

Collective Flow and Soft-QCD Observables in Light-Ion Collisions with ATLAS



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For the ATLAS Collaboration

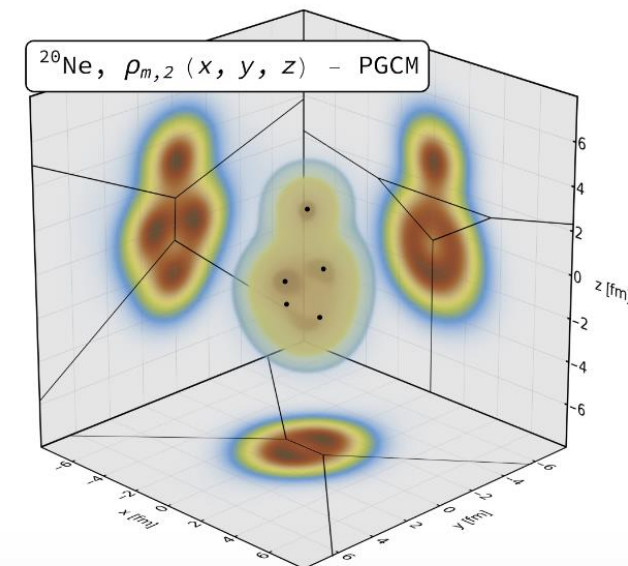
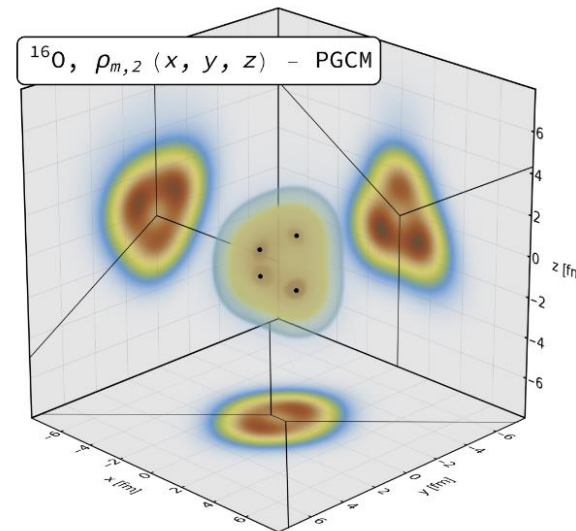
[arXiv:2606.20257](https://arxiv.org/abs/2606.20257)
[Phys. Rev. C 113 \(2026\) 045205](https://arxiv.org/abs/2606.20257)



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DOE-FG02-86ER-40281

Why study light ions

- Collective behavior observed in large (A+A) and in small (pp, p/D/He+A) systems
 - Similar p_T dependence of 'flow'
 - Strong indication that flow in small systems is geometry driven
 - However, theoretical modelling difficult in small systems
- Strong incentive to study intermediate-size collisions
 - Is QGP production and evolution smooth with transverse size down a proton?
 - Increased role of viscosity & fluctuations as system-size decreases
 - Can also probe nuclear geometries of Ne and O nuclei:
 - α -Clustering in O
 - Bowling-pin shape of Ne



p_T spectra and $\langle p_T \rangle \rightarrow$ Radial Flow

Observables studied

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p_T spectra and $\langle p_T \rangle \rightarrow$ Radial Flow

$v_n\{2\}$ and $v_n\{4\} \rightarrow$ Flow and flow fluctuations

Observables studied

5

p_T spectra and $\langle p_T \rangle \rightarrow$ Radial Flow

$v_n\{2\}$ and $v_n\{4\} \rightarrow$ Flow and flow fluctuations

$\frac{dn}{d\eta} \rightarrow$ Entropy

Observables studied

6

p_T spectra and $\langle p_T \rangle \rightarrow$ Radial Flow

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$\frac{dn}{d\eta} \rightarrow$ Entropy



Nuclear structure

α -Clustering

Equation of state

Shear and bulk viscosity

...

Observables studied

7

p_T spectra and $\langle p_T \rangle \rightarrow$ Radial Flow

$v_n\{2\}$ and $v_n\{4\} \rightarrow$ Flow and flow fluctuations

$\frac{dn}{d\eta} \rightarrow$ Entropy

Ratios:

- Ne+Ne/O+O
- Central/Peripheral
- Mid-rapidity/forward-rapidity

Nuclear structure

α -Clustering

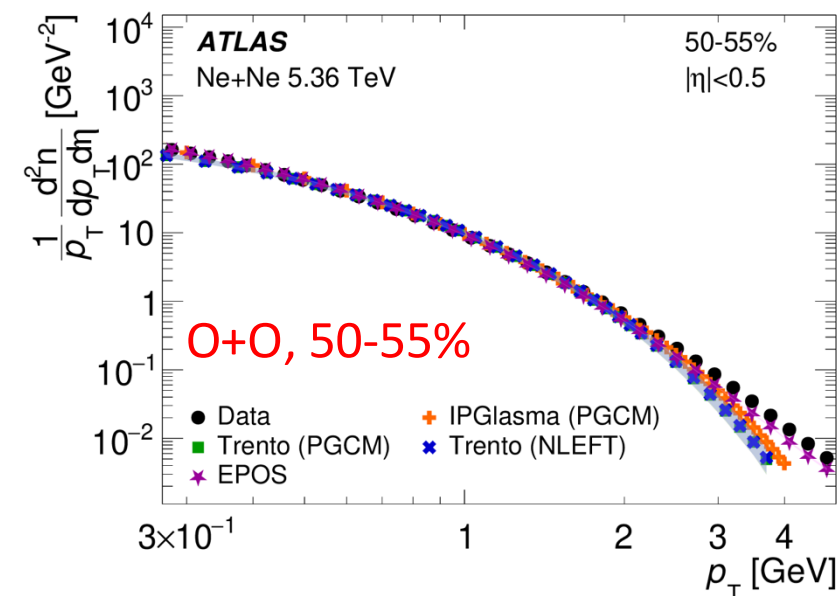
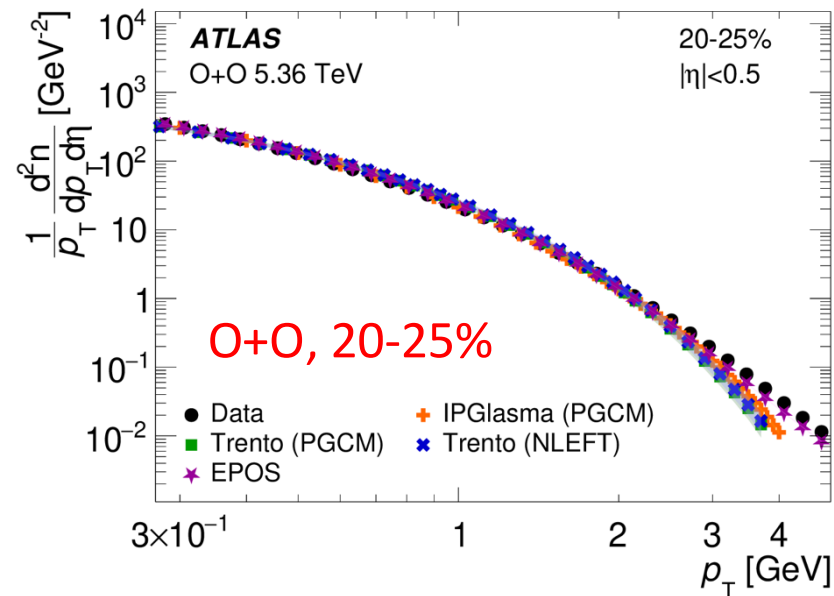
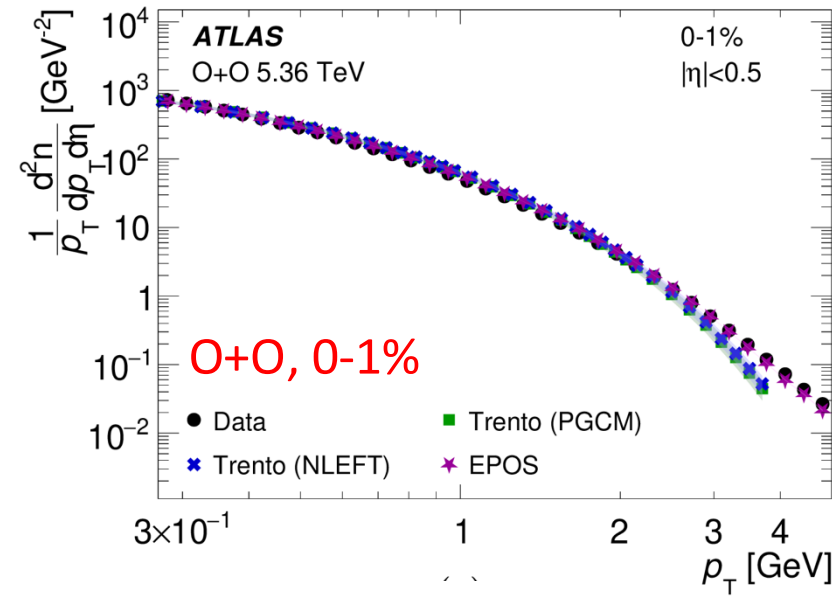
Equation of state

Shear and bulk viscosity

...

Enhanced sensitivity to individual sources
Cancellation of experimental uncertainties.

p_T spectra



- p_T spectra and comparison to models

- Left : central collisions
- Center: mid-central collisions
- Right : peripheral collisions

- Hydro model calculations

- IPGlasma or Trento initial conditions
- Using PGCM or NLEFT nuclear modelling
- Data generally well described by models.
 - Within 5-15% for $p_T < 2 \text{ GeV}$
 - Except for EPOS, deviations at higher p_T

p_T spectra ratios : Ne+Ne/O+O

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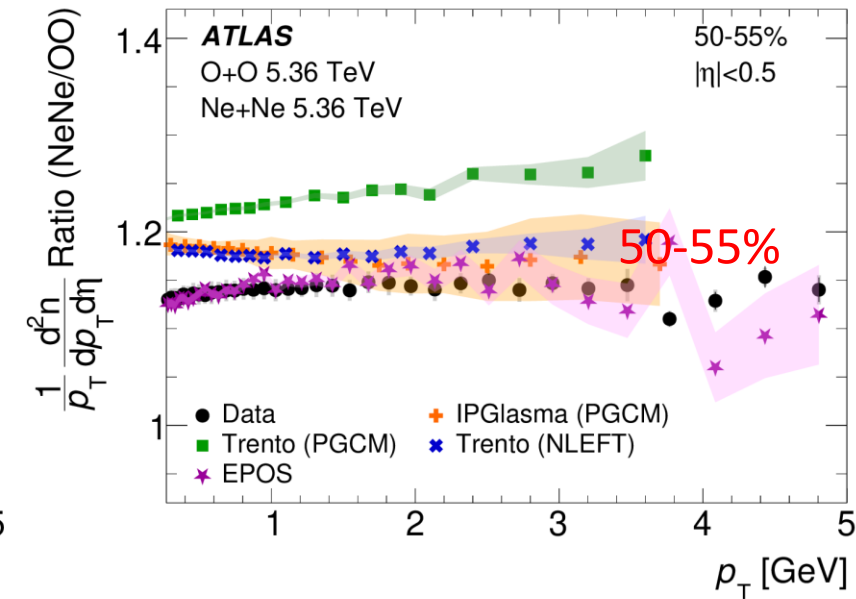
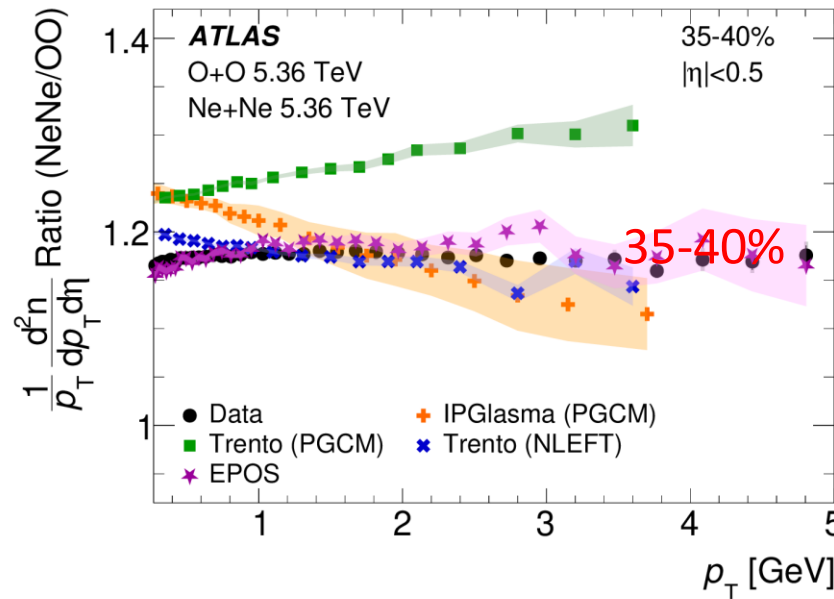
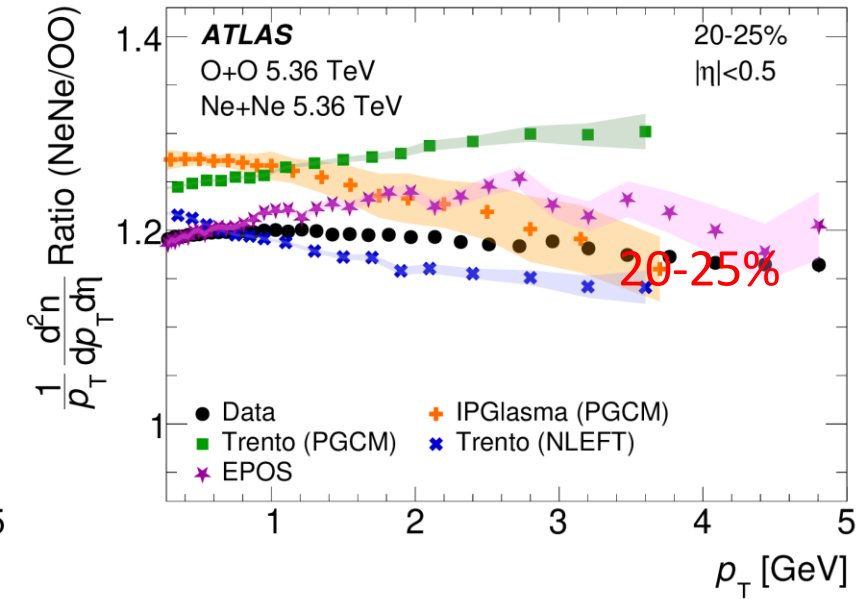
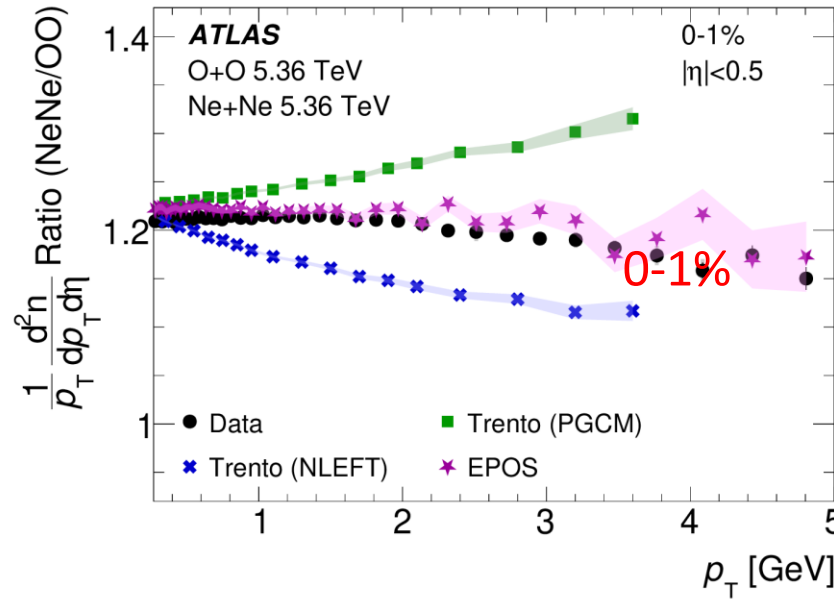
Ne+Ne/O+O ratios in data;
nearly flat vs p_T

Best reproduced by EPOS

Hydro Models show stronger p_T
dependence: Spectra harder or
softer than in data

Larger/Smaller radial flow in
models, depending on nuclear
modelling.

Uncertainties in measurements
much smaller than model
differences.



p_T spectra ratios : Central/Peripheral

10

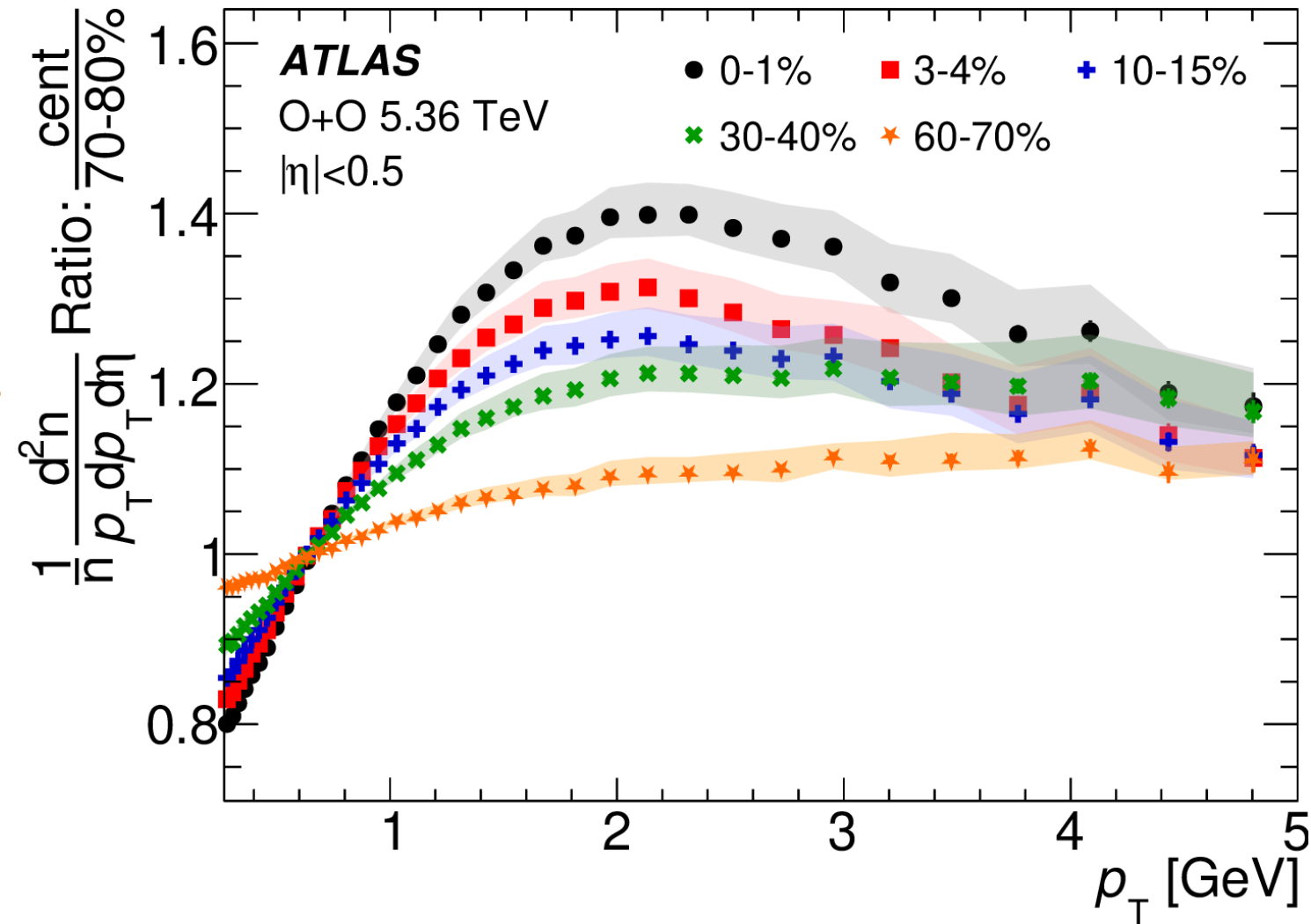
Central/Peripheral ratios in O+O

Reference periph. centrality: 70-80%

Spectra: progressively harder in central collisions for $p_T < 2$ GeV:

Stronger radial flow in central collisions.

