Recent open heavy-flavor and jet results in heavy-ion collisions from ATLAS

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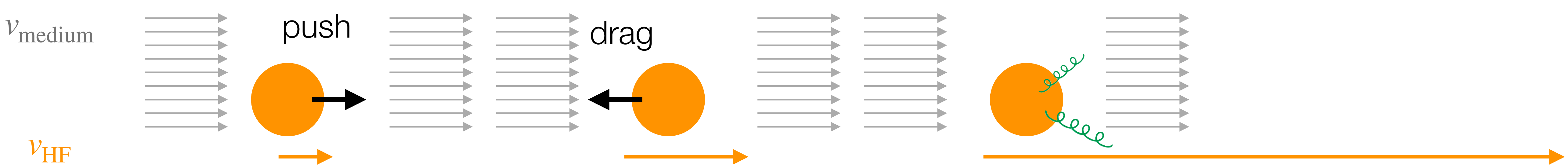
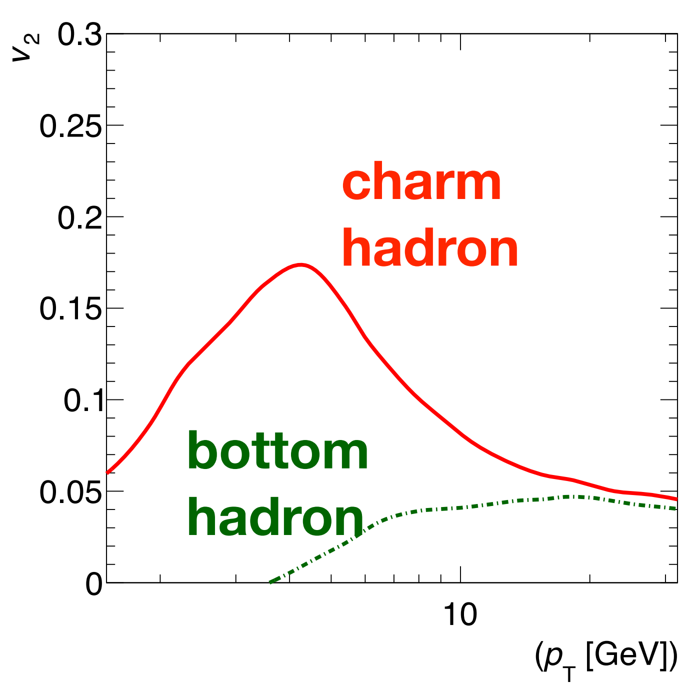
ATLAS EXPERIMENT

Heavy quark flow

- Heavy flavor (HF) quarks, charm (~1.28 GeV) and bottom (~4.18 GeV), are expected to be produced isotropically prior to QGP formation
- Azimuthal anisotropy of QGP is expected to propagate to heavy quark in a p_T dependent way:



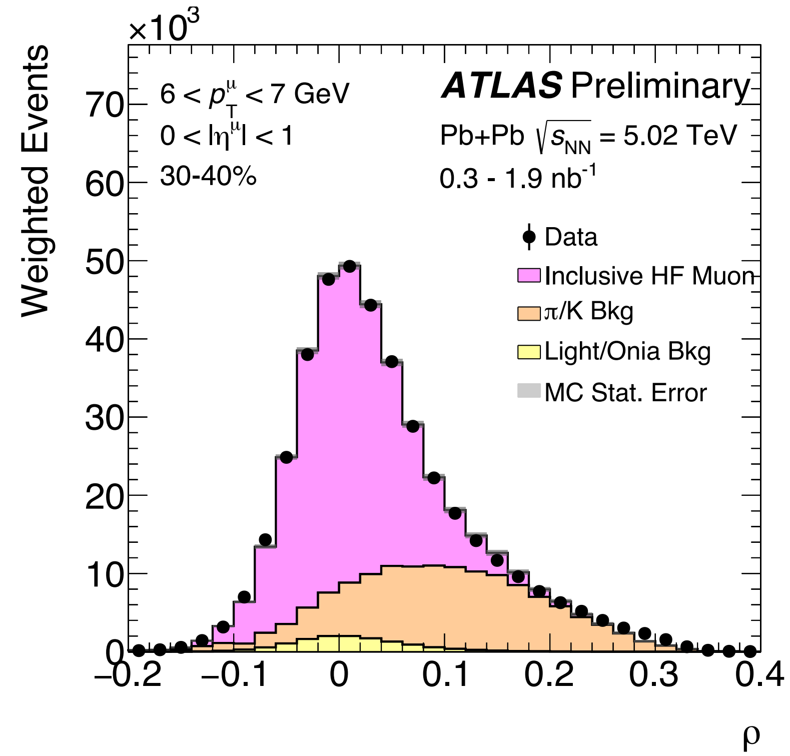


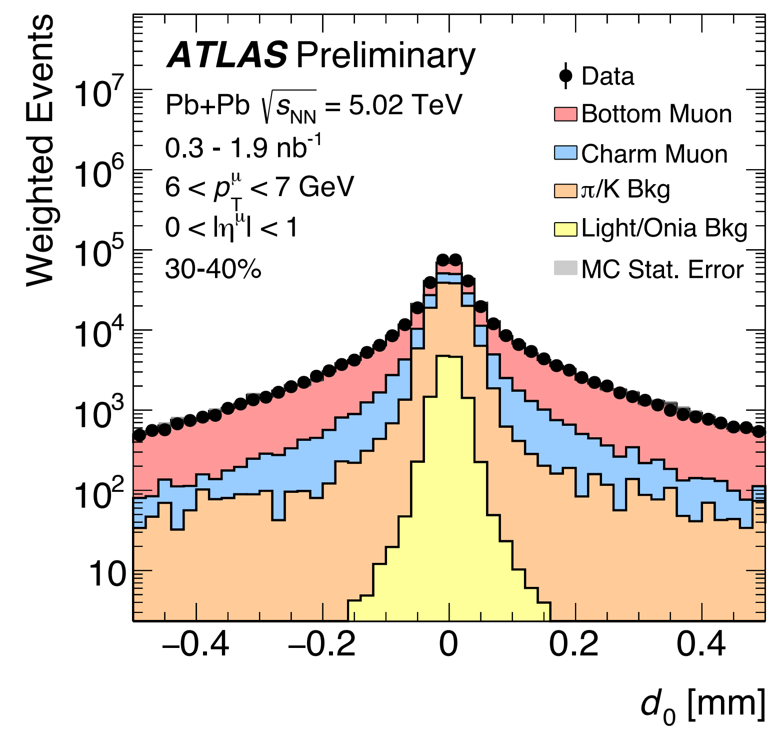
- Hadronization effects
- Mass dependence

HF muon identification

ATLAS-CONF-2019-053

muons from heavy flavor hadron decays used as the proxy to heavy quarks in ATLAS





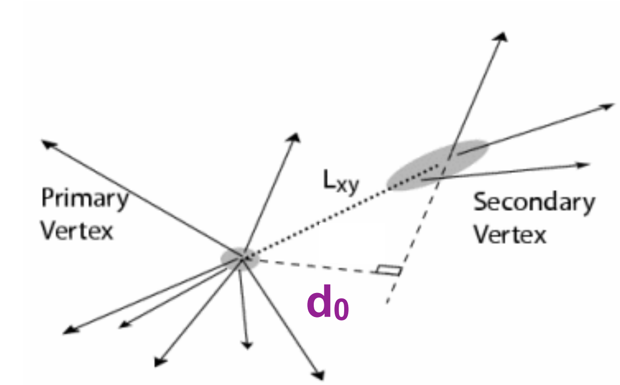
Removed based on momentum imbalance:
$\rho = (p_T^{ID} - p_T^{MS})/p_T^{ID}$

Background:

- Hadron punch-through (leading)
- π/K decay-in-flight
- muon from Light/EW/quarkonium

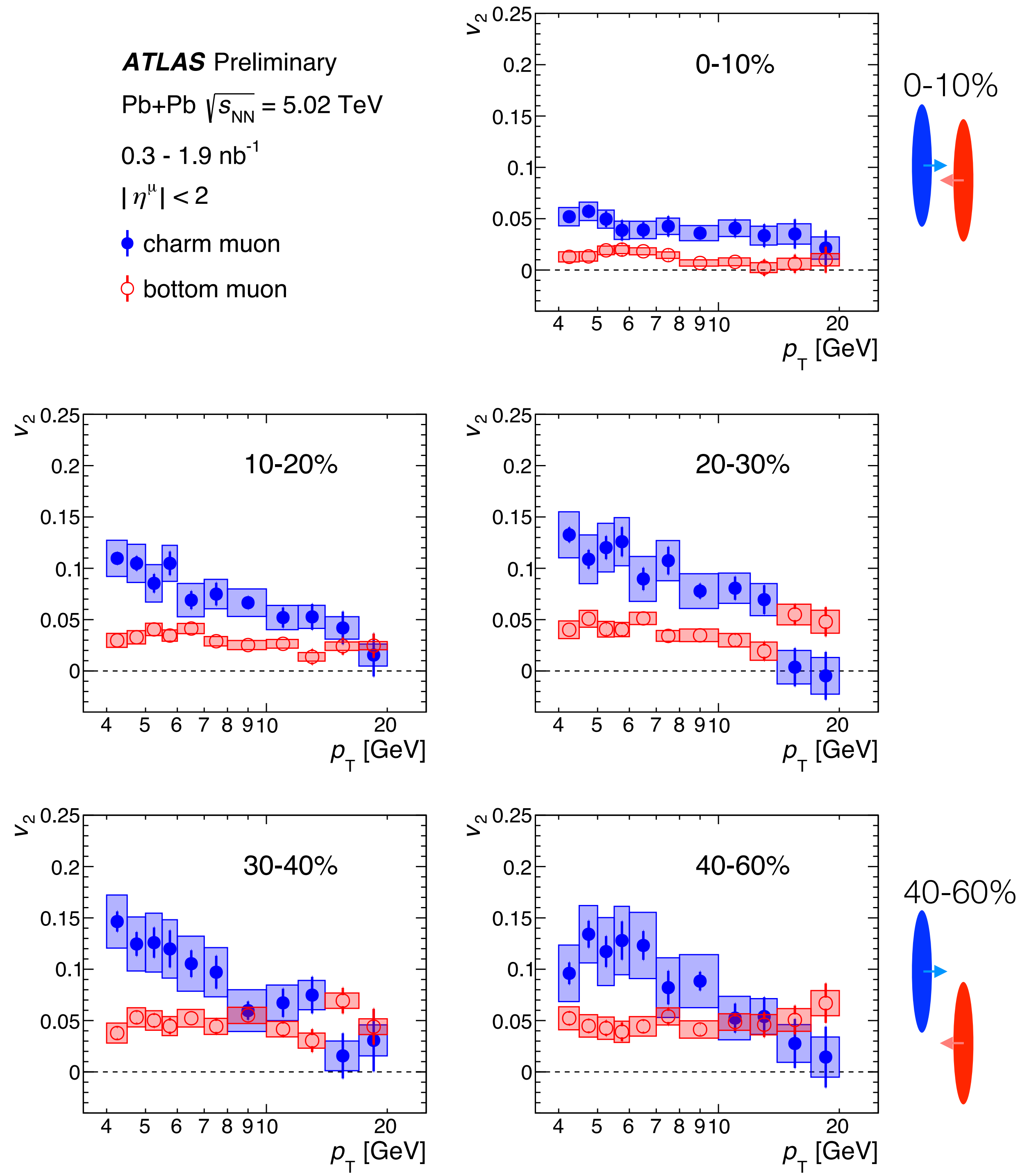
Remove based on Pythia

Charm/bottom separation via transverse impact parameter: d_0



HF muon v_2 in Pb+Pb

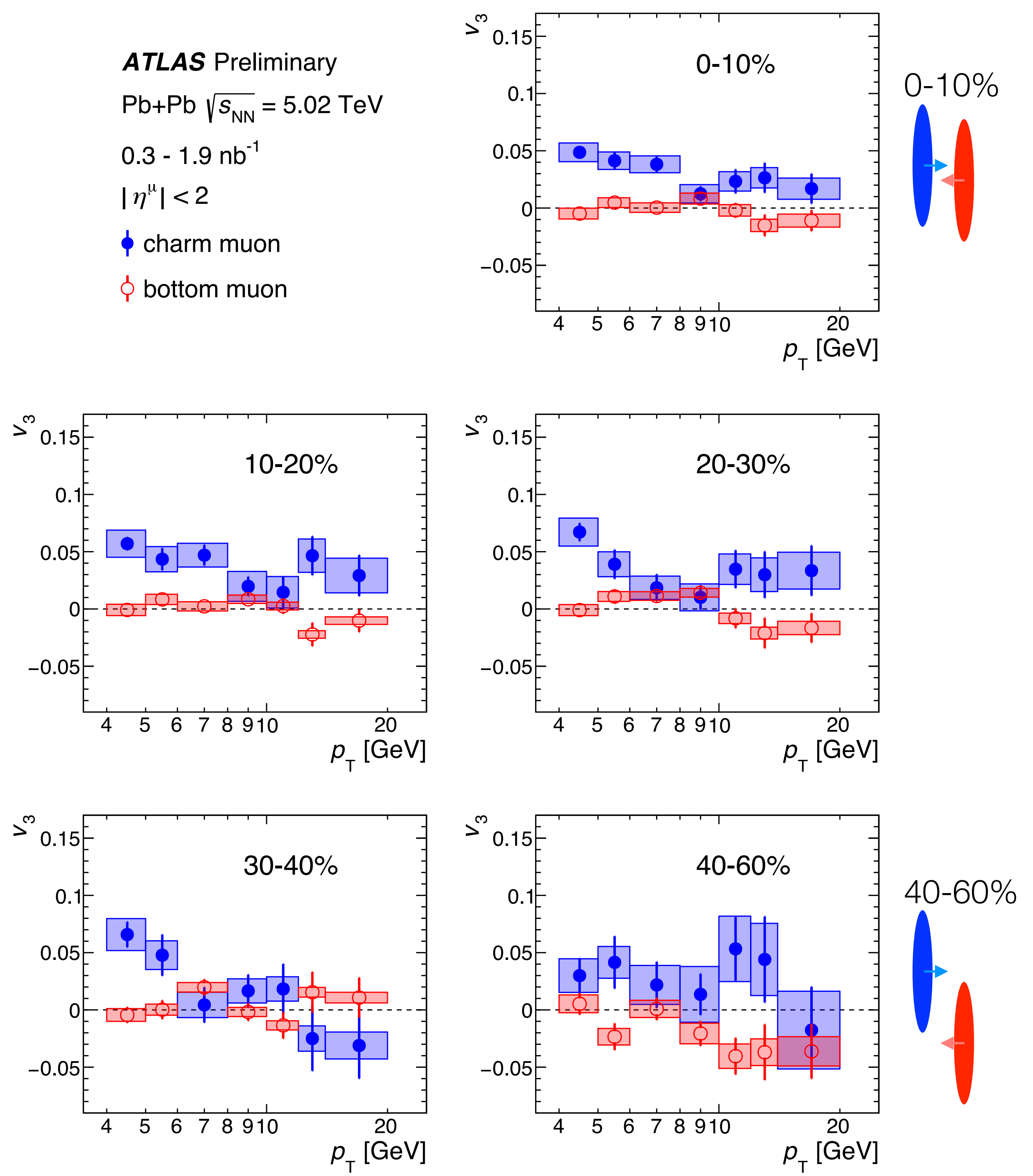
ATLAS-CONF-2019-053



- 2015+2018 Pb+Pb data with event-plane method
- Significant non-zero v_2 for c and b muon
- **v_2(c)** > **v_2(b)** at low p_T
- **v_2(c)** ~ **v_2(b)** at high p_T
- Anti-correlated stat. uncertainty (ρ = -0.9)

HF muon v_3 in Pb+Pb

ATLAS-CONF-2019-053

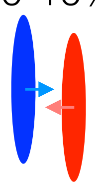


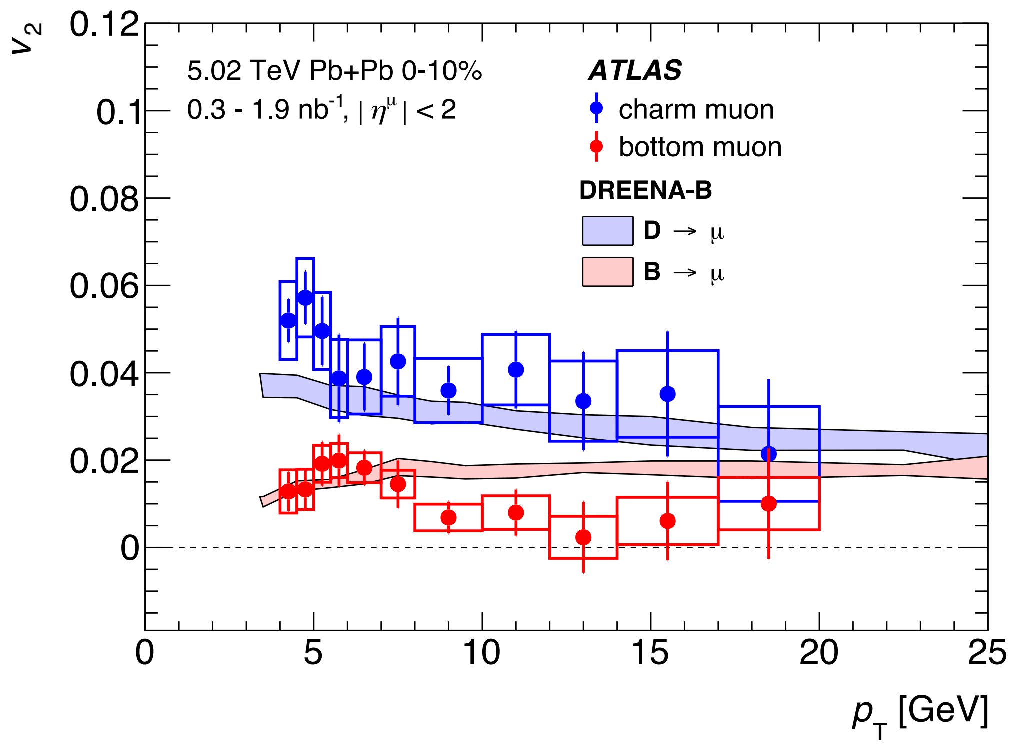
- ***v_3(c) ~ 2-5%***
- ***v_3(b) ~ 0***
- No obvious centrality dependence

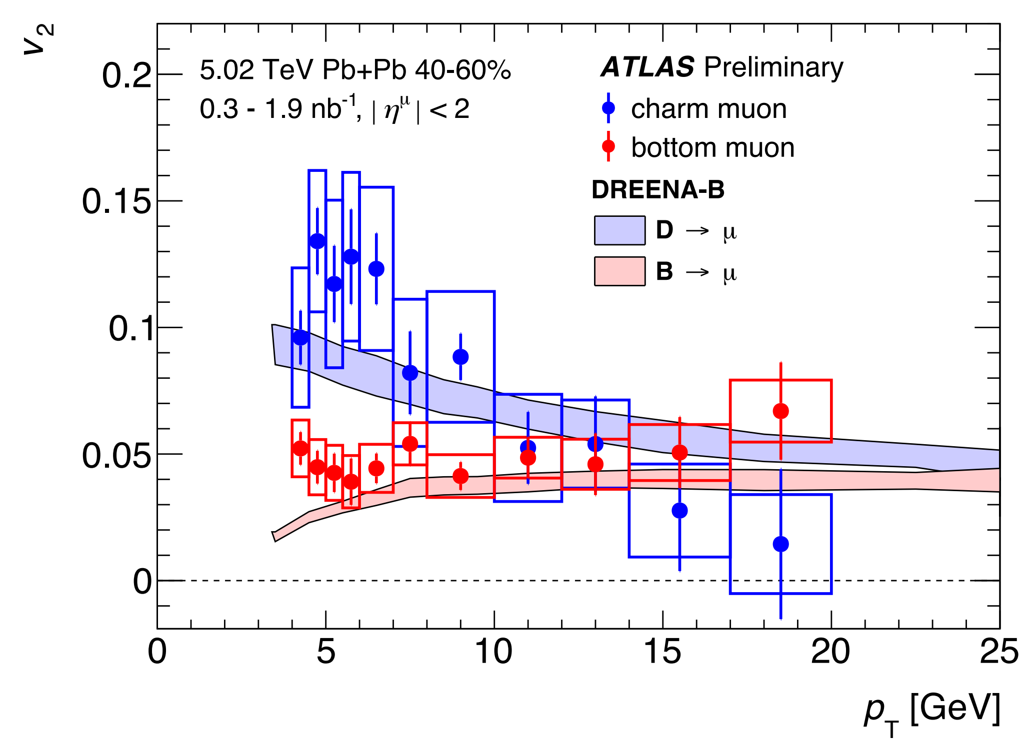
Comparison to model calculations

ATLAS-CONF-2019-053

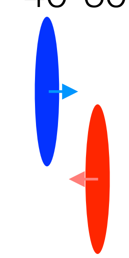
0-10%







40-60%

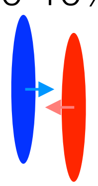


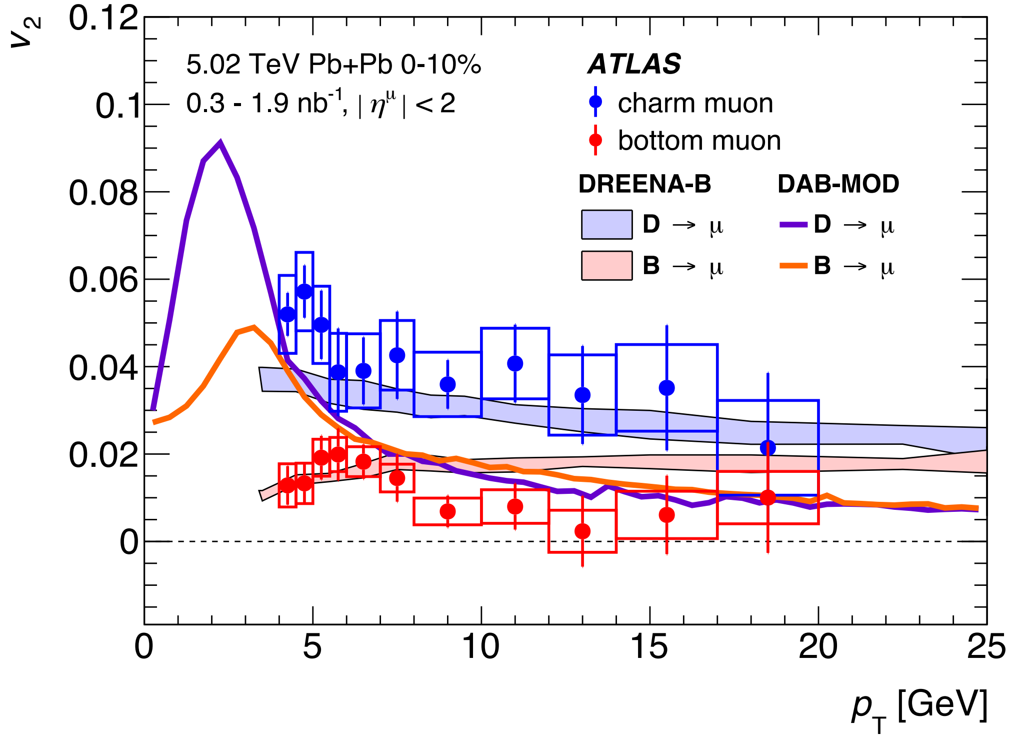
- **DREENA-B** (1805.04786): 1+1D medium, dynamical radiative + collisional energy loss

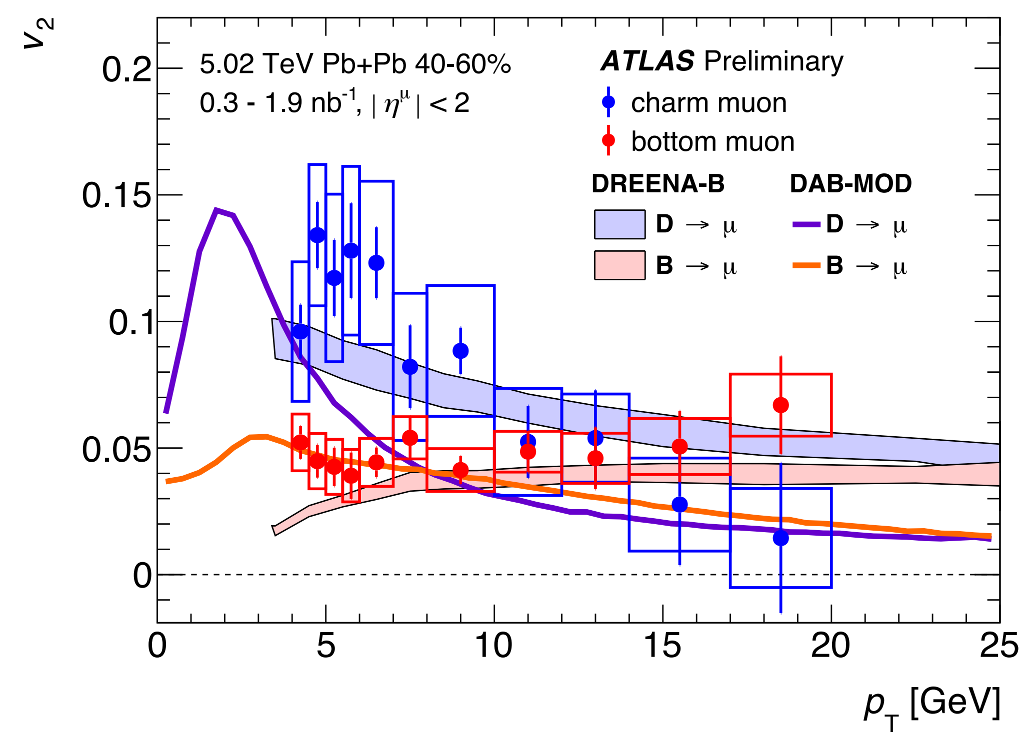
Comparison to model calculations

ATLAS-CONF-2019-053

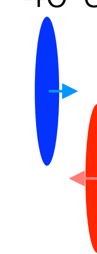
0-10%







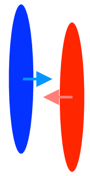
40-60%

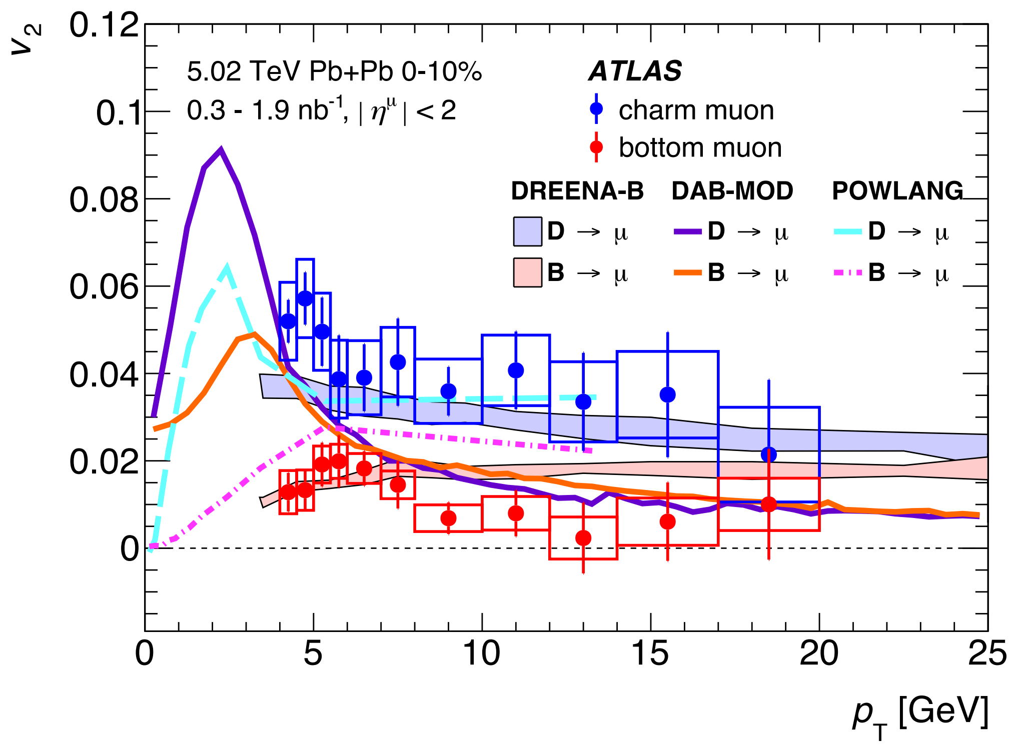


- **DREENA-B** (1805.04786): 1+1D medium, dynamical radiative + collisional energy loss
- **DAB-MOD** (1906.10768): 2+1D medium, TRENTO initial geometry, Langevin with $2\pi T D_S = 2.23$ (2.79) for charm (bottom), no energy loss included

