Search for jet quenching in small systems

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Fundamental constituents of matter through frontier technologies

LHCP Boston 2024

ALICE ATLAS EXPERIMENT CMS

Co-funded by the European Union

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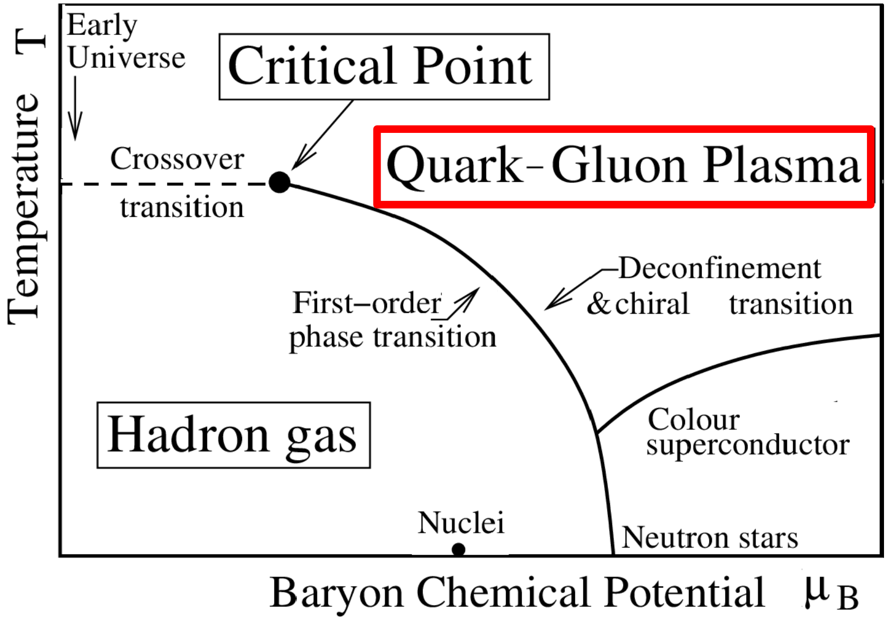
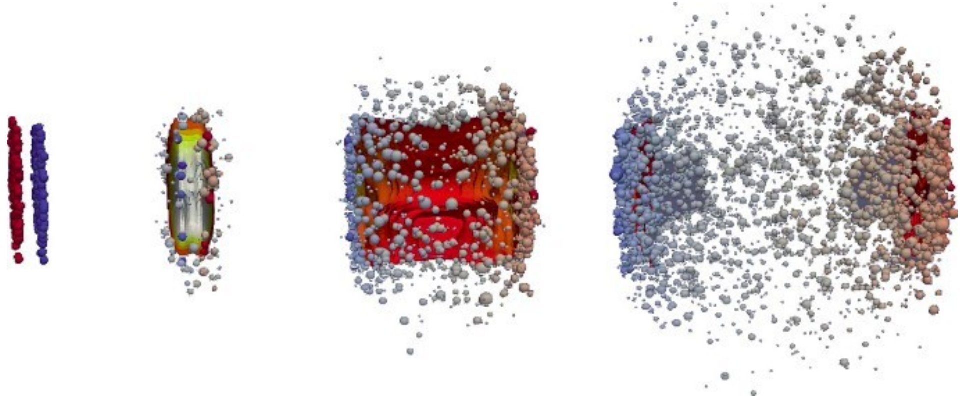
FORTE

