Quarkonia and EM probe

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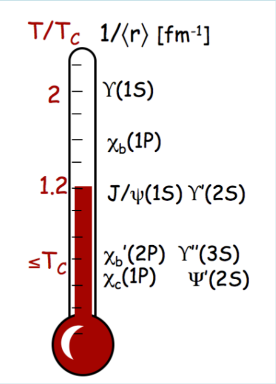
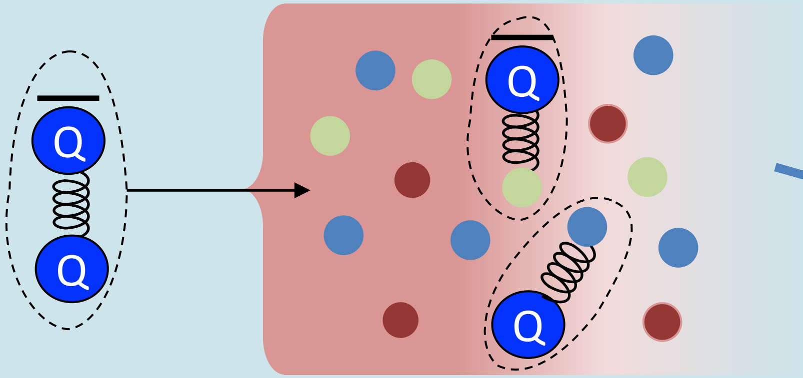
POST-QM2022 @ Nagoya University
30 APRIL, 2022

Quarkonia

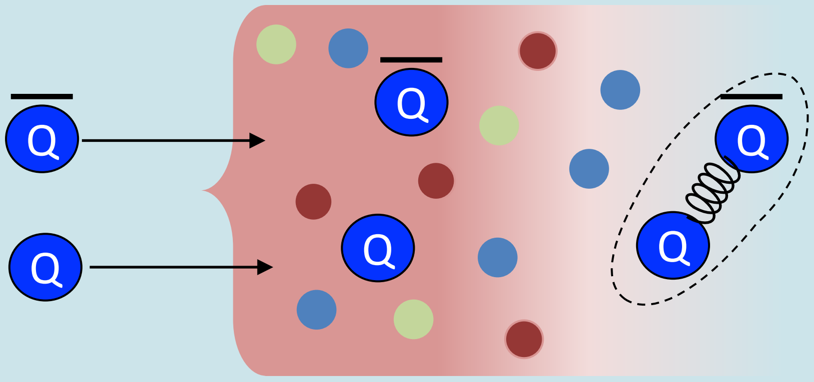
Quarkonia in QGP

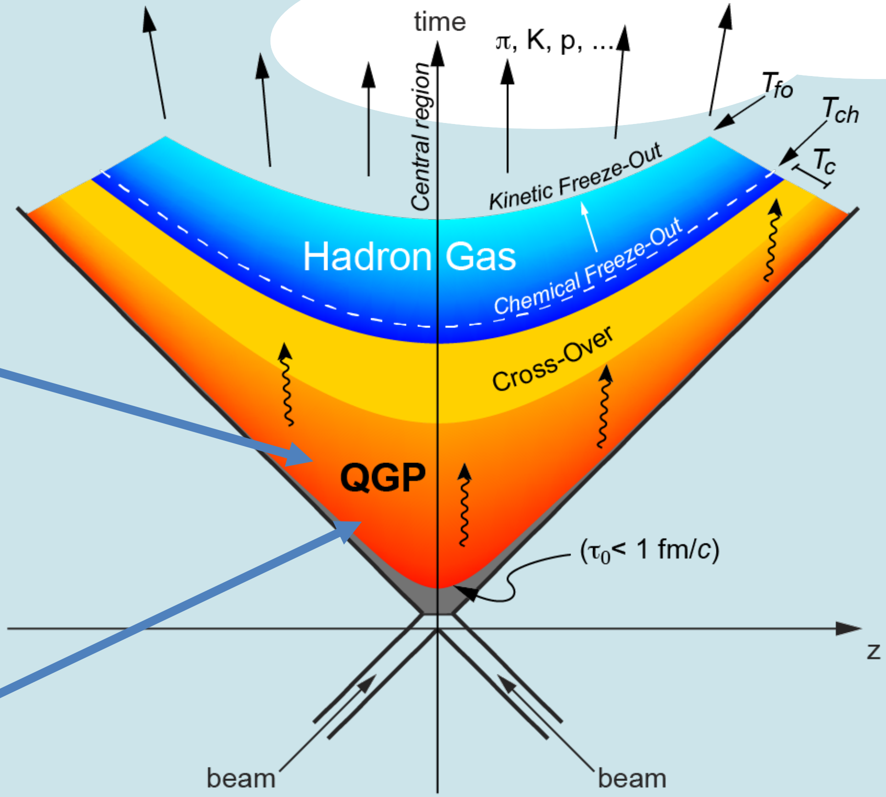


Sequential melting



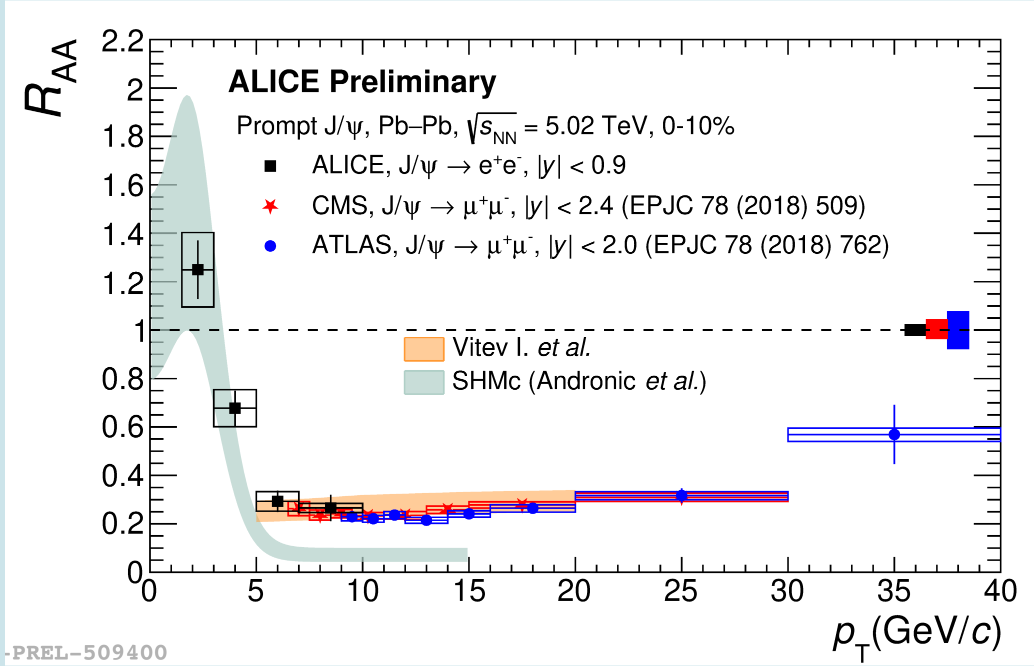
Regeneration

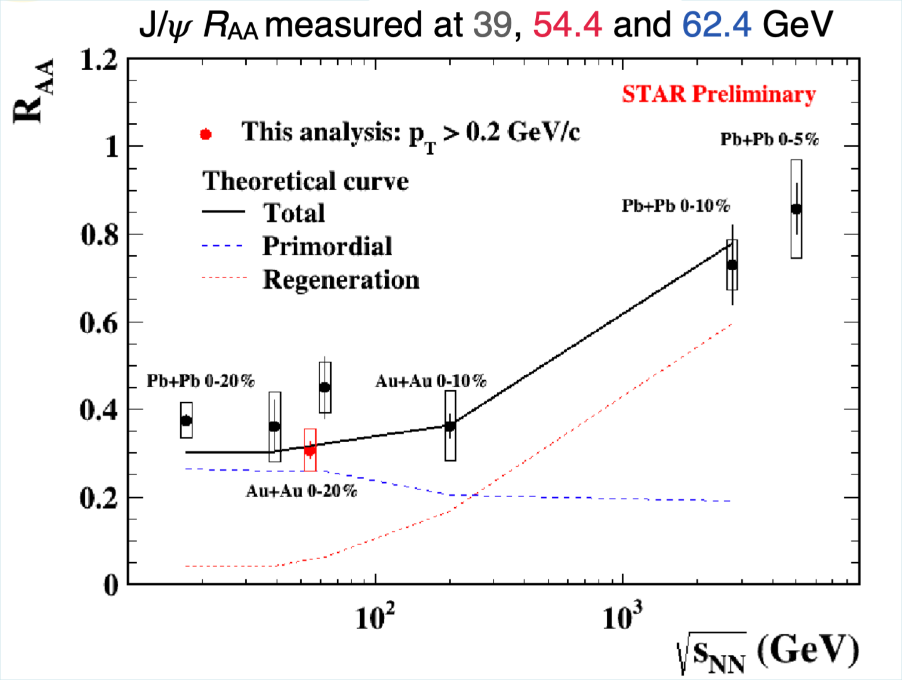




- QQ_bar pairs are produced in only the initial stage of the collision

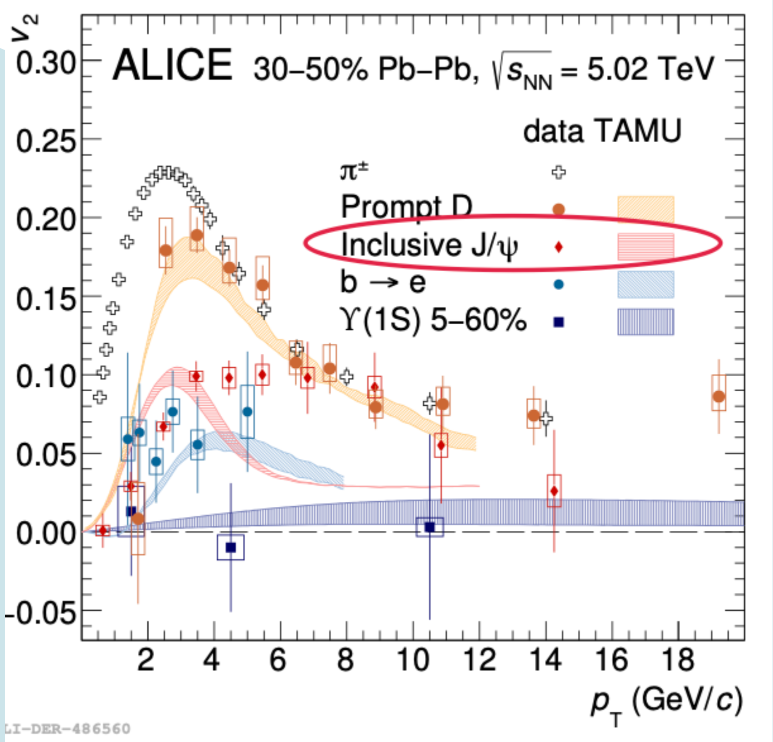
Nuclear modification factor of prompt-J/ψ

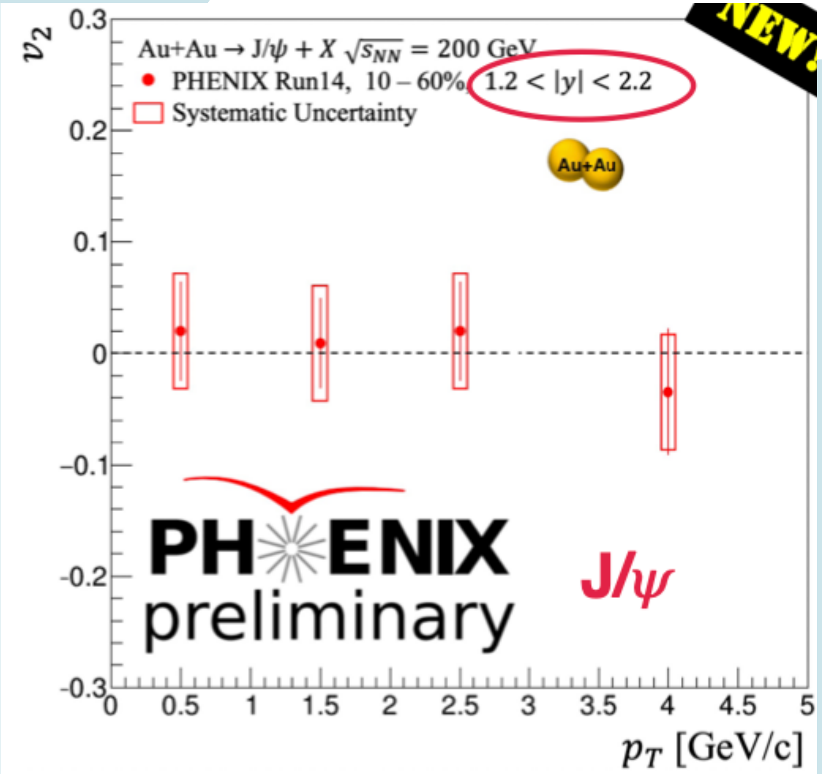



J/ψ R_{AA} measured at 39, 54.4 and 62.4 GeV

- R_{AA} of prompt-J/ψ has been measured with full statistics in PbPb @ 5.02 TeV
  - Increasing RAA at low p_T compatible with a regeneration model
- Regeneration effect is dominant from > 200 GeV collision energy

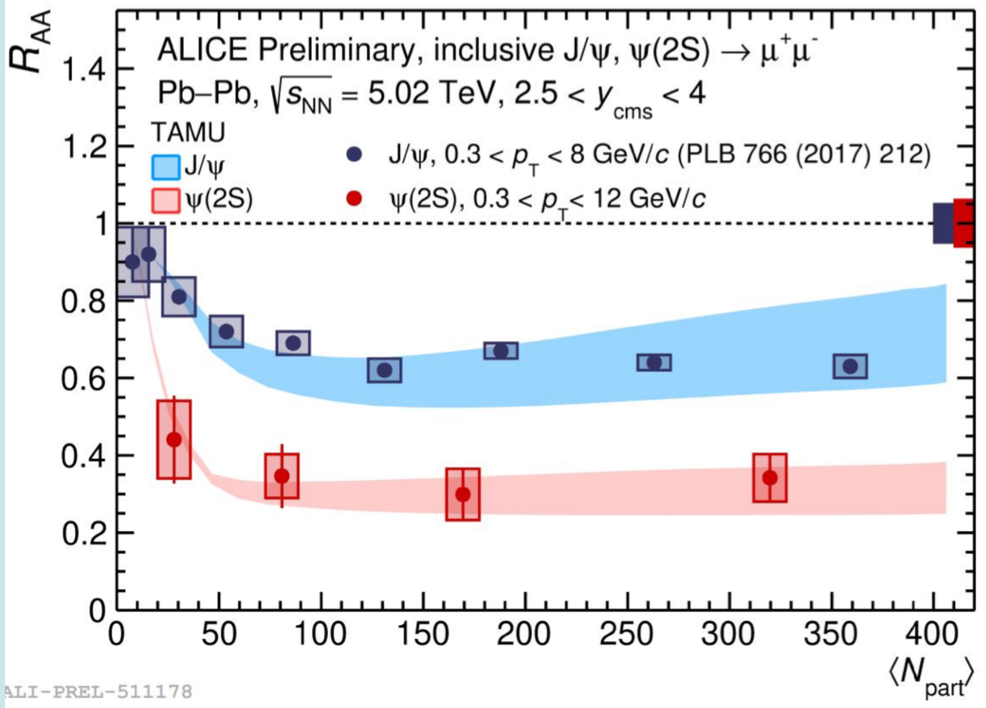
Elliptic flow of J/ψ

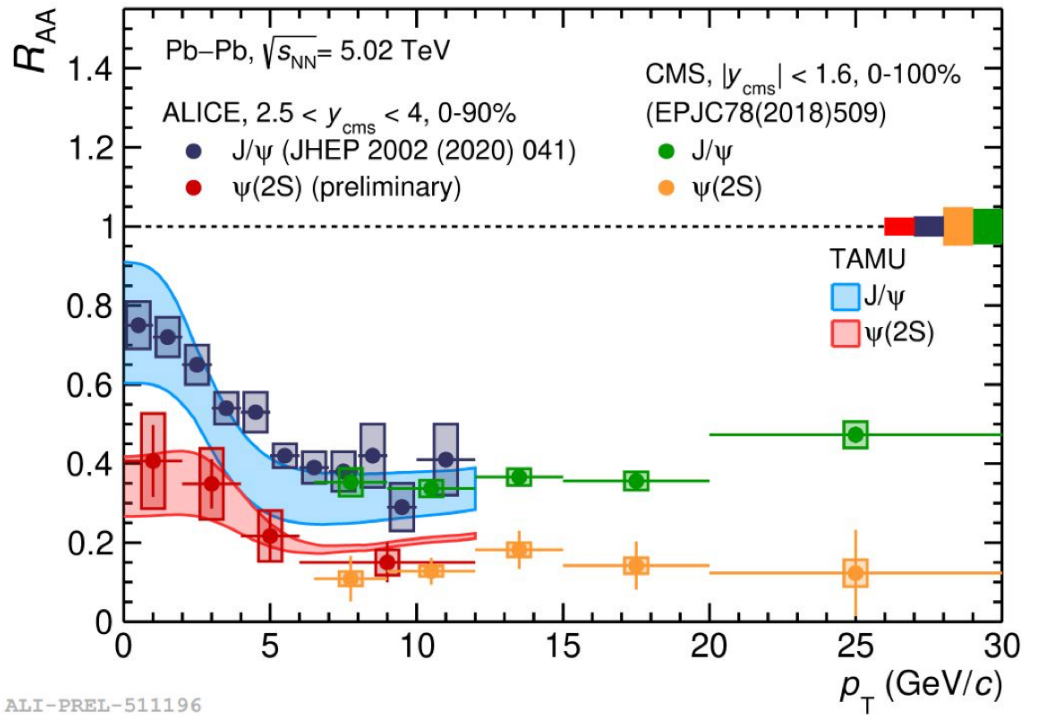




- J/ψ v2 at RHIC is consistent with 0, but that of LHC has it
- The result indicates the importance of regeneration effect on v2
- How about J/ψ v2 at high p_T at RHIC?