Comparison to model calculations

0-10%





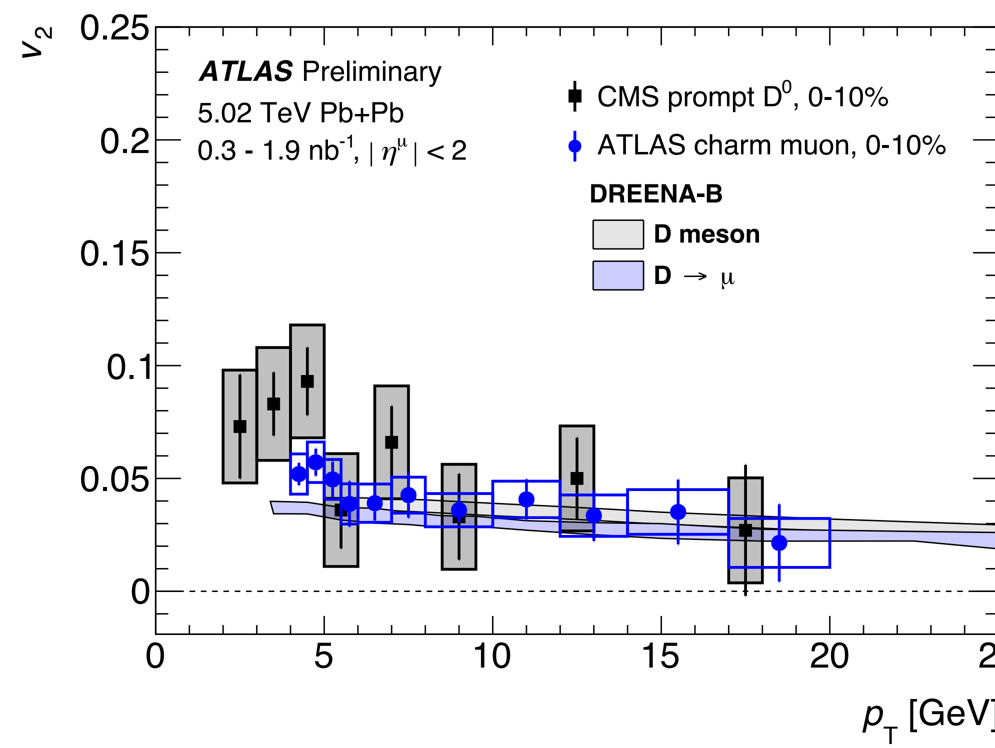
- Our data provide tight constrains to energy loss modeling
- Radiative energy loss is playing an important role in the measured kinematic region

- **DREENA-B** (1805.04786): 1+1D medium, dynamical radiative + collisional energy loss
- **DAB-MOD** (1906.10768): 2+1D medium, TRENTO initial geometry, Langevin with $2\pi TD_s$ = 2.23 (2.79) for charm (bottom), no energy loss included
- **POWLANG** (1712.00588): 2+1D medium, Glauber-MC initial geometry, Langevin with $2\pi TD_s$ ~ 3, collisional energy loss only

HF muon vs. HF hadron

HF decay leptons vs. D^0 or non-prompt J/ψ

ATLAS-CONF-2019-053



Pros:

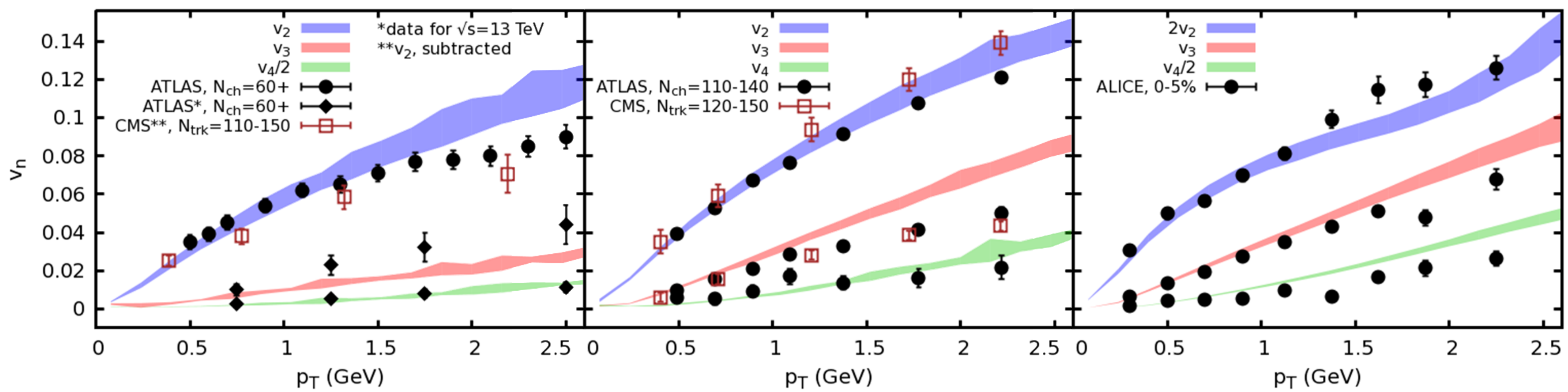
- Easy to trigger
- Better precise in central event than D^0
- More statistics than non-prompt J/ψ

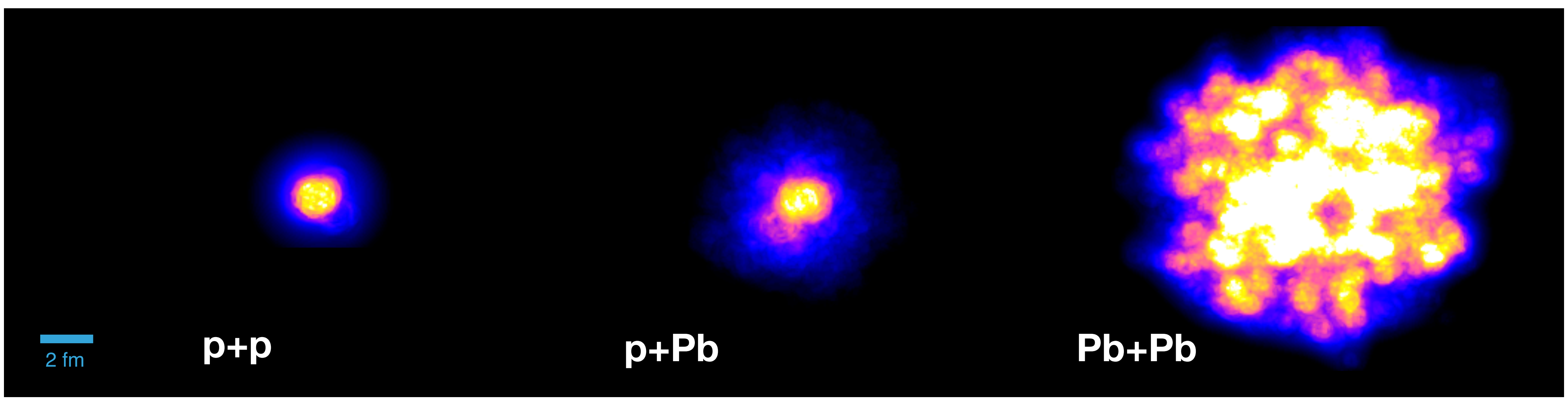
Cons:

- No access to low p_T in ATLAS
- kinematic smearing due to the HF hadron semileptonic decay

From Pb+Pb to smaller systems

arXiv:1701.07145

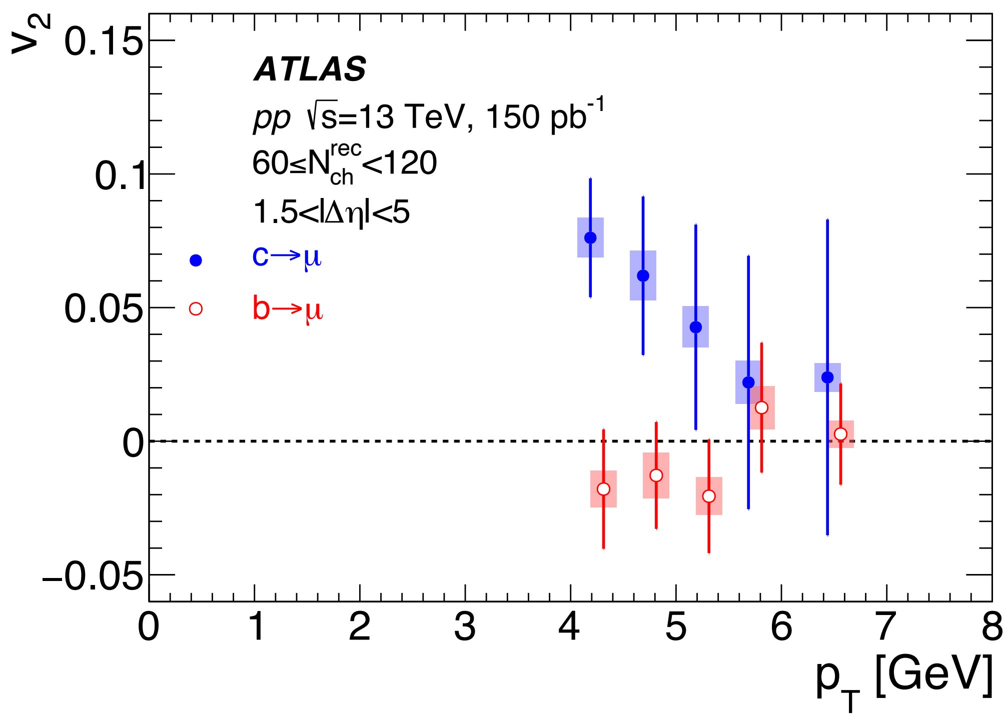




- Similar collective motions/azimuthal anisotropy observed in all systems
- What can we learn from heavy quarks about “smaller" systems

HF muon v_2 in *pp*

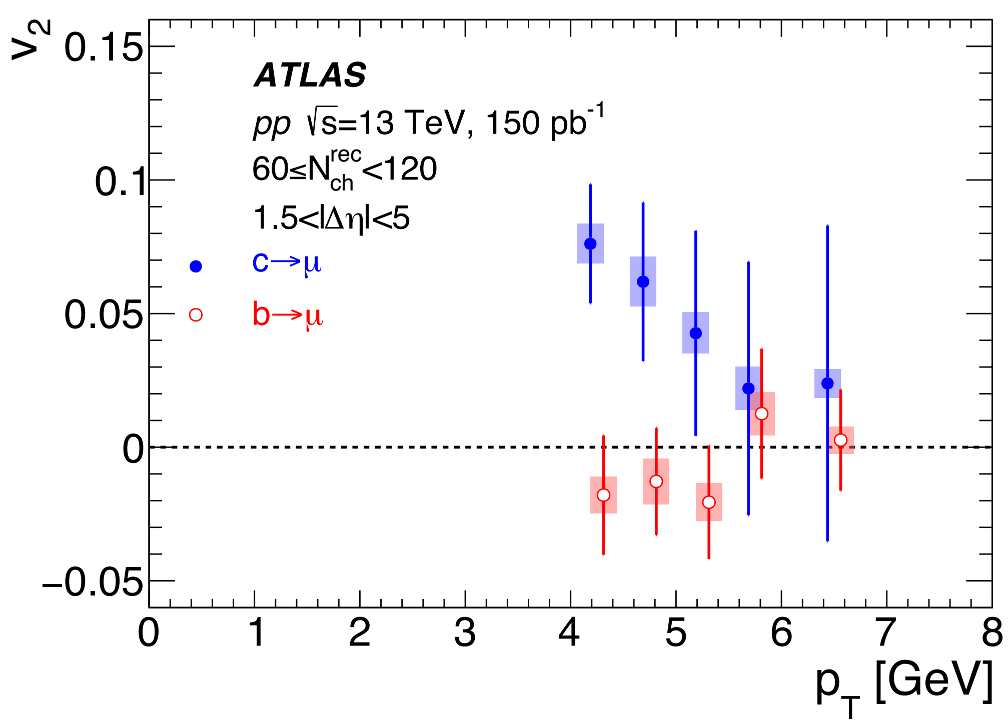
arXiv:1909.01650

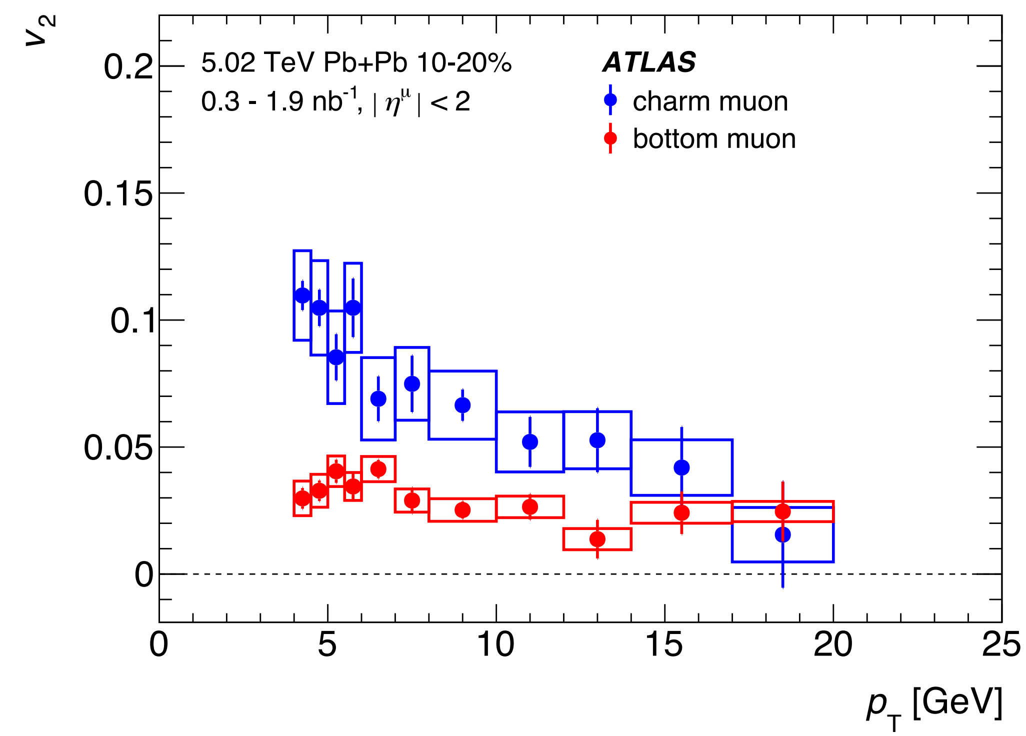


- 2017 *pp* collisions at 13 TeV with low pile-up
- Charm/bottom muon extracted with the same methods as in Pb+Pb; v_2 from 2PC with template fit for non-flow subtraction
- **v_2(c) > 0** and **v_2(b) ~ 0**

HF muon flow in *pp*

arXiv:1909.01650



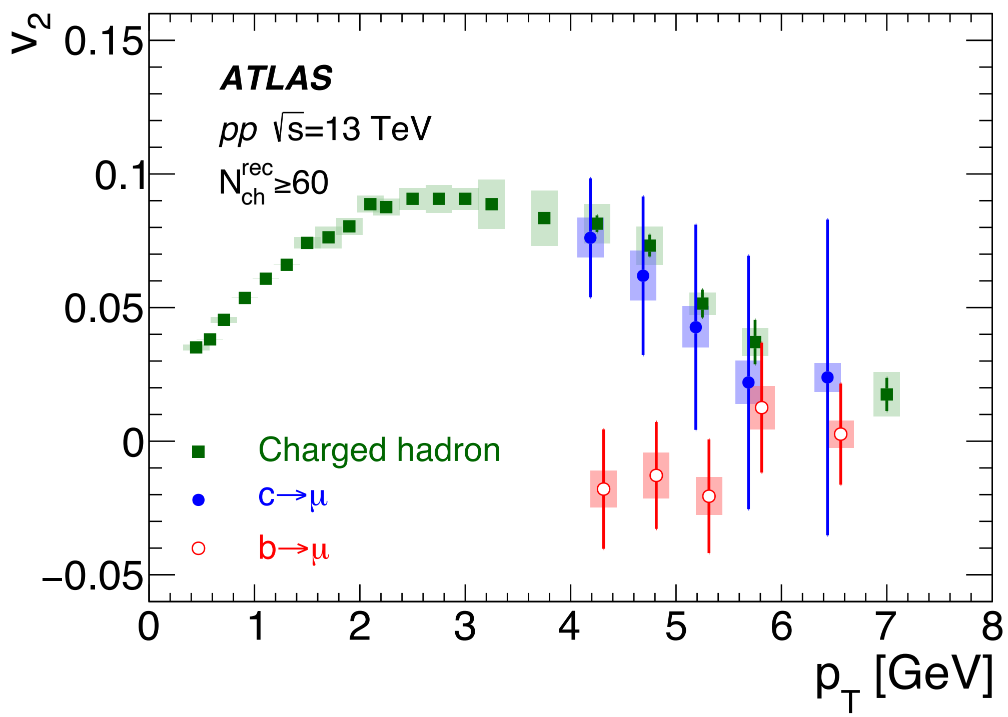


Small droplet of QGP?

- Measured HF muon flow seems to be attributed to path-length dependence of energy loss in Pb+Pb
- How can charm undergo such strong energy loss
- Are we missing anything for Pb+Pb?

HF muon flow in *pp*

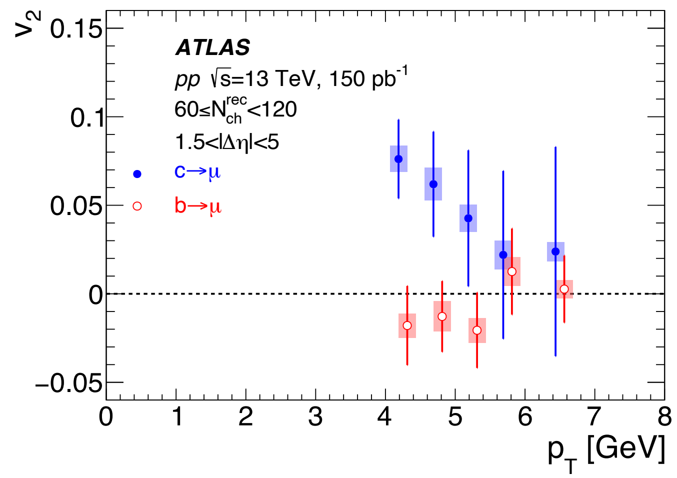
arXiv:1909.01650



Initial state correlation / hadronization?

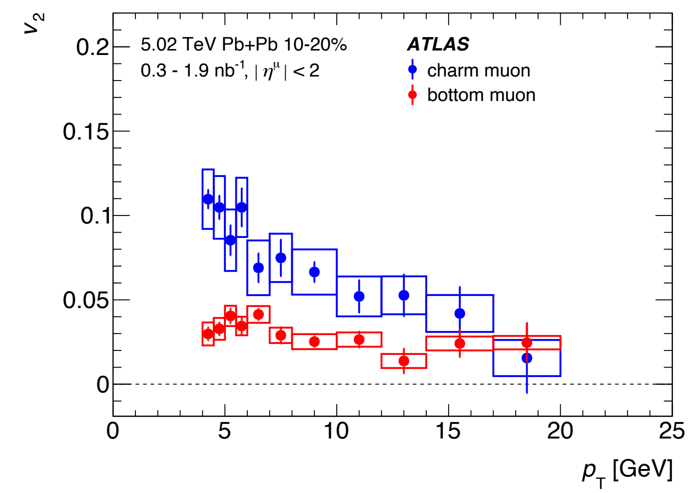
- why charm has as strong anisotropy as light flavor; while bottom has none

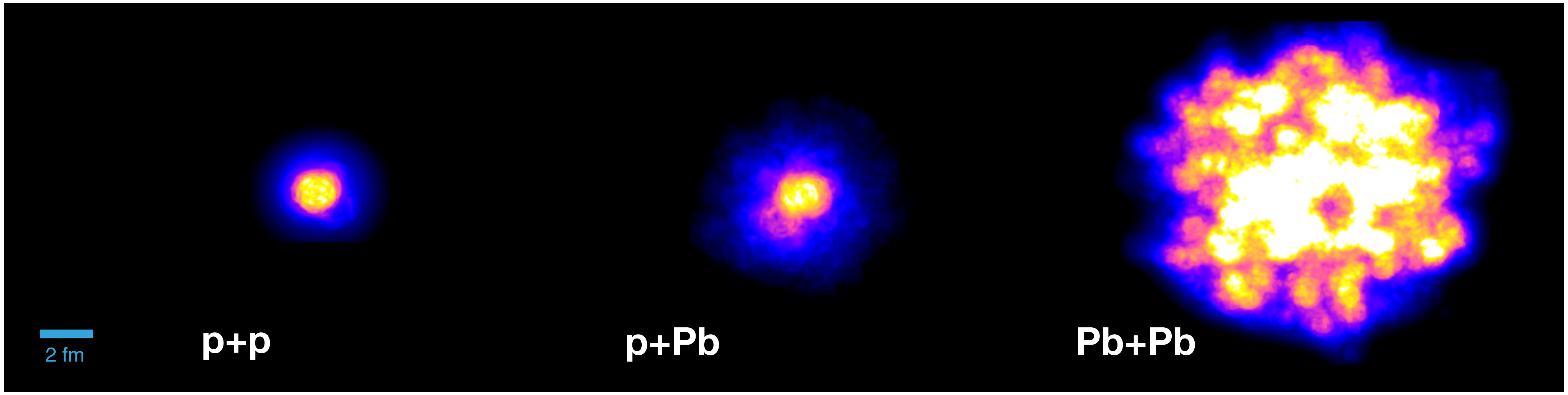
What about *p*+Pb

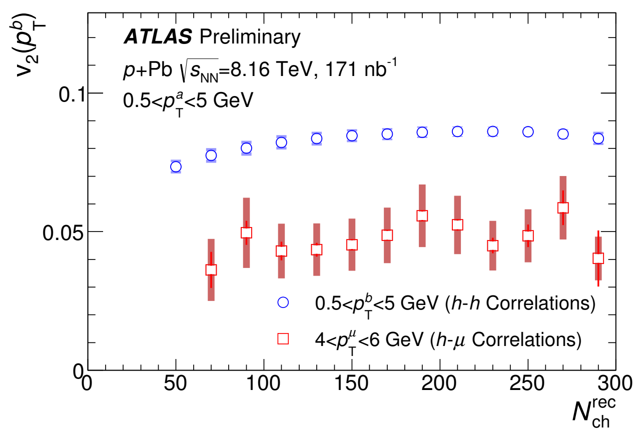


?

