Flow and production of heavy-flavors with ATLAS

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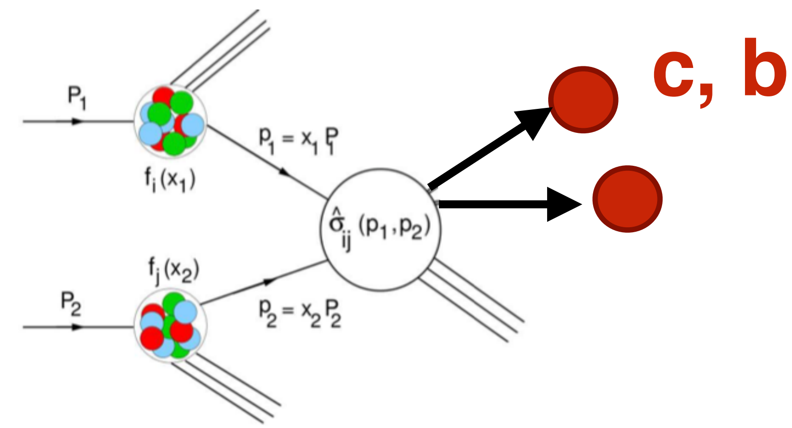
for the ATLAS collaboration

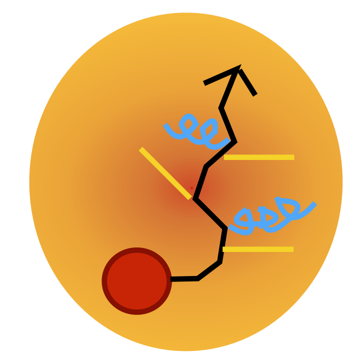
Heavy-Flavour Hadronization 2020
CERN, Switzerland
March 2nd 2020

Heavy quarks in heavy-ion collisions

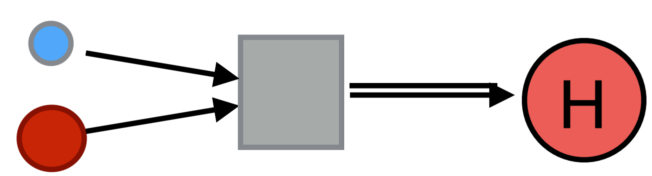
- **Production**
  - by hard scattering at the early stage of collisions
    $\tau_{b\bar{b}} \sim 0.02 < \tau_{c\bar{c}} \sim 0.07 < \tau_{QGP} \sim 0.1\text{-}1$ fm/c
  - $m_Q >> \Lambda_{QCD}$: calculable with pQCD

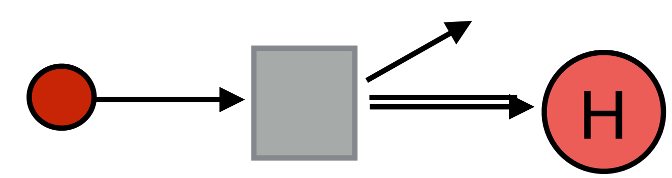


- **Traversing In QGP**
  - Collisional & radiative energy loss
  - Drag and diffusion described by Langevin Dynamics

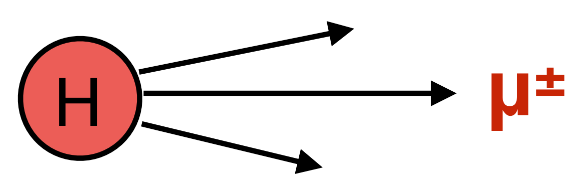


- **Hadronization**
  - Coalescence
  - Fragmentation





- **Decay** into final-state particles
  - hadronic, semileptonic, etc.



Observables

- **Nuclear modification factor R_{AA}**

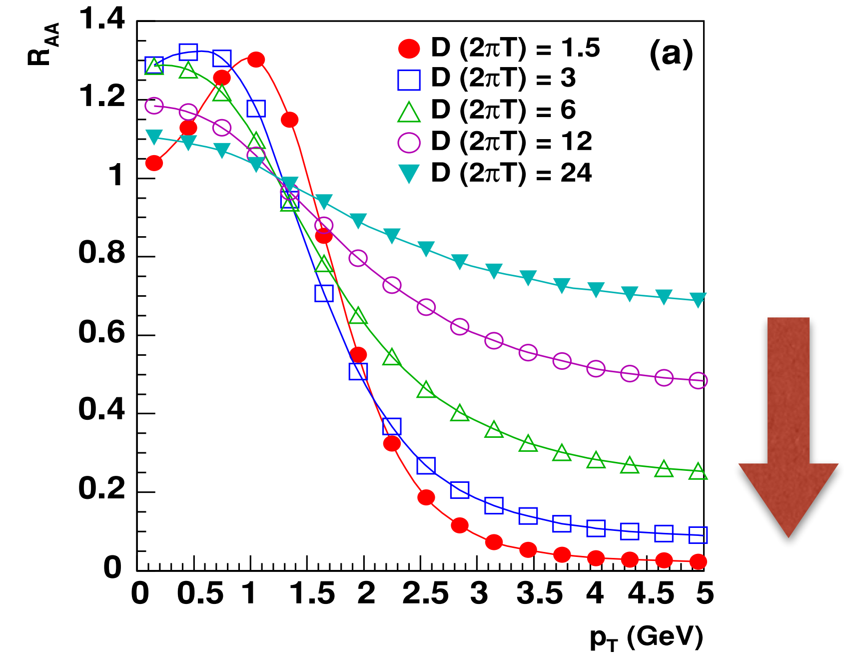
$$R_{\mathrm{AA}} = \frac{N_{AA}}{\langle T_{\mathrm{AA}} \rangle \times \sigma^{pp}}$$

Per-event yields in AA

cross-section in pp

Nuclear overlap function

PRC 71 (2005) 064904



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PRC 71 (2005) 064904

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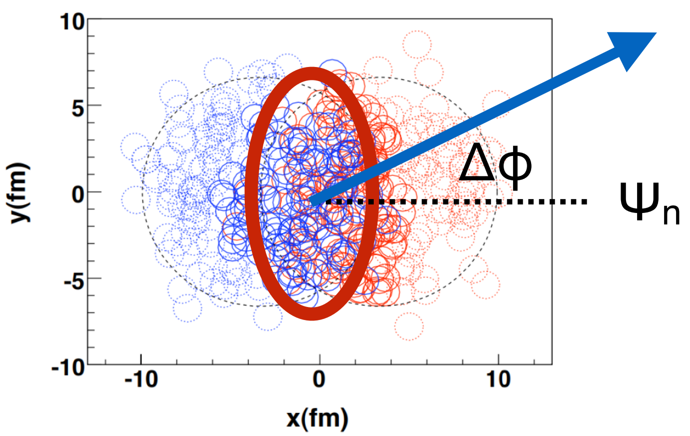
Nuclear overlap function

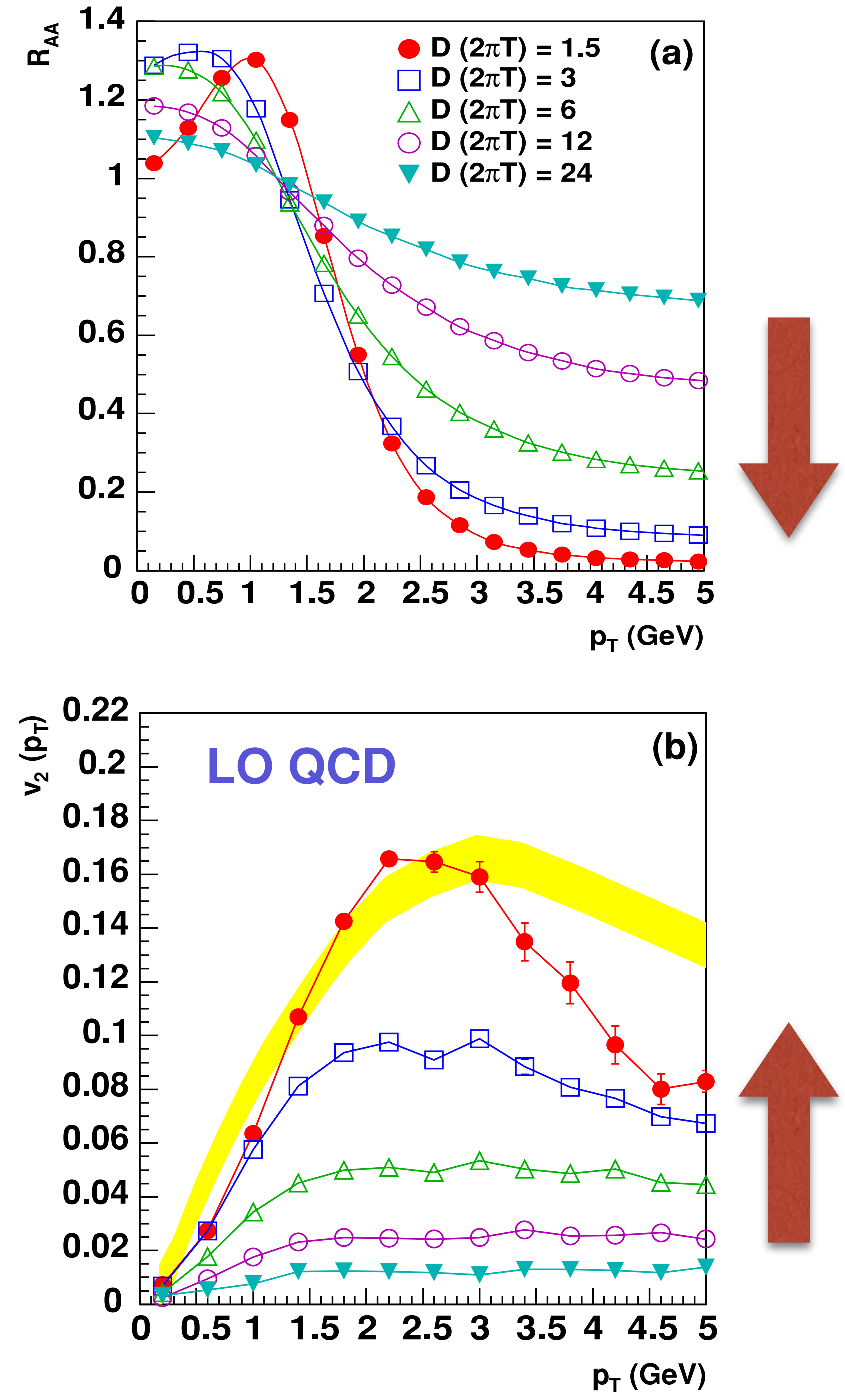
- **Azimuthal anisotropy (flow coefficients v_n)**

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$



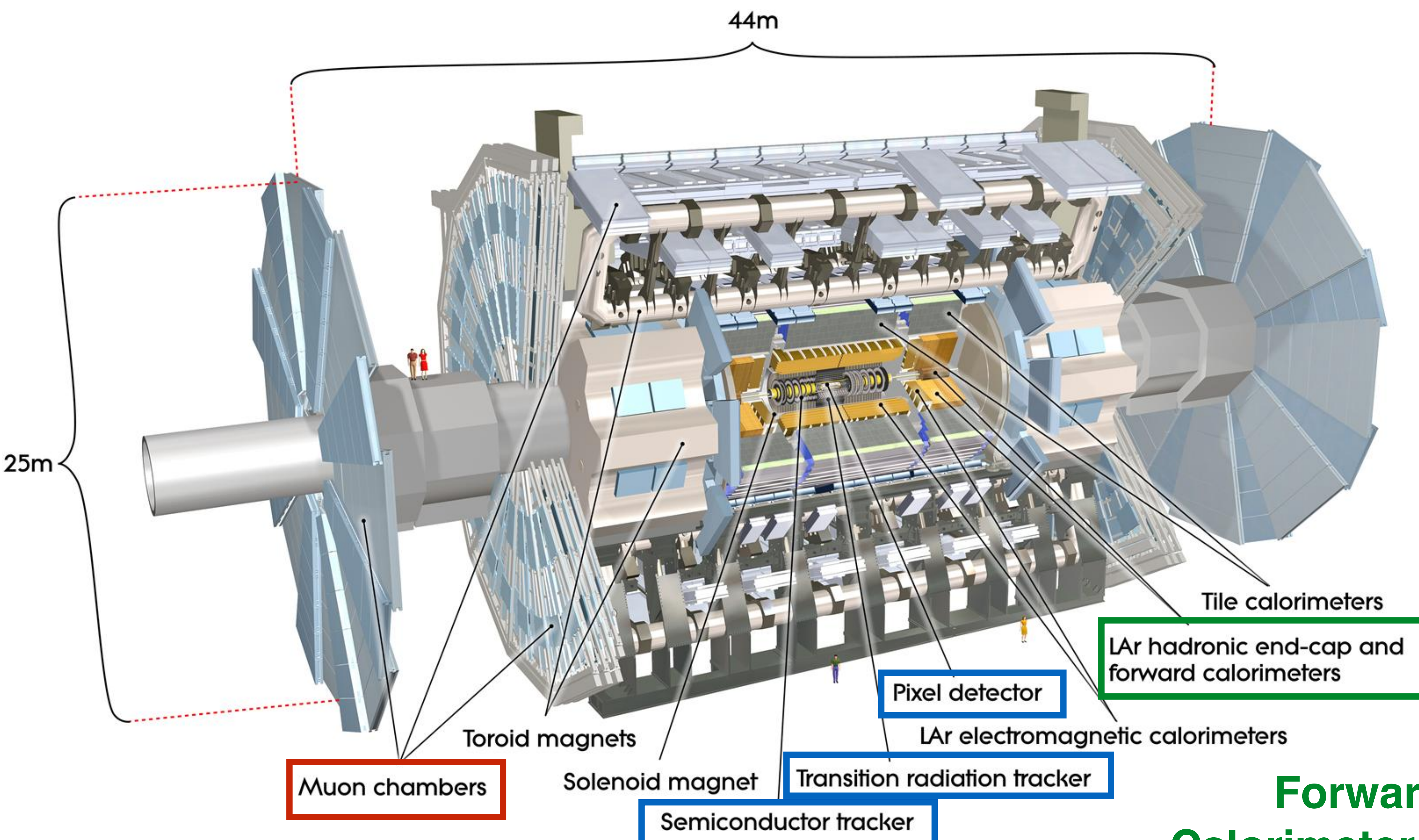
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

Anisotropic particle density
- Initial geometry
- Hydrodynamic property



- R_{AA} =1 and v_2 =0 without any medium effects
- R_{AA} gets **smaller** and v_2 gets **larger** as there are more interactions with medium

ATLAS detector

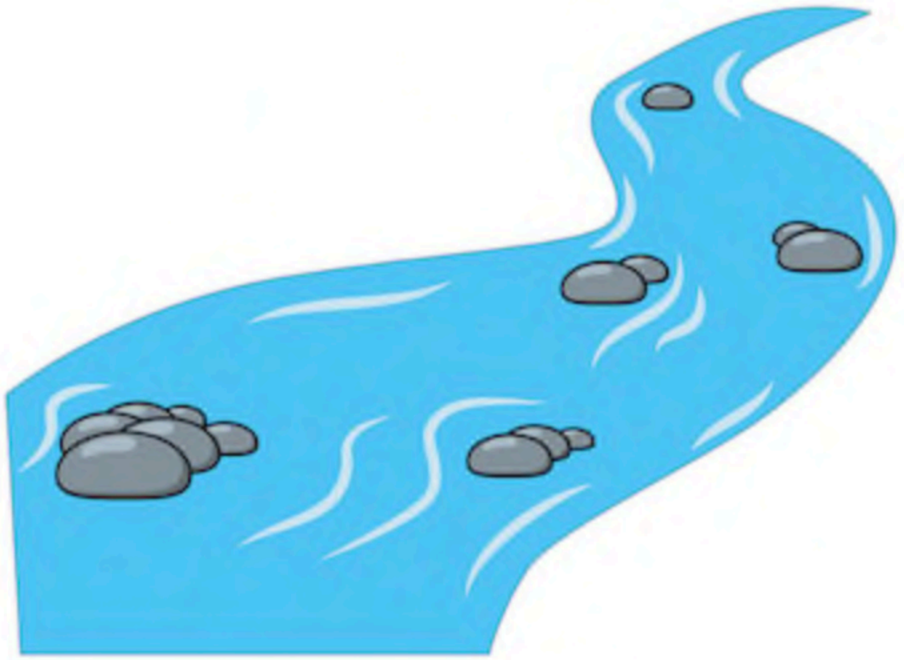


Muon Spectrometer (MS)
|η| < 2.7

Inner Detector (ID)
|η| < 2.5

Forward Calorimeter (FCal)
3.1 < |η| < 4.9

HF muons flow
in Pb+Pb at 5.02 TeV

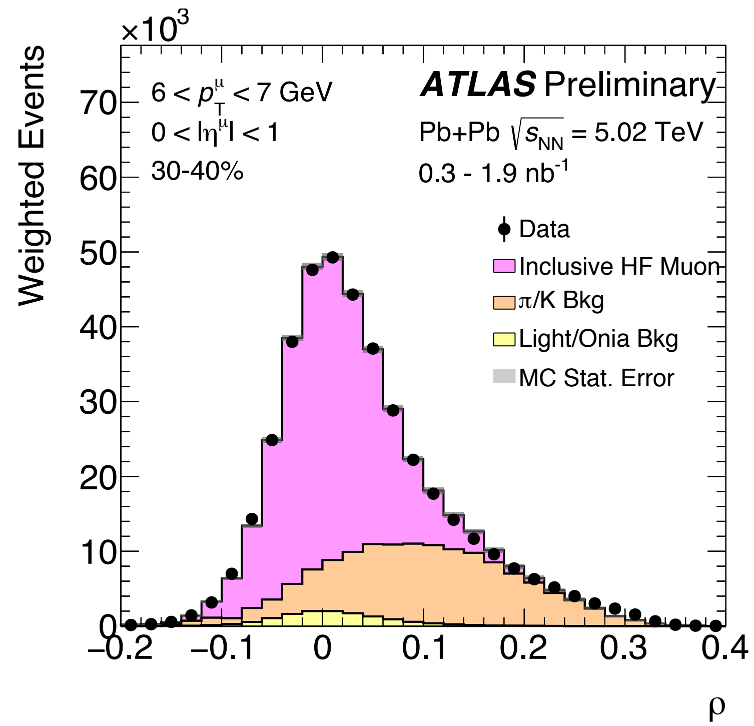


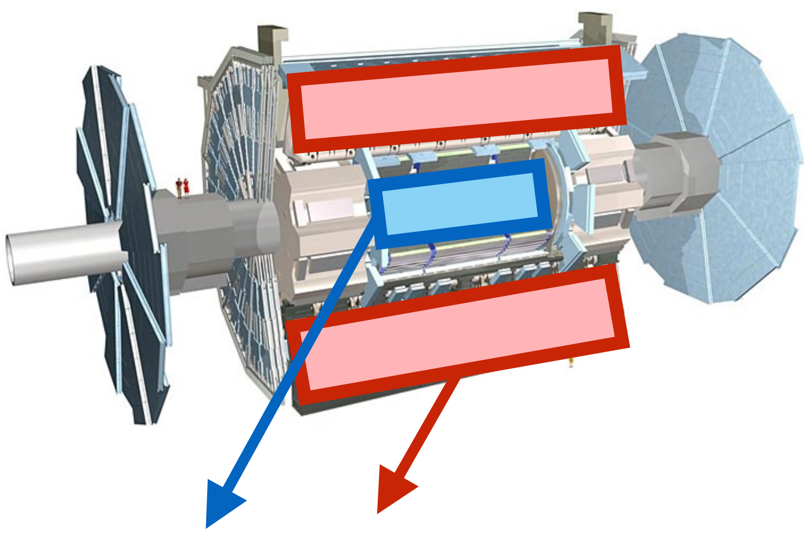
Are heavy quarks too "heavy" to flow with medium?

Template fit to extract signals

ATLAS-CONF-2019-053

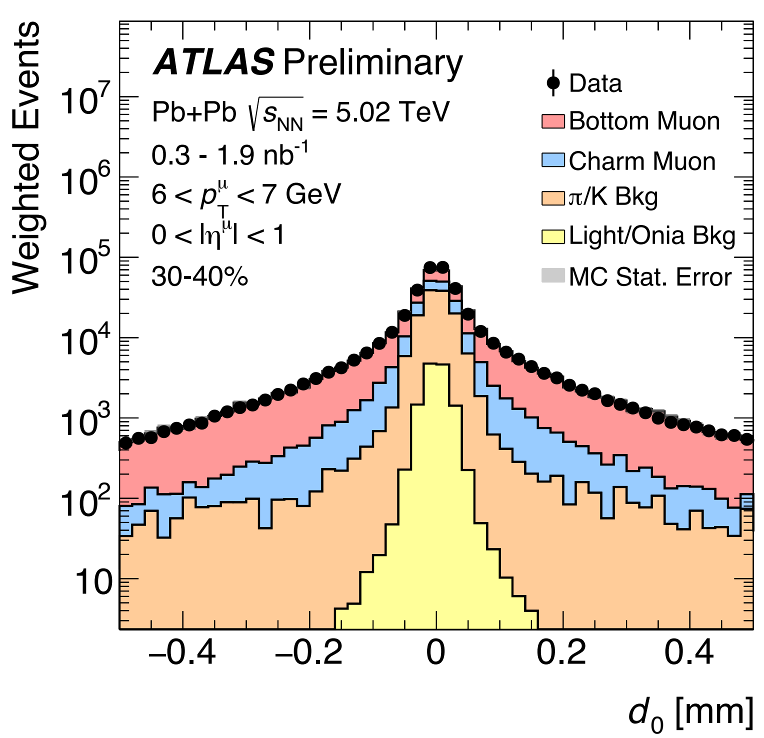
- Momentum imbalance: **Signal** vs. **background**

