University of Colorado Boulder

Recent heavy-flavor results from ATLAS

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HENPIC Seminar
Jan 16, 2020

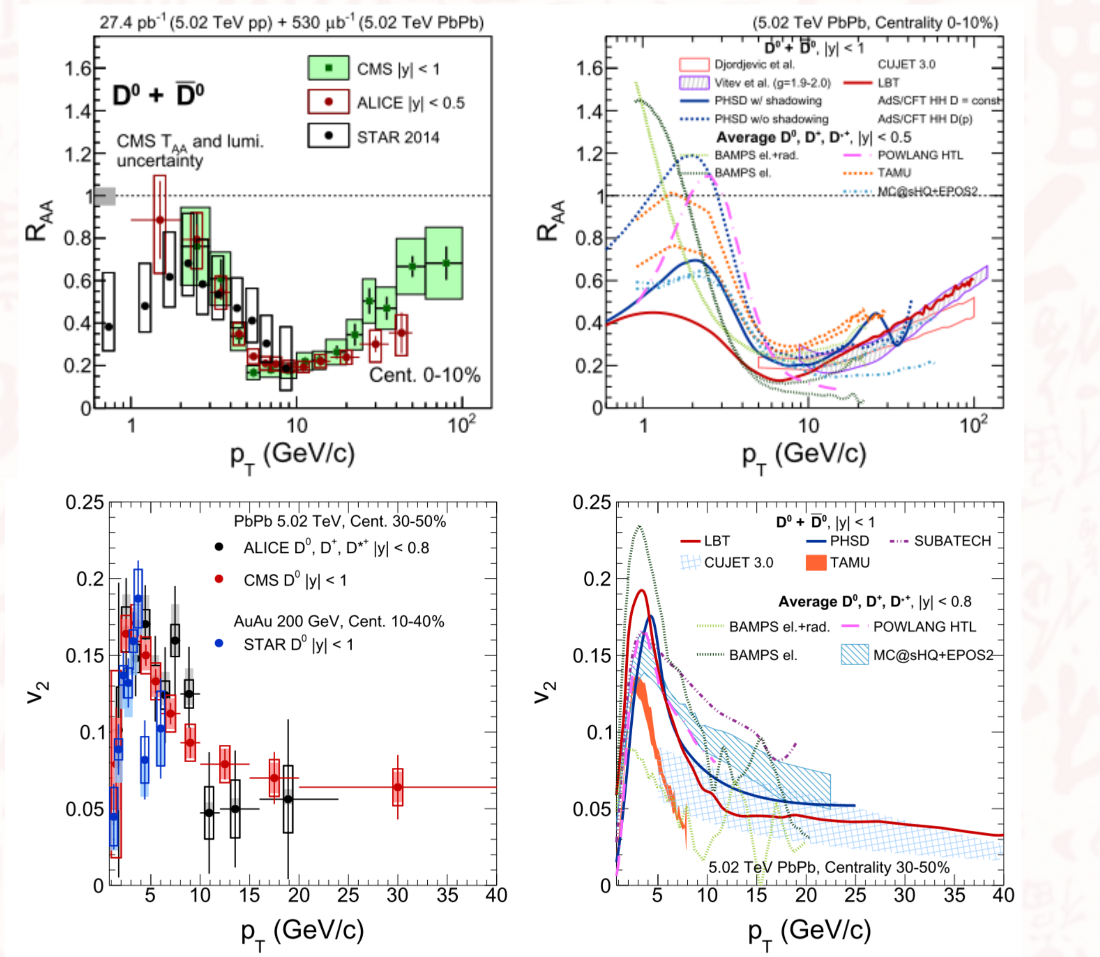
ATLAS EXPERIMENT

Introduction — heavy flavor in HIC

- Two of the most important and simplest phenomena in HIC: collective flow and jet quenching, quantified by v_n and R_{AA}

- Open heavy flavors (charm and bottom) are produced early in the collision. R_{AA} and v_n of heavy flavor provide unique insights into entire evolution of QGP: transport property, energy loss, hadronization, etc.

- Precise charm and bottom results in different systems would provide tighter constrains on various model calculations.



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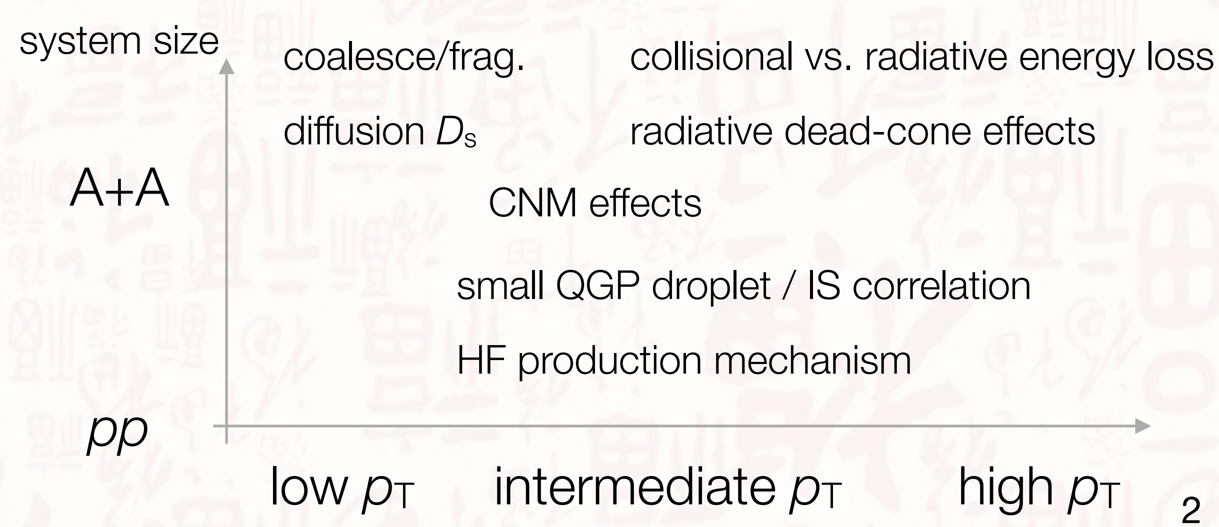
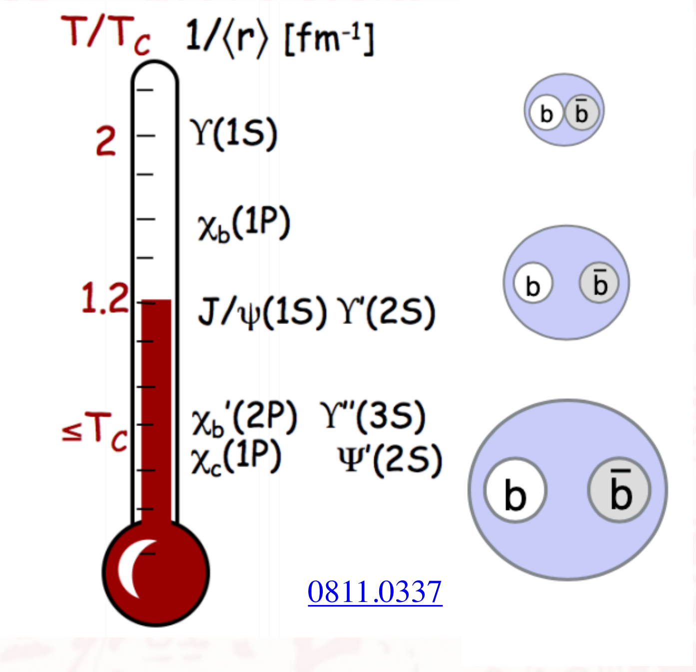


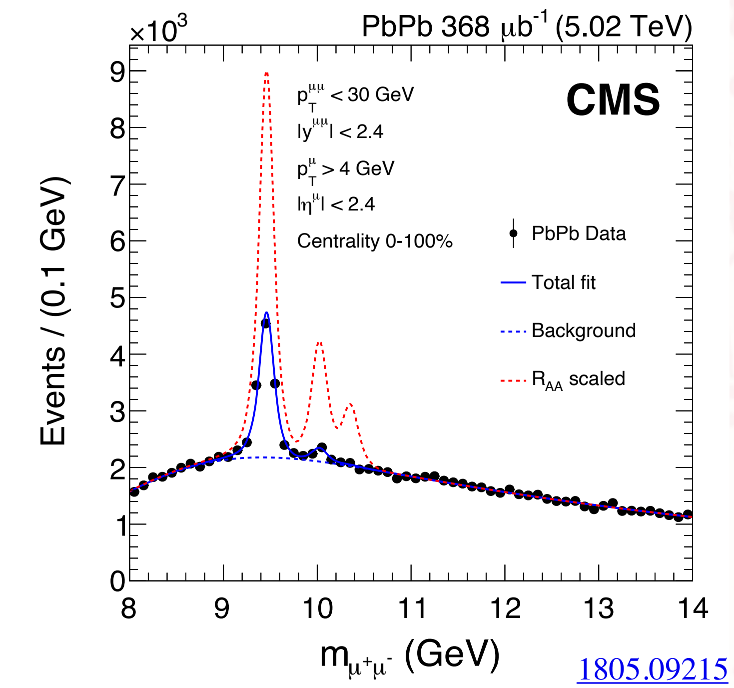
Introduction — quarkonium in HIC

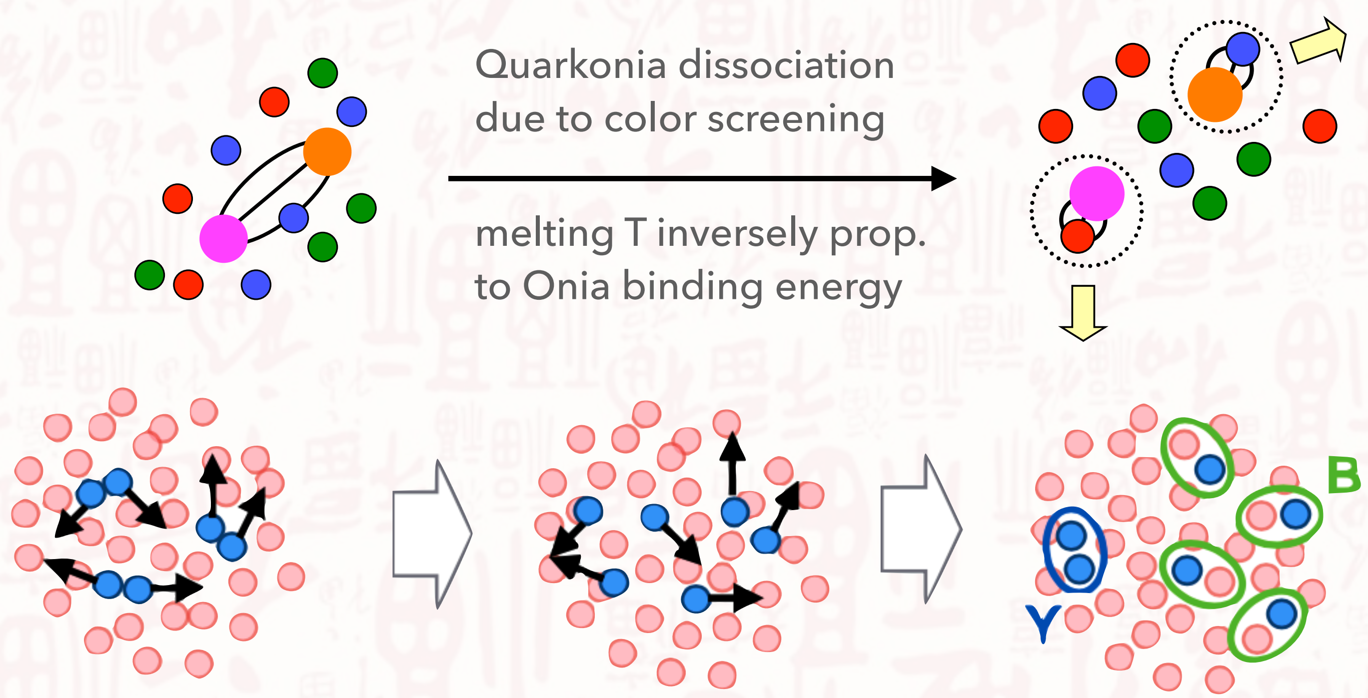
Quarkonium states are clean and easy to trigger experimentally, can also be used to probe QGP medium evolution via two competing processes:

- (Sequential) Dissociation
- Recombination

Clear understanding requires: 1) proper medium modeling 2) simultaneous description of full set of quarkonium observations





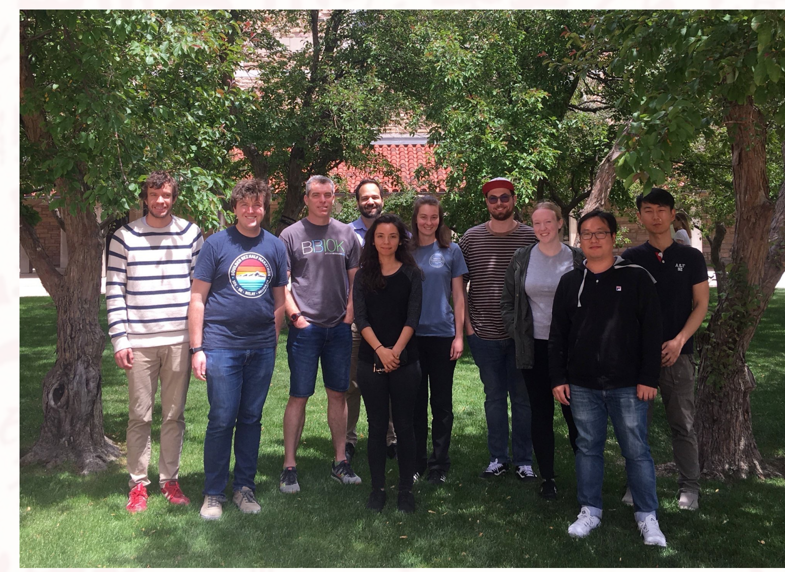


ATLAS collaboration

Active ATLAS member: ~5600

Active member on heavy ion: ~50

Heavy ion papers / ATLAS papers: 7% (63/910)



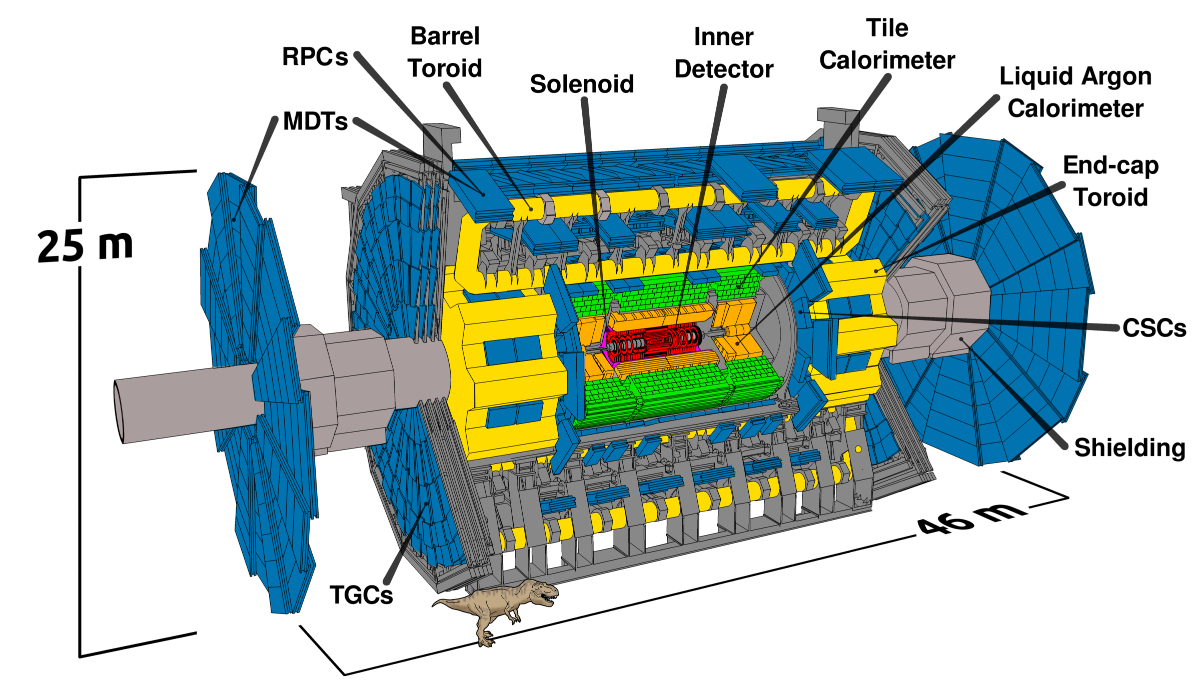
ATLAS datasets related to this talk

Year	Species	CoM energy per nucleon pair [TeV]	Int. Luminosity [nb^{-1}]	No. of collisions per bunch-crossing
2015	Pb+Pb	5.02	0.49	0.001-0.004
2016	*p*+Pb	8.16	170	0.05-0.2
2017	*pp*	13	150,000	2
2017	*pp*	5.02	260,000	2
2018	Pb+Pb	5.02	1.38	0.001-0.005

Boulder ATLAS heavy ion group:

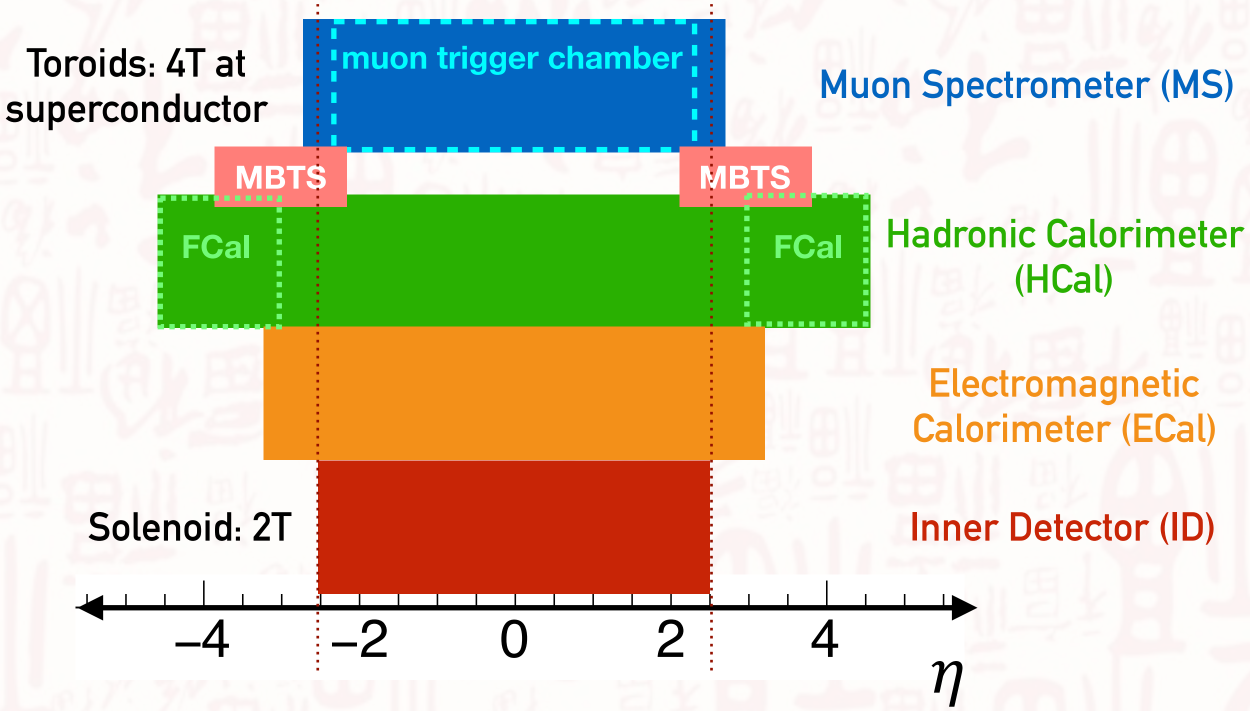
- Jet/prompt photon
- HF/quarkonia
- Flow in small systems
- UPC

ATLAS detector



Typical kinematic boundaries of reco. objects in heavy ion collisions:

- charged tracks: $p_T > 400$ MeV, $|\eta| < 2.5$
- muon: $p_T > 4$ GeV, $|\eta| < 2.0$
- e/γ: $p_T > 25$ GeV, $|\eta| < 1.37$ & $1.52 < |\eta| < 2.37$
- jet: $p_T > 40$ GeV, $|\eta| < 2.8$



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%

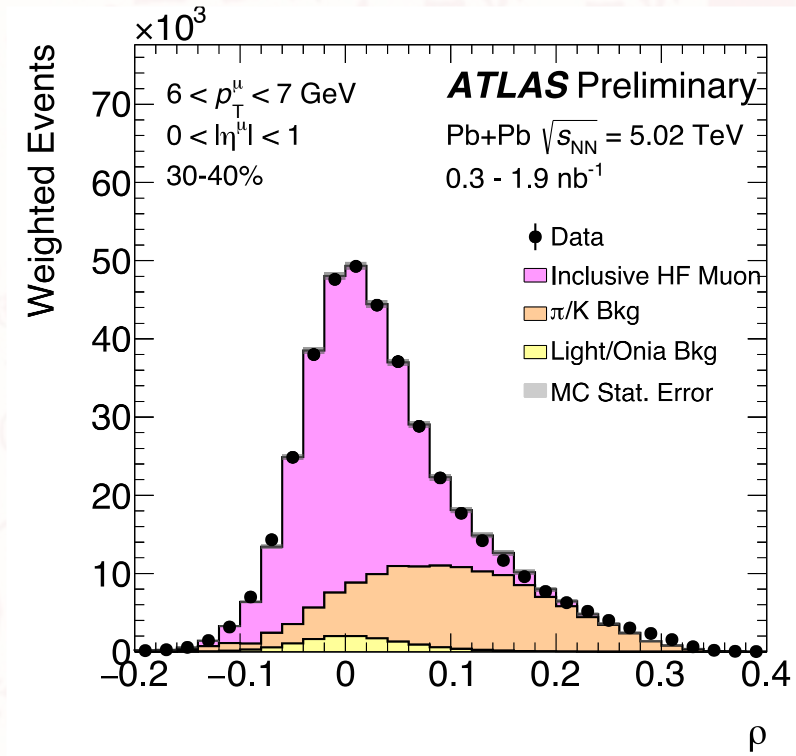
Azimuthal anisotropy of heavy-flavor decay muons

