Run 2 Results on Heavy Ions from ATLAS Experiment

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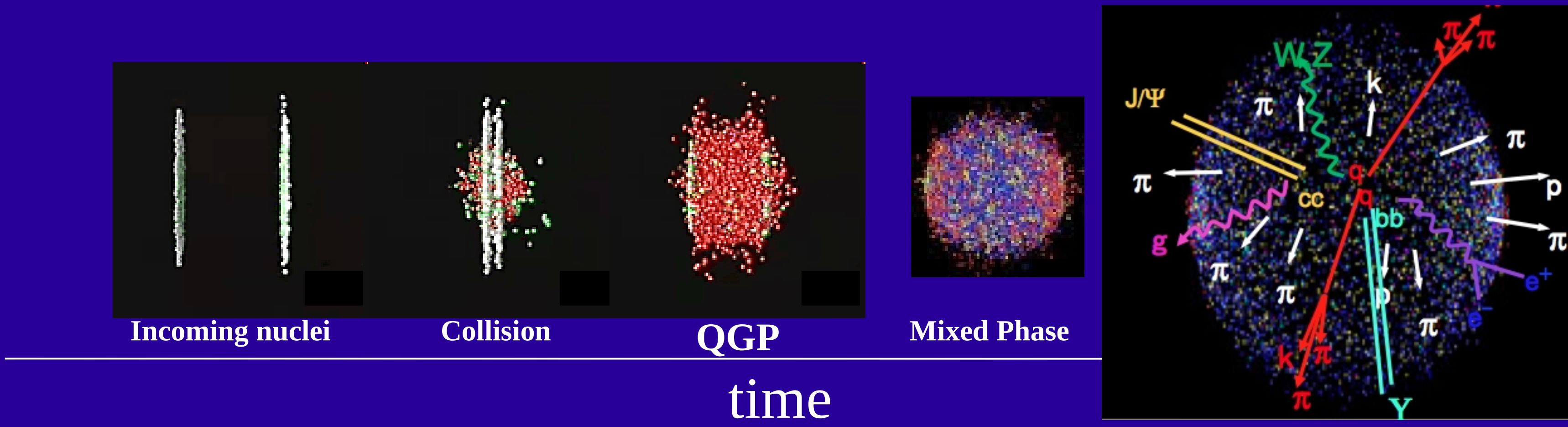
Heavy Ion Collisions



Final states providing insight into the QGP:

Global observables

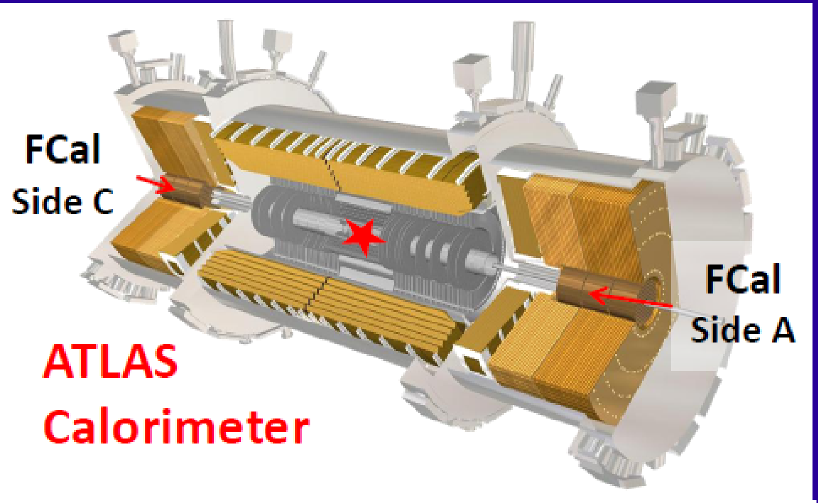
Particle correlations - initial conditions, geometry, collective behaviour

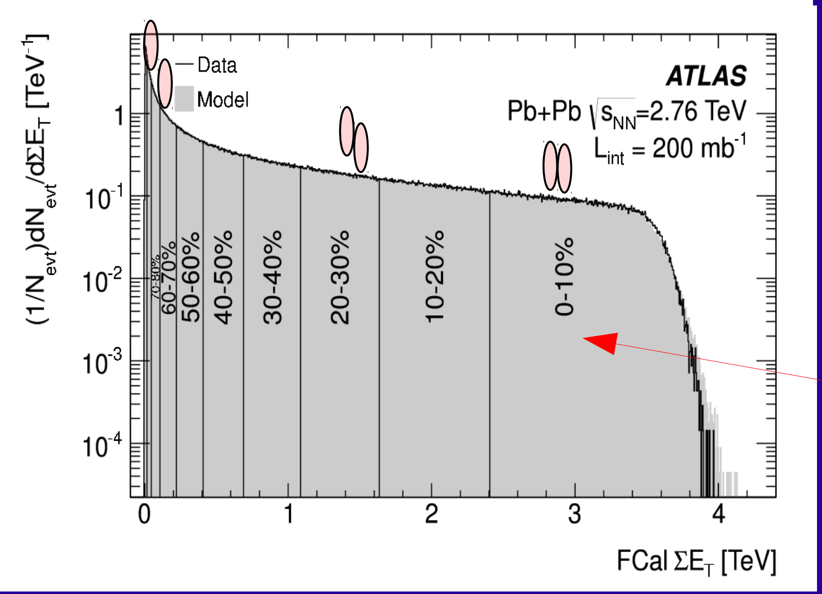
Hard probes

Colorless objects: electroweak bosons – reference, nPDFs

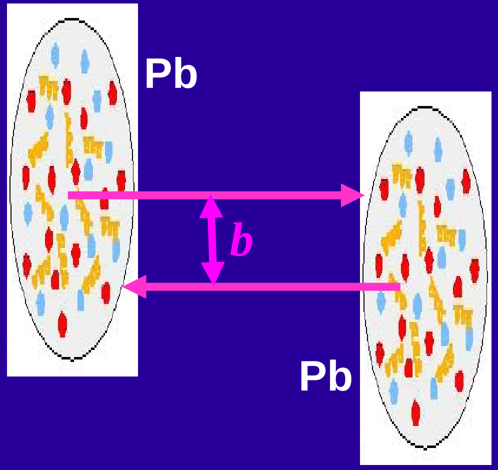
Colored objects: hadrons, jets, quarkonia – Debye screening, partonic energy loss

Collisions Centrality





HI collision's dynamics controlled by impact parameter "*b*"



Transverse energy, E_T, deposited in Forward Calorimeter.

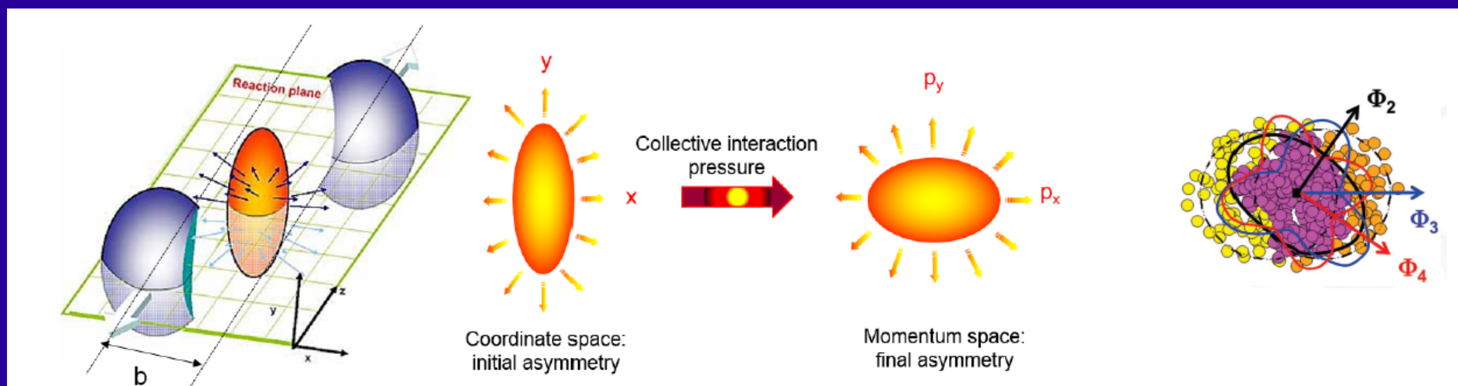
The nuclear thickness function, T_{AA}, and number of participants in a collision, N_{part}, for each centrality interval is estimated using the Glauber model.

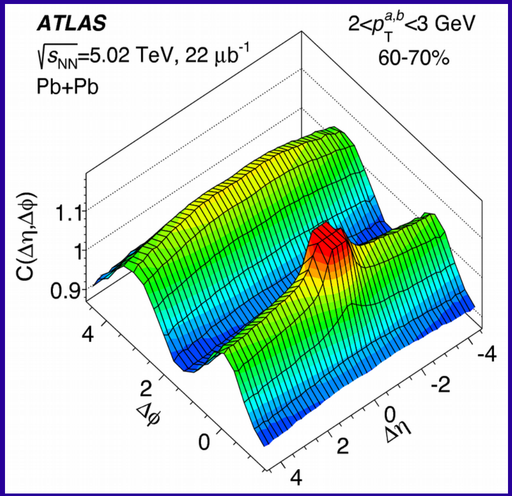
Flow

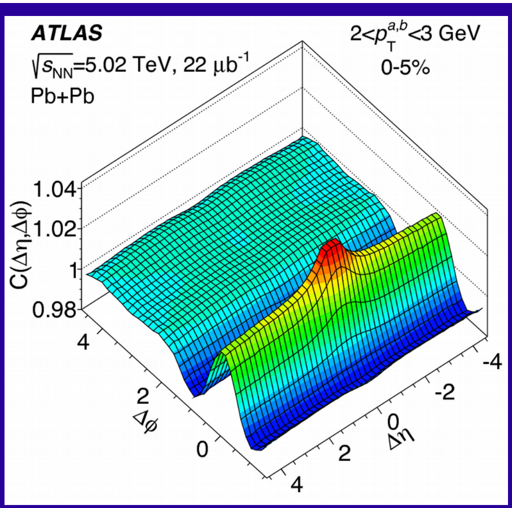
Anisotropic spatial collective motion is described by a Fourier expansion of particle distribution in azimuthal angle ϕ

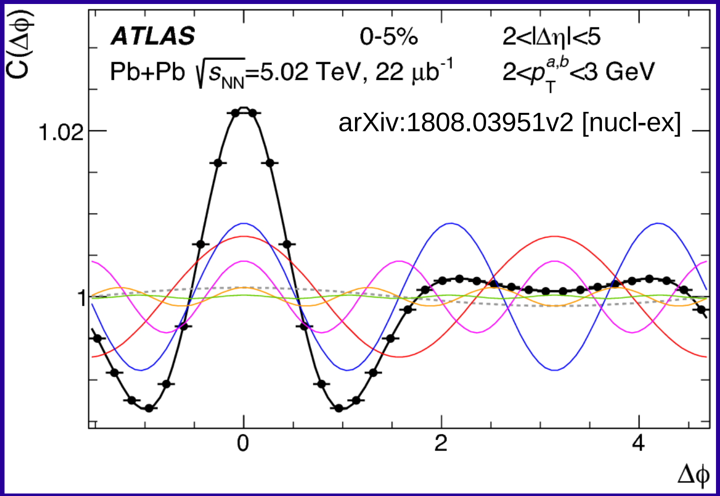
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

High order coefficients are associated with fluctuations of nucleon positions in the overlap







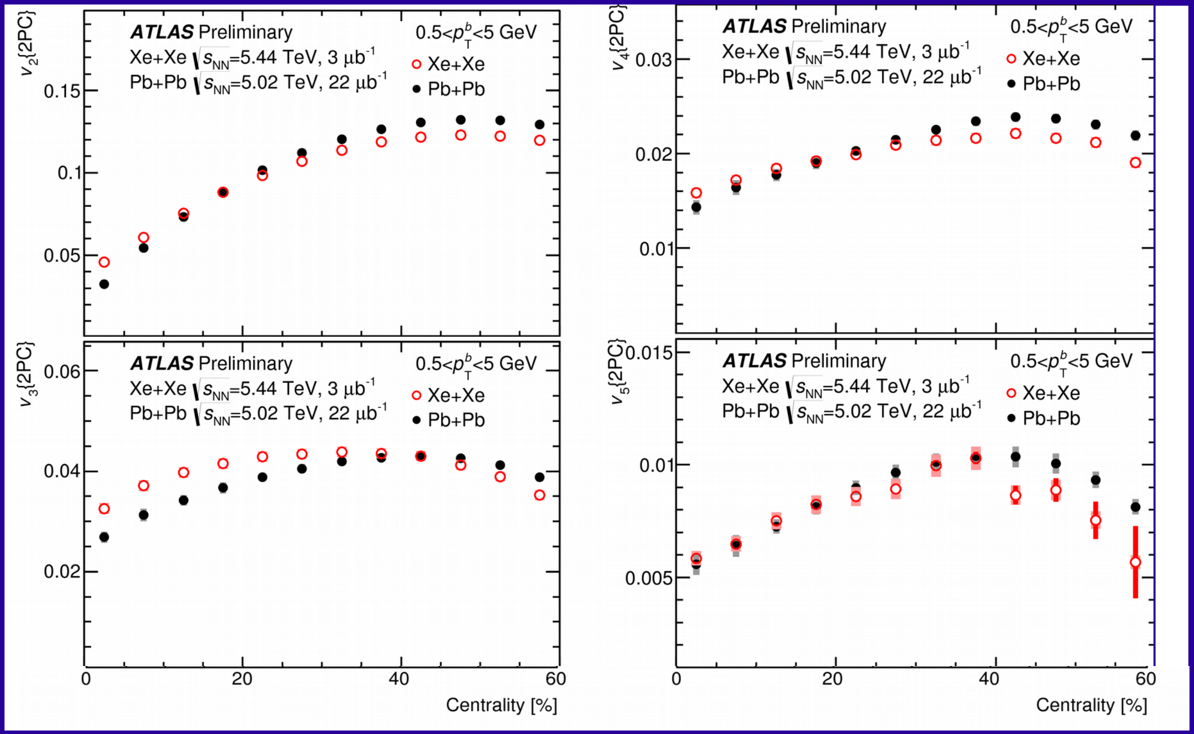


v_n{2PC} in Xe+Xe and Pb+Pb collisions

ATLAS-CONF-2018-011

Xe is smaller than Pb → larger EbyE fluctuations → larger eccentricities

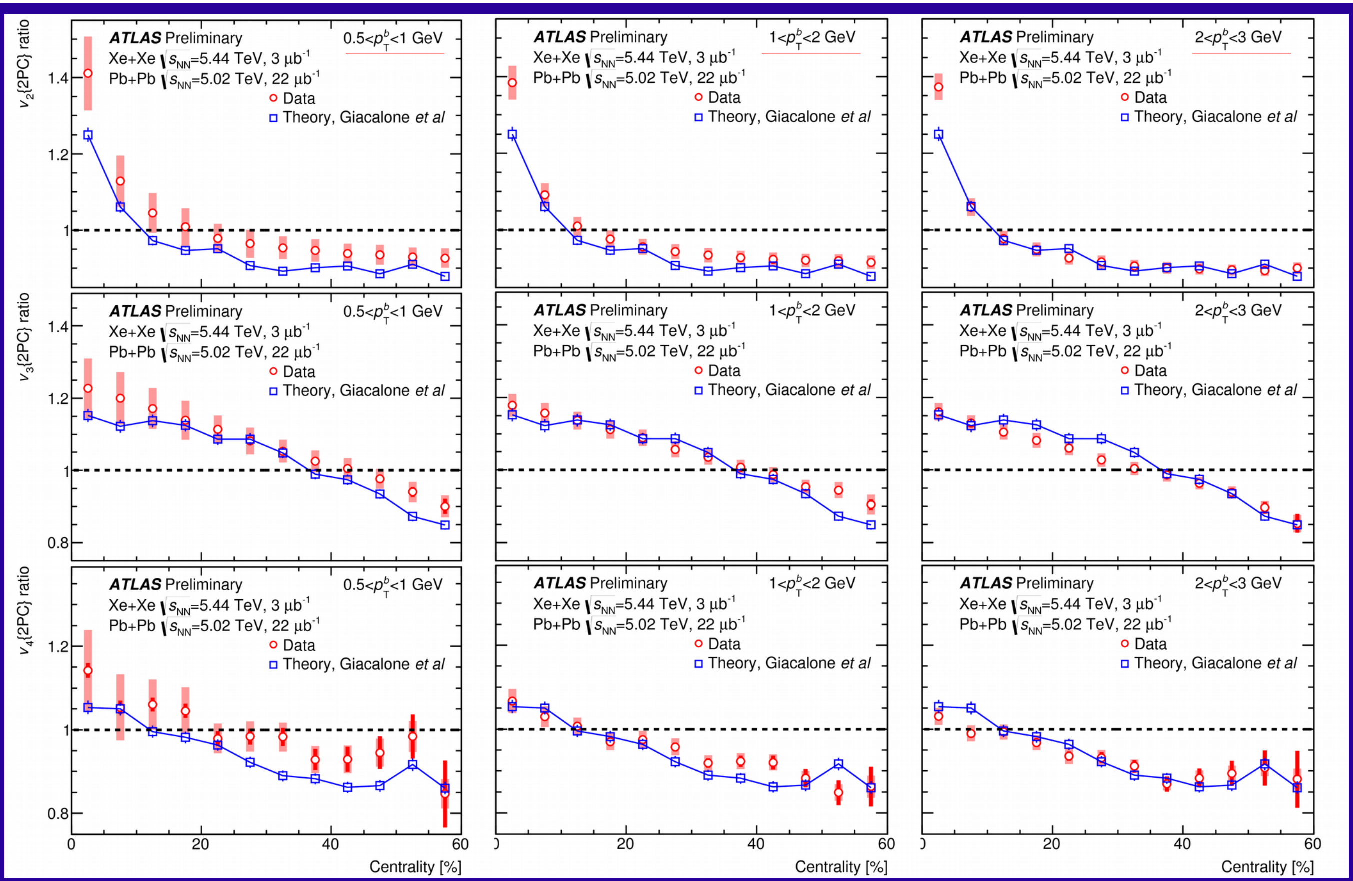
→ larger viscous effects (1711.08499)



- v_n increases from central to peripheral collisions, peaking around 30–40% centrality.
- v_2 and v_3 are clearly larger in central Xe+Xe collisions.

v_n in Xe+Xe and Pb+Pb collisions - ratios

ATLAS-CONF-2018-011



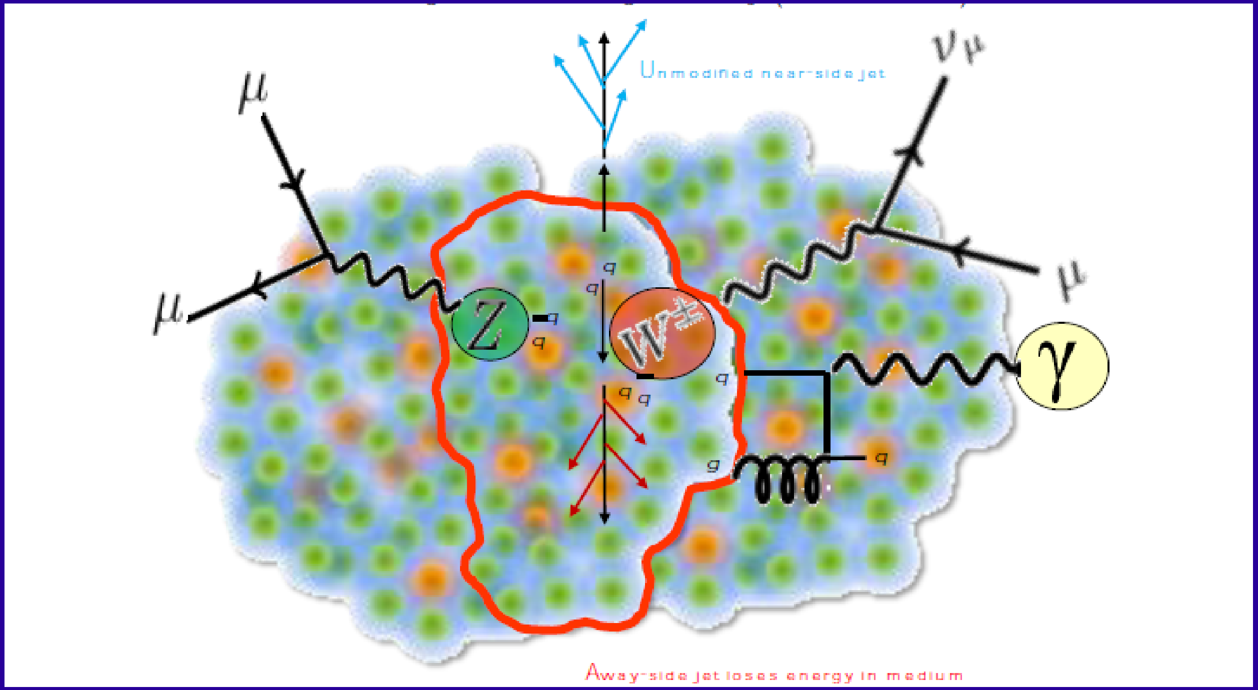
- Ratios have weak dependence in p^b_T. ($0.5 < p^a_T < 5.0$ GeV)
- Ratios for v_2 decrease with decreasing centrality becoming smaller than unity by 10–15% centrality.
- For v_3 the Xe+Xe values are larger than Pb+Pb over 0–30% centrality.
- Hydrodynamic predictions (1711.08499) describe data well.

Messages from flow

- Significant harmonic (v_2-v_5) observed in Pb+Pb collisions reflecting the nuclear overlap and fluctuations of the initial nucleon-nucleon positions.
- The long range “ridge” and “cone” structures in two-particle correlation function at low p_T can be explained by flow effects.
- Hydrodynamics (also) describes flow in Xe+Xe collisions.

Electroweak probes

W/Z, photons, are not supposed to interact with QGP.



Can be used as benchmarks for in-medium effects.

Can also be used to check models of collision geometry (Glauber). Their production is expected to scale with number of nucleon-nucleon collisions.

Systematic study of partonic energy loss in Z and photon associated to jets.

