New results on the heavy-flavor and quarkonia measurements with ATLAS

Wenkai Zou for the ATLAS collaboration

ICHEP

Jul 9, 2022

Motivation

- Heavy flavor (HF) quarks (*b*/*c*): large masses compared to the quark-gluon plasma (QGP) temperature

➢ Produced primarily at early times in the collisions

➢ May not completely thermalize

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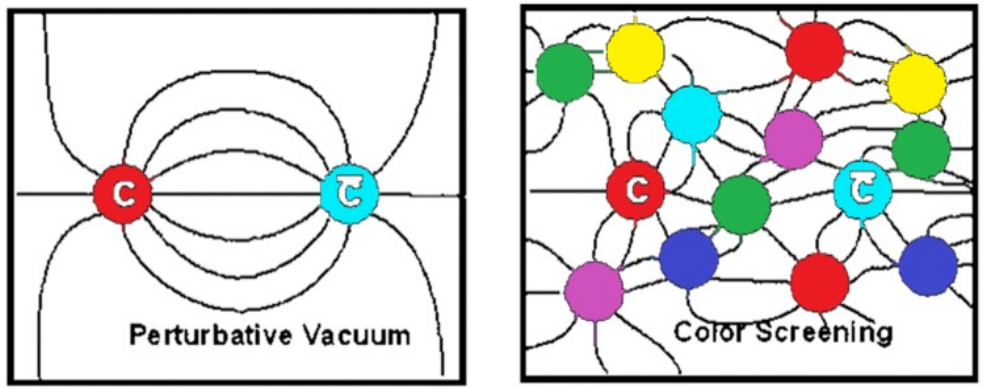
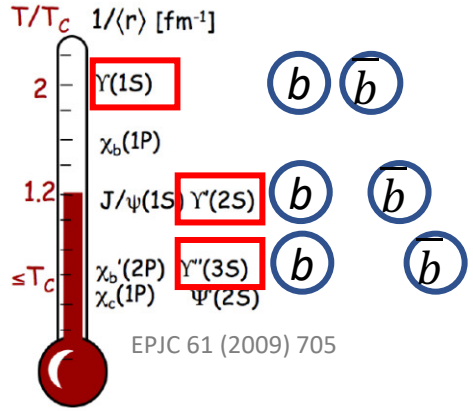
- Color screening from the deconfined medium
- Three Υ meson states (quarkonia) have different binding energies.

➢Their "sequential melting" serves as a QGP "thermometer".





Motivation

- Heavy flavor (HF) quarks (*b*/*c*): large masses compared to the quark-gluon plasma (QGP) temperature

➢Produced primarily at early times in the collisions

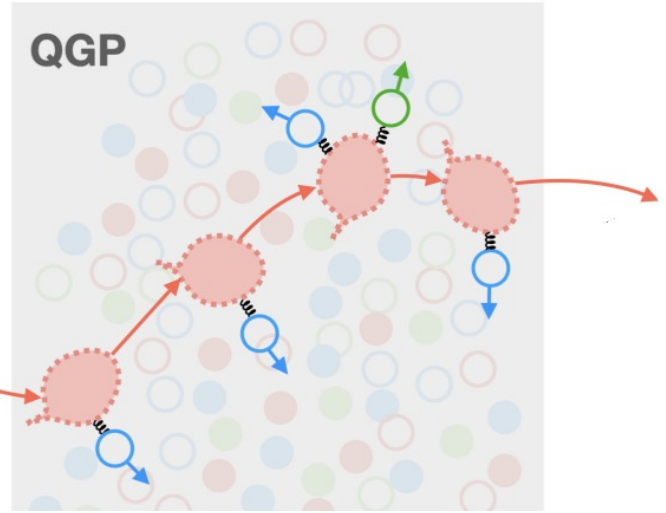
➢May not completely thermalize

- Open HF quarks lose energy and deflect in the QGP.

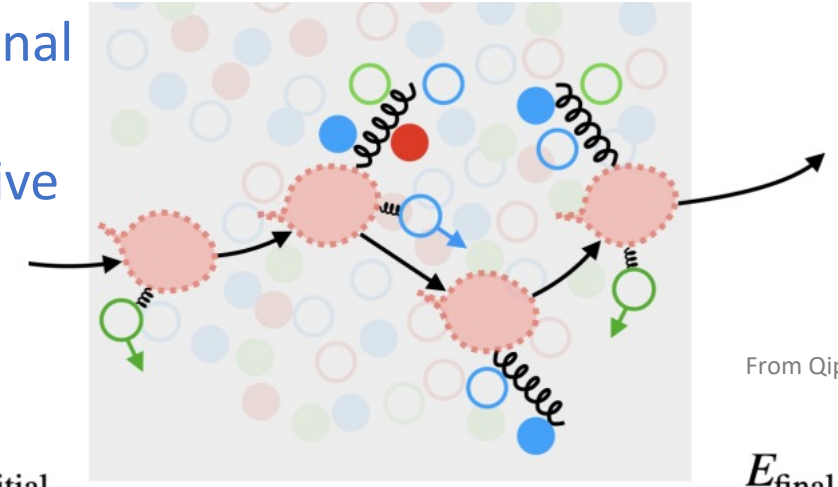
➢Probe the properties of the medium

collisional

HF quark (*b*/*c*)



collisional + radiative



From Qipeng Hu

E_{initial}

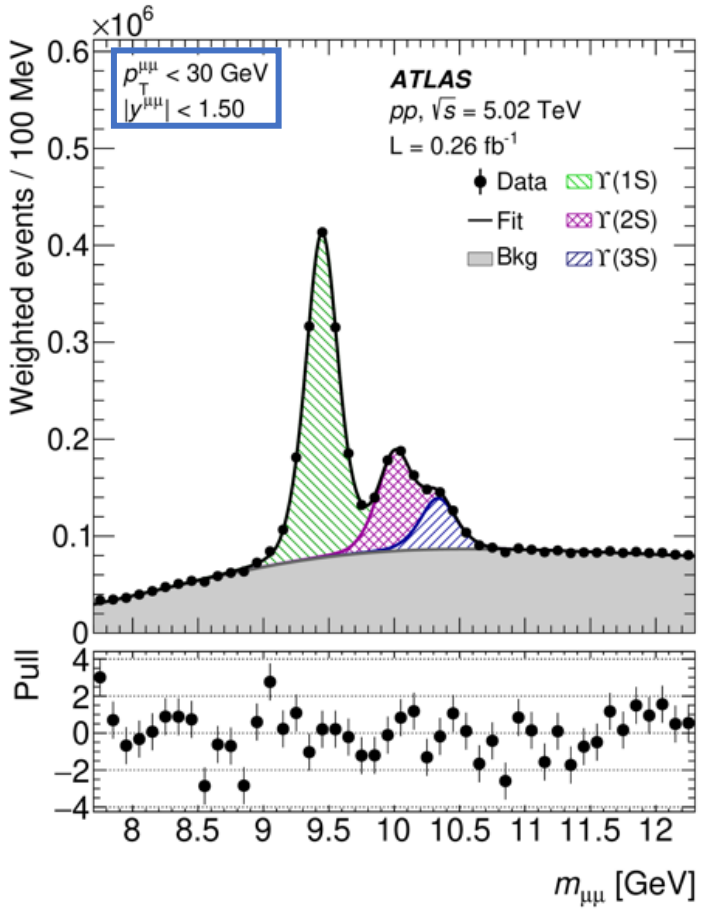
$E_{\text{final}} < E_{\text{initial}}$

Υ signal extraction

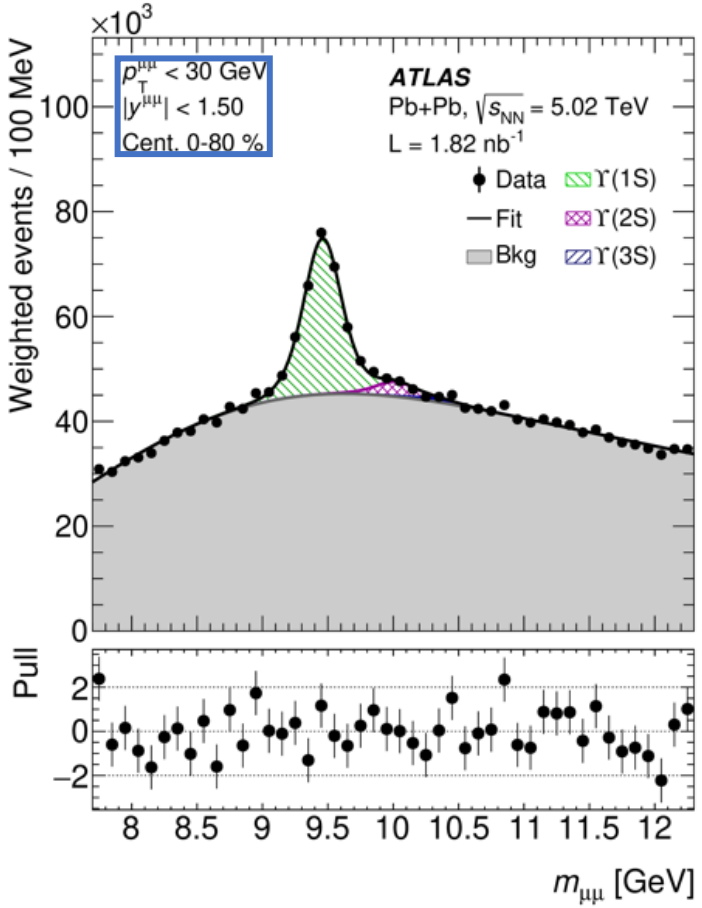
HION-2021-12 (submitted to PRC)

- Υ states measured in the di-muon channel at midrapidity.

2017 *pp*



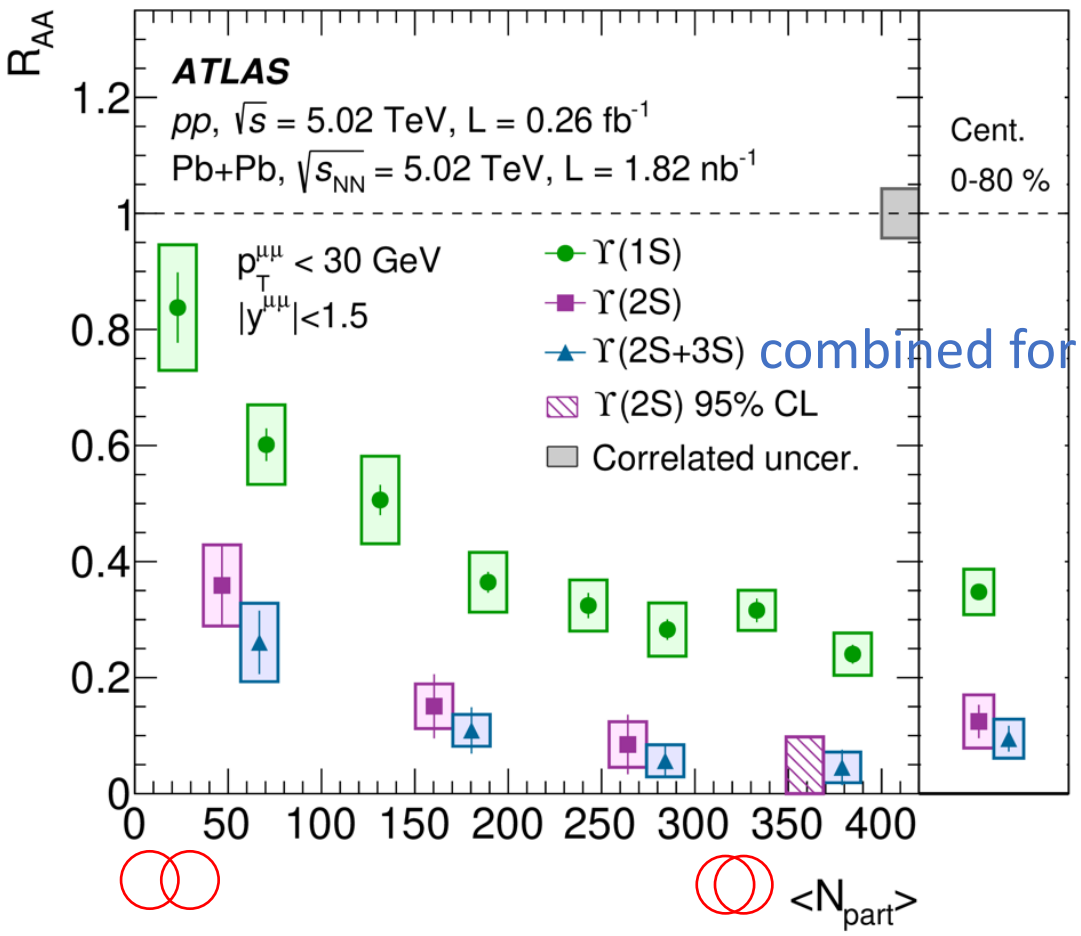
2015 + 2018 Pb+Pb



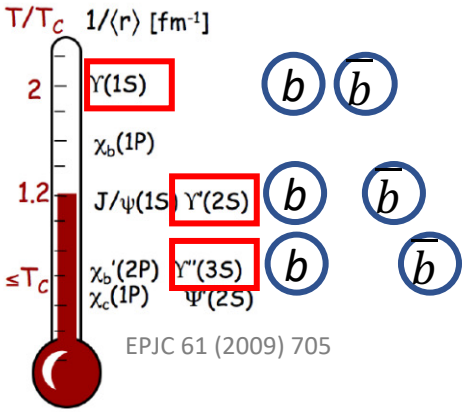
Nuclear modification factor

HION-2021-12 (submitted to PRC)

