ATLAS Results on Hard and Electromagnetic Probes in Heavy-Ion Collisions

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for the ATLAS Collaboration

27 March 2023

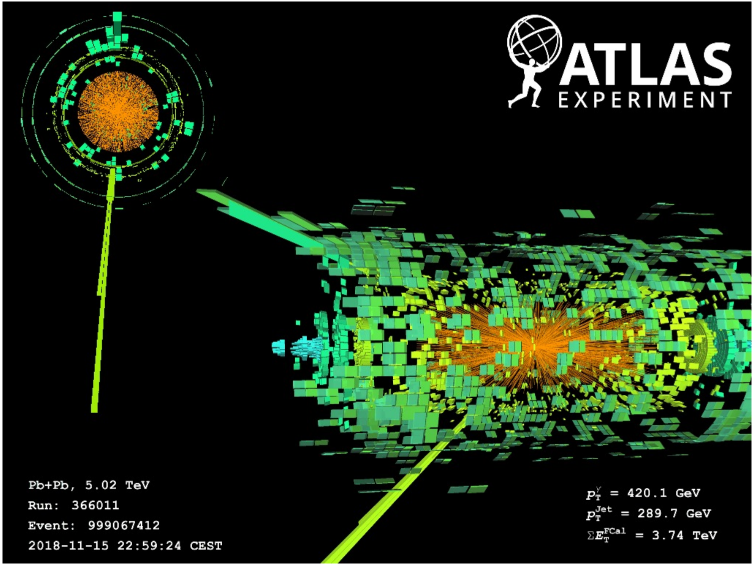
introduction

- we use hard probes to learn about QGP
- large systems: Pb+Pb, Xe+Xe
  - what phenomena are driving jet quenching?
    sub-structure? QCD color charge? quark flavour?
  - how do azimuthal anisotropies fit into this?
- small systems: p+Pb, pp
  - what is the origin of flow?
  - are jets modified?
  - how are quarkonia formed?
- UPC
  - technically Pb+Pb, but more interested in $\gamma + \gamma$ or $\gamma +$ Pb
  - impact parameter for photon flux
  - nuclear PDFs

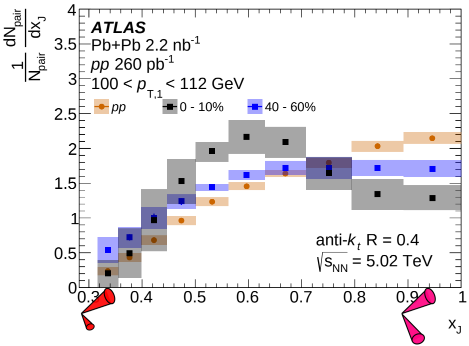
- all ATLAS results

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

large systems: Pb+Pb, Xe+Xe



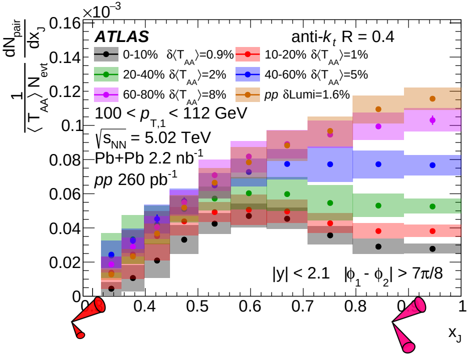
- di-jet p_{T} imbalance shown before
- $x_J = p_{\mathrm{T}}^{subleading} / p_{\mathrm{T}}^{leading}$
- development of a peak at $x_J \approx 0.6$?

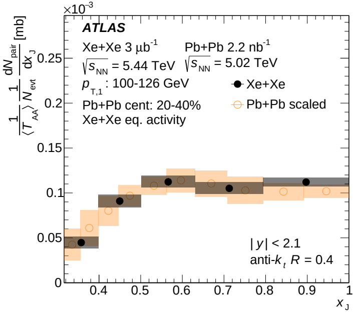


→ **talk by Martin Krivos, Tuesday, 9:40**

jet quenching & di-jet imbalance

- di-jet p_{T} imbalance shown before
- $x_J = p_{\mathrm{T}}^{subleading} / p_{\mathrm{T}}^{leading}$
- balanced di-jets are more suppressed





- in Xe+Xe, the results are consistent to Pb+Pb
- if considering the same energy in forward calorimeter
- and if correcting for higher center-of-mass energy

➔ talk by Martin Krivos, Tuesday, 9:40

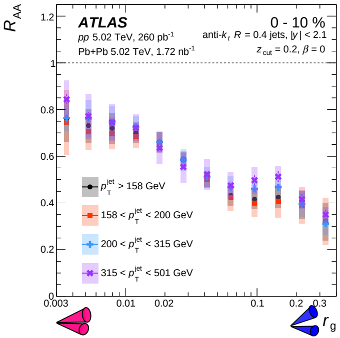
jet quenching with substructure

arXiv:2211.11470, arXiv:2301.05606

- the anti-k_t jets (R=0.4) are re-clustered with Cambridge–Aachen algorithm
- used soft-drop to identify the first hard splitting of the jet:

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} < z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

- r_g - angle between the two subjets
- with larger r_g comes larger suppression



➔ **talk by Martin Rybar, Tuesday, 11:50**

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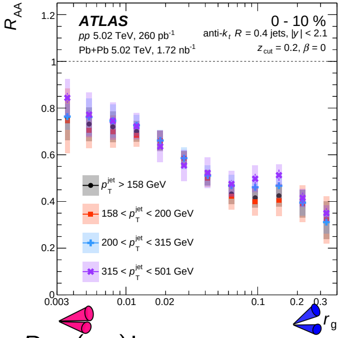
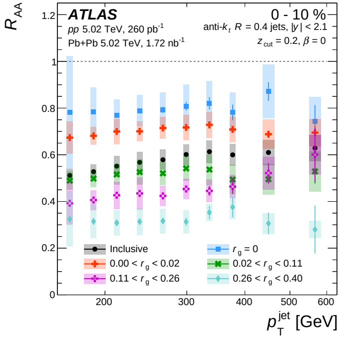
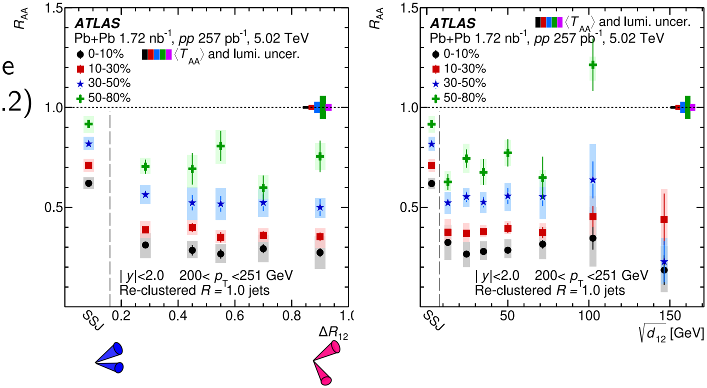




- with larger r_g comes larger suppression
- jets with a similar r_g have flat $R_{AA}(p_T)$!
- inclusive jets have rising R_{AA} with p_T
  $\Rightarrow$ this means r_g distribution depends on p_T

➔ talk by Martin Rybar, Tuesday, 11:50

- large anti-k_t jets (R=1.0) made from smaller anti-k_t jets (R=0.2)
- classify jets based on the hardest splitting:
  - $\sqrt{d_{12}} = min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$
  - $\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2}$
  - SSJ = single sub-jet



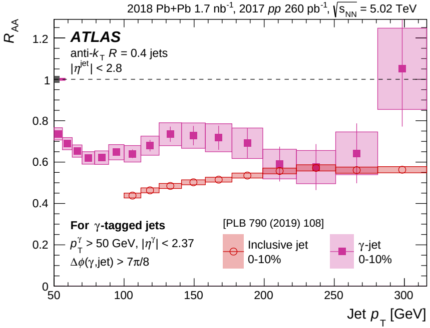
- sub-jets "farther" away
  $\Rightarrow$ decoherent partons $\Rightarrow$ lose more energy
- sub-jets "closer" to each other
  $\Rightarrow$ coherent partons $\Rightarrow$ lose less energy

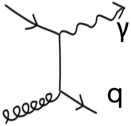
→ talk by Martin Rybar, Tuesday, 11:50

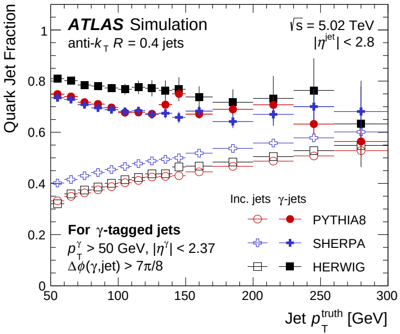
photon+jet quenching

arXiv:2303.10090, ATLAS-CONF-2023-008

- γ-tagged jets are predominantly quark-jets







- γ-tagged jets are less suppressed
  - inclusive jets have steeper falling spectrum
  - isospin and nPDFs
  - color charge

➔ talk by Christopher McGinn, Wednesday, 9:00

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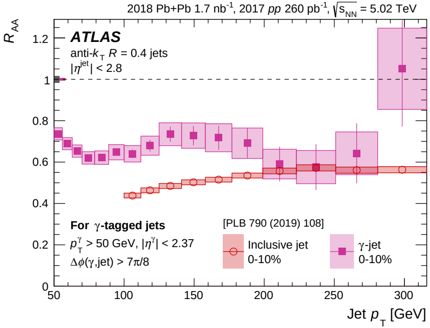