At higher p_T trends reverse; region dominated by hard processes.



p_T spectra ratios : Central/Peripheral

11

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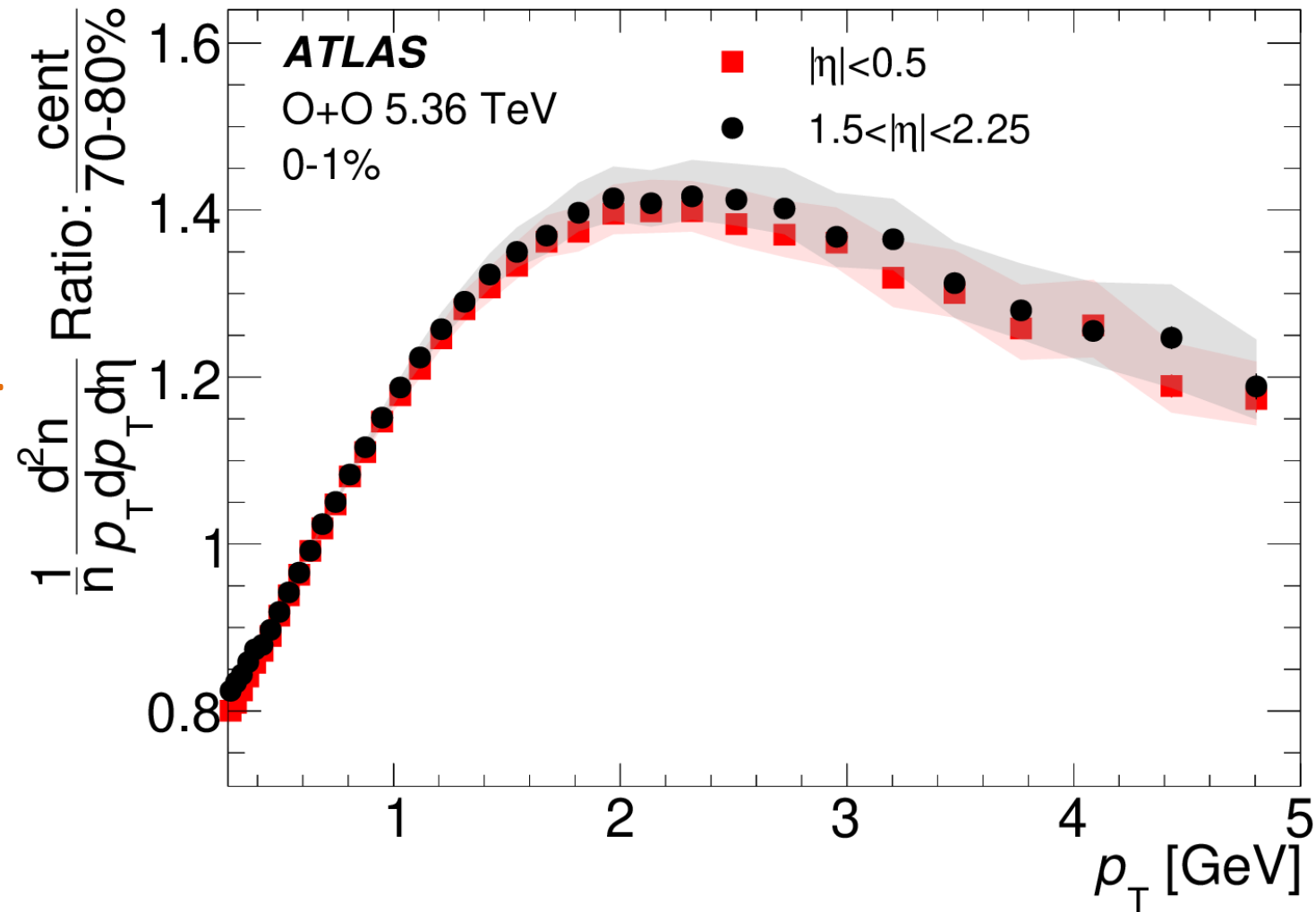
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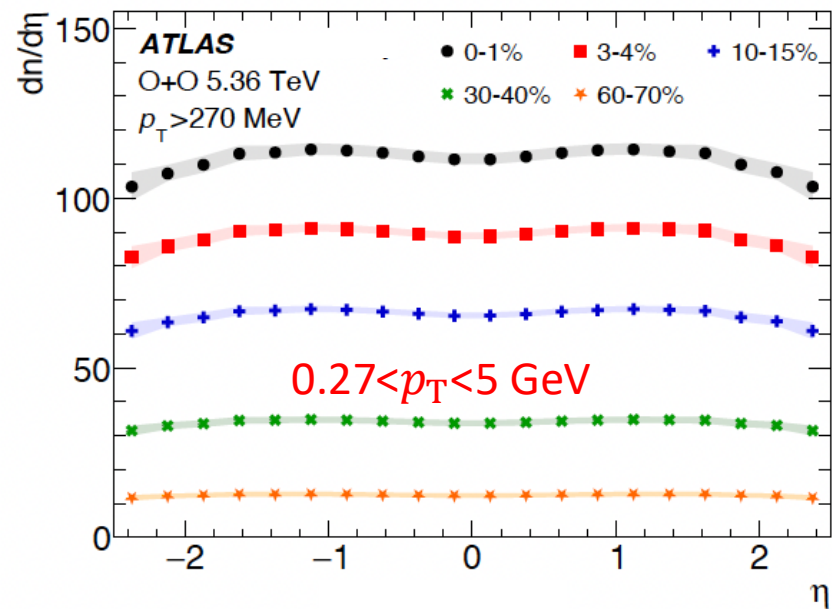
At higher p_T trends reverse; region dominated by hard processes.

Compare ratios at mid- and forward rapidity:

See boost invariance of radial flow (and non-flow).

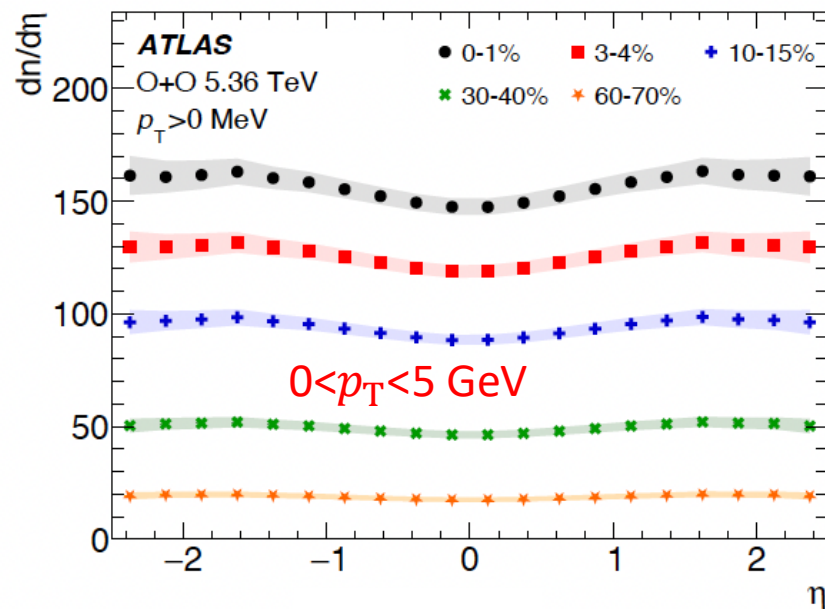
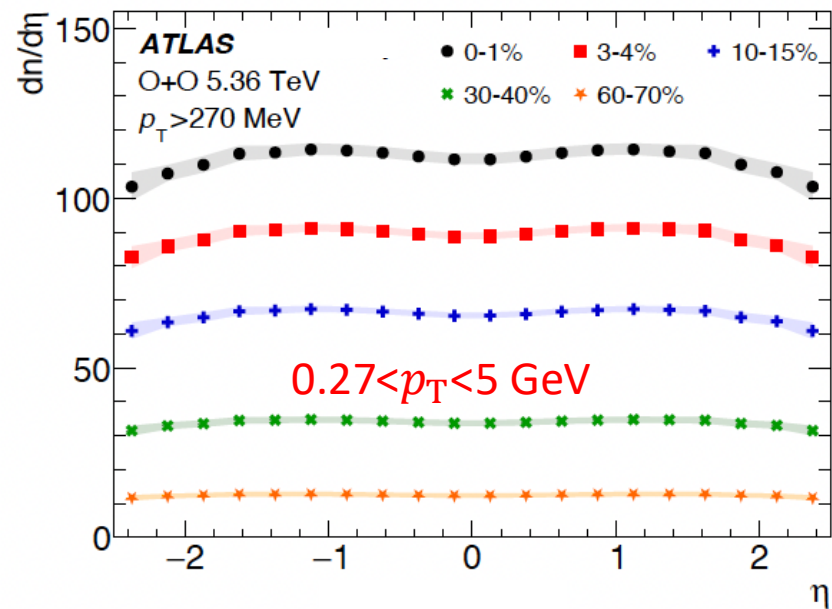


$dn/d\eta$ and dn/dy_π



- Multiplicity vs (psuedo) rapidity
 - Left : $dn/d\eta$ for $0.27 < p_T < 5$ GeV : Fiducial region

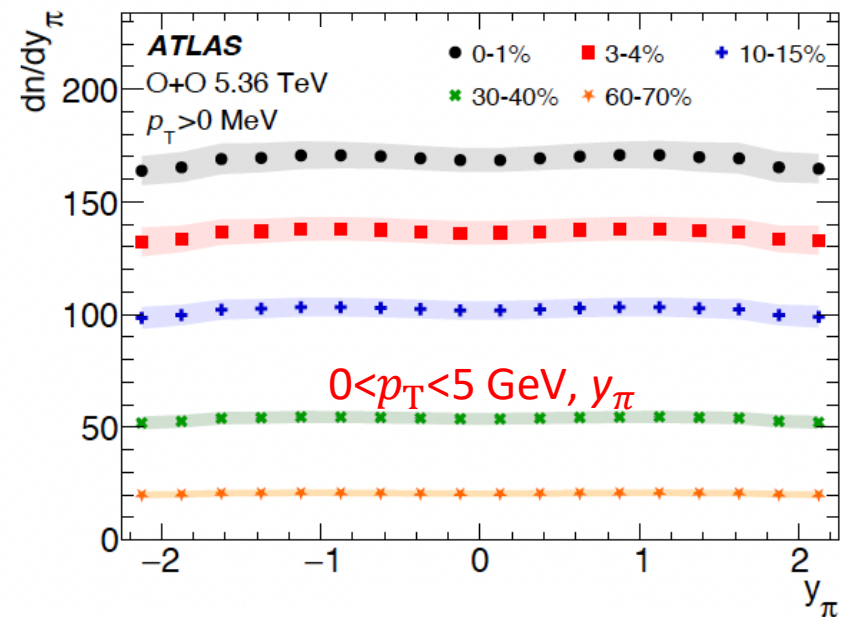
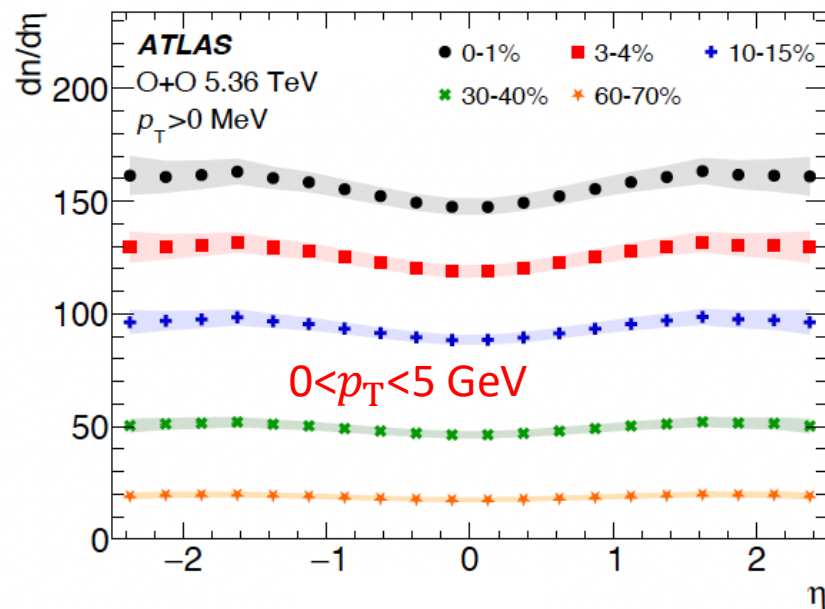
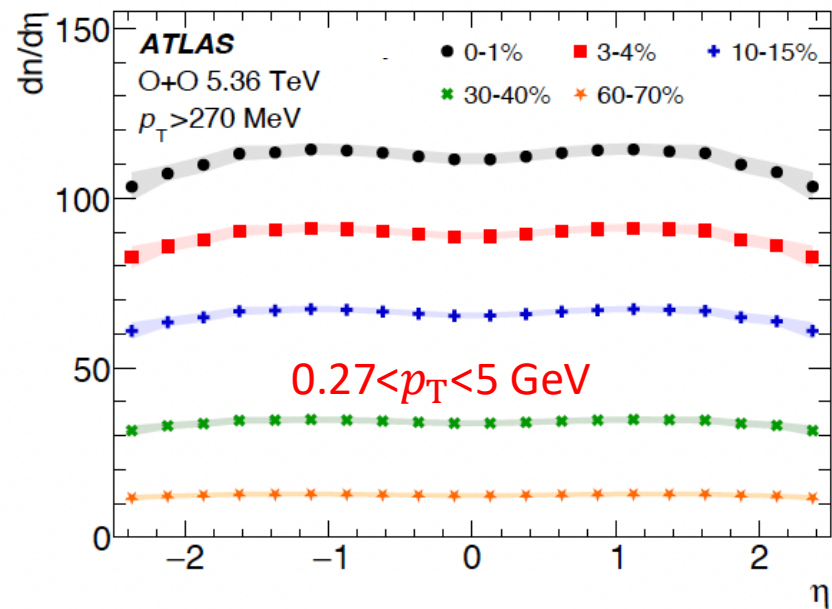
$dn/d\eta$ and dn/dy_π



■ Multiplicity vs (psuedo) rapidity

- Left : $dn/d\eta$ for $0.27 < p_T < 5$ GeV : Fiducial region
- Center: $dn/d\eta$ for $0 < p_T < 5$ GeV : Extrapolated to 0 GeV

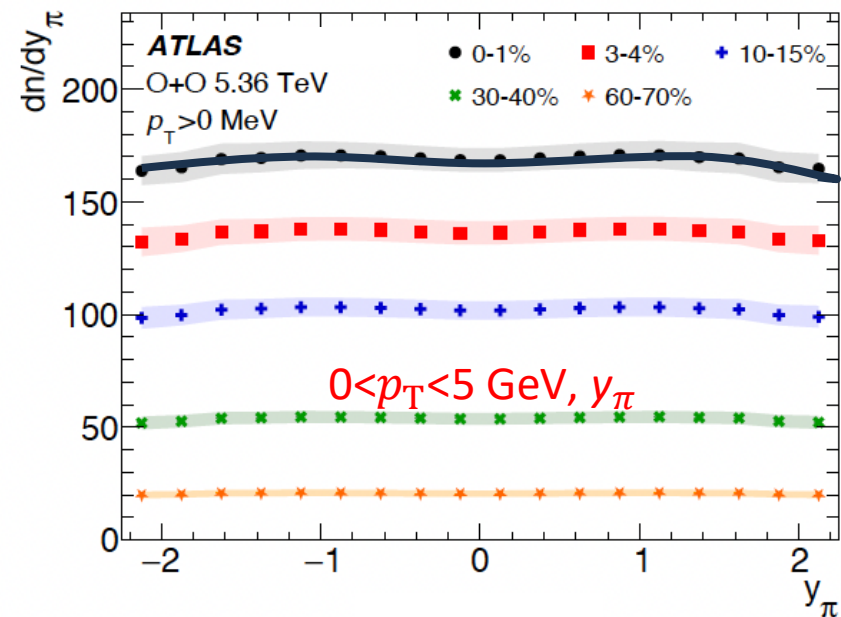
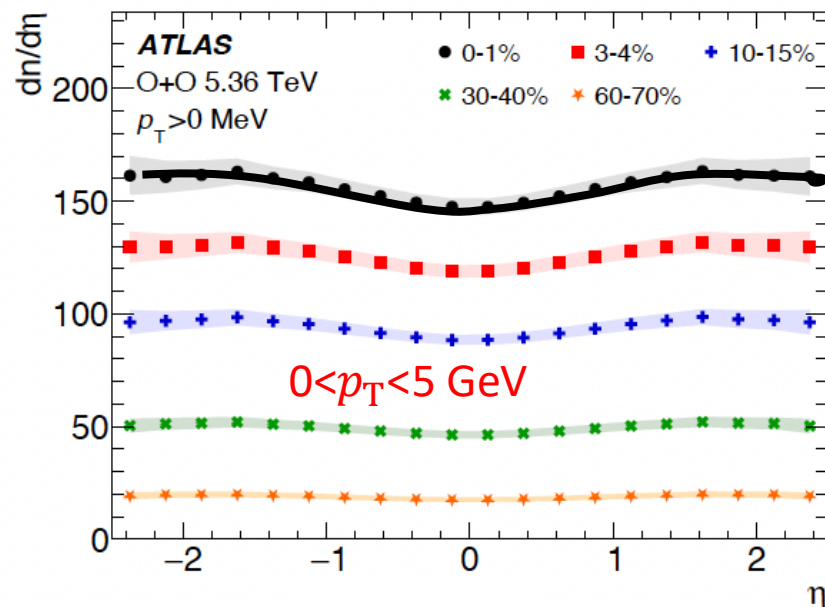
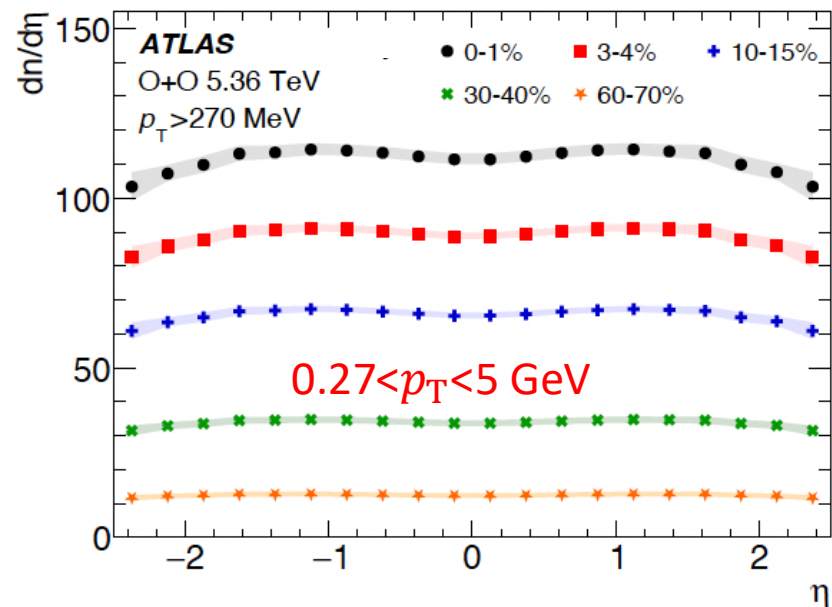
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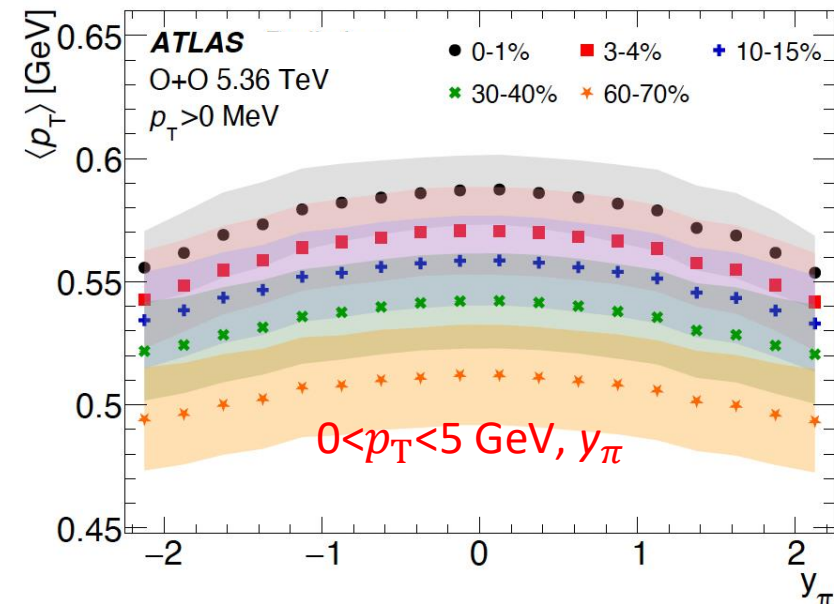
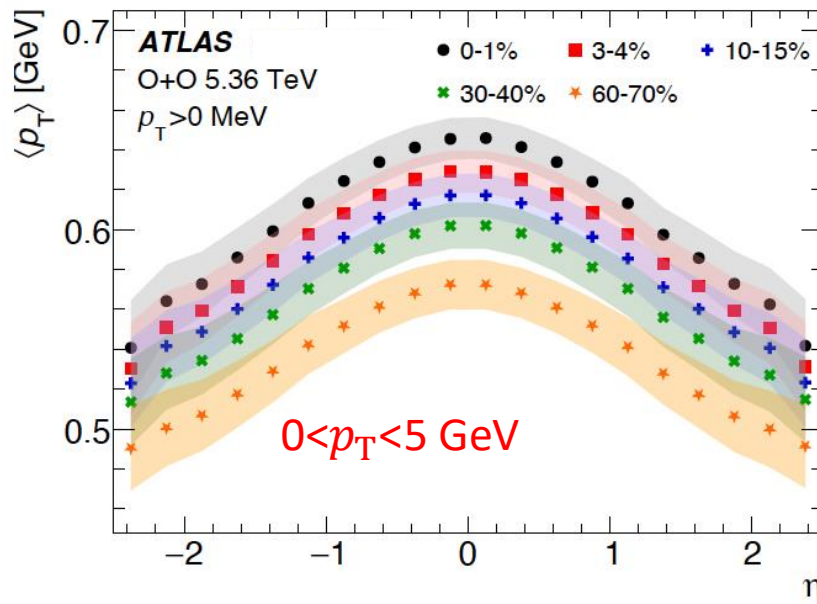
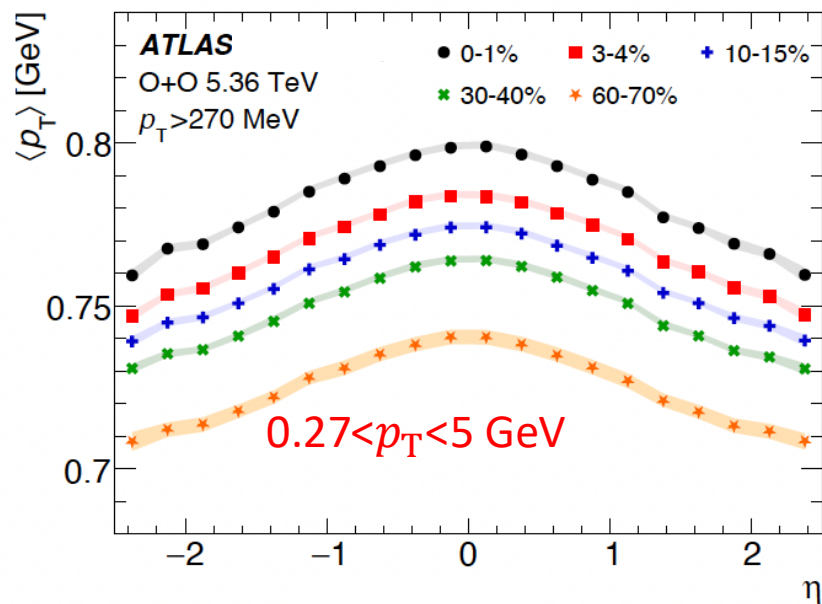
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$dn/d\eta$ and dn/dy_π