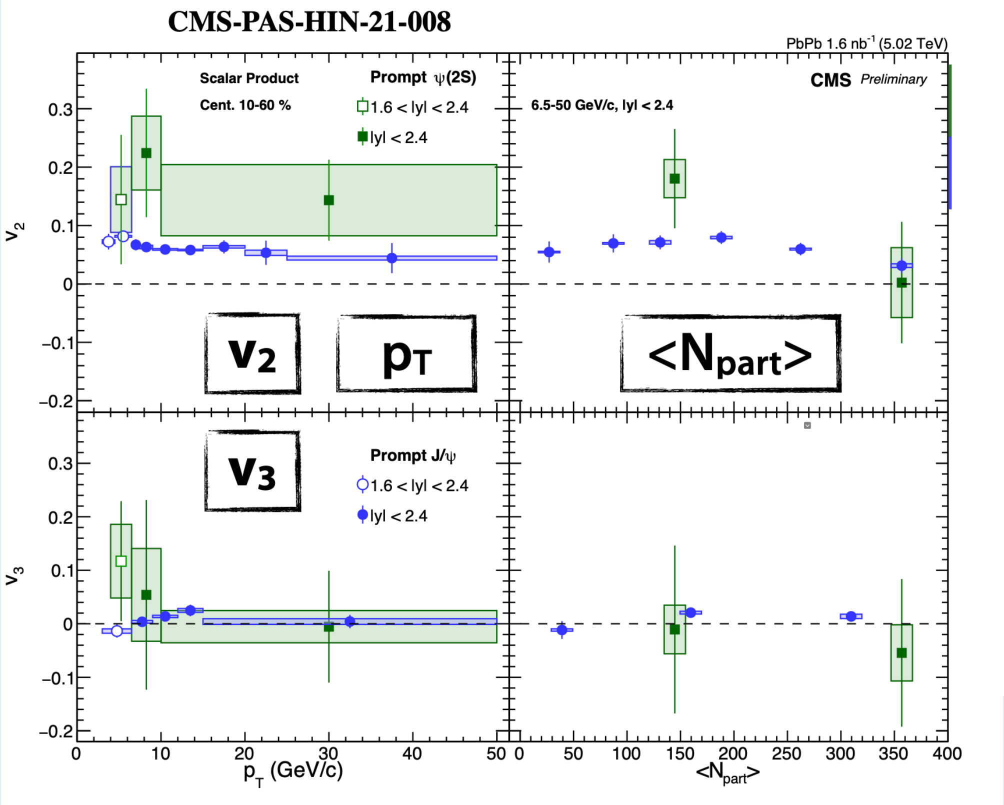
Nuclear modification factor of ψ(2S)





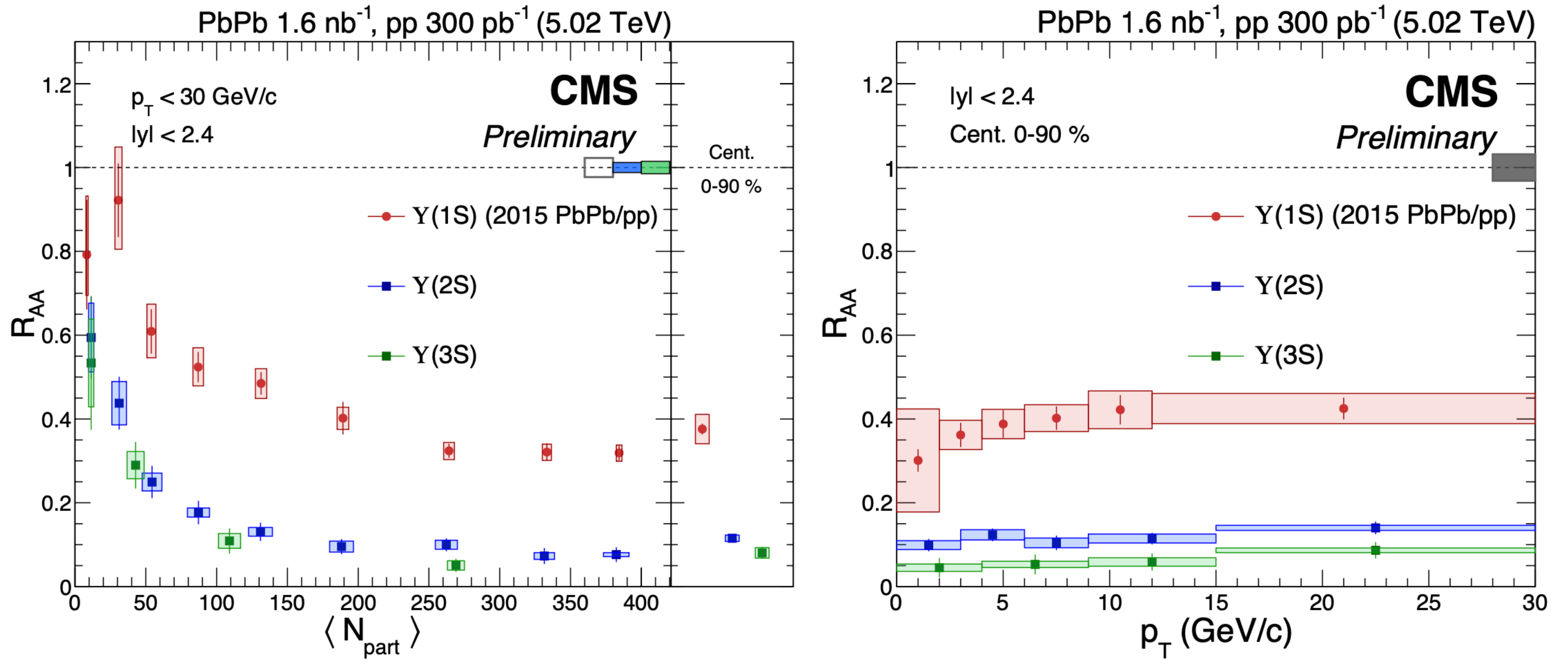
- First observation of low-p_T Ψ(2S) in PbPb collisions has been done
- Larger R_{AA} suppression w.r.t J/ψ has been reported
- Regeneration effect can be seen at low-p_T

Elliptic and triangular flow of ψ(2S)



- ψ(2S) v2 is larger than that of J/ψ in wide p_T range
- ψ(2S) v3 is consistent with zero
- The difference may come from the contribution of regeneration

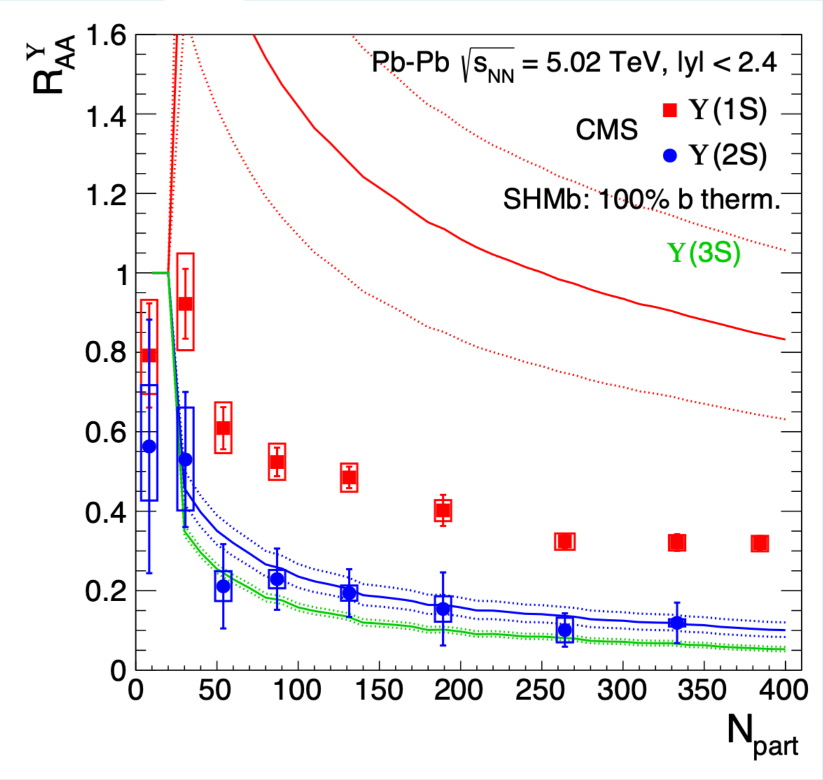
Nuclear modification factor of Υ family



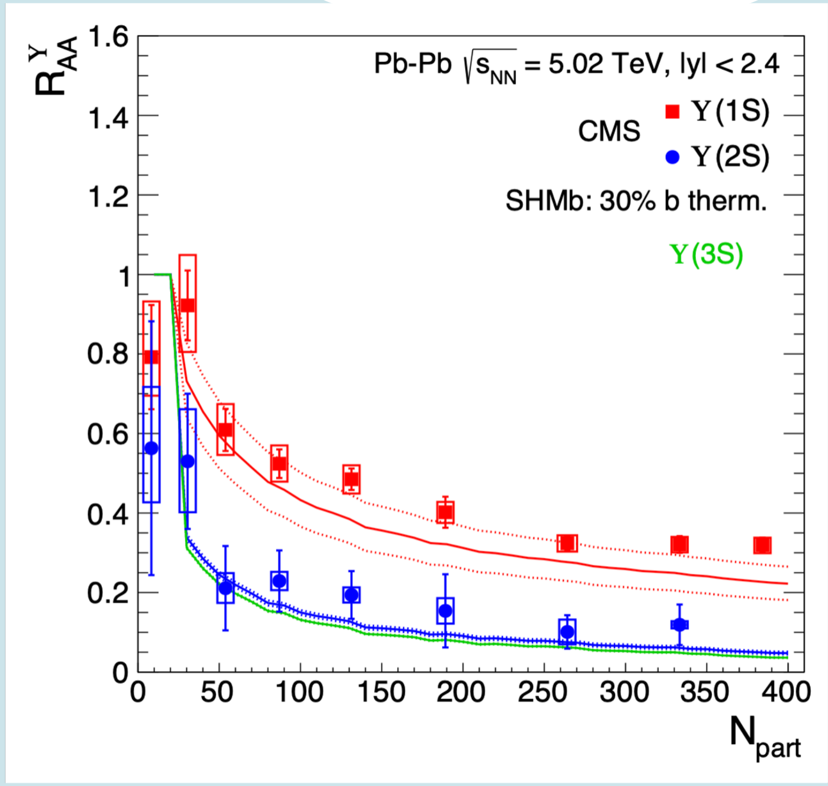
- First measurement of Υ(3S) nuclear modification factor has been reported
- Clear hierarchy has been observed, Υ(1S) > Υ(2S) > Υ(3S)

Beauty quark thermalization in QGP

100% thermalization



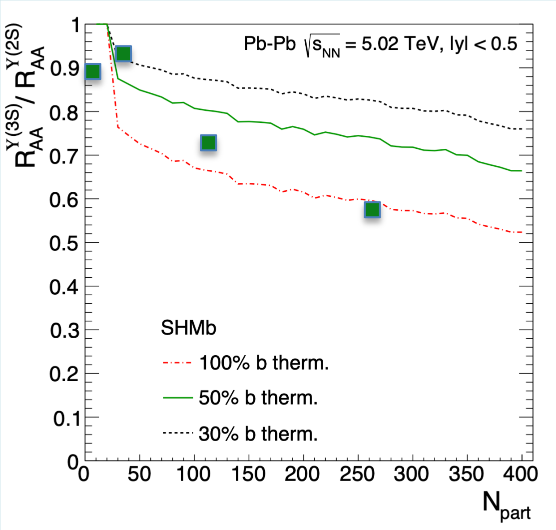
30% thermalization

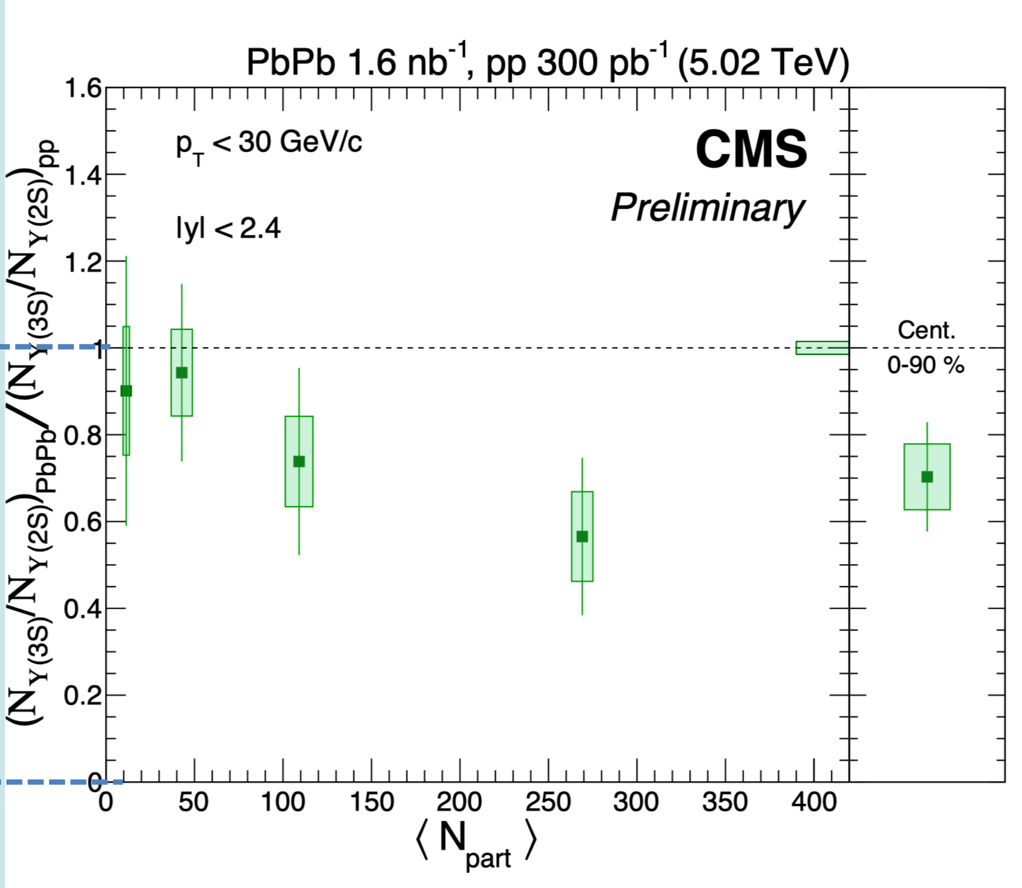


- SHM is extended to beauty quark
- Beauty quark with 30% thermalization describes Y(1S) and Y(2S)

Beauty quark thermalization with double ratio of Y(3S)/ Y(2S)

30% b thermalization





- The result of the Y(3S)/Y(2S) double ratio indicates more thermalization?