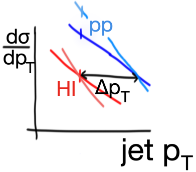

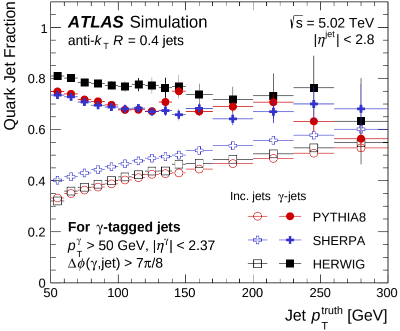

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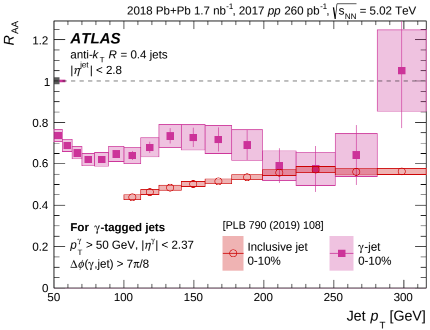
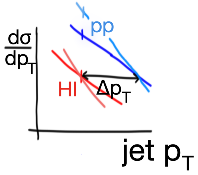
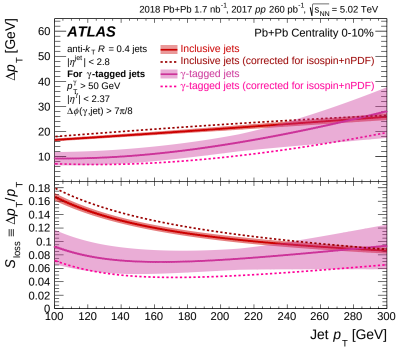


- radiative energy loss depends on the color charge
- extract S_{loss}





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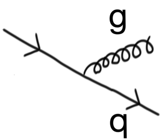
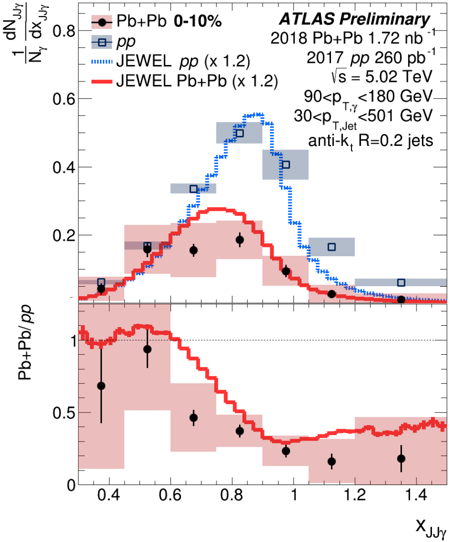
- study jet quenching with respect to γ
- what if there are more recoiled jets?
  - this could complicate the interpretation of the measurement
- first analysis of $\gamma + 2$ jets $+$ X
  - di-jet system in the opposite direction than γ
  - $x_{JJ\gamma} = (\vec{p_1} + \vec{p_2})_{\mathrm{T}} / p_{\mathrm{T},\gamma}$





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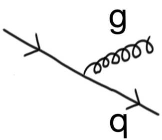
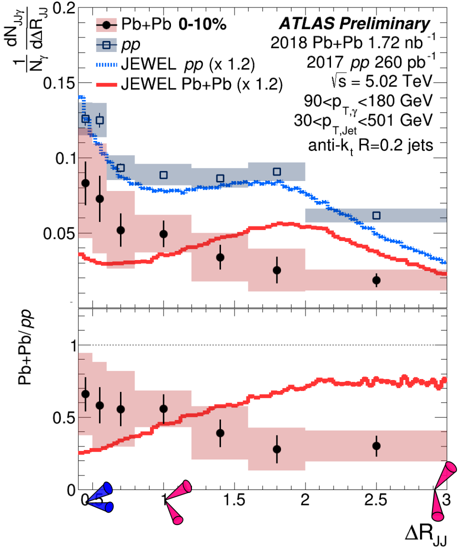
photon+jet quenching

- study jet quenching with respect to γ
- what if there are more recoiled jets?
  - this could complicate the interpretation of the measurement
- fist analysis of $\gamma + 2$ jets $+$ X
  - di-jet system in the opposite direction than γ
  - $\Delta R_{JJ} =$ distance between the two jets





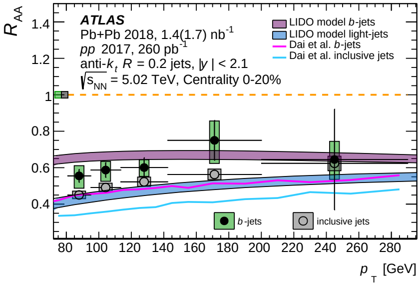
➔ talk by Christopher McGinn, Wednesday, 9:00