Nuclear Modification Factor - R_{AA}

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

Yields in Pb+Pb collisions, (in medium)

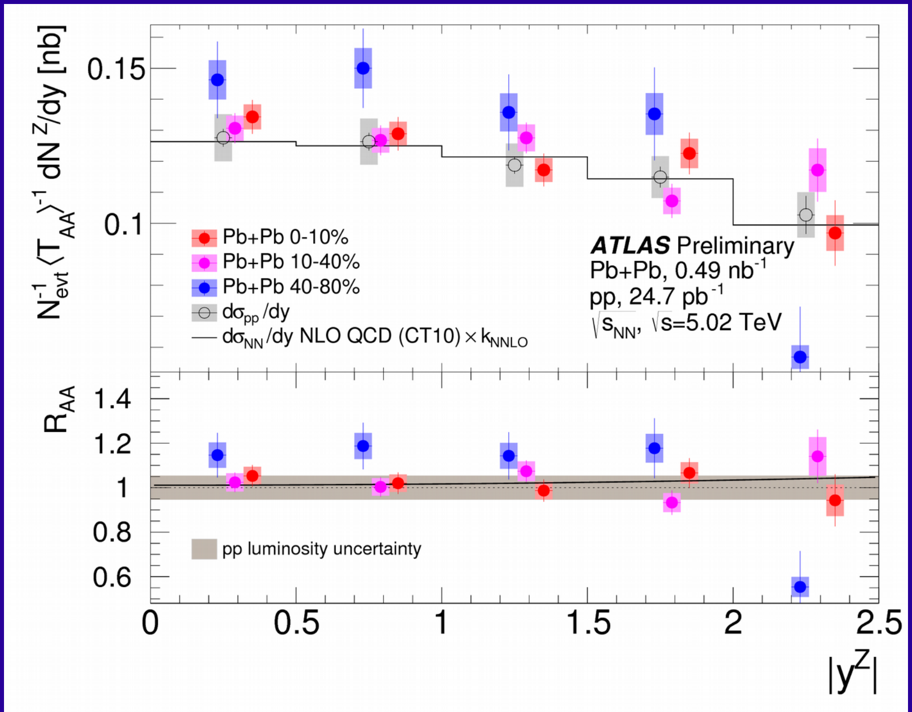
Nuclear thickness function $\langle N_{coll} \rangle / \sigma_{NN}$

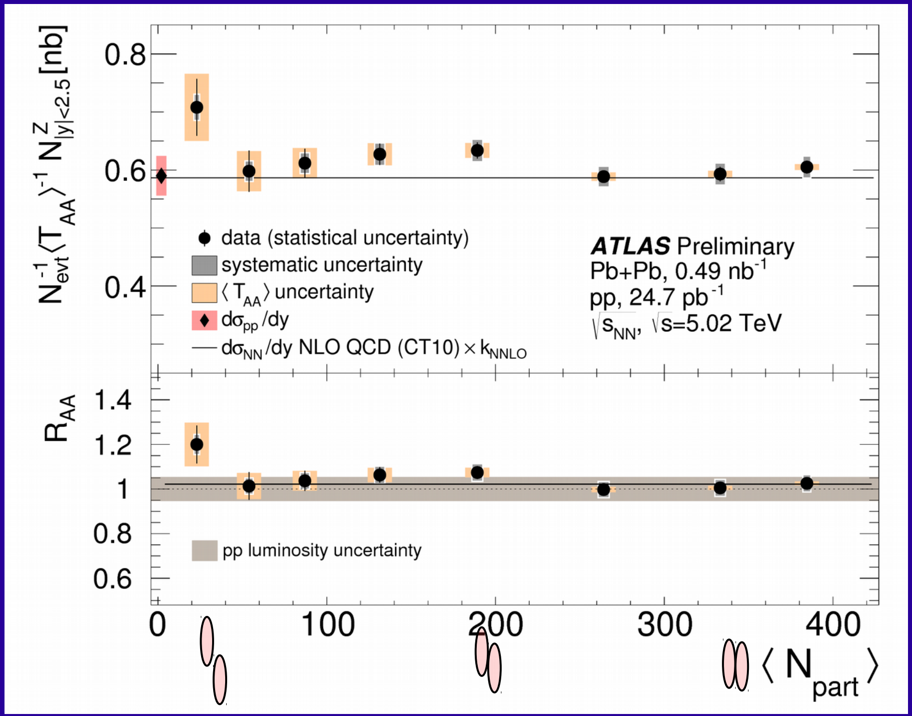
Cross section in pp collisions (in vacuum)

- **Nuclear modification factor quantifies the change of yields, relatively to the production in vacuum.**
- **Any deviation from unity points to suppression or enhancement of yields.**

Electroweak probes in Pb+Pb collisions – Z^0

ATLAS-CONF-2017-010



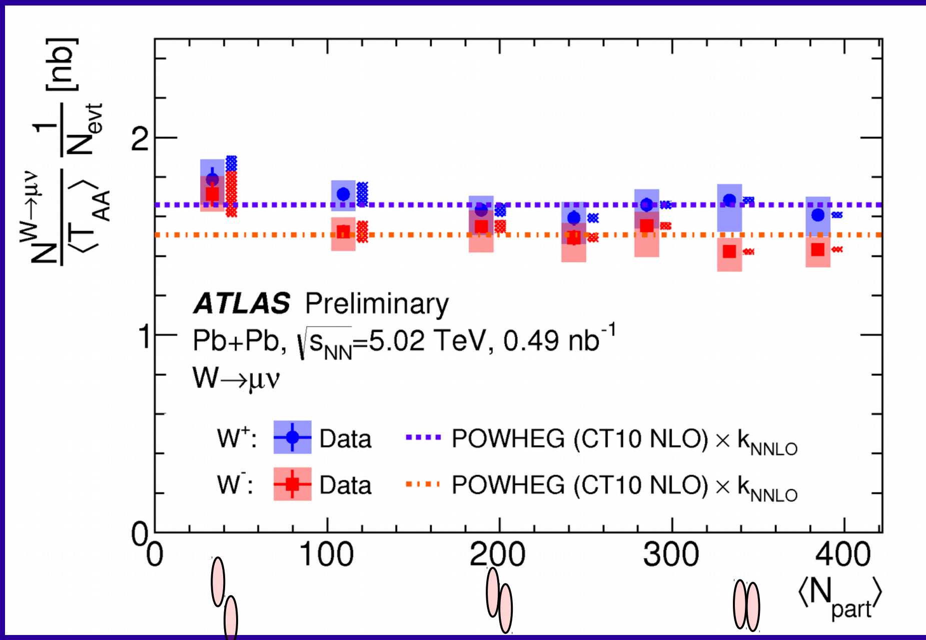


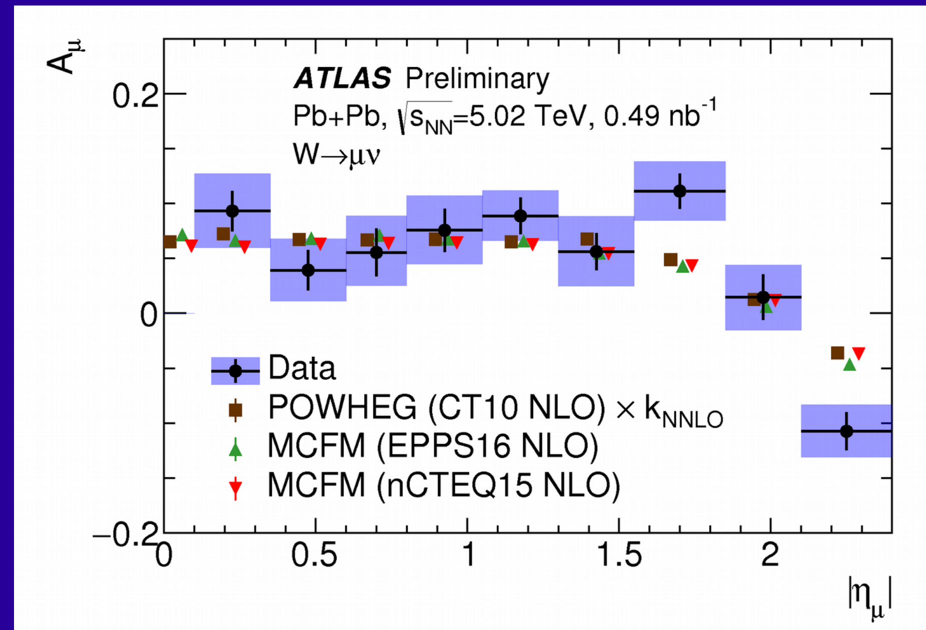
- R^Z_{AA} is expected to be greater than unity by about 2.5% due to isospin effect.
- Consistent with unity within uncertainties. Excess in the most peripheral bin?

Electroweak probes in Pb+Pb collisions - W$^{\pm}$

ATLAS-CONF-2017-067

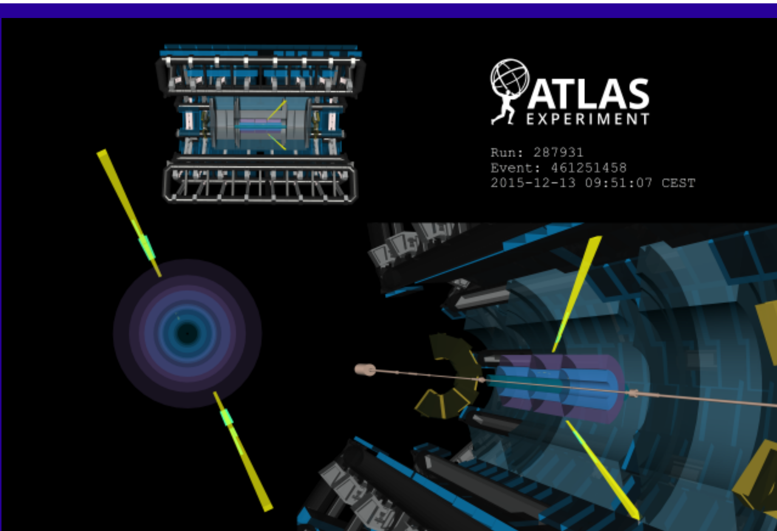
$$A_\ell(\eta_\ell) = \frac{\mathrm{d}N_{W^+\to\ell^+\nu}/\mathrm{d}\eta_\ell - \mathrm{d}N_{W^-\to\ell^-\bar{\nu}}/\mathrm{d}\eta_\ell}{\mathrm{d}N_{W^+\to\ell^+\nu}/\mathrm{d}\eta_\ell + \mathrm{d}N_{W^-\to\ell^-\bar{\nu}}/\mathrm{d}\eta_\ell}$$

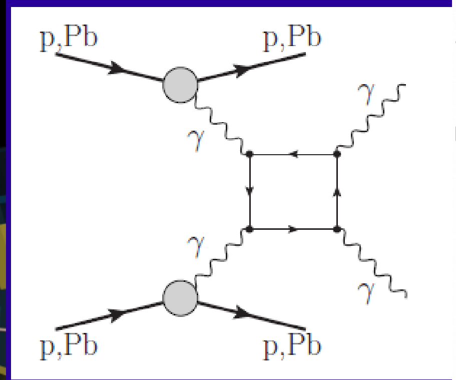


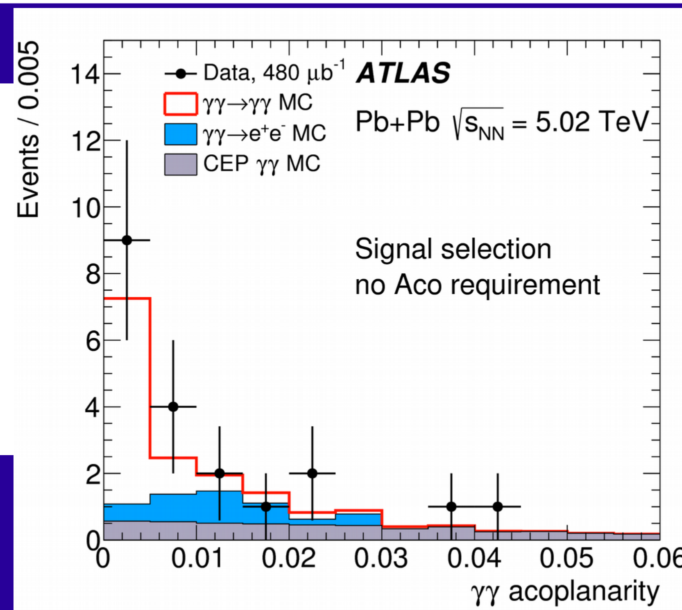


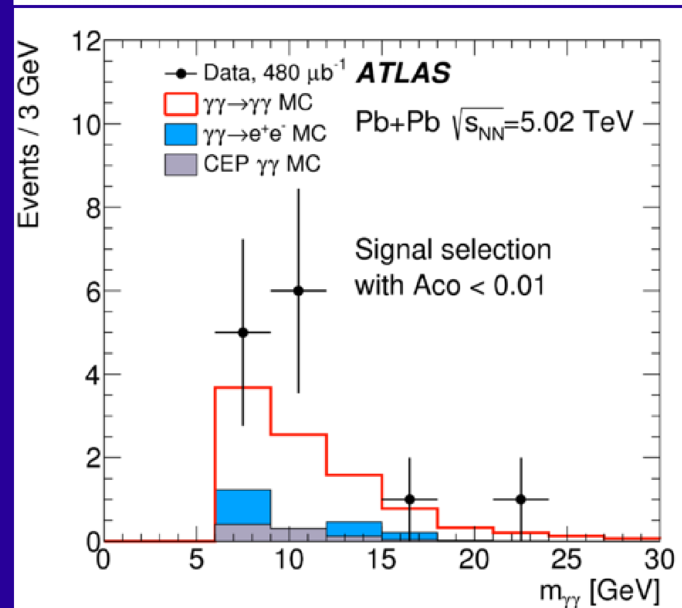
- Yields of W bosons divided by T_{AA} are independent of centrality.
- $W^+ \to \mu^+\nu$ yields are systematically ~10% larger than $W^- \to \mu^-\bar{\nu}$ yields.
- Good agreement with predictions, both that ascribe free-nucleon PDF and nPDF, for $|\eta_\mu| < 1.4$. Three sigma at forward.

Electroweak probes - LbyL









Evidence of LbyL scattering: 4.4 (3.8) σ

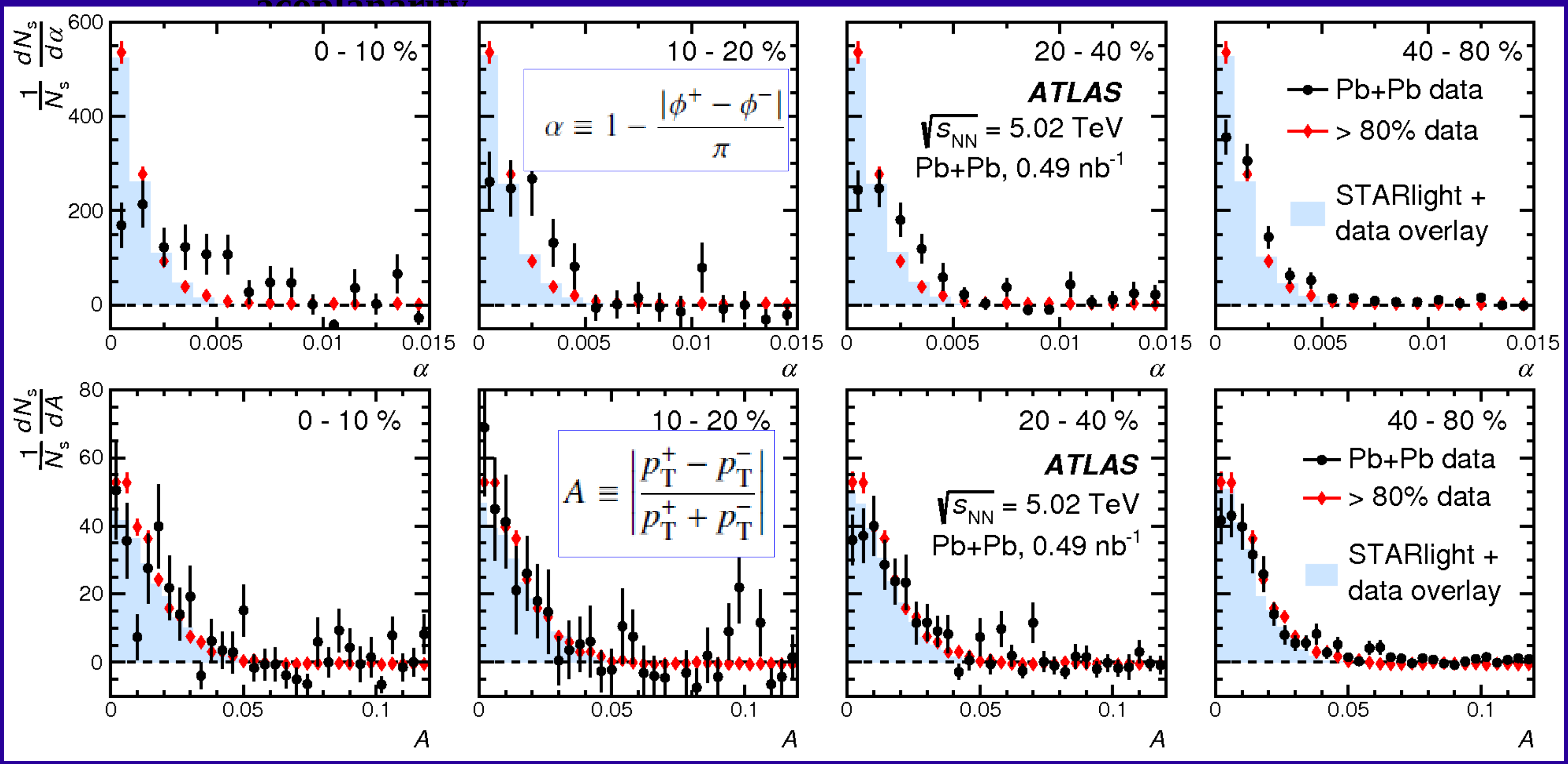
σ_{fid} = 70 ± 24 (stat) ± 17 (syst) nb, in agreement with SM predictions.

Stay tuned for Pb+Pb 2018 data analysis (more than factor 2 statistics) and LHC Run 4 with increased tracking acceptance.

$\gamma\gamma \rightarrow \mu^+\mu^-$ in non-UPC

Phys. Rev. Lett. 121 (2018) 212301

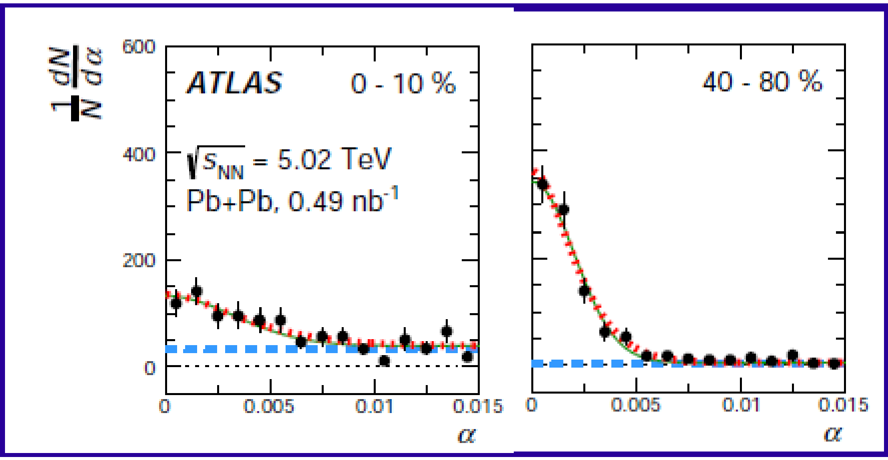
Dimuon pairs resulting from photonuclear interactions occurring simultaneously with the hadronic collision.



- Data reveals balance in energy, but acoplanarity broadning with centrality.
- STARlight agrees in peripheral, but not in central collisions.

$\gamma\gamma \rightarrow \mu^+\mu^-$ in non-UPC

Phys. Rev. Lett. 121 (2018) 212301



if broadmimg results ftom small k_T transfer:

$$\langle\alpha^2\rangle = \langle\alpha^2\rangle_0 + \frac{1}{\pi^2}\frac{\left\langle \vec{k}_T^2 \right\rangle}{\left\langle p_{T\,avg}^2 \right\rangle}$$

Centrality	$\langle N_{part}\rangle$	$p_{T\,avg}^{RMS}$ [GeV]	Gaussian fit			Convolution fit
			$\sigma_A(\times 10^3)$	$\sigma_\alpha(\times 10^3)$	k_T^{RMS} [MeV]	k_T^{RMS} [MeV]
0–10%	359±2	7.0±0.1	$17.9^{+1.0}_{-0.9}$	3.3±0.4	66±10	70±10
10–20%	264±3	7.7±0.4	$13.6^{+1.2}_{-1.0}$	2.3±0.3	40±7	42±7
20–40%	160±3	7.4±0.3	$17.2^{+0.4}_{-0.4}$	2.5±0.2	48±6	44±5
40–80%	47±2	6.8±0.3	$16.1^{+0.1}_{-0.1}$	2.0±0.1	35±4	32±2
> 80%	–	7.0±0.3	$15.5^{+0.1}_{-0.1}$	1.40±0.03	-	-

- Modifications are qualitatively consistent with re-scattering of the muons while crossing the QGP.

Electroweak probes in p+Pb collisions – γ

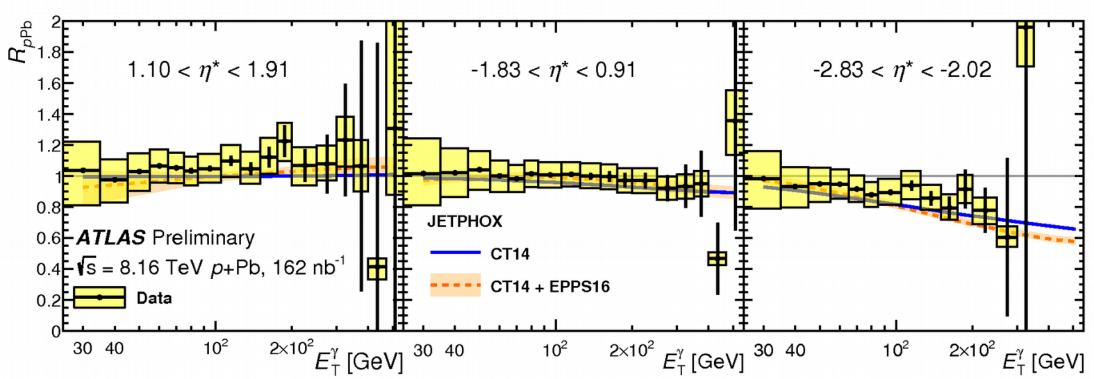
ATLAS-CONF-2017-072

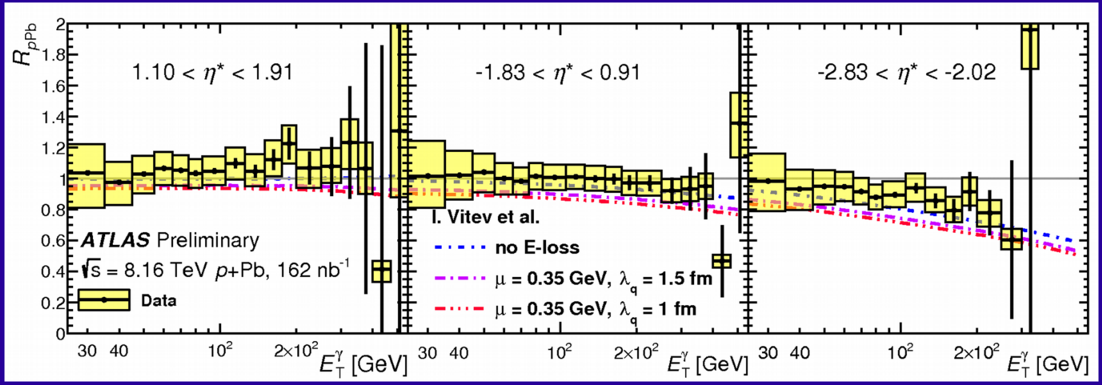
- Inclusive prompt photons in p+Pb collisions at 8.16 TeV.

