Highlights from the ATLAS experiment

Martin Spousta
for the ATLAS Collaboration

Charles University
Prague

Some of
key questions ...

- What is the origin of the flow at high-p_T?
- What is the origin of the flow in small systems?
- Is there a universality of flow / particle production among collision systems?
- What is the role of geometry / initial state and its fluctuation?
- What is the mechanisms of the suppression of hadrons?
- How do the particles radiate when going trough the plasma?

  …
- What are the properties of the plasma?

New / finalized results ~since last QM

- vn-pt correlations in 5.02 TeV Pb+Pb and p+Pb, arXiv:1907.05176
- HF muon+hadron correlations in 13 TeV pp, arXiv:1909.01650
- HF muon+hadron correlations in 5.02 TeV Pb+Pb, ATLAS-CONF-2019-053
- High-pT correlations in 8.16 TeV p+Pb, arXiv:1910.13978
- XeXe flow, CERN-EP-2019-227
- Decorrelation in XeXe and PbPb, ATLAS-CONF-2019-055
- Flow fluctuations, arXiv:1904.04808
- Photonuclear Ridge, ATLAS-CONF-2019-022
- Z-tagged ridge in pp, arXiv:1906.08290
- Z-hadron correlations in Pb+Pb, ATLAS-CONF-2019-052
- Jet fragmentation in γ+jet Pb+Pb, PRL 123 (2019) 042001
- γ+jet asymmetry in Pb+Pb, PLB 789 (2019) 167-190
- Track-jet correlations in Pb+Pb, arXiv:1908.05264
- Large-R jets in Pb+Pb, ATLAS-CONF-2019-056
- Upsilons in Pb+Pb, ATLAS-CONF-2019-054
- Non-upc dimuons in 2015+2018 Pb+Pb, ATLAS-CONF-2019-051
- W in Pb+Pb, arXiv:1907.10414
- Z in Pb+Pb, arXiv: arXiv:1910.13396
- Azimuthal dijets in p+Pb, PRC 100 (2019) 034903
- Prompt photons in p+Pb, PLB 796 (2019) 230
- Light-by-light in 2018 Pb+Pb, PRL 123 (2019) no.5, 052001

Flow phenomenon

Penetrating probes of QGP

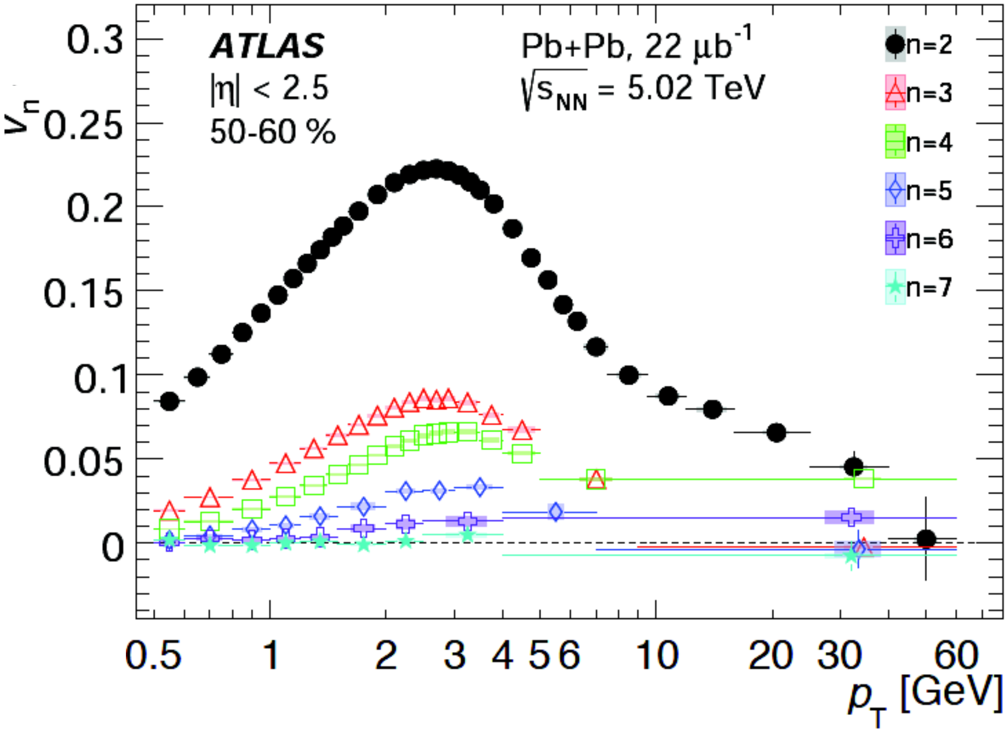
Physics of initial state and geometry

Physics of ultra-peripheral collisions

Flow phenomenon

Flow phenomenon

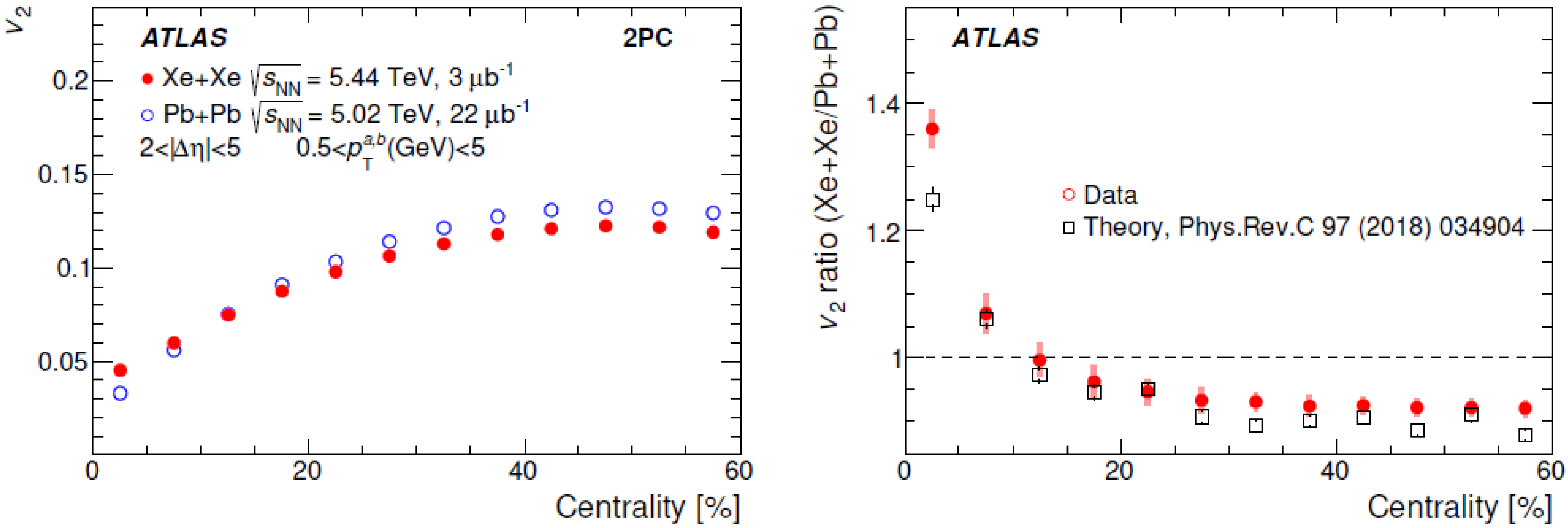
EPJC 78 (2018) 997



- Flow – one of the main signatures of QGP creation.
- Precision measurements reaching high p_T and high n available.
- Open issues => need more differential and “targeted” measurements ...

Flow in Xe+Xe collisions

CERN-EP-2019-227



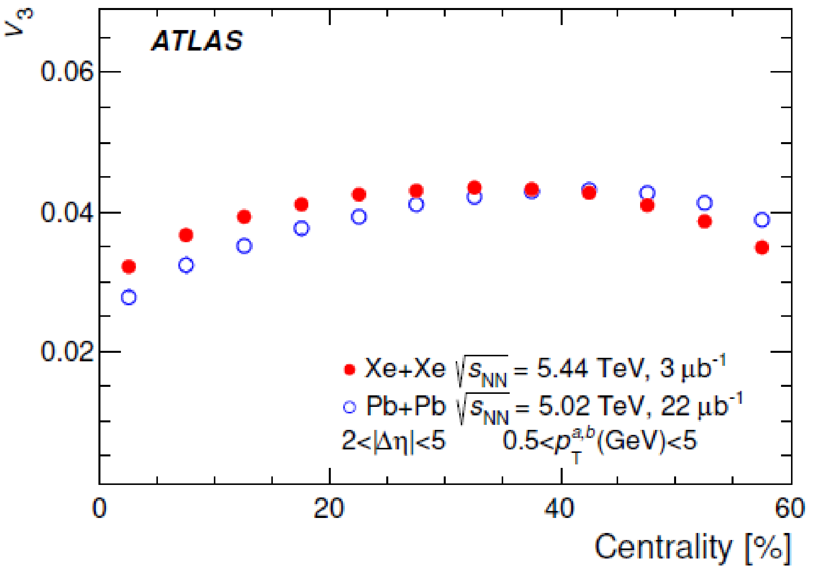
- Detailed measurements of the flow up to v_6.
- v_2 **smaller in mid-central** and peripheral collisions for Xe+Xe compared to Pb+Pb (… smaller eccentricity in Xe+Xe).

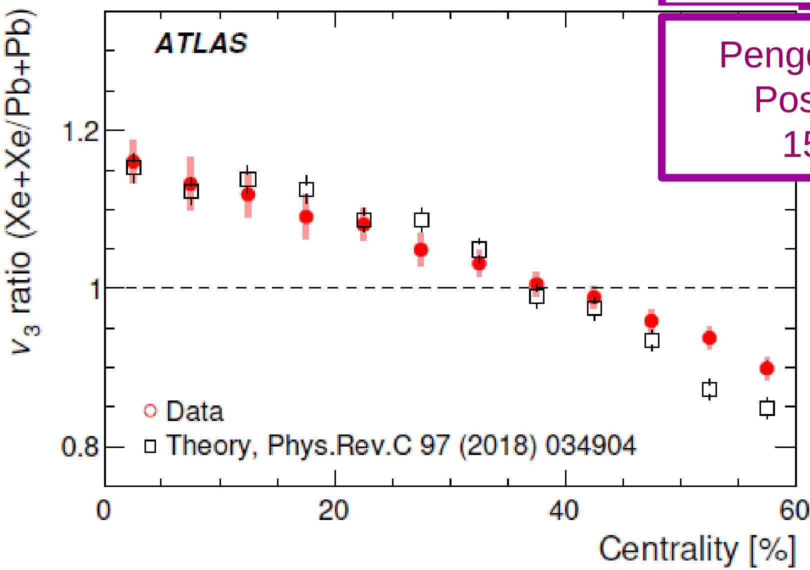
Flow in Xe+Xe collisions

CERN-EP-2019-227

Soumya Mohapatra, Tue 8:40 (Collective 1)

Pengqi Yin, Poster 151





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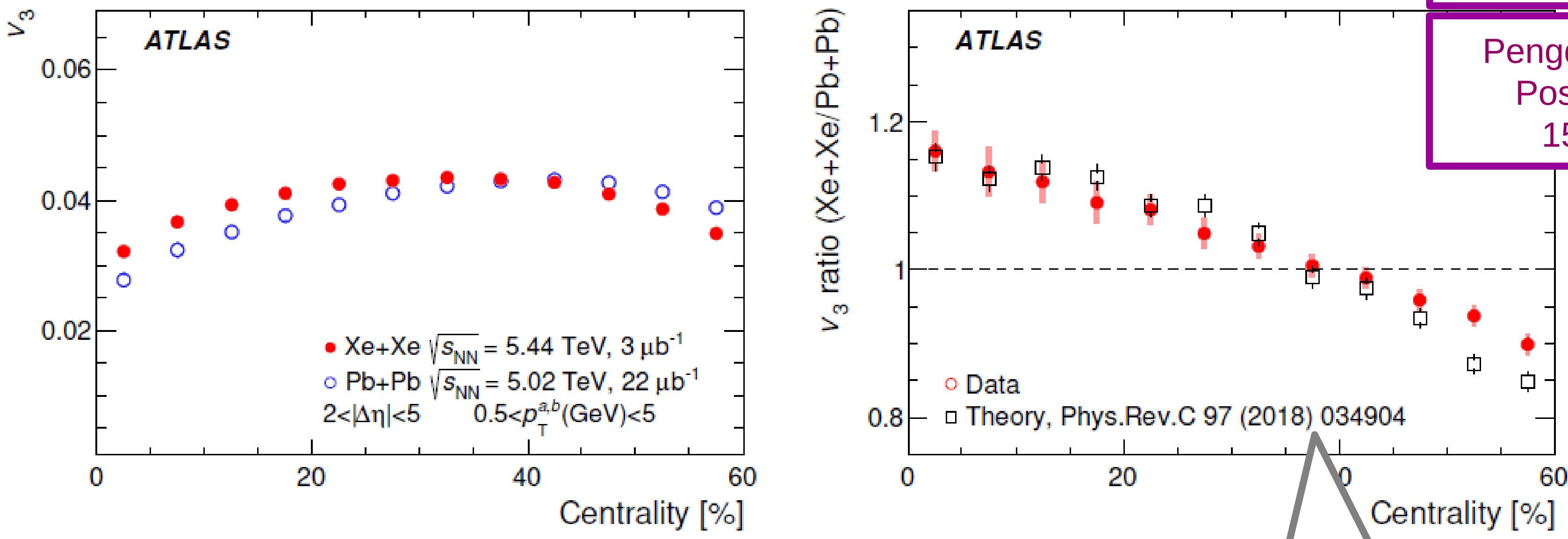

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In agreement with hydro predictions

Longitudinal flow decorrelations in Xe+Xe / Pb+Pb

ATLAS-CONF-2019-055

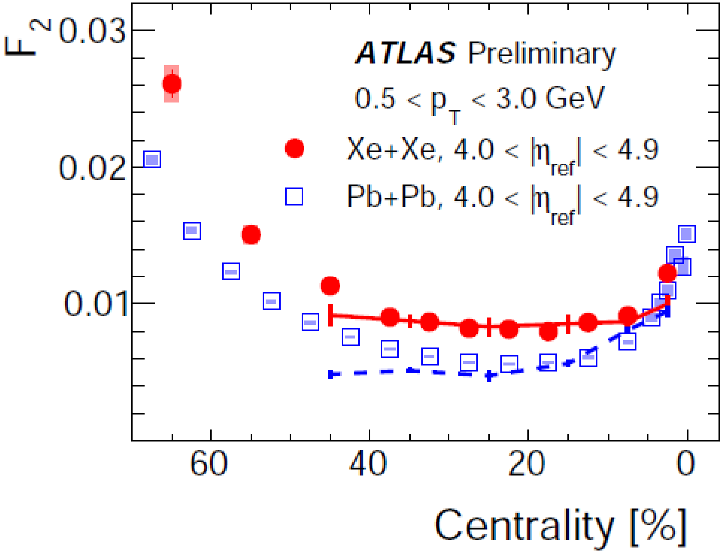
- Fluctuations => asymmetry of $v_n(\eta)$ and torque / twist of $\psi_n(\eta)$

$$r_{n|n} = \frac{\langle q_n(-\eta)\ q_n^*(\eta_{\rm ref})\rangle}{\langle q_n(+\eta)\ q_n^*(\eta_{\rm ref})\rangle}$$

where

$$q_n = \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i}$$

$$F_n = \frac{\sum_i (1 - r_{n|n}(\eta_i))\eta_i}{2\sum_i \eta_i^2}$$



- Decorrelation **larger for v_2** in Xe+Xe compared to Pb+Pb

Longitudinal flow decorrelations in Xe+Xe / Pb+Pb

ATLAS-CONF-2019-055

Soumya Mohapatra, Tue 8:40 (Collective 1)

Arabinda Behera Poster CD-4

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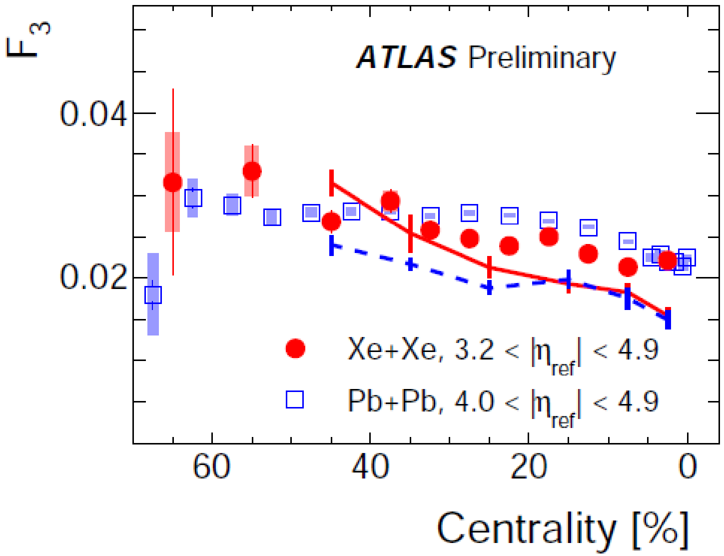

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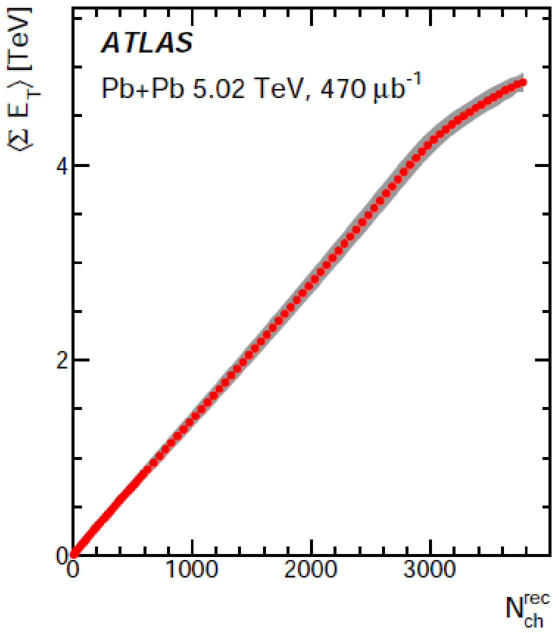
- Decorrelation **smaller for v_3** in Xe+Xe compared to Pb+Pb

Flow and centrality fluctuations in Pb+Pb

arXiv:1904.04808

- Centrality fluctuations may have an impact on flow values ...



