Recent Jet Measurements in Pb-Pb Collisions with ALICE

ISMD 2023

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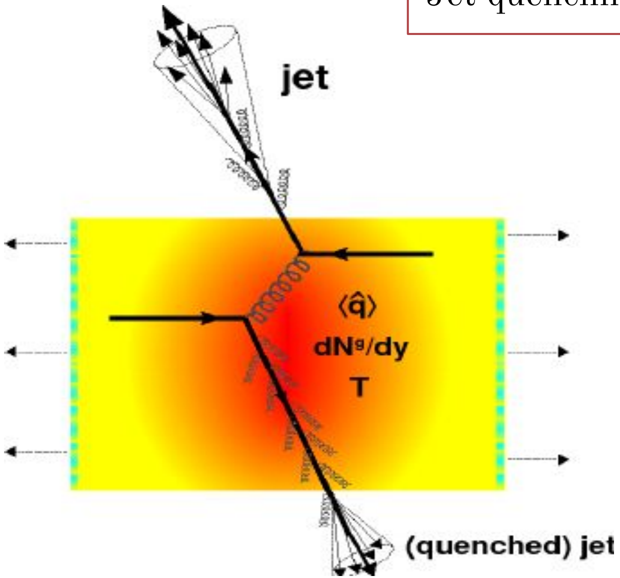
Graduiertenkolleg 2149 Research Training Group

ALICE

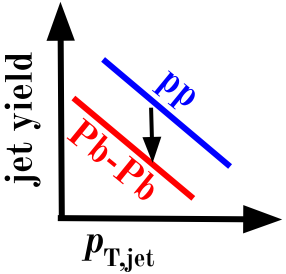
Jet Quenching: tool to investigate QGP

Jet quenching = jet energy loss + jet substructure modification

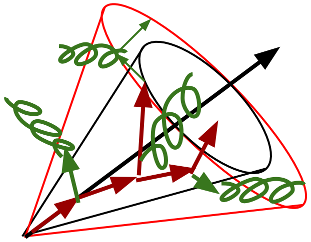


Sarkar, Sourav & Satz, Helmut & Sinha, Bikash. (2010). The Physics of the Quark-Gluon Plasma: Introductory Lectures. 10.1007/978-3-642-02286-9

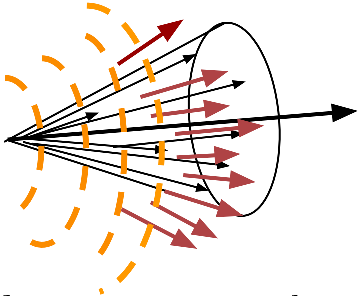
- different manifestations of jet quenching



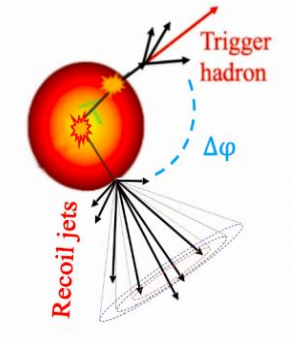
1. Jet yield suppression



2. Soft gluon emissions: momentum broadening , widening of jet



3. Medium response: wake of soft particles to the jets

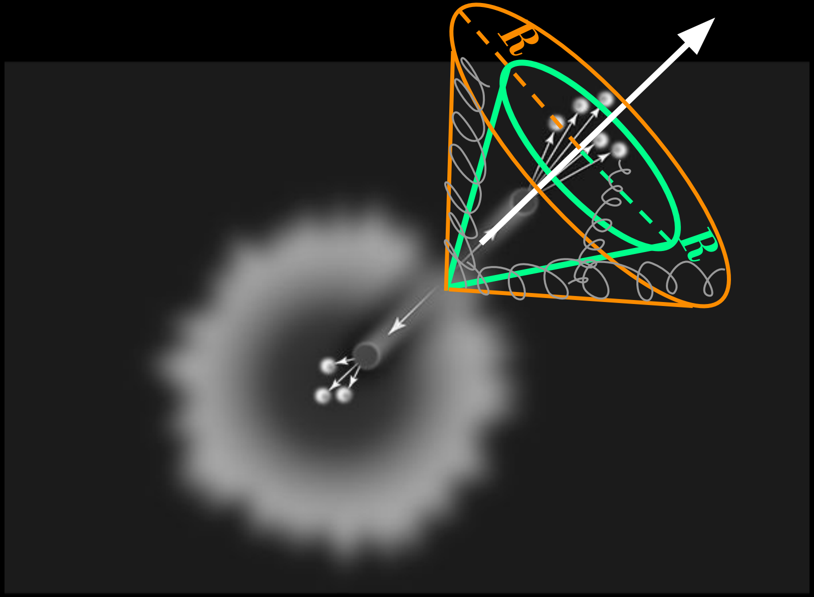


4. Azimuthal broadening/ deflection

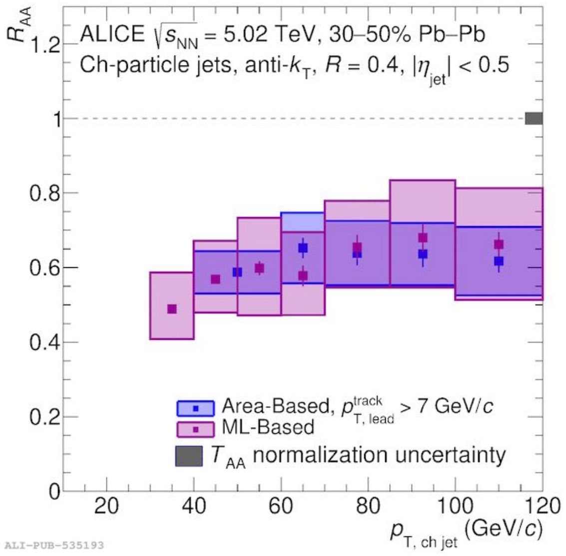
Differential jet measurements using different jet observables to study these different jet quenching effects

A novel ML-based approach for jet suppression studies

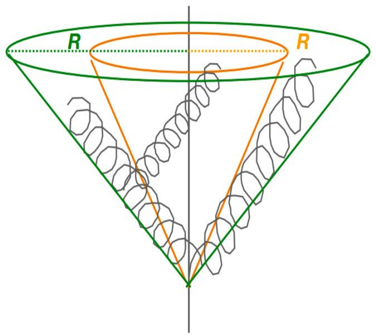
"Radius dependence of charged-particle jet suppression"
(arXiv:2303.00592)



R-dependence of jet suppression(R_{AA})



