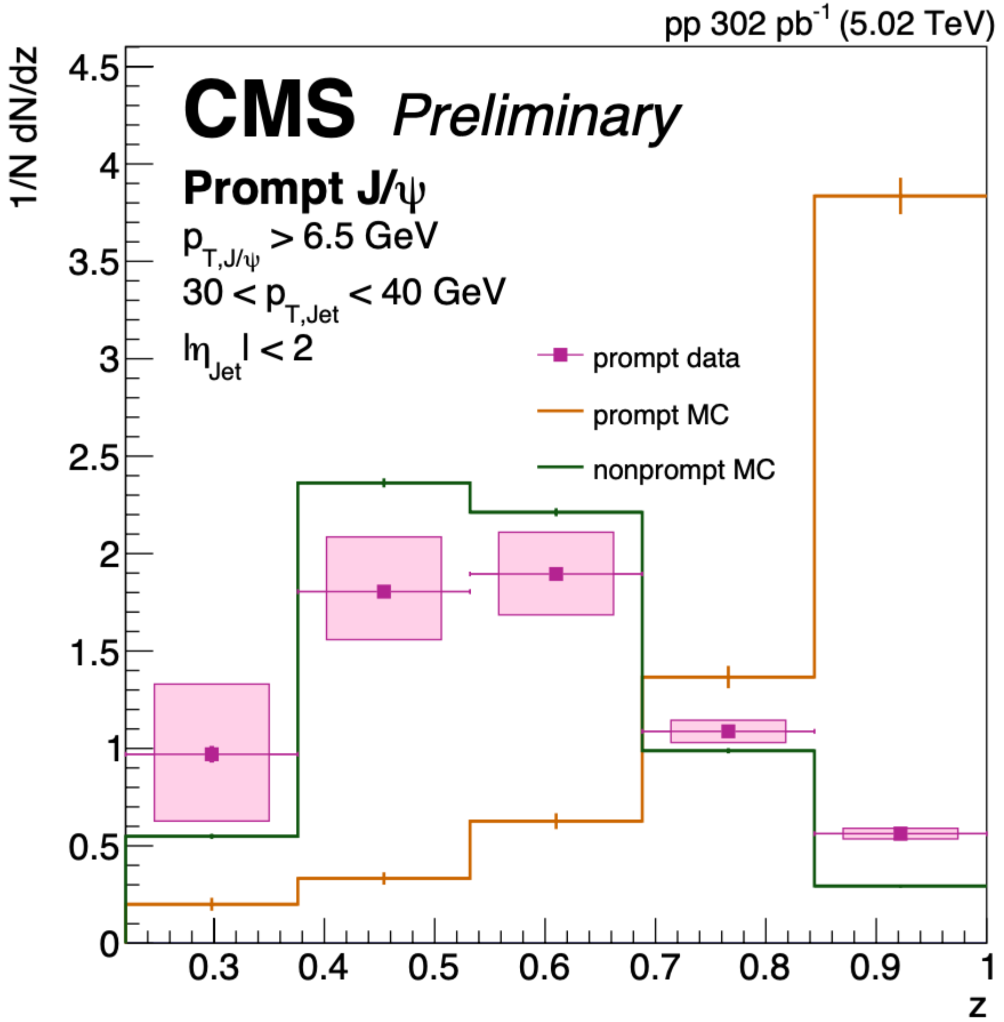
Rapidity dependence

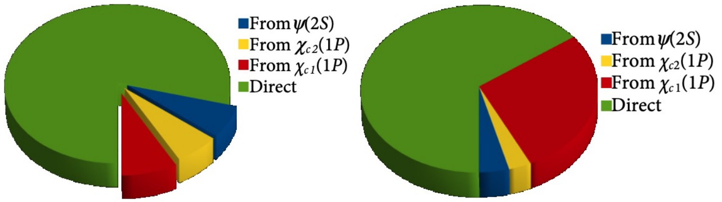


Larger energy density


ALICE 20 - 40% Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Inclusive J/ψ
e^+e^-, $|y|$ < 0.9, v_2{EP, Δη = 0}
$\mu^+\mu^-$, 2.5 < y < 4, v_2{EP, Δη = 1.1}
- global syst : 1%
X. Du et al.
Inclusive J/ψ, $|y|$ < 0.9
Inclusive J/ψ, 2.5 < y < 4
Primordial J/ψ, 2.5 < y < 4
K. Zhou et al. (2.5 < y < 4)
Inclusive J/ψ w non-collective
Inclusive J/ψ w/o non-collective
Primordial J/ψ
v_2{EP}
p_T (GeV/c)
0.25
0.2
0.15
0.1
0.05
0
–0.05
–0.1
0
2
4
6
8
10
12

