UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

FSP ALICE
Erforschung von Universum und Materie

ALICE

# New measurements of inclusive jet suppression and jet $v_2$ in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE


**Nadine Alice Grünwald**

(Physikalisches Institut Universität Heidelberg)

on behalf of the ALICE Collaboration


QM 2023

Quark Matter 2023, Houston Texas - 2023-09-05

# Jets as probe of the QGP

- Jet quenching effects from the interaction of high energetic partons with the medium:

**Jet energy loss**
This talk

**Jet substructure modifications**
Talk by Hannah Bossi
Tues. 05.09, 11:20-11:40

**Jet deflection**
Talk by Jaime Norman
Wed. 06.09, 9:50-10:10

➜ **Used to constrain properties of the structure and the dynamics of the QGP**

**This talk covers jet energy loss:**

- Measurement of inclusive jet suppression with a novel mixed-event approach **New preliminary**
- Charged-particle jet spectra in event-shape engineered Pb–Pb collisions **Submitted for publication arXiv:2307.14097**
- Measurement of inclusive charged-particle jet $v_2$ **New preliminary**

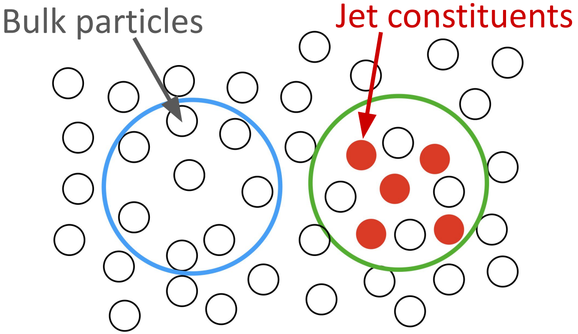
# Inclusive jet measurement

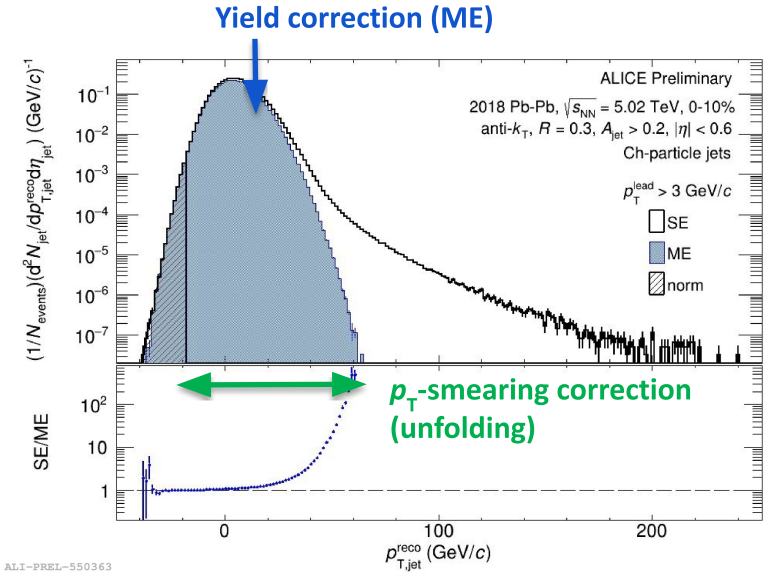
- Current ALICE jet $R_{AA}$ measurement: low $p_T$ reach achieved using Machine Learning (arXiv:2303.00592)
- **Goal: extend to much lower $p_T$**

- Measurement of reconstructed jets in heavy-ion collisions is challenging, due to huge non-uniform uncorrelated background
- **Combinatorial ("fake") jet yield** arising from random combination of products from soft (low $Q^2$) interactions
- **Smearing of $p_T$** of true jets arising from hard processes

Background correction methods:

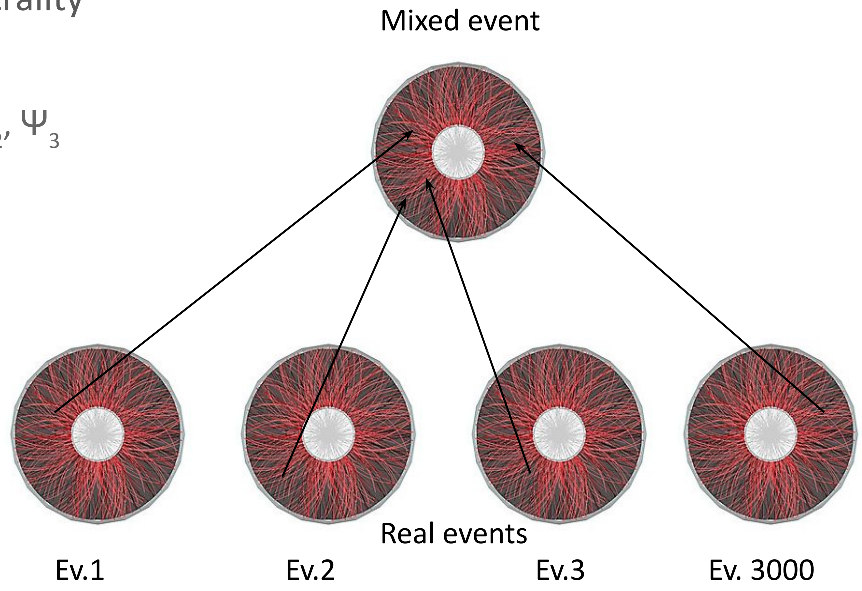
- **Use Mixed Events (ME) to determine the distribution of combinatorial jets**
  - Purely statistical approach
  - ME successfully used at STAR (*Phys.Rev.C* 96 (2017) 2, 024905)
- **Unfolding**



# Jet analysis with mixed event technique

- ALICE 2018 Pb–Pb data, $\sqrt{s_{NN}}$ = 5.02 TeV, 0–10% centrality
- How to create the ME:
  - Categorization of events into multiplicity, z-vertex, $\Psi_2$, $\Psi_3$ & $p_T^{sum}$ (9600 categories)
  - Assembling of full events
  - Only one random track from each real event:
    ➜ by construction **no multi-hadron correlations**
- Same jet analysis for real events (same events = SE) and ME
  - Jet finder: **anti-$k_T$ , $R$ = 0.3**
  - Charged-particle jet reconstruction
  - "Jet wise" background subtraction: $p^{reco}_{T,jet} = p^{raw}_{T,jet} - \rho A_{jet}$



# Raw quasi-incl. jet distribution, $R = 0.3$

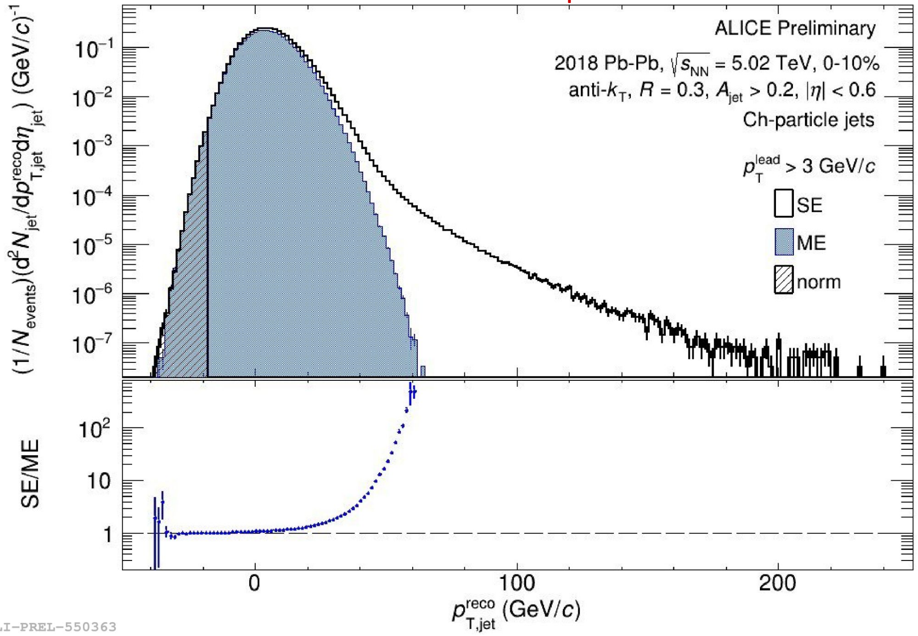
New

- Leading track cut of 3 GeV/$c$ and 4 GeV/$c$
- Inclusive distribution of partons at low $p_T$: many overlapping objects, cannot reconstruct as distinct jets