Sketch: Hannah Bossi, CERN EP Seminar 2023



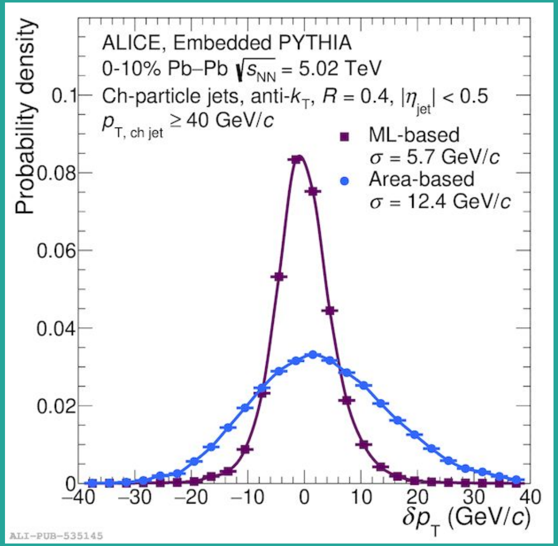
$$R_{\mathrm{AA}} = \frac{1}{\langle N_{coll} \rangle} \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{dN_{pp}/dp_T}$$

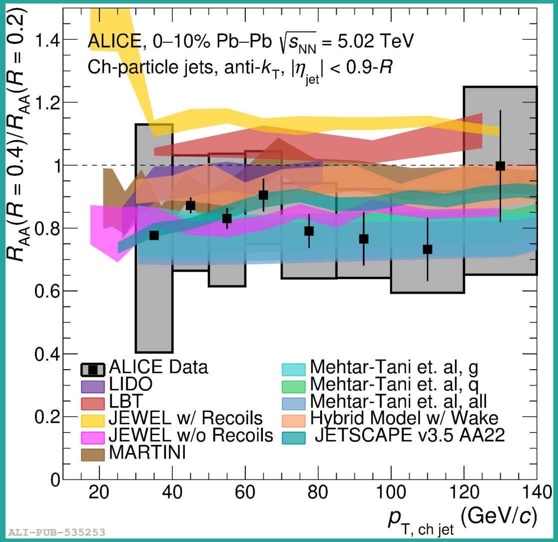
$$R^{R/0.2}_{AA} = \frac{R^{R}_{AA}}{R^{0.2}_{AA}} = \frac{\sigma_{AA}(R)}{\sigma_{AA}(0.2)} \Big/ \frac{\sigma_{pp}(R)}{\sigma_{pp}(0.2)}$$

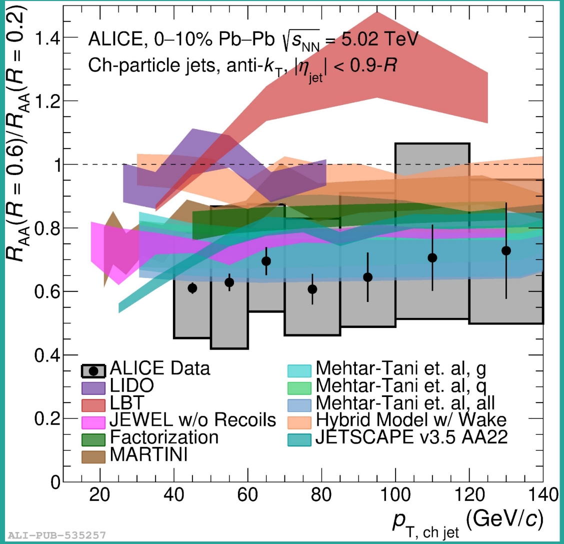
large R jets include more wide-angle radiation, but are more sensitive to background

- new ML-based background subtraction enables measurement in low p_{T} and large R (R=0.6)! https://arxiv.org/abs/1810.06324
- use of **differential R_{AA}** to determine relative strength of effects

A novel Machine Learning based approach for p_T-smearing due to background (UE) + a new differential R_{AA} measurement





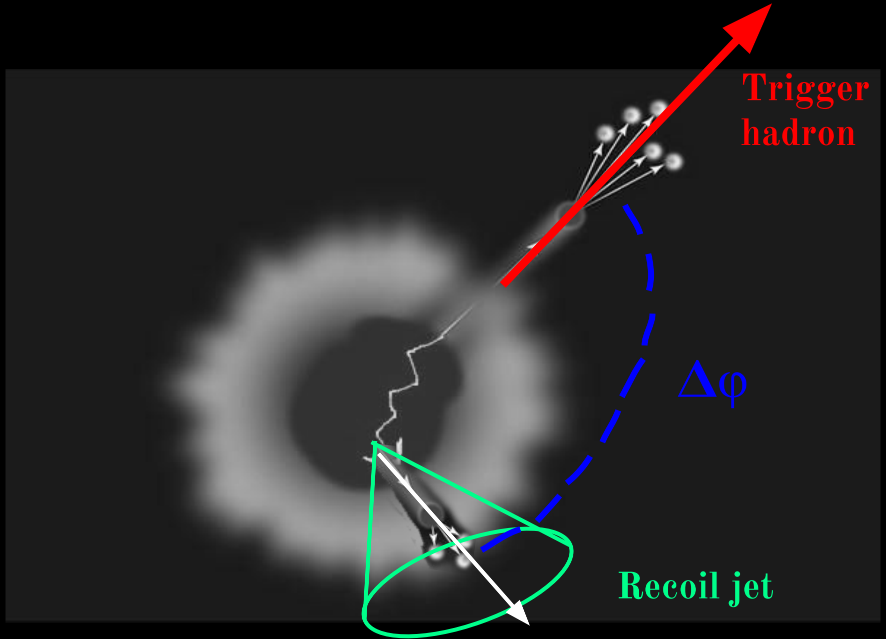


- significant reduction in residual background fluctuations for ML-based approach

- no significant R- dependence between $R = 0.2$ and $R = 0.4$
- hint of $R = 0.6$ jets (more complex substructure) more suppressed
- largest R ever measured at low p_T in HI collisions at LHC
- **JETSCAPE, JEWEL w/o recoils, MARTINI, Mehtar-Tani et al.,** factorization (in central) : Very **GOOD agreement** with data indicating decreasing R_{AA} with increasing R

Jet Deflection (Acoplanarity)

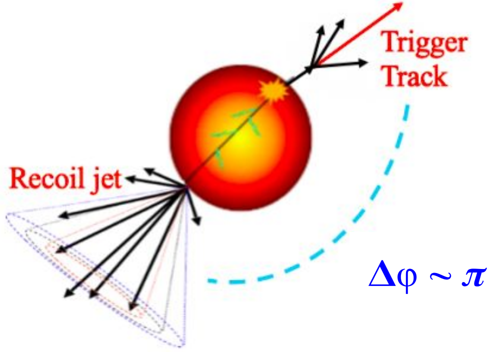
"Recoil of jets from a high-p_T trigger hadron"
(ALICE PRELIMINARY)