Fragmentation into charmonium





(b) Low P_T J/ψ (c) High P_T J/ψ

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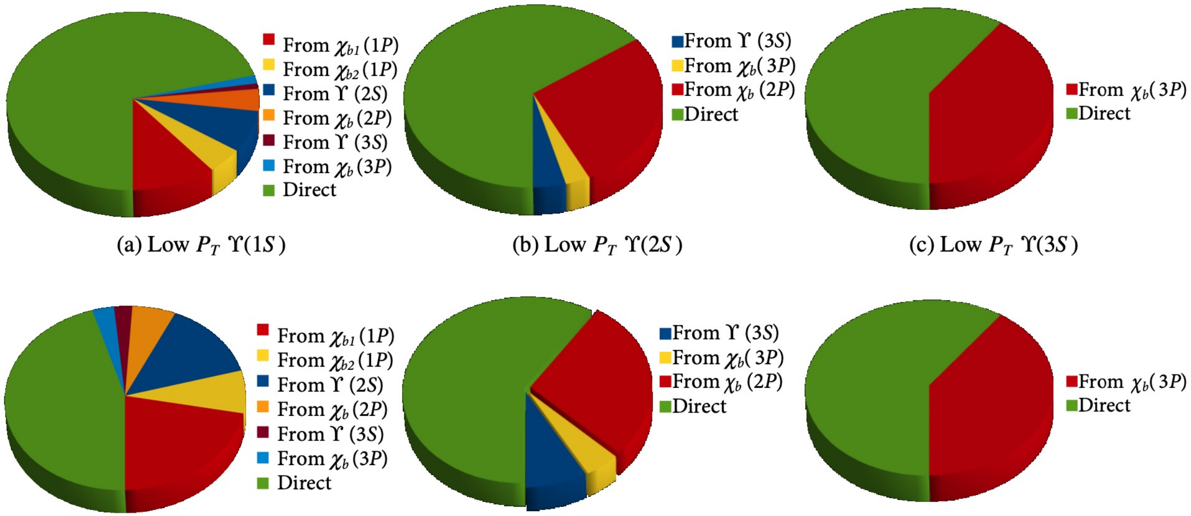
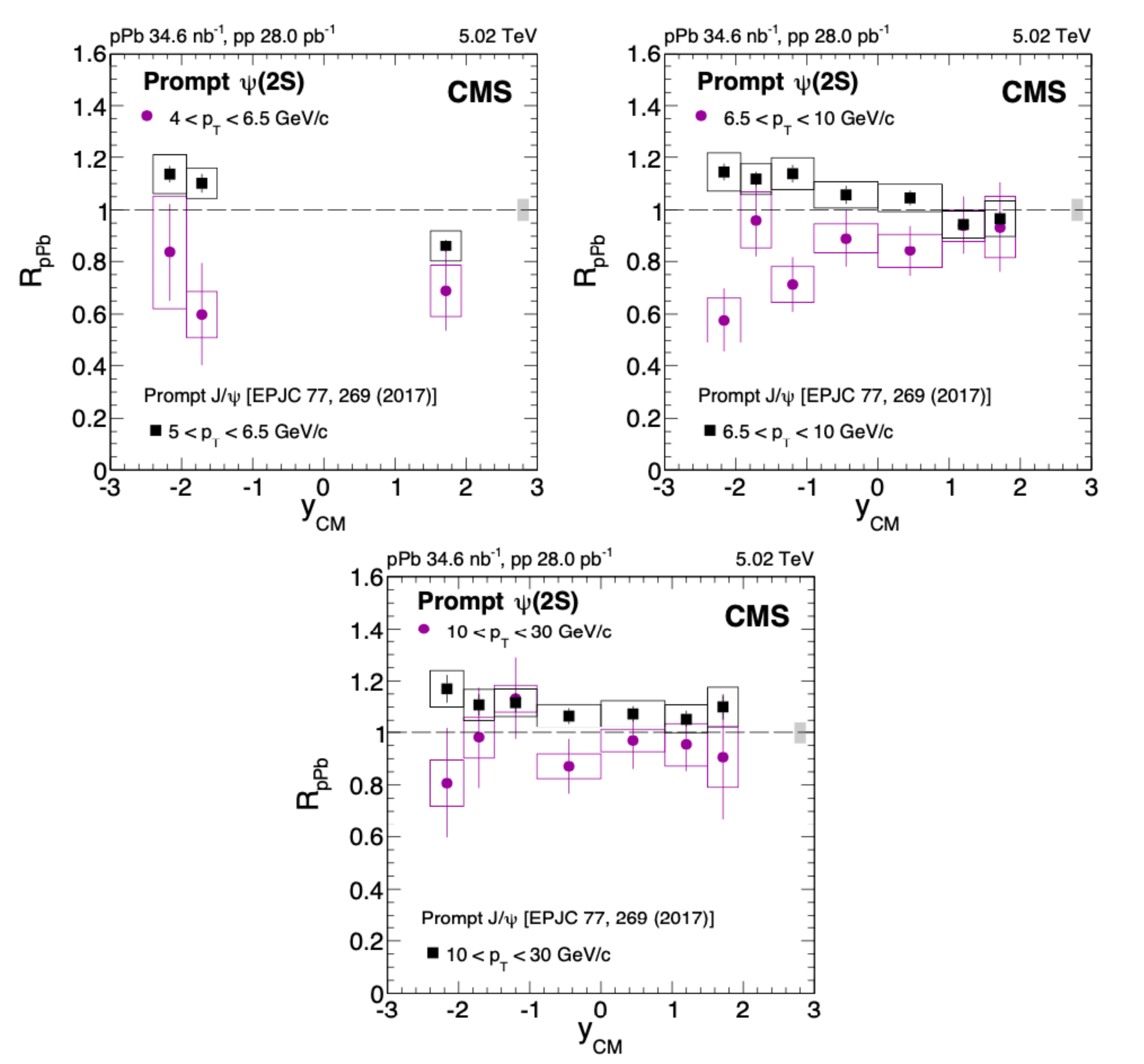
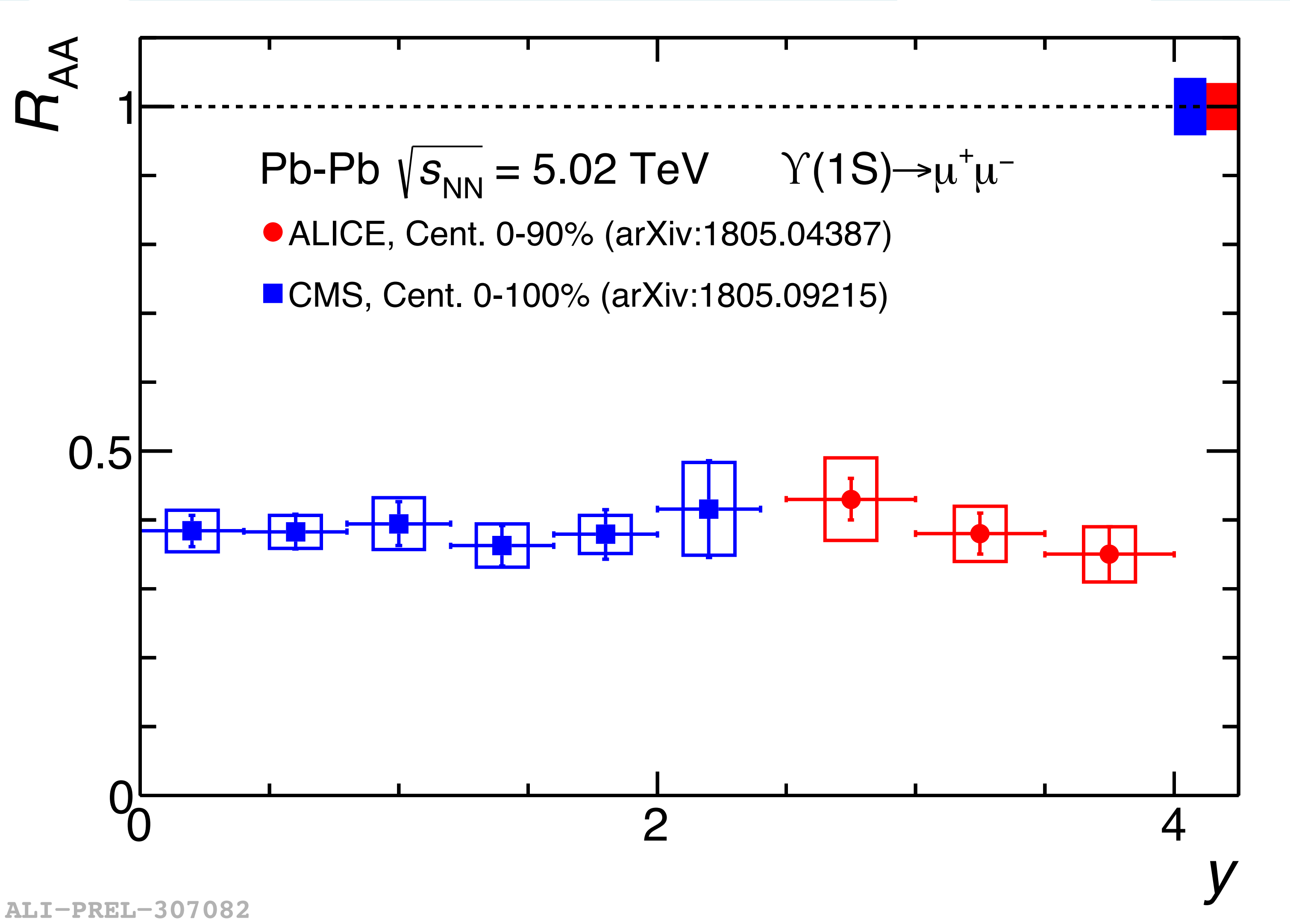