~~EM probe~~
Thermal photon and dilepton

Thermal photon and dilepton

Photon emission stages

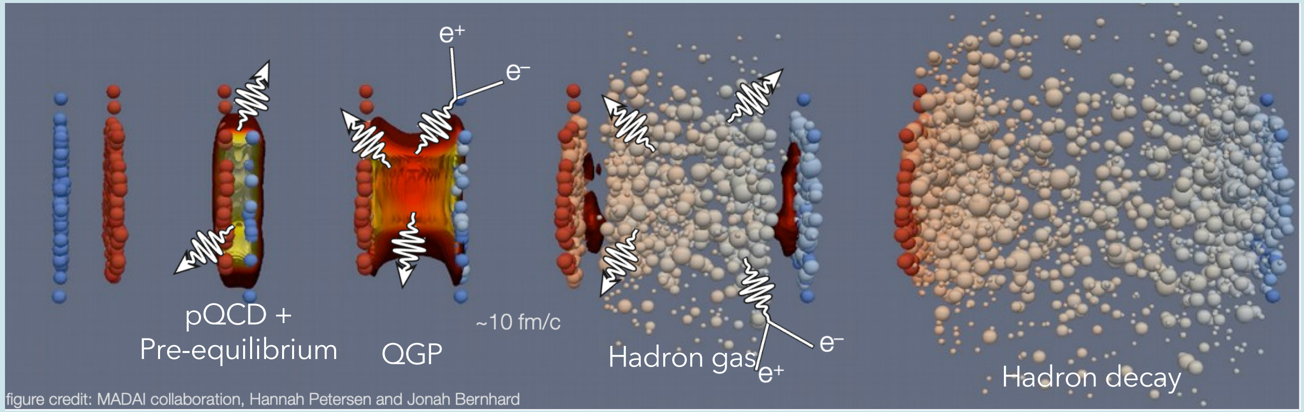
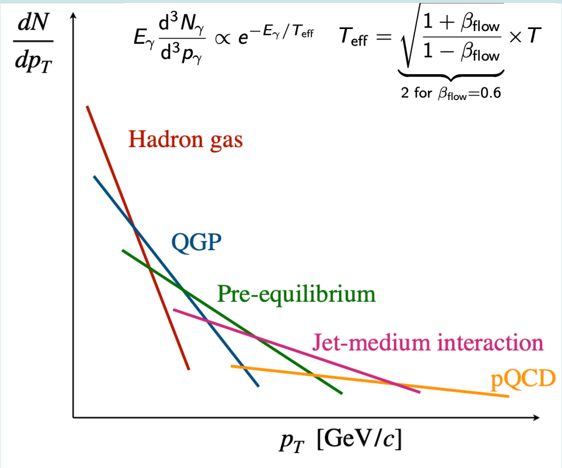


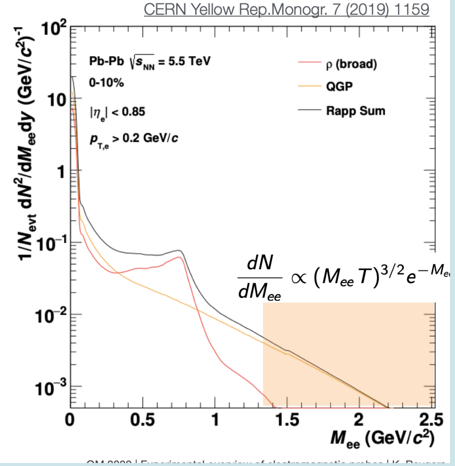
figure credit: MADAI collaboration, Hannah Petersen and Jonah Bernhard

Real photon p_T spectrum



$$E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}} \qquad T_{\text{eff}} = \underbrace{\sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}}}_{2 \text{ for } \beta_{\text{flow}}=0.6} \times T$$

Dilepton mass spectrum



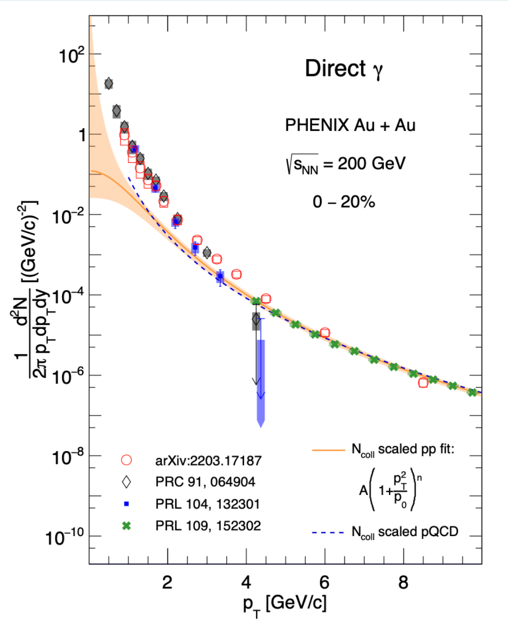
CERN Yellow Rep.Monogr. 7 (2019) 1159

$$\frac{dN}{dM_{ee}} \propto (M_{ee} T)^{3/2} e^{-M_{ee}}$$

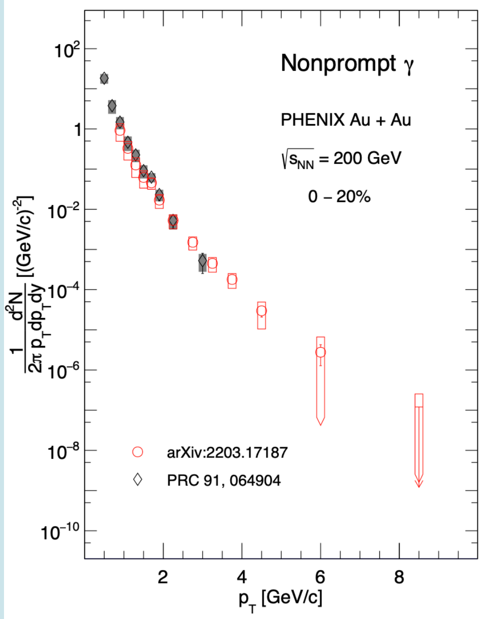
- The measurement of medium temperature is accessed through thermal radiation
- Real photon p_T spectrum has information about the matter temperature w/ blue shift effect
- The dilepton mass spectrum shape is affected by the medium temperature w/o blue shift effect

Non-prompt direct photon extraction

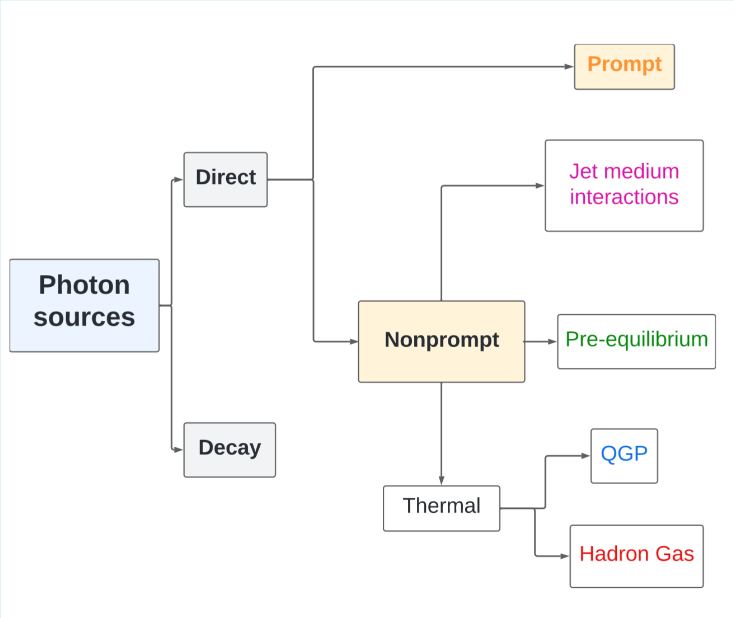
Direct photon



Non-prompt direct photon



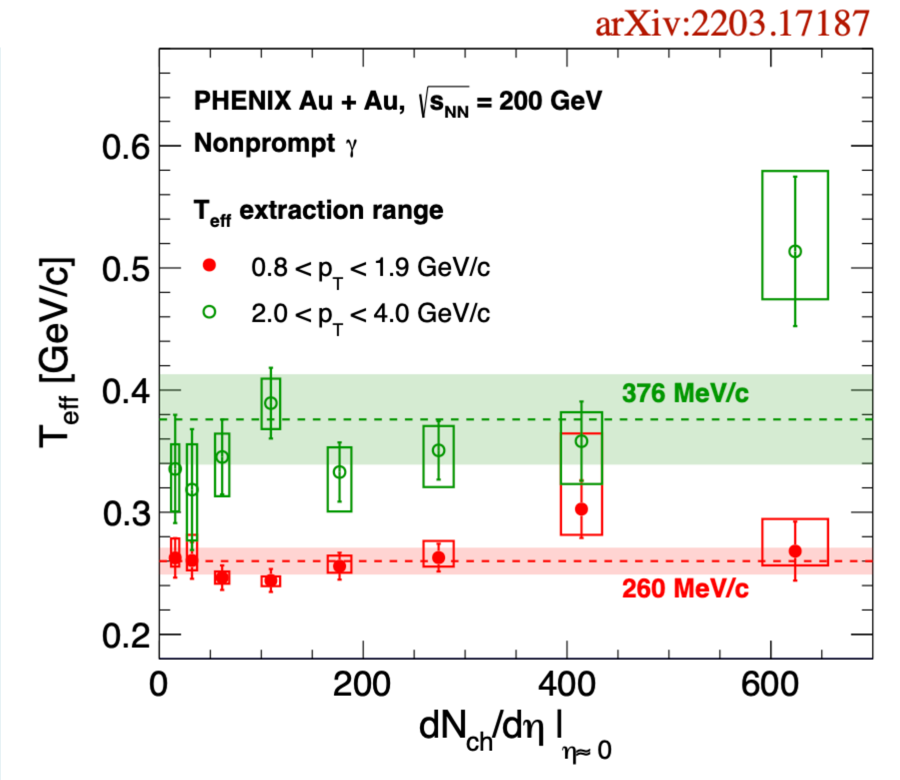
Photon sources

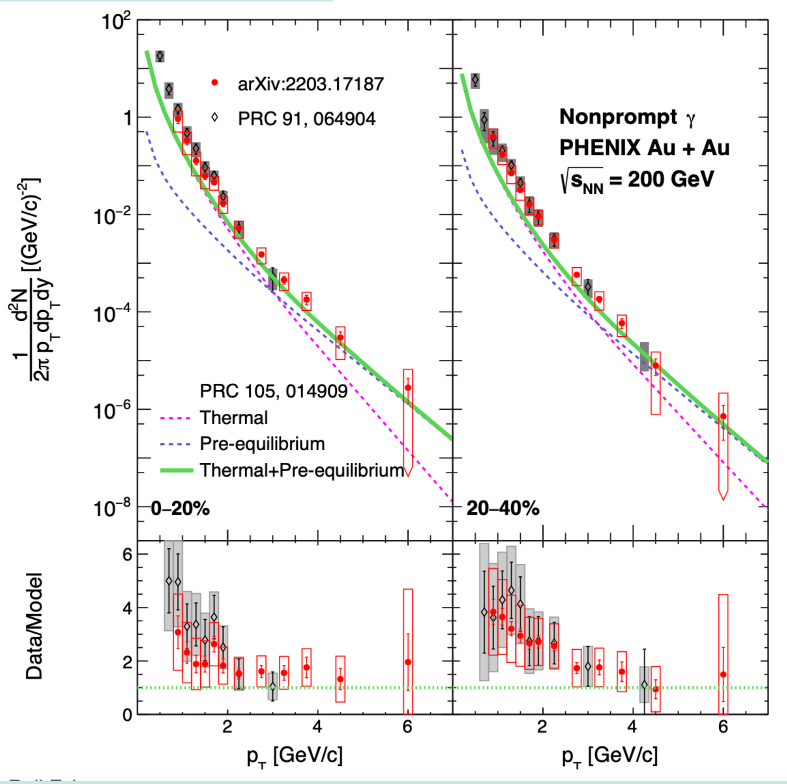


- Photon sources
  - Direct
    - Prompt
    - Nonprompt
      - Jet medium interactions
      - Pre-equilibrium
      - Thermal
        - QGP
        - Hadron Gas
  - Decay

- Non-prompt direct photon has been measured by extracting pQCD photon
  - Non-prompt direct photon = direct photon – pQCD photon
- The higher p_T photon is expected to be emitted at earlier stage

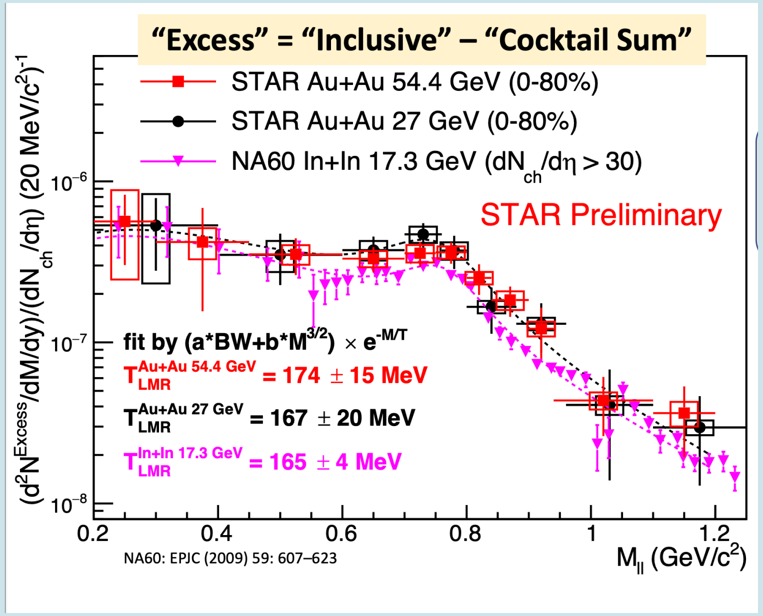
Temperature for non-prompt direct photon



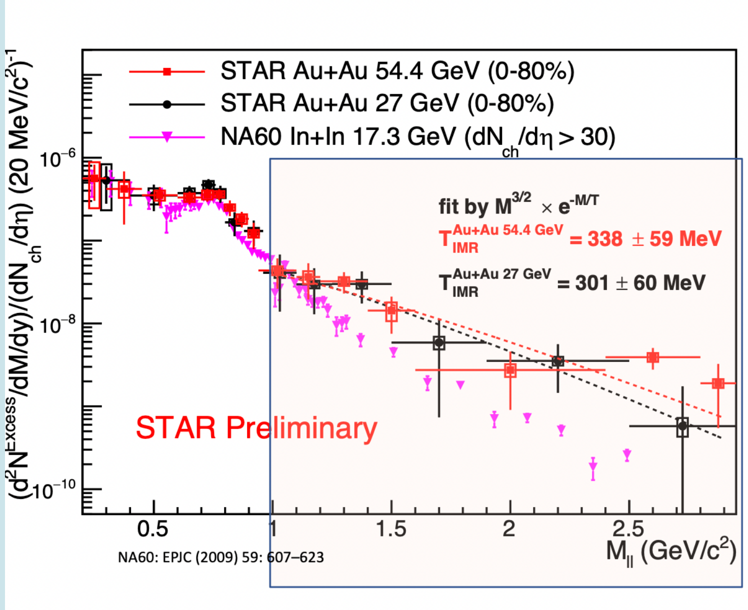


- The effective temperature at higher-p_T is larger than the lower-p_T region
  - $T_{eff}^{high\text{-}pT}$ = 376 MeV $T_{eff}^{low\text{-}pT}$ = 260 MeV
- Pre-equilibrium contribution is described by the model (p_T >3 GeV/c)
- The overall yield is underestimated especially below 2 GeV/c (QGP photon dominance region)