$E_T^{\gamma} > 25$ GeV

$E_T^{iso} < 4.8$ GeV + $4.2\text{x}10^{-3} E_T^{\gamma}$ [GeV]

- R_{pPb} consistent with unity at central and forward rapidity.
- R_{pPb}<1 for η* < –2 due to isospin effects.
- Data consistent within uncertainties with both free nPDF and with the small effects expected from a nuclear modification of the parton densities.





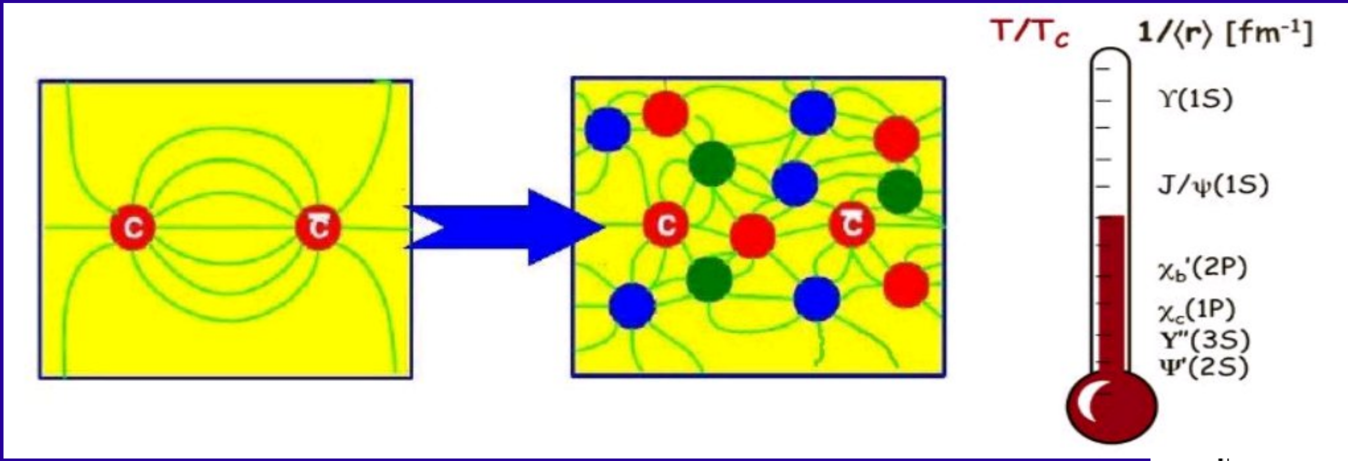
- Data disfavours large suppression due to E-loss.

Messages from EW

- Photons, Z and $W^{\pm}$ productions consistent with expectations from T_{AA} scaling.
- No visible modifications of nuclear PDFs within uncertainties.
- Evidence of LbyL scattering: 4.4 (3.8) σ.
- Modifications in the acoplanarity of dimuons produced in non-UPC by magnetic fields are qualitatively consistent with re-scattering while crossing the QGP.

Quarkonia

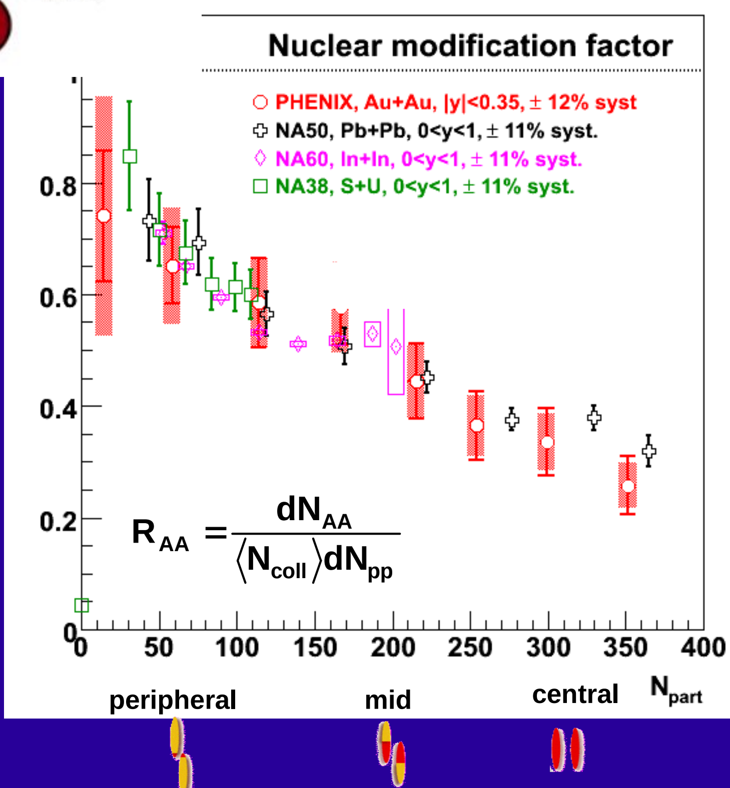
Quarkonia suppression is predicted by lattice QCD calculations



J/psi anomalous suppression by Debye colour screening (Matsui and Satz, 1986)

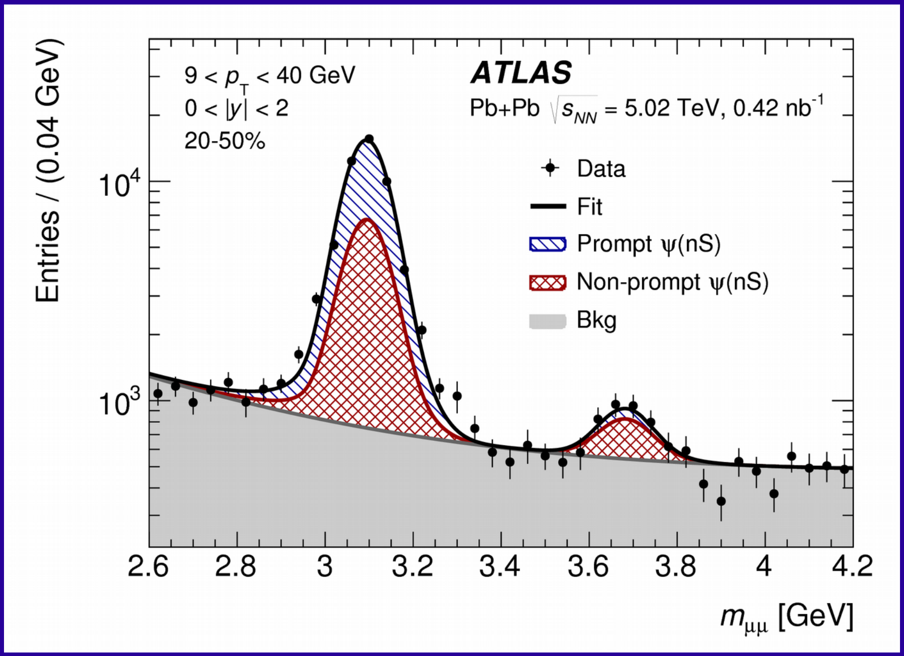
→ One of the most striking signatures for the QGP

→ A major contribution from LIP

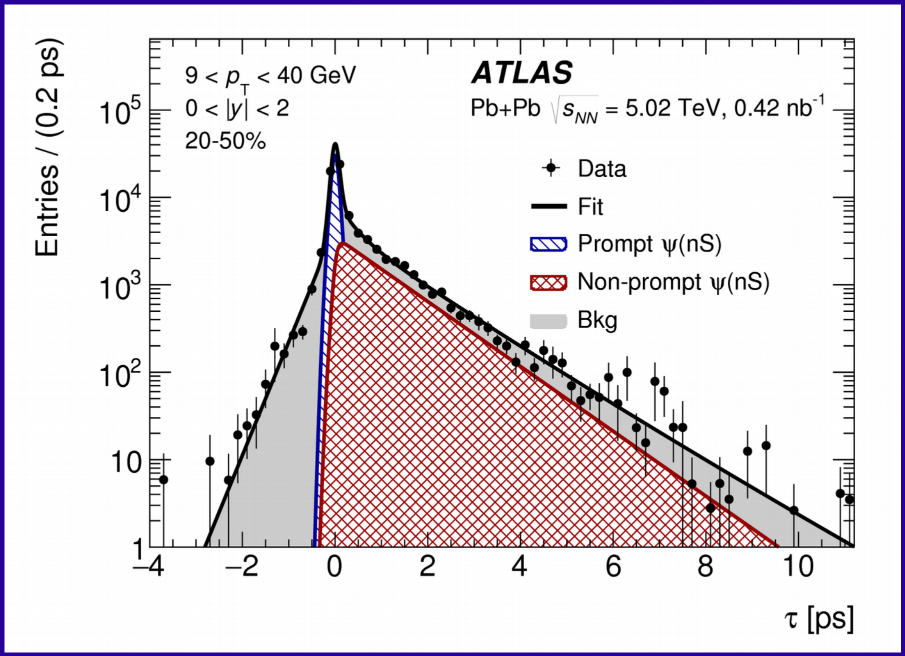


Prompt and Non-prompt Charmonia in Pb+Pb

Dimuon invariant mass

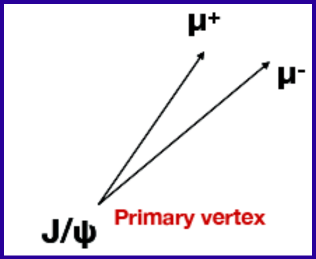


Dimuon pseudo-proper time



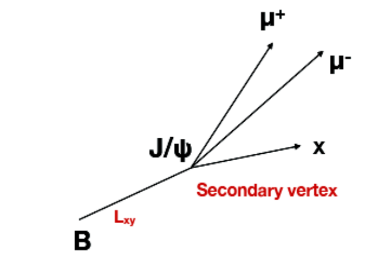
Prompt J/ψ: direct production; feed-down from excited states.

Modified by colour screening and regeneration in the QGP.



Non-prompt J/ψ: decays from B-hadrons

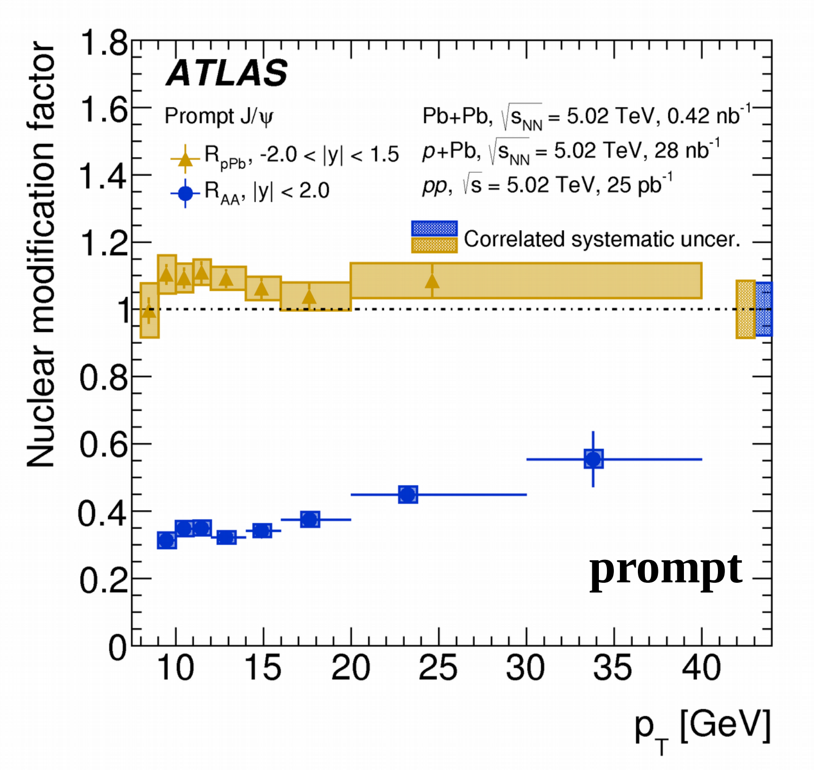
Energy loss of the b-quarks in the QGP.

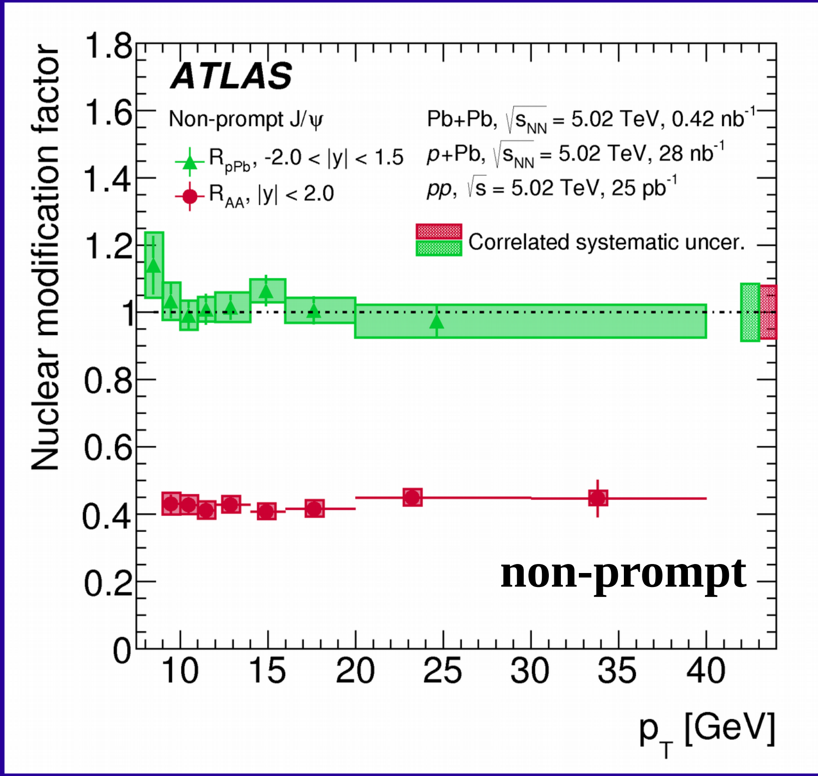


$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}},$$

J/ψ R_{pPb} and R_{AA} as a function of p_T

Quarkonia in p+Pb collisions is a probe of cold nuclear matter effects



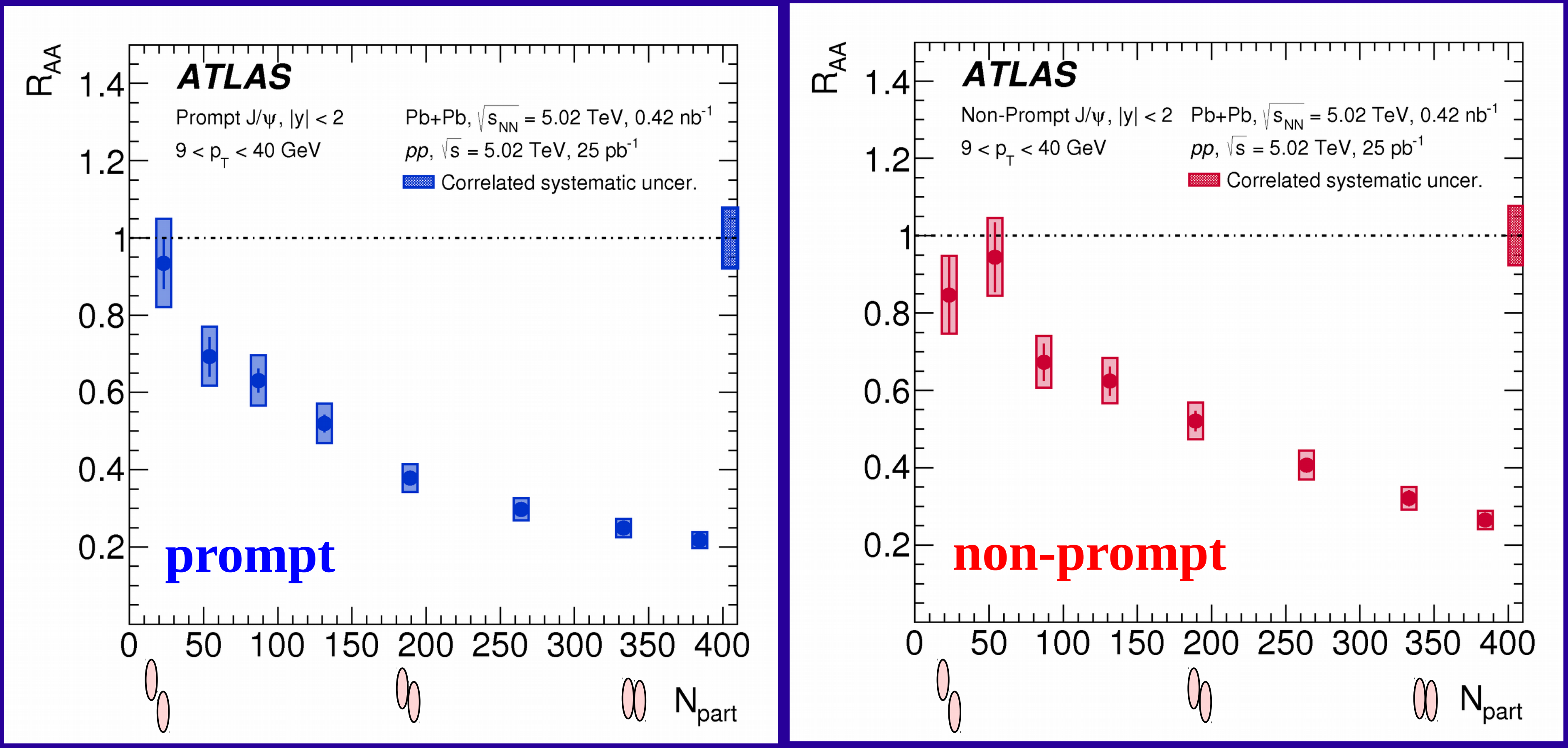


$$R_{pPb} = \frac{1}{208}\frac{\sigma^{O(nS)}_{p+\mathrm{Pb}}}{\sigma^{O(nS)}_{pp}},$$

- **R_{pPb} is consistent with unity.**
- **J/ψ is strongly suppressed in Pb+Pb; prompt and non-prompt mechanisms have different p_T dependence.**

J/ψ R_{AA} as a function of N_{part}

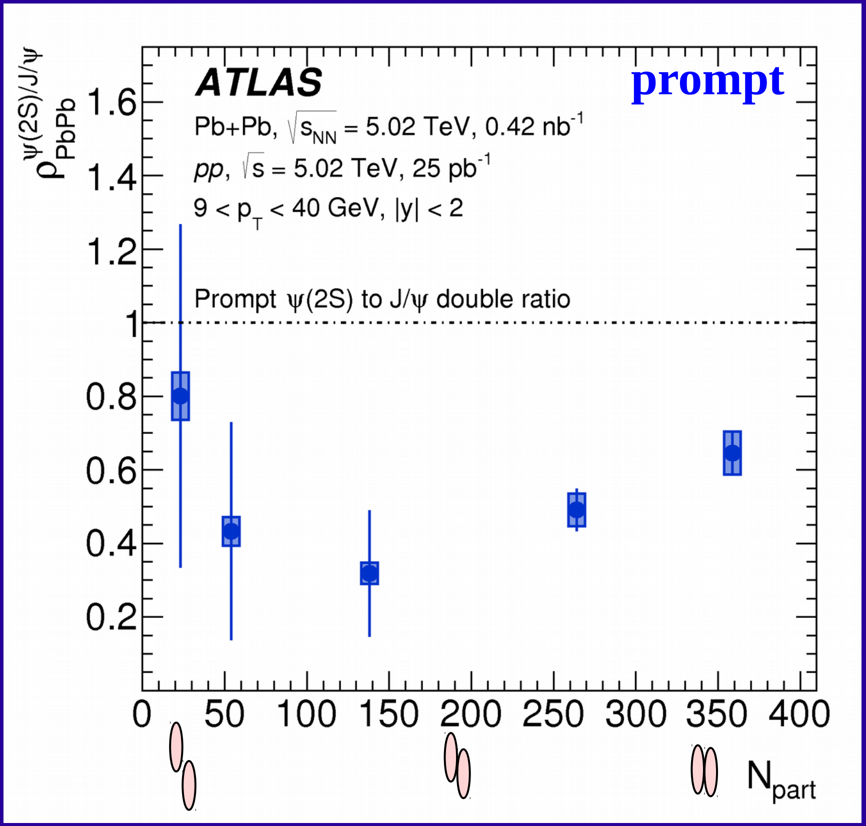
Eur. Phys. J. C 78 (2018) 762

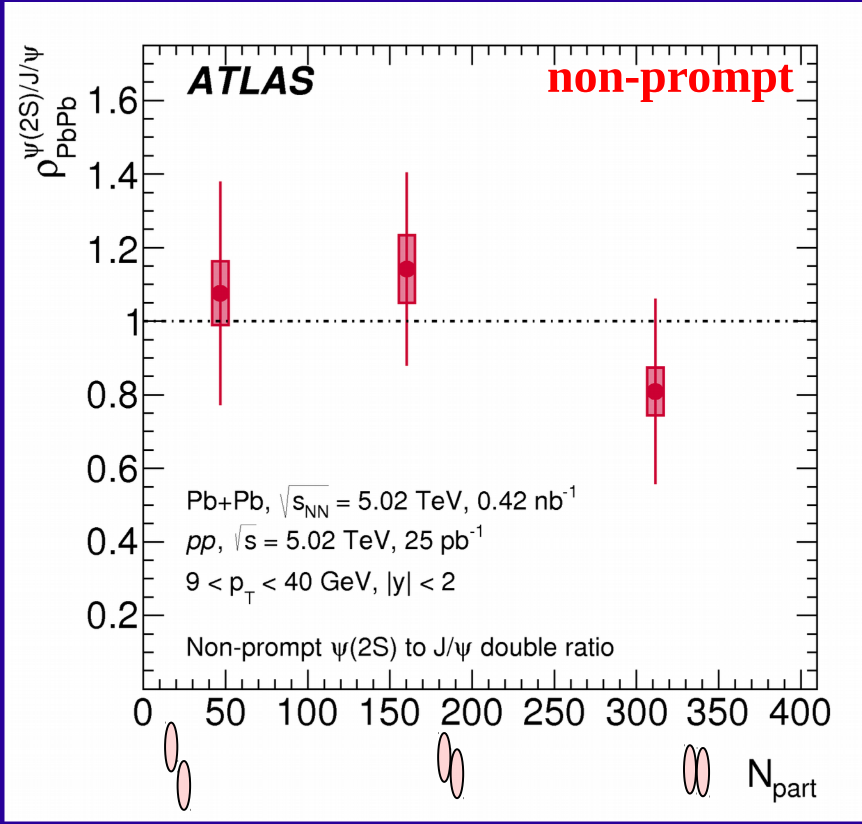


Strong centrality dependence for both **prompt** and **non-prompt** J/ψ, with similar suppression pattern.