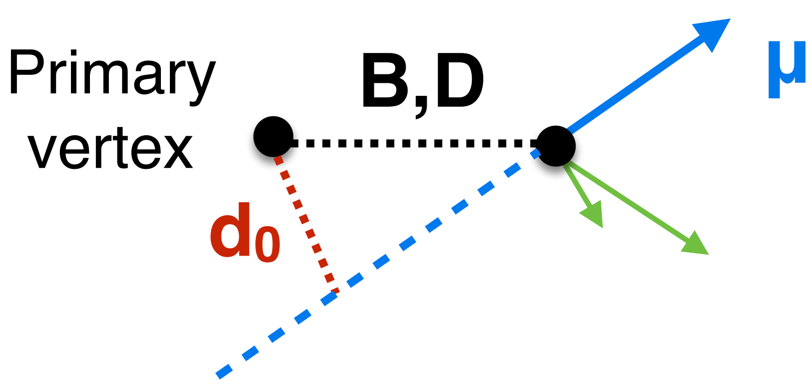




$$\rho = [p_{ID} - (p_{MS} + \Delta p_{CALO})] / p_{ID}$$

- Transverse impact parameter: **charm** vs. **bottom**





Fourier decomposition

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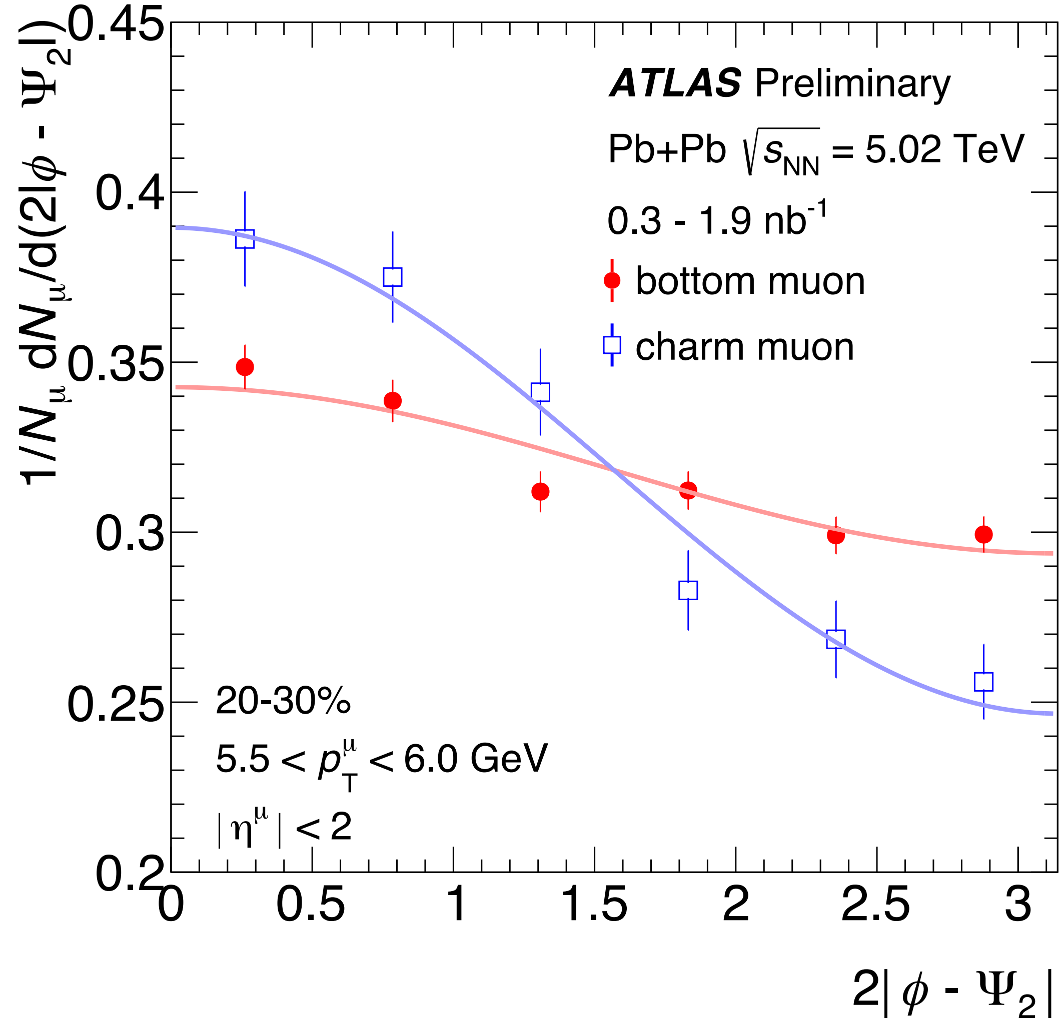
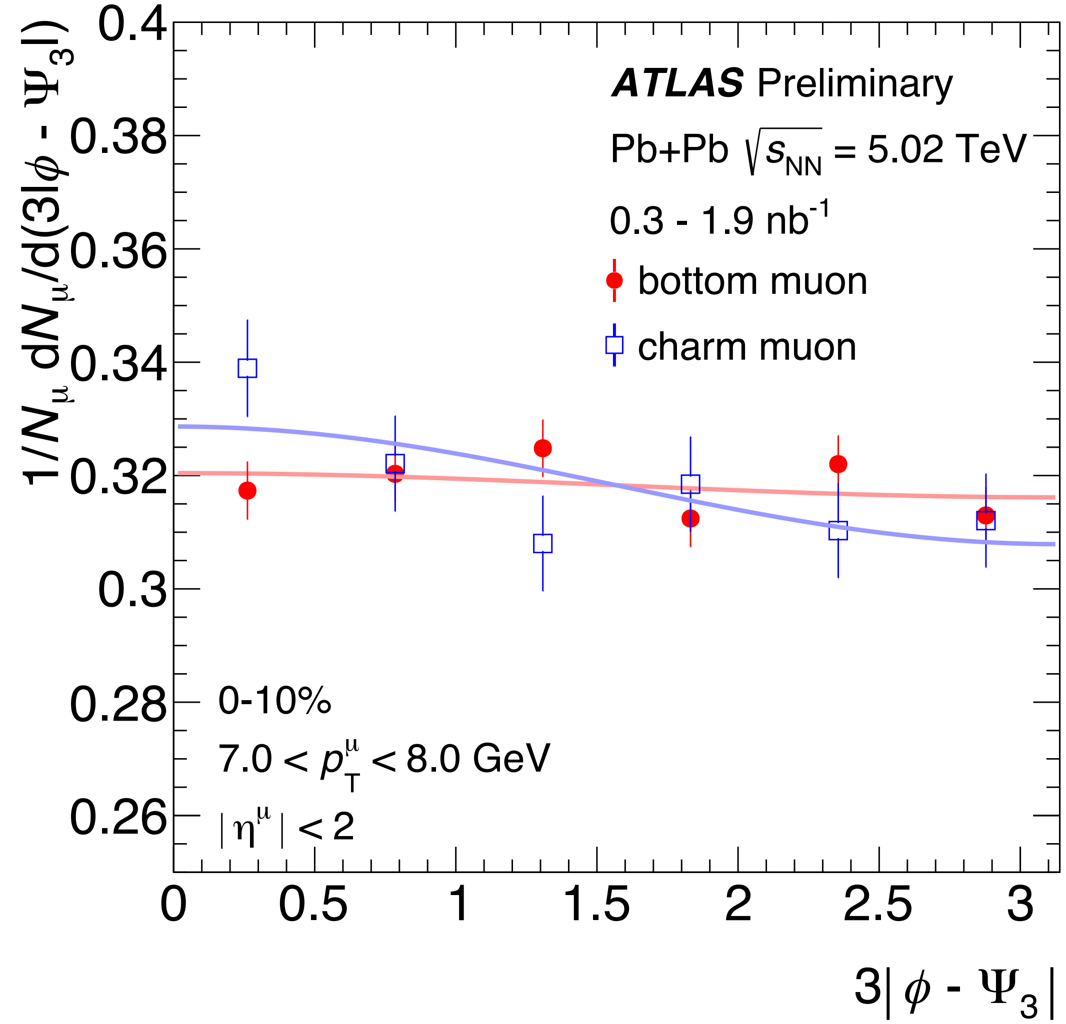
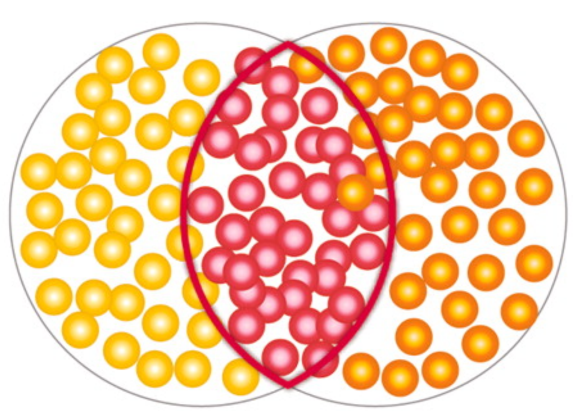
v_2

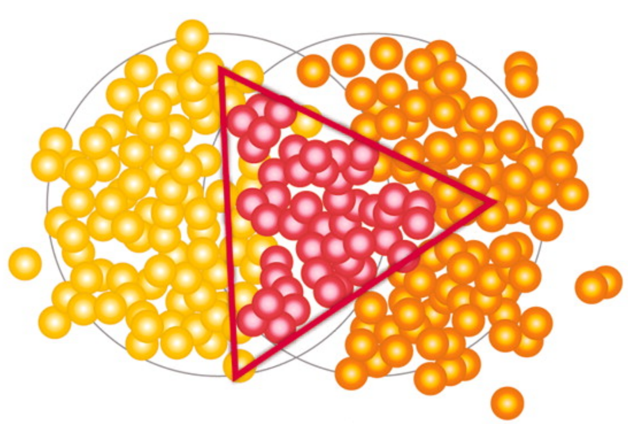


v_3





Elliptic flow



Triangular flow

Charm and bottom v_2

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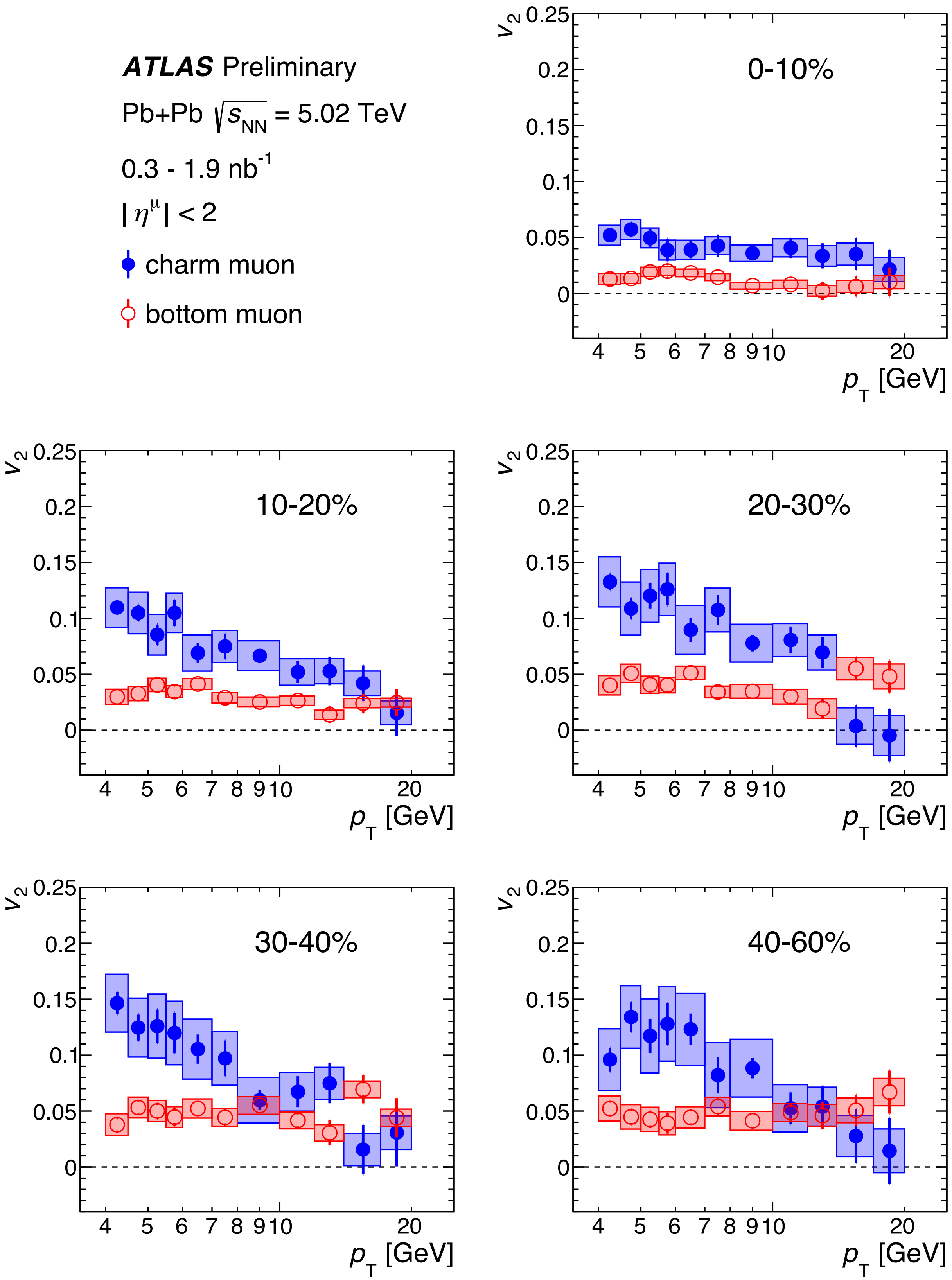

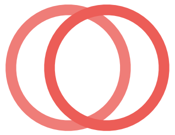

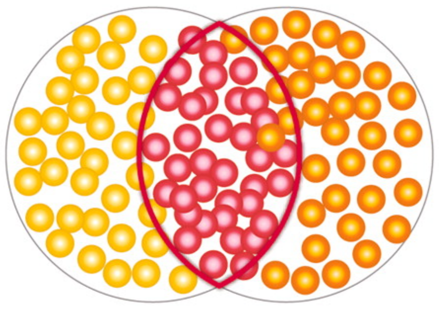

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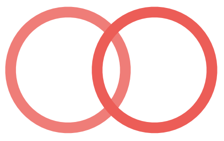

- Non-zero v_2 for both charm and bottom muons
- **charm v_2** > **bottom v_2**

Charm and bottom v_3

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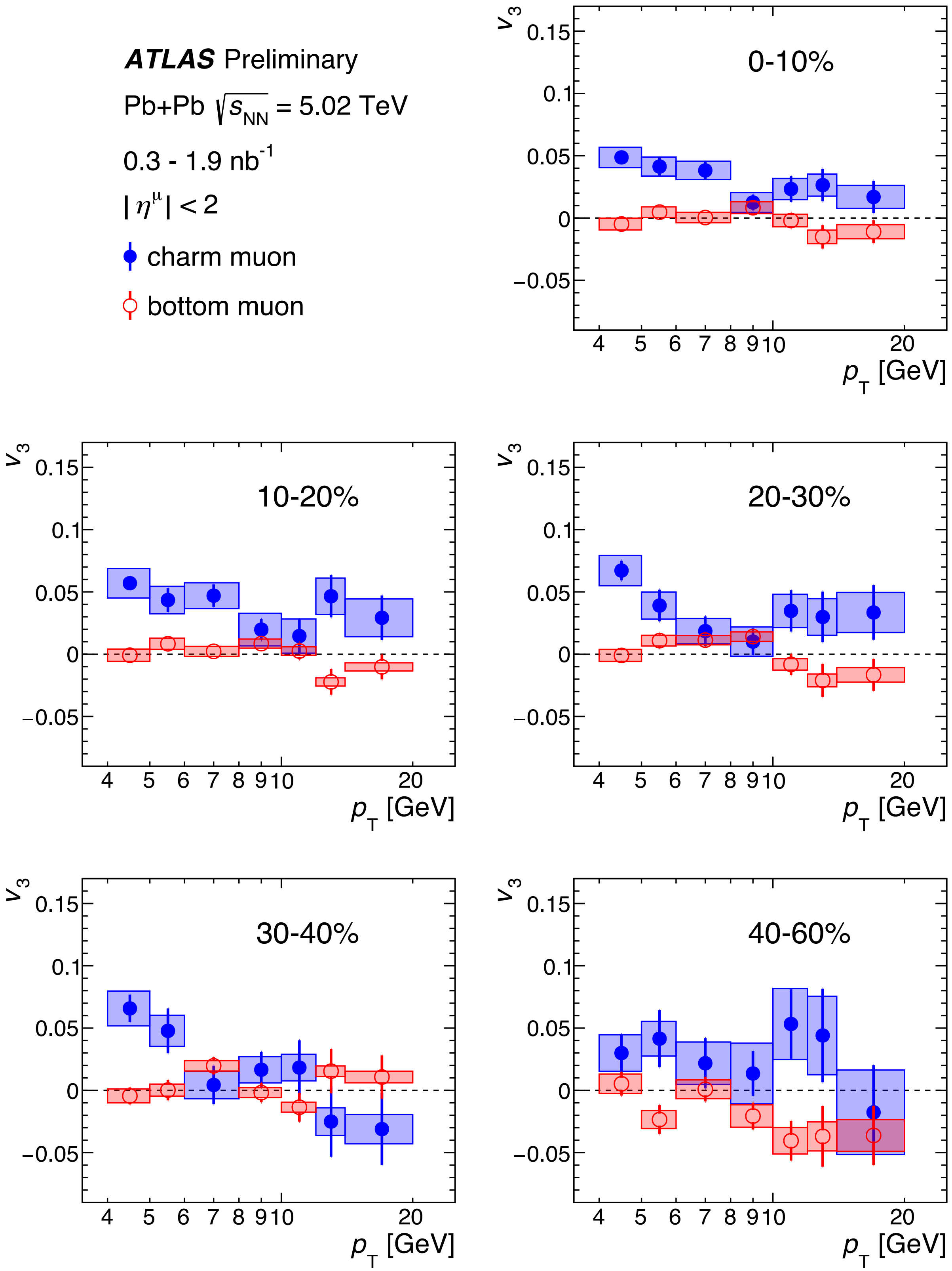

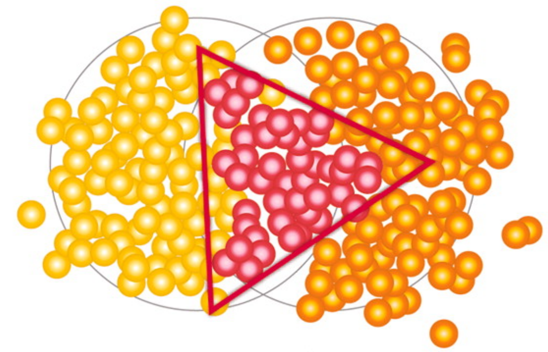

- Non-zero **charm v_3**
- **bottom v_3 ~ 0**
- No clear centrality dependence

Comparison to models

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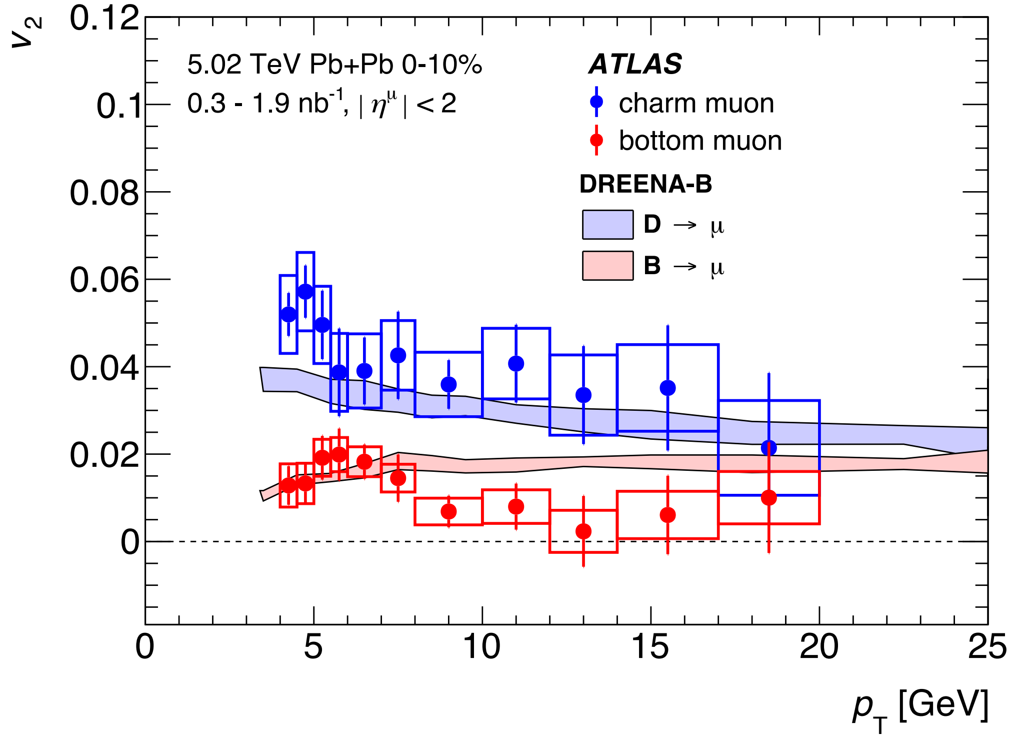
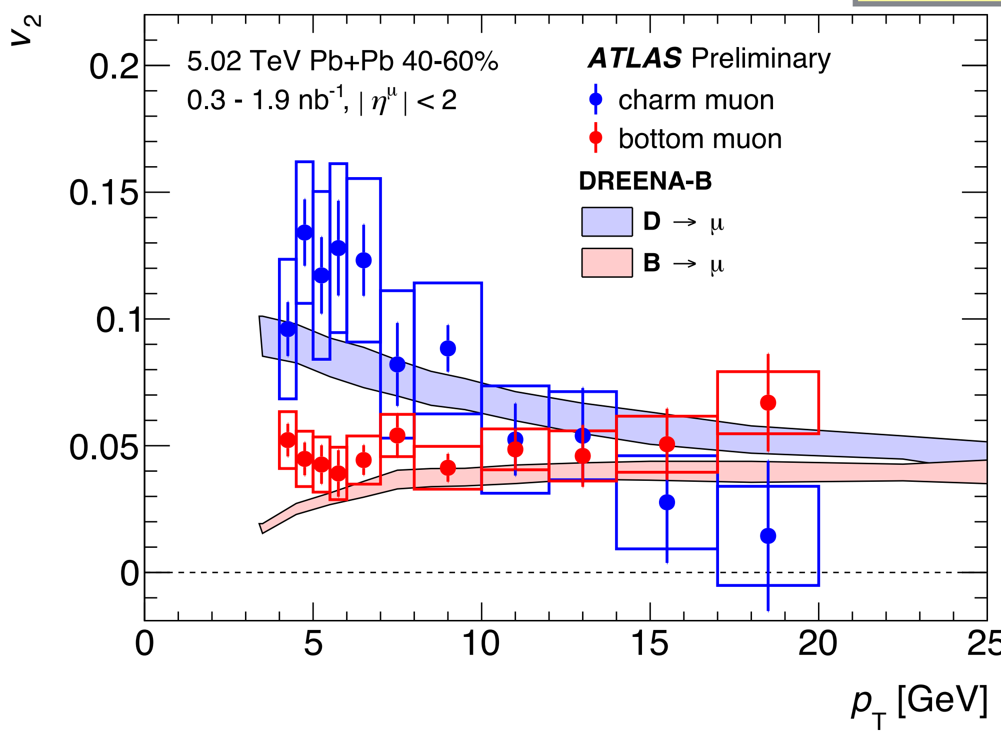
0-10 %



40-60 %

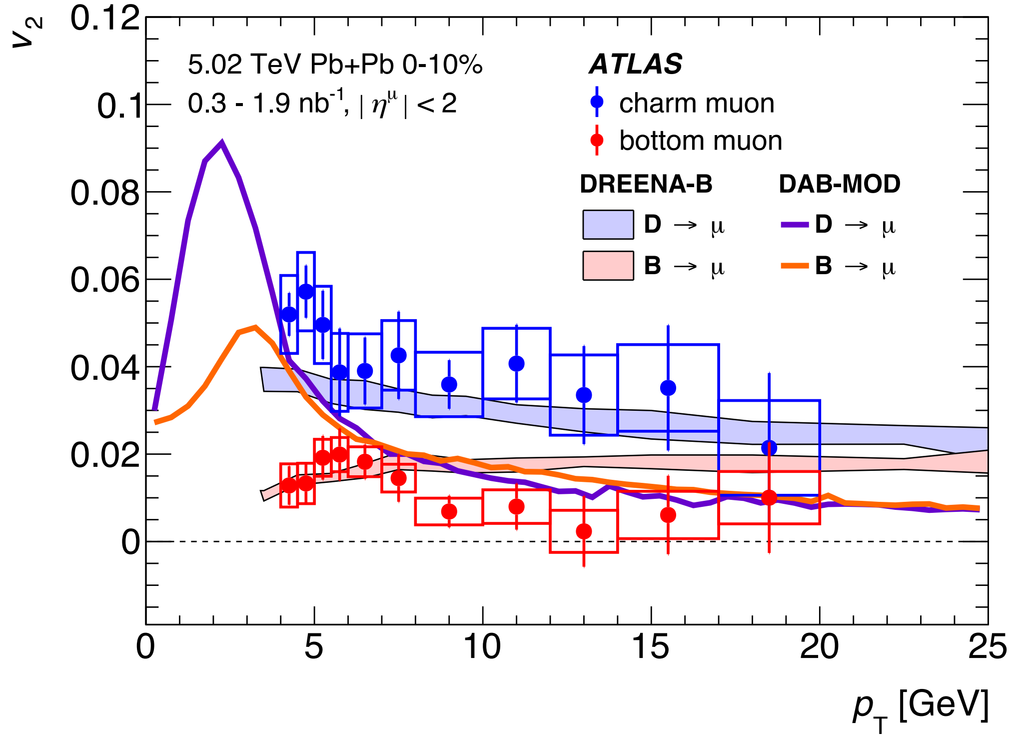


- **DREENA-B** PLB 791 (2019) 236
  - Radiative + collisional energy loss, 1+1D expansion
  - Describes charm and bottom v_2

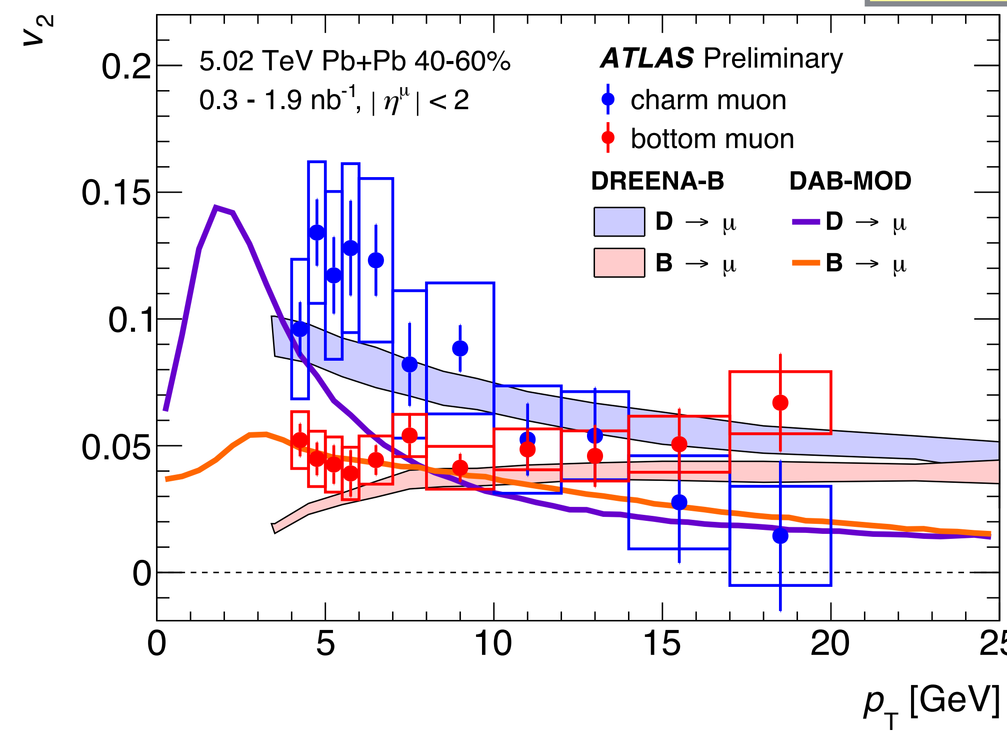
Comparison to models

ATLAS-CONF-2019-053

0-10 %



40-60 %



- **DREENA-B** PLB 791 (2019) 236
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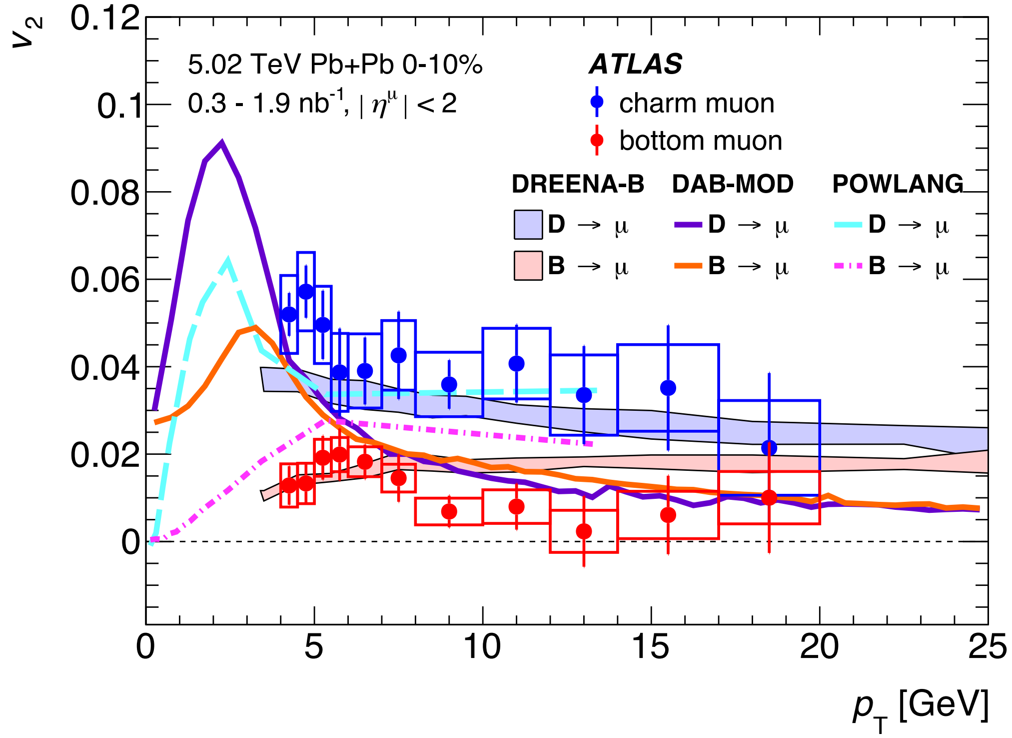
- **DAB-MOD** arXiv:1906.10768
  - Langevin dynamics with $D_s(2\pi T)$ = 2.23 and 2.79, no energy loss, 2+1D expansion
  - Underestimates charm v_2

Comparison to models

ATLAS-CONF-2019-053

0-10 %



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  - Underestimates charm v_2
- **PWOLANG** JHEP 02 (2018) 043
  - Langevin dynamics with $D_s(2\pi T)$ = 3, collisional energy loss, 2+1D expansion
  - Overpredicts bottom v_2

Radiative energy loss is playing an important role?