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}$$



combined for stats



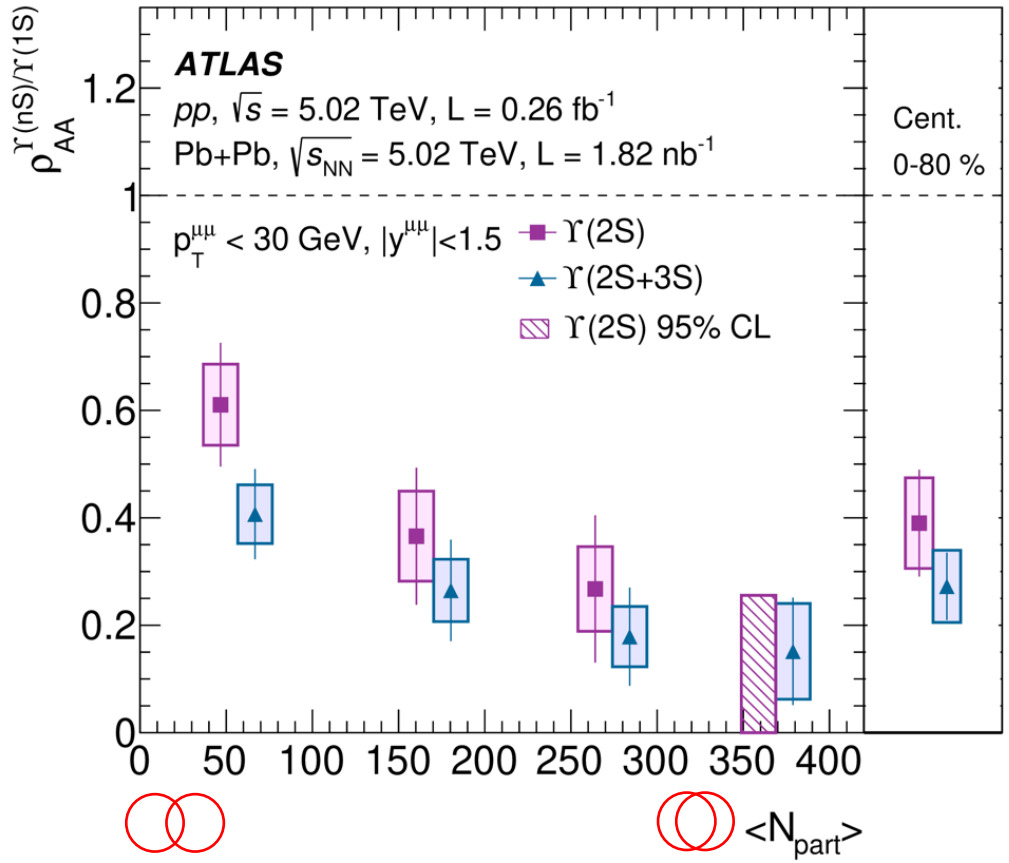
EPJC 61 (2009) 705

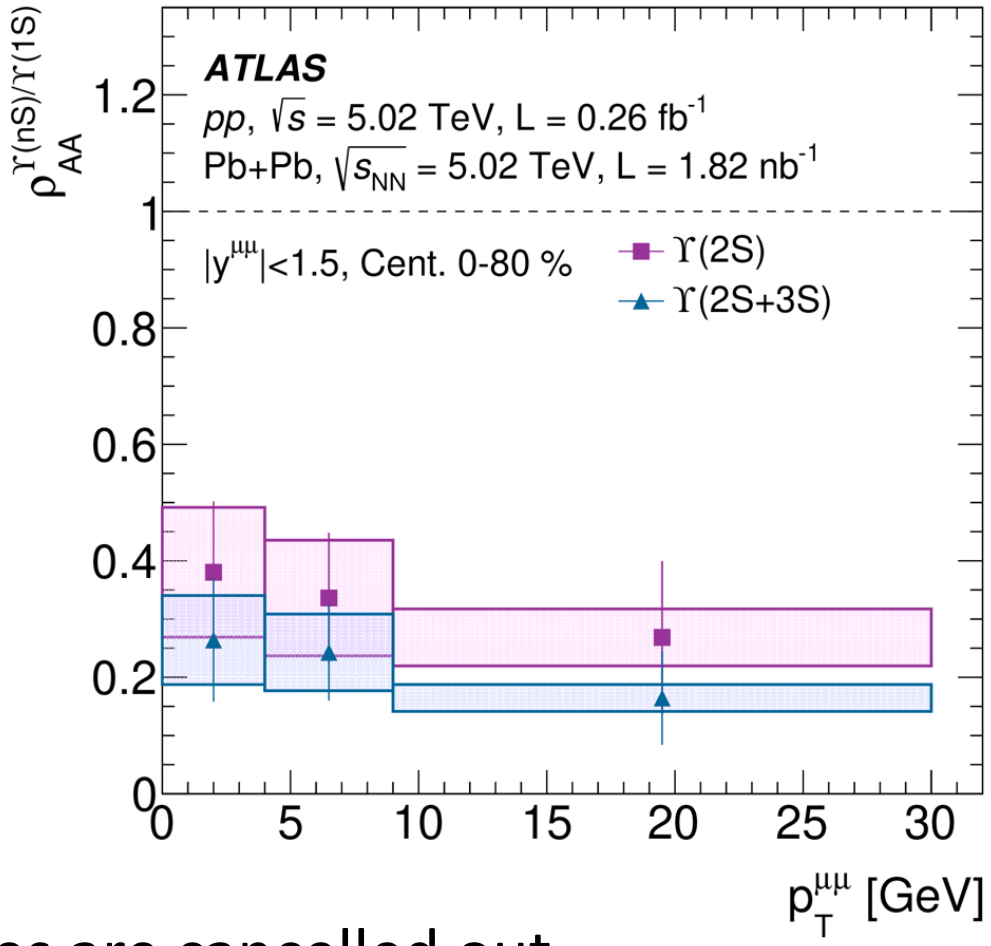
- Sequential suppression: Υ(1S) > Υ(2S) > Υ(2S+3S)
- Stronger suppression in central collisions

Double ratio

HION-2021-12 (submitted to PRC)

$$\rho_{AA}^{\Upsilon(nS)/\Upsilon(1S)} = R_{AA}(\Upsilon(nS))/R_{AA}(\Upsilon(1S))$$



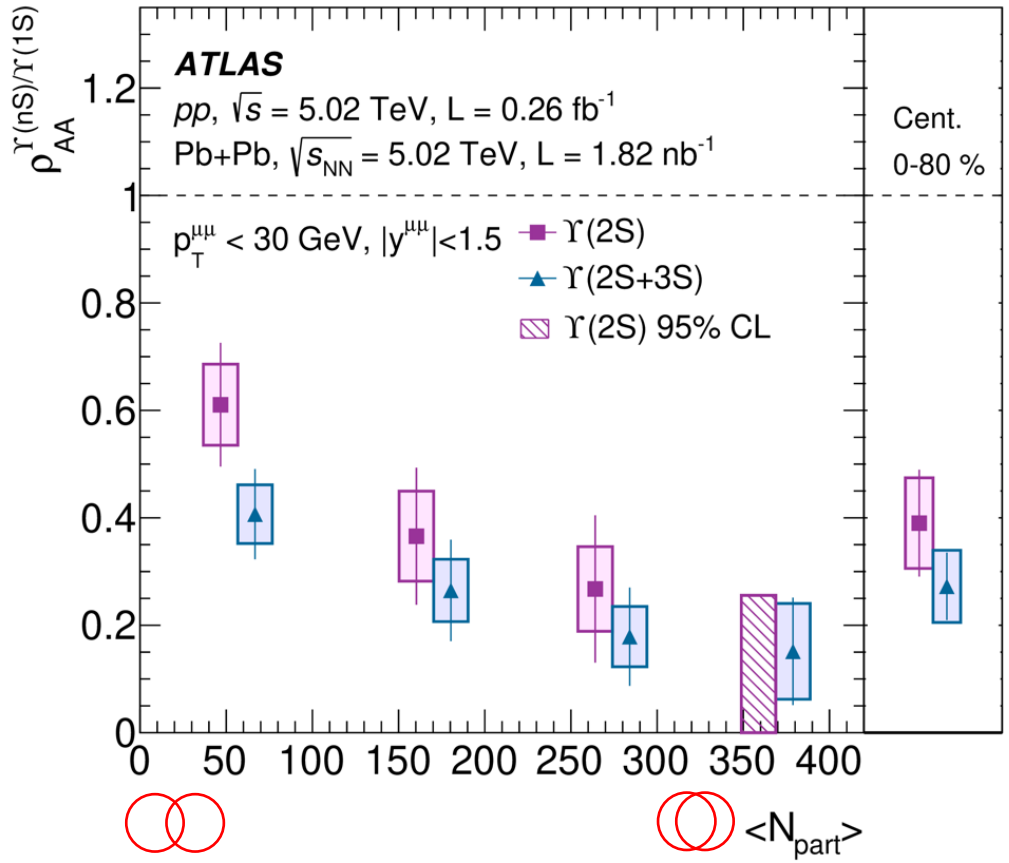


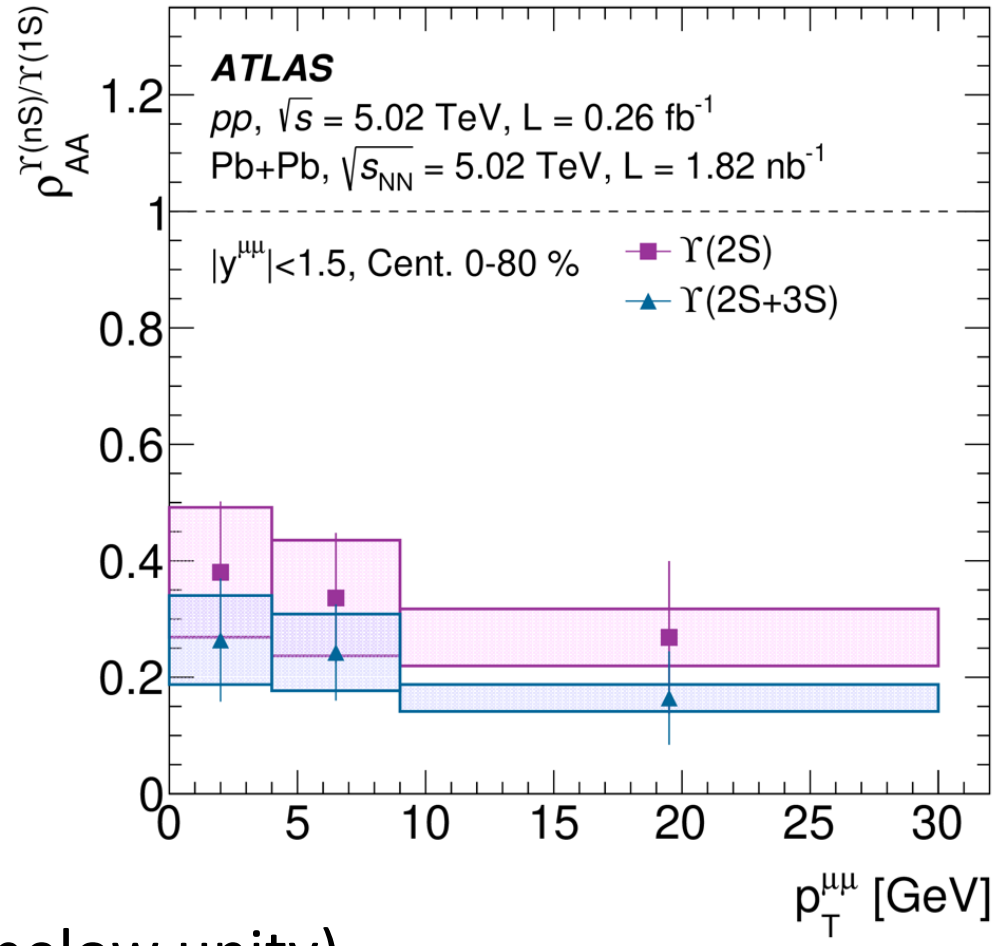
- Some common systematic uncertainties are cancelled out.

Double ratio

HION-2021-12 (submitted to PRC)

$$\rho_{AA}^{\Upsilon(nS)/\Upsilon(1S)} = R_{AA}(\Upsilon(nS))/R_{AA}(\Upsilon(1S))$$



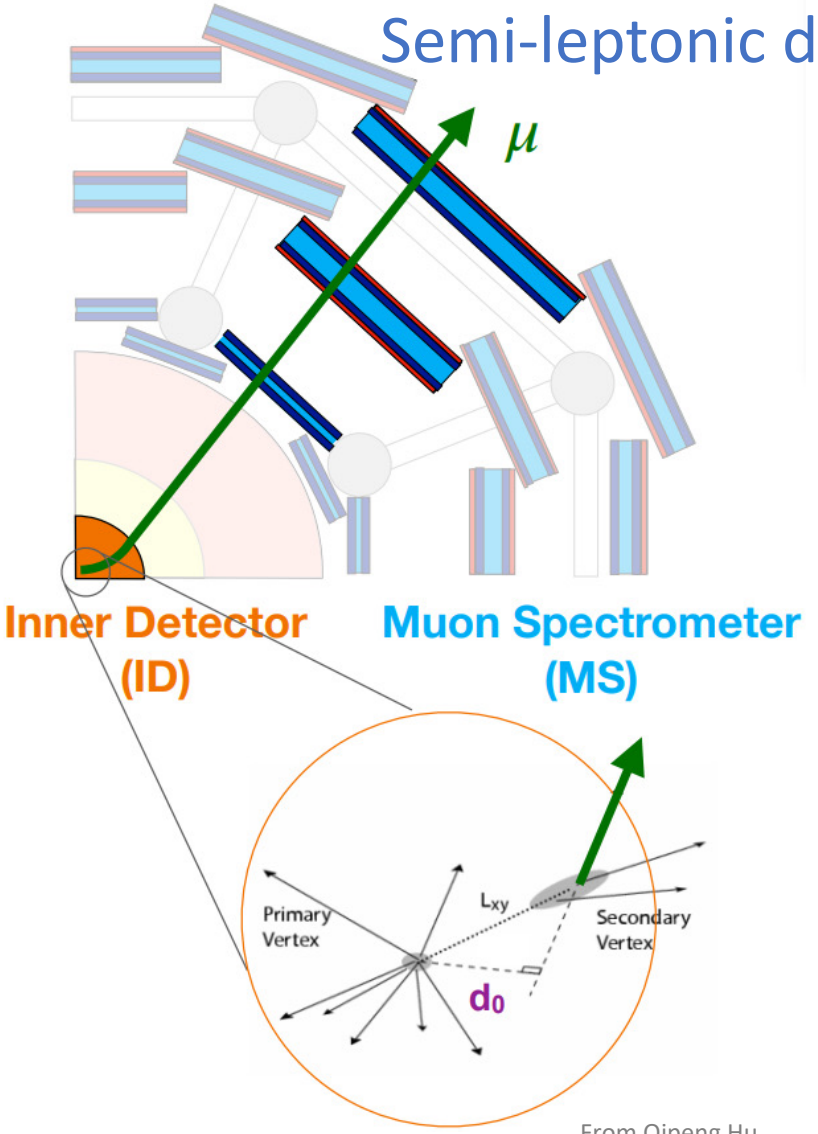


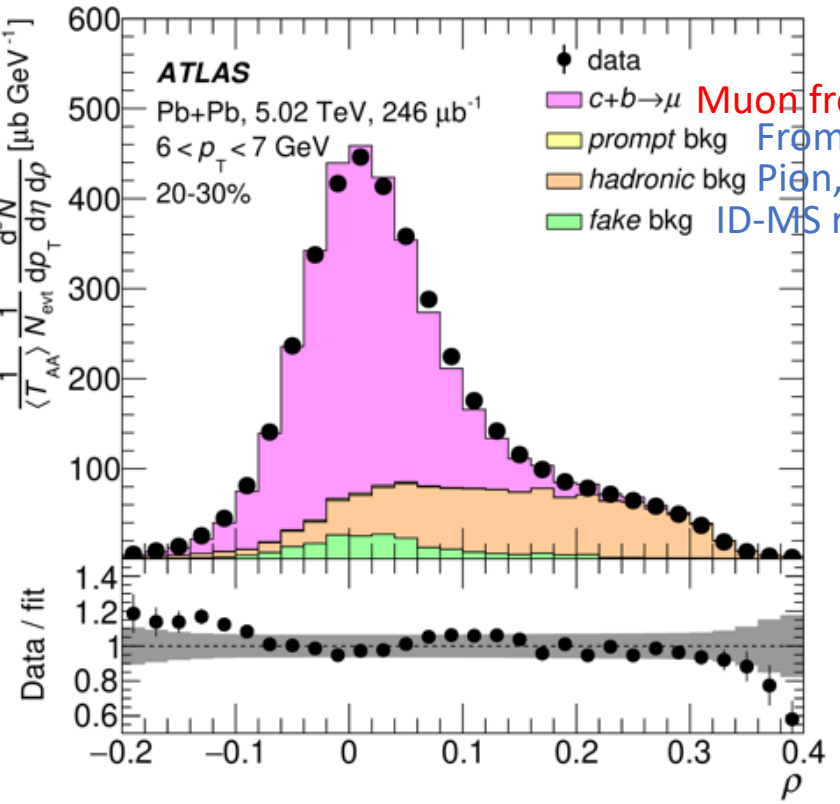
- Sequential suppression is significant (below unity).
- Slightly decreasing toward more central; no significant p_{T} dependence.