- Relation between N_{ch} (barrel) and $\langle \Sigma E_T \rangle$ (forward) is not completely linear

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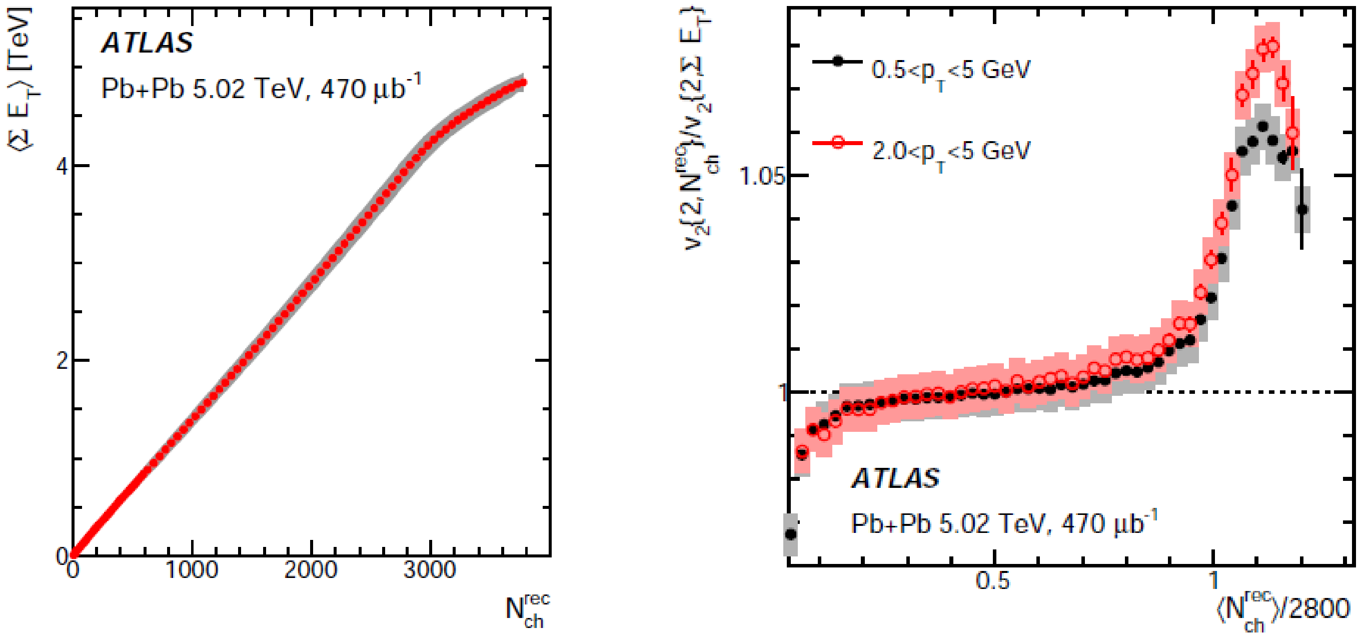

- Relation between N_{ch} (barrel) and $<\Sigma E_T>$ (forward) is not completely linear.
- Ratio of $v_2\{2\}$ for these two event class definitions != 1.

Flow and centrality fluctuations in Pb+Pb

Jiangyong Jia, Tue 2:00 (Collective 2)

arXiv:1904.04808

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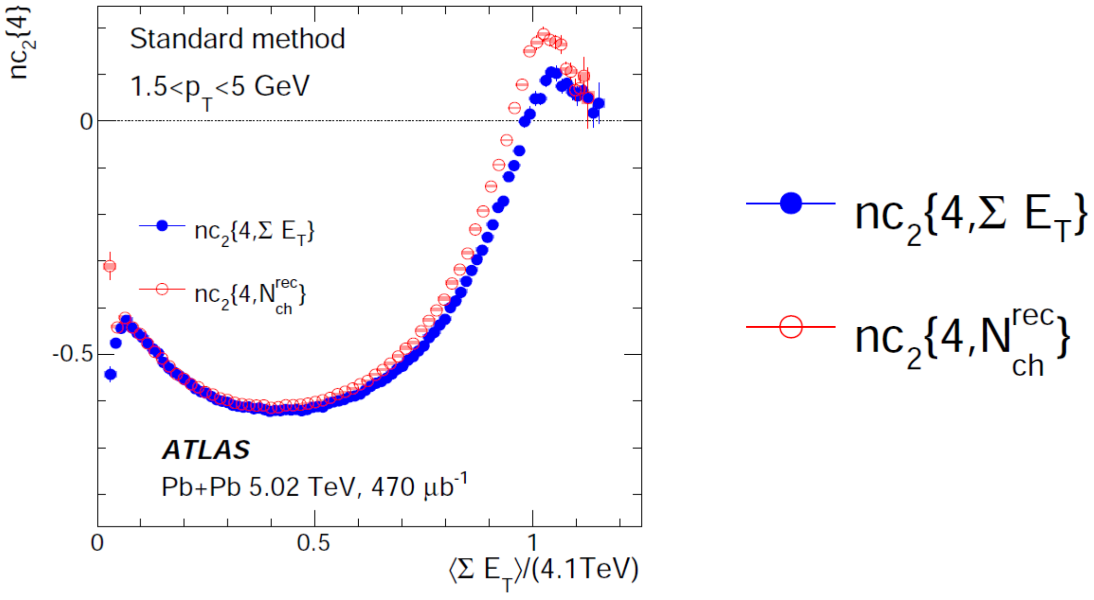


- Change of the **sign of cumulants** in ultra-central collisions - more pronounced for events based on N_{ch} as expected from centrality fluctuations.
- **Centrality** fluctuations have important **impact on measured flow**.

v_n-p_T correlations in Pb+Pb and p+Pb

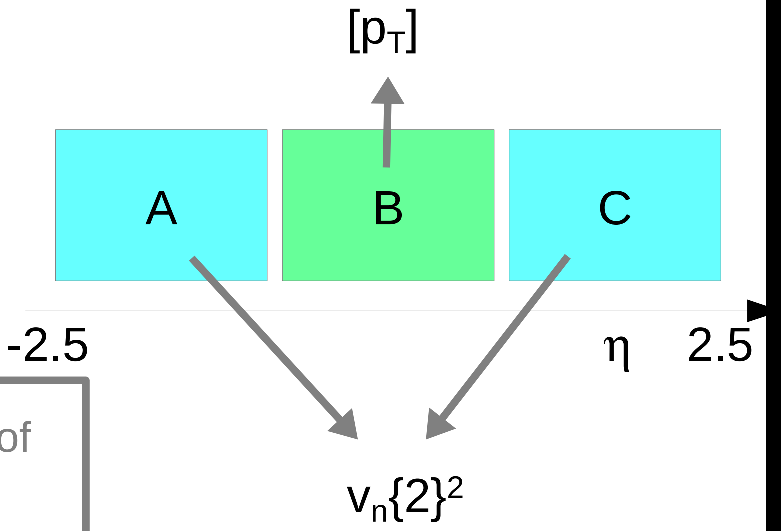
arXiv:1907.05176

- Measuring modified Pearson's coefficient, ρ.
- Variances and mean p_T replaced by dynamical variables to reduce auto-correlations and finite detector effects.

$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_\mathrm{dyn}}\sqrt{c_k}}$$

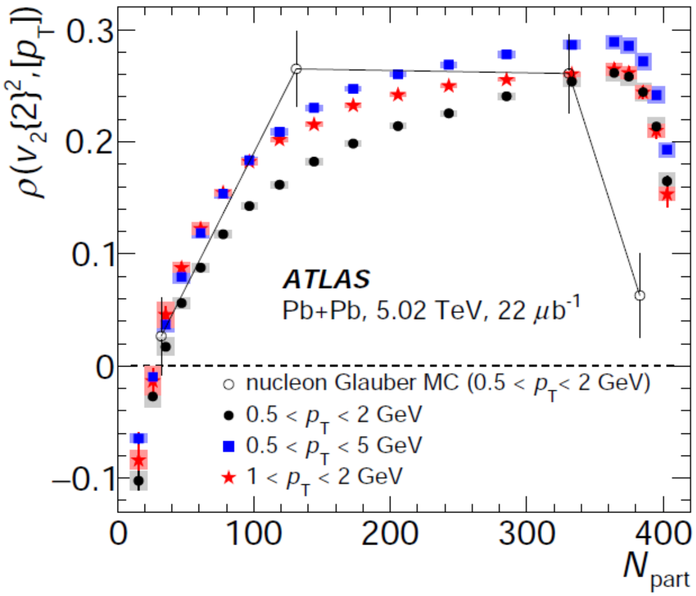
Dynamical variance of $v_n\{2\}^2$

Dynamical variance of $[p_T]$



v_n-p_T correlations in Pb+Pb and p+Pb

arXiv:1907.05176

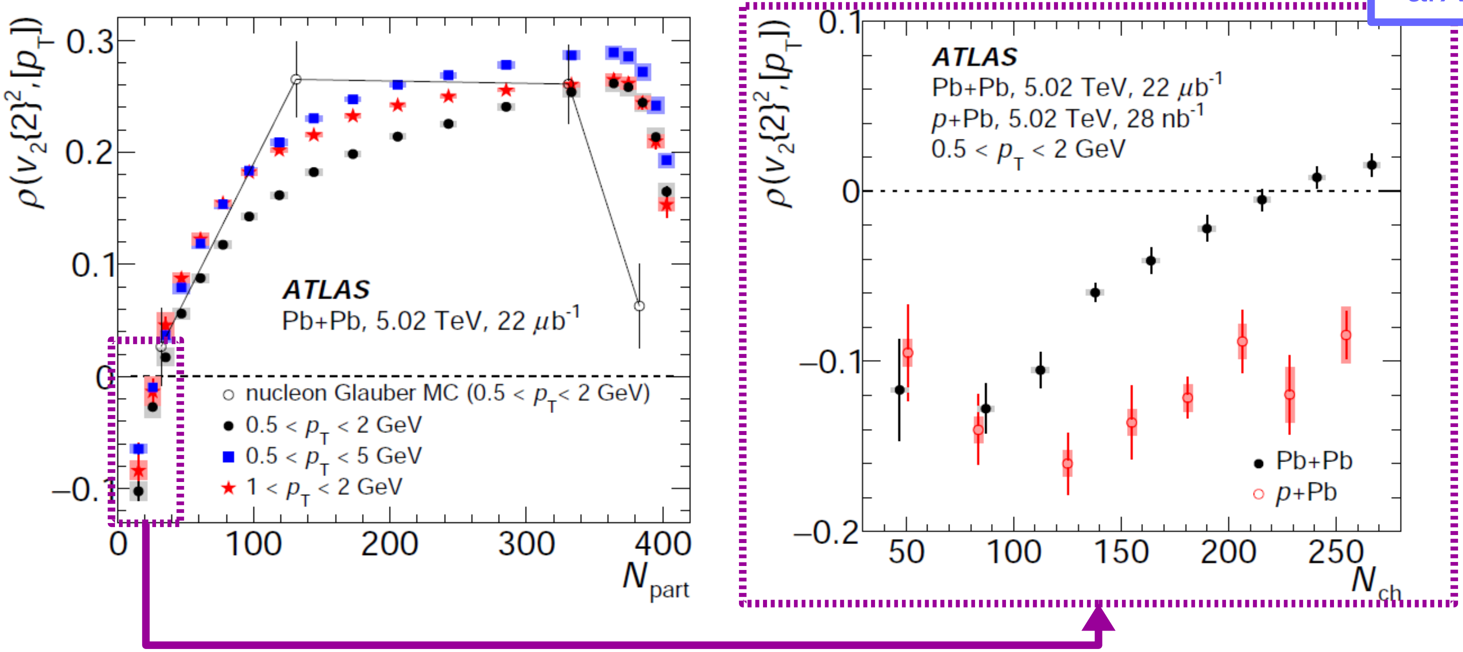


- **Positive correlation**
  - Increases towards central, decreases in ultra-central.
  - Good modeling by hydro calculations based on nucleon Glauber.
  - Supports traditional picture in which flow originates from **pressure gradients**.

v_n-p_T correlations in Pb+Pb and p+Pb

Tomasz Bold
Wed 10:20
(Collective 4)

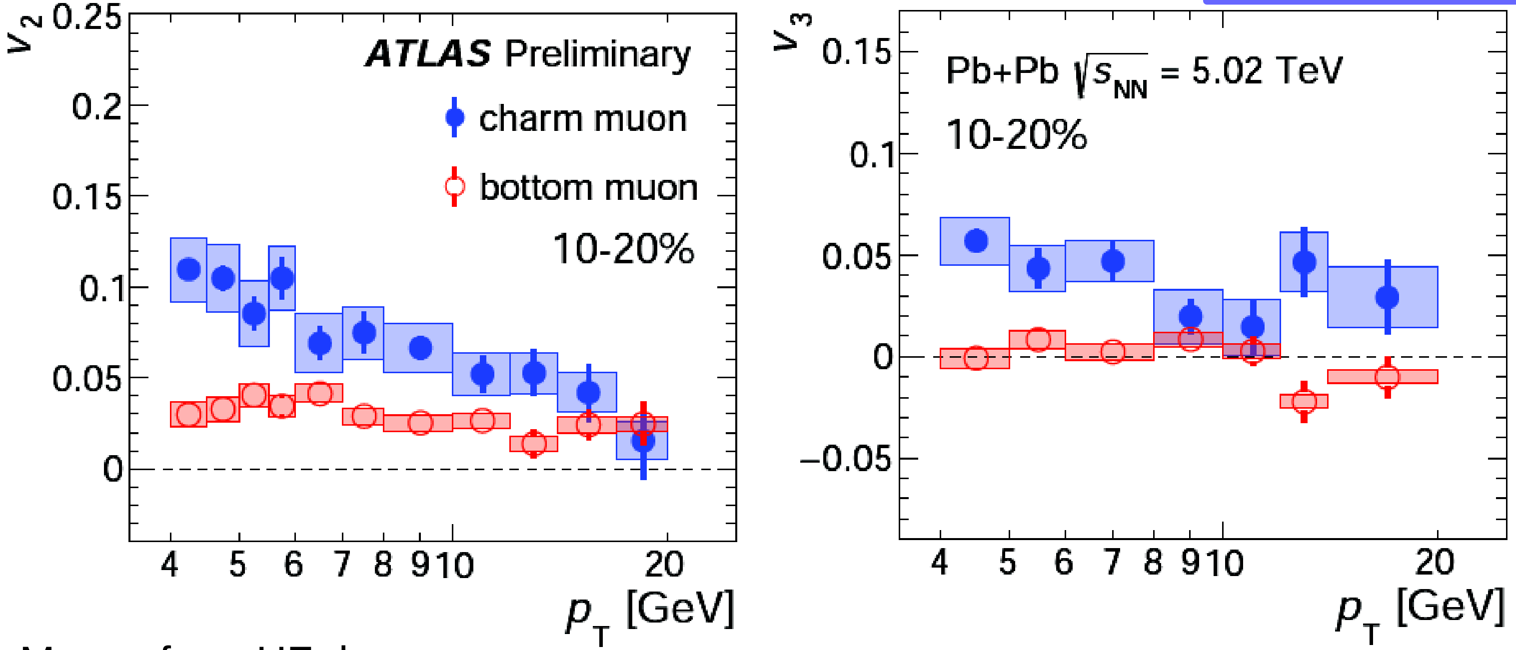
arXiv:1907.05176



- **Anti-correlation**
  - In peripheral Pb+Pb and p+Pb collisions.
  - Should allow to constrain the role of **initial state**.

Charm and beauty flow in Pb+Pb collisions

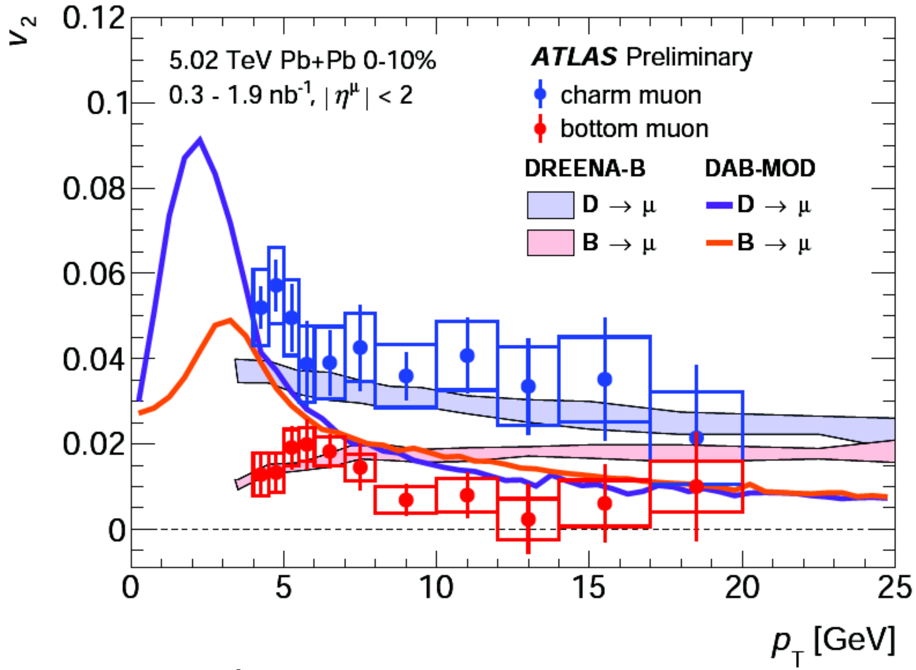
ATLAS-CONF-2019-053



- Muons from HF decays.
- μ from **charm**: non-zero v_2 and v_3 up to ~20 GeV.
- μ from **beauty**: non-zero v_2 up to ~20 GeV, but smaller than for charm.
- First measurement of v_3 for beauty (consistent with zero in all centrality bins).