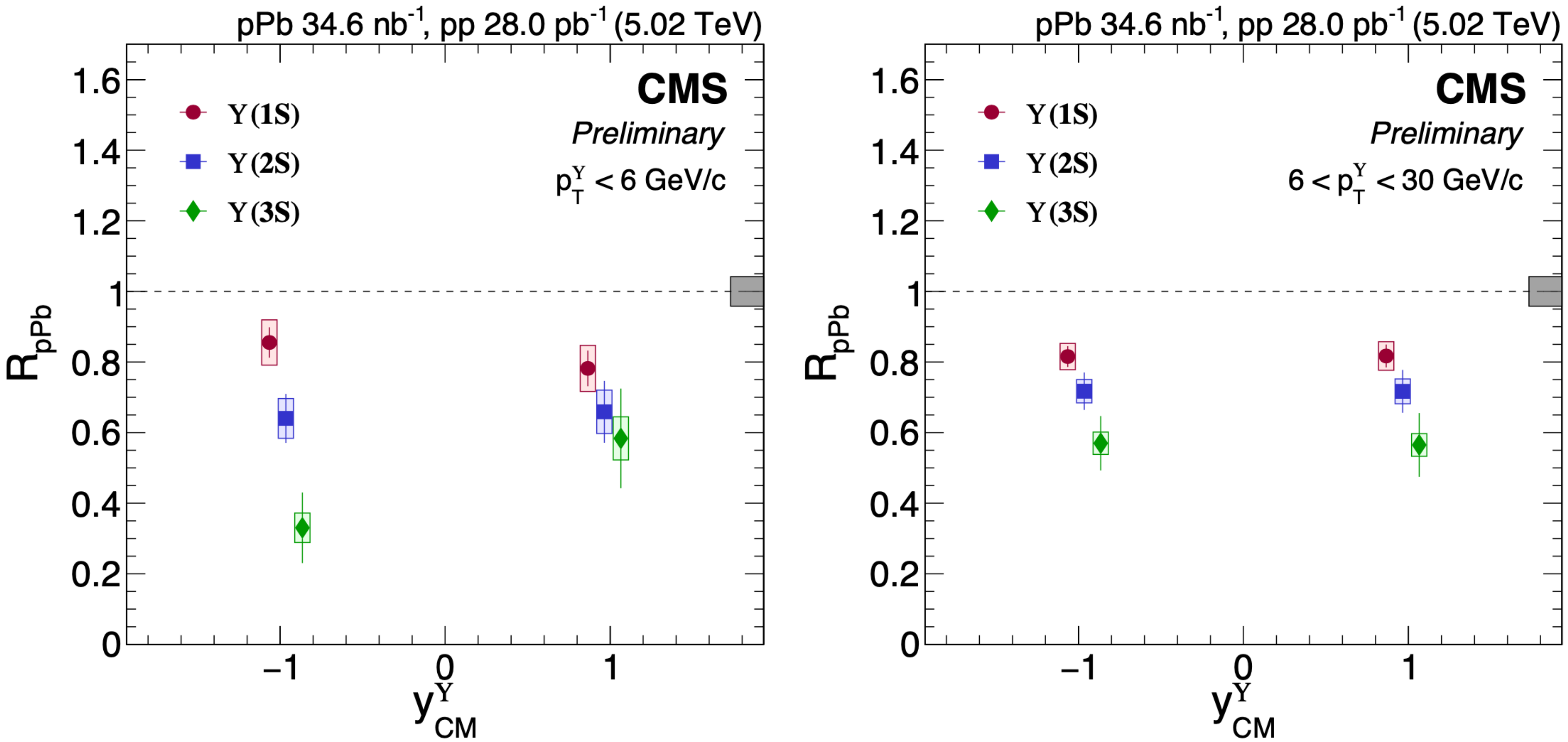
(a) Low P_T $\Upsilon(1S)$ (b) Low P_T $\Upsilon(2S)$ (c) Low P_T $\Upsilon(3S)$