  ➜ **Introduce a small bias to define jet object that can be interpreted in theory**

  ➜ **Vary the bias to measure its effect & determine the $p_T$ region where the bias is negligible**

**Raw biased distribution, $p_T^{lead}$ > 3 GeV/$c$**



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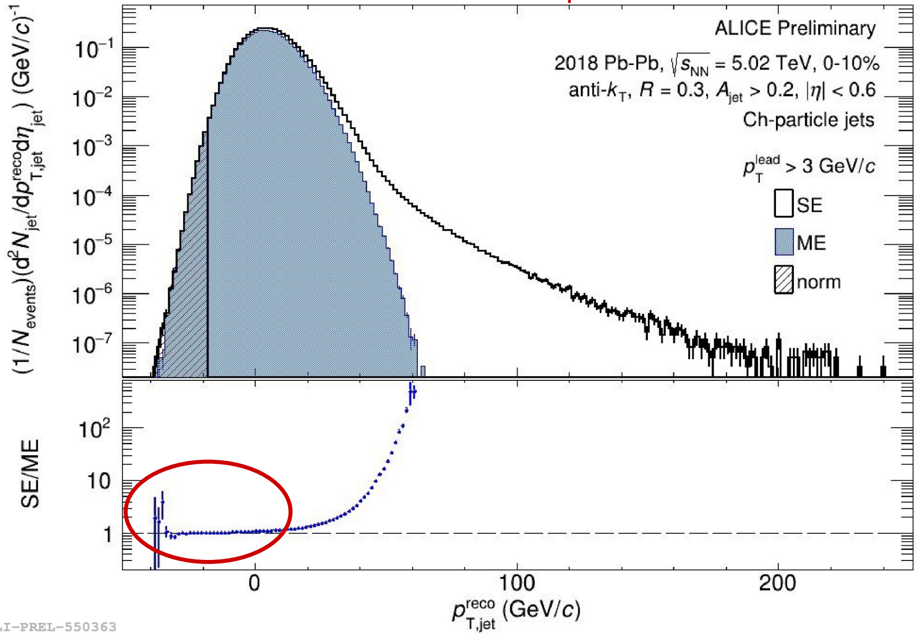
- Essential criterion for ME: Identical shape at the left-hand side

**Raw biased distribution, $p_T^{lead}$ > 3 GeV/*c***



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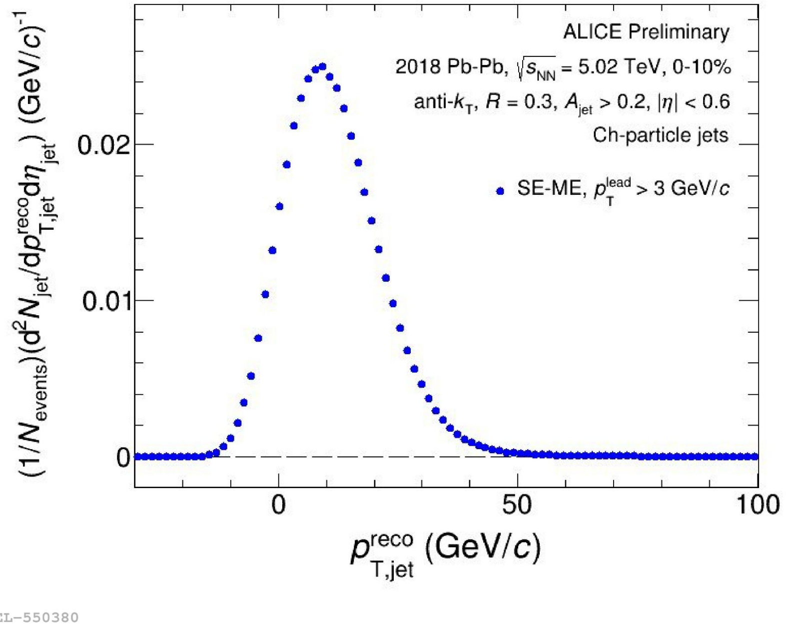
- Essential criterion for ME: Identical shape at the left-hand side
- Subtraction of combinatorial background yield using ME

**Raw correlated biased jet distribution , $p_T^{lead}$ > 3 GeV/$c$: SE-ME**



# Raw quasi-incl. jet distribution, $R = 0.3$

New

- Leading track cut of 3 GeV/*c* and 4 GeV/*c*
- Inclusive distribution of partons at low $p_T$: many overlapping objects, cannot reconstruct as distinct jets

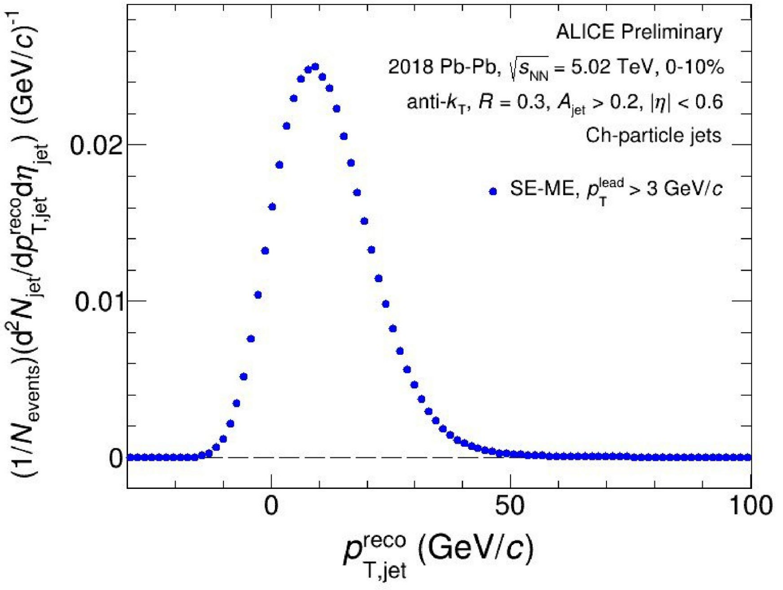
➜ **Introduce a small bias to define jet object that can be interpreted in theory**

➜ **Vary the bias to measure its effect & determine the $p_T$ region where the bias is negligible**

- Essential criterion for ME: Identical shape at the left-hand side
- Subtraction of combinatorial background yield using ME

1. **ME procedure removes uncorrelated background yield**
2. **Leading track $p_T$ cut generates countable objects**
3. **Leading track $p_T$ cut is decoupled from background suppression**