Quark-gluon plasma

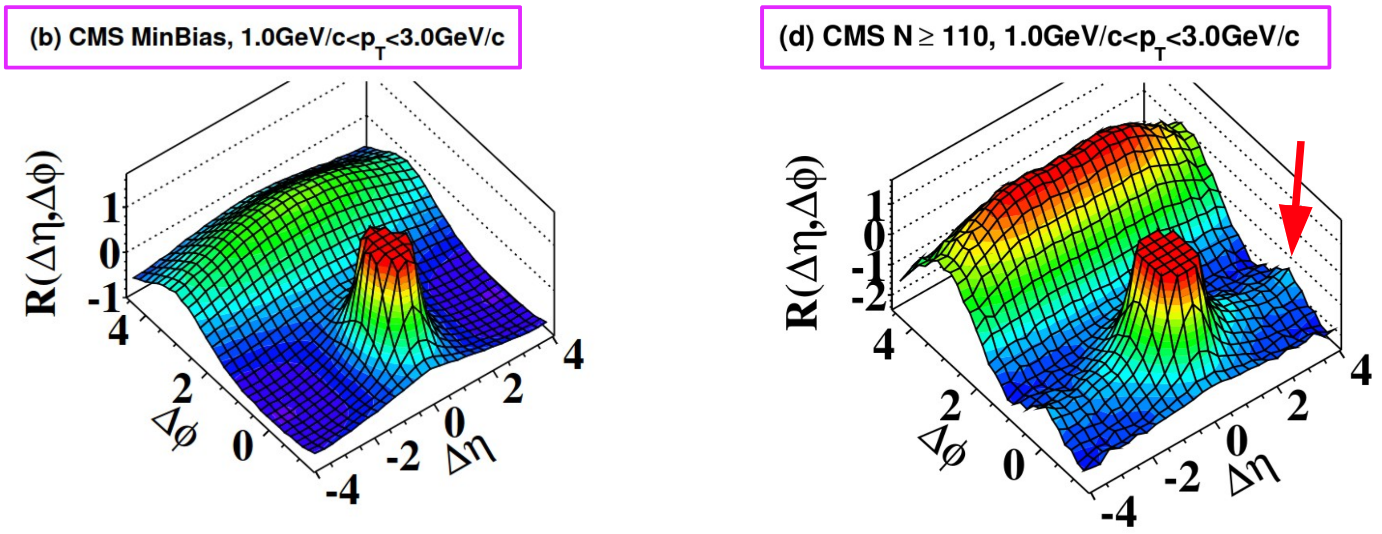


Bhalearo, arXiv:1407.1694



Bernhard, J.E. arXiv:1804.06469

QGP in small collision systems?

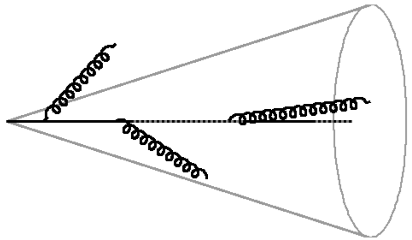


CMS, JHEP 09 (2010) 091

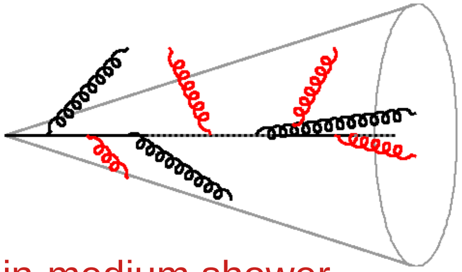
- QGP-like signatures in high-multiplicity pp and p-A
- How do QGP signatures evolve when decreasing system size?
- Is there evidence for jet quenching in small collision systems?

A. Dobrin *Collectivity*, Friday

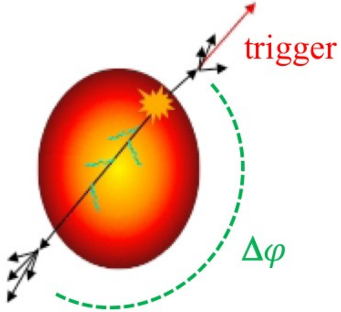
Jet quenching



in-vacuum shower



in-medium shower



Interaction of partonic shower with QGP results in :

- Energy loss ⇒ suppression of yield of high-p_T jets and hadrons
- Jet substructure modification
- Medium induced acoplanarity