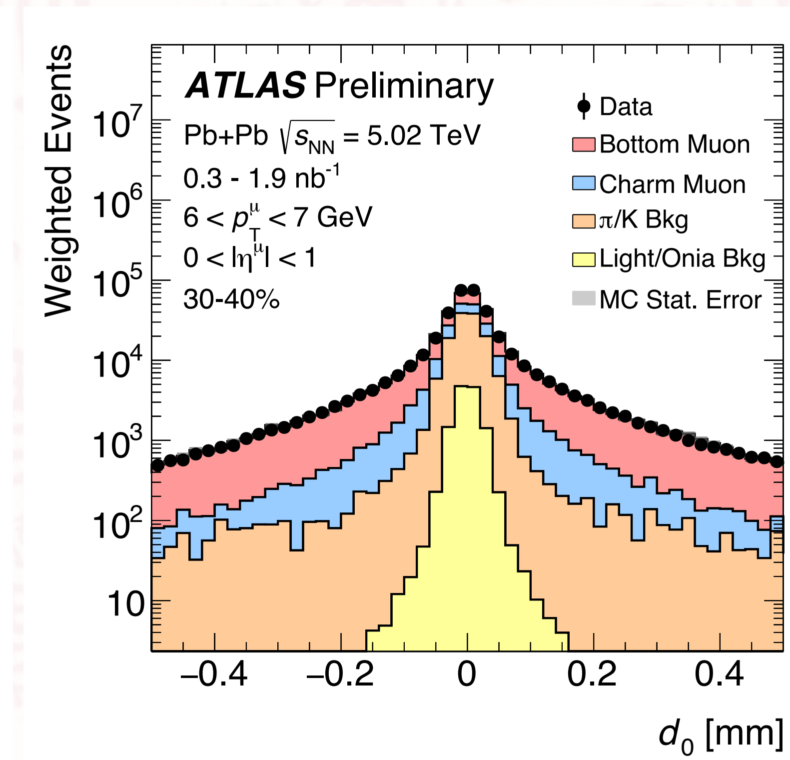
- Pb+Pb analysis: ATLAS-CONF-2019-053
- *pp* analysis: https://arxiv.org/abs/1909.01650

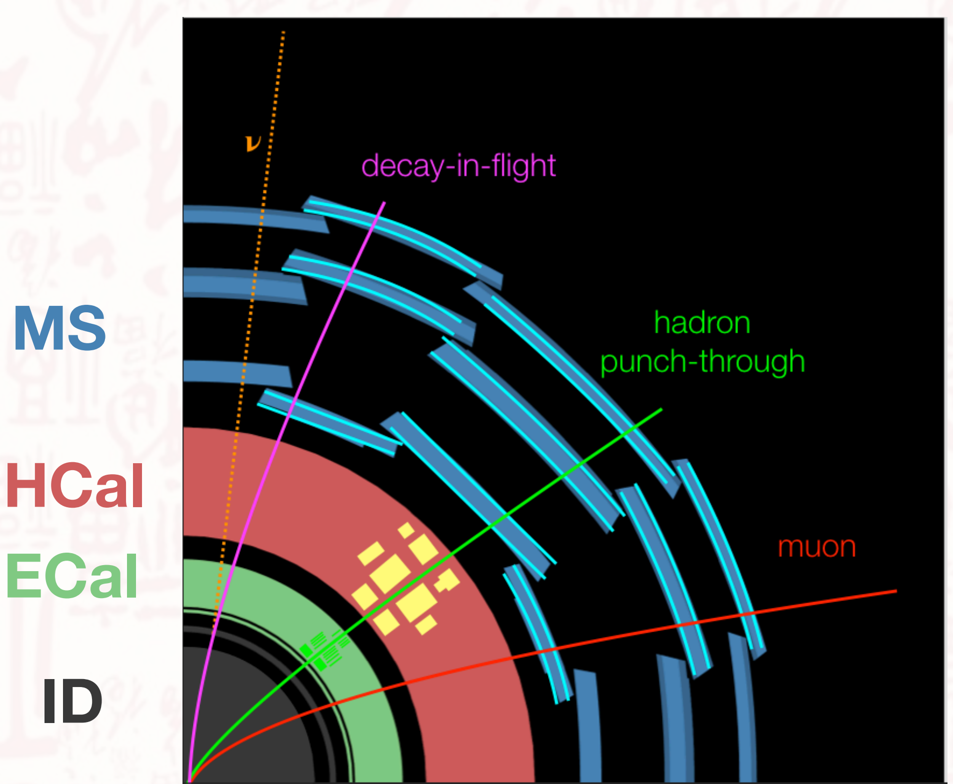
HF muon identification

Background contributions:

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

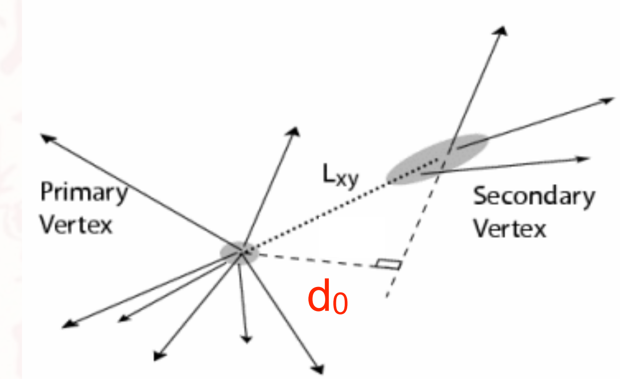




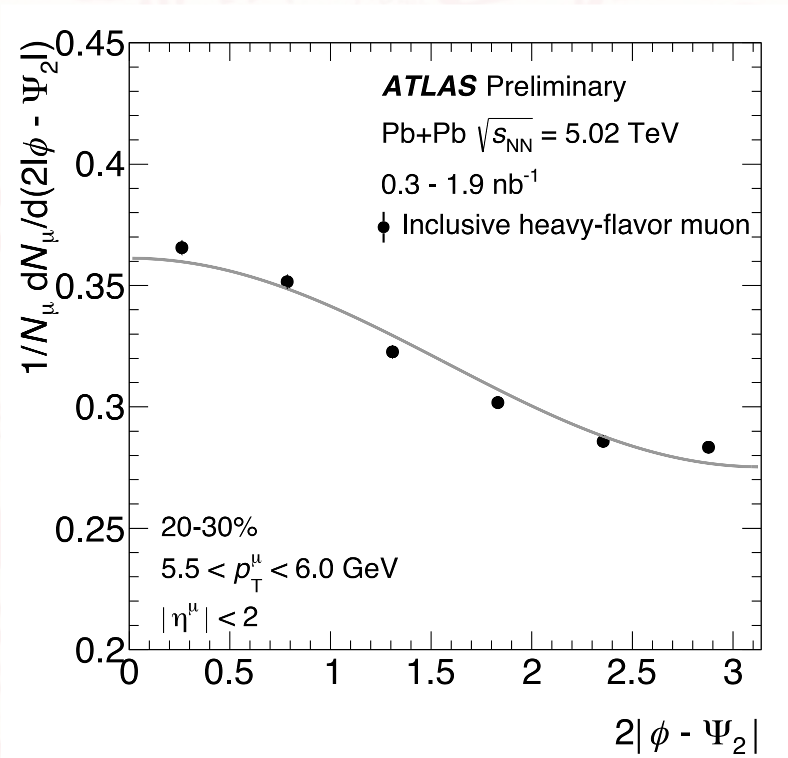


Momentum imbalance: $\rho = (p_T^{ID} - p_T^{MS})/p_T^{ID}$

Transverse impact parameter: d_0

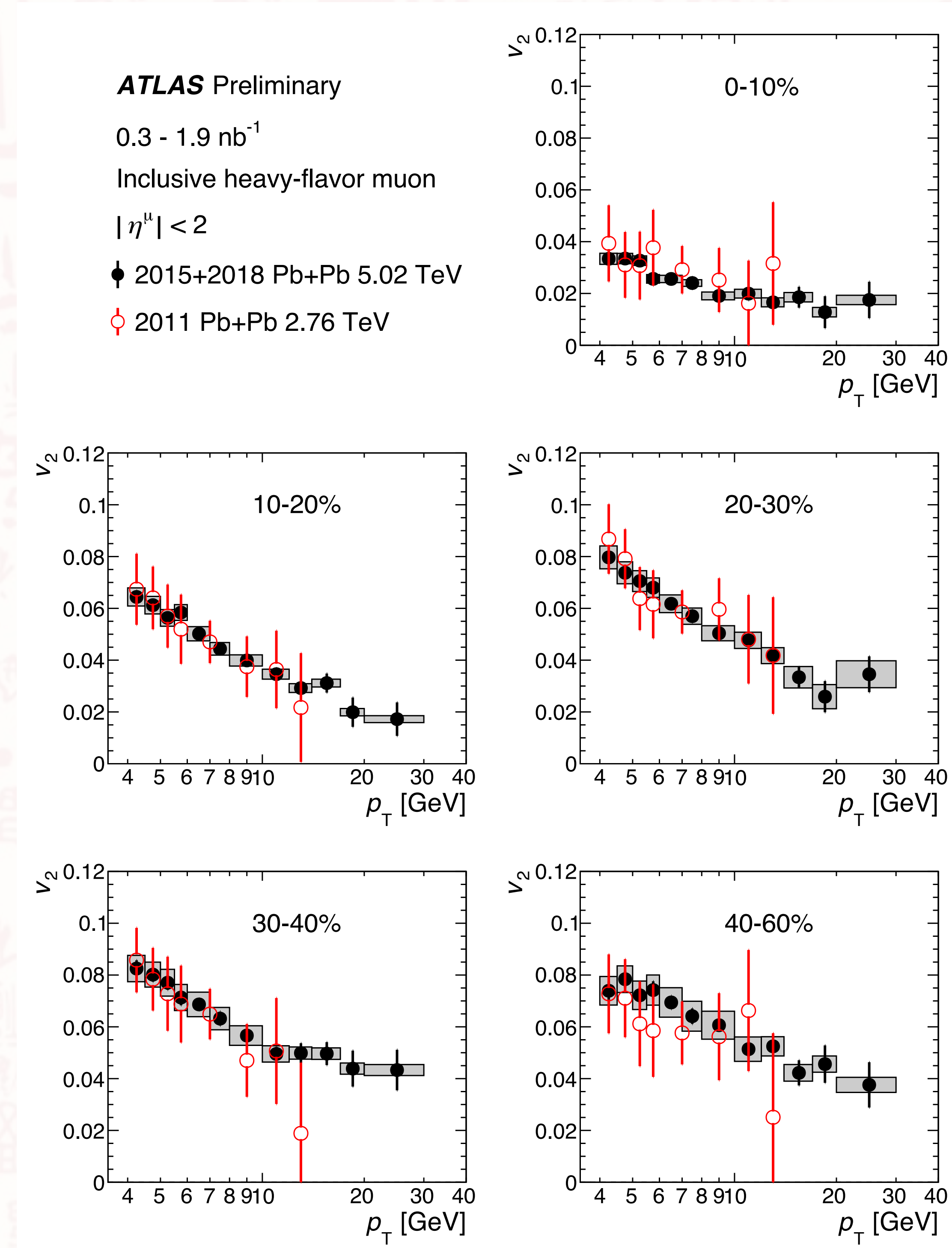


HF muon v_2 in Pb+Pb

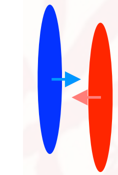


$$\frac{1}{N_X^\mu}\frac{\mathrm{d}N_X^\mu}{\mathrm{d}(n(\phi-\Psi_n))} = 1 + 2v_n^{\mathrm{raw}}\cos\left(n(\phi-\Psi_n)\right)$$

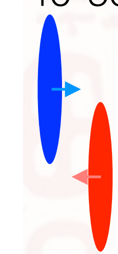
- 2015+2018 Pb+Pb data
- v_n extracted from event-plane method, corrected for resolution
- Good agreement with Run1 ATLAS results



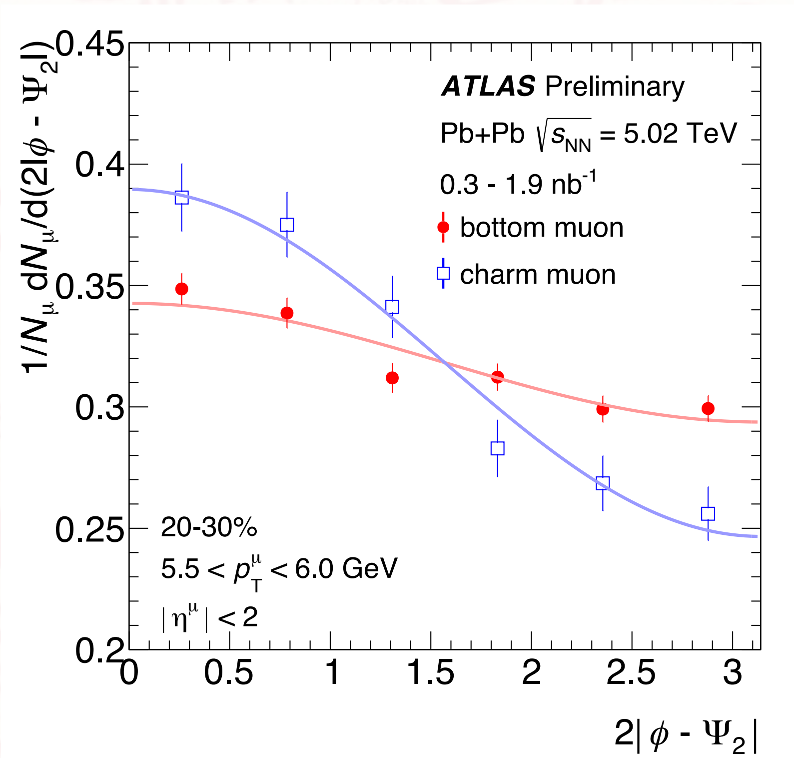
0-10%

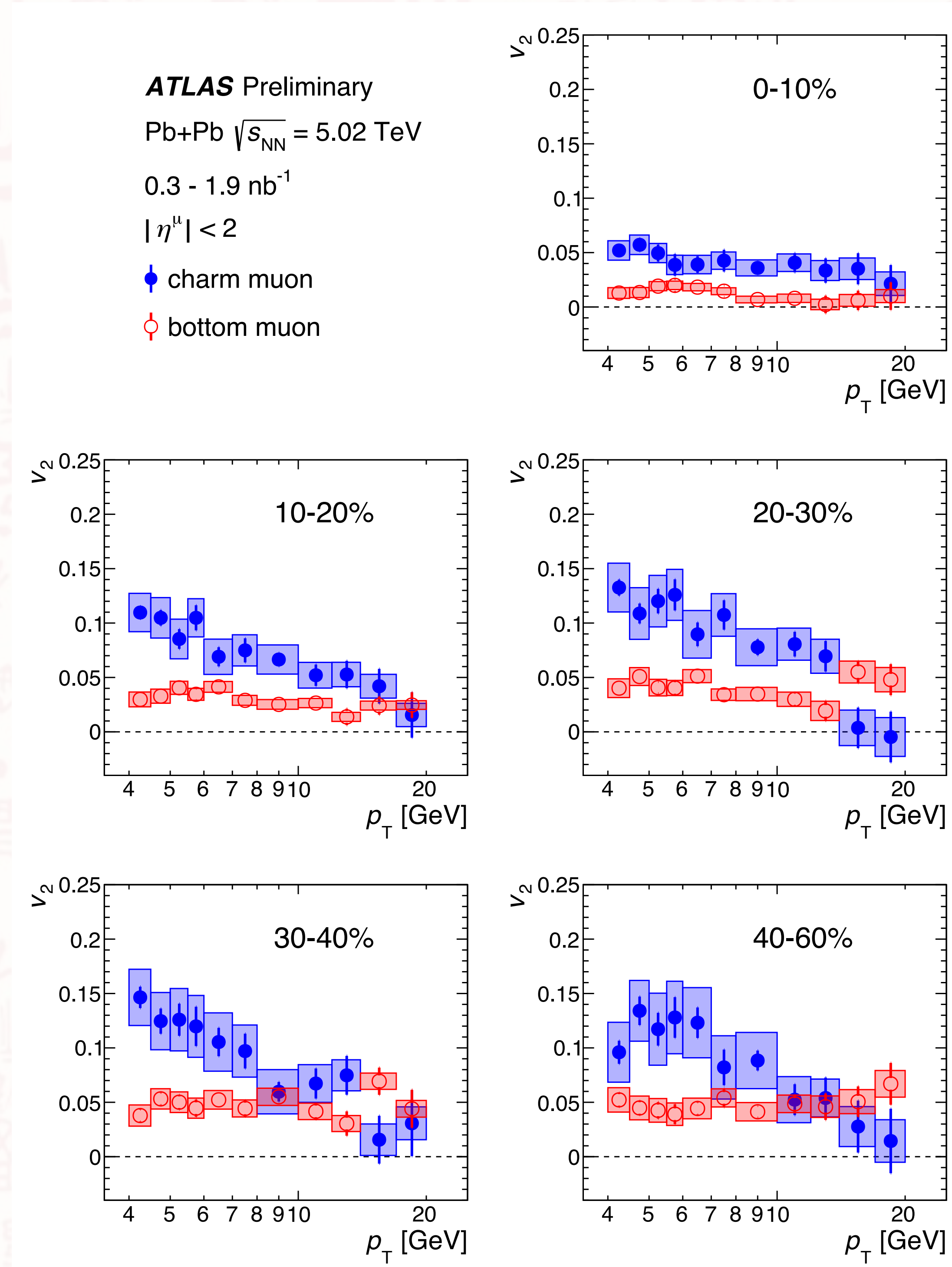


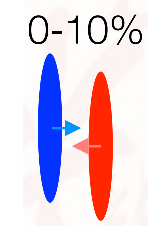
40-60%

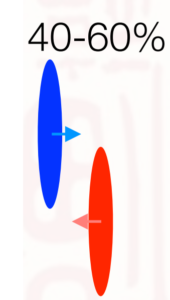


HF muon v_2 in Pb+Pb





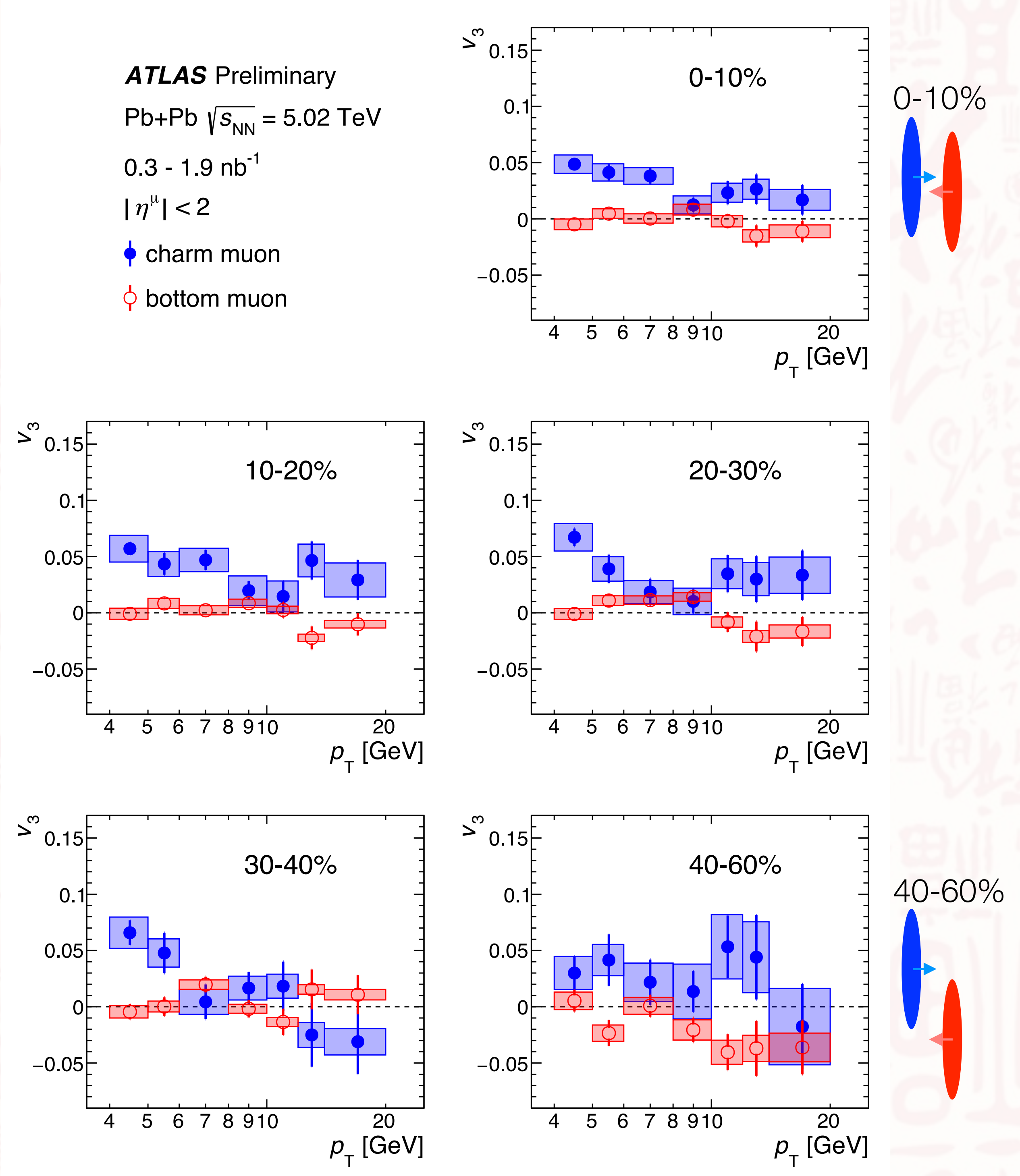




- Separate charm and bottom muons in $\Delta\phi$, extract v_n for charm and bottom muon
- charm muon v_2 > bottom muon v_2 > 0 at low p_T
- charm muon v_2 ~ bottom muon v_2 at high p_T