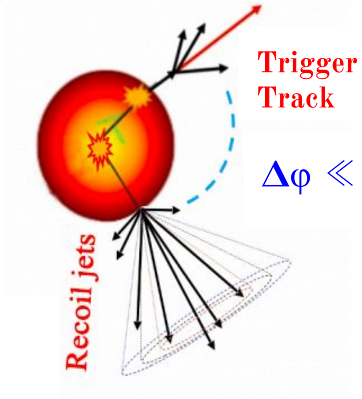


Large-angle jet deflection as a probe of quasi-particles in the QGP ("hadron-jet" coincidence)

- Trigger Track (TT) assigned to a high p_T hadron
  - ➢ no bias on fragmentation of recoil jets (probes large path length)
- **opening angle (Δφ) of jet relative to trigger axis**
  - ➢ 2 regions of interest:
    - i. **$\Delta\varphi \sim \pi$**
      - ➜ multiple soft scattering
      - ➜ sensitive to jet transport coefficients?
    - ii. **$\Delta\varphi \ll \pi$**
      - ➜ single hard scattering
      - ➜ possibility to resolve QGP short-distance structure?
- **transverse momentum ($p_{T,ch}^{jet}$) of recoil jet**
  - ➢ low-p_T jets are most sensitive to Δφ broadening effects

- data-driven subtraction of uncorrelated background allows to access low $p_T \sim 10$ GeV/c and large R jets





Yongzhen HOU, Hard Probes 2023

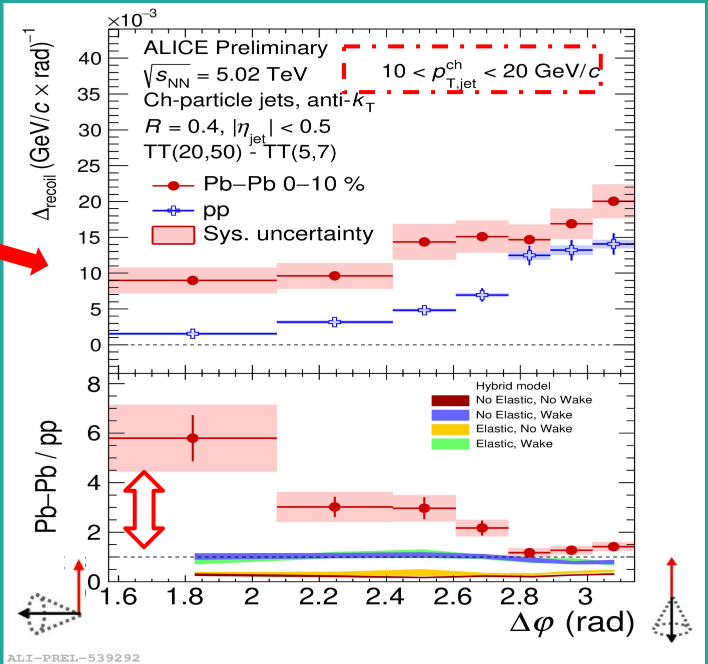
$$\Delta_{\rm recoil}(p_{\rm T,jet}, \Delta\varphi) = \frac{1}{N_{\rm trig}} \frac{{\rm d}^3 N_{\rm jet}}{{\rm d}\eta_{\rm jet}\, {\rm d}p_{\rm T,jet}\, {\rm d}\Delta\varphi}\bigg|_{p_{\rm T}^{\rm trig}\in {\rm TT_{Sig}}} - c_{\rm Ref} \cdot \frac{1}{N_{\rm trig}} \frac{{\rm d}^3 N_{\rm jet}}{{\rm d}\eta_{\rm jet}\, {\rm d}p_{\rm T,jet}\, {\rm d}\Delta\varphi}\bigg|_{p_{\rm T}^{\rm trig}\in {\rm TT_{Ref}}}$$

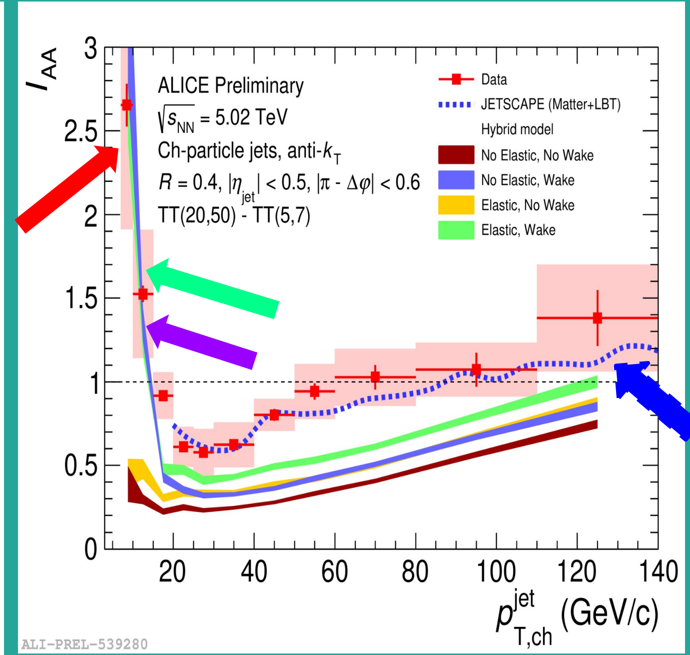
First measurement of fully corrected semi-inclusive jet yield recoiling from a high-p_T hadron trigger

- medium-induced yield excess and **acoplanarity broadening** at low p_T

- **JETSCAPE:** captures the rising trend with p_T

- Hybrid models with "**Wake**" effects: the uprise due to medium response at low p_T
- **Δφ** insensitive to elastic scattering effects





$$\Delta_{recoil} = n(TT_{Sig}) - c_{Ref} \, . \, n(TT_{Ref})$$

$$where \ n = \frac{1}{N^{AA}_{trig}} \frac{d^2 N^{AA}_{jet}}{dp^{jet}_{T,ch} d\eta_{jet}}$$

$$I_{AA} \equiv \frac{\Delta_{recoil}(Pb - Pb)}{\Delta_{recoil}(pp)}$$

$$TT_{Sig} : 20 < p_{T,trig} < 50 \, GeV/c$$

$$TT_{Ref} : 5 < p_{T,trig} < 7 \, GeV/c$$

Summary

✓ jets are indeed excellent probes of the QGP
✓ "Jet-Physics" is one of the most happening fields at the LHC (and of course in ALICE!)
✓ recent jet measurements in **central (0-10%) Pb-Pb** collisions with **ALICE** at the **lowest ever achievable p_{T}** and **largest ever achievable R** values

1. new ML-based R_{AA} measurement reveals R-dependence of jet suppression at low p_{T} ➡
   - ⚡ for the **first time @LHC**: $R = 0.6$, low $p_{\mathrm{T,\,ch\,jet}} = 40$ GeV/c
   - ⚡ wider jets (complex substructure) have more effective energy loss sources, changing q/g fractions, varying jet populations : **more to be studied and understood!**