work in progress

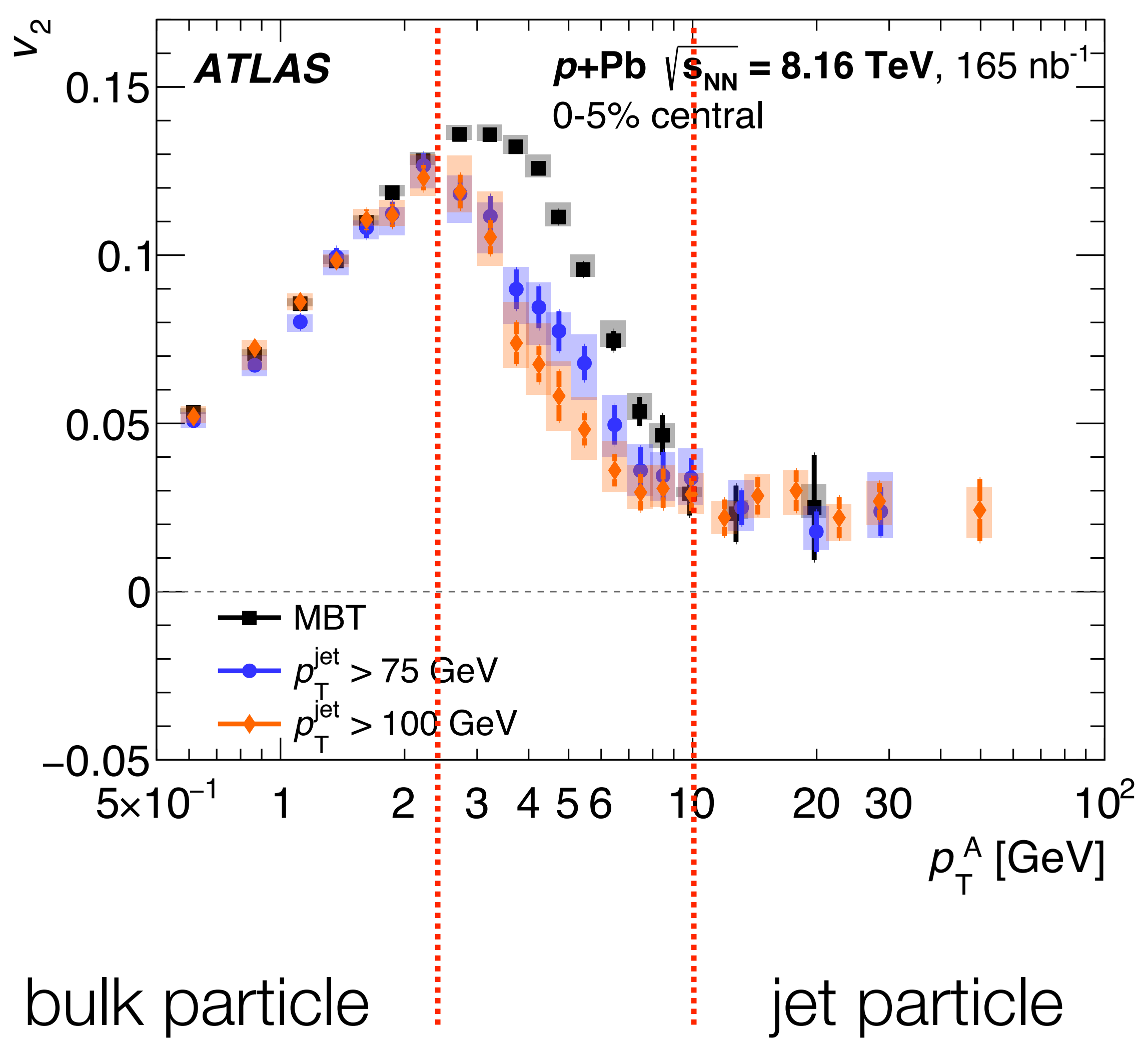






Hadron v_2 in p+Pb

Eur. Phys. J. C 80 (2020) 73



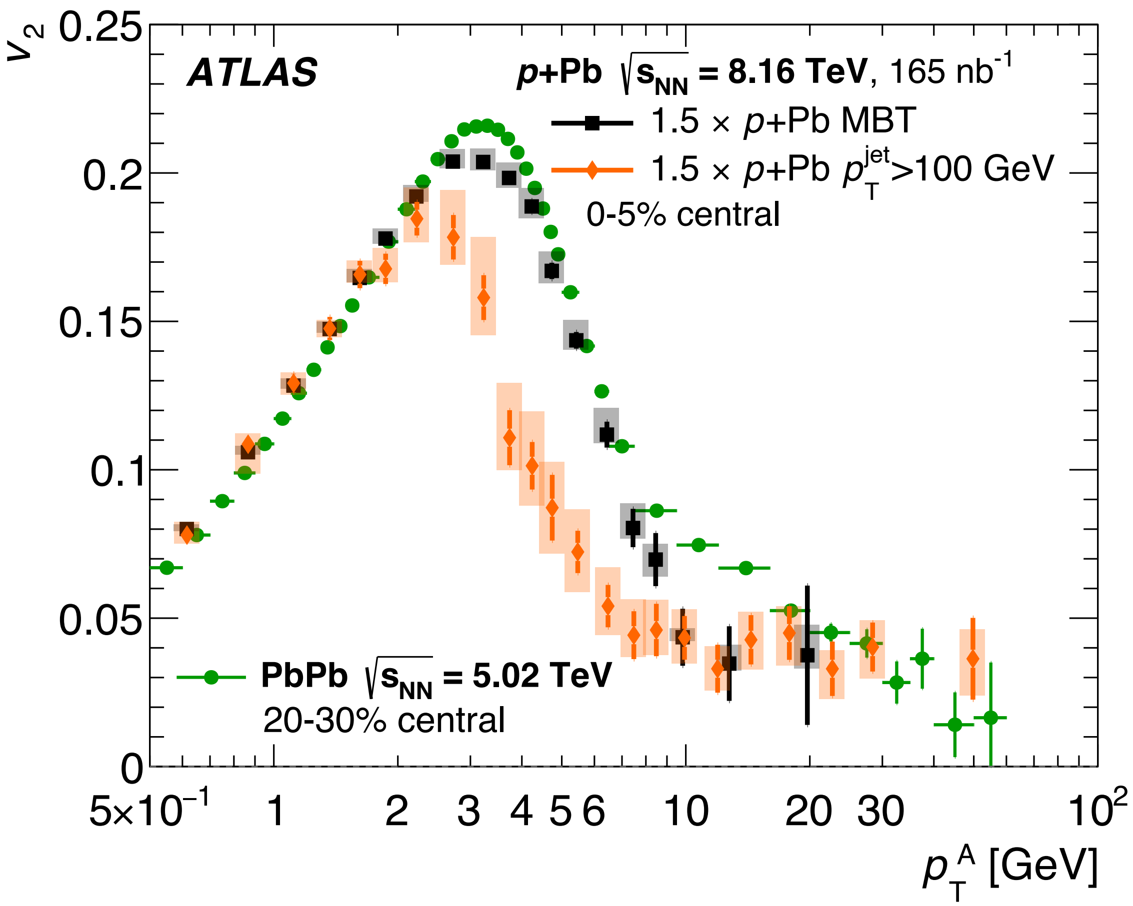
bulk particle dominated

jet particle dominated

- 2016 p+Pb collisions at 8.06 TeV
- *h-h* 2PC in MinBias and jet triggered events in 0-5% centrality
- Remove associated particle in jets, v_2 extracted from template fit
- Can be interpreted in bulk-jet two composition picture

Hadron v_2 in p+Pb vs Pb+Pb

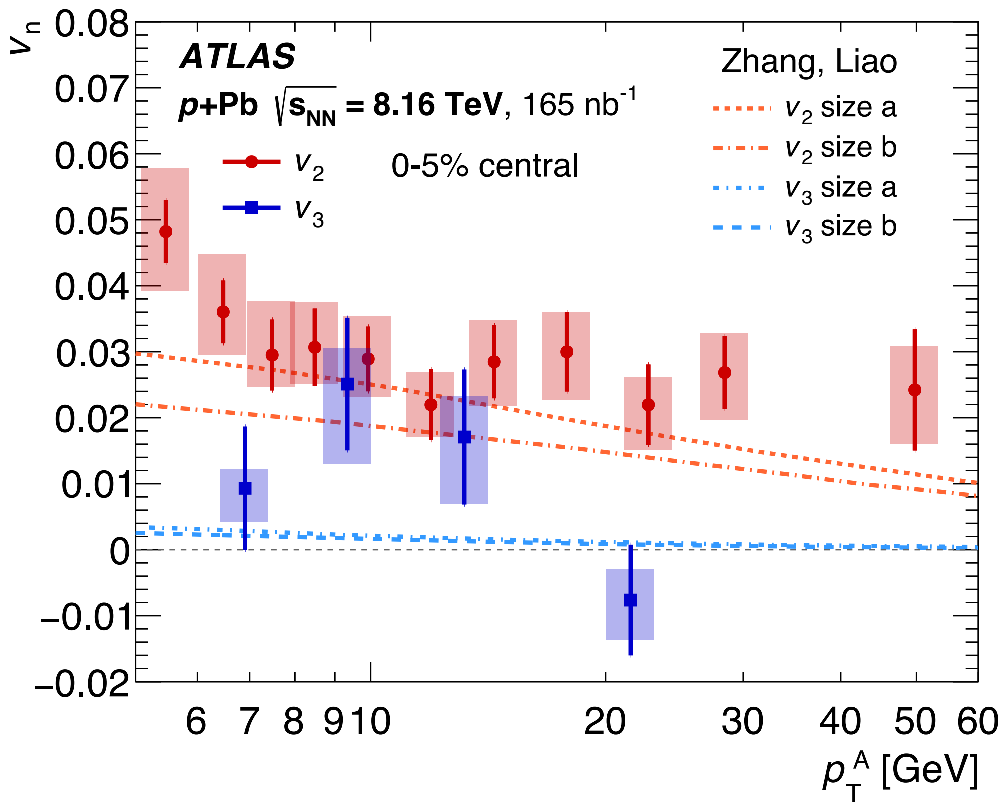
Eur. Phys. J. C 80 (2020) 73

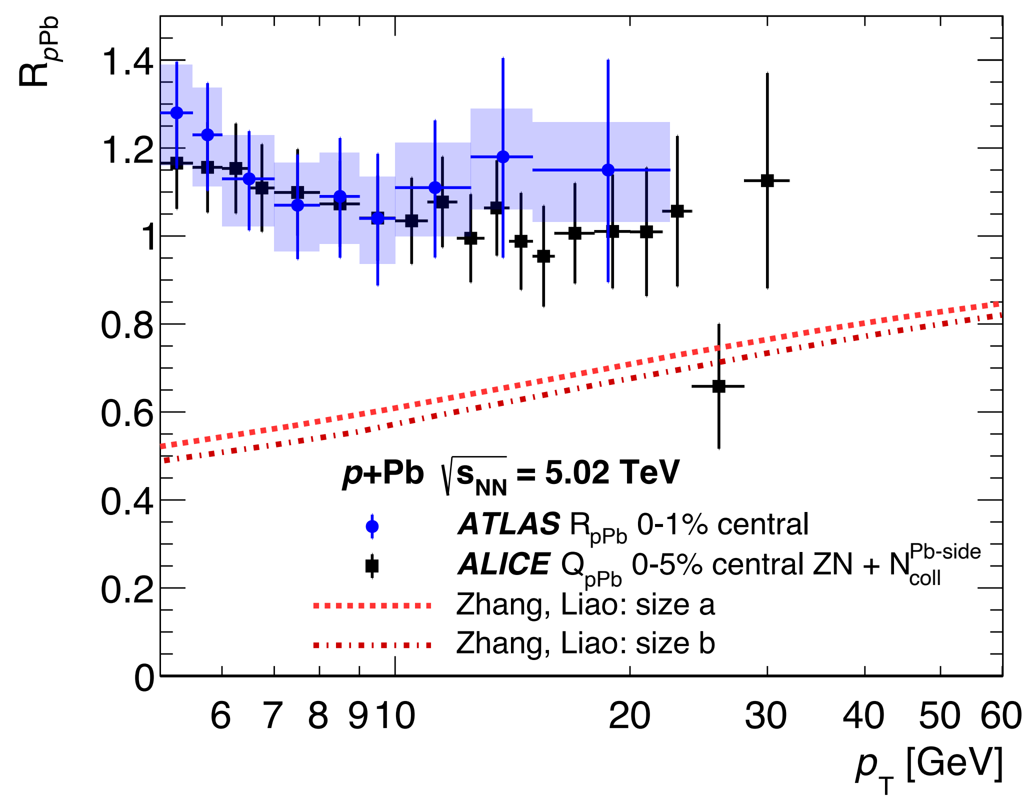


- Scale p+Pb results by 1.5 and compared to Pb+Pb in 20-30%
- Very similar shape up to 60 GeV

v_n vs. R_{pPb} in p+Pb

Eur. Phys. J. C 80 (2020) 73
Phys. Rev. C 91 (2015) 064905
arXiv:1311.5463



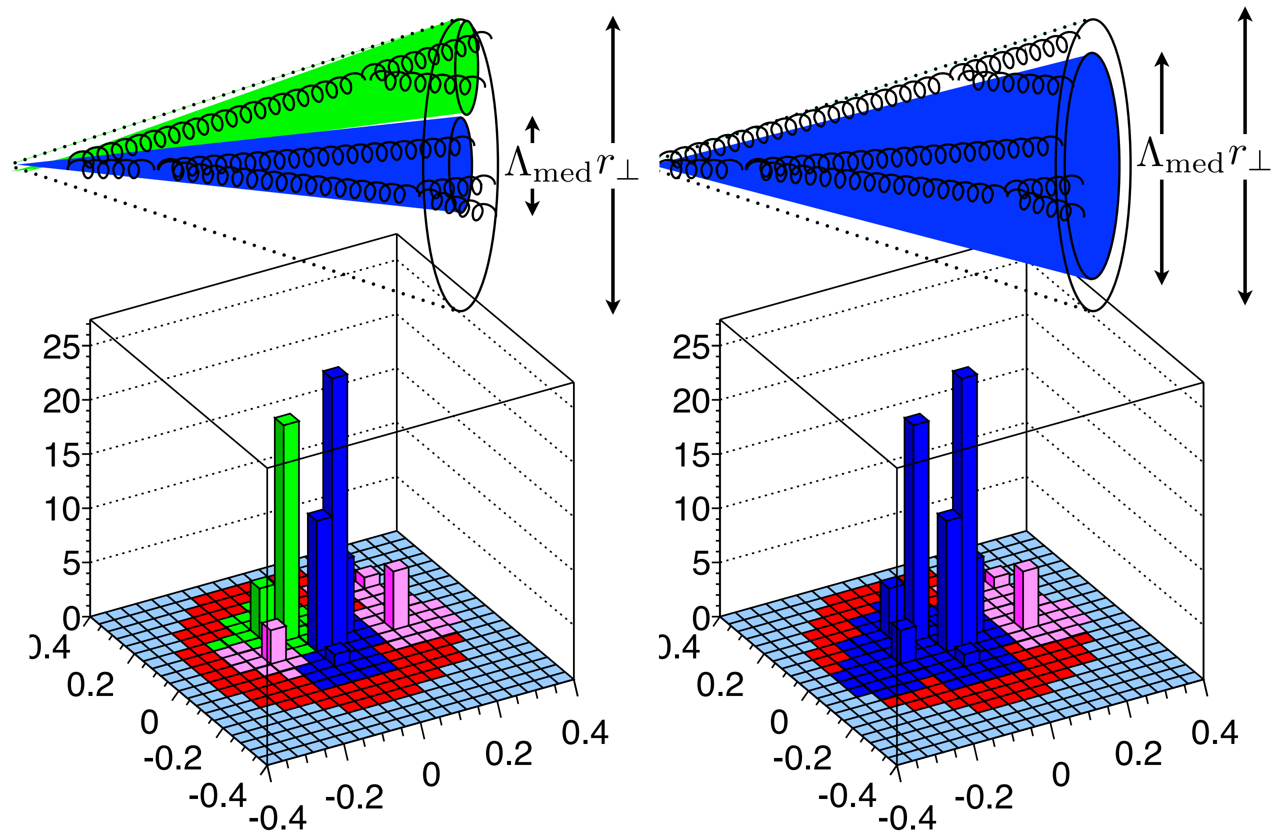


Jet quenching models cannot simultaneously describe both v_n and R_{AA}

Color coherence of in-medium jets

- Larger jet energy loss is expected if medium can break color coherence of gluon emission
- Reclustered large radius jet can be used to probe color coherence

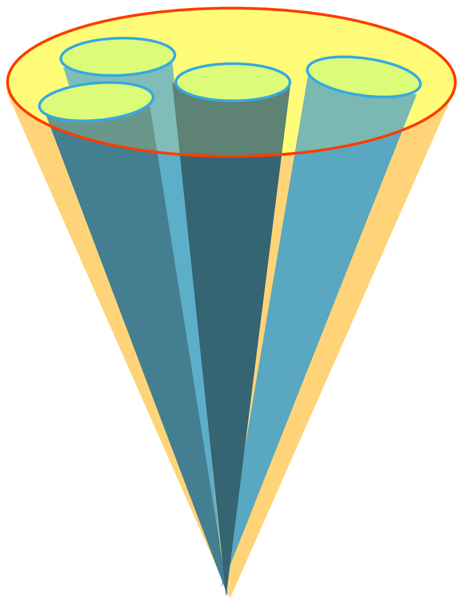
Phys. Lett. B725 (2013) 357



incoherent/resolved coherent/unresolved

$$E_{\rm loss}^{\rm incoherent} > E_{\rm loss}^{\rm coherent}$$

Large radius jet reconstruction



R = 0.2 Jet with p_T > 35 GeV
(w/ UE subtraction in Pb+Pb)

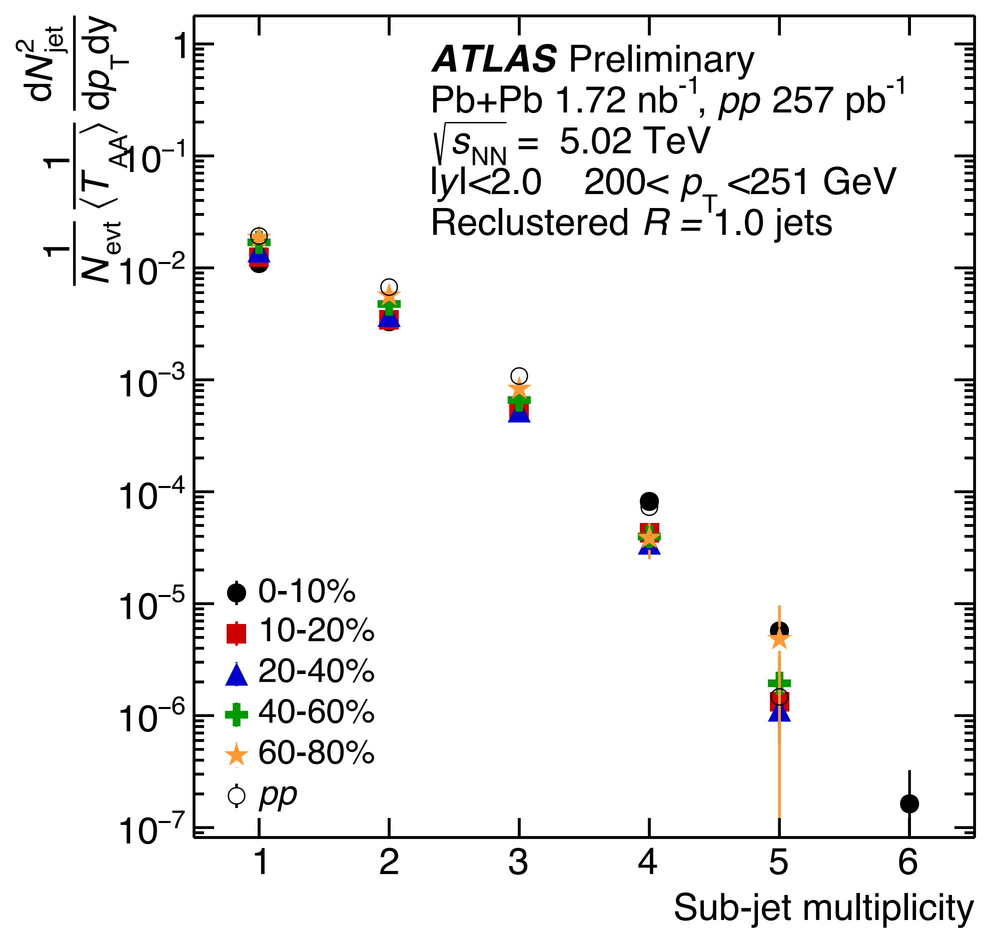
re-cluster with anti-k_t R = 1.0

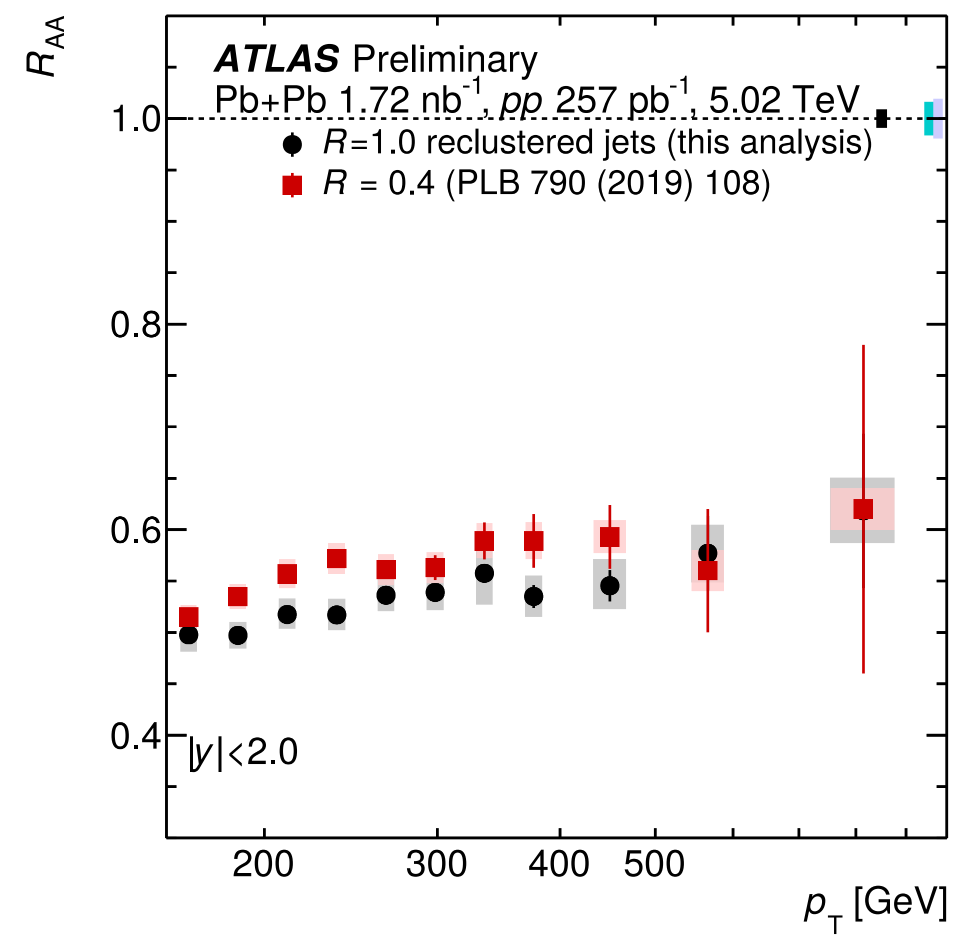
"Reclustered" large radius jet R = 1.0

No recovery of energy outside R = 0.2 jets compared to normal large radius jet

What are these jets

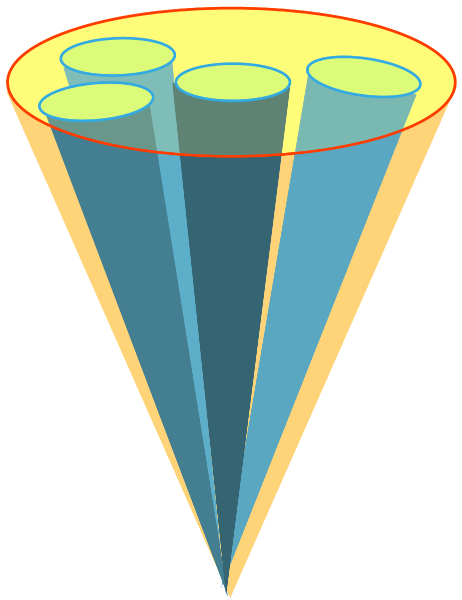
ATLAS-CONF-2019-056





- 2018 Pb+Pb collisions + 2017 *pp* collisions
- *R*=1.0 **reclustered** jets ≠ *R*=1.0 jets
- Typical reclustered *R*=1.0 jet: *R*=0.2 SSJ, ~ *R*=0.2 vs. *R*=0.4

Large radius splitting scale



R = 0.2 Jet with p_T > 35 GeV (w/ UE subtraction in Pb+Pb)