HF flow v_3

- 2-5% charm muon v_3
- Bottom muon v_3 is consistent with 0 within uncertainties in all centralities



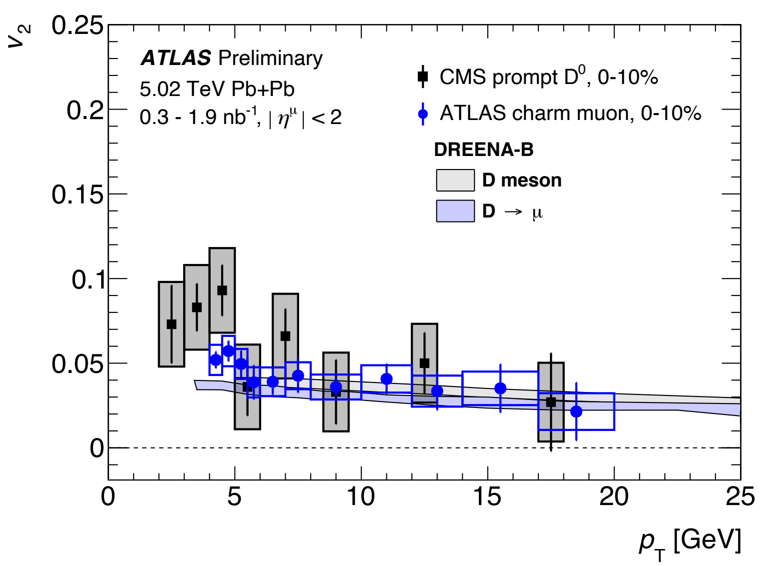
HF muon vs. HF hadron

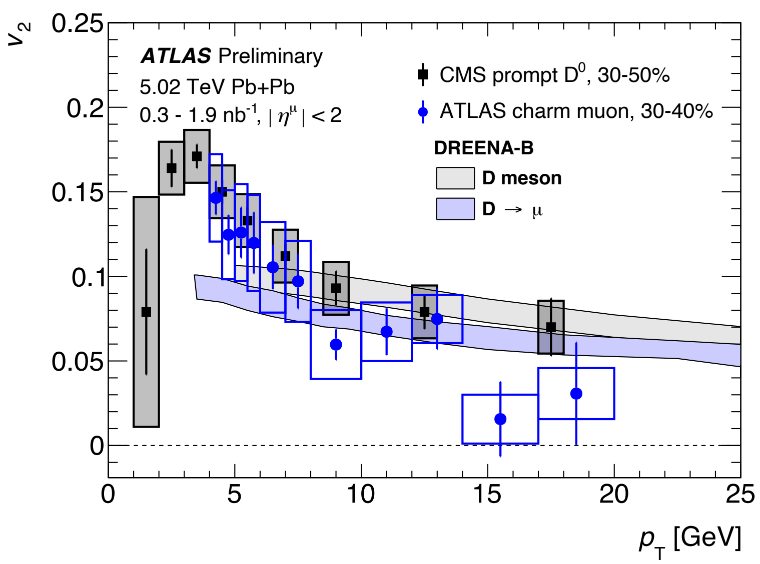
Where does heavy quark go?

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 $(D^0 \to K^-\pi^+) = 4\,\%$

Decay leptons in comparison to D^0 or non-prompt J/ψ:

- Easy to trigger but no easy access to low p_T in ATLAS, kinematic smearing due to the HF hadron semileptonic decay
- Probing c quark: Better precise in more central than prompt D^0
- Probing b quark: Similar systematic control as non-prompt J/ψ, but more statistics; better systematic control than non-prompt D^0

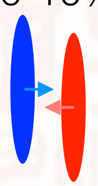


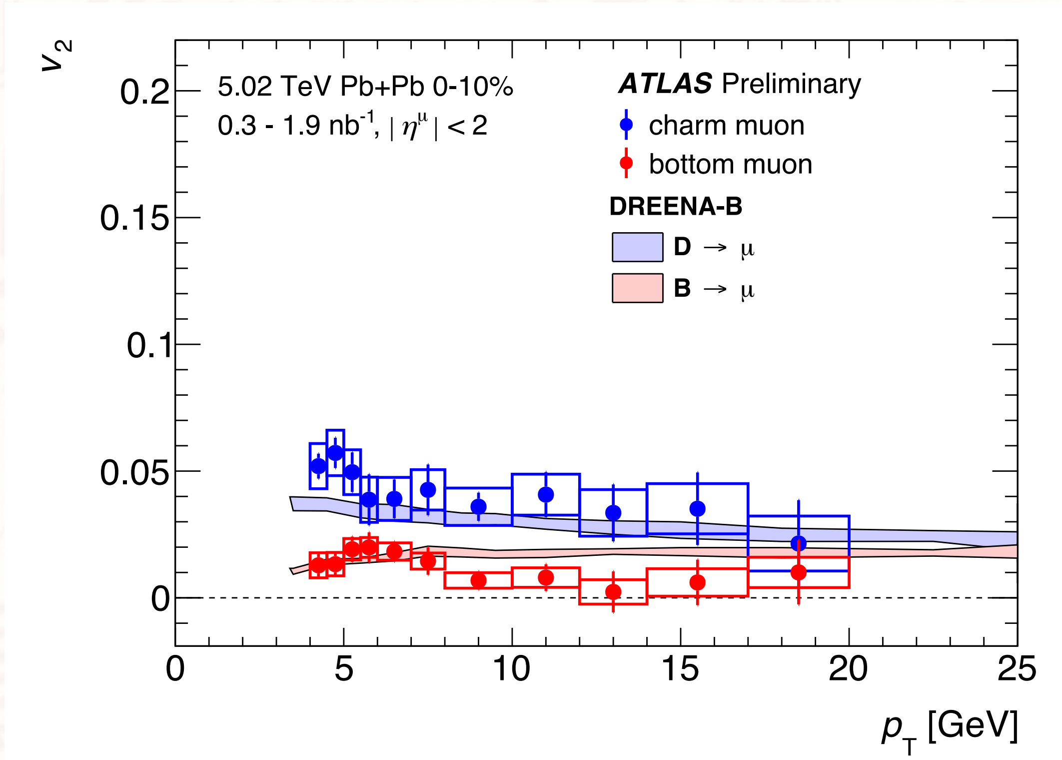


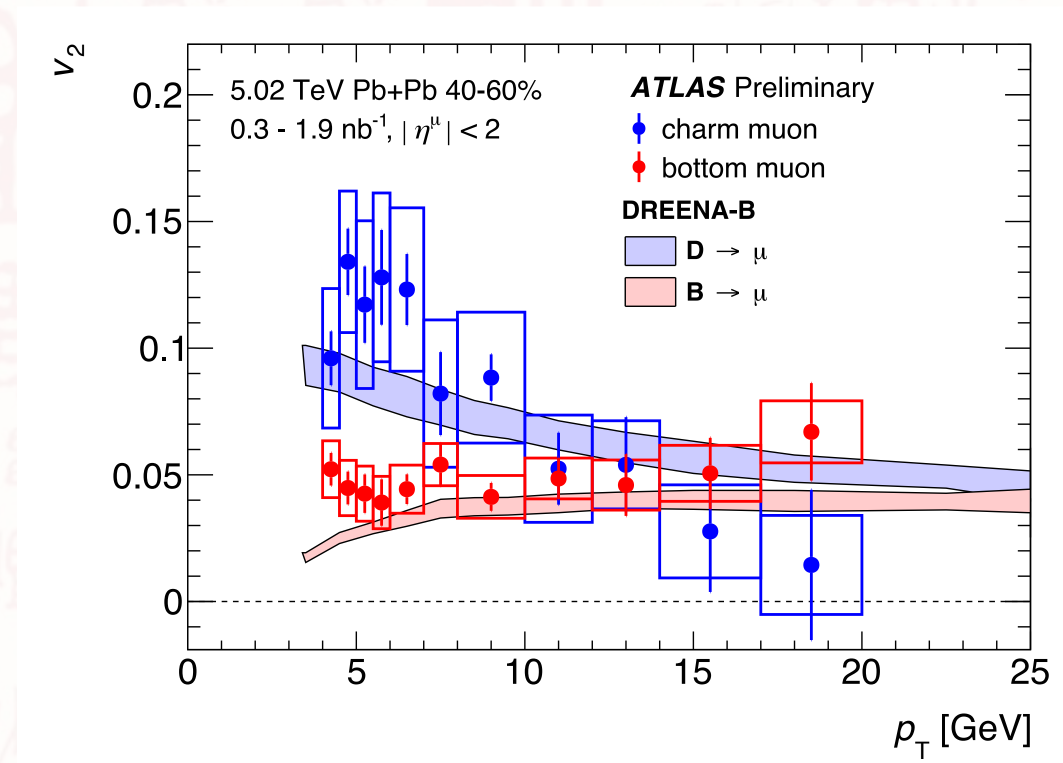
meson/muon difference is consistent with model expectation

Comparison to model calculations

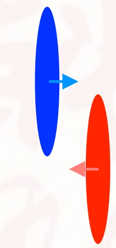
0-10%







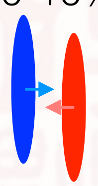
40-60%

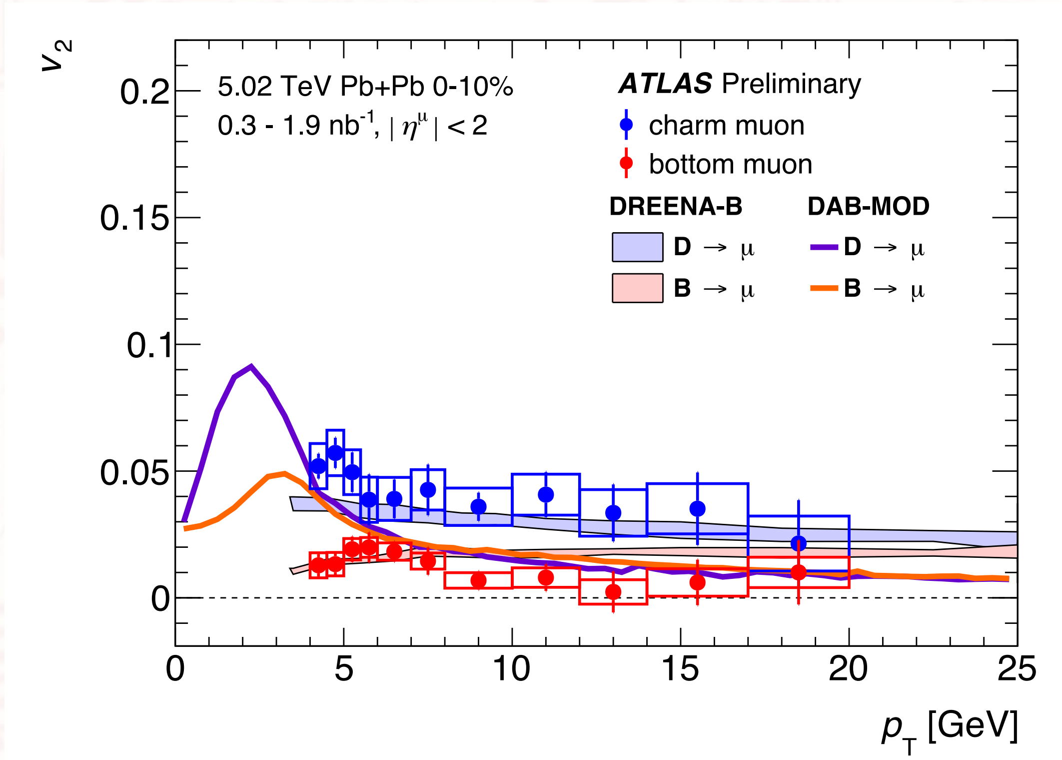


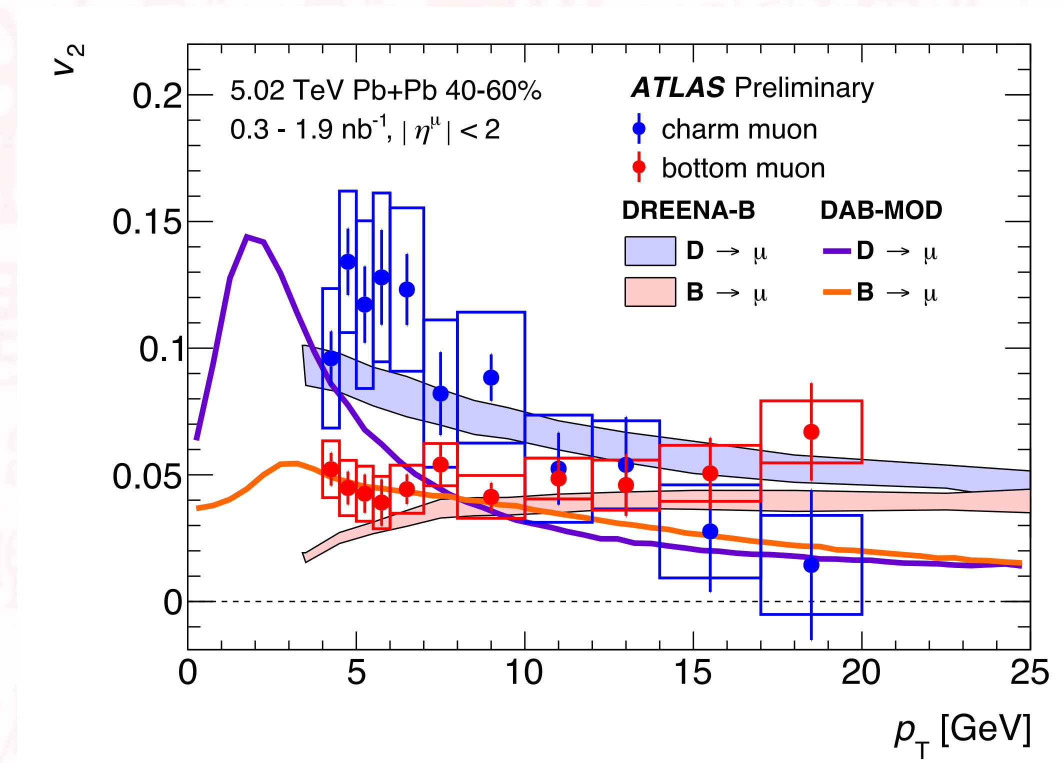
- **DREENA-B** (1805.04786): 1+1D medium, dynamical radiative + collisional energy loss

Comparison to model calculations

0-10%





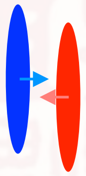


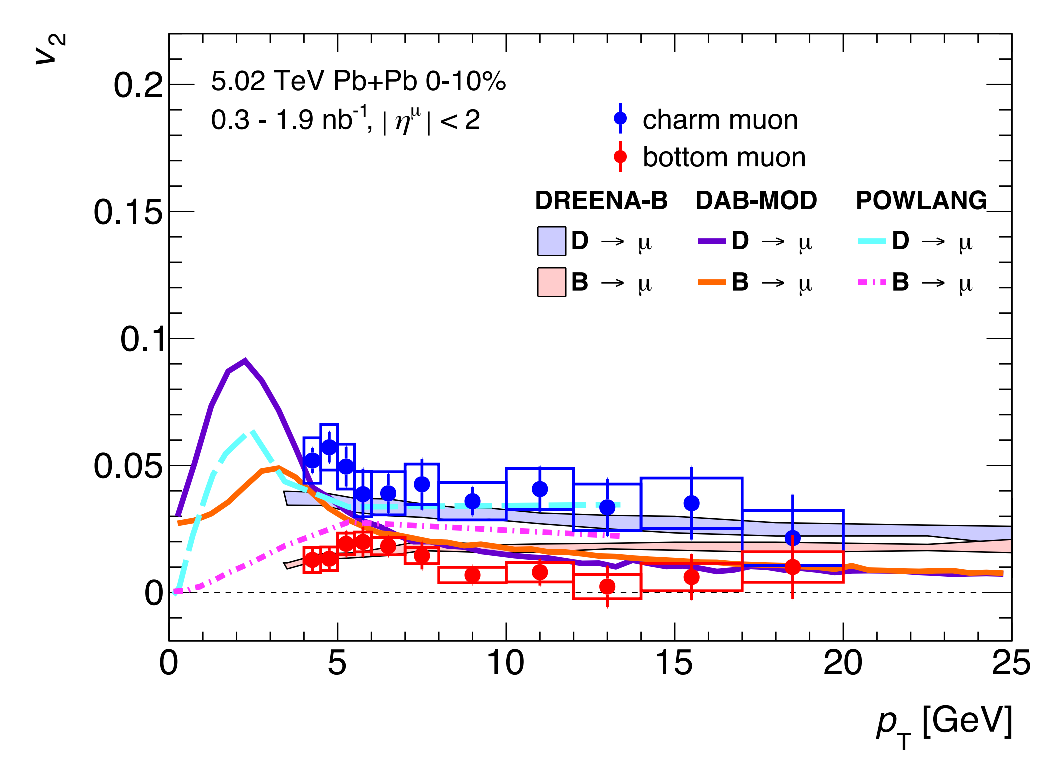
40-60%

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

Comparison to model calculations

0-10%

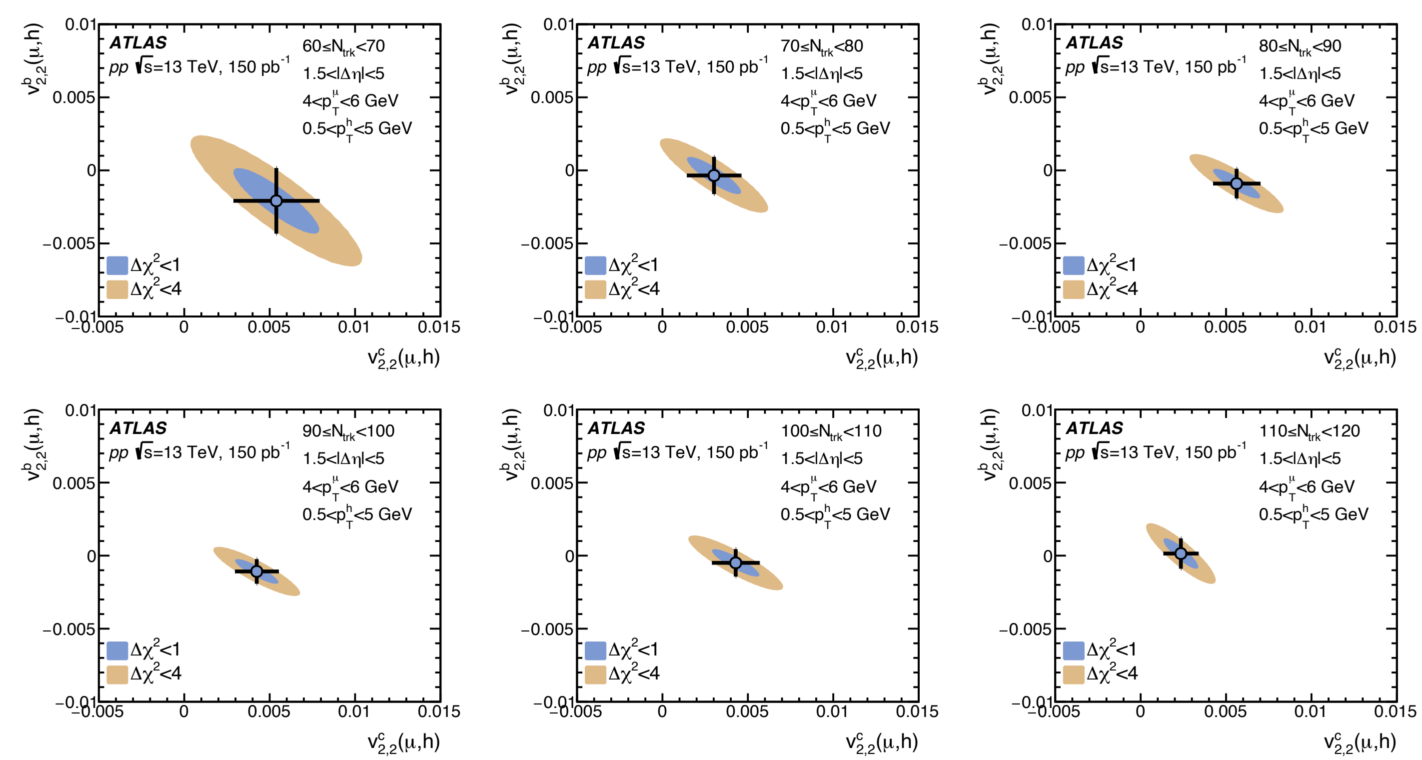


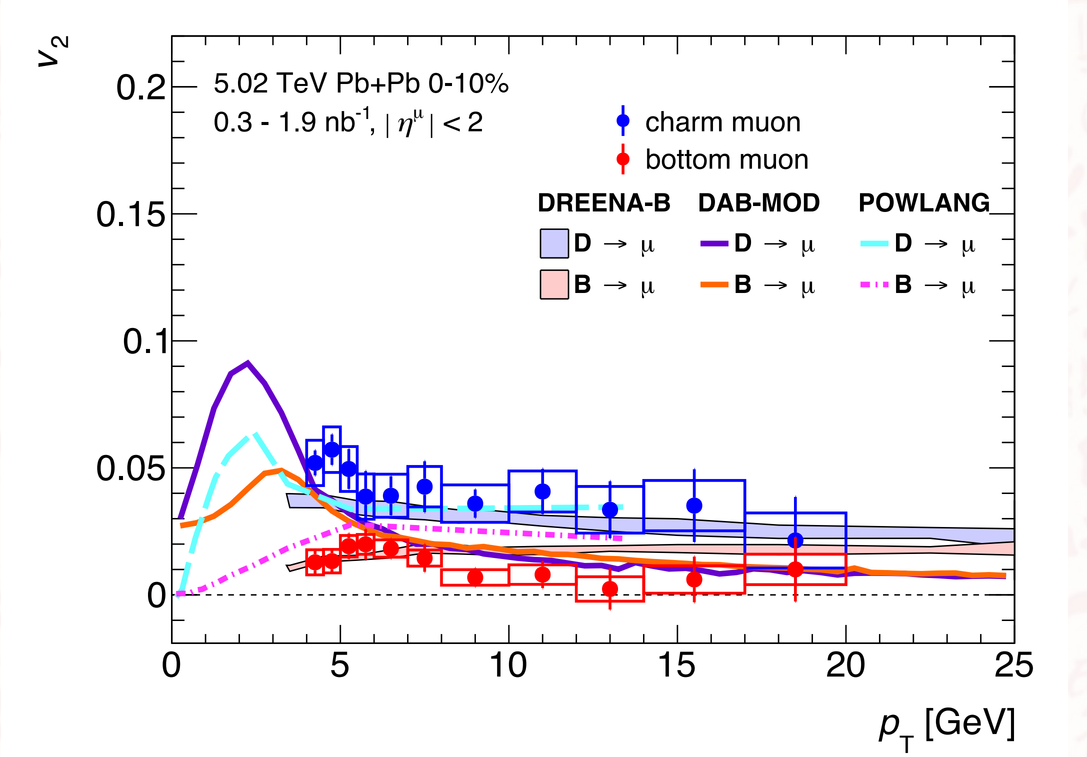


Energy loss modeling seems to be the key to describe our data

- **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

Correlations between c and b results





Due to the methodology of the b/c separation technics, 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