2. first evidence of hadron+jet azimuthal broadening for soft jets (low p_{T}) ➡
   - ⚡ $R = 0.4$, low $p_{\mathrm{T,\,ch\,jet}} = 10$ GeV/c
   - ⚡ low-p_{T} , large-R phase space reveals significant acoplanarity
   - ⚡ Models: due to medium response effects rather than large-angle scattering

✓ more exciting results are yet to come with **LHC Run 3** data

Envisioning the Future of Heavy-Ion Collisions with Jets at ALICE

ALICE 2

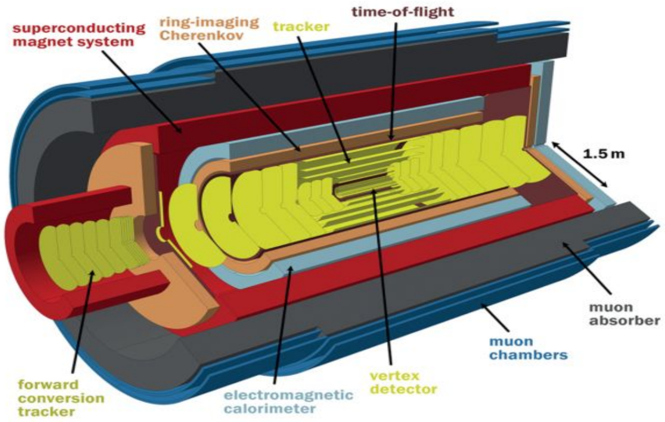
ALICE 3

ALICE

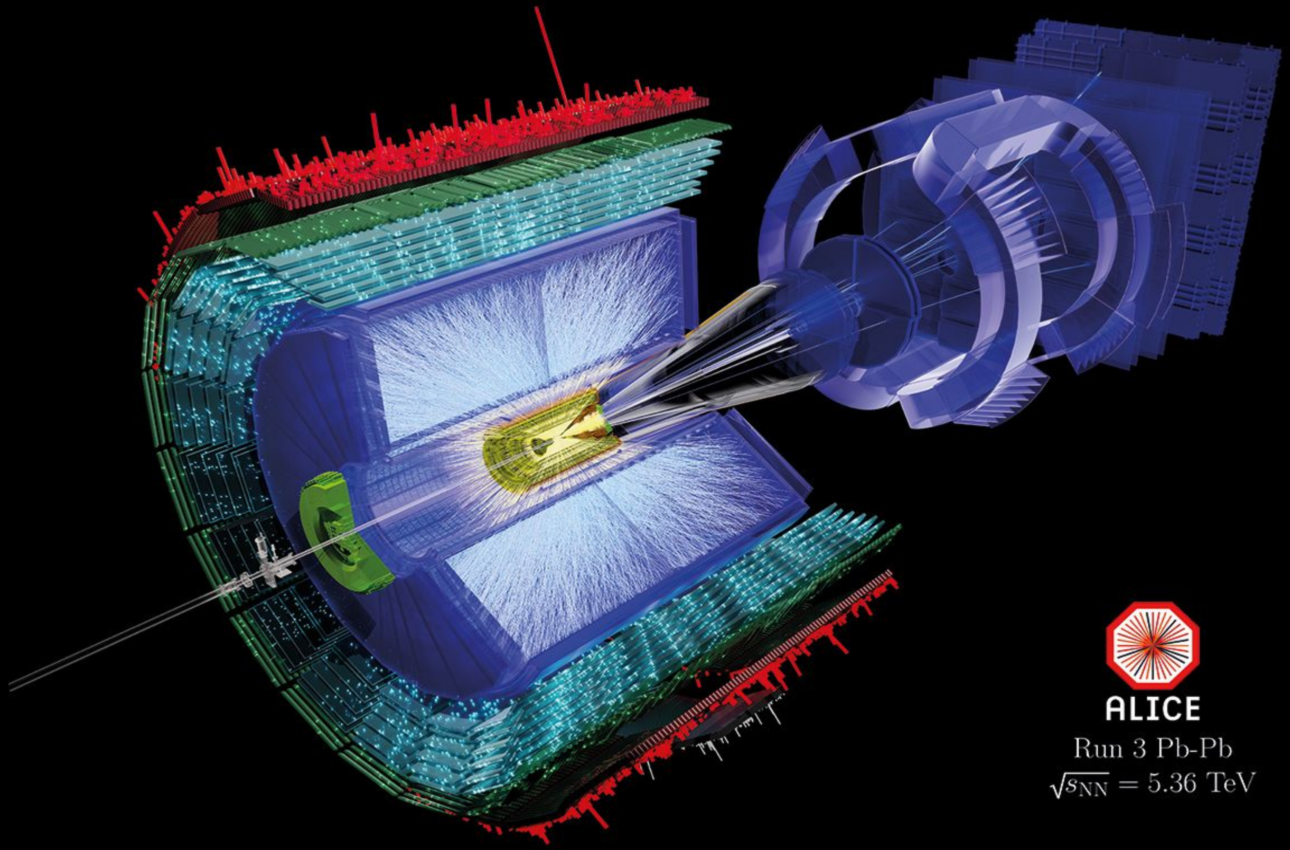
Run 3 → LS3 → Run 4 → LS4 → Run 5

2022 - 2025 | 2029 - 2032 | 2035- 2038

- ✓ new data with increased statistics
- ✓ improved tracking
- ✓ more opportunities to study the internal structure of jets
- ✓ better scope for precise measurements
- ✓ help to improve the physics models



- larger acceptance will facilitate study of full jets at larger R values

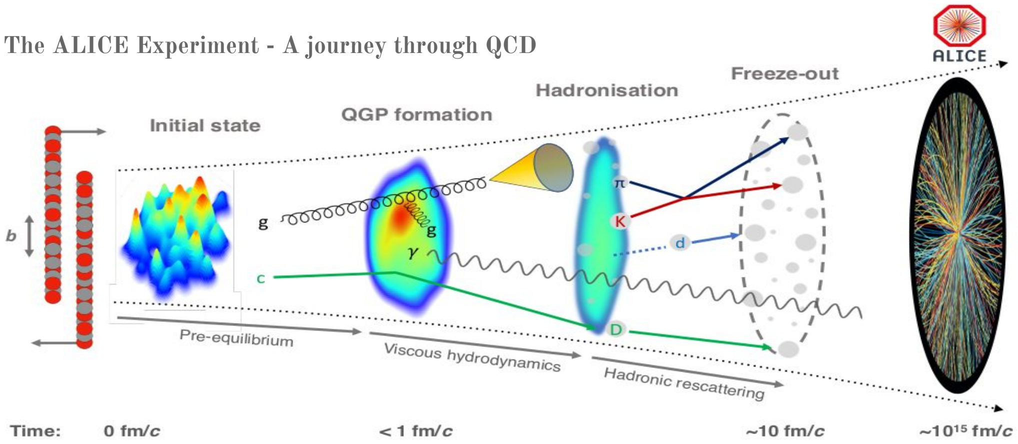


We've indeed learned a lot and we strive for learning a lot more!