ψ(2S) to J/ψ as a function of N_{part}

Eur. Phys. J. C 78 (2018) 762

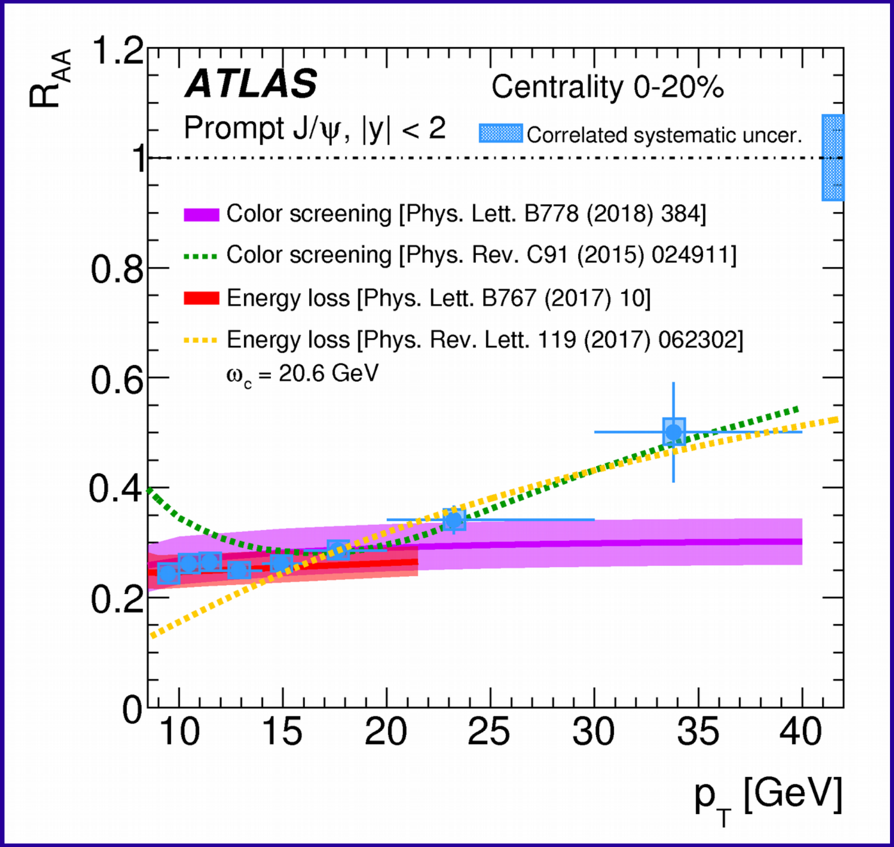




- Prompt ψ(2S) to J/ψ ratio increases in central collisions, supporting the hypothesis of ψ(2S) being produced by regeneration. More data is needed.
- Non-prompt ψ(2S) to J/ψ ratio is consistent with unity, suggesting that both mesons originate from b-quarks hadronising outside the QGP.

Prompt J/ψ R_{AA} as a function of p_T

Eur. Phys. J. C 78 (2018) 762

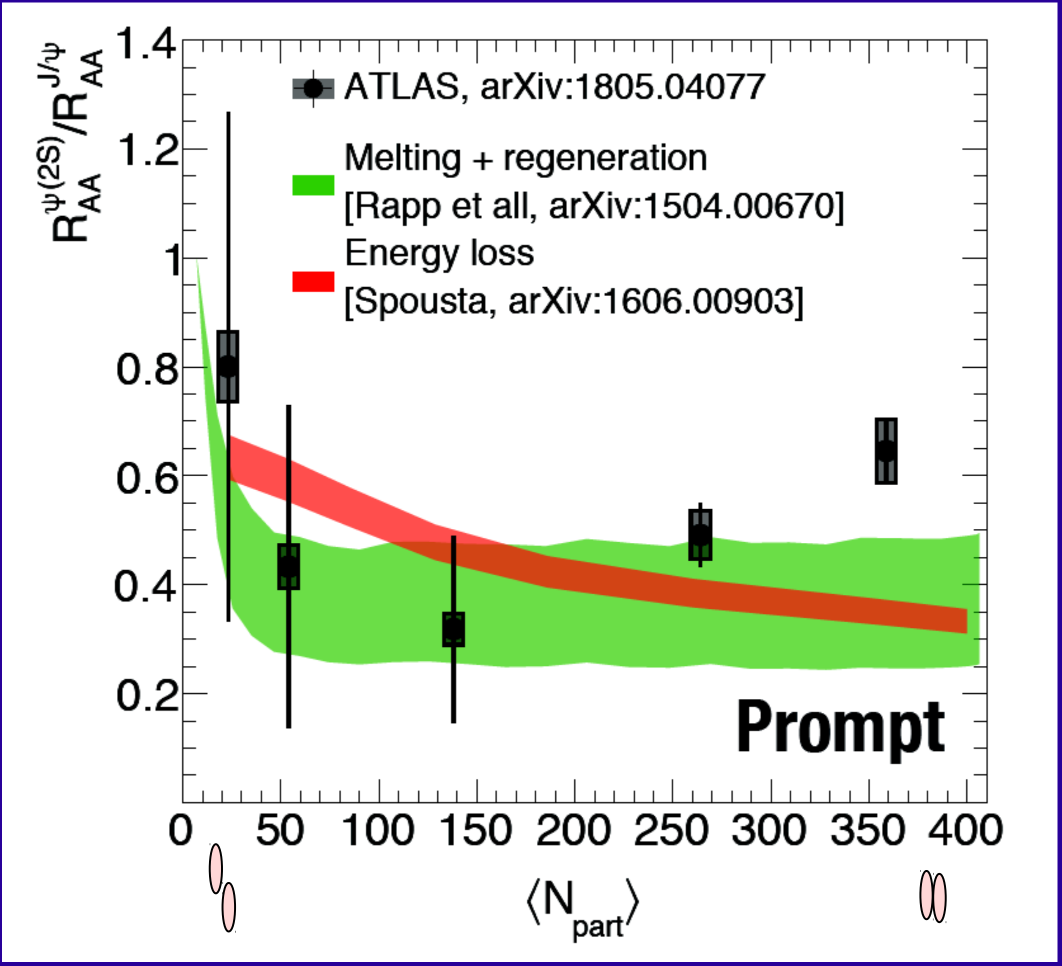


Data at high p_T well described by **color screening** and **energy loss** scenarios, but they miss low p_T.

Different models on **color screening** and **energy loss** agree at low p_T, but fail at high p_T.

Prompt ψ(2S) to J/ψ as a function of N_{part}

Eur. Phys. J. C 78 (2018) 762

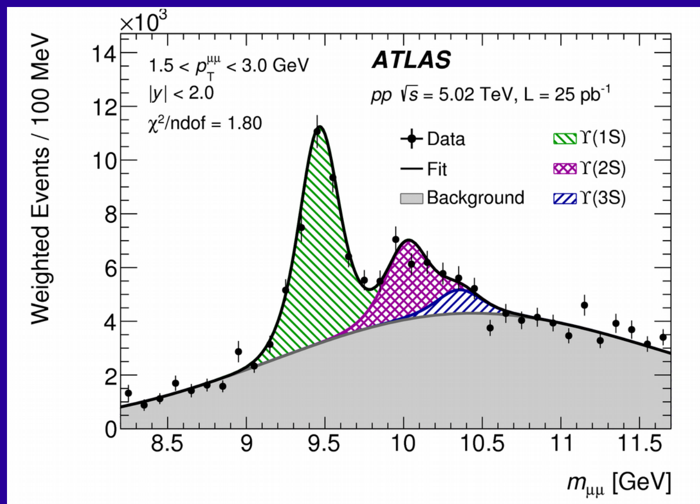


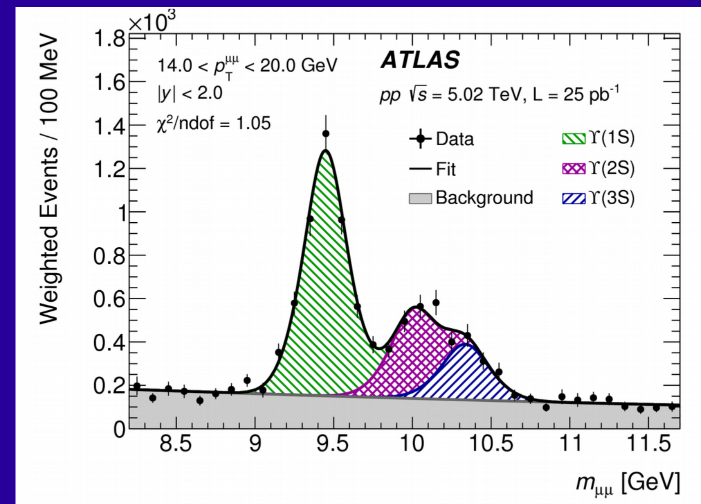
Both models foresee the decrease in the double ratio, but fail in describing simultaneously all centralities.

Bottonium Fits to Dimuon Invariant Mass

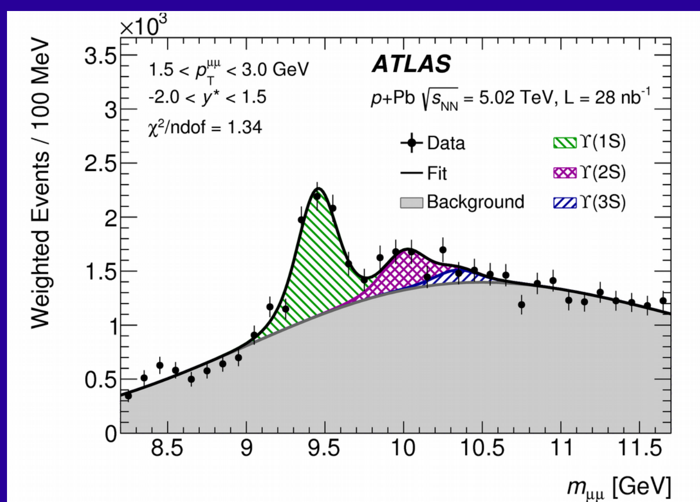
$1.5 < p_T < 3.0$ GeV | $14.0 < p_T < 20.0$ GeV

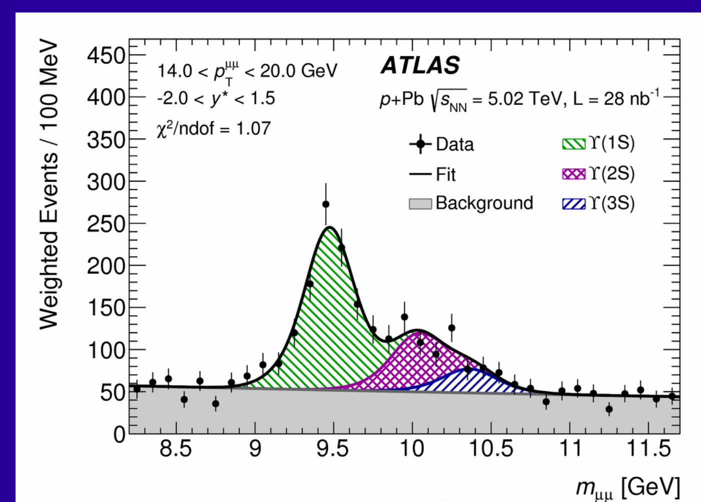
pp





p+Pb

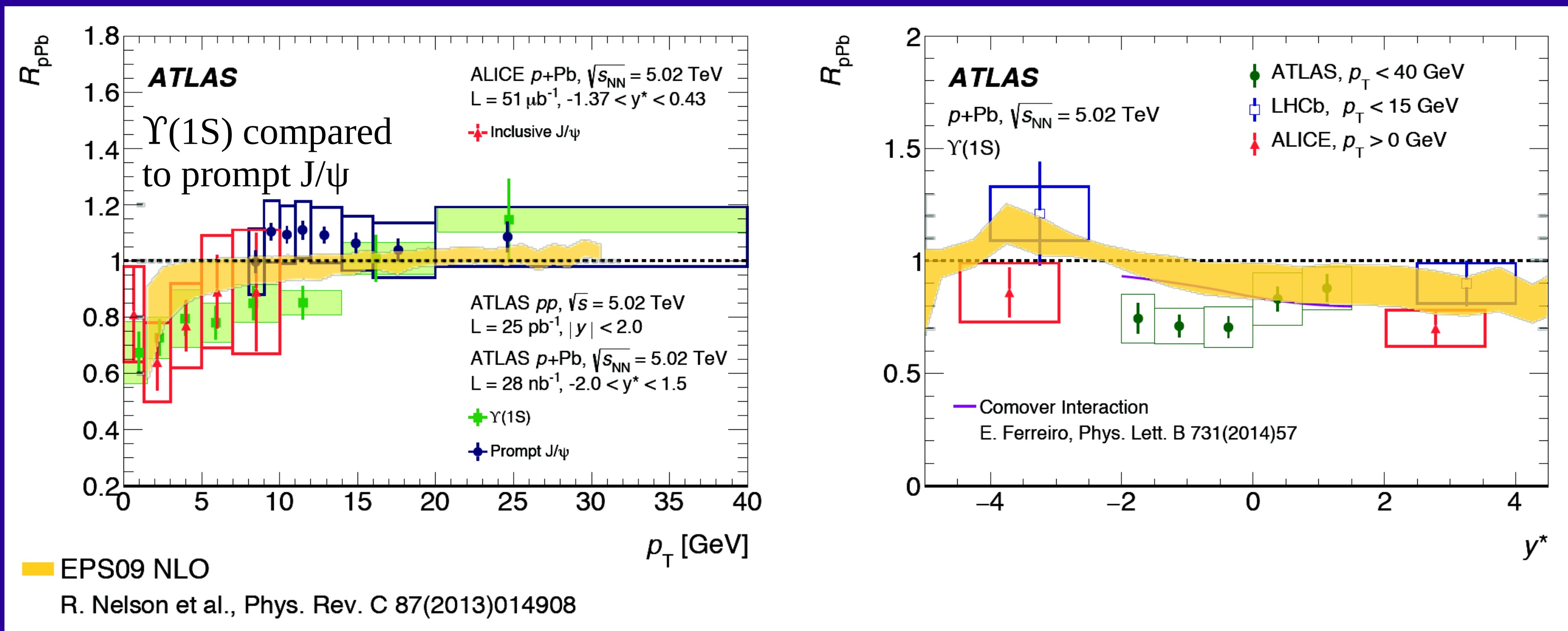




Quarkonia R_{pPb} as a function of p_T and y*

Eur. Phys. J. C 78 (2018) 171

p+Pb collisions are important to disentangle effects due to quarkonium interactions with QGP from those atributed to CNM.



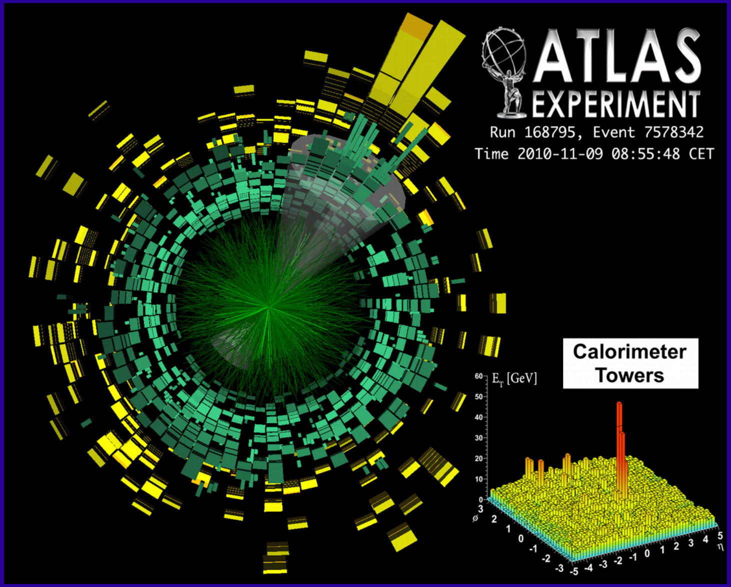
- R_{pPb} is consistent with unity for $p_T > 9$ GeV → important reference for the suppression at high p_T in larger collision systems (Pb+Pb and Xe+Xe).
- Models provide qualitatively good description.

Messages from Quarkonia

- Strong centrality dependence, and with similar suppression, for both prompt and non-prompt J/ψ.
- Modest dependence on |y| (in backup). Different p_T dependence.
- Data at high p_T well described by color screening and energy loss models. But these miss low p_T.
- Indications of prompt ψ(2S) regeneration in central collisions.
- Non-prompt ψ(2S) to J/ψ ratio is consistent with unity.
- ϒ(1S) and J/ψ R_{pPb} is consistent with unity for $p_T > 9$ GeV.

Jets as probes of hot matter

QGP is opaque to coloured partons. How do parton showers in the hot and dense medium differ from those in vacuum?



What is expected:

- Partons lose energy, resulting in jet “quenching”.

- Jets probe the very first phase of the collision

→ they carry relevant information about the QGP.

Different observables allow to disentangle the nature of the Eloss:

Dijet Asymmetry, Acoplanarity

Correlation with colour neutral probes (Z and photons)

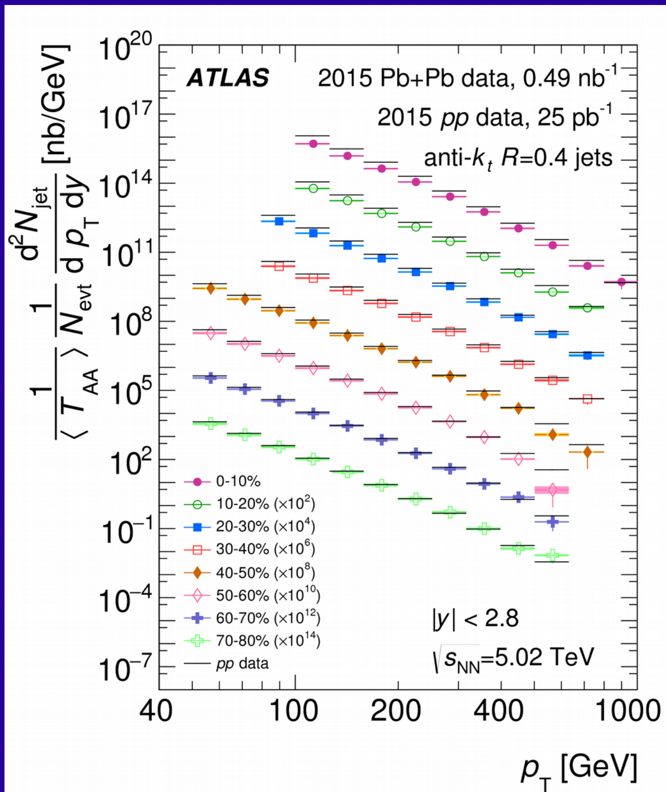
Differential inclusive jet suppression

Jet structure and properties of quenched jets

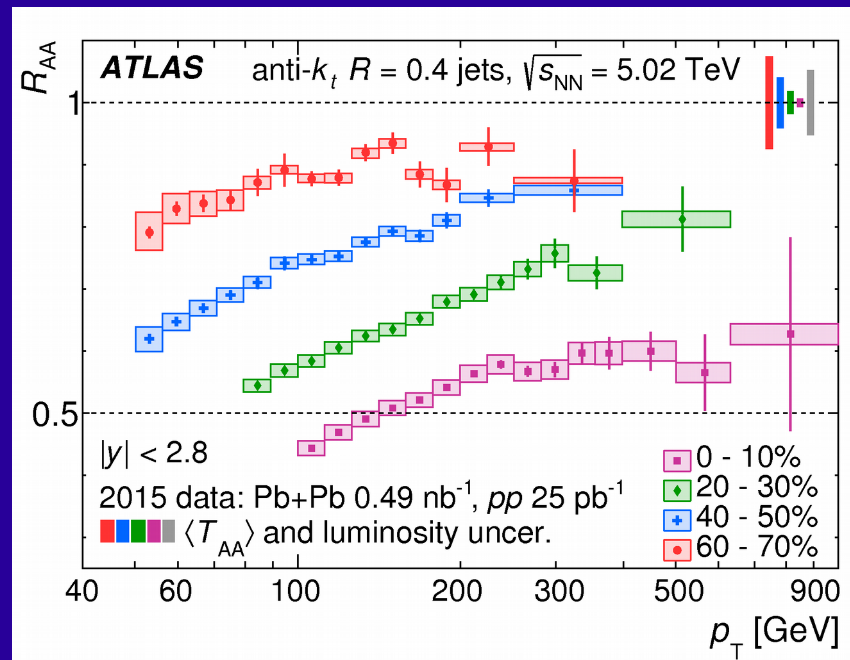
Inclusive jet production in Pb+Pb

arXiv:1805.05635

Per event jet yields in Pb+Pb collisions, divided by <T_{AA}>, as a function of jet p_T for different centrality intervals.



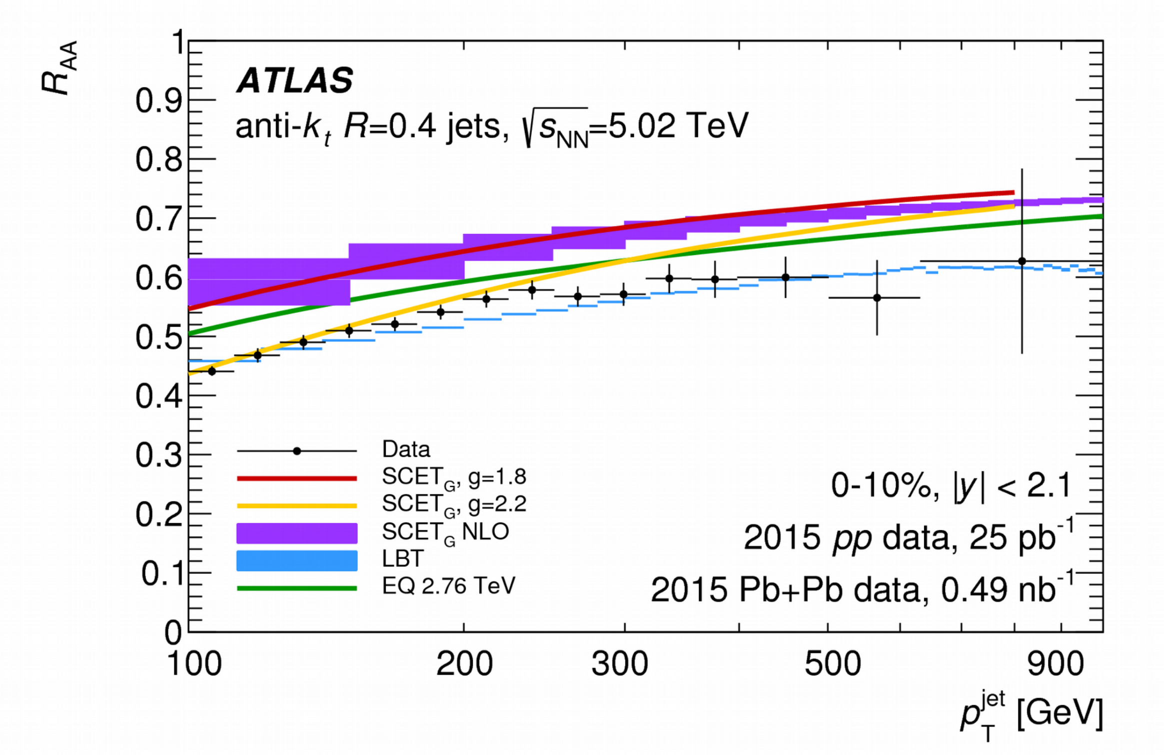
Jet R_{AA} as a function of p_T for different centrality intervals.