**Raw correlated biased jet distribution , $p_T^{lead}$ > 3 GeV/*c*: SE-ME**

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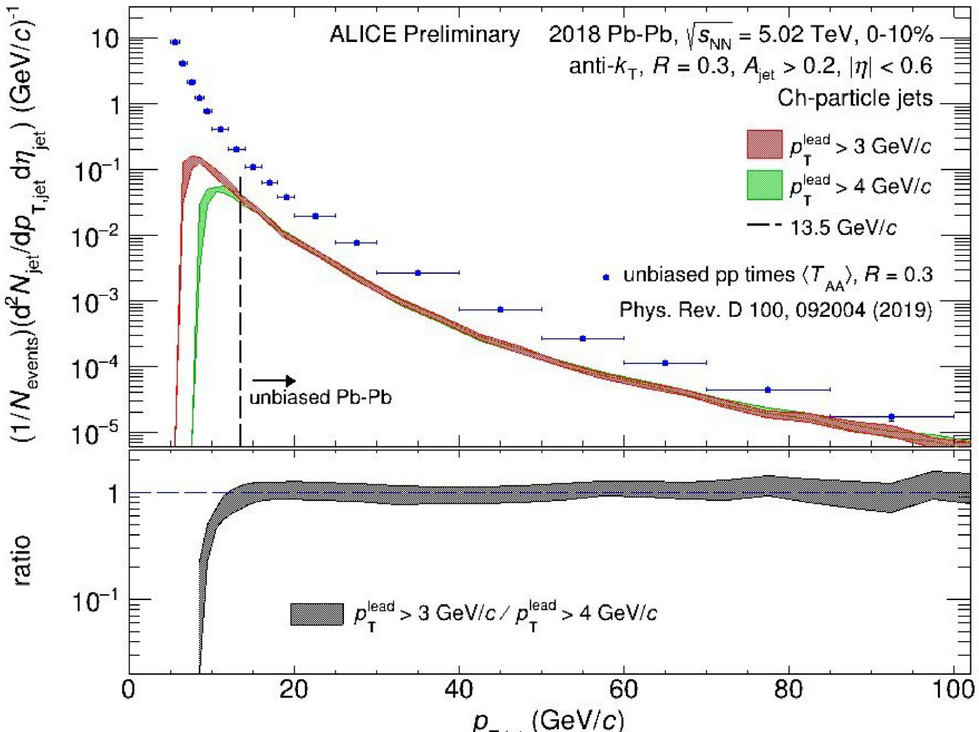
# Corrected charged-particle jet distributions, $R = 0.3$

New

- In addition to yield correction: Correction of $p_T$-smearing due to background and instrumental effects ➜ **Unfolding**
- Fully corrected quasi-incl. charged-particle jet distributions with $p_T^{lead} > 3$ GeV/$c$ and $p_T^{lead} > 4$ GeV/$c$
- Systematic uncertainties from ME, DCA, tracking efficiency & unfolding
- Measuring where the bias is small
- Effect of the leading track bias: **less than 10% difference for $p_{T,jet} > 13.5$ GeV/$c$**

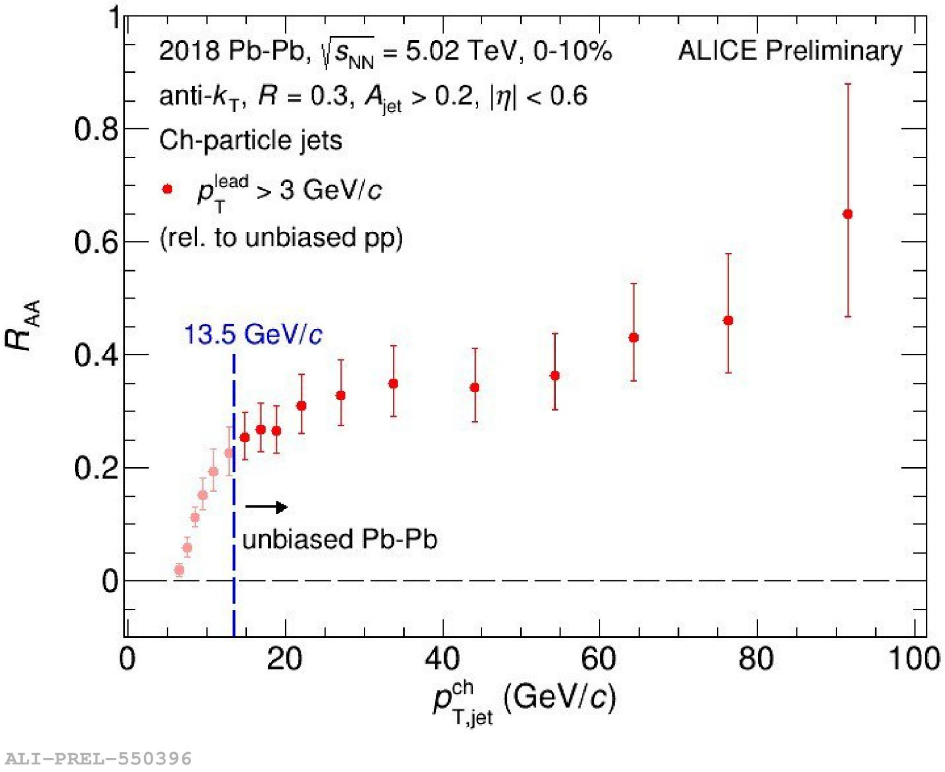
**➜ unbiased Pb–Pb at $p_{T,jet} > 13.5$ GeV/$c$**




**Unbiased pp:** ALICE collaboration, Phys. Rev. D 100, 092004, 2019. arXiv: 1905.02536 [nucl-ex].

# Charged-particle jet $R_{AA}$ with $R$ = 0.3

New




$$R_{AA} = \frac{dN_{jets}^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \, d\sigma_{jets}^{pp}/dp_T d\eta}$$

- $R_{AA}$ is calculated relative to unbiased pp charged-particle jets [1], $R$ = 0.3
- Combined pp and Pb–Pb uncertainties
- Syst. + stat. uncertainties added in quadrature

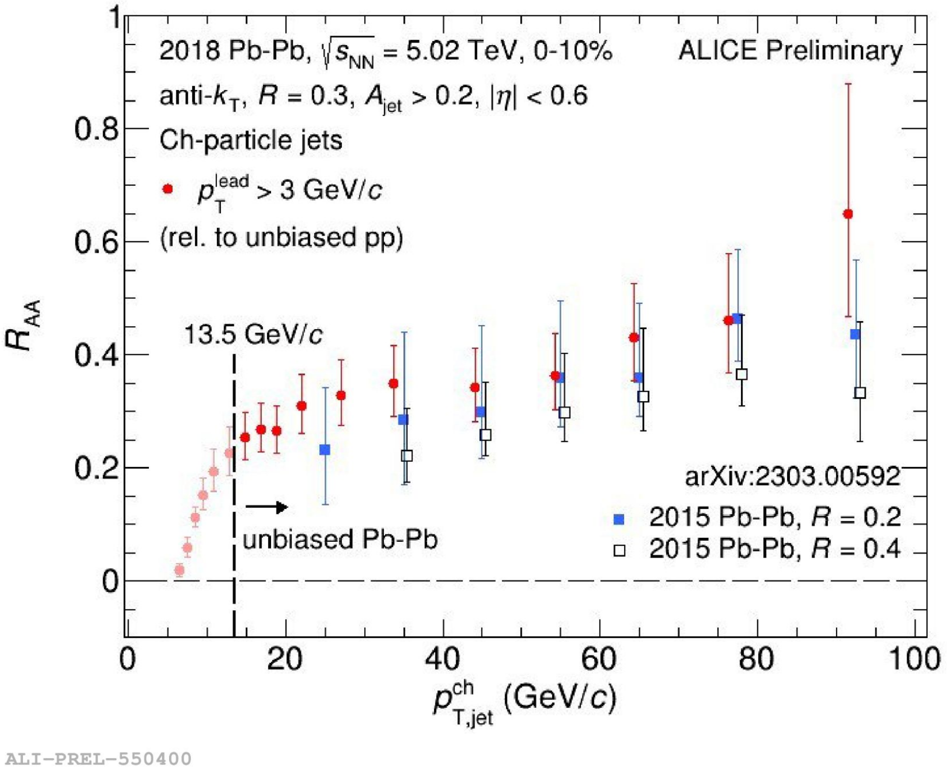
➜ **unbiased Pb–Pb $R_{AA}$ down to 13.5 GeV/$c$**