D. A. Appel, PRD 33, 717 (1986) & J.P. Blaizot et al., PRD 34, 2739 (1986)

P. Jacobs *Jet substructure,* Monday

Y. Go *Medium response to jet,* Monday

R. Ehlers *Jet quenching,* Thursday

Nuclear modification factor

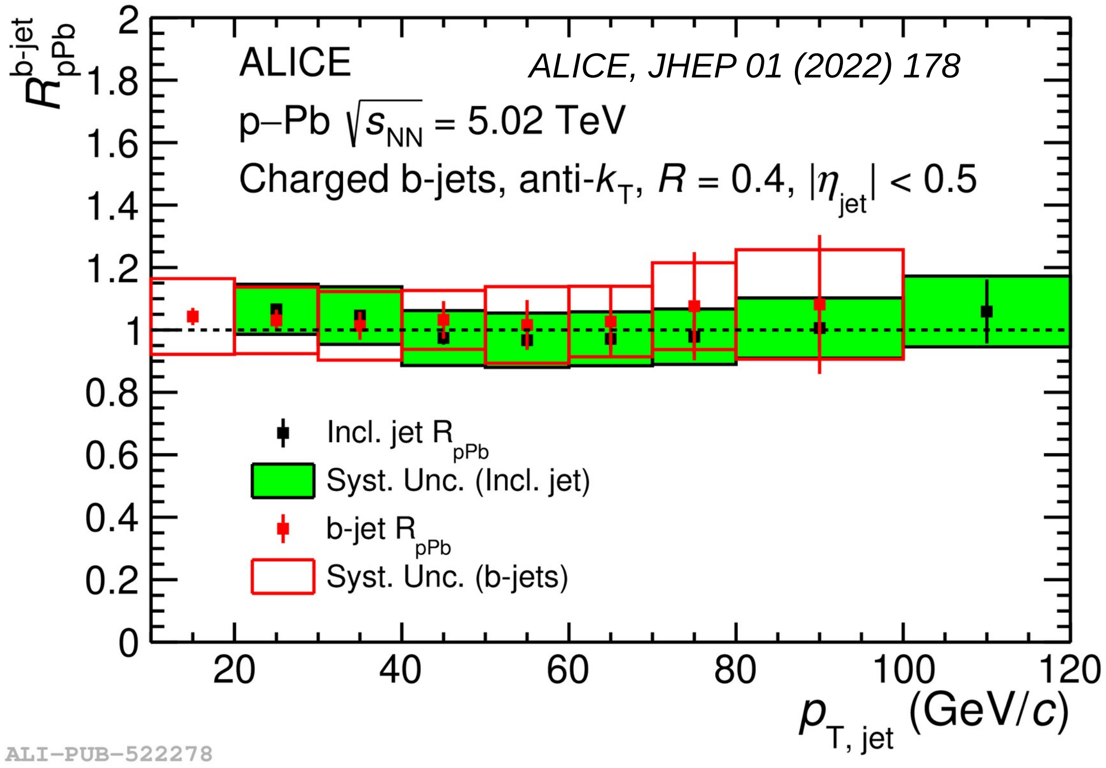
$$R_{\mathrm{pA}}^{\mathrm{min.bias}} = \frac{1}{A} \cdot \frac{\mathrm{d}^2\sigma_{\mathrm{pA}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

$$R_{\mathrm{pA}}^{\mathrm{cent.}} = \frac{1}{\langle T_{\mathrm{pA}}\rangle} \cdot \frac{(1/N_{\mathrm{evt}}) \cdot \mathrm{d}^2 N_{\mathrm{pA}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

- limited precision of $\langle T_{pA} \rangle$ for centrality biased events
- geometry information smeared by fluctuations
- no correlation between hard and soft interactions

Nuclear modification factor is not defined for high-multiplicity pp collisions

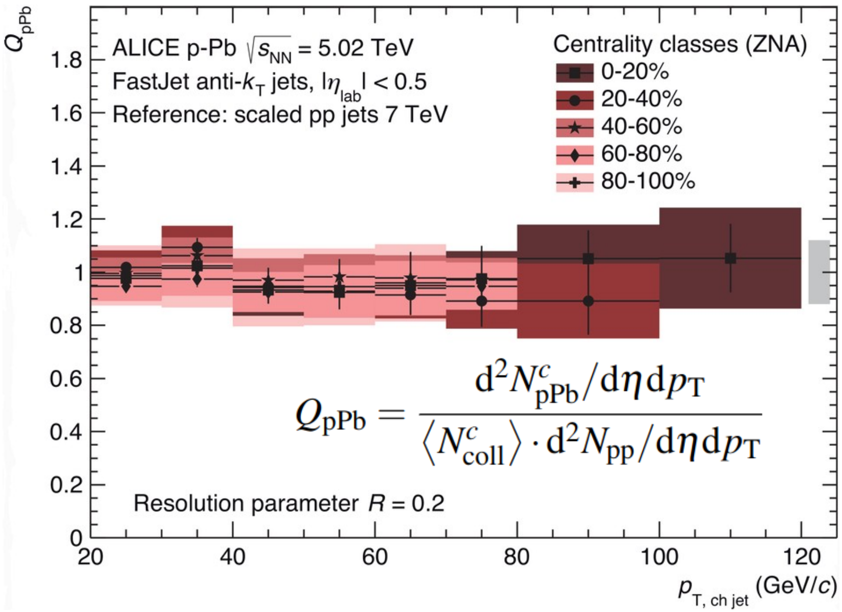
Inclusive jets and b-jets in minimum bias p-Pb