Thank You! :)

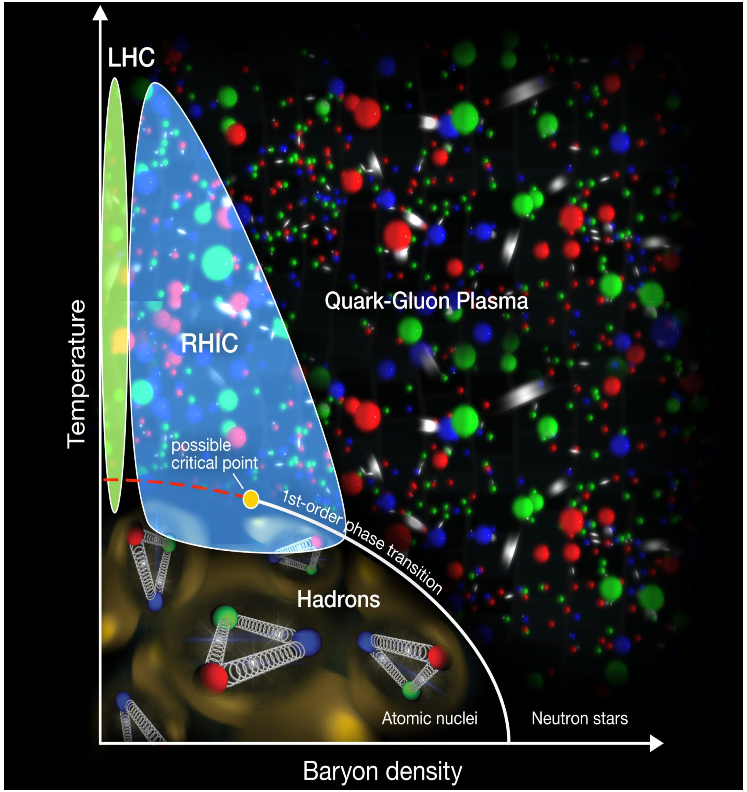
BACK UP!

The Quark Gluon Plasma (QGP) in Heavy-Ion Collisions



- **Quark-gluon plasma (QGP)**:
  - deconfined state of quarks and gluons
  - achieved with temperatures high enough to deconfine QCD matter

- **Lattice QCD** predicts a smooth crossover at $T_C \sim 150$ MeV (baryon potential, $\mu_B = 0$)



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Jets: excellent (hard) probes of QGP

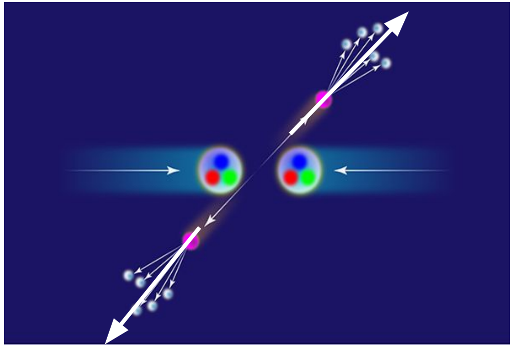
<u>Jets in pp collisions</u>

- exchange of large-momentum (high-Q^2) between 2 quarks or gluons
  - ➢ highly energetic outgoing quark or gluon

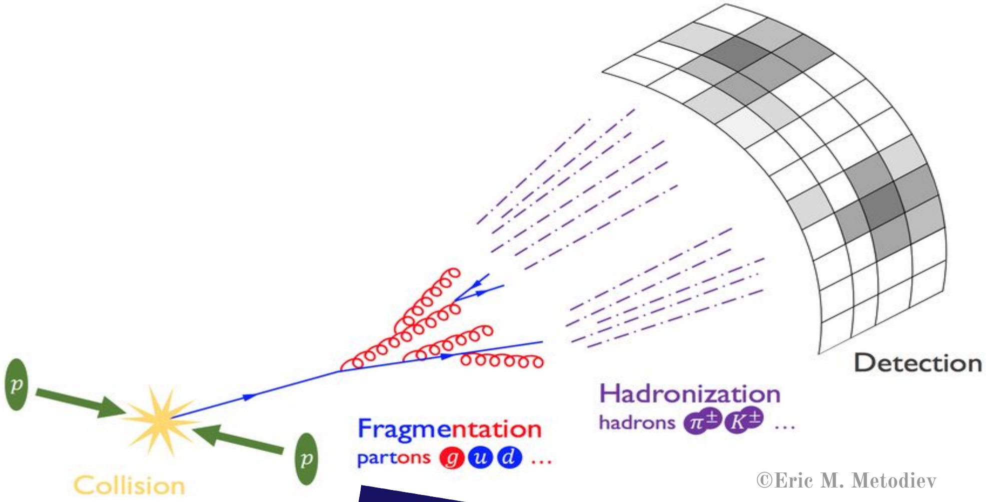
⬇ Fragmentation

collimated shower of particles : “**Jets**”