Charm and beauty flow in Pb+Pb collisions

ATLAS-CONF-2019-053



Example of theory comparison:

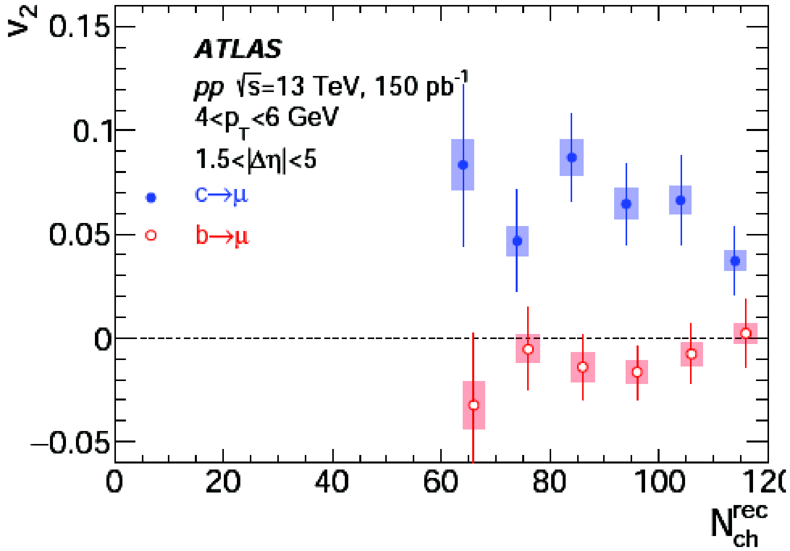
- Good matching of theory to data for DREENA-B (PLB 791 (2019) 296).
- Matching of DAB-MOD (arXiv:1906.10768) worse for the flow from charm.

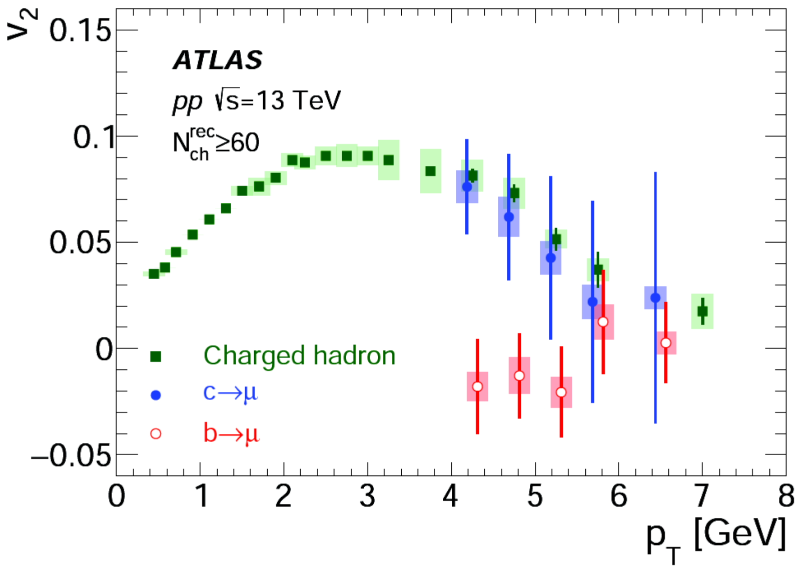
… comparing models with **common QGP expansion** may help

Charm and beauty flow in pp collisions

Sanghoon Lim
Tue 9:00
(Small Sys 1)

arXiv:1909.01650

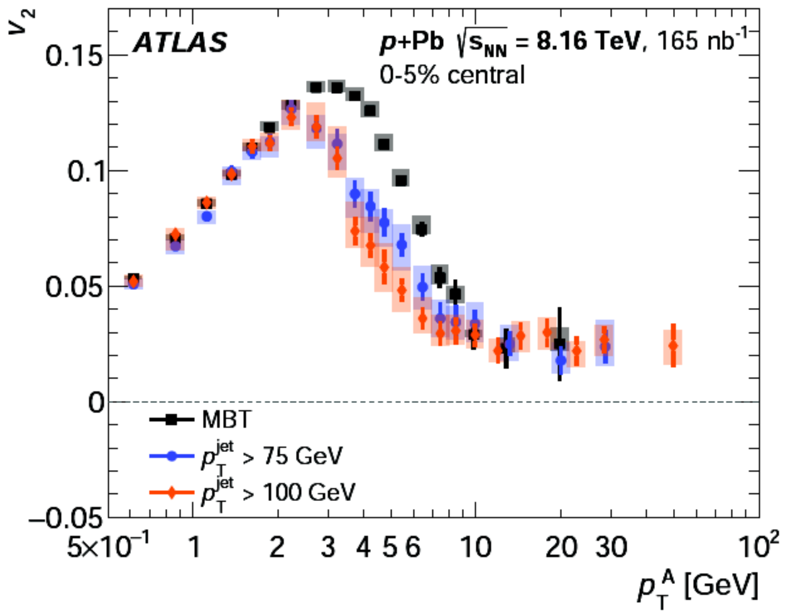




- Muons from heavy flavor decays.
- μ from **charm**: non-zero v_2, similar to inclusive charged hadrons.
- μ from **beauty**: quark v_2 consistent with zero.
- **Collectivity** in *pp* **does not persist** to heavy b-quarks!

High-p_T v_n in p+Pb

arXiv:1910.13978



- Use MB events and events **triggered by jets**. Jet correlations reduced by requiring associated particle being $|\Delta\eta|>1$ from the jet with p_T>15 GeV.

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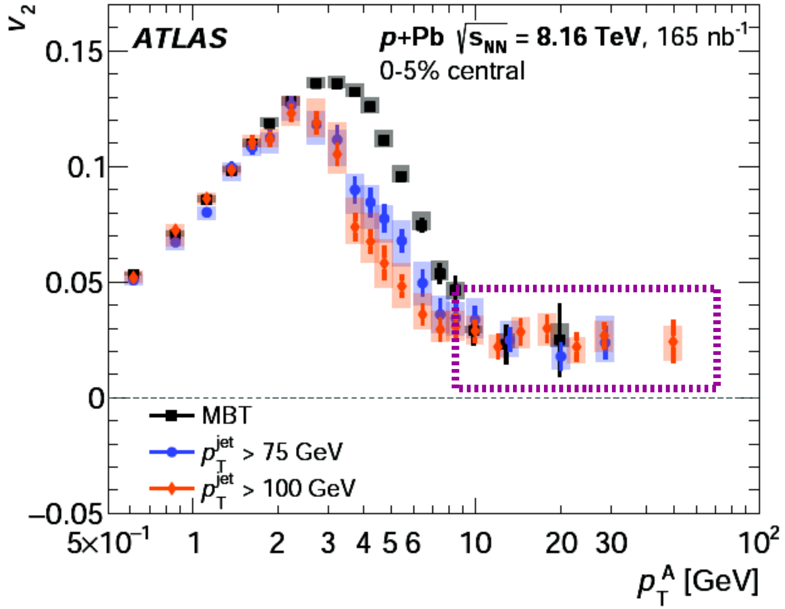

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- Flow signal seen for **p_T=10–50 GeV**

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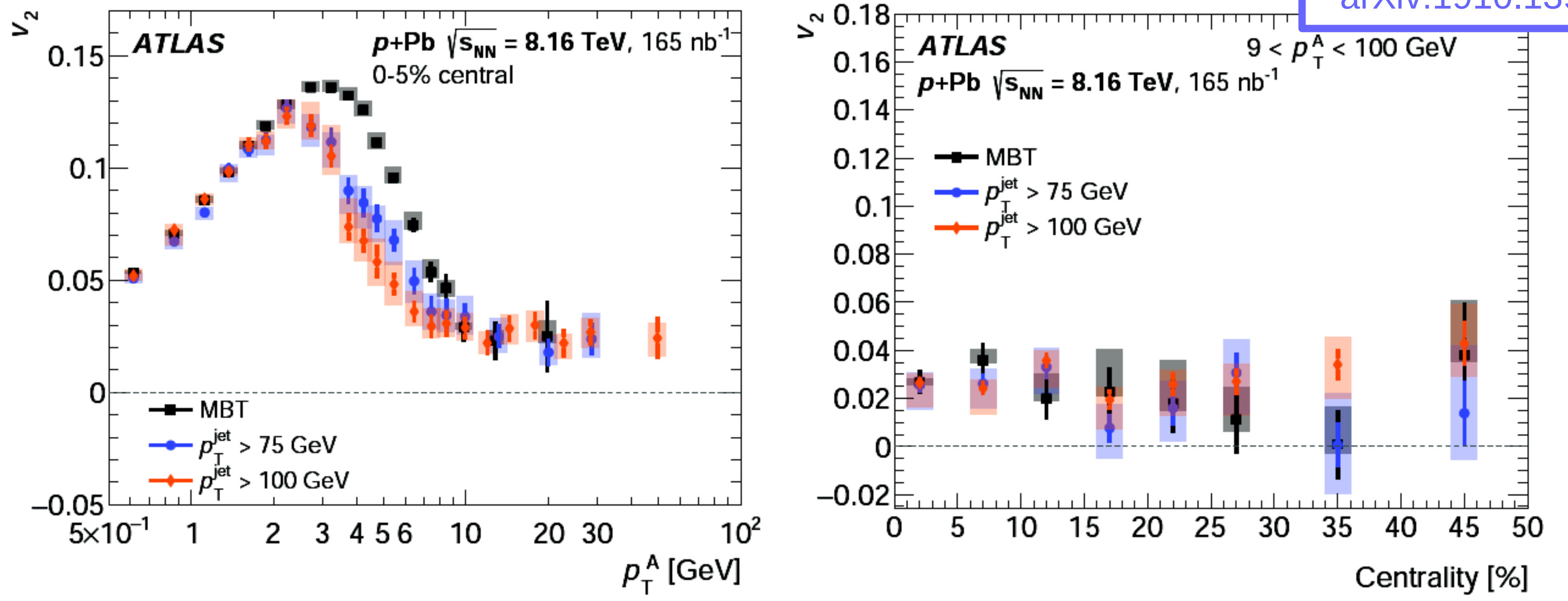

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- Flow signal seen for **p_T=10–50 GeV**, **independent** of centrality within uncertainties.

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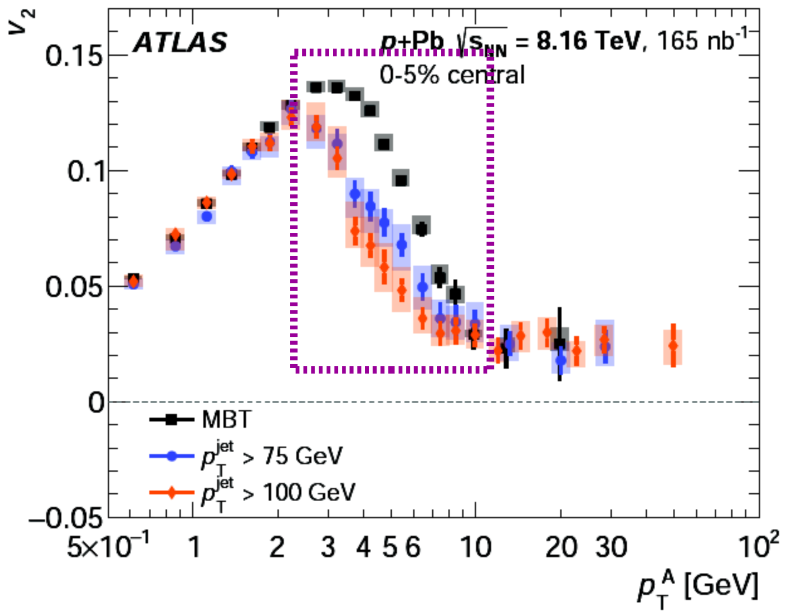

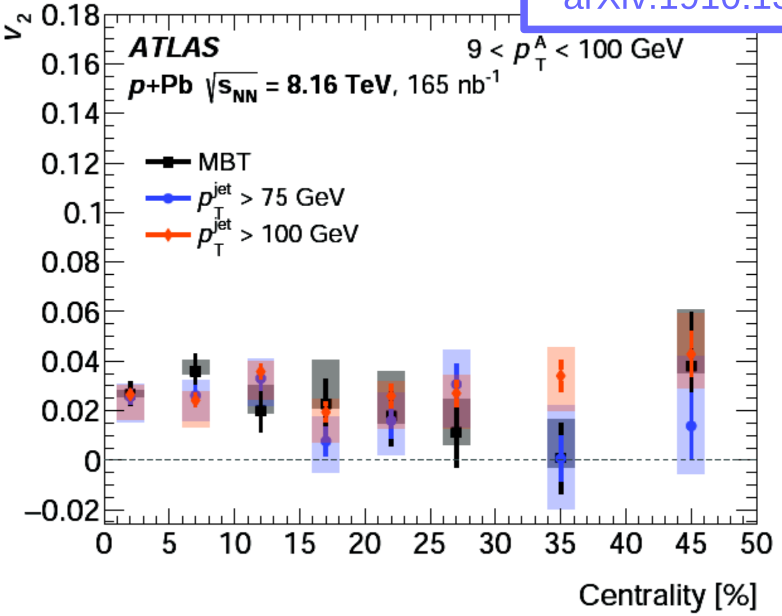

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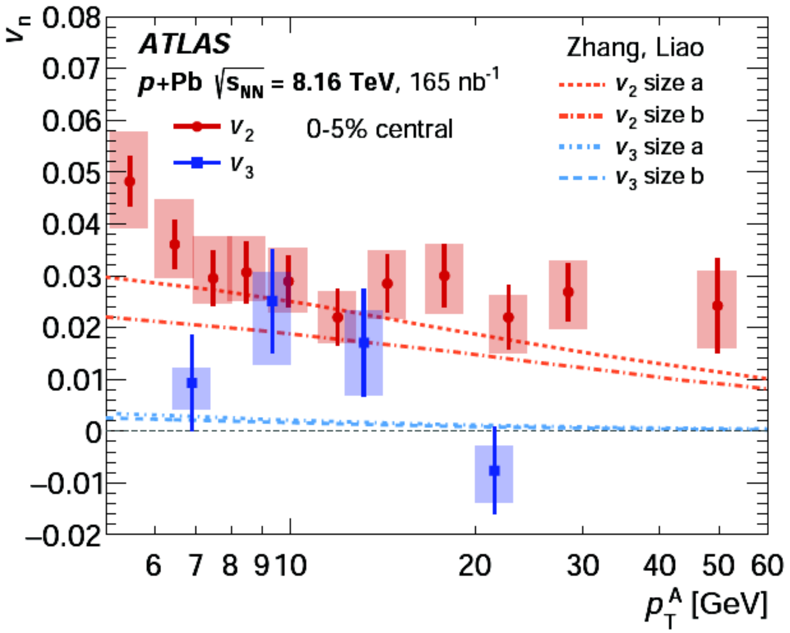
- Flow signal seen for **p_T=10–50 GeV**, **independent** of centrality within uncertainties.
- Differences at **p_T=2–10 GeV**: likely due to smaller anisotropy of particles from hard scattering event.

High-p_T v_n in p+Pb

arXiv:1910.13978

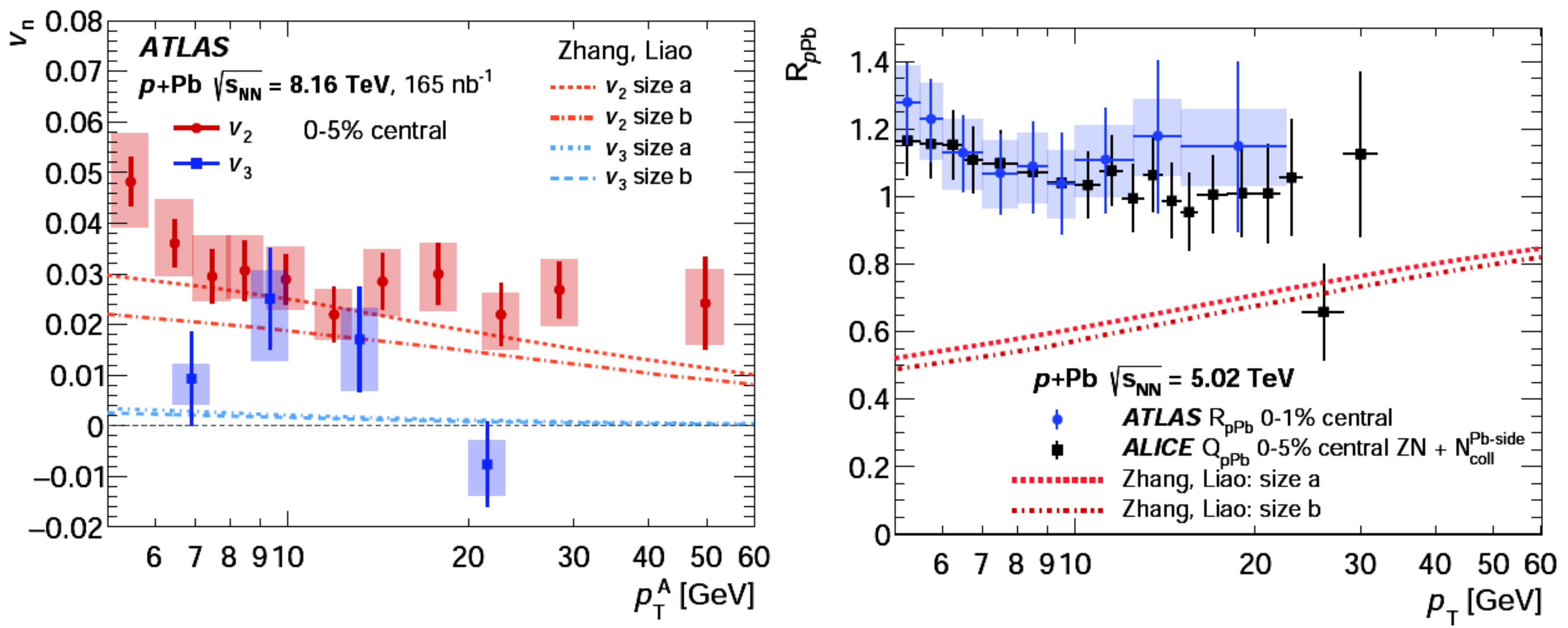


Model (arXiv:1311.5463) able to reproduce the flow …

High-p_T v_n in p+Pb

Kurt Hill
Tue 11:20
(Small Sys 2)

arXiv:1910.13978

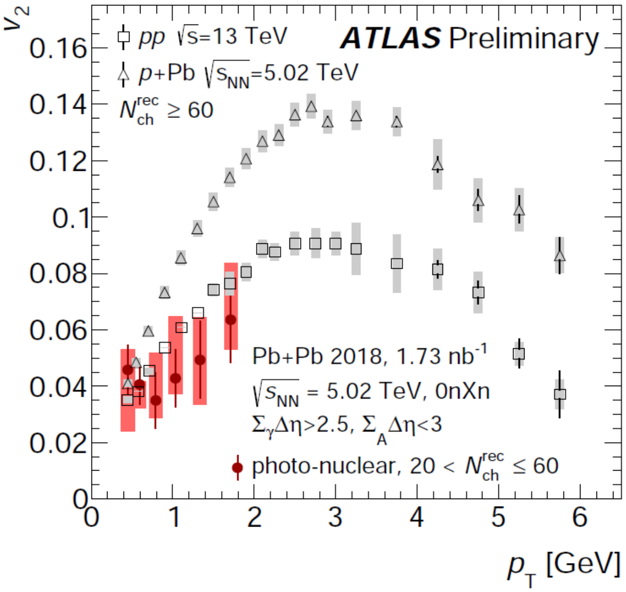


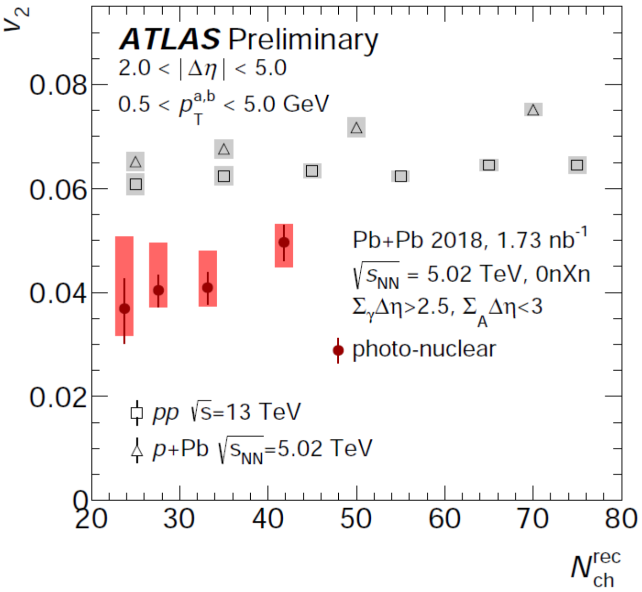
Model (arXiv:1311.5463) able to reproduce the flow … cannot reproduce the R_{pPb}