- R_{pPb} ~ 1 ⇒ no evidence for jet quenchig
- No sign of mass dependent effects

Q_{pPb} and R_{pPb} of jets vs event activity

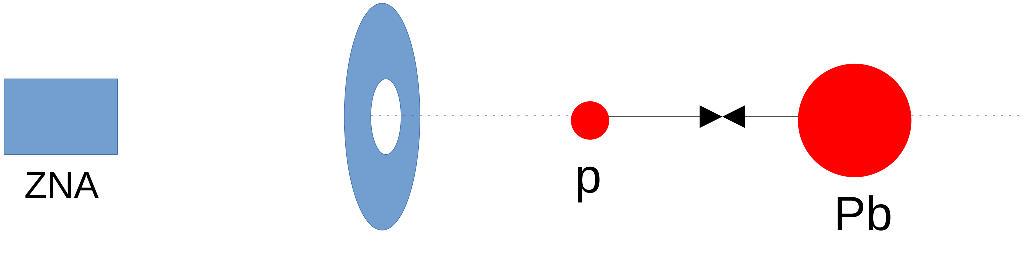
ALICE, Eur. Phys. J C76 (2016) 271



- Event activity in ZNA from Pb spectators
- Model dependent $\langle N_{coll}\rangle$ based on signal from V0A in Pb-going direction

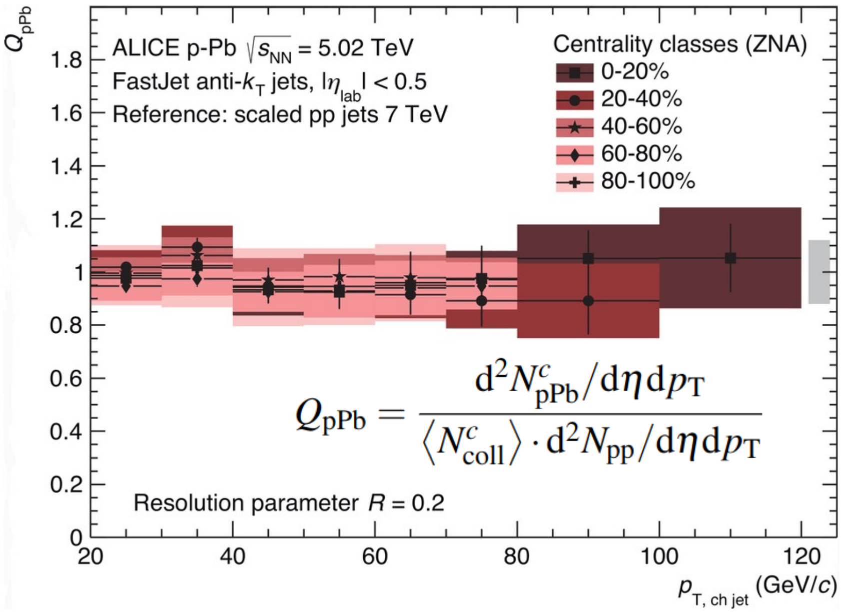
$$\left\langle N_{coll}^{Pb-side}\right\rangle_c = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S\rangle_c}{\langle S\rangle_{MB}}$$