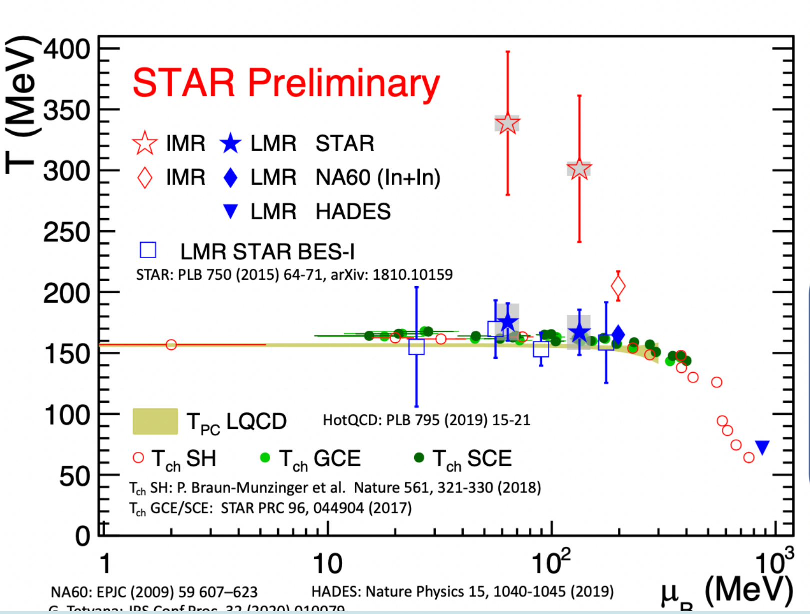
LMR and IMR thermal dilepton



NA60: EPJC (2009) 59: 607–623



NA60: EPJC (2009) 59: 607–623



STAR: PLB 750 (2015) 64-71, arXiv: 1810.10159

HotQCD: PLB 795 (2019) 15-21

T_{ch} SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018)

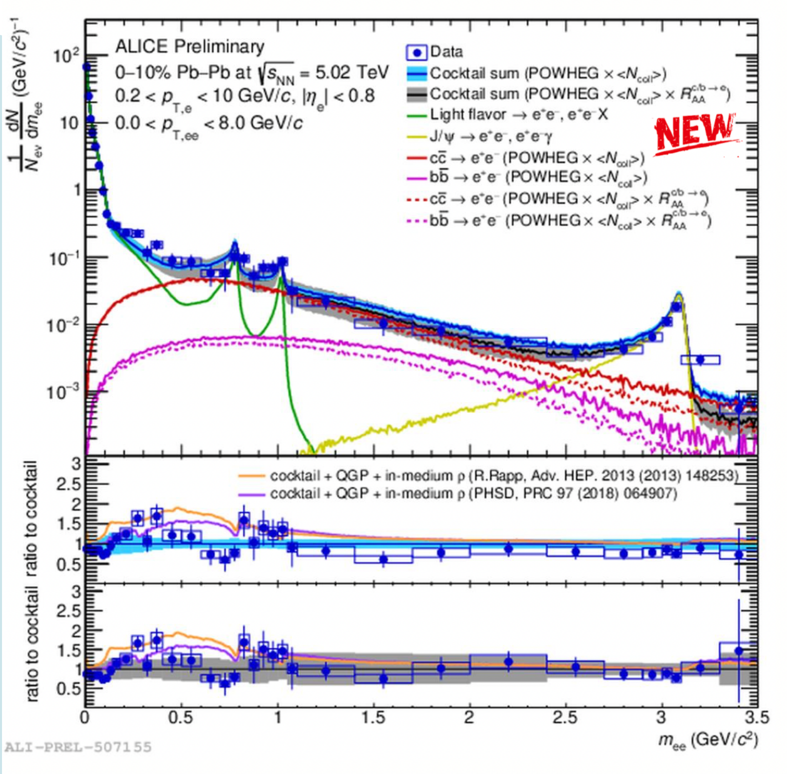
T_{ch} GCE/SCE: STAR PRC 96, 044904 (2017)

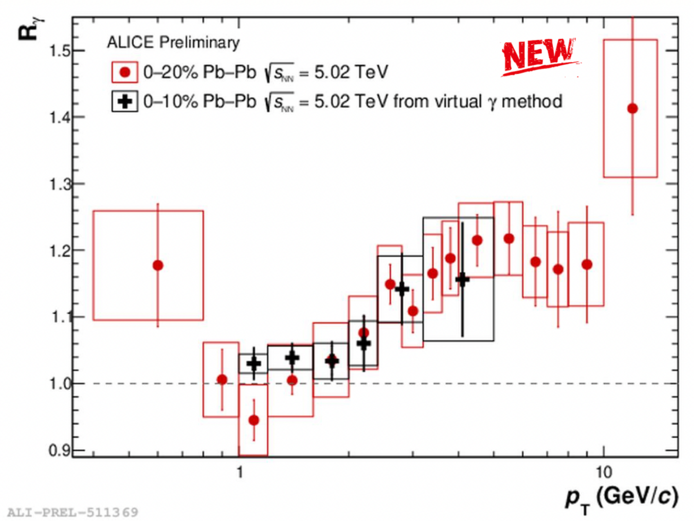
NA60: EPJC (2009) 59 607–623

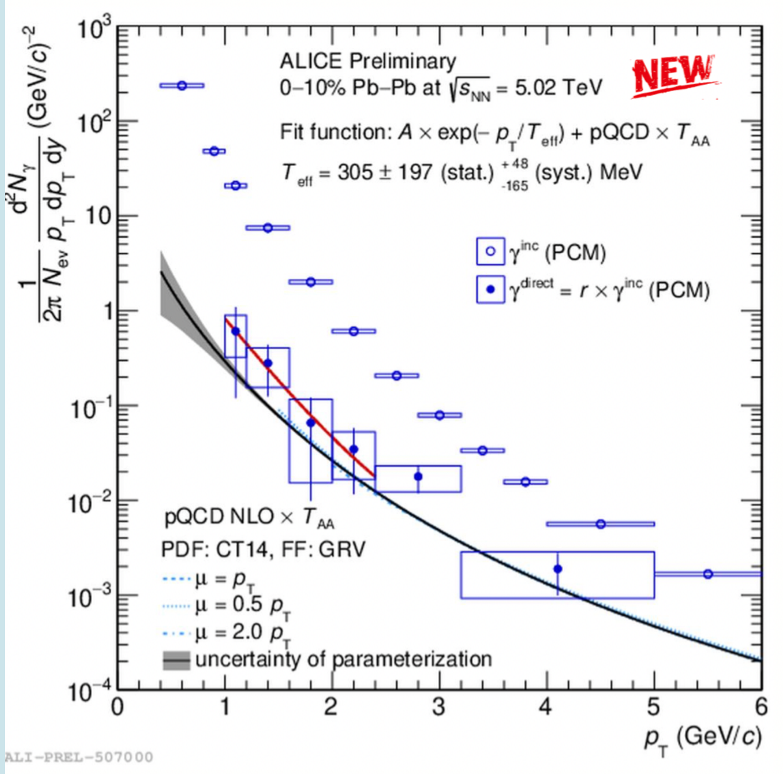
HADES: Nature Physics 15, 1040-1045 (2019)

- Similar temperatures in LMR at three different collision energies T ~ 170 MeV has been observed
- Hotter QGP creation at RHIC than SPS is suggested by the IMR result
  - RHIC achieves T_{RHIC} ~ 300 MeV
- Low mass thermal dilepton is emitted from the hadronic phase, around phase transition

Thermal dilepton at the LHC

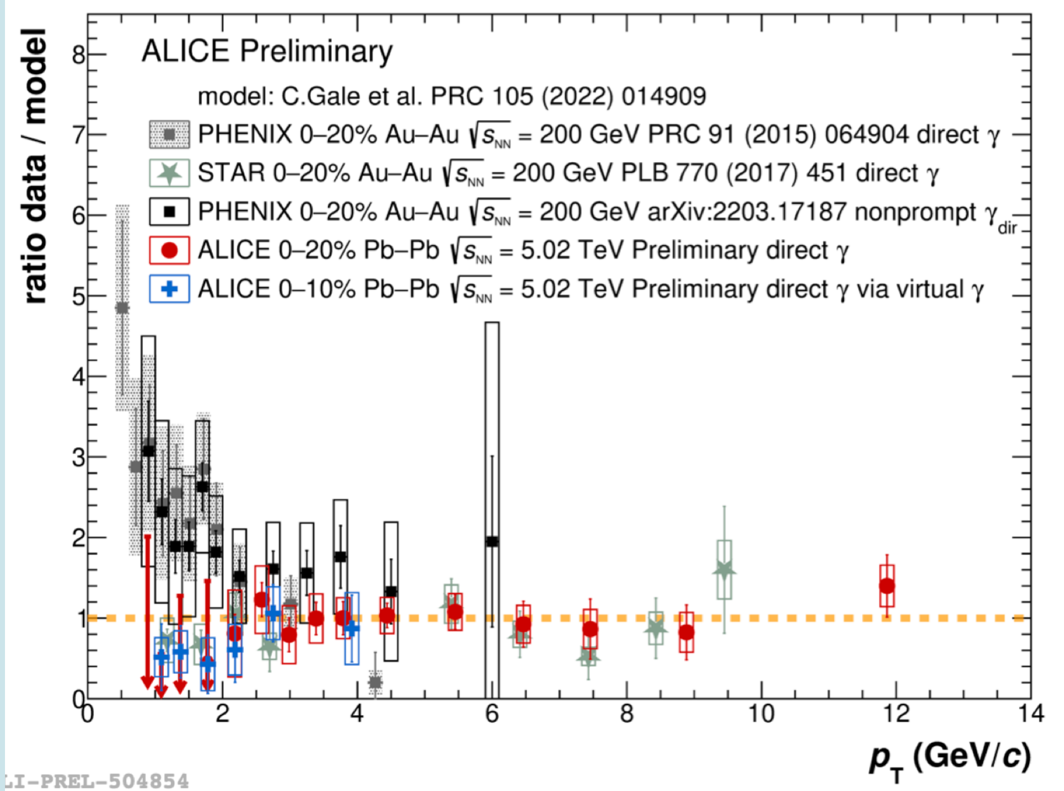


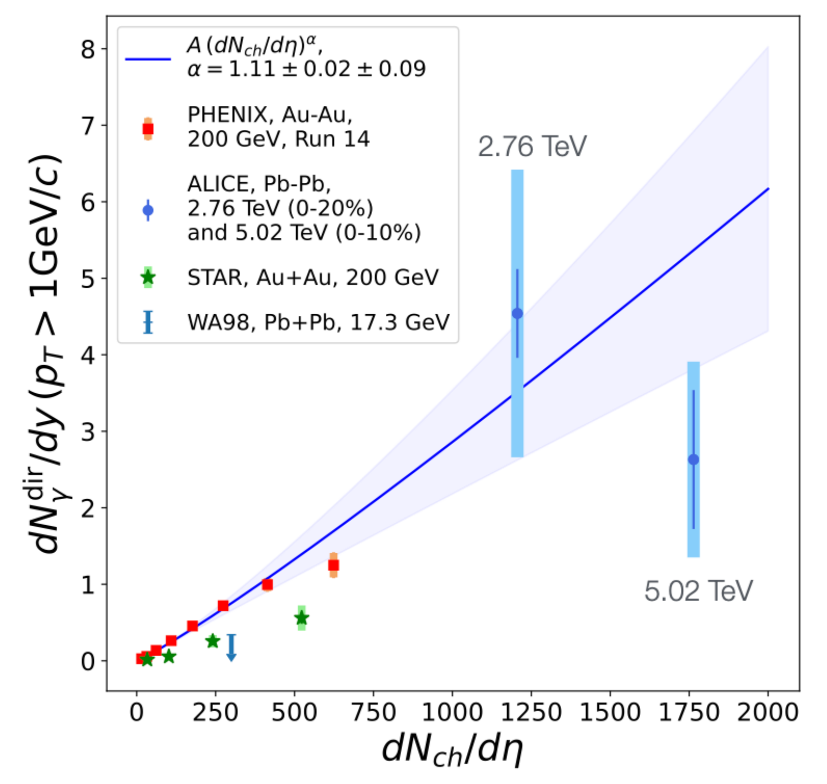




- Virtual photon result is consistent with the real photon method
- The effective temperature has been measured as T_{eff} = 305 MeV with large uncertainty (± 197 MeV)

Photon yield puzzle

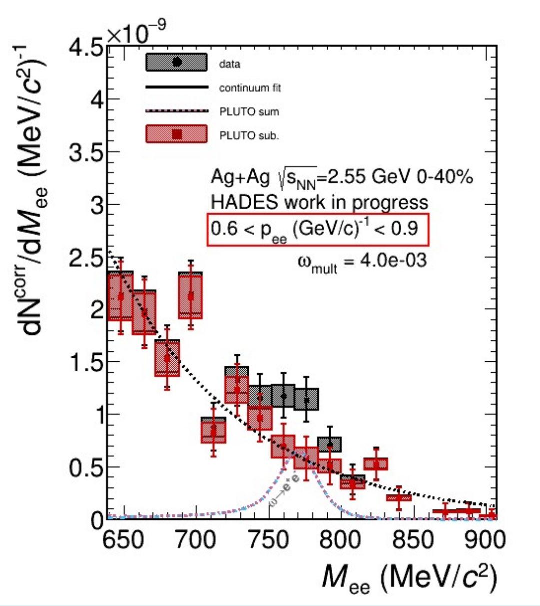


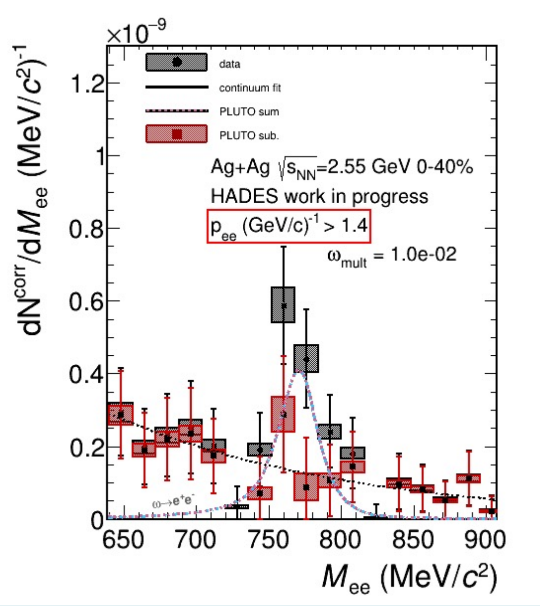


- Discrepancy between PHENIX and STAR experiment was reported
- ALICE points appear to be consistent with PHENIX trend

ρ/ω peak suppression

HADES AuAu @ 2.55 GeV





- HADES has observed the unexpected ρ/ω peak suppression in AuAu collisions @ 2.55 GeV at low-p_T region
- The similar behavior in high multiplicity pp collisions at 13 TeV has been reported
- Both measurement are similar multiplicity bin dN/dη > 30

Summary

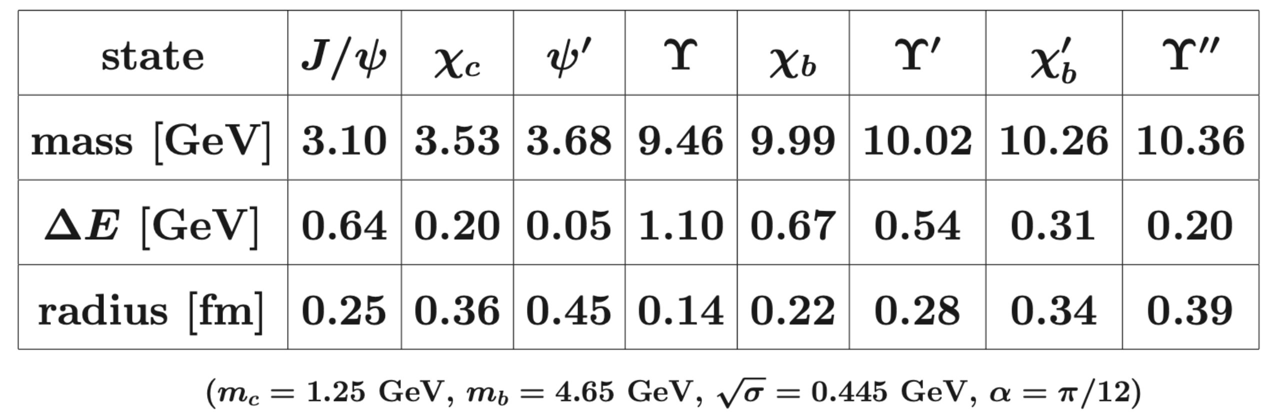
- Quarkonia
  - Precise excited state results have been reported
    - ψ(2S) R_{AA} is smaller than J/ψ
    - ψ(2S) v_2 is smaller than J/ψ
    - R_{AA} Υ(1S) > Υ(2S) > Υ(3S) sequential suppression has been observed
    - 30 % beauty quark thermalization is estimated by Υ(1S) and Υ(2S) measurement, but Υ(2S) and Υ(3S) results indicate more thermalization

