ATLAS EXPERIMENT

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Heavy flavor probes of the Quark Gluon Plasma with ATLAS

Wenkai Zou for the ATLAS collaboration

SQM2022

The 20th International Conference on Strangeness in Quark Matter
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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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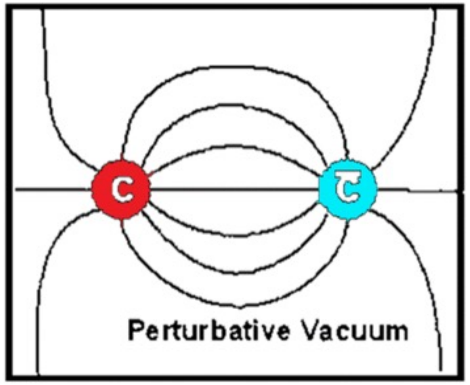
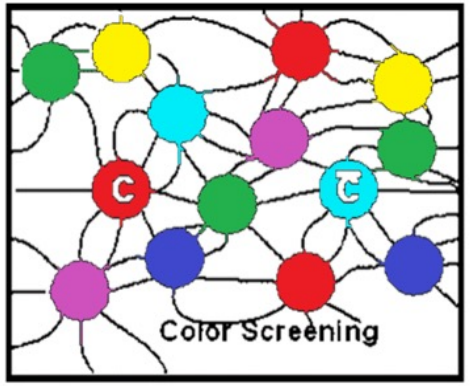
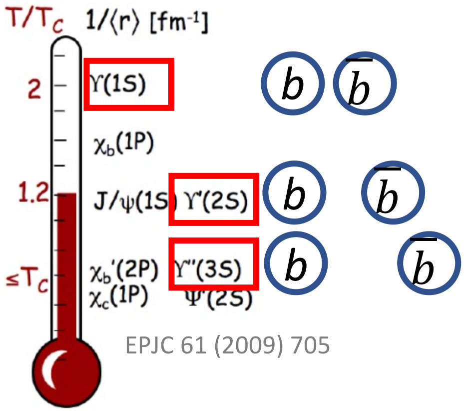
- Color screening from the deconfined medium
- Three Υ meson states (quarkonia) have different binding energies.
  - ➢ Their "sequential melting" serves as a QGP "thermometer".







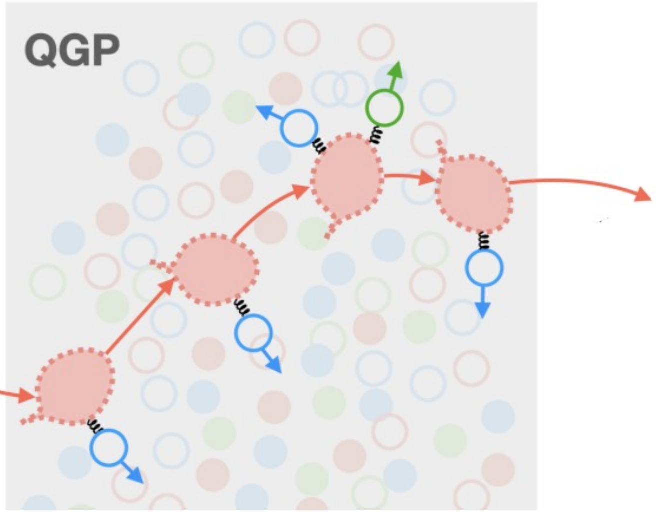
EPJC 61 (2009) 705

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 and these probe the properties of the medium.

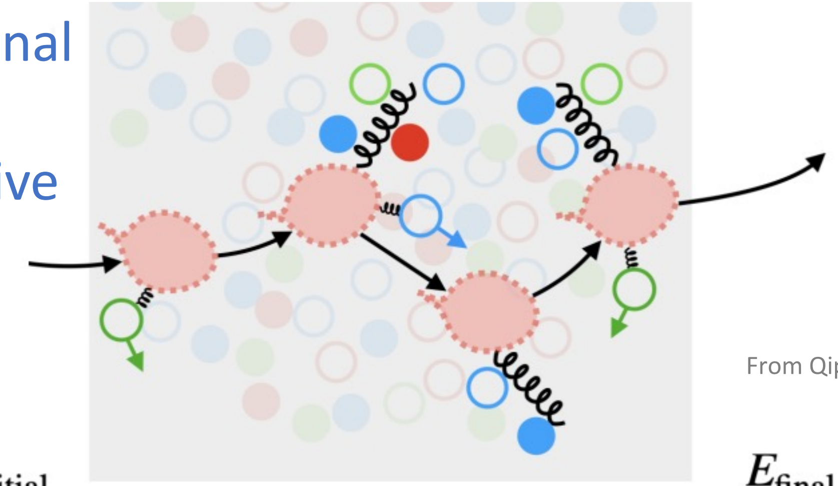
collisional



HF quark (*b*/*c*)

collisional + radiative

E_{initial}



From Qipeng Hu

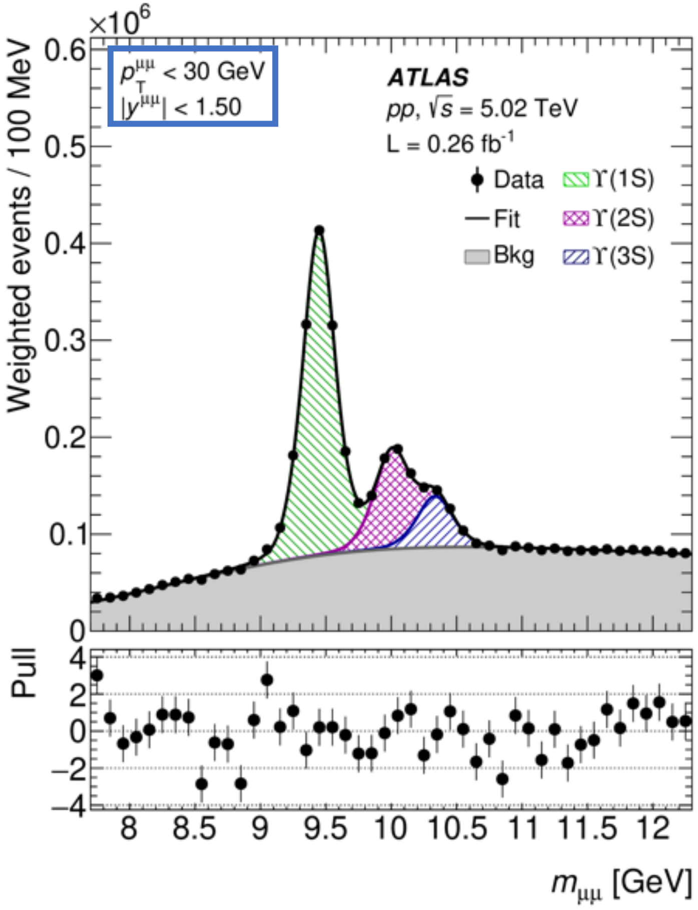
$E_{\text{final}} < E_{\text{initial}}$

Υ signal extraction

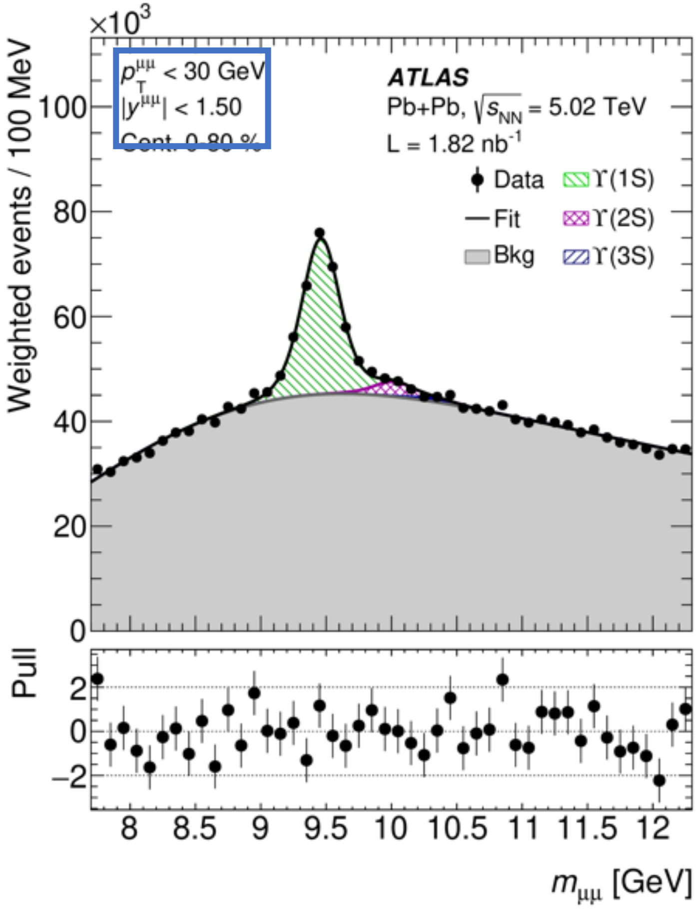
HION-2021-12

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

2017 *pp*



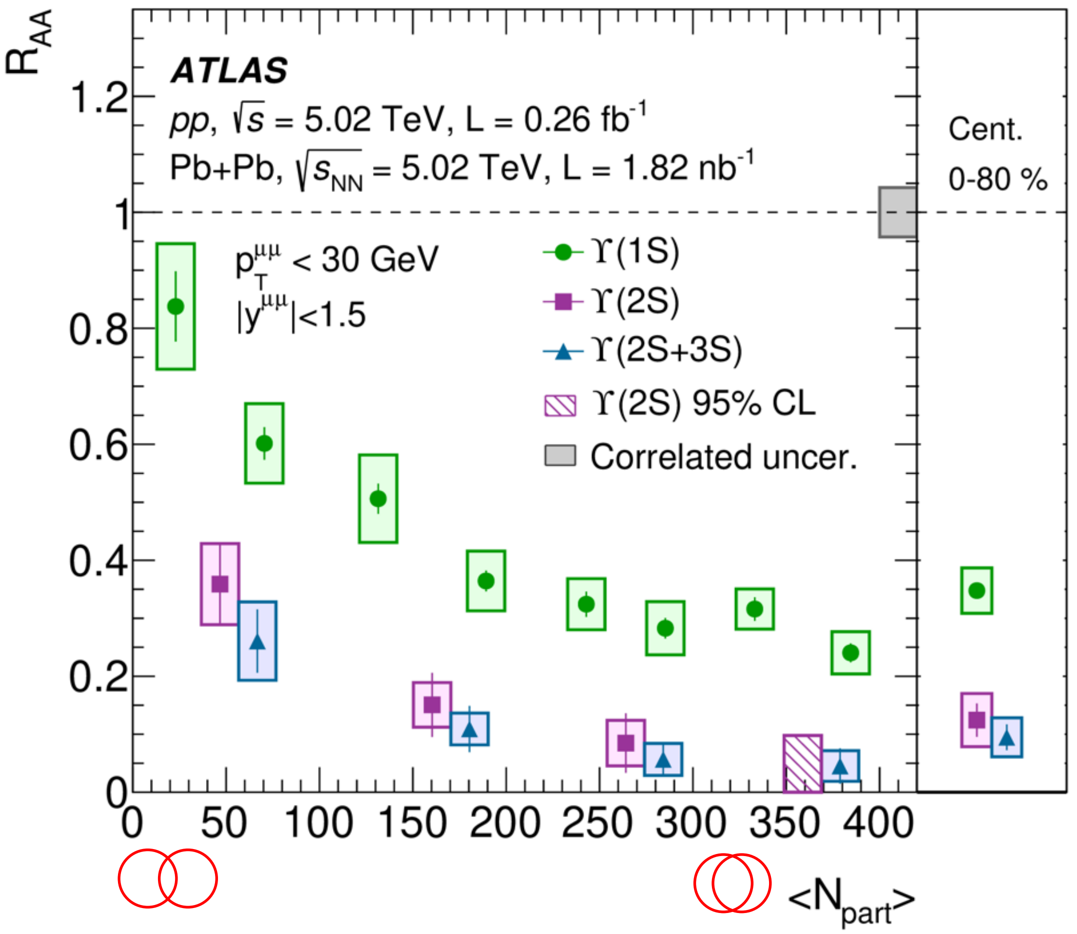
2018 Pb+Pb

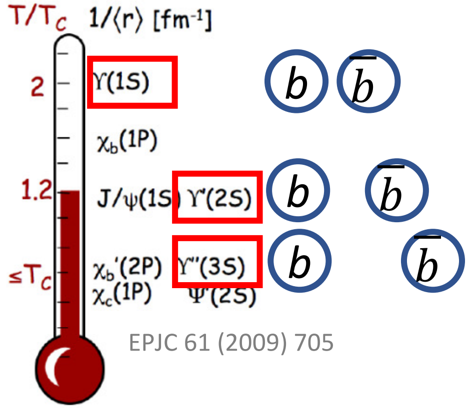


Nuclear modification factor

HION-2021-12

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



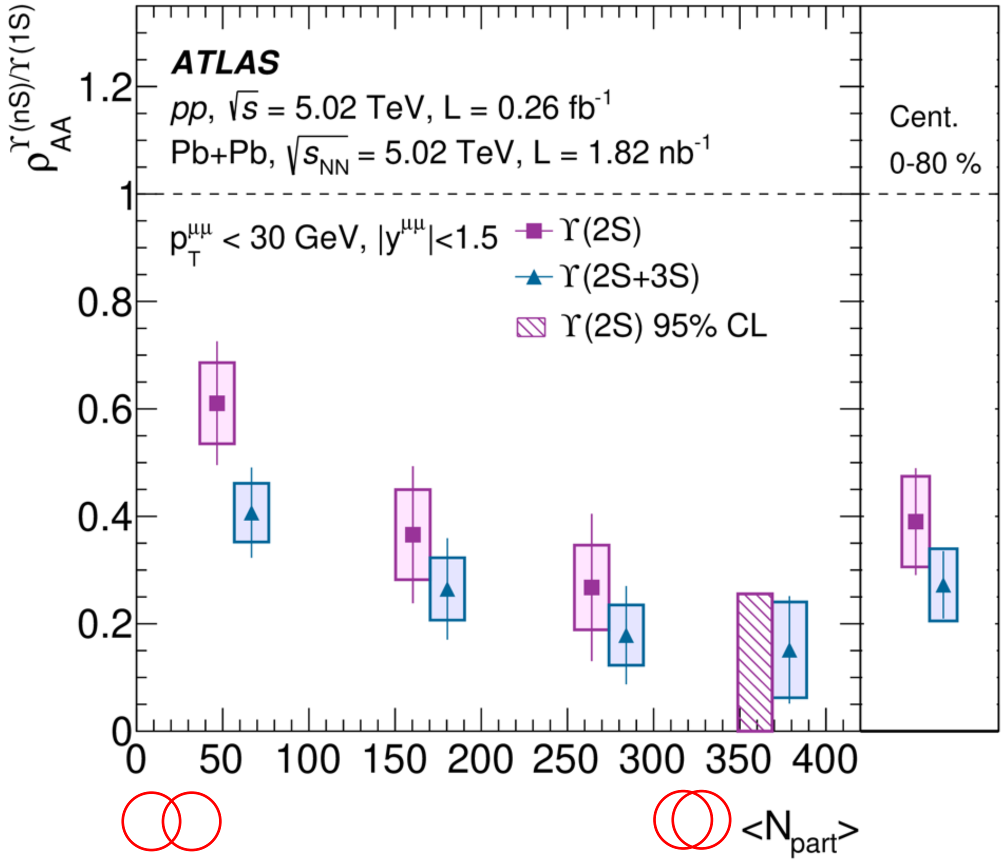


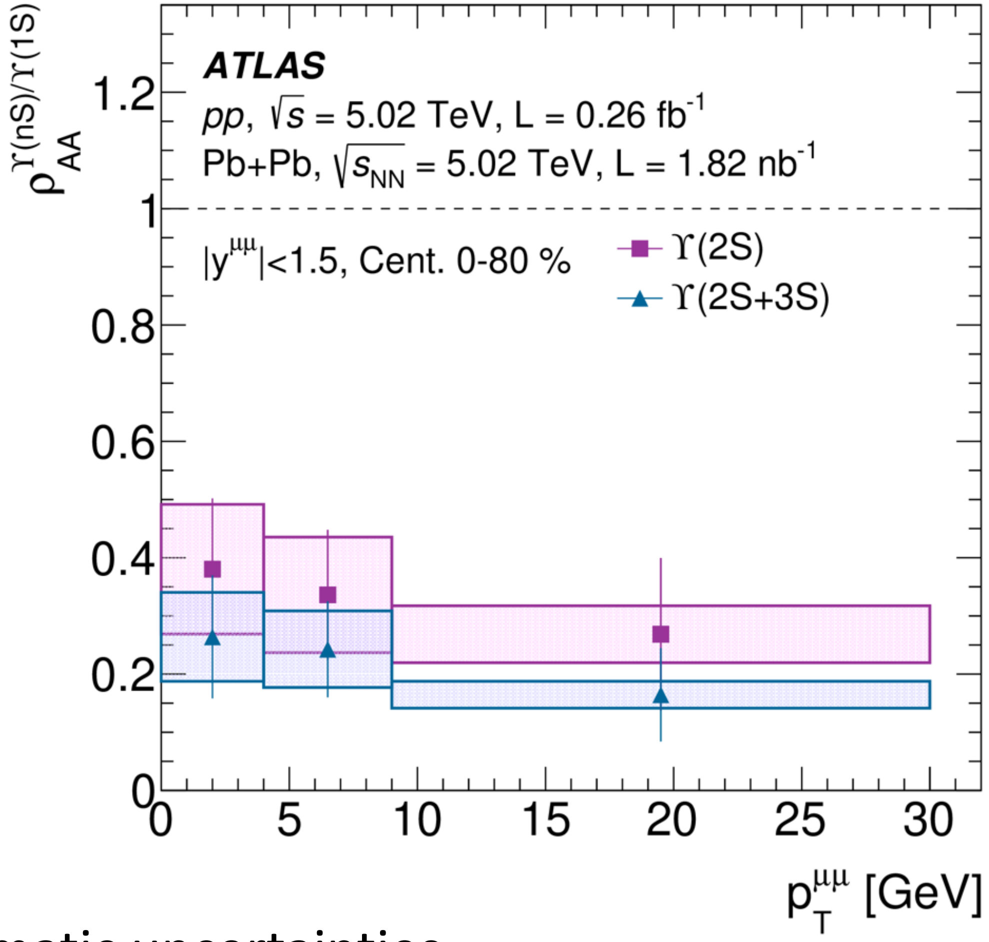
- Stronger suppression in central collisions
- Sequential suppression: Υ(1S) > Υ(2S) > Υ(2S+3S)
  - 3S combined due to its low statistics