Open HF (b/c) muon

Phys. Lett. B 829 (2022) 137077

Semi-leptonic decay





Muon from HF semi-leptonic decay

From quarkonium, W/Z... (small)

Pion, kaon decay

ID-MS random combination

Template fit to remove the background:

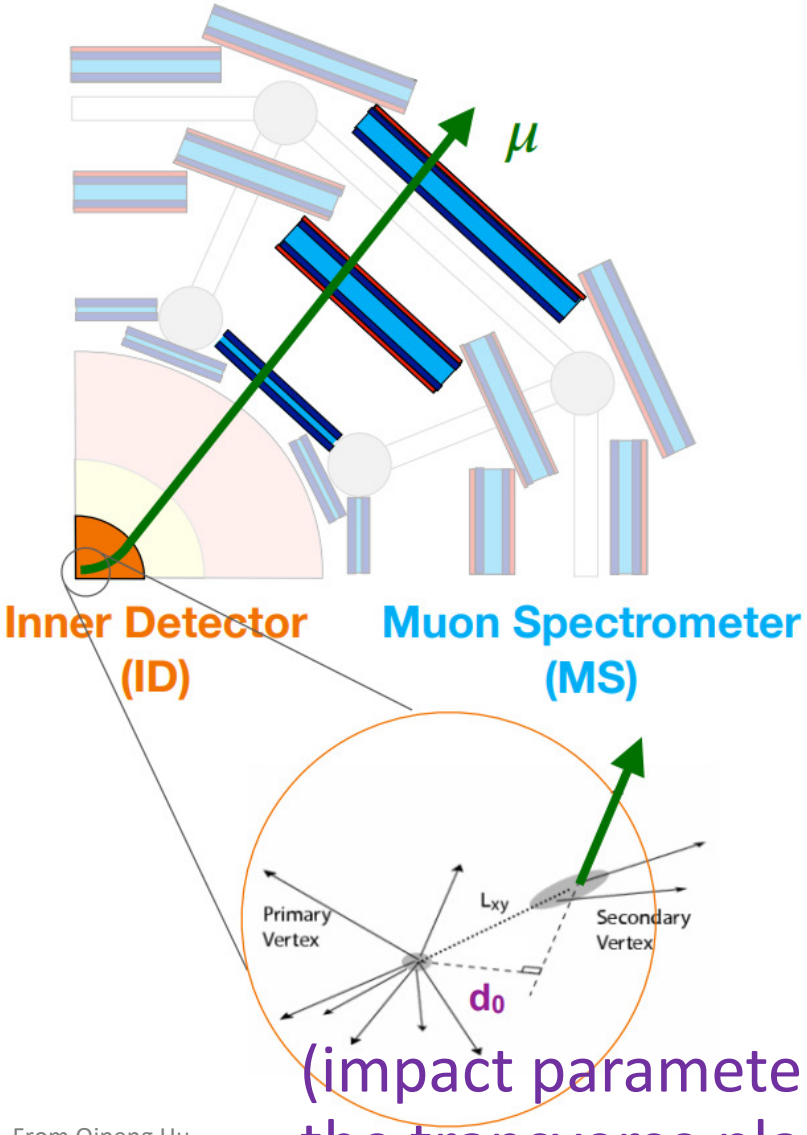
ID-MS momentum imbalance

$\rho = (p^{\mathrm{ID}} - p^{\mathrm{MS}}) / p^{\mathrm{ID}}$

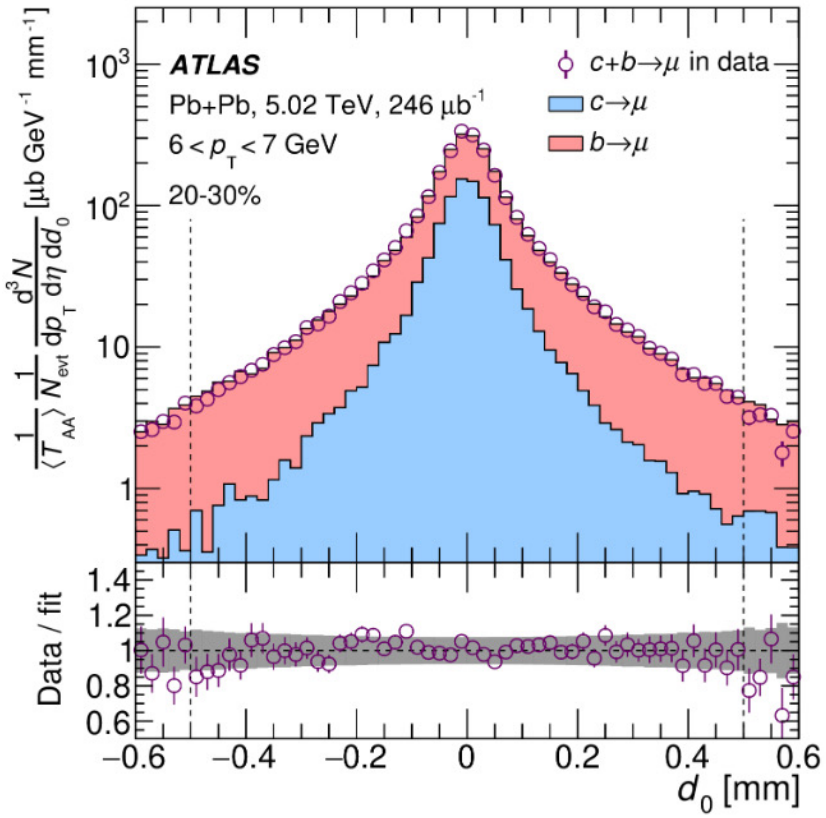
From Qipeng Hu

Open HF (b/c) muon

Phys. Lett. B 829 (2022) 137077



(impact parameter on the transverse plane)



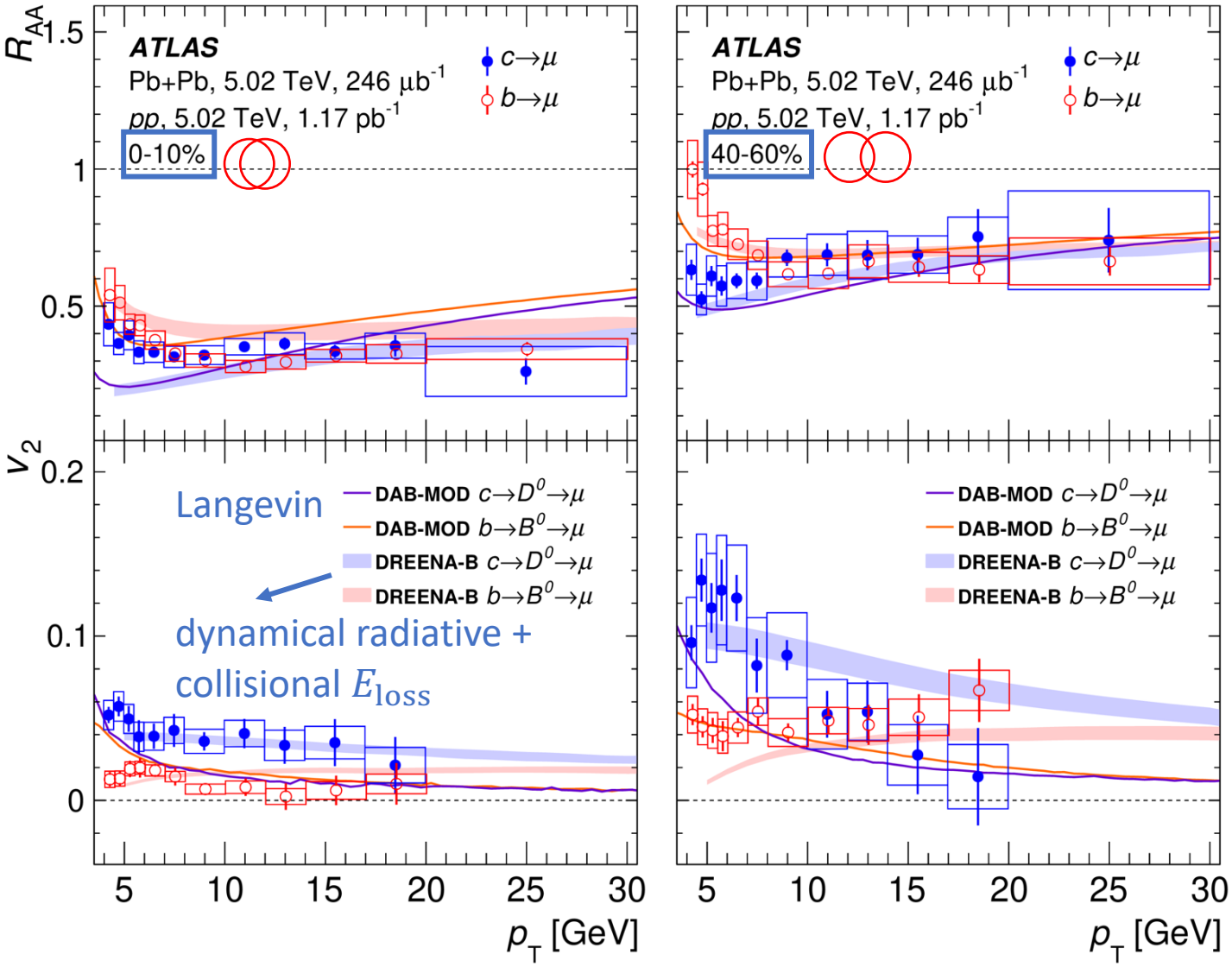
Template fit to statistically separate b/c: muon d_0

<- slightly different lifetime

From Qipeng Hu

Yield suppression and anisotropy

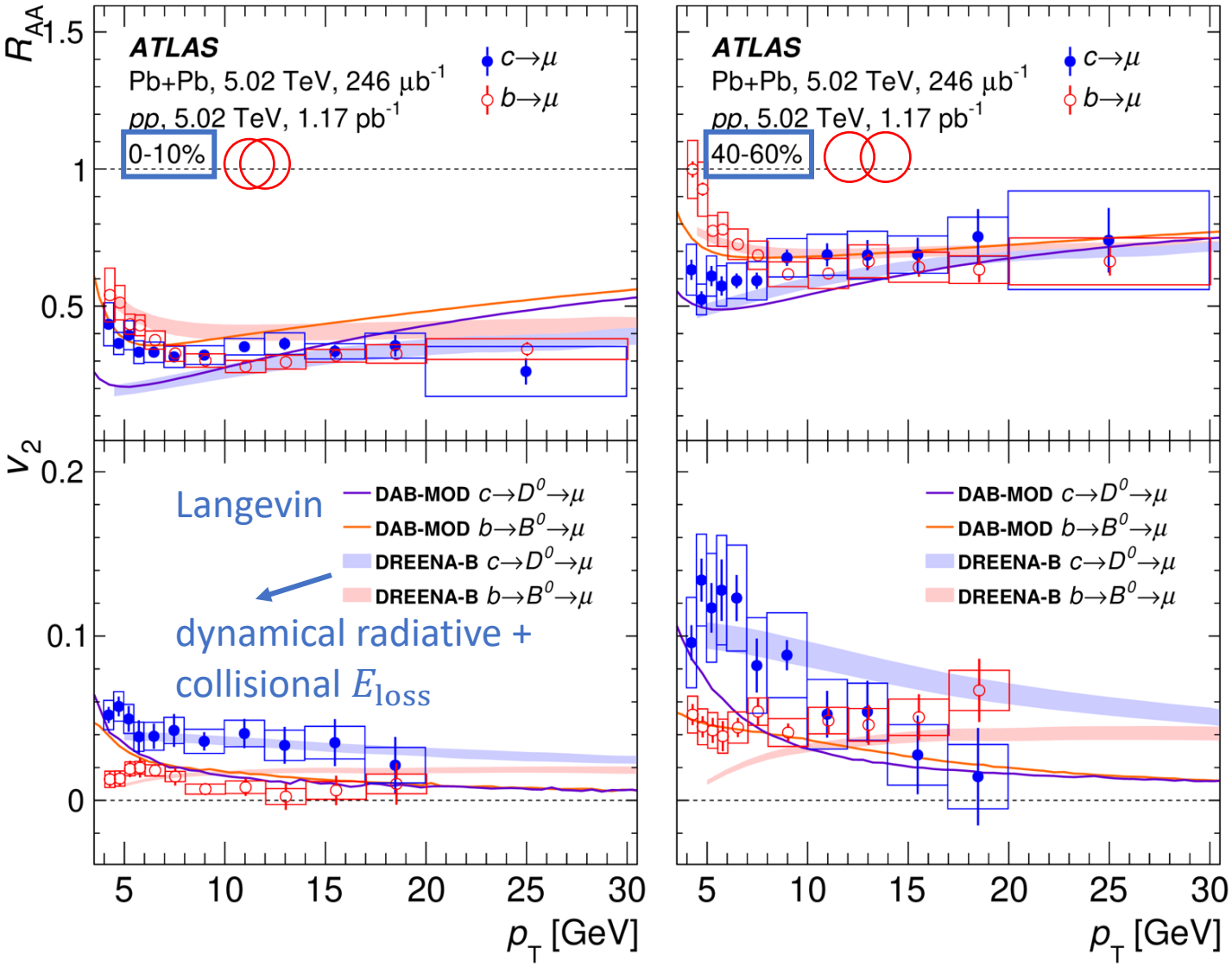
Phys. Lett. B 829 (2022) 137077



- c is more suppressed than b at low p_T
  - Consistent above ~10 GeV
- $v_2(c) > v_2(b)$