↓

re-cluster with anti-k_t R = 1.0 → "Reclustered" large radius jet R = 1.0

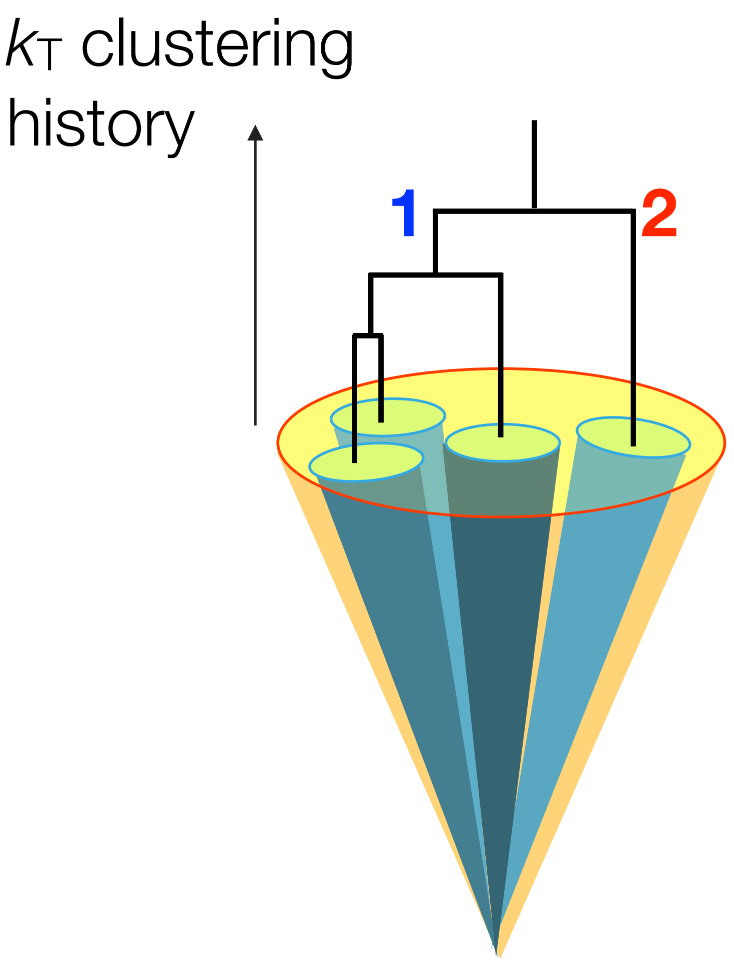
↓

re-cluster with k_t algorithm and determine splitting scale

↓

splitting scale of large radius jet

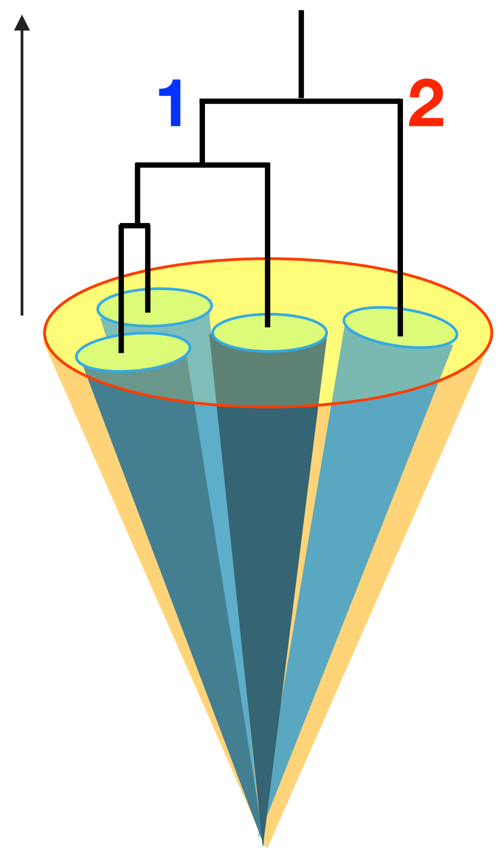
Large radius splitting scale



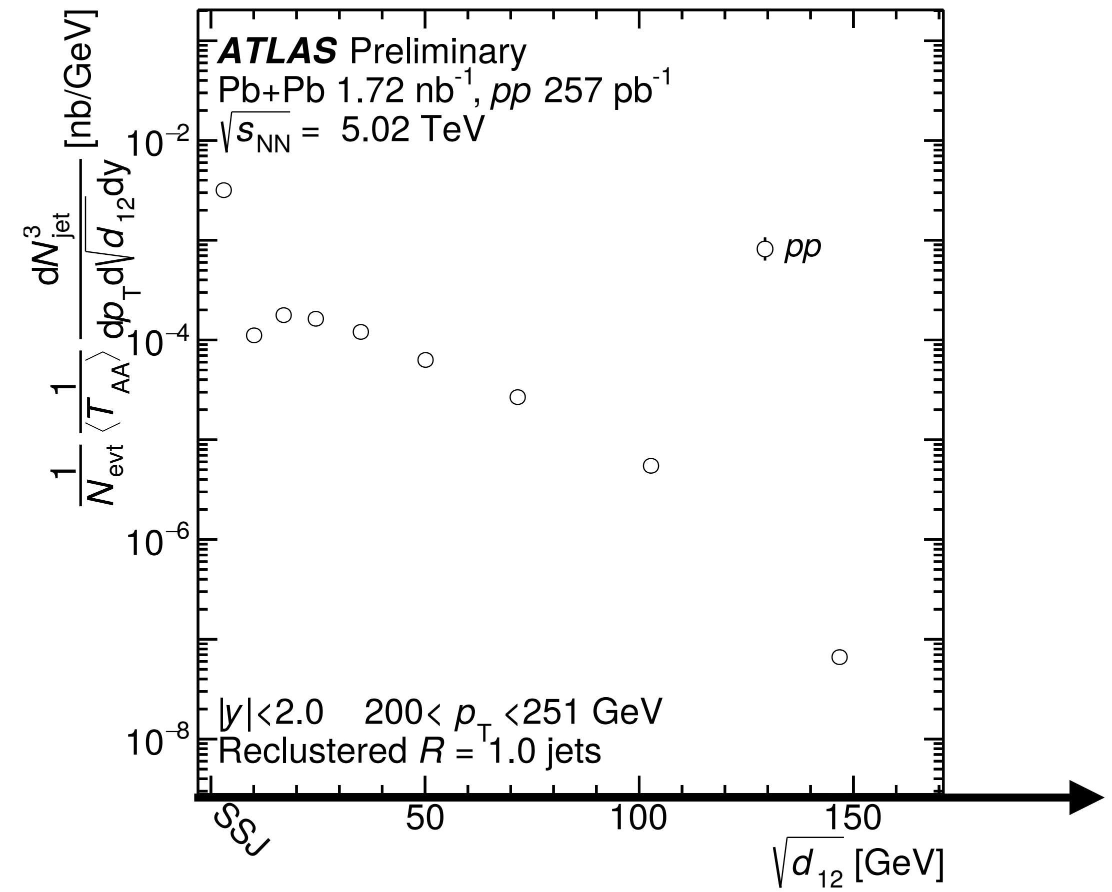
- Splitting scale parameter:
  $d_{12} = \min(p_{\mathrm{T},1}^2, p_{\mathrm{T},2}^2) \cdot \Delta R_{12}^2$
- Single subject jet (SSJ), $d_{12} = 0$

Large radius splitting scale

k_T clustering history



ATLAS-CONF-2019-056

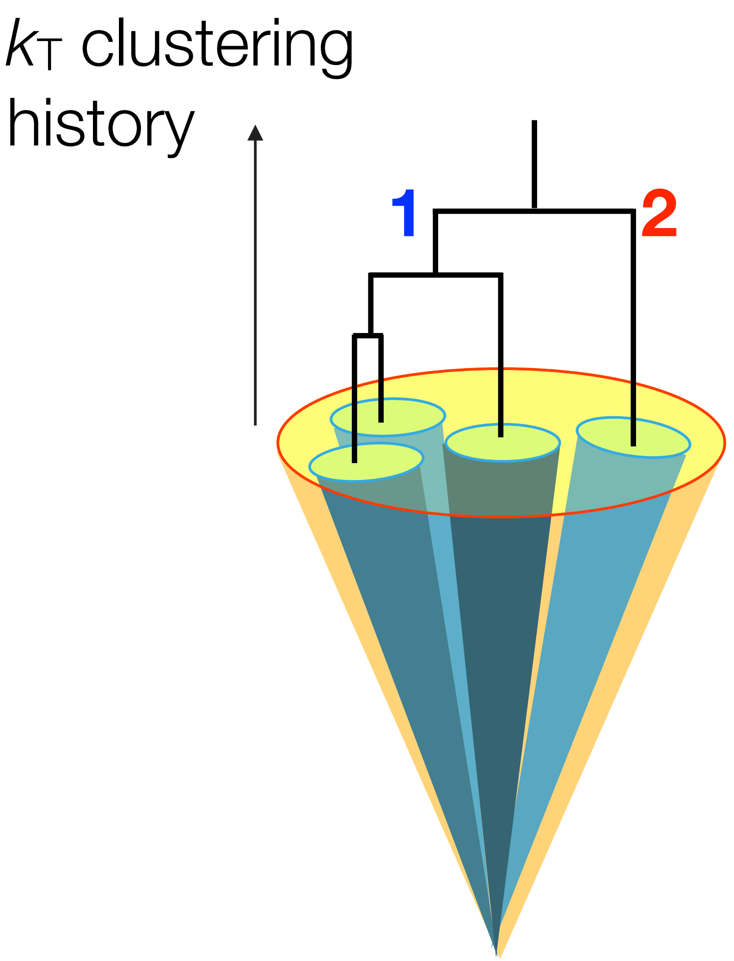


single sub-jet = coherent

hard+soft/small-angle splitting ~ coherent

two semi-hard/ large-angle splitting ~ incoherent

Large radius splitting scale



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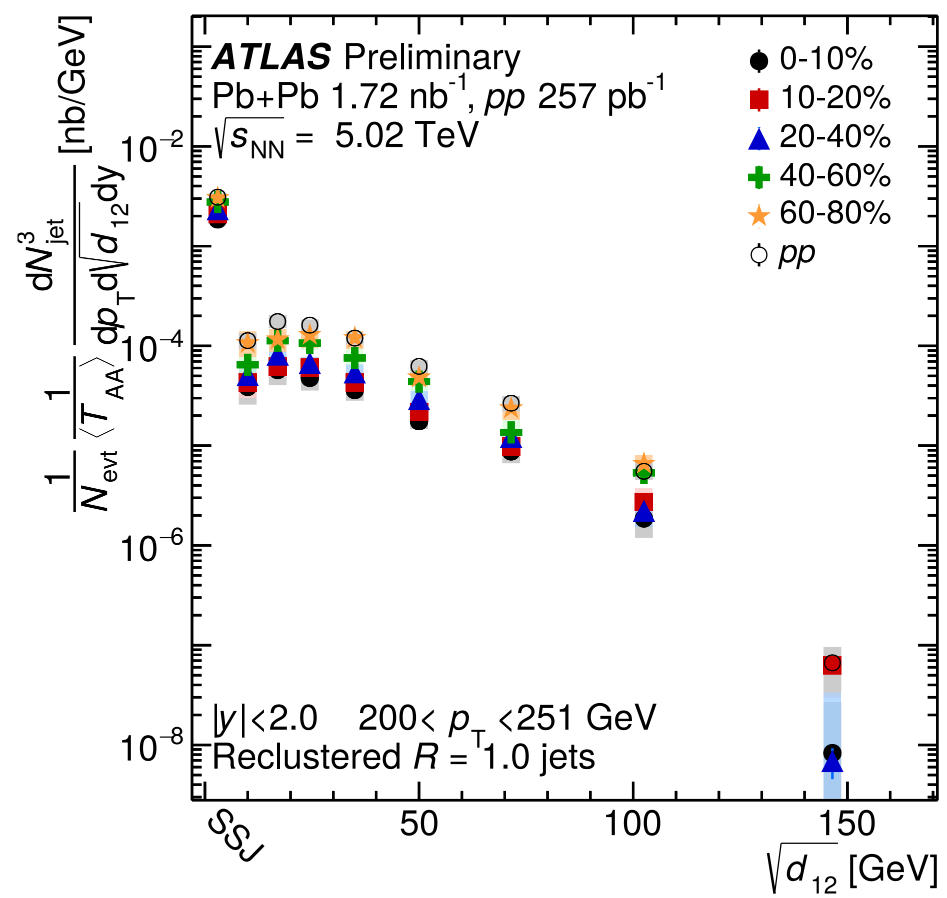
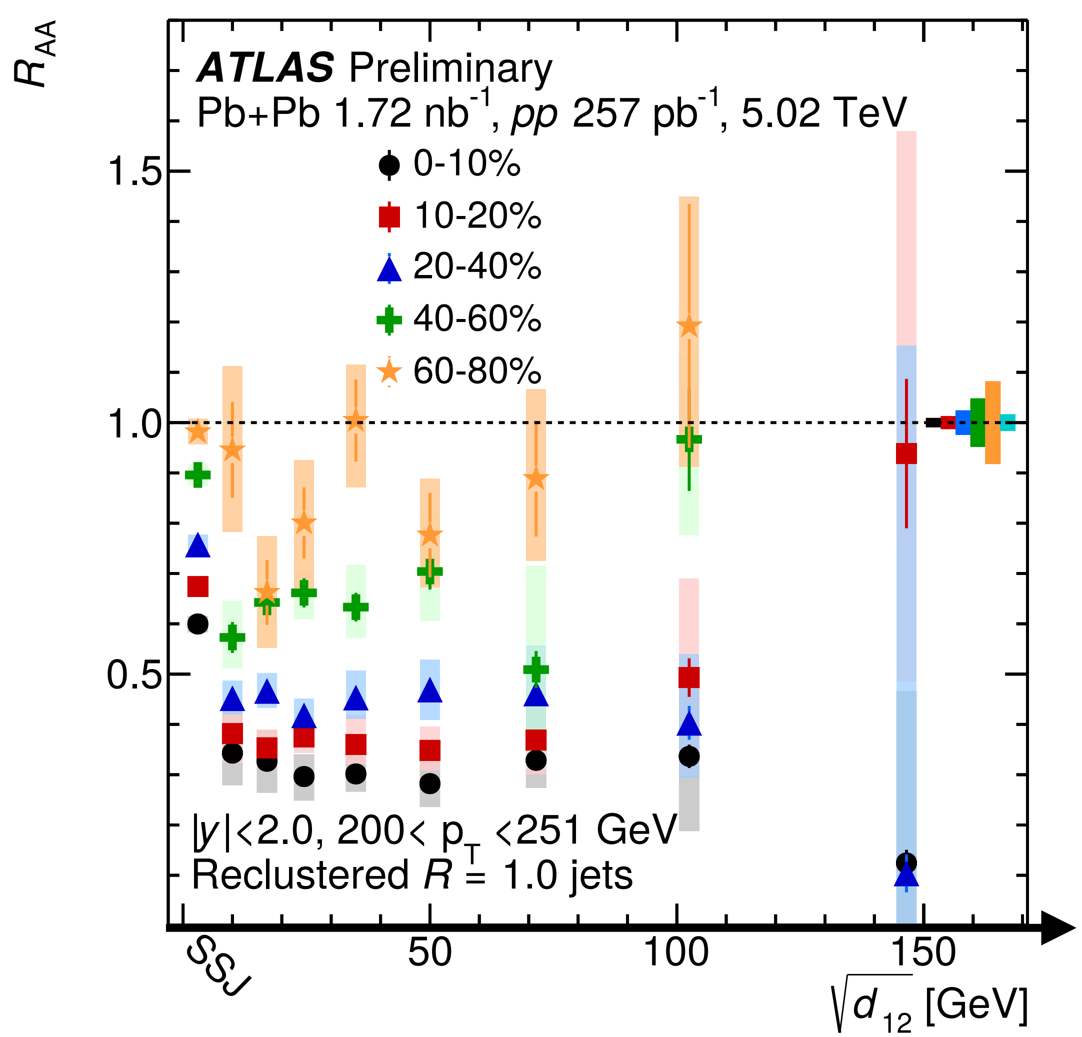


Large radius jet R_{AA} vs splitting scale

ATLAS-CONF-2019-056



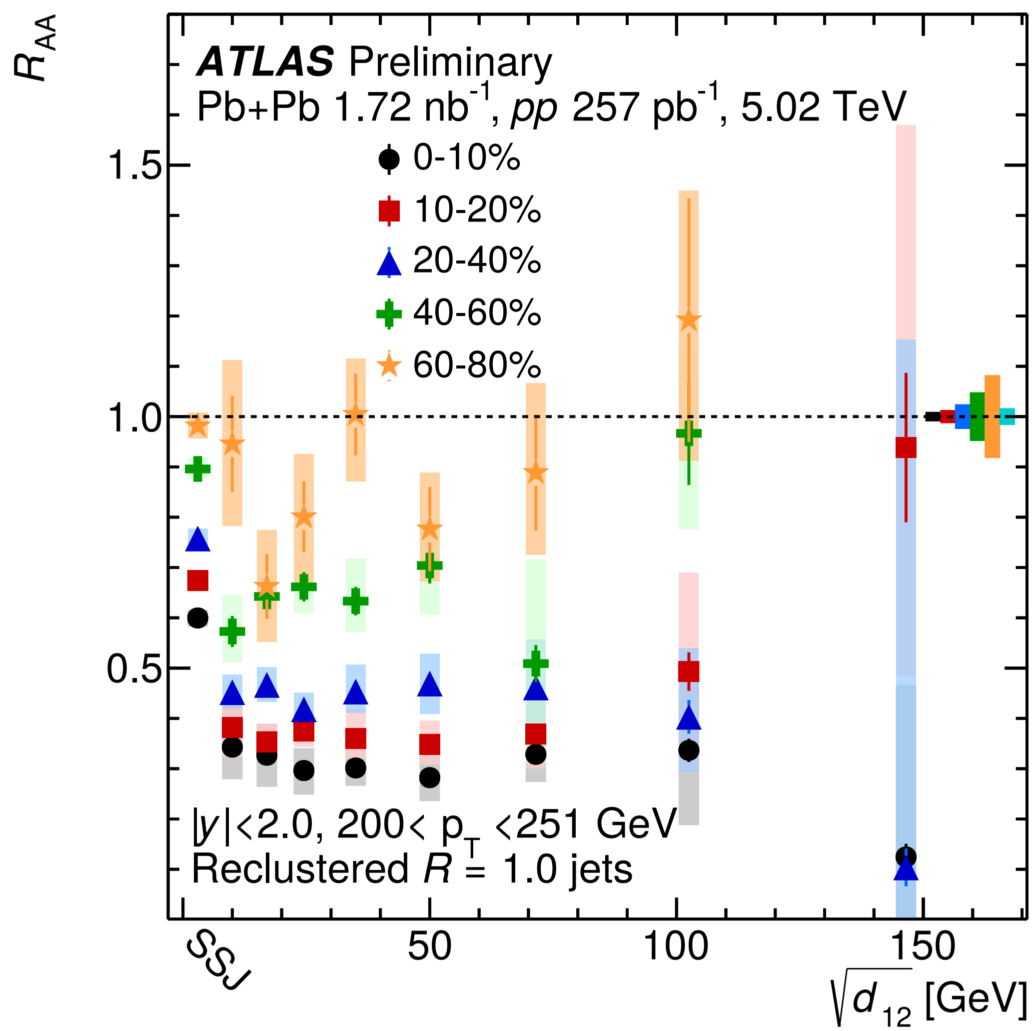
single sub-jet
= coherent

incoherent

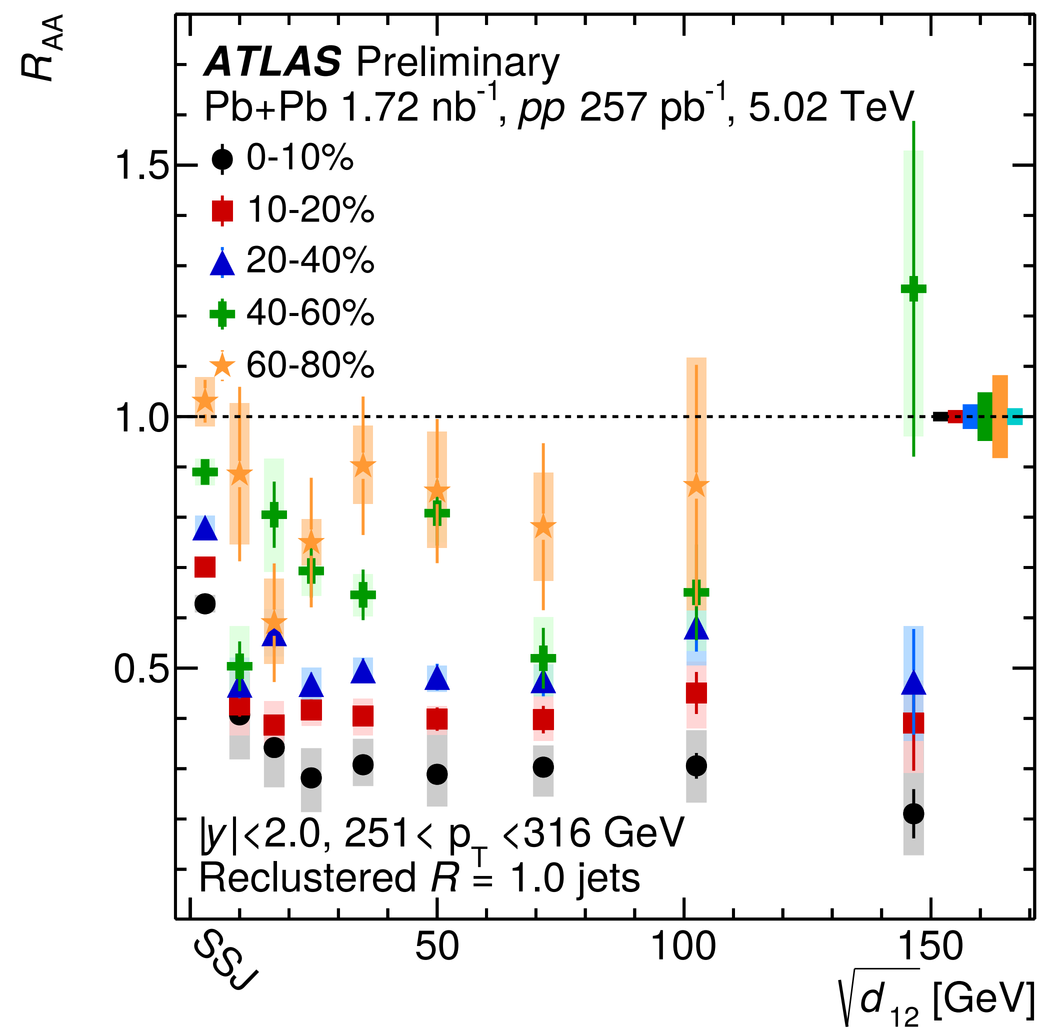
- Jets are all suppressed with the same centrality ordering
- SSJ shows significant less suppression wrt. $\sqrt{d_{12}} > 0$
- No obvious dependence on $\sqrt{d_{12}}$ for $\sqrt{d_{12}} > 0$
- Not able to isolate any color coherent emissions with splitting. 0.2 is still larger than the color correlation scale?

Large radius jet R_{AA} vs splitting scale

ATLAS-CONF-2019-056



$200 < p_{\mathrm{T}}^{\mathrm{jet}} < 251$ GeV

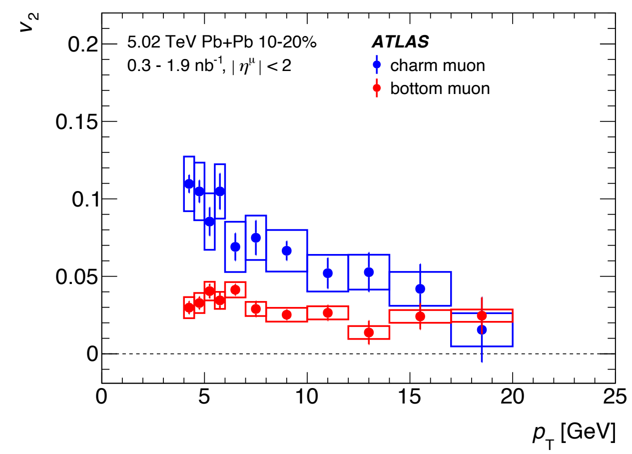


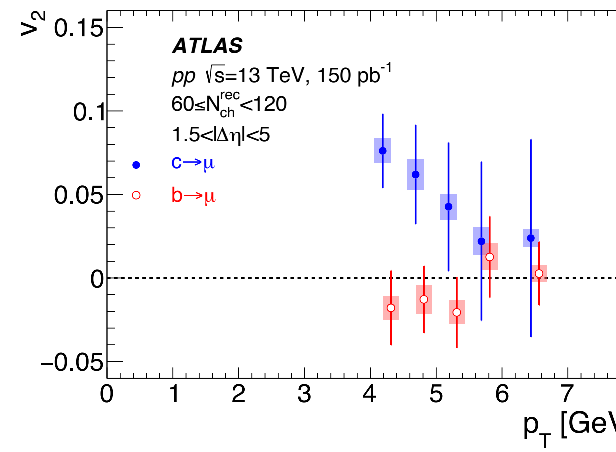
$251 < p_{\mathrm{T}}^{\mathrm{jet}} < 316$ GeV

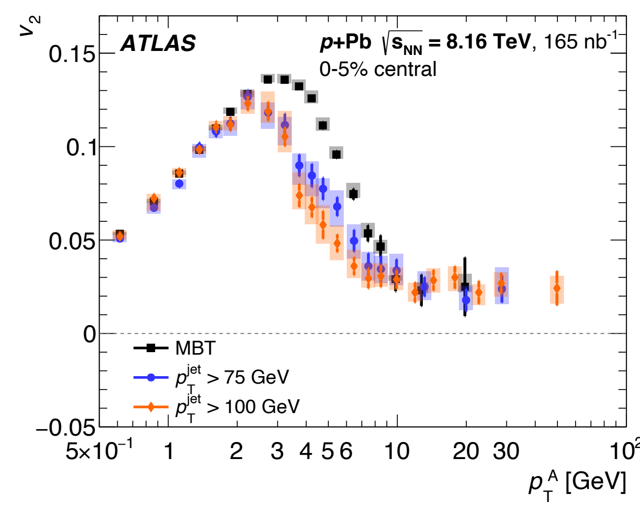
Same story for higher jet p_T

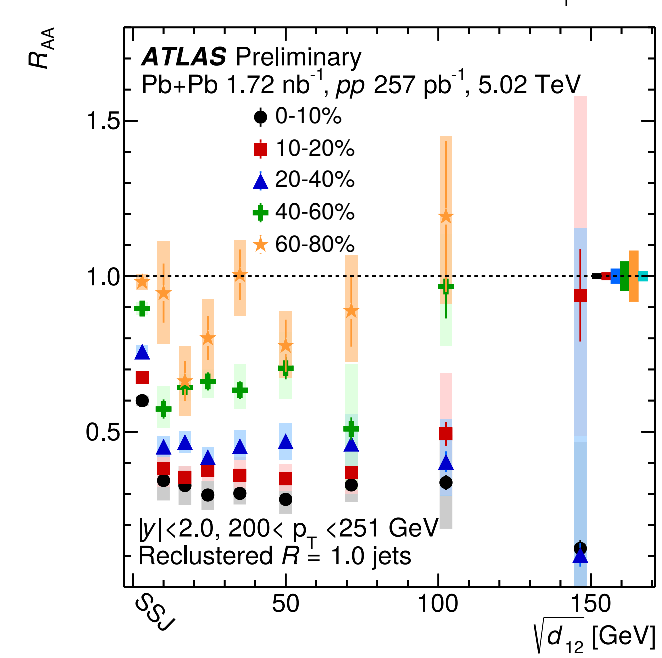
Summary

- HF flow in Pb+Pb: consistent with path-length dependence of energy loss
- HF flow in *pp*: charm is like light hadron while bottom has zero v_2
- High p_T hadron flow in *p*+Pb: similar to Pb+Pb, no convincing interpretation
- Reclustered large radius jet: significant less suppression for single sub-jet, no obvious color coherence with more splitting so far







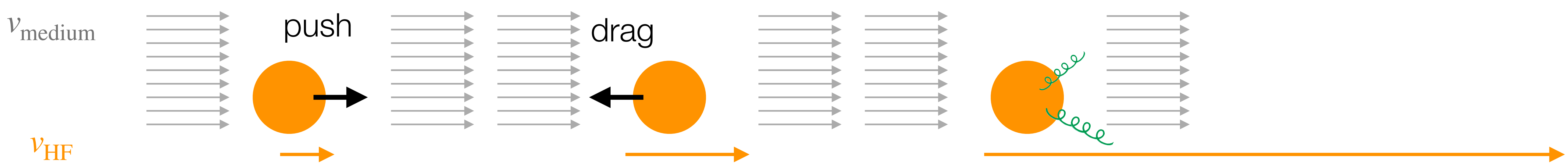


Related publications

- Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in Pb+Pb collisions at 5.02 TeV with the ATLAS detector, ATLAS-CONF-2019-053
- Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions at 13 TeV with the ATLAS detector, arXiv:1909.01650, accepted by *PRL*
- Transverse momentum and process dependent azimuthal anisotropies in 8.16 TeV p+Pb collisions with the ATLAS detector, arXiv:1910.13978, *Eur. Phys. J. C 80 (2020) 73*
- Measurement of suppression of large-radius jets and its dependence on substructure in Pb+Pb at 5.02 TeV by ATLAS detector, ATLAS-CONF-2019-056

Backup

Heavy quarks flow



Low p_T HF:

$v_{\mathrm{HF}} < v_{\mathrm{medium}}$

“elastic” collisions

anisotropy increases with p_T ↑

Intermediate p_T HF:

$v_{\mathrm{HF}} > v_{\mathrm{medium}}$

collisions and gluon emission

anisotropy decreases with p_T ↓

High p_T HF:

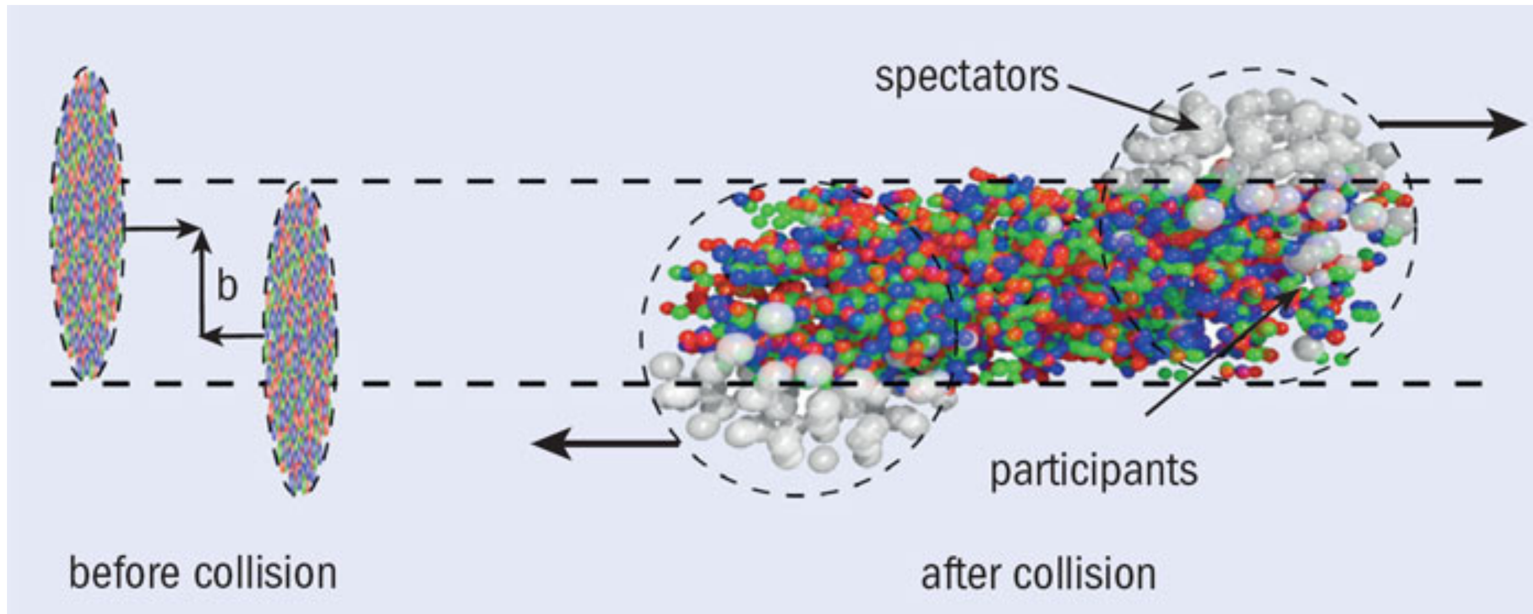
$v_{\mathrm{HF}} \gg v_{\mathrm{medium}}$

gluon emission

anisotropy decreases with p_T ↓

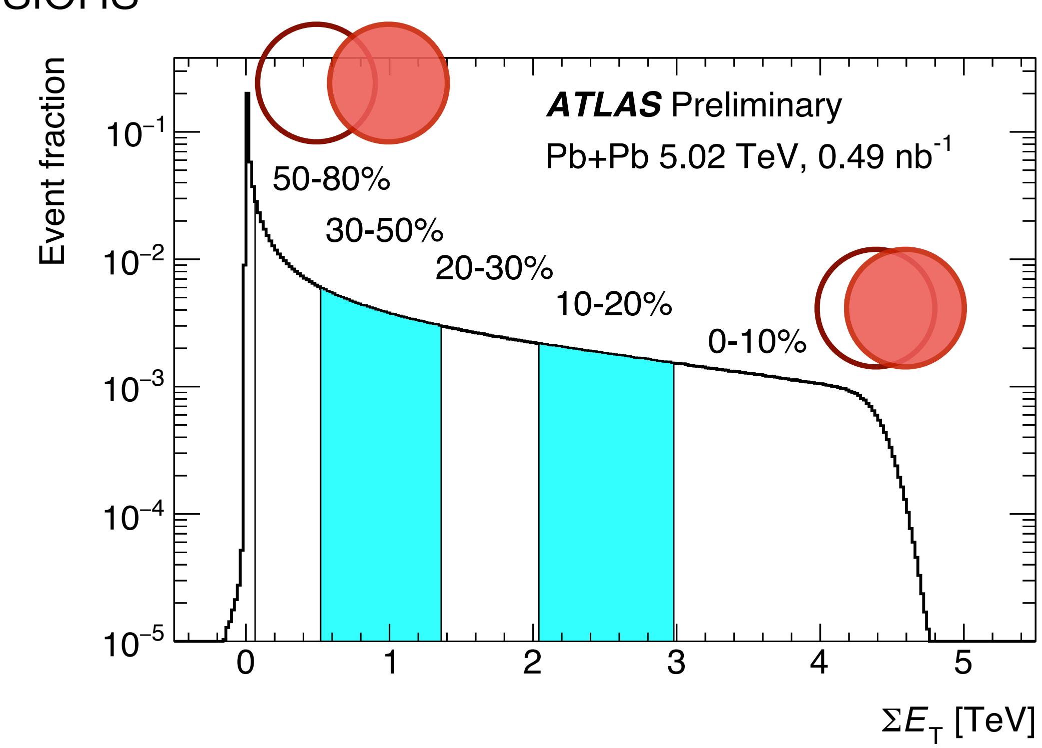
equilibrium, HF quark experiences
largest anisotropy as medium itself

Centrality in Pb+Pb



Peripheral collisions (50-80%)

~ pp collisions

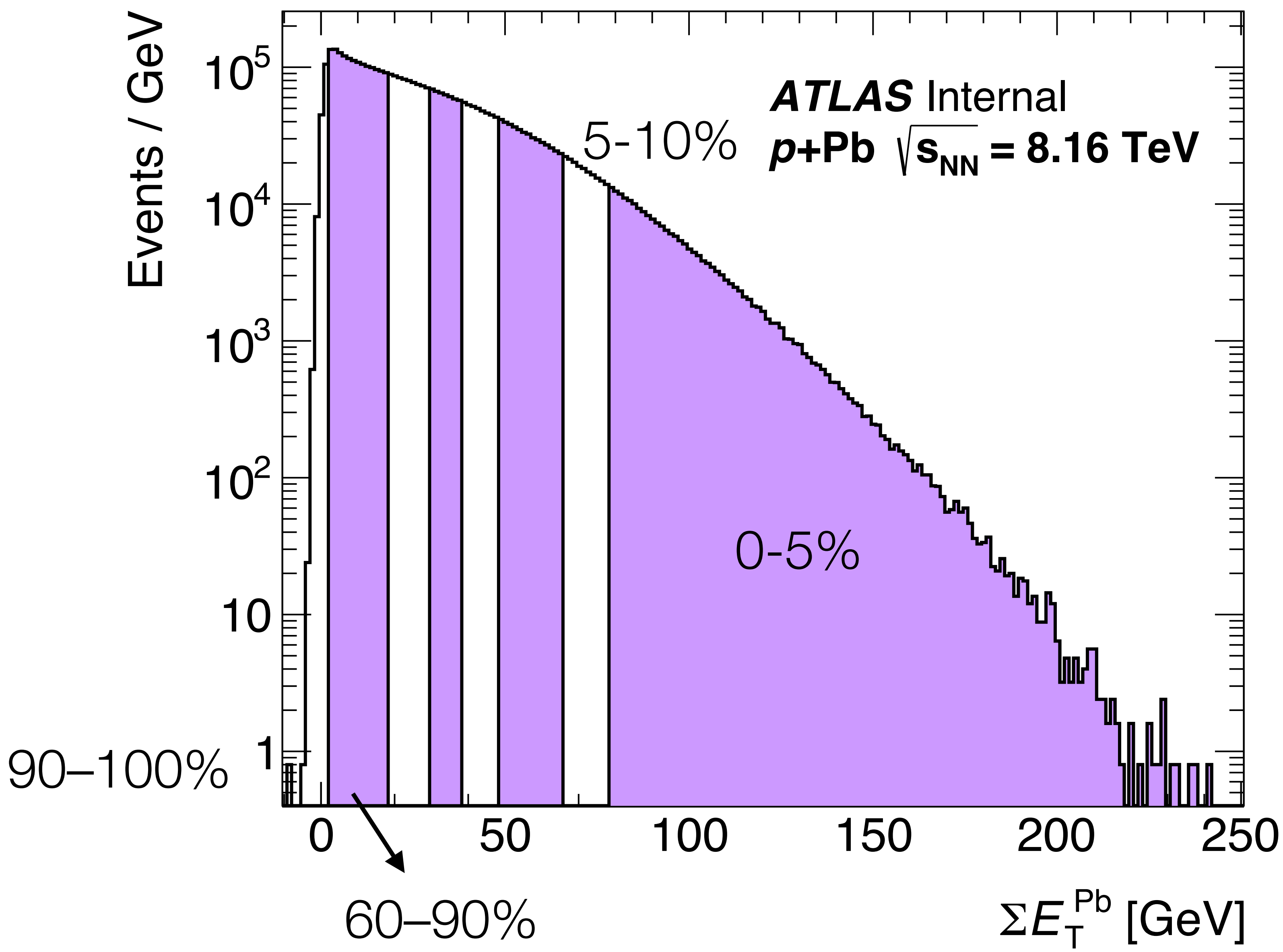


Central collisions (0-10%)

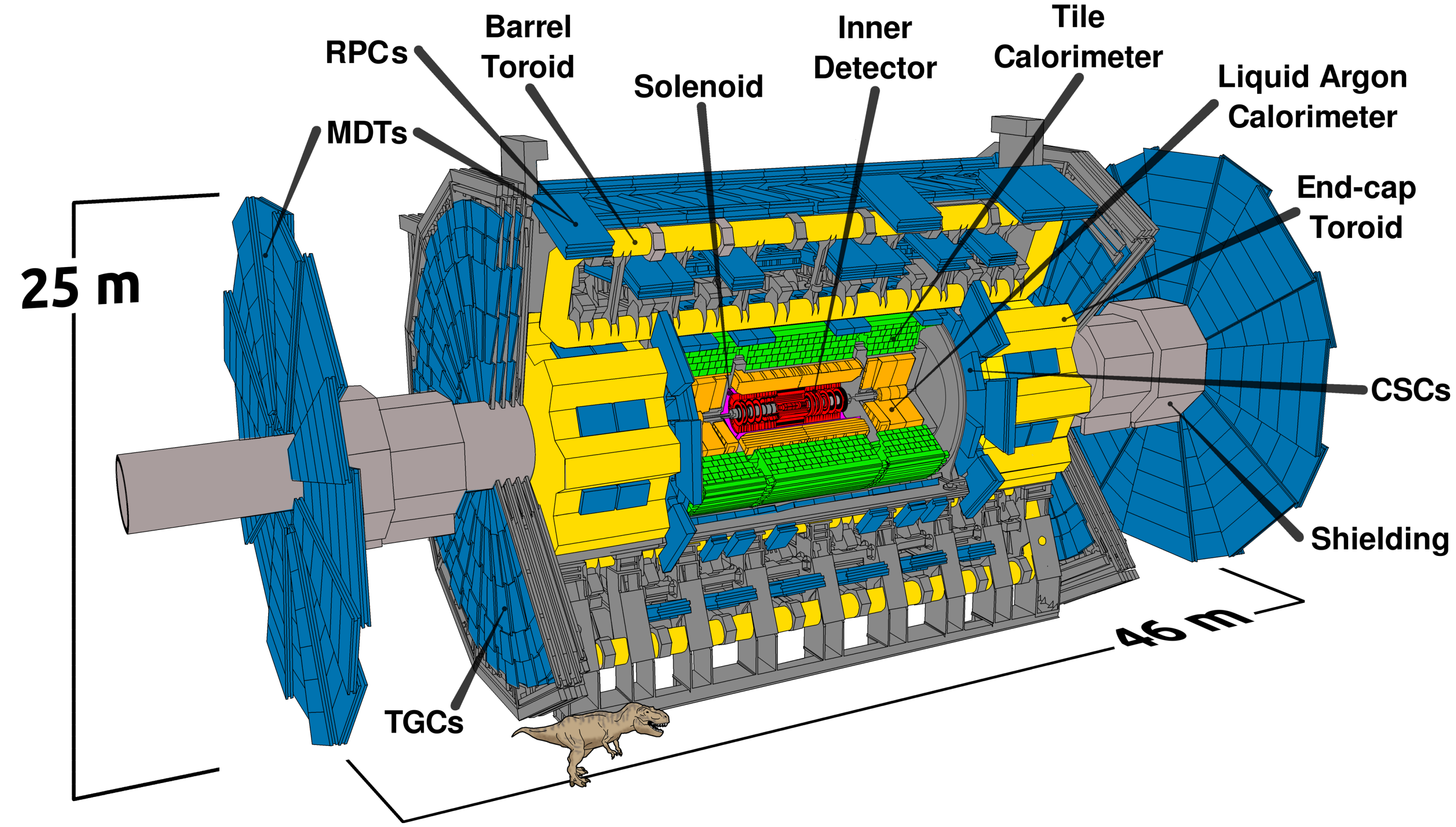
- smaller impact parameters
- more nucleons participated in collision
- larger energy deposition at FCal

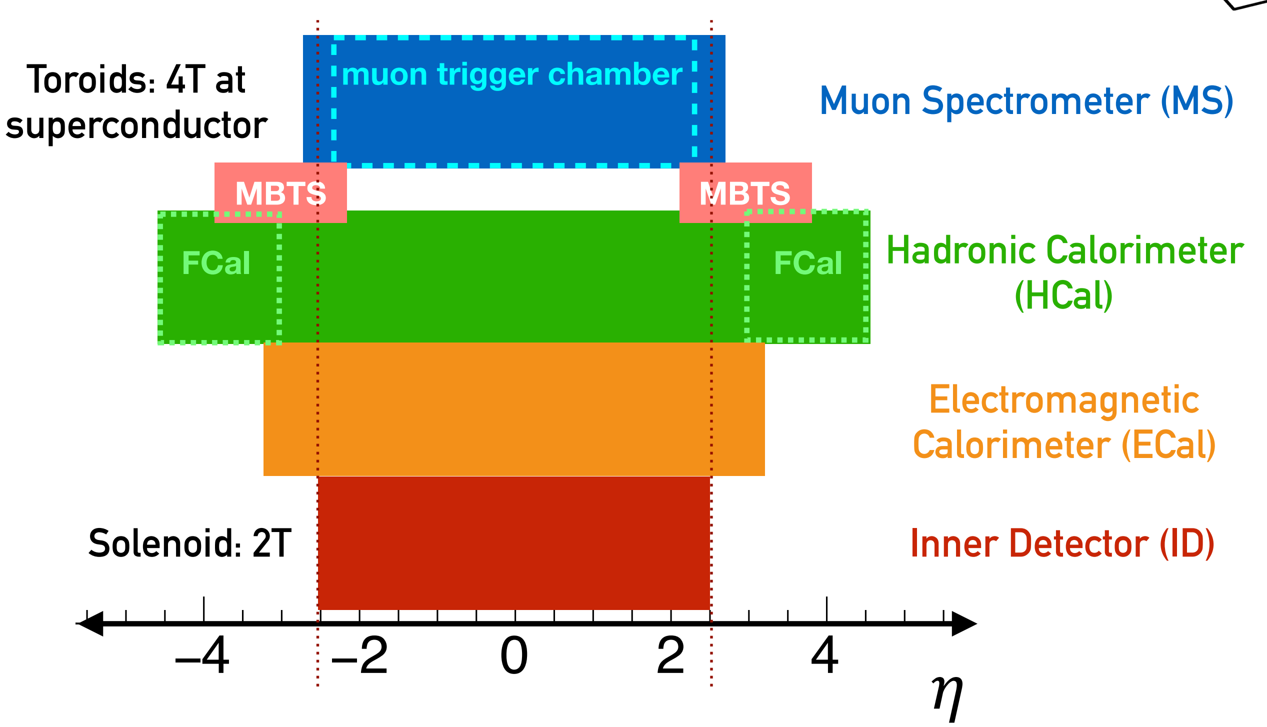
Energy deposition in Forward calorimeter

p+Pb centrality



ATLAS detector

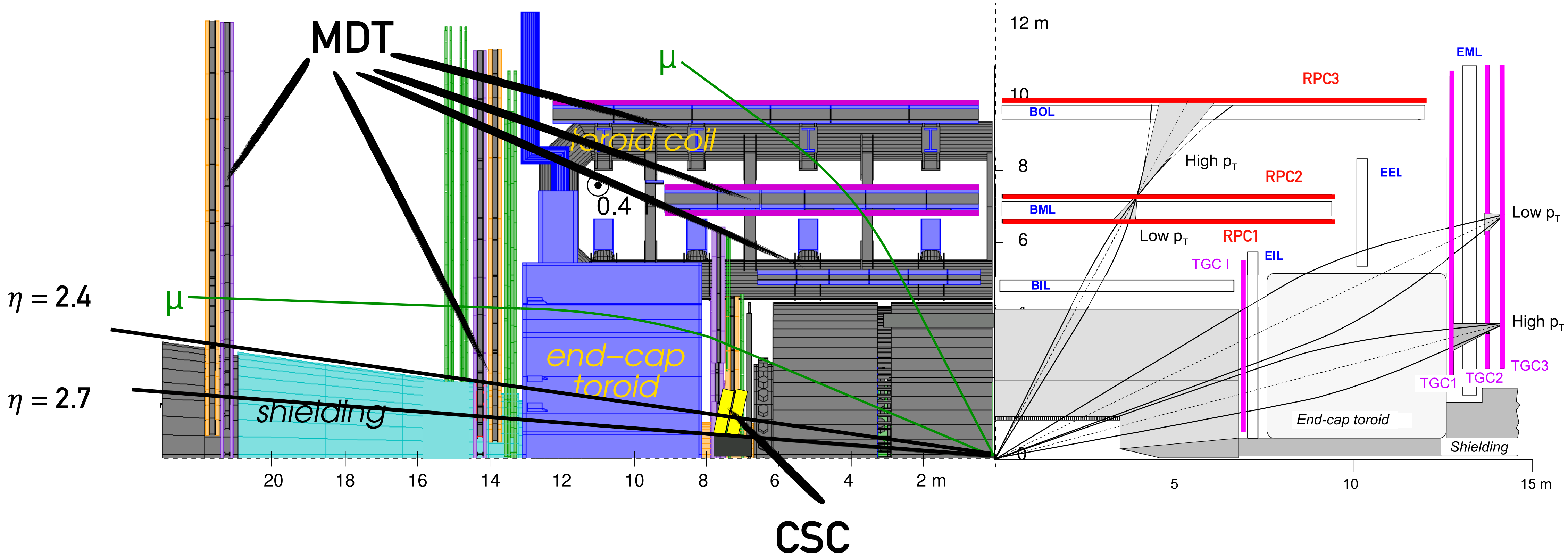




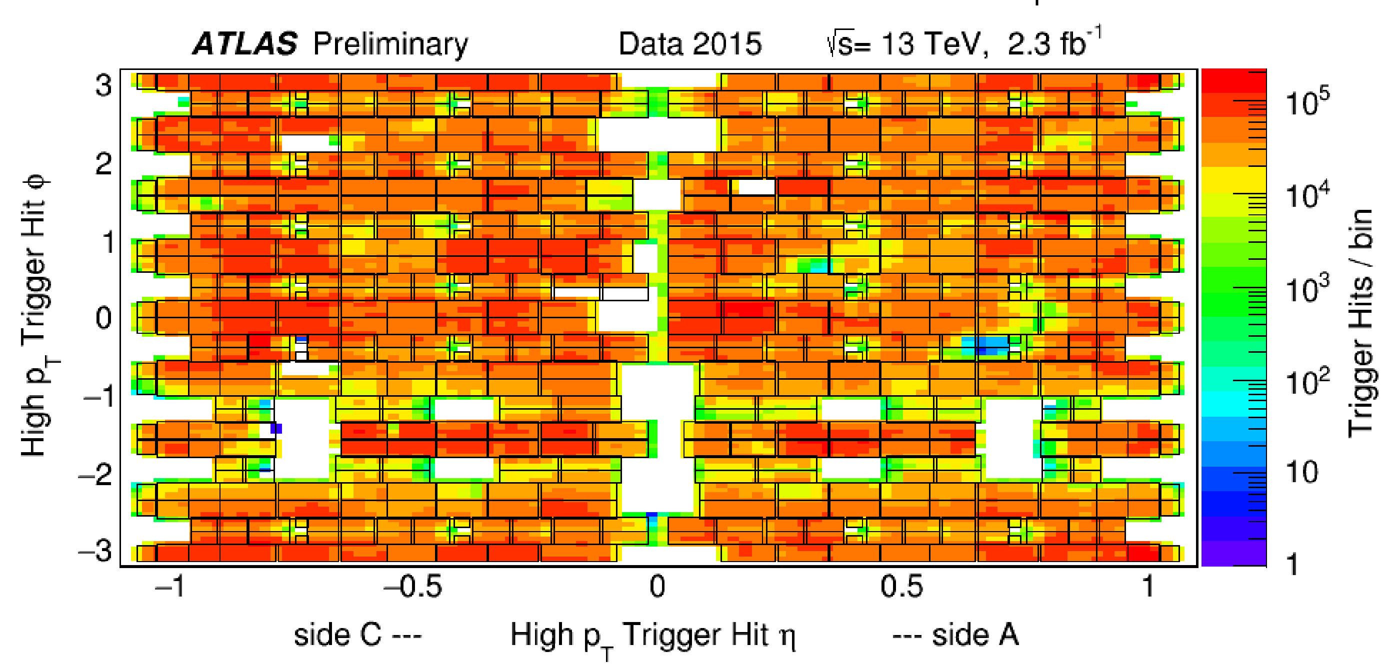
For muon with p_T = 5 GeV, $\eta = 0$:

- d_0 resolution ~ 0.020 mm
- ID p_T resolution ~ 2%
- MS p_T resolution ~ 6%

ATLAS muon system



ATLAS RPC acceptance ~ 80% overall



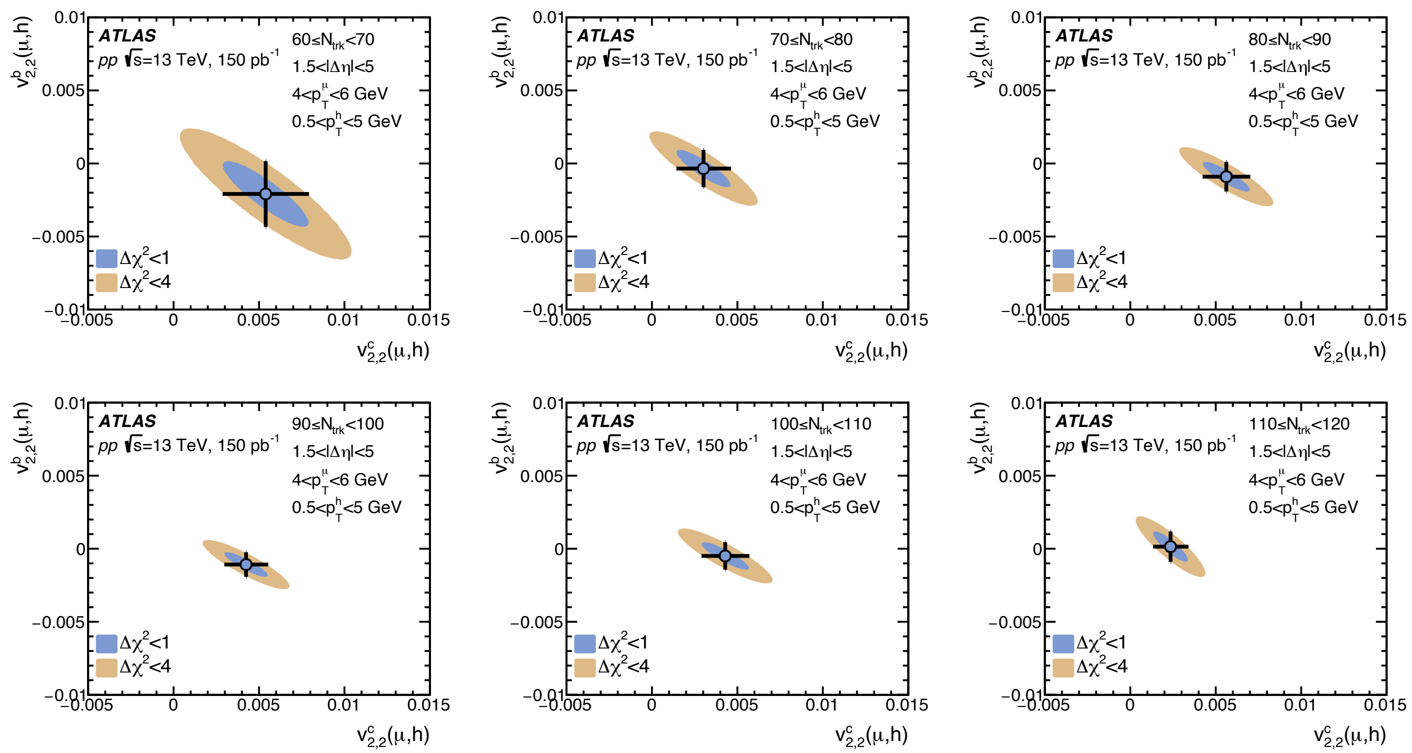
Trigger chambers

RPCs |η| < 1.05 (barrel)

TGCs 1.05 < |η| < 2.4 (end-cap)