... **flow / suppression puzzle** of small systems.

ATLAS-CONF-2019-022

Flow in UPC events





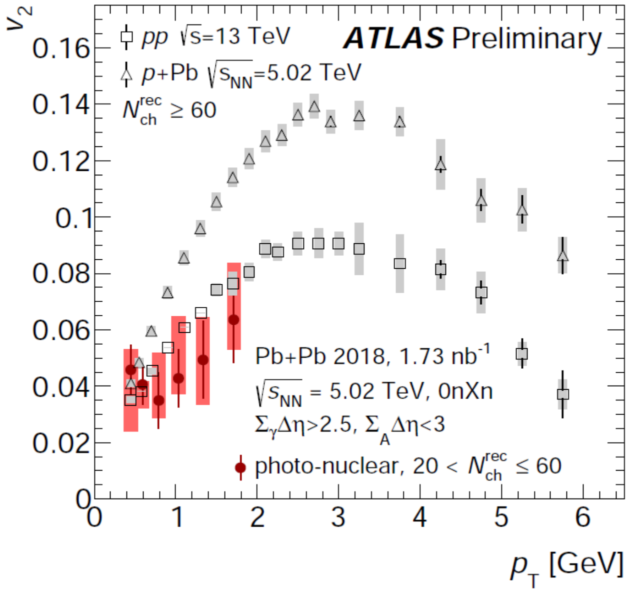
- Flow in photo-nuclear events? … In the vector meson dominance picture, photon fluctuates to vector meson **γ+Pb <=> ρ+Pb**.
- Significant v_2 seen in photo-nuclear events … v_2 is **smaller than in p+Pb or pp**, but similar trends as in p+Pb.

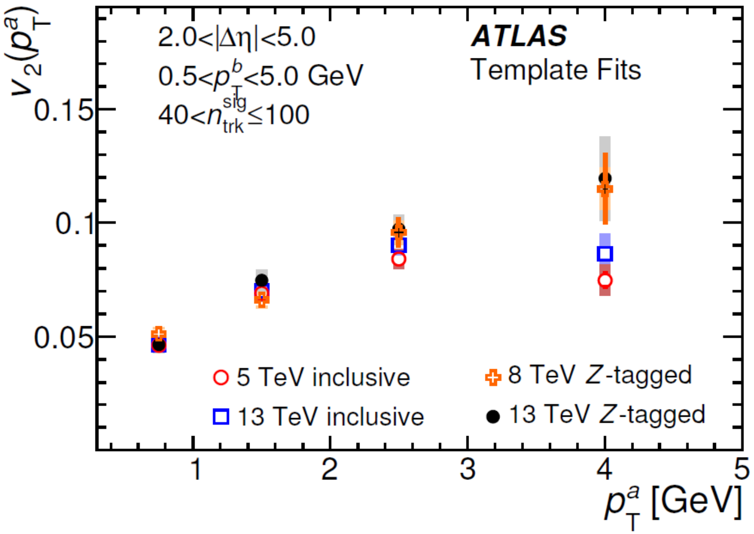
Flow in UPC events

ATLAS-CONF-2019-022

Brian Cole
Wed 2:40
(Small Sys 4)

arXiv:1906.08290





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- Significant v_2 seen in photo-nuclear events … v_2 is **smaller than in p+Pb or pp**, but similar trends as in p+Pb.
- This together with e.g. **ridge in Z-tagged events** may help to understand the origin of flow in small systems

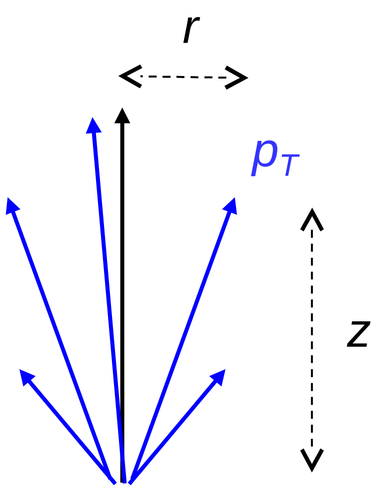
Penetrating probes of QGP

Internal structure of jets

PRC 98 (2018) 024908

EPJC 77 (2017) 379

$$D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}z} \qquad D(p_T) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}p_T}$$



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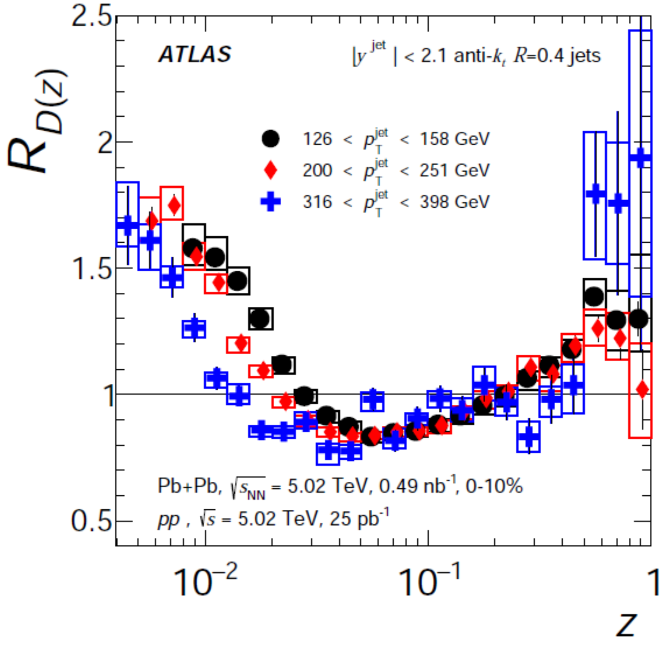

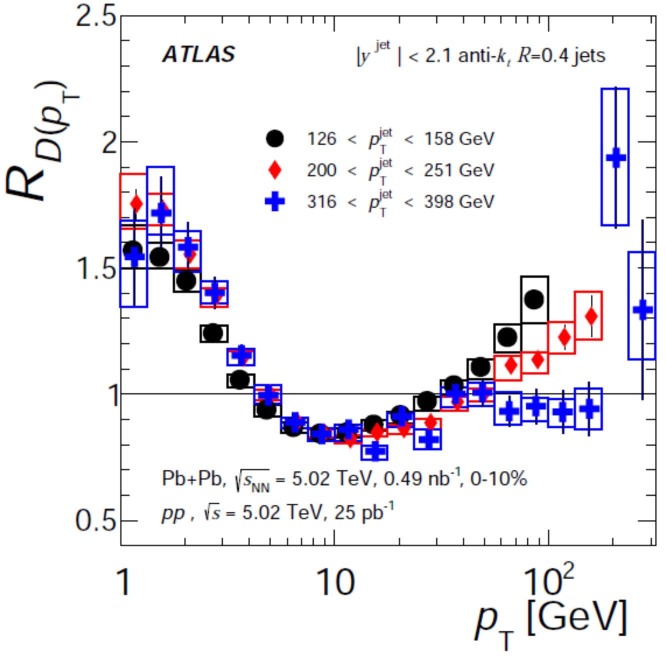

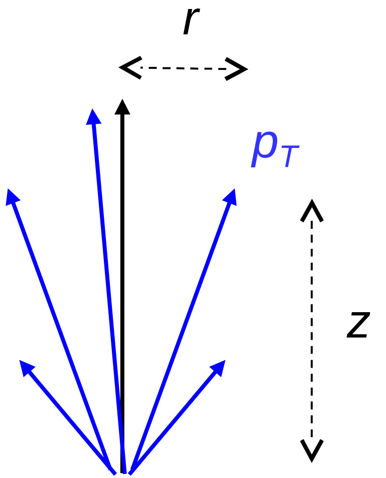

- "Enhancement –> Suppression –> Enhancement"
- Measure in details as a function of $\sqrt{s_{NN}}$, jet p_T, rapidity, ...

Internal structure of jets

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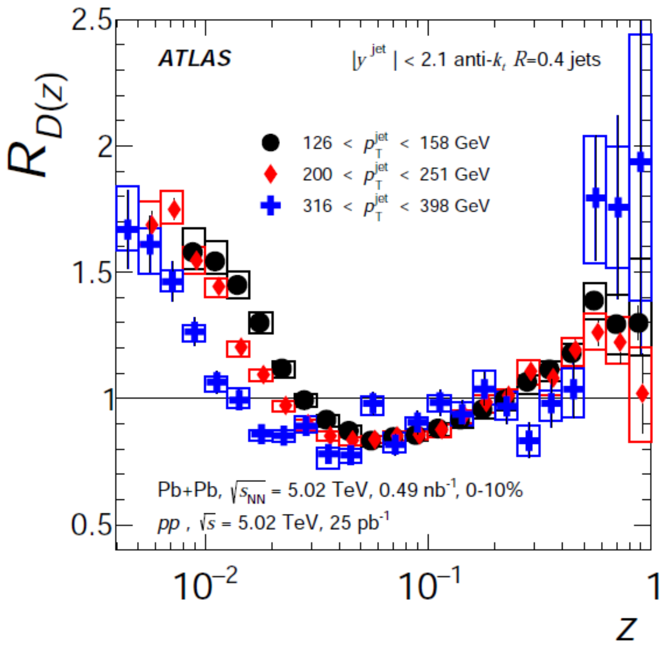
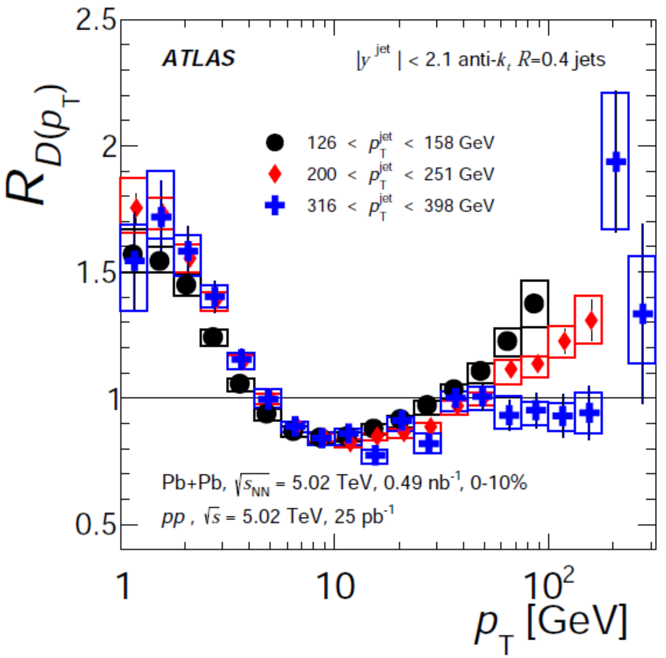
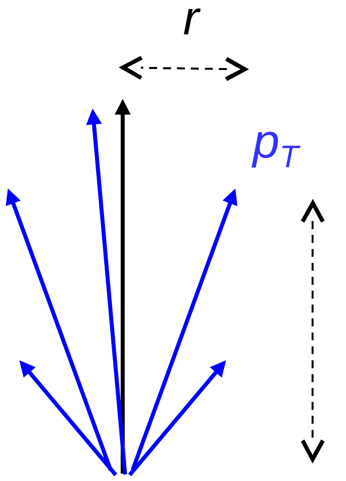






- D(z) modifications scale with $p_{T,jet}$ at high z but not at low z
- D(p_T) modifications scale with $p_{T,jet}$ at low p_T but not at high p_T

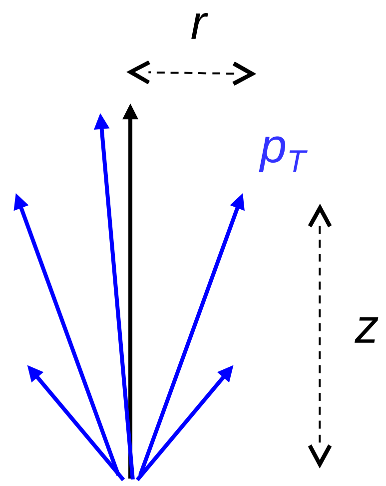
Internal structure of jets

$$D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}z} \qquad D(p_T) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}p_T}$$

Now extending these measurements:

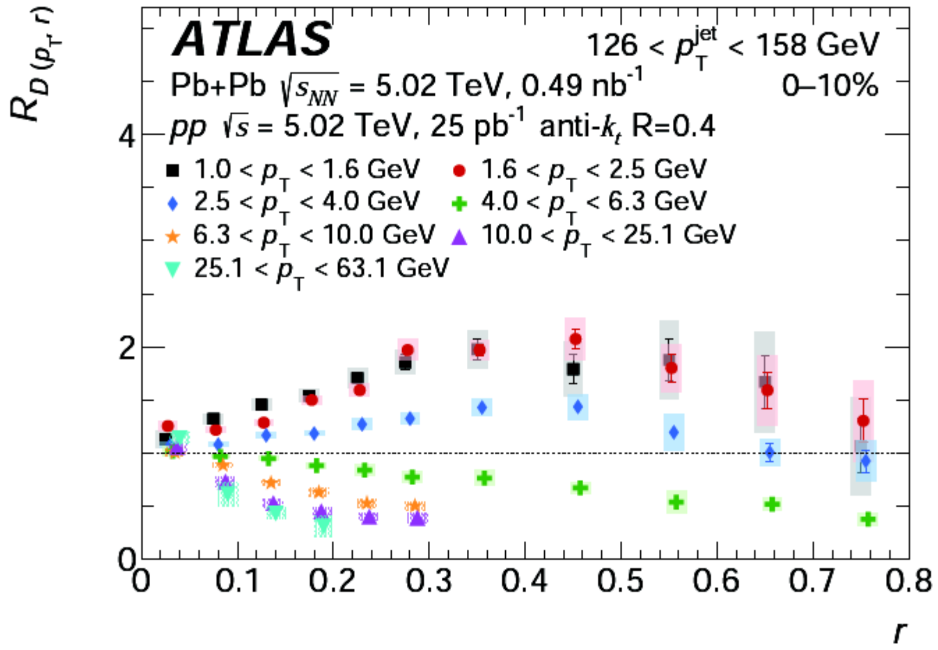
- to γ-jets system
- to Z+jet via hadrons
- to see the *r*-dependence

$$D(p_T, r) = \frac{1}{N_{jet}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 N}{\mathrm{d}p_T \mathrm{d}r}$$



Fragmentation as a function of *r*

arXiv:1908.05264



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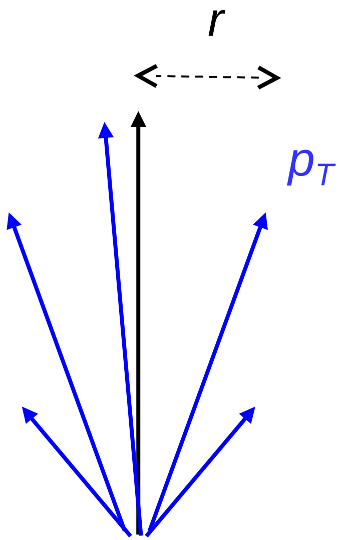

- **Broadening** of jet for **low-p_T** particles
- **Narrowing** of jet for **high-p_T** particles.
- But the jet **core remains** almost **unmodified**.