- EM probe
  - Measurement of direct photon at early stage has been reported
    - Early stage thermal photon has been measured in real photon and virtual photon method
    - Virtual photon has been measured at LHC energy

Back up

Quarkonia

- 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

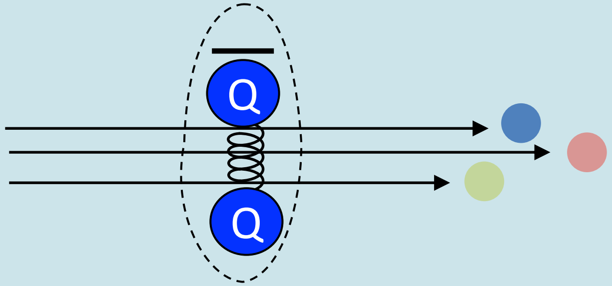
$(m_c = 1.25 \text{ GeV},\ m_b = 4.65 \text{ GeV},\ \sqrt{\sigma} = 0.445 \text{ GeV},\ \alpha = \pi/12)$

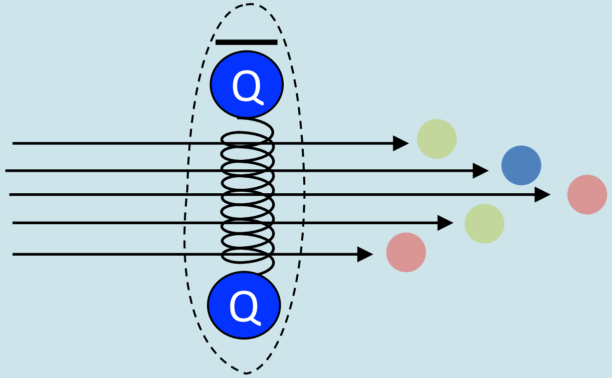
- Heavy quark hadron fraction
  - Quarkonium: ~1%
  - Open heavy quark meson: ~90%
  - Open heavy quark baryon: ~9%

Comover interaction

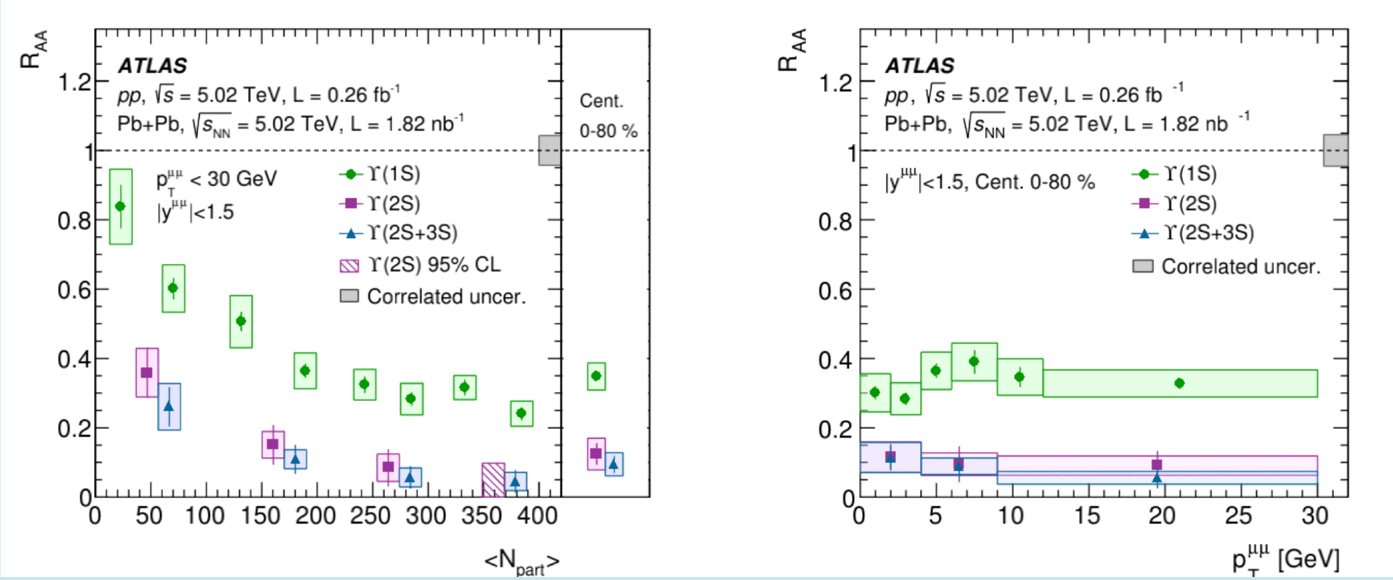
- Quarkonium is produced in initial stage of collisions
  - Hadronization at very early formation time
    - $\tau_{\psi(2S)} \sim 0.35$ fm/*c*
  - Dense condition even in small collision system
    - **Possible to see the effect in small collision system (w/o QGP)**

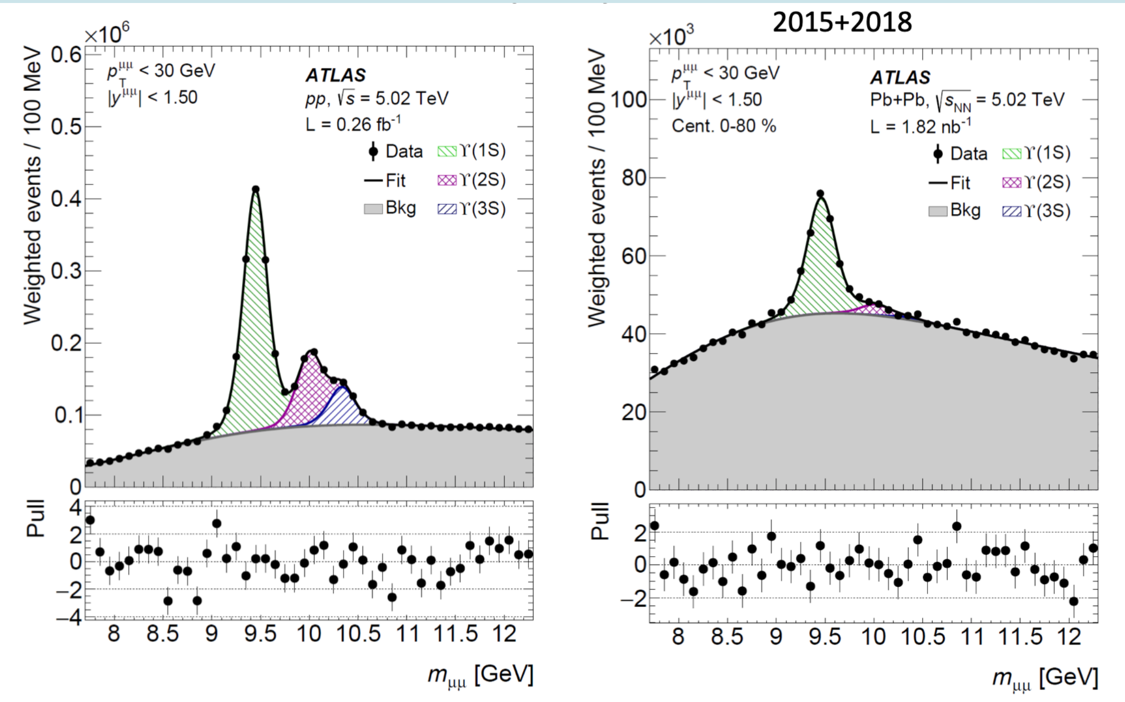
- Break-up quarkonium with passing soft particles
  - Depending on the radius
  - Sequential break-up in J/ψ, ψ(2S), Υ(1S) , Υ(2S) , Υ(3S)…

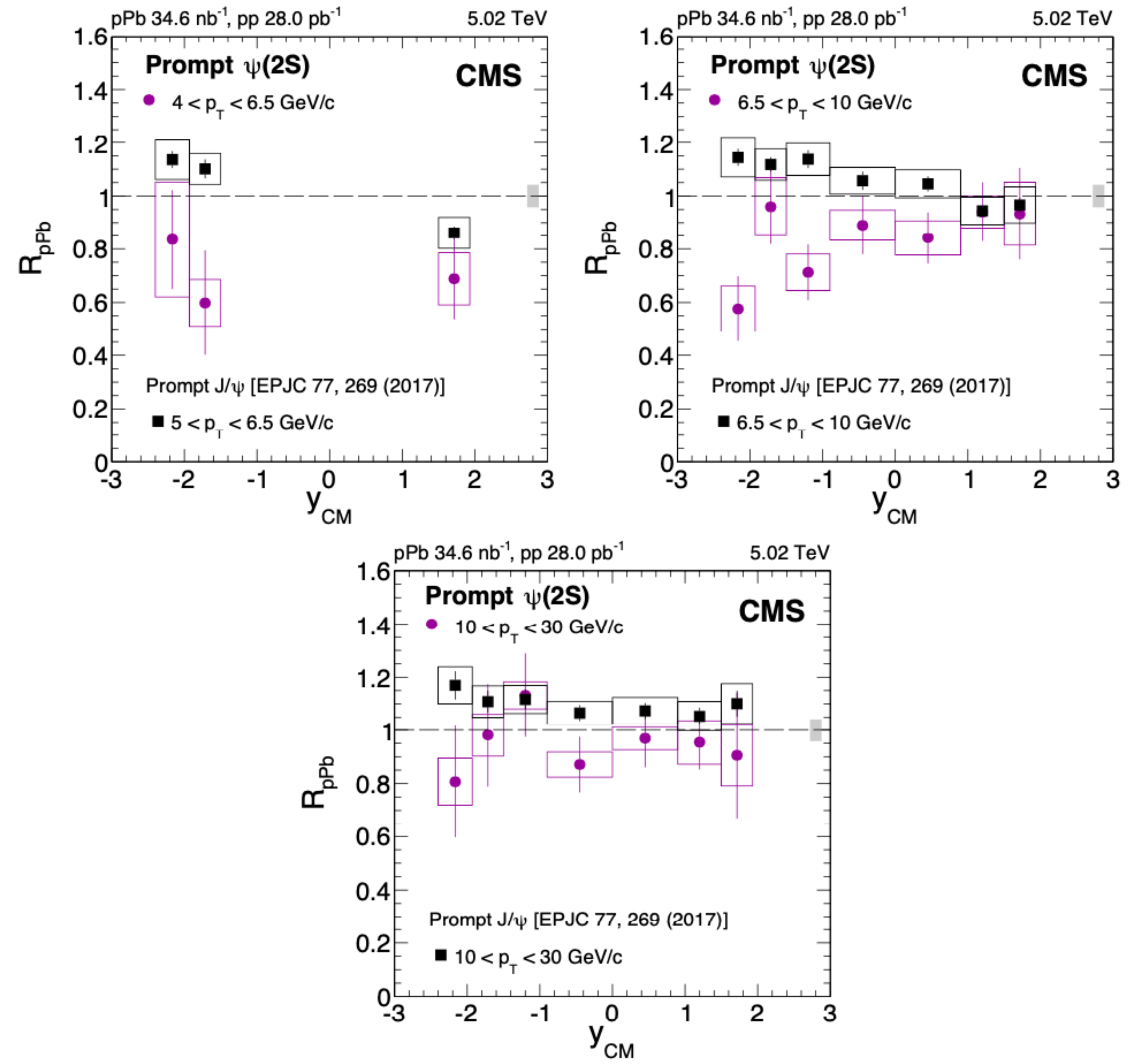


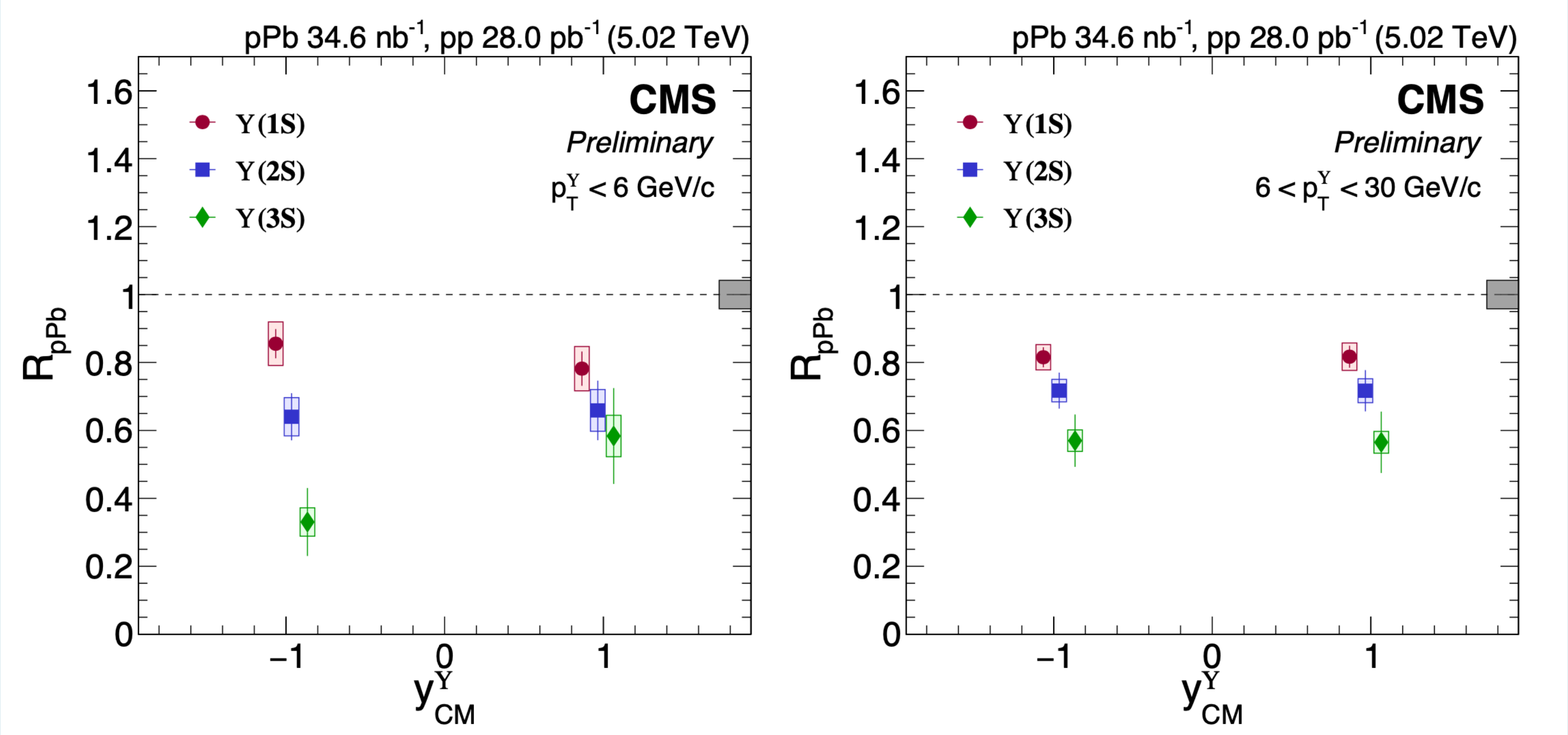


ATLAS


R_AA
ATLAS
pp, √s = 5.02 TeV, L = 0.26 fb^-1
Pb+Pb, √s_NN = 5.02 TeV, L = 1.82 nb^-1
p_T^μμ < 30 GeV
|y^μμ|<1.5
Υ(1S)
Υ(2S)
Υ(2S+3S)
Υ(2S) 95% CL
Correlated uncer.
Cent.
0-80 %
<N_part>
0
50
100
150
200
250
300
350
400
0
0.2
0.4
0.6
0.8
1
1.2
R_AA
ATLAS
pp, √s = 5.02 TeV, L = 0.26 fb^-1
Pb+Pb, √s_NN = 5.02 TeV, L = 1.82 nb^-1
|y^μμ|<1.5, Cent. 0-80 %
Υ(1S)
Υ(2S)
Υ(2S+3S)
Correlated uncer.
p_T^μμ [GeV]
0
5
10
15
20
25
30