- $Q_{pPb} \sim 1 \Rightarrow$ no evidence for jet quenching



Q_{pPb} and R_{pPb} of jets vs event activity

ALICE, Eur. Phys. J C76 (2016) 271



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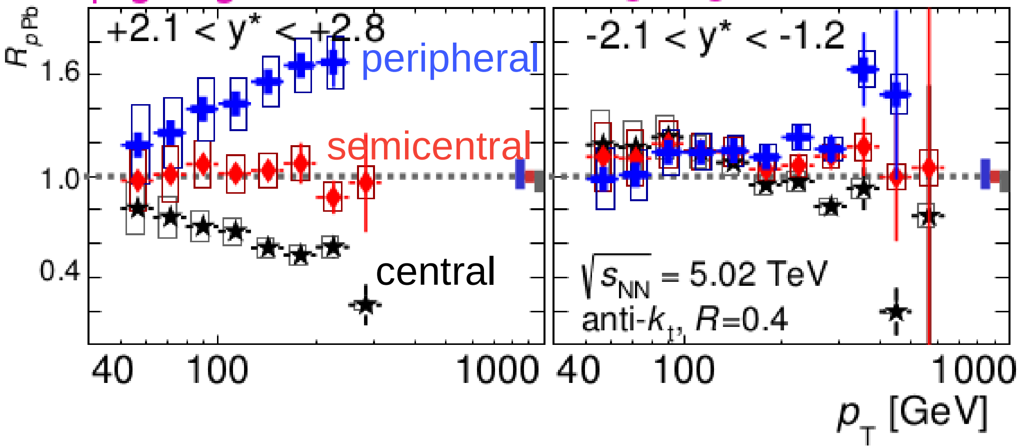
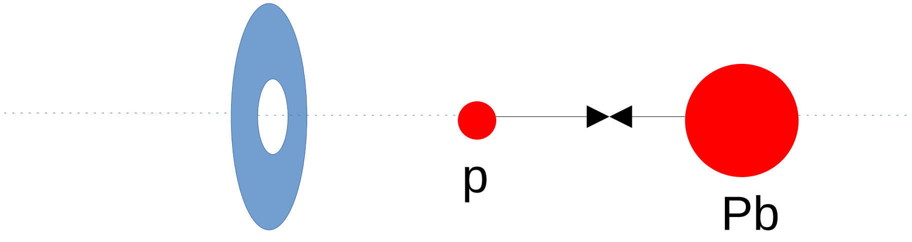
- Q_{pPb} ~ 1 ⇒ no evidence for jet quenching

ATLAS, Phys. Lett. B 748 (2015) 392-413

p-going direction Pb-going direction



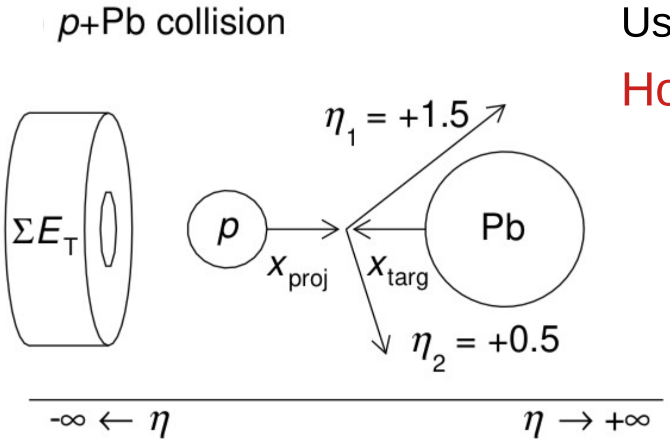
- Minimum bias events: R_{pPb} ~ 1 for all y^* ranges
- Events with activity bias: R_{pPb} depends on jet y^*



ATLAS FCal calo. -4.9 < η < -3.2

Centrality dependence of the dijet yield in p-Pb

ATLAS, Phys. Rev. Lett. 132 (2024) 102301



FCal in Pb going direction
-4.9 < η < -3.2

Use dijets to constrain parton kinematics & measure event activity in FCal

How is R_{CP} affected by x of interacting partons ?