Yield suppression and anisotropy

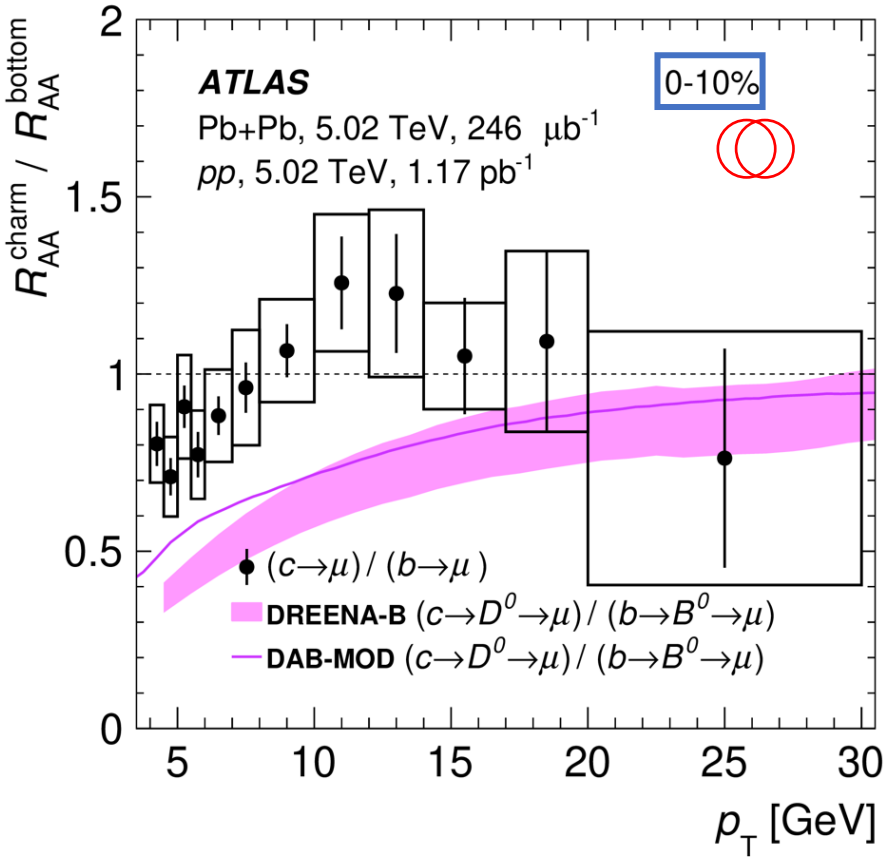
Phys. Lett. B 829 (2022) 137077

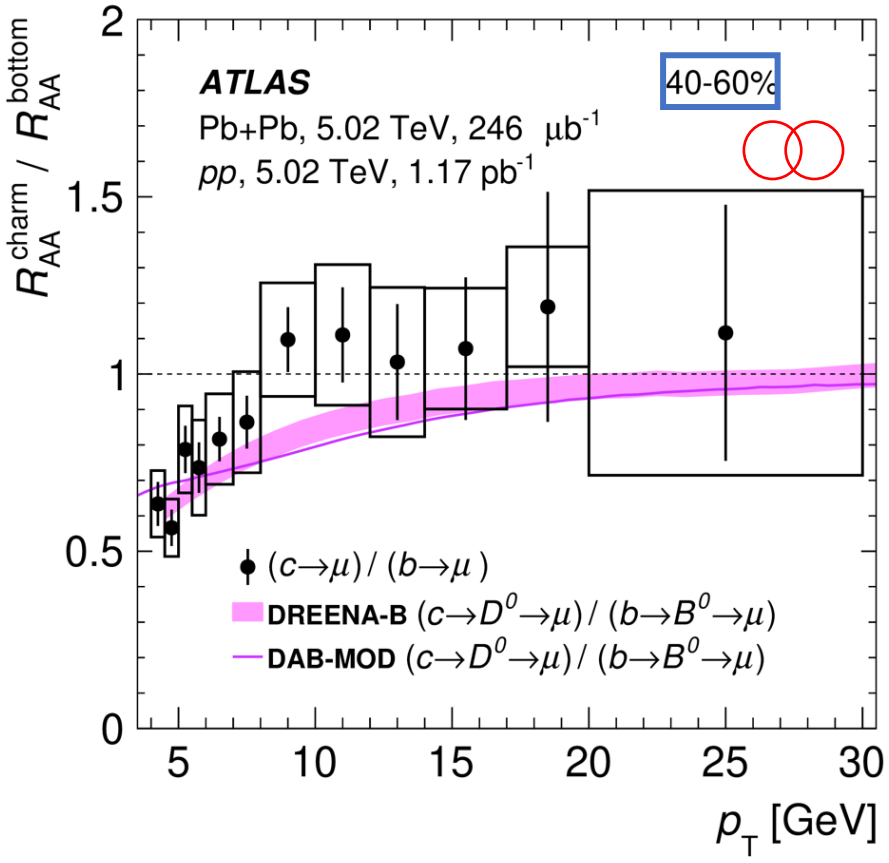


- c is more suppressed than b at low p_T
  - Consistent above ~10 GeV
- $v_2(c) > v_2(b)$
- Strong centrality dependence observed
- No theory model describes b/c R_{AA}/v_2 simultaneously.

Yield suppression double ratio

Phys. Lett. B 829 (2022) 137077

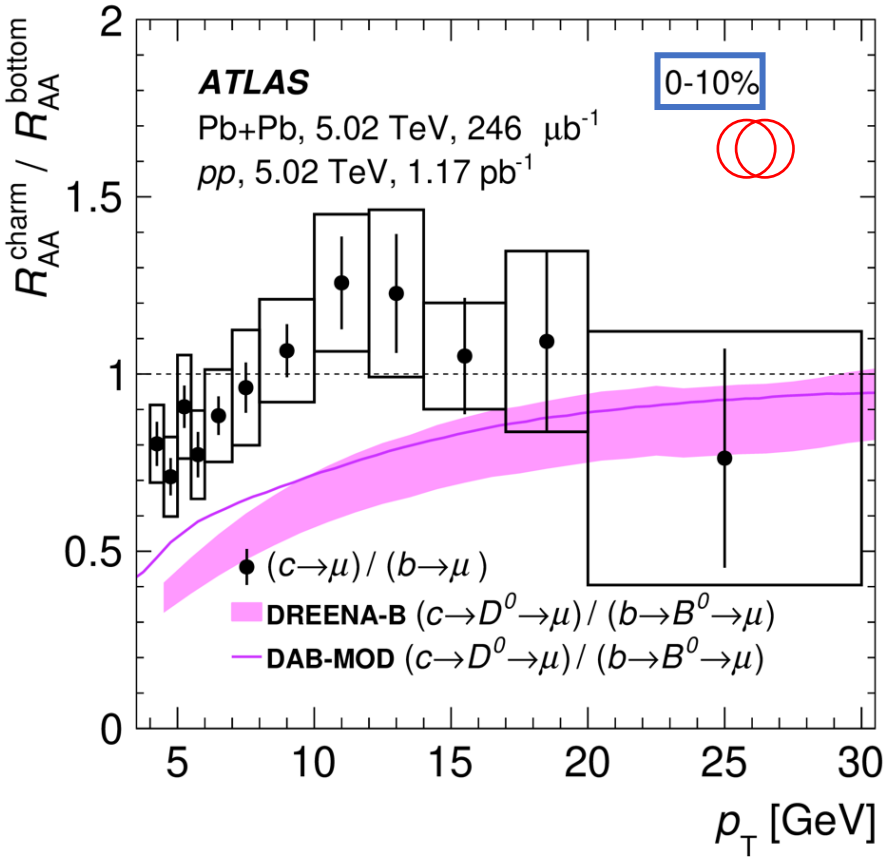


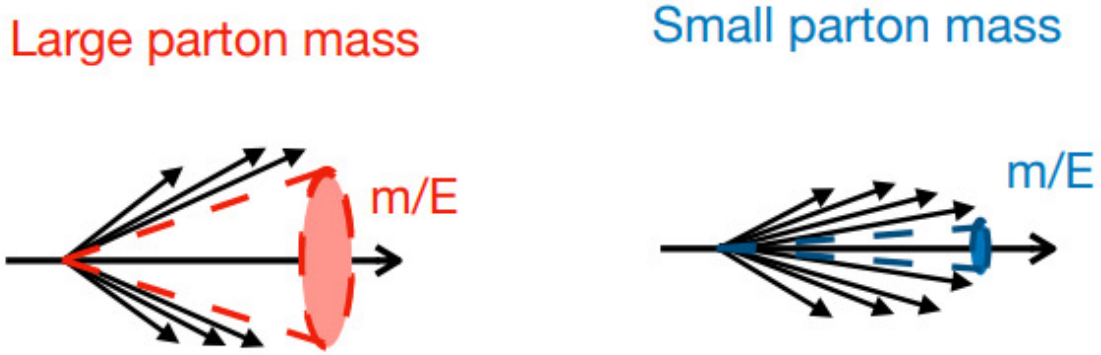


- Large uncertainties due to anti-correlation between *b* and *c*
- Charm is more suppressed at low p_T; comparable at higher p_T.
  - Model underestimates *c* R_{AA} (and the double ratio) at low p_T in 0-10%.

Yield suppression double ratio

Phys. Lett. B 829 (2022) 137077



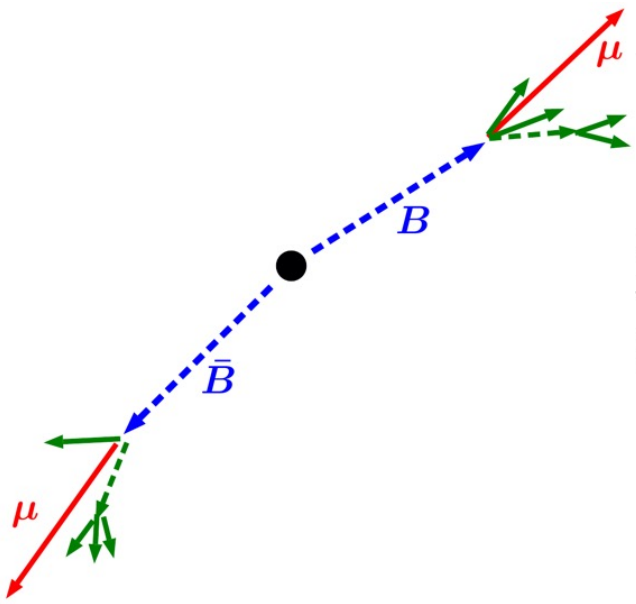


- Charm is more suppressed at low pT; comparable at higher p_{T}.
- Mass ordering consistent with the dead-cone effect

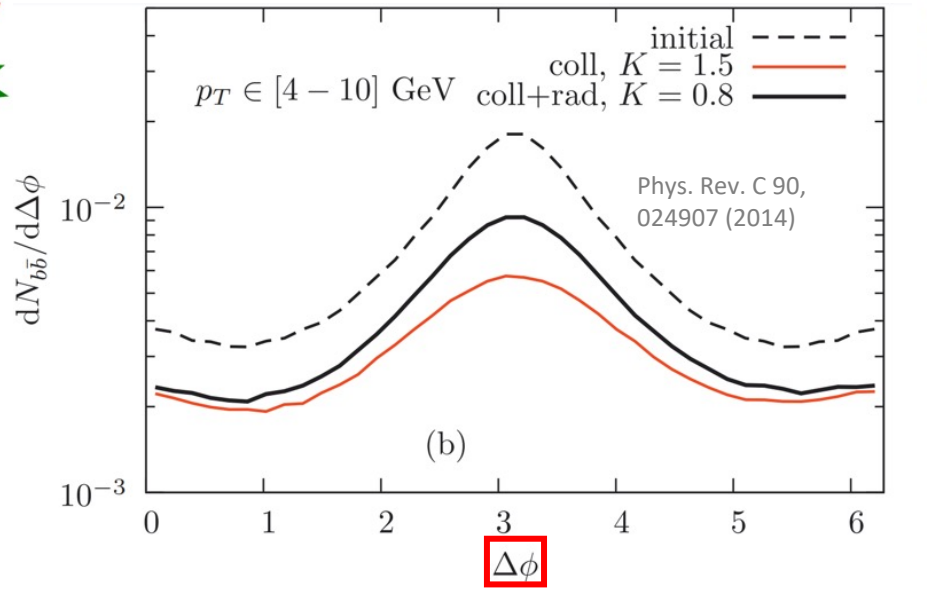
HF muon pair

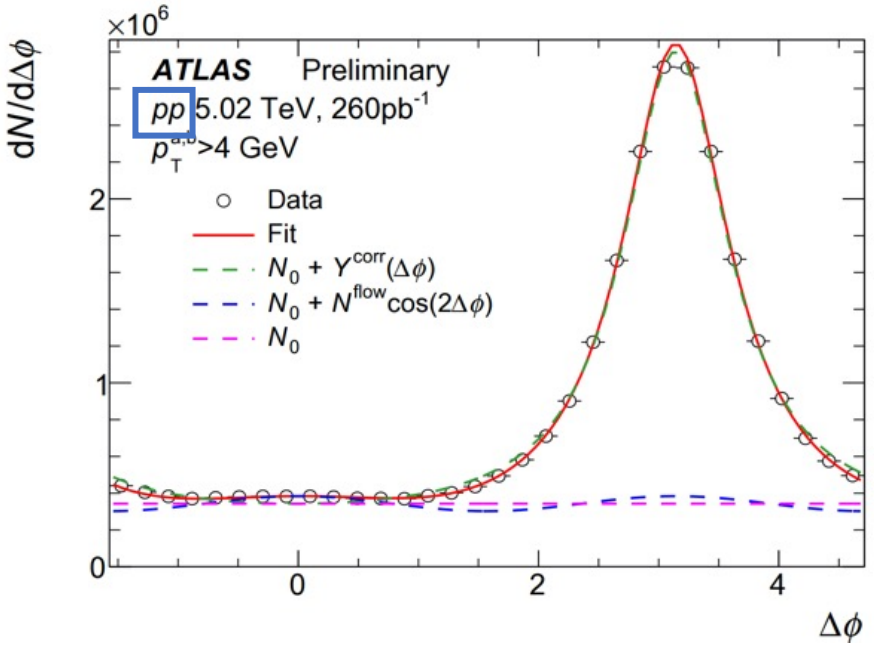
CONF-2022-022

- Back-to-back muon pair from semi-leptonic decays of HF quarks:
  - $|\Delta\eta| > 0.8$ -> remove the near-side jet peak
  - Invariant mass cuts (only on opposite sign pairs) -> remove J/ψ, Υ etc.
- $b\bar{b}$ dominate in the same-sign (neutral B mixing) and inclusive di-muon pairs (kinematic) <- MC