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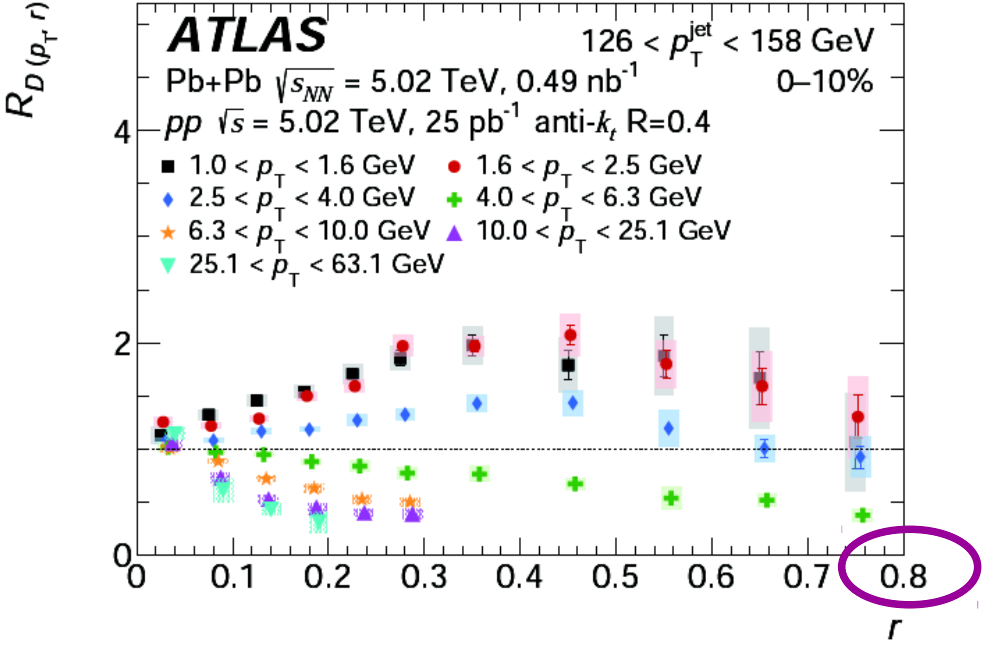

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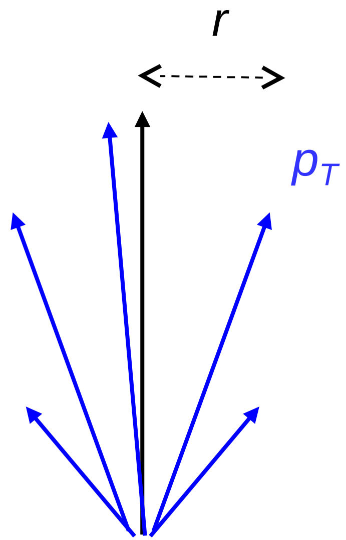
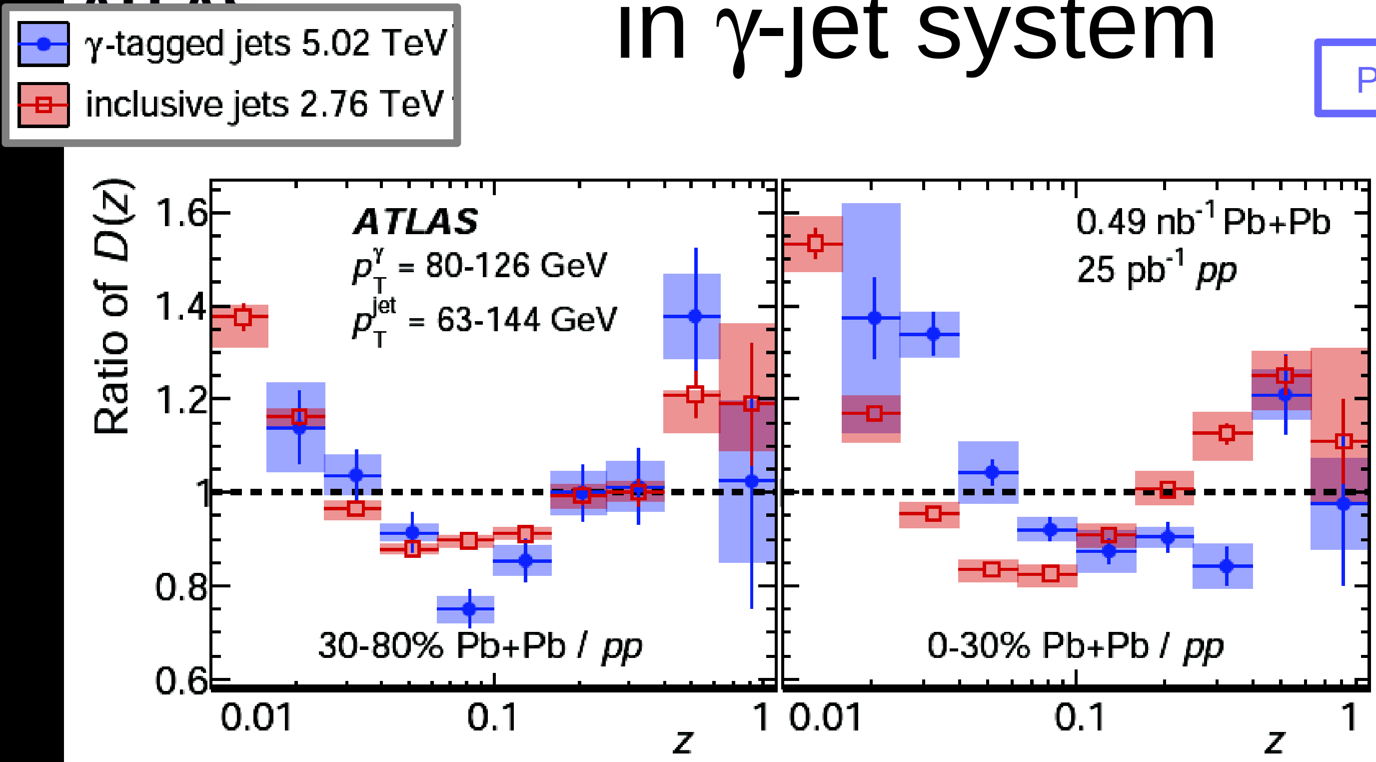
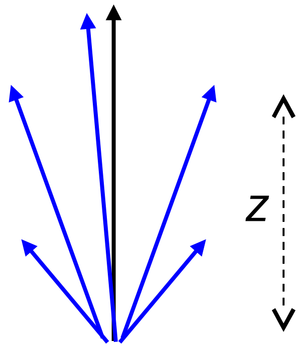


- **Broadening** of jet for **low-p_T** particles
- **Narrowing** of jet for **high-p_T** particles.
- But the jet **core remains** almost **unmodified**.
- Yield of soft particles starts to drop down when *r* –> 0.8.

Internal structure of jets in γ-jet system

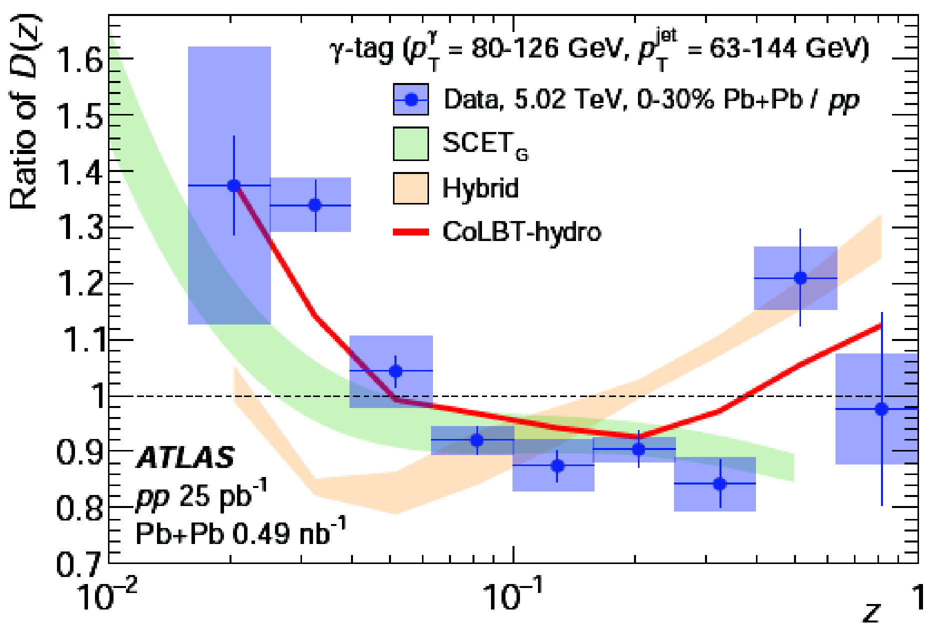
PRL 123 (2019) 042001

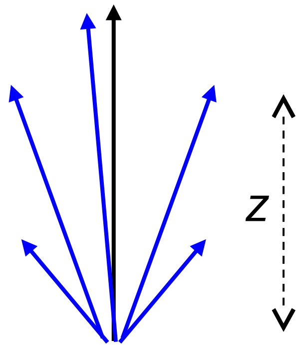




- Photon-tagged jet fragmentation: **quark/gluon dependence**.
- More peripheral bin: ratios similar between photon-tagged and inclusive.
- **Central bin: ratios different** between photon-tagged and inclusive.
- Result fully corrected to particle level.

Internal structure of jets in γ-jet system

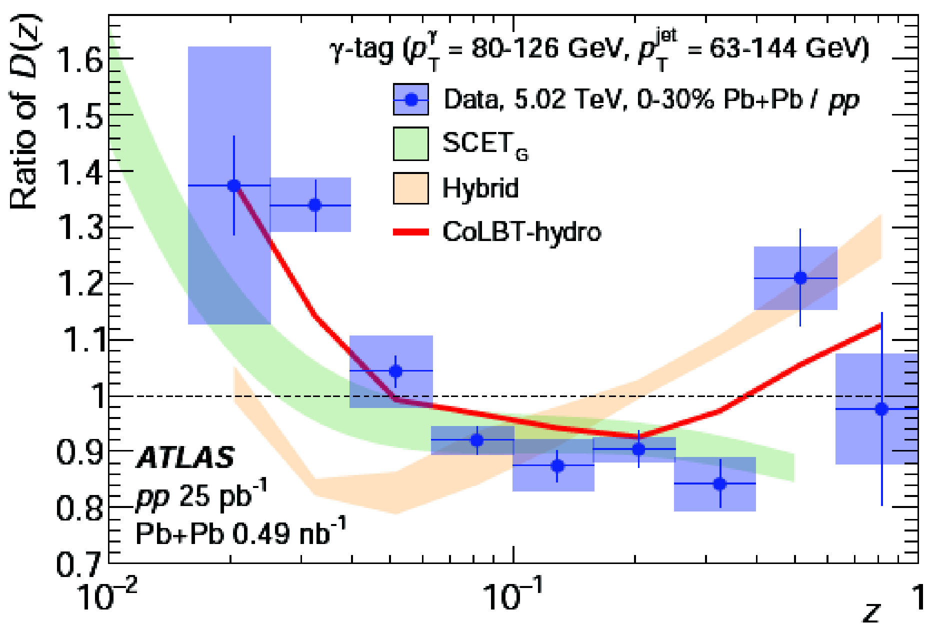


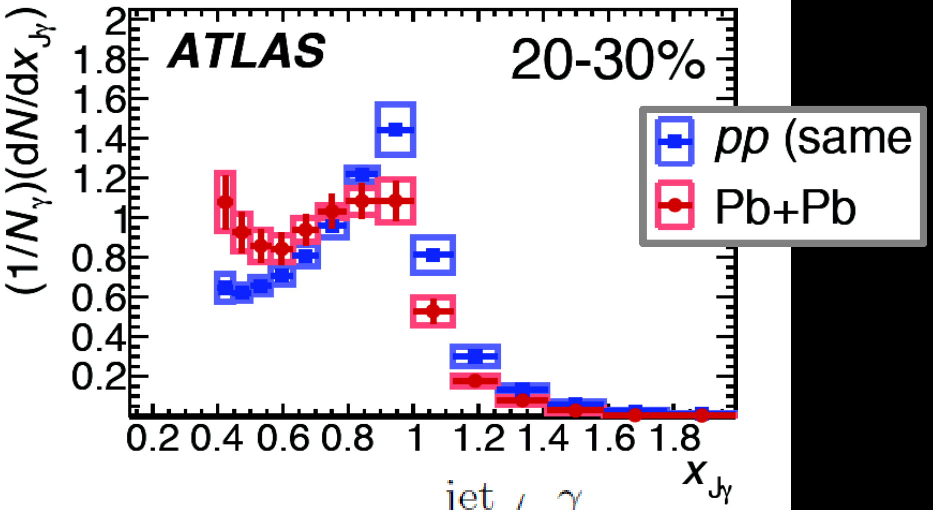


- Theory comparison example: in general, models often have problems simultaneously reproducing the **low-z and high-z** trends … here e.g. CoLBT-hydro seems to be doing a good job.

Internal structure of jets in γ-jet system

PLB 789 (2019) 167



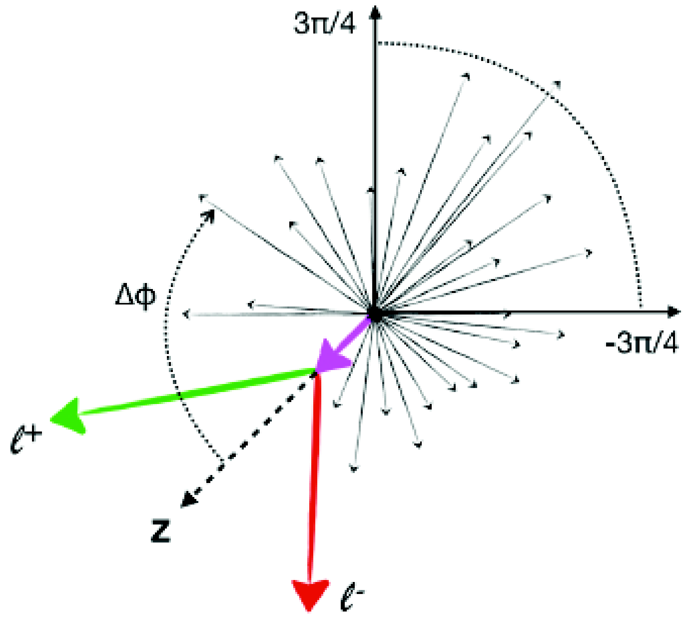


$$x_{J\gamma} = p_T^{\rm jet}/p_T^{\gamma}$$

- Theory comparison example: in general, models often have problems simultaneously reproducing the **low-z and high-z** trends … here e.g. CoLBT-hydro seems to be doing a good job.
- May be interpreted together with the measurement of **γ-jet asymmetry**.

Z-tagged charged particle yields in Pb+Pb

ATLAS-CONF-2019-052



- Measure charged hadron yield integrated over $|\Delta\phi|>3\pi/4$
- **Per-Z yield** in Pb+Pb and *pp*:

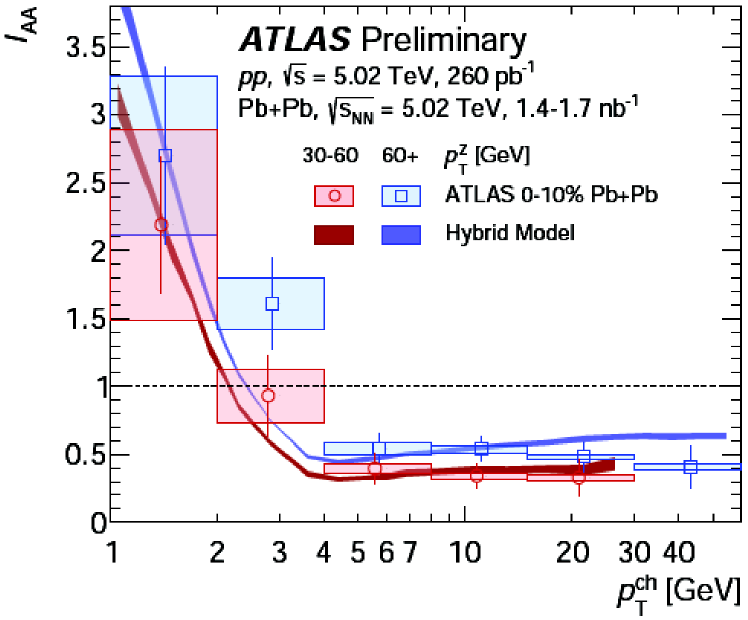
$$I_{\mathrm{AA}} = Y_{\mathrm{Pb+Pb}}/Y_{pp}$$

- Similar to fragmentation functions, but **no explicit jet** requirement – complementary to Z-jet and γ-jet measurements

Z-tagged charged particle yields in Pb+Pb

Dennis Perepelitsa, Wed 2:40 (Jets 4)

ATLAS-CONF-2019-052



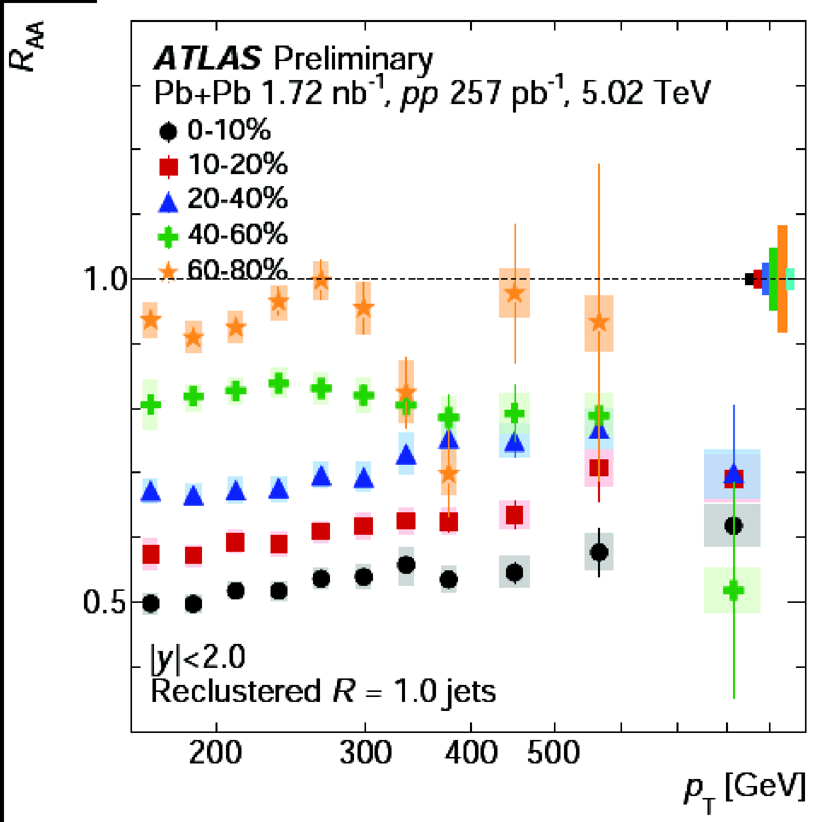
- Measure charged hadron yield integrated over $|\Delta\phi|>3\pi/4$
- **Per-Z yield** in Pb+Pb and *pp*:

$$I_{\mathrm{AA}} = Y_{\mathrm{Pb+Pb}} / Y_{pp}$$

- Similar to fragmentation functions, but **no explicit jet** requirement – complementary to Z-jet and γ-jet measurements
- Similar behavior as in jet fragmentation measurements: enhancement at low-p_T, suppression at p_T>4 GeV, but **larger amplitude** of the modification ... due combining the jet suppression with modified fragmentation