(conservative estimate)

**Unbiased pp:** ALICE collaboration, Phys. Rev. D, 100, 092004, 2019. arXiv: 1905.02536 [nucl-ex].

# Comparison to previous ALICE $R_{AA}$

New

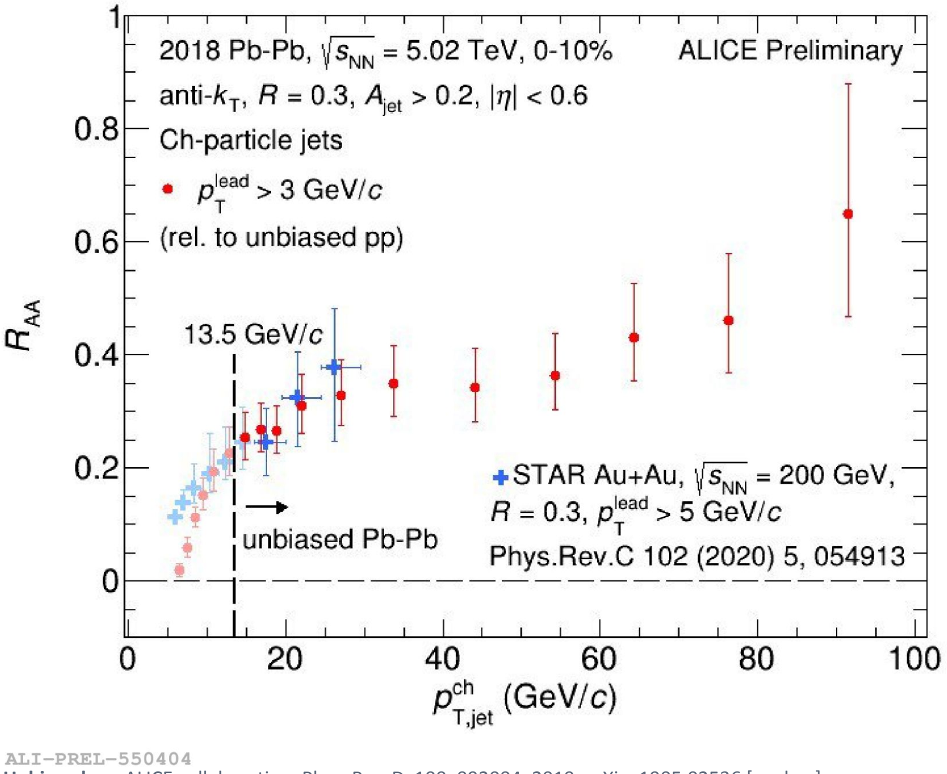



- Consistency with ALICE $R_{AA}$ results with 2015 Pb–Pb data
- **Lower in $p_T$ & smaller uncertainties**

**Unbiased pp:** ALICE collaboration, Phys. Rev. D, 100, 092004, 2019. arXiv: 1905.02536 [nucl-ex].

# Comparison to RHIC $R_{AA}$

New




**Unbiased pp:** ALICE collaboration, Phys. Rev. D, 100, 092004, 2019. arXiv: 1905.02536 [nucl-ex].

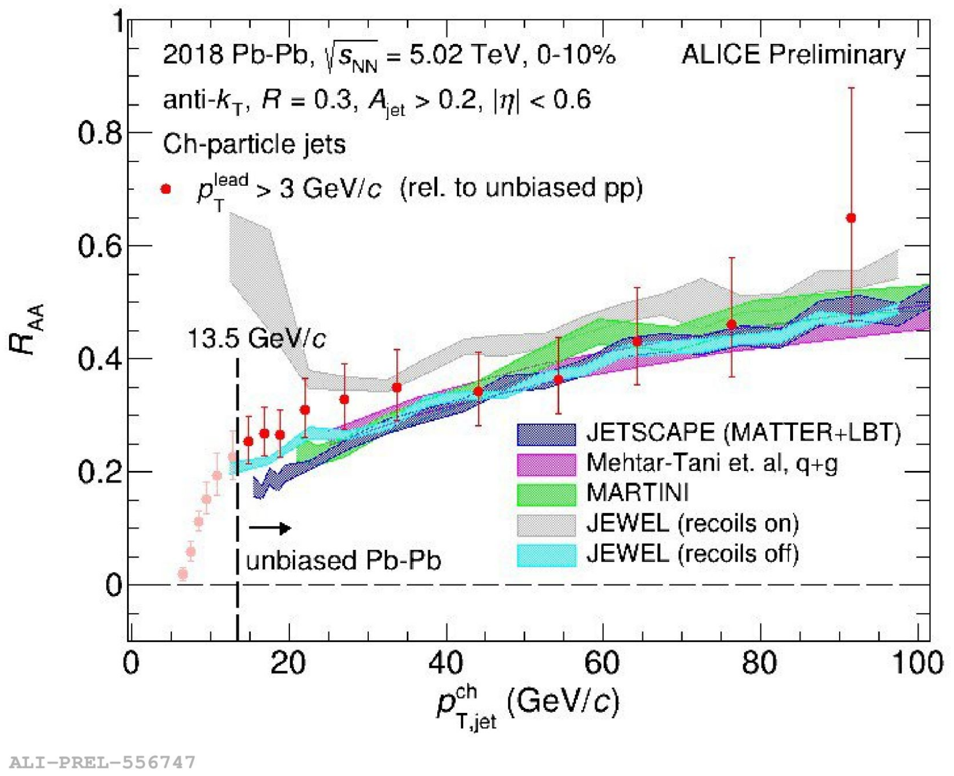
**STAR:** *Phys.Rev.C* 102 (2020) 5, 054913

- First direct comparison of reconstructed jet suppression at LHC & RHIC in same kinematic range
- Unbiased Au+Au at $p_{T,jet}$ > 16 GeV/$c$
- Comparable $R_{AA}$ between $\sqrt{s_{NN}}$= 200 GeV and $\sqrt{s_{NN}}$= 5.02 TeV
  - Yield suppression is combined effect of spectrum shape and energy loss
  - Inclusive jet spectrum much harder at LHC than RHIC
  - q/g composition is different at LHC (gluon-dominated) & RHIC (larger quark fraction)