Correlations between c and b results

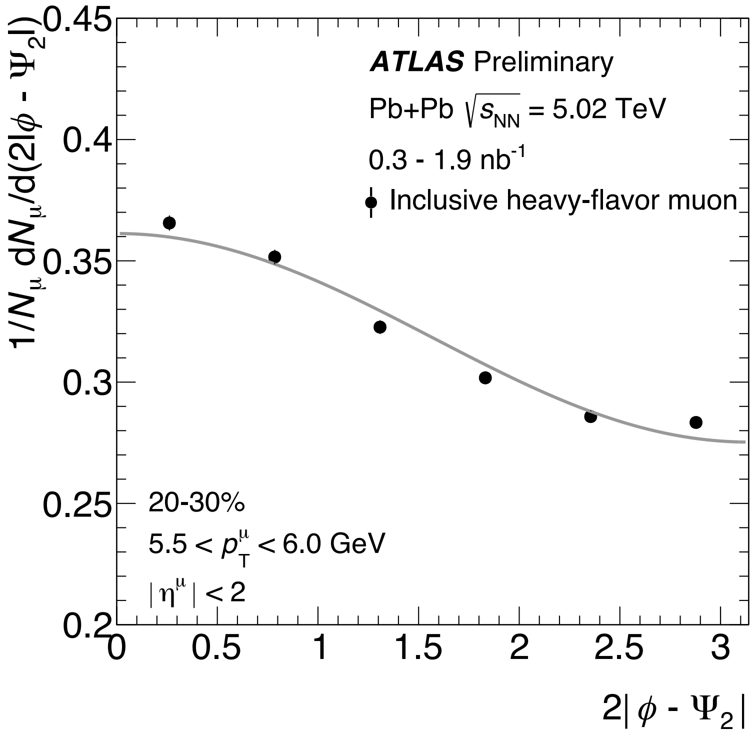
ATLAS-CONF-2019-053



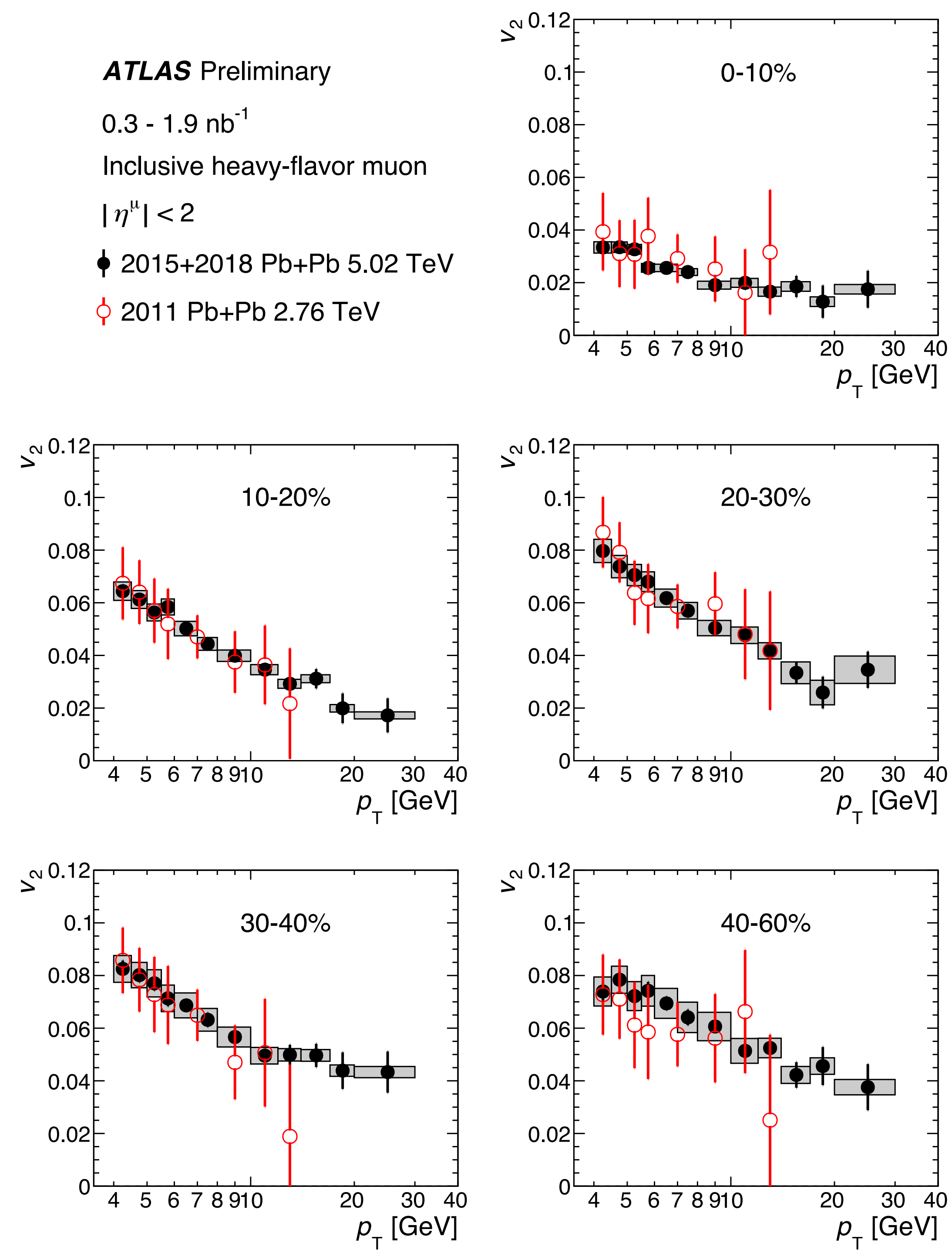
Due to the methodology of the b/c separation, the results are anti-correlated. Statistical correlation of the results are also provided by ATLAS for theorists to perform a simultaneous comparison to charm and bottom results

Inclusive HF muon v_2 in Pb+Pb

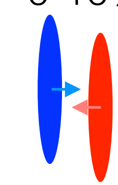
ATLAS-CONF-2019-053



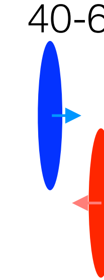
$$\frac{1}{N_X^\mu}\frac{\mathrm{d}N_X^\mu}{\mathrm{d}(n(\phi-\Psi_n))} = 1 + 2v_n^{\mathrm{raw}}\cos\left(n(\phi-\Psi_n)\right)$$



0-10%

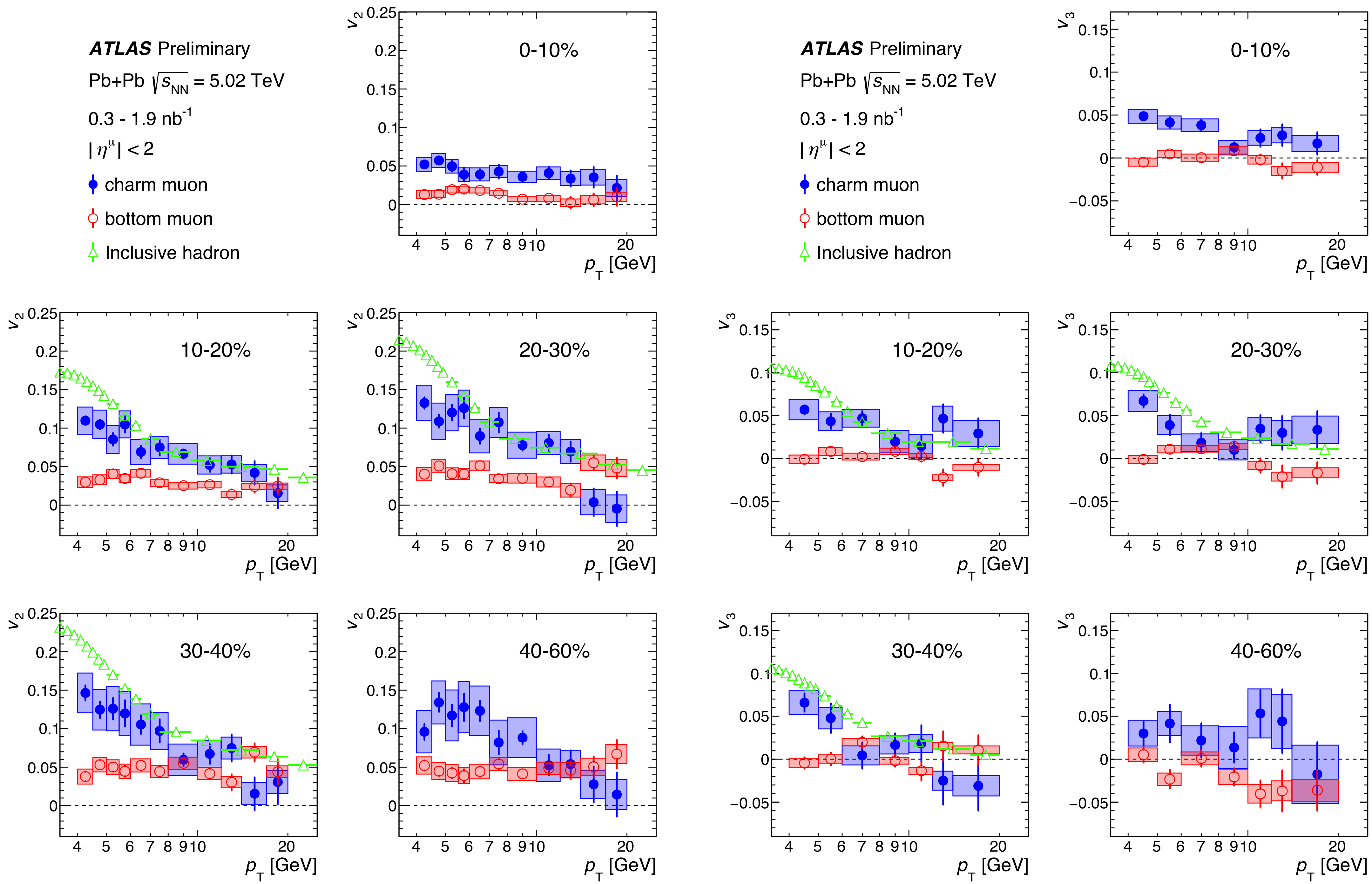


40-60%

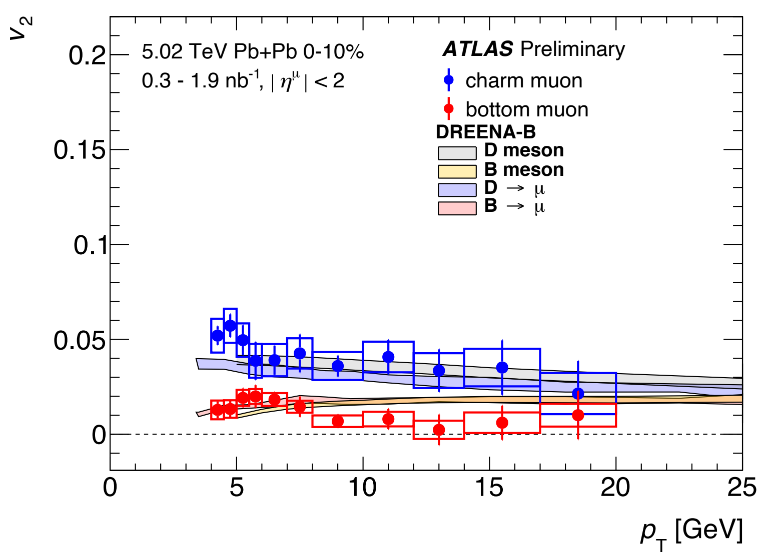


- 2015+2018 Pb+Pb data
- v_n extracted from event-plane method, corrected for resolution
- Good agreement with Run1 ATLAS results

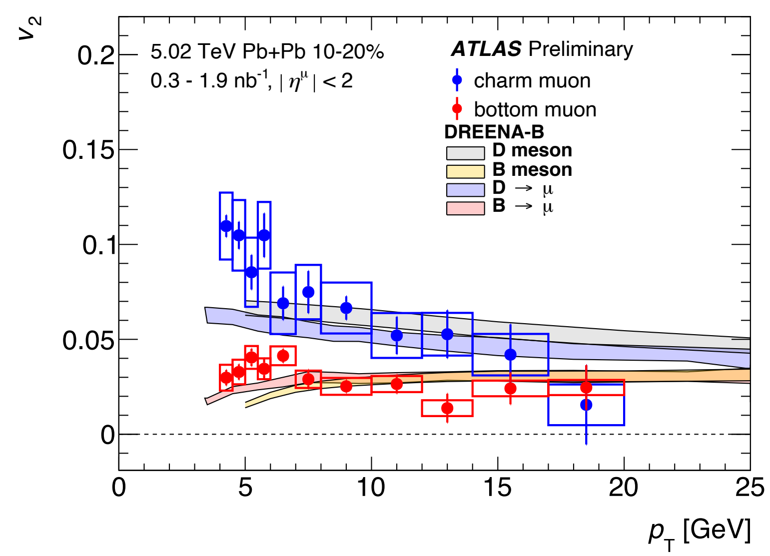
HF muon vs. hadron in Pb+Pb



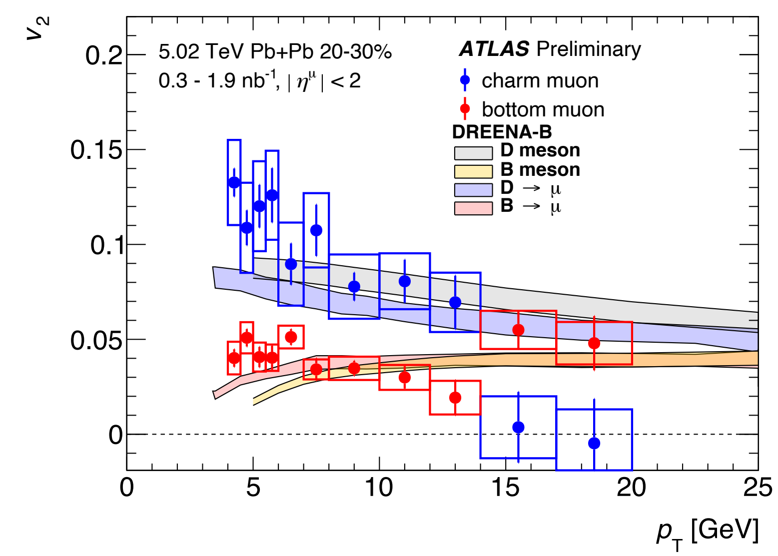
DREENA-B



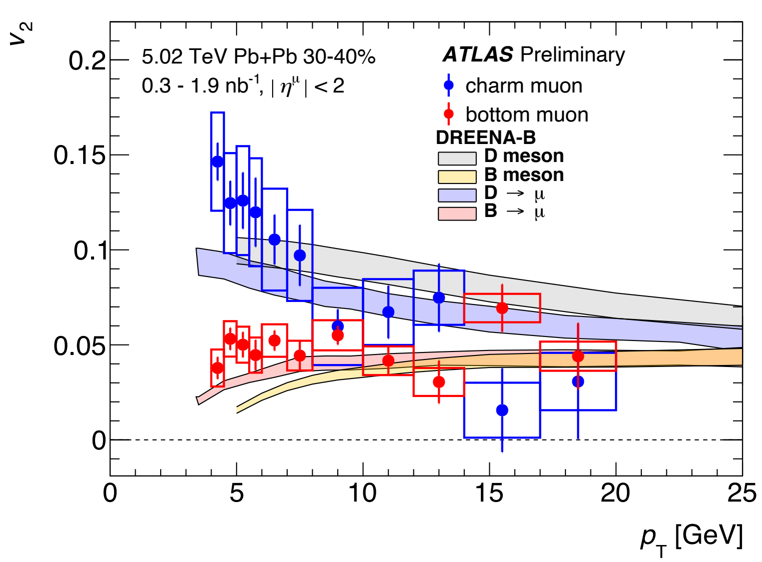
5.02 TeV Pb+Pb 0-10%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DREENA-B
D meson
B meson
D → μ
B → μ
v_2
p_T [GeV]



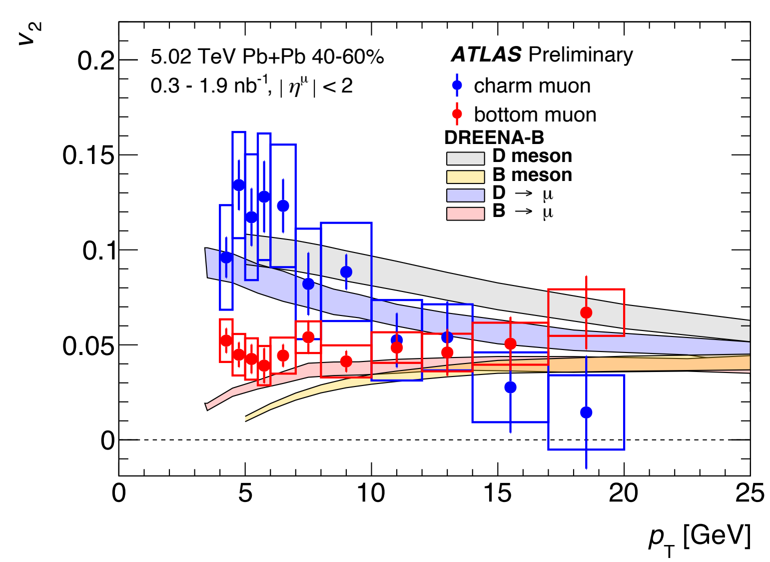
5.02 TeV Pb+Pb 10-20%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DREENA-B
D meson
B meson
D → μ
B → μ
v_2
p_T [GeV]



5.02 TeV Pb+Pb 20-30%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DREENA-B
D meson
B meson
D → μ
B → μ
v_2
p_T [GeV]

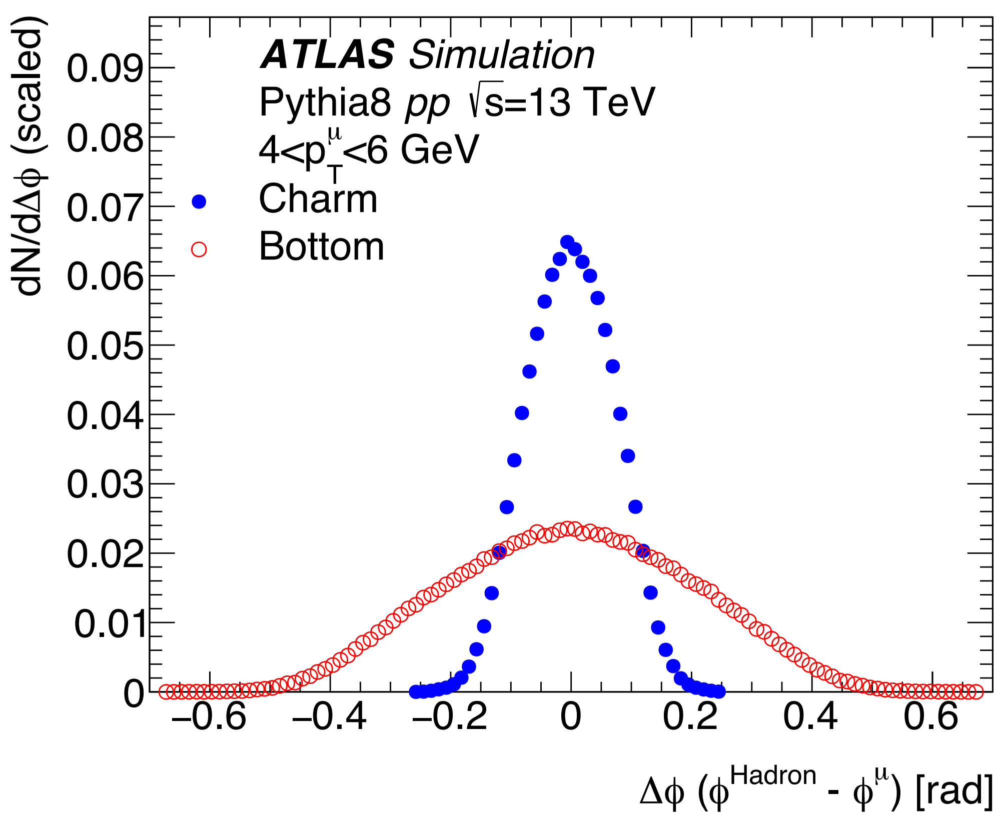


5.02 TeV Pb+Pb 30-40%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DREENA-B
D meson
B meson
D → μ
B → μ
v_2
p_T [GeV]

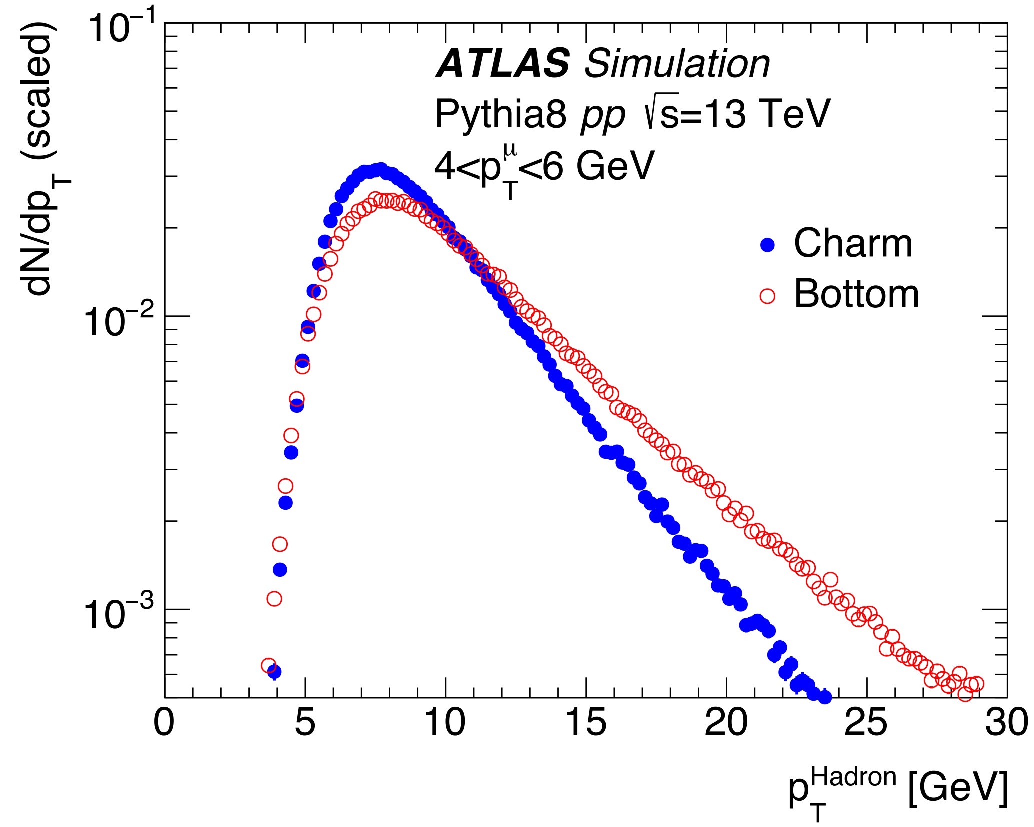


5.02 TeV Pb+Pb 40-60%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DREENA-B
D meson
B meson
D → μ
B → μ
v_2
p_T [GeV]

Hadron to muon smearing in Pythia

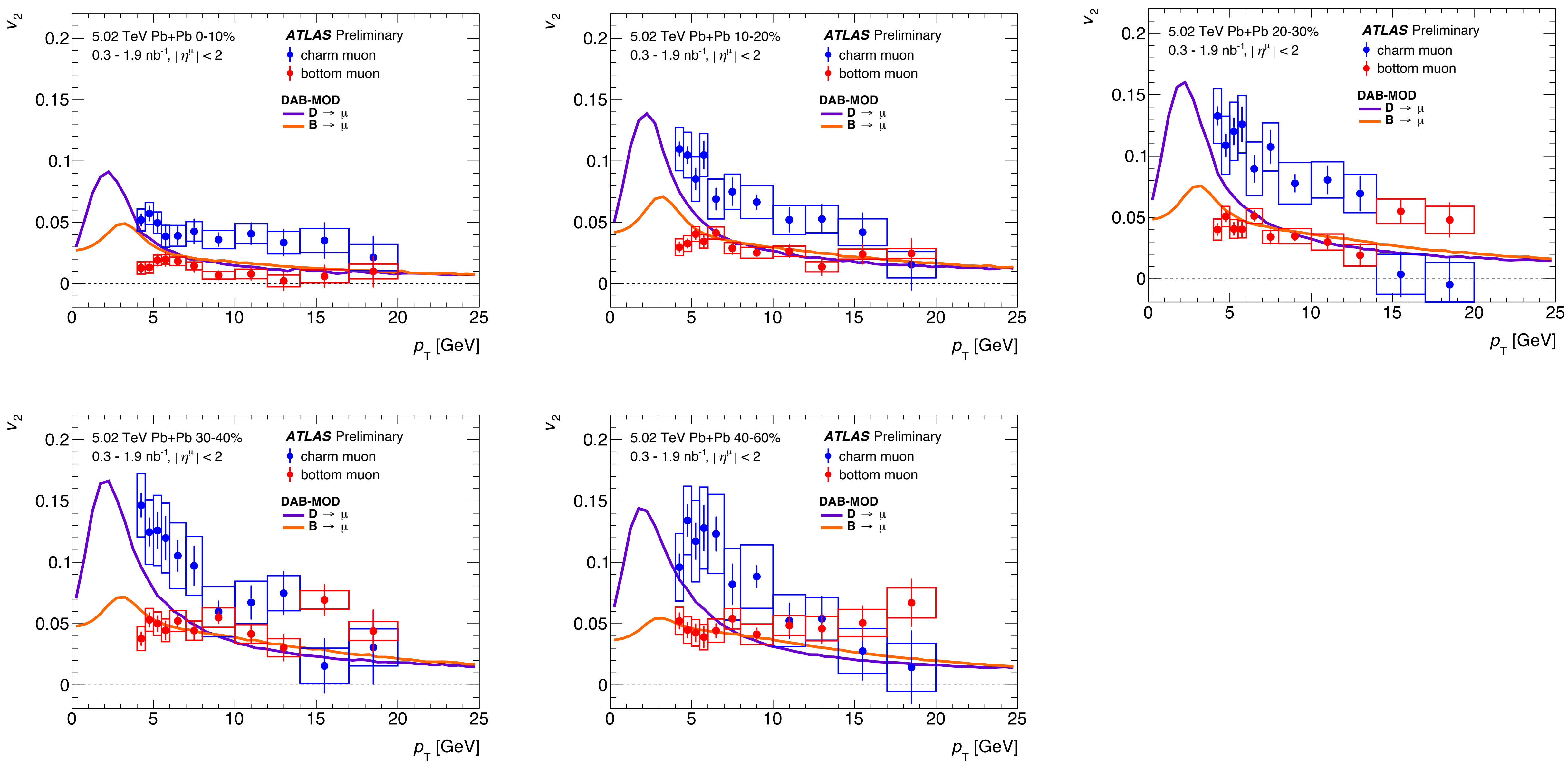


azimuthal angle smearing



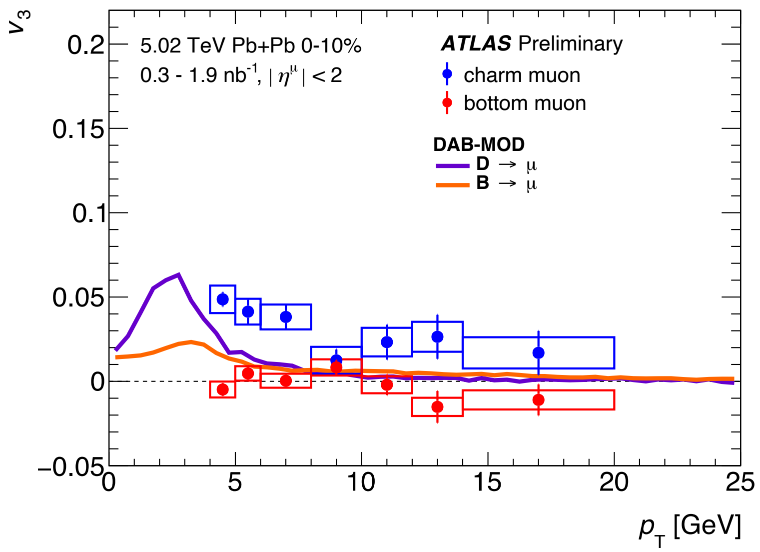
p_T shift and smearing

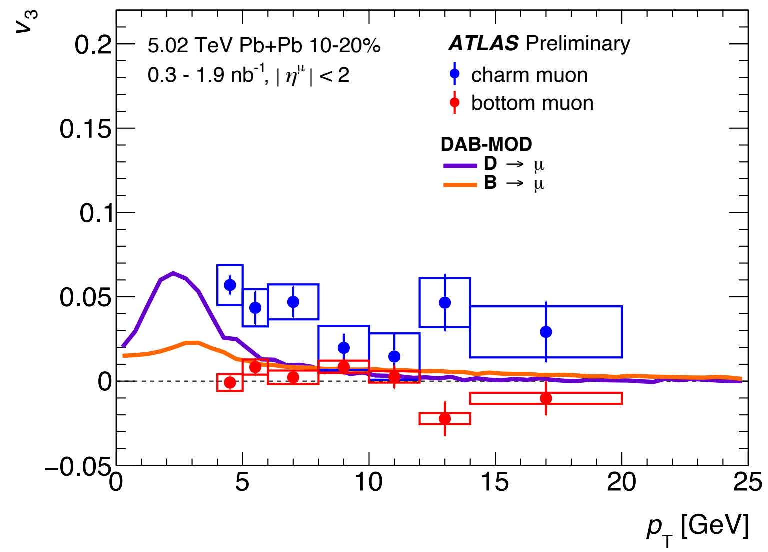
DAB-MOD — v_2

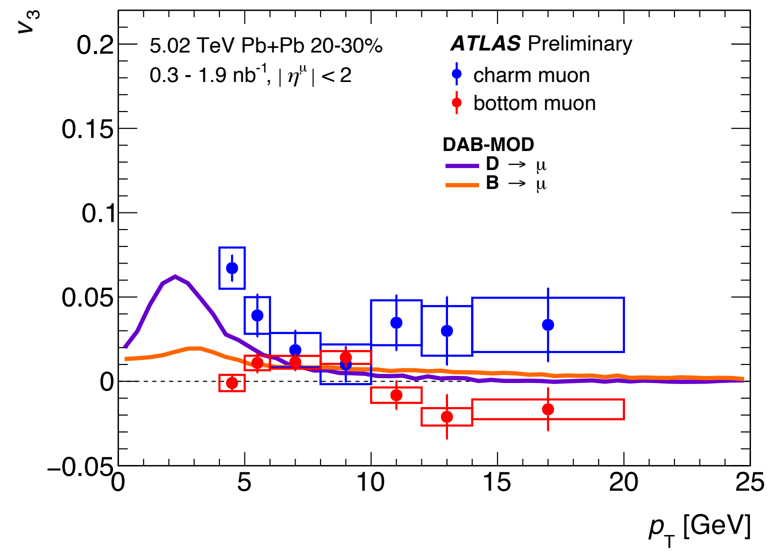

5.02 TeV Pb+Pb 0-10%
0.3 - 1.9 nb⁻¹, |η^μ| < 2
ATLAS Preliminary
charm muon
bottom muon
DAB-MOD
D → μ
B → μ
5.02 TeV Pb+Pb 10-20%
5.02 TeV Pb+Pb 20-30%
5.02 TeV Pb+Pb 30-40%
5.02 TeV Pb+Pb 40-60%
v₂
p_T [GeV]