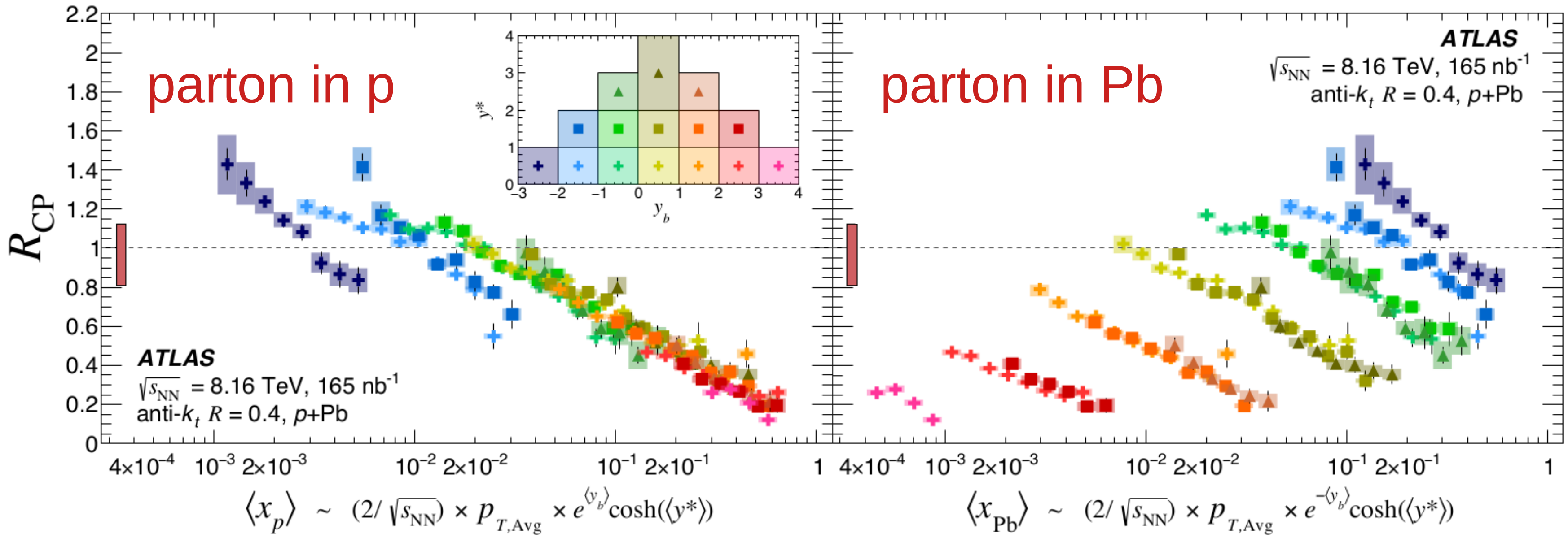
$$x_p = \frac{p_{\mathrm{T},1} e^{y_1^{\mathrm{c.m.}}} + p_{\mathrm{T},2} e^{y_2^{\mathrm{c.m.}}}}{\sqrt{s_{\mathrm{NN}}}} \simeq \frac{2 p_{\mathrm{T,Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{y_b} \cosh(y^*),$$

$$x_{\mathrm{Pb}} = \frac{p_{\mathrm{T},1} e^{-y_1^{\mathrm{c.m.}}} + p_{\mathrm{T},2} e^{-y_2^{\mathrm{c.m.}}}}{\sqrt{s_{\mathrm{NN}}}} \simeq \frac{2 p_{\mathrm{T,Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_b} \cosh(y^*),$$

$$p_{\mathrm{T,Avg}} = \frac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2}, \quad y_{\mathrm{b}} = \frac{y_1^{\mathrm{c.m.}} + y_2^{\mathrm{c.m.}}}{2}, \quad \text{and} \quad y^* = \frac{|y_1^{\mathrm{c.m.}} - y_2^{\mathrm{c.m.}}|}{2}$$