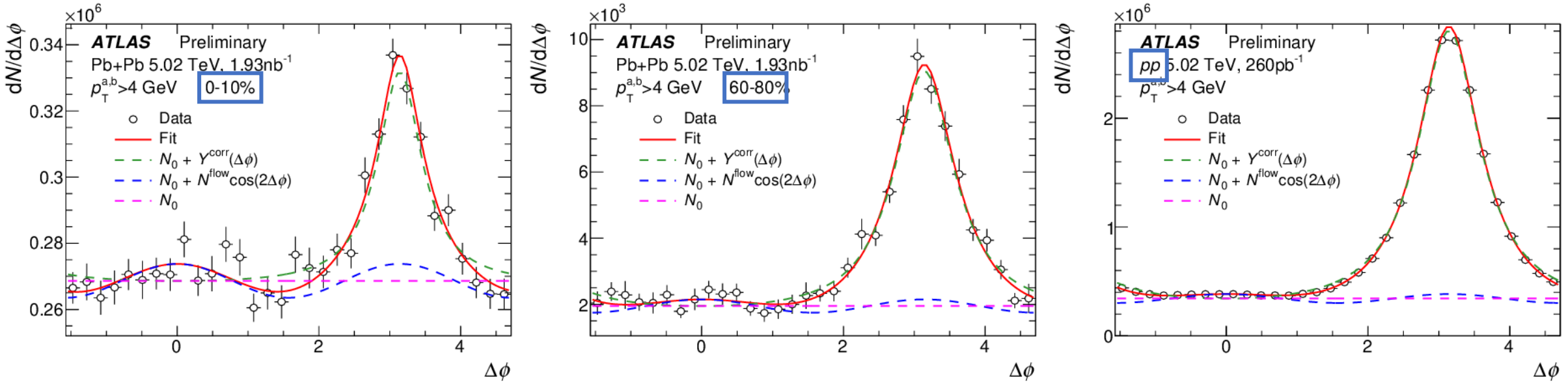
Theory prediction for broadening





Back-to-back yield extraction

CONF-2022-022



The following fit function is used to extract the signal:

$$dN/d\Delta\phi = N_0 + N^{\text{flow}} \cos(2\Delta\phi) + Y^{\text{corr}}(\Delta\phi),$$

Modulated background Back-to-back correlation yields

With (Lorentzian)

$$Y^{\text{corr}}(\Delta\phi) = \frac{N^{\text{corr}}}{(\Delta\phi - \pi)^2 + \tau^2} - N^{\text{pedestal}},$$

Yield = integral of Y

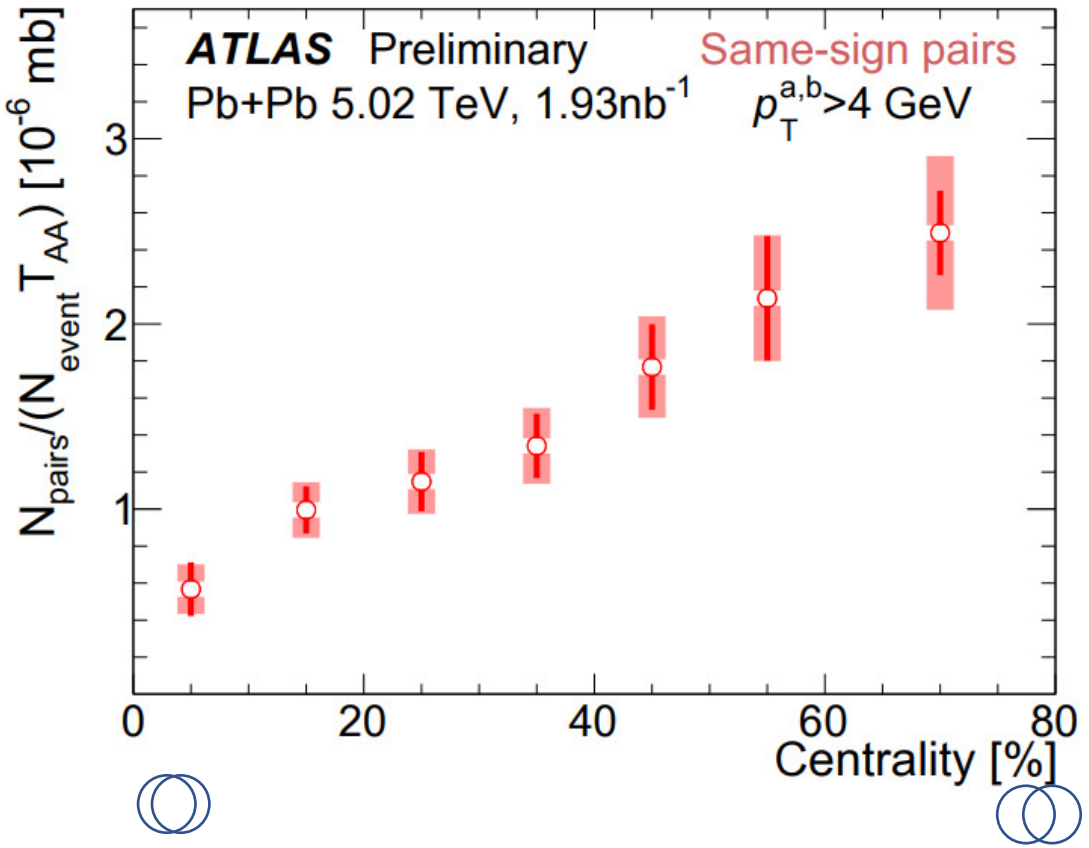
Width = std deviation of Y

(pedestal term chosen such that Y(0) = 0)

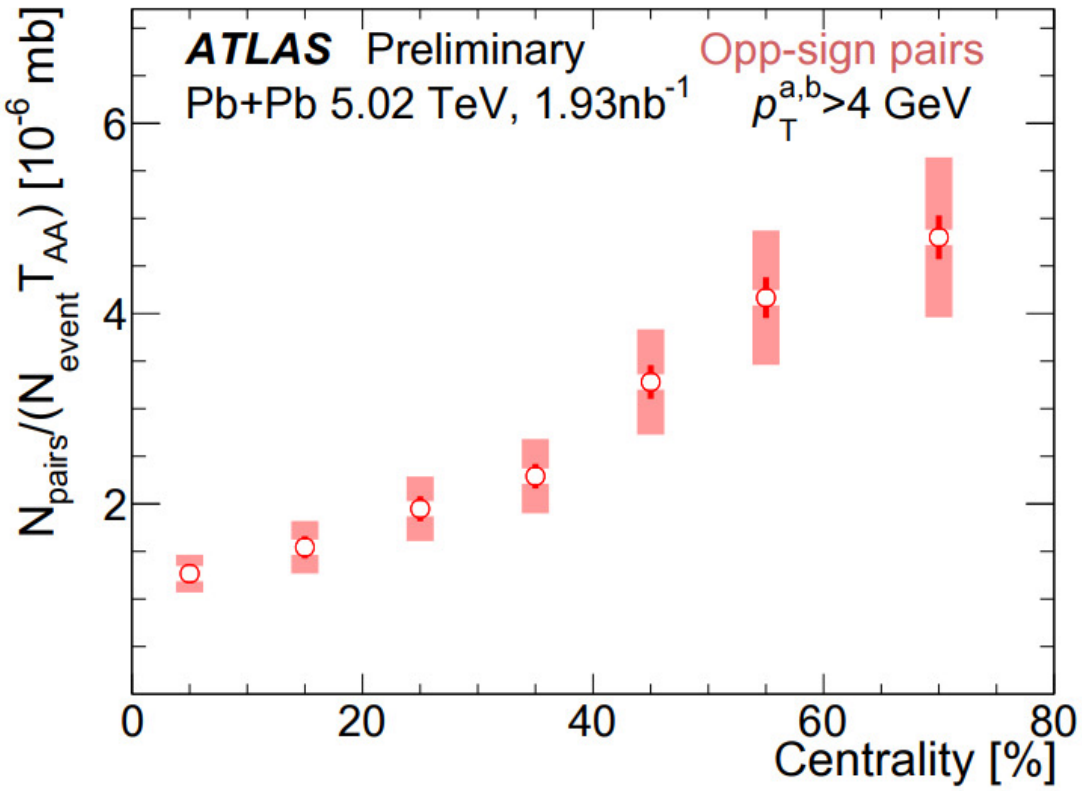
Di-muon correlation: yields

CONF-2022-022

Same sign (dominated by $b\bar{b}$)



Opposite sign ($b\bar{b}$ + $c\bar{c}$)

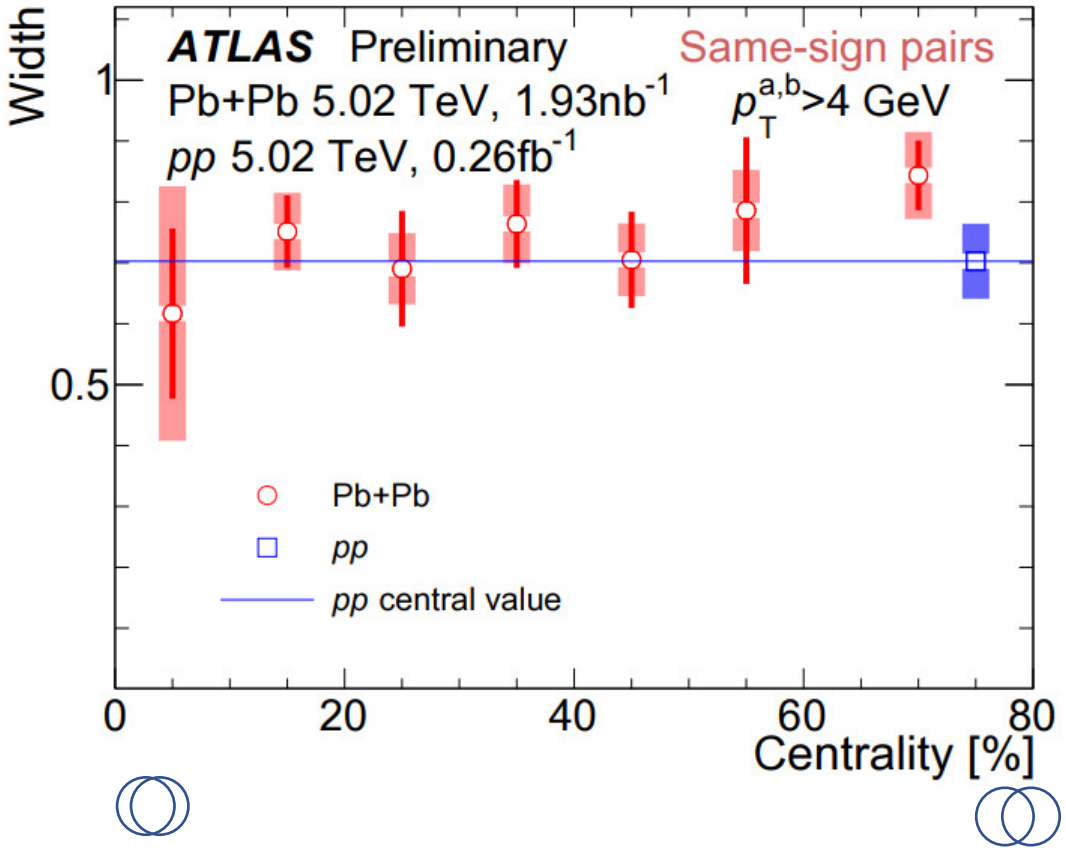


- Similar trend for both the same sign and opposite sign.
- T_{AA} scaled yields suggest stronger suppression in more central collisions.

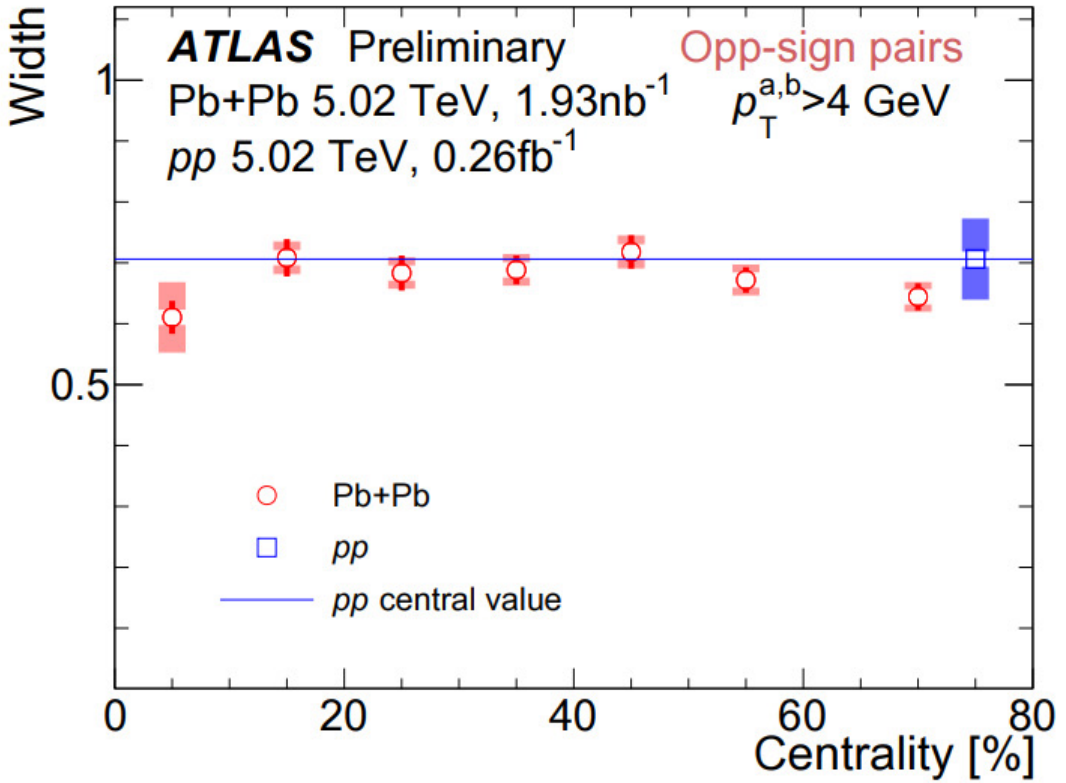
Di-muon correlation: width

CONF-2022-022

Same sign (dominated by $b\bar{b}$)



Opposite sign ($b\bar{b}$ + $c\bar{c}$)

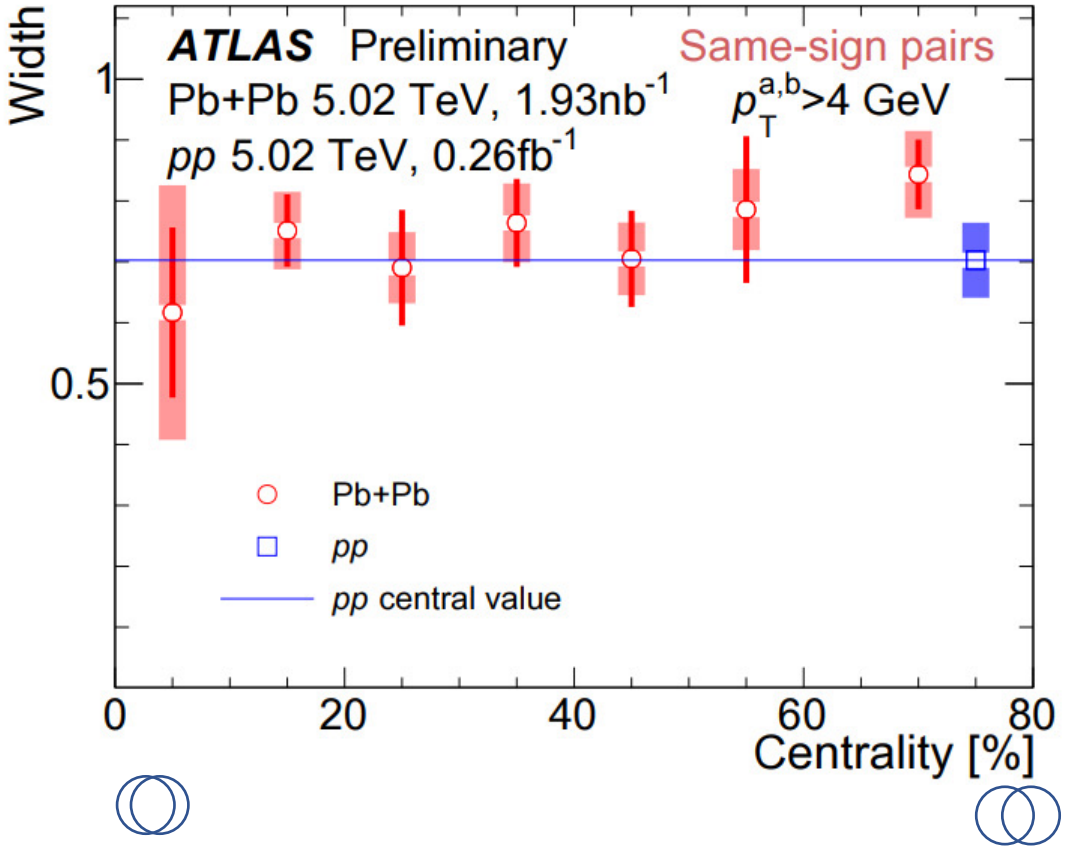


- Centrality-independent width indicates no significant change in the width.