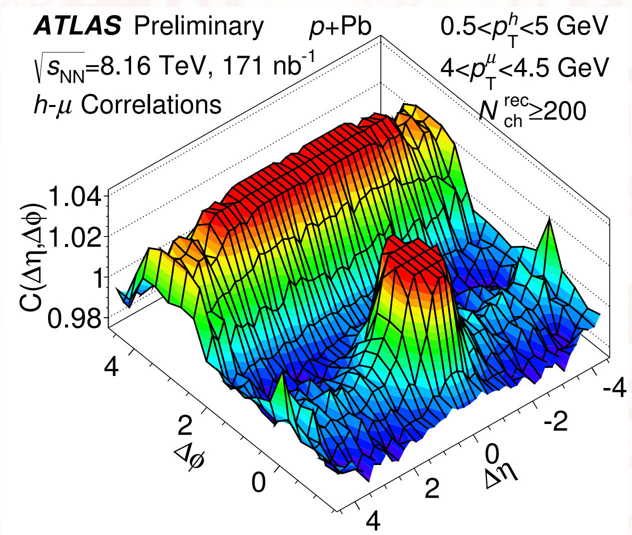
HF muon flow in small systems

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

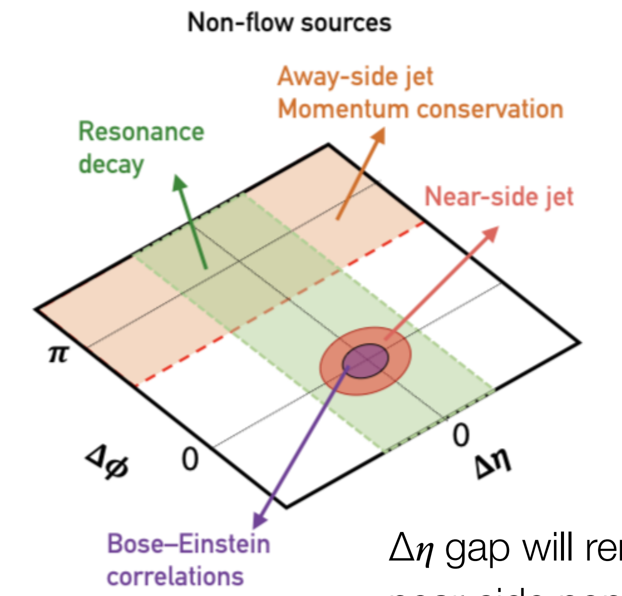
2PC + $\Delta\eta$ gap + non-flow subtraction

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

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



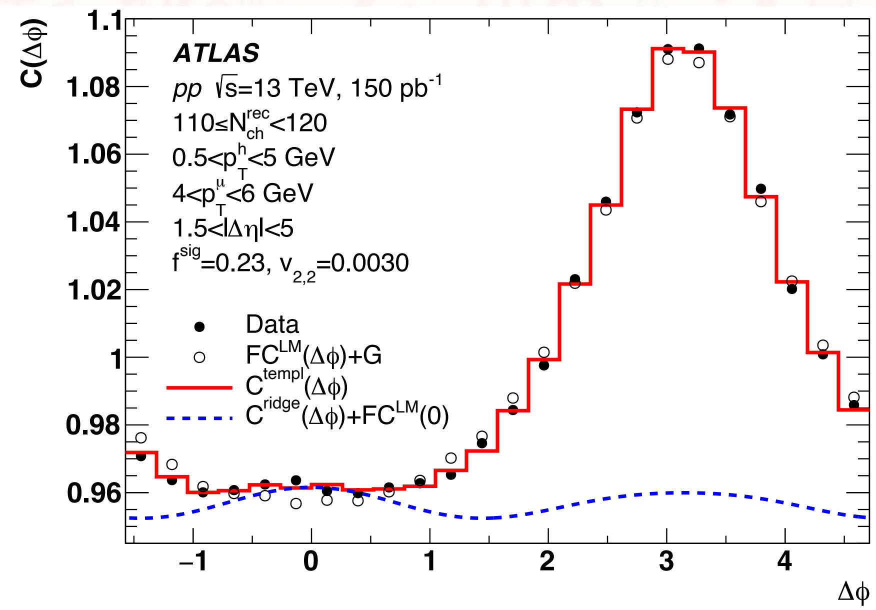
ATLAS-CONF-2017-006



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

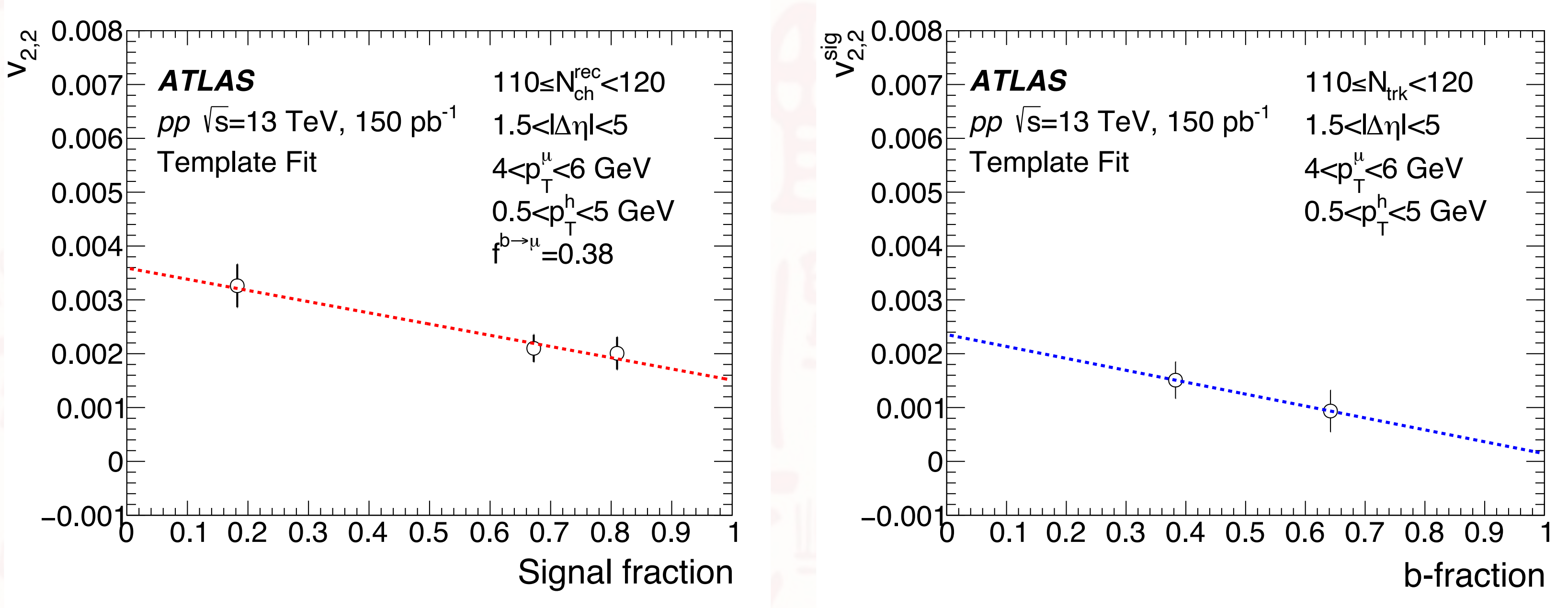
Assumptions of non-flow subtraction:

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



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*



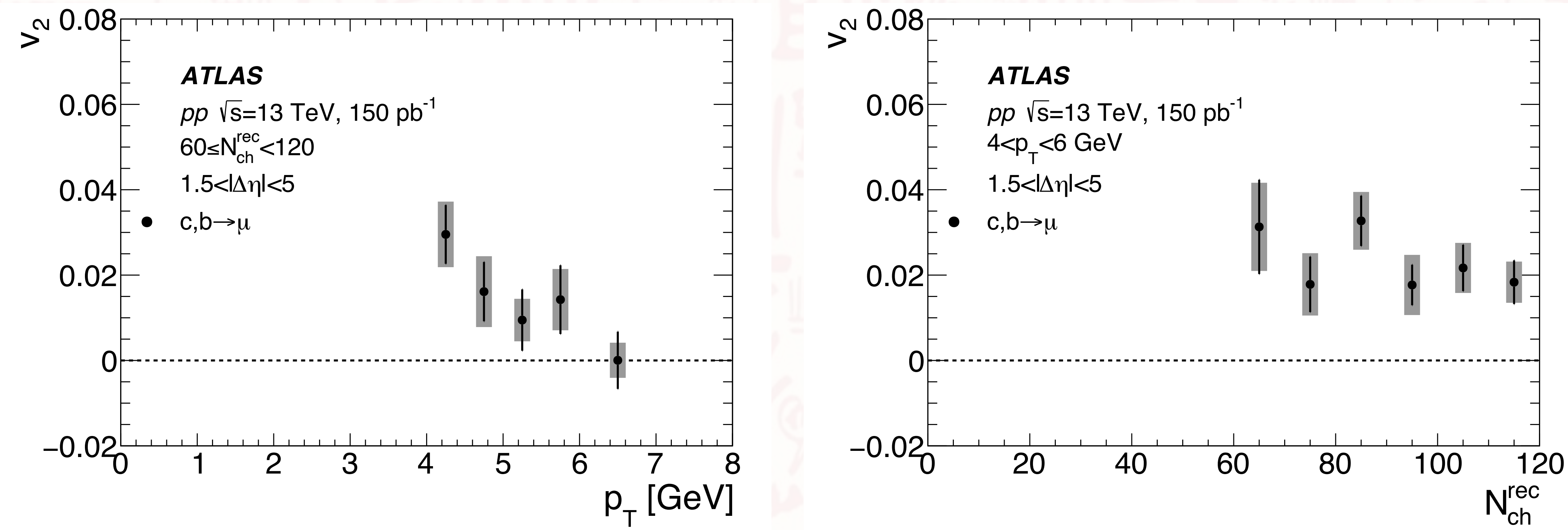
- Low pile-up *pp* collision data at 13 TeV collected in 2017
- Correlation coefficients $v_{n,n}$ is additive, so a linear combination of different contributions:

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

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

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

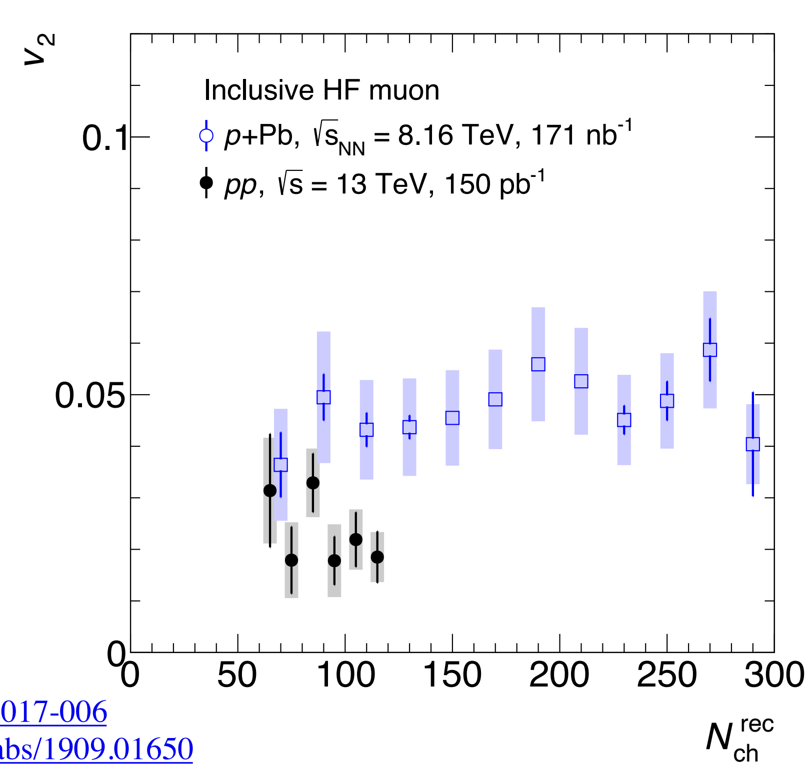
Inclusive HF muon flow in *pp*



- Results cover $4 < p_{\mathrm{T}} < 7$ GeV and $60 < N_{\mathrm{ch}}^{\mathrm{rec}} < 120$

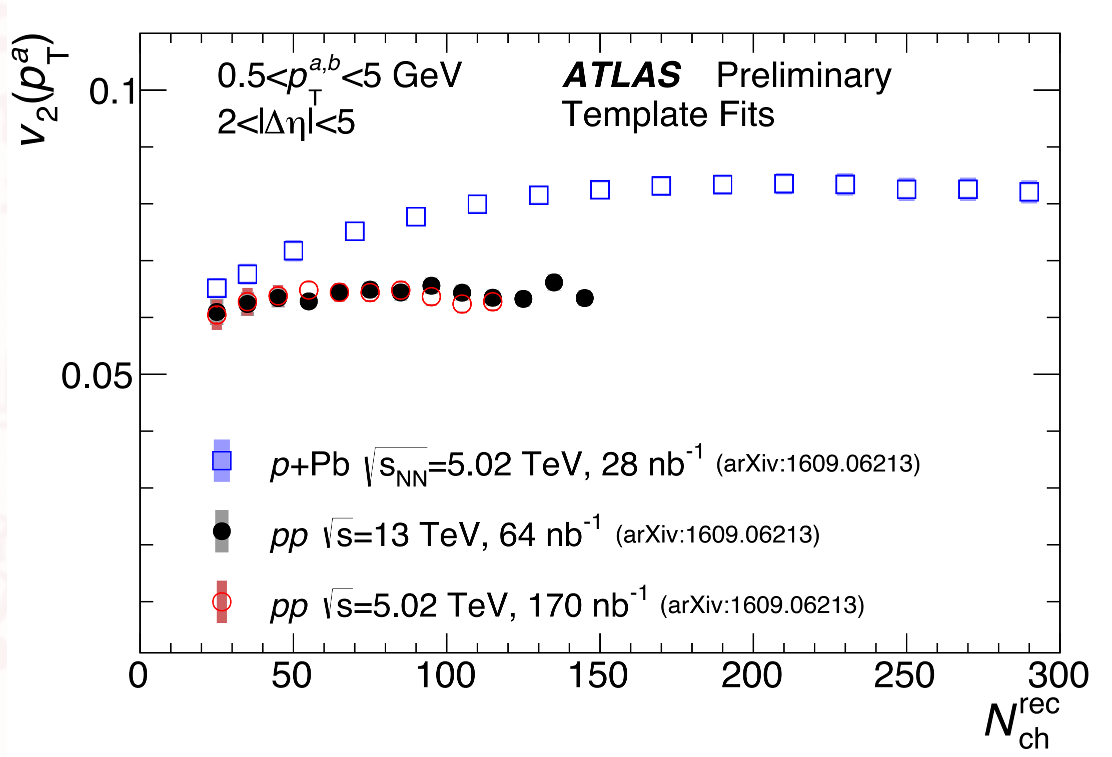
pp vs. *p*+Pb

HF muon



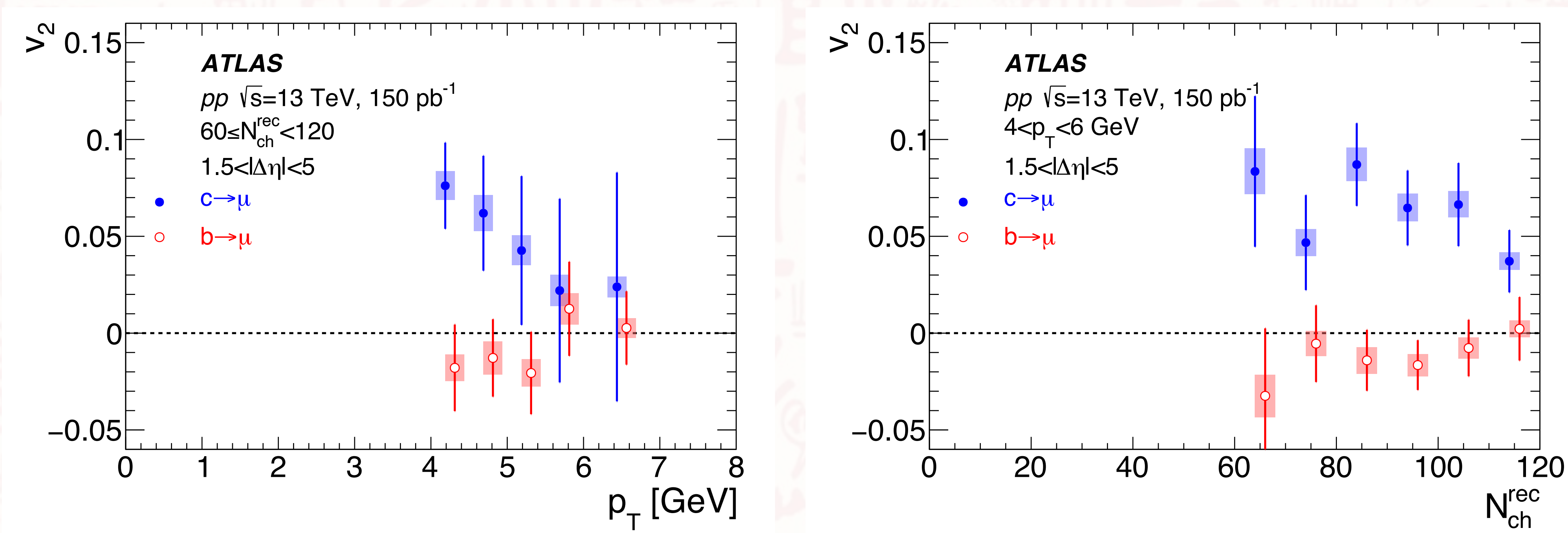
ATLAS-CONF-2017-006
https://arxiv.org/abs/1909.01650