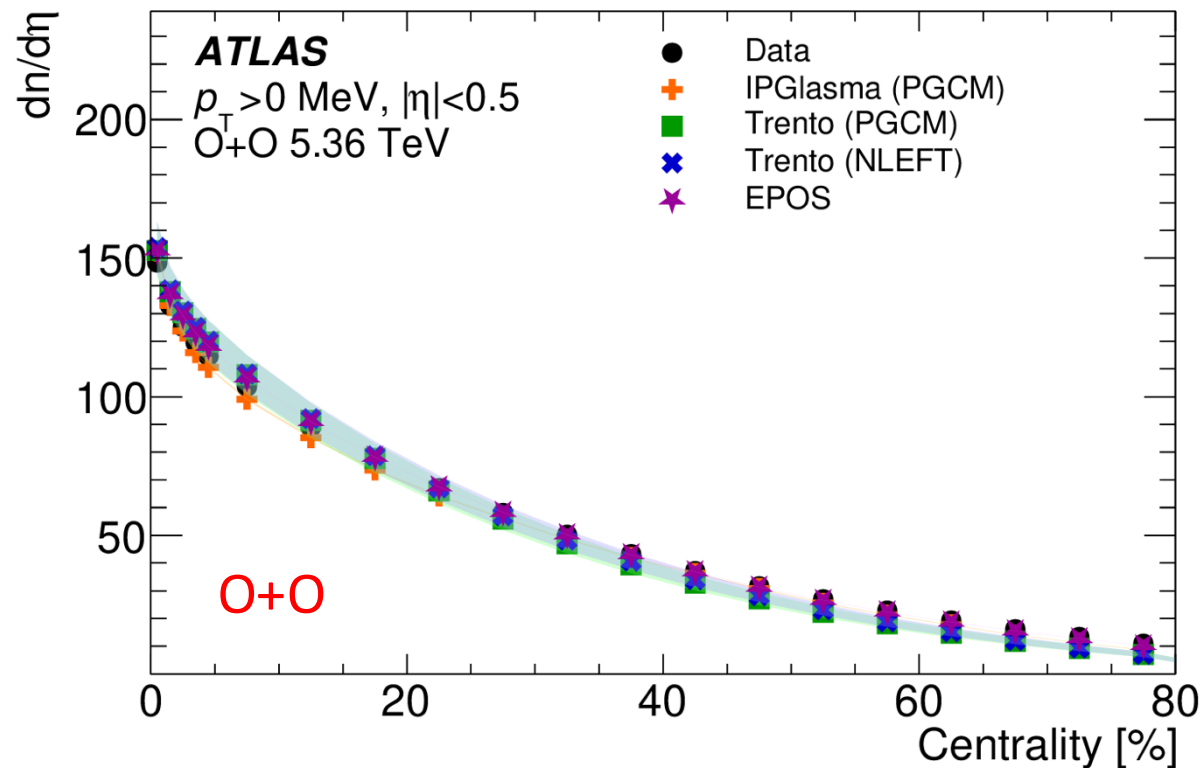
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 - Right : dn/dy_π for $0 < p_T < 5$ GeV : Extrapolated to 0 GeV, pion mass assumption
- Multiplicities increase from peripheral to central collisions
 - Dip at $\eta = 0$ in $dn/d\eta$ distributions
 - Dip weaker in dn/dy_π : demonstrates approx boost invariance

$\langle p_T \rangle$ vs η and y_π



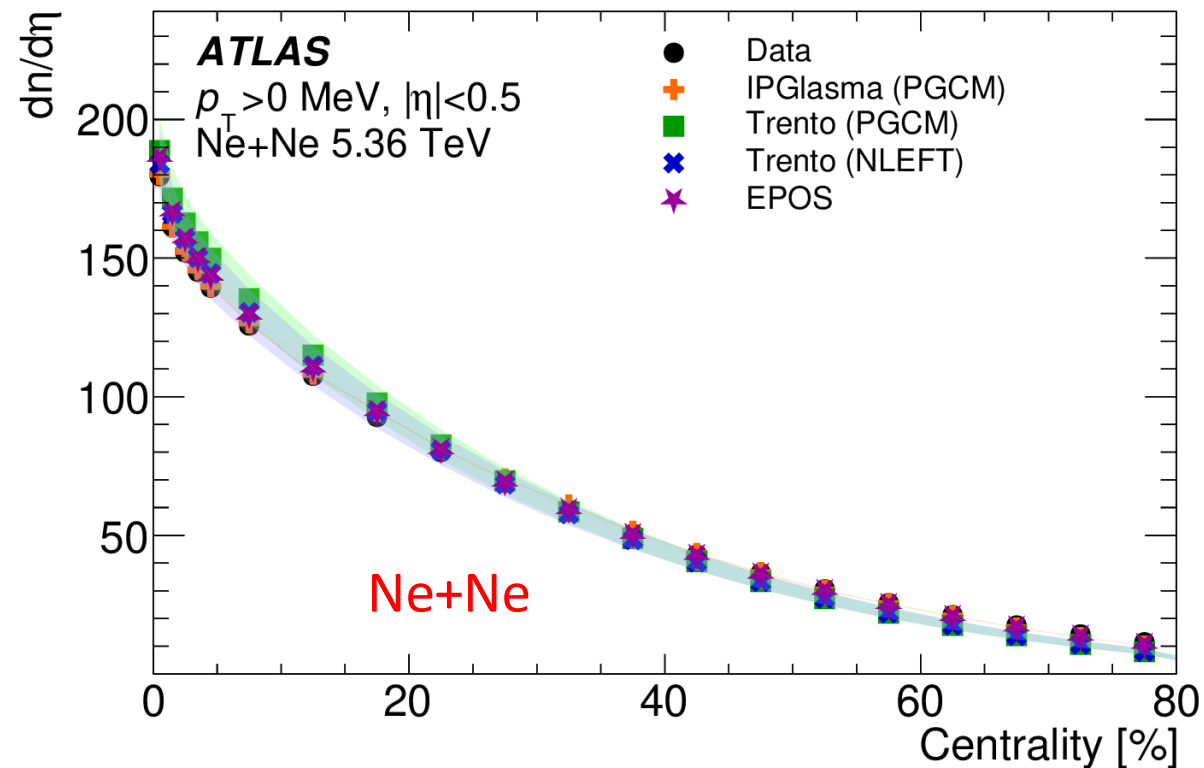
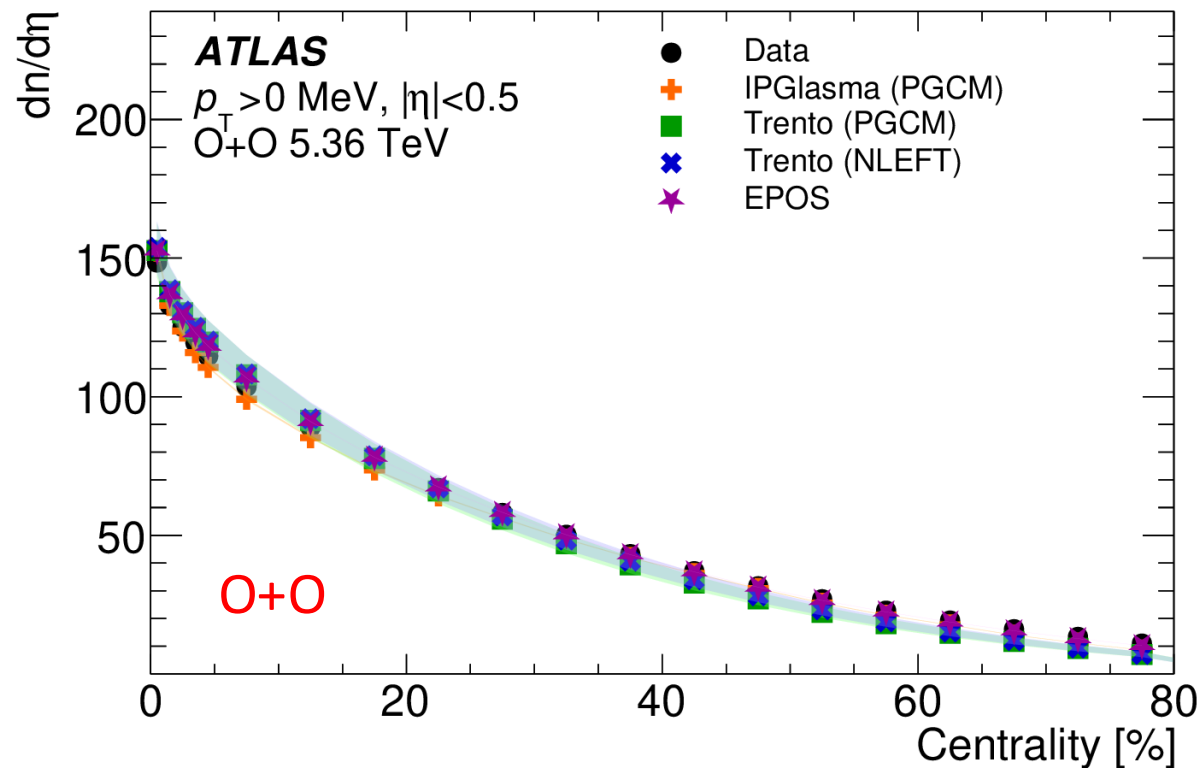
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 - Right : dn/dy_π for $0 < p_T < 5$ GeV : Extrapolated to 0 GeV, pion mass assumption
- Only ~ 70 MeV change from central to peripheral collisions
 - Distributions much flatter as function of y_π

$dn/d\eta$ vs centrality



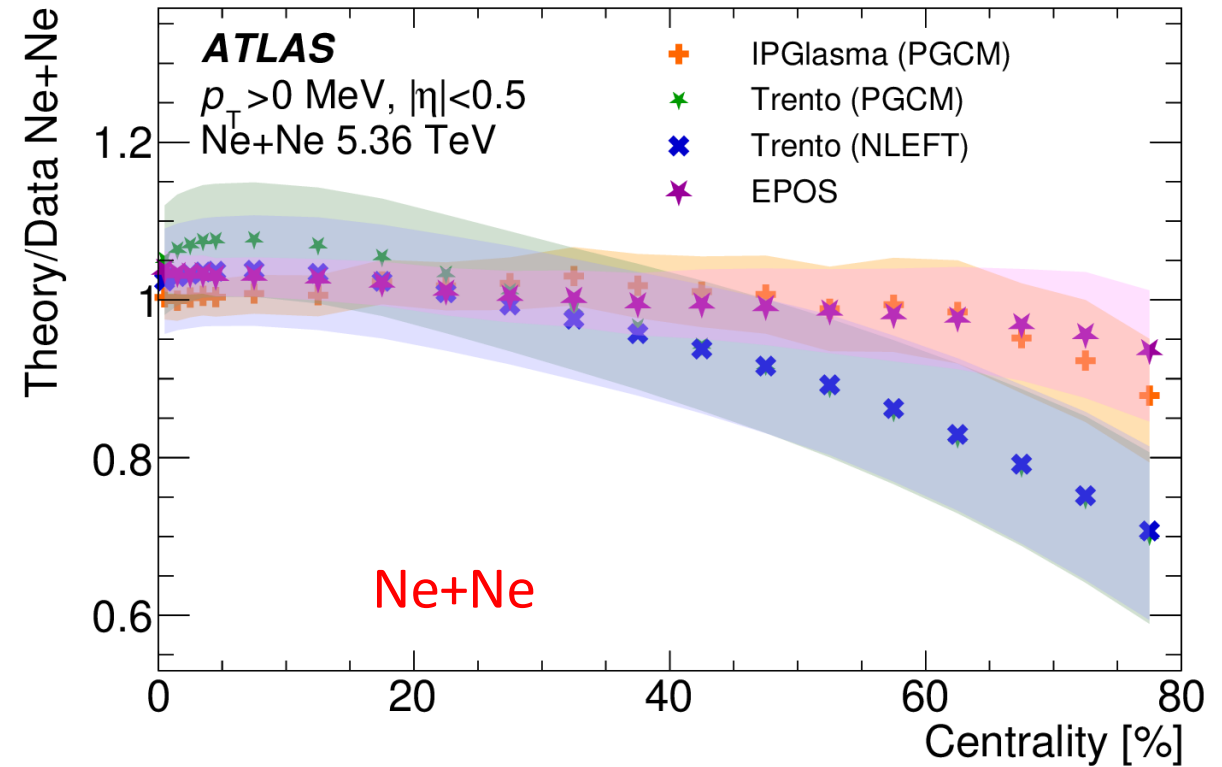
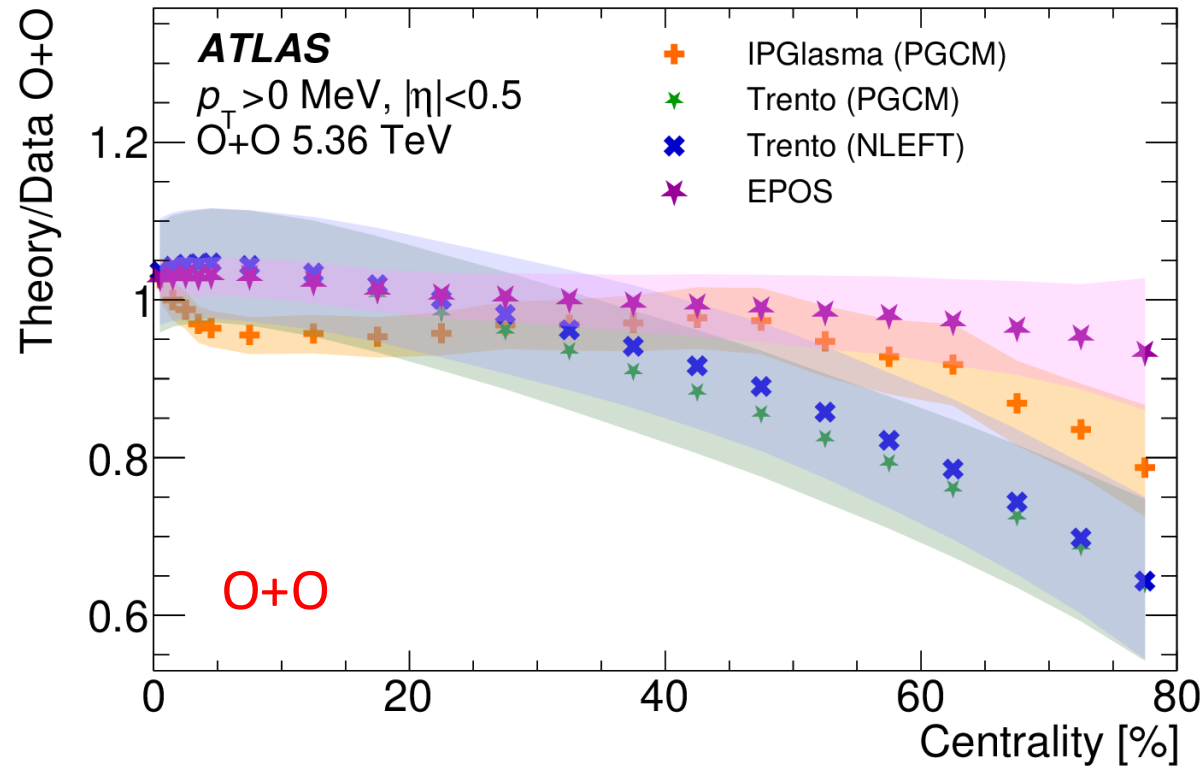
- $dn/d\eta$ vs centrality for $|\eta| < 0.5$
 - Model calculations generally reproduce O+O measurements

$dn/d\eta$ vs centrality



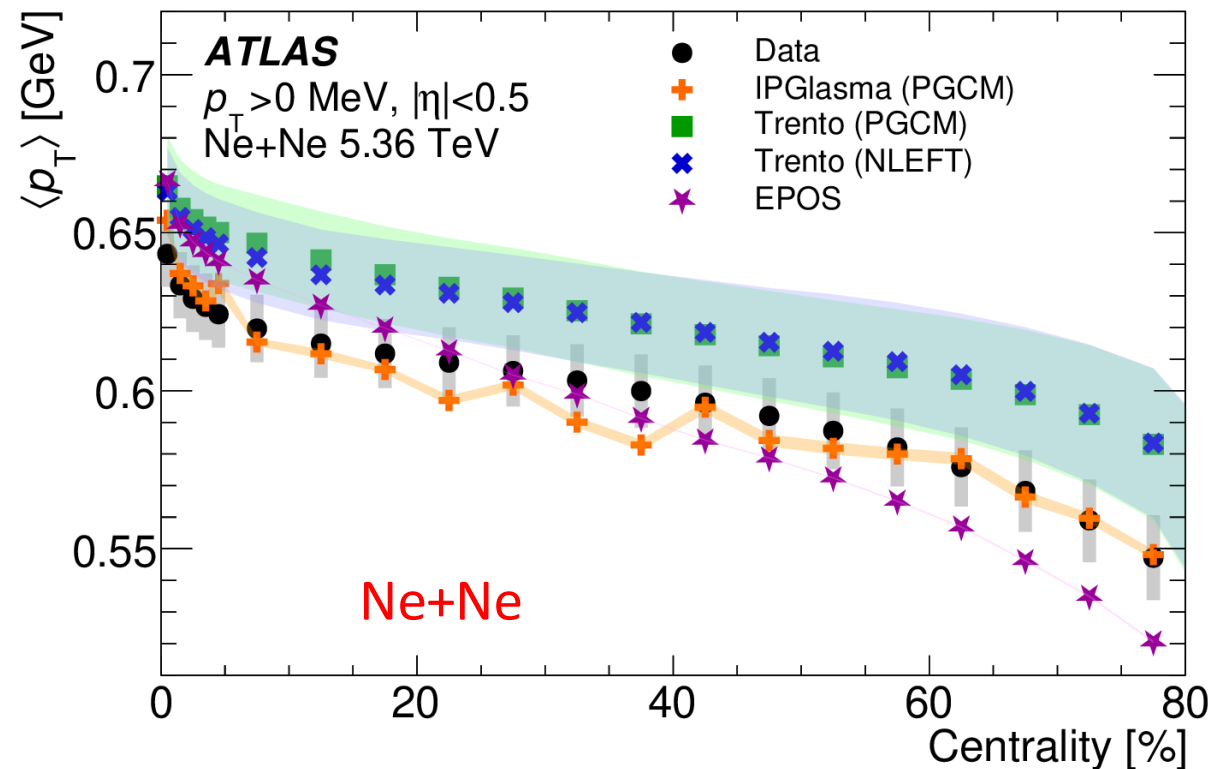
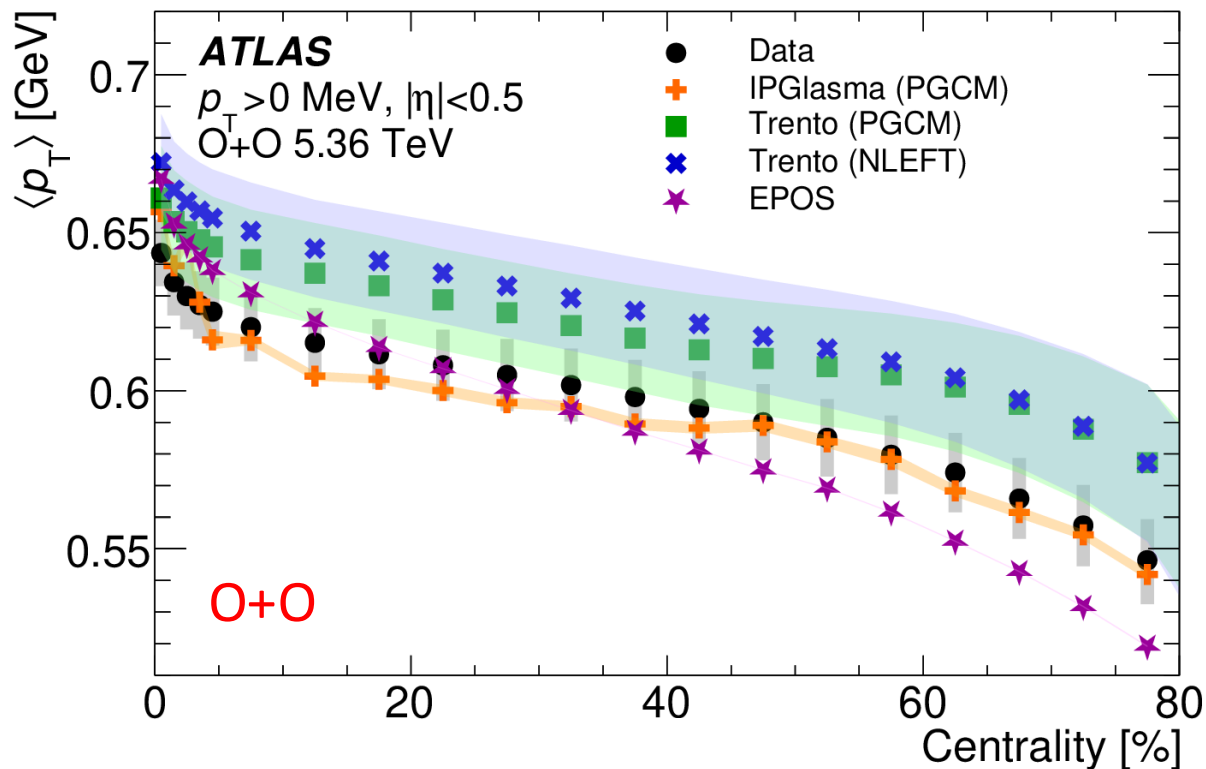
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- And Ne+Ne measurements