Double ratio

HION-2021-12

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



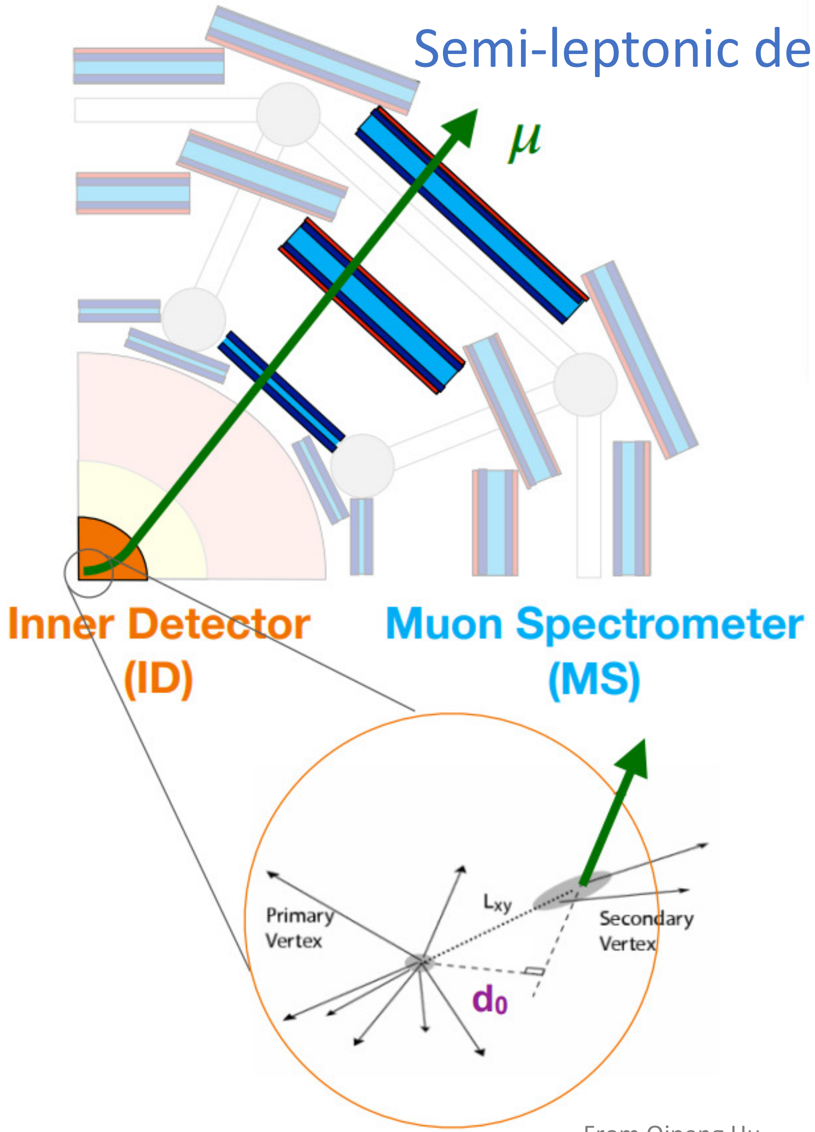


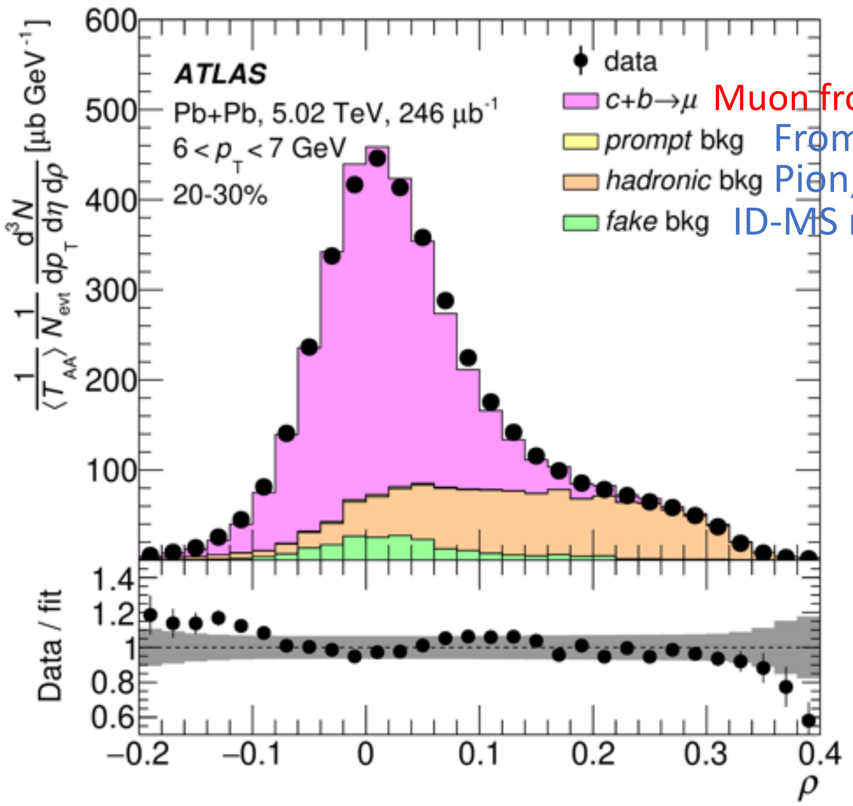
- Double ratio cancel out some common systematic uncertainties.
- Sequential suppression is significant (below unity).
- Slightly decreasing trend toward more central collisions; no significant p_T dependence.

Open HF (b/c) muon

HION-2019-58

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:

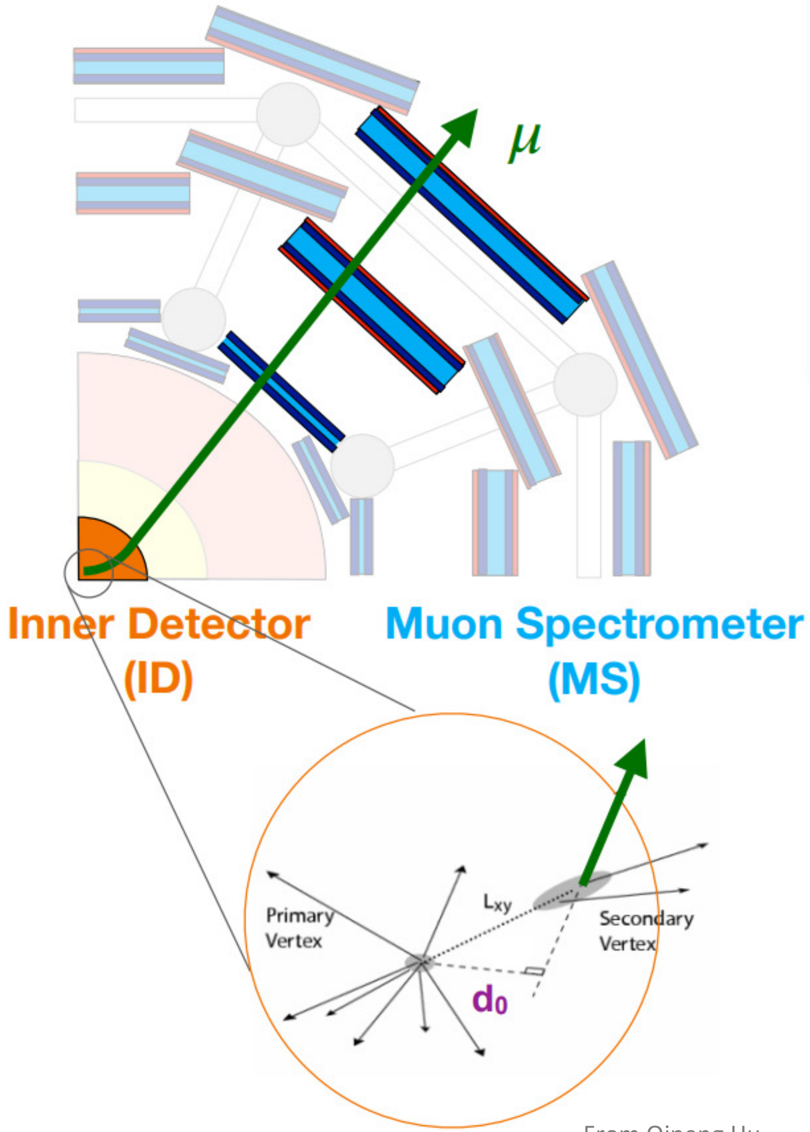
based on the ID-MS momentum imbalance:

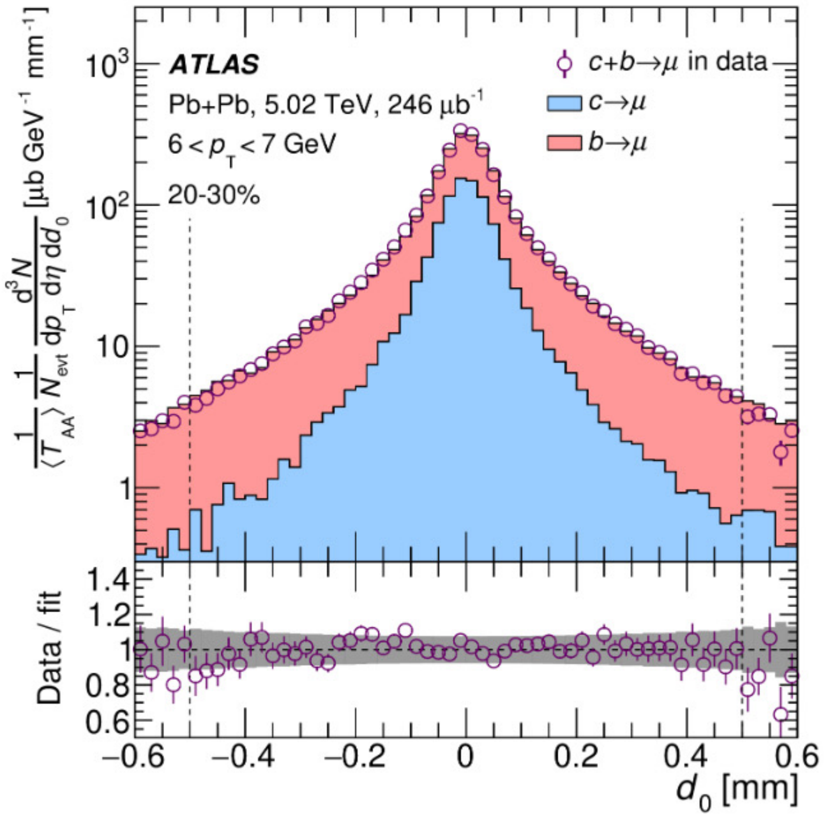
$\rho = (p^{ID} - p^{MS}) / p^{ID}$

From Qipeng Hu

Open HF (b/c) muon

HION-2019-58



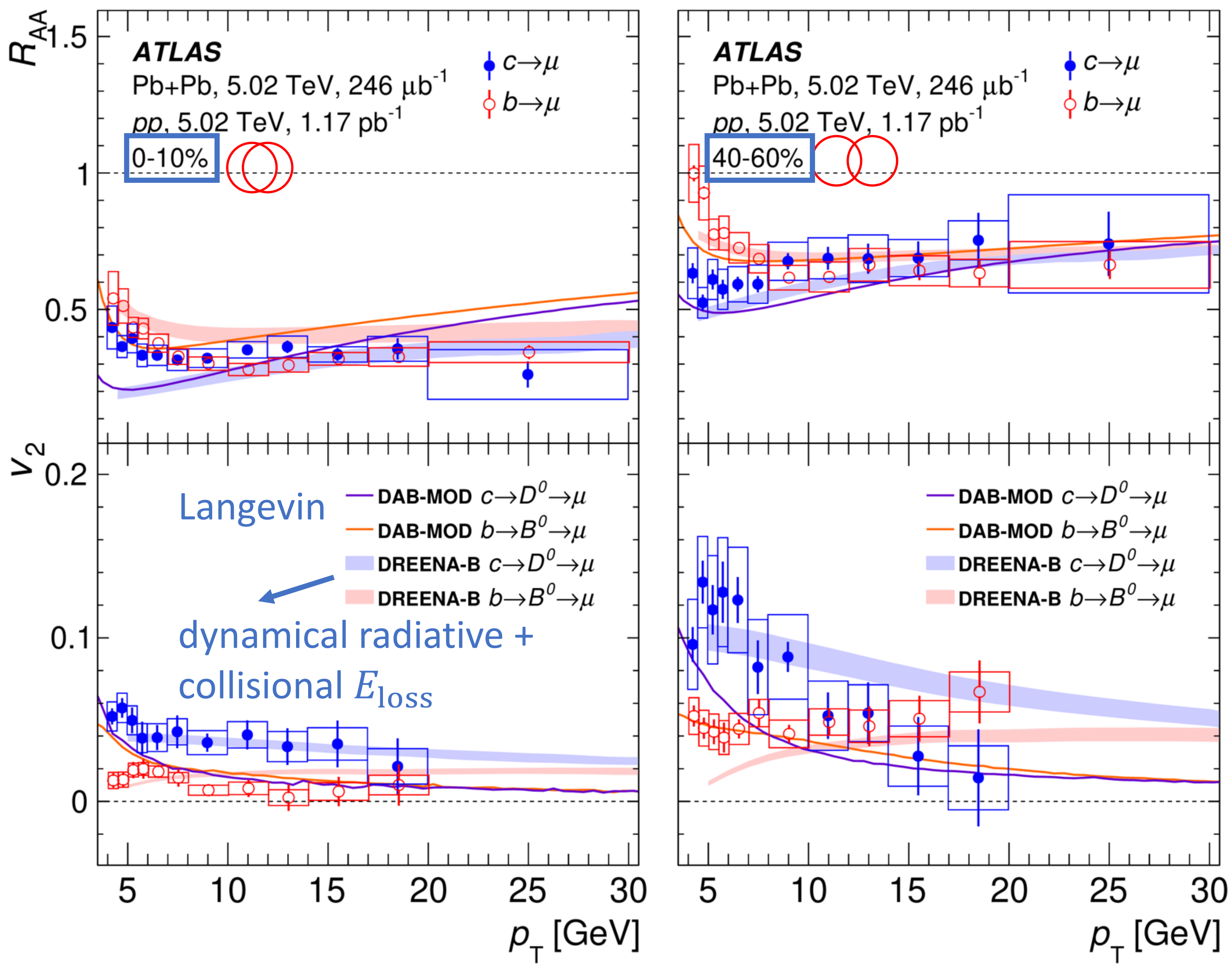


Template fit to separate b/c: based on muon d_0
(ID impact parameter on the transverse plane)
<- due to slightly different lifetime

From Qipeng Hu

Yield suppression and anisotropy

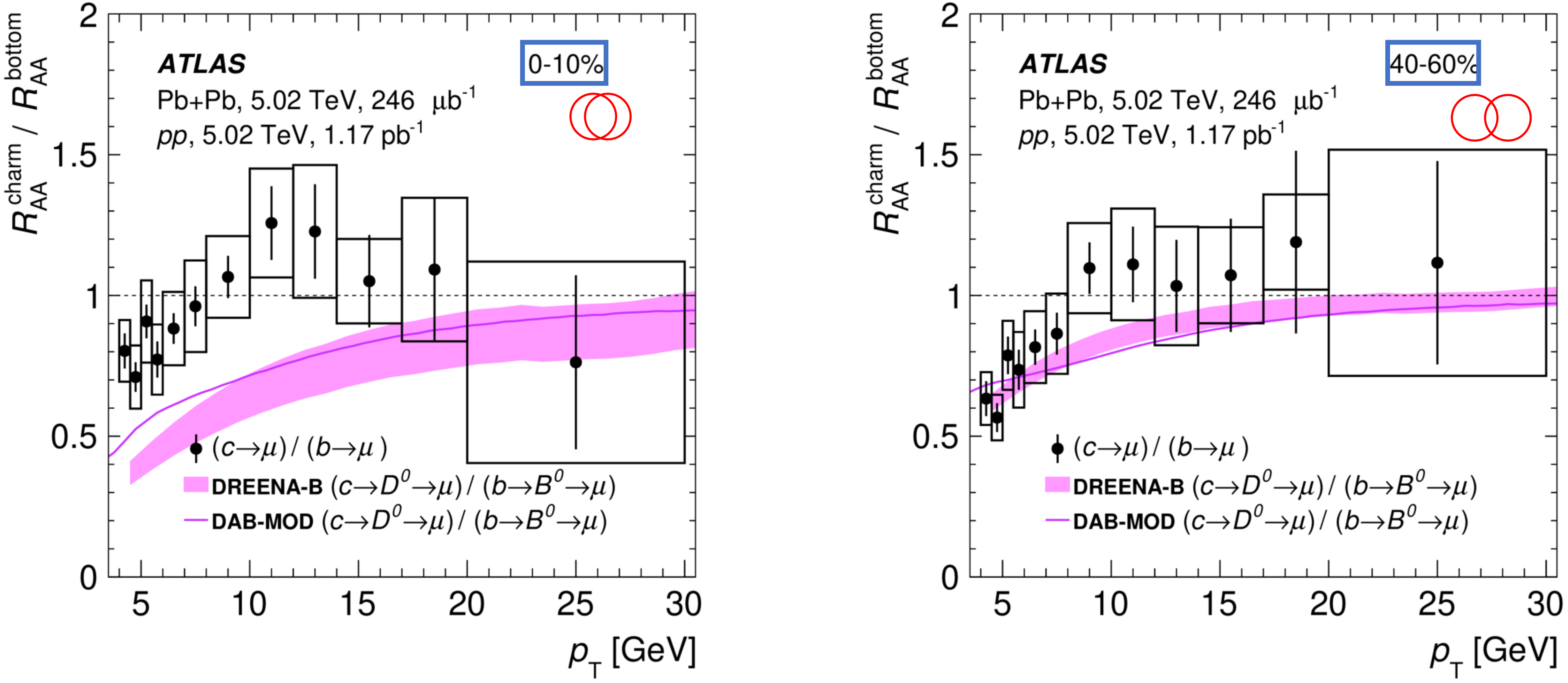
HION-2019-58



- 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

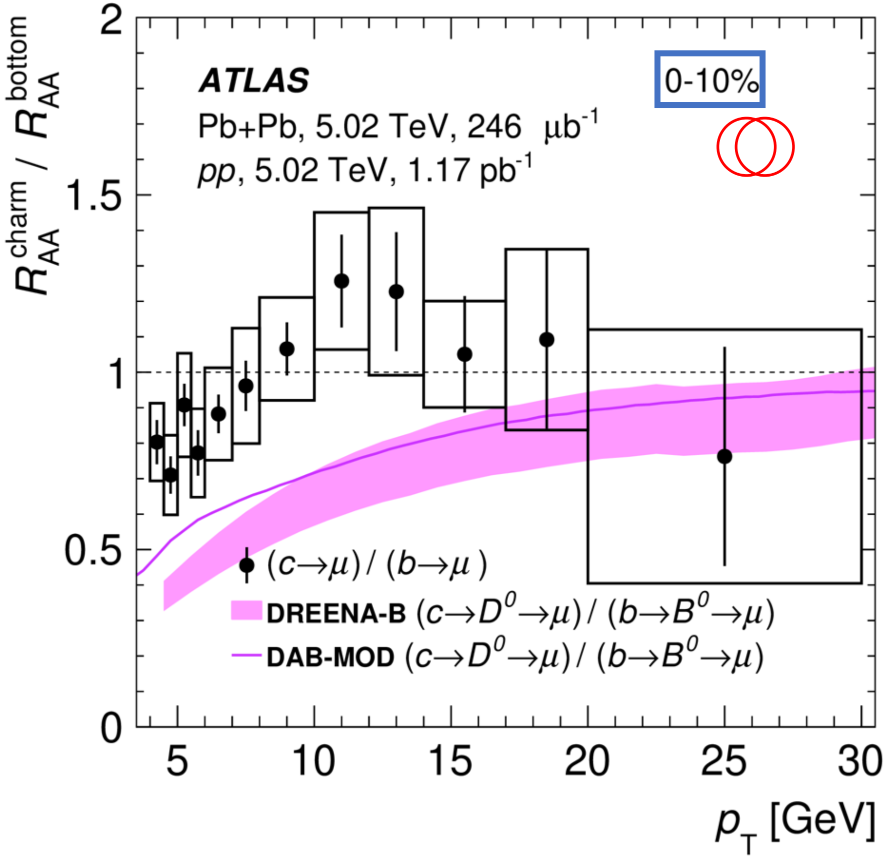
HION-2019-58

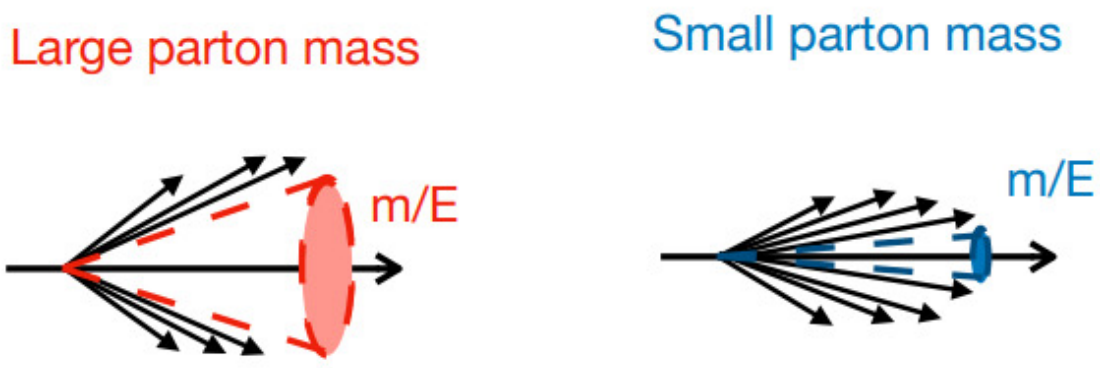


- Large uncertainties due to anti-correlation between *b* and *c*
- Charm is more suppressed at low p_T; comparable at higher p_T.
  - Model captures the qualitative behavior but underestimates *c* R_{AA} and thus also the double ratio at low p_T in 0-10%.