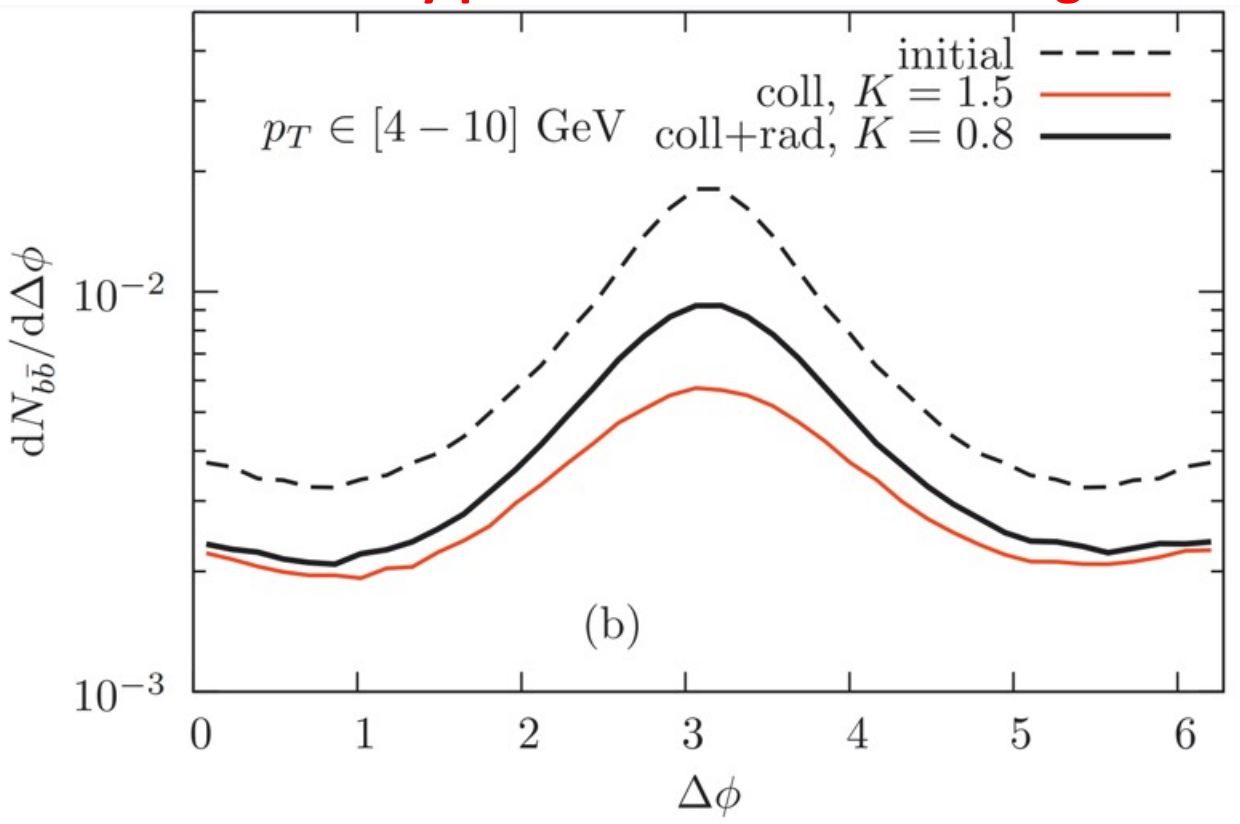
Di-muon correlation: width

CONF-2022-022

Same sign (dominated by $b\bar{b}$)



Theory prediction for broadening



- Both coll and coll + rad lead to the broadening <- not observed

❖However, some recent new results suggest that the rad. may largely cancel out broadening from the coll.

b-jet

HION-2018-24 (submitted to EPJC)

- *b*-jet reconstruction: containing muons from the semi-leptonic decay
  - *b*-quark: directly produced in the hard scattering or from a gluon splitting

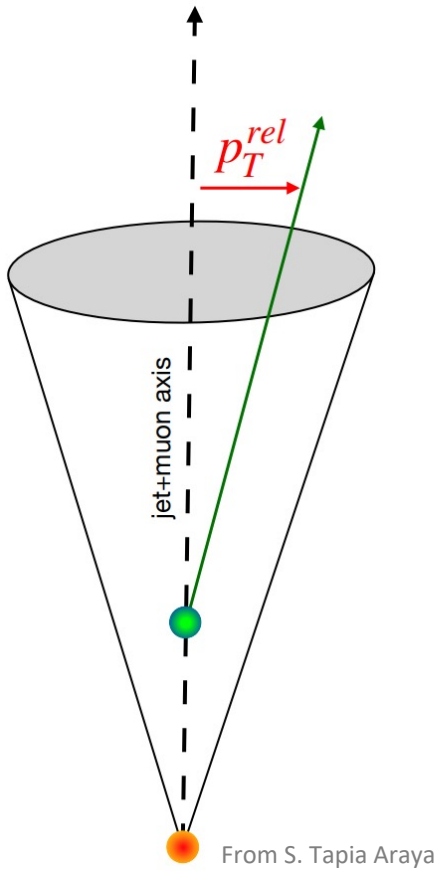
- Template fit:
  - Jet + μ axis:

$$\vec{u}_{\mathrm{T}}^{\mathrm{jet}+\mu} = \frac{\vec{p}_{\mathrm{T}}^{\mu} + \vec{p}_{\mathrm{T}}^{\mathrm{jet}}}{\left|\vec{p}_{\mathrm{T}}^{\mu} + \vec{p}_{\mathrm{T}}^{\mathrm{jet}}\right|}$$

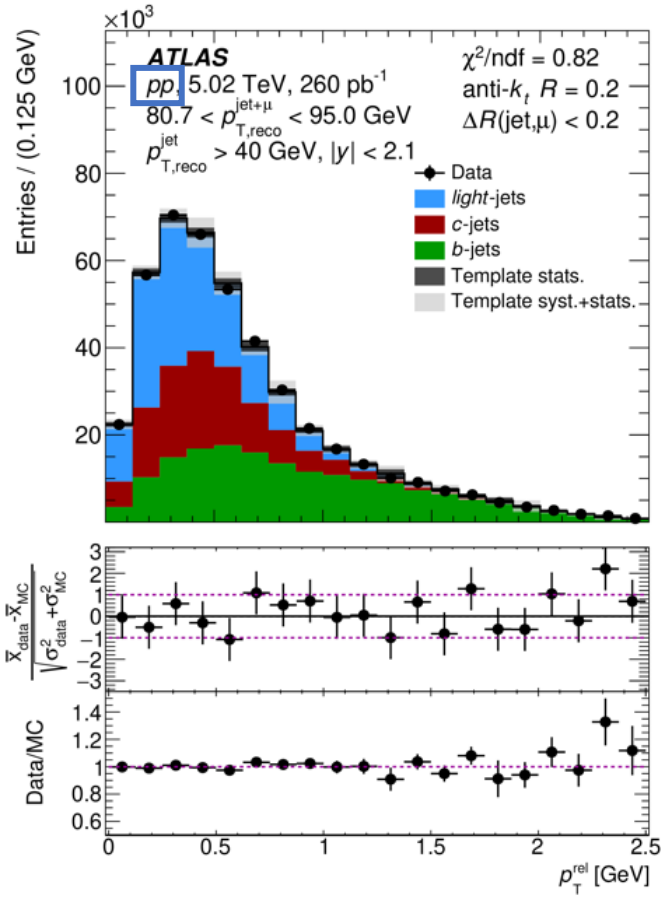
  - ➢ Muon p_{T} projection:

$$p_{\mathrm{T}}^{\mathrm{rel}} = \left|\vec{p}_{\mathrm{T}}^{\mu} \times \vec{u}_{\mathrm{T}}^{\mathrm{jet}+\mu}\right|$$

- Muon candidates:
  - $p_{\mathrm{T}} > 4$ GeV
  - Within the jet cone (R)



From S. Tapia Araya



b-jet signal extraction

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$$\vec{u}_{\mathrm{T}}^{\mathrm{jet}+\mu} = \frac{\vec{p}_{\mathrm{T}}^{\mu} + \vec{p}_{\mathrm{T}}^{\mathrm{jet}}}{\left|\vec{p}_{\mathrm{T}}^{\mu} + \vec{p}_{\mathrm{T}}^{\mathrm{jet}}\right|}$$

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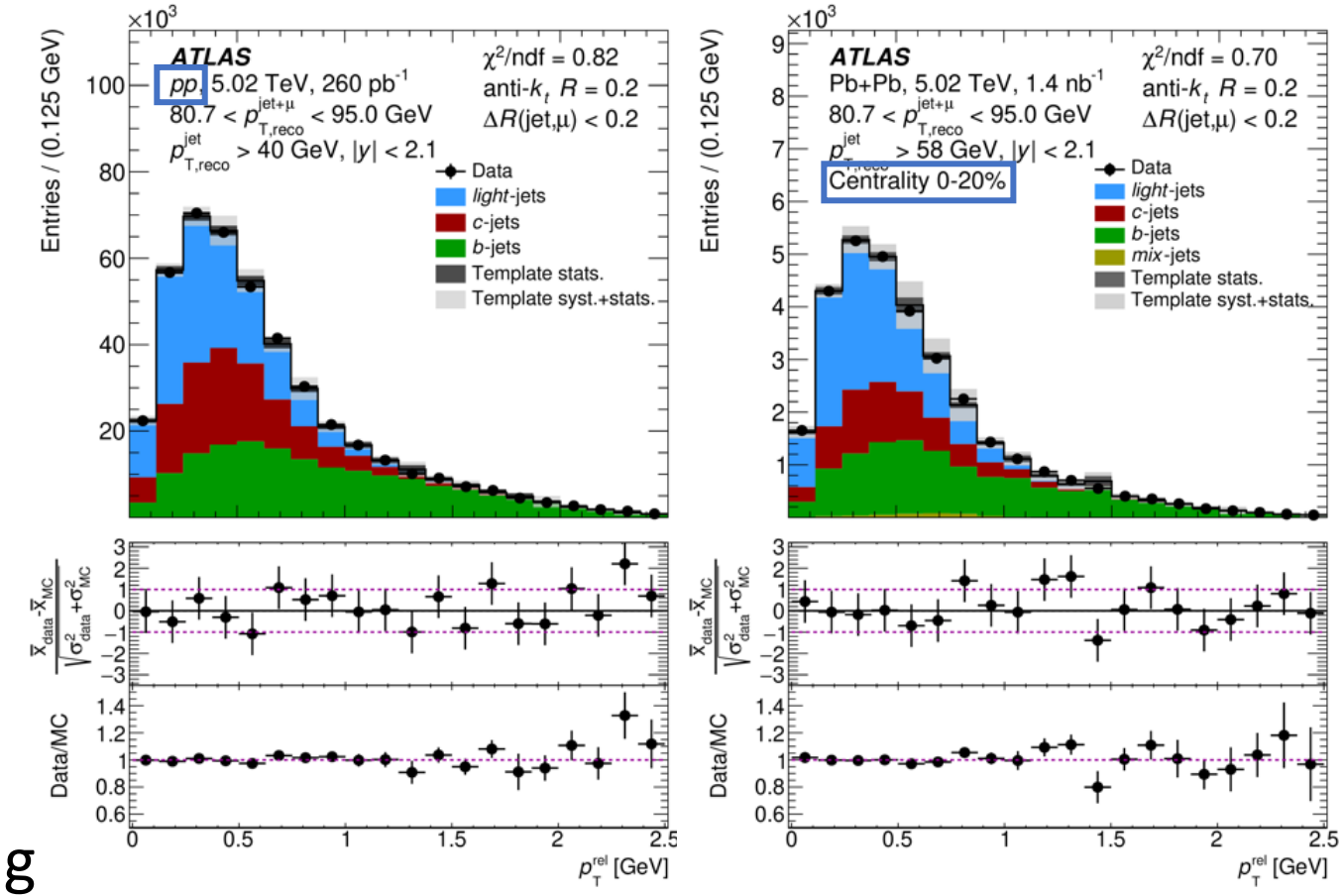
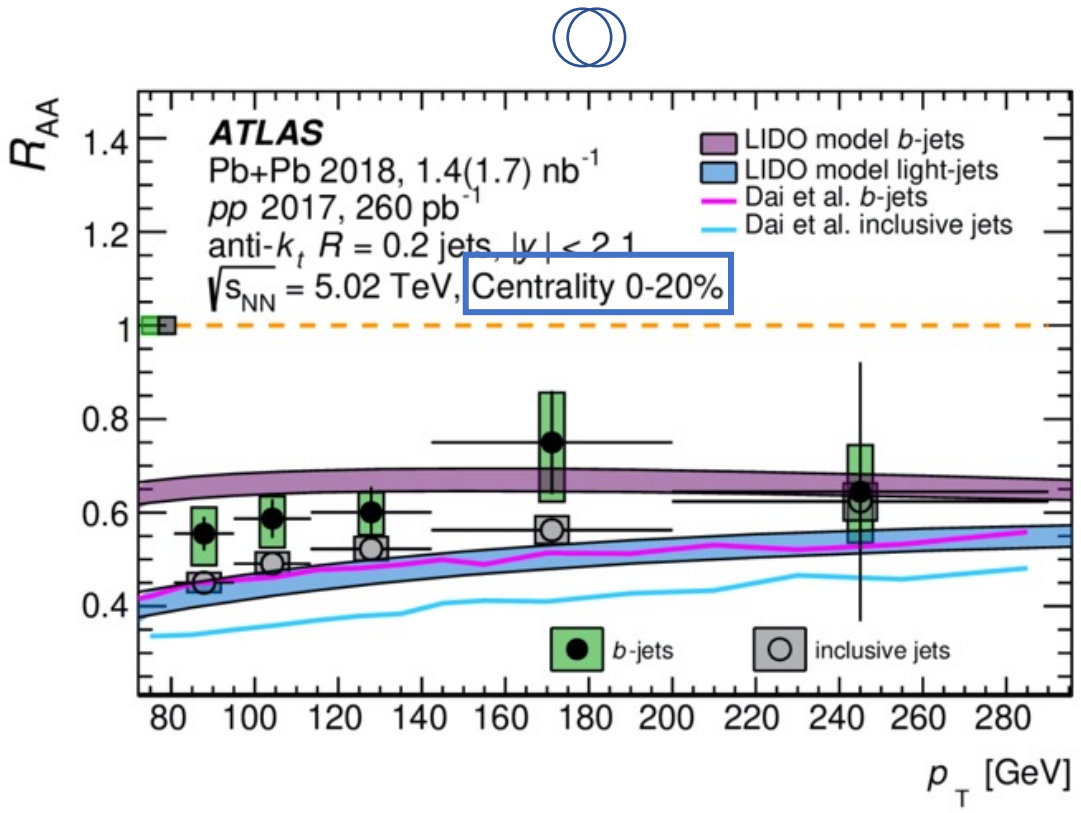
- Muon candidates:
  - $p_{\mathrm{T}} > 4$ GeV
  - Within the jet cone (R)