Comparison with CMS D^0

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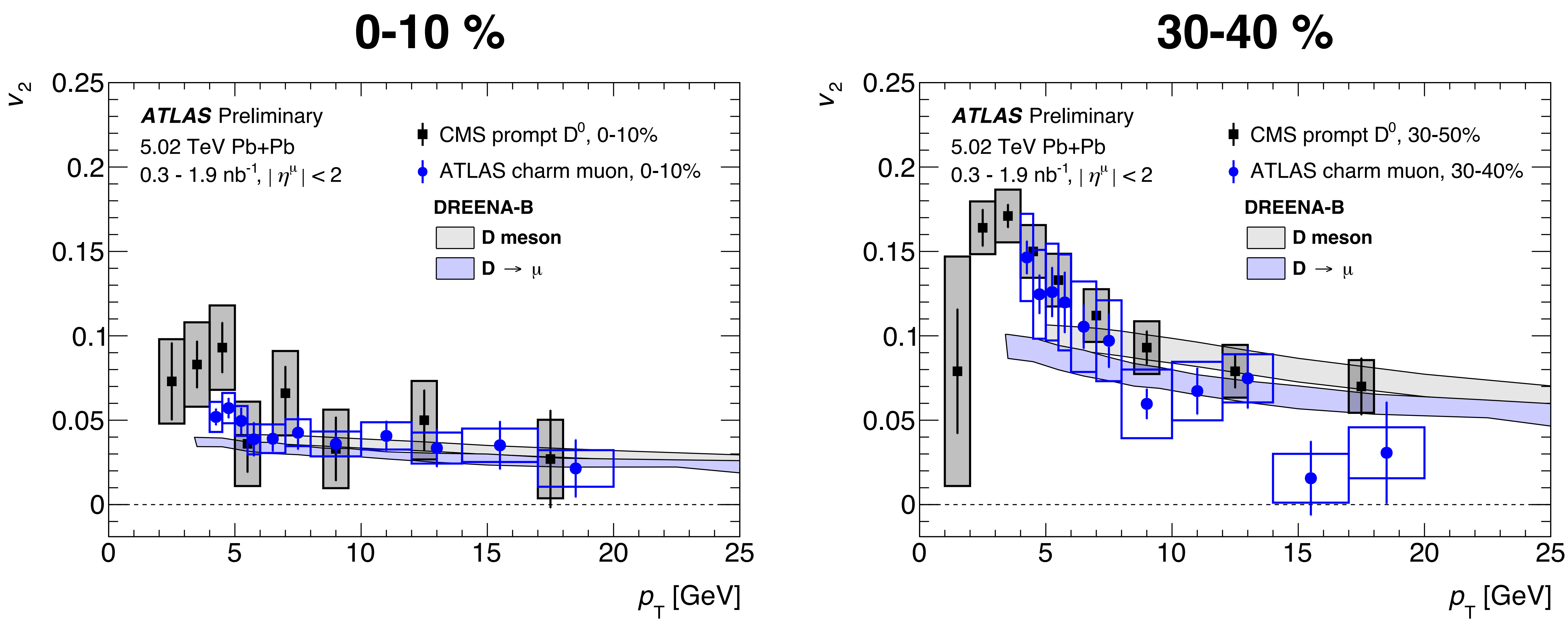
CMS: PRL 120 (2018) 202301



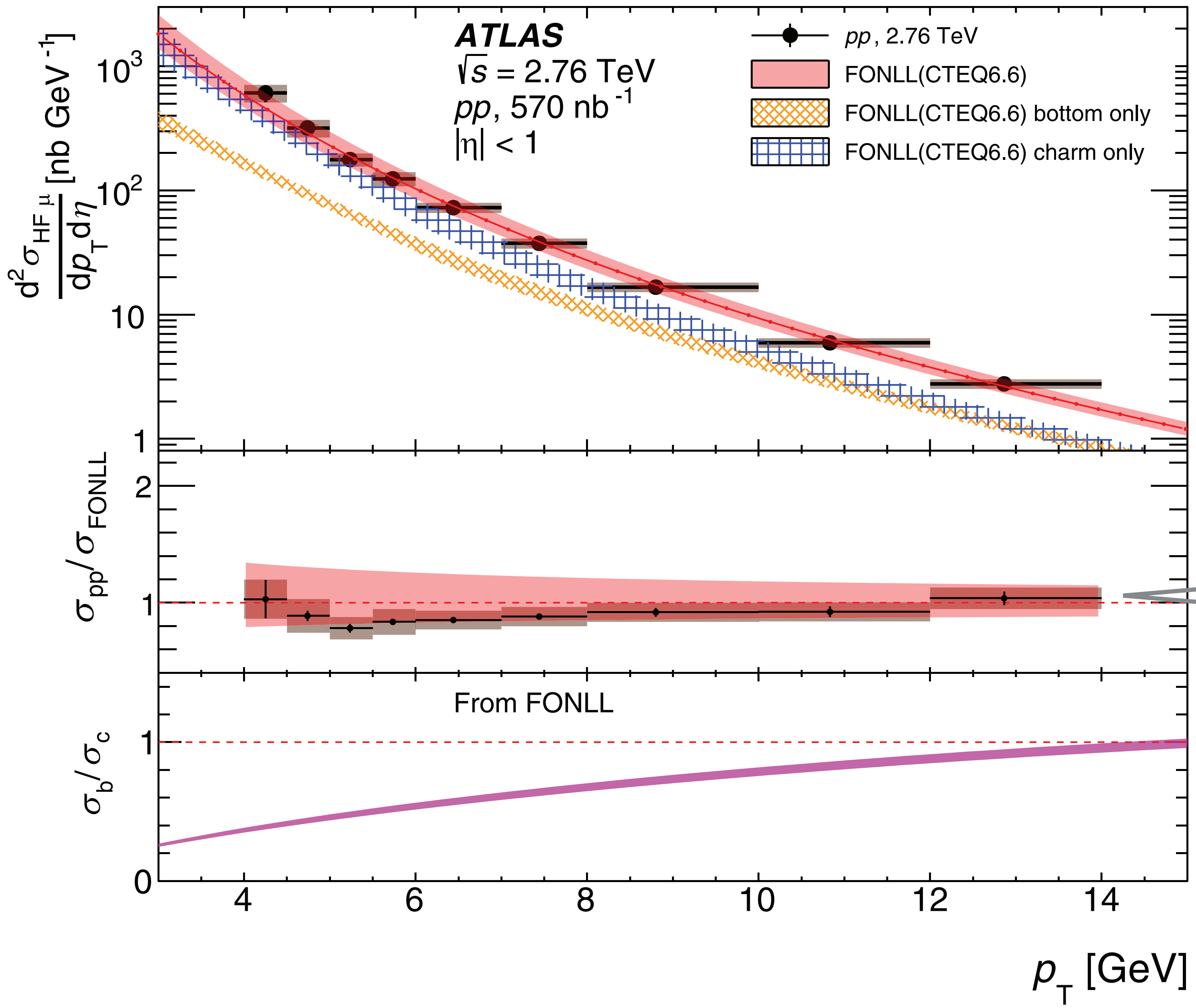
- Results agree with each other (N.B. a shift downward in p_T for HF muons)
- Charm muons give a better precision compared to D mesons

HF muons R_{AA}
in Pb+Pb at 2.76 TeV

Ok, heavy quarks interact with medium.
What about their yields?

pp cross-sections as a baseline

PRC 98 (2018) 044905



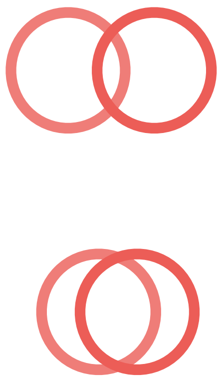
FONLL uncertainties

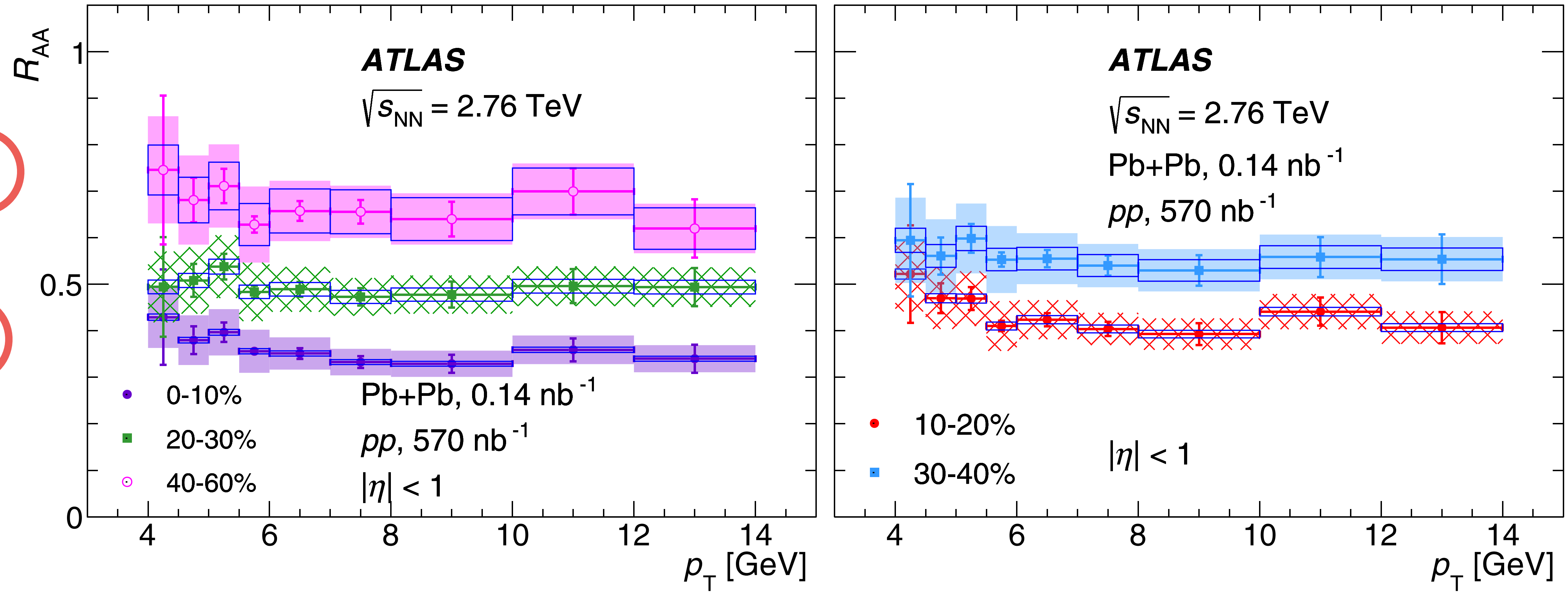
- Renormalisation and factorization scale (~35% at low p_T)
- Heavy quark mass (~9% at low p_T)
- PDF-related (< 8%)
- Value of α_s (~1%)
- Fragmentation function (< 5%)

- Inclusive cross section without separating charm and bottom muons
- pp cross-section agrees with the FONLL calculations using CTEQ6.6 PDFs
- Relative contributions of b quark increases monotonically with muon p_T

HF muons R_{AA} vs. p_T

PRC 98 (2018) 044905

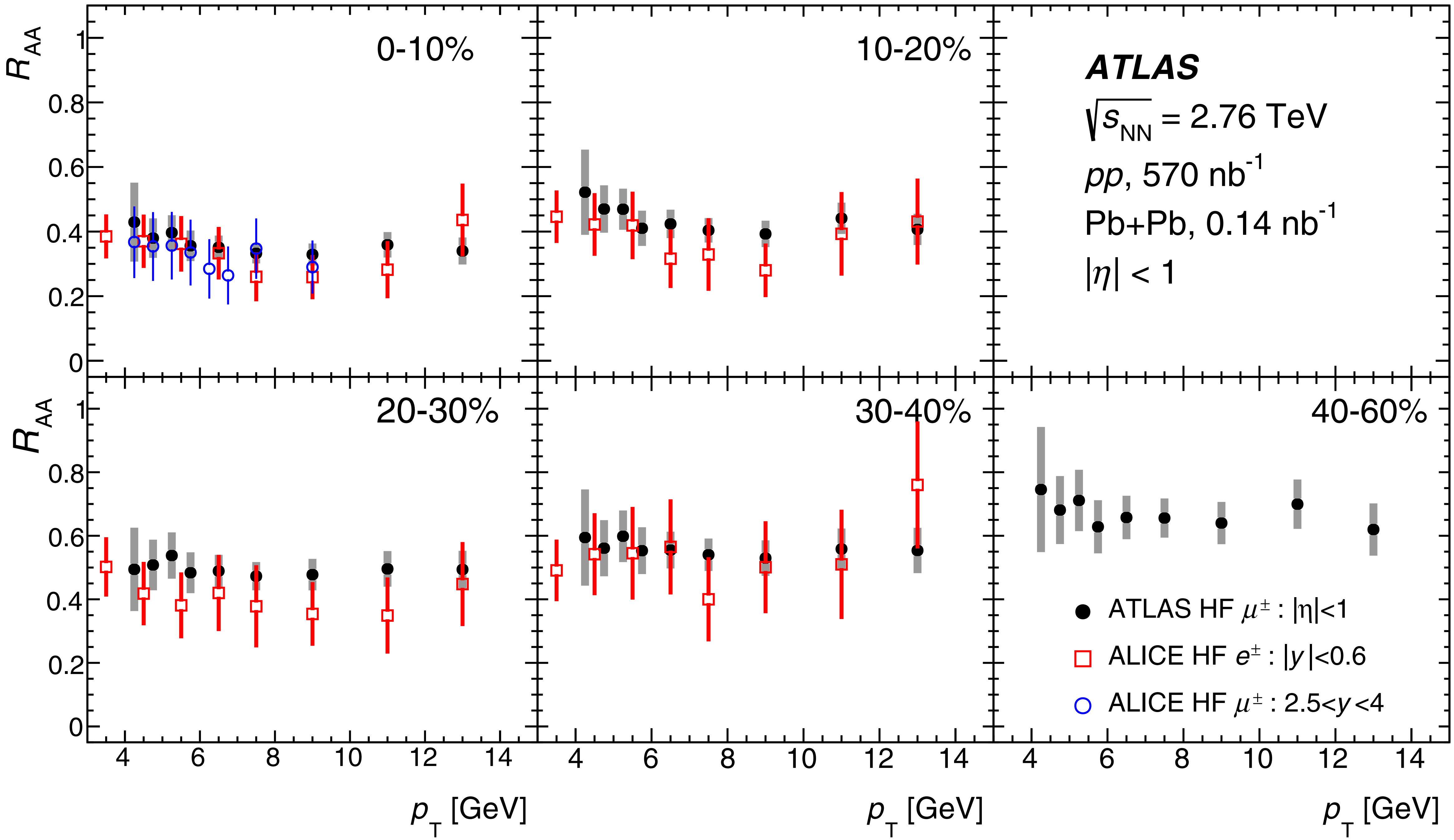




- Clear centrality dependence (R_{AA}~ 0.35 at most central 0-10%)
- No p_T dependence within uncertainties
  - Suppression of charm and bottom is expected to be different
  - Contribution of charm and bottom to cross-sections changes with p_T in pp

Comparison with ALICE

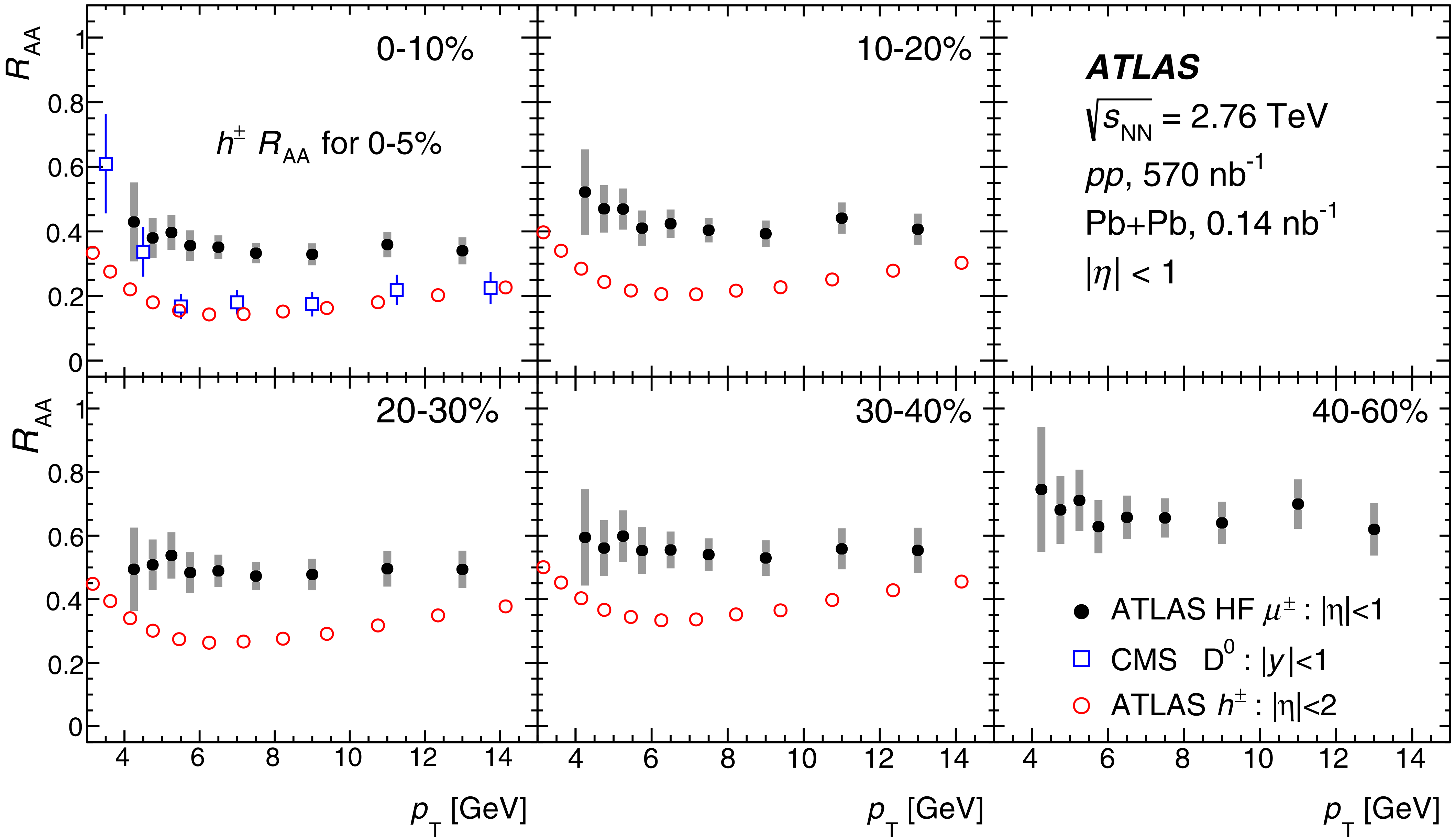
PRC 98 (2018) 044905



- Results are consistent with each other

HF muons vs. D^0 vs. hadrons

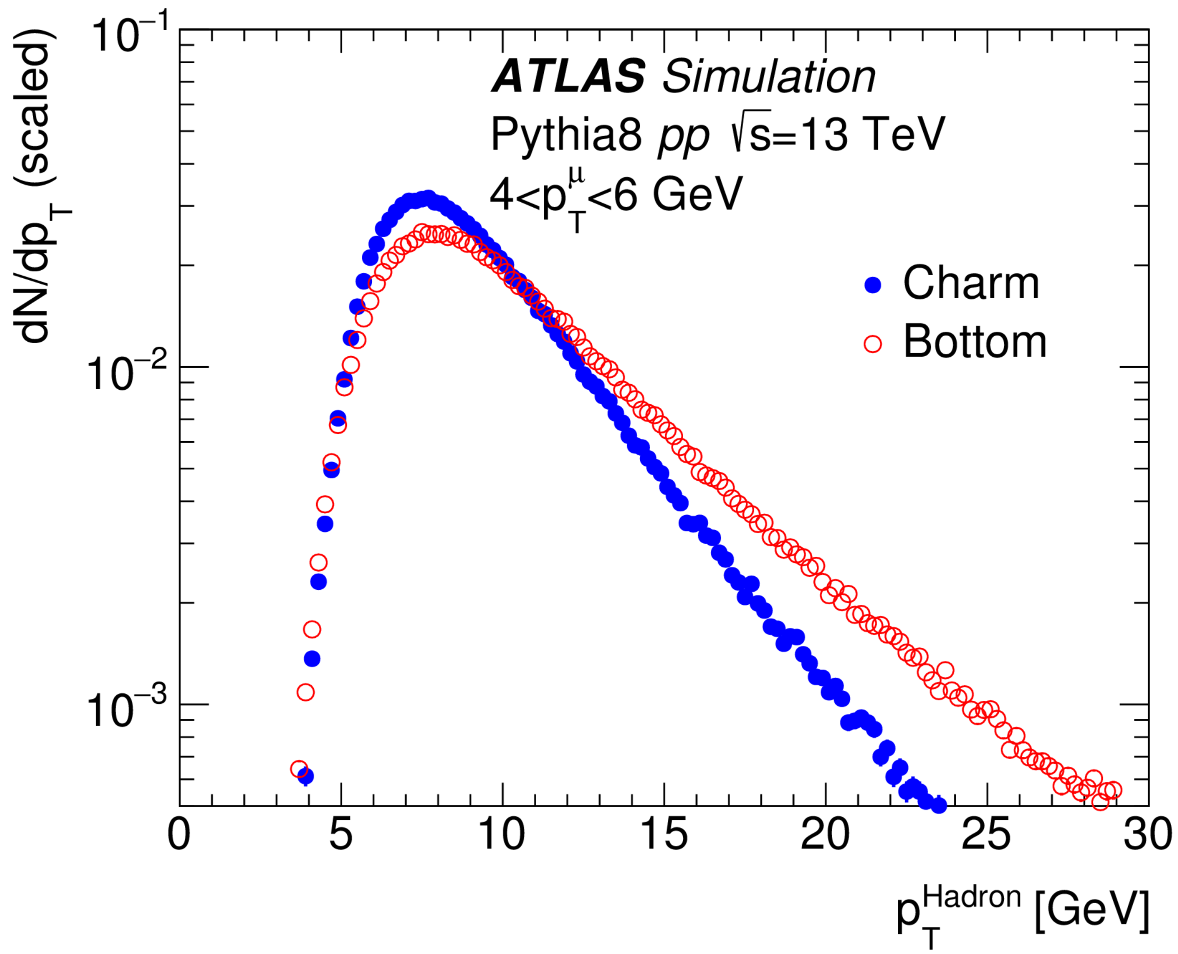
PRC 98 (2018) 044905



- D^0 R_{AA} (**c quarks**) is similar to hadrons R_{AA} (**light quarks**) at $p_T > 5$ GeV
- Heavy-flavor muons (**c + b quarks**) R_{AA} is larger than hadrons R_{AA}
  - Implies less suppression for muons from bottoms

HF muons vs. D^0 vs. hadrons

PRC 98 (2018) 044905



- Note that decay muons p_T is lower than hadrons p_T

p_T [GeV] p_T [GeV] p_T [GeV]