Yield suppression double ratio

HION-2019-58



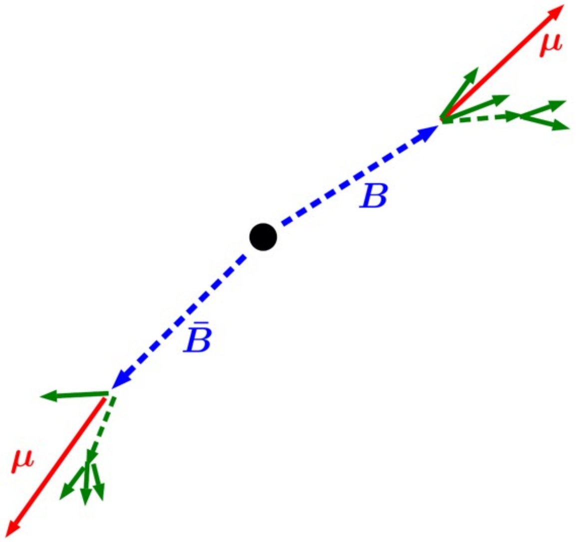


- Large uncertainties due to anti-correlation between *b* and *c*
- Charm is more suppressed at low pT; comparable at higher p_T.
  - Model underestimates *c* quark R_{AA} and thus also the double ratio at low p_T in 0-10%.
- Mass ordering consistent with the dead-cone effect in the radiative energy loss

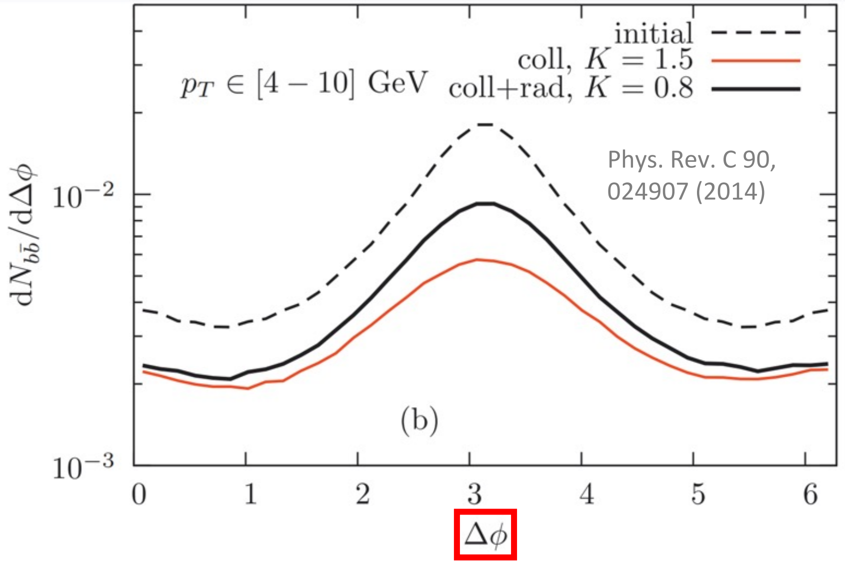
HF muon pair

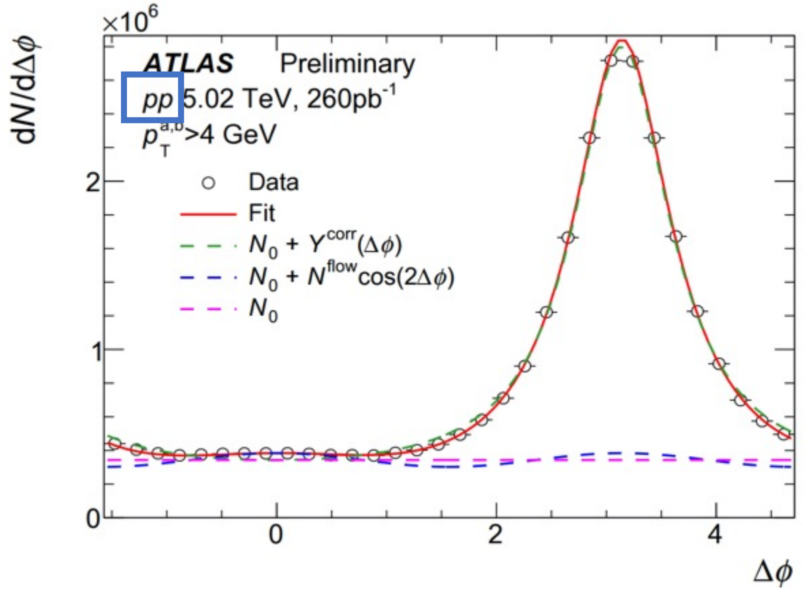
CONF_2022_022

- Measure back-to-back muon pair production from semi-leptonic decays of HF quarks:
  - |Δη| > 0.8 to remove the near-side jet peak
  - Invariant mass cuts to remove $J/\psi, \Upsilon$ etc. (only on opposite sign pairs)
  - $b\bar{b}$ dominates in the same-sign and inclusive di-muon pairs (according to the MC).



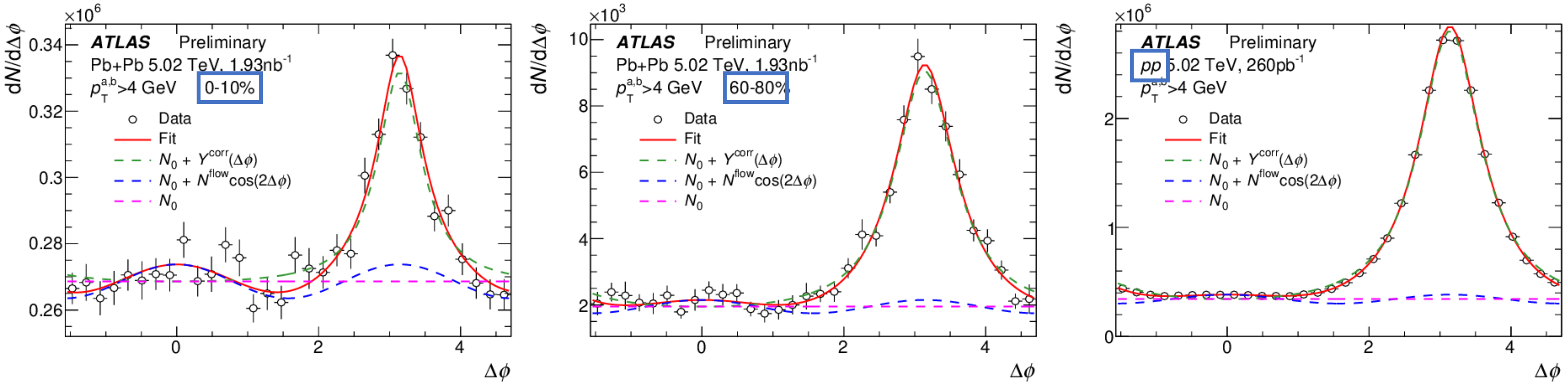
Theory prediction for broadening





Back-to-back yield extraction

CONF_2022_022



The following fit function is used to extract the signal:

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

Background w/ modulation   Back-to-back correlation yields

With (Lorentzian)

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

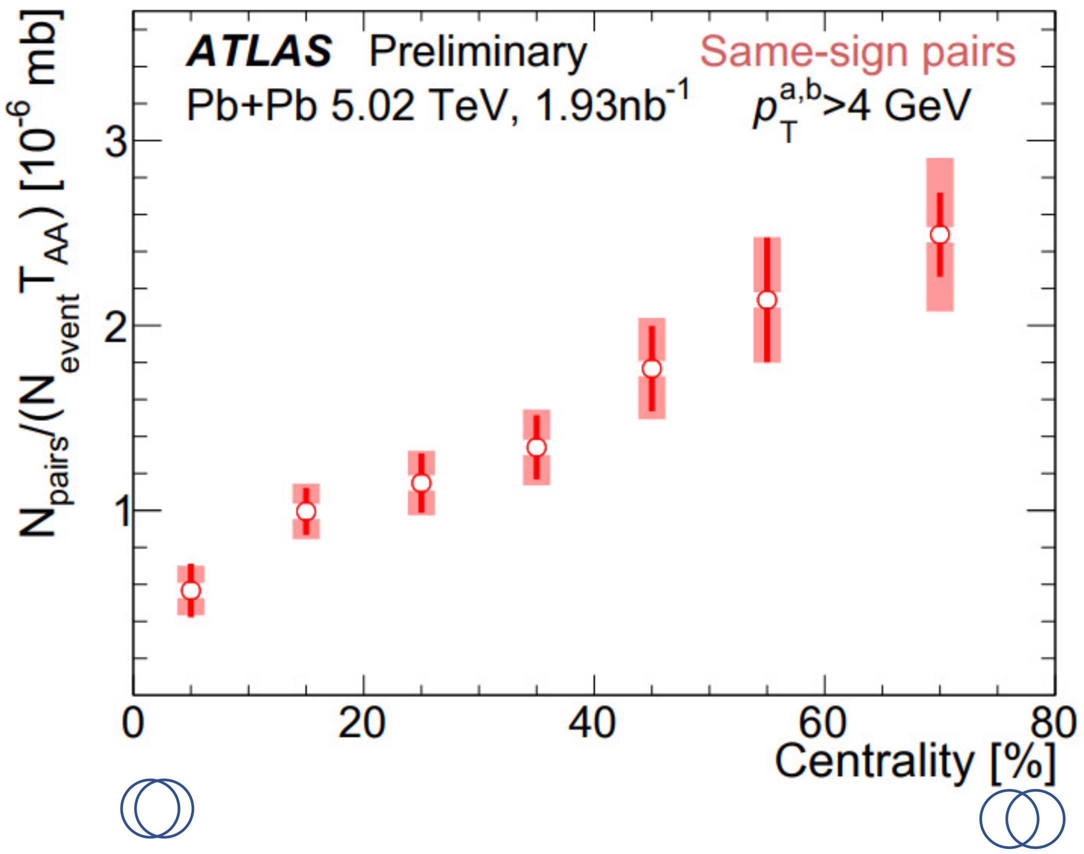
Yield = integral of Y
Width = std deviation of Y

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

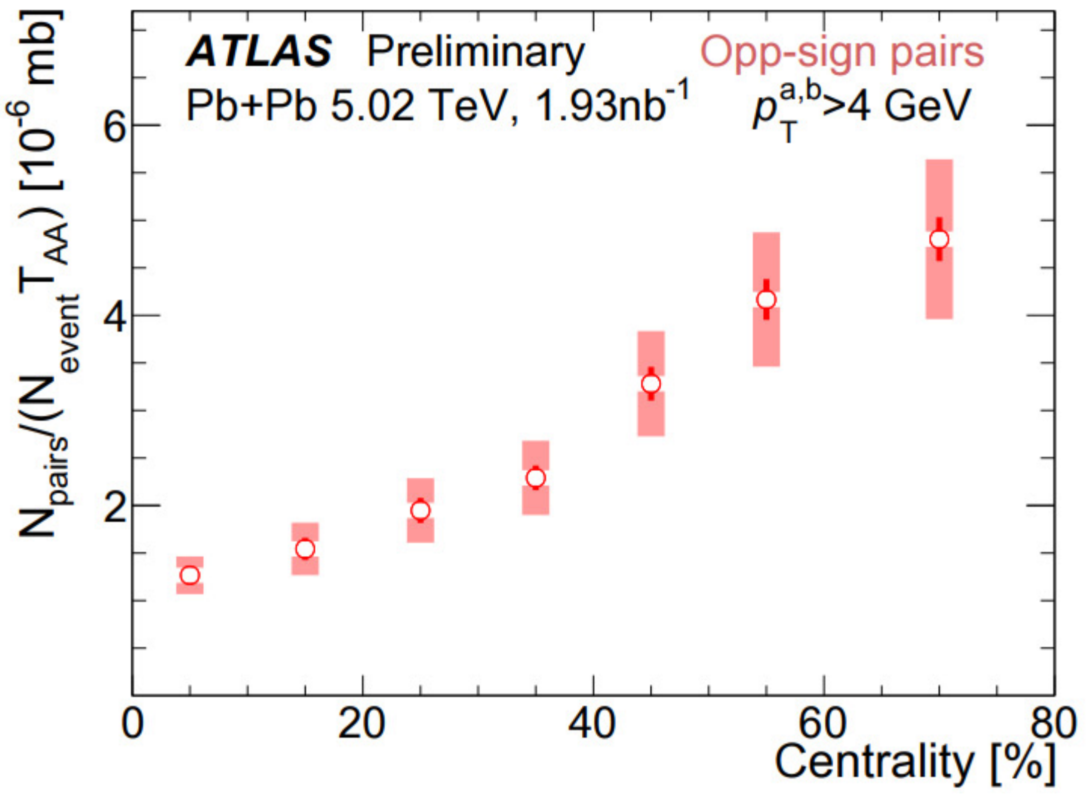
Di-muon correlation: yields

CONF_2022_022

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



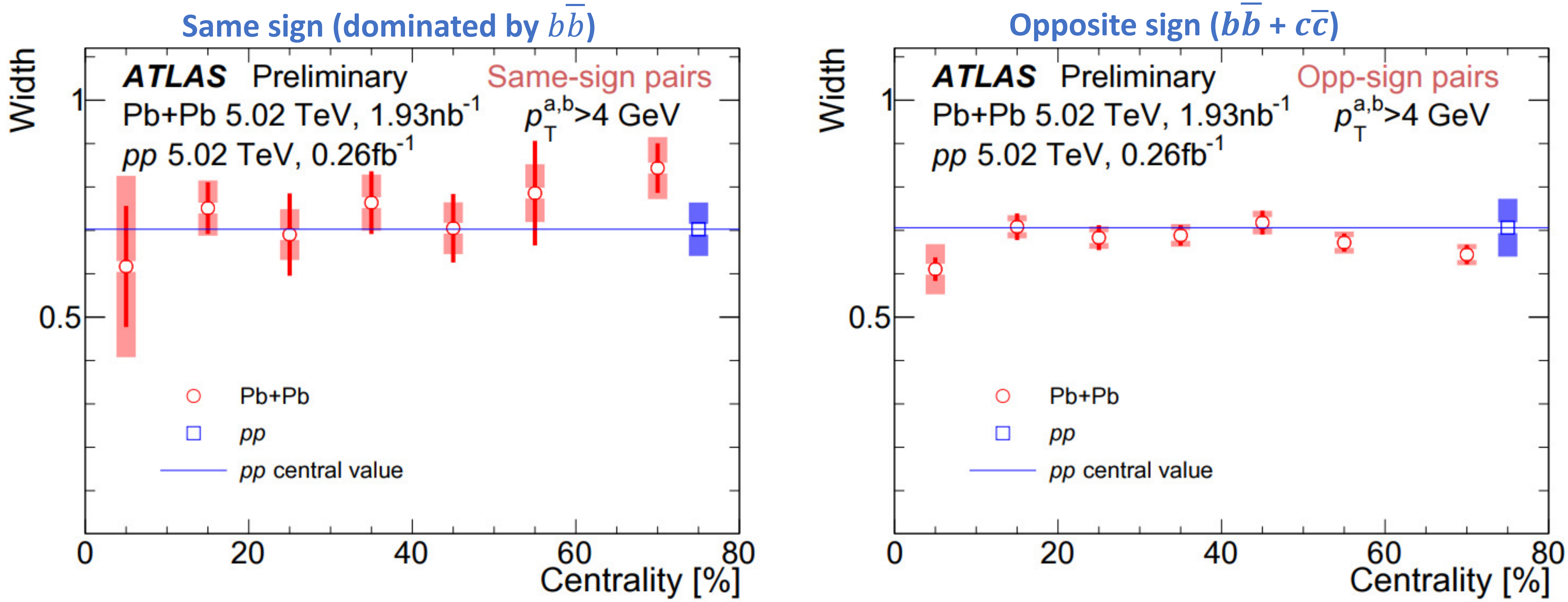
Opposite sign ($b\bar{b}$ + $c\bar{c}$)



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

Di-muon correlation: width

CONF_2022_022

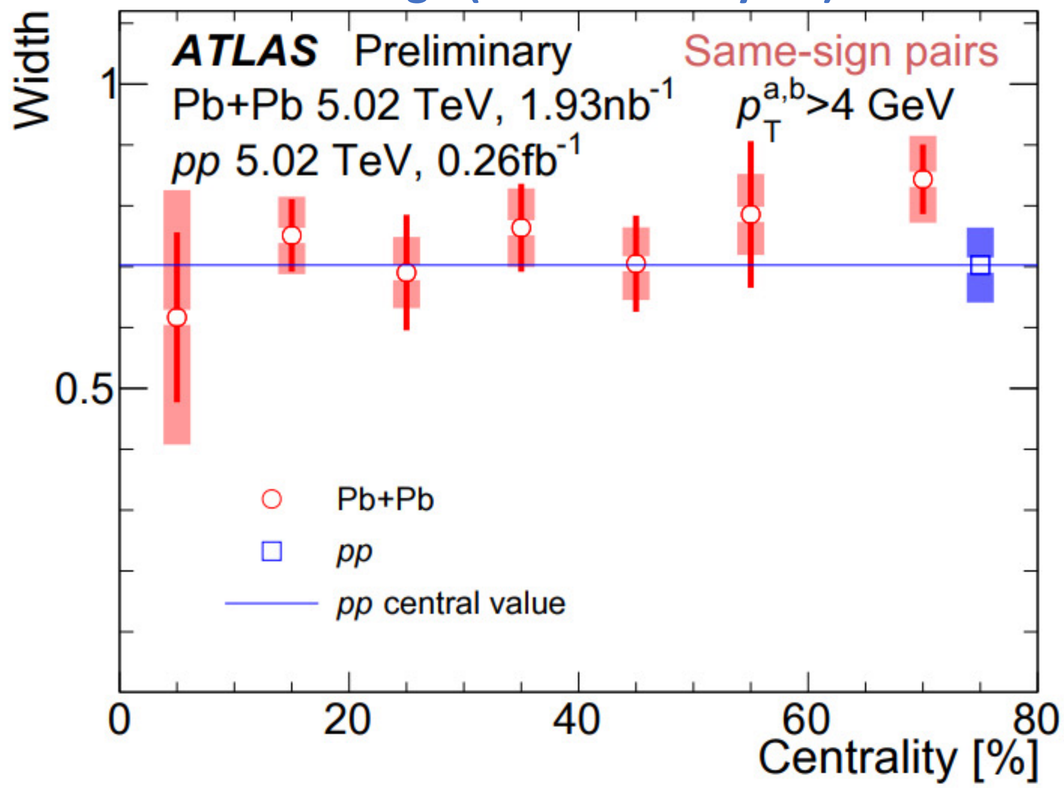


- Centrality-independent width indicates no significant change in the width.