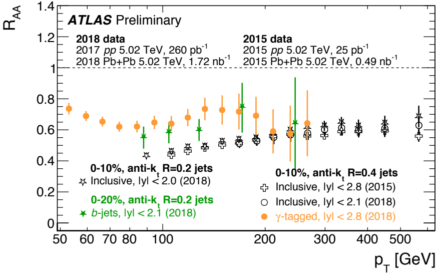
b-jets in Pb+Pb

arXiv:2204.13530, ATL-PHYS-PUB-2023-009

- b-jet identified by a presence of a muon
- unfolded to correct also for a missing neutrino
- in central collisions, b-jets less suppressed than inclusive jets by ∼20%
- in peripheral collisions, suppression is comparable
- b-jets have similar suppression as γ-jets but the quark-/gluon-jet fraction is similar to inclusive jets

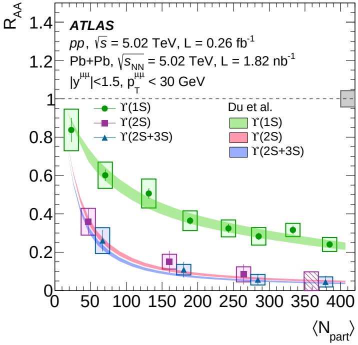
➔ **talk by Sebastian Tapia Araya, Wednesday, 10:50**

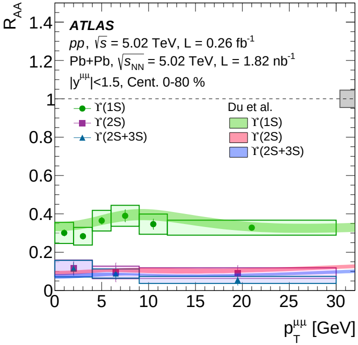




ϒ(nS) in Pb+Pb

arXiv:2205.03042





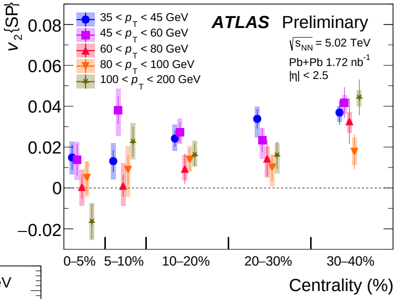
- using $\Upsilon \to \mu\mu$ channel
- measurement of ϒ(nS) in Pb+Pb shows suppression for all states
- suppression combination of energy loss and Debye screening