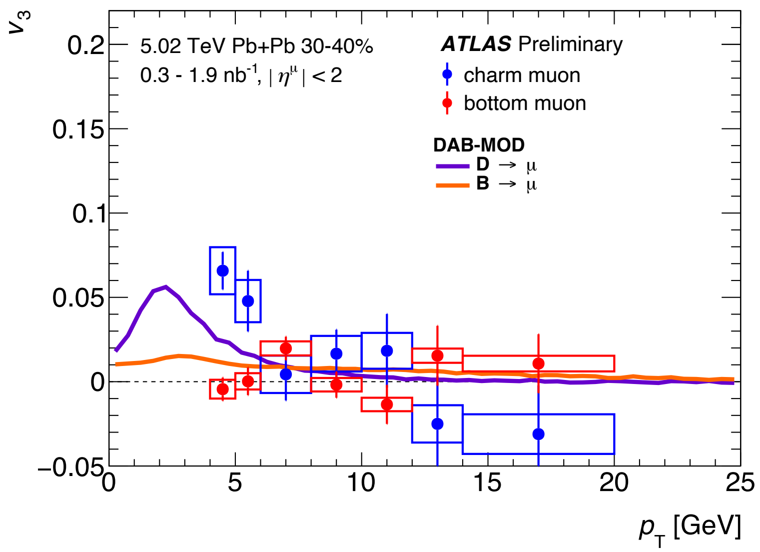
DAB-MOD — v_3

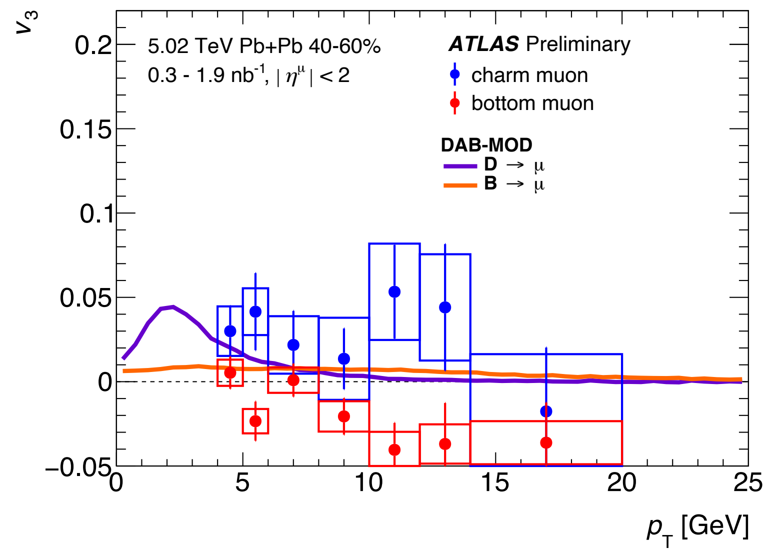
ATLAS EXPERIMENT











HF muon vs. HF hadron

Where does heavy quark go?

flavor	decay mode	Branching fraction	comments
b quark	$b \to Xl\nu$	11%	easy to trigger
	$b \to c \to Xl\nu$	8%	
	$b \to XD^0$	60%	BR $(D^0 \to K^-\pi^+) = 4\,\%$
	$b \to X\psi \to \mu^+\mu^-$	0.07%	easy to trigger
c quark	$c \to Xl\nu$	10%	easy to trigger
	$c \to XD^0$	55%	BR $(D^0 \to K^-\pi^+) = 4\,\%$

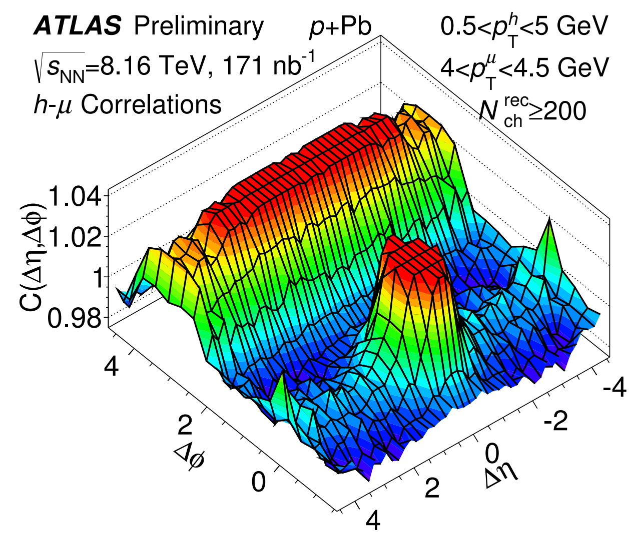
HF muon flow in small systems

In small systems (*pp* and *p*+Pb):

2PC + $\Delta\eta$ gap + non-flow subtraction

$$C(\Delta\phi) = FC^{\text{periph}}(\Delta\phi) + G\left\{1 + 2\sum v_{n,n}\cos(n\Delta\phi)\right\}$$

$v_{n,n}$ factories and v_n is extracted.



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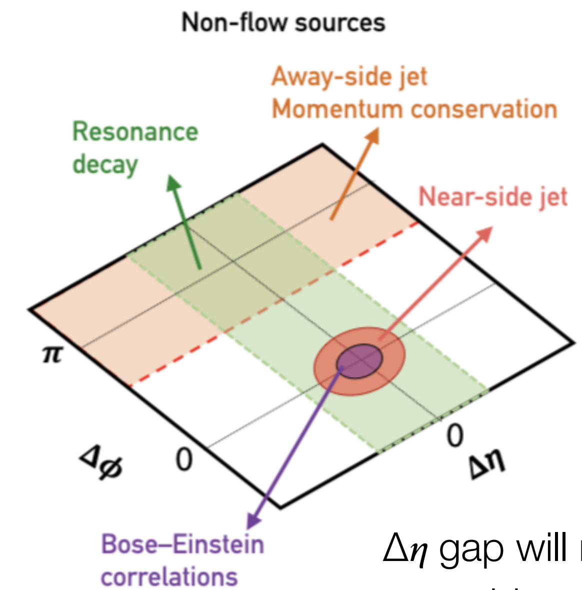
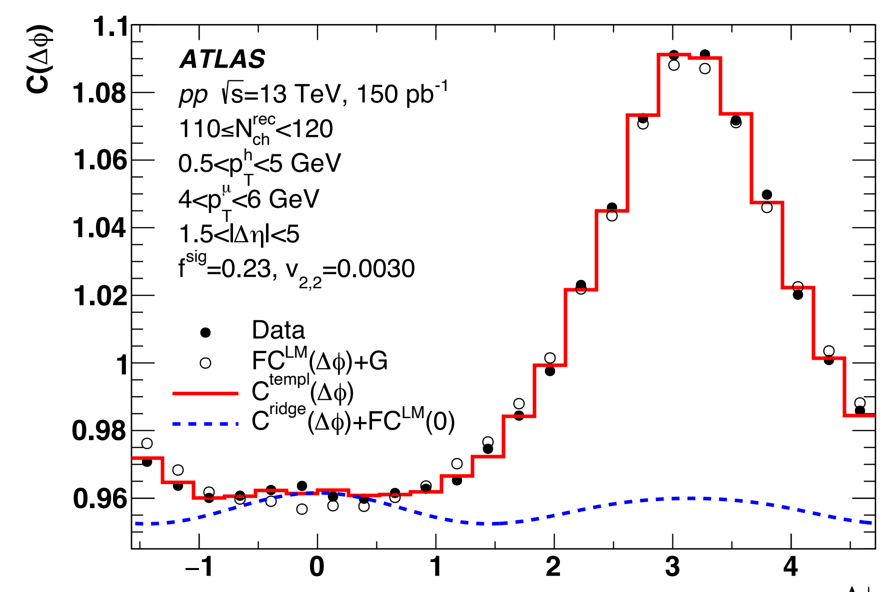


$\Delta\eta$ gap will remove near-side non-flow

Assumptions of non-flow subtraction:

- Universal jet-correlation shape
- Non-zero flow for low multiplicity (difference wrt. CMS)

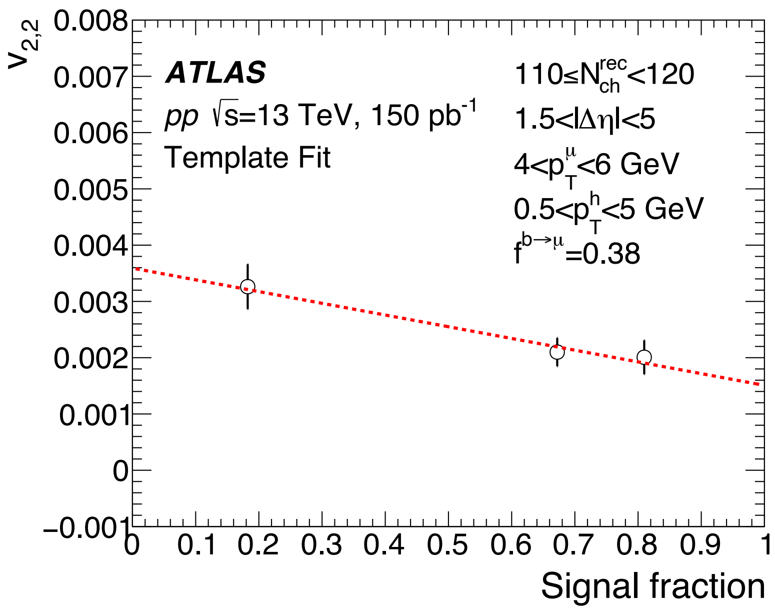


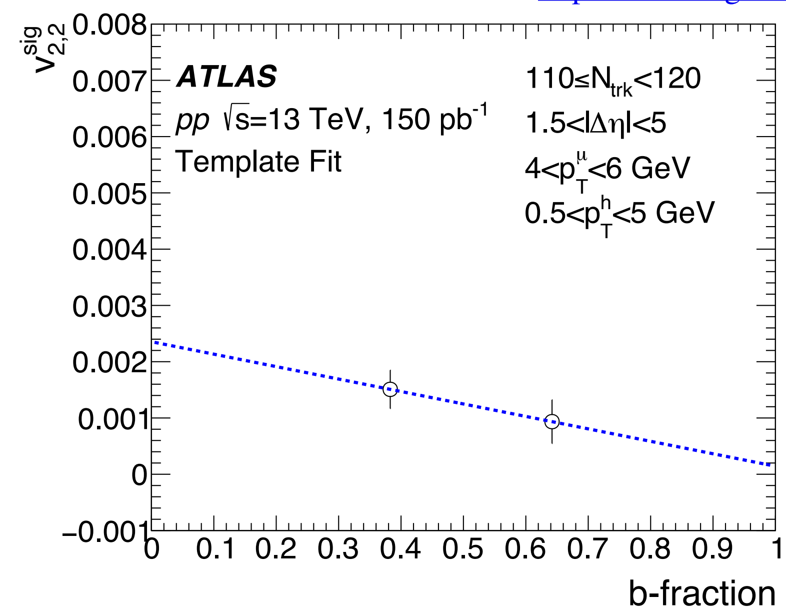
https://arxiv.org/abs/1909.01650

v_n is called “flow” coefficient in this talk just for simplicity.
Hydrodynamic flow is not the only explanation of the results

HF muon flow extraction in *pp*

https://arxiv.org/abs/1909.01650





- Low pile-up *pp* collision data at 13 TeV collected in 2017
- Correlation coefficients $v_{n,n}$ is additive, so a linear combination of different contributions:

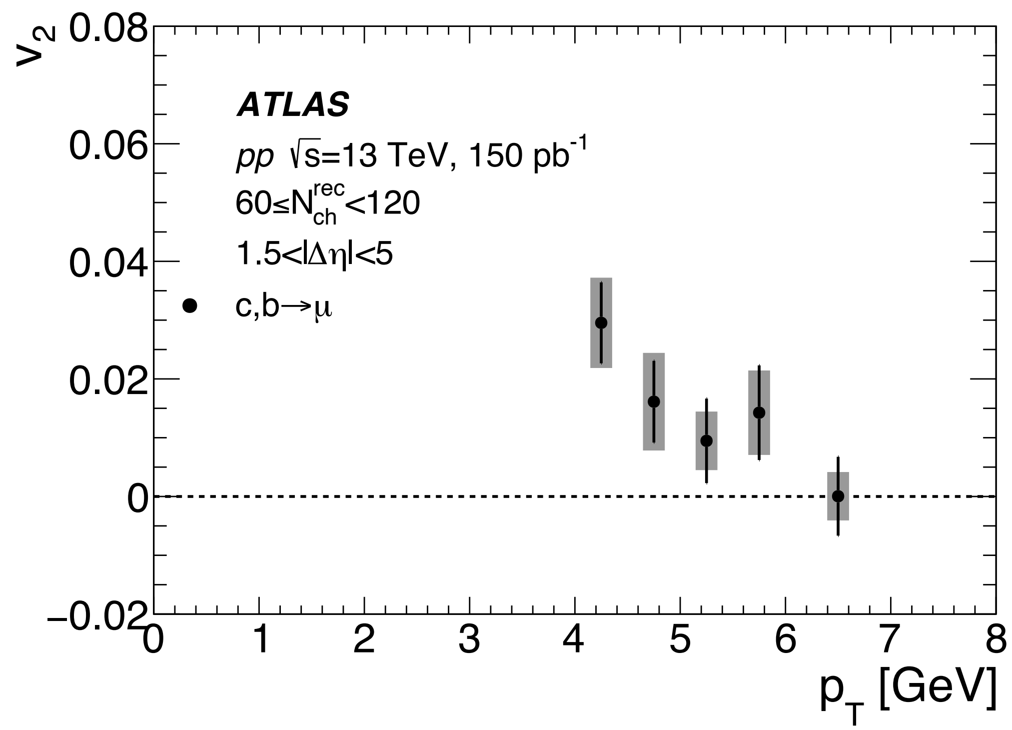
$$v_{2,2} = f^{\rm sig} v_{2,2}^{\rm sig} + (1 - f^{\rm sig}) v_{2,2}^{\rm bkg}$$

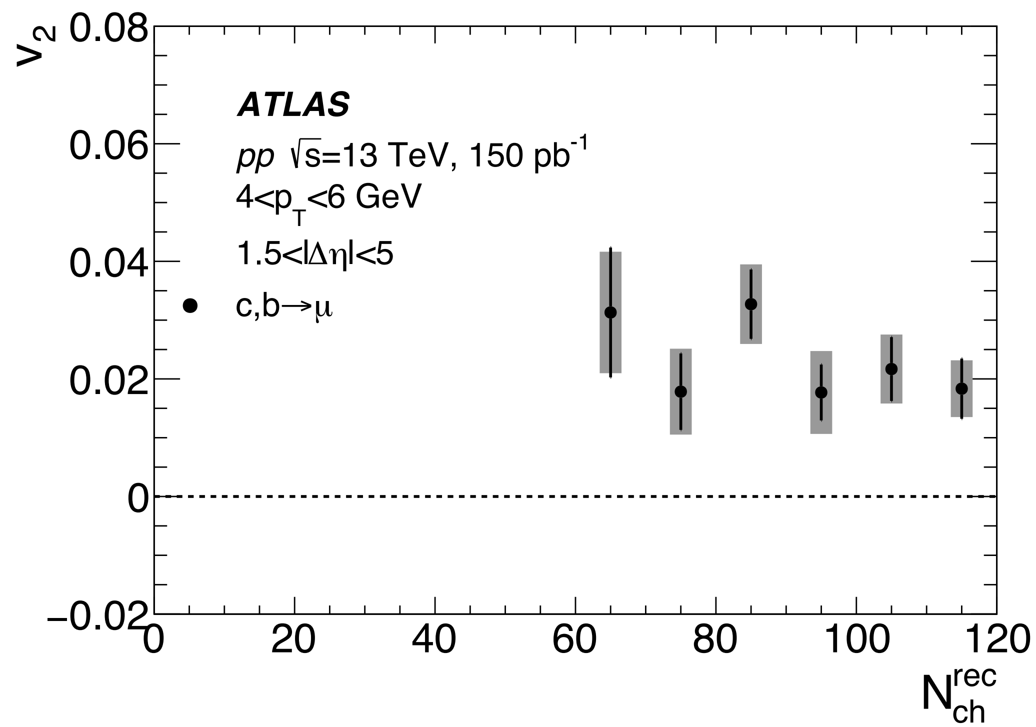
$$v_{2,2}^{\rm sig} = f^{b} v_{2,2}^{b} + (1 - f^{b}) v_{2,2}^{c}$$

- Intervals in momentum imbalance to allow variation on signal fraction
- Intervals in impact parameter to allow variations on b-fraction

Inclusive HF muon flow in *pp*

https://arxiv.org/abs/1909.01650

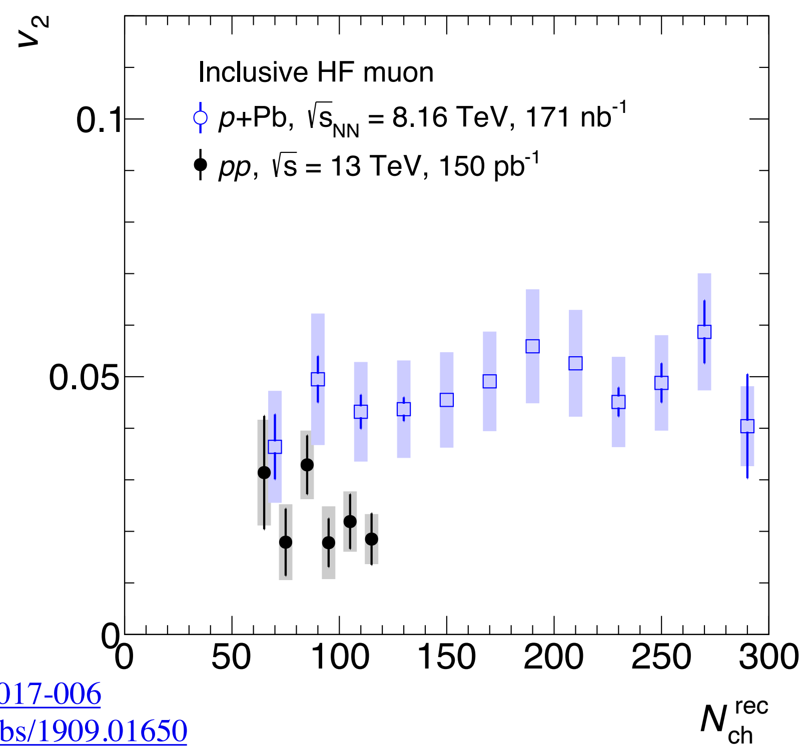




- Results cover $4 < p_{\mathrm{T}} < 7\ \mathrm{GeV}$ and $60 < N_{\mathrm{ch}}^{\mathrm{rec}} < 120$
- Significant non-zero v_2 for inclusive HF muon

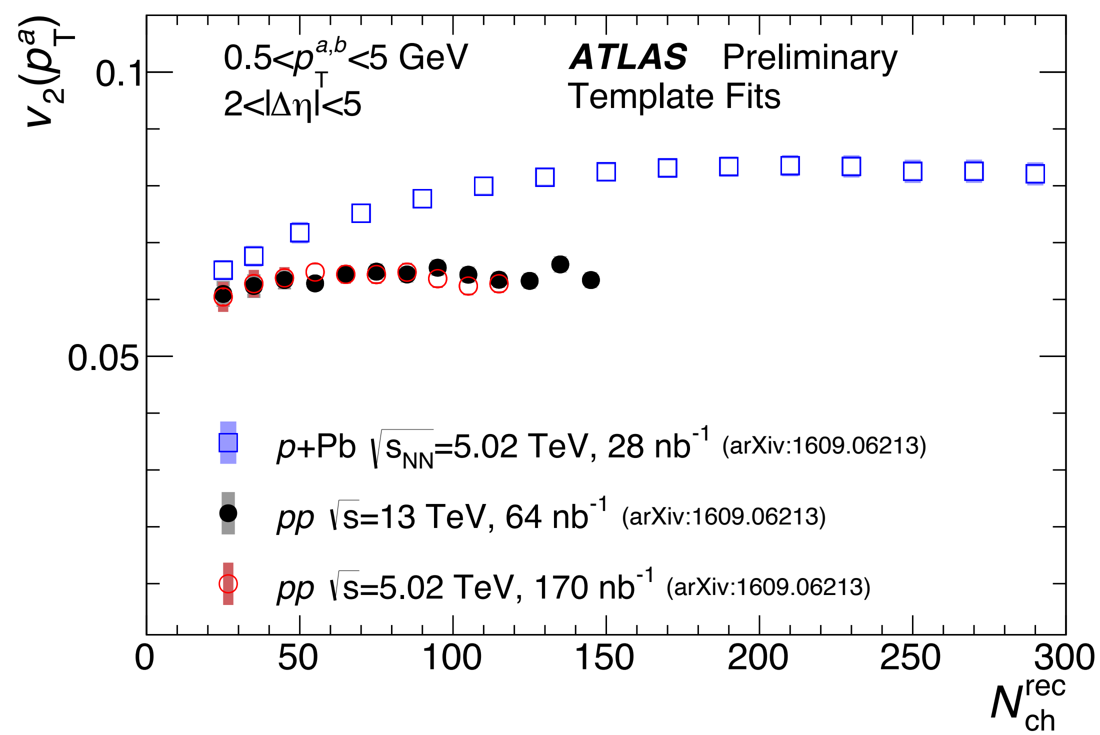
pp vs. *p*+Pb

HF muon



ATLAS-CONF-2017-006
https://arxiv.org/abs/1909.01650

Inclusive charged particle

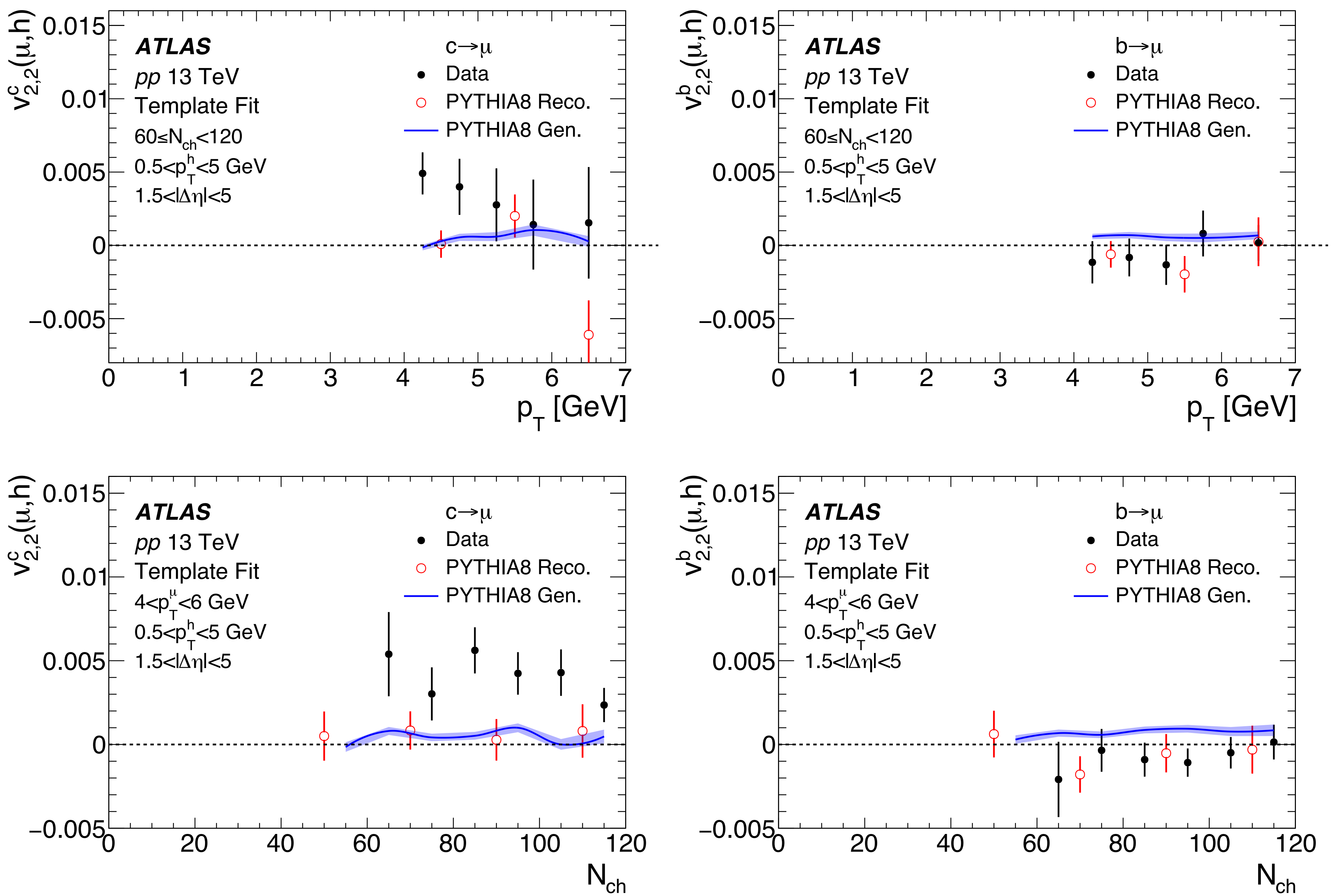


- Smaller v_2 for muons than charged hadron in *pp* and *p*+Pb
- Similar difference between *pp* and *p*+Pb