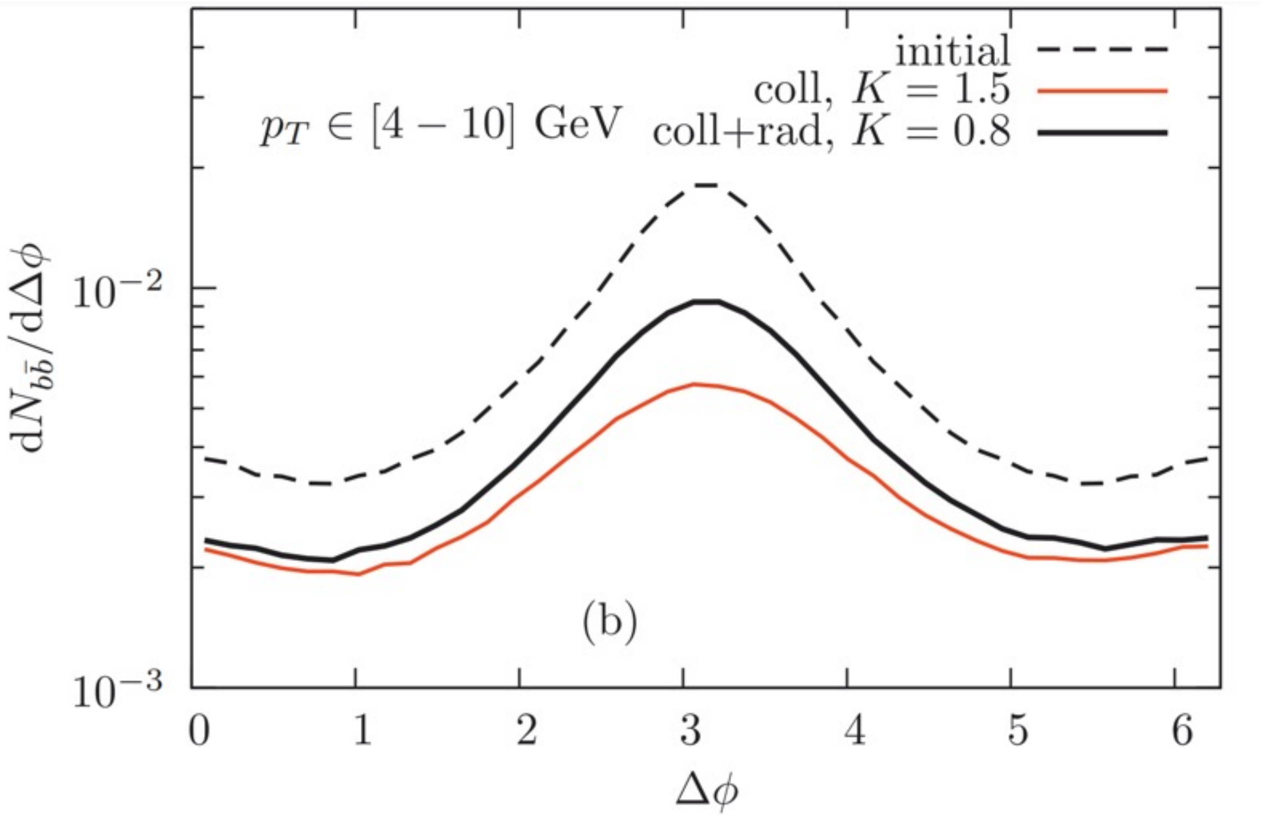
Di-muon correlation: width

CONF_2022_022

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



Theory prediction for broadening



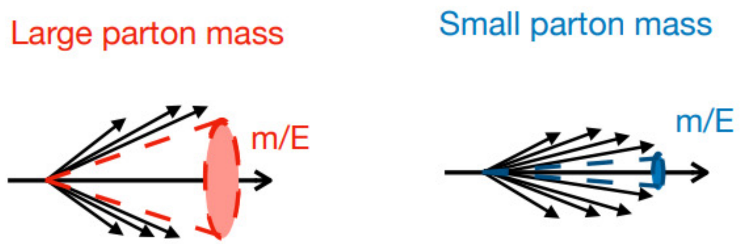
- Both collisional and collisional + radiative lead to the broadening <- not observed
  - Although with the radiative, the broadening is weaker.

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

b-jets vs inclusive jets

HION_2018_24

- *b*-jets (quark jets) are expected to lose less energy via radiation compared to gluon-initiated jets.



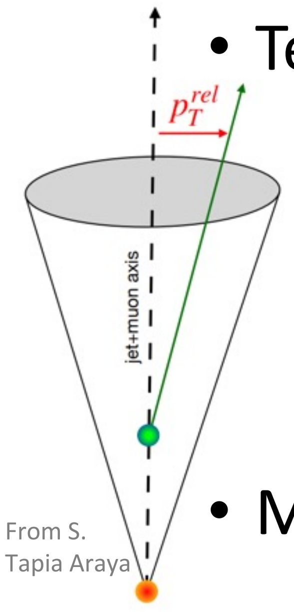
- Due to the dead-cone effect, radiation is suppressed for *b* compared to lighter quarks.

➢Both reduce the (radiative) energy loss.

b-jet signal extraction

HION_2018_24

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



From S. Tapia Araya

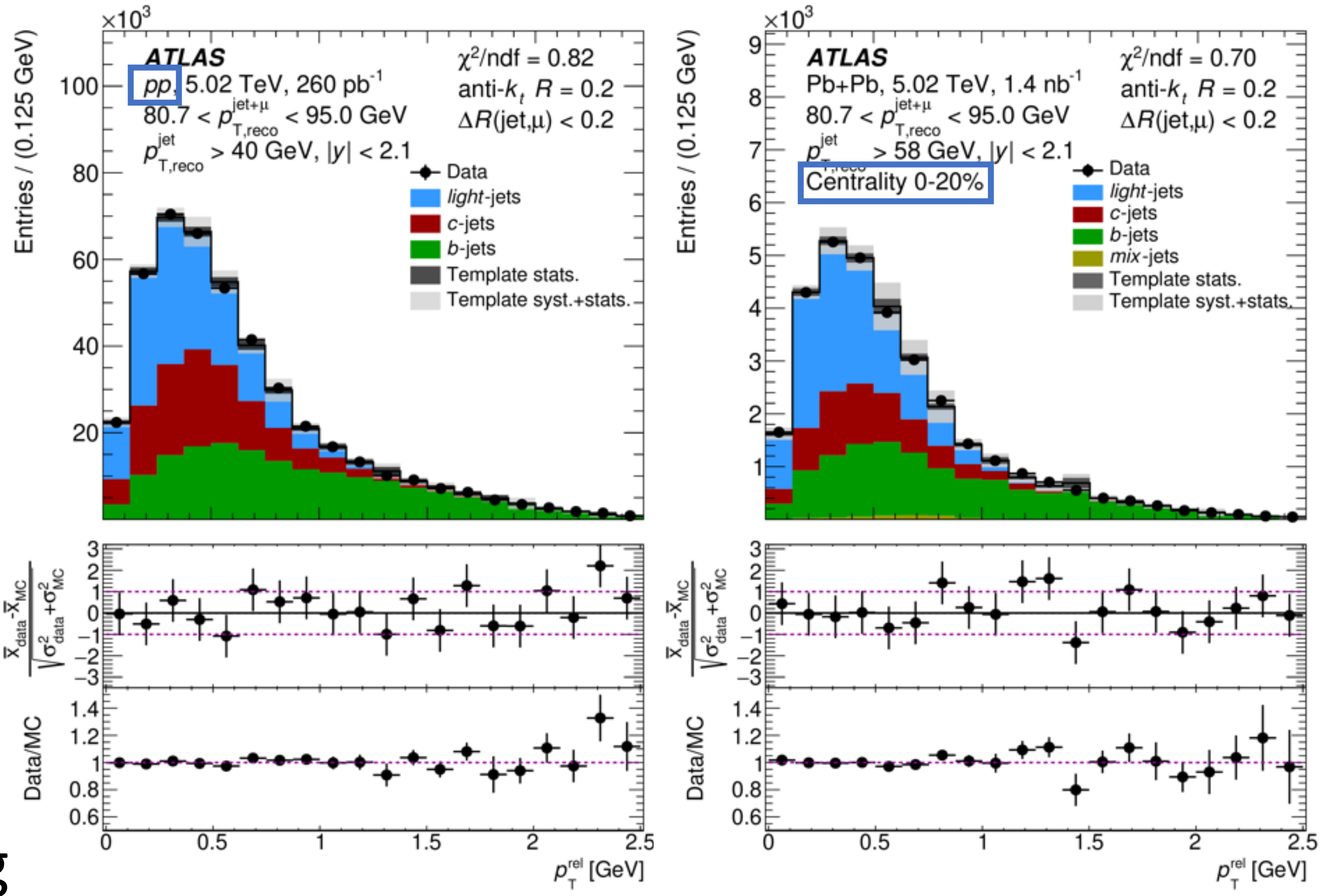
- Template fit:
  - Jet + μ axis:

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

  - Muon p_{T} projection:

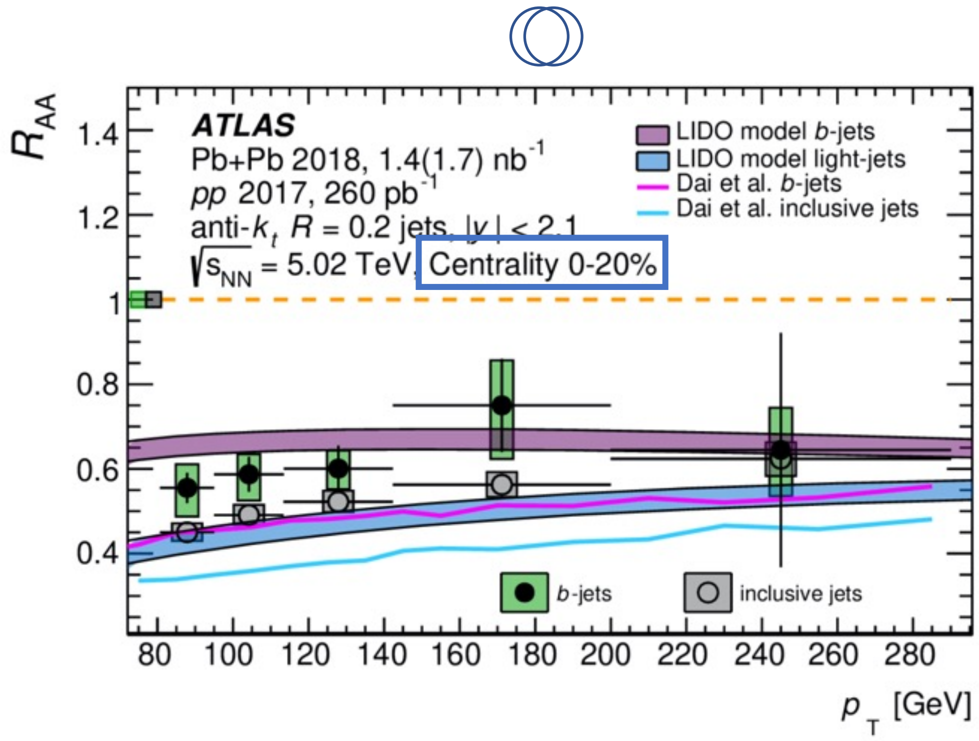
$$p_{\mathrm{T}}^{\mathrm{rel}} = \left|\vec{p}_{\mathrm{T}}^{\,\mu} \times \vec{u}_{\mathrm{T}}^{\,\mathrm{jet}+\mu}\right|$$

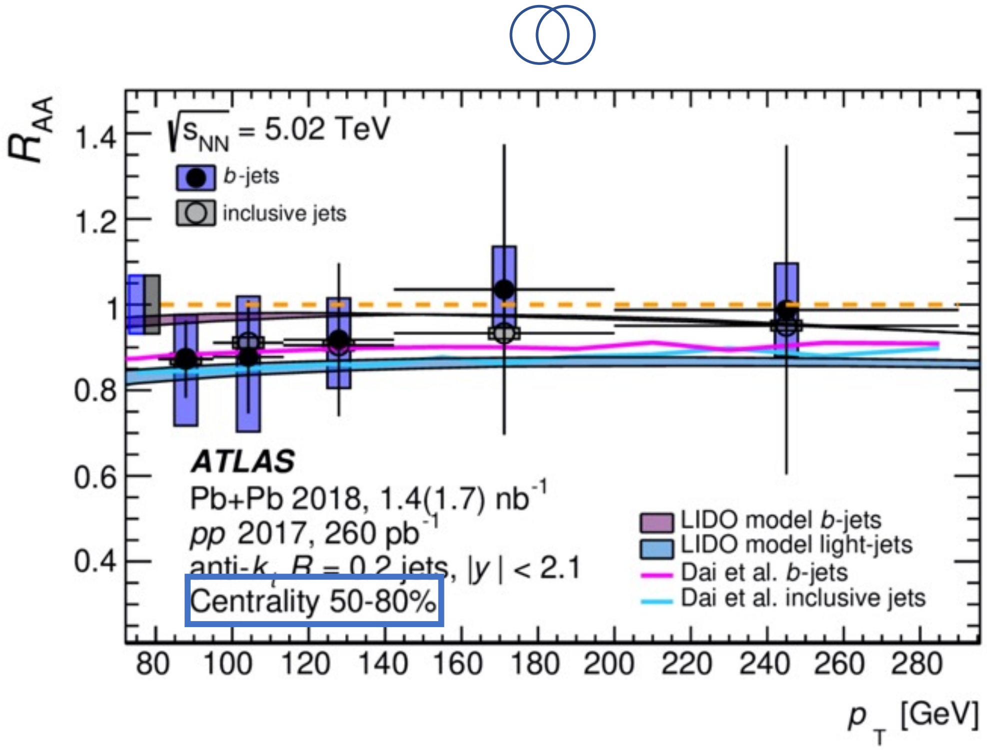
- Muon candidates:
  - $p_{\mathrm{T}} > 4$ GeV
  - Within the jet cone (R)
- Pb+Pb combinatoric term estimated from event mixing



Nuclear modification factor

HION_2018_24

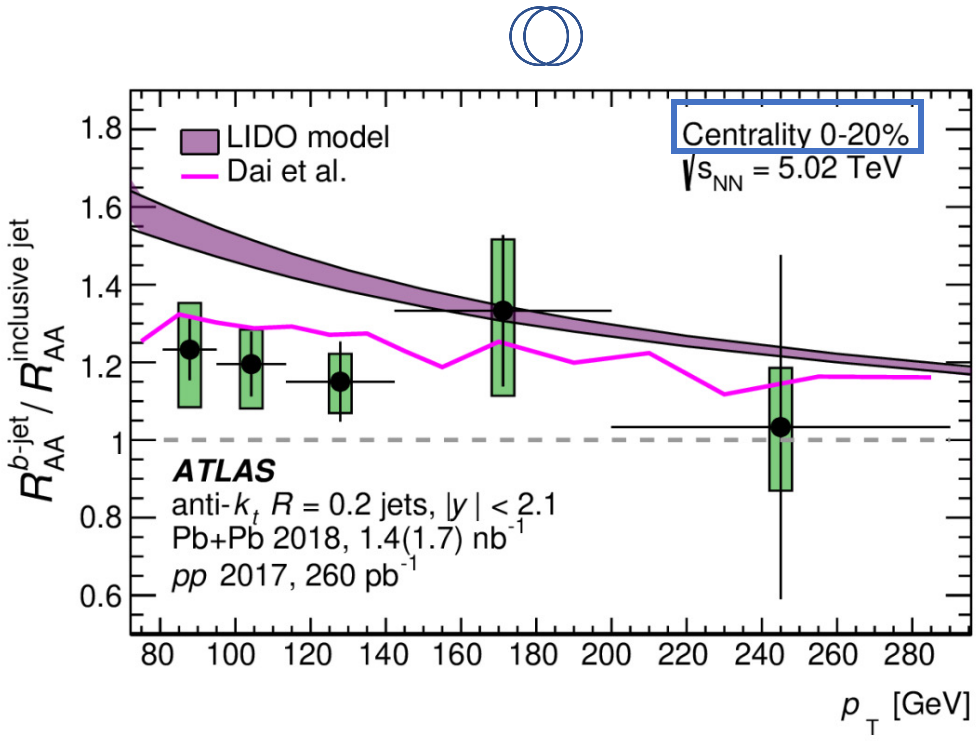


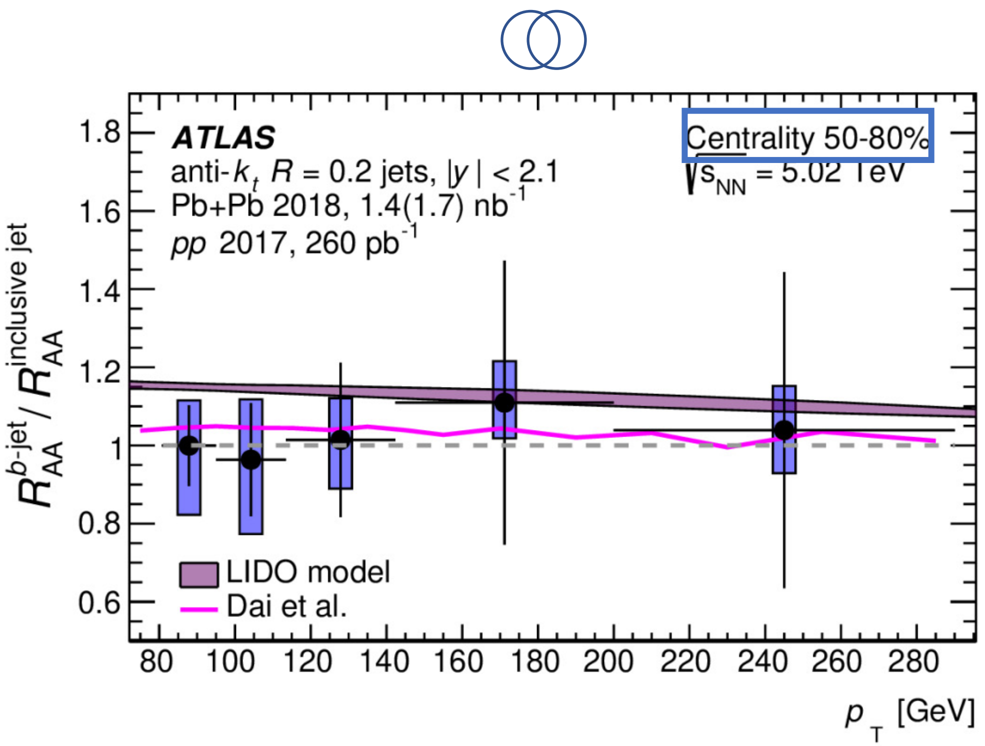


- Both b-jets and inclusive jets are suppressed, especially in more central collisions.
- b-jets are less suppressed compared to inclusive jets in central collisions.