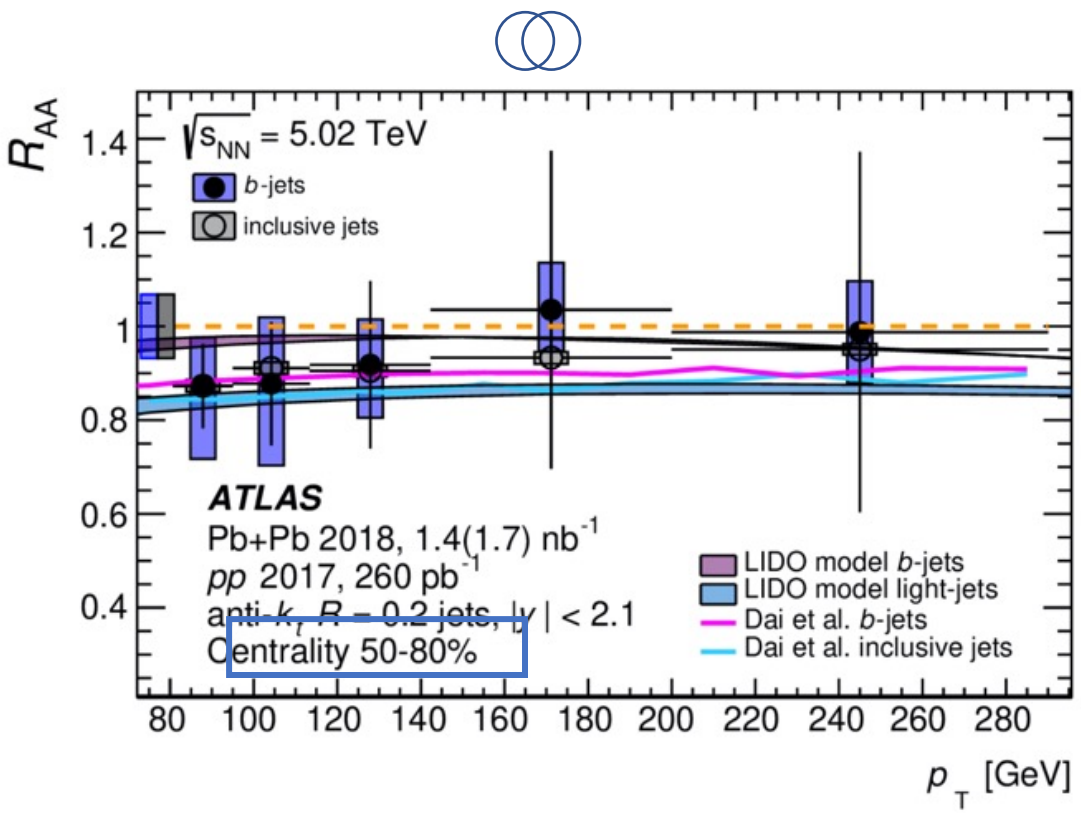
- Pb+Pb combinatoric term estimated from event mixing



Nuclear modification factor

HION-2018-24 (submitted to EPJC)

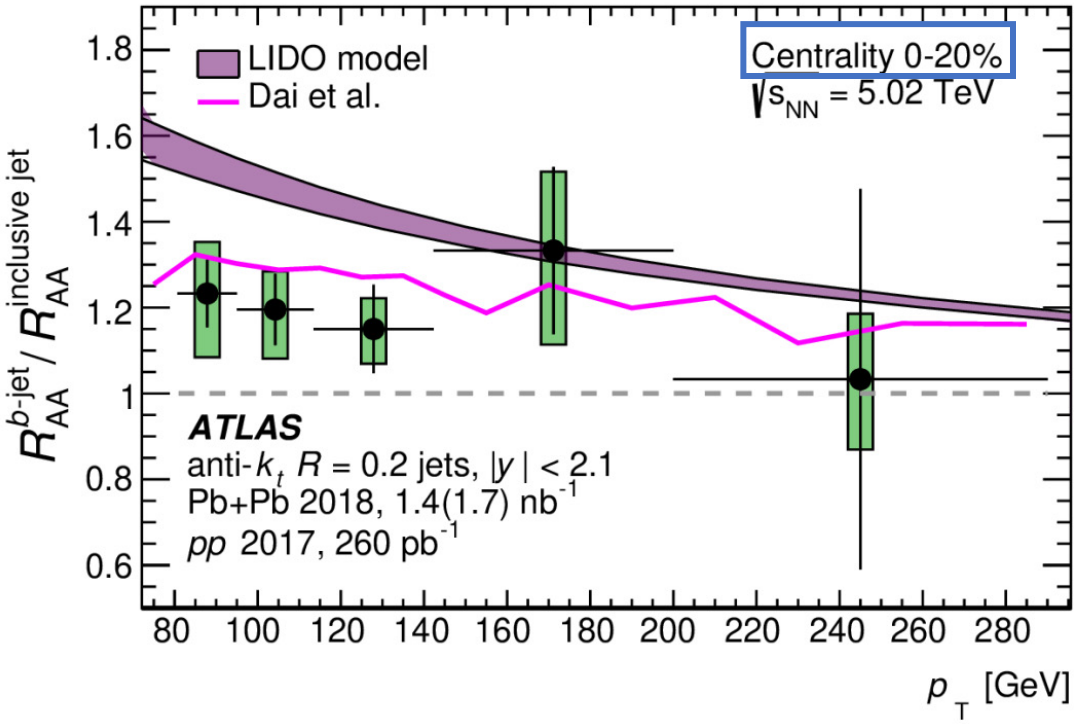


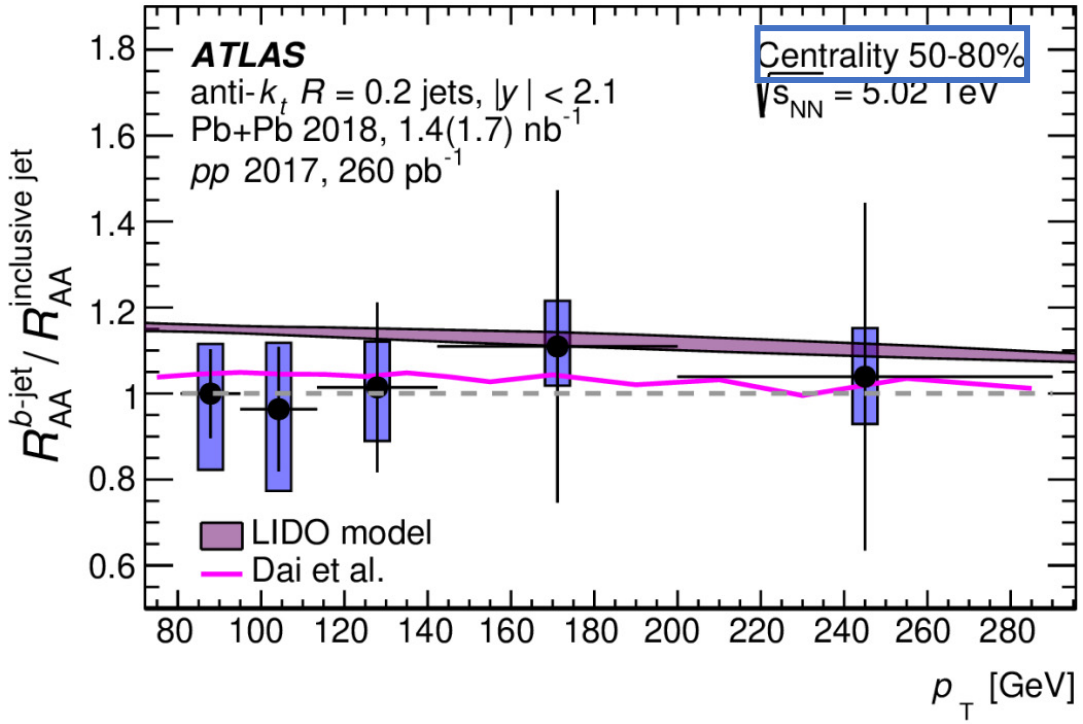


- b-jets are less suppressed compared to inclusive jets in central collisions.
- Stronger suppression in more central collisions.

Double ratio

HION-2018-24 (submitted to EPJC)

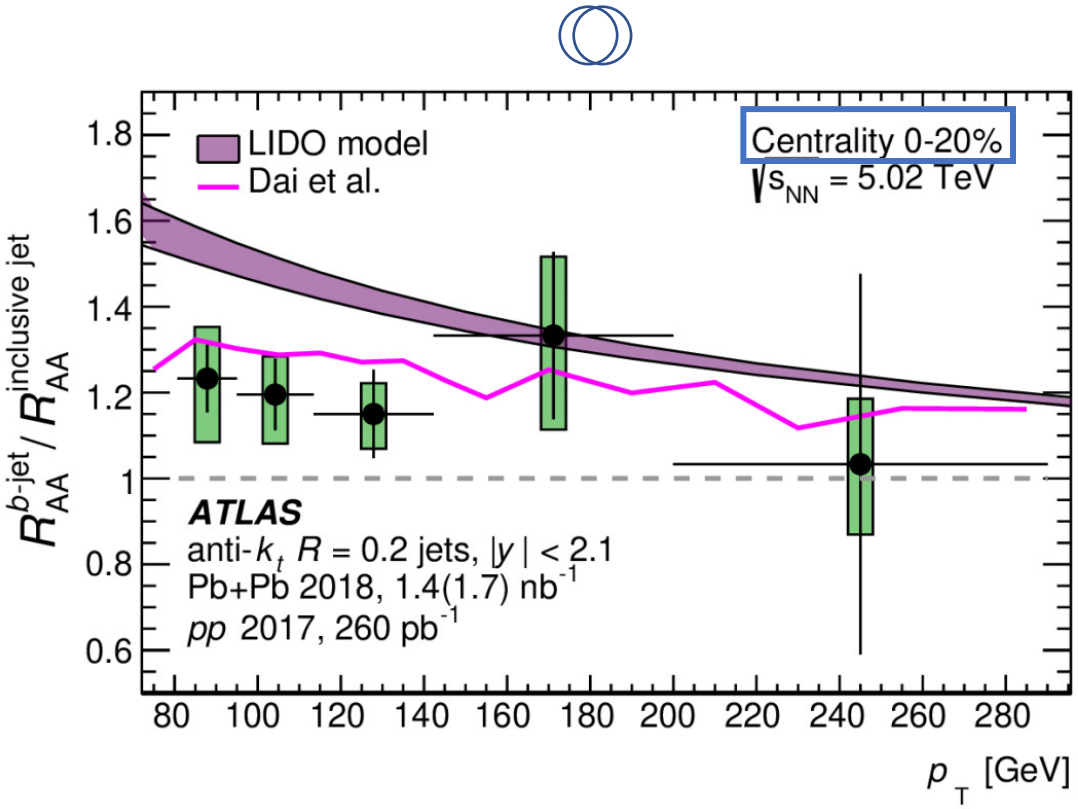




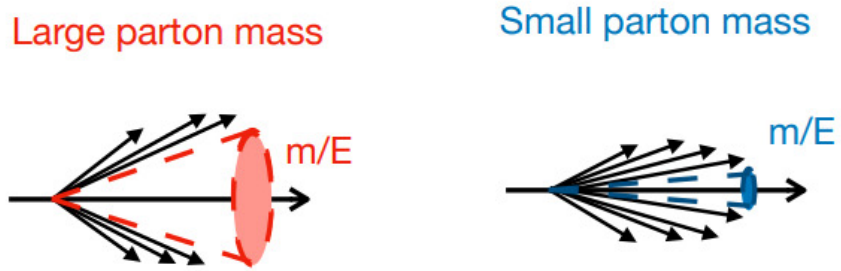
- Some common uncertainties are cancelled out in the double ratio.
- ~unity in peripheral; about 20% above unity in central collisions.
- b-jets' suppression < inclusive jets in central.