➜ **Same $R_{AA}$ does not mean same energy loss**

# Model comparisons

New



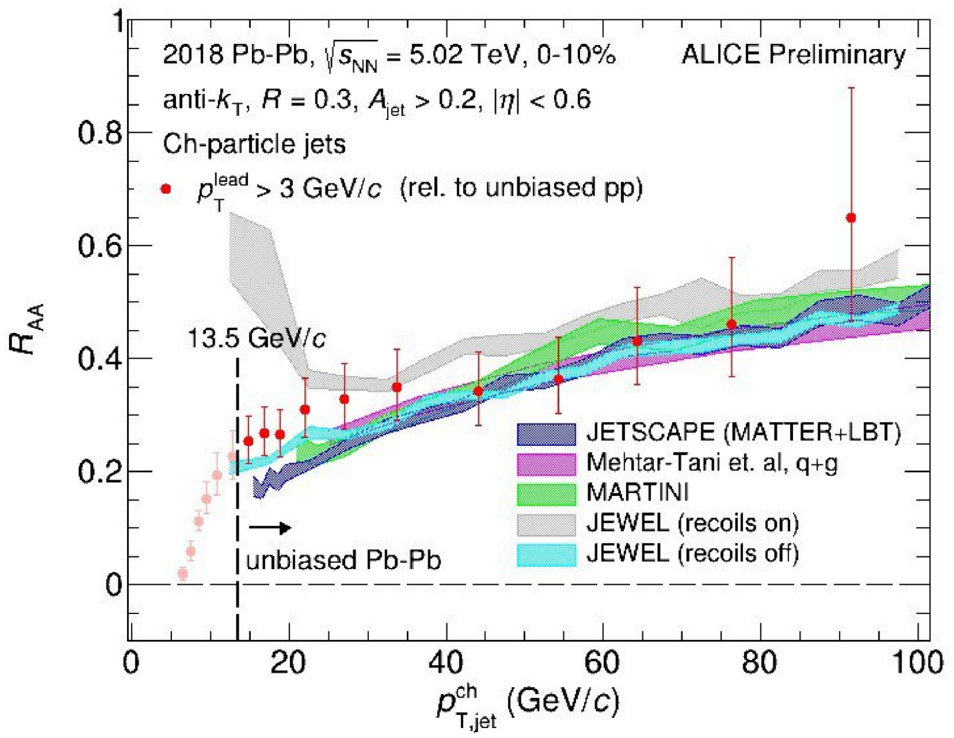

**Unbiased pp:** ALICE collaboration, Phys. Rev. D, 100, 092004, 2019. arXiv: 1905.02536 [nucl-ex].

- Models describe $R_{AA}$ at high $p_T$ but disagree at low $p_T$

**JETSCAPE:** JETSCAPE Collaboration, Phys. Rev. C 107, 034911, 16 March 2023, arXiv:1903.07706
**Mehtar-Tani et. al:** *Phys.Rev.Lett.* 127 (2021) 25, 252301, arXiv:2101.01742
**JEWEL:** JHEP 1707 (2017) 141
**MARTINI:** *Phys.Rev.C* 107 (2023) 3, 034908, arXiv:2212.05944

# Model comparisons

New

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**Unbiased pp:** ALICE collaboration, Phys. Rev. D, 100, 092004, 2019. arXiv: 1905.02536 [nucl-ex].

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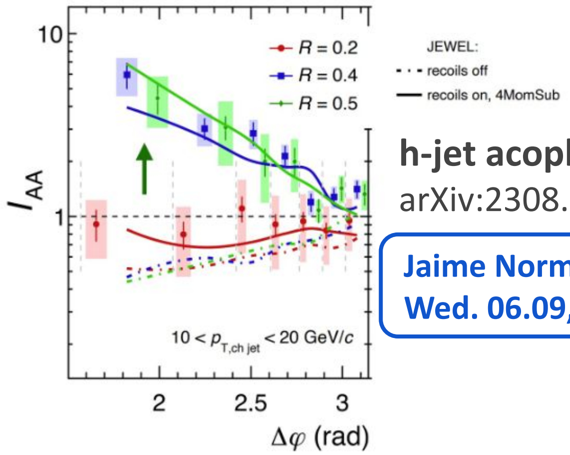


**h-jet acoplanarity**
arXiv:2308.16131

**Jaime Norman**
**Wed. 06.09, 9:50**

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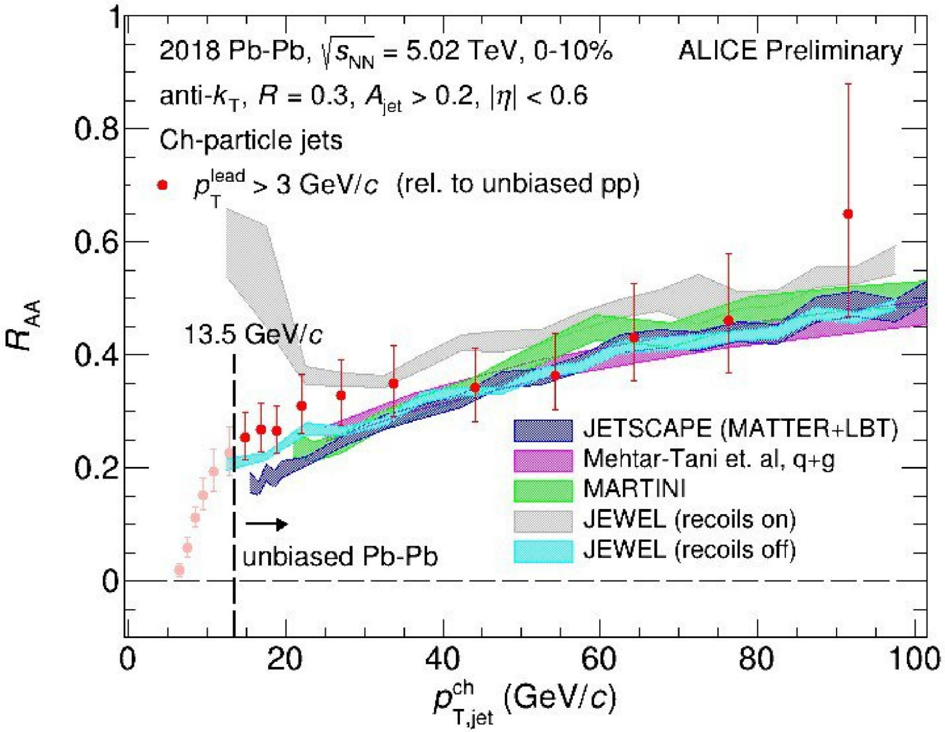


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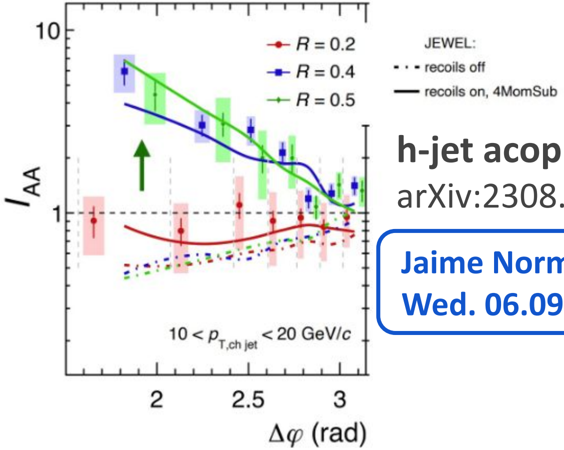


**h-jet acoplanarity**
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**Jaime Norman**
**Wed. 06.09, 9:50**

- JEWEL recoils on/off: inclusive and coincidence give opposite pictures

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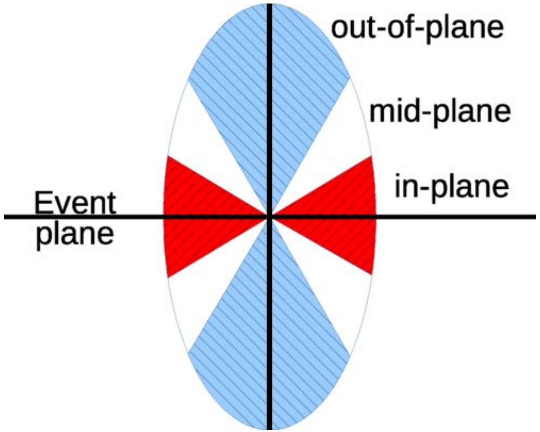
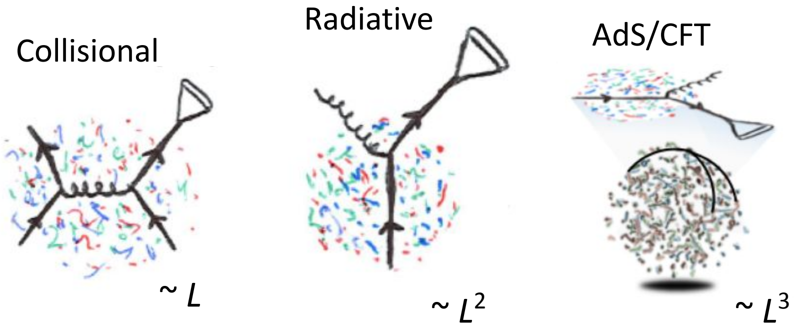
# Pathlength dependent energy loss

- Energy loss mechanism: Radiative and collisional
  ➜ Mechanisms show different pathlength dependence