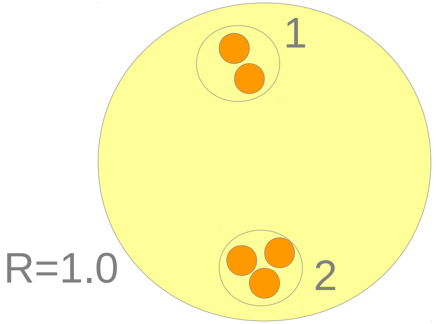
Large-R jets

ATLAS-CONF-2019-056



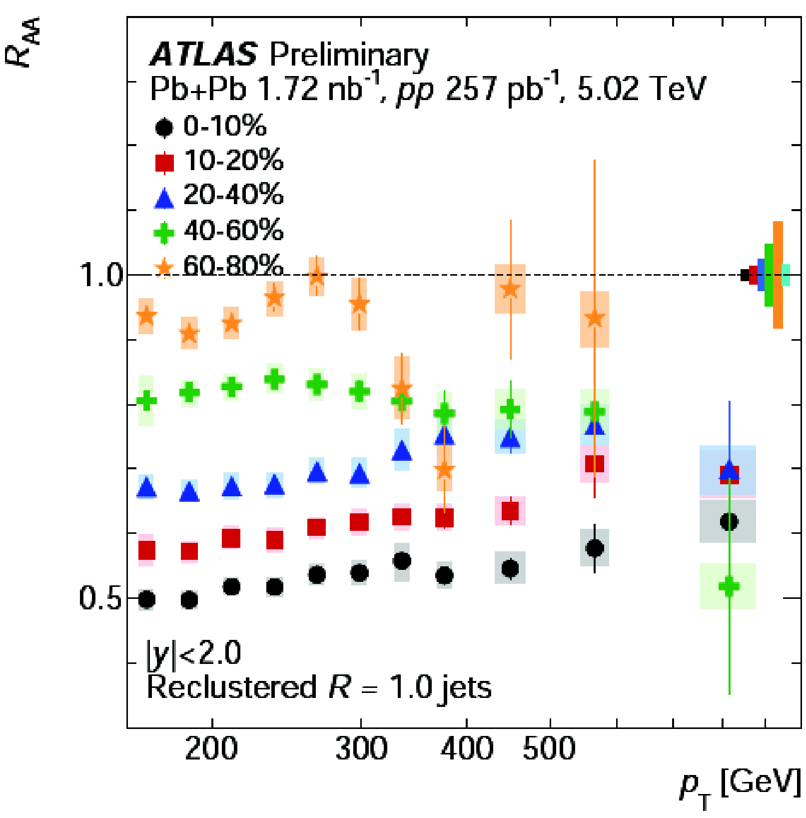
- No measurement of large-R jets in heavy-ion collisions done before.
- R=0.2 jets with p_T>35 GeV reclustered using anti-k_T R=1.0
  - Soft contributions removed
  - Allows to study k_T splitting scale

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$



Large-*R* jets

ATLAS-CONF-2019-056



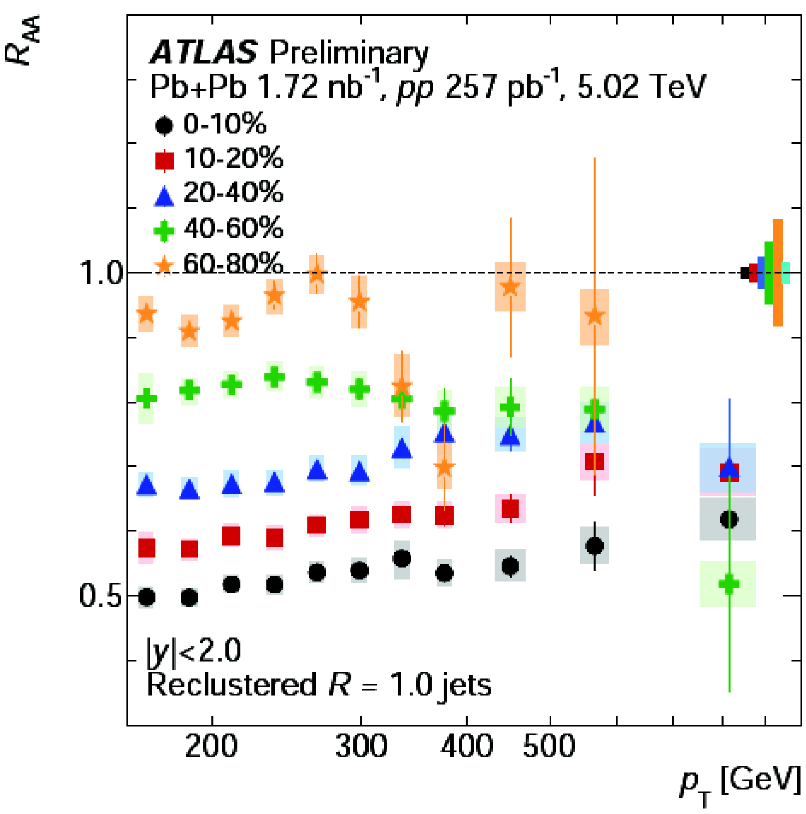
- No measurement of large-*R* jets in heavy-ion collisions done before.
- *R*=0.2 jets with p_T>35 GeV reclustered using anti-k_T *R*=1.0
  - Soft contributions removed
  - Allows to study k_T splitting scale:

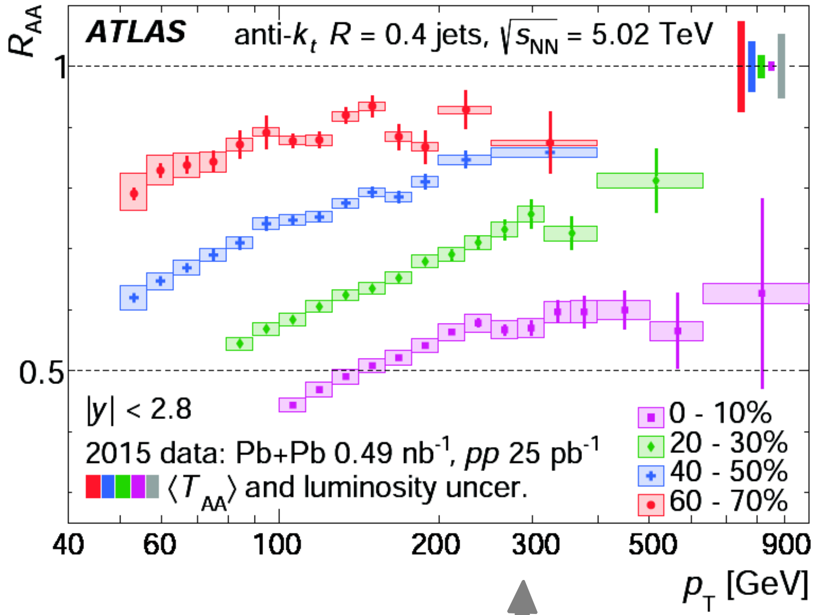
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

- Similar trends and magnitude of the R_{AA} for *R*=0.4 jets

Large-R jets

PLB 790 (2019) 108

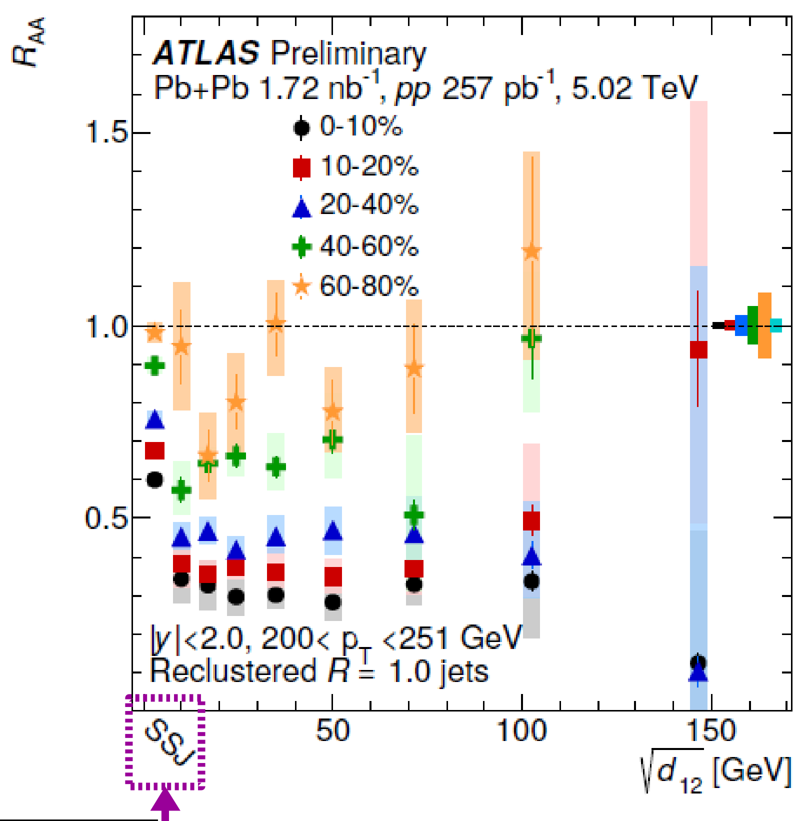




- Similar trends and magnitude of the R_{AA} for R=0.4 jets

Large-R jets

ATLAS-CONF-2019-056



- No measurement of large-R jets in heavy-ion collisions done before.
- R=0.2 jets with p_T>35 GeV reclustered using anti-k_T R=1.0
  - Soft contributions removed
  - Allows to study k_T splitting scale:

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

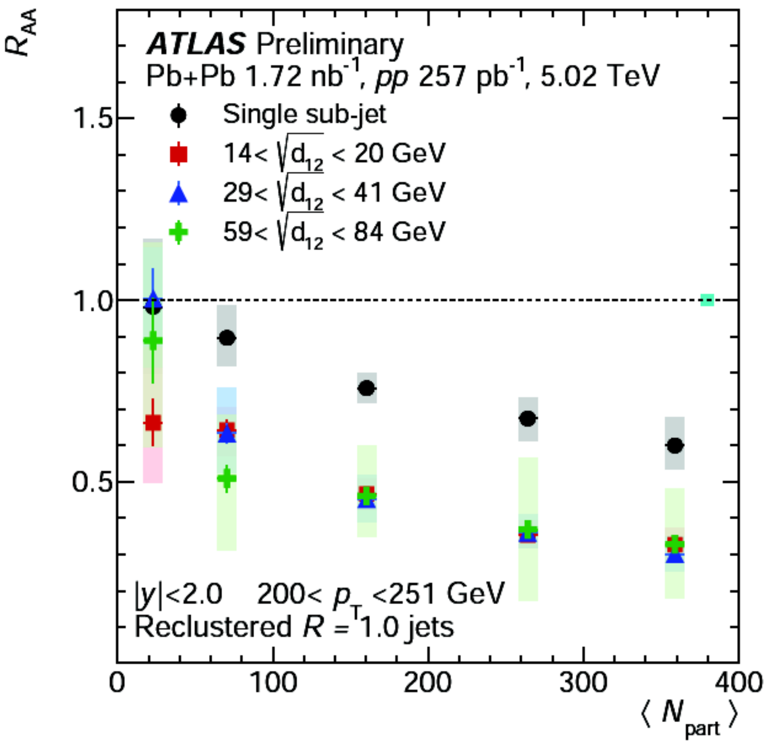
- Similar trends and magnitude of the R_{AA} for R=0.4 jets
- Larger suppression of jets with more "complex" structure compared to jets with "one-prong" structure.

Large-*R* jets

Martin Rybar
Wed 11:00
(Jets 3)

Wenkai Zou,
Poster
145

ATLAS-CONF-2019-056

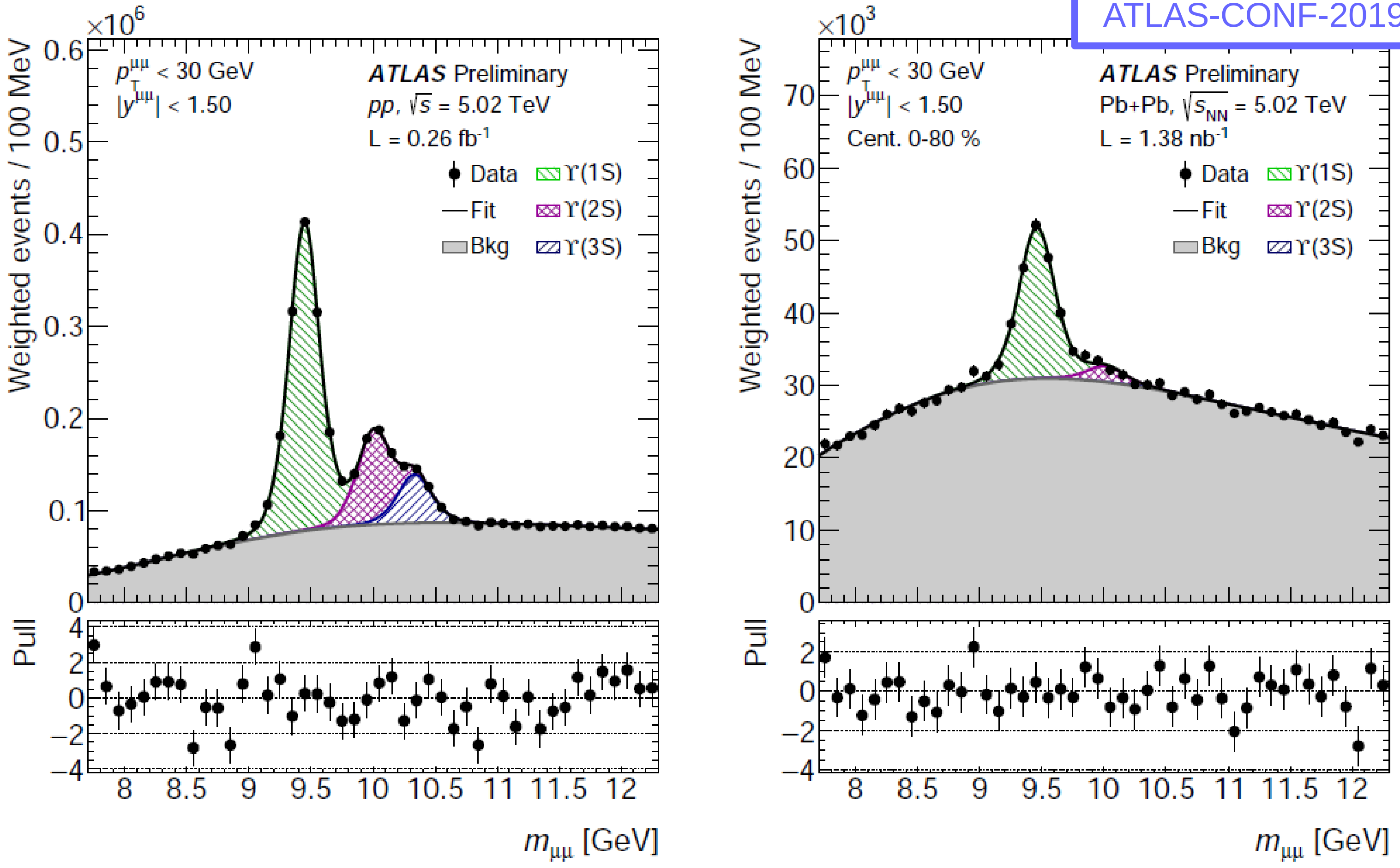


- … now as a function of N_{part}
- These meaurements:
  - Small *r* behavior of $D(p_T)$
  - Large *z* behavior of $D(z)$
  - $R_{AA}(\sqrt{d_{12}})$

… seem to support the presence of coherence effects in the jet quenching

Upsilon suppression

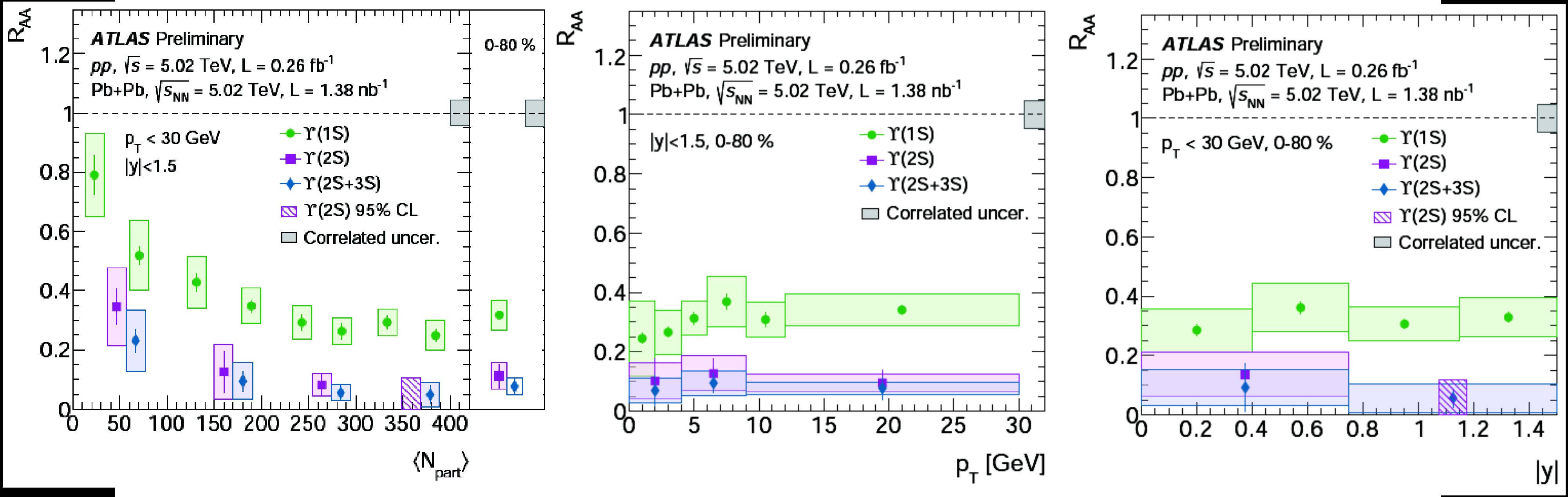
ATLAS-CONF-2019-054



Upsilon suppression

Songkyo Lee,
Tue 2:00
(HF 2)