Double ratio

HION-2018-24 (submitted to EPJC)



quark jets lose less energy than gluon jets

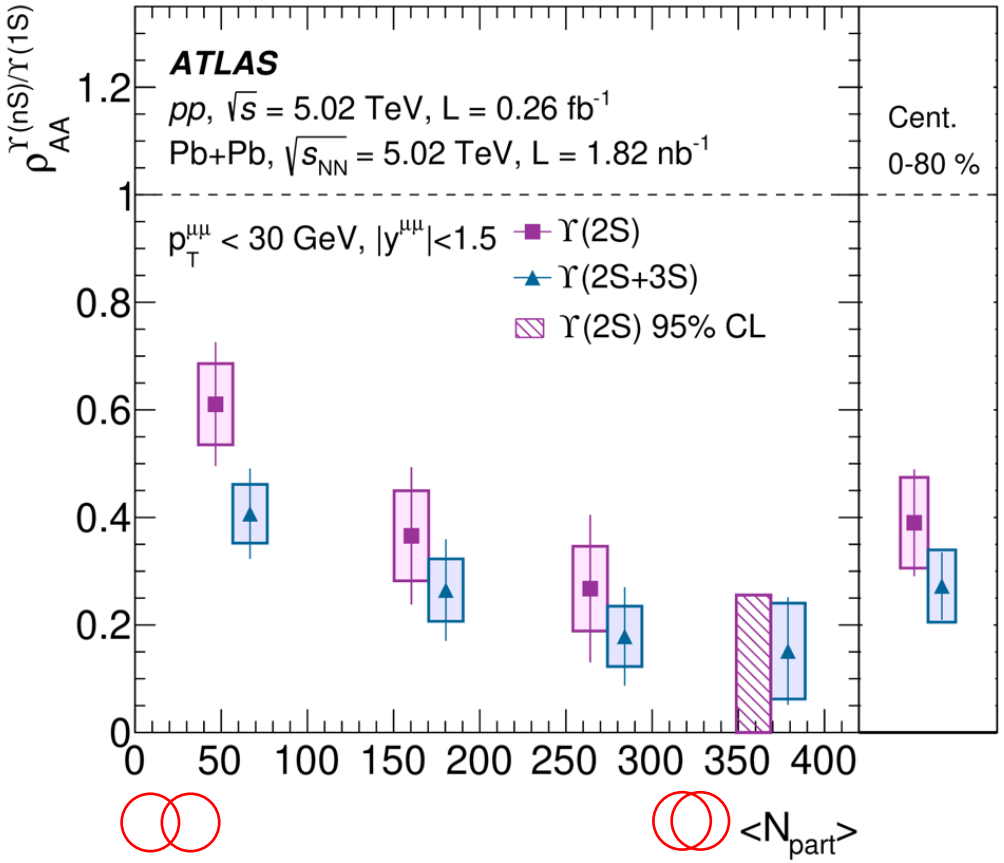


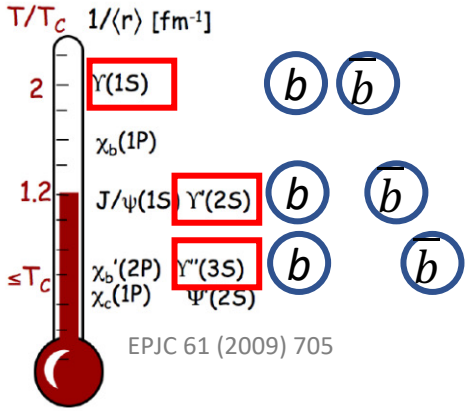
dead-cone effect

- b-jets' suppression < inclusive jets in central.
- Both effects could reduce b-jet energy loss.

Summary

- Quarkonium:
  - Sequential suppression for the three Υ states observed.

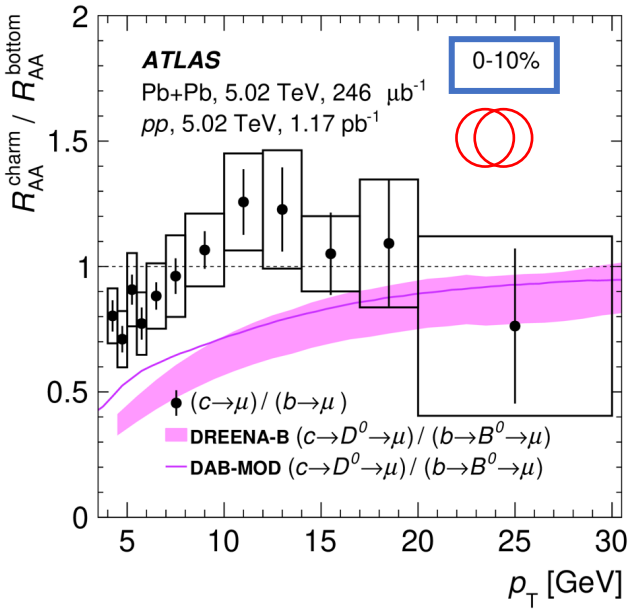


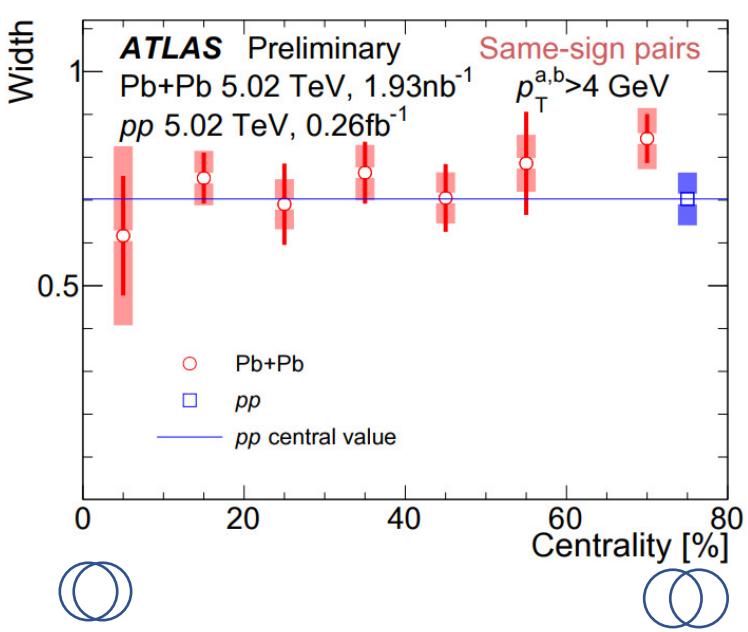


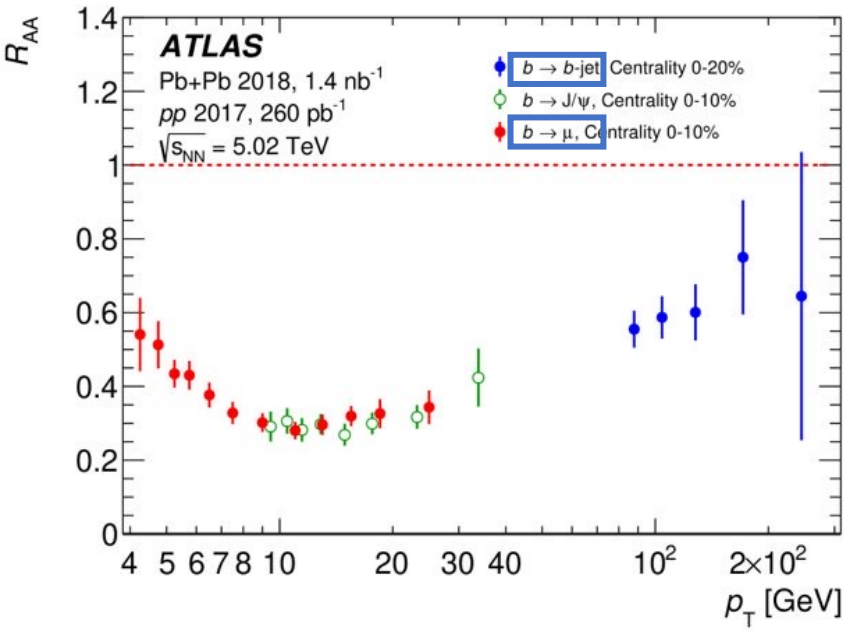
EPJC 61 (2009) 705

Summary

- Open heavy flavor and hard-probes:
  - *c* muon more suppressed than *b* at lower p_{T}.
  - HF back-to-back muon pairs: no significant open angle broadening observed.
  - *b*-jets less suppressed than inclusive jets in central collisions.

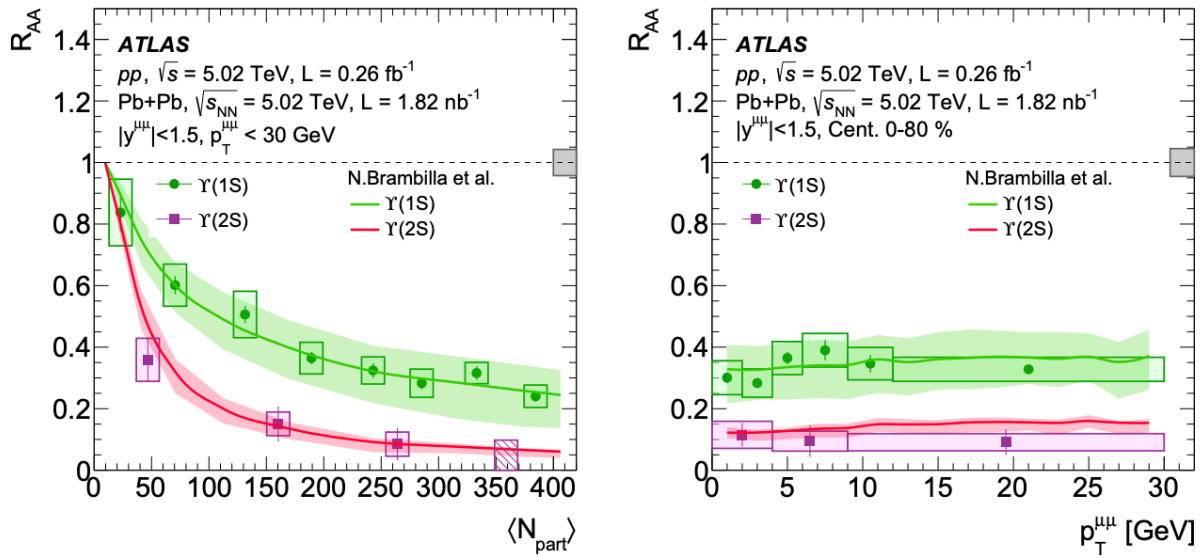


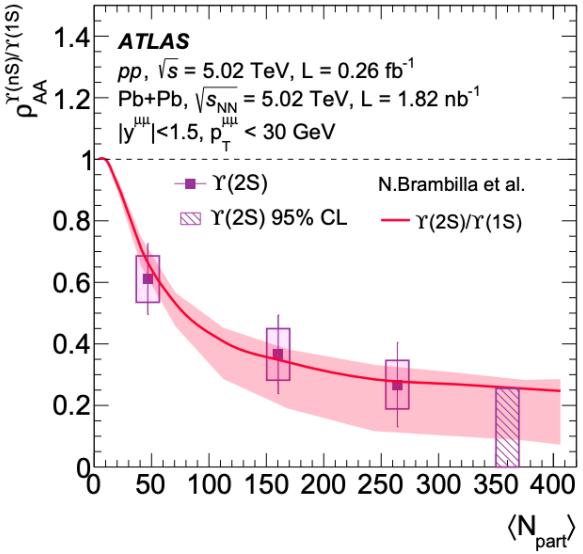


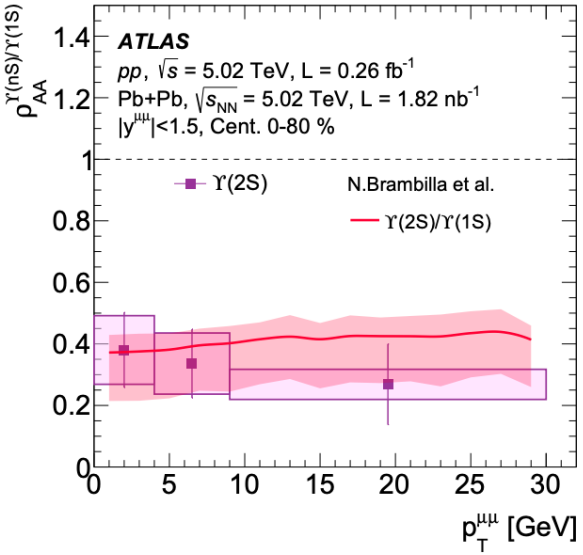


Backup

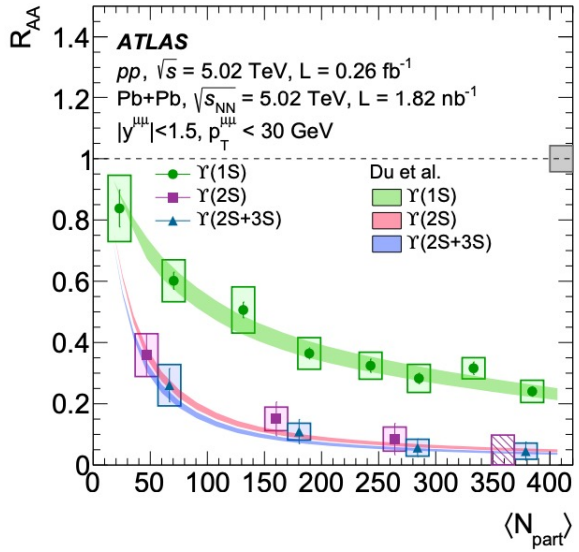
Υ: Comparison with models

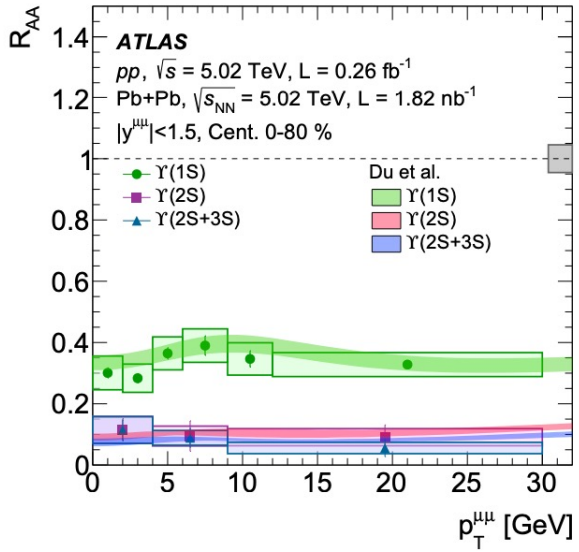


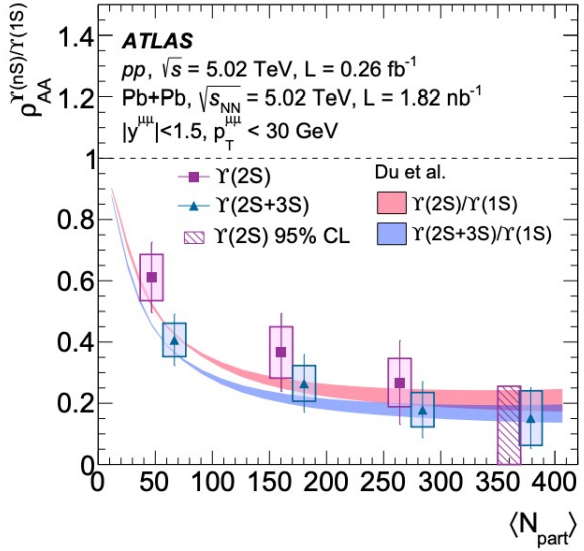


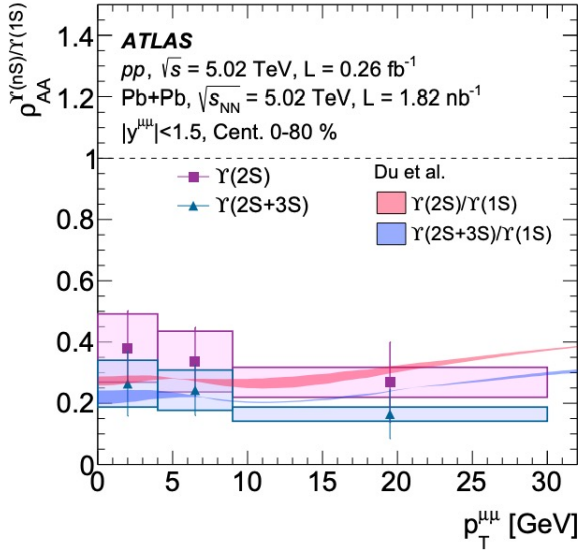


Comparison with models









Comparison with models