Inclusive charged particle



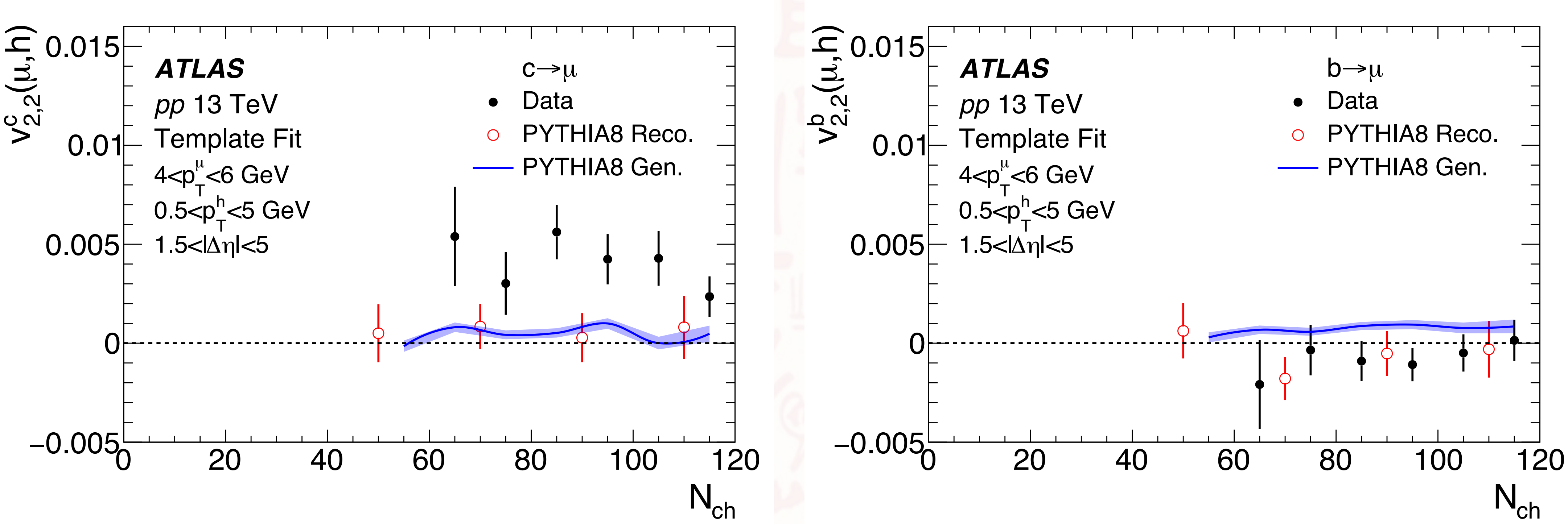
- Smaller v_2 for muons than charged hadron in *pp* and *p*+Pb
- Similar difference between *pp* and *p*+Pb

charm/bottom muon flow in *pp*



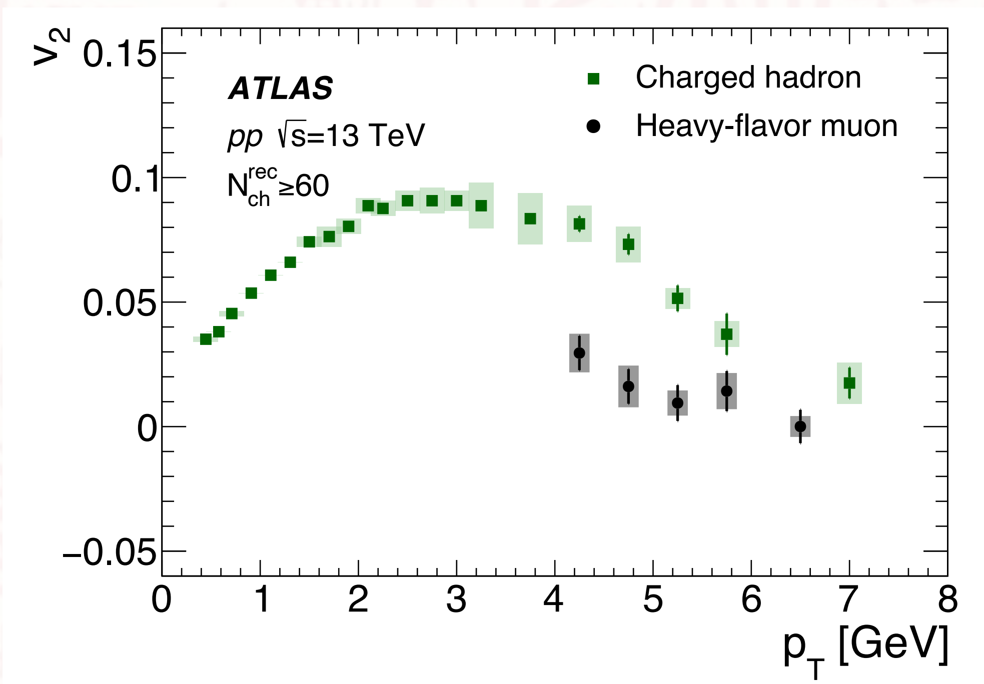
- Charm muon $v_2 > 0$, approaching 0 at high p_T, no strong multiplicity dependence
- Bottom muon $v_2 \sim 0$
- HF muon flow in Pb+Pb with similar kinematic can be described by energy loss (useless in pp); Will IS correlation able to describe large charm v_2 and zero bottom v_2 ?

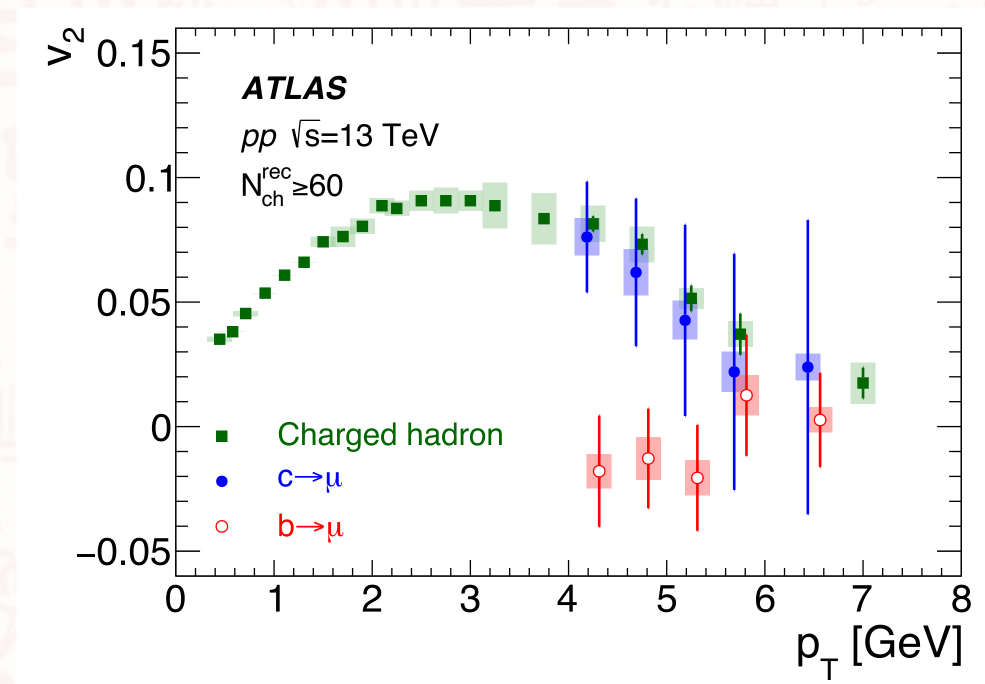
Closure test in Pythia8



- Closure test in Generator level and reconstruction level Pythia events excludes obvious biases from selection/non-flow subtraction

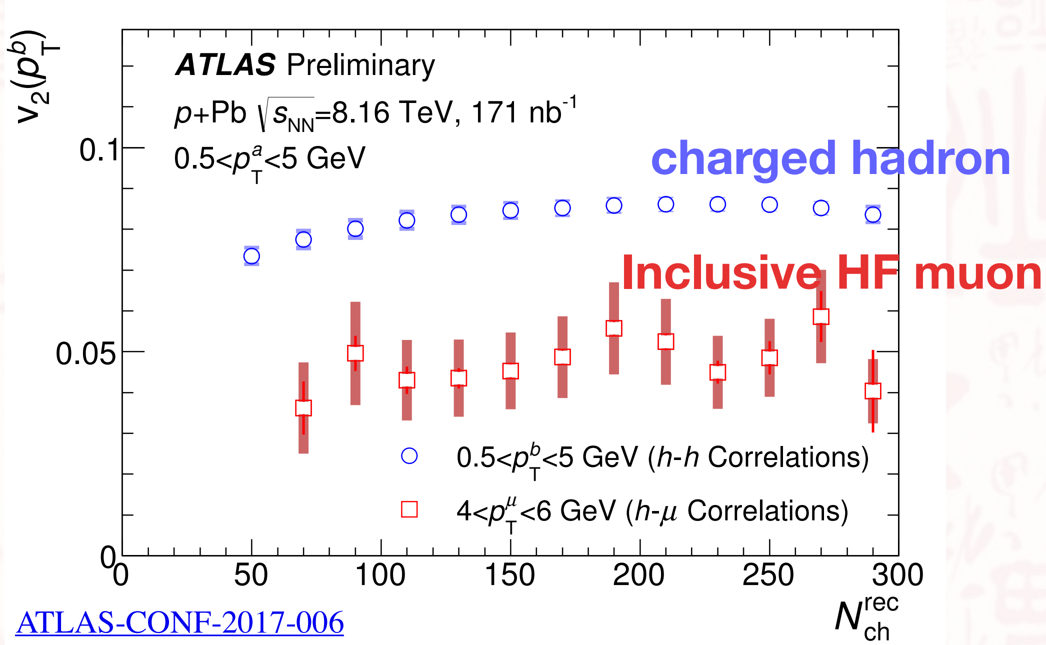
HF muon vs. charged hadron in *pp*





- Inclusive HF muon v_2 < inclusive charged hadron v_2
- Charm muon v_2 ~ inclusive charged hadron v_2, despite small kinematic smearing from hadron to muon; bottom muon v_2 ~ 0

What about *p*+Pb



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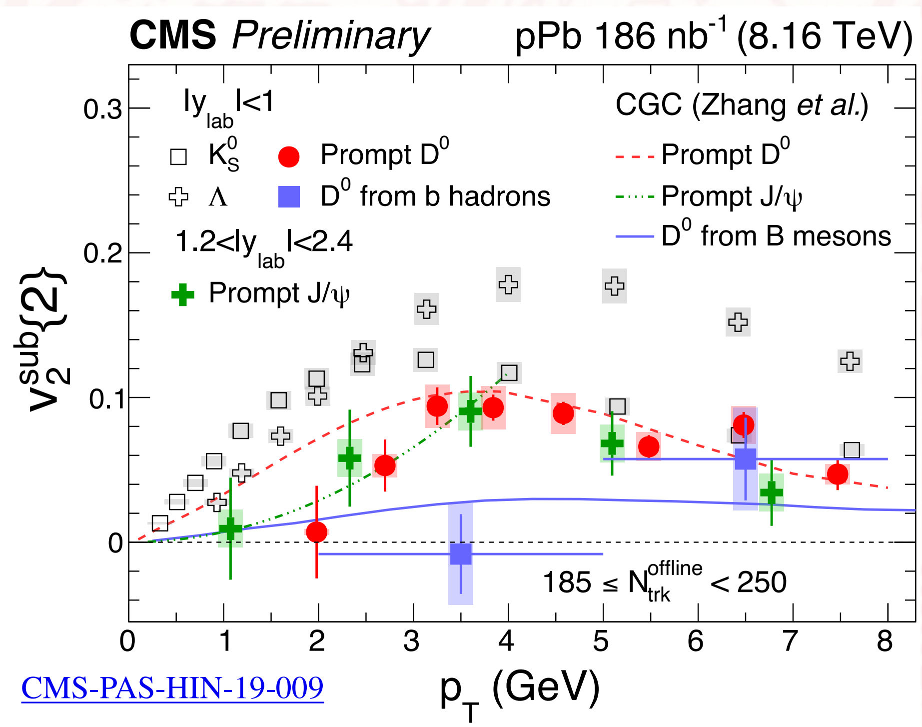
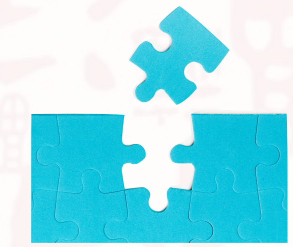


CMS-PAS-HIN-19-009



- Inclusive HF muon v_2 < charged particle v_2
- prompt D^0 v_2 ~ charged particle v_2
- charm v_2 ~ charged particle v_2 > bottom v_2 (?) 0

Non-prompt D^0 v_2 from CMS has large uncertainty.

HF muon from bottom decays may be the only way to probe bottom with good precision without more data

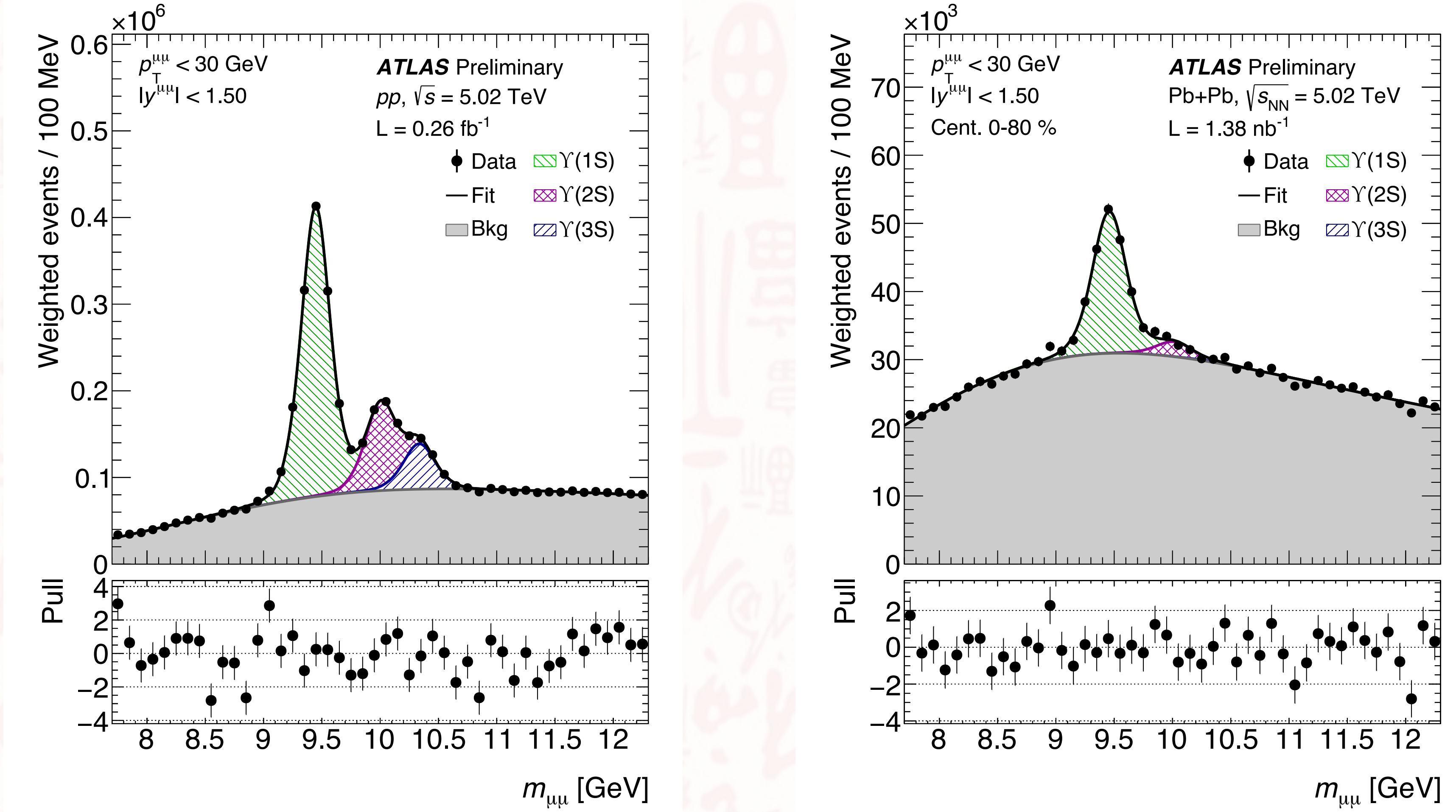
To be completed in 1~2 years

	Yields	Flow
Pb+Pb	*Phys. Rev. C* 98 (2018) 044905 To be updated with b/c separation	ATLAS-CONF-2019-053
p+Pb	- To be analyzed	ATLAS-CONF-2017-006 To be updated with b/c separation
pp	*Phys. Rev. C* 98 (2018) 044905 To be updated with b/c separation	1909.01650

Upsilon Production in *pp* and Pb+Pb

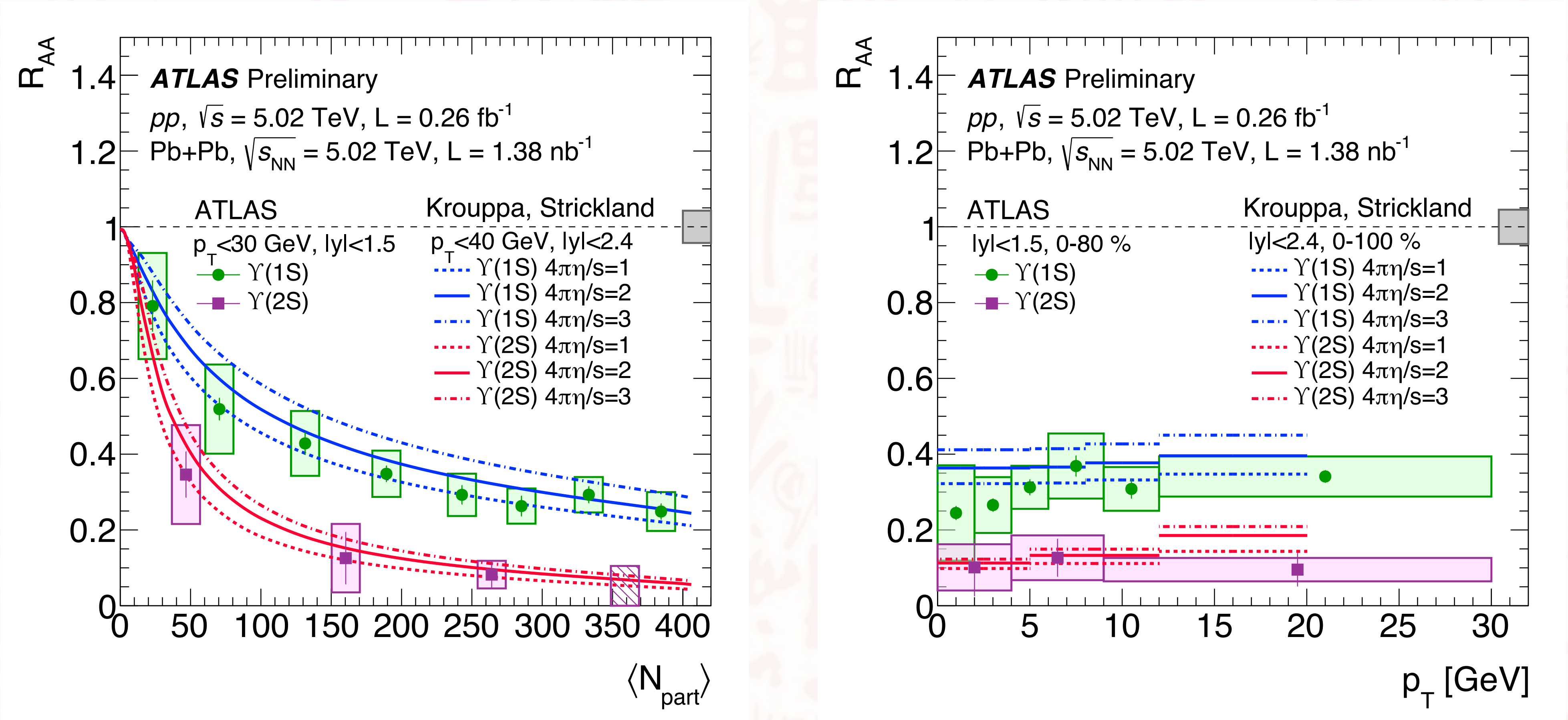
ATLAS-CONF-2019-054

Upsilon yield extraction



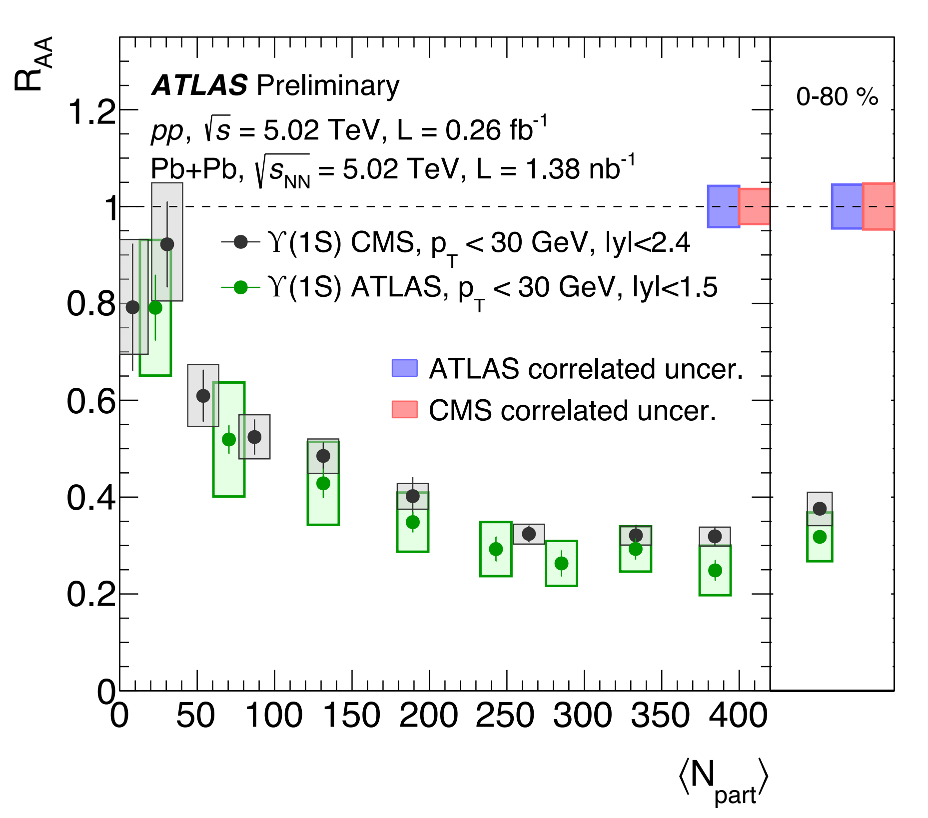
- 2017 *pp* data and 2018 Pb+Pb data at 5.02 TeV. First Pb+Pb Upsilon results from ATLAS
- Cannot avoid overlapping between different states due to ID resolution
- *pp* data is used to constrain invariant mass fit in Pb+Pb
- No significant Upsilon(3S) contribution observed