- Jets are suppressed by a factor of two in central Pb+Pb collisions with clear dependence on transverse momentum, p_T.
- Peripheral collisions (60 – 70%) show also significant suppression.

Jet R_{AA} compared with theory

arXiv:1805.05635

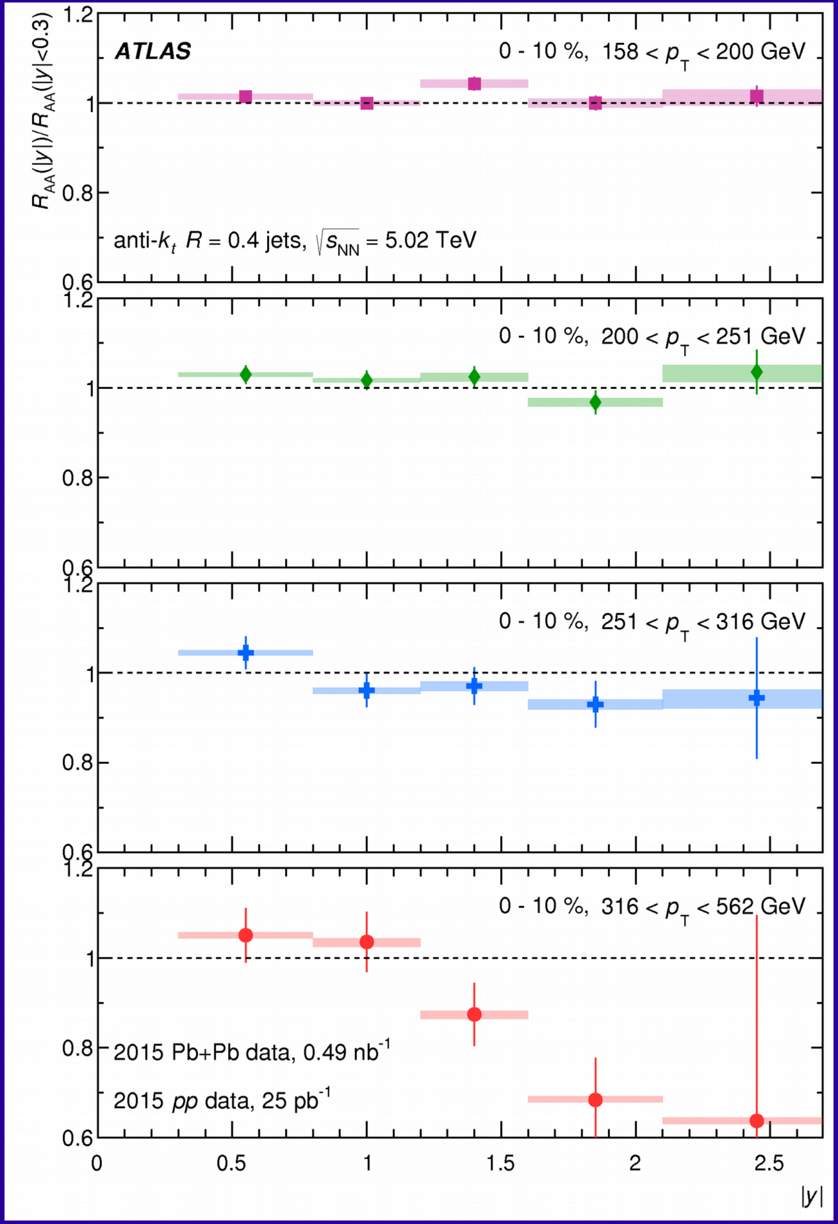


Linear Boltzmann Transport (LBT - 1503.03313)
Soft Collinear Effective Field Theory (SCETg - 1509.02936)
Effective Quenching (EQ - 1504.05169)

All models reproduce the trend shown by the data. EQ and SCETg (with exception for g=2.2) clearly underestimate the suppression.

$R_{AA}^{|y|}$ to the $R_{AA}^{|y|<0.3}$ as a function of |y|

arXiv:1805.05635



Two effcts competing (1504.05169):

1 - Fraction of quark jets increases with $|y|$ at fixed jet $p_{T;}$ Quarks should lose less energy than gluons

→ Increase R_{AA} with $|y|$

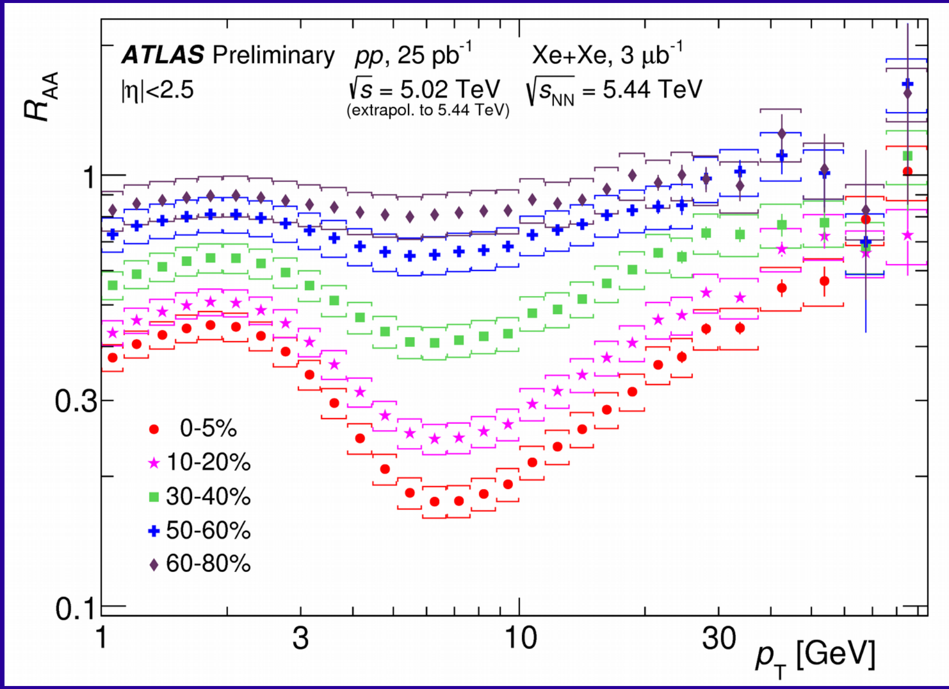
2 - Spectra become steeper with increasing $|y|$

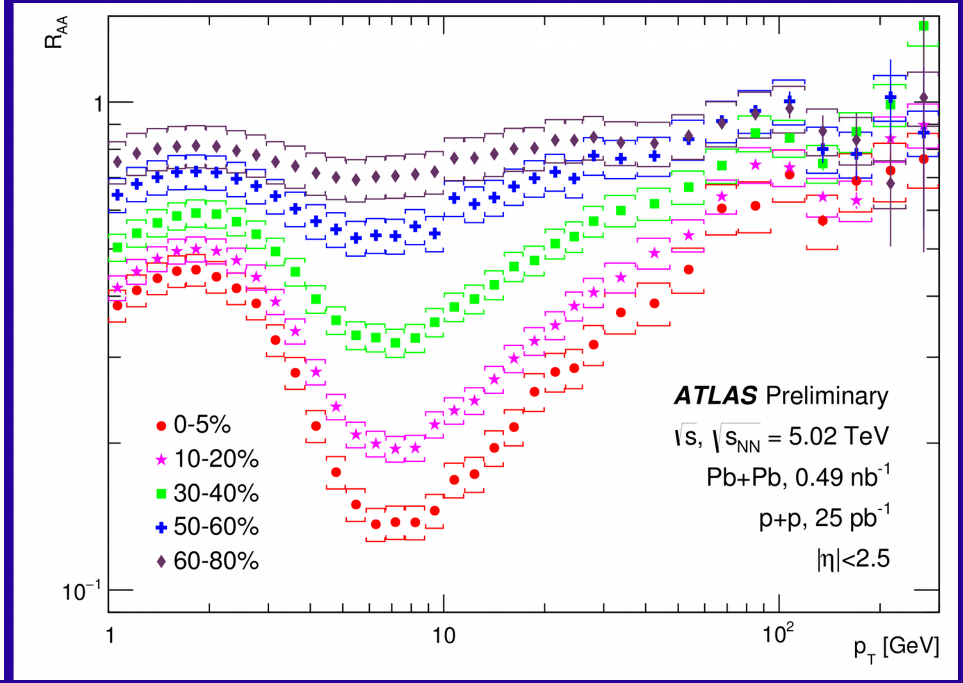
→ Decrease R_{AA} with $|y|$

For high p_T the effect of the steeper spectra dominates.

Charged Hadron R_{AA} in Xe+Xe and Pb+Pb

ATLAS-CONF-2018-007

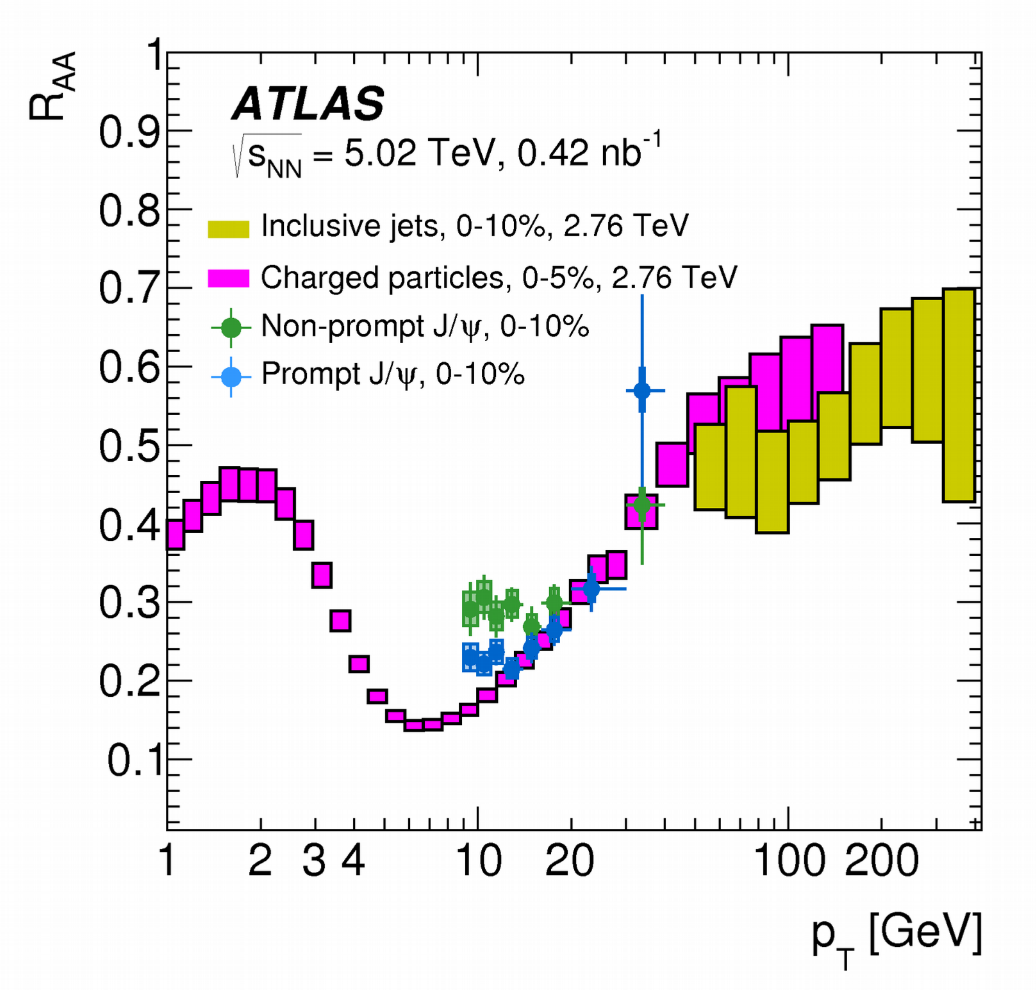




Note different x-axis

Qualitatively similar

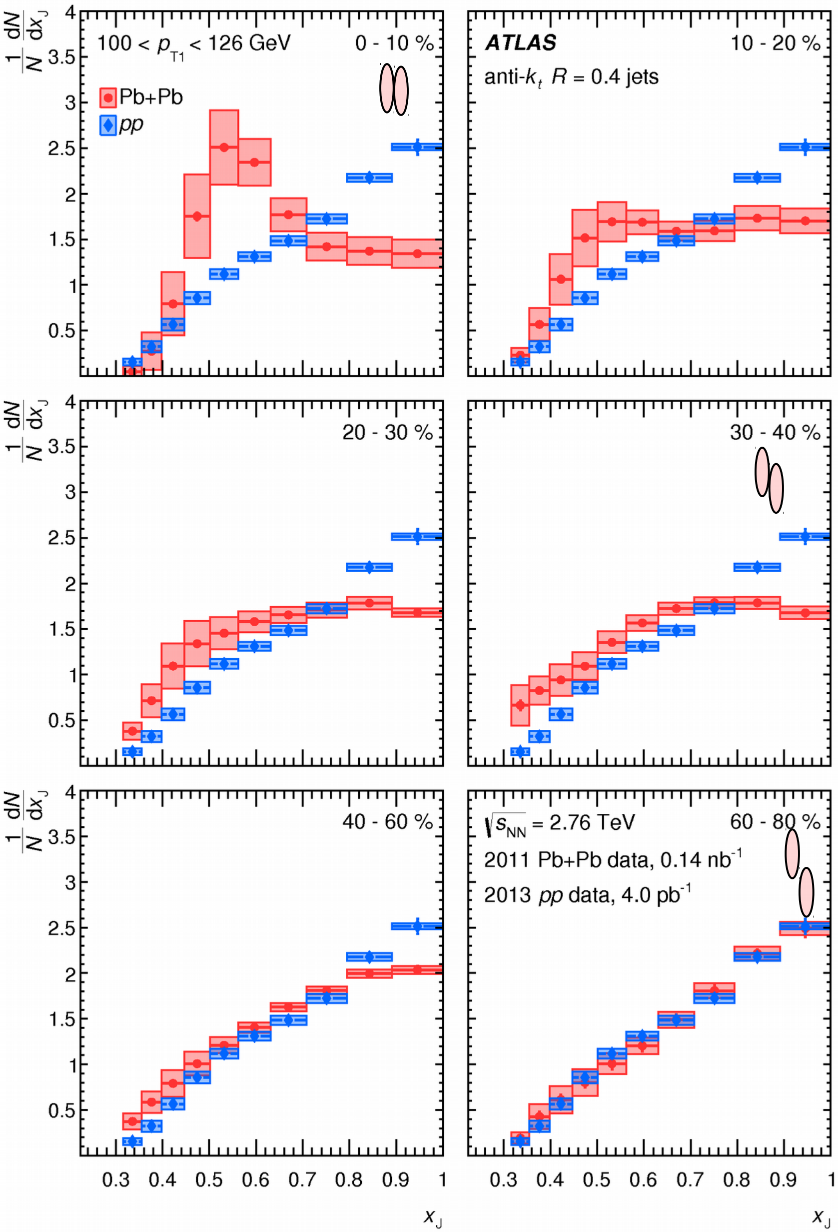
R_{AA} as a function of p_T in different channels



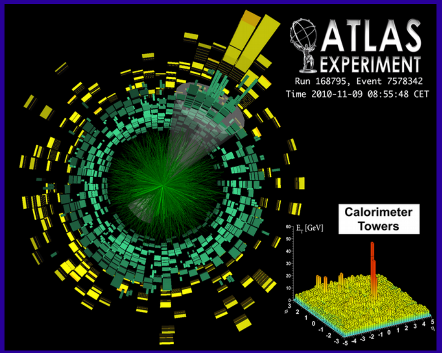
Suggestion of high p_T universality from suppression of several different probes → prompt J/ψ may also be sensitive to parton energy loss.

Dijet asymmetry in Pb+Pb and pp collisions

arXiv:1706.09363 [hep-ex]



Centrality dependence of $x_J = p_{T2}/p_{T1}$ for jet 100 < p_{T1} < 126 GeV

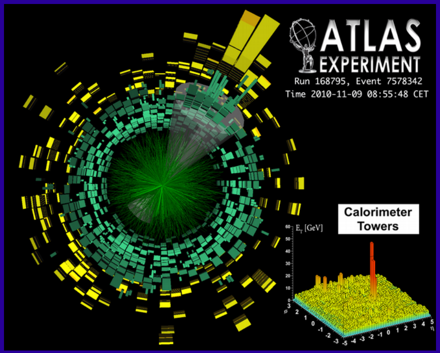


Dijet asymmetry probes differences in quenching between the two parton showers.

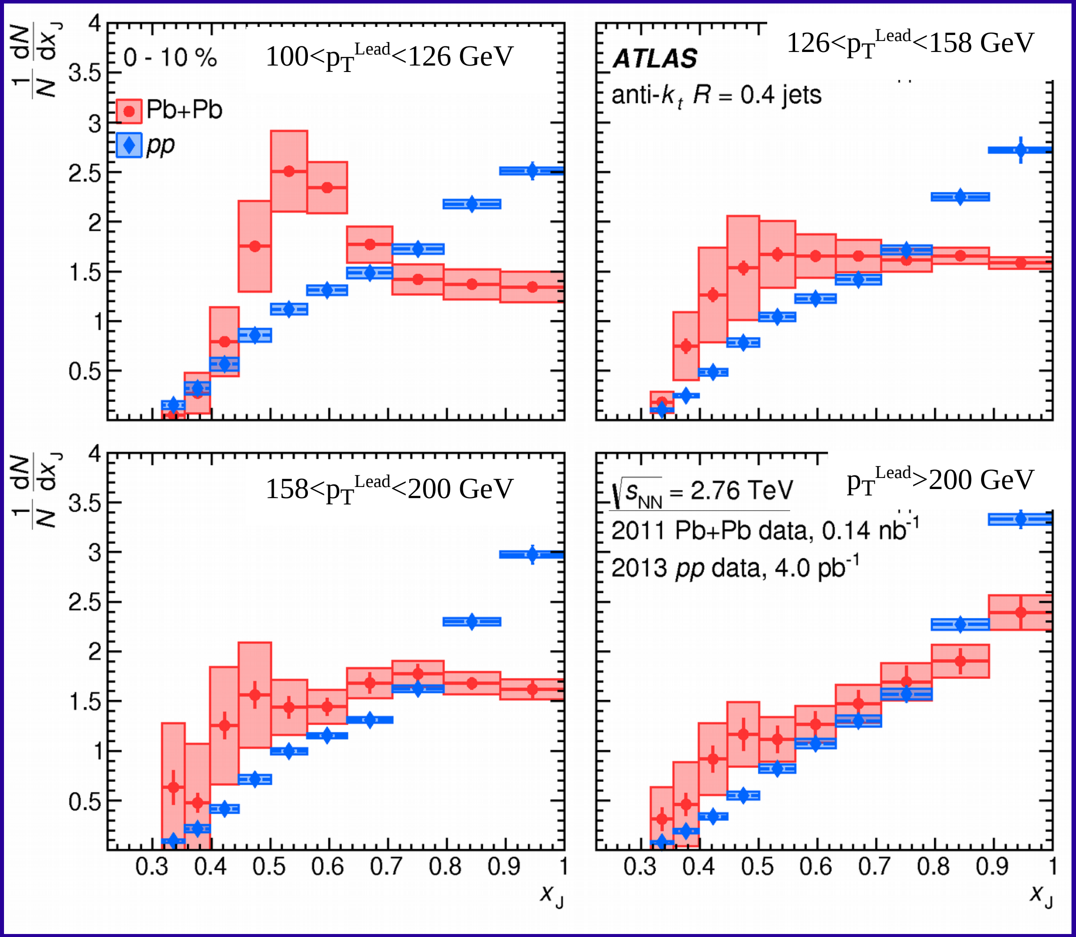
- The asymmetry in peripheral collisions is well compatible with pp collisions
- The asymmetry increases with collision centrality

Dijet asymmetry in Xe+Xe and pp collisions

arXiv:1706.09363 [hep-ex]



p_{T1} dependence of $x_J = p_{T2}/p_{T1}$ in central collisions



Discrepancy between Pb+Pb and pp dilutes with increasing p_{T1}.

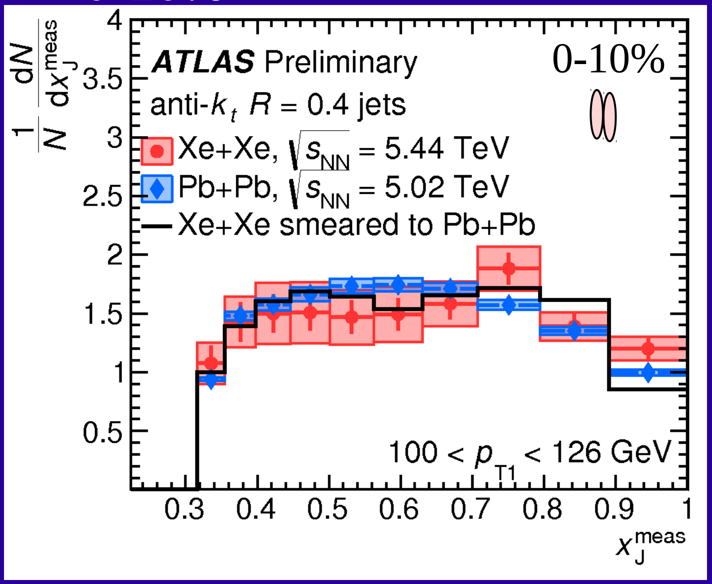
Much smaller modification at high p_T^{Lead}.