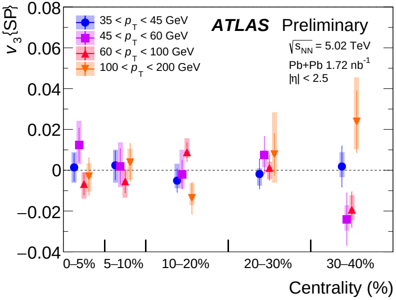
➔ talk by Zvi Citron, Tuesday, 14:00

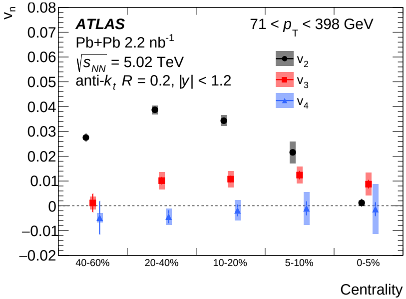
azimuthal anisotropy

arXiv:2111.06606, ATLAS-CONF-2023-007

- part of understanding of QGP
- measurement of v_2, v_3, v_4 up to high p_T



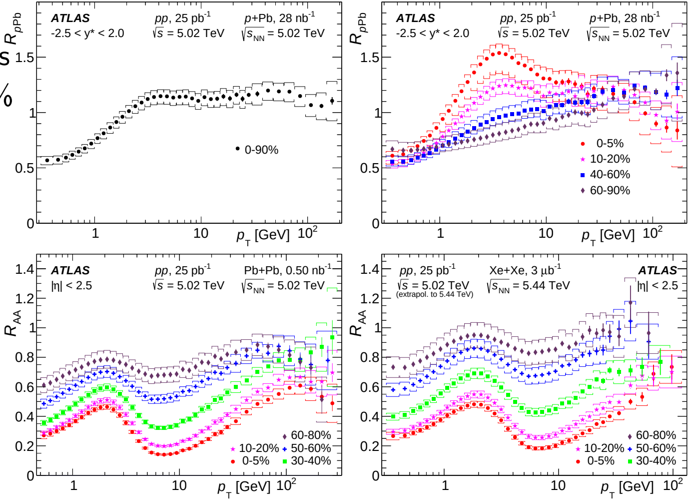




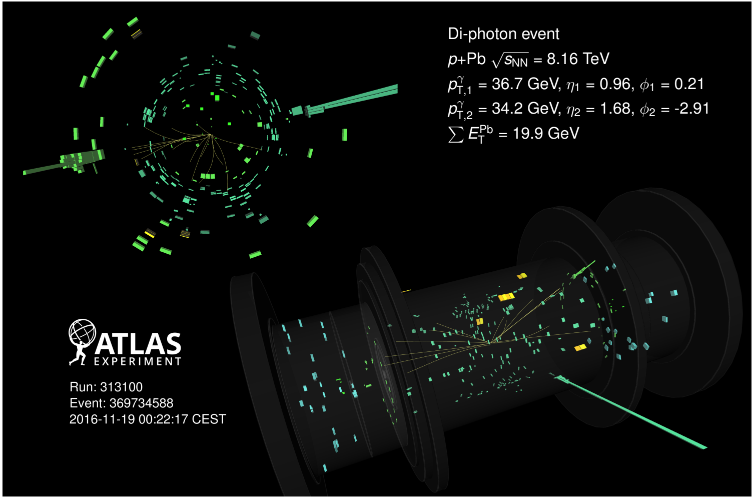
- v_2 positive even at high p_T
- v_3 at high p_T consistent with zero
- in jets, same conclusion for v_2 but not v_3
  - jets in $|y| < 1.2$, particles in $|\eta| < 2.5$

→ talk by Xiaoning Wang, Tuesday, 15:00

- ATLAS final words regarding charged hadron production in pp, p+Pb, Pb+Pb, Xe+Xe
- precise measurement in 4 systems
- $R_{\mathrm{pPb}} = 1.14^{+0.06}_{-0.08}$ (syst.) in 0–90%
  - consistent with measurements of jet R_{AA} and jet fragmentation functions
- Pb+Pb R_{AA} changes slope at $p_{\mathrm{T}} \approx 100$ GeV
- Xe+Xe R_{AA} shows the same trends as Pb+Pb at $p_{\mathrm{T}} \lesssim 100$ GeV



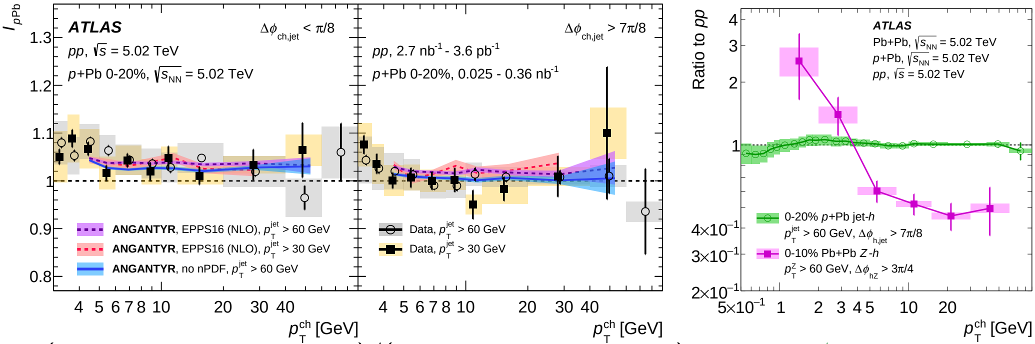
small systems: pp, p+Pb



strong constraints on jet modification

arXiv:2206.01138

- in p+Pb collisions, there is no jet quenching
- maybe some jet modifications are hidden under the surface



- $I_{pPb} = \text{(tracks per jet in p + Pb)/(tracks per jet in p + p)}$
- small enhancement in the near side of the jets ($\sim$ 5%)
- consistency with unity in the opposite side of the jets
  - very small energy loss of the partons
  - different story than seen in Pb+Pb

pPb/pp: jet-hadron
PbPb/pp: Z-hadron

→ talk by James Nagle, Thursday, 10:20

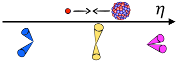
dijets in p+Pb

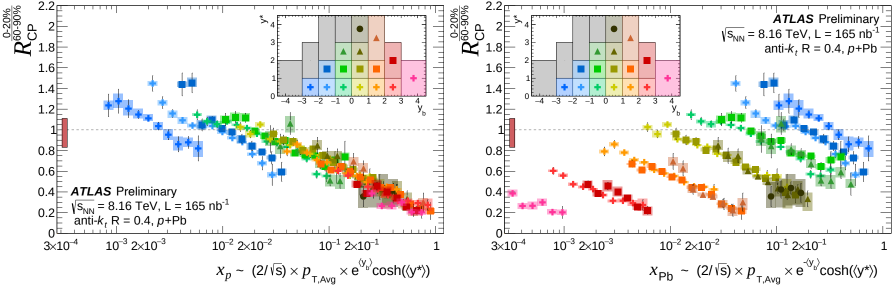
ATLAS-CONF-2023-011

- detailed study of di-jet production in p+Pb

$$p_{\mathrm{T,Avg}} = \frac{p_{\mathrm{T},1}+p_{\mathrm{T},2}}{2} \qquad y_b = \frac{y_1^{CM}+y_2^{CM}}{2} \qquad y^* = \frac{y_1^{CM}-y_2^{CM}}{2}$$

- separate results for boost (y_b) and rapidity separation (y^*)
- x_p and x_{Pb} = momentum fractions