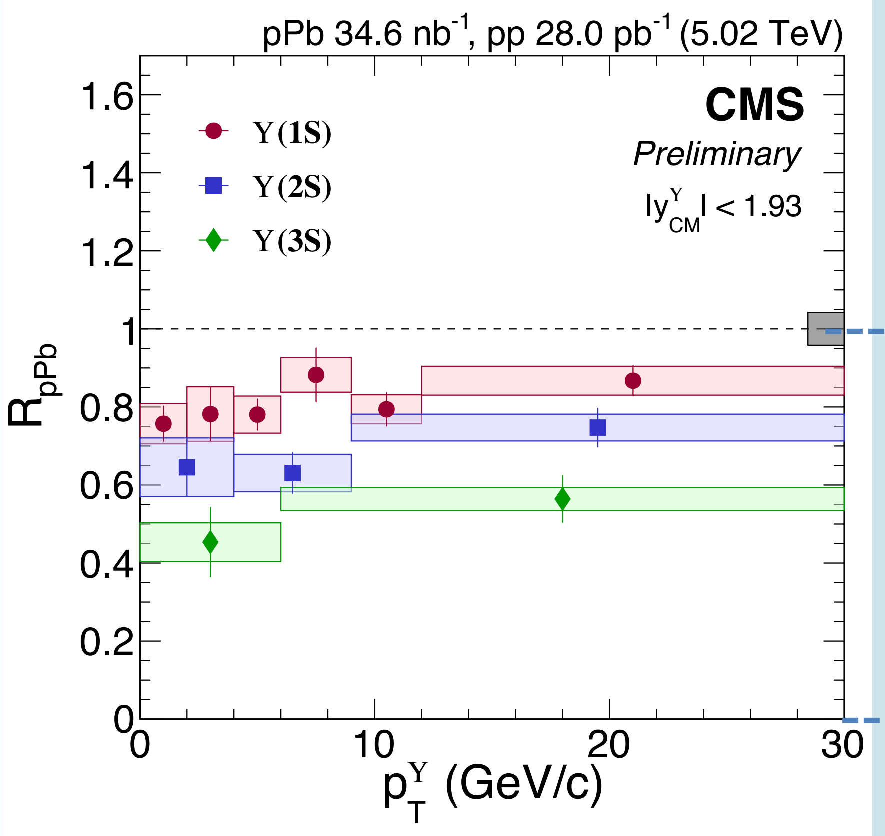

×10^6
Weighted events / 100 MeV
p_T^μμ < 30 GeV
|y^μμ| < 1.50
ATLAS
pp, √s = 5.02 TeV
L = 0.26 fb^-1
Data
Fit
Bkg
Υ(1S)
Υ(2S)
Υ(3S)
0
0.1
0.2
0.3
0.4
0.5
0.6
Pull
4
2
0
−2
−4
8
8.5
9
9.5
10
10.5
11
11.5
12
m_μμ [GeV]
2015+2018
×10^3
Weighted events / 100 MeV
p_T^μμ < 30 GeV
|y^μμ| < 1.50
Cent. 0-80 %
ATLAS
Pb+Pb, √s_NN = 5.02 TeV
L = 1.82 nb^-1
Data
Fit
Bkg
Υ(1S)
Υ(2S)
Υ(3S)
0
20
40
60
80
100
Pull
2
0
−2
8
8.5
9
9.5
10
10.5
11
11.5
12
m_μμ [GeV]

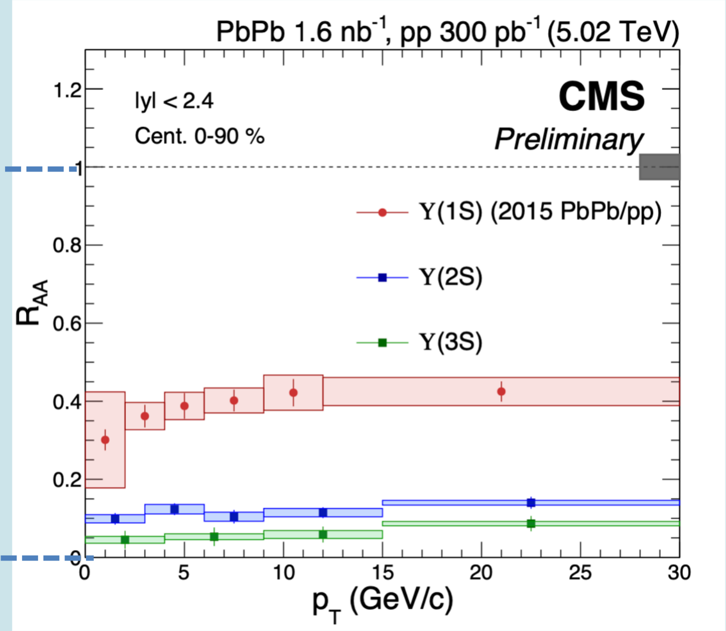

pPb 34.6 nb^{-1}, pp 28.0 pb^{-1}
5.02 TeV
Prompt ψ(2S)
CMS
4 < p_T < 6.5 GeV/c
Prompt J/ψ [EPJC 77, 269 (2017)]
5 < p_T < 6.5 GeV/c
R_{pPb}
y_{CM}
pPb 34.6 nb^{-1}, pp 28.0 pb^{-1}
5.02 TeV
Prompt ψ(2S)
CMS
6.5 < p_T < 10 GeV/c
Prompt J/ψ [EPJC 77, 269 (2017)]
6.5 < p_T < 10 GeV/c
R_{pPb}
y_{CM}
pPb 34.6 nb^{-1}, pp 28.0 pb^{-1}
5.02 TeV
Prompt ψ(2S)
CMS
10 < p_T < 30 GeV/c
Prompt J/ψ [EPJC 77, 269 (2017)]
10 < p_T < 30 GeV/c
R_{pPb}
y_{CM}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
-3
-2
-1
0
1
2
3

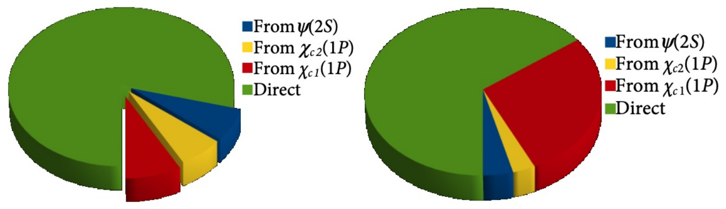

pPb 34.6 nb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)
CMS
Preliminary
$p_T^{\Upsilon} < 6$ GeV/c
Υ(1S)
Υ(2S)
Υ(3S)
R_{pPb}
y_{CM}^{Υ}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
−1
0
1
pPb 34.6 nb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)
CMS
Preliminary
$6 < p_T^{\Upsilon} < 30$ GeV/c
Υ(1S)
Υ(2S)
Υ(3S)
R_{pPb}
y_{CM}^{Υ}

Bottomonium family suppression
Comparison with pPb

- Stronger suppression w.r.t. pPb collisions has been observed







(b) Low P_T J/ψ (c) High P_T J/ψ

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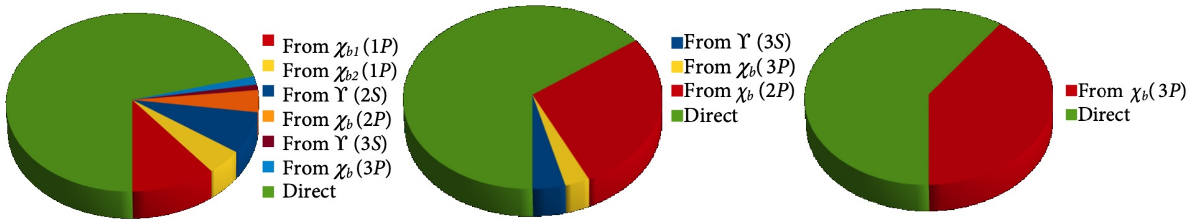
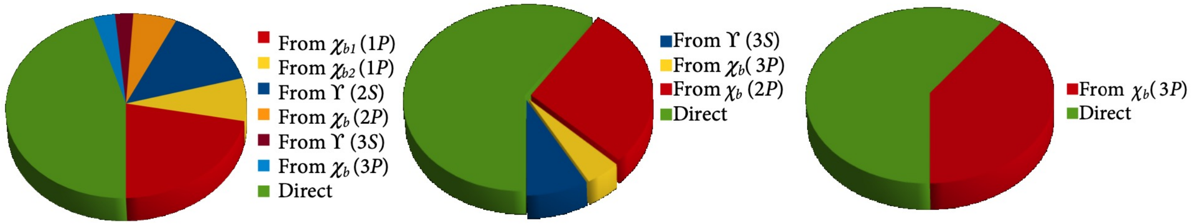
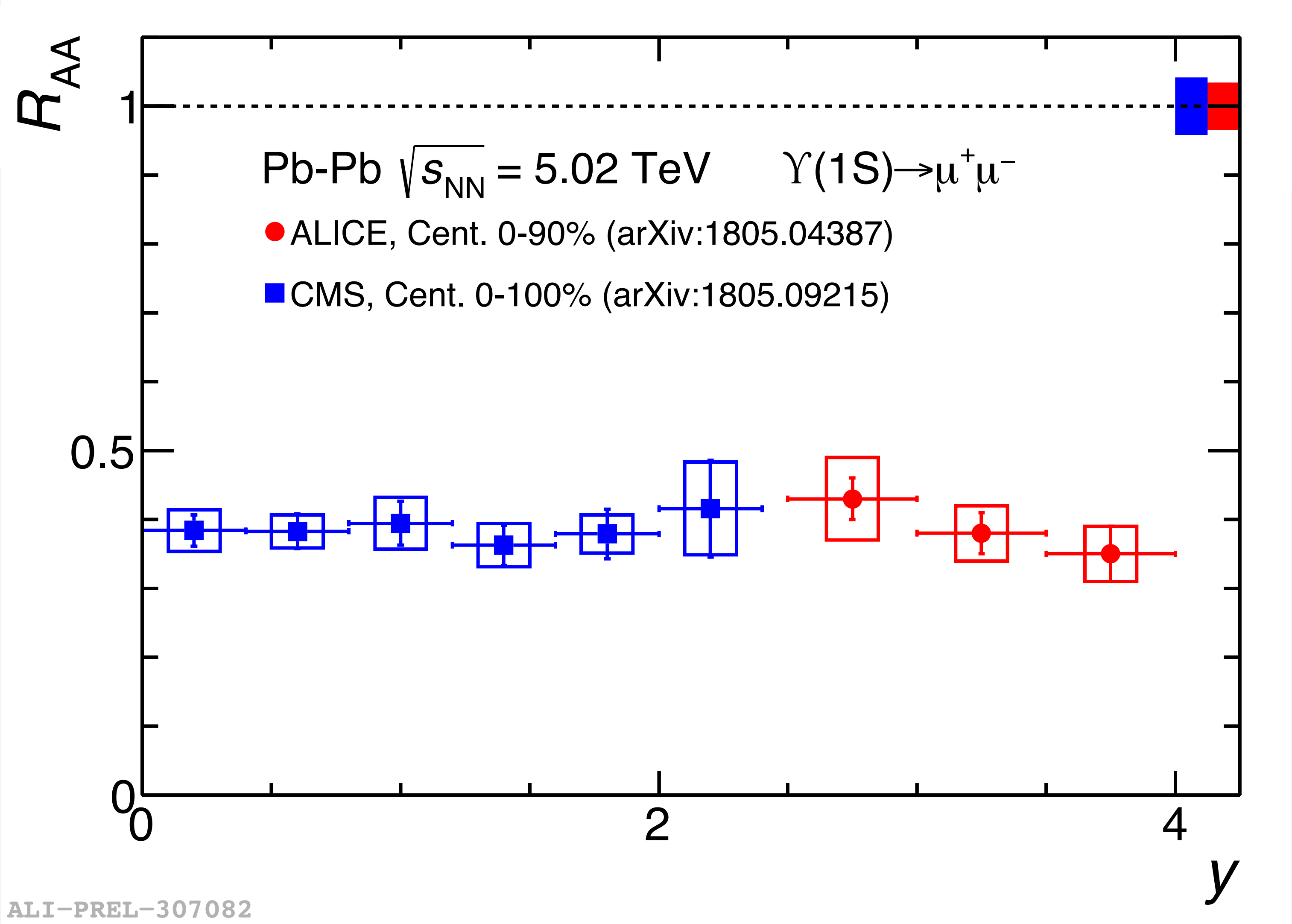


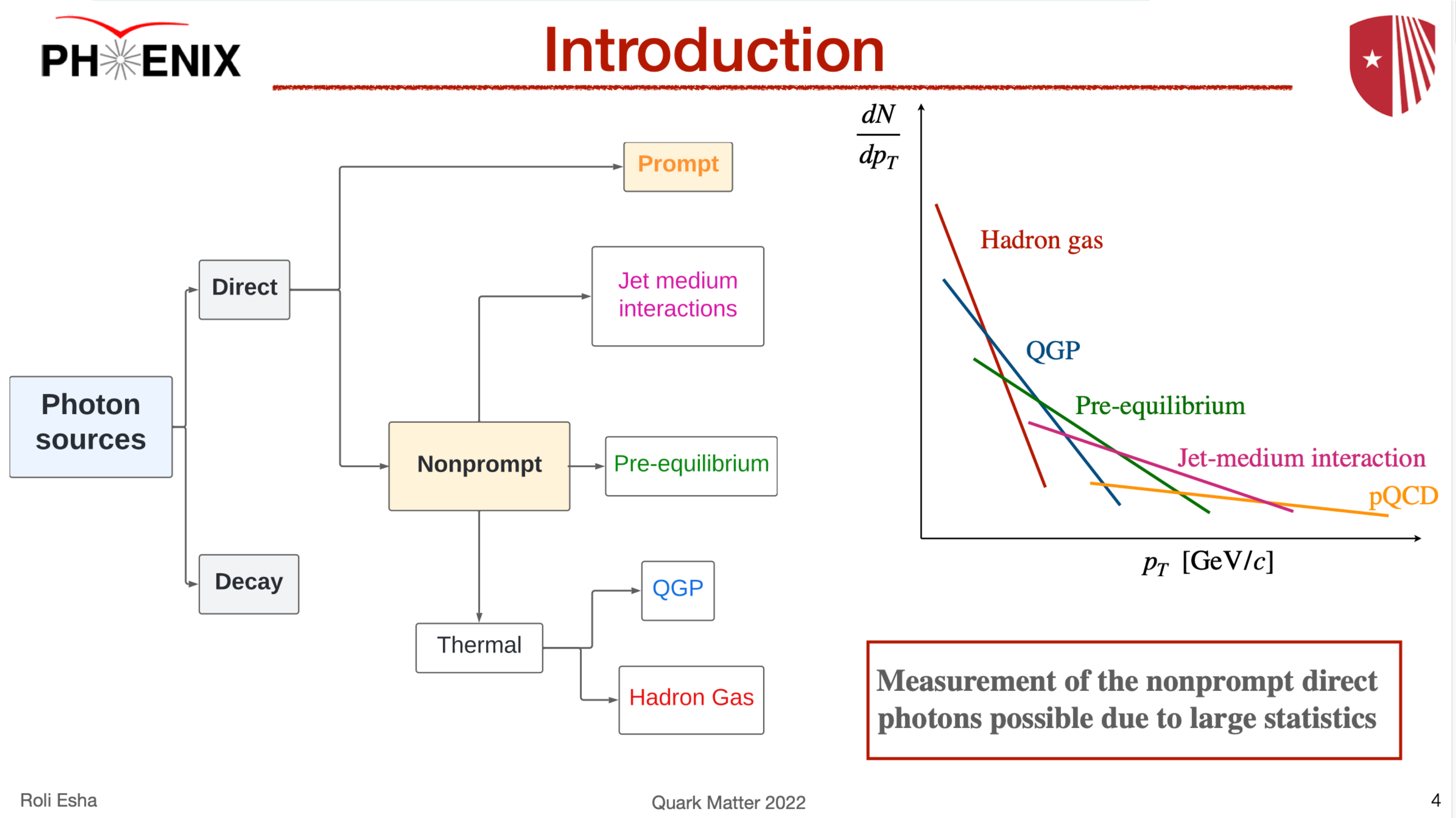
(a) Low P_T $\Upsilon(1S)$ (b) Low P_T $\Upsilon(2S)$ (c) Low P_T $\Upsilon(3S)$



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


R_{AA}
1
0.5
0
0
2
4
y
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)
ALI−PREL−307082