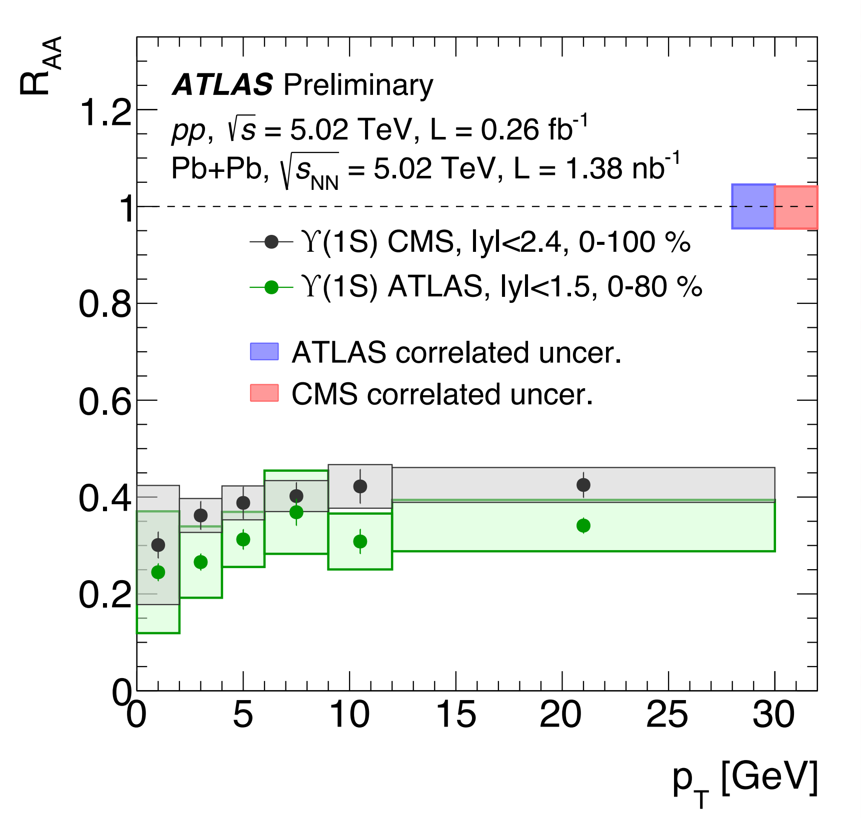
Upsilon R_{AA}



- pNRQCD + 3+1D hydro gives good descriptions of the data trends
- Cannot distinguish different η/s values due to limit experimental precision (systematics dominated)

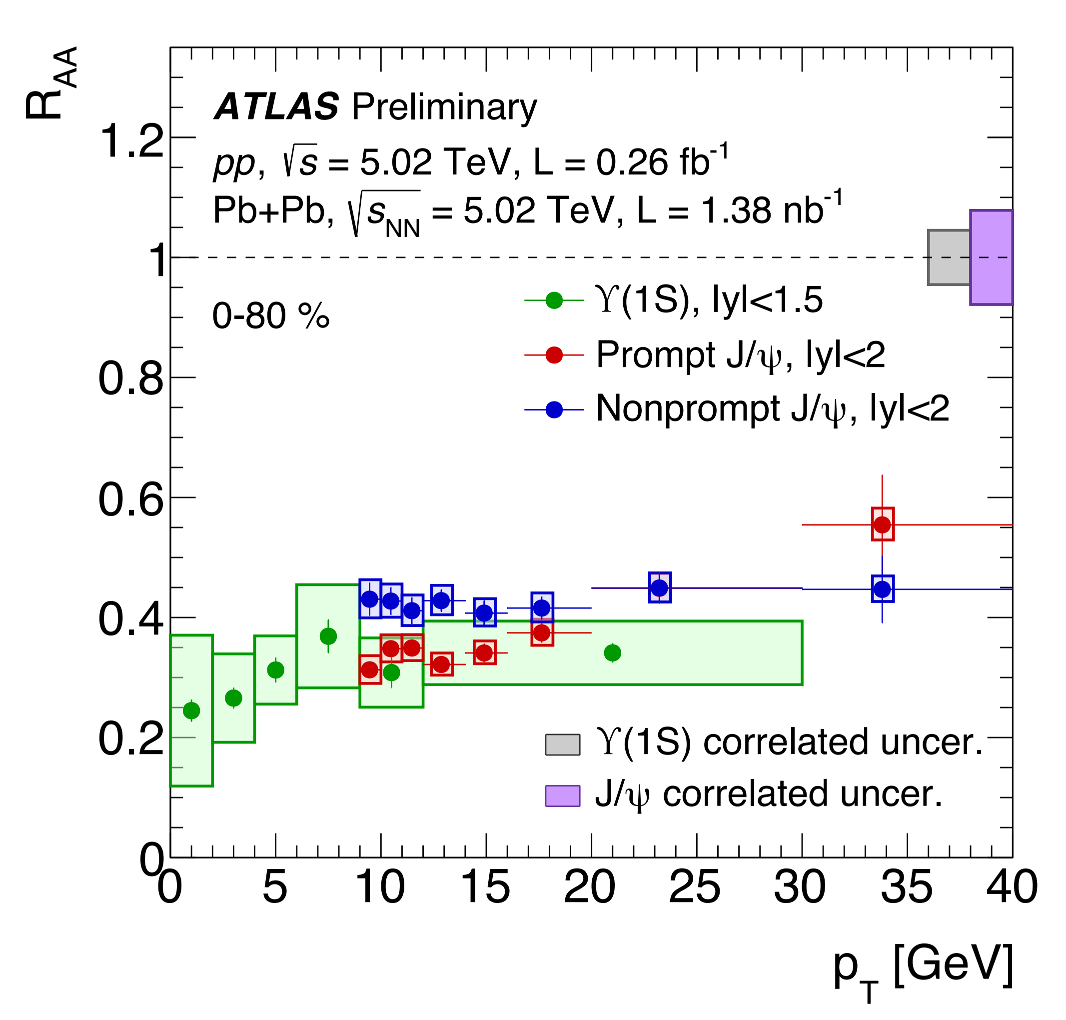
Comparison to CMS





- Comparable with CMS within uncertainties while the central values are systematic lower
- Good confirmation of our control on the muon performance in 2018 Pb+Pb data, benefit future muon based analysis

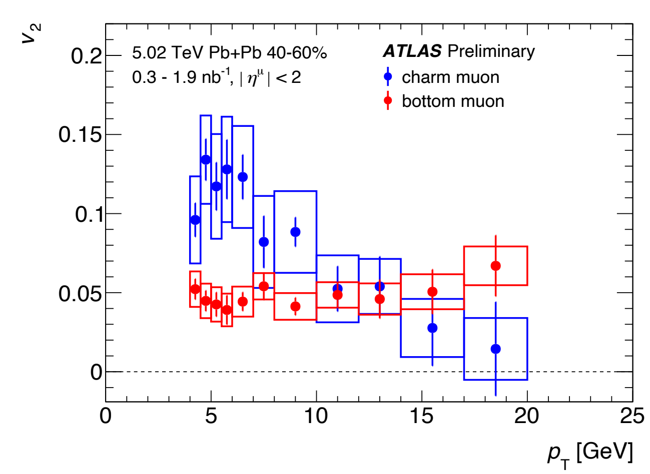
Bottomonium vs. charmonium

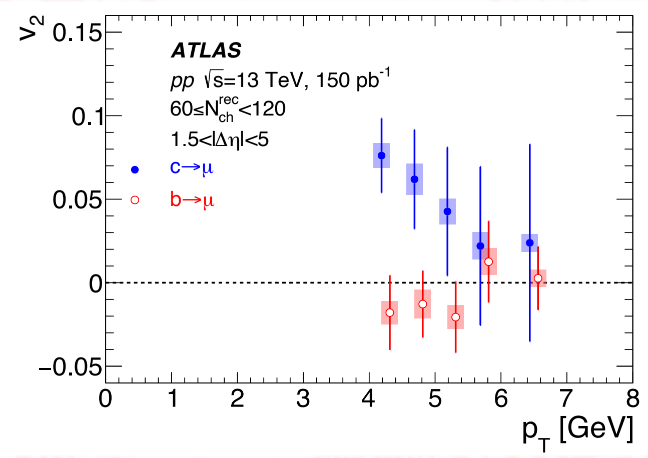


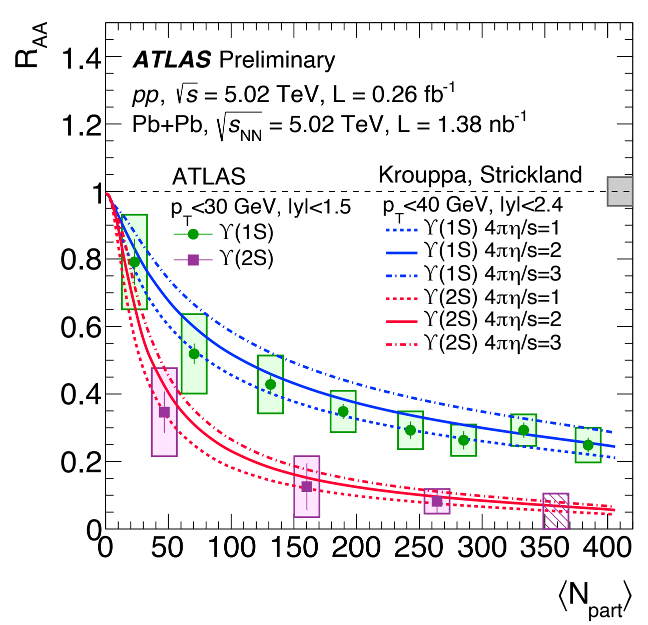
- Upsilon(1S) R_{AA} ~ prompt J/ψ R_{AA}
- A coincidence of admixture of less suppressed ground state and more suppressed excited state?

Summary

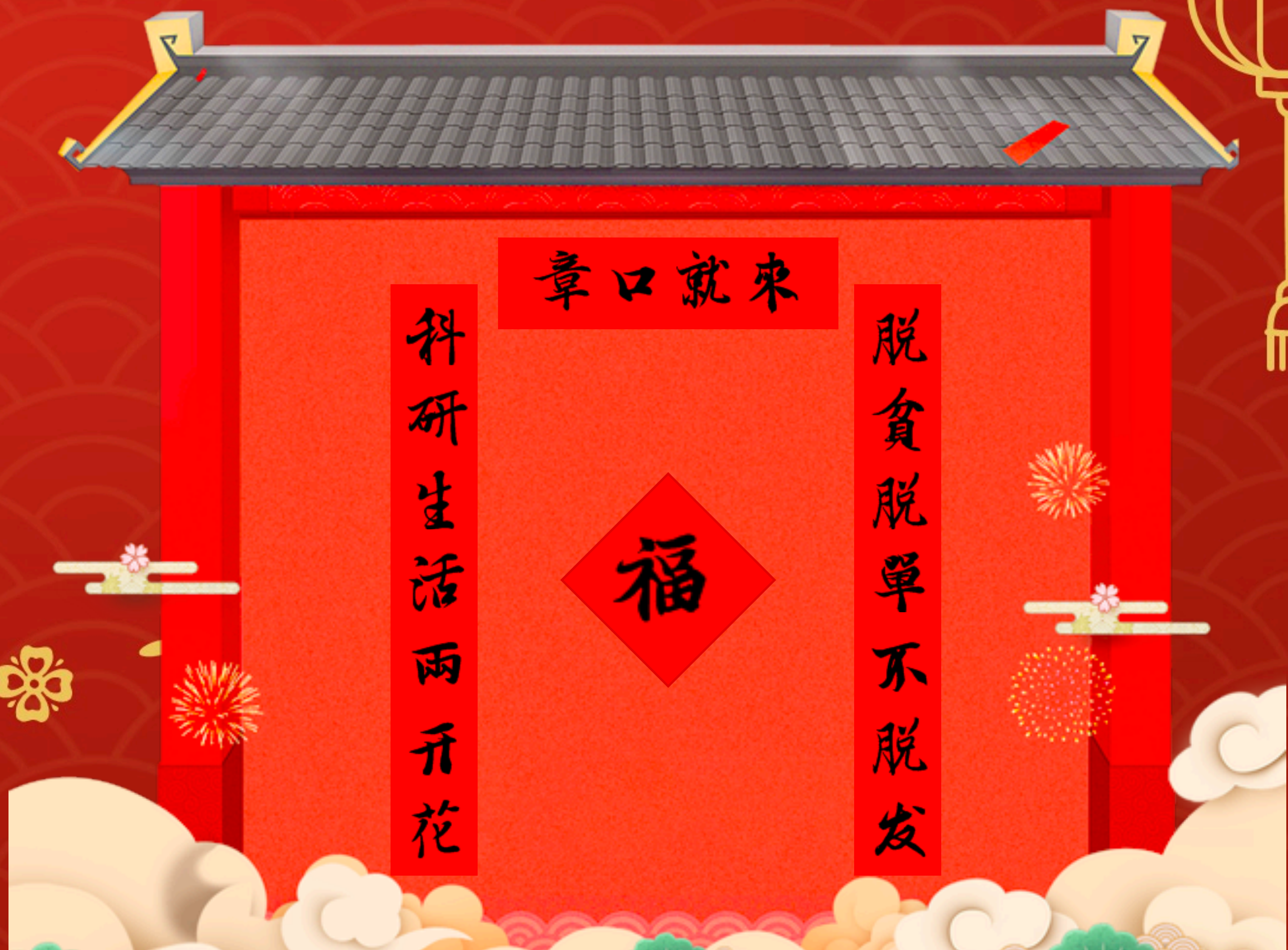
- Pb+Pb: non-zero bottom muon v_2 and zero v_3 observed in Pb+Pb
- *pp*: zero bottom muon v_2 while charm muon v_2 is comparable with inclusive charged hadrons
- Upsilon RAA in agreement with CMS and model calculations





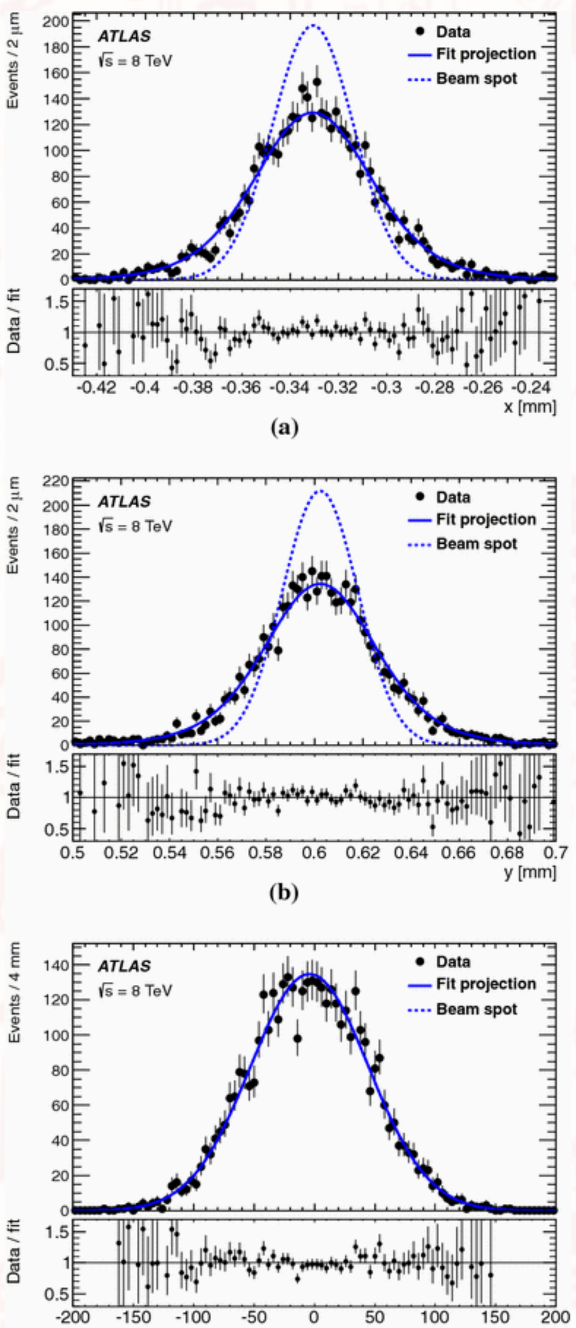


预祝各位老师、同仁新春快乐！



Backup

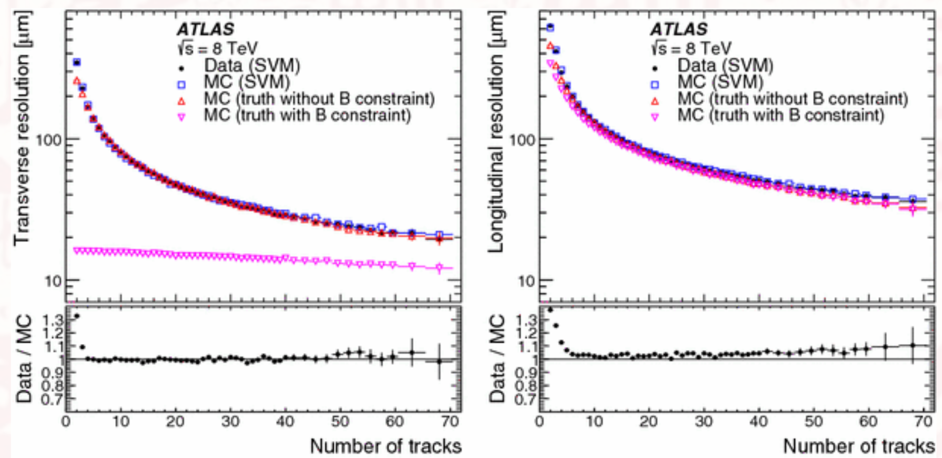
ATLAS ID performance



(a)

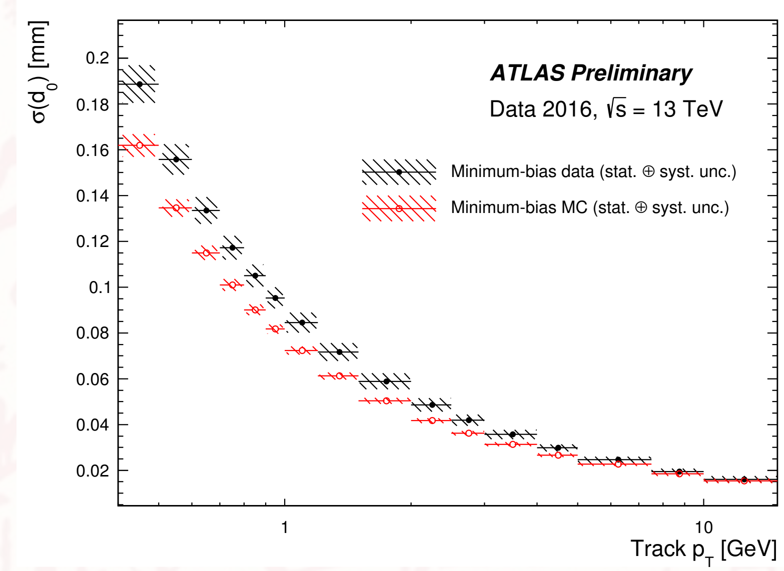
(b)

(c)

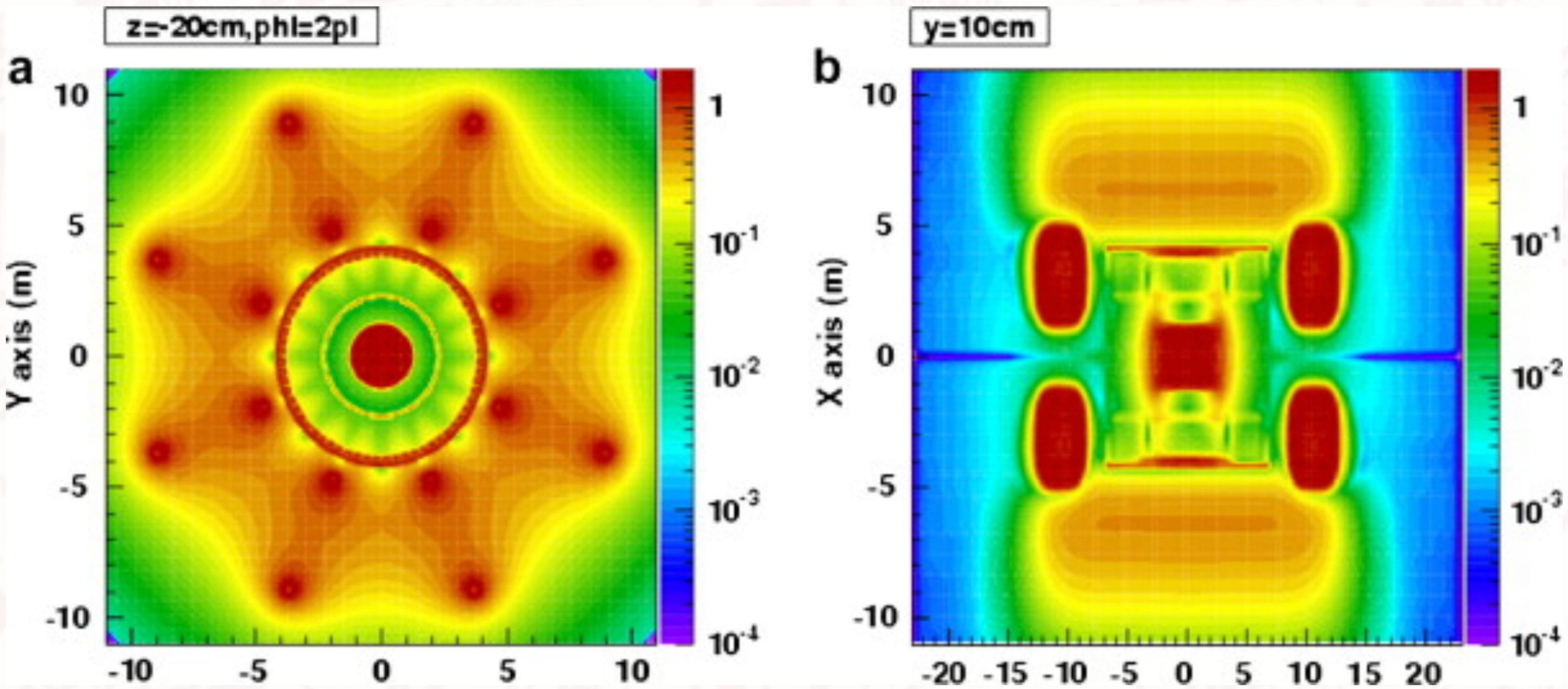


(a) (b)