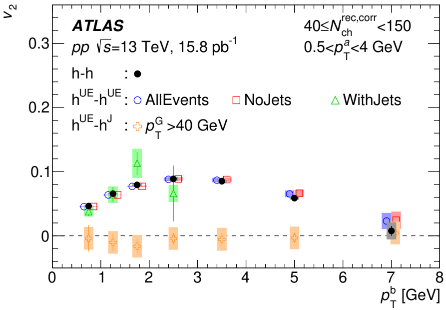


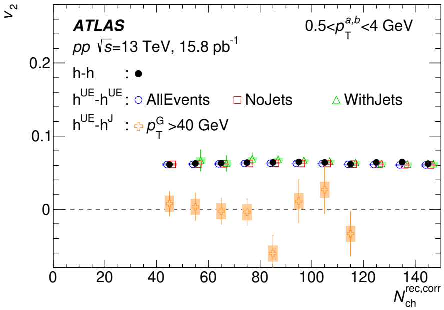
- "apparent" jet suppression, no jet quenching

→ talk by Riccardo Longo, Wednesday, 9:40

two particle correlations with jets in pp collisions

- non-zero flow even in pp collisions



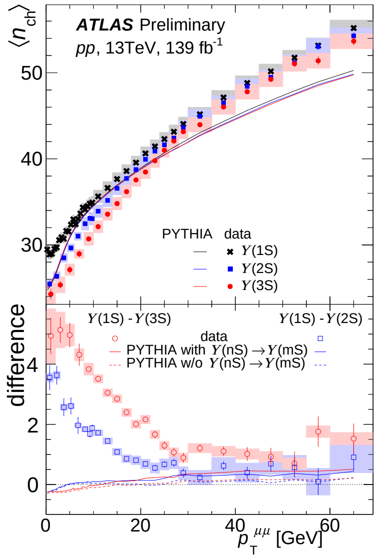


- inclusive h-h correlations are non-zero
  - h^{UE}-h^{UE} correlations follow the same trend
  - presence of a jet in the event has very little impact
- h^{UE}-h^{Jet} is consistent with zero
- defactorization of soft and hard processes in pp **→ talk by Brian Cole, Tuesday, 10:00**

Υ(nS) in pp

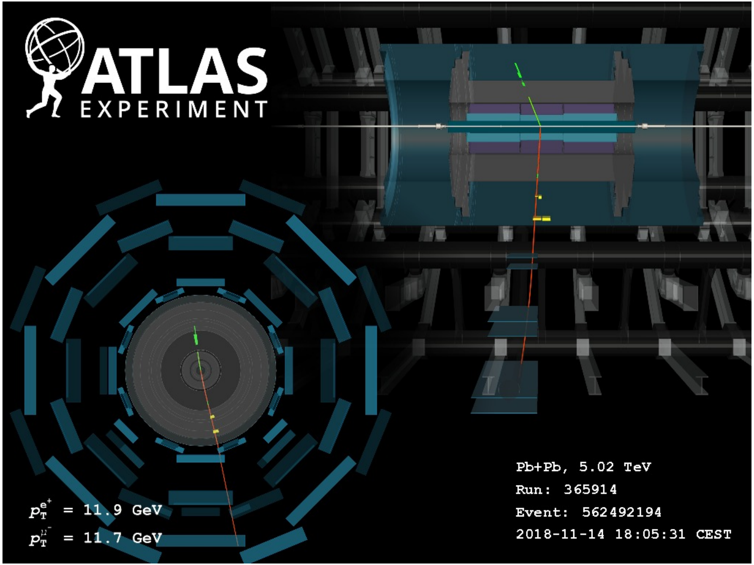
ATLAS-CONF-2022-023

- measurement of Υ in pp collisions with high pile-up
- using $\Upsilon \to \mu\mu$ channel
- precise subtraction of pile-up and separation of UE
- with increasing multiplicity (i.e. UE particles), Υ(2S) and Υ(3S) are less likely to be found with respect to the ground state Υ(1S)
- this suggests some correlation between UE and hard processes



➔ talk by Zvi Citron, Tuesday, 14:00

UPC


ATLAS
EXPERIMENT
$p_T^{e^+}$ = 11.9 GeV
$p_T^{\mu^-}$ = 11.7 GeV
Pb+Pb, 5.02 TeV
Run: 365914
Event: 562492194
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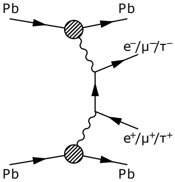
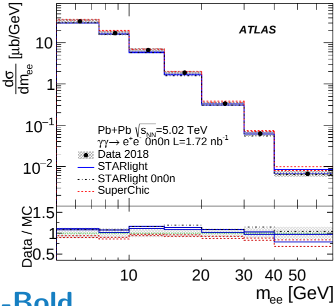
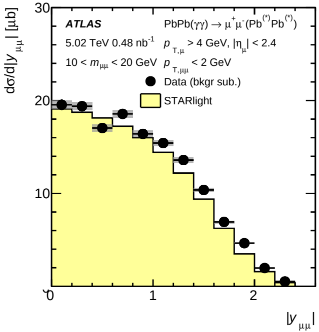