- Shorter in-plane axis compared to out-of-plane axis is expected




- Event-plane dependence of suppression can provide new insight into mechanisms underlying jet energy loss

- Limited by medium fluctuations

# Event-shape engineering

New arXiv: 2307.14097

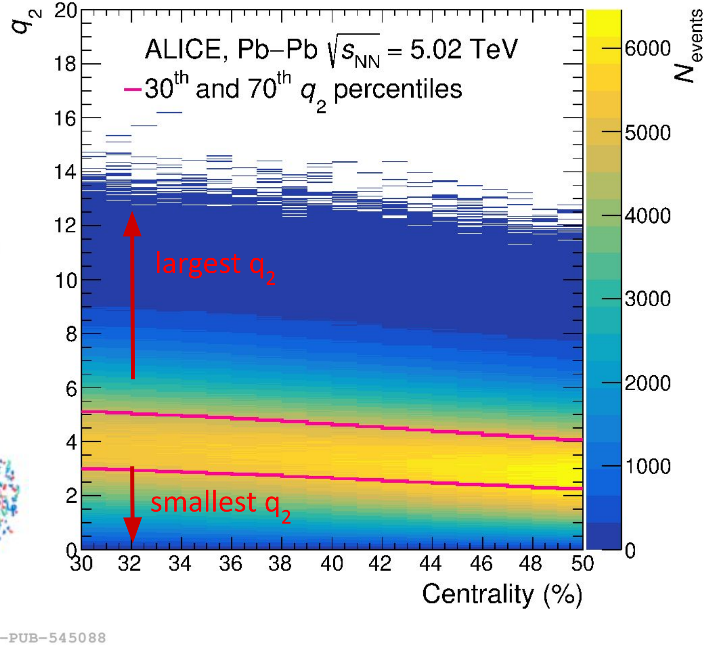
- **Event-shape engineering (ESE)**: Classification of events according to their anisotropy in a centrality class

$$Q_2 = \left(\sum_i w_i \cos(2\varphi_i), \sum_i w_i \cos(2\varphi_i)\right) \qquad q_2 = \frac{|Q_2|}{\sqrt{M}}$$

azimuthal angle

Multiplicity

- ALICE 2018 Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, 30–50 % semi-central

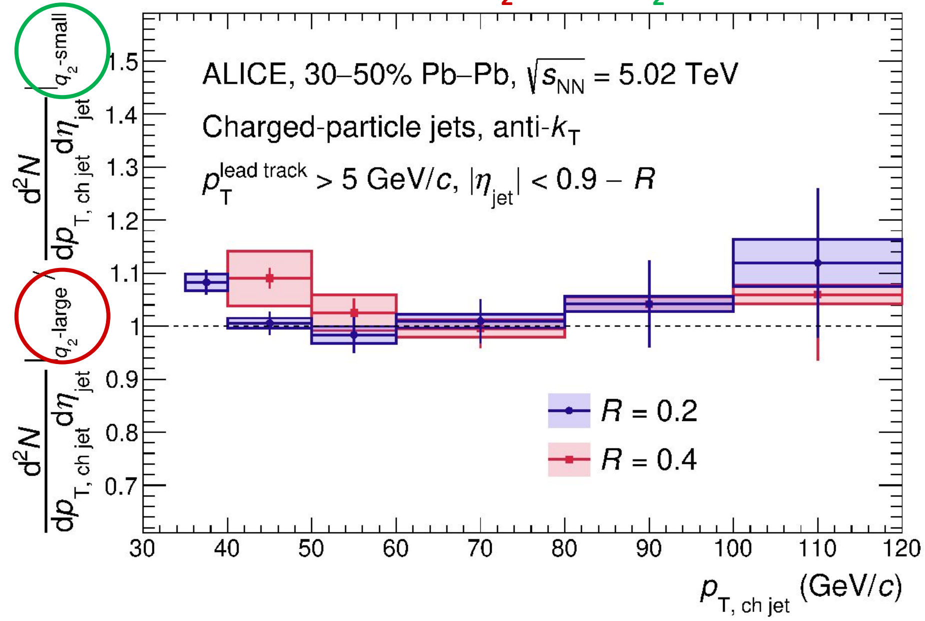



# ESE and jets in Pb-Pb

**New arXiv: 2307.14097**

**Azimuthally averaged**

Ratio of jet spectra in $q_2$**-large** / $q_2$**-small** events

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- Combine jet measurement with information from underlying event
- Jet reconstruction with **anti-$k_T$** and ***R* = 0.2** & ***R* = 0.4**
- Unfolding & efficiency corrections
- Only small difference between $q_2$-large & $q_2$-small in the azimuthally averaged measurement

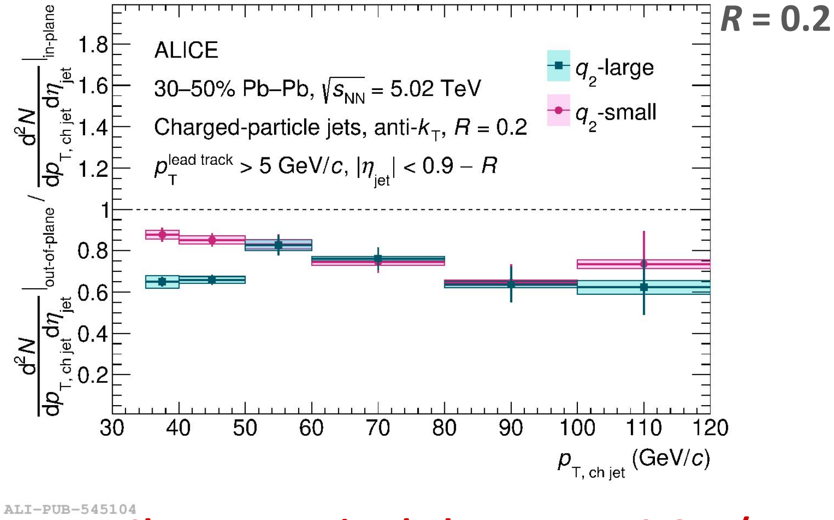
# Event-plane angles and ESE

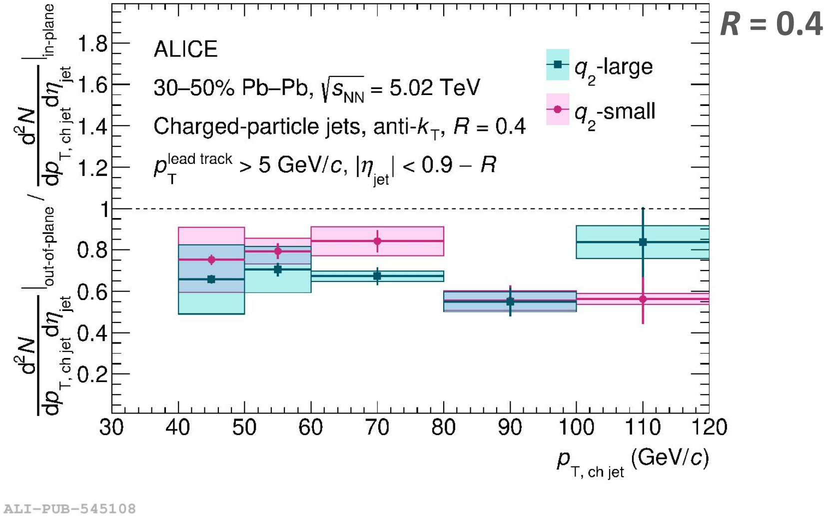
New arXiv: 2307.14097

## Azimuthally differential

- Ratios of **out-of-plane/in-plane** jet spectra for $q_2$ large & small events
  ➜ Suppression of out-of-plane jets
  ➜ Consistency with expectation from Trajectum calculations: ESE maximizes the pathlength differences