- production of high-p_T calculable in pQCD



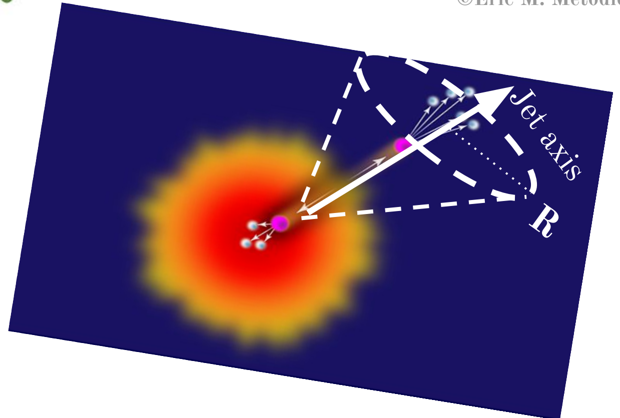
https://physics.aps.org/articles/v7/97



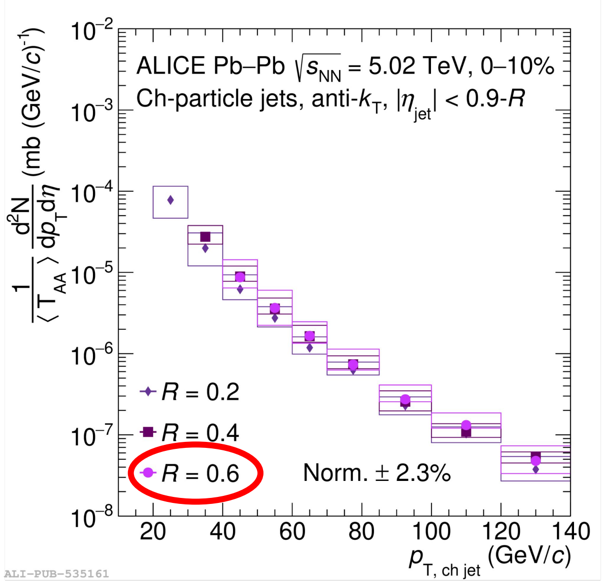
©Eric M. Metodiev

<u>Jets in heavy-ion collisions</u>

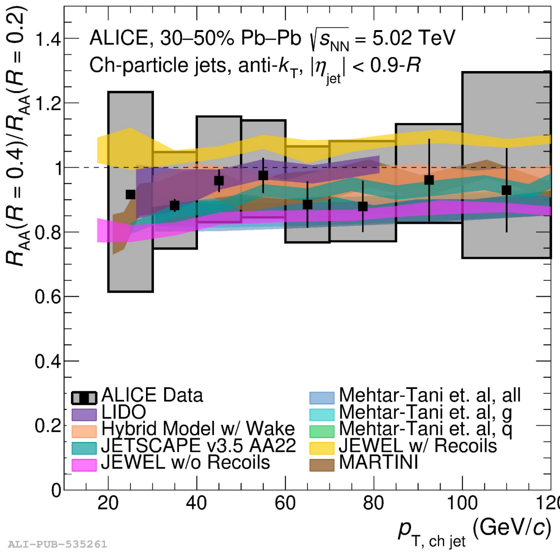
- QGP formation in a heavy-ion collision ➡ “**jet quenching**”
- fragmentation pattern gets modified in QGP
- jet cluster algorithm + recombination scheme

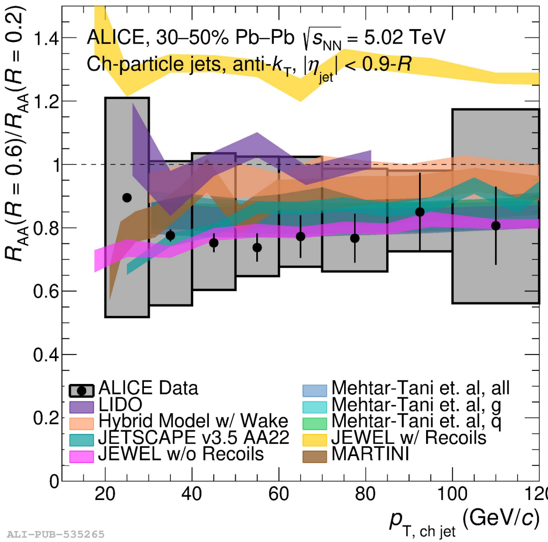


R- dependence of R_{AA} (new ML-based approach)



semi-central





- ML allows exploring the low p_T and large R

- Models: No-significant R-dependence in semi-central collisions
- JEWEL with Recoils: increasing R_{AA} with increasing R due to medium response (in contrast with the data)
- LBT : increasing R_{AA} with increasing R (not supported by data)
- HYBRID and LIDO: double ratio ~ 1 (mild R-dependence in these models)

Jet Deflection

- trigger-normalised jet yield recoiling from a trigger hadron: (ratio of high p_T hadron and jet cross-sections)

$$\left.\frac{1}{N_{\rm trig}^{\rm AA}}\frac{{\rm d}^2N_{\rm jet}^{\rm AA}}{{\rm d}\eta_{\rm jet}\,{\rm d}p_{\rm T,jet}}\right|_{p_{\rm T}^{\rm trig}\in{\rm TT}} = \left.\left(\frac{1}{\sigma^{\rm AA\to h+X}}\cdot\frac{{\rm d}^2\sigma^{\rm AA\to h+jet+X}}{{\rm d}\eta_{\rm jet}\,{\rm d}p_{\rm T,jet}}\right)\right|_{p_{\rm T,h}\in{\rm TT}}$$

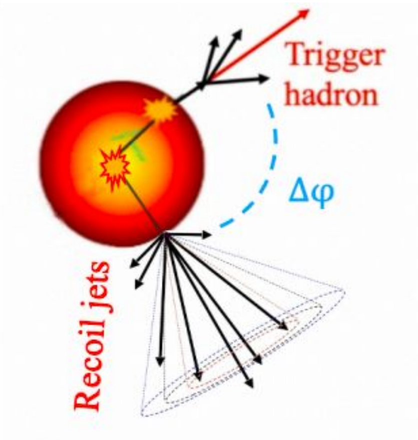
pQCD observable
Chen et al., PLB 773 (2017) 672

- data-driven uncorrelated background subtraction:
  - ➢ achieved by taking difference between signal and reference spectra measured in two exclusive Trigger Track classes - $\mathrm{TT}_{\mathrm{Sig}}$ and $\mathrm{TT}_{\mathrm{Ref}}$
  - ➢ $$\Delta_{\rm recoil}(p_{\rm T,jet},\Delta\varphi) = \left.\frac{1}{N_{\rm trig}}\frac{{\rm d}^3N_{\rm jet}}{{\rm d}\eta_{\rm jet}\,{\rm d}p_{\rm T,jet}\,{\rm d}\Delta\varphi}\right|_{p_{\rm T}^{\rm trig}\in{\rm TT}_{\rm Sig}} - c_{\rm Ref}\cdot\left.\frac{1}{N_{\rm trig}}\frac{{\rm d}^3N_{\rm jet}}{{\rm d}\eta_{\rm jet}\,{\rm d}p_{\rm T,jet}\,{\rm d}\Delta\varphi}\right|_{p_{\rm T}^{\rm trig}\in{\rm TT}_{\rm Ref}}$$

- $\mathrm{TT}_{\mathrm{Sig}} : 20 < p_{\mathrm{T,\,trig}} < 50\ \mathrm{GeV}/c$
  $\mathrm{TT}_{\mathrm{Ref}} : 5 < p_{\mathrm{T,\,trig}} < 7\ \mathrm{GeV}/c$

Trigger Tracks

- **high p_T trigger hadrons**
  - ➢ originate from fragmentation of energetic jets in pp and Pb-Pb
  - ➢ experimentally provide clean triggers w/o uncorrelated background correction
  - ➢ biased towards events with high Q^2 partonic interaction
- **Trigger Track (TT)**
  - ➢ close to the collision surface and headed outward
  - ➢ small path length in QGP
  - ➢ no bias on fragmentation of recoil jets (probes large path length)



- This measurement: jets aligned nearly back-to-back in the azimuth wrt the p_T trigger hadron ($|\phi_{trig} - \phi_{jet} - \pi| < \mathbf{0.6\ rad}$)

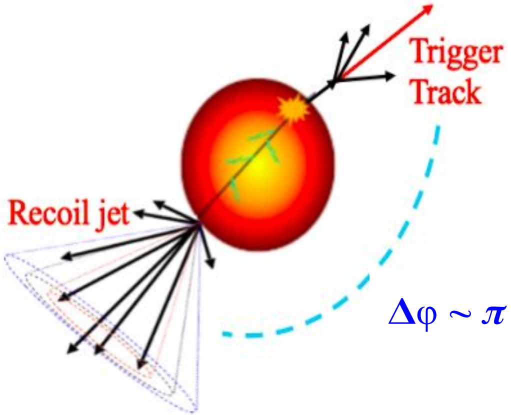
- Advantage: outgoing high-p_T trigger hadron biases the hard scattering to be located close to the surface and the mother parton to be directed toward the outside of the collision zone