Closure test in Pythia8

ATLAS EXPERIMENT

https://arxiv.org/abs/1909.01650

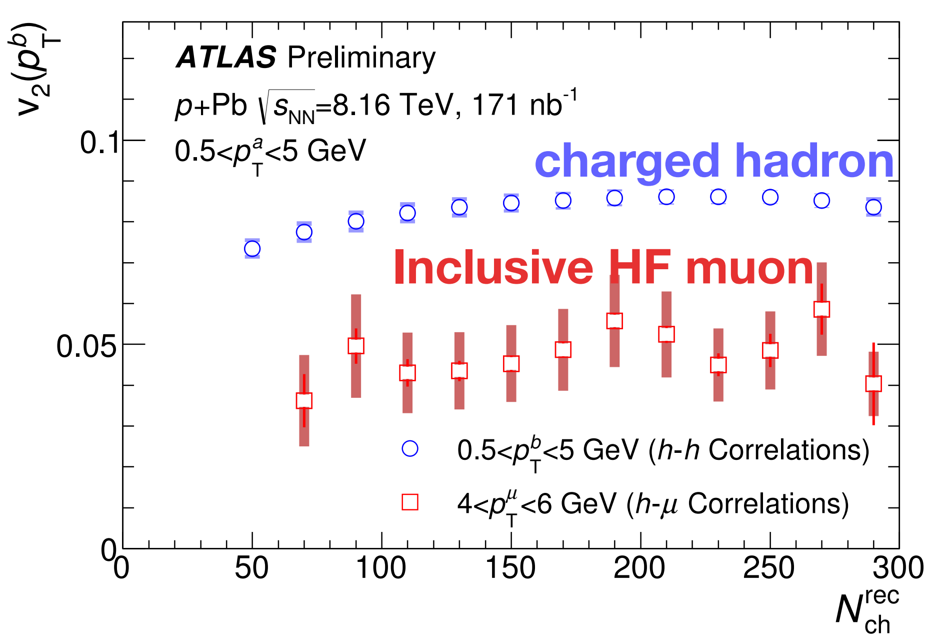


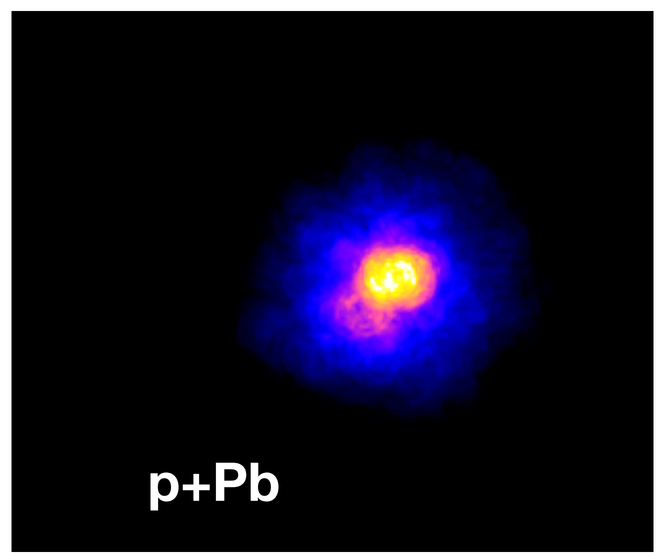
- Closure test in Generator-level and reconstruction-level Pythia events
- No azimuthal anisotropy in Pythia as expected → no bias from selection/ non-flow subtraction

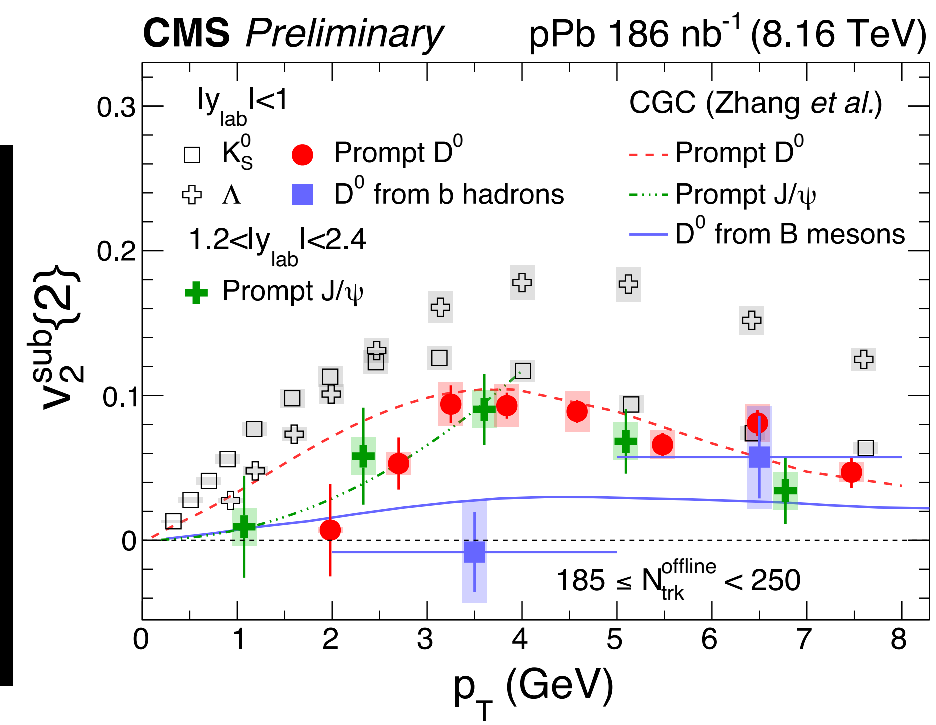
What about p+Pb

CMS-PAS-HIN-19-009

ATLAS-CONF-2017-006

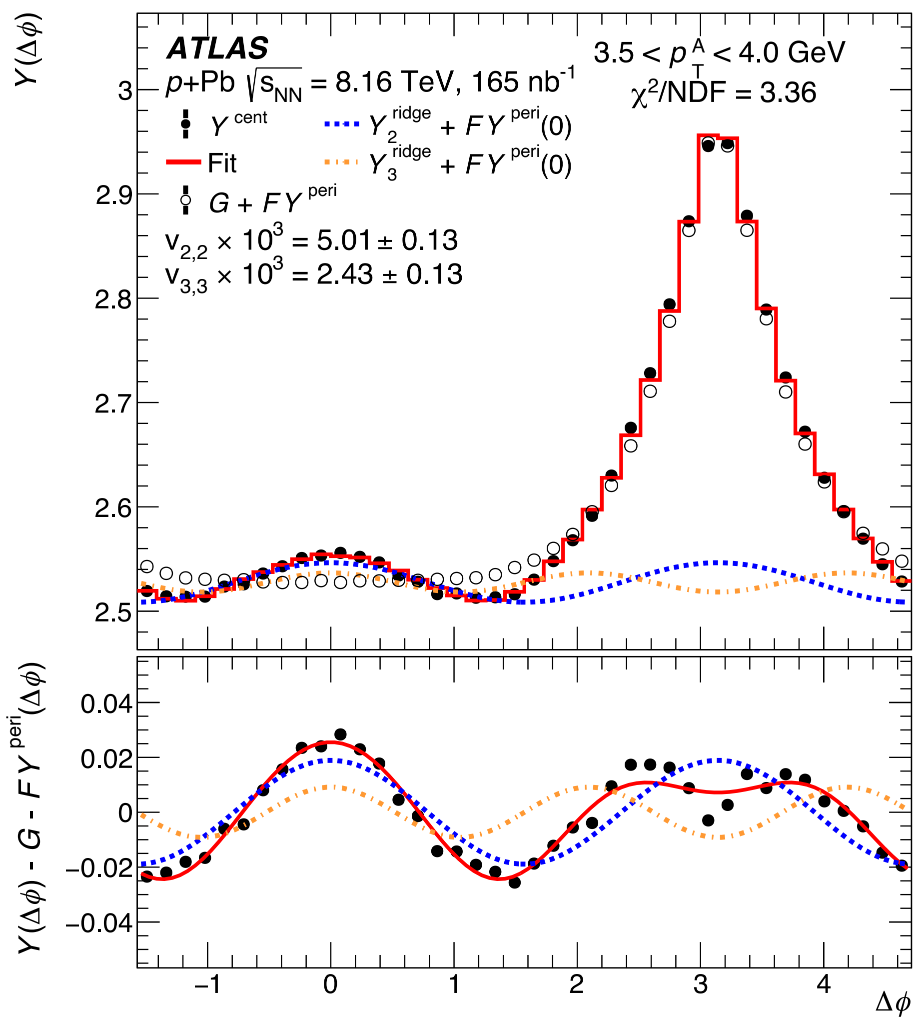




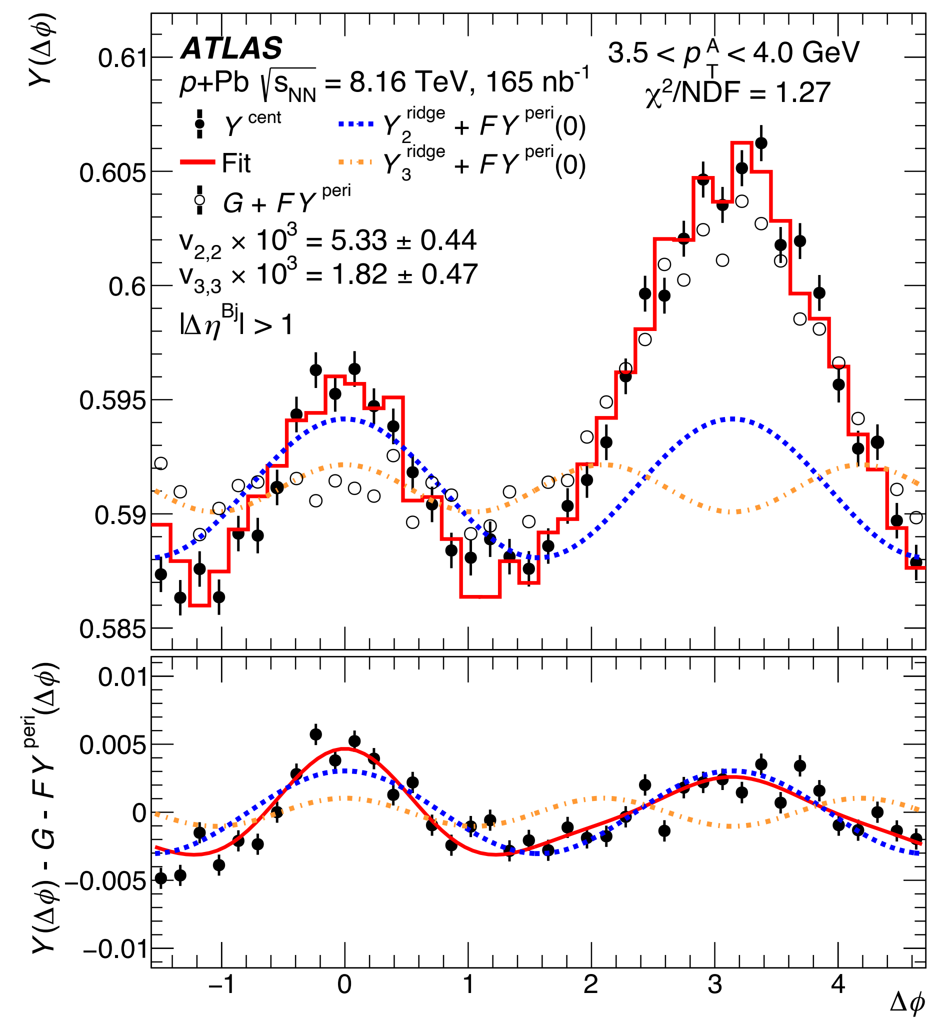


charm v_2 ~ charged particle v_2 > bottom v_2 **?** 0

Template fit in p+Pb jet events

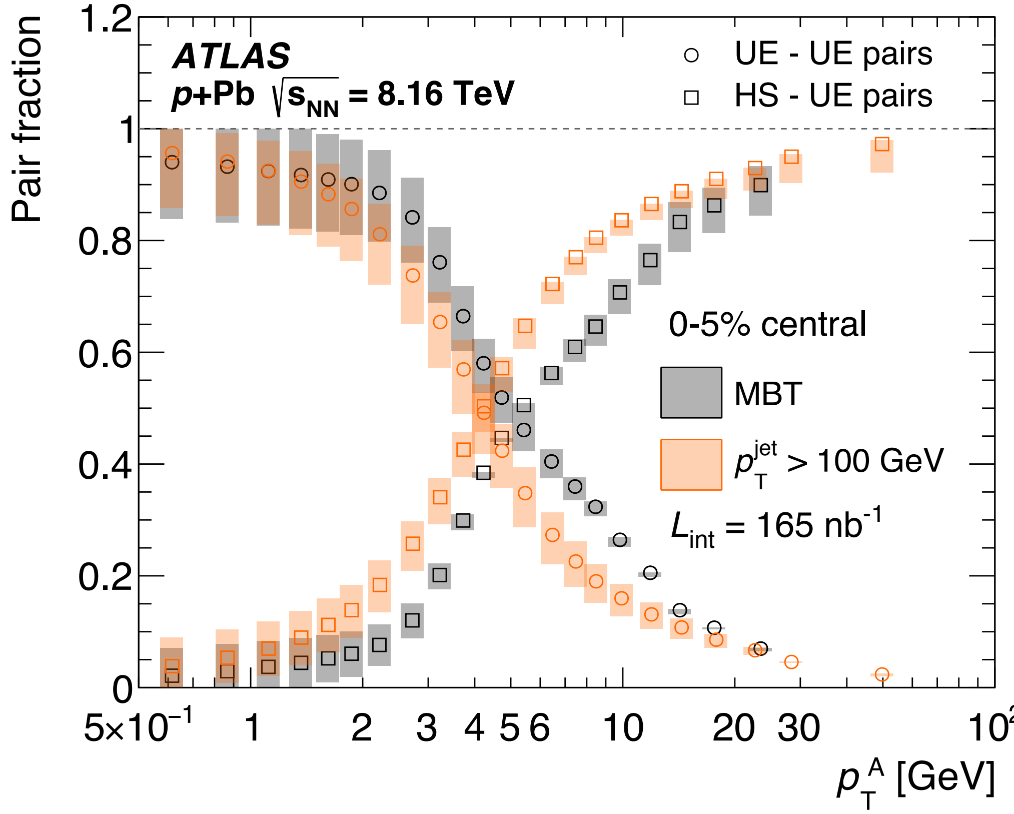


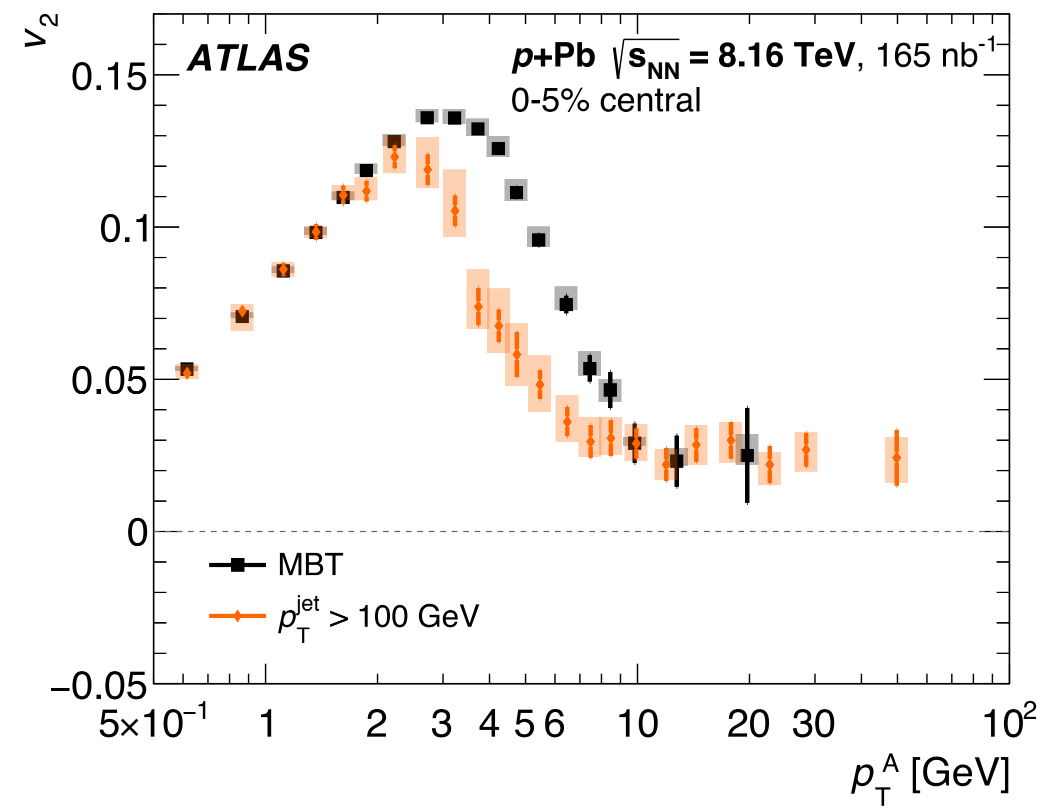
w/o in-jet associate
particle removal



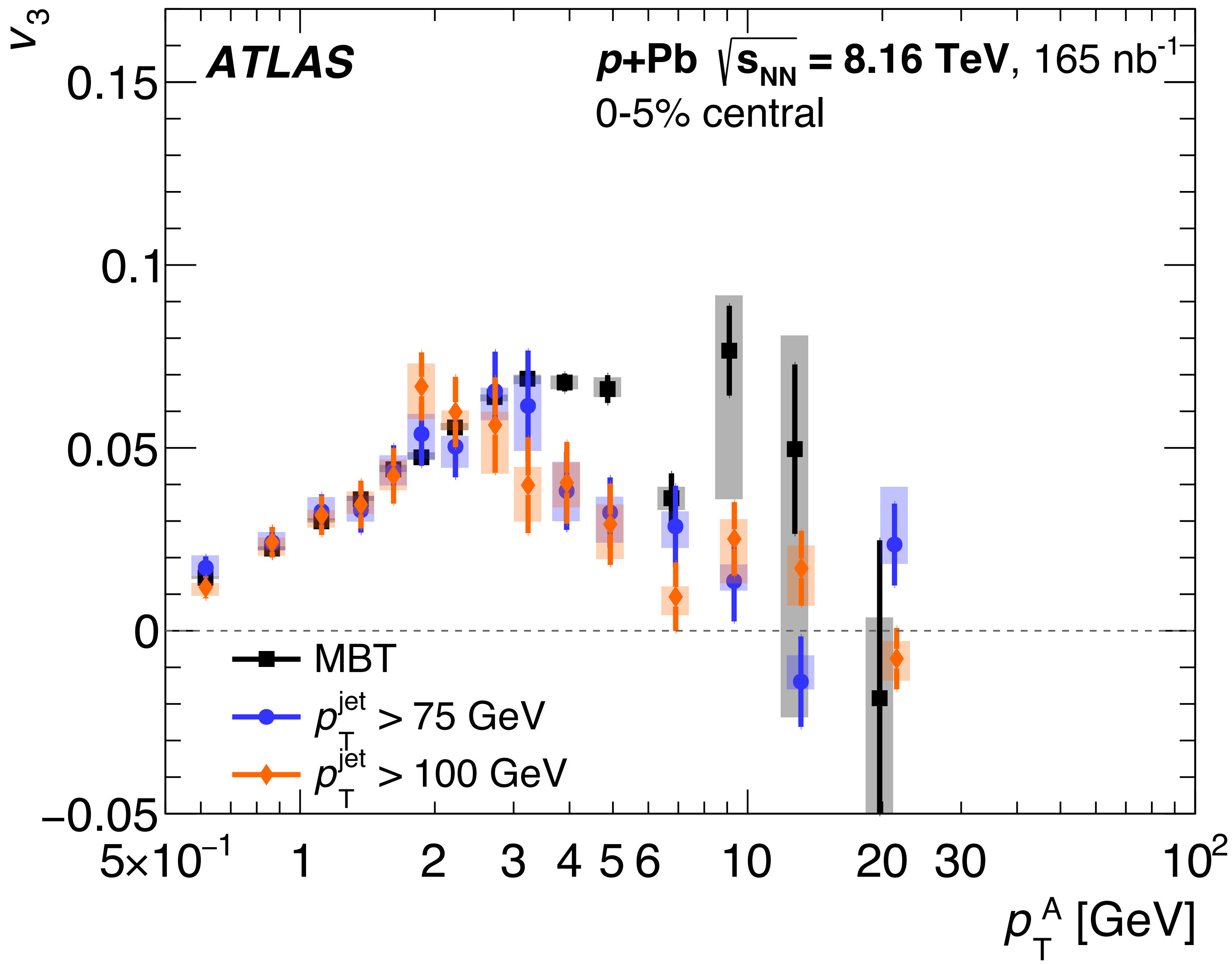
w/ in-jet associate
particle removal

Pair fraction vs. particle v_2



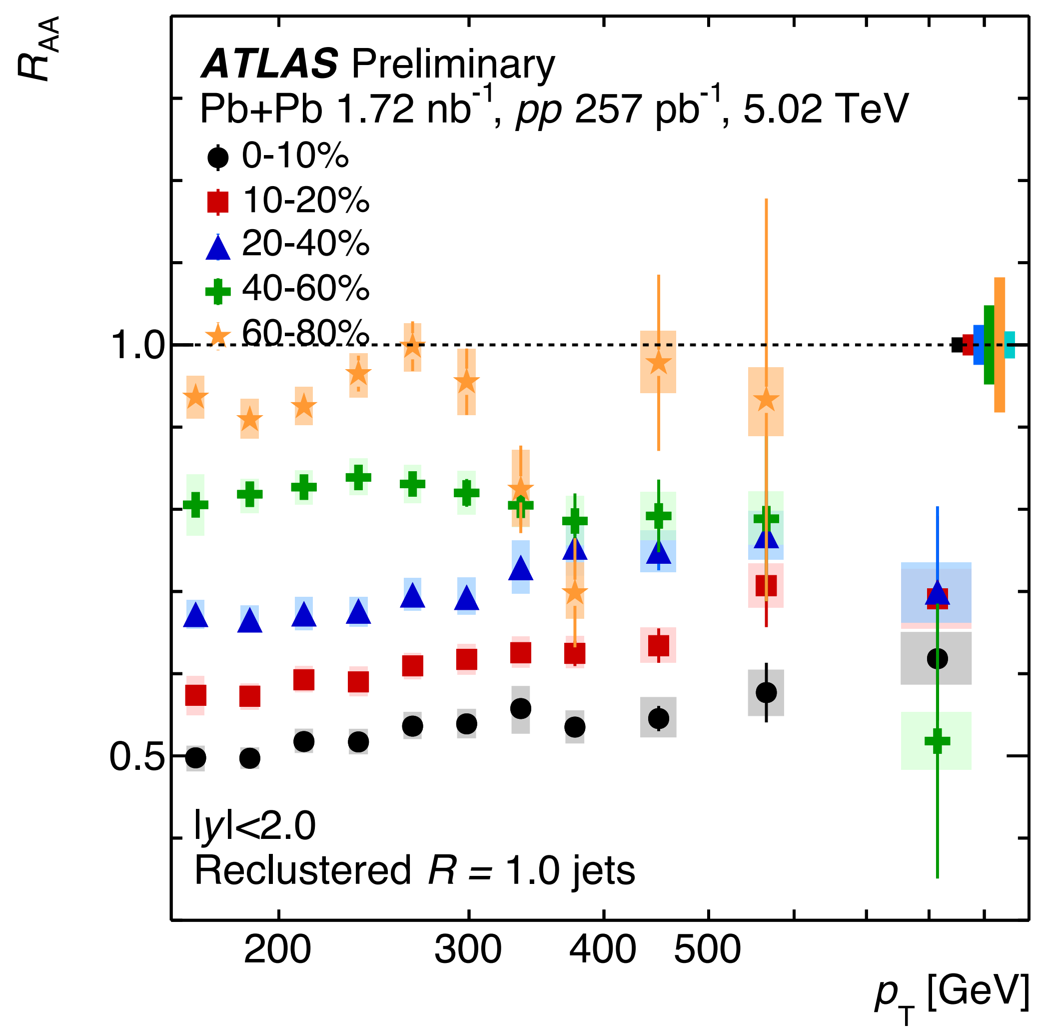


Hadron v_3 in p+Pb



Large radius jet R_{AA}

ATLAS-CONF-2019-056



Large R jet R_{AA}

ATLAS-CONF-2019-056