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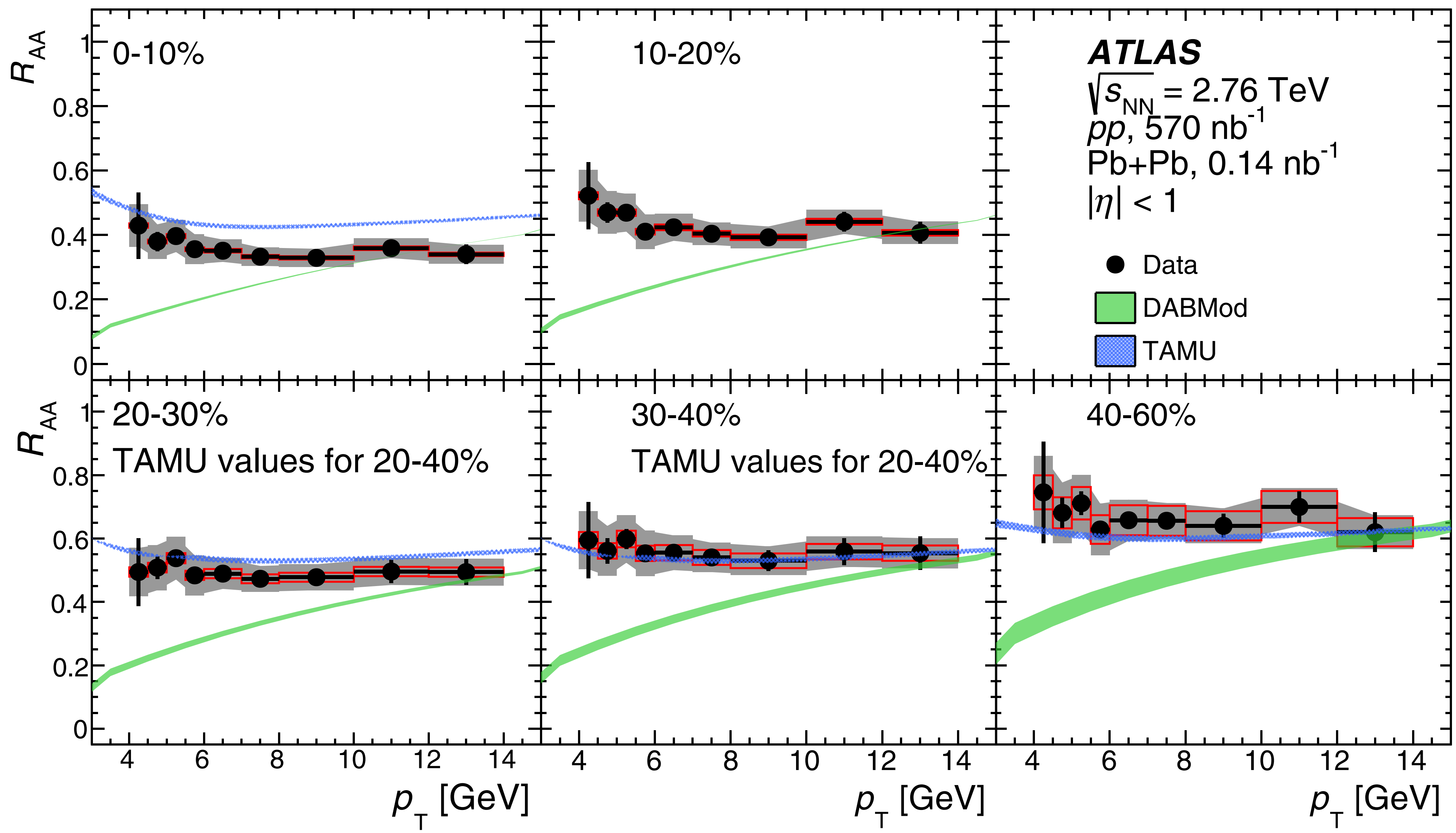
Comparison to models

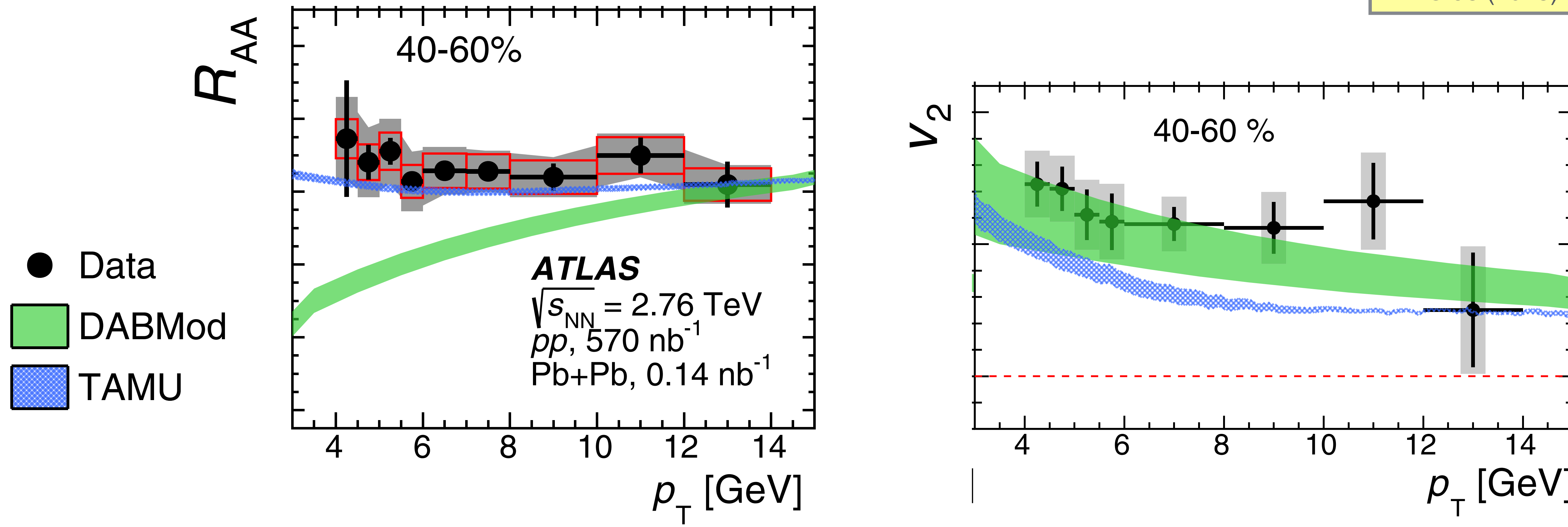
PRC 98 (2018) 044905



- **TAMU** PLB 735 (2014) 445
    - Describes many features of the data well
- **DABMod** PRC 96 (2017) 064903
    - Only reproduces p_T > 12 GeV

R_{AA} vs. v_2

PRC 98 (2018) 044905



- **TAMU** PLB 735 (2014) 445
  - describes the suppression well but underestimate flow
- **DABMod** PRC 96 (2017) 064903
  - matches flow results well but overestimate the suppression at low p_T
  - Event-by-event fluctuations are expected to increases v_2

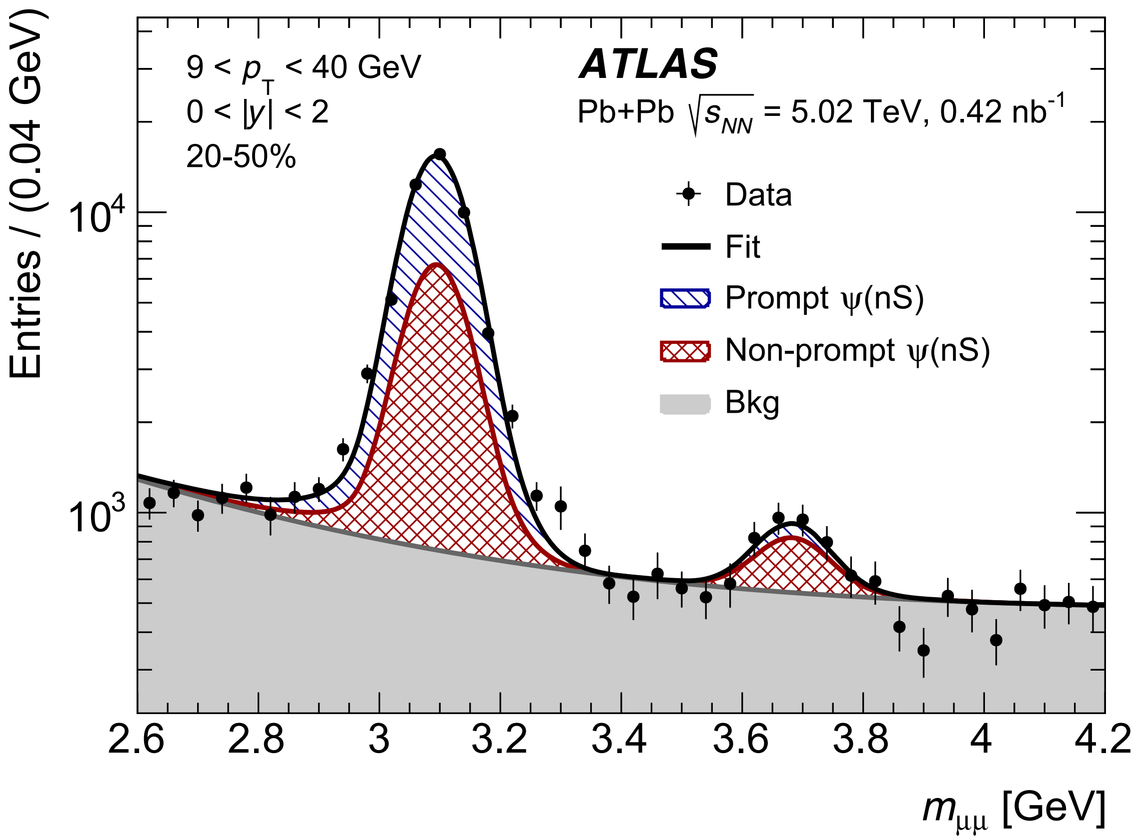
A simultaneous description of R_{AA} and v_2 is challenging!

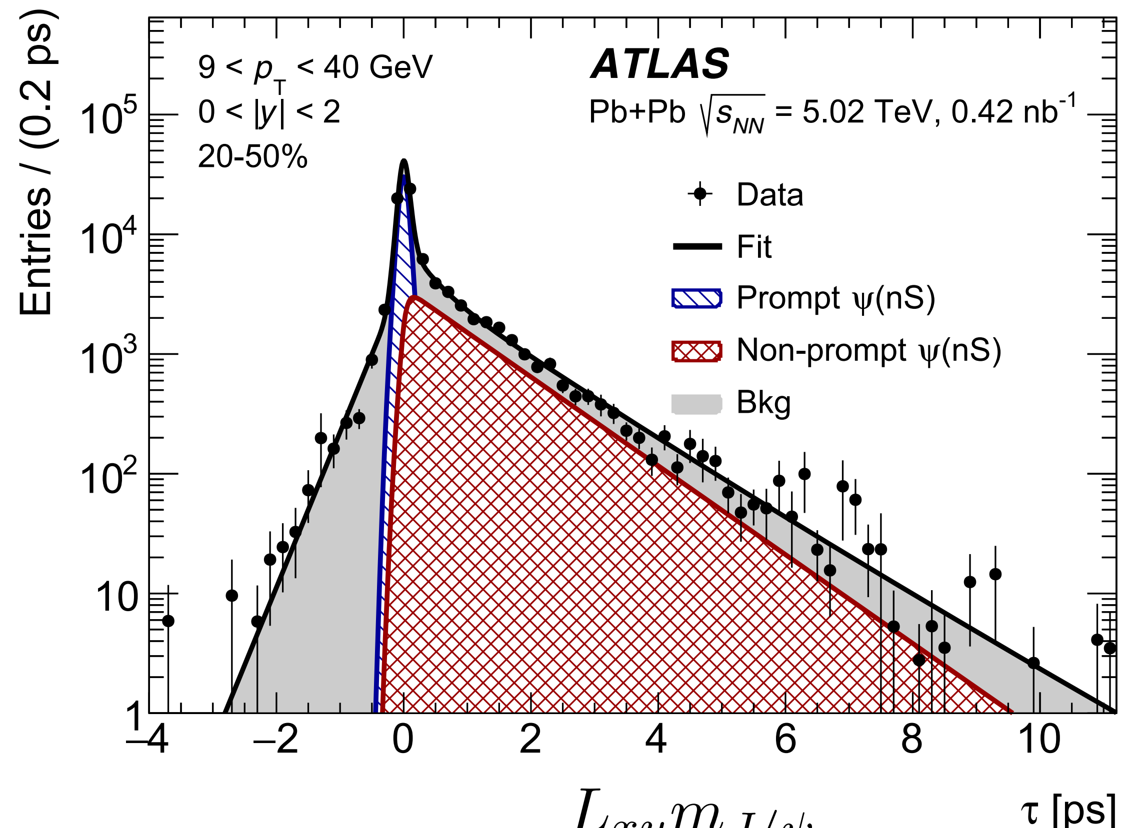
Nonprompt J/ψ R_{AA} and flow in Pb+Pb at 5.02 TeV

An indirect way of investigating bottom quarks!

Prompt vs. nonprompt J/ψ

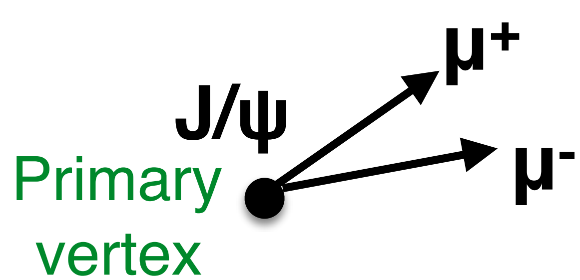
EPJC 78 (2018) 762

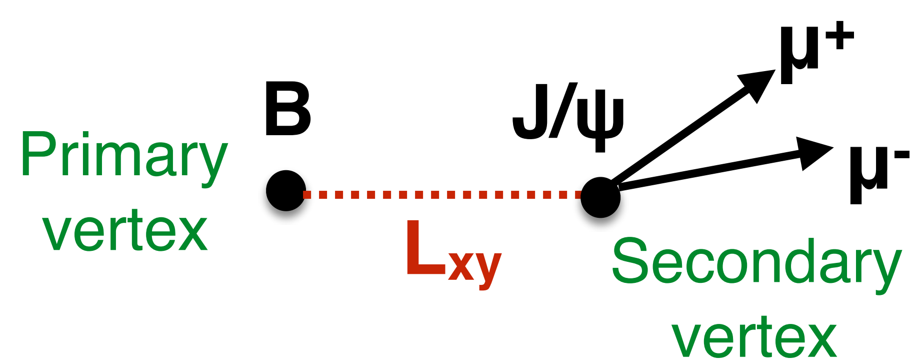




$$\tau_{\mu\mu} = \frac{L_{xy} m_{J/\psi}}{p_{\mathrm{T}}^{\mu\mu}}$$

- Seperation of **prompt** and **nonprompt** using pseudo-proper decay time τ

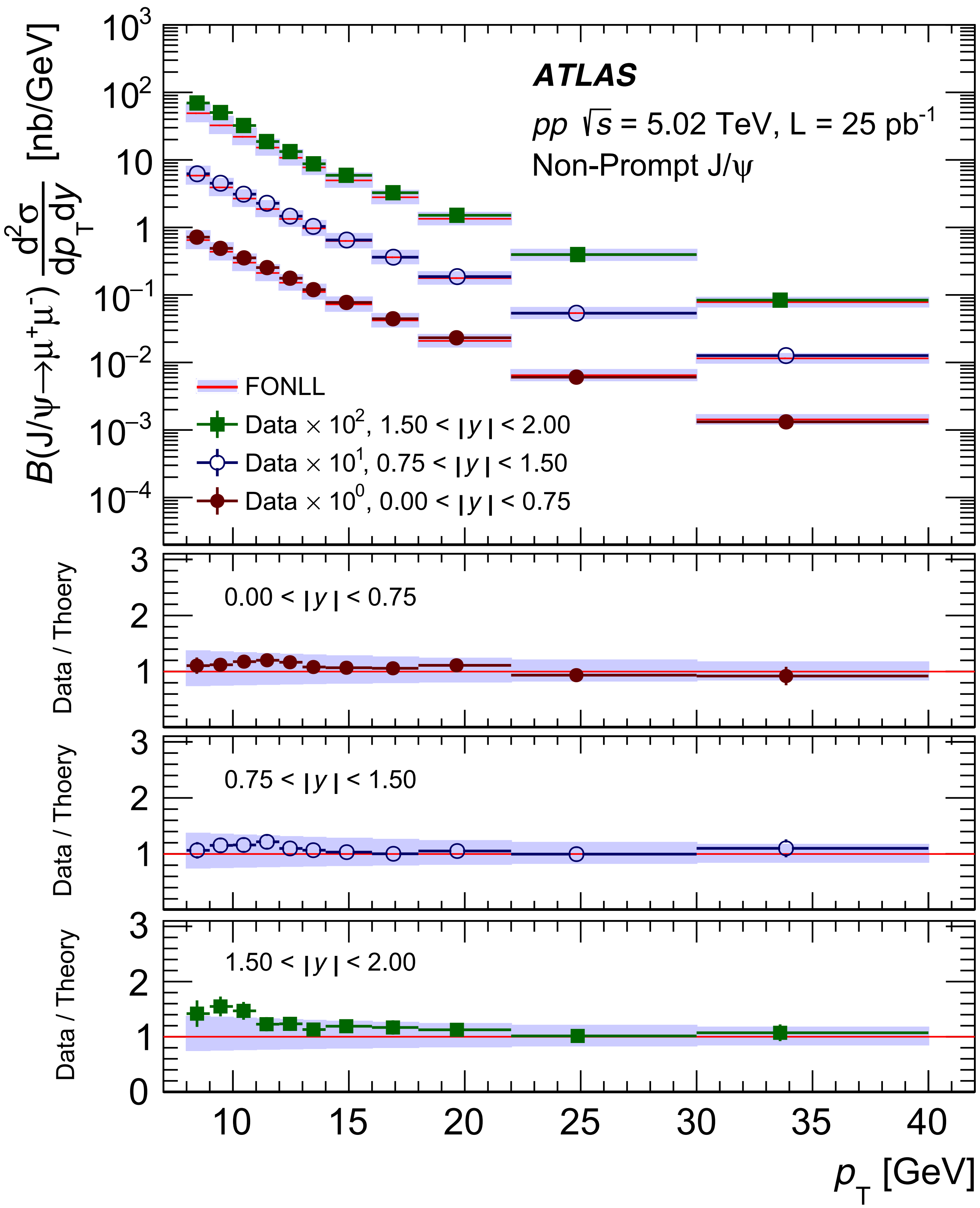




[prompt] **[Nonprompt]**

pp cross-sections as a baseline

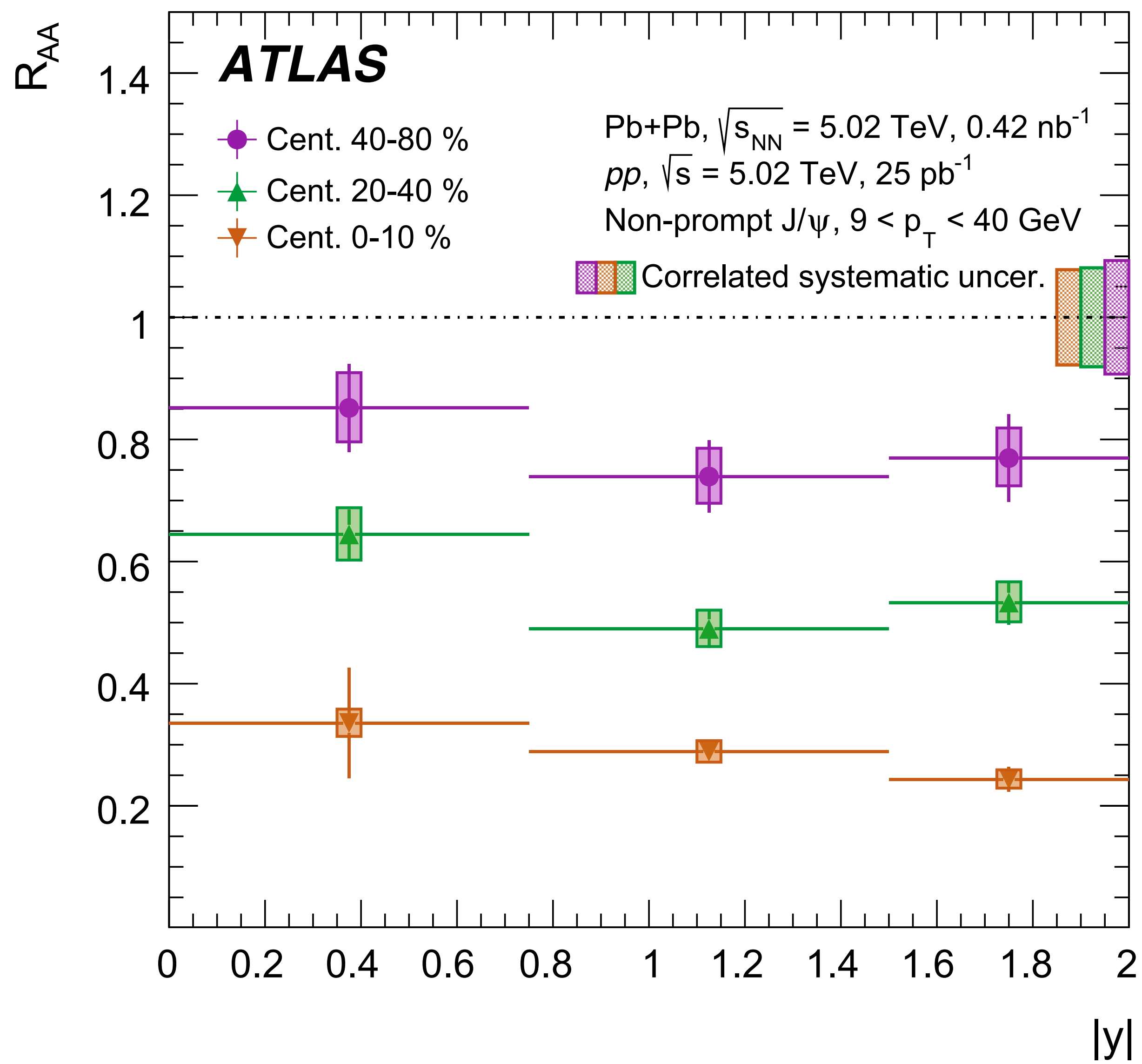
EPJC 78 (2018) 171

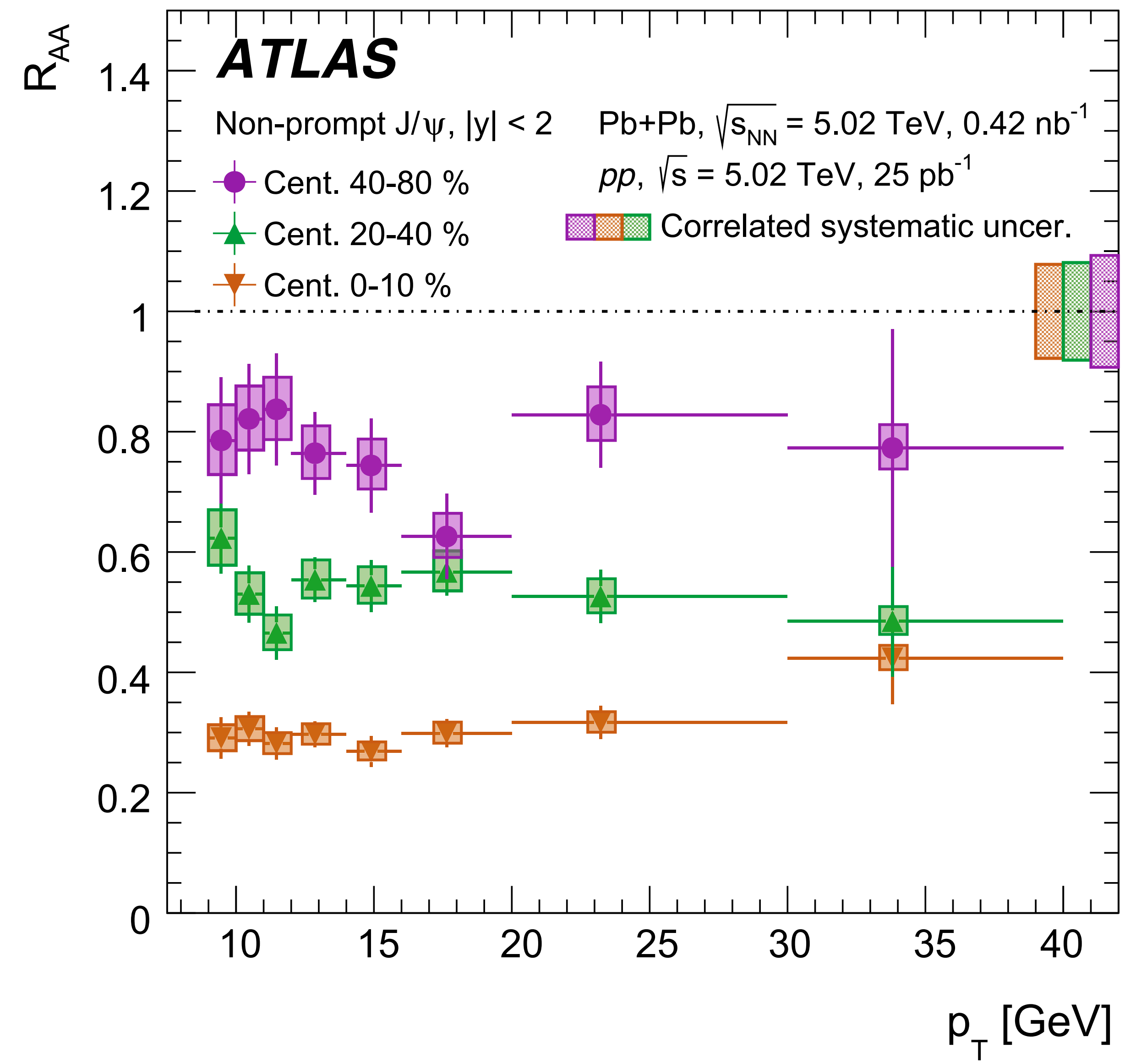


- Good agreements with FONLL predictions over the p_T range

Nonprompt J/ψ R_{AA}

EPJC 78 (2018) 762

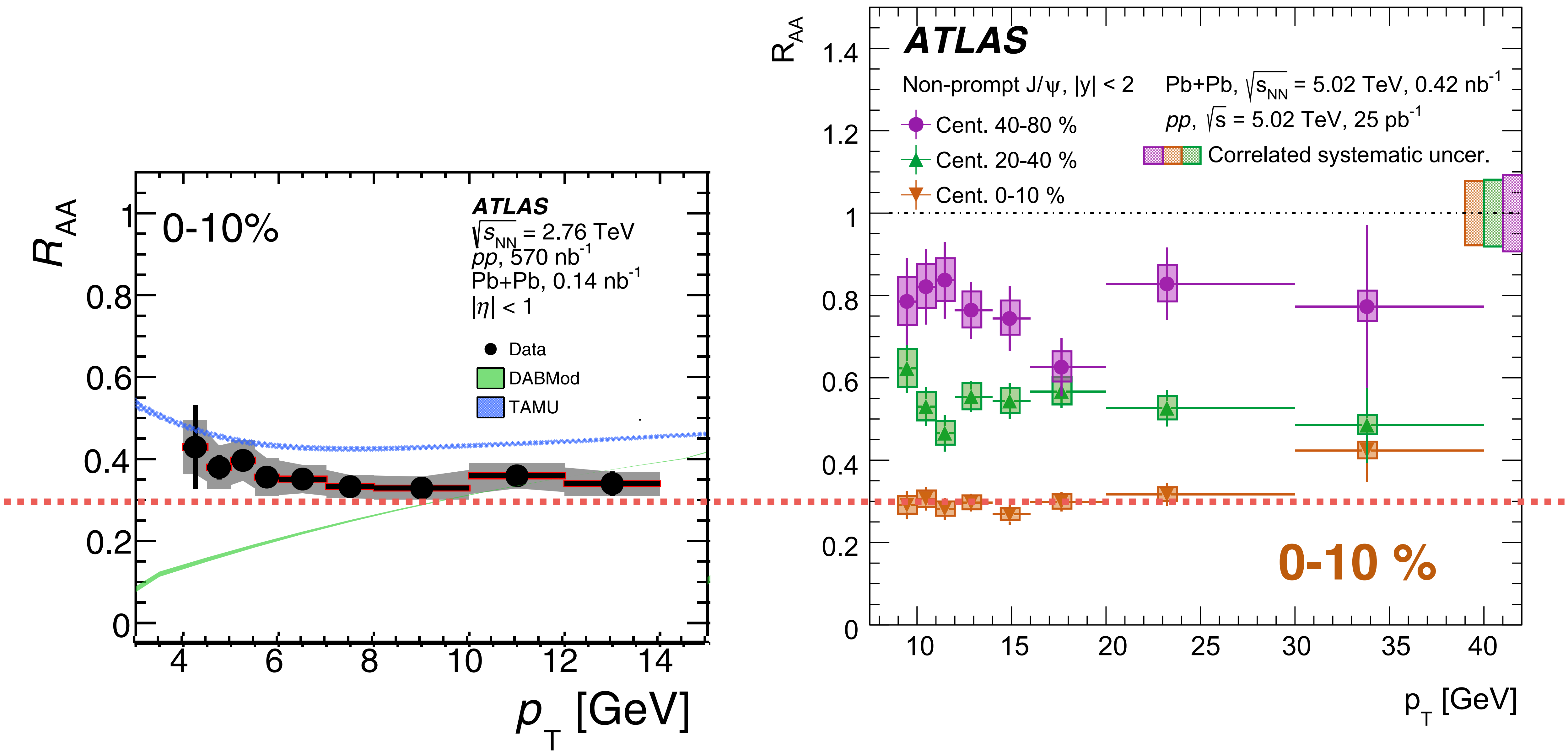




- Stronger suppression for more central collisions
- No clear p_T or rapidity dependence