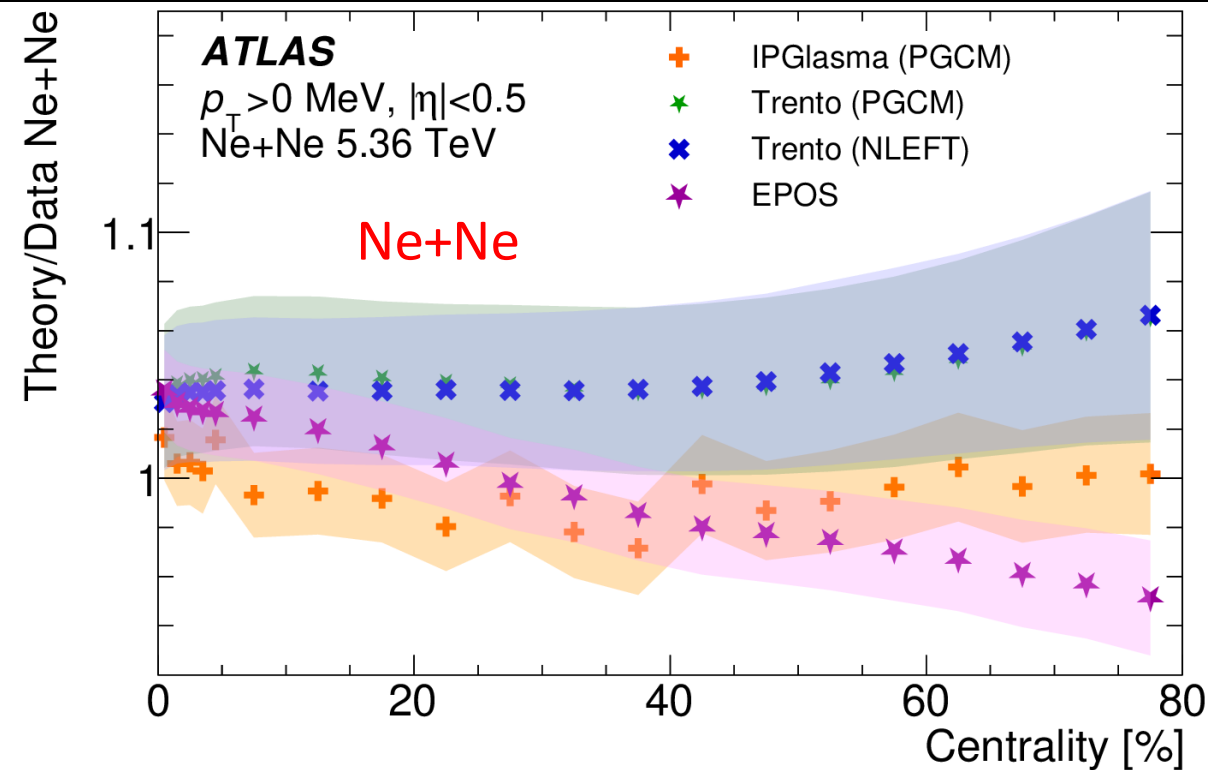
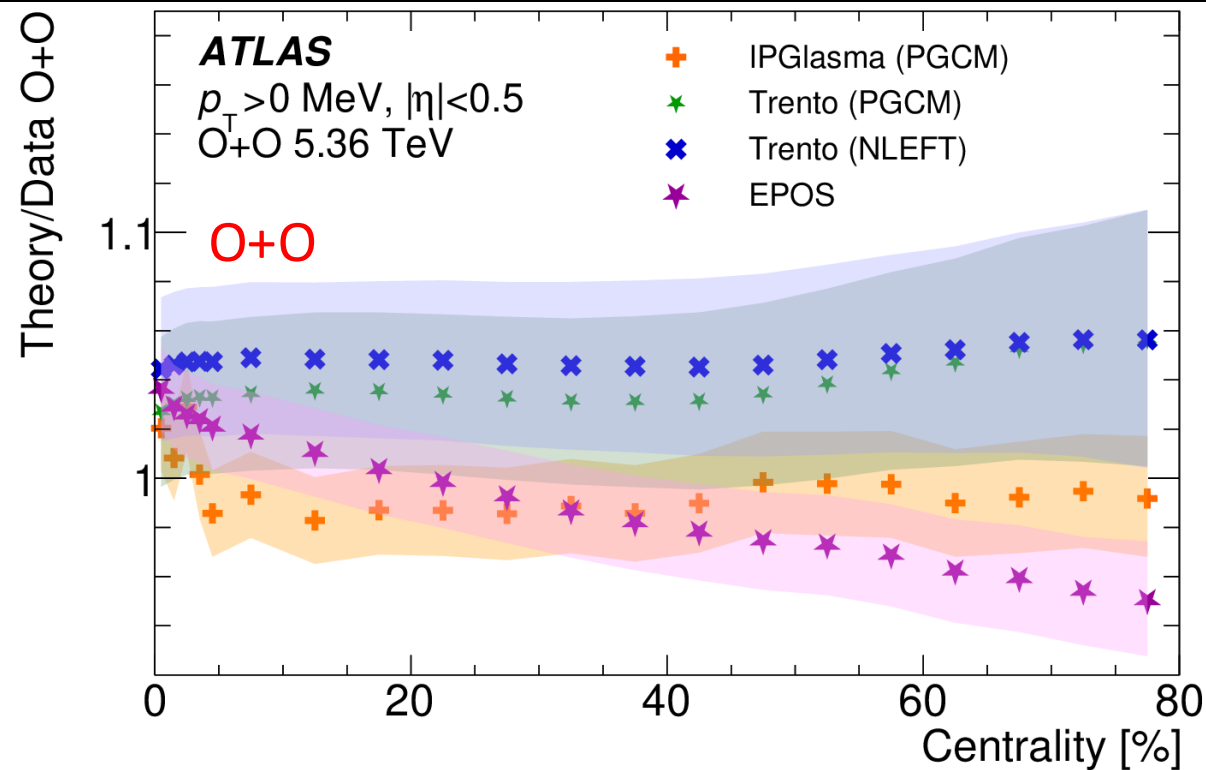
- $dn/d\eta$ vs centrality for $|\eta| < 0.5$
 - Model calculations generally reproduce O+O measurements
 - And Ne+Ne measurements
- Model/data ratios
 - Systematic increase in different from central $\rightarrow$ peripheral collisions
 - IPGlasma (+Music) offers better description than Trento (+Trajectum)
 - Overall EPOS is closest to data

$\langle p_T \rangle$ vs centrality



- $\langle p_T \rangle$ vs centrality for $|\eta| < 0.5$
 - 'S' Shape
 - ~100 MeV variation across measured centrality range
 - IPGlasma (+MUSIC) very close; Trento off by ~3 MeV

$\langle p_T \rangle$ vs centrality



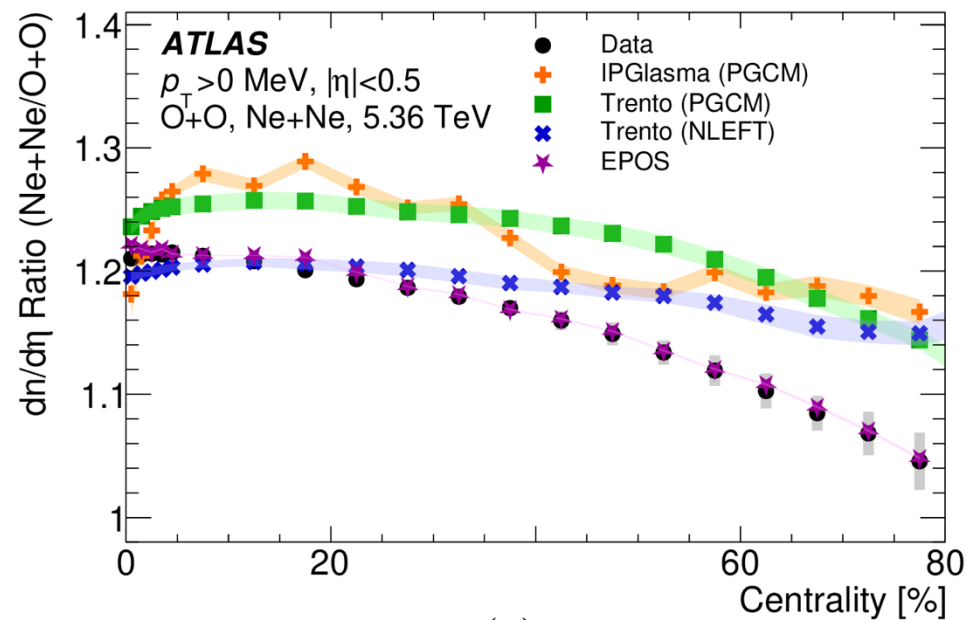
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 - 'S' Shape
 - ~100 MeV variation across measured centrality range
 - IPGlasma (+MUSIC) very close; Trento off by ~3 MeV
- Model/data ratios
 - Ratios flat vs centrality
 - Consistent with data within uncertainties.

Ne+Ne/O+O ratios

Ne+Ne/O+O :
 $dn/d\eta$ ratio vs centrality

Hydro models comparable
 at 0% central collisions.
 Deviations for more
 peripheral events.

EPOS shows best
 comparison to data

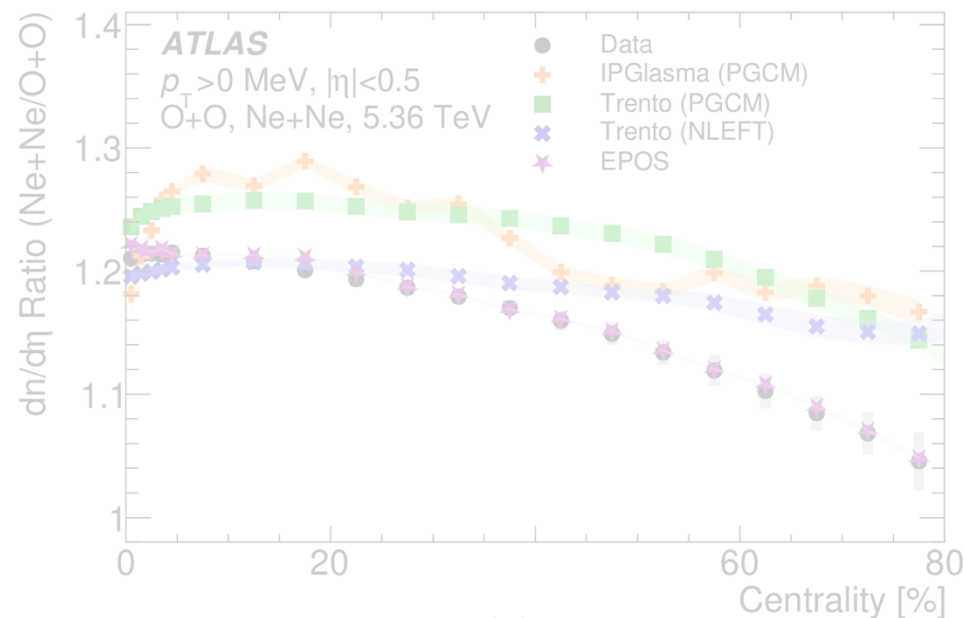


Ne+Ne/O+O ratios

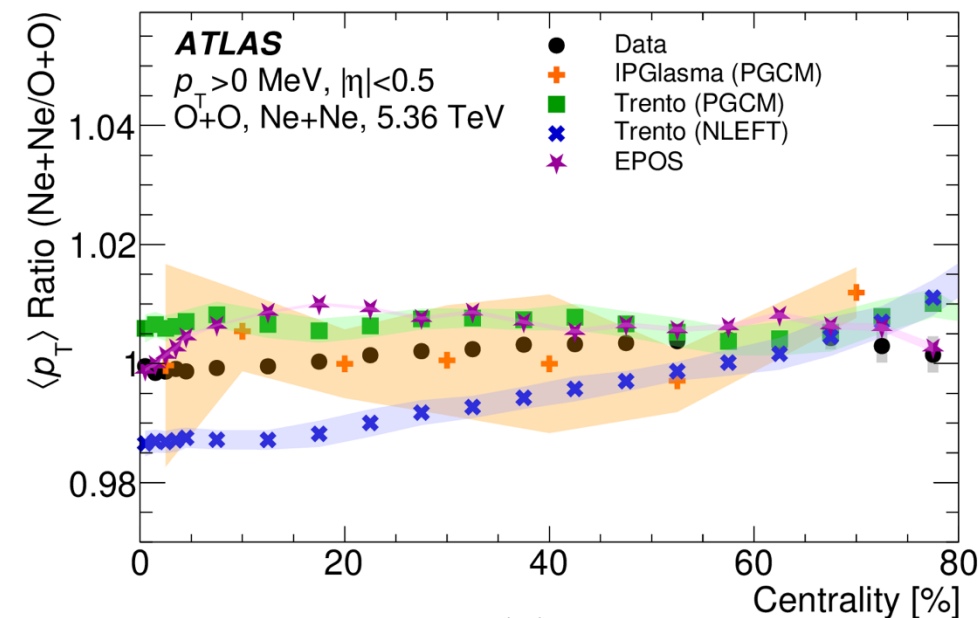
Ne+Ne/O+O :
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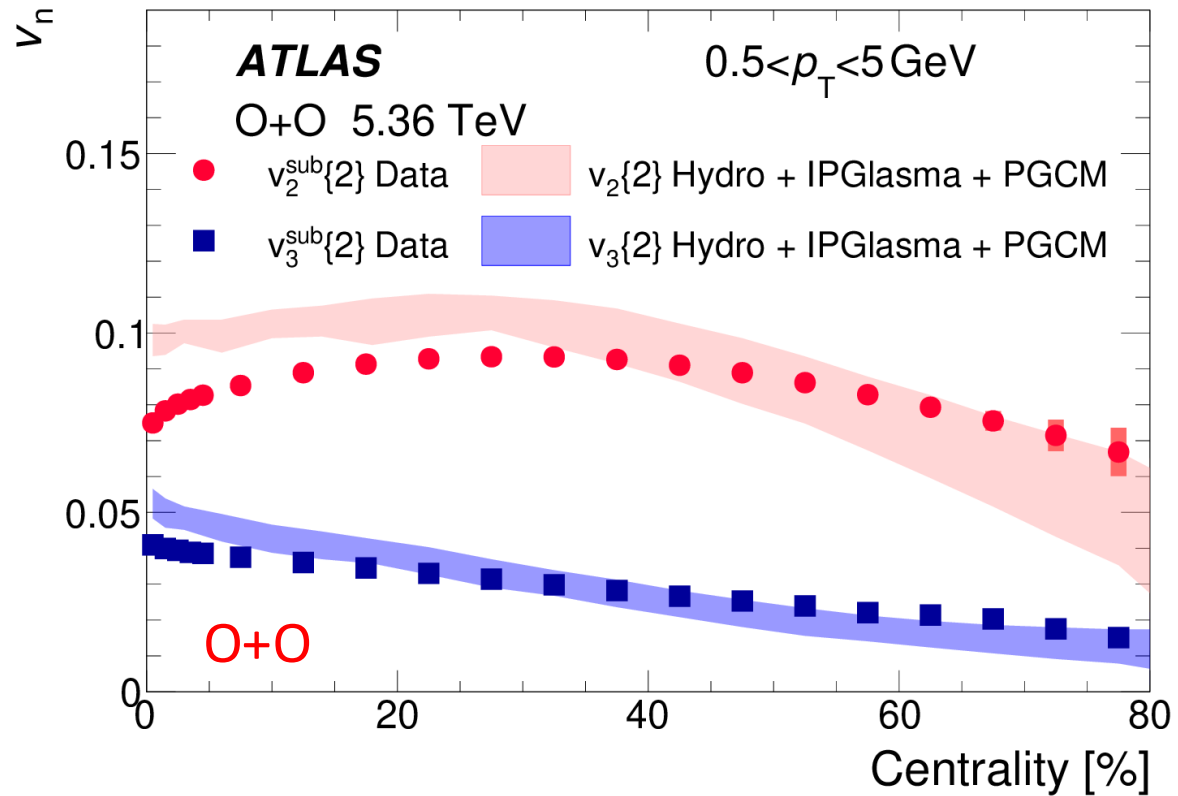
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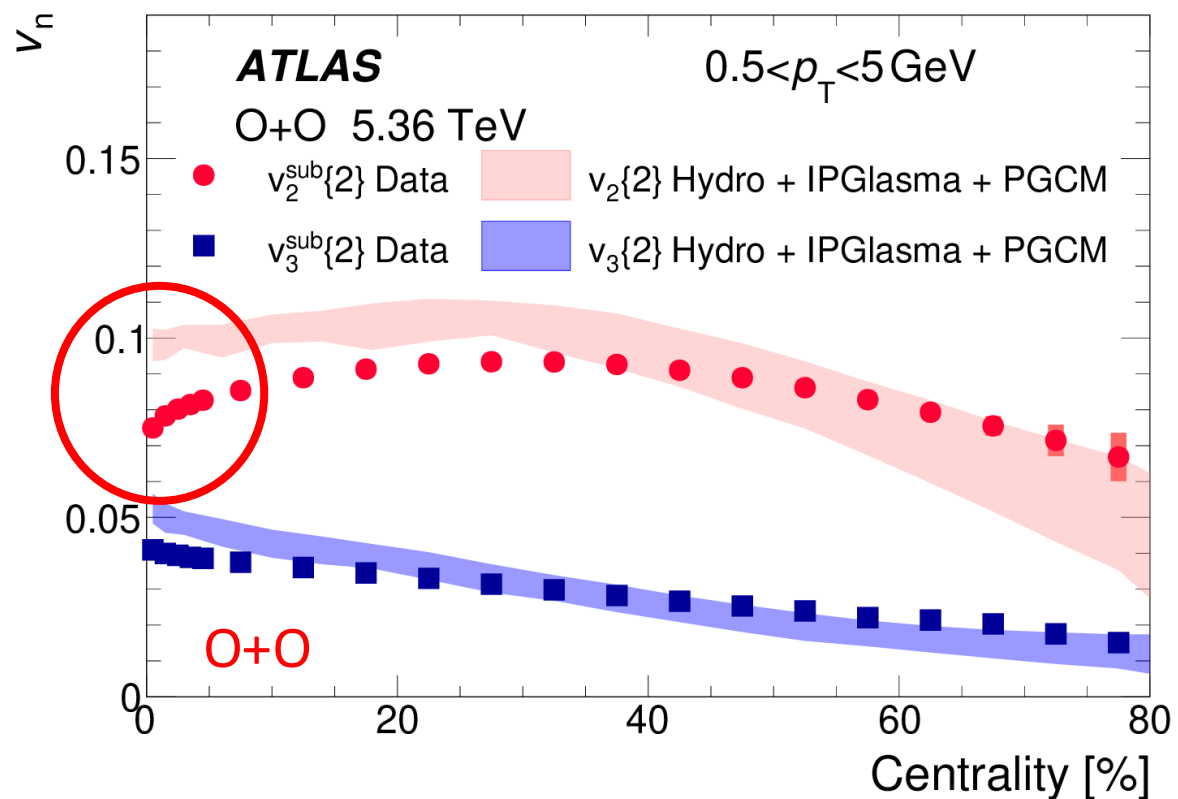
$\langle p_T \rangle$ ratio vs centrality :
 Models within 1-2% of data.



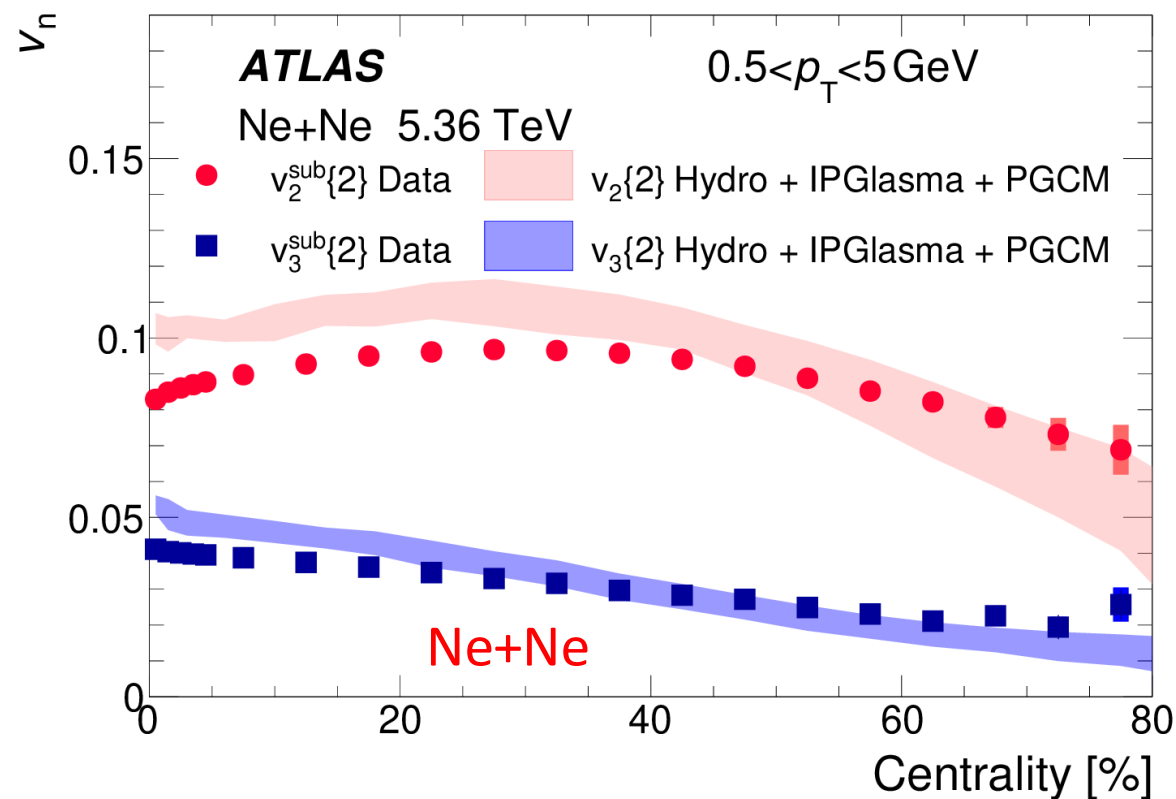
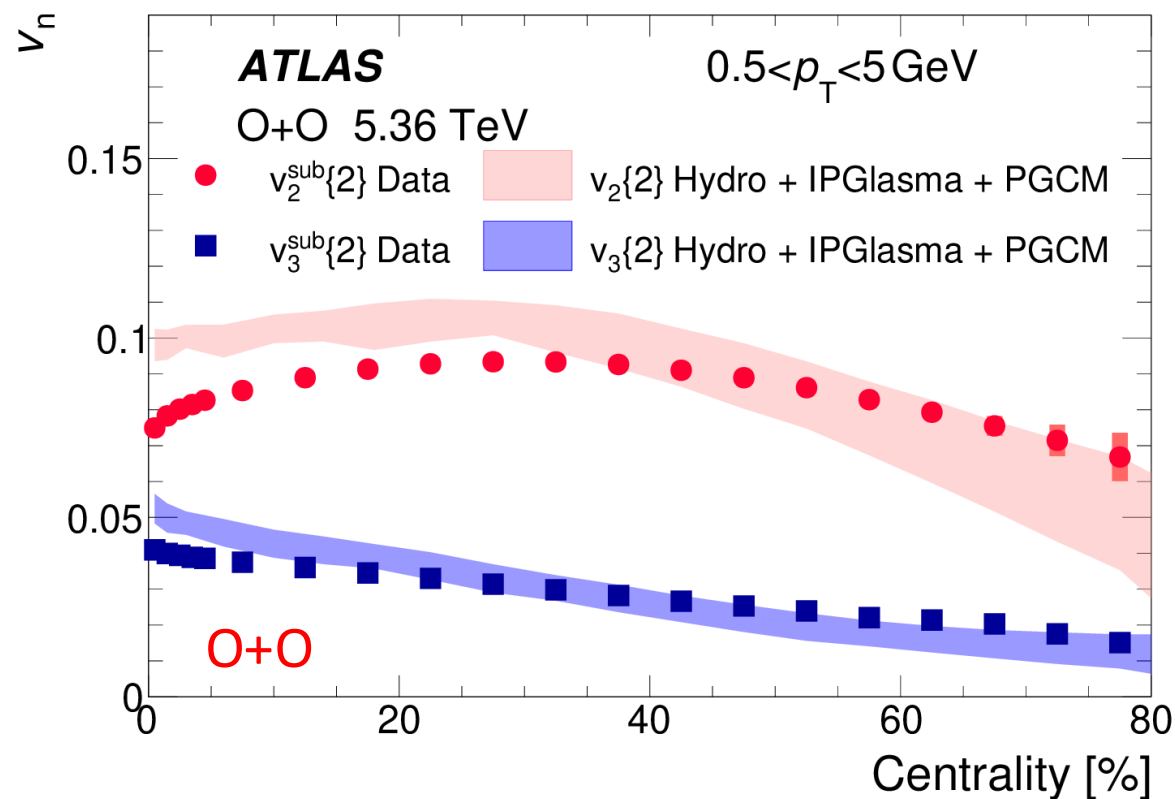