(Beattie, Nijs, Sas, van der Schee, Phys. Lett. B 836 (2023) 137596)

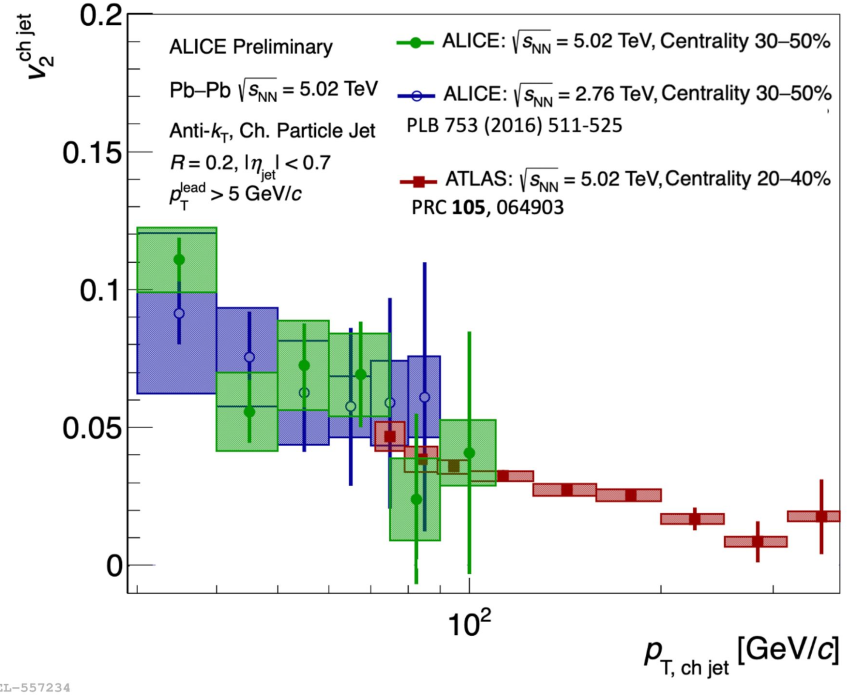


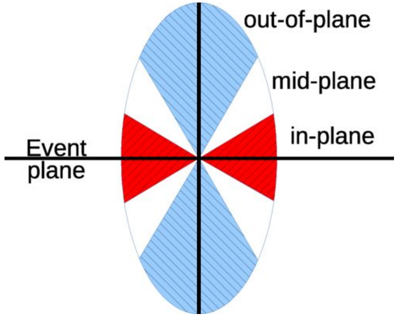

- **Clear separation below $p_{T,jet}$ < 50 GeV/c**
- Dominated by systematics at low $p_{T,jet}$

New

# Charged-particle jet $v_2$




$$v_2 = \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$




- Suppression of out-of-plane jets
- Larger **positive charged-particle jet $v_2$** at low $p_{T,jet}$
- Consistency of this measurement with ATLAS results within the uncertainties between 70 and 110 GeV/$c$

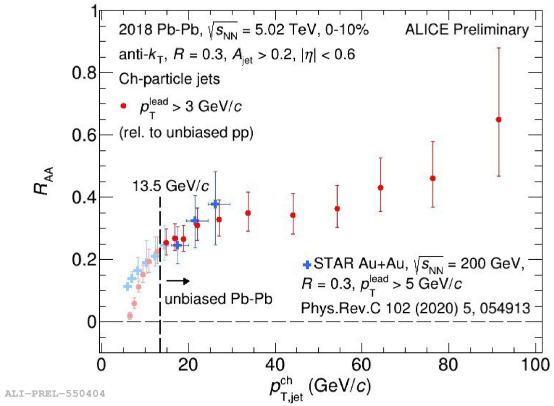
**Poster by Takuya Kumaoka**

# Summary

**Measurements to address the jet energy loss**

- **ME technique** can address **background yield** problem in heavy-ion jet measurements

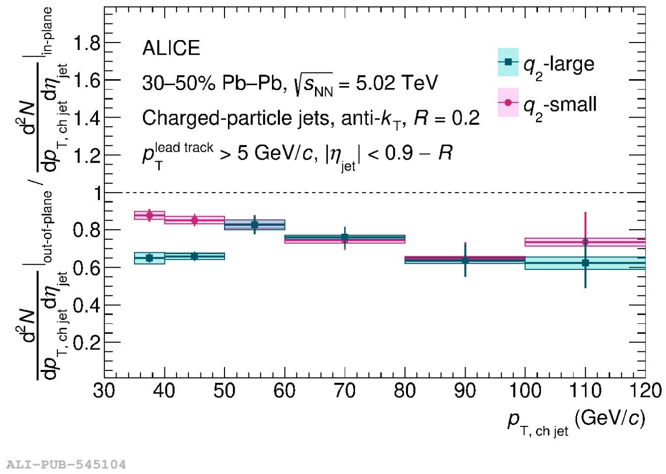
➜ Unbiased **charged-particle jet $R_{AA}$** down to **13.5 GeV/*c***
➜ First direct comparison of jet suppression at RHIC & LHC
➜ Comparison to h-jet: new tools to explore jet quenching mechanisms




- **ESE + event-plane angle** information are promising techniques to constrain pathlength dependence of jet quenching

➜ Consistency with expectation of **pathlength dependent suppression** for low to mid $p_T$