Leading contribution from LIP ATLAS group

Dijet asymmetry in Xe+Xe and Pb+Pb

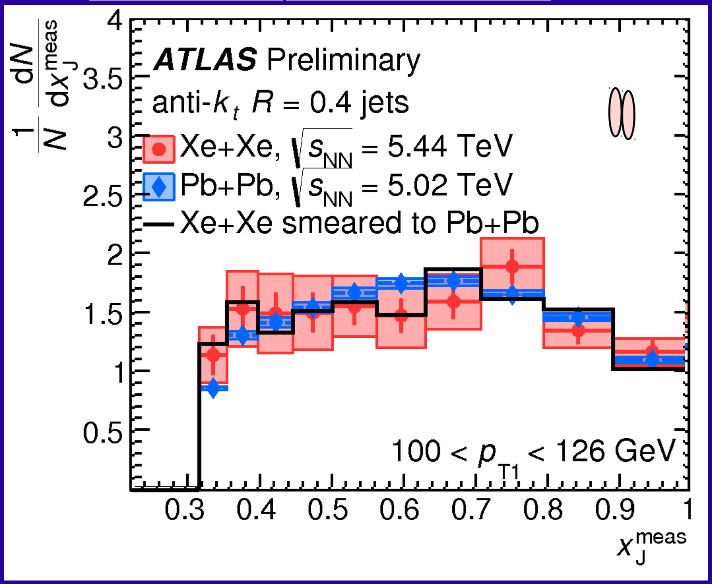
ATLAS-CONF-2018-007

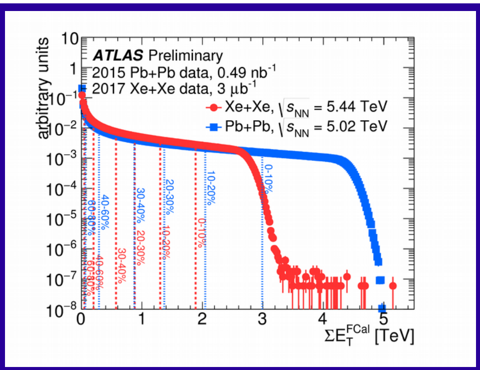
Same collision centrality, 0-10%



Same ΣE_T^{FCal} range

$2.05 < \Sigma E_T^{FCal} < 2.99$ TeV





Both Xe+Xe and Pb+Pb results are not corrected for detector effects. Black line represents Xe+Xe smeared to Pb+Pb.

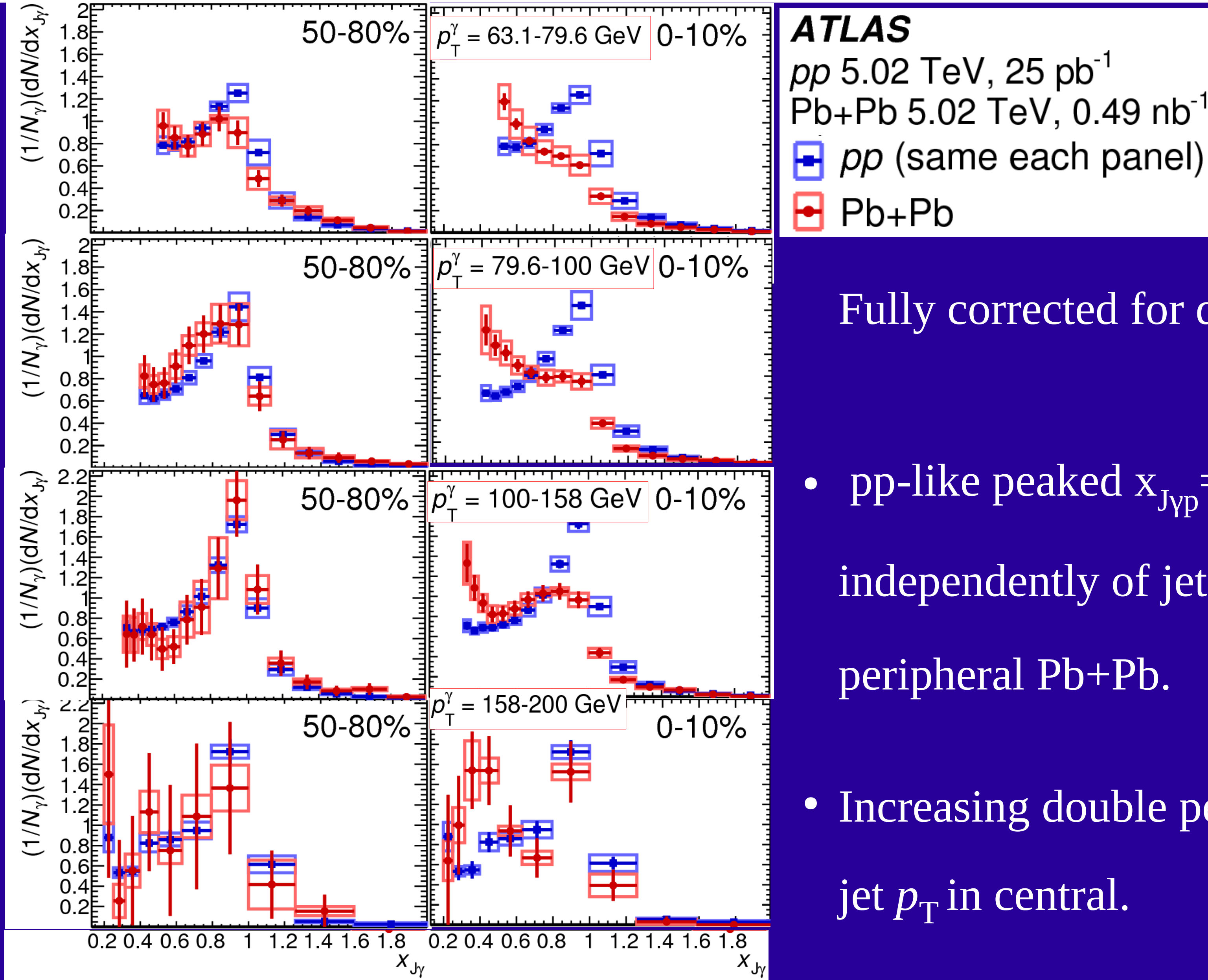
→ Difference in underlying event fluctuations has minimal impact in the result.

Consistencey between Xe+Xe and Pb+Pb in both centrality and ΣE_T^{FCal} ranges.

No dependence on geommetry of the collision within uncertainties.

Electroweak probes: γ + jet p_T balance

Phys. Lett. B 789 (2019) 167

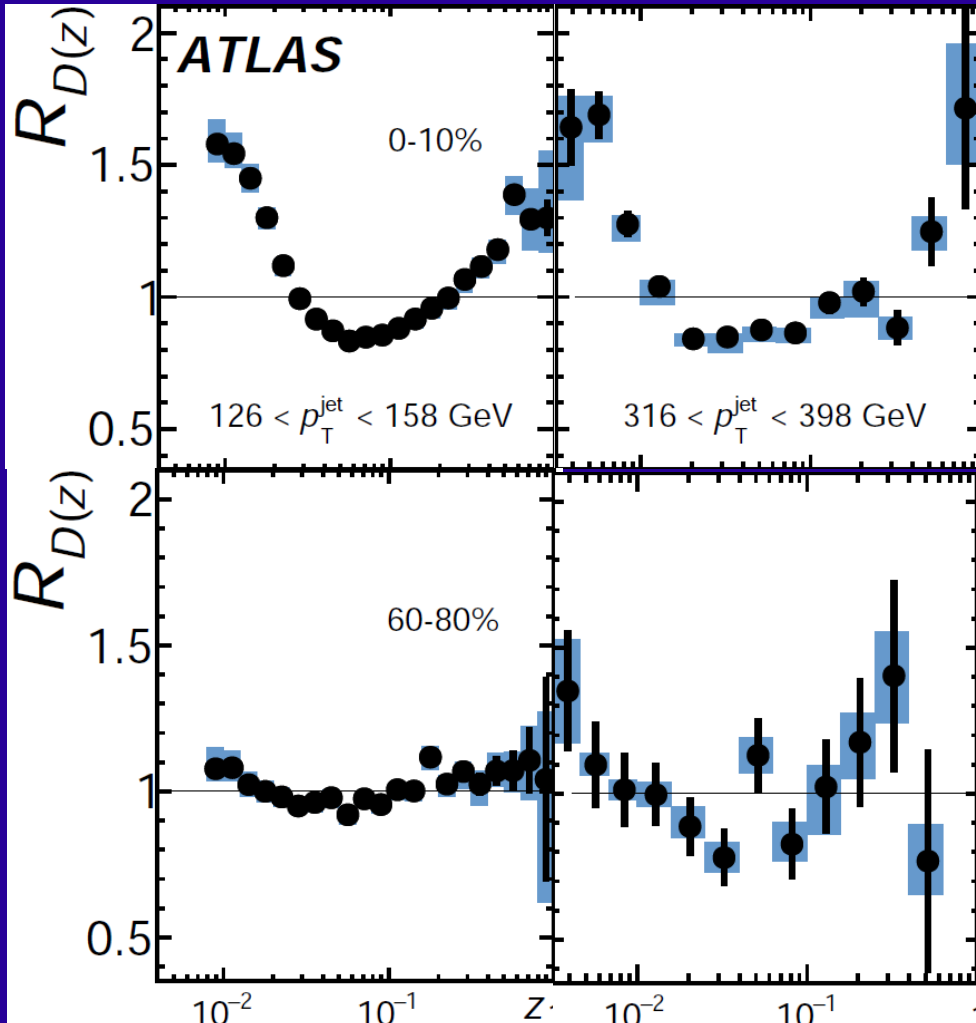


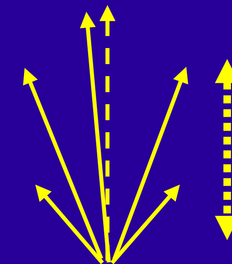
Fully corrected for detector effects

- pp-like peaked $x_{J\gamma p} = p^J_T/p^\gamma_T$, independently of jet p_T, in peripheral Pb+Pb.
- Increasing double peak shape with jet p_T in central.

Jet structure

Phys. Rev. C 98 (2018) 024908





$$z \equiv \frac{p_T}{p_T^{jet}} \cos \Delta R$$

$$D(z) \equiv \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

$$R_{D(z)} = D(z)_{cent} / D(z)_{p+p}$$

Internal jet structure shows enhancement of particle yields at low z;

enhancement at high z; depletion at intermediate.

Messages from Jets

- Inclusive jets in Pb+Pb are suppressed relatively to p+p up to a factor of 2.

- Hadrons also suppressed (as expected), with characteristic dependence on the transverse momentum.
- Internal jet structure shows enhancement of particle yields at low z; enhancement at high z,depletion at intermediate.
- Enhancement of asymmetric dijets in Xe+Xe and Pb+Pb, relatively to p+p as the centrality increases.
- Clear dependence with the p_T of the leading.

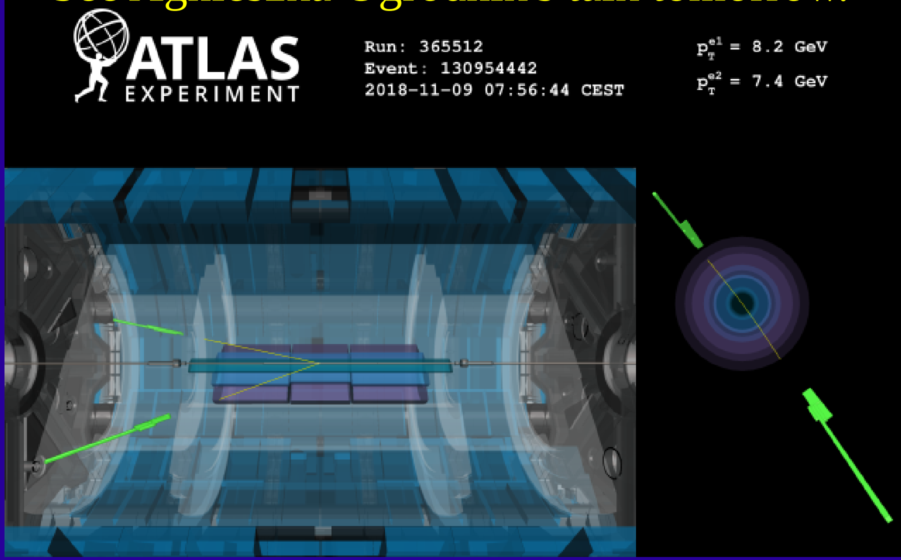
Outlook

Stay tuned to the results provided by the 1.75^{-nb} recorded by ATLAS during 2018 Pb+Pb @ 5.02 TeV data acquisition. A factor of 3.5 w.r.t. 2015.

Peak luminosity of 6e27 $cm^{-2}s^{-1}$ reached several times

=> good prospects for the Run 3.

See Agnieszka Ogrodnik's talk tomorrow.



$\gamma\gamma \rightarrow ee$ candidate in ultra-peripheral collision in 2018 Pb+Pb dataset. $p_T(e_1)$ = 8.2 GeV and $p_T(e_2)$ = 7.4 GeV; m_{ee} = 16 GeV.

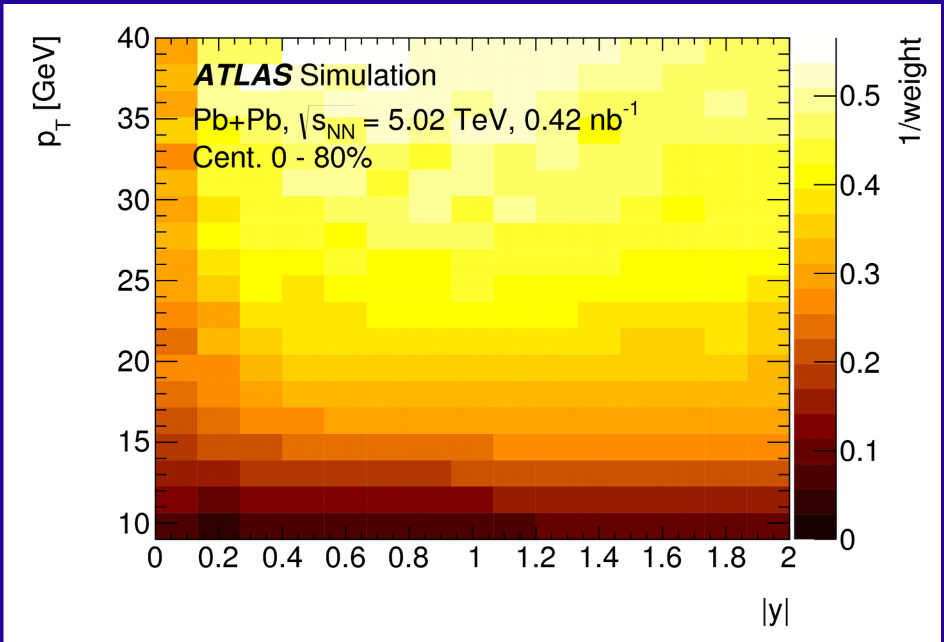
Not covered in this talk, but unmissable:

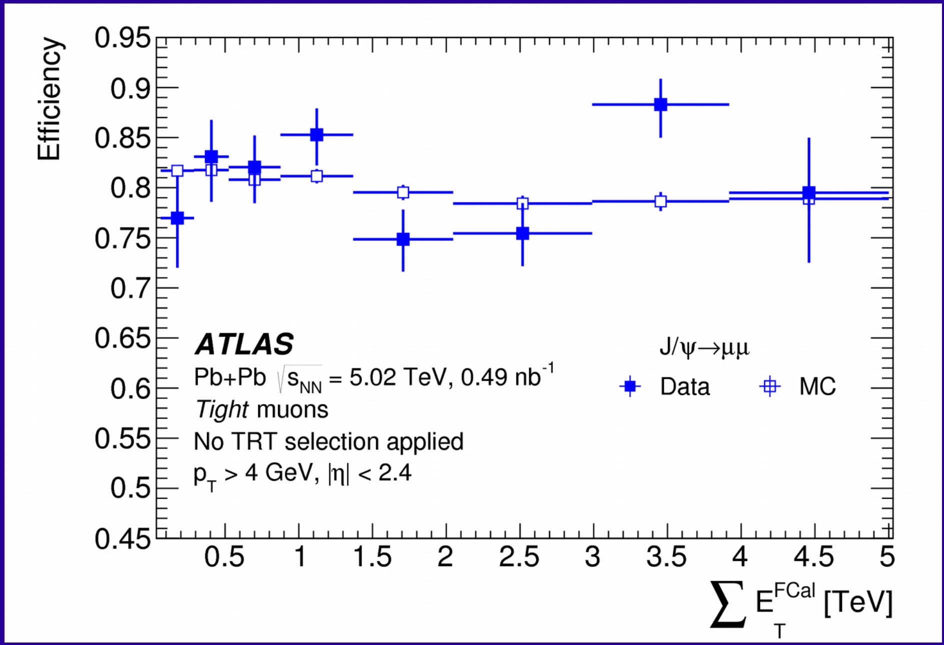
- Jet fragmentation functions at 5.02 TeV - 1805.05424
- Flow cumulants - 1807.02012
- J/ψ elliptic flow - 1807.05198
- R_{AA} and flow of HF muons - 1805.05220

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Backup

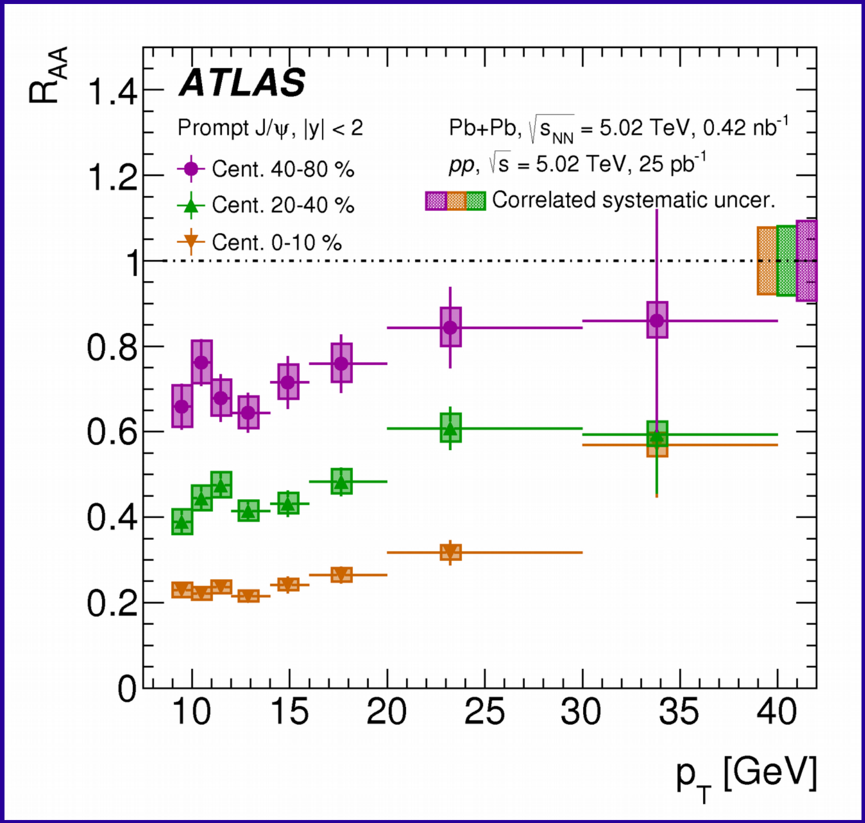
ATLAS Performance

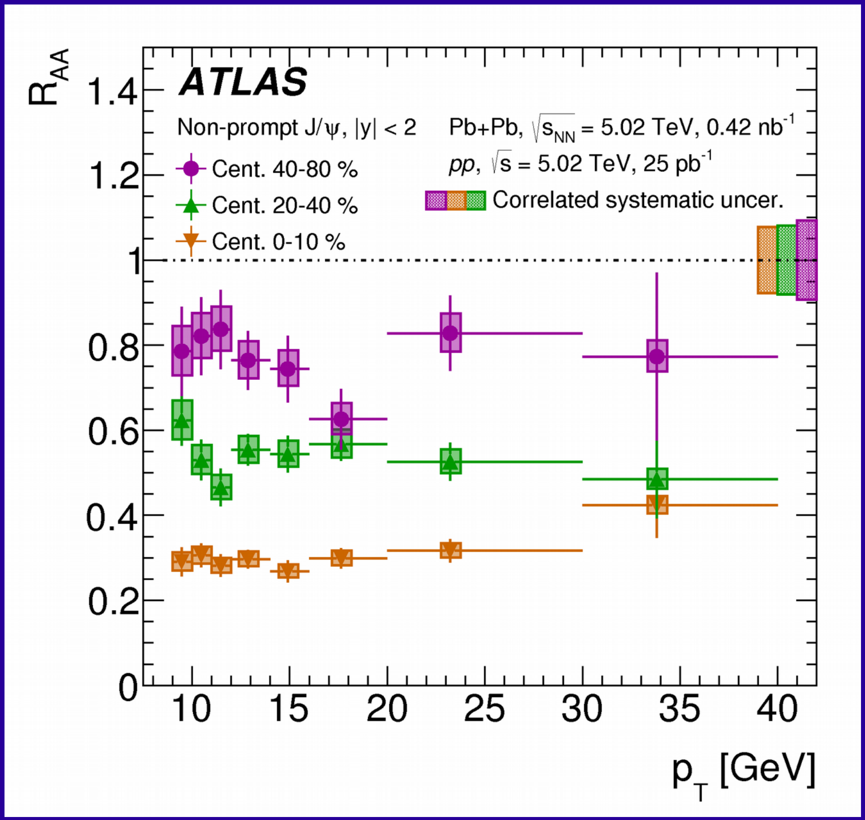




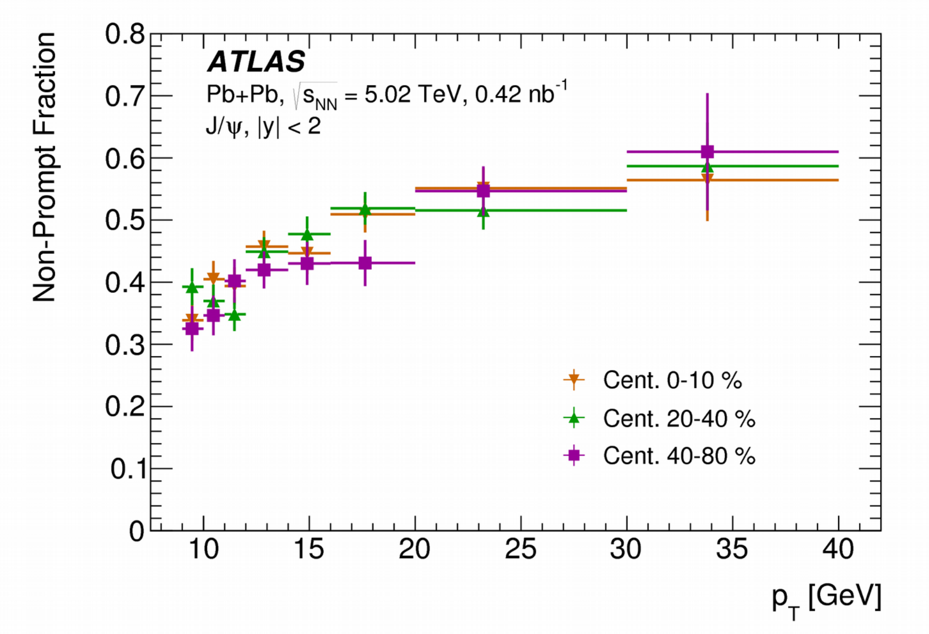
No dependence of the muon reconstruction efficiency on centrality.