Nonprompt J/ψ vs. HF muons

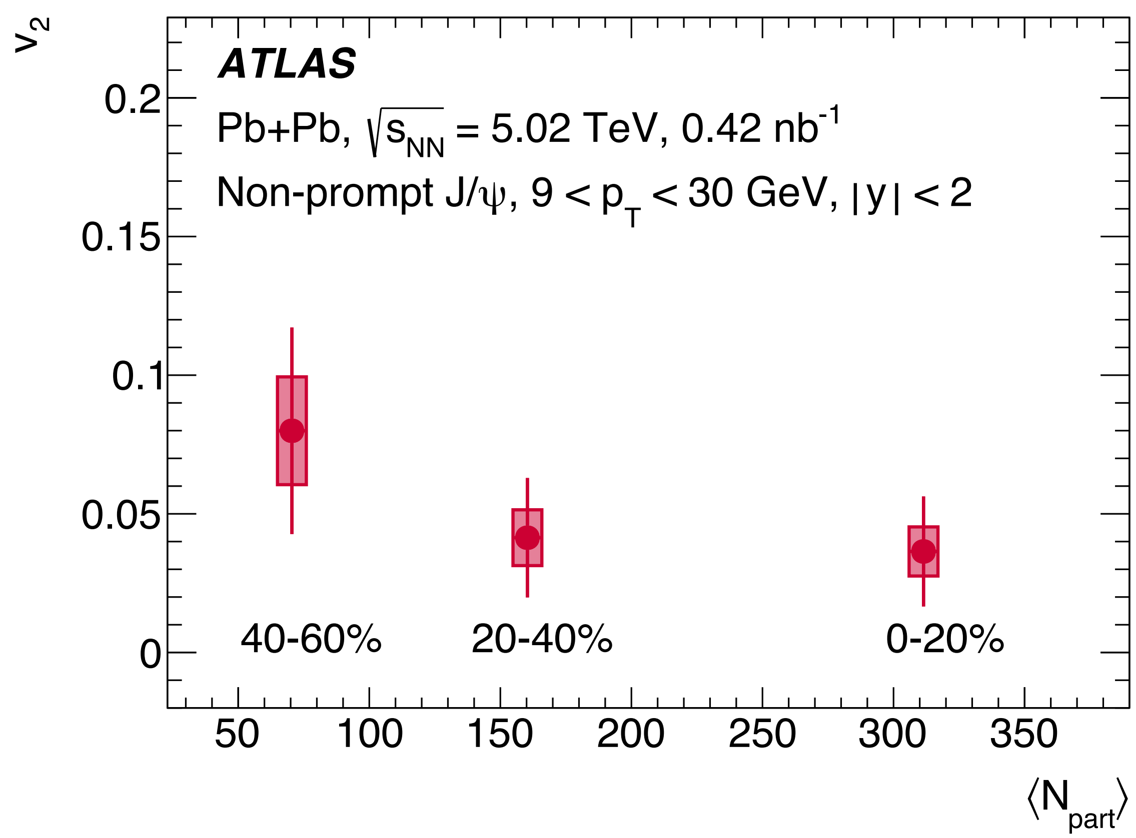
EPJC 78 (2018) 762

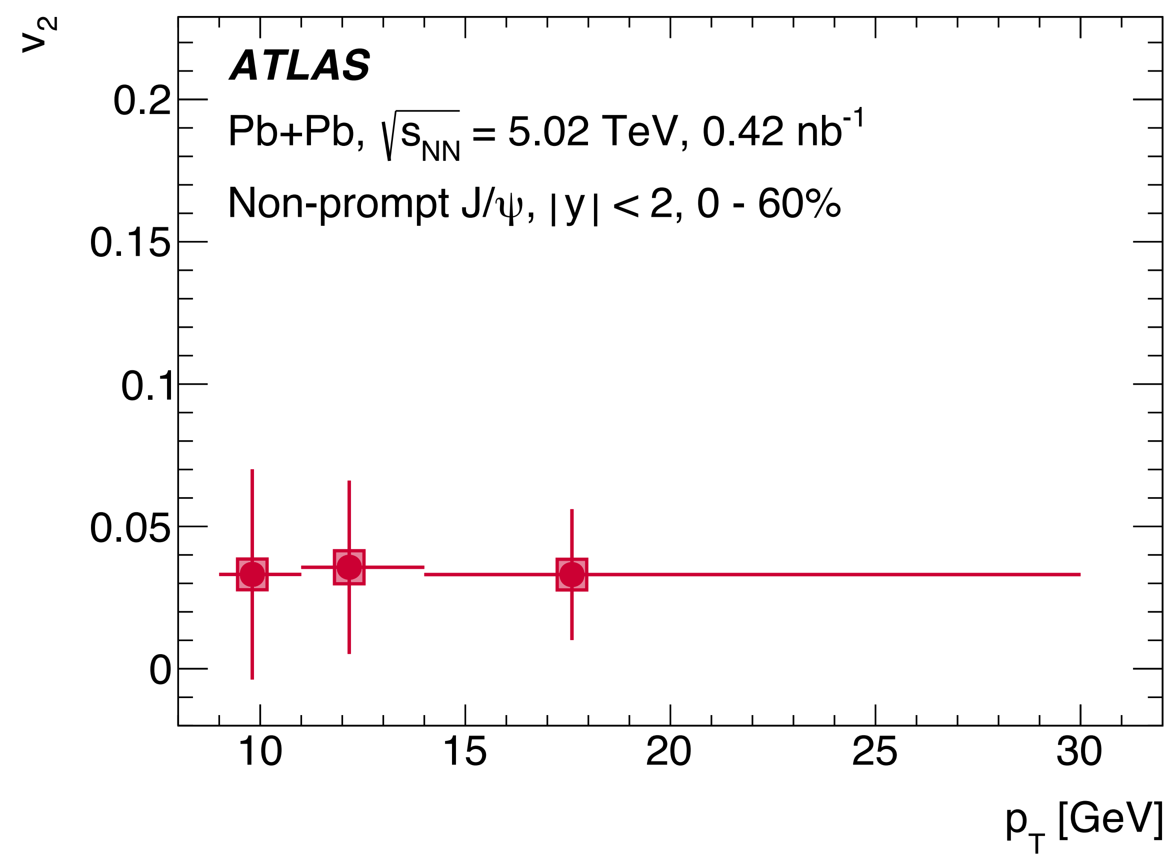


- Similar suppression of inclusive HF and nonprompt J/ψ at $p_T > 9$ GeV

Nonprompt J/ψ v_2

EPJC 78 (2018) 784

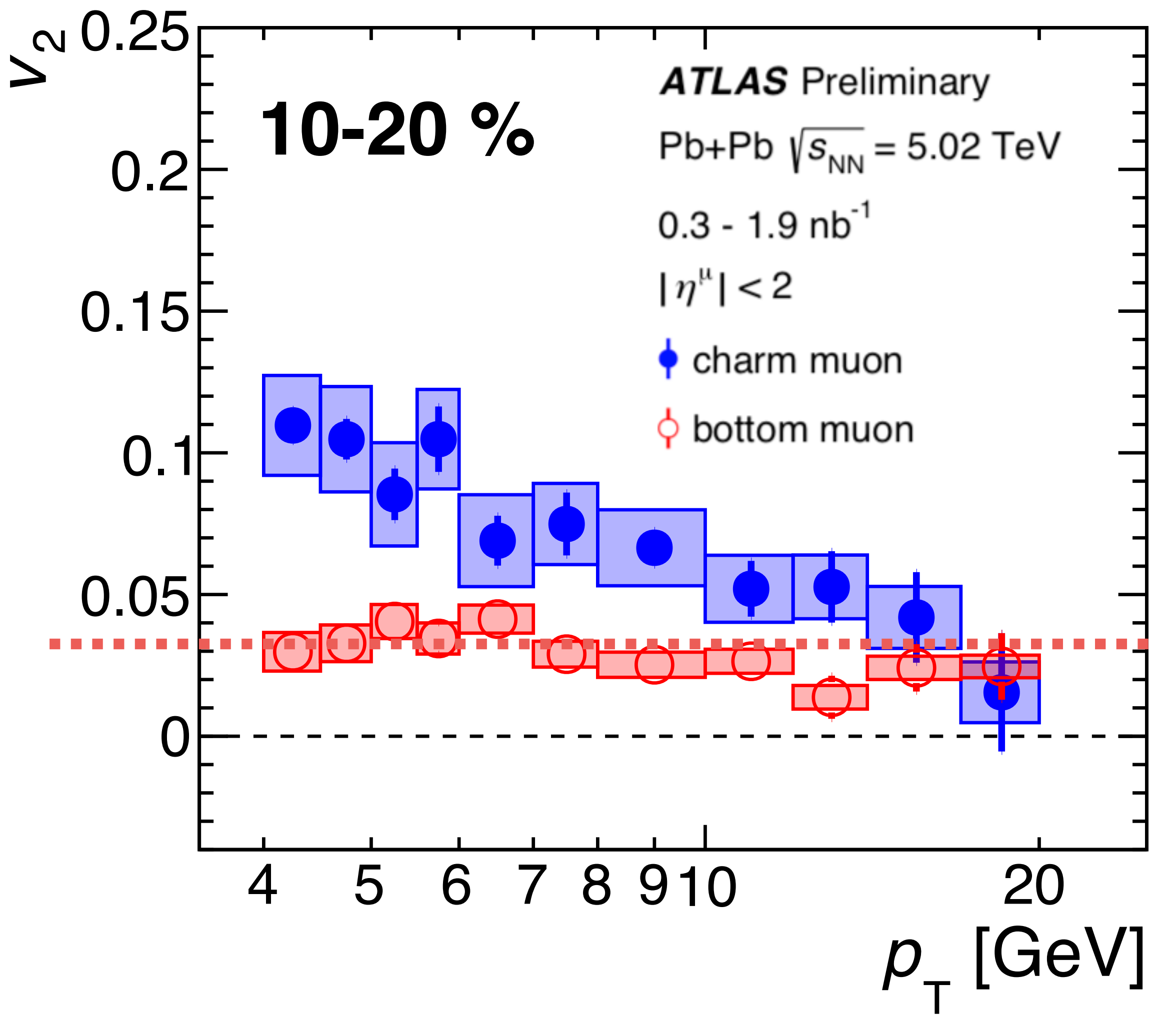


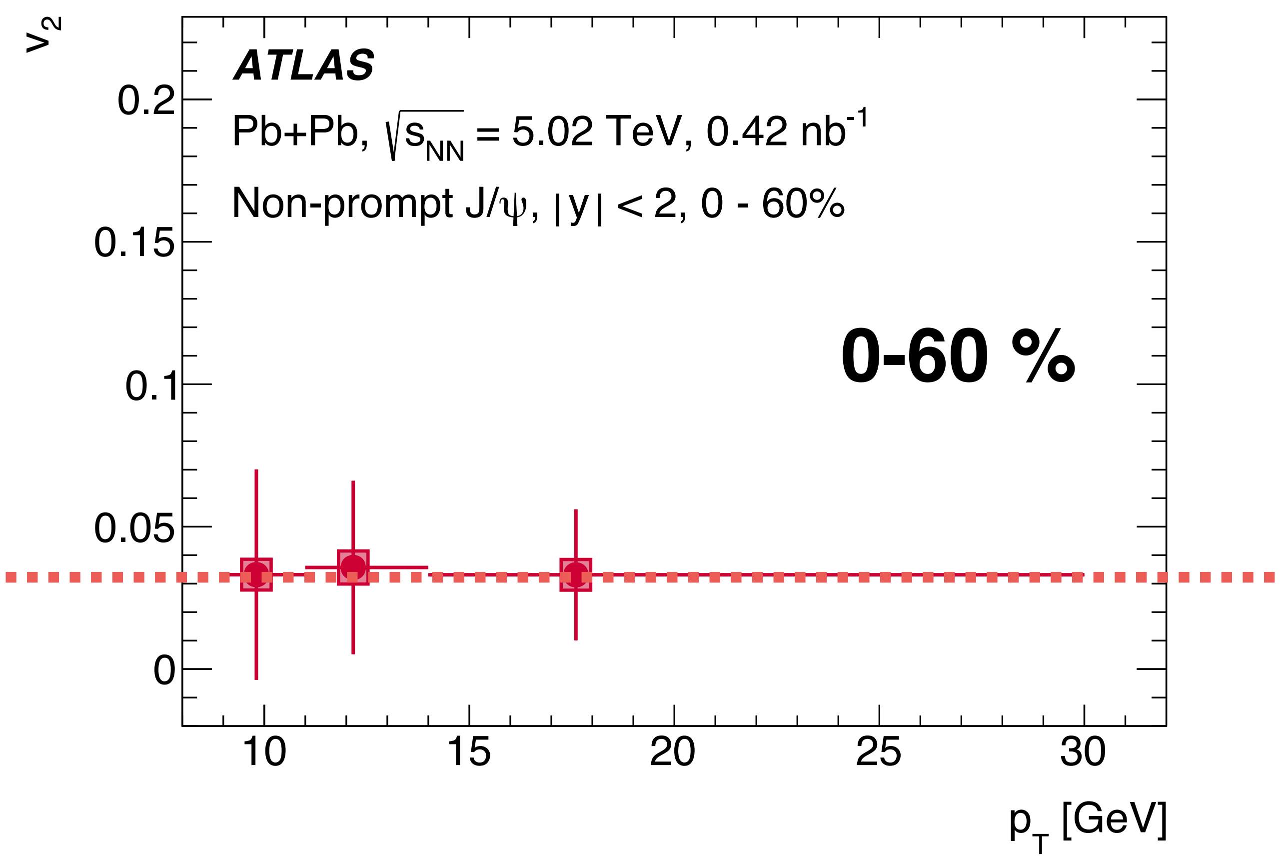


- v_2 extracted using event plane method
- Non-zero v_2 observed in the kinematic range investigated
- No significant centrality or p_T dependence

Nonprompt J/ψ vs. bottom muons

EPJC 78 (2018) 784





- Nonprompt J/ψ v_2 are in good agreement with bottom muons v_2 in overlapping p_T regions ($9 < p_T < 20$ GeV)

HF muons flow in pp at 13 TeV

My 9-month-old small system

What is happening in small system?

Muon-hadron correlations

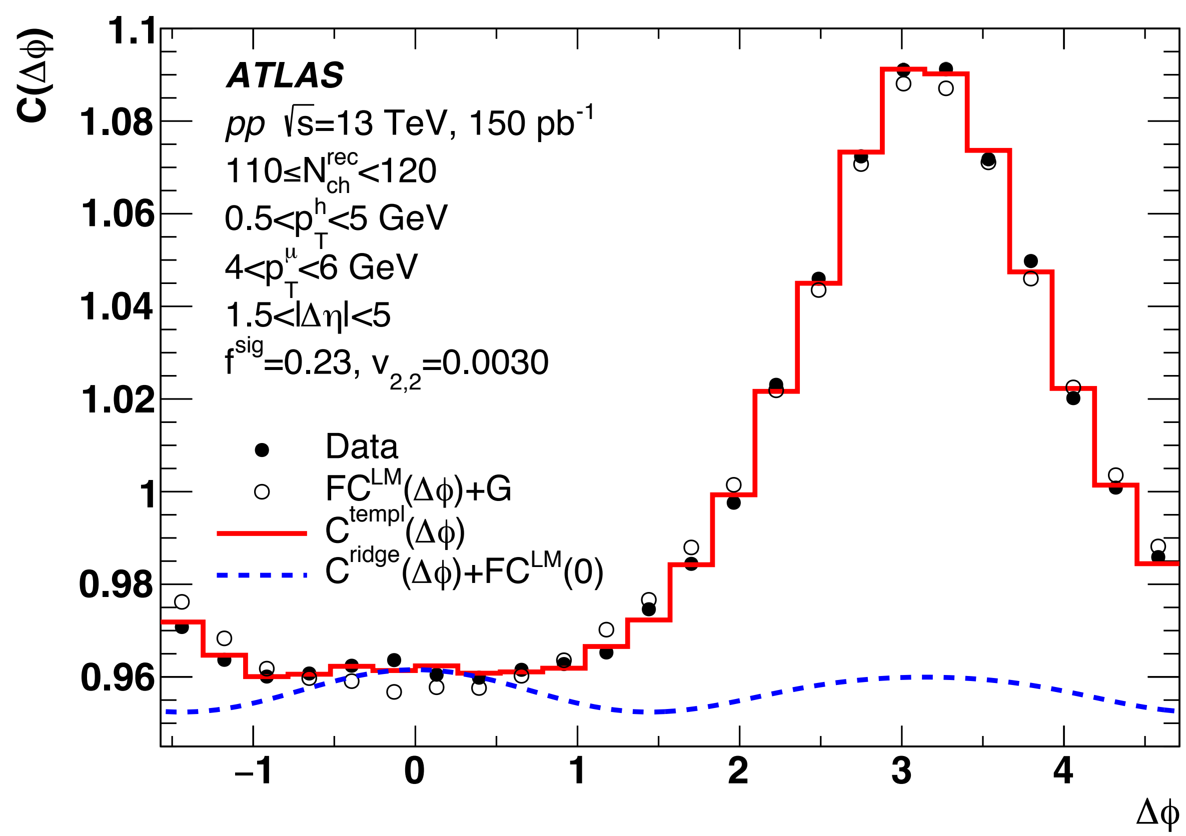
PRL 124 (2020) 082301

- v_2 extracted using two-particle correlation method
- Template fit method to subtract non-flow components
- Charm vs. bottom muon separated same as PbPb using d_0

$$C^{\mathrm{templ}}(\Delta\phi) = F \cdot C^{\mathrm{LM}}(\Delta\phi) + C^{\mathrm{ridge}}(\Delta\phi)$$

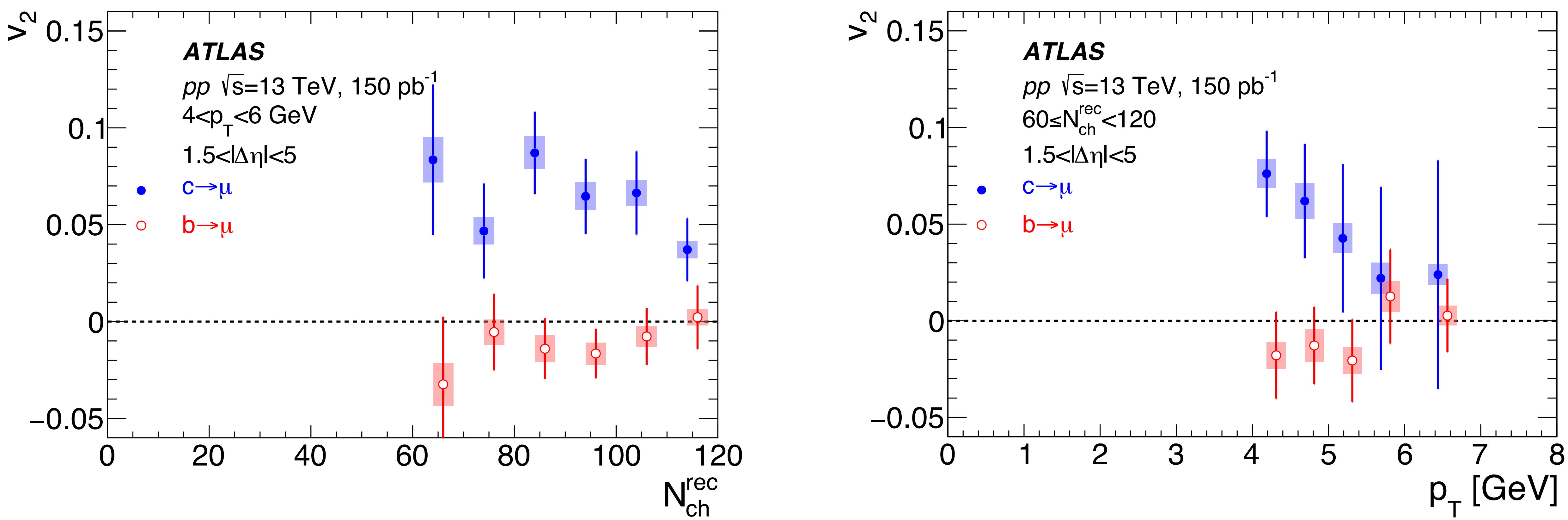
Low multiplicity events
(dominated by non-flow)

$$C^{\mathrm{ridge}}(\Delta\phi) = G\left[1 + \sum_{n=2}^{4} 2 v_{n,n} \cos(n\Delta\phi)\right]$$



Charm and bottom muons v_2

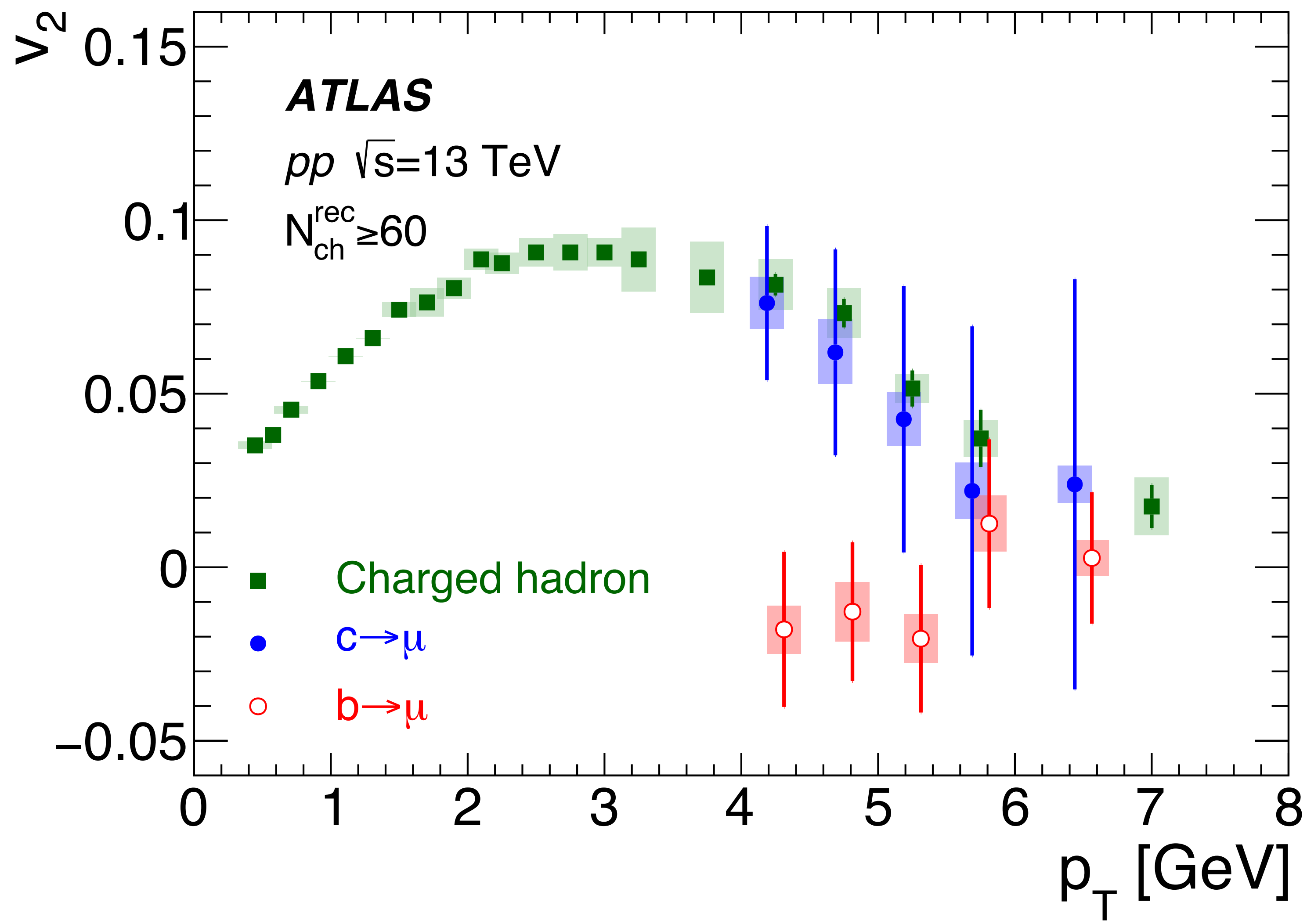
PRL 124 (2020) 082301



- Significant nonzero v_2 for **charm muons**
  - almost independent of multiplicity
  - Decreases with p_T
- **bottom muons** v_2 is consistent with zero!