Centrality dependence of the dijet yield in p-Pb

ATLAS, Phys. Rev. Lett. 132 (2024) 102301



leading jet:
$p_{Tjet} > 40$ GeV

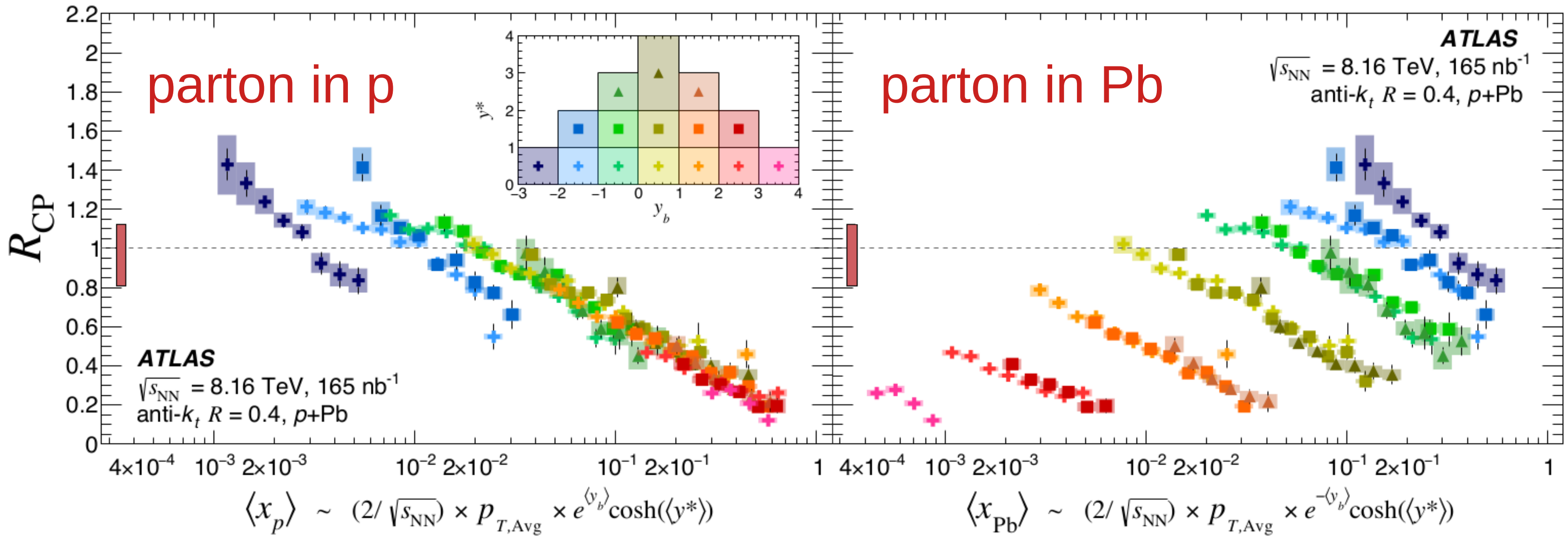
subleading jet:
$p_{Tjet} > 30$ GeV

$$R_{CP}(p_{T,Avg}, y_b, y^*) = \frac{\dfrac{1}{\langle T_{AB}^{0-10\%}\rangle}\dfrac{1}{N_{evt}^{0-10\%}}\dfrac{d^3N_{dijet}^{0-10\%}}{dp_{T,Avg}dy_b dy^*}}{\dfrac{1}{\langle T_{AB}^{60-90\%}\rangle}\dfrac{1}{N_{evt}^{60-90\%}}\dfrac{d^3N_{dijet}^{60-90\%}}{dp_{T,Avg}dy_b dy^*}},$$

- Collisions involving larger x partons are likely to be characterized as more peripheral

Centrality dependence of the dijet yield in p-Pb

ATLAS, Phys. Rev. Lett. 132 (2024) 102301



leading jet:
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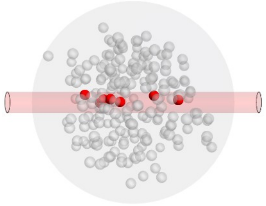
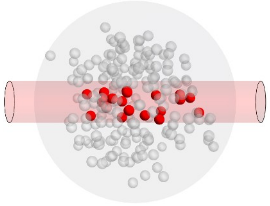


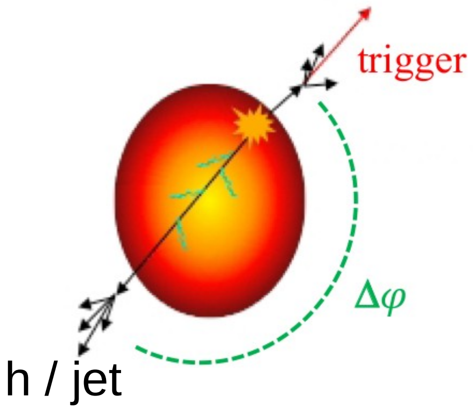
p with high-x parton ⇒ peripheral



proton with low-x parton ⇒ central

- Collisions involving larger x partons are likely to be characterized as more peripheral
- Qualitatively in agreement with the x_p-dependent color fluctuation effects Phys. Rev. D 98 (2018) 071502