Double ratio

HION_2018_24



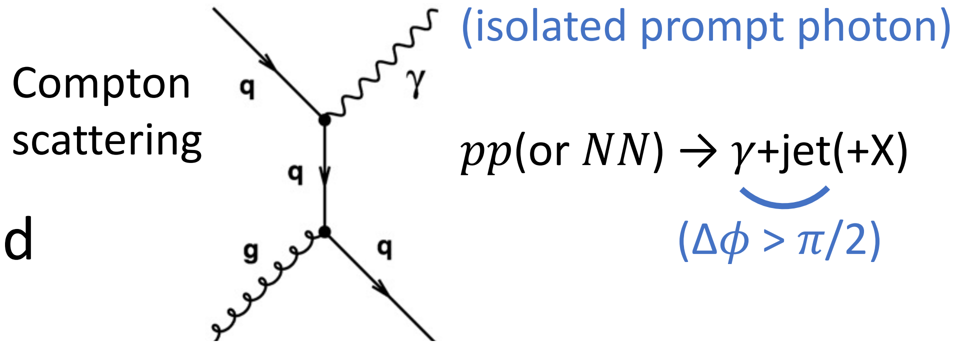


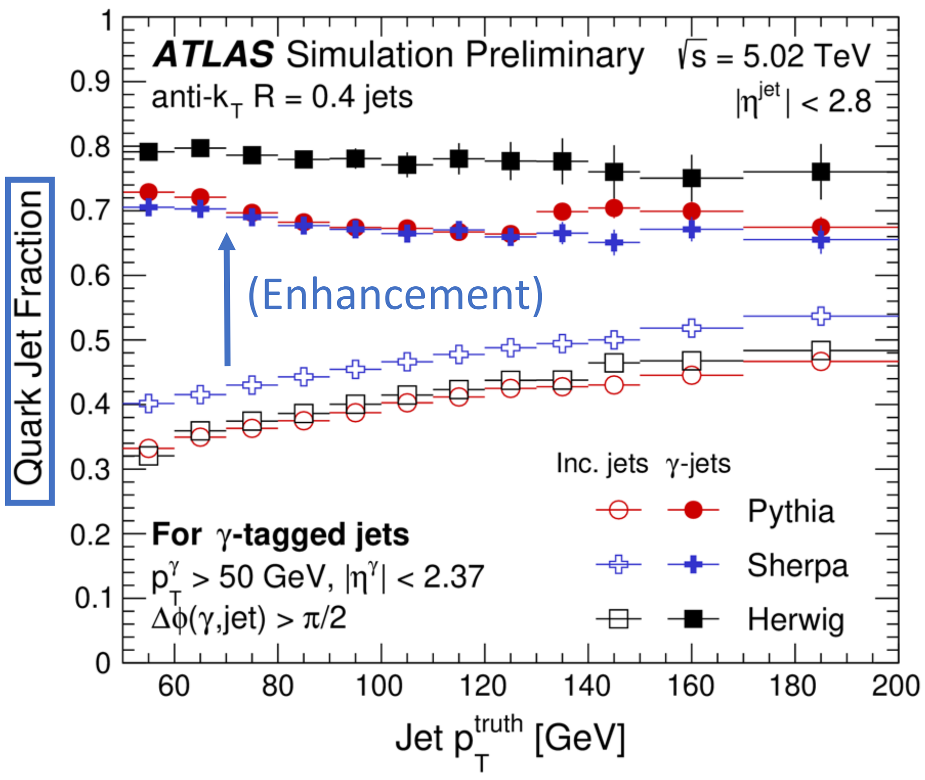
- Some common uncertainties are cancelled out in the double ratio.
- The double ratio is consistent with unity in peripheral and about 20% above unity in central collisions.
- b-jets are less suppressed compared to inclusive jets in central collisions.
- Is it a color effect or a mass effect (dead cone)?

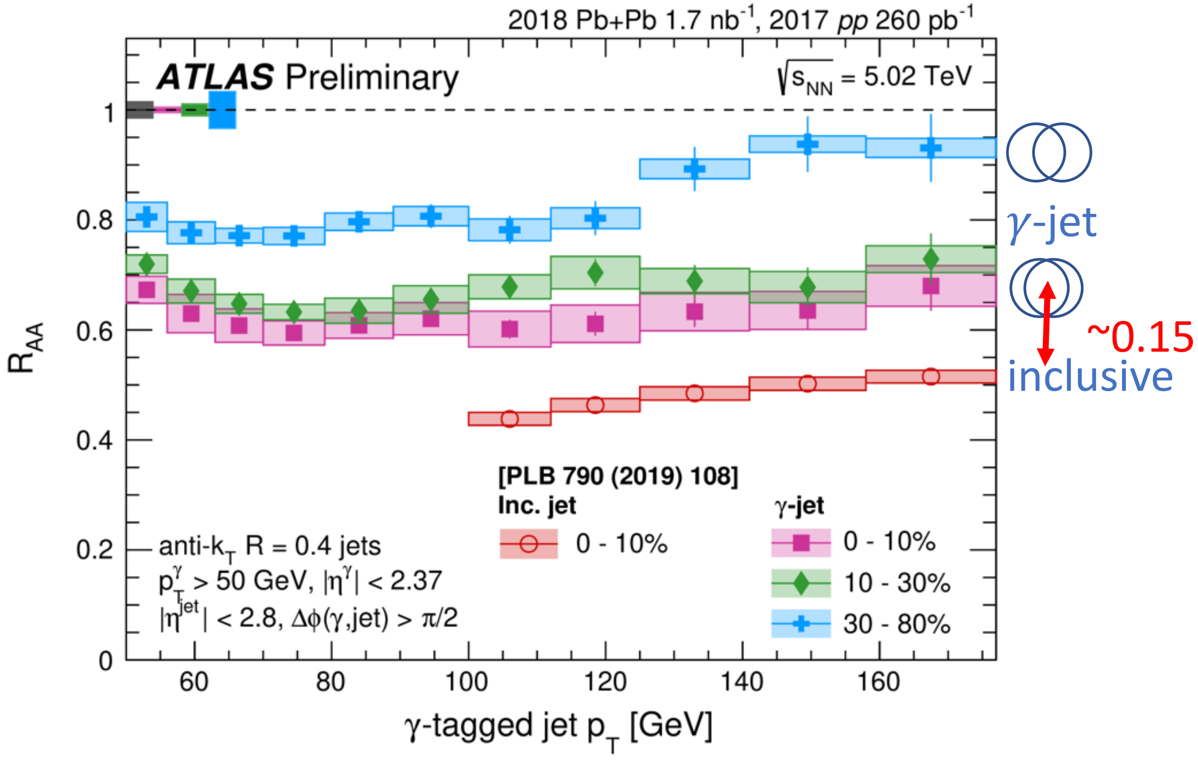
Photon-tagged jets vs inclusive jets

CONF-2022-019

- Photon-tagged jets:
  - More likely to be initiated by a quark
  - Colorless photon not significantly modified by the QGP

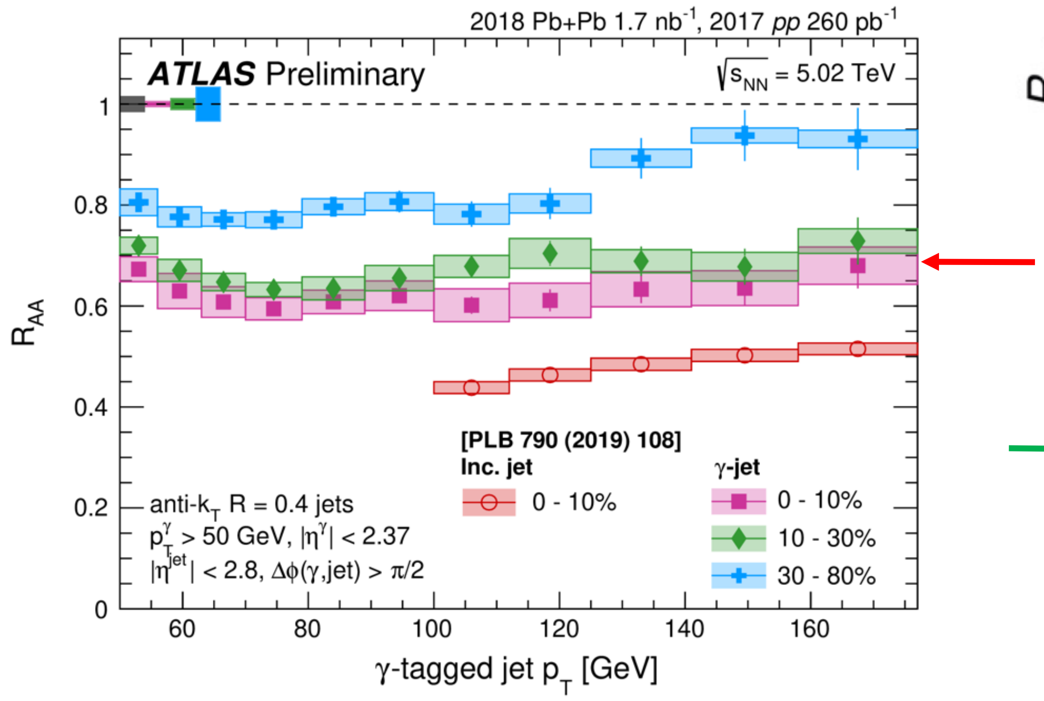


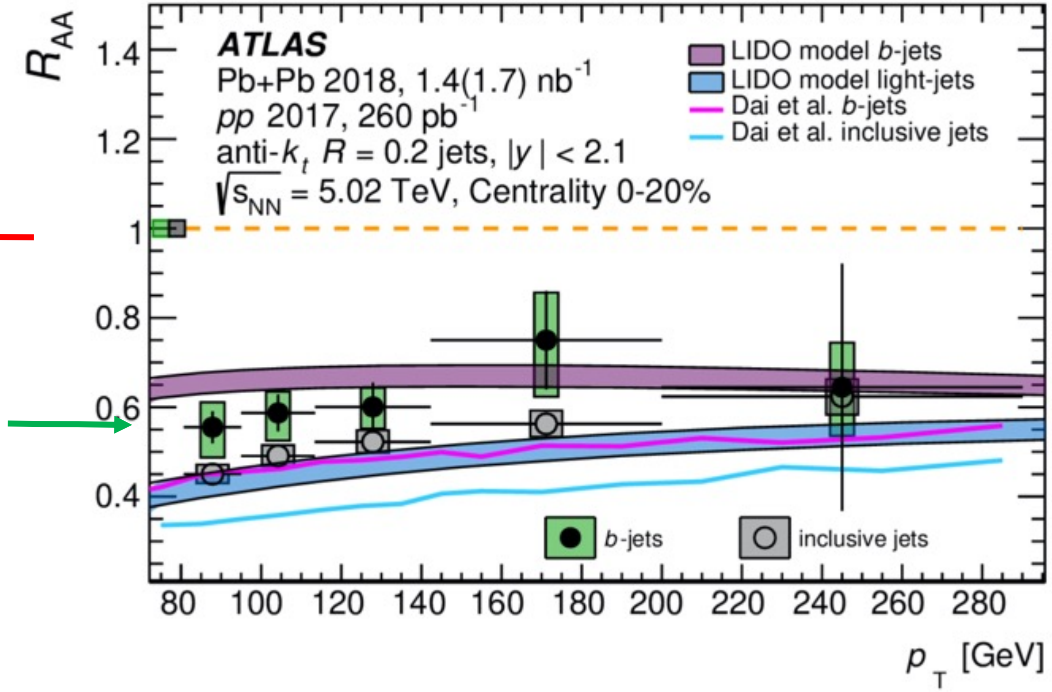




Photon-tagged jets vs *b*-jets

CONF-2022-019

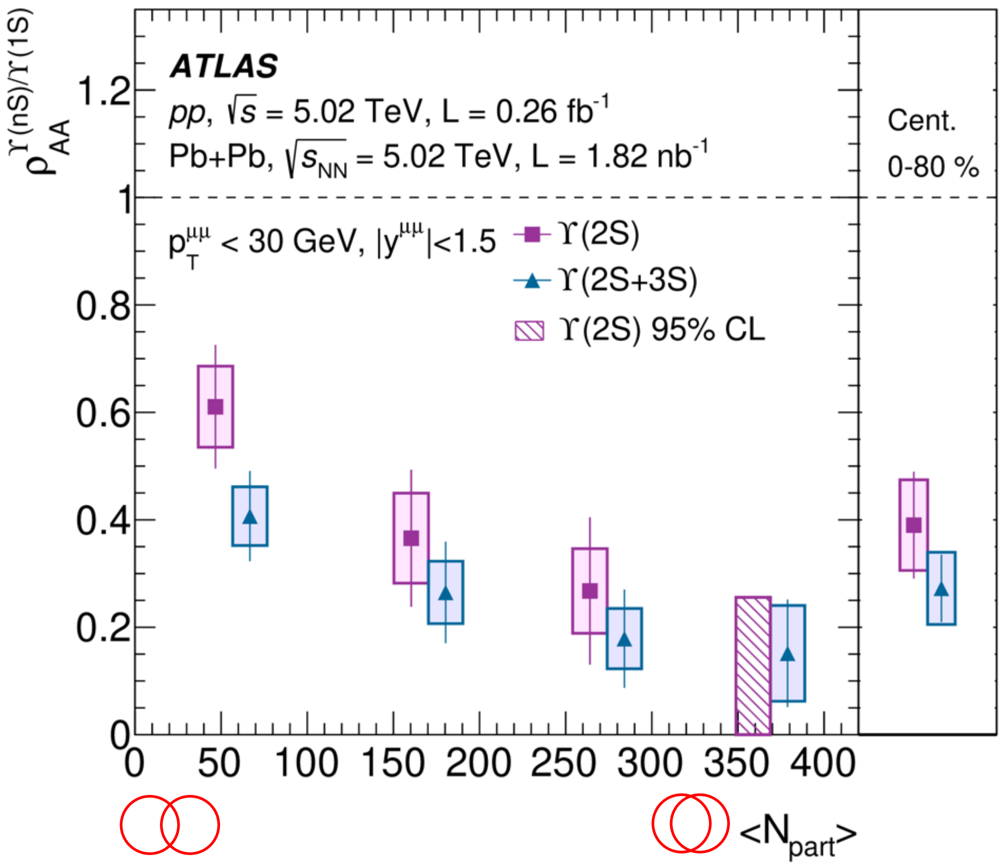


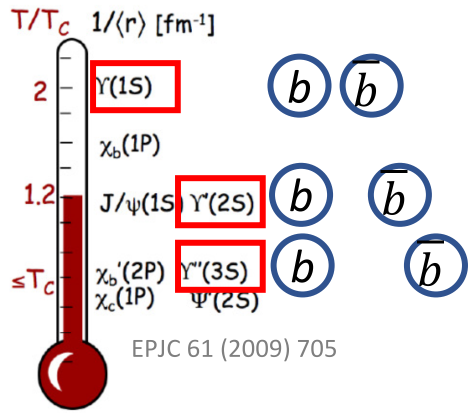


- *b*-jets and photon-tagged jets are close (e.g.: ~0.6 at 100 GeV).
- This might be a sign that *b*-jets are less suppressed more because of the color-charge effect than the parton mass (dead cone) effect.
  - *b*-jet spectrum falls more steeply so close R_{AA} might indicate a smaller energy loss.
  - Isospin/nPDF effect reduces the Compton scattering in Pb+Pb -> γ-jet R_{AA} decreases by ~0.05-0.1.

Summary

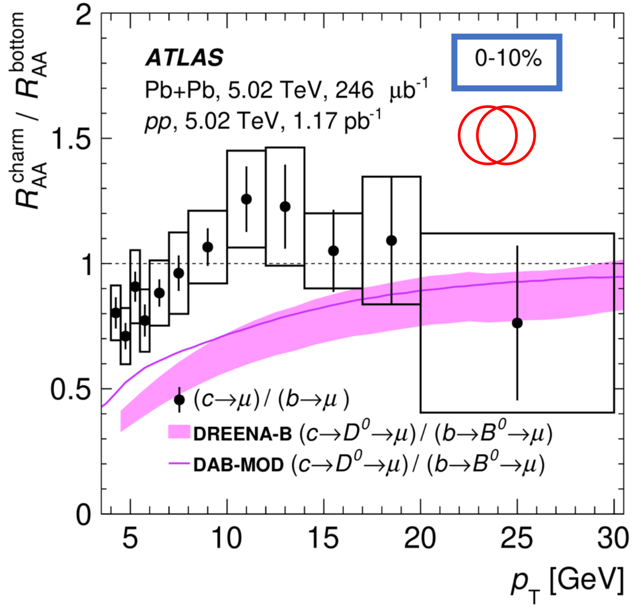
- Quarkonium:
  - Sequential suppression for the three Υ states observed.