ATLAS-CONF-2019-054



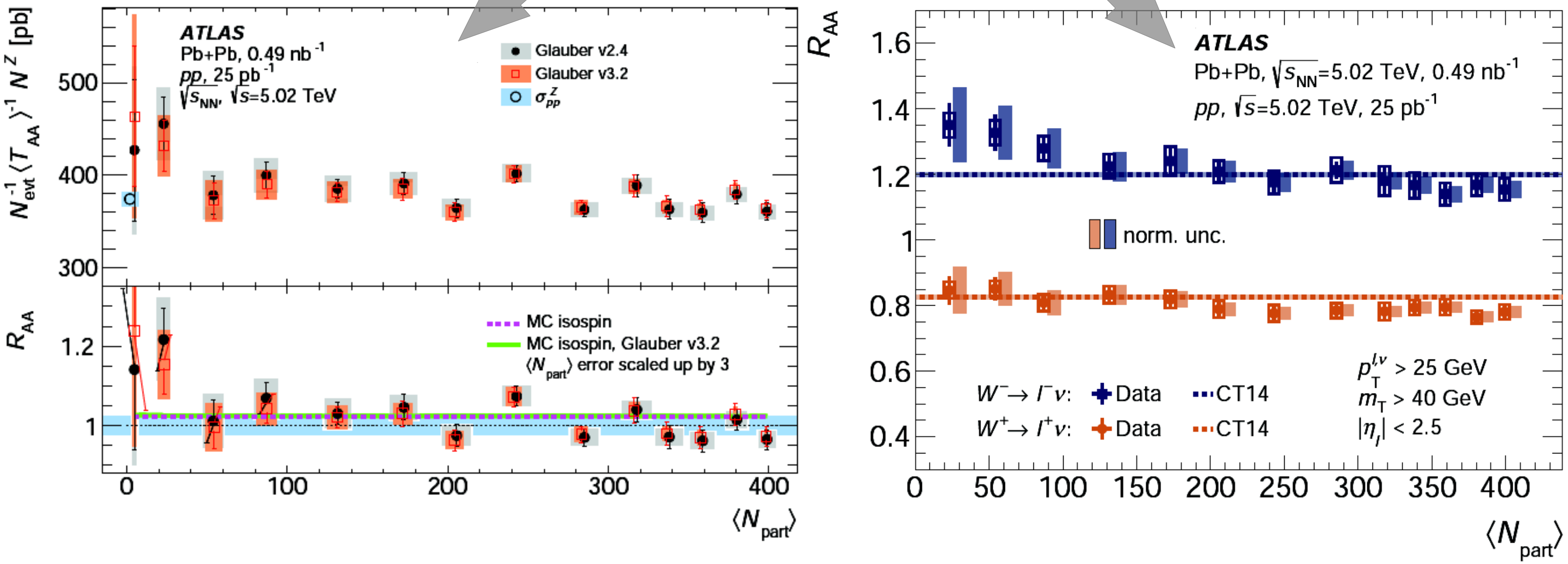
- Expected ordering observed: Y(1S) > Y(2S) > Y(2S+3S)
- Larger suppression in central collisions
- No significant p_T and rapidity dependence

Physics of initial state and nuclear geometry

Z & W in Pb+Pb

arXiv:1910.13396

arXiv:1907.10414

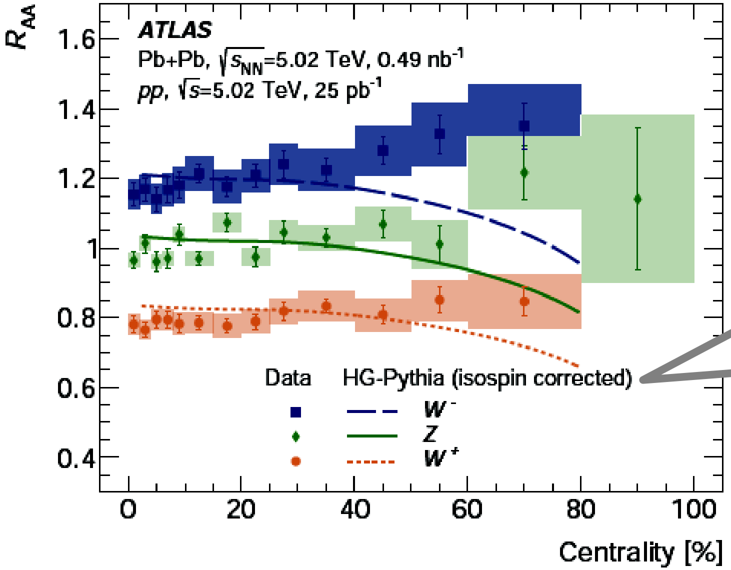


- Impact of **isospin effects** is clearly seen.
- **nPDF effects** small in this kinematic region, good constraints from data.
- No significant modifications seen in T_{AA}-scaled yields wrt MC prediction
  – good **understanding of geometry**

Z & W in Pb+Pb

arXiv:1910.13396

Anne Sickles, Poster 139



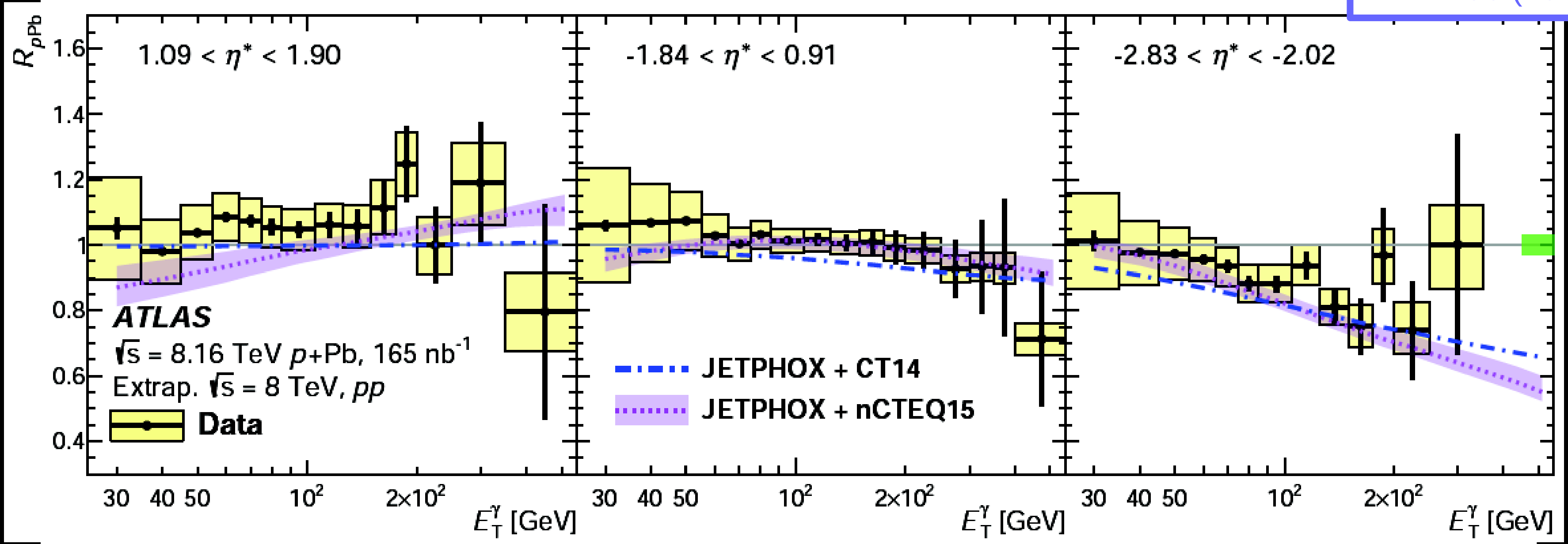
HG-PYTHIA model able to describe trends seen in peripheral events for inclusive hadrons measured by ALICE

- Impact of **isospin effects** is clearly seen.
- **nPDF effects** small in this kinematic region, good constraints from data.
- No significant modifications seen in T_{AA}-scaled yields wrt MC prediction
  – good **understanding of geometry** …but Z&W different than hadrons in peripheral?

Prompt photons in p+Pb

$$R_{p\mathrm{Pb}} = (d\sigma^{p+\mathrm{Pb}\rightarrow\gamma+X}/dE_{\mathrm{T}}^{\gamma})/(A \cdot d\sigma^{pp\rightarrow\gamma+X}/dE_{\mathrm{T}}^{\gamma})$$

PLB 796 (2019) 230

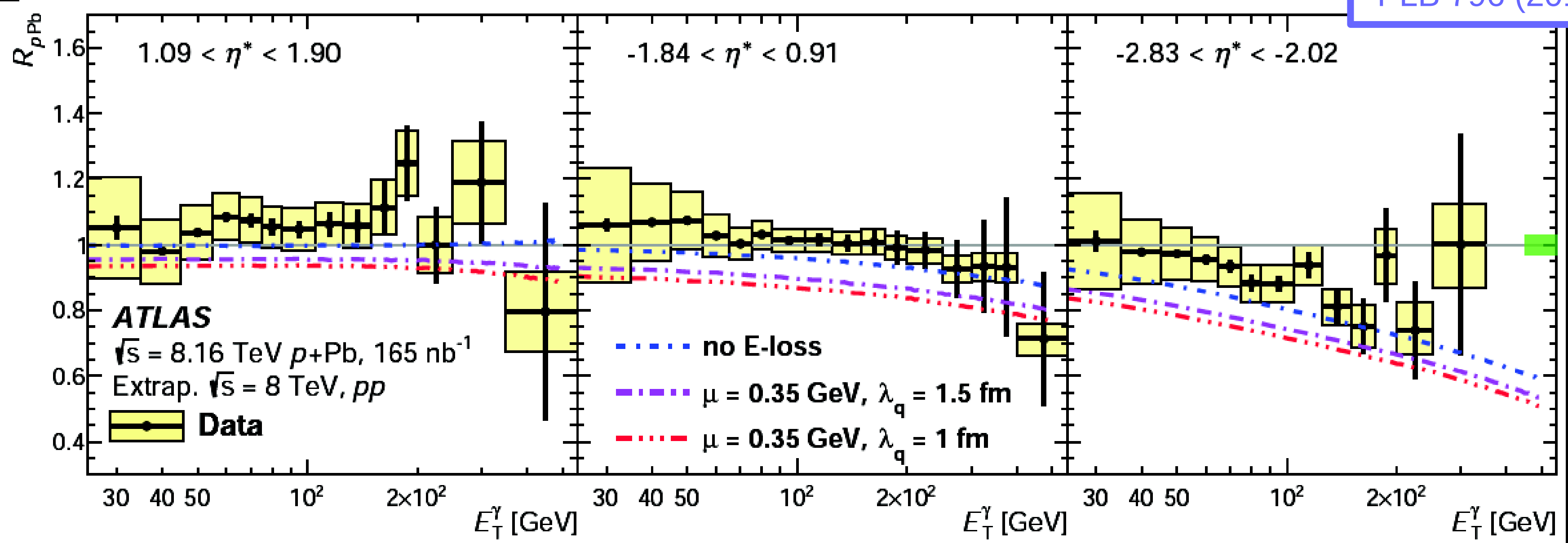


- Consistent with unity except for backward (Pb-going) direction: consistent with **expected isospin effects**.
- Data compared to **two nPDF sets**: CT14+EPPS16, nCTEQ15 – data confirm small effects from nPDFs.

Prompt photons in p+Pb

$$R_{p\mathrm{Pb}} = (d\sigma^{p+\mathrm{Pb}\to\gamma+X}/dE_T^\gamma)/(A\cdot d\sigma^{pp\to\gamma+X}/dE_T^\gamma)$$

PLB 796 (2019) 230



- Consistent with unity except for backward (Pb-going) direction: consistent with **expected isospin effects**.
- Data favor **no energy loss** in the initial state.

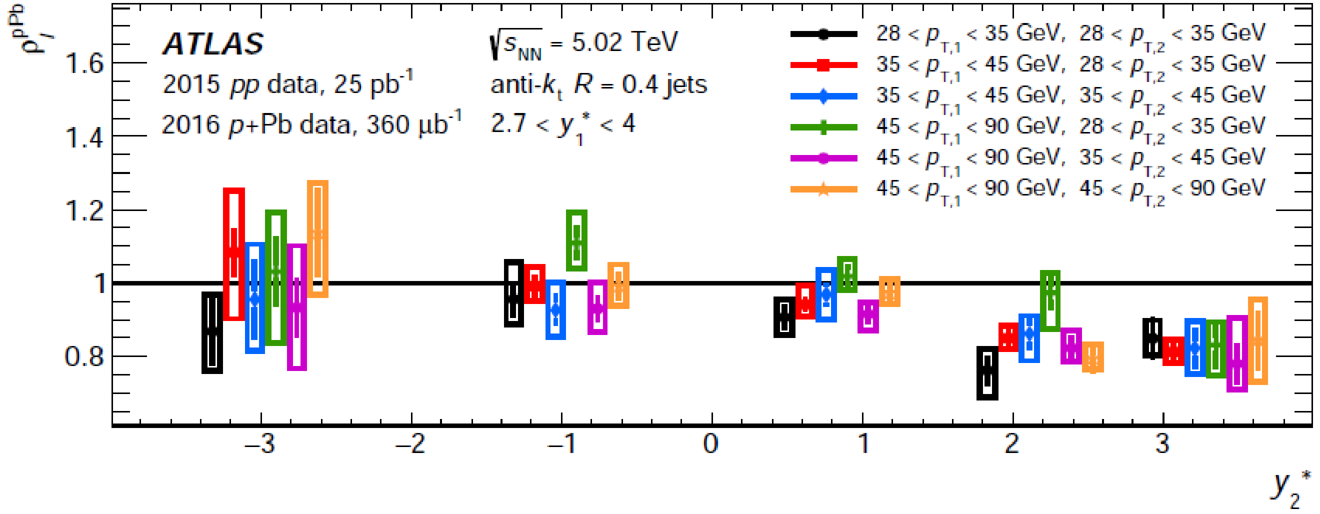
Dijet yields and Δϕ correlations in p+Pb

Anne Sickles, Poster 139

PRC 100 (2019) 034903

Dijet conditional yield

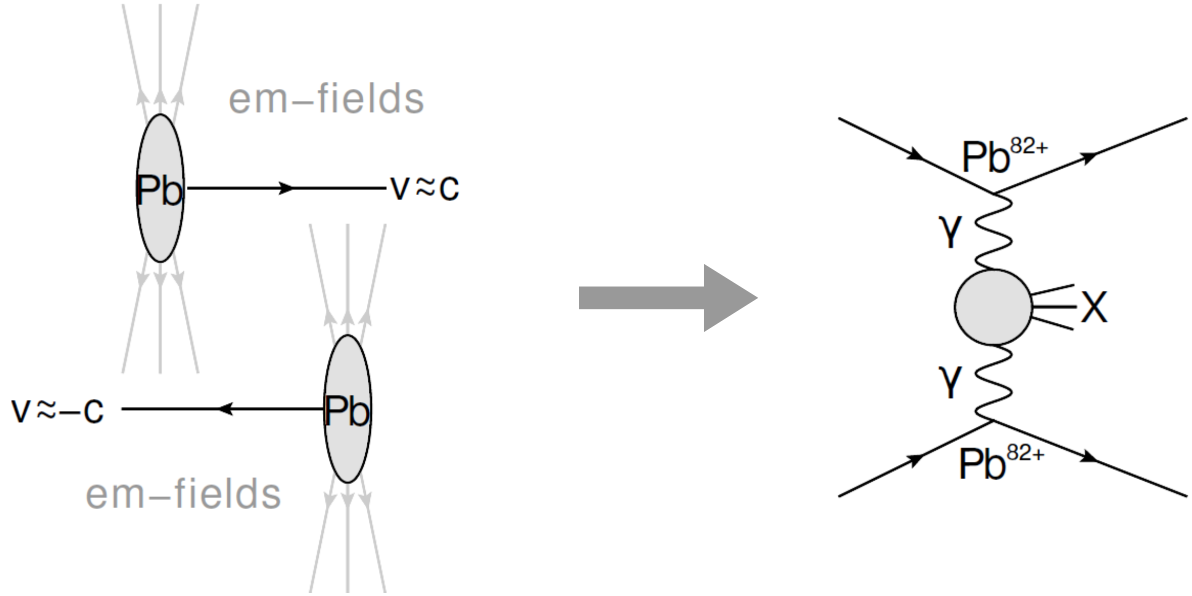
$$I_{12} = \frac{1}{N_1}\frac{dN_{1,2}}{dy_1^* dy_2^* dp_{T,1} dp_{T,2}} \quad \longrightarrow \quad \rho_I^{pPb} = \frac{I_{12}^{p+Pb}}{I_{12}^{pp}}$$



- 20% **suppression** in yield seen for **forward-forward** jets in p+Pb collisions in proton-going direction.
- No significant broadening of azimuthal correlations seen in p+Pb compared to *pp*.