arXiv:2307.14097

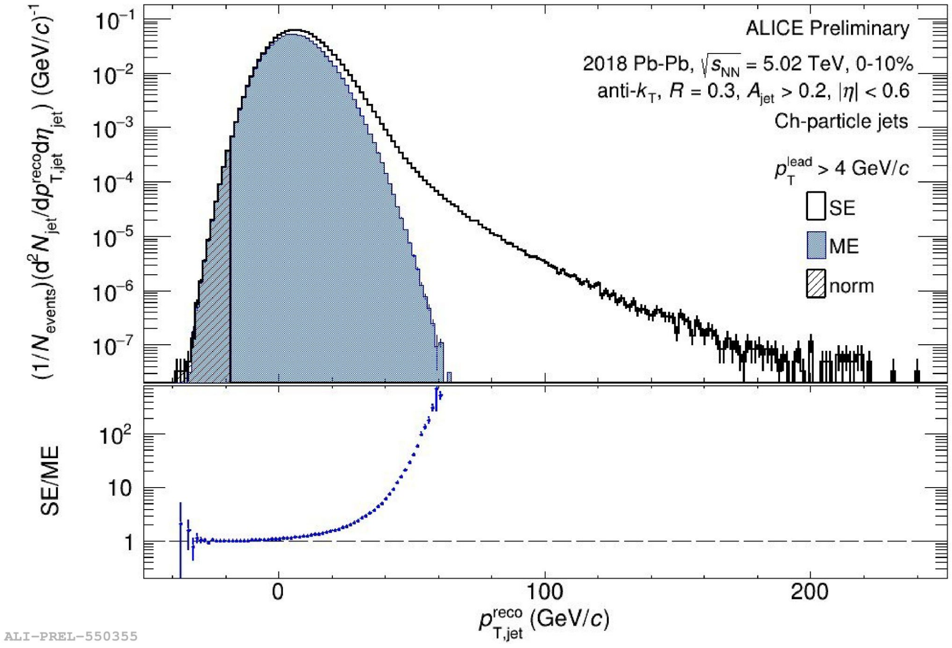


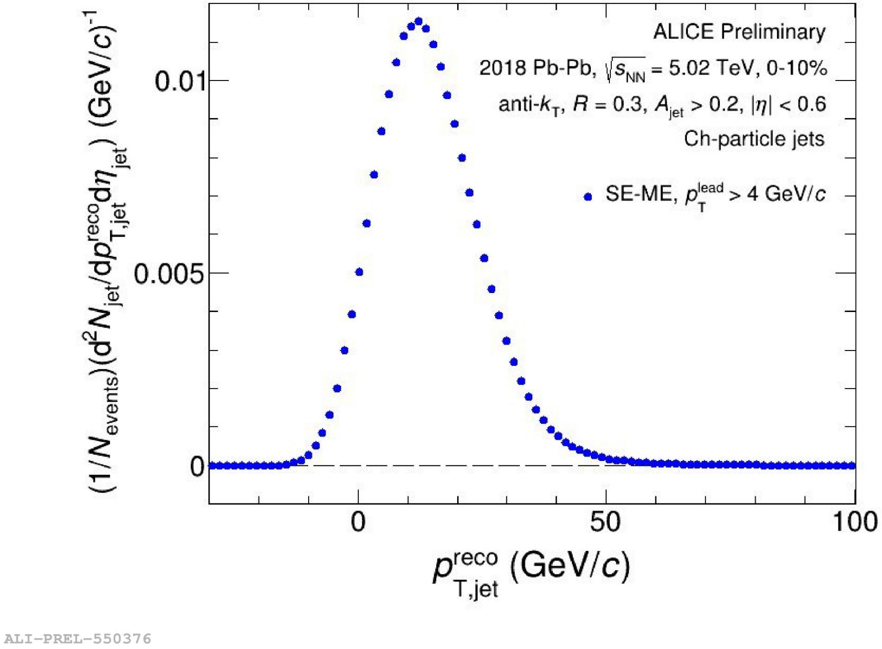

- **Positive charged-particle jet $v_2$** at $\sqrt{s_{NN}}$= 5.02 TeV

➜ Suppression of out-of-plane jets

# Backup

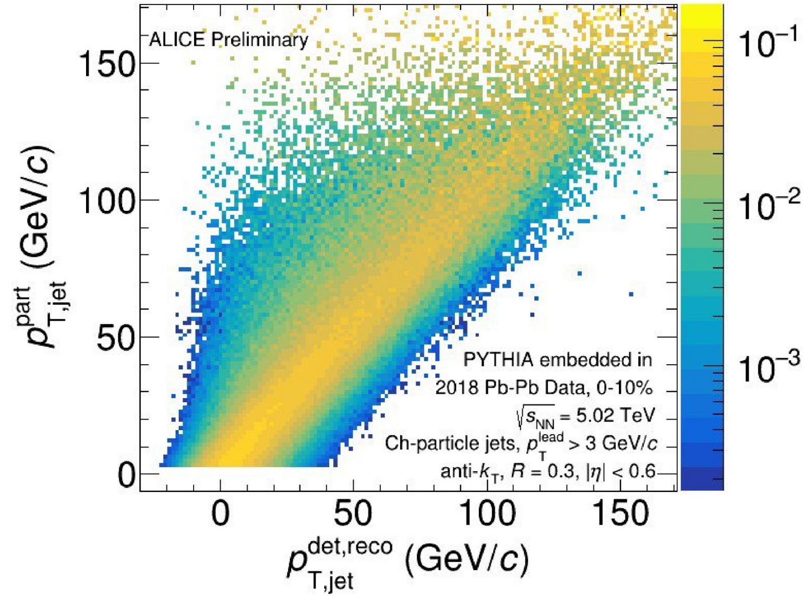
# Raw quasi-incl. jet distribution, $R$ = 0.3



# Corrections for $p_T$-smearing

- In addition to yield correction: Correction of $p_T$-smearing due to background and instrumental effects ➞ **Unfolding**
- **Instrumental effects**: Corrections for efficiency & $p_T$ resolution
- **Background effects:** Correction for local fluctuations
- Response matrix calculation with embedding of PYTHIA jets into SE
- ROOT unfolding framework **RooUnfold** with **Bayesian unfolding** method & 7 iterations
- Prior: PYTHIA particle level
- Additional correction after unfolding: **Jet reconstruction efficiency**

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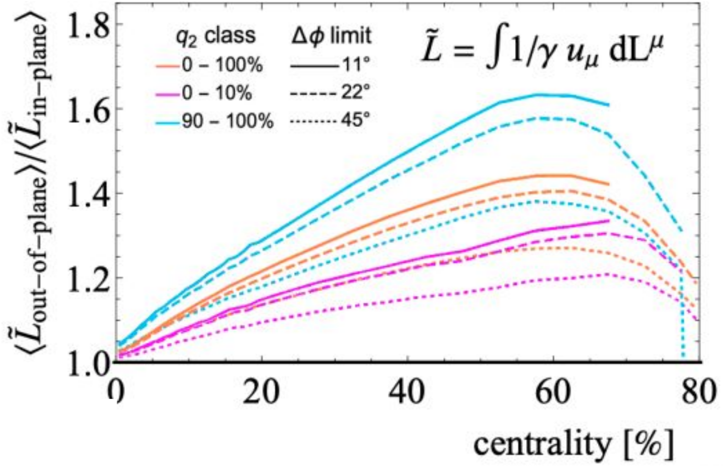
# Model comparisons

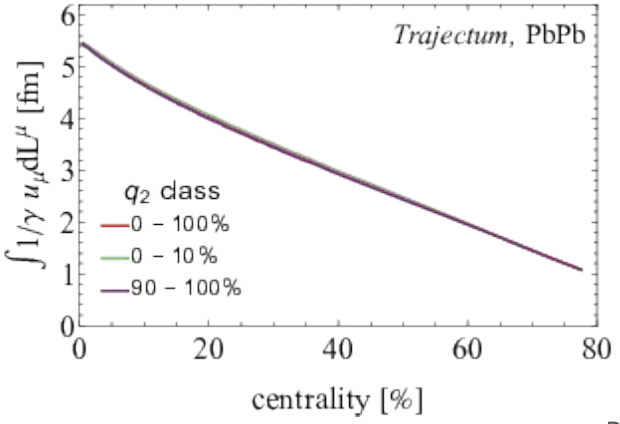
- **JETSCAPE**: Framework for pp and heavy-ion event simulation and Bayesian inference
- **Jet interactions, no medium response**:
  - MATTER: High virtuality shower
  - MARTINI: Low virtuality shower. Includes elastic scattering processes similar to LBT and radiative energy loss according to AMY formalism
- **Jet interactions with medium response**:
  - **LBT**: Transport of parton in QGP is described by linear Boltzmann equation. Medium particles can become part of the jet due to scattering: “recoiled partons”
  - **JEWEL**: PYTHIA based, microscopic response, energy-momentum locally conserved
  - **Hybrid**: PYTHIA based, hard (soft) jet-medium interaction based on DGLAP evolution (AdS/CFT)
- **Mehtar-Tani et. al**: Analytic calculation based on BDMPS/GLV and hydrodynamics

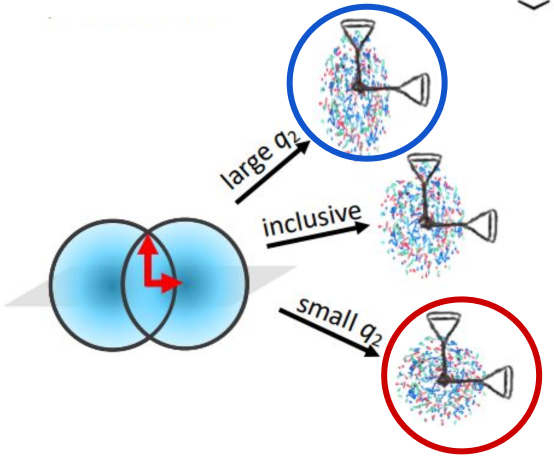
# Event-plane angles and ESE

- Pathlength differences not predicted in theory when considering only event shapes

  ➜ Add event-plane information




- Prediction of greater in- vs. out-of-plane differences for **$q_2$-large** events than for **$q_2$-small** events

Beattie, Nijs, Sas, van der Schee, Phys. Lett. B 836 (2023) 137596