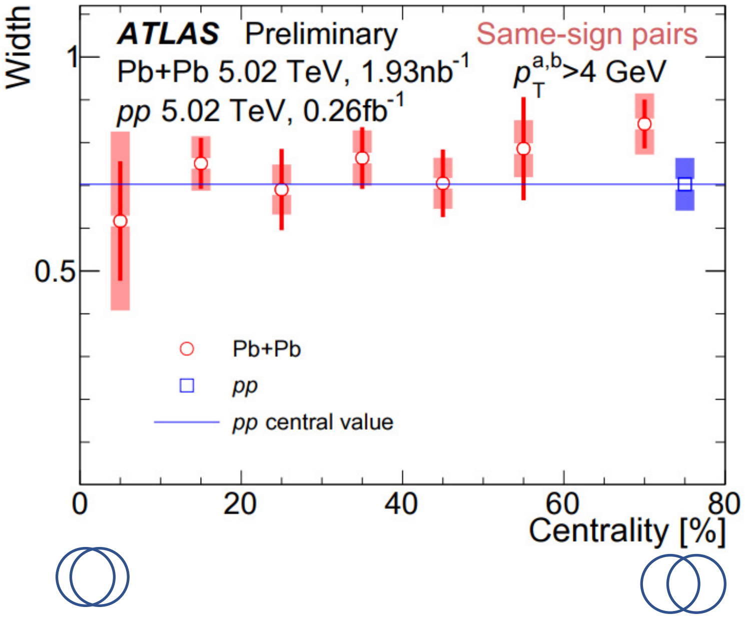


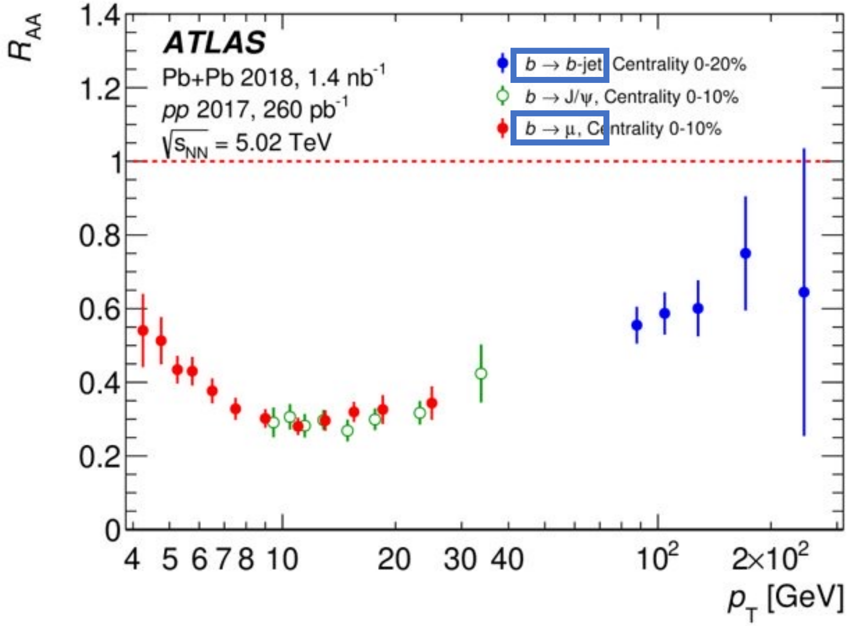


Summary

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

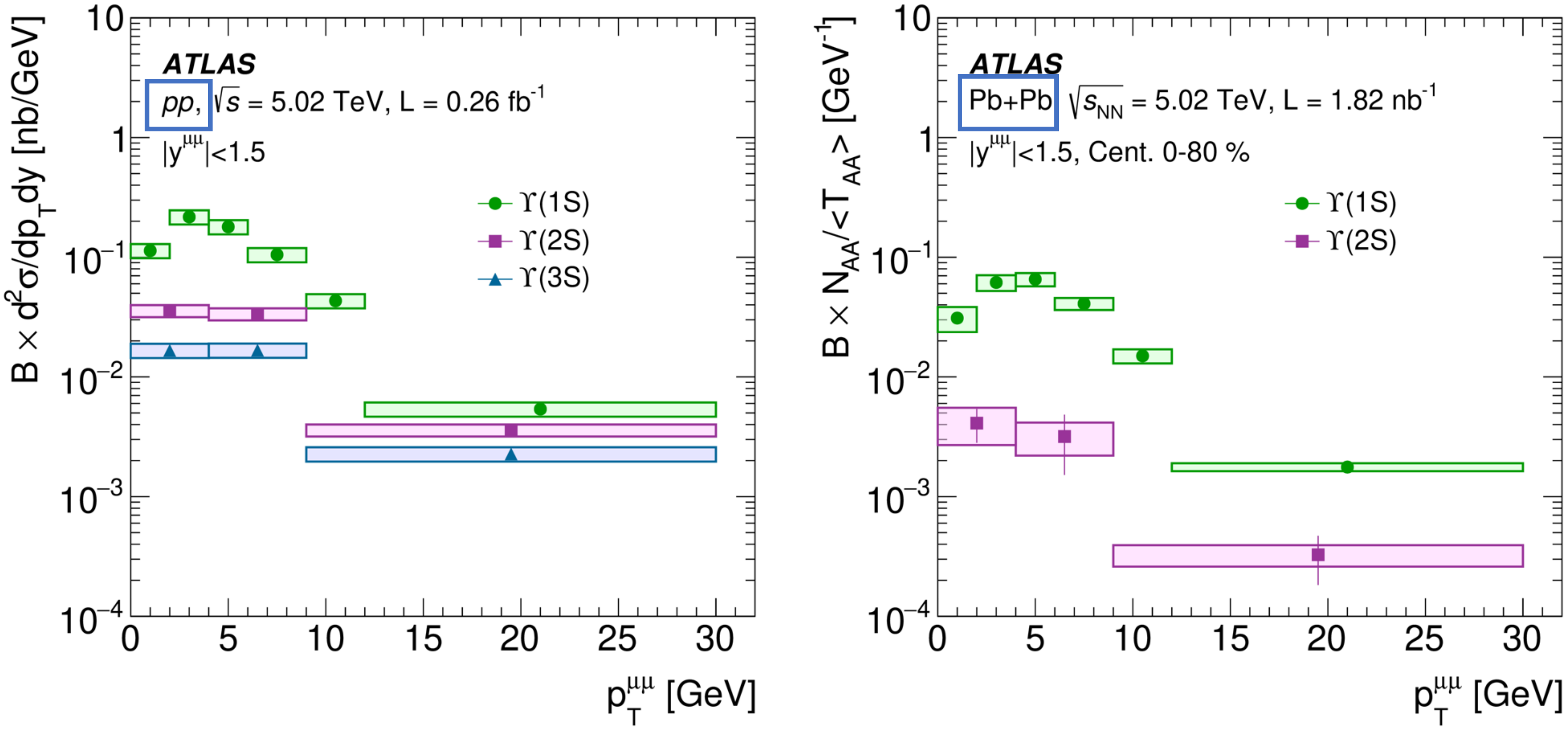






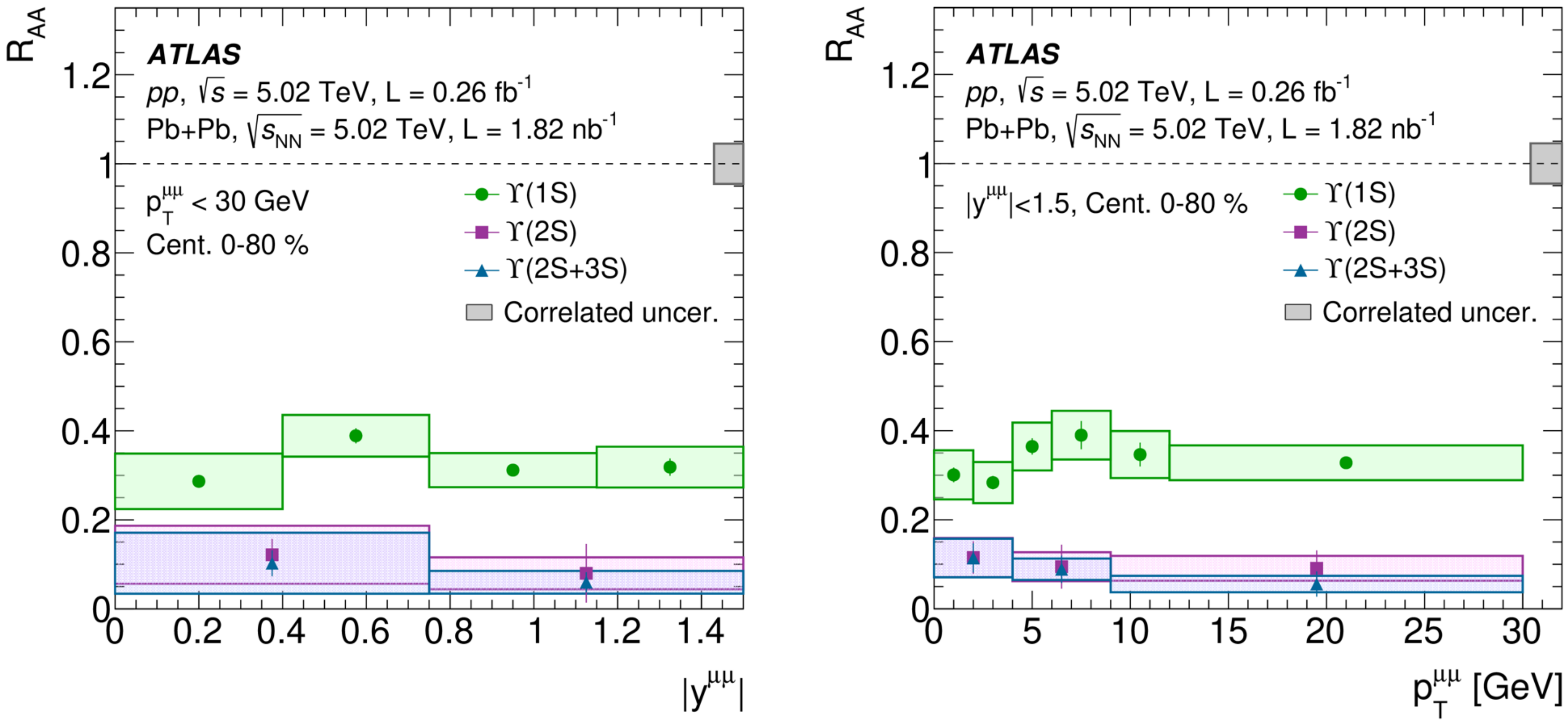
Backup

Cross-sections in *pp* and Pb+Pb



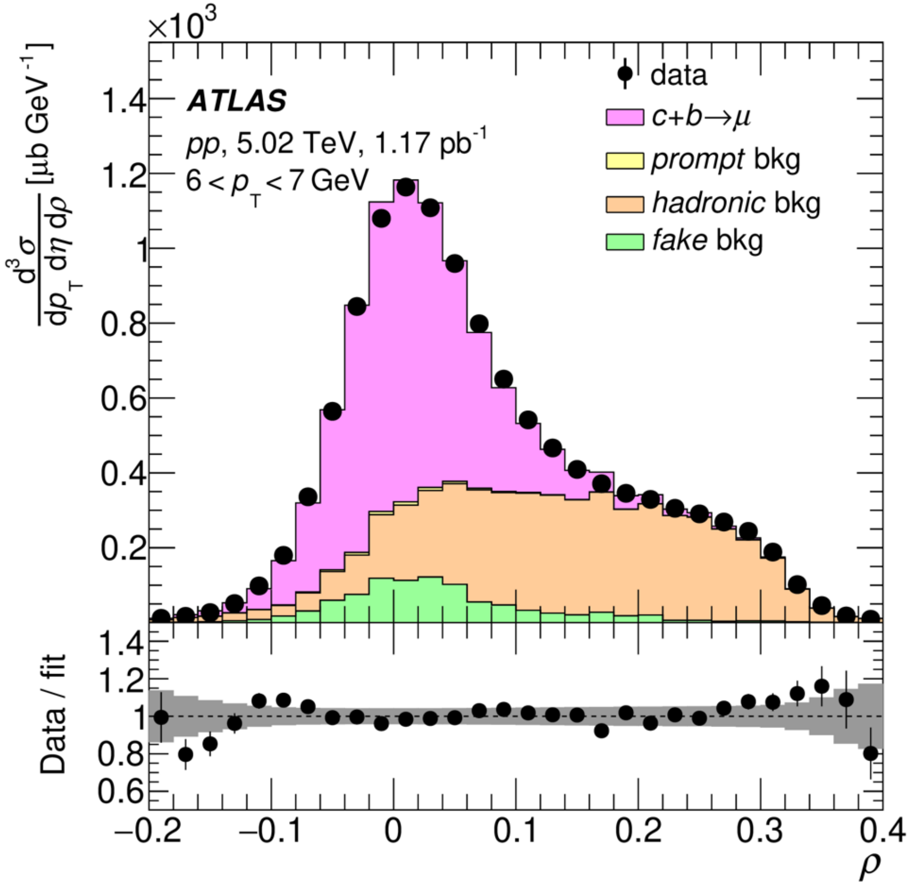
- Y(3S) not shown in Pb+Pb due to its low statistics.

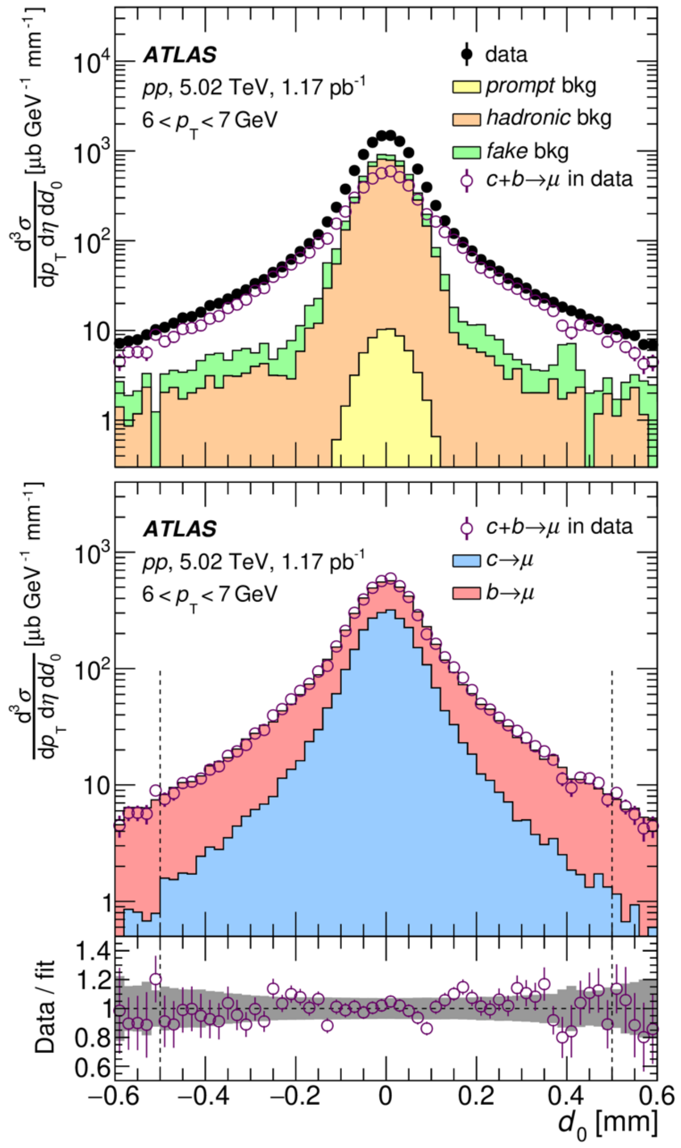
Nuclear modification factor



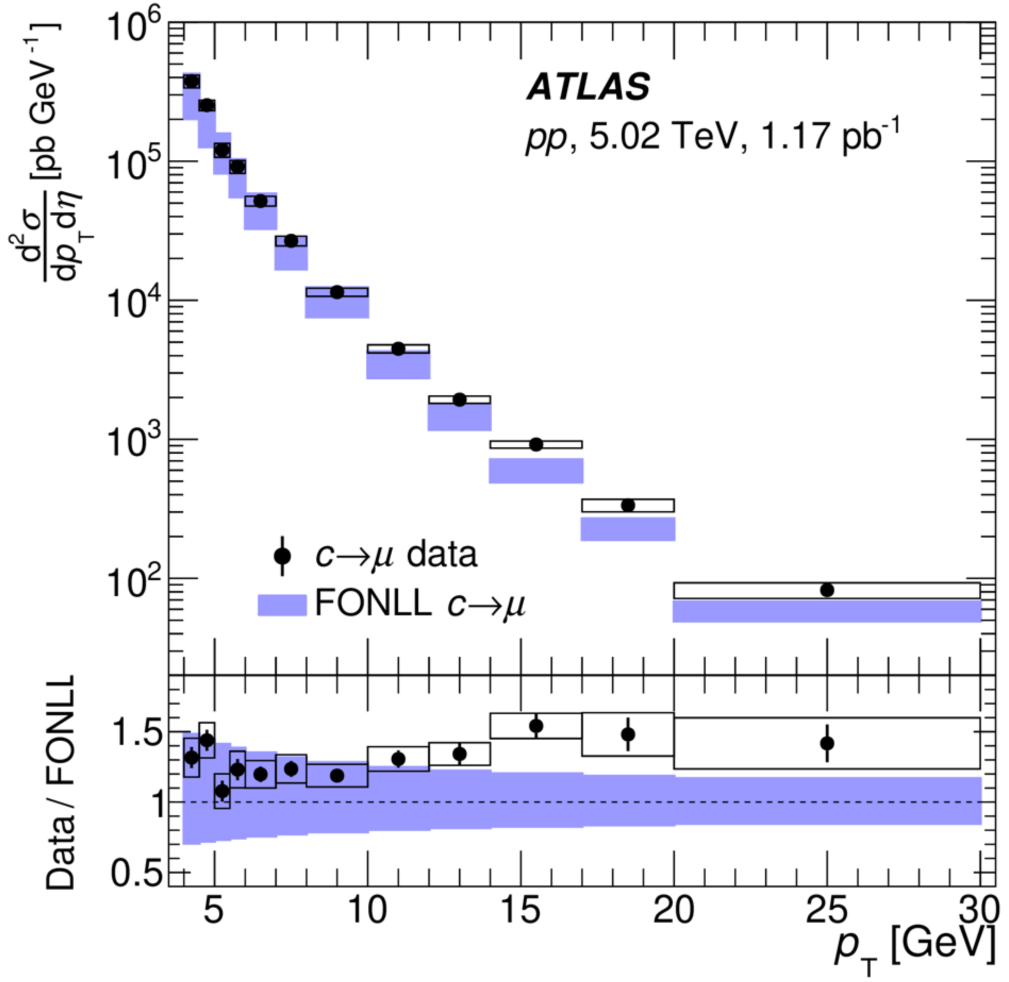
- No significant rapidity or pT dependence observed

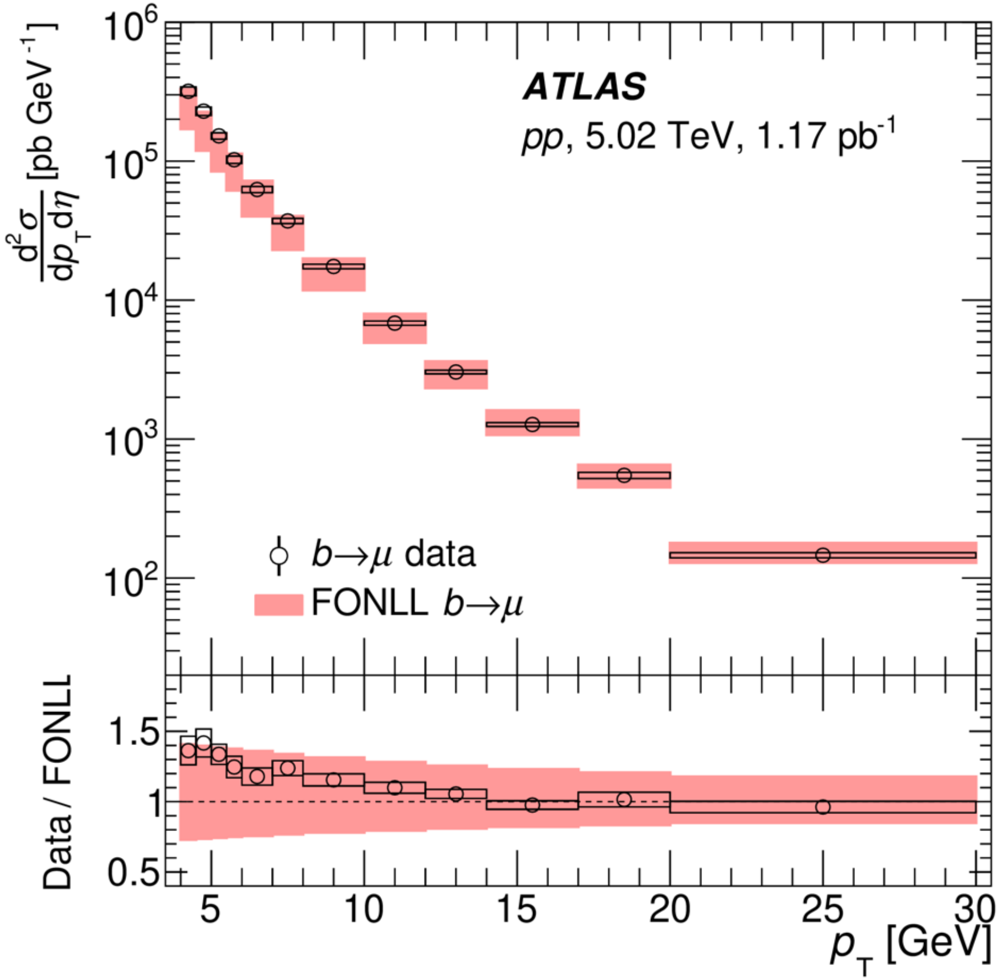
HF muon


ATLAS
pp, 5.02 TeV, 1.17 pb-1
6 < pT < 7 GeV
data
c+b→μ
prompt bkg
hadronic bkg
fake bkg
Data / fit
ρ