- v_2 and v_3 vs centrality for O+O
- Average geometry effects seen in v_2

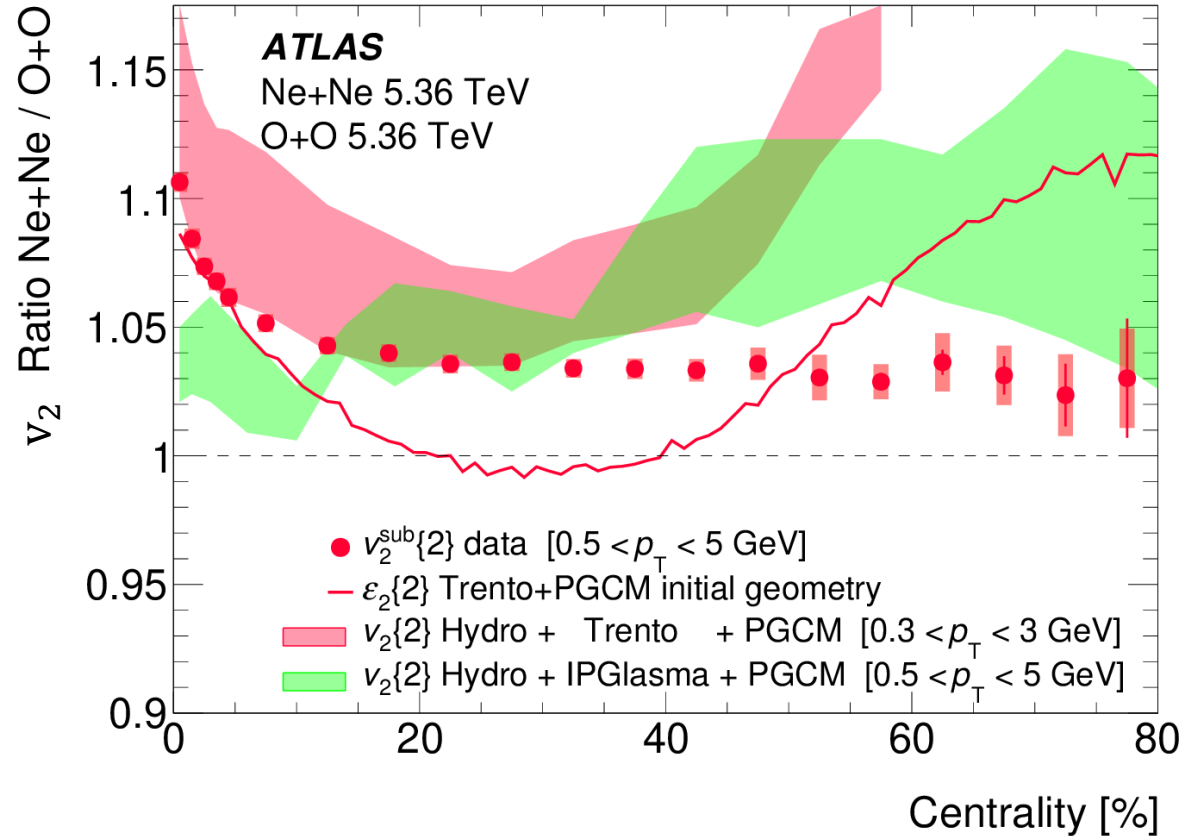
Anisotropic flow



- v_2 and v_3 vs centrality for O+O
 - Average geometry effects seen in v_2
 - Theory models overpredict in central collisions



- v_2 and v_3 vs centrality for O+O
 - Average geometry effects seen in v_2
 - Theory models overpredict in central collisions
- Similar trends seen for Ne+Ne



- v_2 ratio Ne+Ne/O+O vs centrality
 - Bump up in v_2 ratio, over 0-5% centrality
 - Attributed to “bowling-pin” shape of Ne nucleus in models
 - Significant data-theory disagreement in peripheral collisions

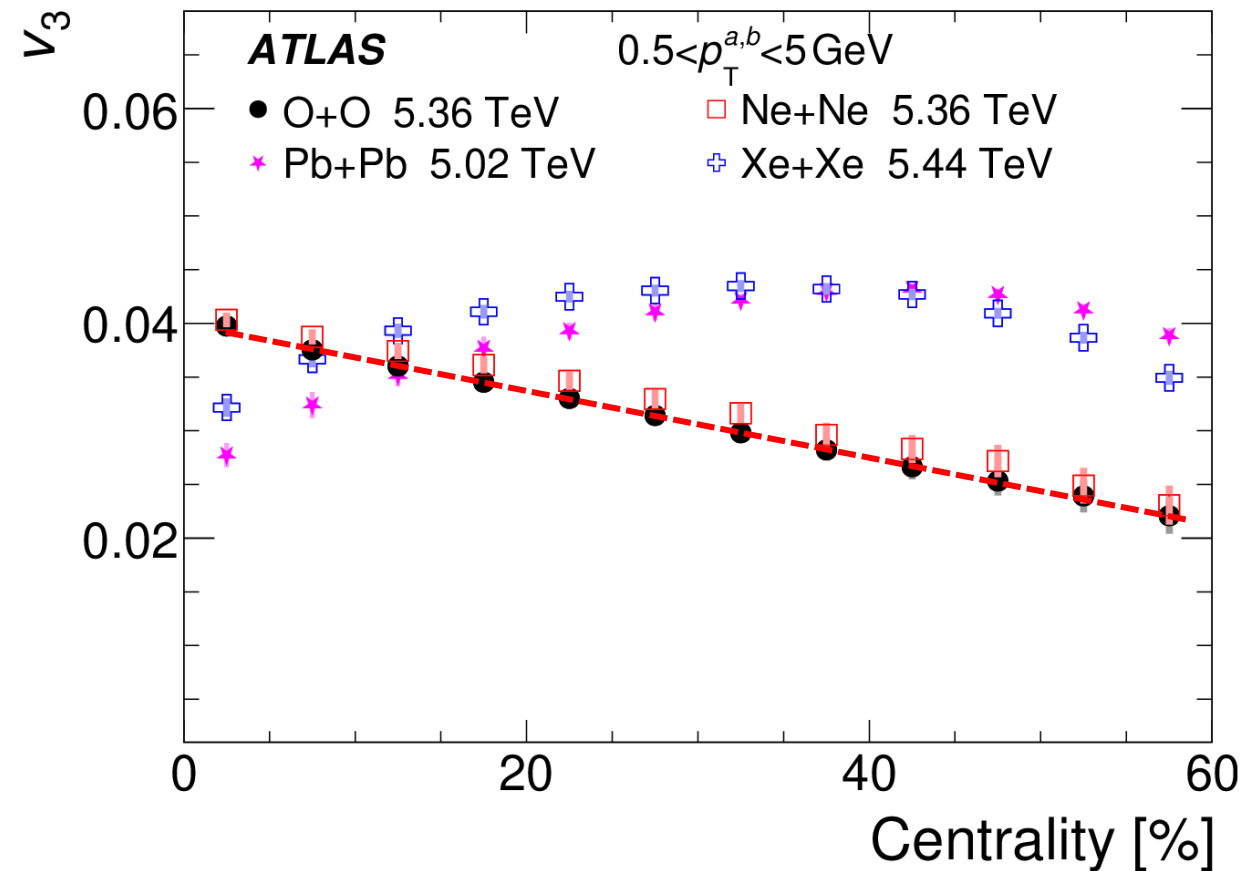
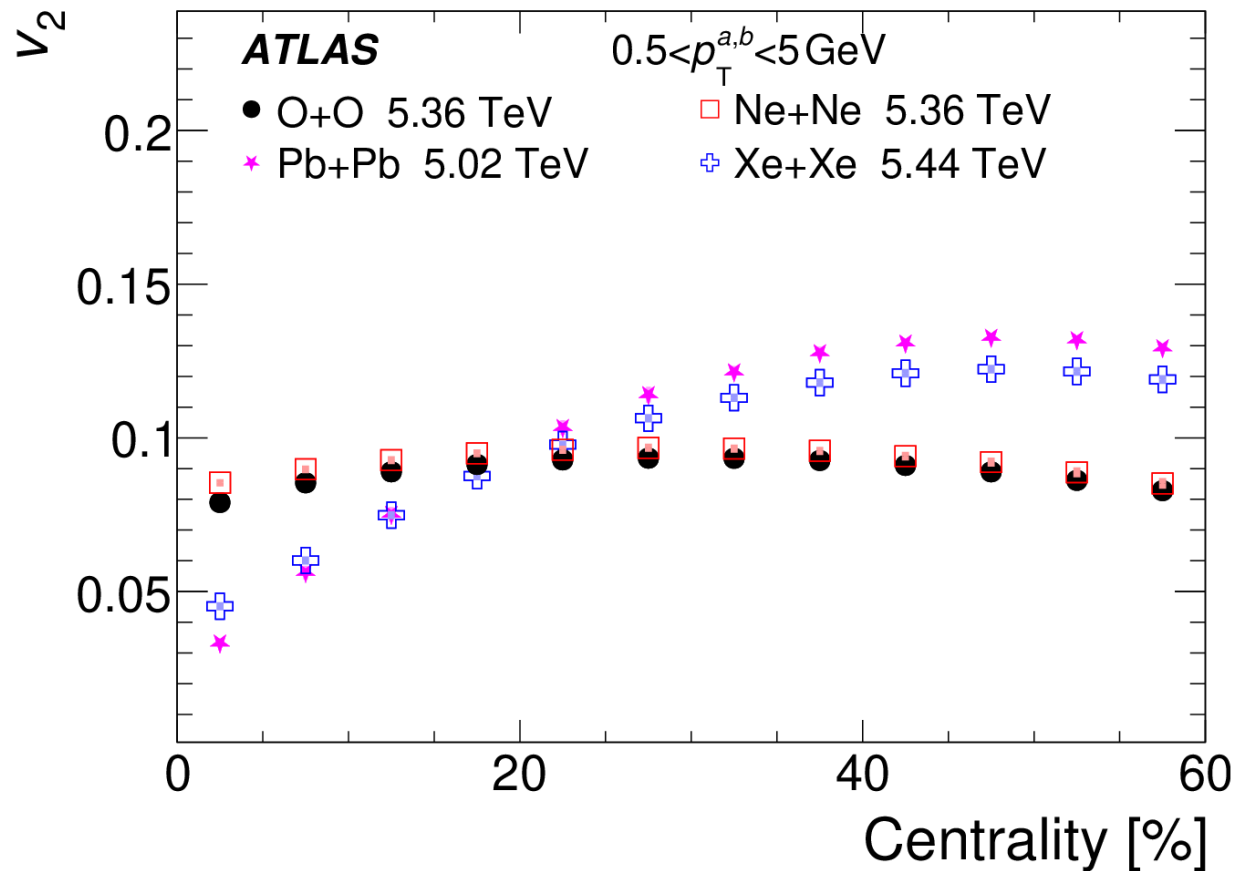
Summary

- Comprehensive set of measurements probing particle production
 - p_T spectra and $\langle p_T \rangle$ [arXiv:2606.20257](https://arxiv.org/abs/2606.20257) (hepdata.net/record/ins3170344)
 - $dn/d\eta$ and dn/dy_π [arXiv:2606.20257](https://arxiv.org/abs/2606.20257) (hepdata.net/record/ins3170344)
 - $v_n\{2\}$ and $v_n\{4\}$ [arXiv:2606.20257](https://arxiv.org/abs/2606.20257) (hepdata.net/record/ins3170344)
- Ratios : Central/peripheral, mid/forward-rapidity, Ne+Ne/O+O
 - Stronger sensitivity to one aspect vs another
 - Largely insensitive to p_T selections
- High precision, not statistics limited
 - Strong constraints for models
- Measurements able to probe multiple facets of soft physics
 - Hydrodynamics
 - Geometry fluctuations
 - Nuclear structure

Backup

Flow: Light-ions vs Heavy-ions, centrality dependence

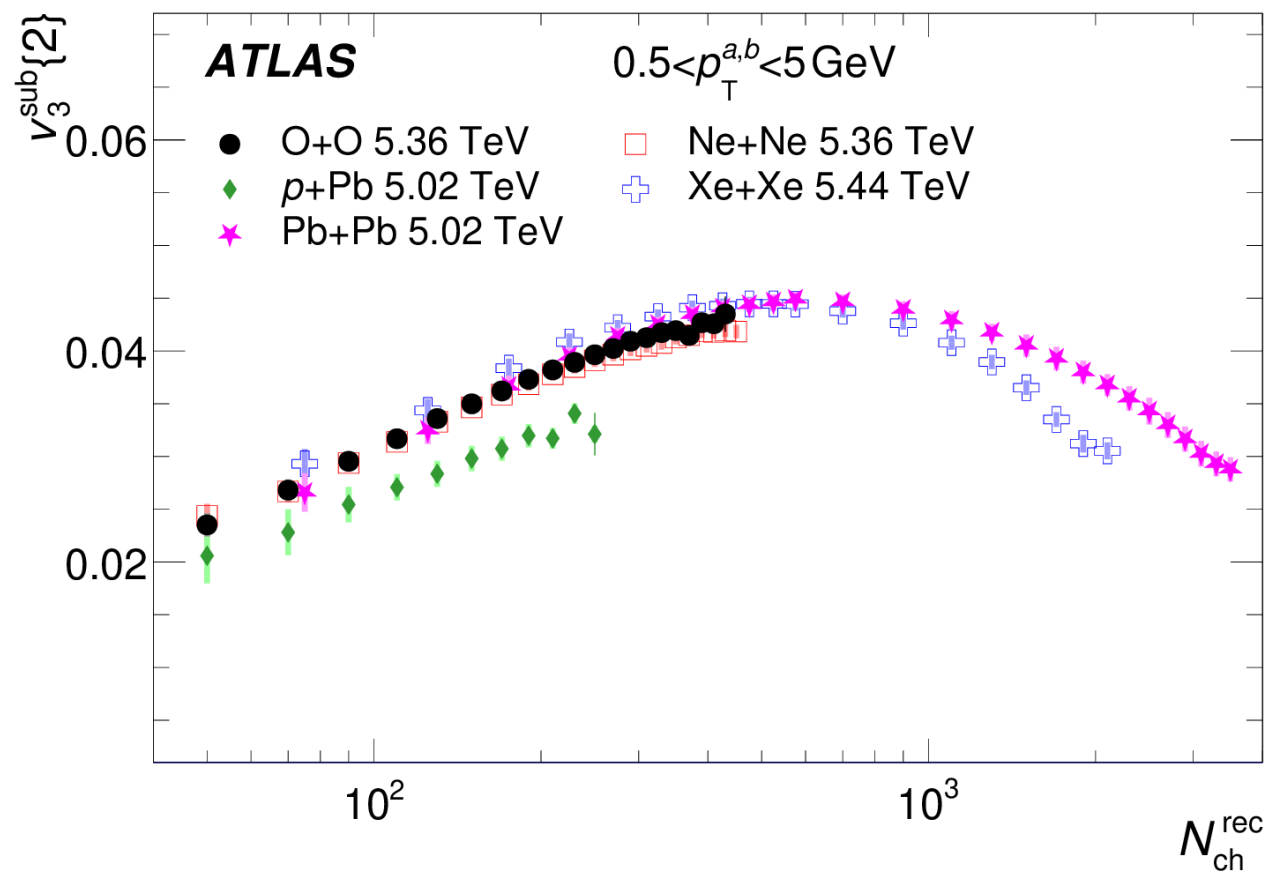
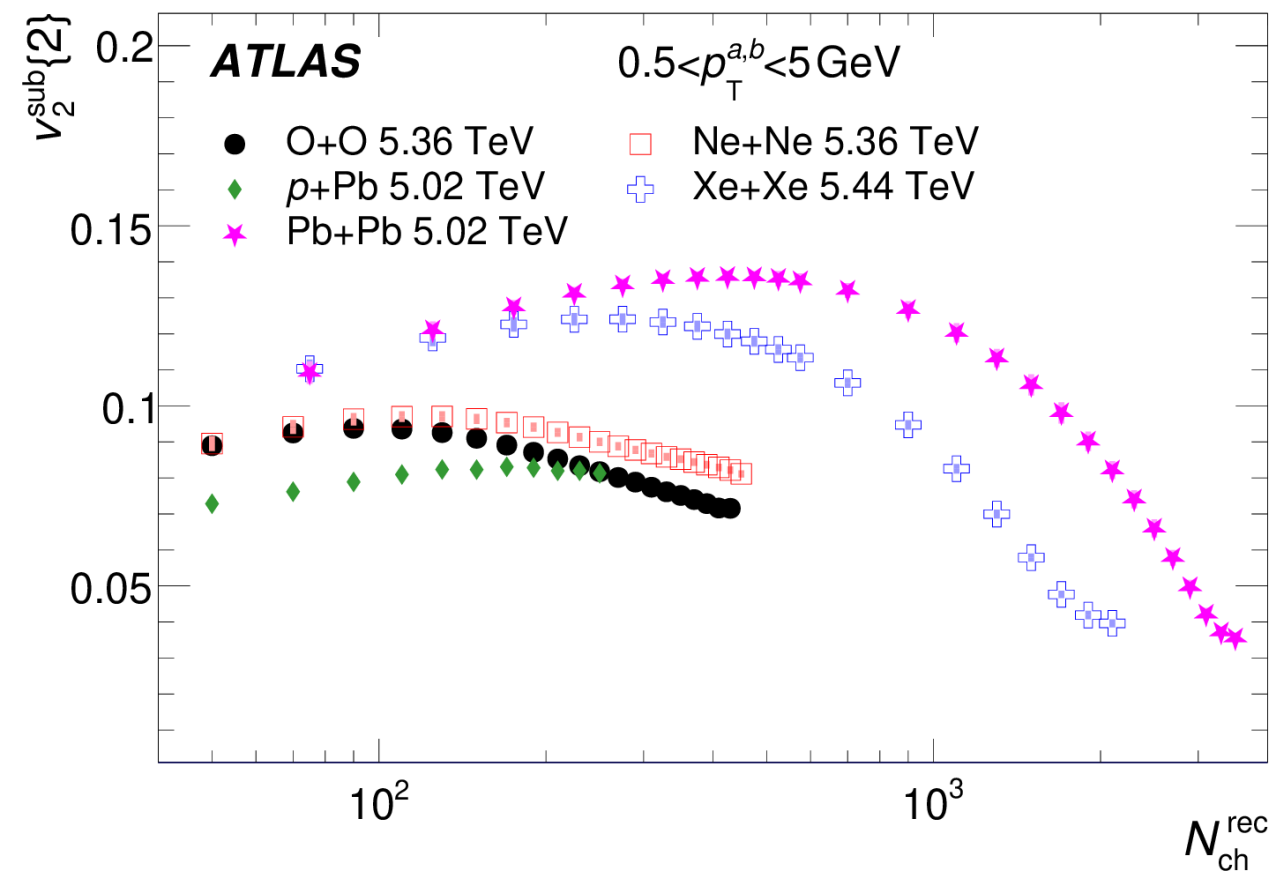
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- For v_2 :
 - Light ions: much flatter centrality dependence
 - Result of large event-by-event geometry fluctuations
- For v_3 :
 - Different trends between light & heavy