Charm vs. bottom vs. light quarks

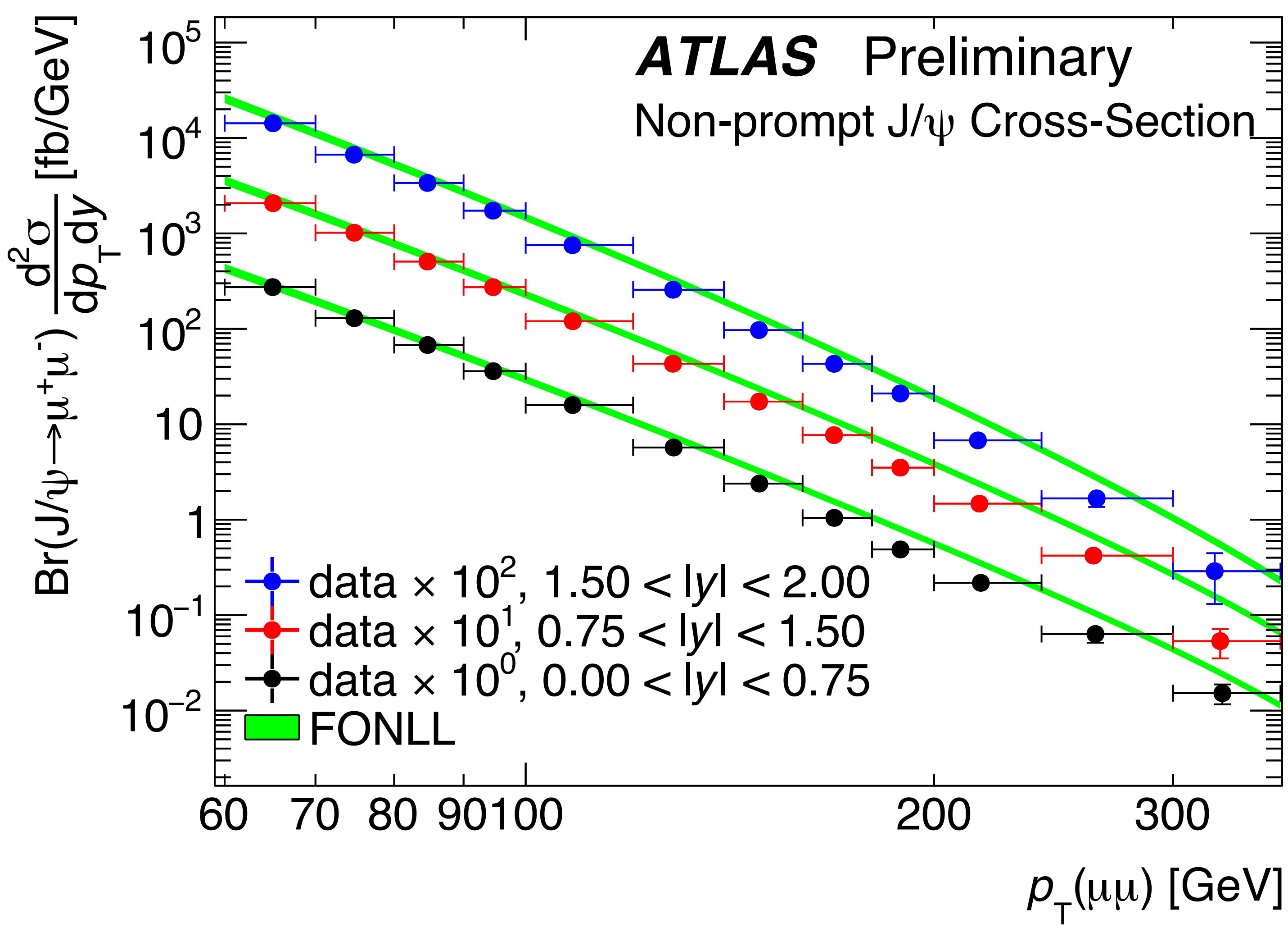
PRL 124 (2020) 082301

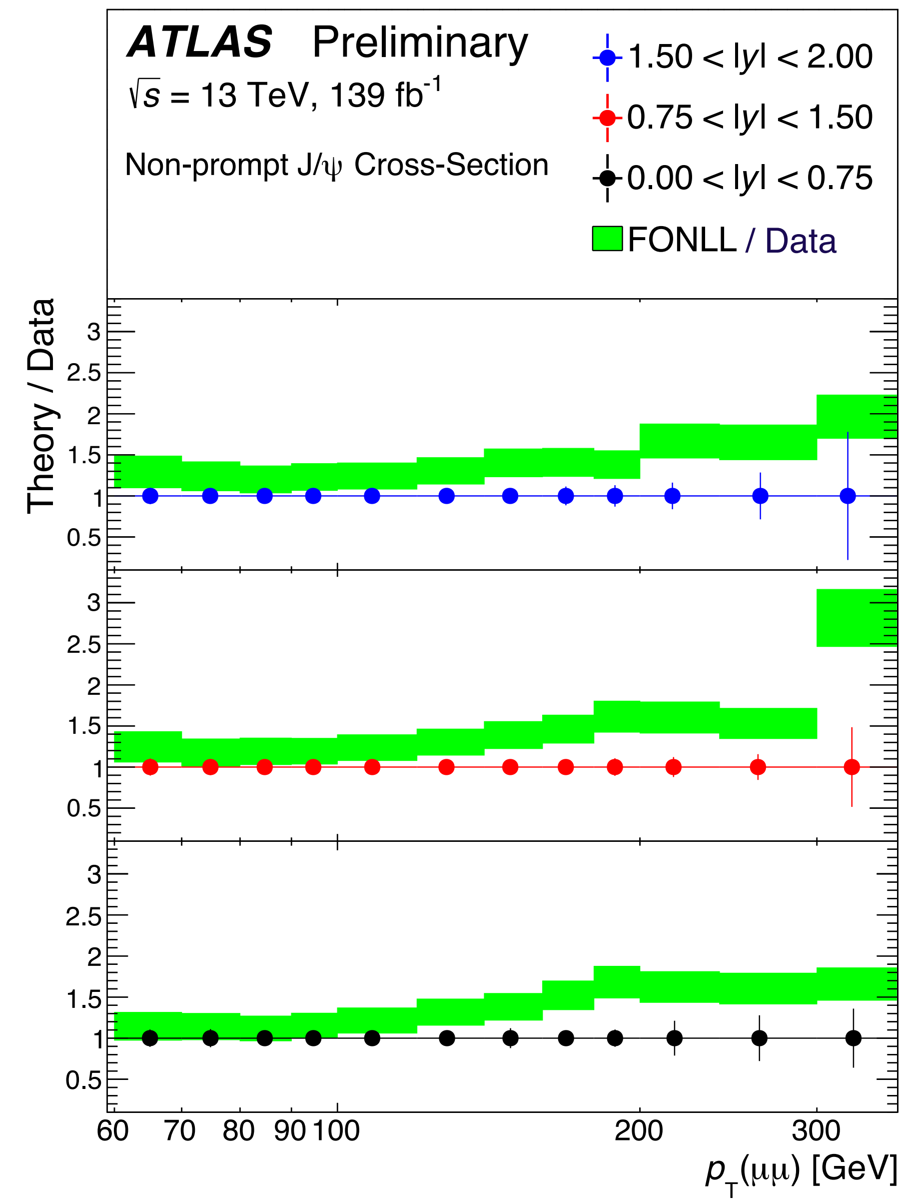


- **Charm v_2** is comparable to **light quarks v_2** while **bottom v_2** is zero
- Small QGP droplet in pp?
- Why charm and bottom quarks behave differently?
- No model/theory comparison available

Nonprompt J/ψ cross-sections in pp

ATLAS-CONF-2019-047

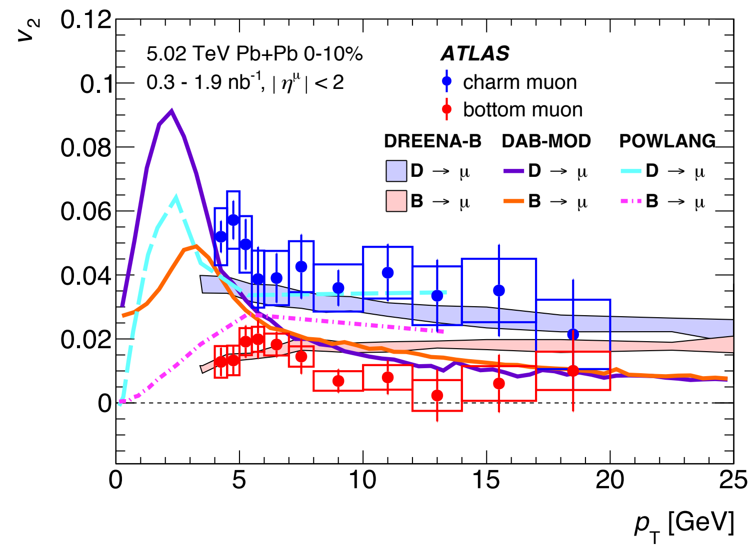


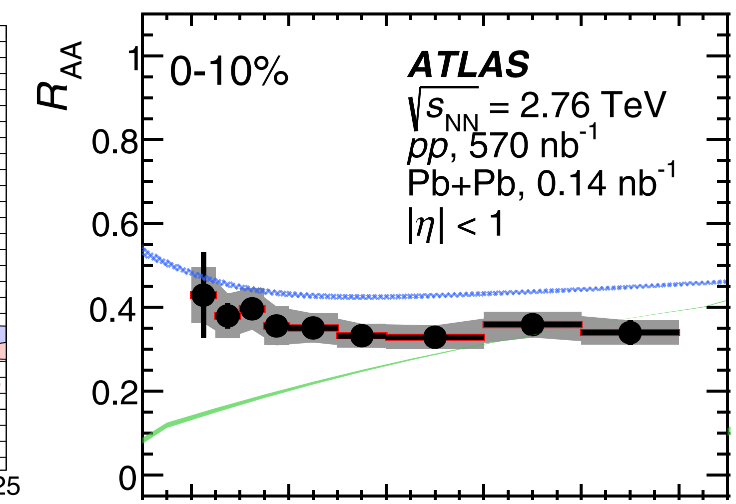


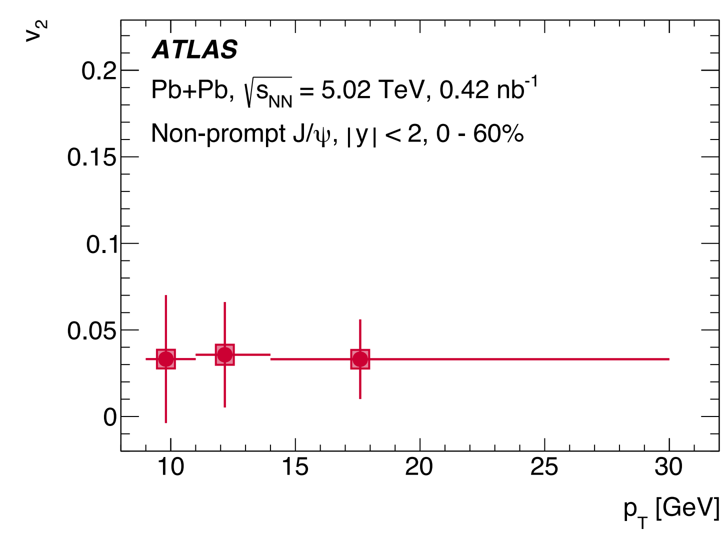
- Full Run2 pp collision data allows to reach p_T up to 360 GeV
- FONLL calculations exceed experimental data at high p_T

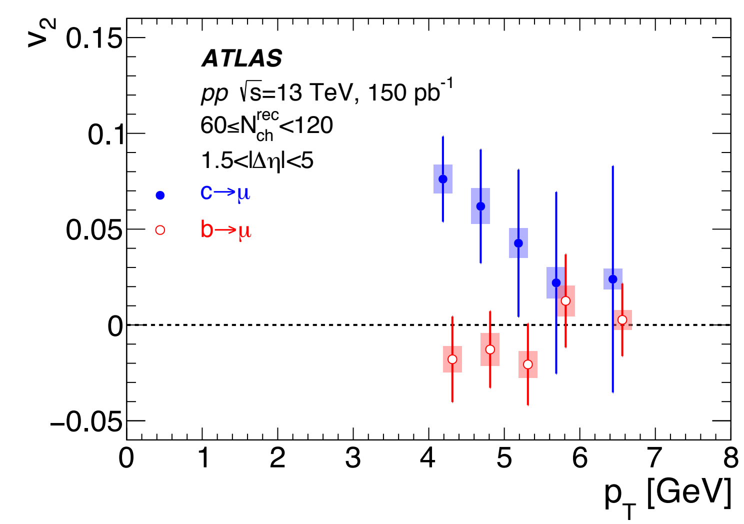
Summary

- Both charm and bottom quarks flow in Pb+Pb
- HF muons yields are suppressed in Pb+Pb compared to pp
- Results of Nonprompt J/ψ coming from b hadrons are consistent with those of HF muons
- Charm flows similar to light quarks but bottom does not in pp





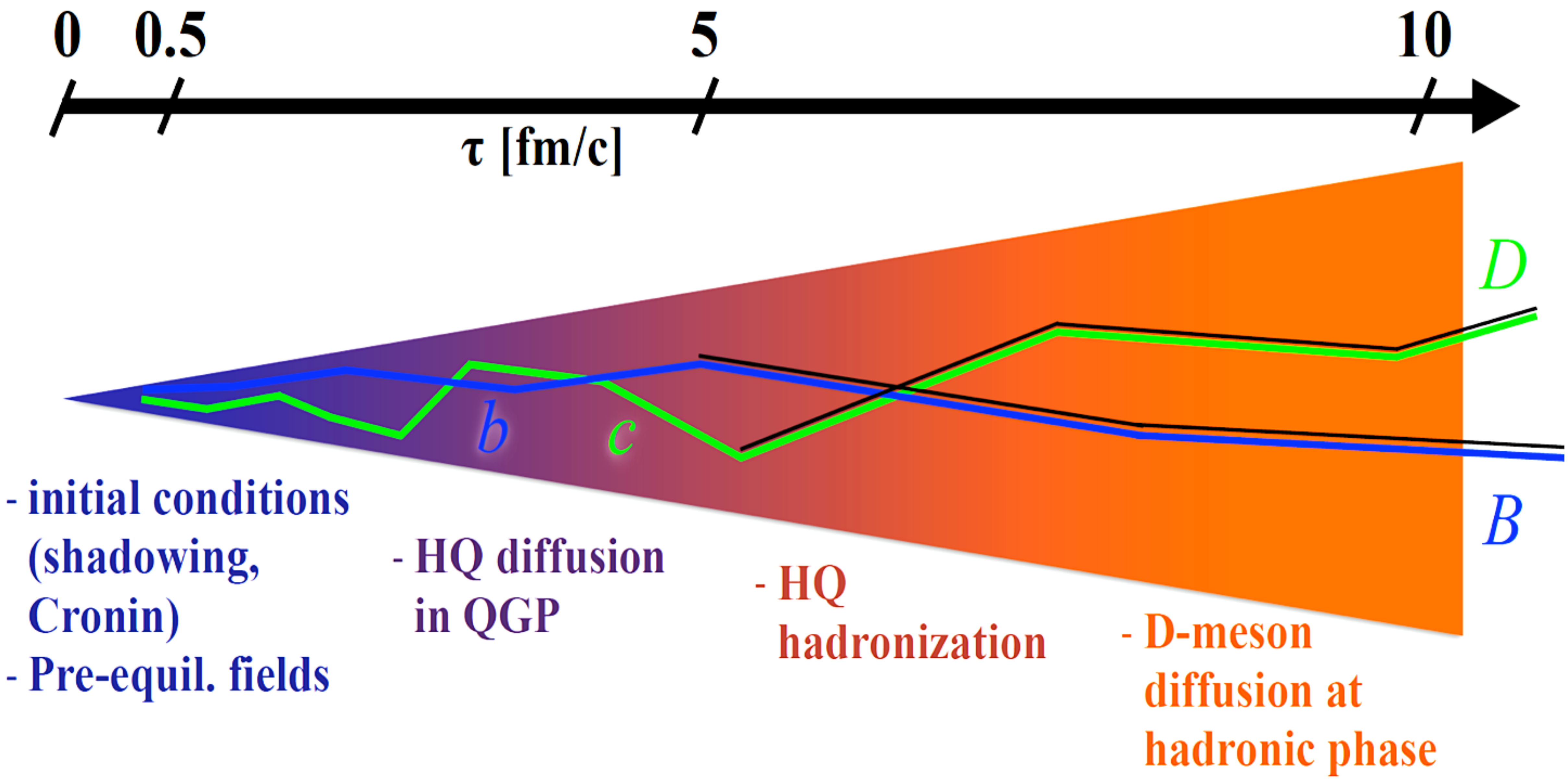




A simultaneous understanding of both yields and flow from PbPb to pp is still puzzling!

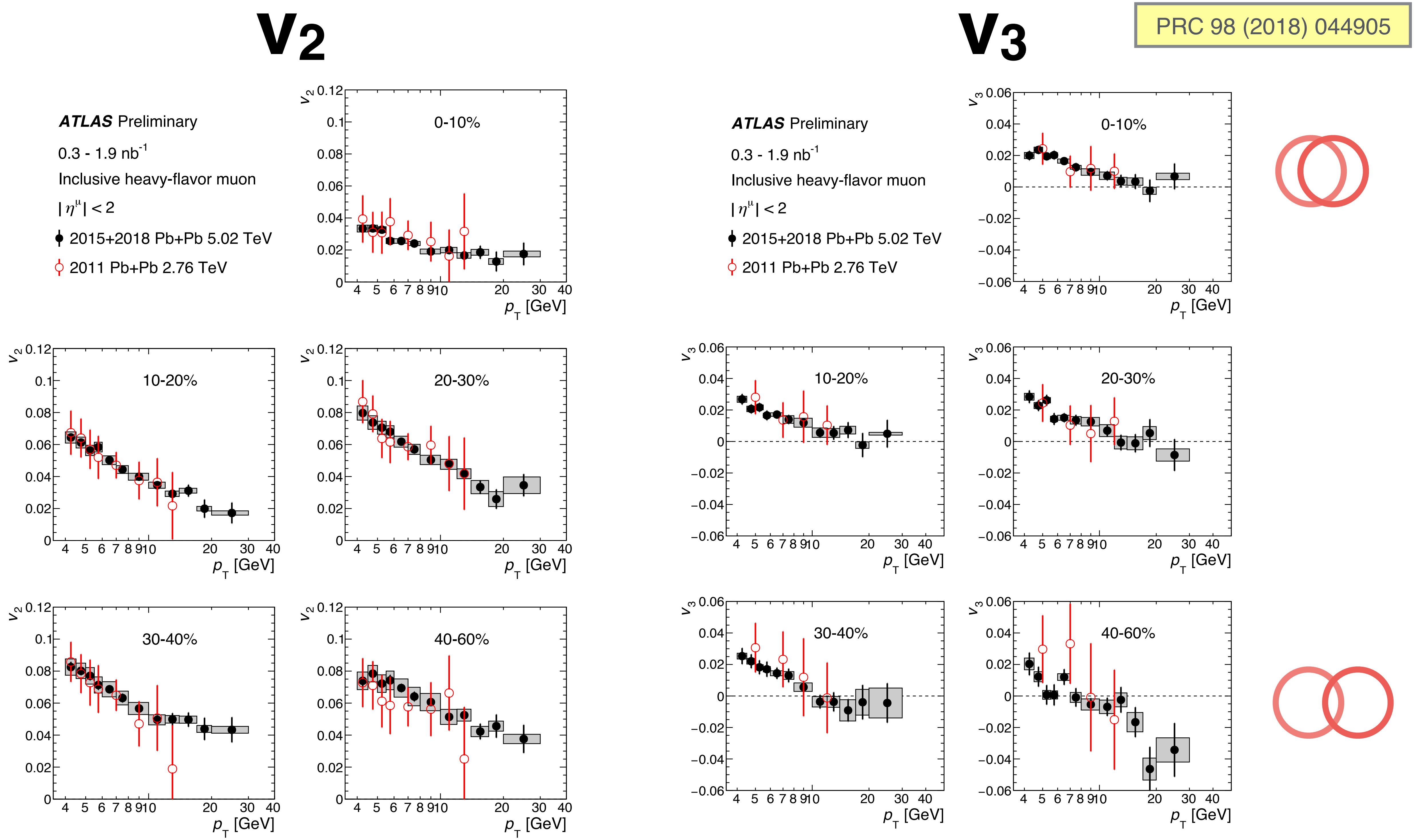
Backups

Heavy quark evolution in QGP



Pb+Pb at 2.76 TeV vs. 5.02 TeV

PRC 98 (2018) 044905



- Inclusive HF v_2: steadily decrease with p_T
- Results at 2.76 TeV and 5.02 TeV agree with each other

Pb+Pb at 2.76 TeV

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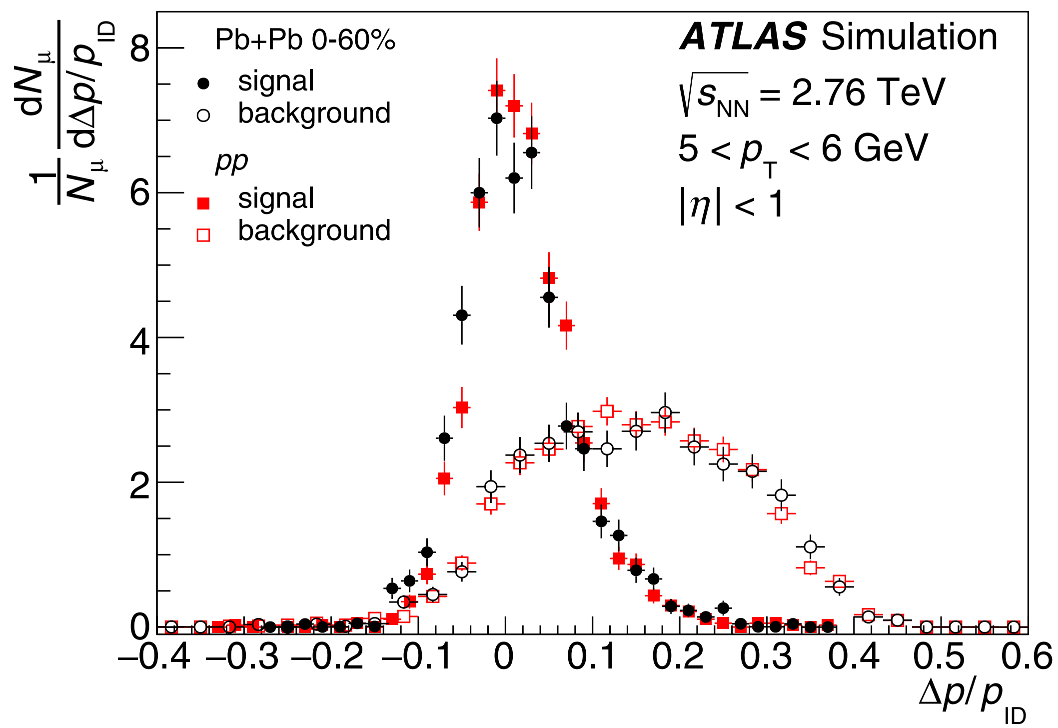
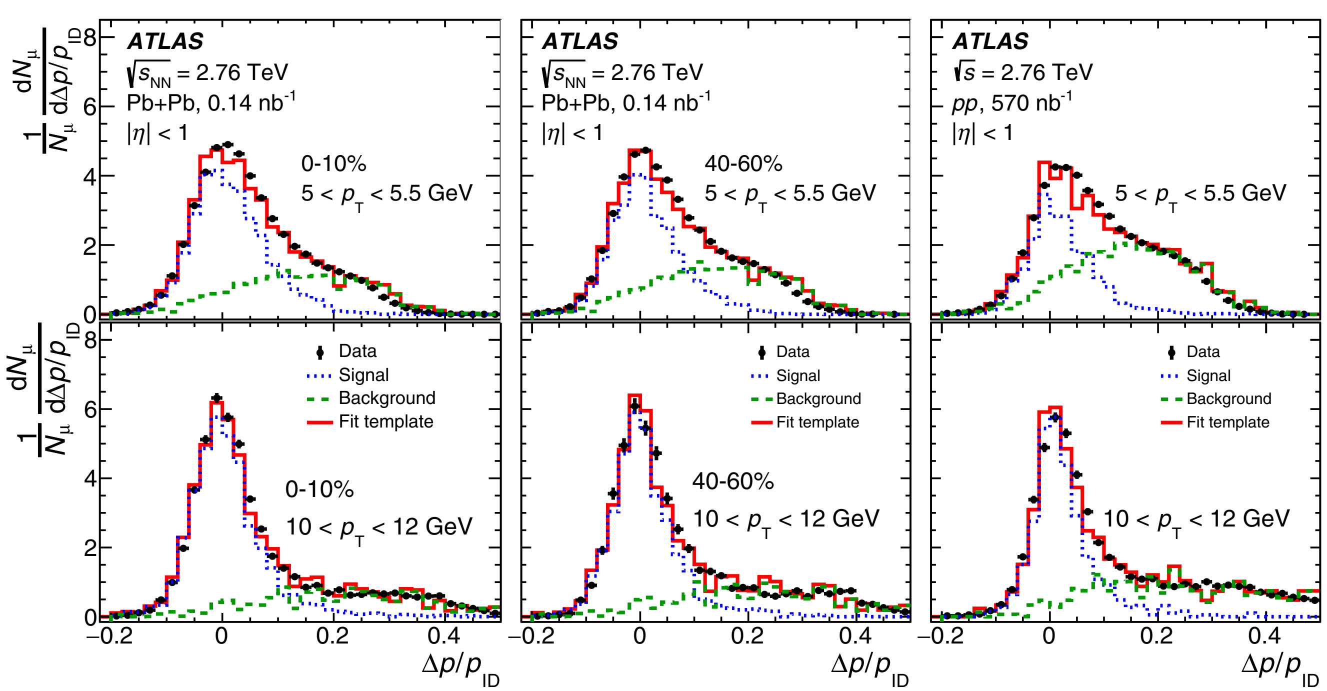
$\Delta p/p_{ID}$ distributions from MC