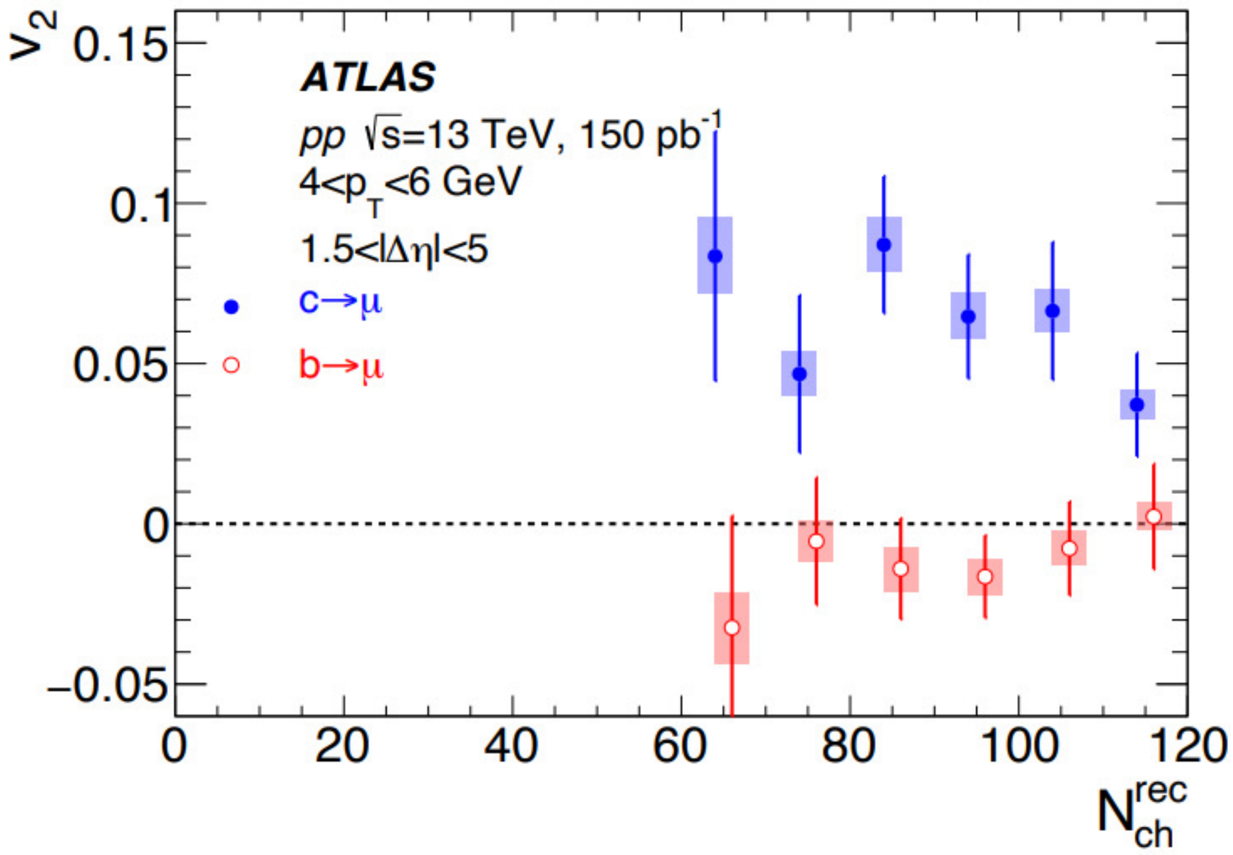

ATLAS
pp, 5.02 TeV, 1.17 pb-1
6 < pT < 7 GeV
data
prompt bkg
hadronic bkg
fake bkg
c+b→μ in data
c→μ
b→μ
Data / fit
d0 [mm]

pp


ATLAS
pp, 5.02 TeV, 1.17 pb-1
c→μ data
FONLL c→μ
d2σ/dpTdη [pb GeV-1]
Data / FONLL
pT [GeV]

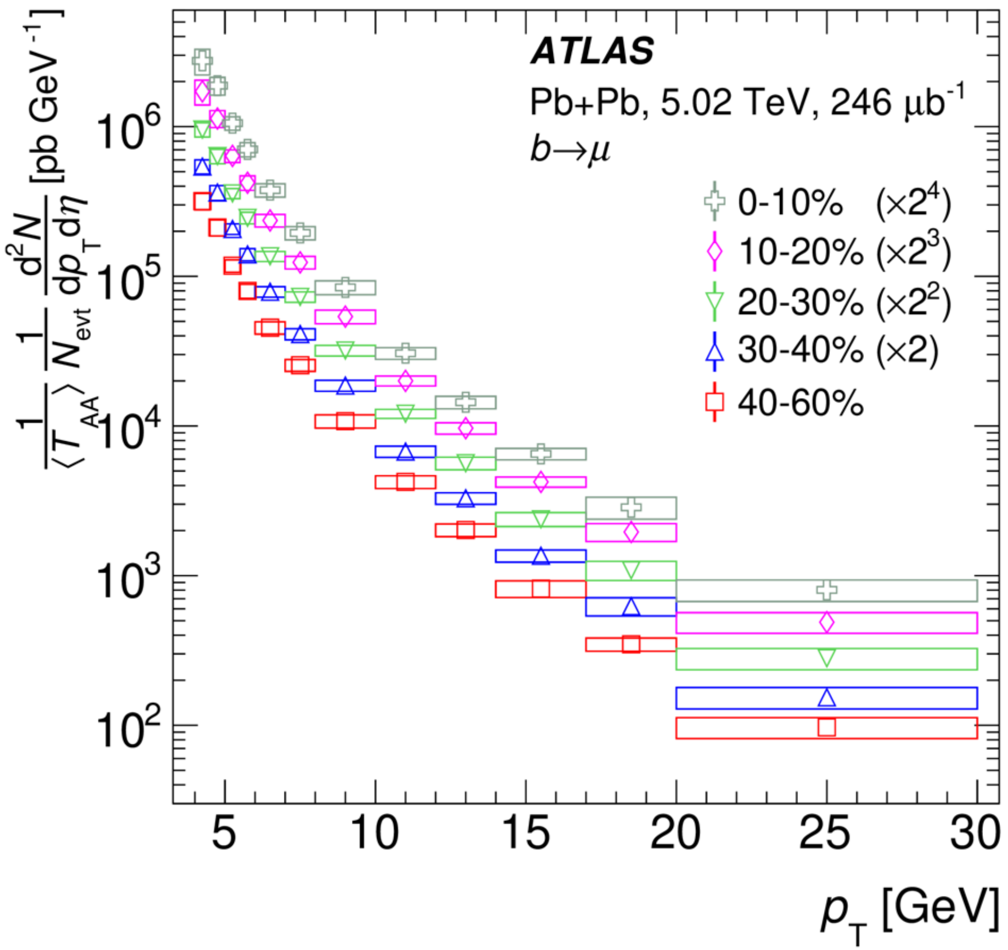

ATLAS
pp, 5.02 TeV, 1.17 pb-1
b→μ data
FONLL b→μ
d2σ/dpTdη [pb GeV-1]
Data / FONLL
pT [GeV]

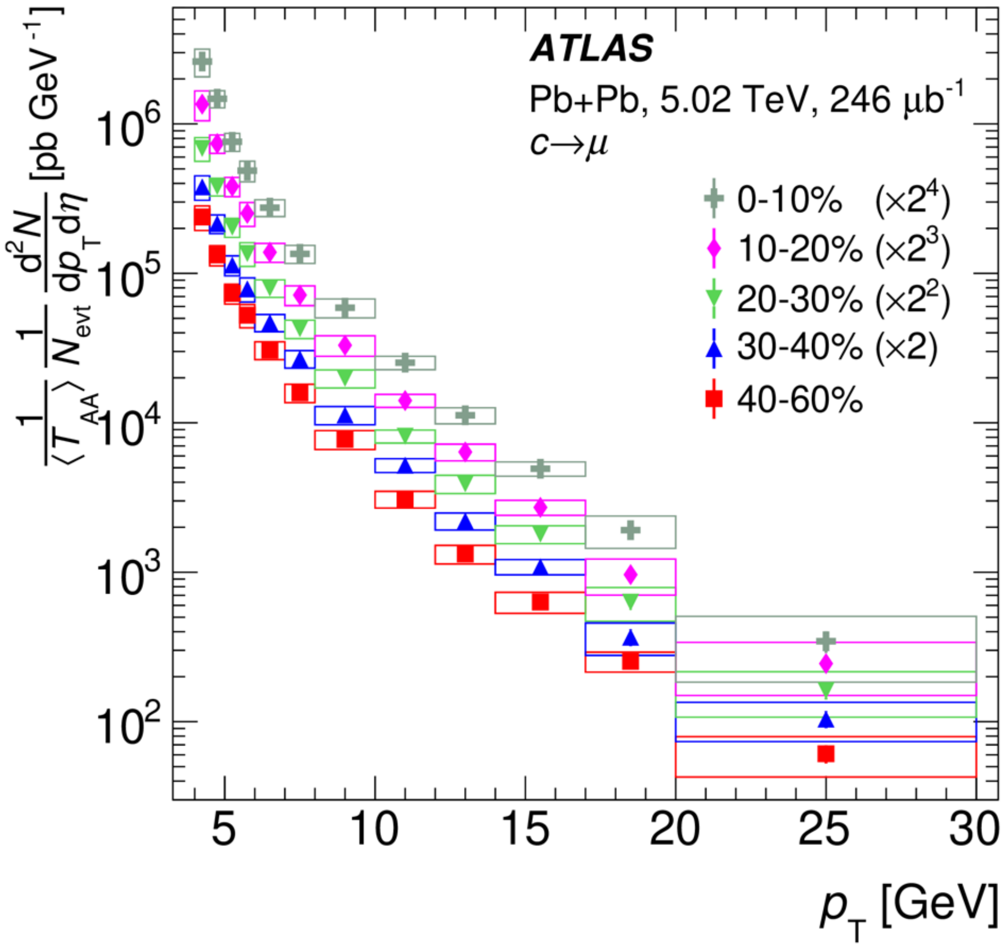
pp v2



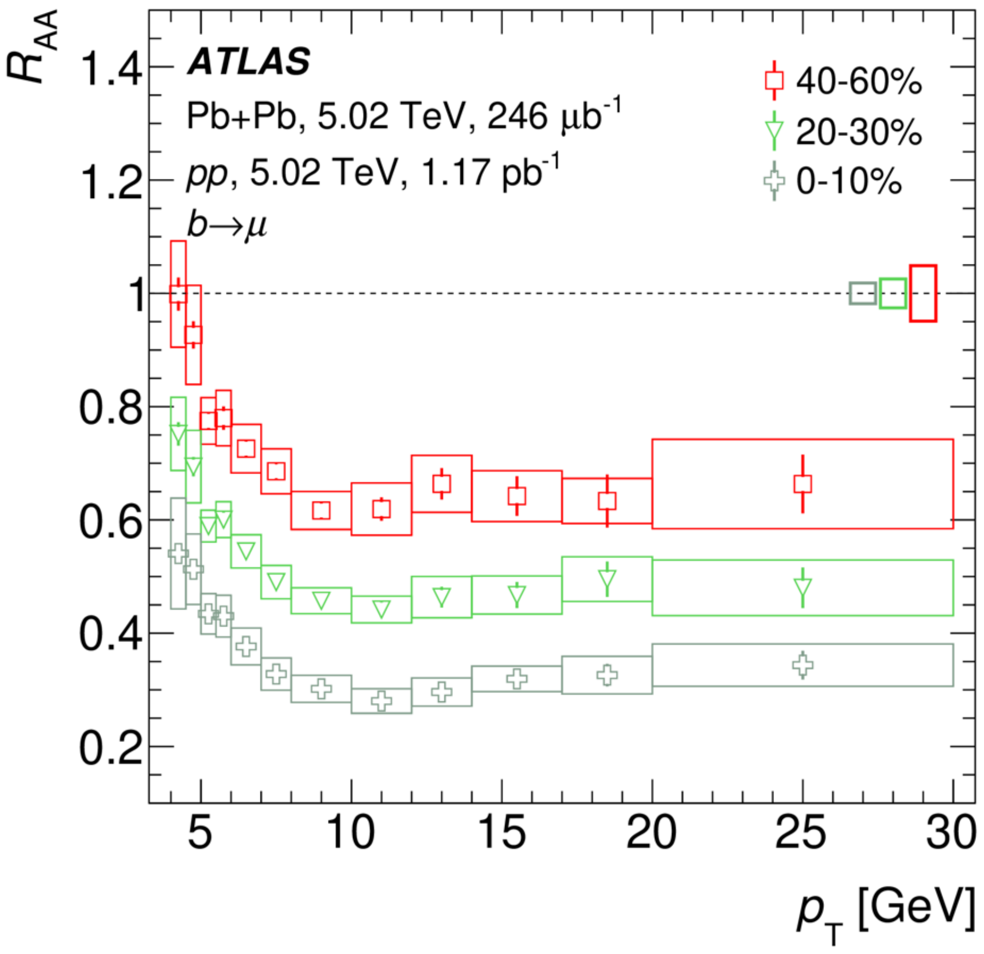
ATLAS
pp √s=13 TeV, 150 pb-1
4<pT<6 GeV
1.5<|Δη|<5
c→μ
b→μ
v2
0.15
0.1
0.05
0
−0.05
0
20
40
60
80
100
120
Nch rec

Pb+Pb

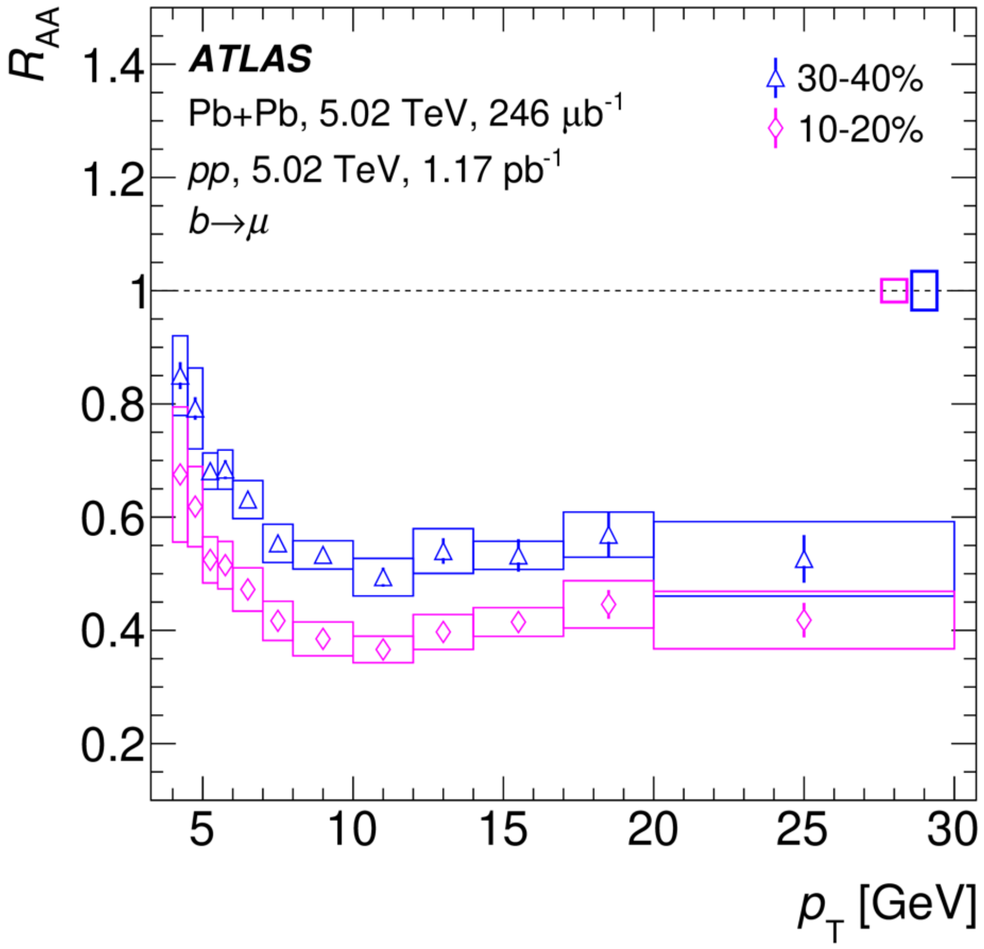

ATLAS
Pb+Pb, 5.02 TeV, 246 μb⁻¹
b→μ
0-10% (×2⁴)
10-20% (×2³)
20-30% (×2²)
30-40% (×2)
40-60%
$\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{d^2N}{dp_T d\eta}$ [pb GeV⁻¹]
p_T [GeV]


ATLAS
Pb+Pb, 5.02 TeV, 246 μb⁻¹
c→μ
0-10% (×2⁴)
10-20% (×2³)
20-30% (×2²)
30-40% (×2)
40-60%
$\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{d^2N}{dp_T d\eta}$ [pb GeV⁻¹]
p_T [GeV]