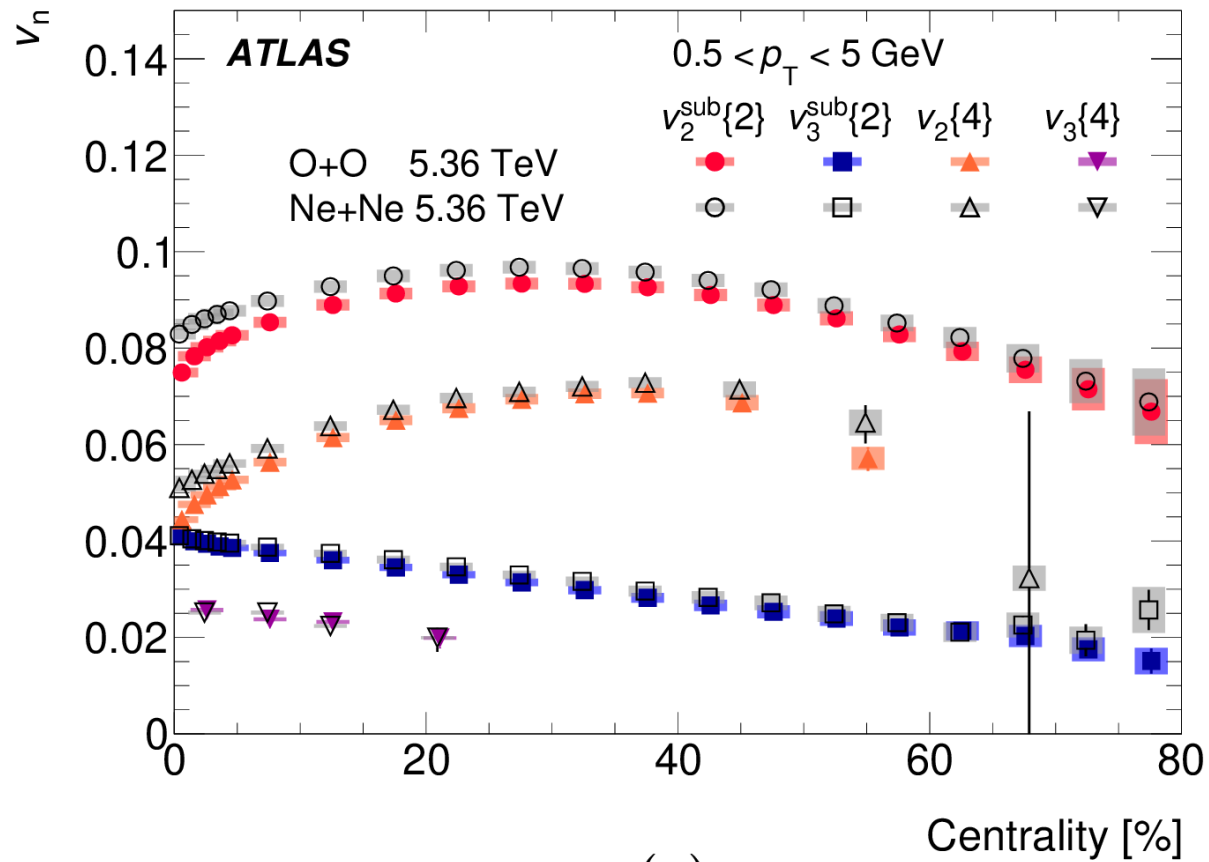
Flow: Light-ions vs Heavy-ions, multiplicity dependence

31

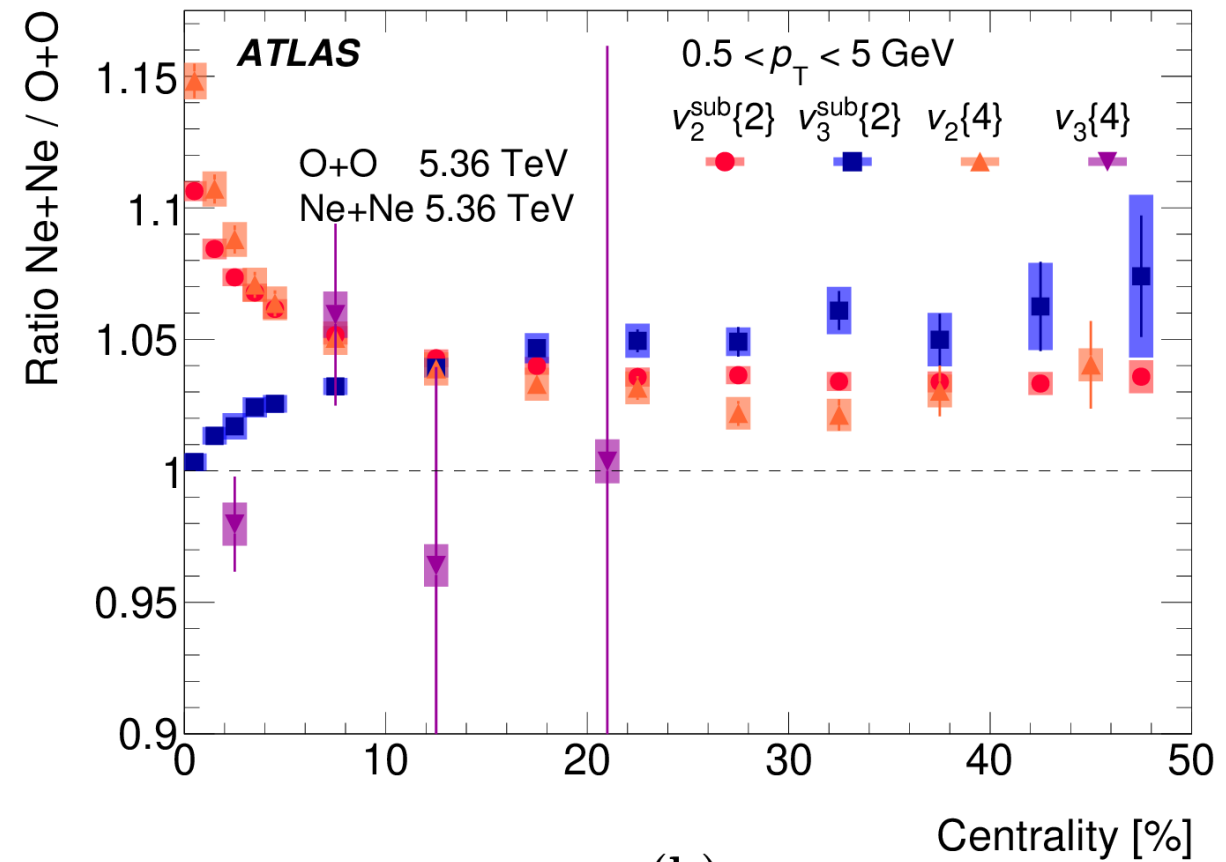


- For v_3 :
 - Universal behavior seen as function of multiplicity
 - v_3 : mostly driven by “size” of QGP droplet

Anisotropic flow : Ne+Ne/O+O ratios



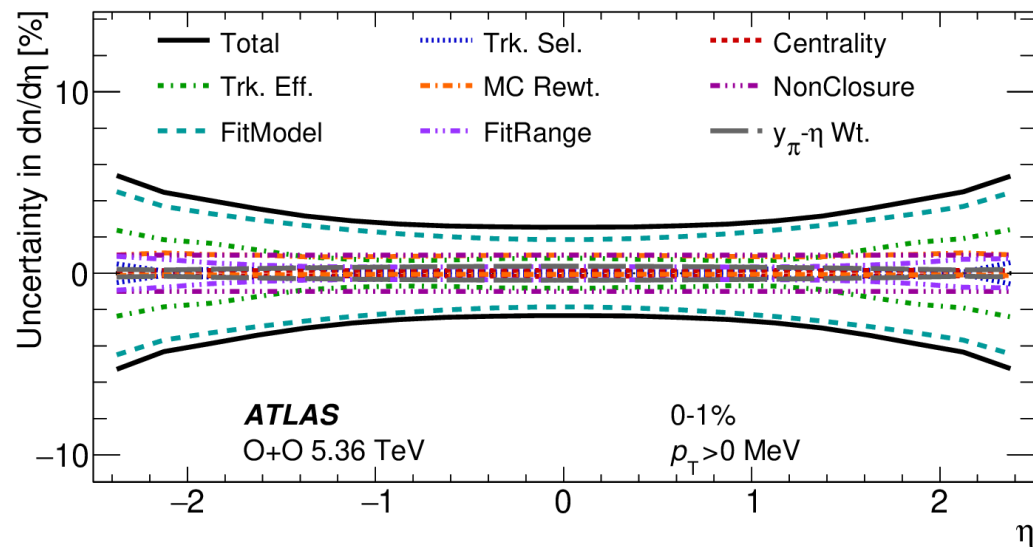
(a)



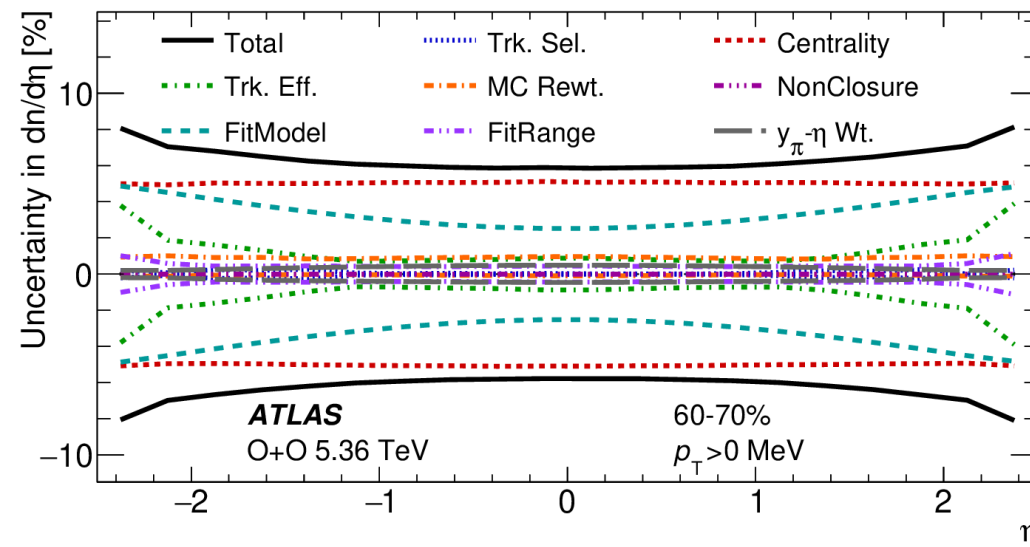
(b)

Systematic uncertainties : η -differential

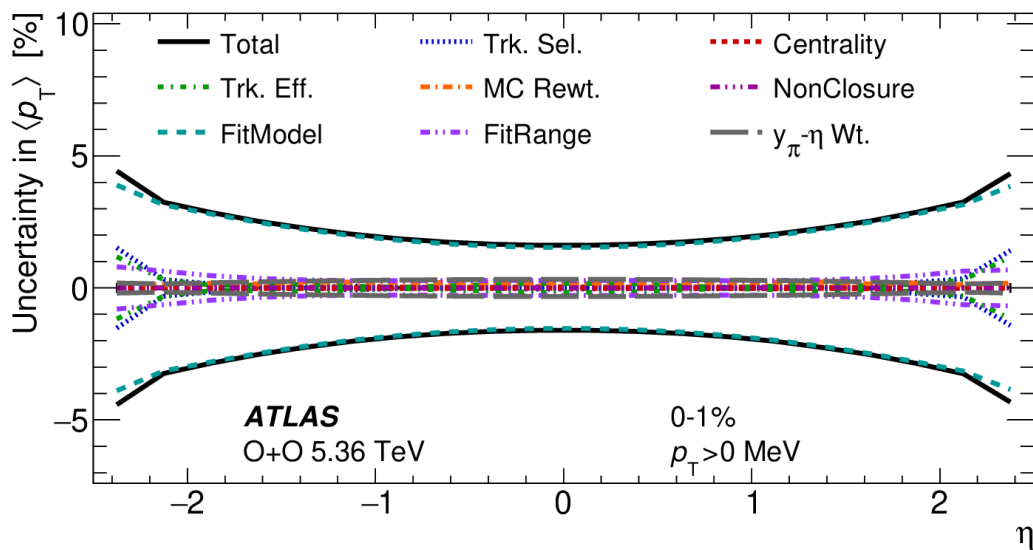
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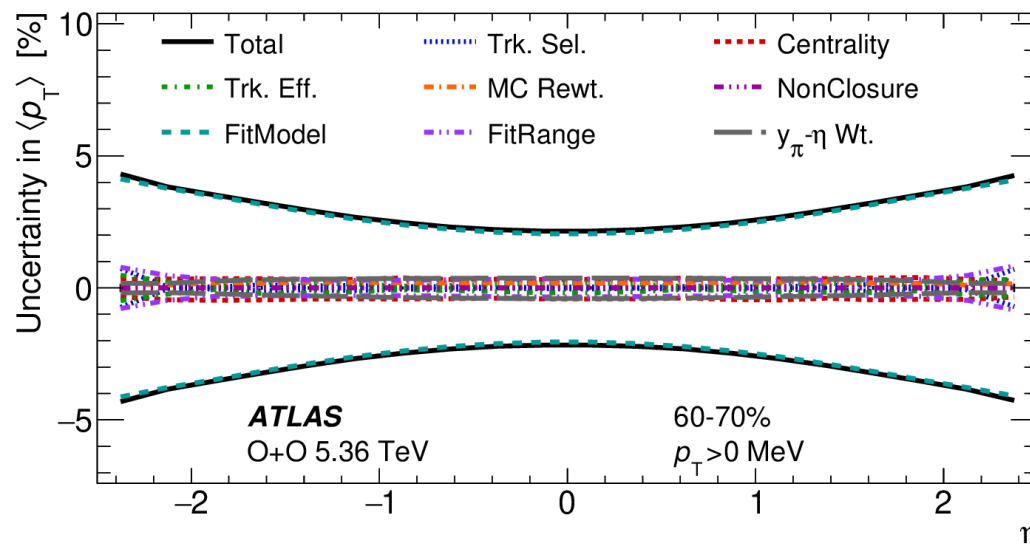
(a)



(b)



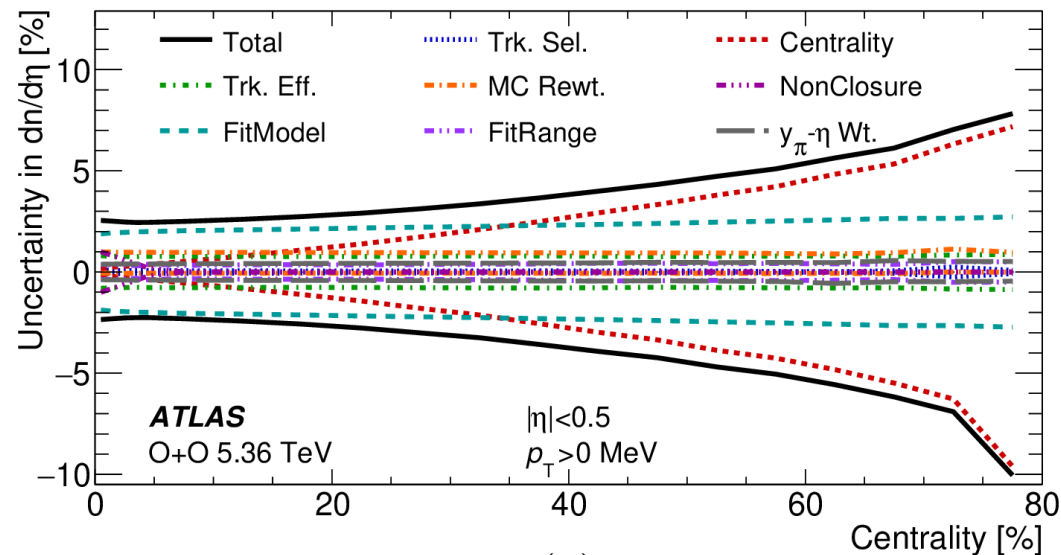
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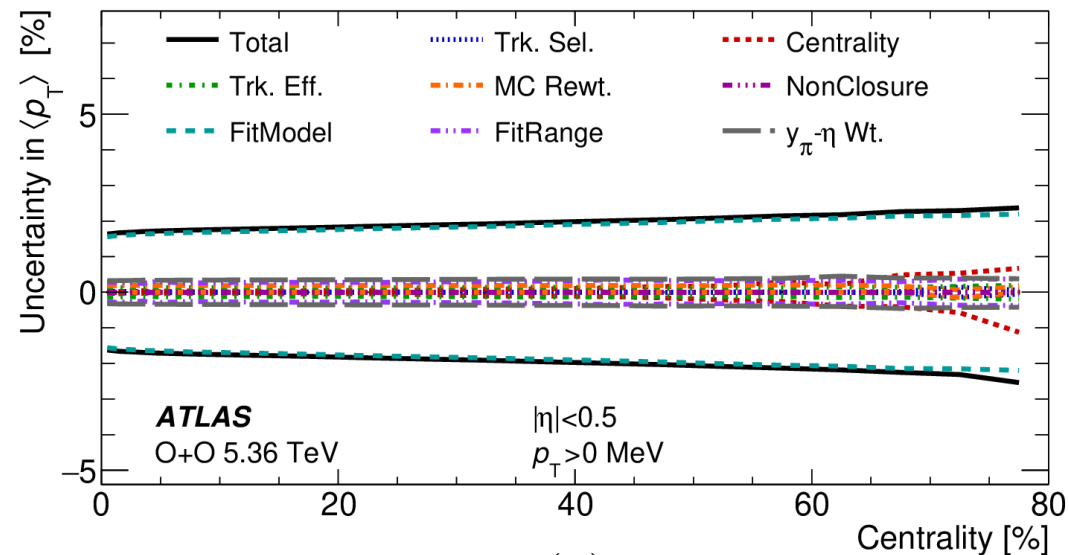
(d)

Systematic uncertainties : Centrality dependence

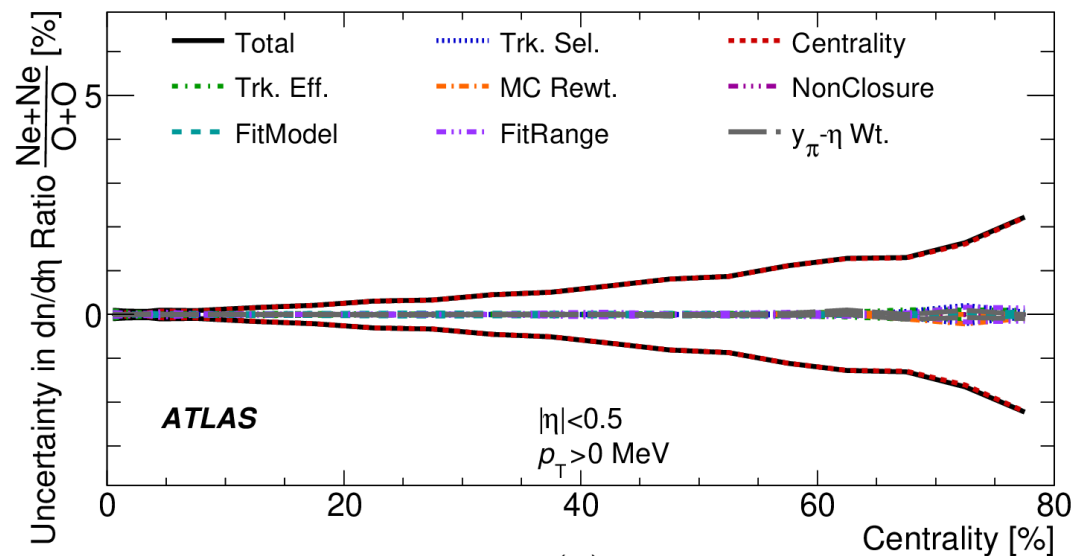
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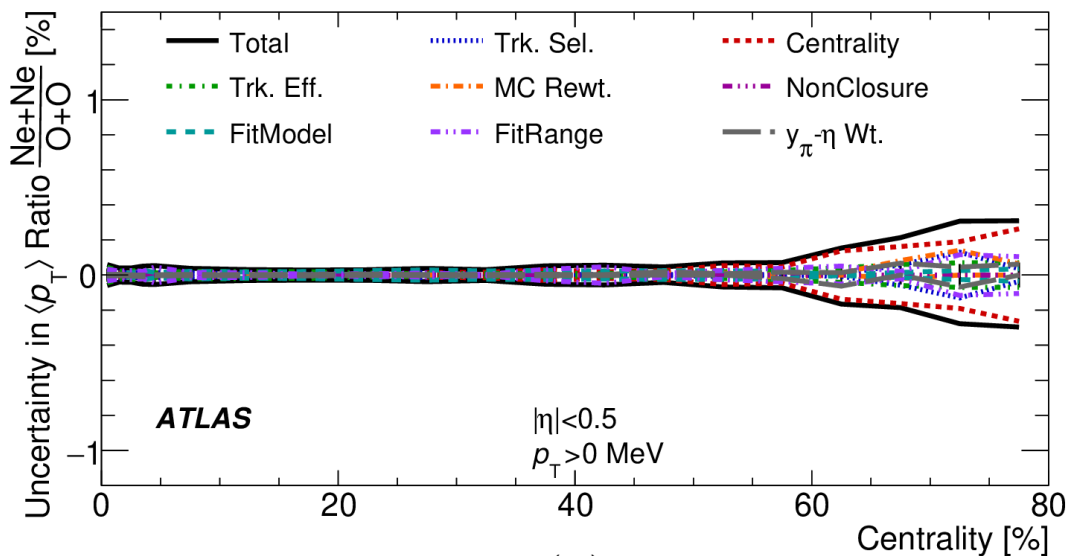
(a)



(b)



(c)

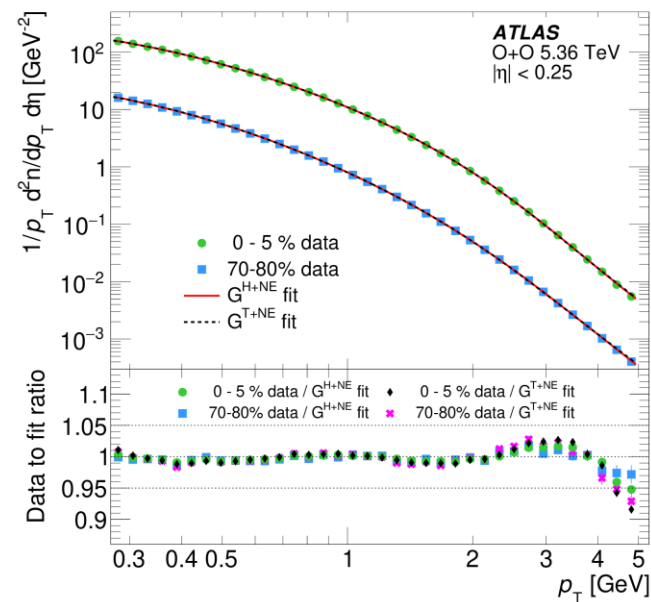


(d)