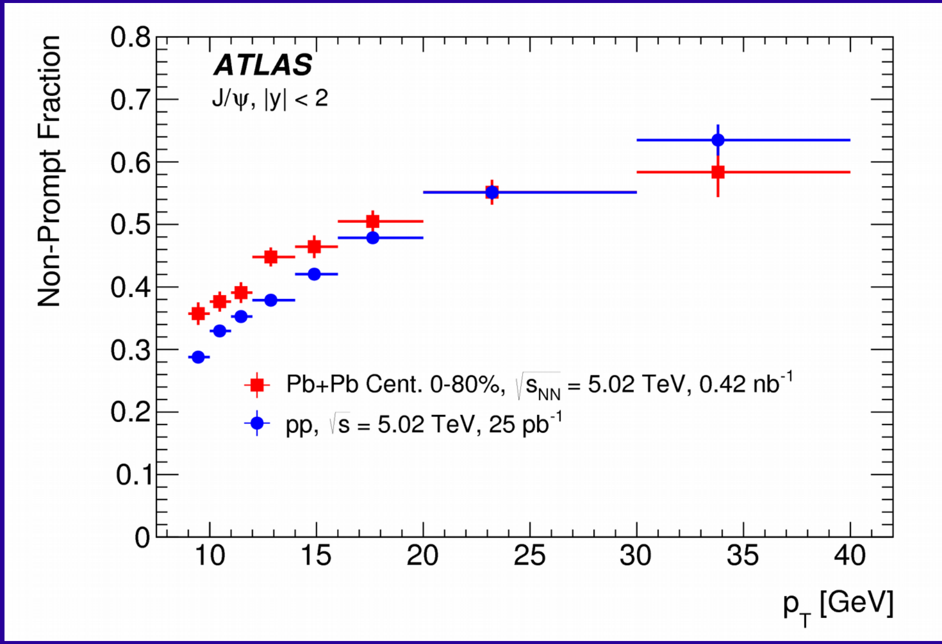
J/ψ R_{AA} as a function of p_T





non-prompt fraction

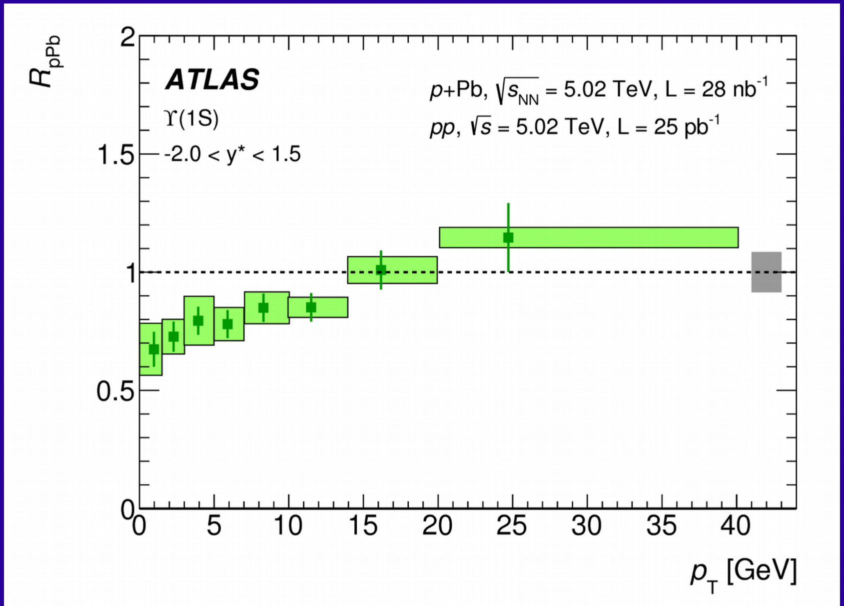


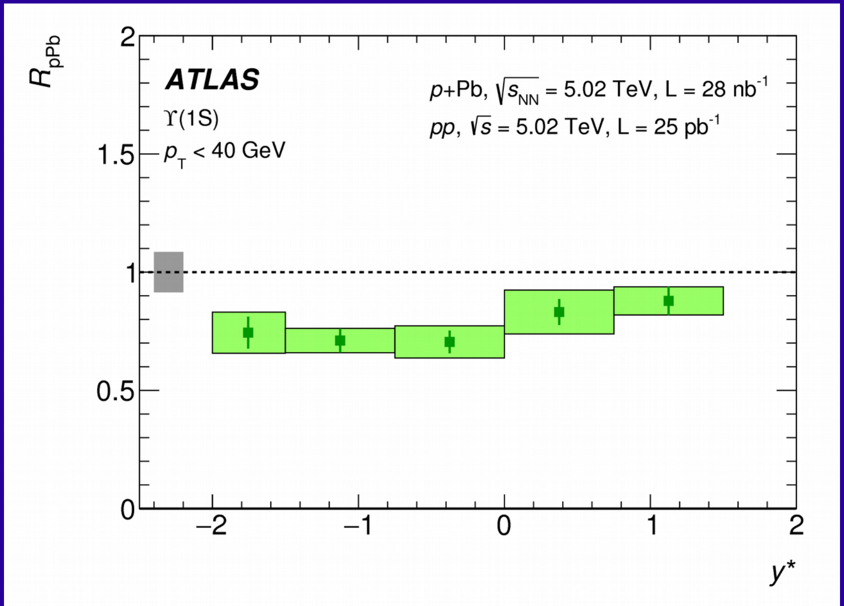


- Nearly independent on centrality.
- Slight difference from pp.

Upsilon R_{pPb}

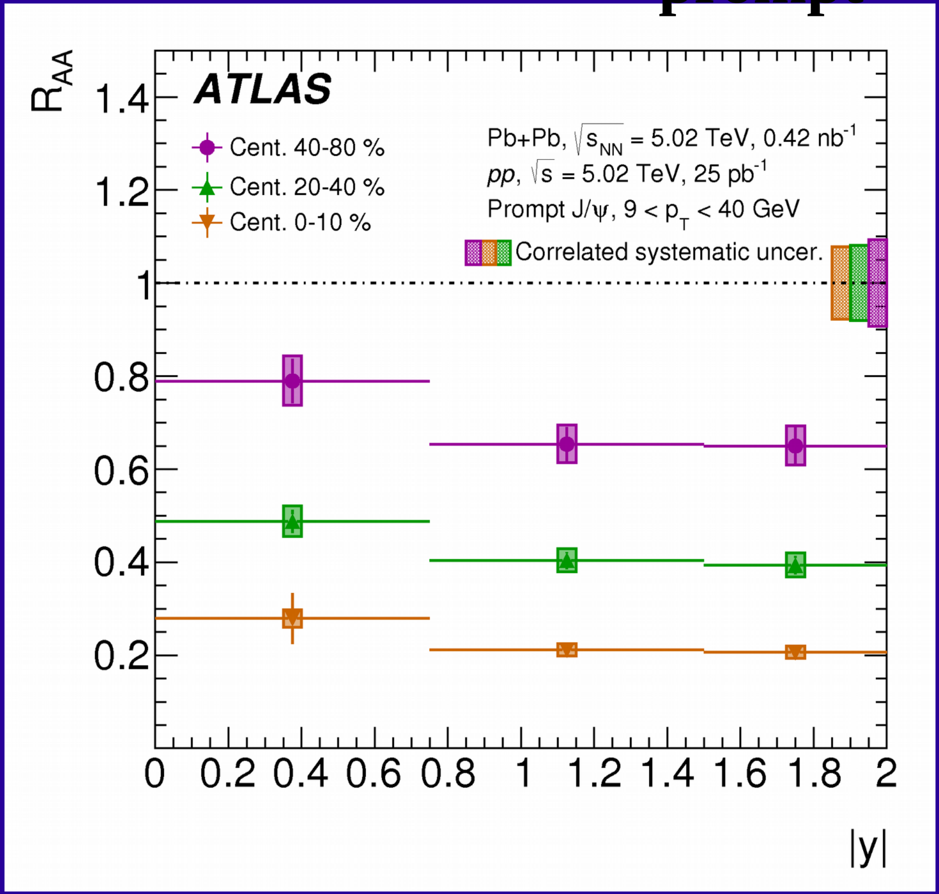
arXiv1709.03089



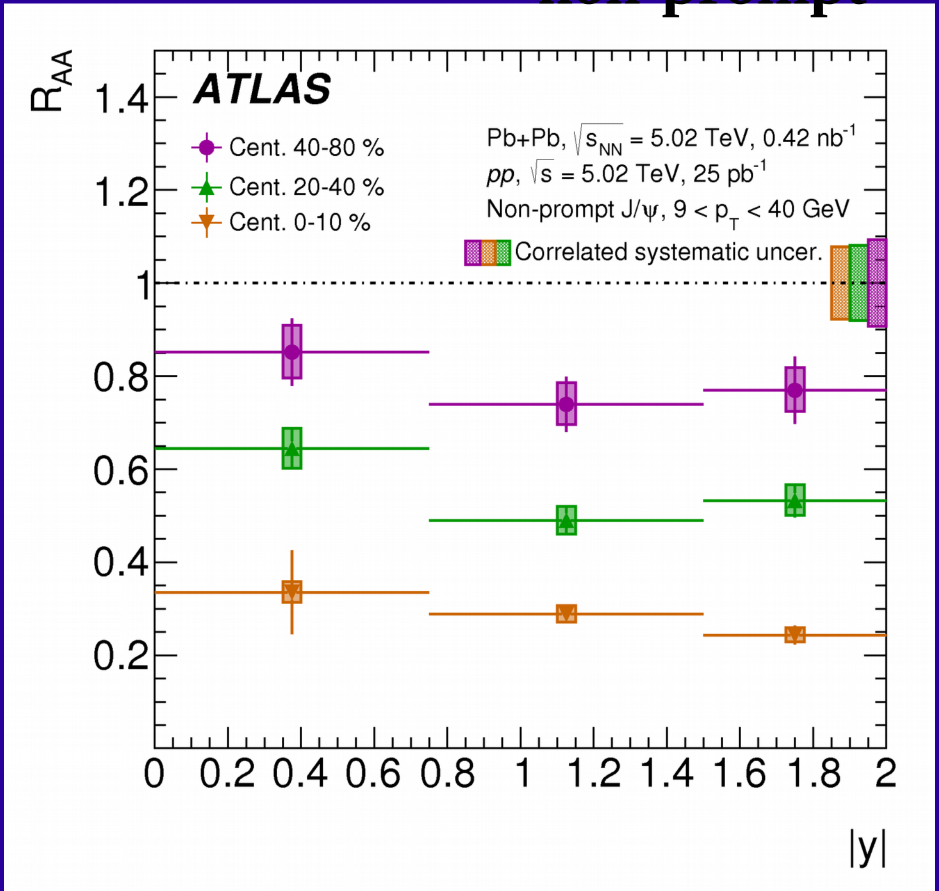


J/ψ R_{AA} as a function of |y| and centrality

prompt



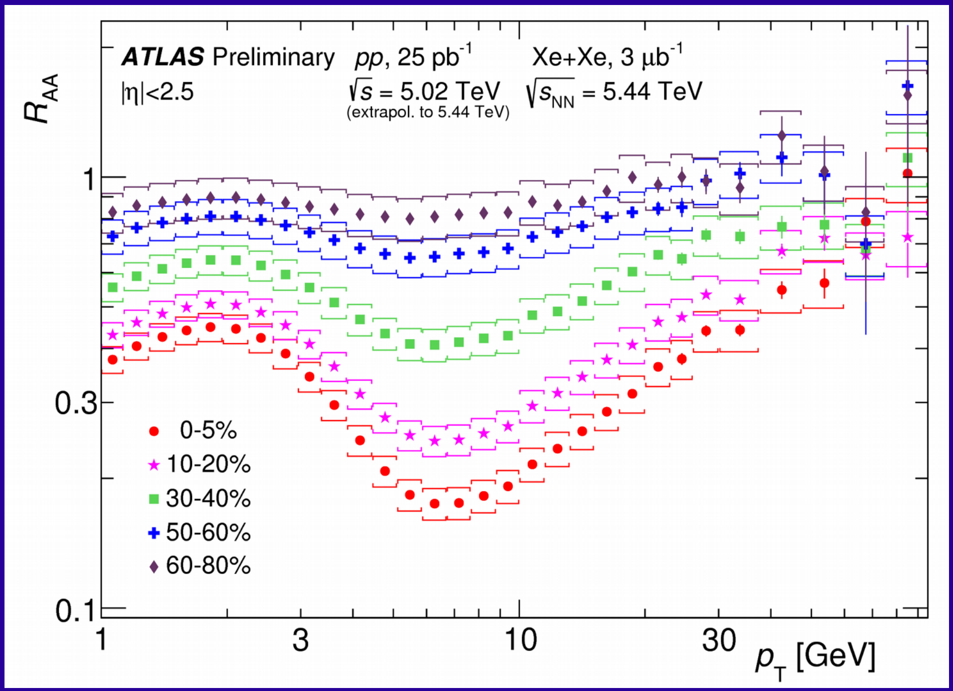
non-prompt

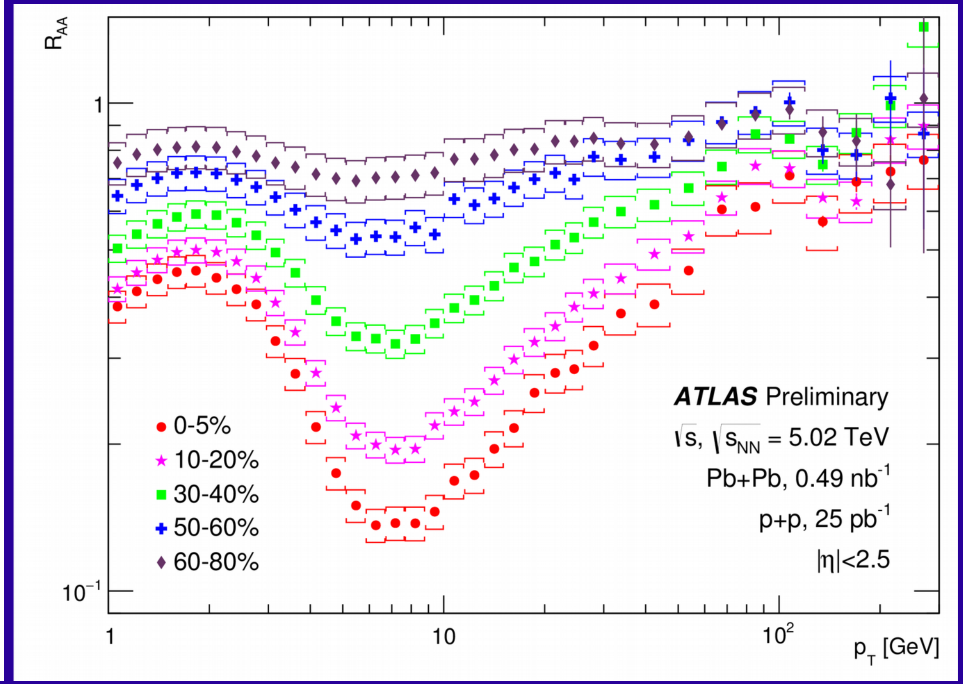


Modest dependence on rapidity for both prompt and non-prompt J/ψ.

Charged Hadron R_{AA} in Xe+Xe and Pb+Pb

ATLAS-CONF-2018-007

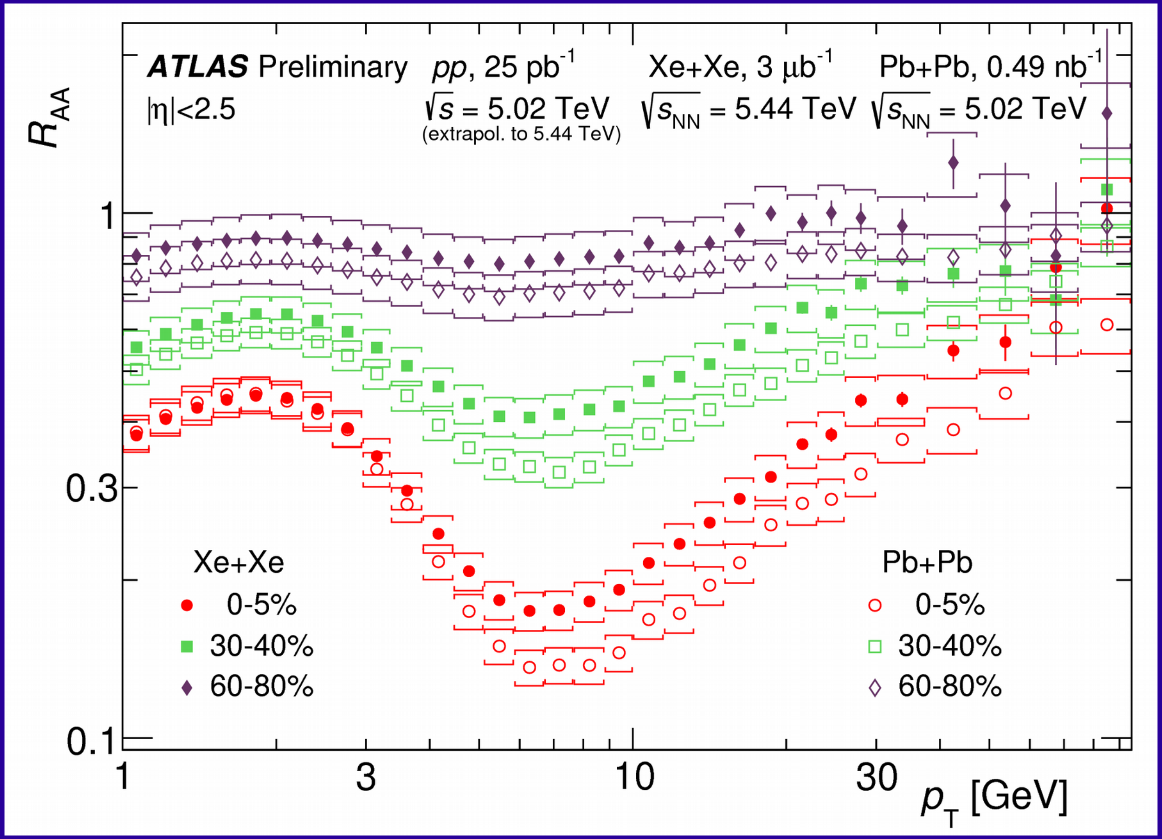




- Note different x-axis
- Qualitatively similar

Charged Hadron R_{AA} in Xe+Xe and Pb+Pb

ATLAS-CONF-2018-007

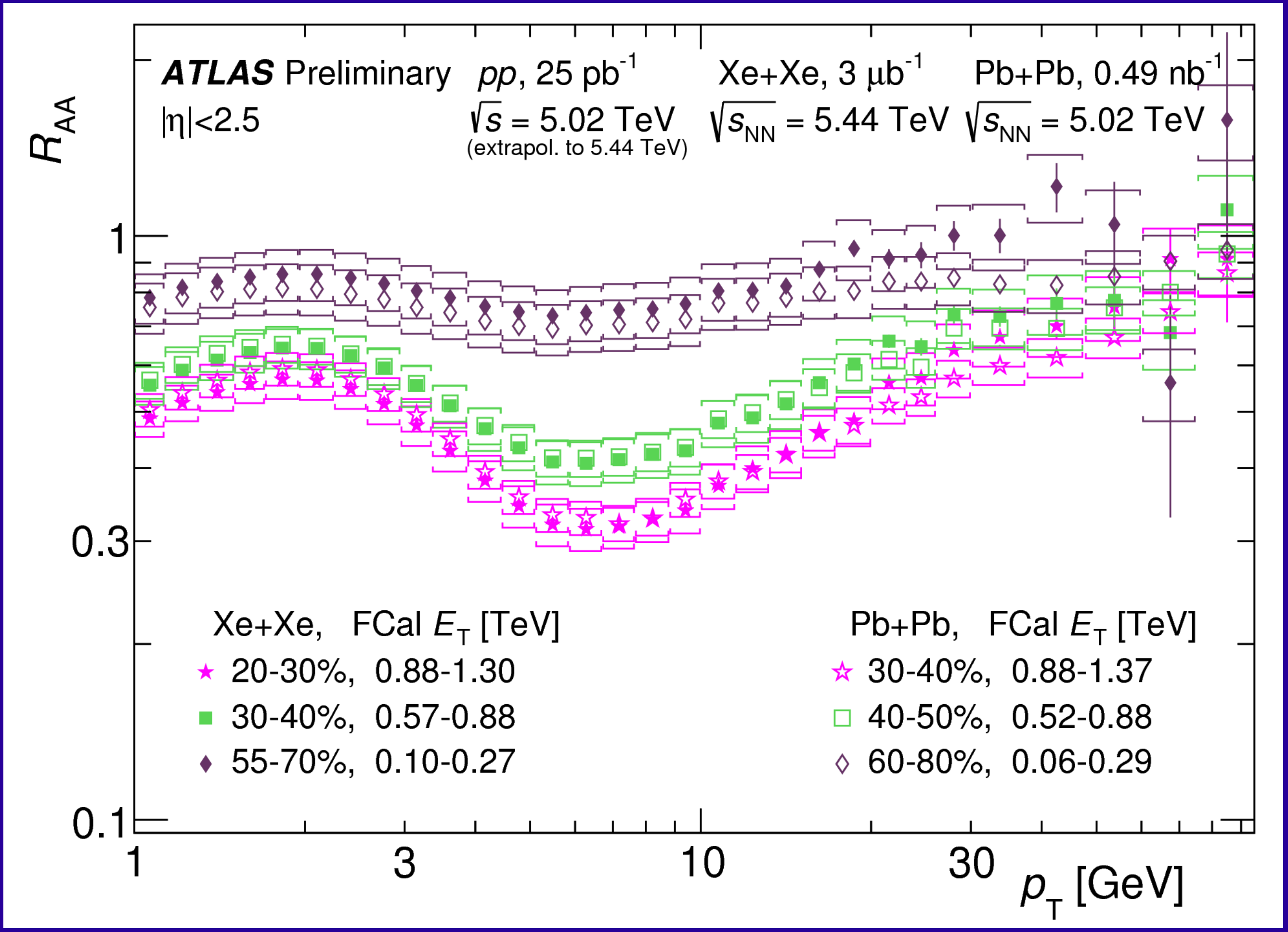


Same colours, same centrality

- **R_{AA} is very similar at low pT in central collisions.**
- **Otherwise Xe+Xe is less suppressed than Pb+Pb.**