Large-angle jet deflection as a probe of quasi-particles in the QGP ("hadron-jet" coincidence)

$\Delta\varphi \sim \pi$

L. Chen et al, Phys. Lett. B773 (2017) 672
M. Gyulassy et al., arxiv:1808.03238
B. G. Zakharov, arxiv:2003.10182

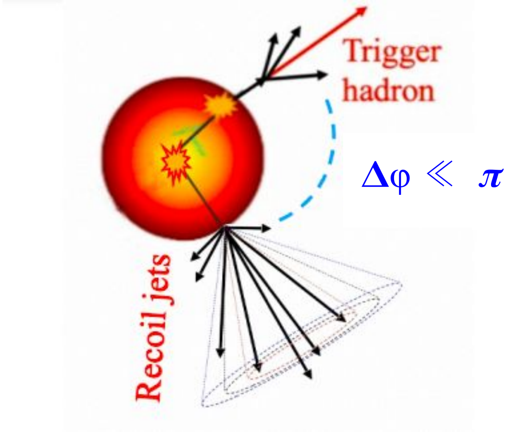
- vacuum broadening (Sudakov radiation)
- multiple soft scattering in the QGP may further broaden $\Delta\varphi$
  - transport coefficie $\hat{q} \sim \langle p_\perp^2 \rangle / L \sim \langle \Delta\varphi^2 \rangle / L$
- negative radiative correction leading to reduction of $\Delta\varphi$ broadening



$\Delta\varphi \ll \pi$

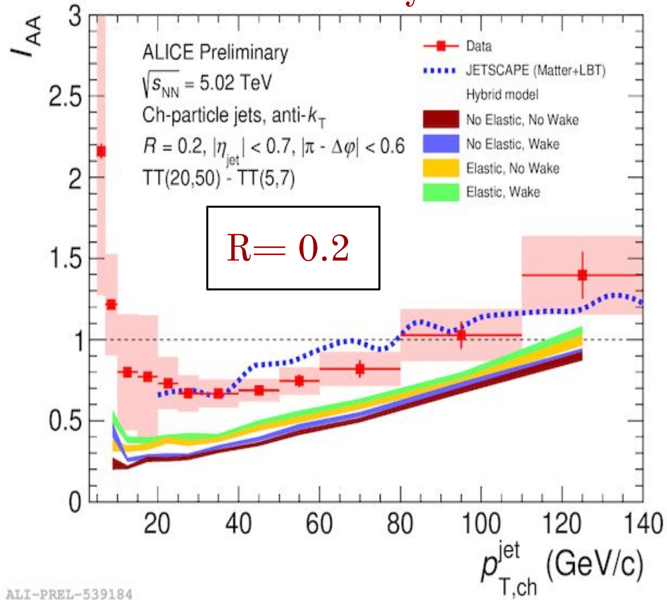
F. D'Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172

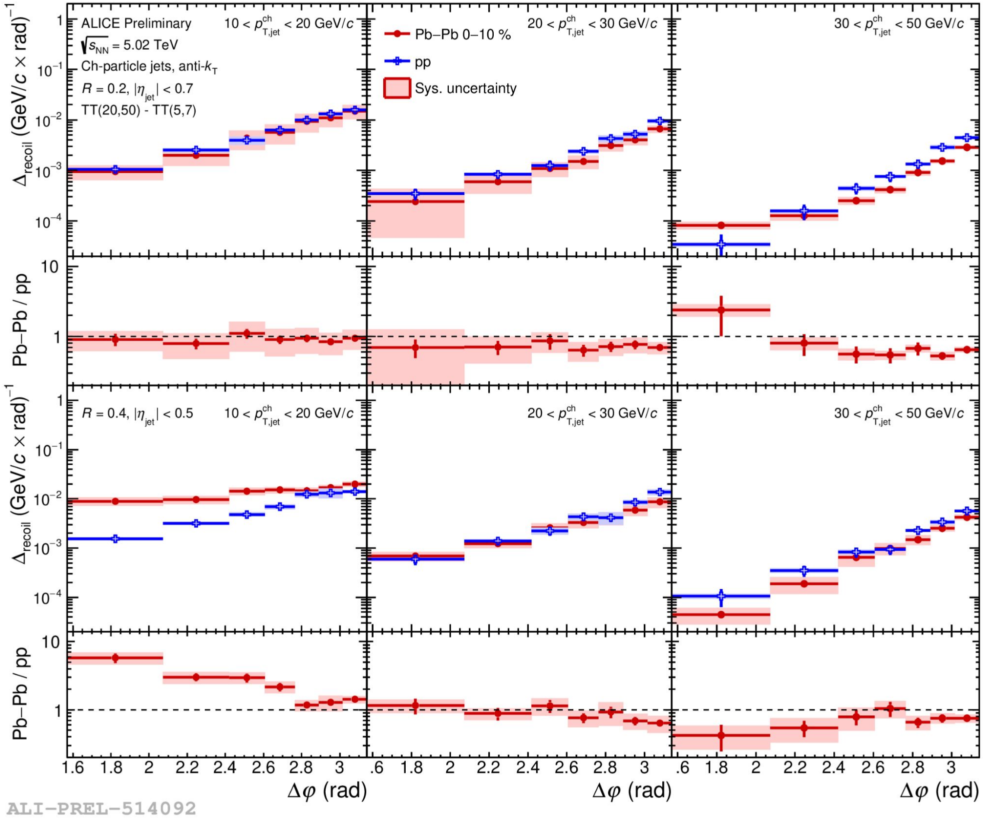
- large-angle deflection of hard partons off quasi-particles
- probe short distance partonic structure of the QGP