(d) High P_T $\Upsilon(1S)$ (e) High P_T $\Upsilon(2S)$ (f) High P_T $\Upsilon(3S)$


pPb 34.6 nb-1, pp 28.0 pb-1
5.02 TeV
Prompt ψ(2S)
CMS
4 < pT < 6.5 GeV/c
Prompt J/ψ [EPJC 77, 269 (2017)]
5 < pT < 6.5 GeV/c
RpPb
yCM
pPb 34.6 nb-1, pp 28.0 pb-1
5.02 TeV
Prompt ψ(2S)
CMS
6.5 < pT < 10 GeV/c
Prompt J/ψ [EPJC 77, 269 (2017)]
6.5 < pT < 10 GeV/c
RpPb
yCM
pPb 34.6 nb-1, pp 28.0 pb-1
5.02 TeV
Prompt ψ(2S)
CMS
10 < pT < 30 GeV/c
Prompt J/ψ [EPJC 77, 269 (2017)]
10 < pT < 30 GeV/c
RpPb
yCM



R_{AA}
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
$\Upsilon(1S) \rightarrow \mu^+\mu^-$
ALICE, Cent. 0-90% (arXiv:1805.04387)
CMS, Cent. 0-100% (arXiv:1805.09215)
1
0.5
0
0
2
4
y
ALI−PREL−307082


pPb 34.6 nb-1, pp 28.0 pb-1 (5.02 TeV)
CMS
Preliminary
pTϒ < 6 GeV/c
ϒ(1S)
ϒ(2S)
ϒ(3S)
RpPb
yϒCM
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−1
0
1
pPb 34.6 nb-1, pp 28.0 pb-1 (5.02 TeV)
CMS
Preliminary
6 < pTϒ < 30 GeV/c
ϒ(1S)
ϒ(2S)
ϒ(3S)
RpPb
yϒCM