[Eur. Phys. J. C 77 (2017) 332]



Magnetic fields



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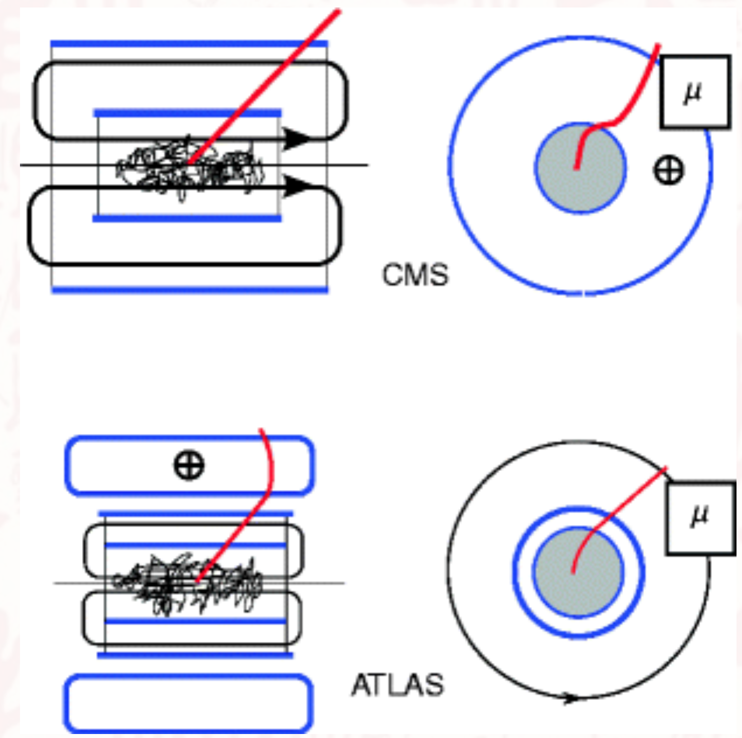
link



Barrel Toroid

- 25.3 m length
- 20.1 m outer diameter
- 8 separate coils
- 1.08 GJ stored energy
- 370 tonnes cold mass
- 830 tonnes weight
- 4 T magnetic field on superconductor
- 56 km Al/NbTi/Cu conductor
- 20.5 kA nominal current
- 4.7 K working point temperature
- 100 km superconducting wire

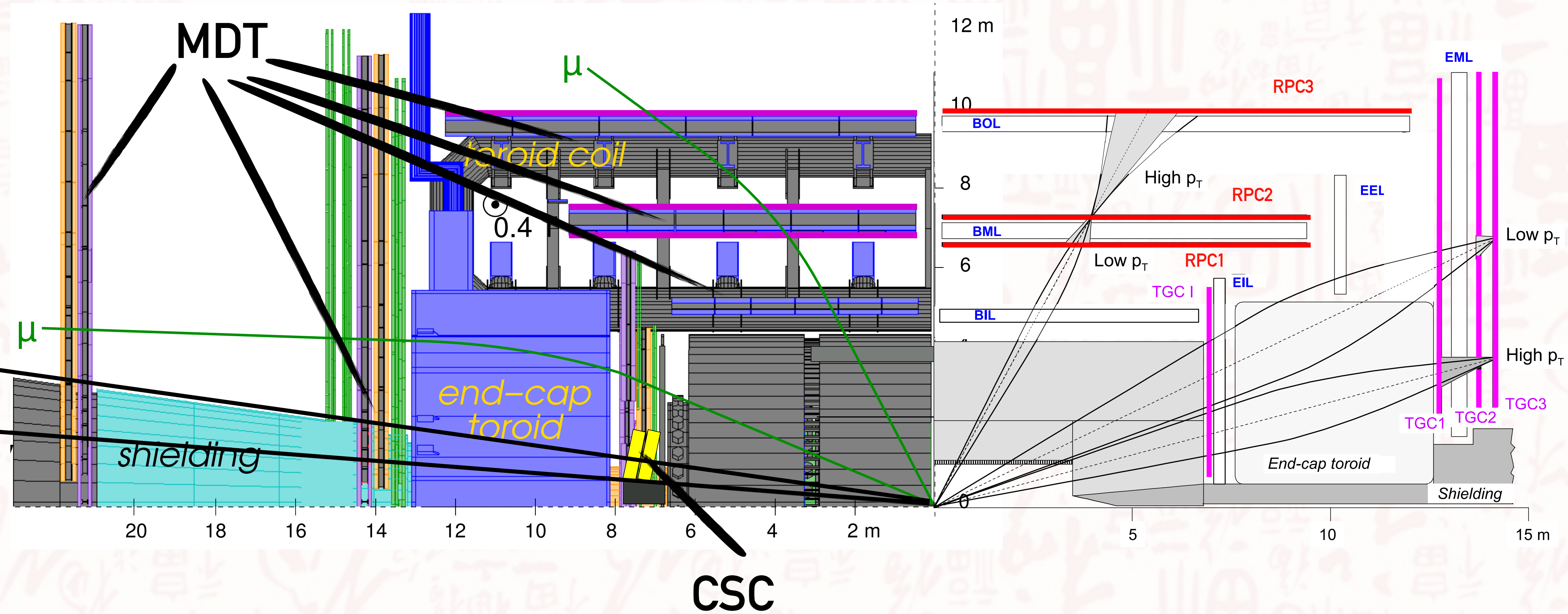
End-cap Toroid

- 5.0 m axial length
- 10.7 m outer diameter
- 8 coils 8 coils in a common cryostat each
- 0.25 GJ stored energy in each
- 160 tonnes cold mass each
- 240 tonnes weight each
- 4 T magnetic field on superconductor
- 13 km Al/NbTi/Cu conductor each
- 20.5 kA nominal current
- 4.7 K working point temperature

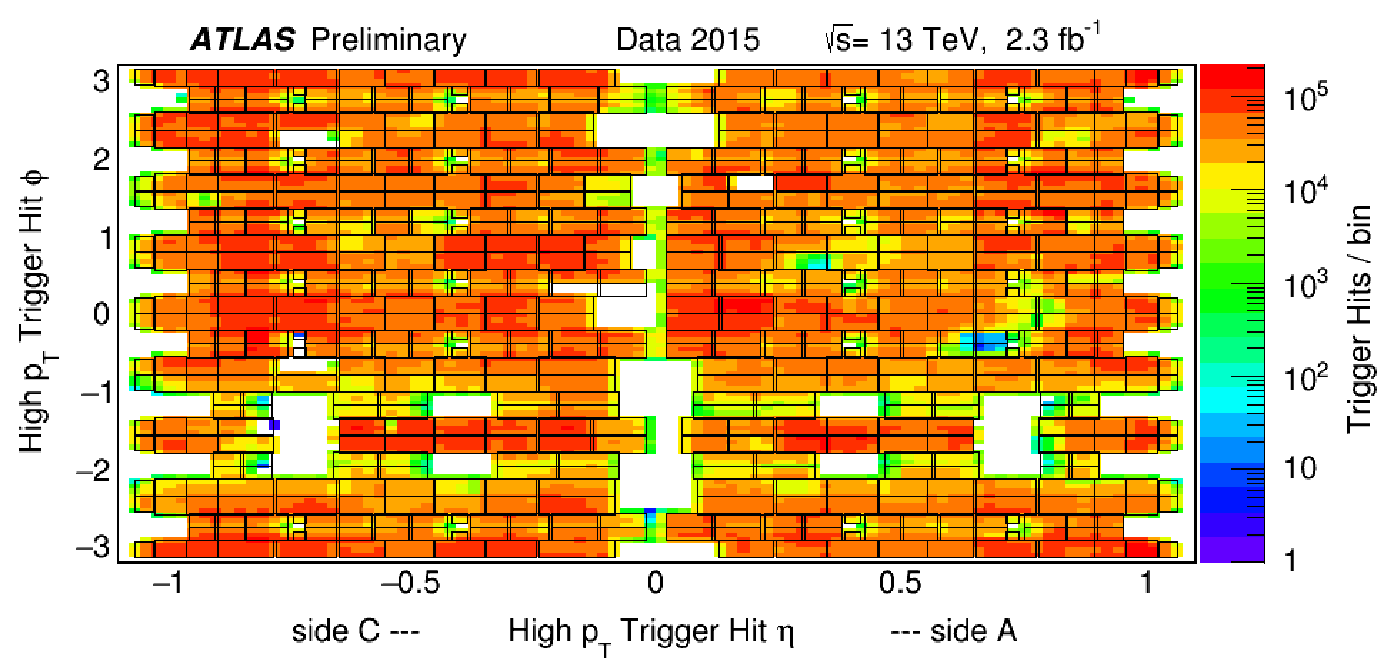
Central Solenoid Magnet

- Bends charged particles for momentum measurement
- 5.3 long, 2.4 m diameter, 4.5 cm thick
- 5 tonne weight
- 2 tesla (T) magnetic field with a stored energy of 38 megajoules (MJ)
- 9 km of superconducting wire
- Nominal current: 7.73 kiloampere (kA)

ATLAS muon system



ATLAS RPC acceptance ~ 80% overall



Trigger chambers

RPCs |η| < 1.05 (barrel)

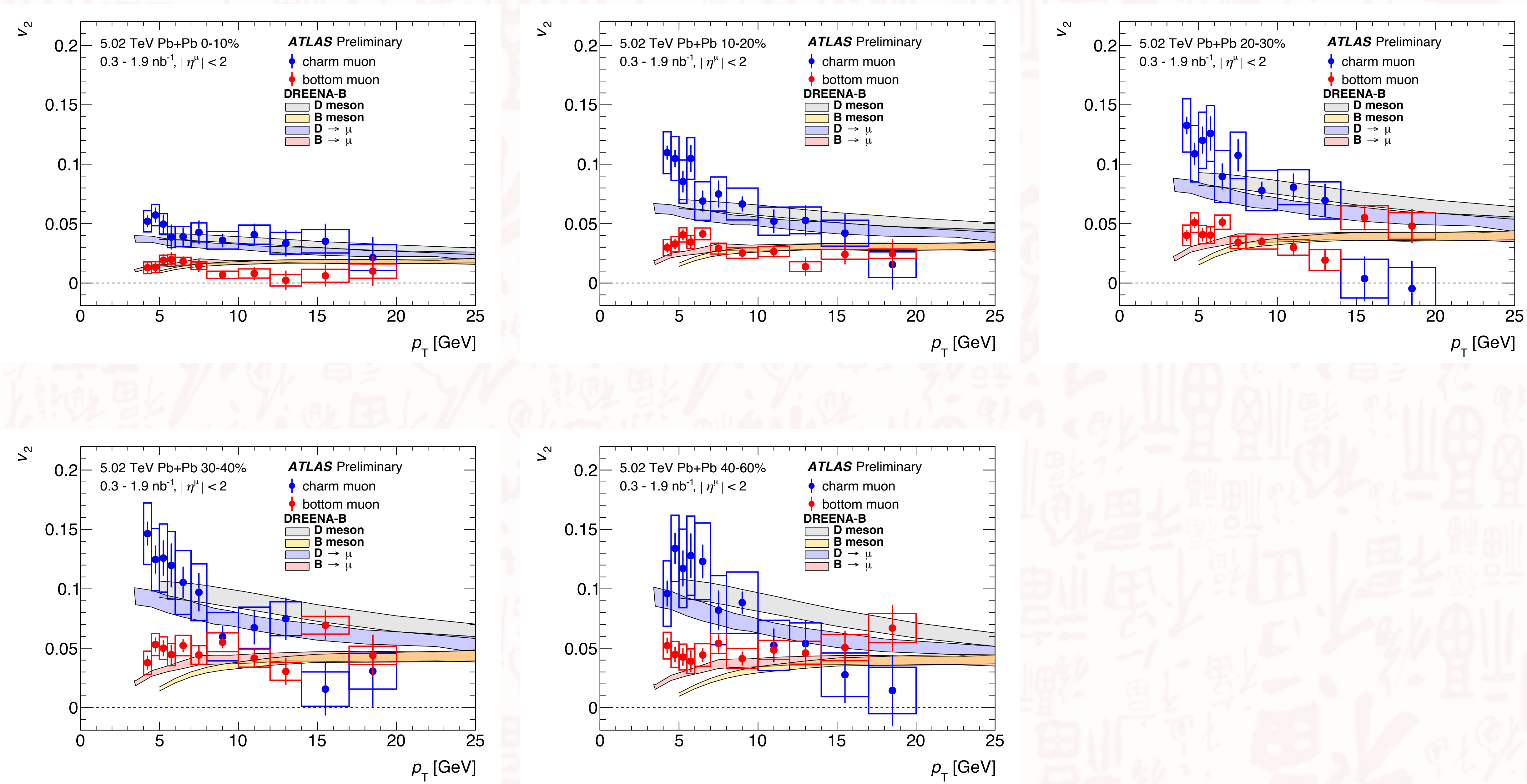
TGCs 1.05 < |η| < 2.4 (end-cap

Precision chambers

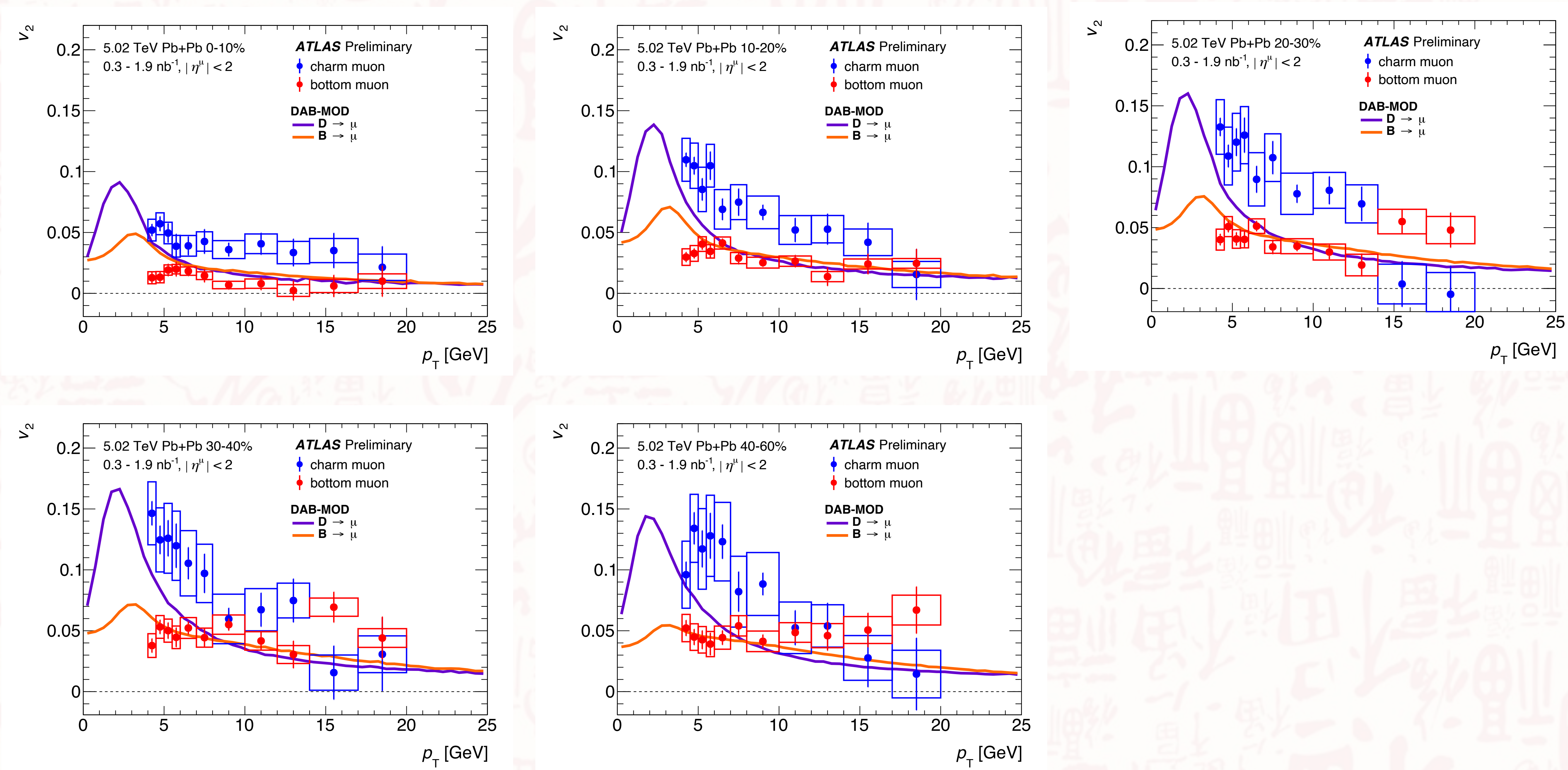
MDTs |η| < 1.05

CSCs 1.05 < |η| < 2.4

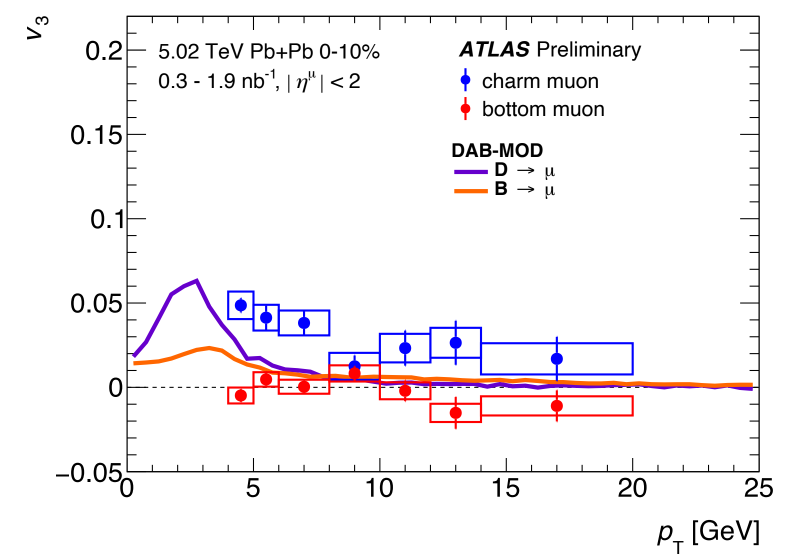
DREENA-B


5.02 TeV Pb+Pb 0-10%
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%
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]

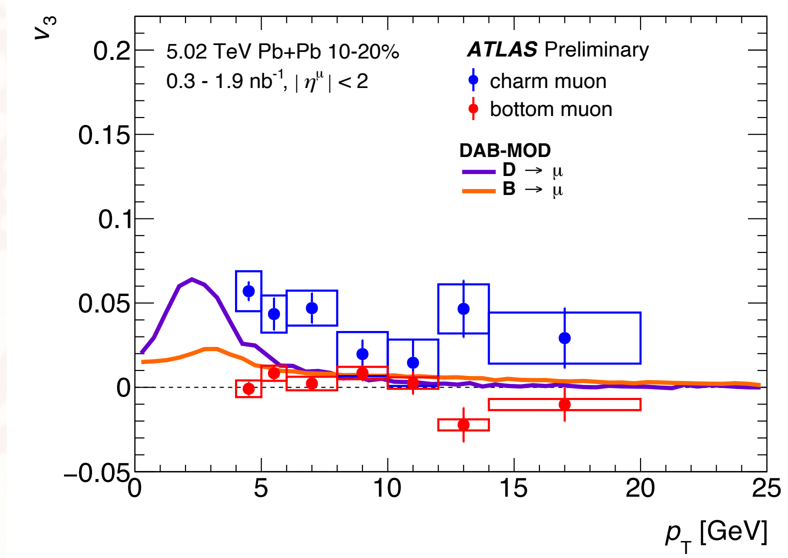
DAB-MOD — v_2


5.02 TeV Pb+Pb 0-10%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
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%
v_2
p_T [GeV]
0
0.05
0.1
0.15
0.2
5
10
15
20
25