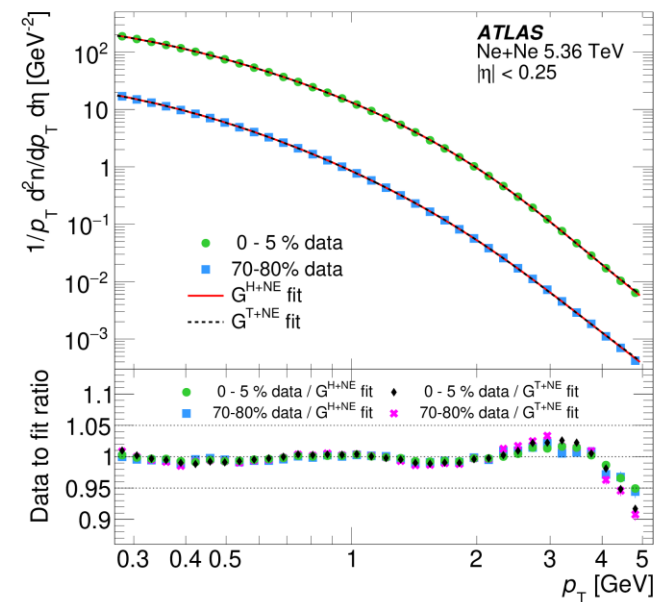
Extrapolation to $p_T > 0$

$$G^{H+NE}(p_T) \equiv A / \left(1 + \frac{p_T}{p_0} \right)^n + B e^{-p_T/T}$$

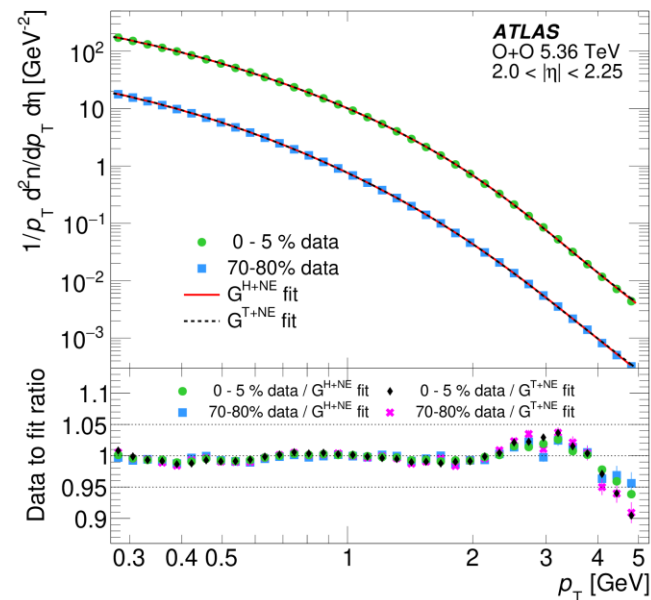
$$G^{T+NE}(p_T) \equiv A / \left(1 + \frac{m_T}{p_0} \right)^n + B e^{-m_T/T}$$



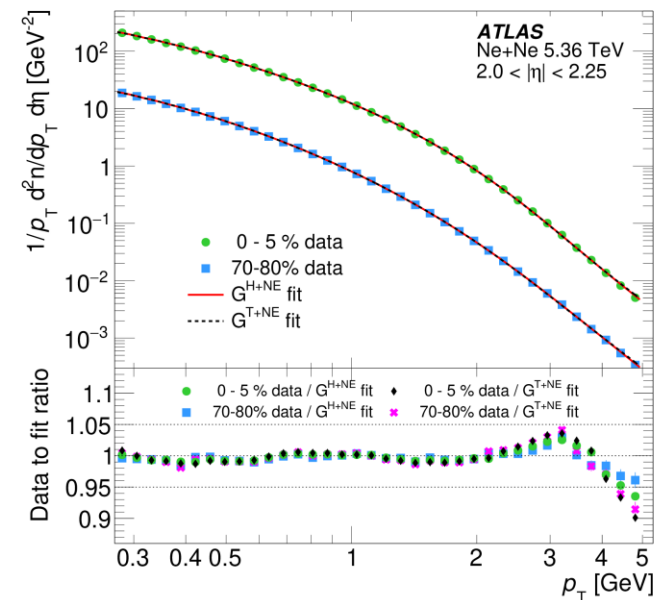
(a)



(b)

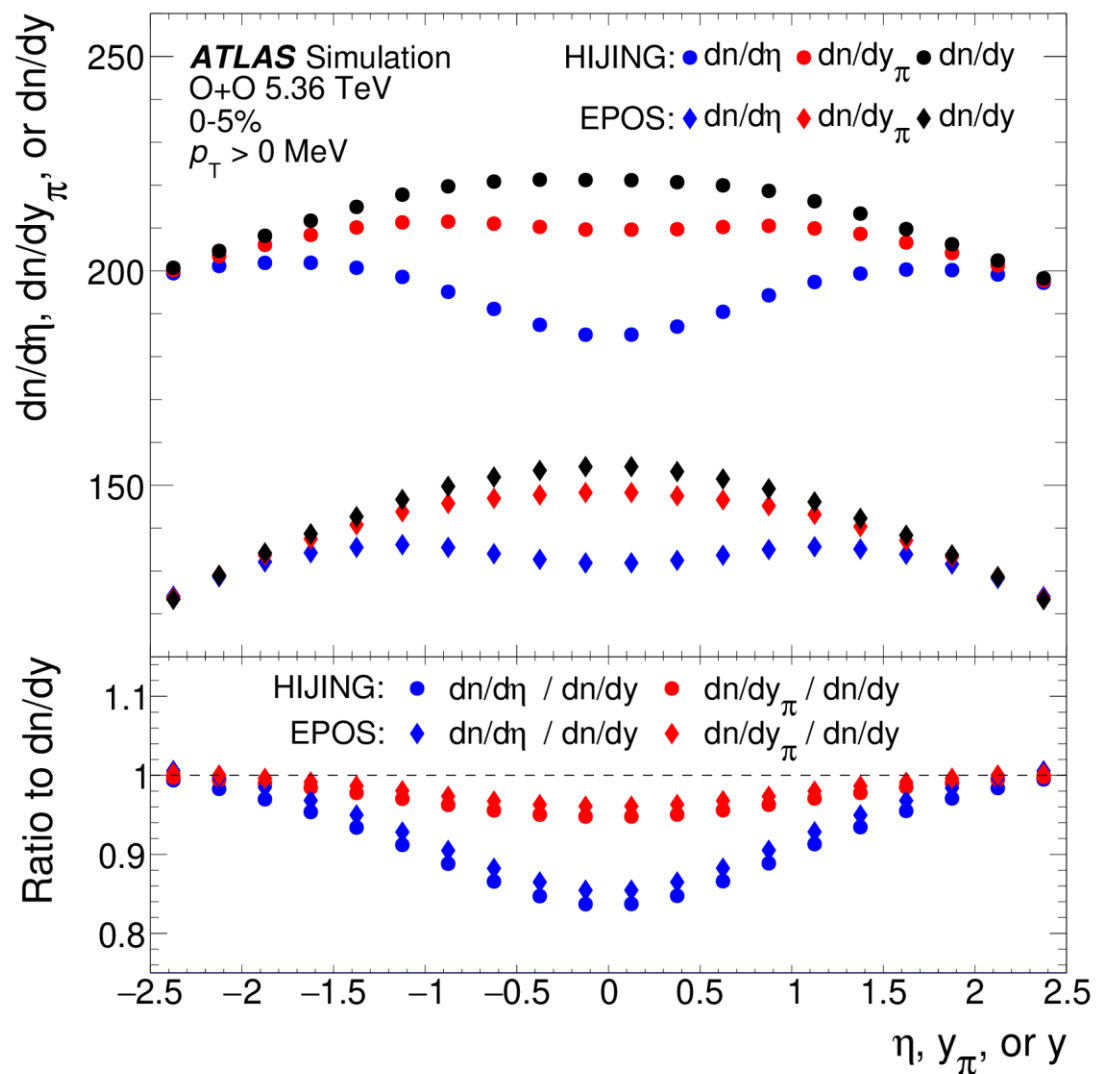


(c)

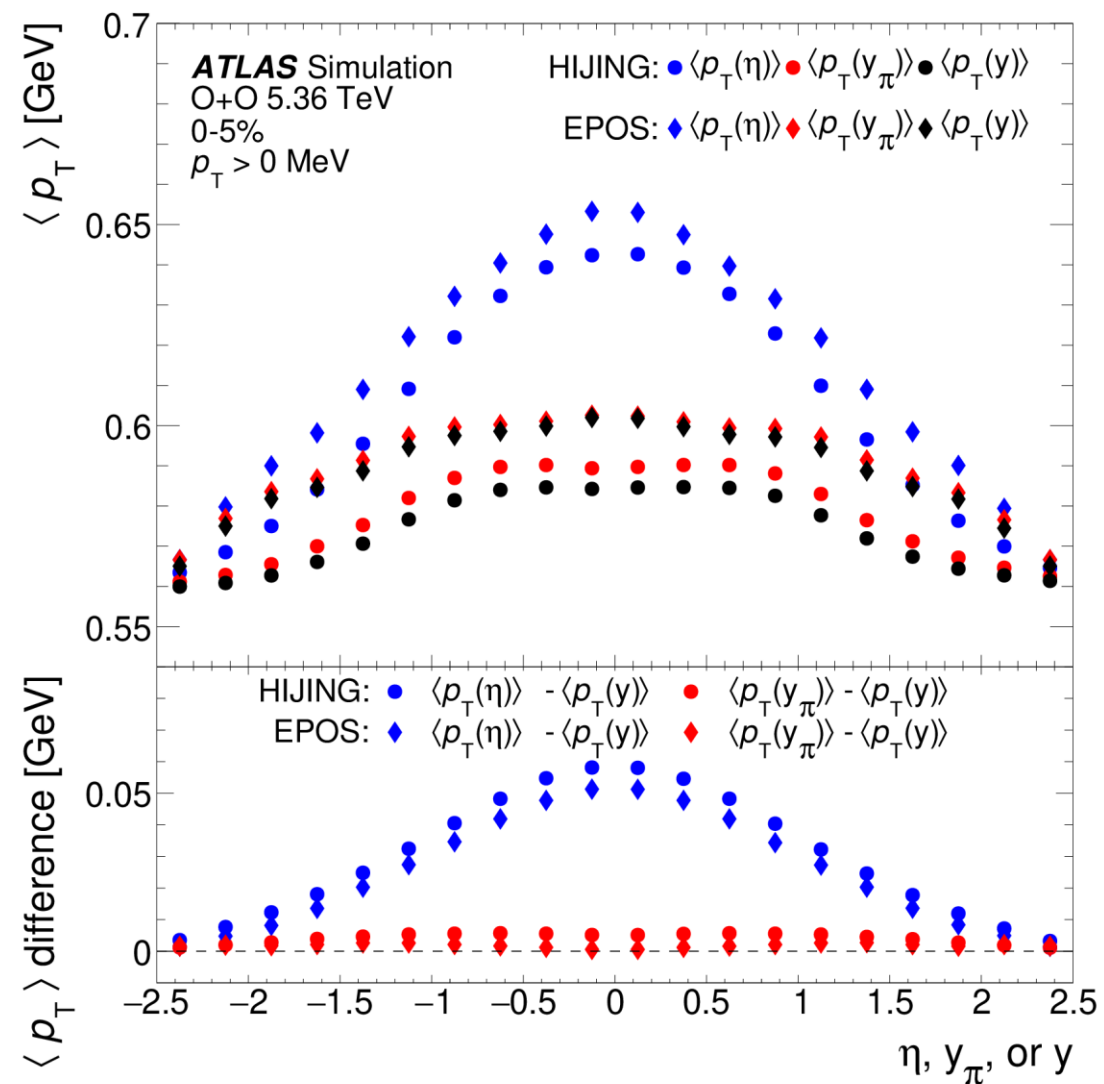


(d)

$dn/d\eta$ vs dn/dy_π vs dn/dy

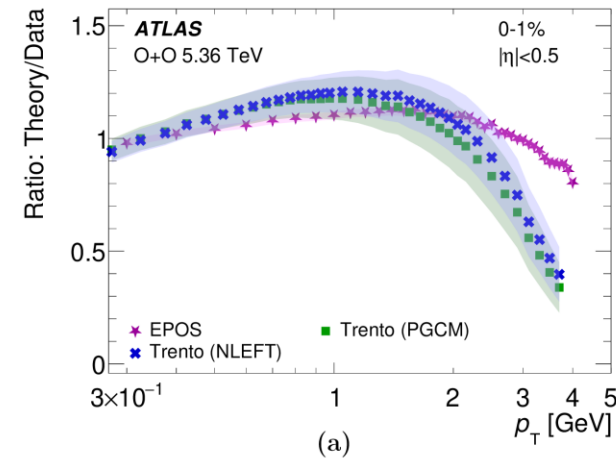


(a)

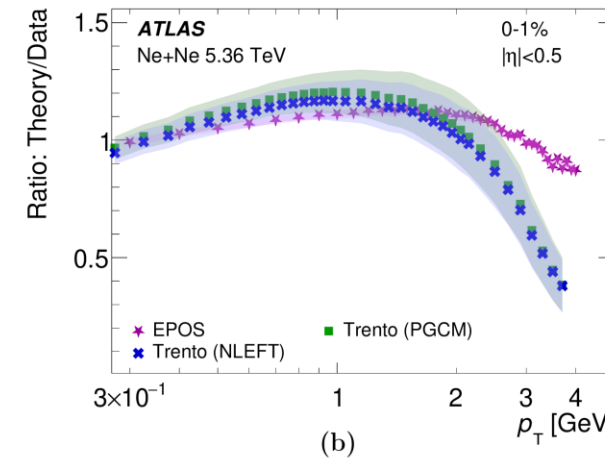


(b)

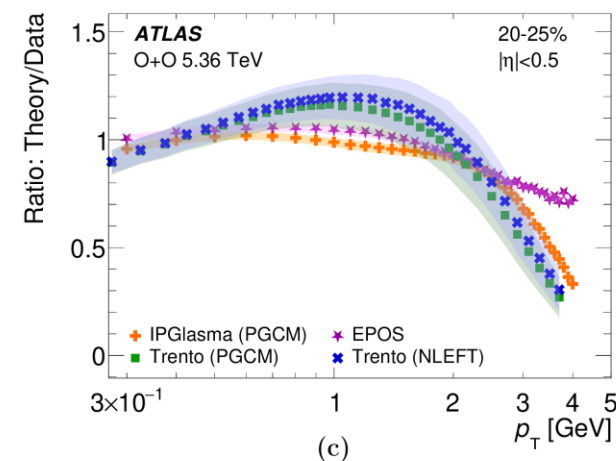
p_T spectra: Theory/Data



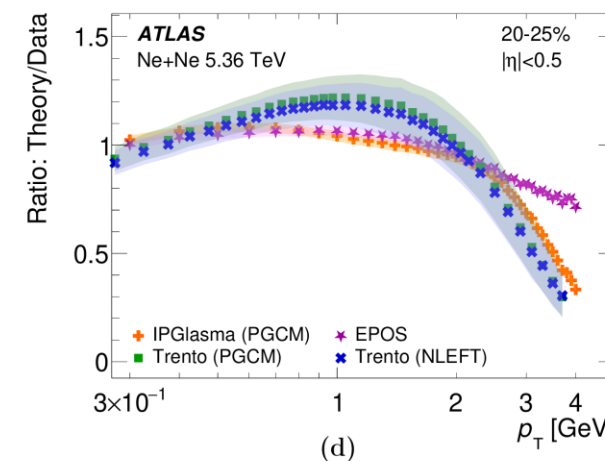
(a)



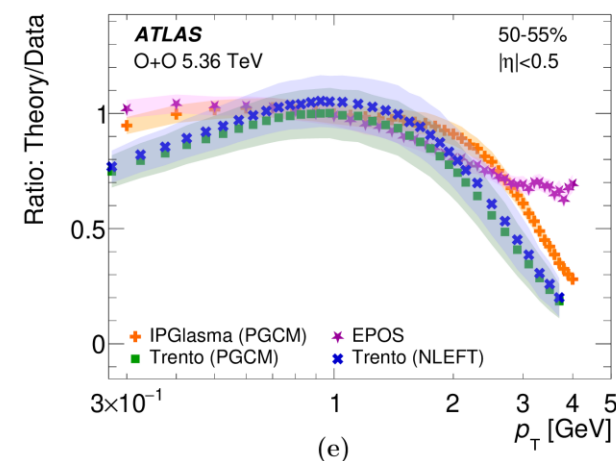
(b)



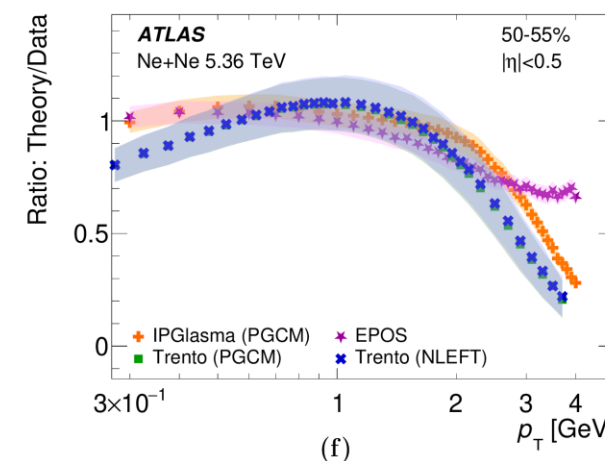
(c)



(d)

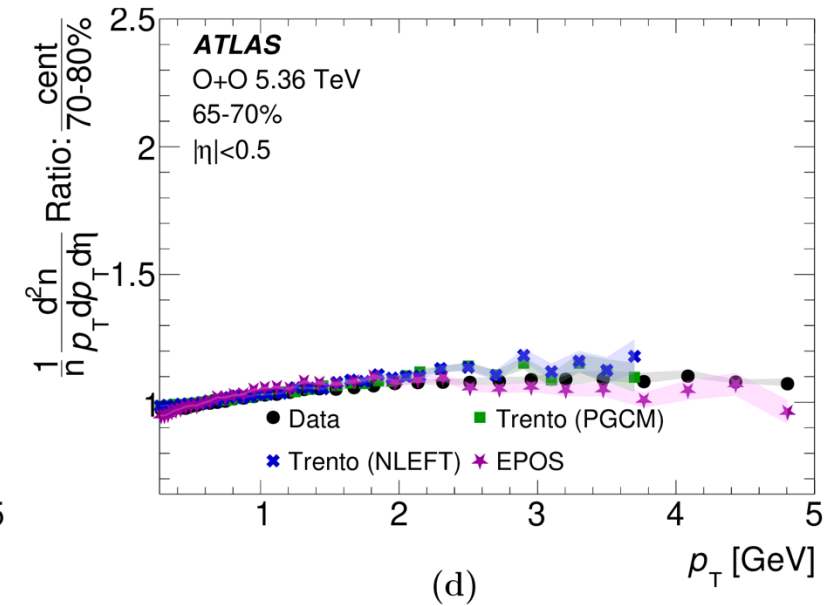
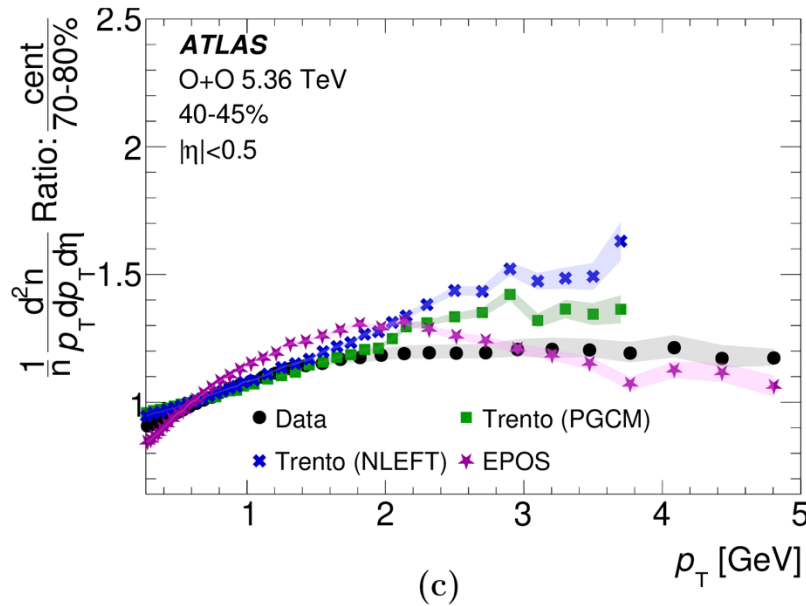
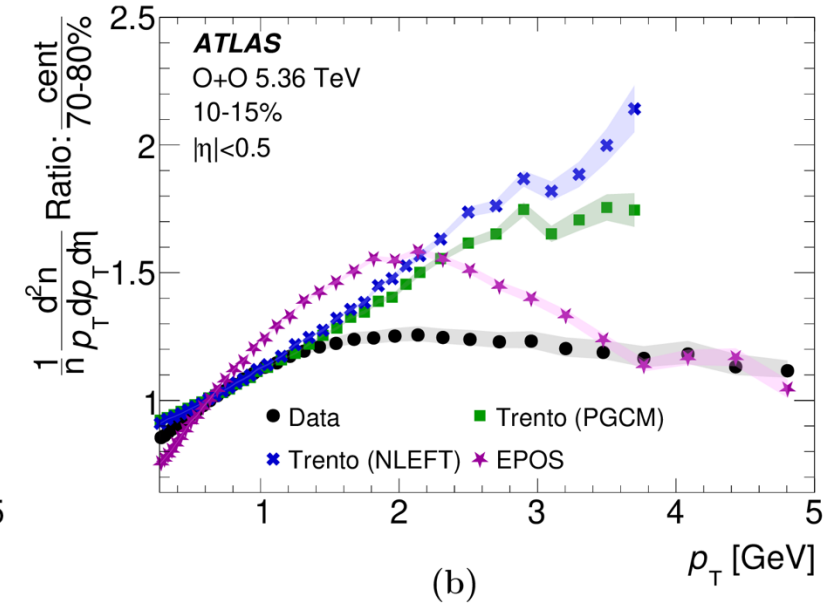
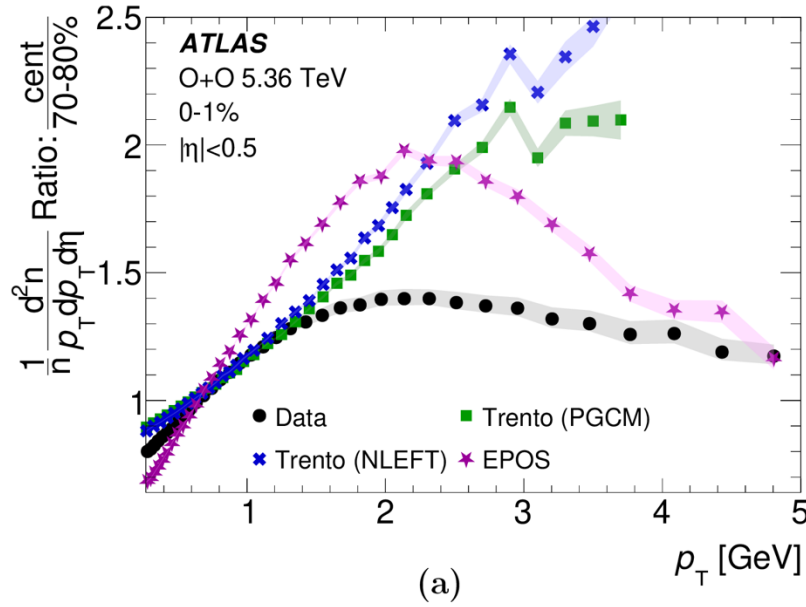