Photon source



PHENIX

Introduction

- Photon sources
  - Direct
    - Prompt
    - Nonprompt
      - Jet medium interactions
      - Pre-equilibrium
      - Thermal
        - QGP
        - Hadron Gas
  - Decay

Measurement of the nonprompt direct photons possible due to large statistics

Roli Esha

Quark Matter 2022

4

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)

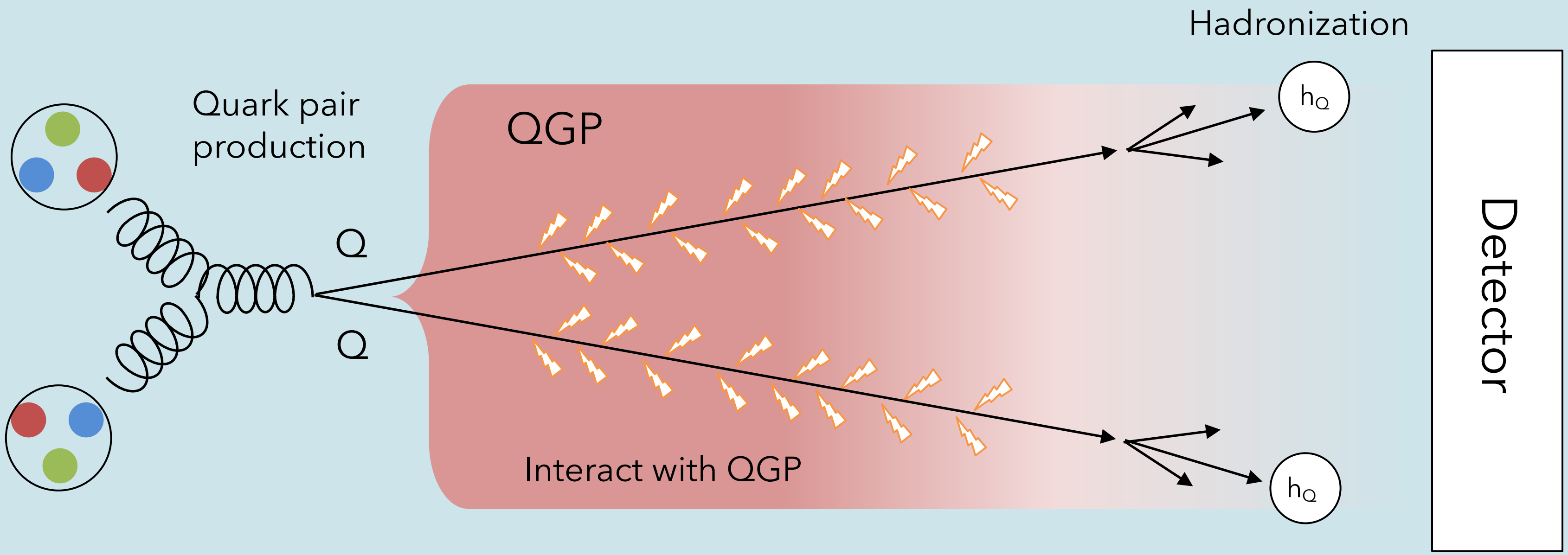
- Produced initial hard scattering processes
  - Accurate interpretation by pQCD

- 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

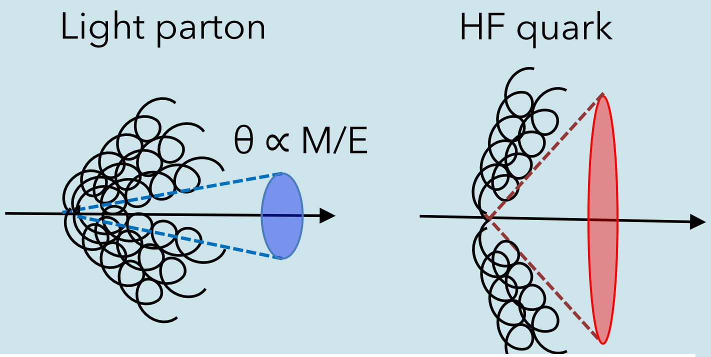
- Ideal probe for a tomography of QGP
  - Produced at only initial stage of collisions
  - Conservation of the number of HF quark



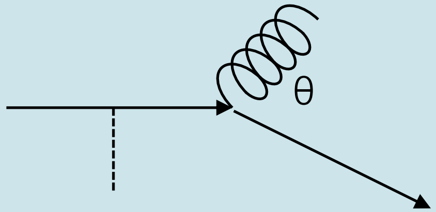
HF is one of the cleanest probe!

Energy loss

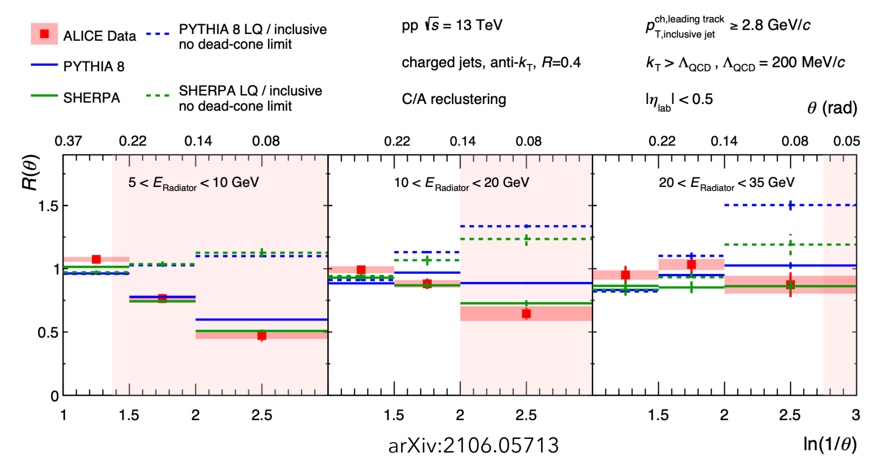
- Passing partons lose their energy via elastic scattering and gluon radiation
  - Depending on
    - Color charge (Casimir factor)
    - Quark mass (Dead cone effect)
    - Path length in medium
  - $\Delta E_{loss}(g) > \Delta E_{loss}(u,d,s) > \Delta E_{loss}(c) > \Delta E_{loss}(b)$



Radiative energy loss



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

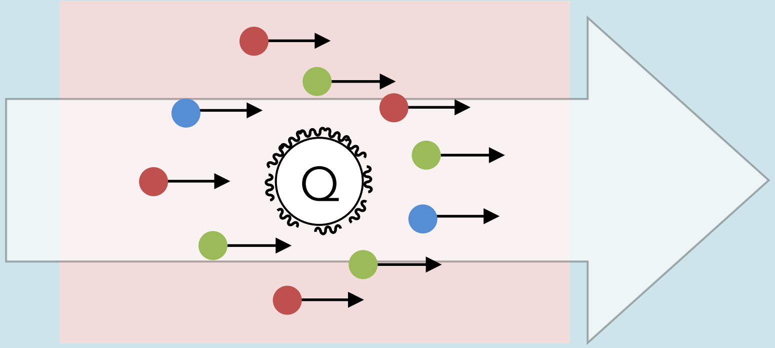


arXiv:2106.05713

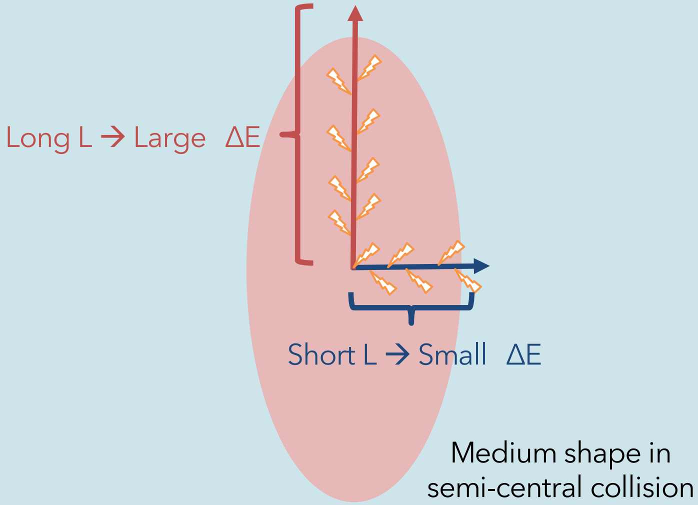
D^0 p_T

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



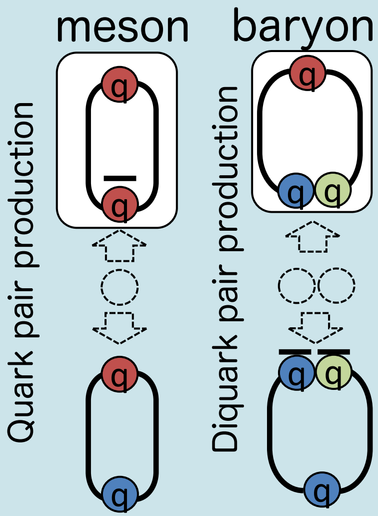
Medium shape in
semi-central collision

Energy loss depends on L

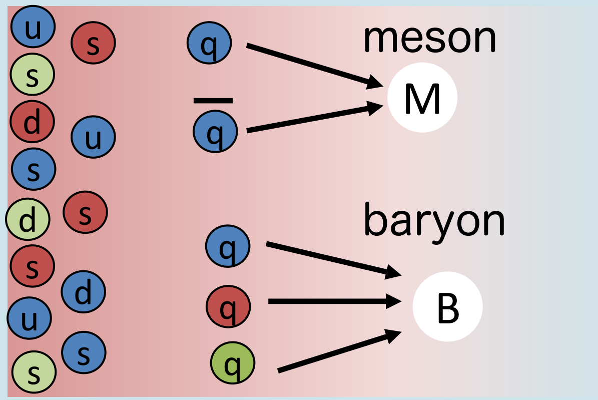
Coalescence

- 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}

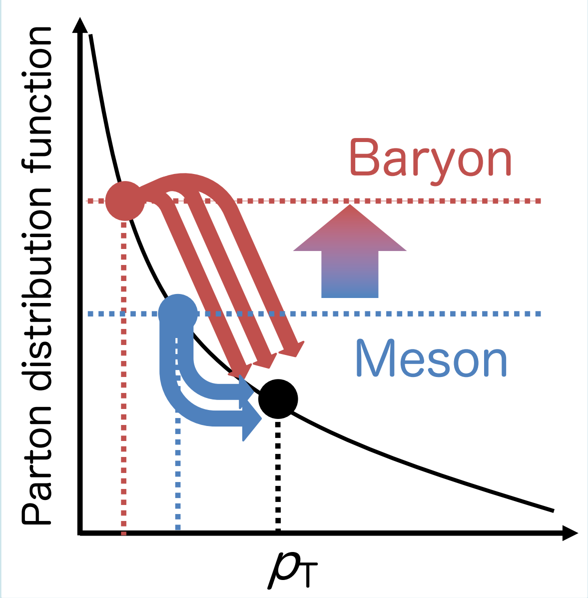
In vacuum



In QGP



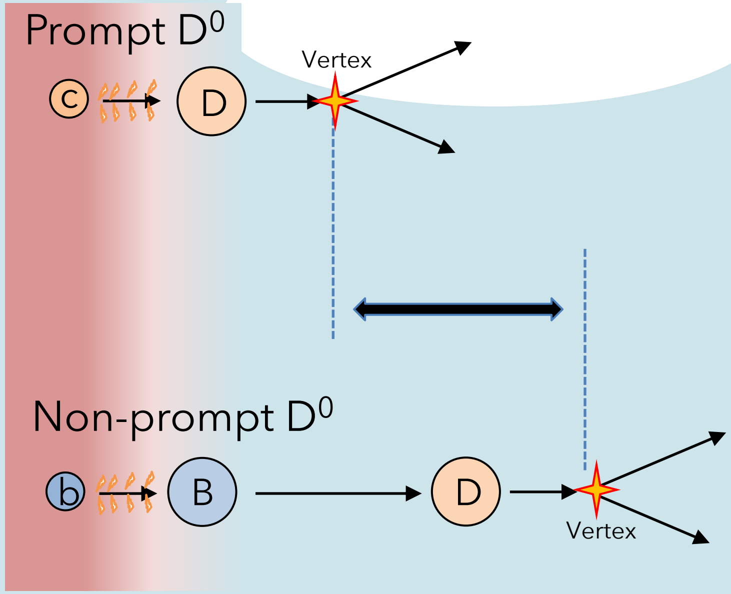
Strangeness-rich environment

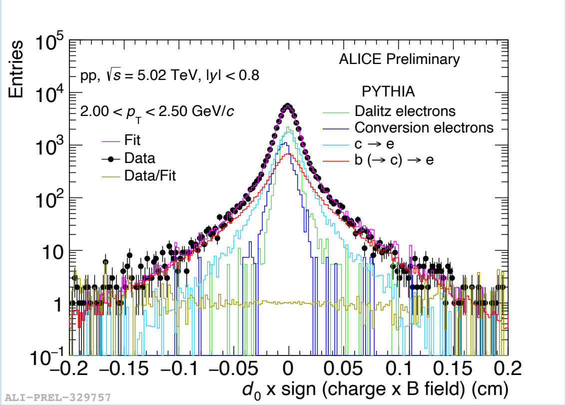


How to measure HFs?

- 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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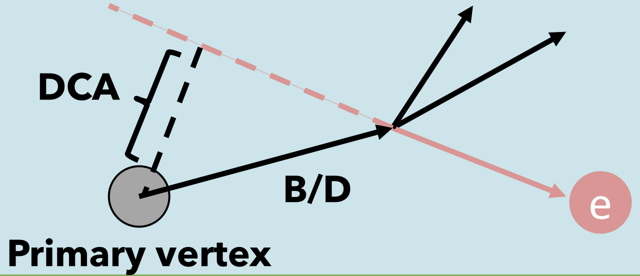
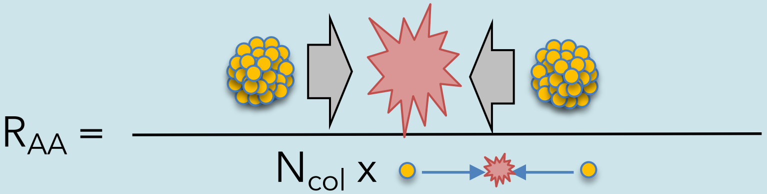


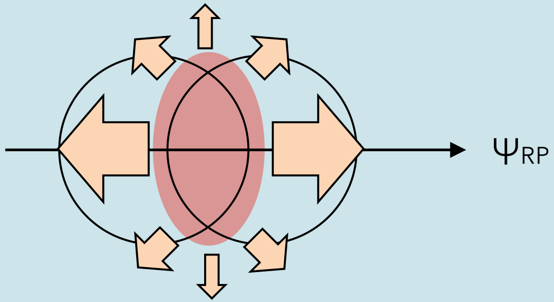
Main observation

- 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 → $R_{AA} \neq 1$

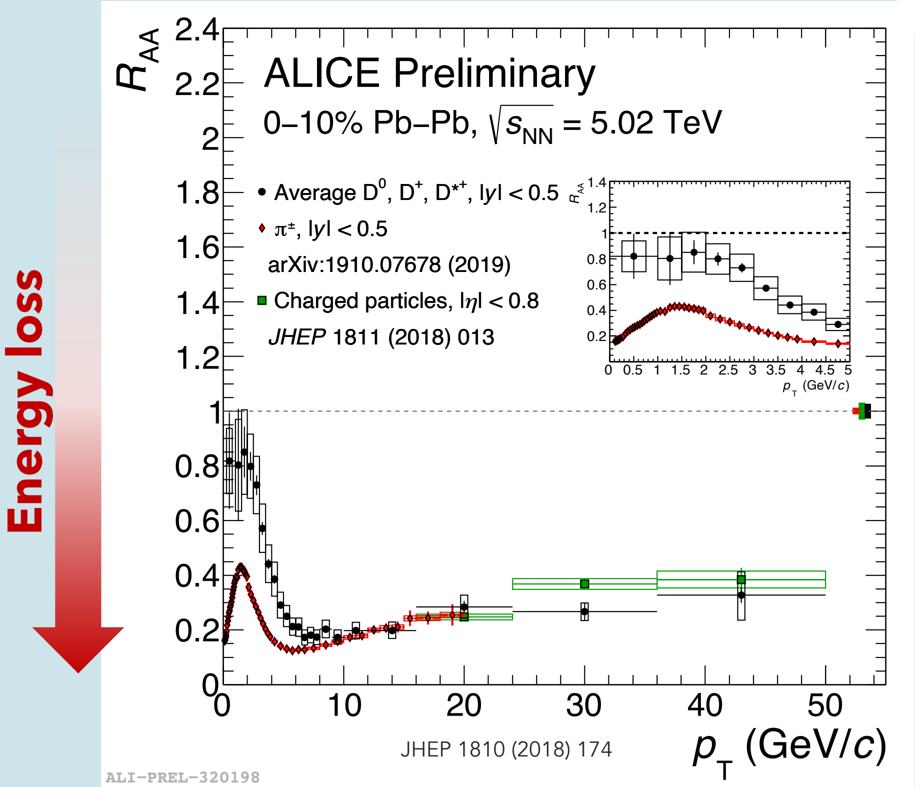
- Elliptic flow (v_2):
  - Study azimuthal distribution of produced particle with respect to the reaction plane (ψ_{RP})