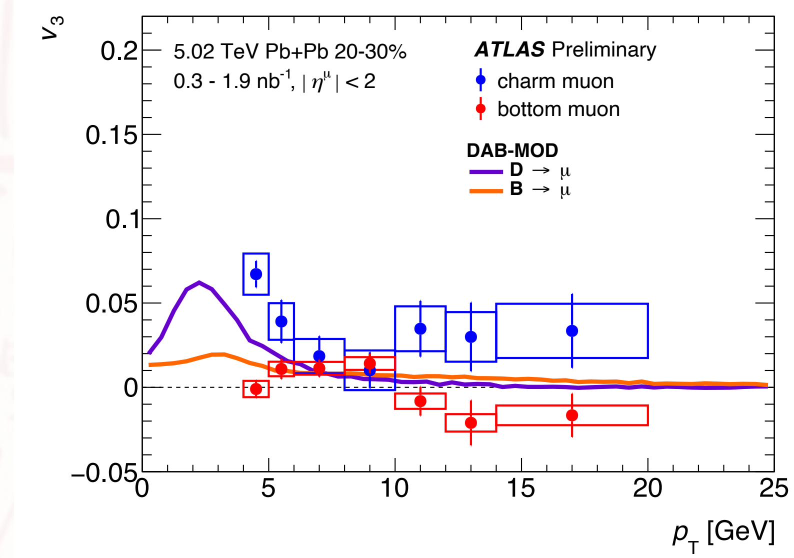
DAB-MOD — v_3



v_3
0.2
0.15
0.1
0.05
0
−0.05
0
5
10
15
20
25
p_T [GeV]
5.02 TeV Pb+Pb 0-10%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DAB-MOD
D → μ
B → μ



v_3
0.2
0.15
0.1
0.05
0
−0.05
0
5
10
15
20
25
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
DAB-MOD
D → μ
B → μ



v_3
0.2
0.15
0.1
0.05
0
−0.05
0
5
10
15
20
25
p_T [GeV]
5.02 TeV Pb+Pb 20-30%
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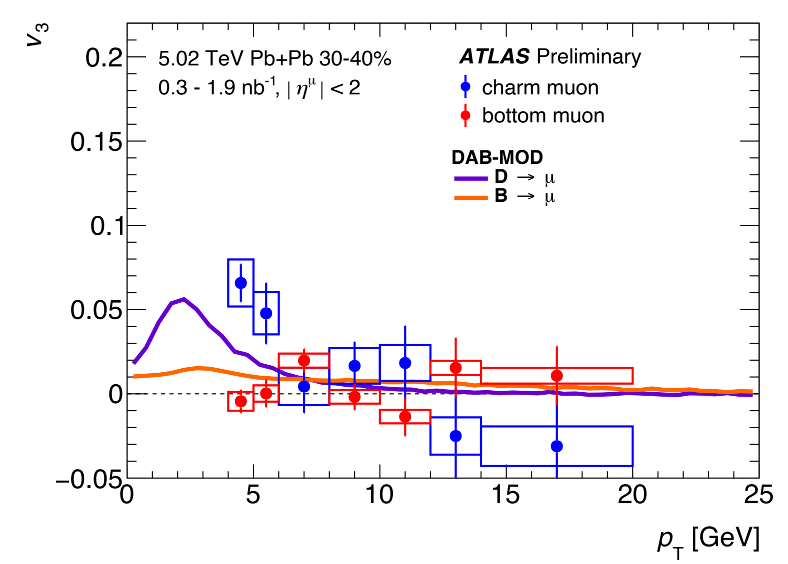
ATLAS Preliminary
charm muon
bottom muon
DAB-MOD
D → μ
B → μ



v_3
0.2
0.15
0.1
0.05
0
−0.05
0
5
10
15
20
25
p_T [GeV]
5.02 TeV Pb+Pb 30-40%
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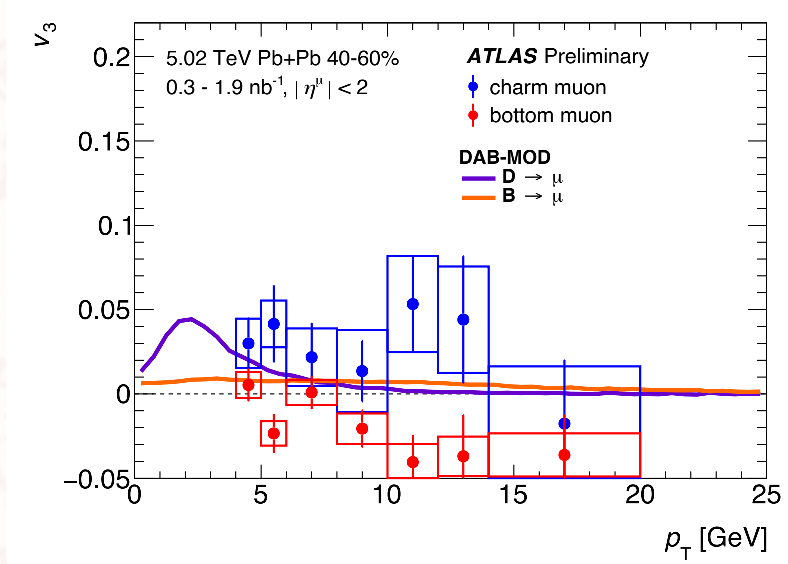
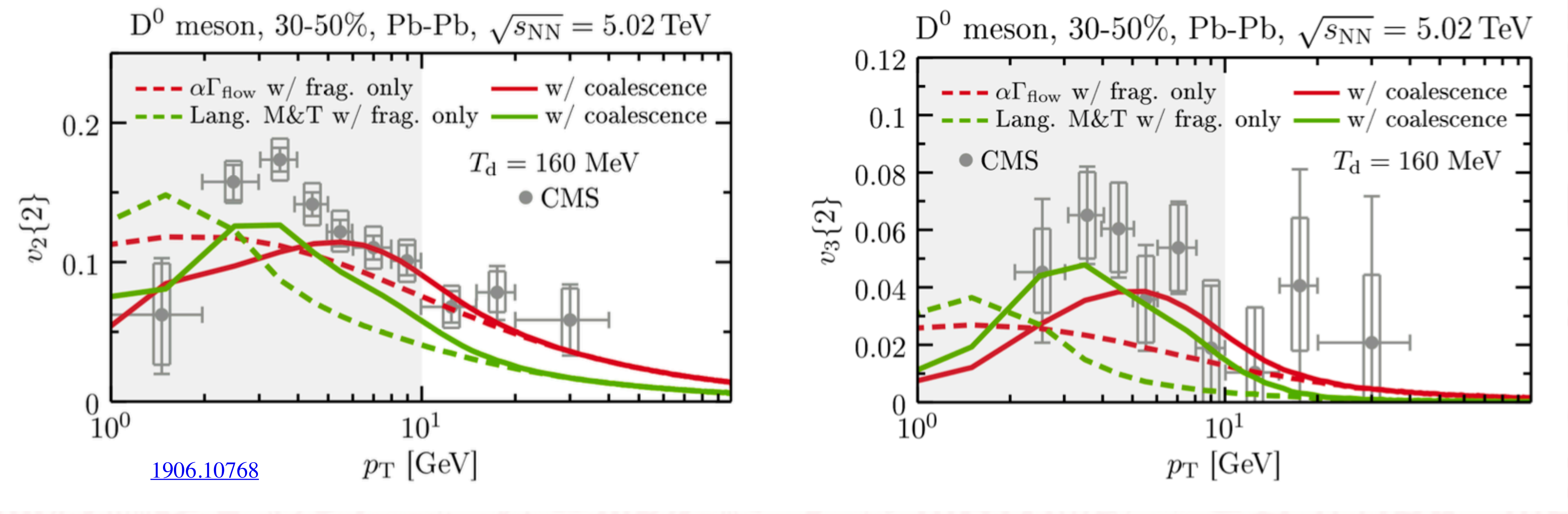
ATLAS Preliminary
charm muon
bottom muon
DAB-MOD
D → μ
B → μ



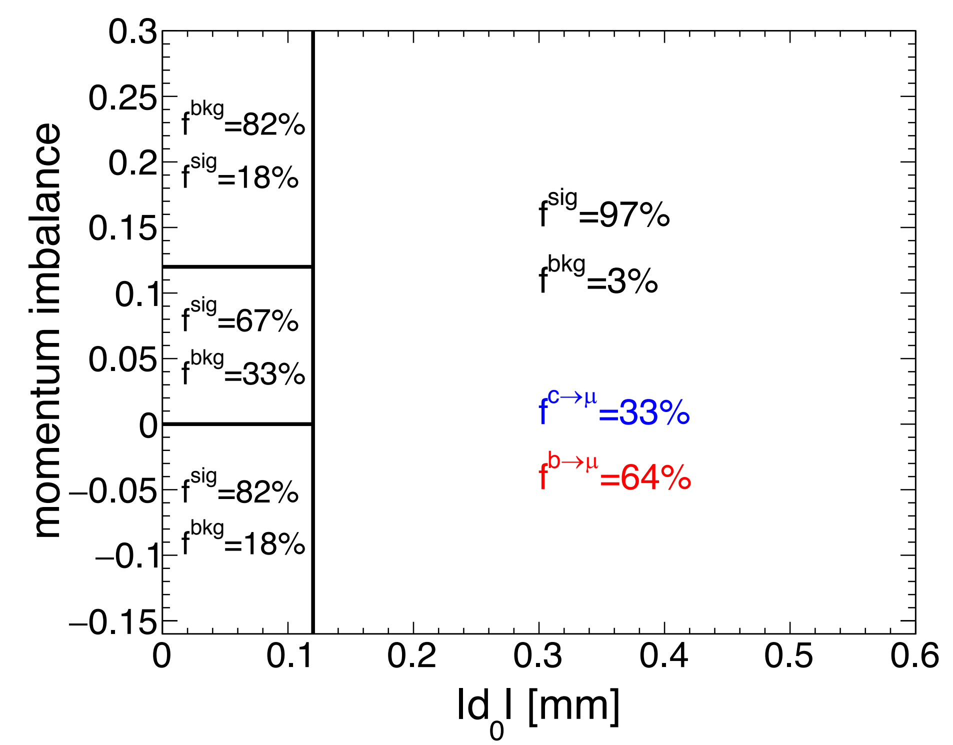
v_3
0.2
0.15
0.1
0.05
0
−0.05
0
5
10
15
20
25
p_T [GeV]
5.02 TeV Pb+Pb 40-60%
0.3 - 1.9 nb^{-1}, $|\eta^{\mu}| < 2$
ATLAS Preliminary
charm muon
bottom muon
DAB-MOD
D → μ
B → μ

energy loss in DAB-MOD



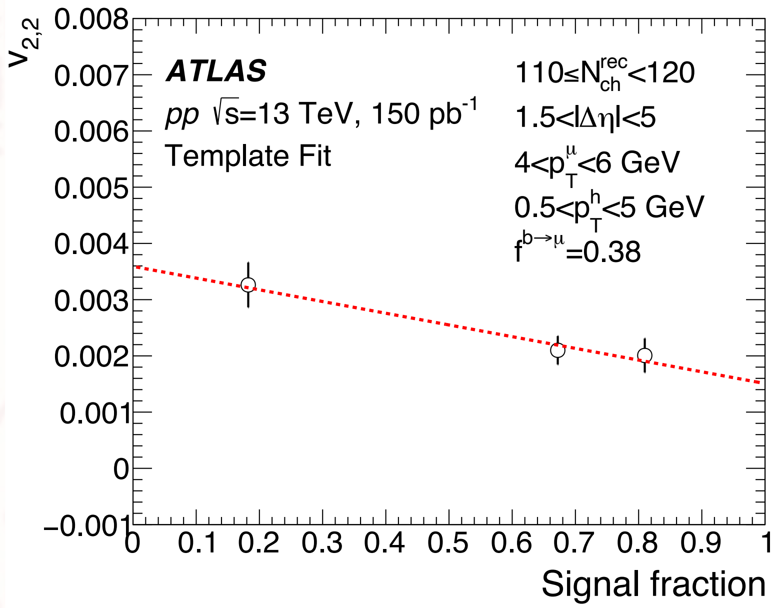
1906.10768

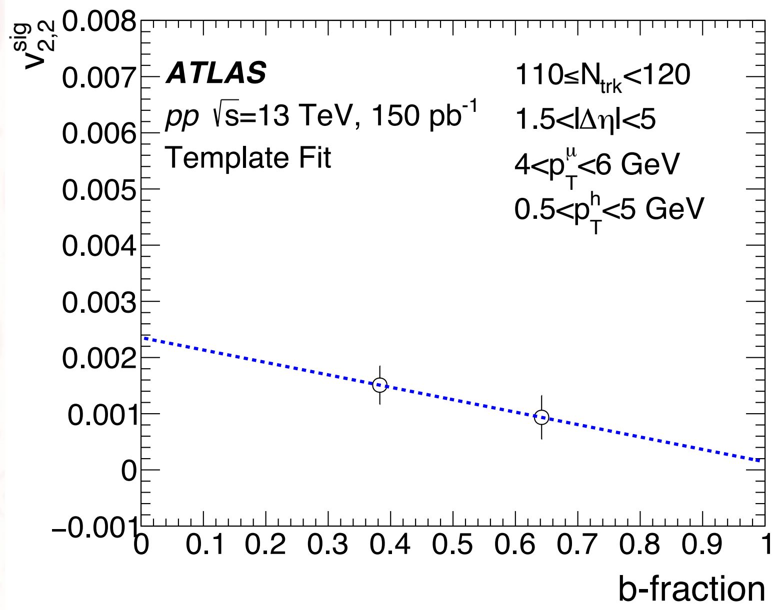
Flow coefficient extraction in *pp*



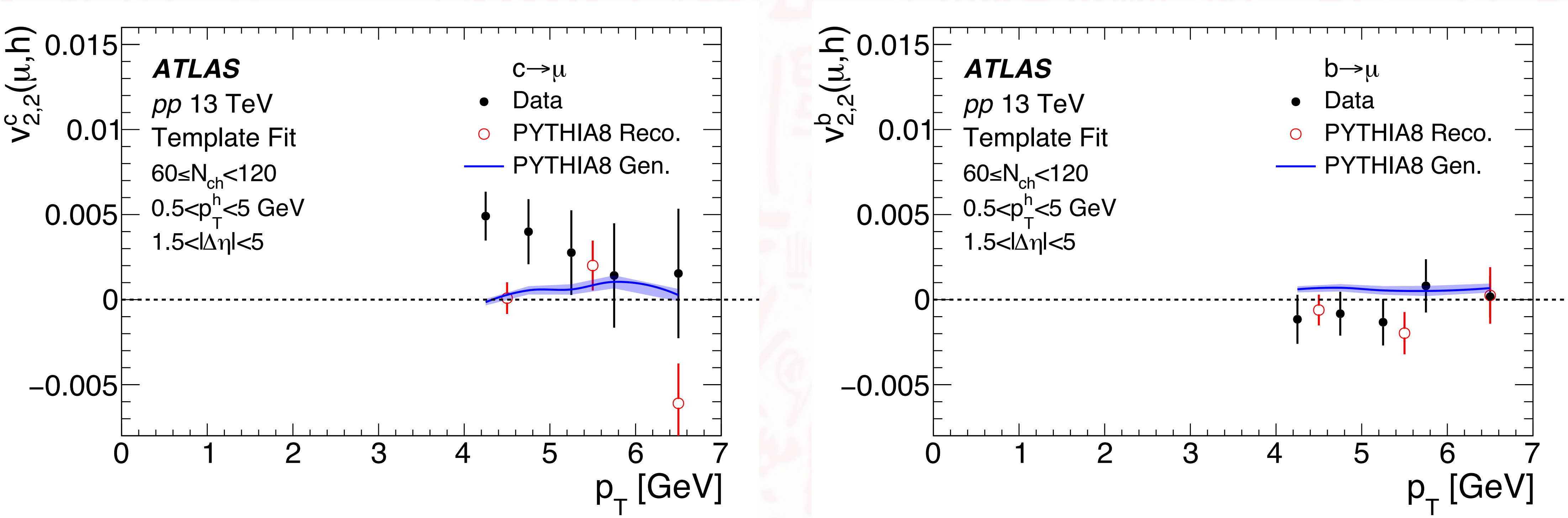
$$v_{2,2} = f^{\text{sig}} v_{2,2}^{\text{sig}} + (1 - f^{\text{sig}}) v_{2,2}^{\text{bkg}}$$

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

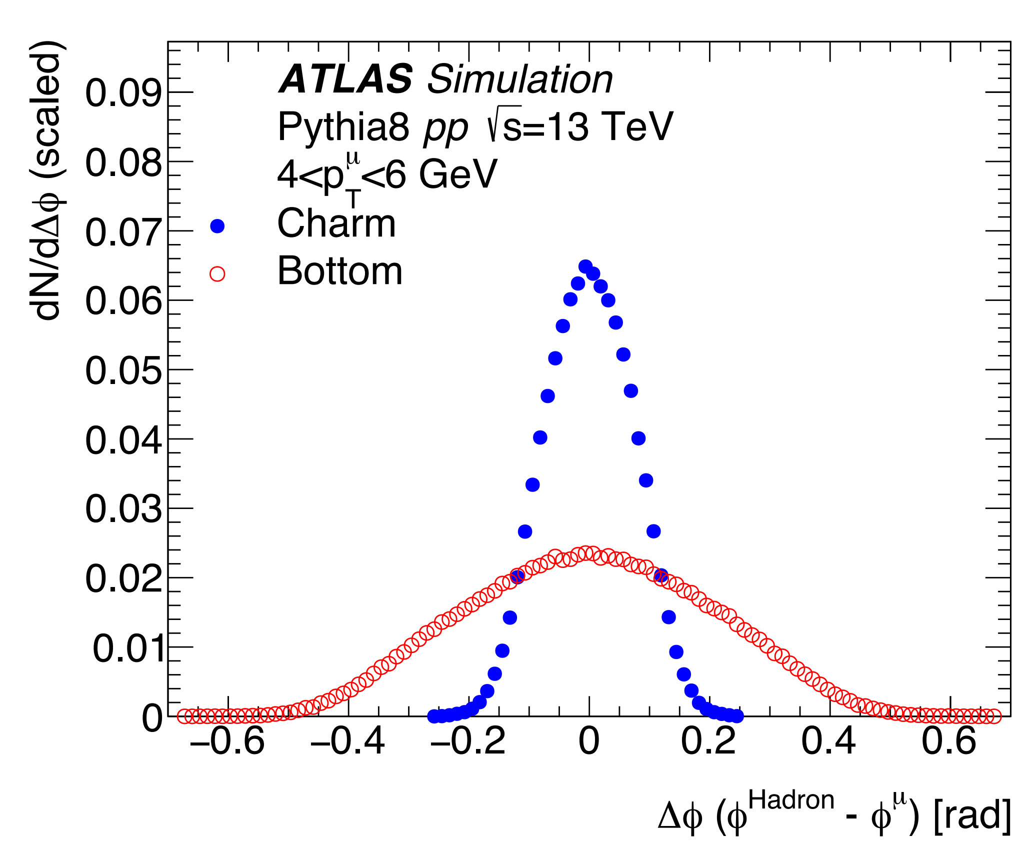




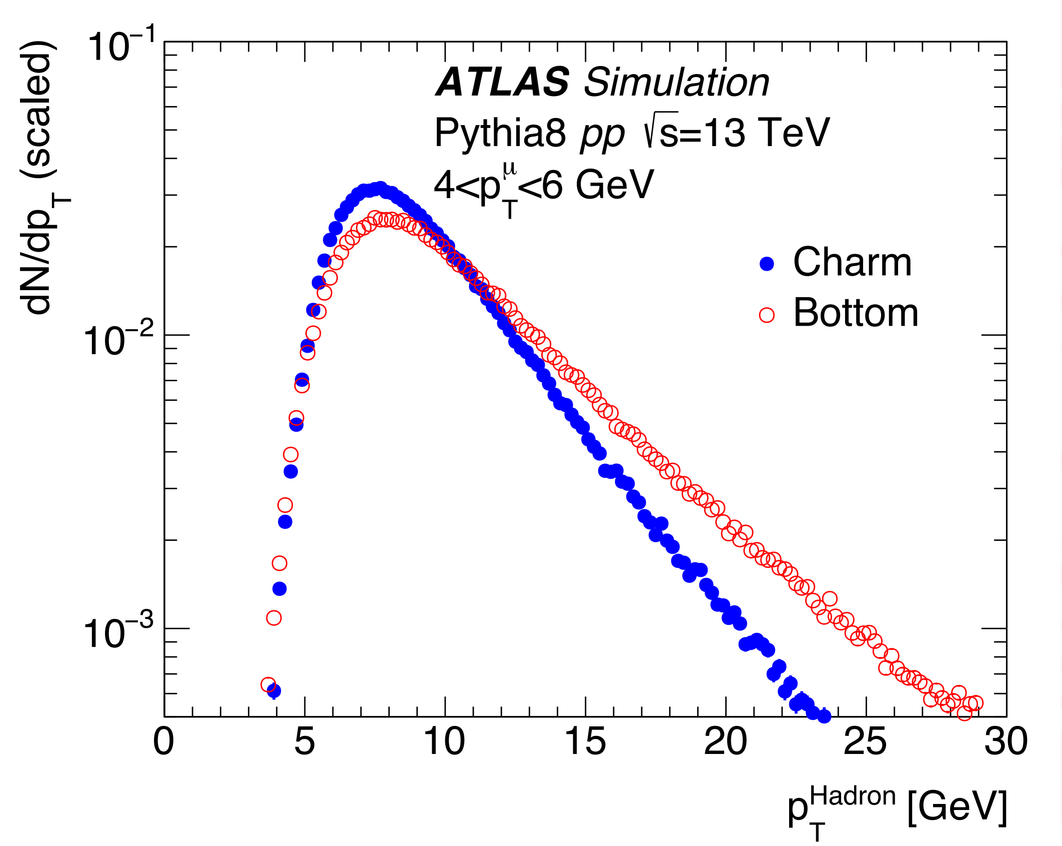
PYTHIA Closure in *pp*



Hadron to muon smearing in Pythia



azimuthal angle smearing



p_T shift and smearing