Charged Hadron R_{AA} in Xe+Xe and Pb+Pb

ATLAS-CONF-2018-007



Same colours, same energy deposited in FCal

Electroweak probes: γ + jet p_T balance

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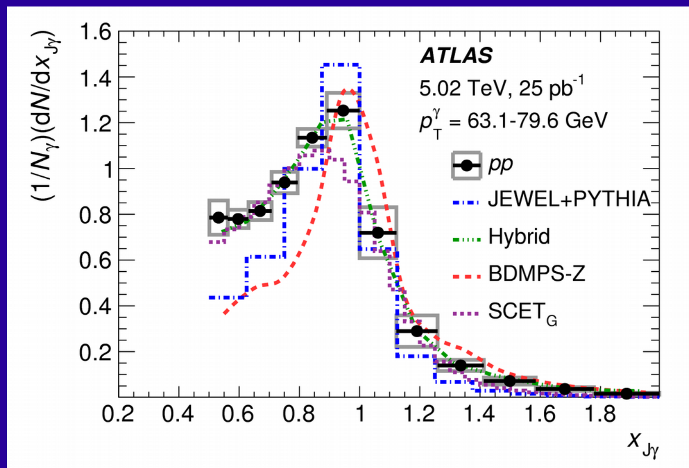
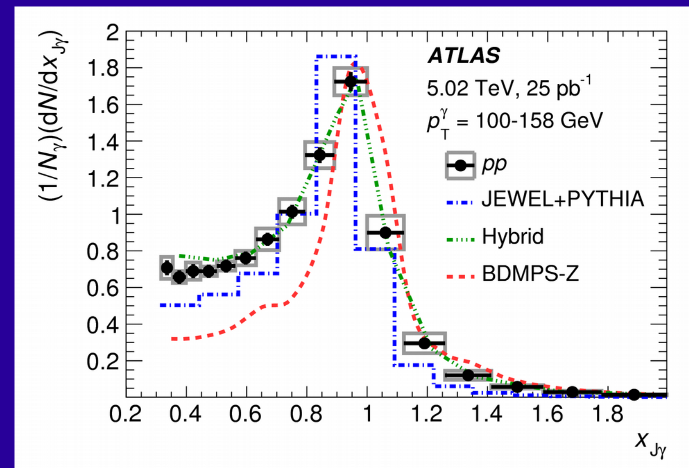
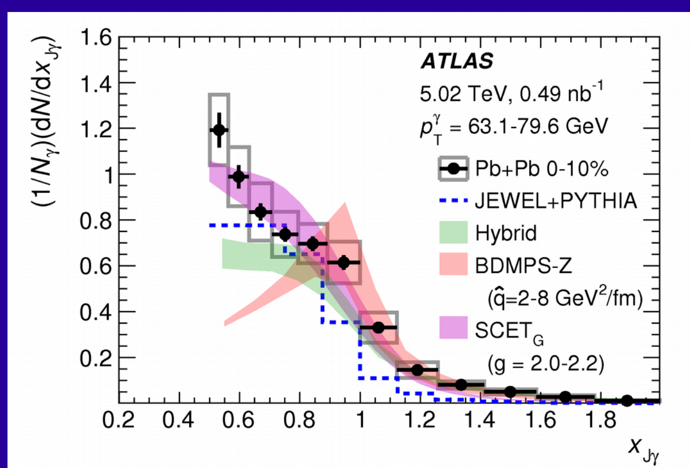
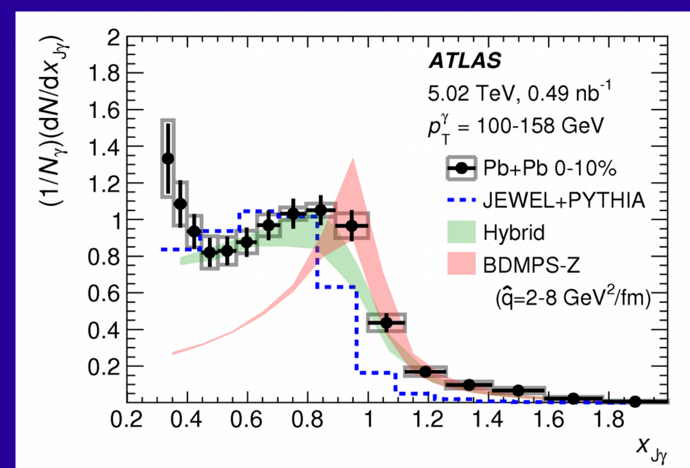




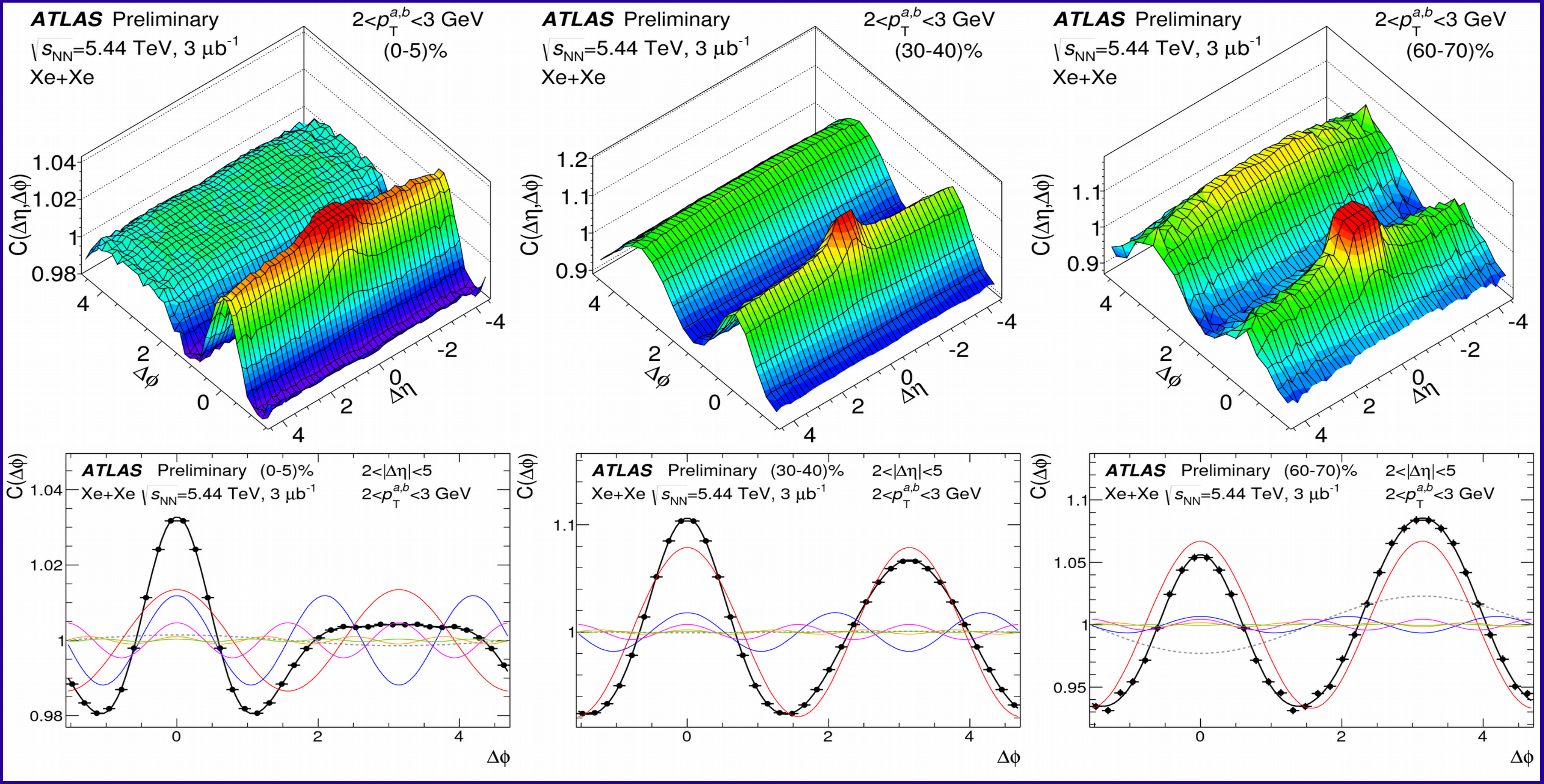




Two-particle correlations in Xe+Xe collisions

ATLAS-CONF-2018-011

Flow harmonics, v2—v5, have been measured in Xe+Xe at 5.44 TeV using 2-PC



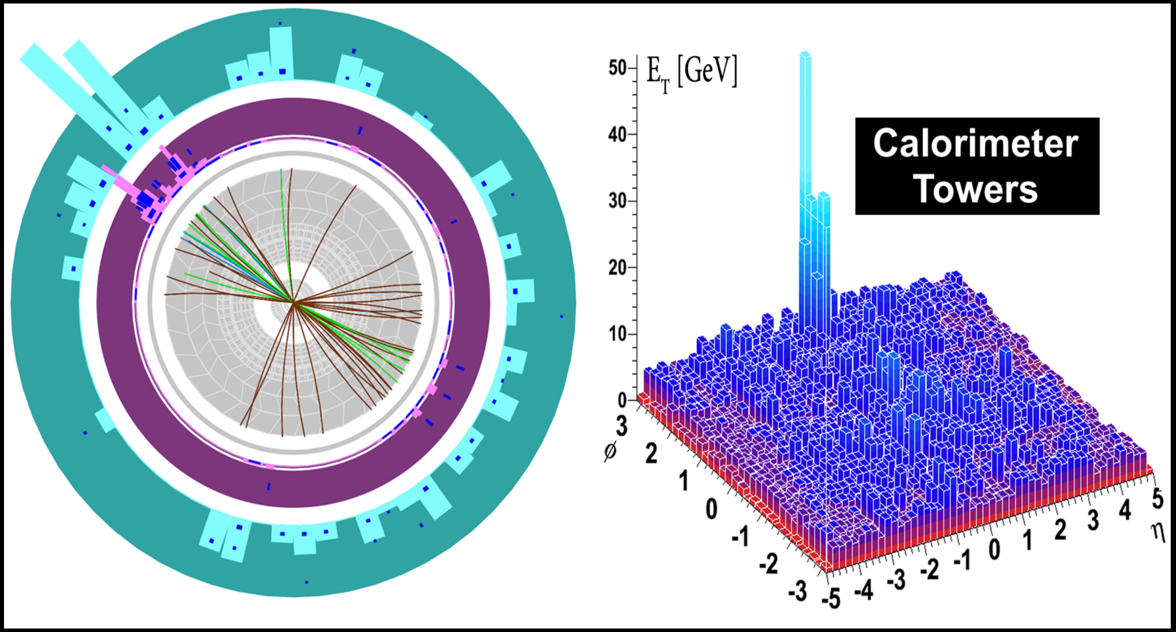
• Short-range (Δη,Δφ ~ 0,0) correlations in all centralities are due to non-flow processes.

• Long-range (Δη large) correlations are the result of the global anisotropy of the event.

Jet Reconstruction in the Detector

- Jets are reconstructed by computational algorithms that group “towers” of energy deposited in the calorimeters.

- The Underlying Event (“background”) is estimated event-by-event, excluding the jet candidate.



Jet Reconstruction

- Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$:

$$E_{T,subt}^{cell} = E_T^{cell} - \rho x A^{cell}$$

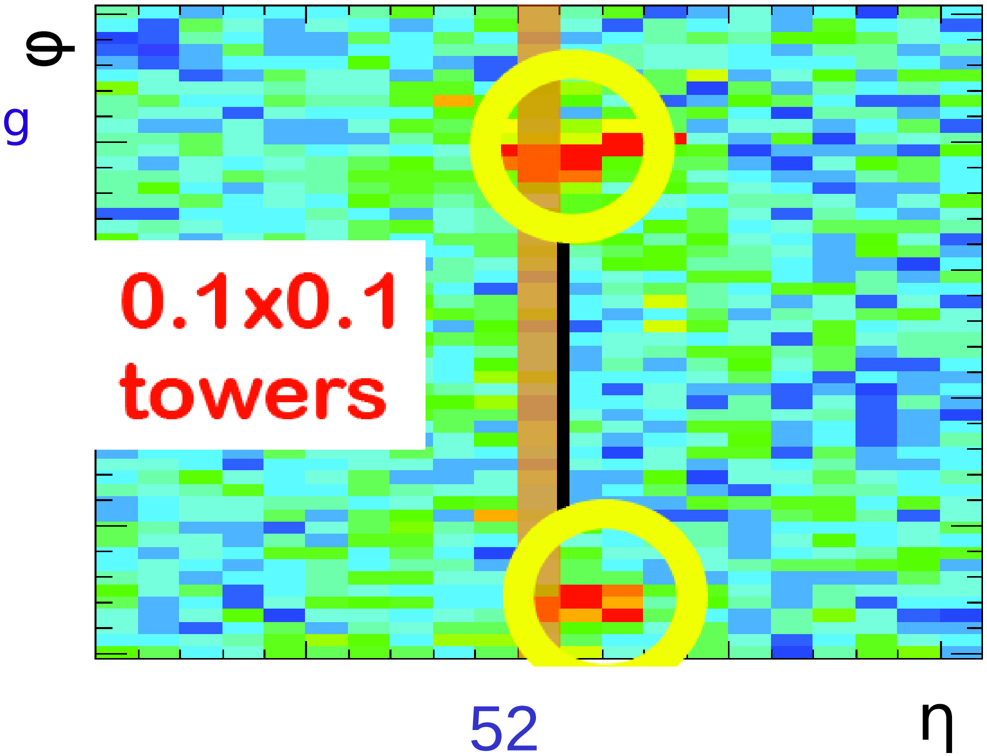
ρ is energy density estimated event-by-event from average over $0<\varphi<2\pi$

- Two methods to avoid biasing ρ due to jets

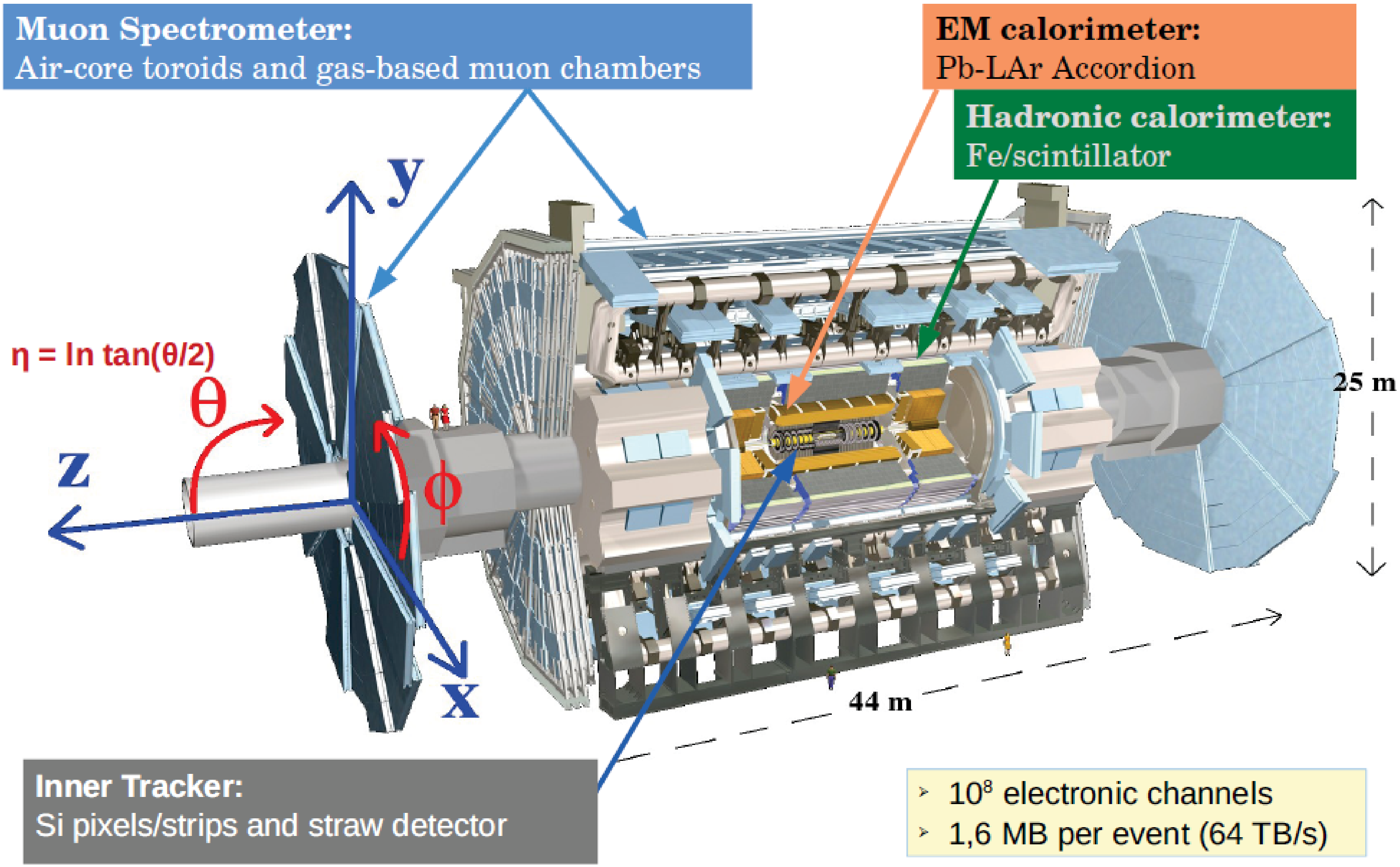
  1 - Sliding window exclusion
  2 - Exclude cells in jets satisfying

$$D = E_{T,max}^{tower} / \langle E_T^{tower} \rangle > 5$$

- For R = 0.4, add an iteration step to ensure jets with E_T>50 GeV are always excluded from ρ estimate
- Correct for underlying event v_2



ATLAS



- 10^8 electronic channels
- 1,6 MB per event (64 TB/s)

Longitudinal flow decorrelations

Space-time evolution of the matter created is not boost-invariant in the longitudinal direction: $v_n(\eta_1) \neq v_n(\eta_2)$ → FB asymmetry

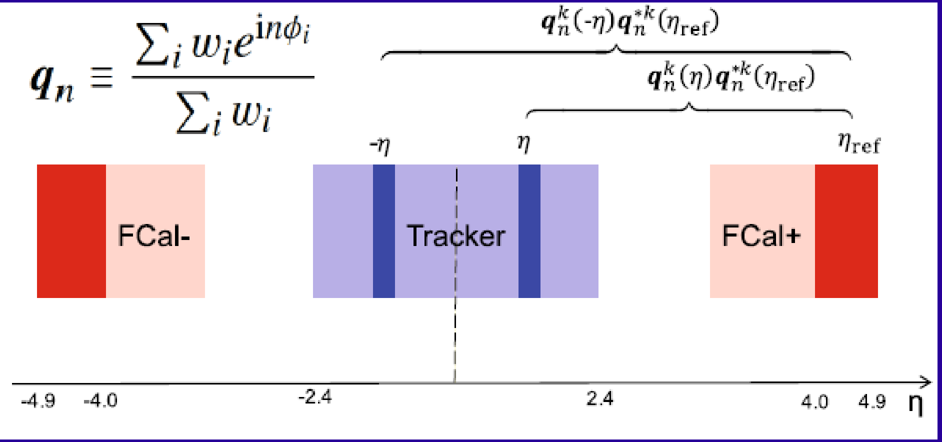
$\Phi_n(\eta_1) \neq \Phi_n(\eta_2)$ → sensitivity to twists

Harmonic flow vectors measured with charged particles over |η| < 2.5:

$$\vec{\mathrm{v}}_n(\eta) = \mathrm{v}_n(\eta)e^{in\Phi_n(\eta)}$$

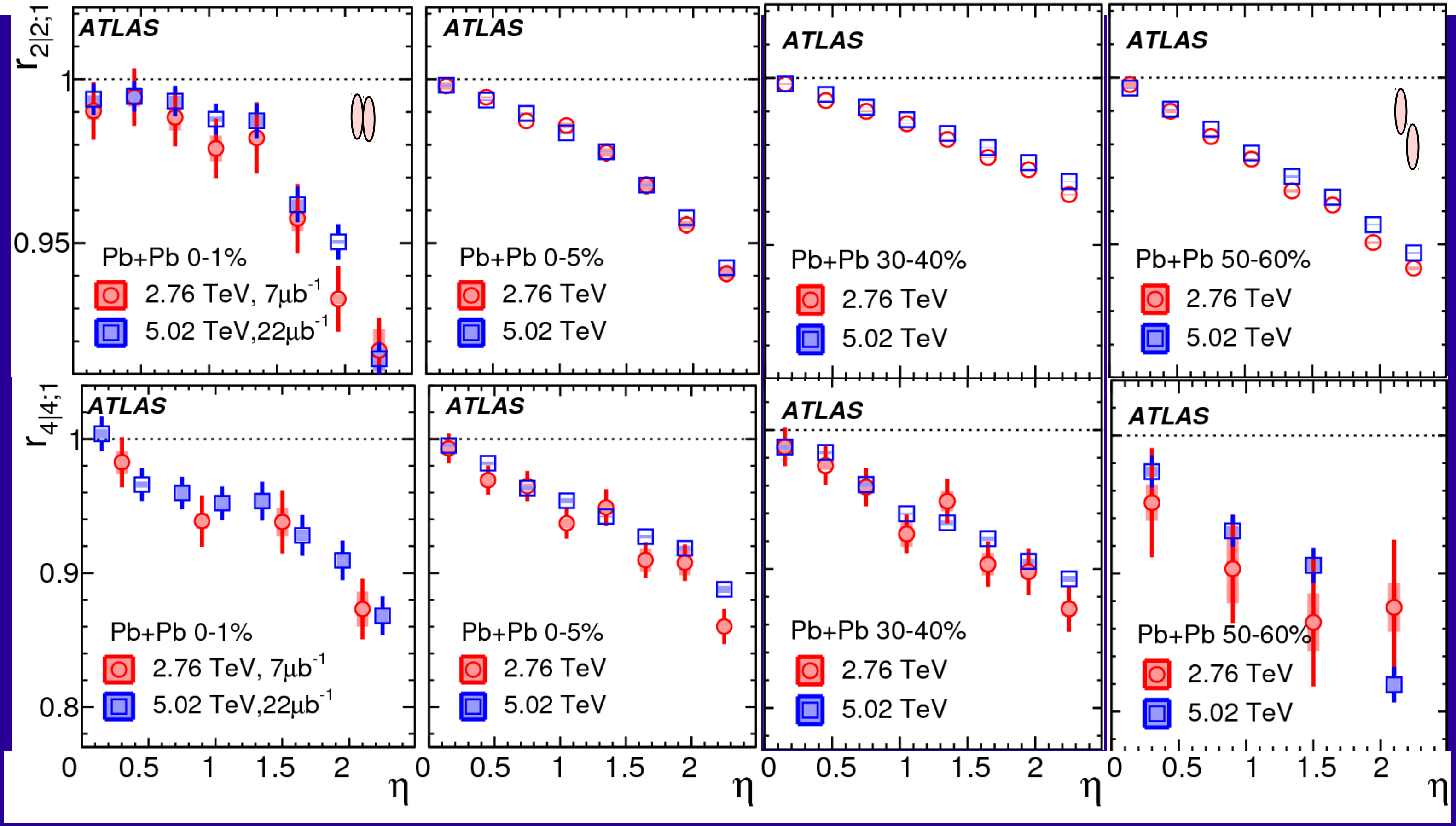
Decorrelations → use $\boldsymbol{r}_{\mathbf{n|n,k}}$ between the ***k*th**-moment of the ***n*th**-order flow vectors in two different η intervals:

$$r_{n|n;k}(\eta) = \frac{\left\langle \boldsymbol{q}_n^k(-\eta)\boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\right\rangle}{\left\langle \boldsymbol{q}_n^k(\eta)\boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\right\rangle}$$



Longitudinal flow decorrelation in Pb+Pb collisions

Eur. Phys. J. C 76 (2018) 142



- $r_{n|n,k}$ shows a linear decrease with η_{ref}, except in the most central collisions.
- The decreasing trend of $r_{n|n,k}$ for $n \equiv 2$—4 indicates significant breakdown of the factorisation of two-particle flow harmonics.
- The decreasing trend is slightly stronger at 2.76 TeV (collision system less boosted).