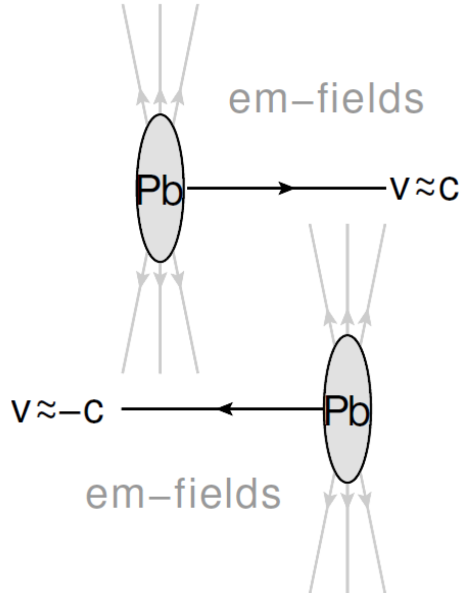
Ultra-peripheral collisions

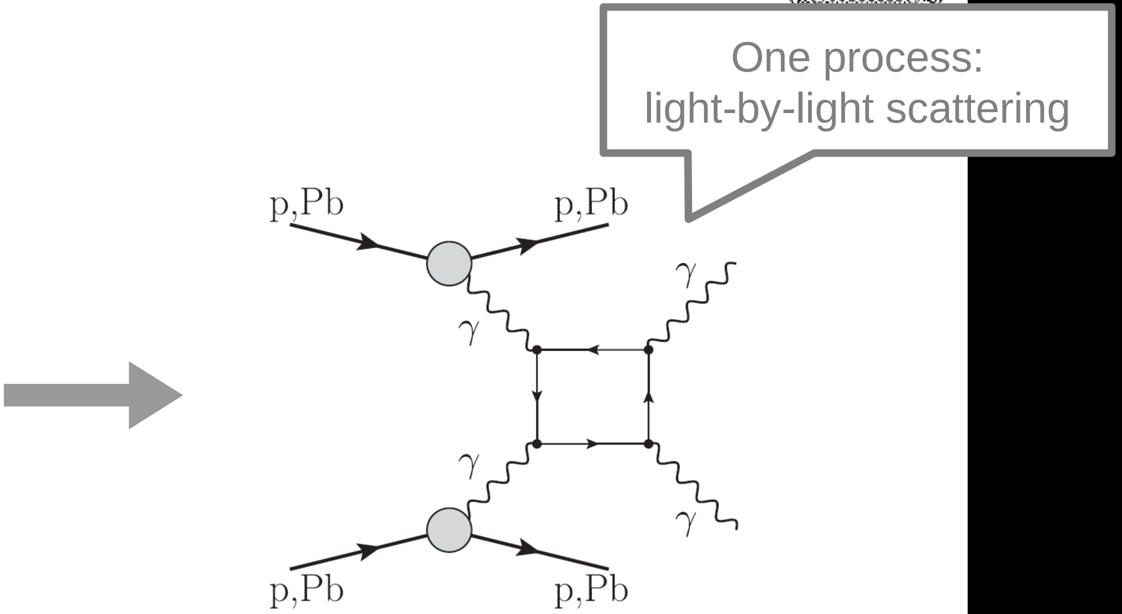
Ultraperipheral collisions



- Boosted protons / nuclei are source of photons of small virtuality ($Q^2<1/R^2=10^{-3}GeV^2$) described using equivalent photon approximation.
- Electromagnetic interactions dominate at large impact parameters.

Ultraperipheral collisions

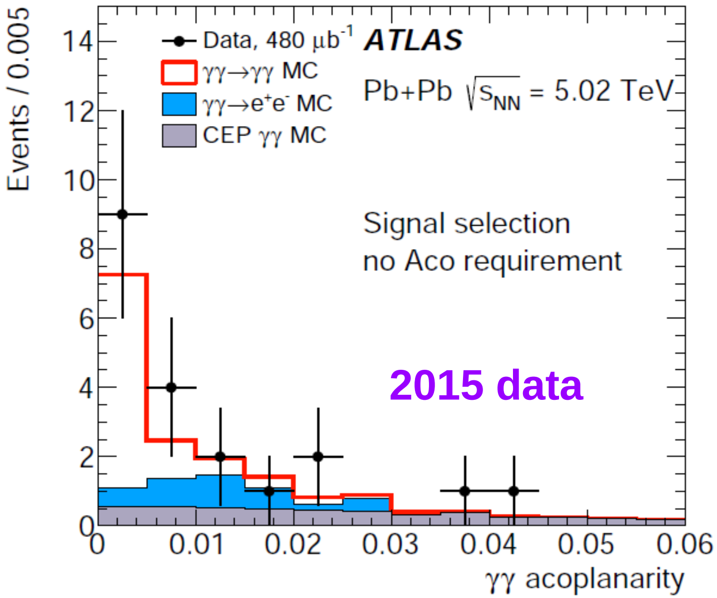




- Boosted protons / nuclei are source of photons of small virtuality ($Q^2<1/R^2=10^{-3}GeV^2$) described using equivalent photon approximation.
- Electromagnetic interactions dominate at large impact parameters.

Light-by-light scattering

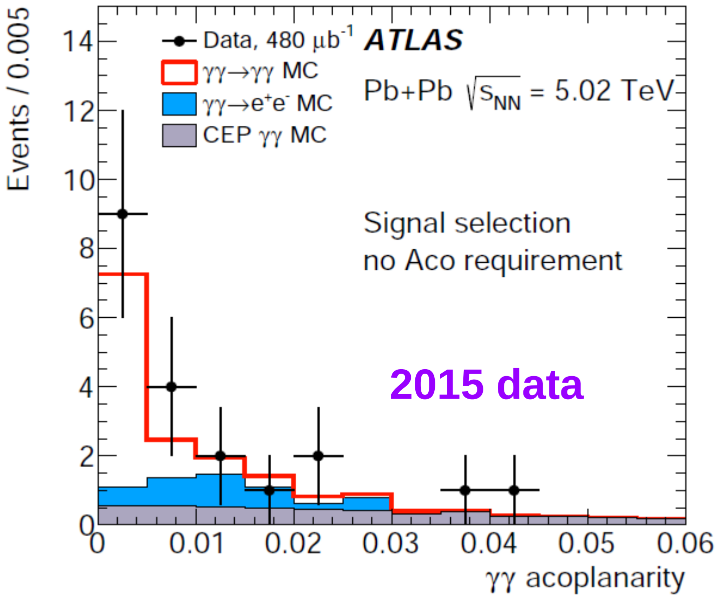
Nat. Phys. 13 (2017) 852



- Event selection: 2 photons: E_T>6 GeV, $|\eta|$<2.37, $m_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < (1)2 GeV, Aco = $(1-\Delta\phi/\pi)$<0.01; no tracks
- **2015:** 13 events (2.6 expected bkgr), **4.4 σ evidence**

Light-by-light scattering

Nat. Phys. 13 (2017) 852



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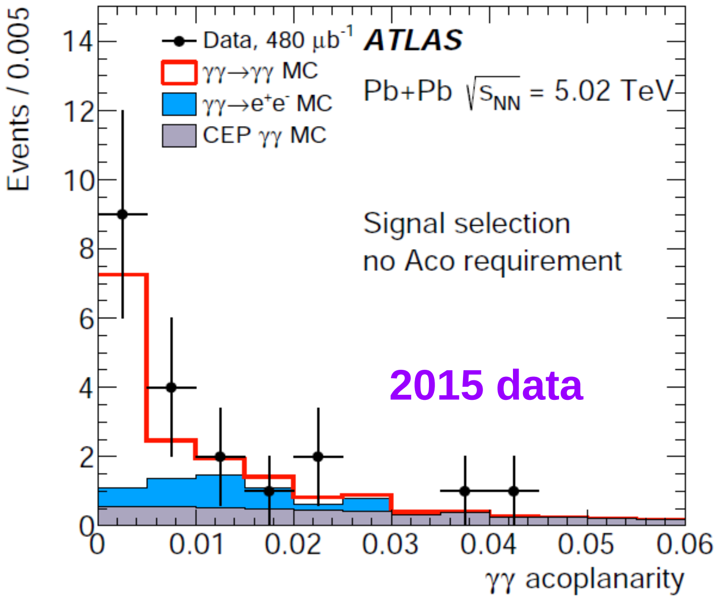
- **2015:** 13 events (2.6 expected bkgr), **4.4 σ evidence**
- **2018:** many technical improvements, lowering thresholds, 3.5 x more data

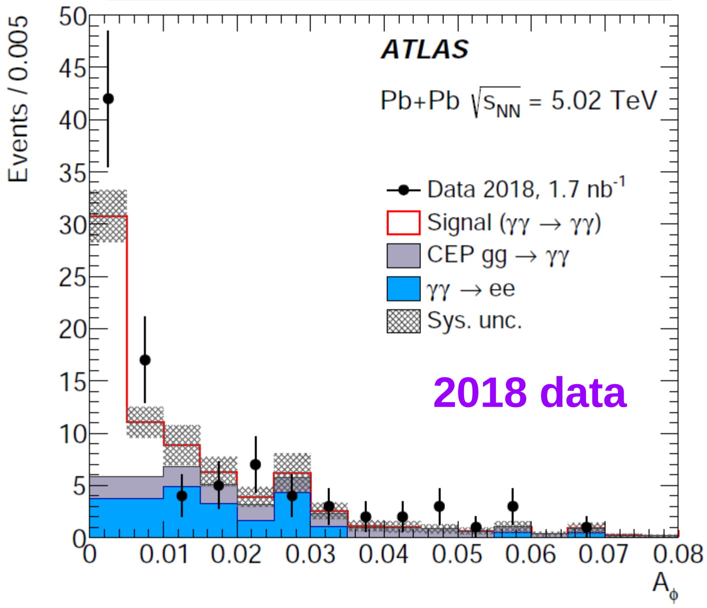
Light-by-light scattering

Prabi Palni
Tue 8:40
(EM Probes 1)

Nat. Phys. 13 (2017) 852

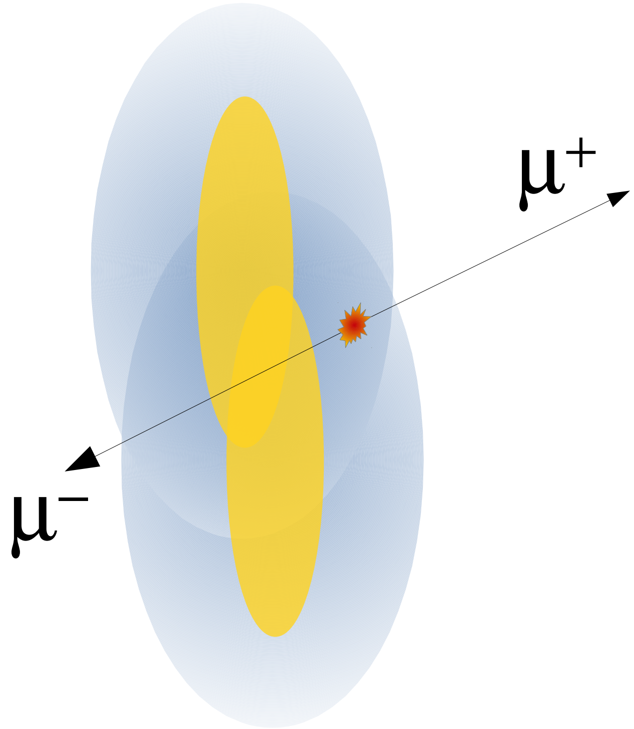
PRL 123 (2019) no.5, 052001





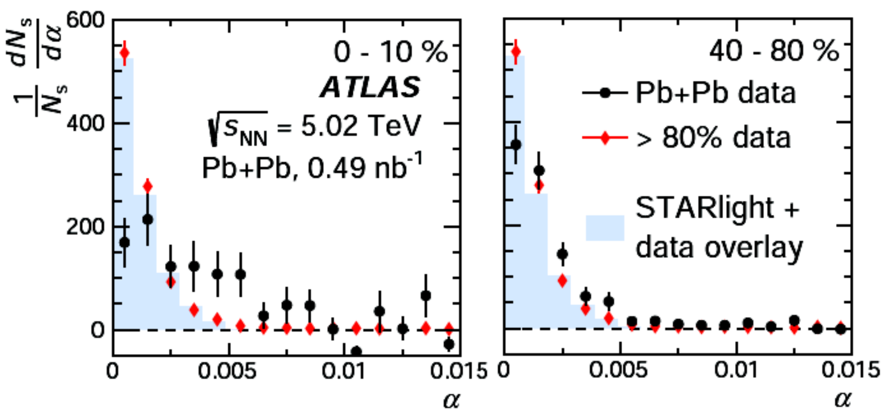
- Event selection: 2 photons: E_T>6 GeV, $|\eta|$<2.37, $m_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < (1)2 GeV, Aco = $(1-\Delta\phi/\pi)$<0.01; no tracks
- **2015:** 13 events (2.6 expected bkgr), **4.4 σ evidence**
- **2018:** 59 events (12 expected bkgr), **8.2 σ observation**

Non-UPC dimuons



- EM fields can give rise dimuons which may penetrate trough plasma
- Dimuons may probe EM degrees of freedom of QGP

Non-UPC dimuons



PRL 121 (2018) 212301

- EM fields can give rise dimuons which may penetrate trough plasma
- Dimuons may probe EM degrees of freedom of QGP
- Momentum transfer to muons via EM interaction with plasma quantified by acoplanarity:

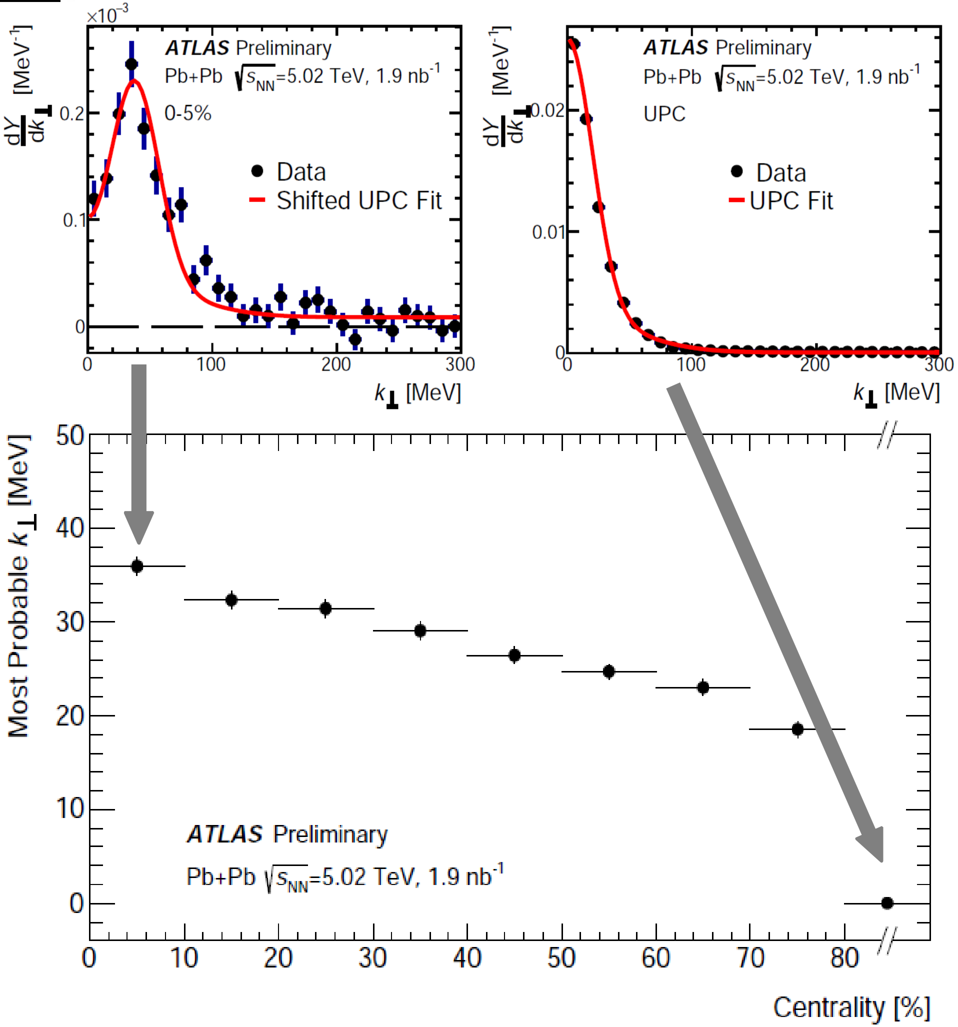
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

- Clear centrality dependence seen …

Non-UPC dimuons

Prabi Palni
Tue 8:40
(EM Probes 1)

ATLAS-CONF-2019-051



- EM fields can give rise dimuons which may penetrate trough plasma
- Dimuons may probe EM degrees of freedom of QGP
- Momentum transfer to muons via EM interaction with plasma quantified by acoplanarity:

$$k_\perp = \frac{p_T^+ + p_T^-}{2}(\pi - |\phi^+ - \phi^-|)$$

- Clear centrality dependence of <$k_\perp$>
- Most probable $k_\perp$ of ~36 MeV in 0-10%
- Similar features just from QED seen in arXiv:1812.02820 (Sep'19 revision)

Summary

- Please visit the parallel session talks and poster presentations to see details:

Jiangyong Jia, Tue 2:00 (Collective 2)	Songkyo Lee, Tue 2:00 (HF 2)	Tomasz Bold Wed 10:20 (Collective 4)	Kurt Hill Tue 11:20 (Small Sys 2)	Prabi Palni Tue 8:40 (EM Probes 1)
Soumya Moha-patra, Tue 8:40 (Collective 1)	Brian Cole Wed 2:40 (Small Sys 4)	Sanghoon Lim Tue 9:00 (Small Sys 1)	Martin Rybar Wed 11:00 (Jets 3)	Dennis Pere-pelitsa, Wed 2:40 (Jets 4)
Pengqi Yin, Poster 151	Wenkai Zou, Poster 145	Songkyo Lee, Poster HF 9	Anne Sickles, Poster 139	Arabinda Behera CD 4

- All results available from here:

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

Backup slides