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

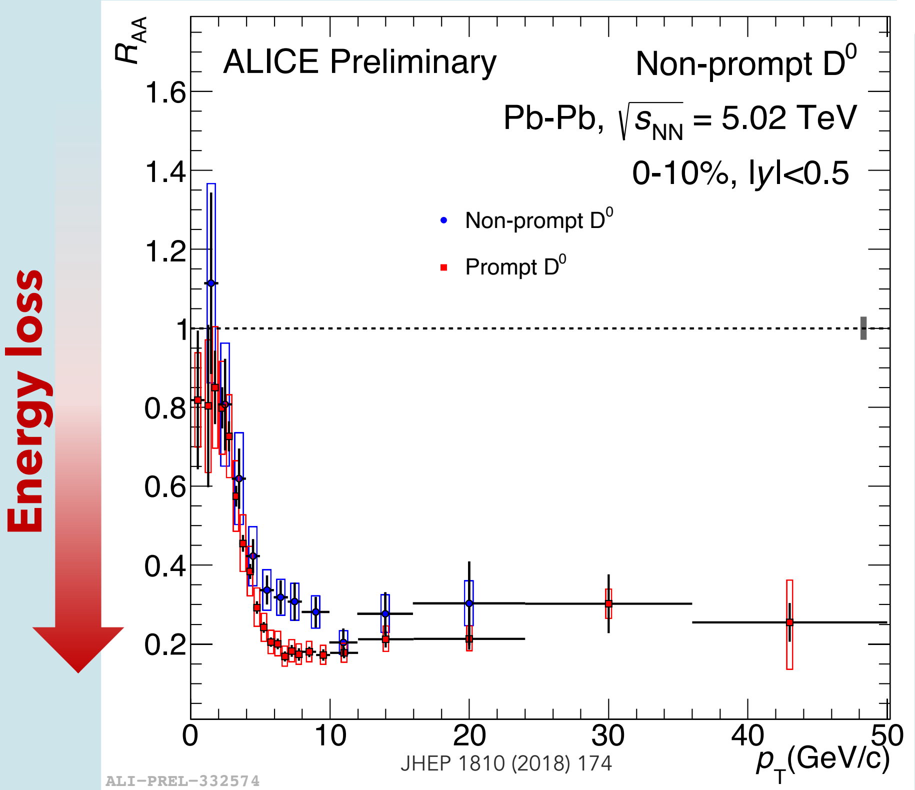
If the collectivity effects are present → $v_2 > 0$ (low-p_T)
If the path-length effects are present → $v_2 > 0$ (high-p_T)

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



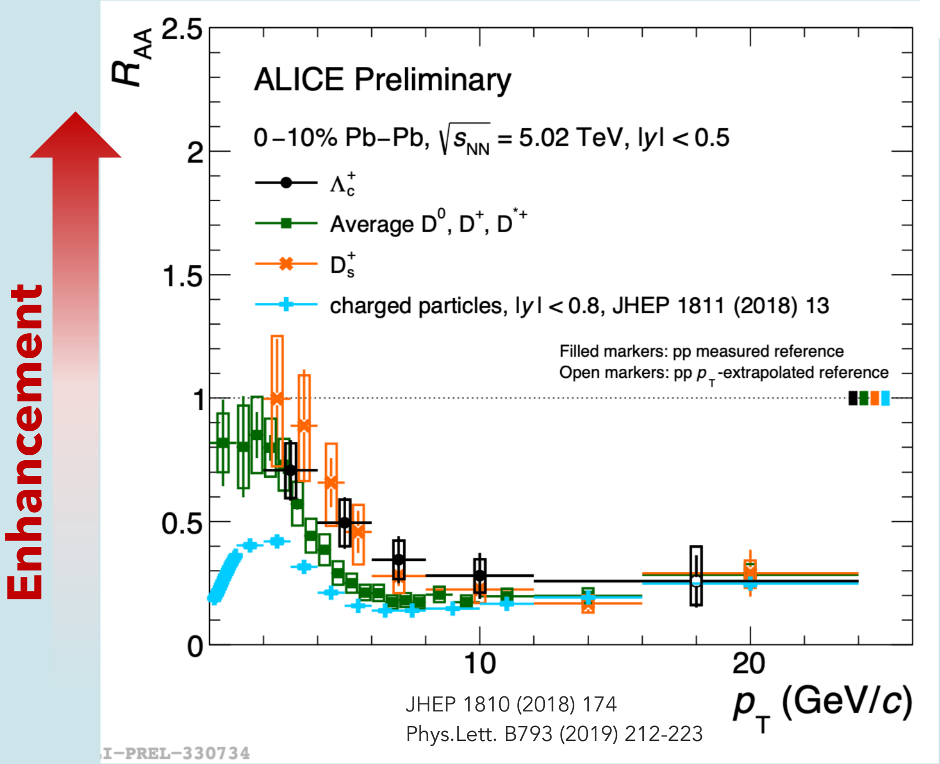
- At low-p_T (<10 GeV/$_c$): ΔE_{loss}(light) > ΔE_{loss}(c)
  - Indicating smaller energy loss in charm hadron
- At high-p_T (>10 GeV/$_c$): ΔE_{loss}(light) ~ ΔE_{loss}(c)
  - Indicating the same energy loss mechanism in light and charm hadron

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



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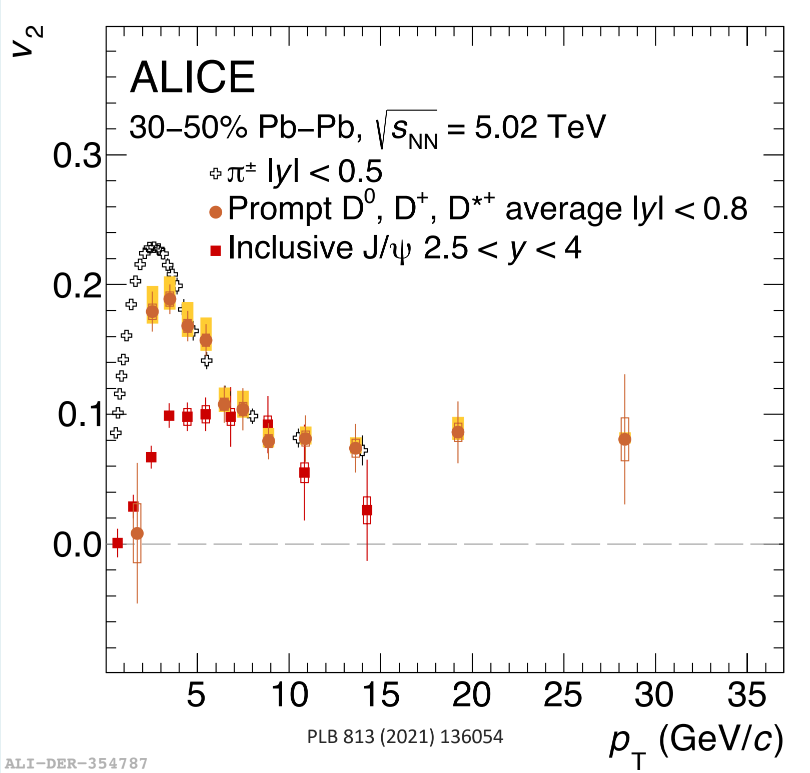
Phys.Lett. B793 (2019) 212-223

- 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



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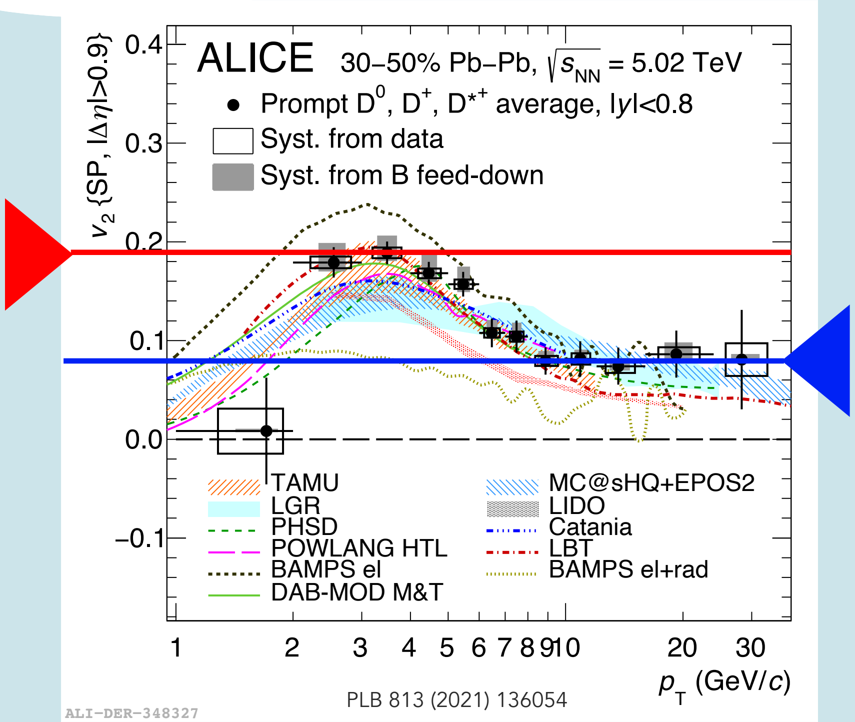
- Almost the same v_2 as light hadron
  - Contribution from thermalized charm?
- Flattened and compatible with light hadron at high-p_T (> 7GeV/c)
  - Energy loss path-length dependence?

Elliptic flow (v2)
Charm v.s. Beauty



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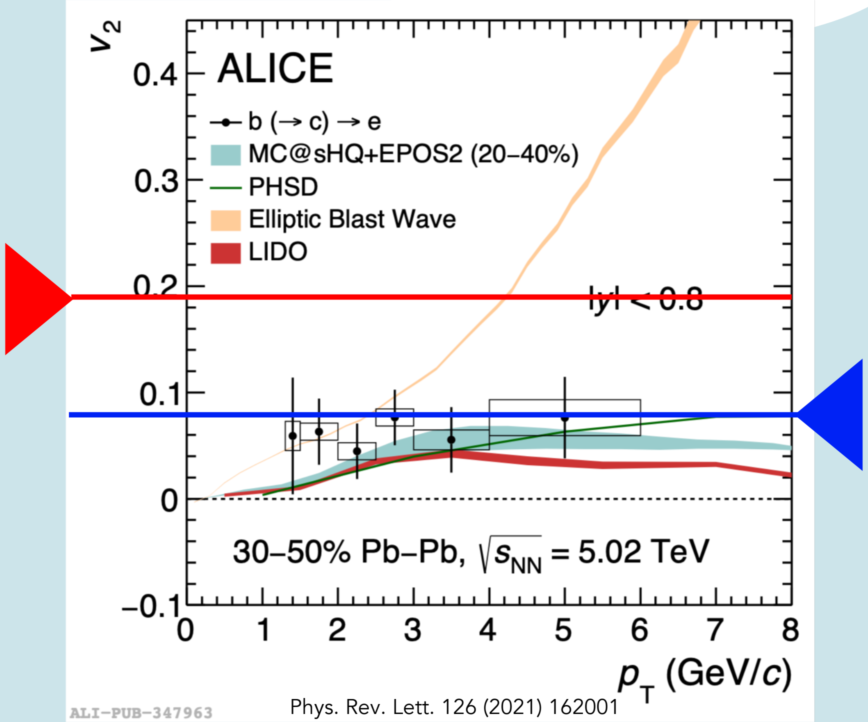

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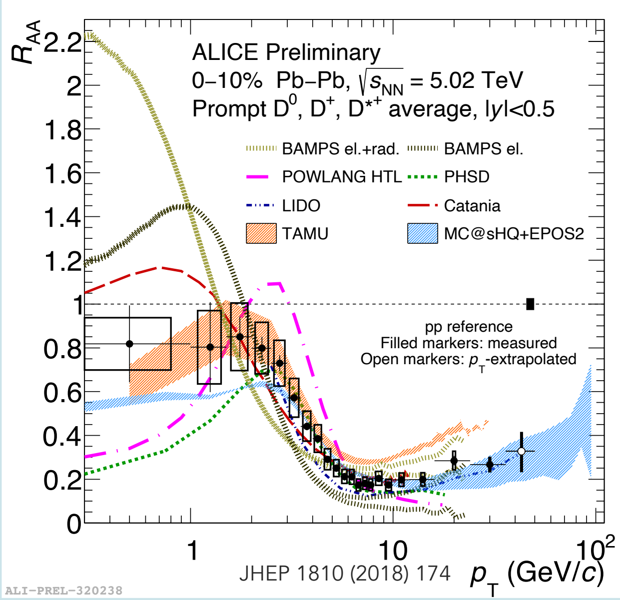
- Positive beauty v_2!
  - Different shape from the other particle (no significant p_T dependence)
- Beauty v_2 compatible with charm v_2 at high-p_T
  - Energy loss path-length dependence?

Comparison with models



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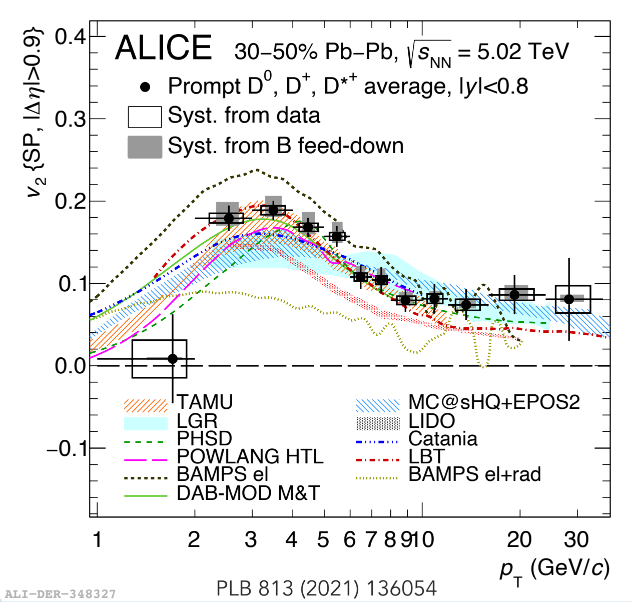

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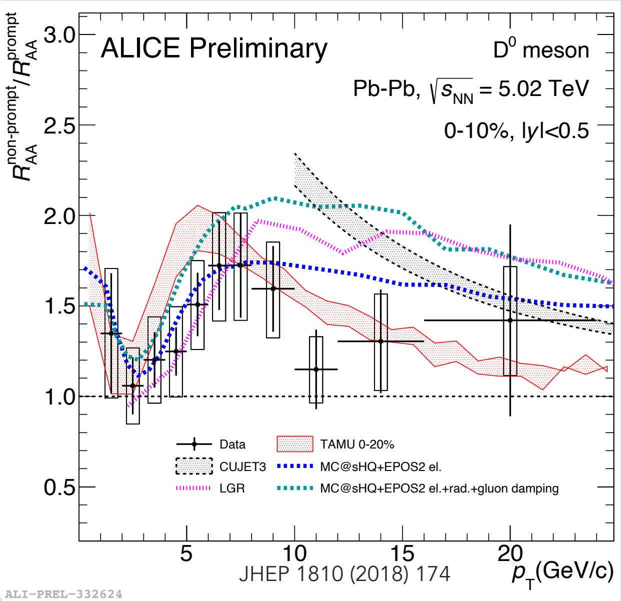

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- There are many models, and they describe the trend well