b RAA

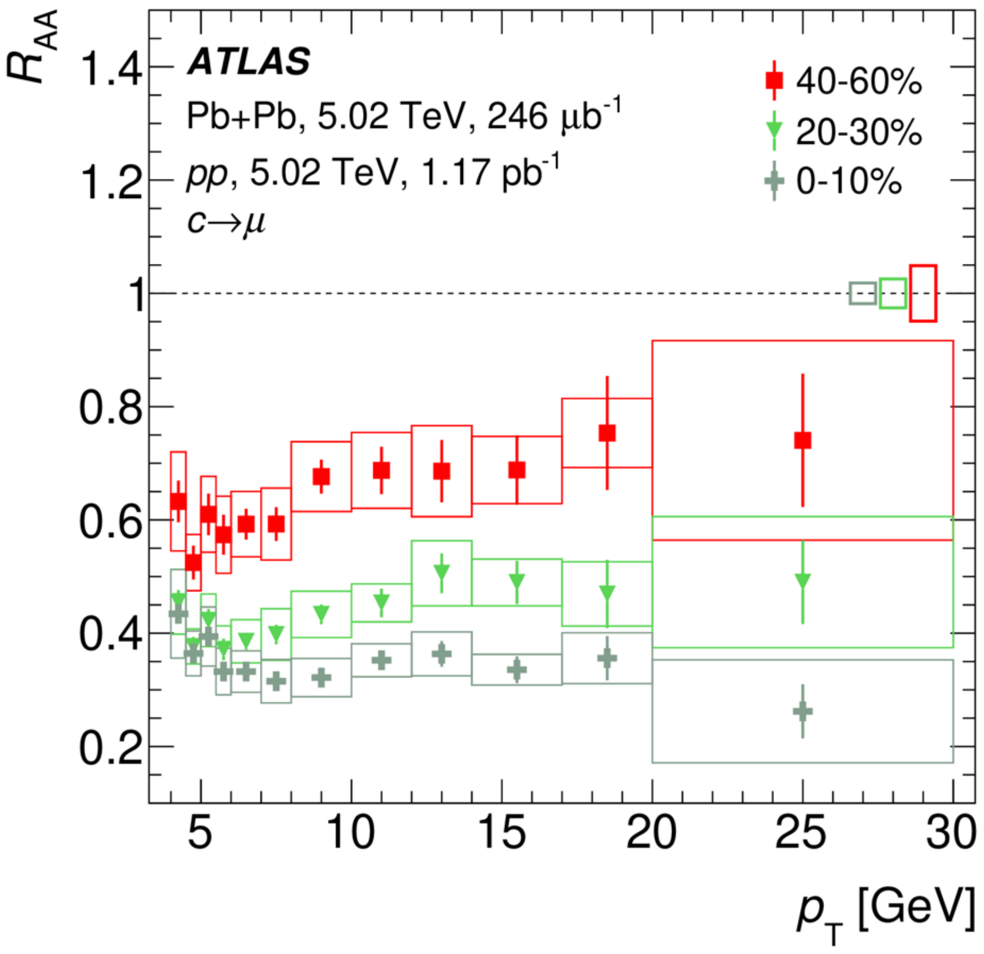


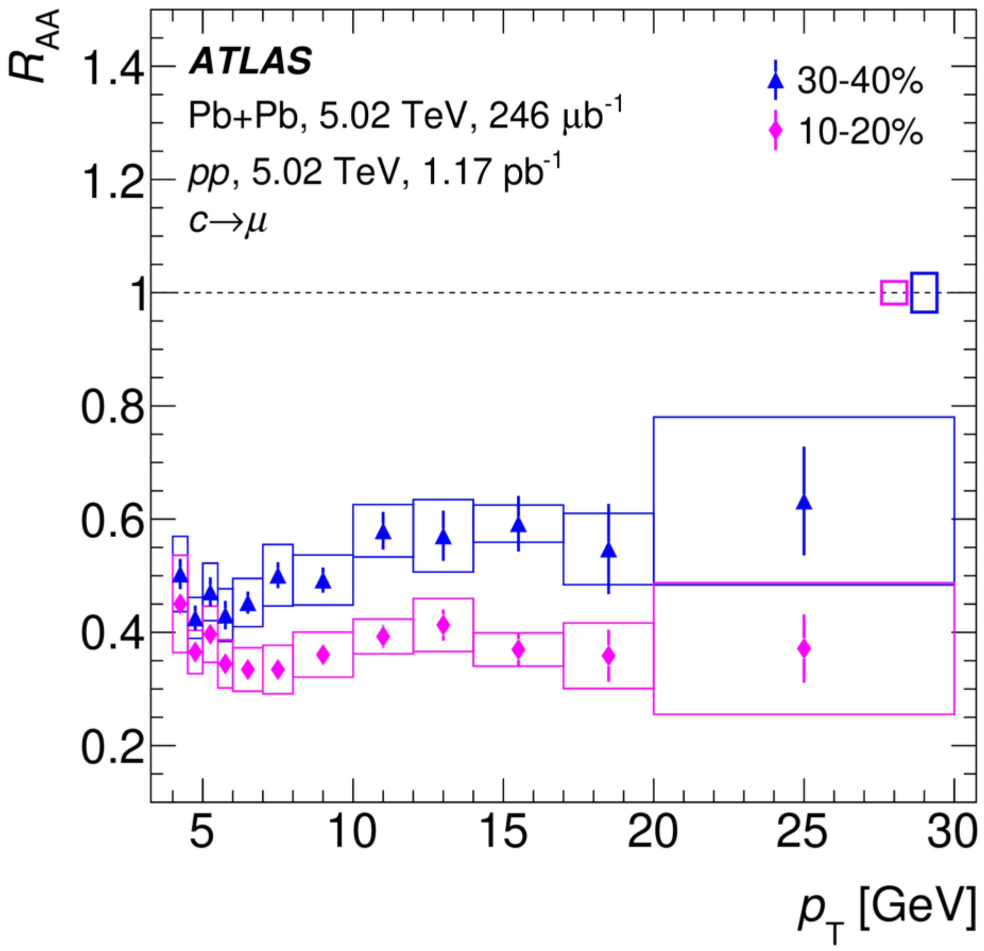
ATLAS
Pb+Pb, 5.02 TeV, 246 μb-1
pp, 5.02 TeV, 1.17 pb-1
b→μ
40-60%
20-30%
0-10%
RAA
pT [GeV]



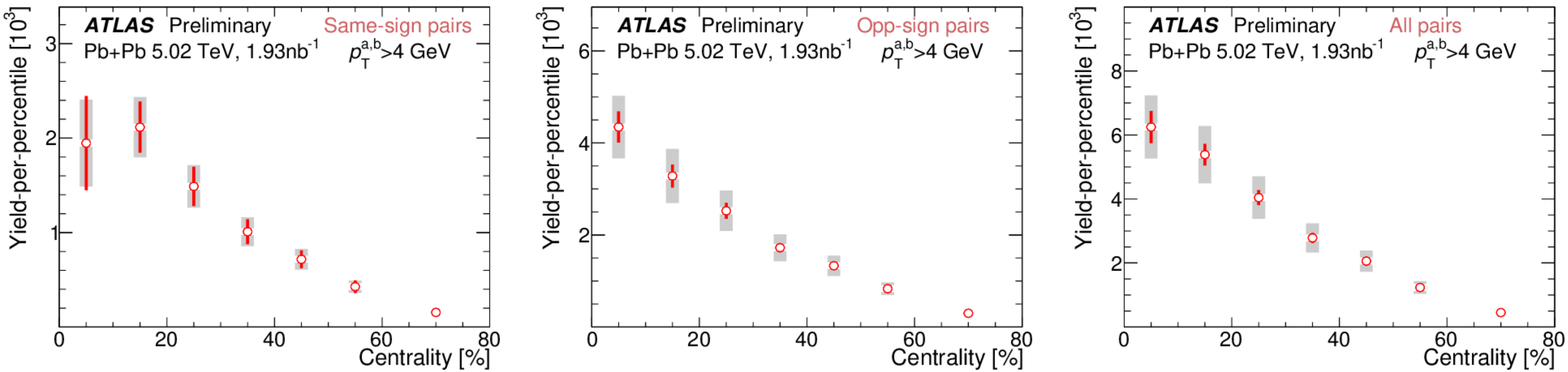
ATLAS
Pb+Pb, 5.02 TeV, 246 μb-1
pp, 5.02 TeV, 1.17 pb-1
b→μ
30-40%
10-20%
RAA
pT [GeV]

c RAA

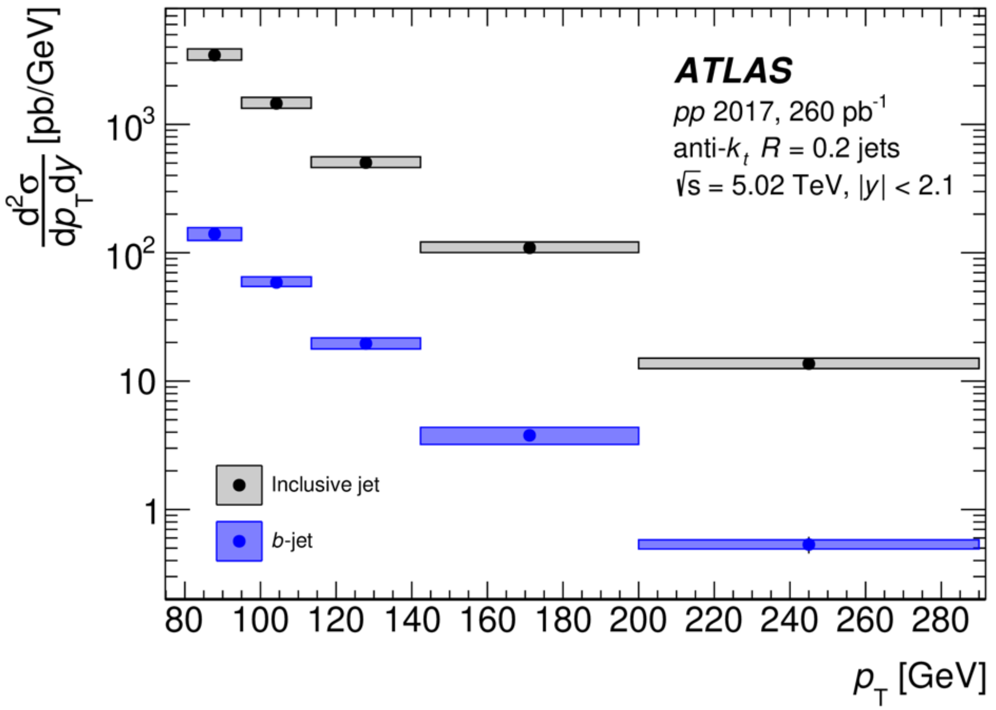

ATLAS
Pb+Pb, 5.02 TeV, 246 μb-1
pp, 5.02 TeV, 1.17 pb-1
c→μ
40-60%
20-30%
0-10%
RAA
pT [GeV]

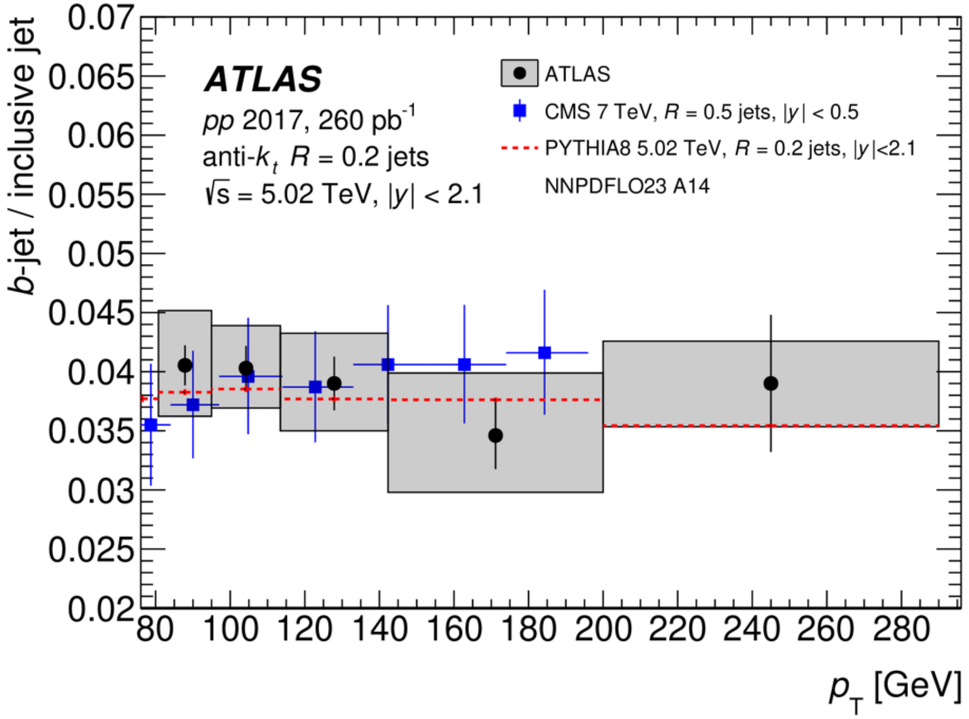

ATLAS
Pb+Pb, 5.02 TeV, 246 μb-1
pp, 5.02 TeV, 1.17 pb-1
c→μ
30-40%
10-20%
RAA
pT [GeV]

Di-muon correlation: yields



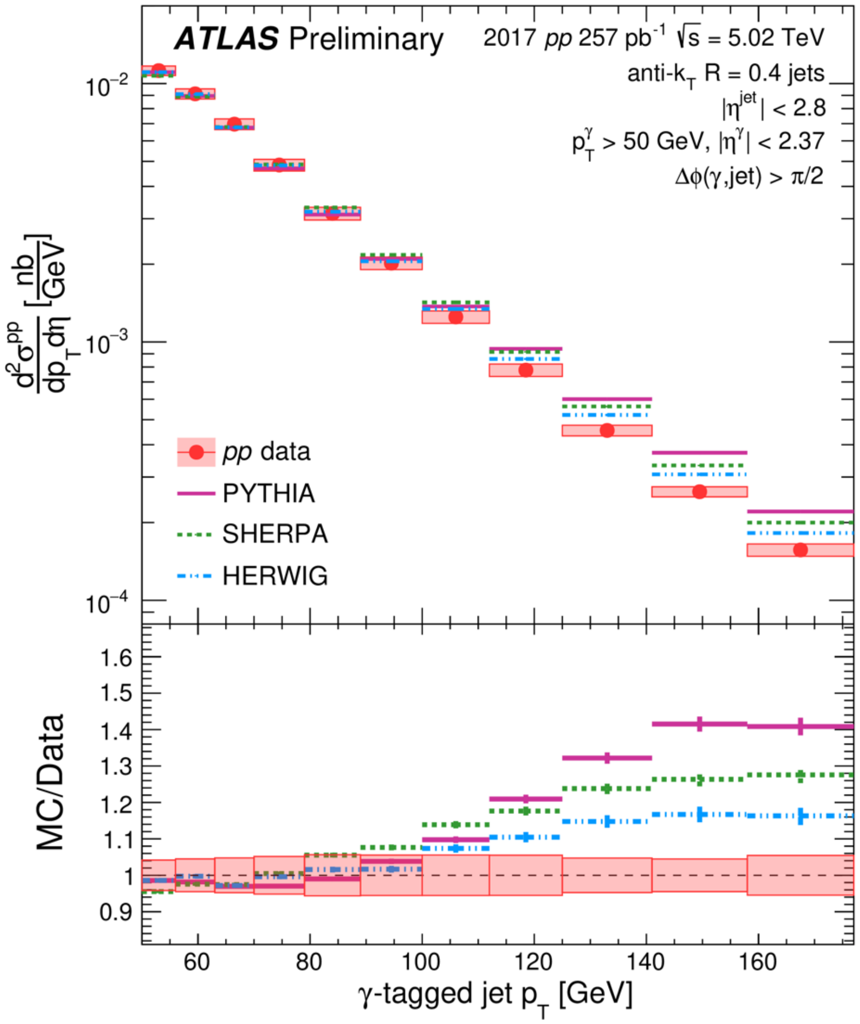
b-jet cross-sections in *pp*

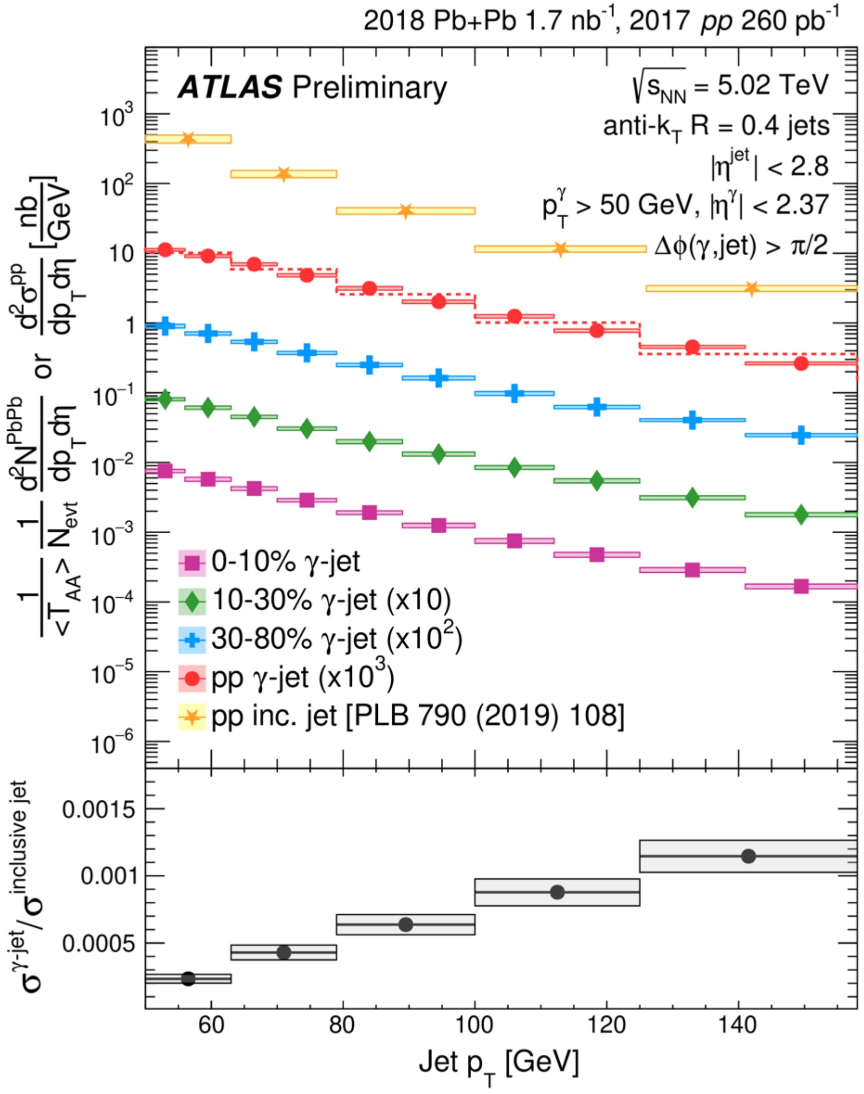




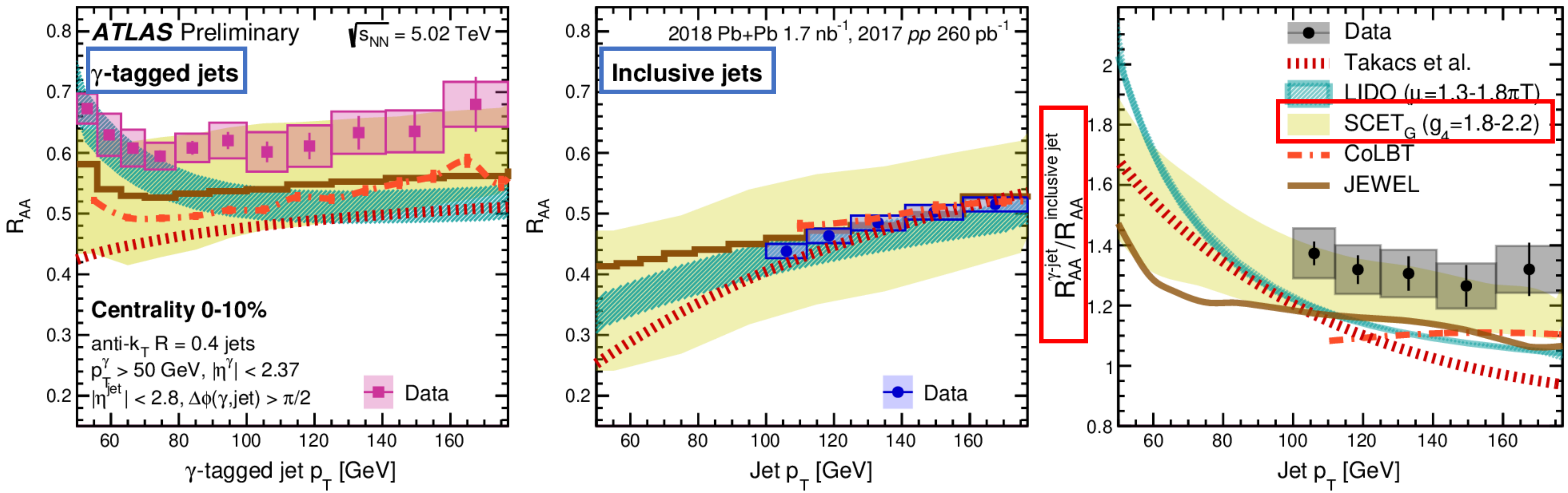
- b-jet to inclusive ratio in pp consistent with simulation and the CMS result
- No significant pT dependence observed

Photon-tagged jet





Theory comparison



- Double ratio above unity: γ-tagged jets are less suppressed.
- This could indicate a reduced energy loss of quark-initiated jets compared to gluon-initiated (or inclusive) jets.
  - However, 2 other effects of opposite sign and likely similar magnitude should be taken into consideration when interpreting this result.
  - γ-tagged jet spectrum is steeper -> RAA increases by ~0.1 (same energy loss, a simple model of fractional energy loss).
  - Isospin/nPDF effect reduces the Compton scattering in Pb+Pb -> RAA decreases by ~0.05-0.1.