(e)



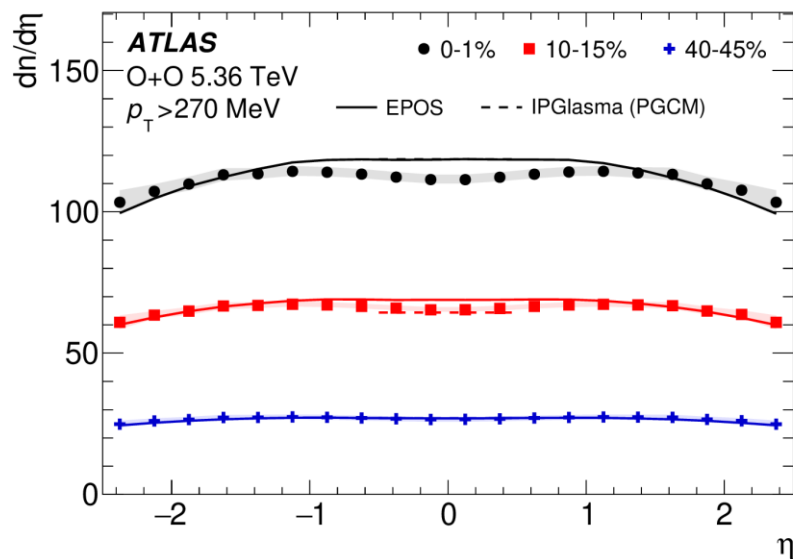
(f)

p_T spectra ratios : Central/Peripheral: Theory comparison ³⁸

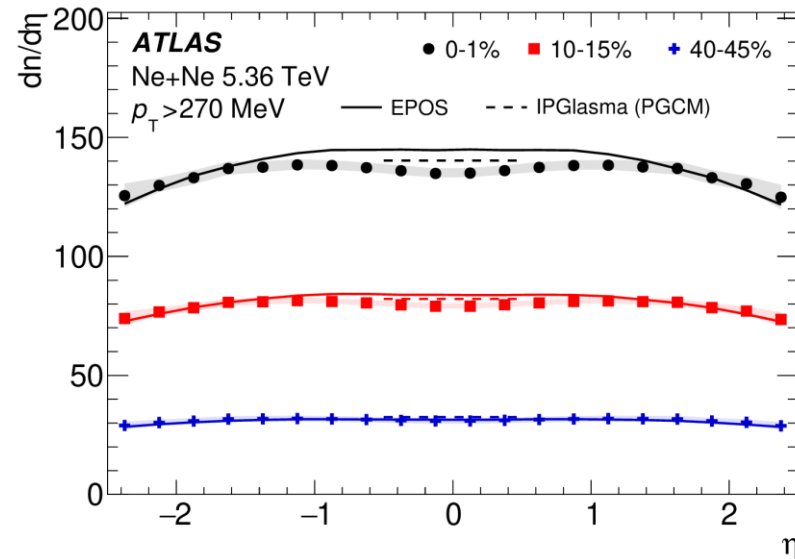


$dn/d\eta$ Theory Comparisons

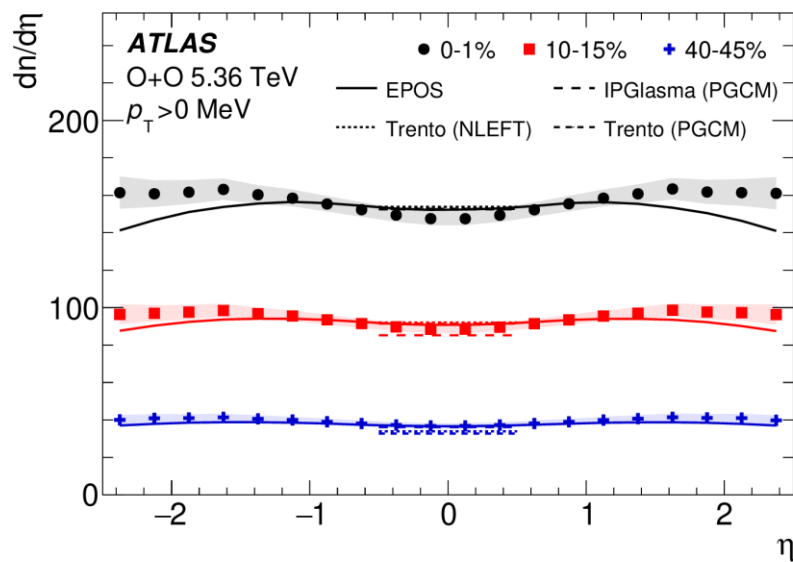
39



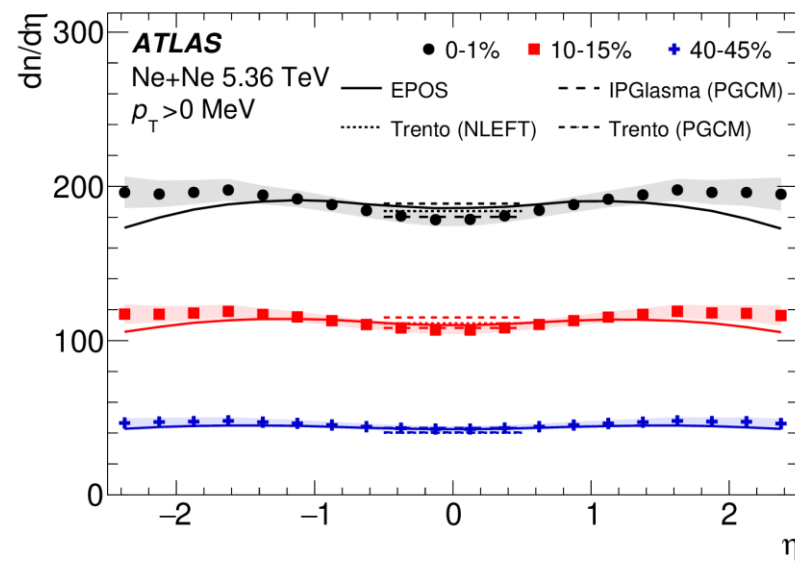
(a)



(b)



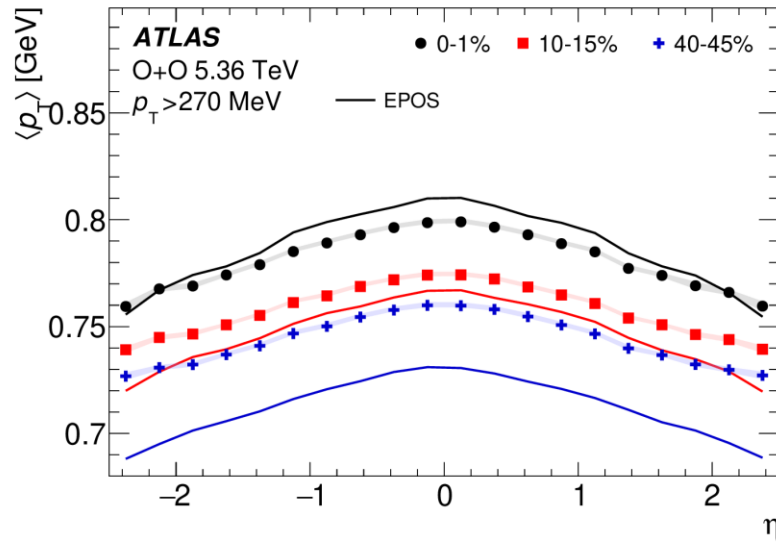
(c)



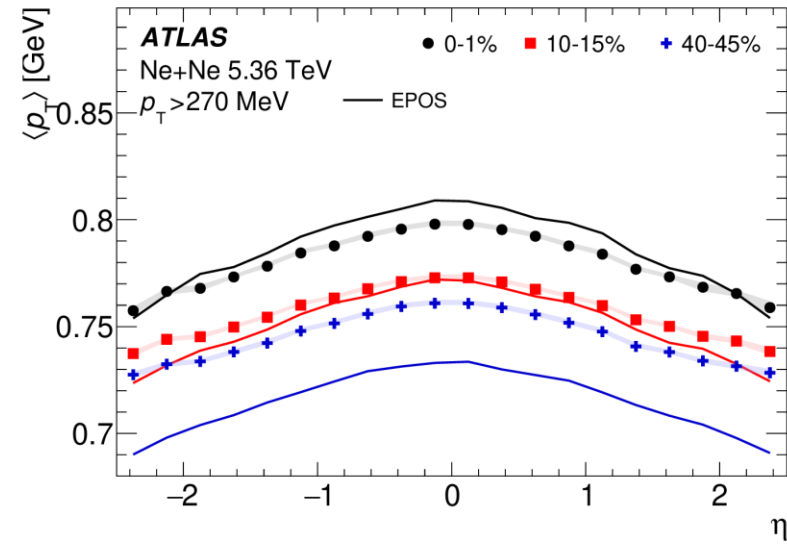
(d)

$\langle p_T \rangle$ Theory Comparisons

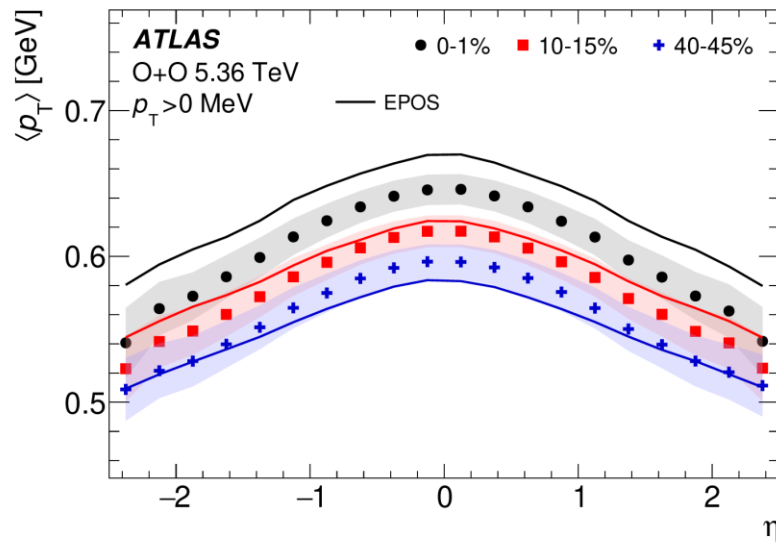
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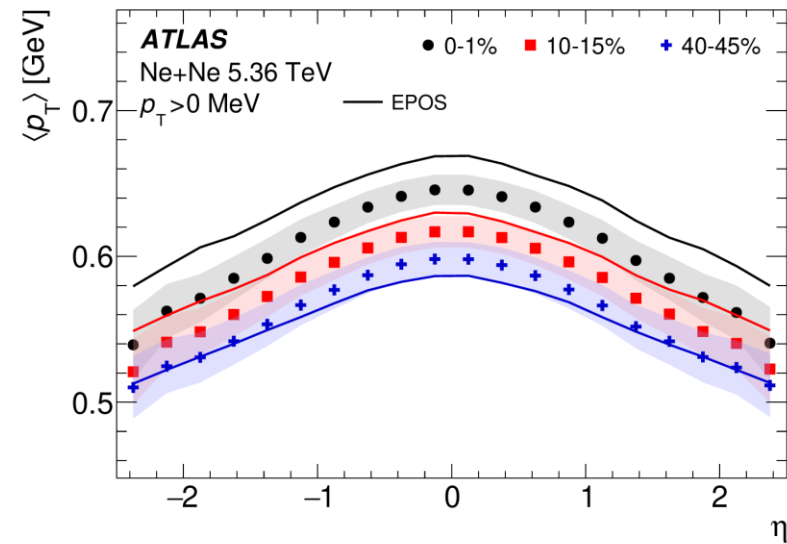
(a)



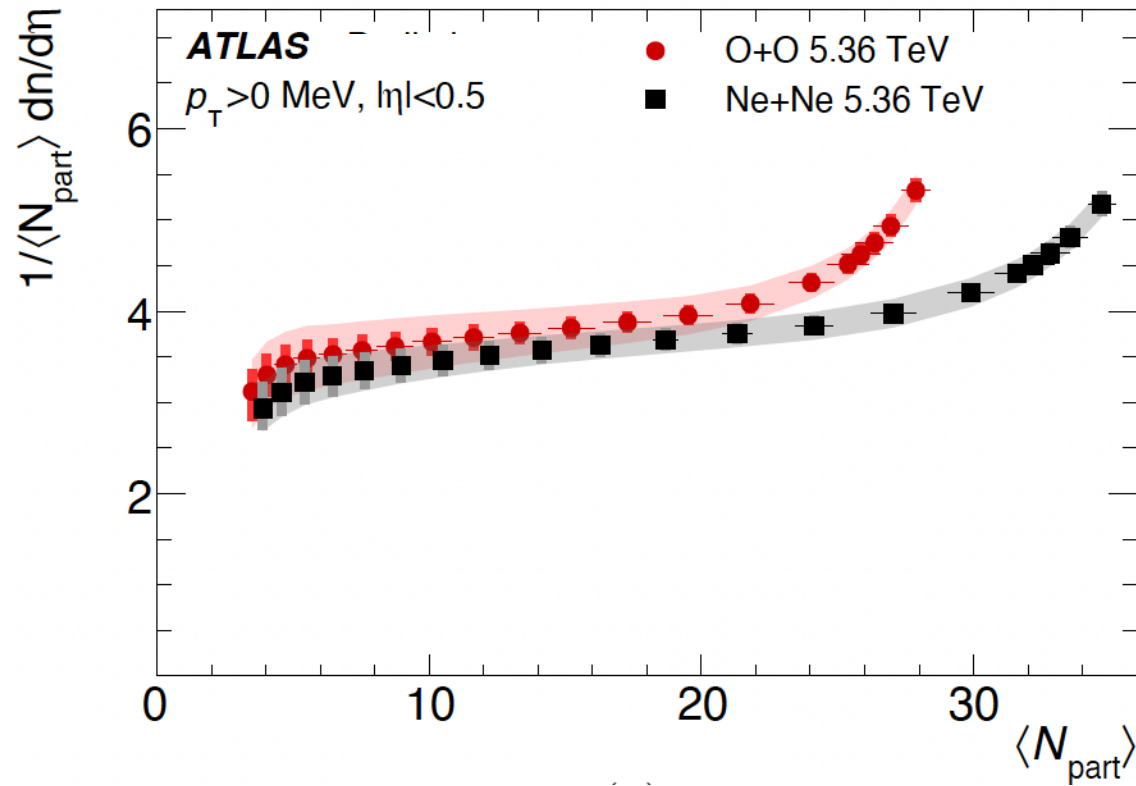
(b)



(c)

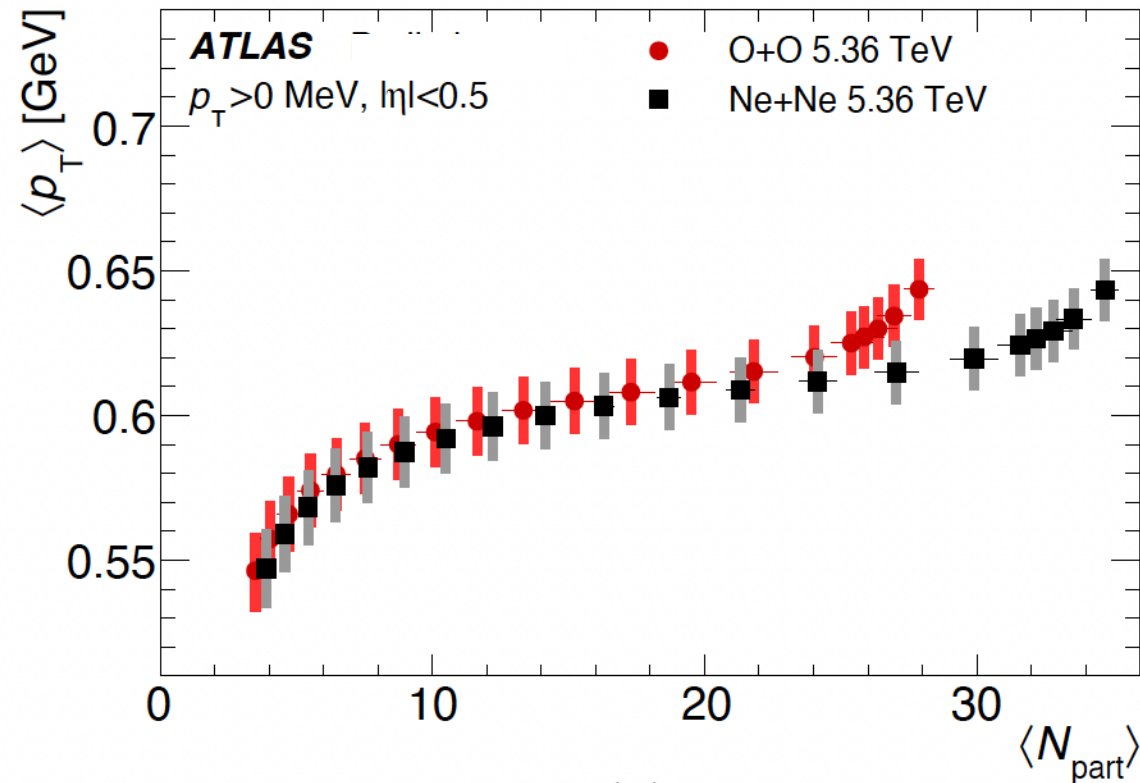
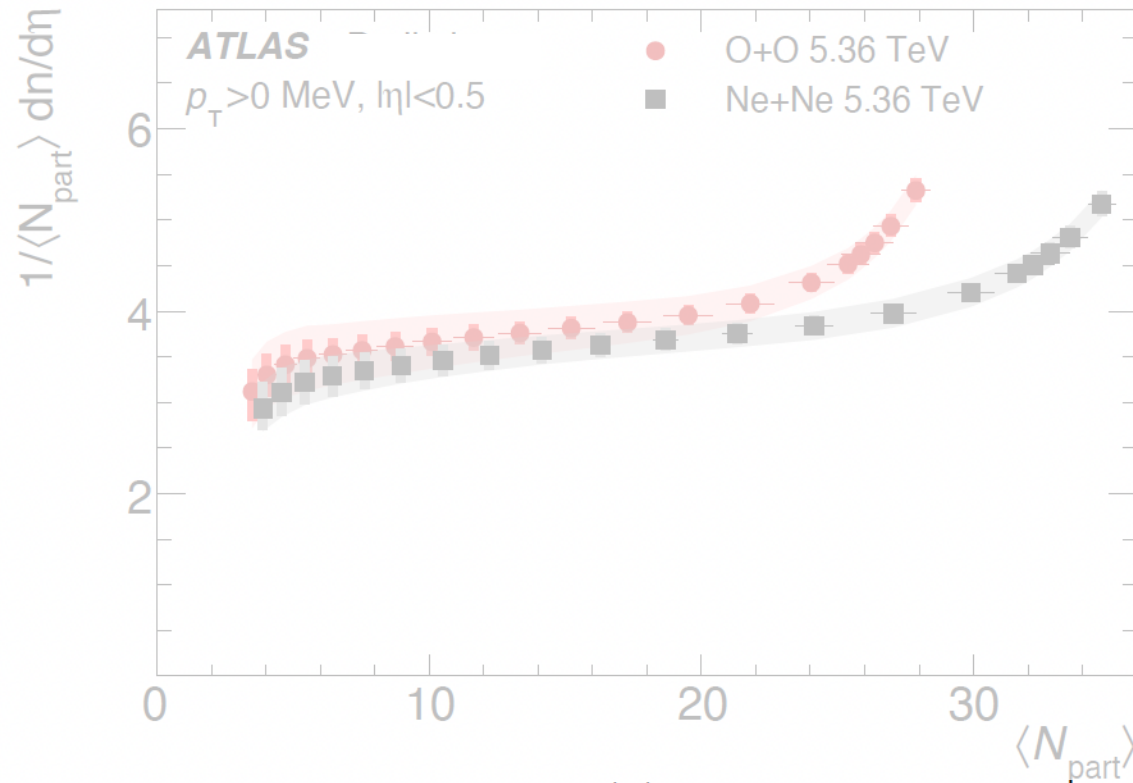


(d)



- $dn/d\eta$ vs $\langle N_{\text{part}} \rangle$ (for $|\eta| < 0.5$)
 - O+O, Ne+Ne consistent for $\langle N_{\text{part}} \rangle < 20$
 - Strong increase for most-central collisions

$\langle N_{\text{part}} \rangle$ dependence



- $dn/d\eta$ vs $\langle N_{\text{part}} \rangle$ (for $|\eta| < 0.5$)
 - O+O, Ne+Ne consistent for $\langle N_{\text{part}} \rangle < 20$
 - Strong increase for most-central collisions
- $\langle p_T \rangle$ vs $\langle N_{\text{part}} \rangle$ (for $|\eta| < 0.5$)
 - Similar trends