- learning about photon flux in $\gamma\gamma$ with respect to the impact parameter
- require no neutrons on either side
  - i.e. Pb nuclei remain intact
- $\gamma\gamma \to e^- e^+$
  - SuperChic higher than data
  - STARlight lower than data



- $\gamma\gamma \to \mu^- \mu^+$
  - STARlight lower than data, depending on $y_{\mu\mu}$

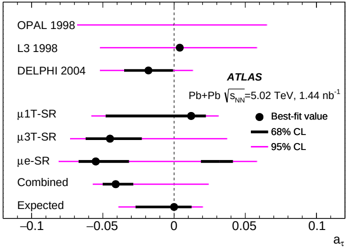


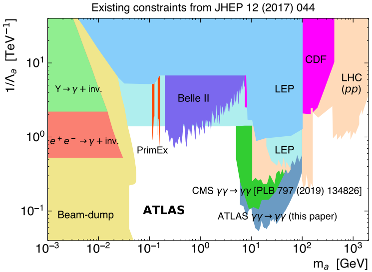
→ talk by Iwona Grabowska-Bold, Tuesday, 14:20

BSM physics in UPC

arXiv:2204.13478, arXiv:2008.05355

- $\gamma\gamma \rightarrow \tau\tau$
  - constraints of anomalous magnetic moment:
    $$a_\tau = (g-2)_\tau/2$$
  - non-zero due to higher order corrections
  - might be modified due to presence of BSM particles
- similar limits on a_τ as DELPHI experiment
  - consistent with SM
  - ATLAS results can be improved with more data in Run 3
- set exclusions limit for axion-like particles
  - $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$



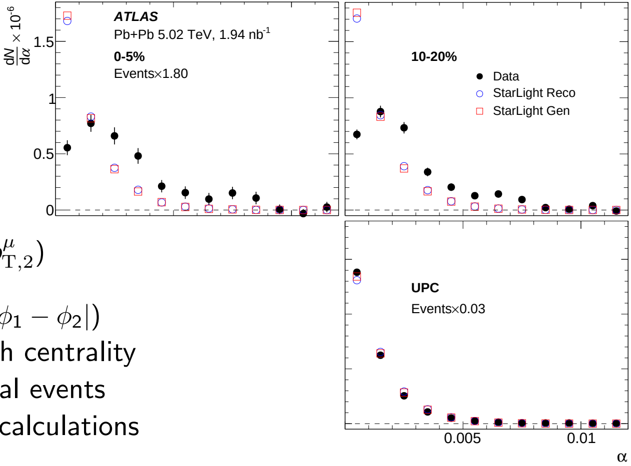


→ **talk by Agnieszka Ogrodnik, Tuesday, 16:50**

non-UPC di-muons

arXiv:2206.12594

- $\gamma\gamma \to \mu^-\mu^+$
  - produced in $\gamma\gamma$ scattering, measured in non-UPC events
  - acoplanarity:
    $$\alpha = 1 - |\phi_1 - \phi_2|/\pi$$
  - asymmetry:
    $$A = |p^{\mu}_{\mathrm{T},1} - p^{\mu}_{\mathrm{T},2}|/(p^{\mu}_{\mathrm{T},1} + p^{\mu}_{\mathrm{T},2})$$
  - transverse momentum scale:
    $$k_{\perp} = \frac{1}{2}(p^{\mu}_{\mathrm{T},1} + p^{\mu}_{\mathrm{T},2})/(1 - |\phi_1 - \phi_2|)$$
- observed broadening of α and $k_{\perp}$ with centrality
- depletion in small α and $k_{\perp}$ for central events
- both can be described by theoretical calculations



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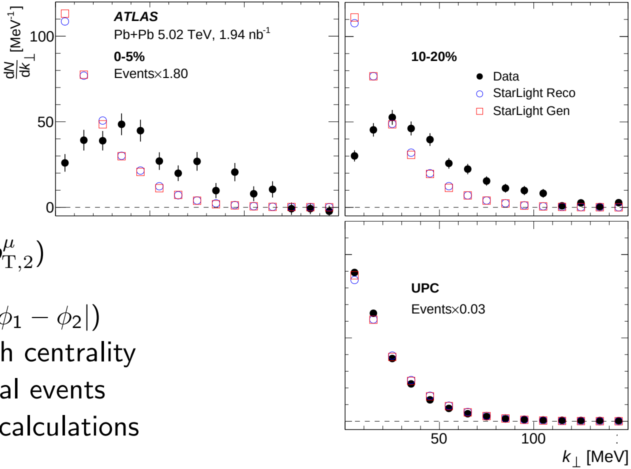