- Template fit to separate Signal from Background

$$\frac{\Delta p}{p_{\rm ID}} = \frac{p_{\rm ID} - p_{\rm MS} - \Delta p_{\rm calo}(p, \eta, \phi)}{p_{\rm ID}}$$

Pb+Pb at 2.76 TeV

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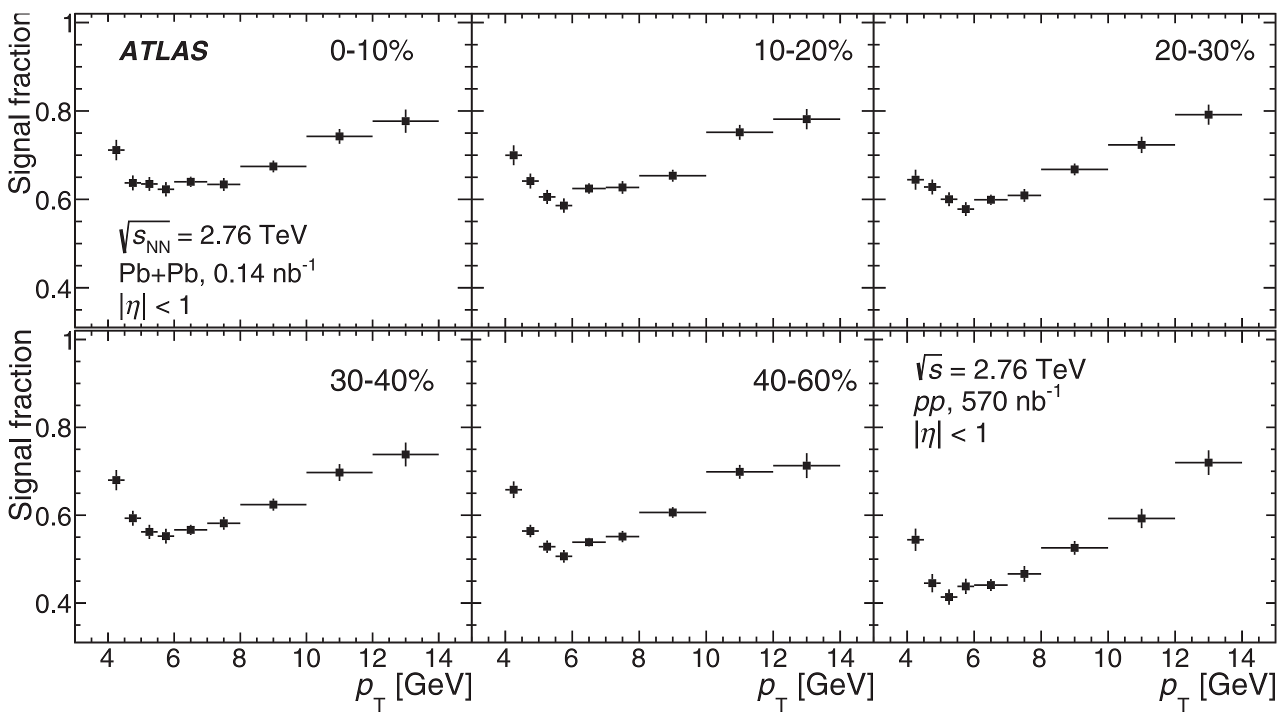
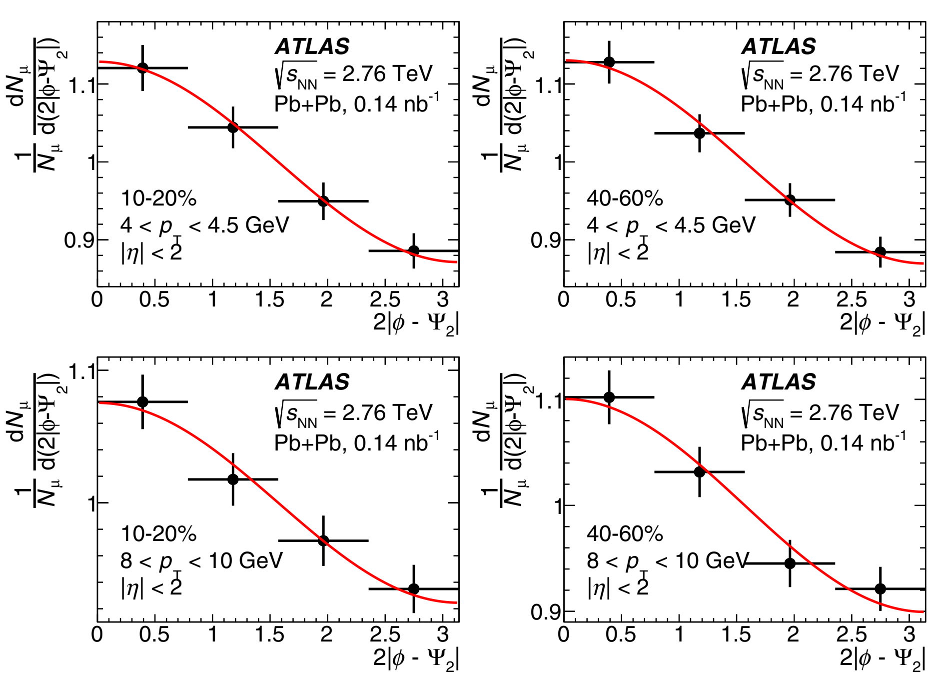
Signal fraction obtained from template fit



- Larger fraction of HF mouns at high p_T
- Trigger effects at low p_T (less efficient for backgrounds with low p_T^{MS})

HF muons yields vs. 2|ϕ-Ψ$_2$|



- Yields are fitted with 2nd-order Fourier function

$$\frac{dN}{d\phi} = N_0\left[1 + 2\sum_{n\geqslant 1} v_n^{\mathrm{obs}}\cos[n(\phi - \Psi_n)]\right]$$

Pb+Pb at 2.76 TeV

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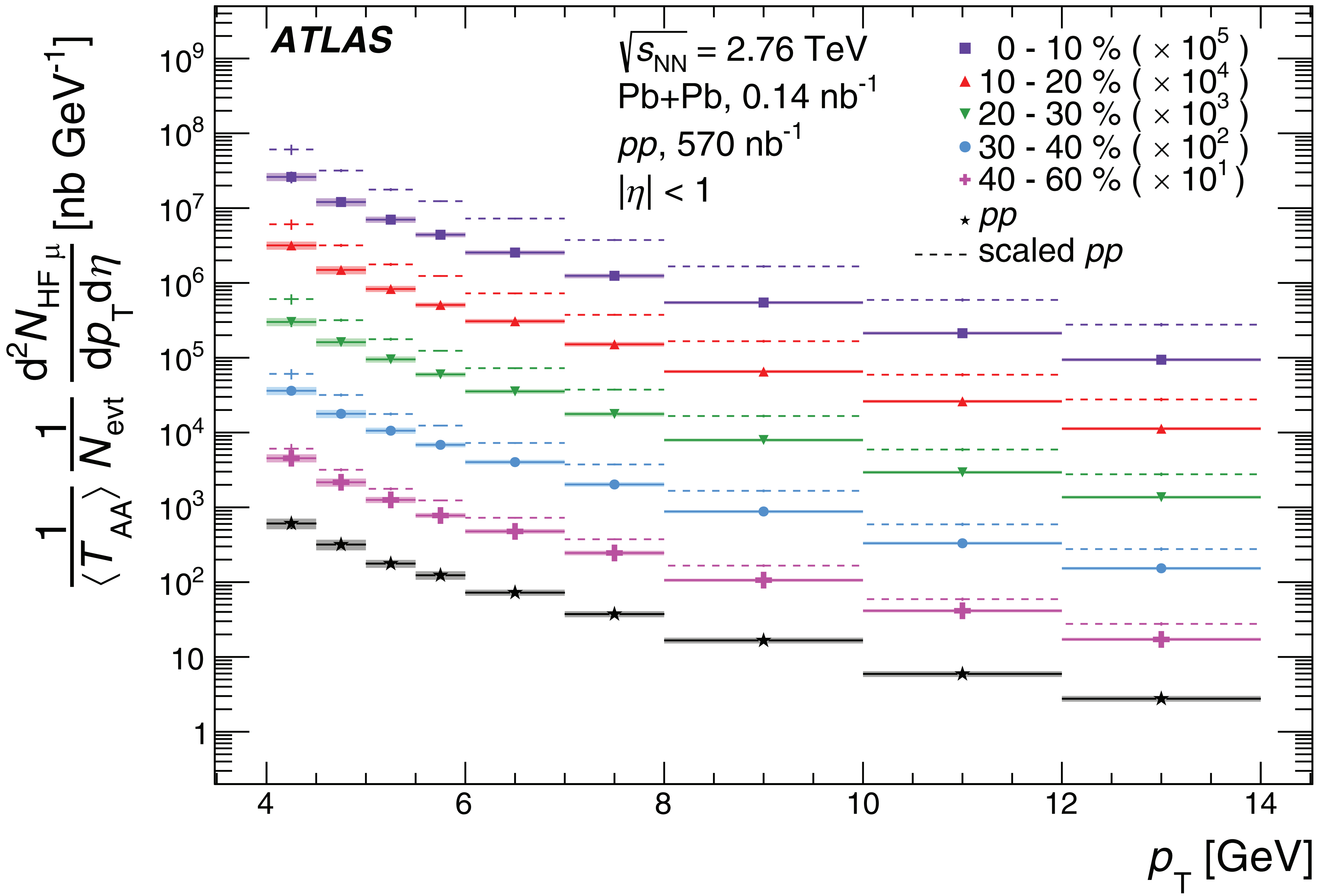

TAMU vs. DABmod

- **TAMU** PLB 735 (2014) 445
  - Initial p_T spectra from FONLL + shadowing effects
  - QGP evolution by ideal relativistic hydrodynamics: tuned to reproduce charged-hadron spectra and inclusive elliptic flow in Pb+Pb at the LHC
  - The initial condition for hydrodynamic modeling from Glauber model and no initial state fluctuations or initial flow included
  - Hadronization via recombination and fragmentation
  - Diffusion of HF hadrons continued until kinetic freeze-out

- **DABMod** PRC 96 (2017) 064903
  - Energy loss is a parameterized analytic function of the heavy quark velocity and local Temperature
  - Initial p_T spectra from FONLL
  - QGP evolution by (2+1)D relativistic viscous hydrodynamics: tuned to describe experimental flow at low p_T
  - Event-by-event fluctuations in initial condition and expansion included
  - Heavy quarks evolution until they reach a decoupling temperature
  - Hadronization via fragmentation (hadronic rescattering neglected)

Pb+Pb at 2.76 TeV

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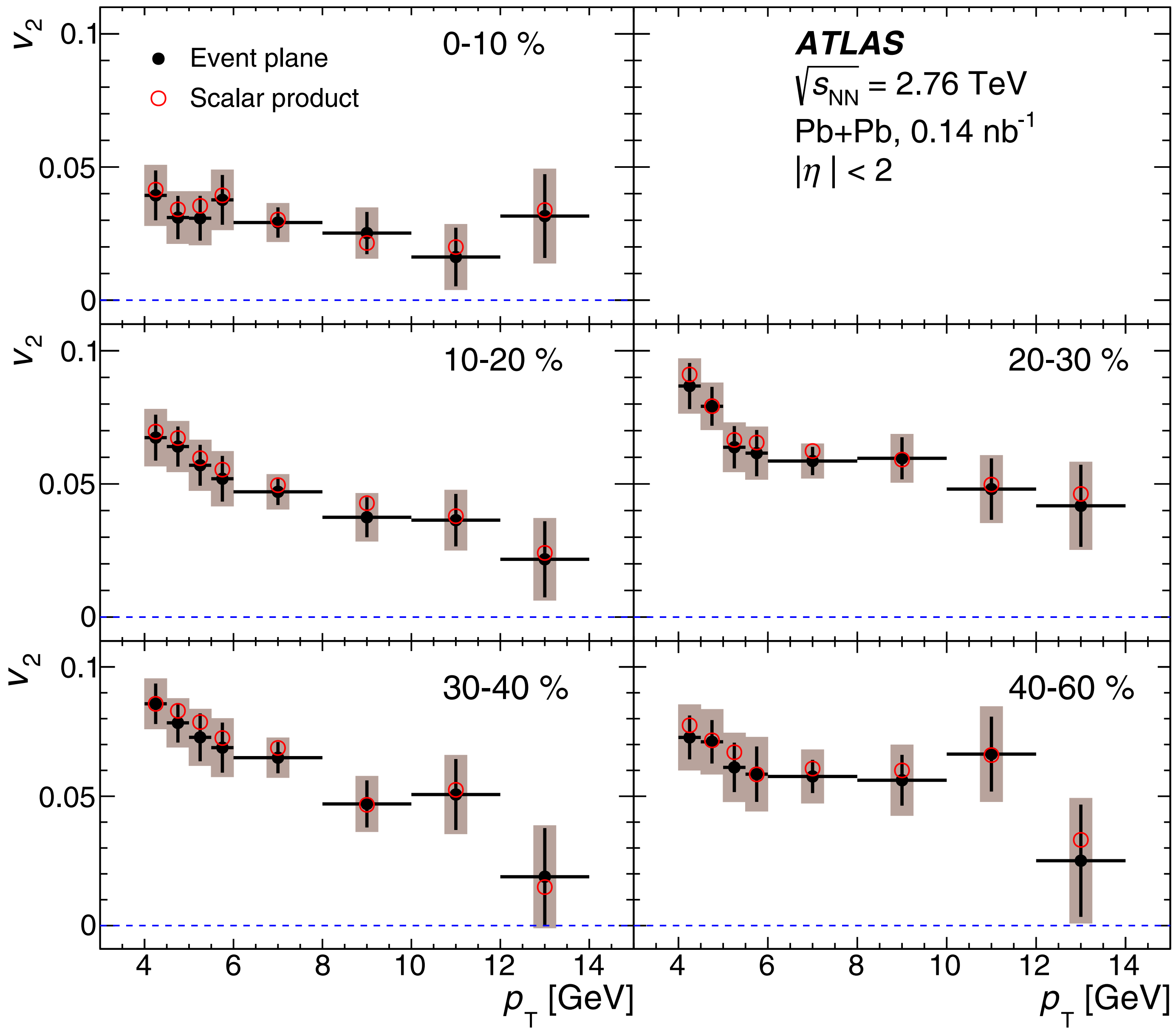

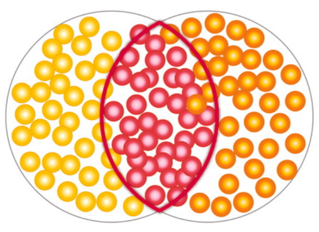

Elliptic flow

- Significant non-zero v_2 up to hight p_T in all centrality bins
- 10-40% centrality: v_2 decreases with p_T
- Most central (0-10%) and peripheral (40-60%): no clear p_T dependence
- Event plane method and scale product method are consistent

Pb+Pb at 2.76 TeV

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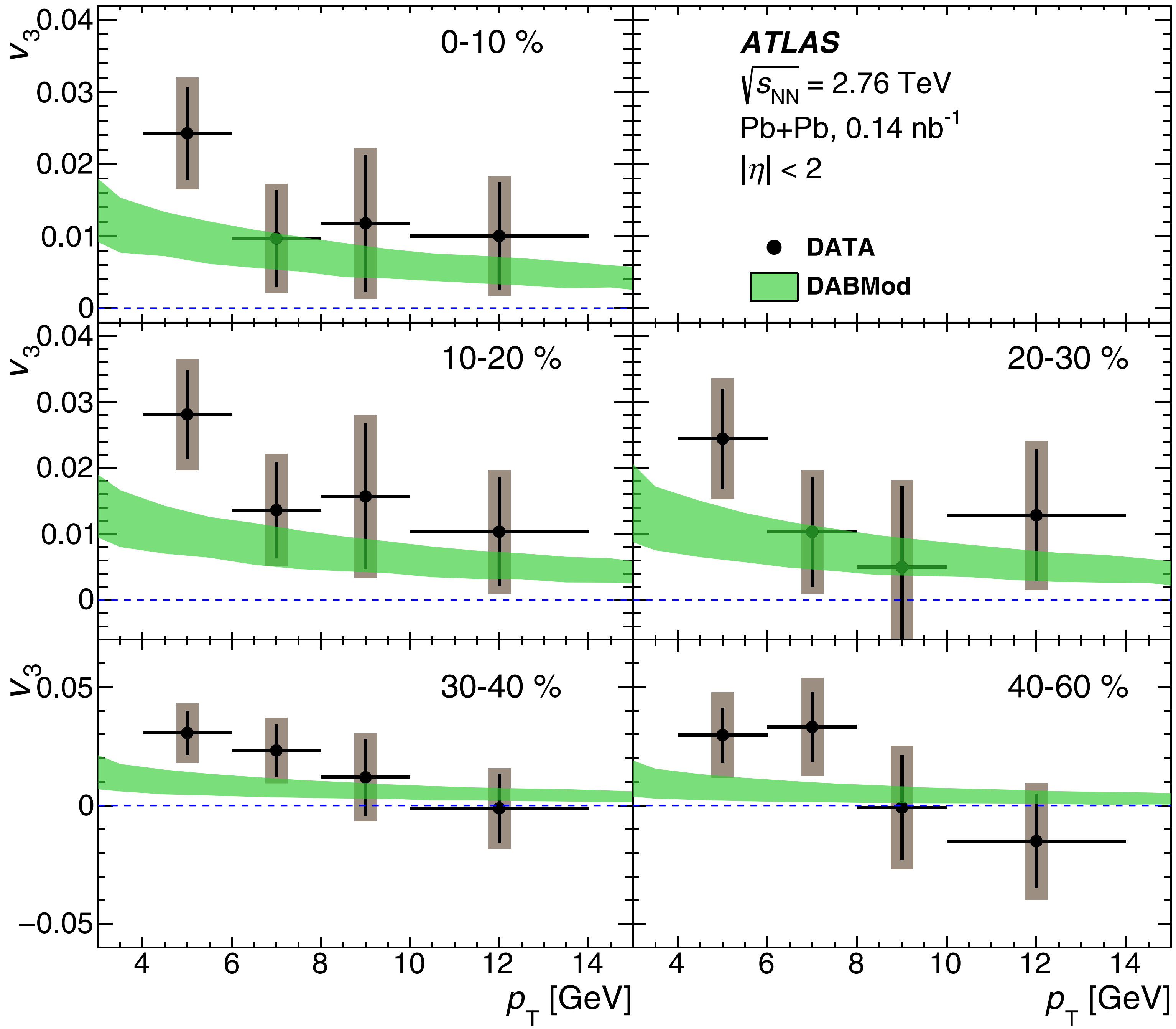

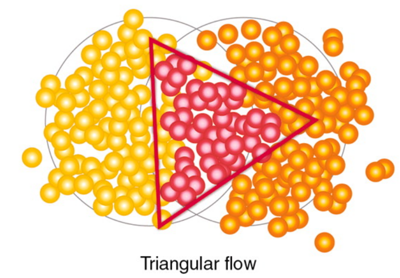

- Theoretical calculation is smaller at $4 < p_T < 6$ GeV and similar to data at high p_T

Pb+Pb at 2.76 TeV

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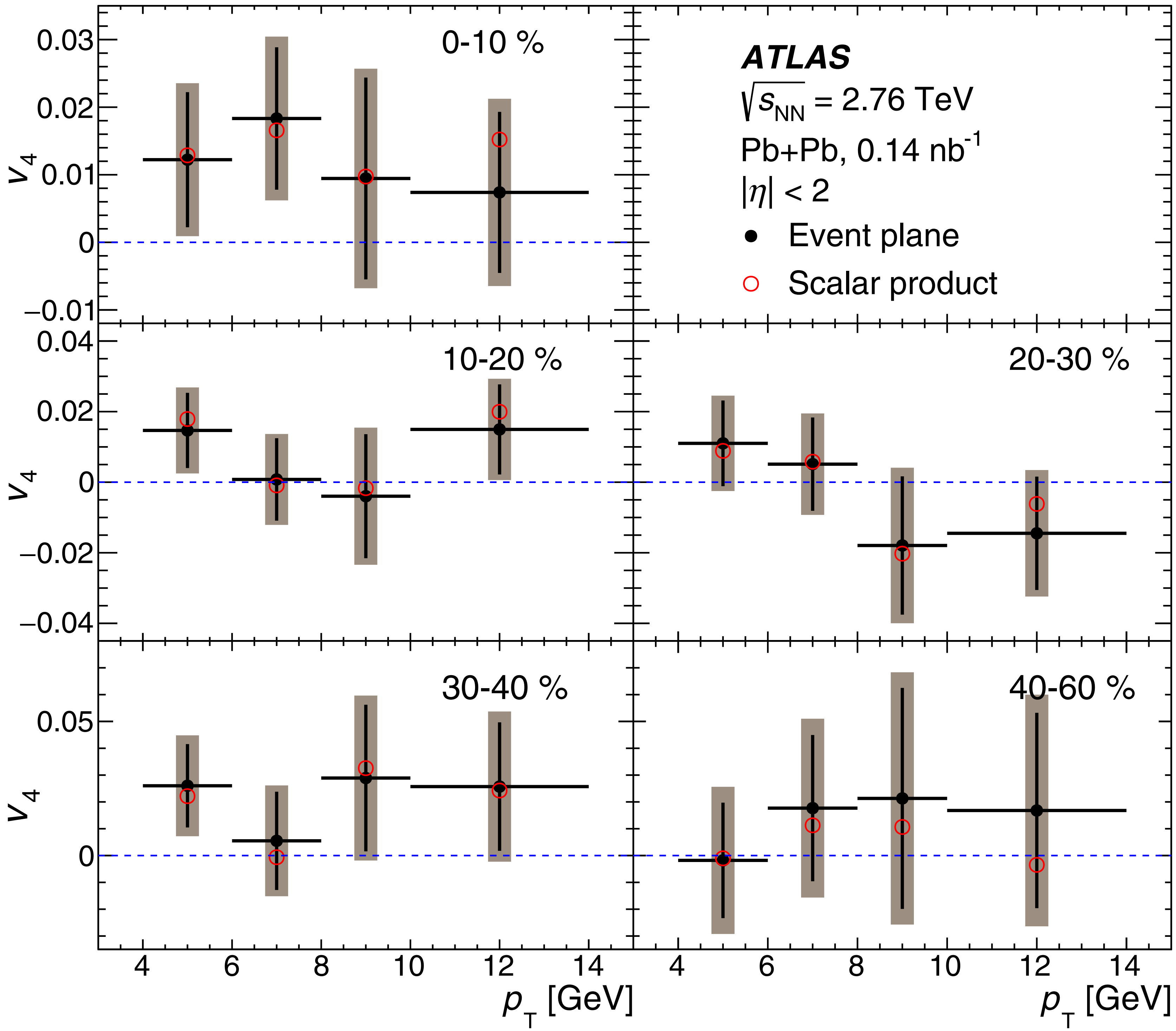
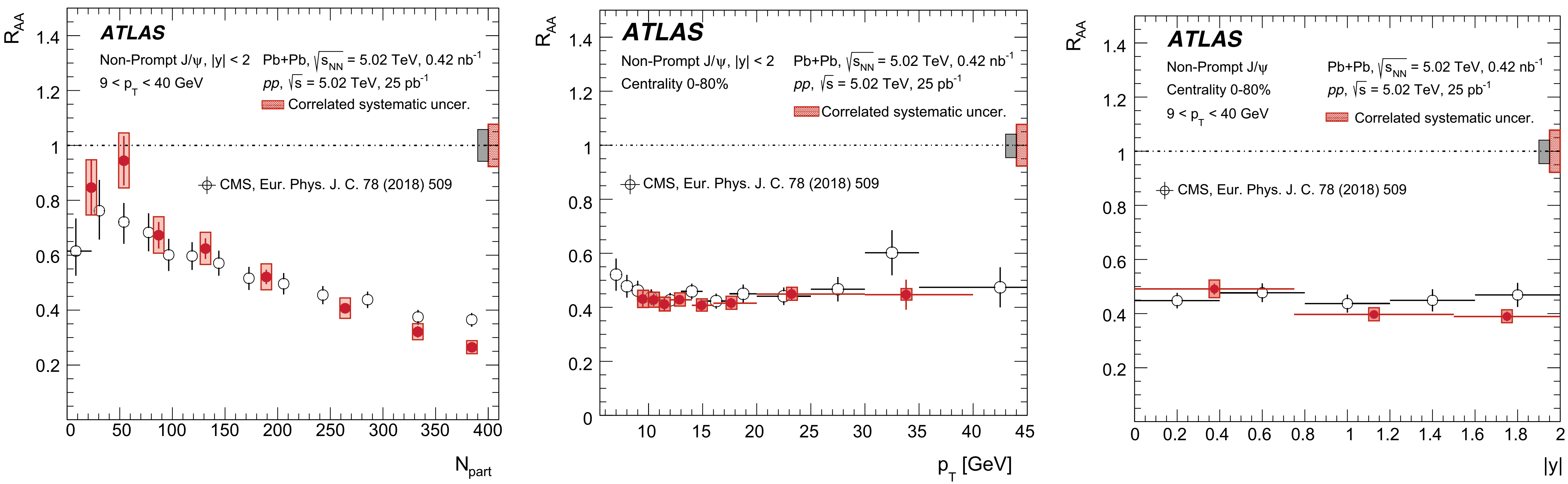