Jet Acoplanarity distributions

0-10% centrality in Pb-Pb





R= 0.2

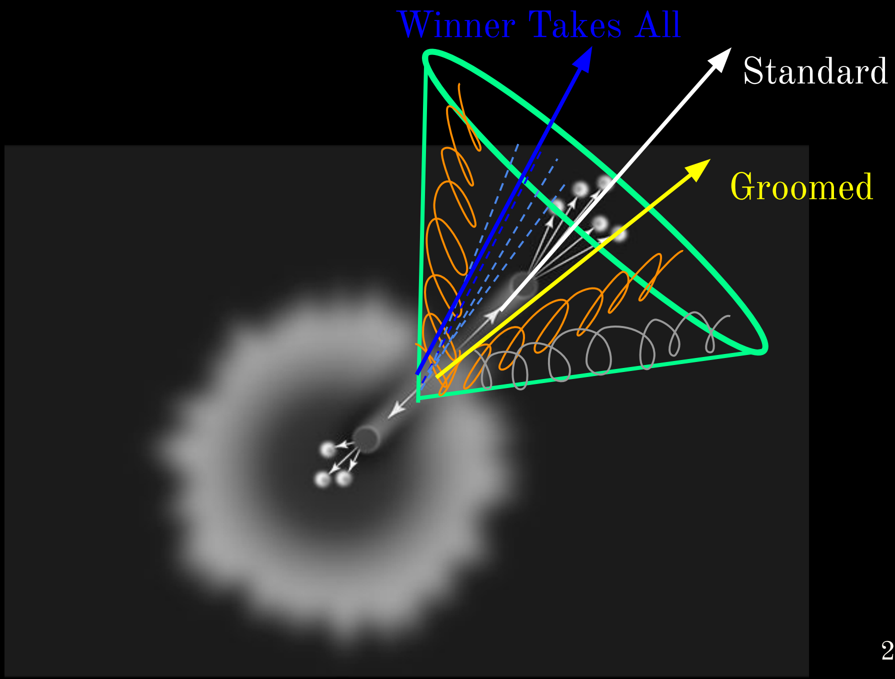
R= 0.4

- significant acoplanarity modification at large R and low p_T
- no modification for small R and high p_T

Jet Substructure Modification

"Angle between the jet axes"
(arXiv:2303.13347)

groomed-away radiation
soft radiation
collinear radiation



Different types of jet axes

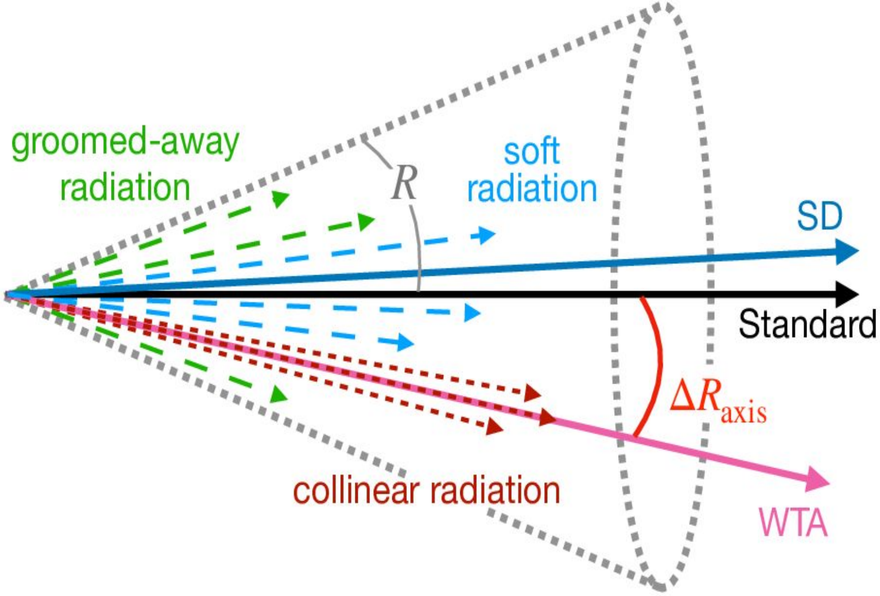
P. Cal et al., JHEP 04 (2020) 211
ALICE, arXiv:2303.13347

ALICE

1. **Standard axis:**
   - **constrained by all the jet constituents (soft + hard)**
   - **anti-k_T jet clustering algorithm with E recombination scheme**

2. **Groomed axis (SD):**
   - **constrained by particles (hard) left in the jet after Soft Drop grooming**
   - **Cambridge-Aachen (C/A) reclustering algorithm**

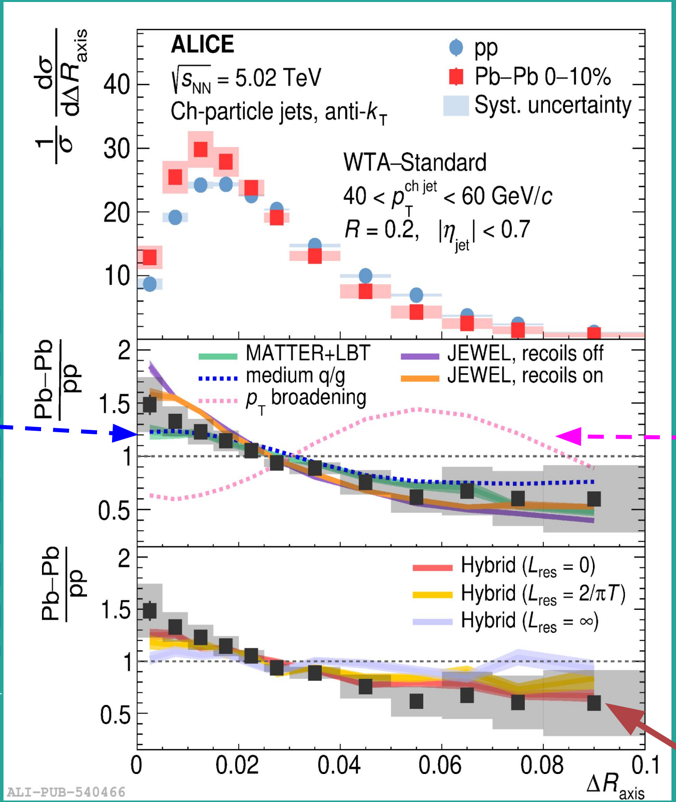
3. **Winner-Takes-All (WTA) axis:**
   - **Cambridge-Aachen (C/A) reclustering algorithm with p_T**
   - **aligned with the hardest jet constituent**



$$\Delta R_{\text{axis}} = \sqrt{(y_{\text{standard}} - y_{\text{WTA}})^2 + (\varphi_{\text{standard}} - \varphi_{\text{WTA}})^2}$$

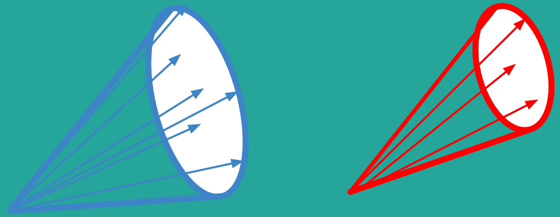
First Measurement of the angle between the WTA and Standard jet axes

- narrowing of the ΔR_{axis} distribution in Pb-Pb
  - ➢ jets selection bias



Gluon jet $C_A = 3$

Quark jet $C_F = 4/3$



- **medium q/g** (phenomenological model)
  - ➢ gluon-initiated jets interact more with the medium than quark-initiated jets in Pb-Pb

- **p_T broadening model**
  - ➢ discards intra-jet p_T broadening

- **Hybrid model**
  - ➢ data favors incoherent jet energy loss

- ΔR_{axis} is sensitive to the medium resolution length L_{res}