→ **talk by Iwona Grabowska-Bold, Tuesday, 14:20**

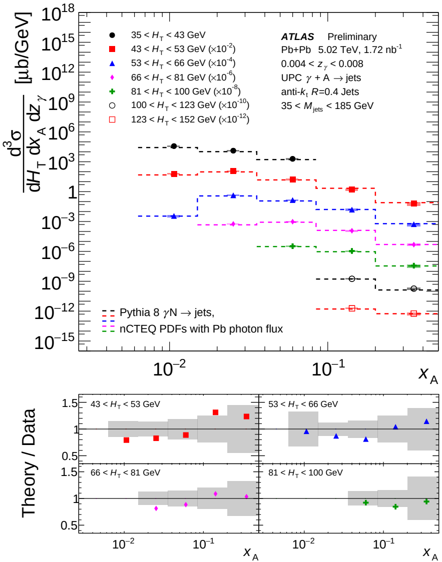
photo-nuclear di-jet production in UPC

ATLAS-CONF-2022-021

- require neutrons on exactly one side
- cross-section measured triple-differentially:

$$H_T = \sum_j p_{\mathrm{T},\mathrm{j}} \qquad z_\gamma = \frac{M_{jets}}{\sqrt{s_{NN}}} e^{+y_{jets}} \qquad x_A = \frac{M_{jets}}{\sqrt{s_{NN}}} e^{-y_{jets}}$$

- will help to constrain nuclear PDFs
  - systematic uncertainties up to 10%
  - possibly to decrease, once jet low-$\langle\mu\rangle$ response studies finalized
- connected to early physics goals for the EIC



→ talk by Benjamin Gilbert, Tuesday, 11:30

summary

- new results for jet quenching in Pb+Pb and Xe+Xe
  - jet structure plays a significant role
  - energy loss depends on color charge and quark flavour
- v_n up to high p_{T} for jets and particles
- detailed study of the modification of jet production in p+Pb
- no correlations between tracks from jets and UE in pp
- correlations between Υ and UE
- better understanding of the photon flux in UPC

- this year, expecting at least 2x more statistics than in results shown

- these and all other ATLAS results

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

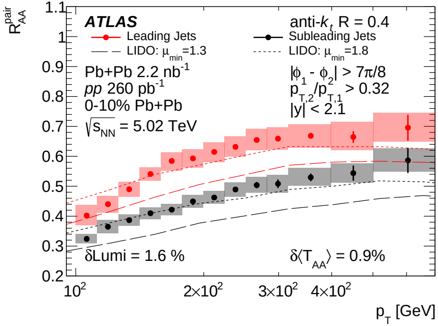
list of ATLAS talks and posters

Martin Krivos	Novel measurements of dijet quenching with ATLAS	Tue, 9:40
Brian Cole	ATLAS measurement of the two-particle correlation sensitivity to jets in *pp* collisions	Tue, 10:00
Benjamin Gilbert	Measurement of dijet production in UPC with the ATLAS detector	Tue, 11:30
Martin Rybar	Jet quenching studies with new jet substructure and suppression measurements in ATLAS	Tue, 11:50
Zvi Citron	Υ(nS) meson production in Pb+Pb and *pp* collisions with ATLAS	Tue, 14:00
Iwona Grabowska-Bold	Dilepton production and BSM physics from photon fusion processes in UPC and non-UPC Pb+Pb collisions with the ATLAS detector	Tue, 14:20
Xiaoning Wang	Measurements of the azimuthal anisotropy of jets and high-p_{T} charged particles in Pb+Pb collisions with the ATLAS detector	Tue, 15:00
Agnieszka Ogrodnik	BSM physics using photon-photon fusion processes in UPC in Pb+Pb collisions with the ATLAS detector	Tue, 16:50
Christopher McGinn	Exploring the QCD color charge dependence of jet quenching with photon+jet events in ATLAS	Wed, 9:00
Riccardo Longo	Investigation of initial state effects in p+Pb collisions at ATLAS via measurement of both top quark and dijet production	Wed, 9:40
Sebastian Tapia Araya	ATLAS measurements of *b*-jet suppression and heavy-flavor azimuthal correlations in 5.02 TeV Pb+Pb collisions	Wed, 10:50
James Nagle	Strong constraints on jet modification in centrality-dependent p+Pb collisions by ATLAS	Thu, 10:20
Ivan Gnesi	Flow and transverse momentum fluctuations in Pb+Pb and Xe+Xe collisions with ATLAS: assessing the initial condition of the QGP	poster
Patrycja Potepa	Observation of top-quark pair production with the ATLAS Detector	poster
Martin Spousta	Studies of large-*R* jets and their substructure in Pb+Pb and *pp* collisions with ATLAS	poster
Aric Tate	Dijet probes of the initial state in p+Pb collisions with ATLAS	poster

bonus slides

a.k.a. back-up slides

jet quenching & di-jet imbalance



- sub-leading jets more suppressed than leading
- at $p_T \gtrsim 200\,\text{GeV}$, virtually all inclusive jets are included

jet quenching with substructure