Nonprompt J/ψ compared to CMS

EPJC 78 (2018) 762

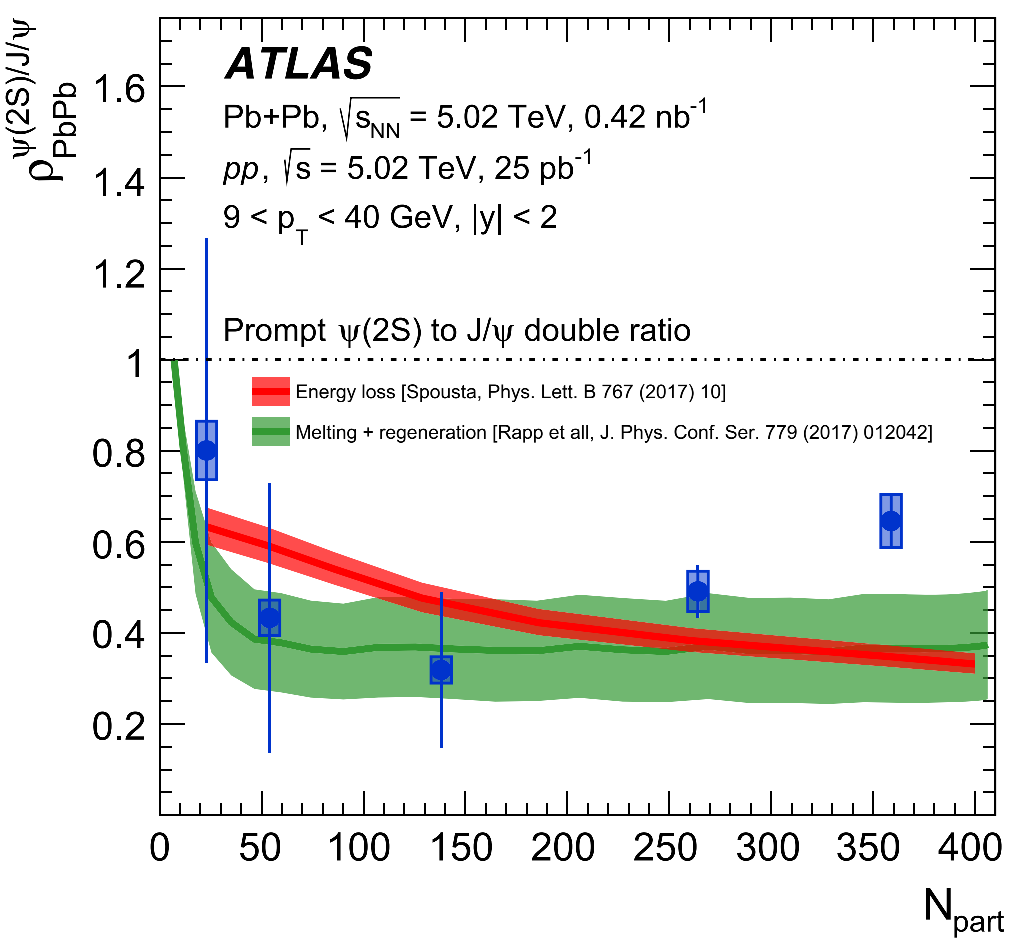


- Two experiments agree well with each other

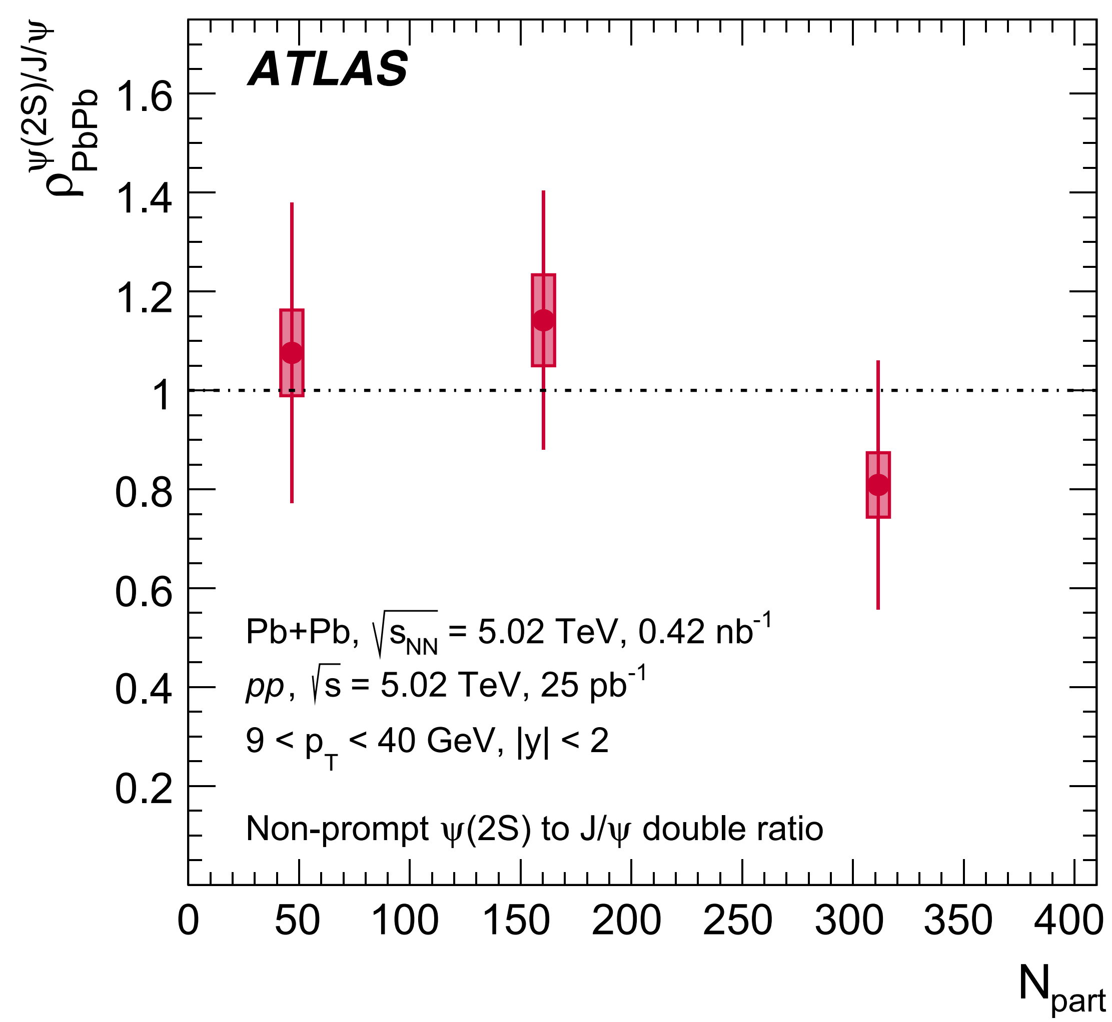
J/ψ Double ratios 2S/1S

EPJC 78 (2018) 762

[prompt]



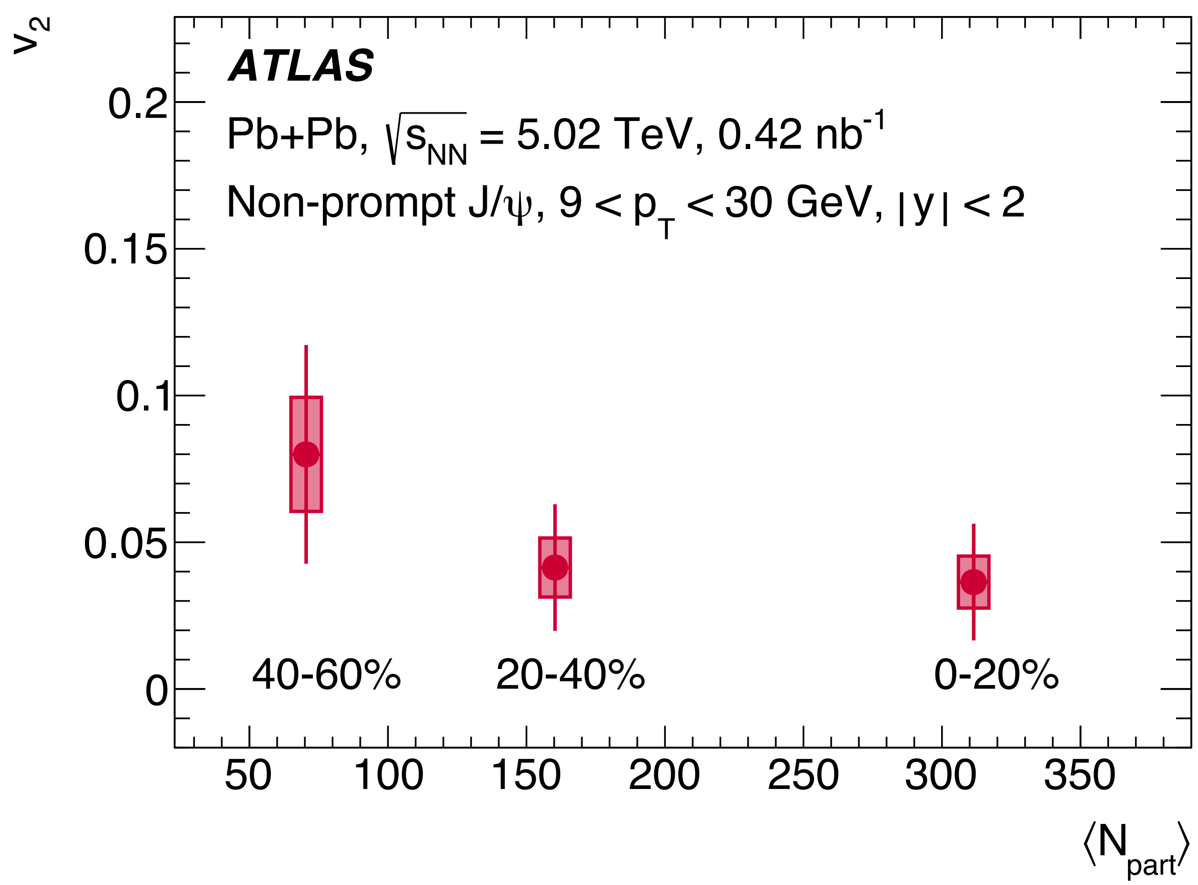
[Nonprompt]

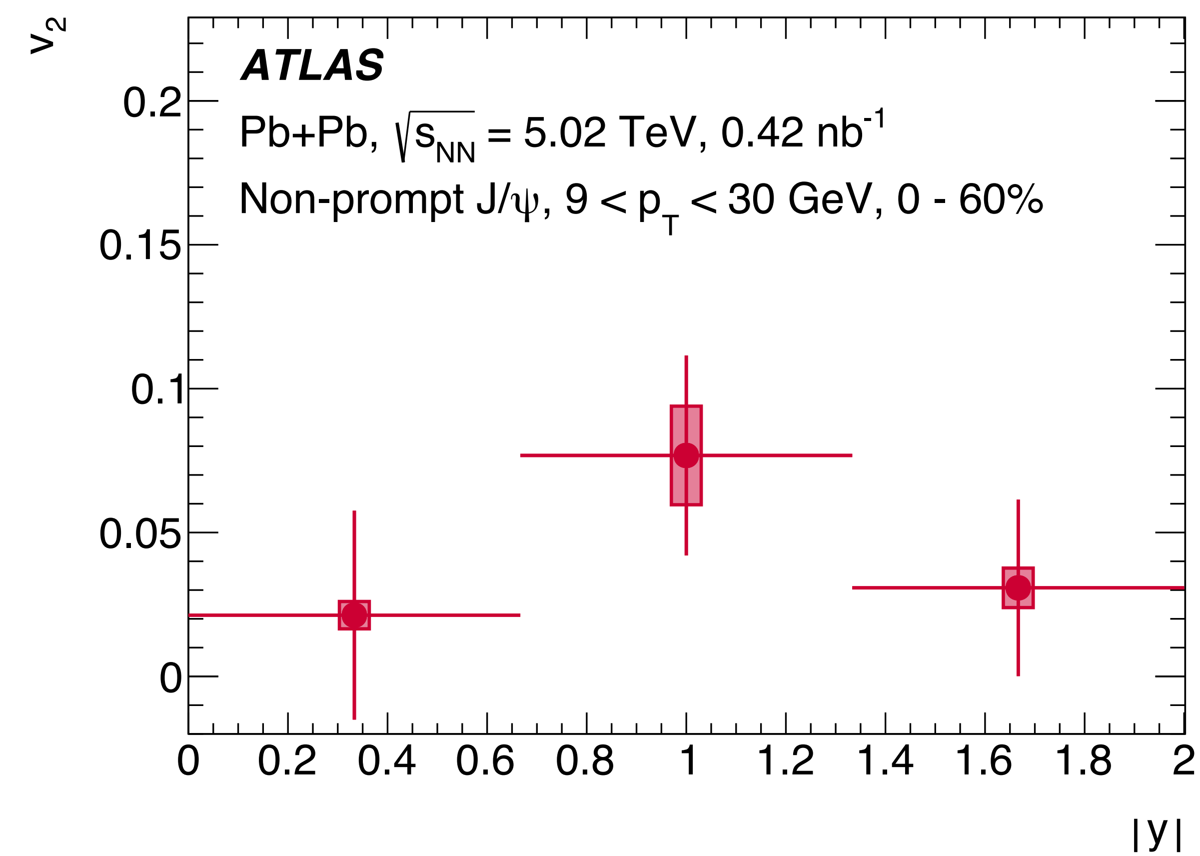


- Nonprompt Jpsi double ratios ~ 1
- Suppression of both 1S and 2S from the decay of B hadrons outside the medium

Nonprompt J/ψ v_2

EPJC 78 (2018) 784





- No clear centrality or rapidity dependence within uncertainties

pp at 13 TeV (two particle correlation)

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$$\Delta\phi \equiv \phi^{\mu} - \phi^{h}$$
$$\Delta\eta \equiv \eta^{\mu} - \eta^{h}$$

- For each muon
  - S(Δϕ, Δη) with hadrons from the same events
  - B(Δϕ, Δη) with hadrons from the different events of similar N_{ch} and z^{vtx}
  - Each muon-hadron pair is corrected for efficiencies (acceptance largely cancels in S/B)
- 1D correlation function (η gap reduces the contributions from jet fragmentation)

$$C(\Delta\phi) = \frac{\int_{1.5}^{5} d|\Delta\eta| S(|\Delta\eta|, \Delta\phi)}{\int_{1.5}^{5} d|\Delta\eta| B(|\Delta\eta|, \Delta\phi)} \equiv \frac{S(\Delta\phi)}{B(\Delta\phi)}$$

- Template fit to remove non-flow (back-to-bak dijet, resonance decays, etc)

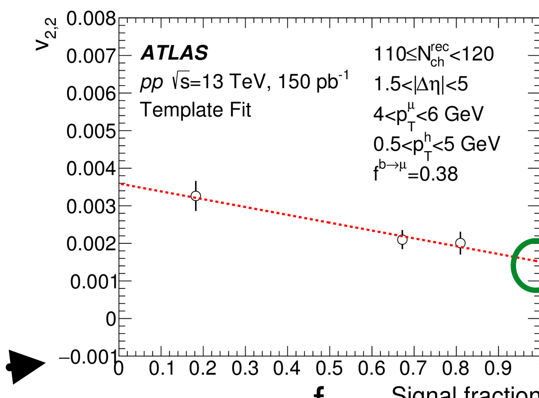
$$C^{\mathrm{templ}}(\Delta\phi) = F \cdot C^{\mathrm{LM}}(\Delta\phi) + C^{\mathrm{ridge}}(\Delta\phi)$$

Low multiplicity events
(dominated by non-flow)

$$C^{\mathrm{ridge}}(\Delta\phi) = G\left[1 + \sum_{n=2}^{4} 2 v_{n,n} \cos(n\Delta\phi)\right]$$

- $v_{2,2}$ determined in three different $\Delta p/p_{ID}$ region
  - signal fraction f_{sig} is extracted from a linear fit to the points to get $\mathbf{v_{2,2}^{sig}}$

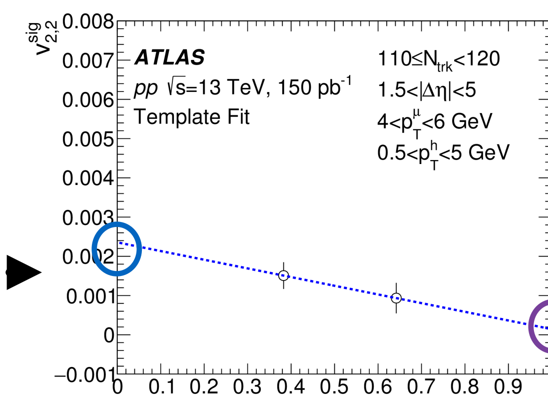
$$v_{2,2}(p_{\mathrm{T}}^{\mu}, p_{\mathrm{T}}^{h}) = f^{\mathrm{sig}} v_{2,2}^{\mathrm{sig}}(p_{\mathrm{T}}^{\mu}, p_{\mathrm{T}}^{h}) + (1 - f^{\mathrm{sig}}) v_{2,2}^{\mathrm{bkg}}(p_{\mathrm{T}}^{\mu}, p_{\mathrm{T}}^{h})$$



f_{sig}

- $v_{2,2}^{sig}$ determined in two different d_0 region
  - $\mathbf{v_{2,2}^{b\to\mu}}$ and $\mathbf{v_{2,2}^{c\to\mu}}$ are determined from a linear fit

$$v_{2,2}^{\mathrm{sig}}(\mu, h) = f^{b\to\mu} v_{2,2}^{b\to\mu}(\mu, h) + (1 - f^{b\to\mu}) v_{2,2}^{c\to\mu}(\mu, h)$$



$f_{b\to\mu}$

- Flow factorization assumption $v_n^{\mu}(p_{\mathrm{T}}^{\mu}) = v_{n,n}(p_{\mathrm{T}}^{\mu}, p_{\mathrm{T}}^{h}) / v_n^{h}(p_{\mathrm{T}}^{h})$

pp at 13 TeV: Inclusive HF v2

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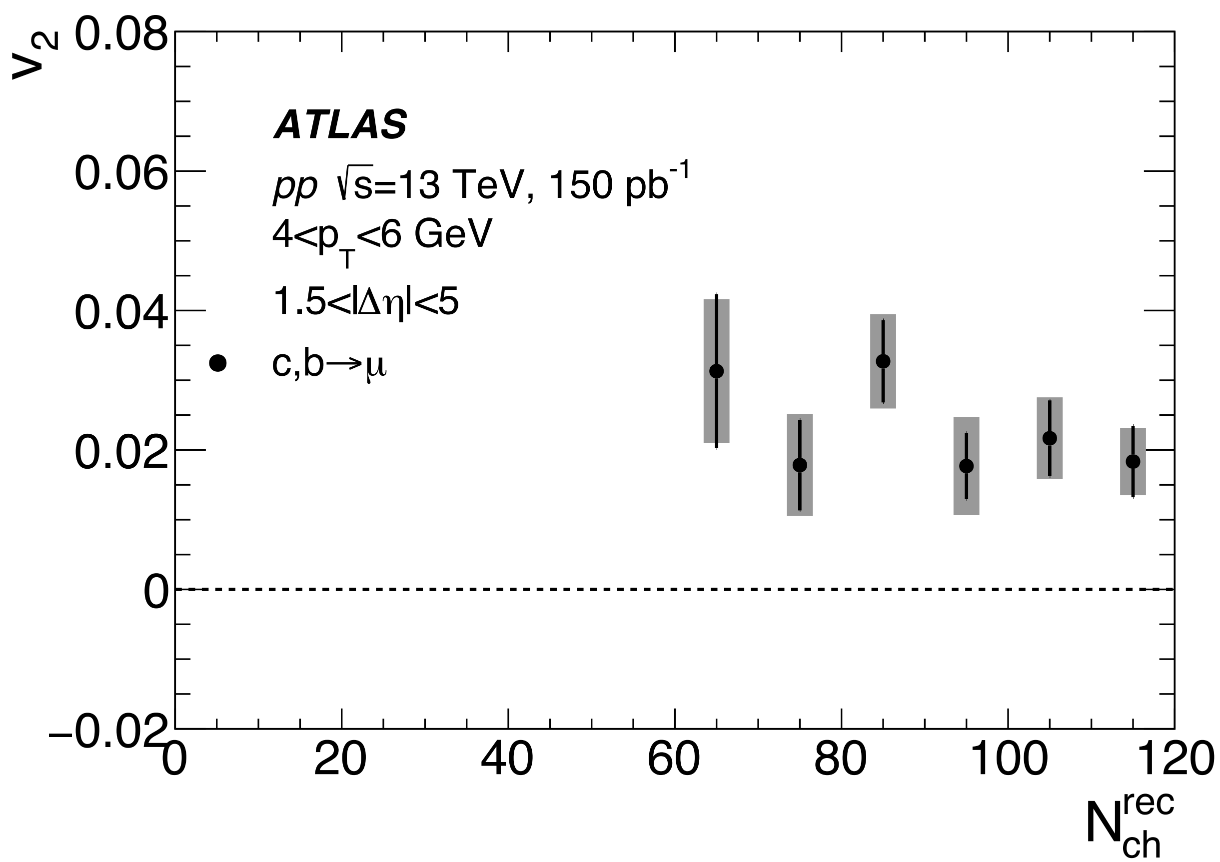

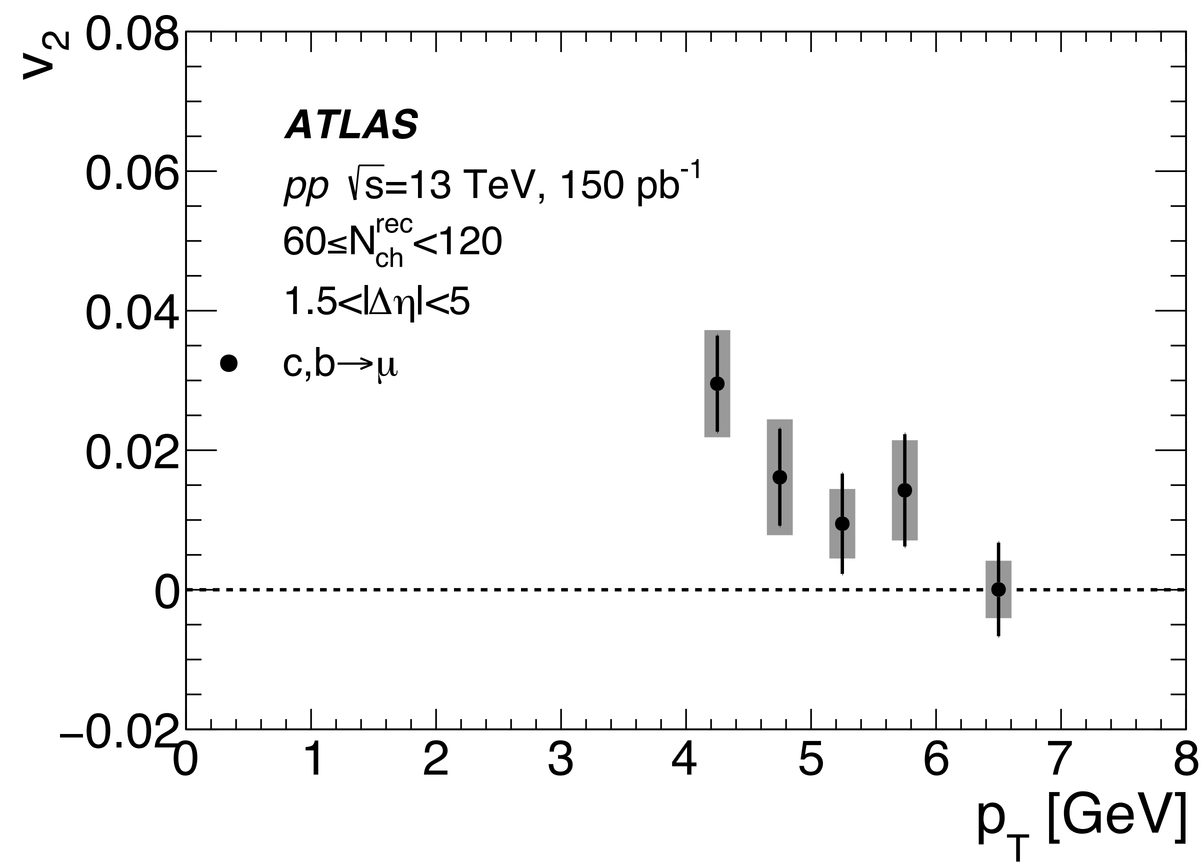

- Non-zero v_2: almost independent of multiplicity
- Decreases with p_T