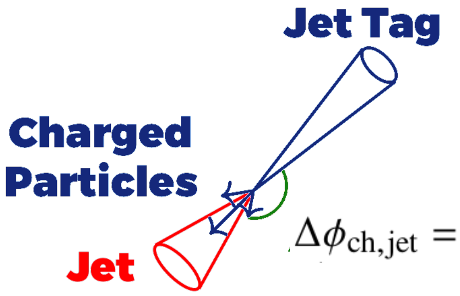
Semi-inclusive measurements



$$\frac{1}{N_{\mathrm{trig}}^{AA}} \frac{\mathrm{d}^2 N_{\mathrm{h/jet}}^{AA}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T,trig}}} \xrightarrow{\text{w/o nuclear effects}} \frac{1}{N_{\mathrm{trig}}^{\mathrm{pp}}} \frac{\mathrm{d}^2 N_{\mathrm{h/jet}}^{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T,trig}}}$$

Constraints on jet quenching in centrality-dependent p-Pb

ATLAS, Phys. Rev. Lett. 131 (2023) 072301

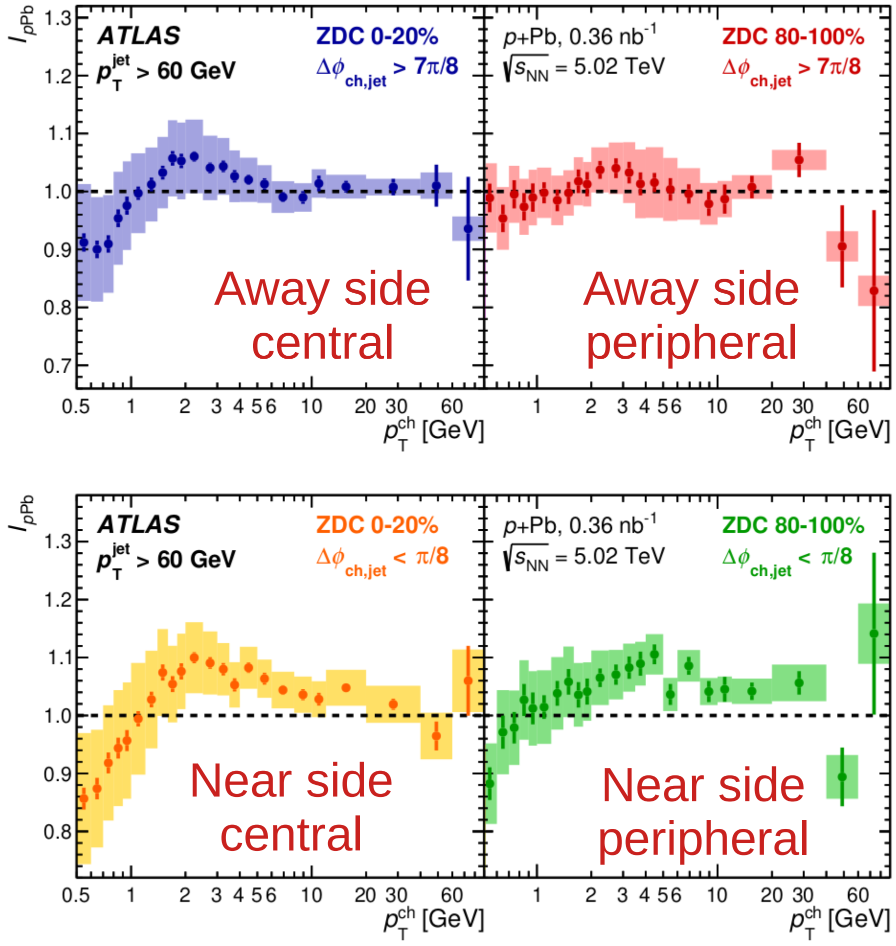


$$\Delta\phi_{\mathrm{ch,jet}} = |\phi_{\mathrm{ch}} - \phi_{\mathrm{jet}}|$$

$$I_{pPb} = \frac{Hadron\ yield\ per\ jet|_{p+Pb}}{Hadron\ yield\ per\ jet|_{p+p}}$$

- Corrected for UE using MB events with similar FCal signal
- Centrality ZDC (spectator neutrons)
- I_{pPb} selfnormalized ⇒ does not need $\langle N_{\mathrm{coll}} \rangle$

- Enhancement at near side
- Cronin-like enhancement at low p_T



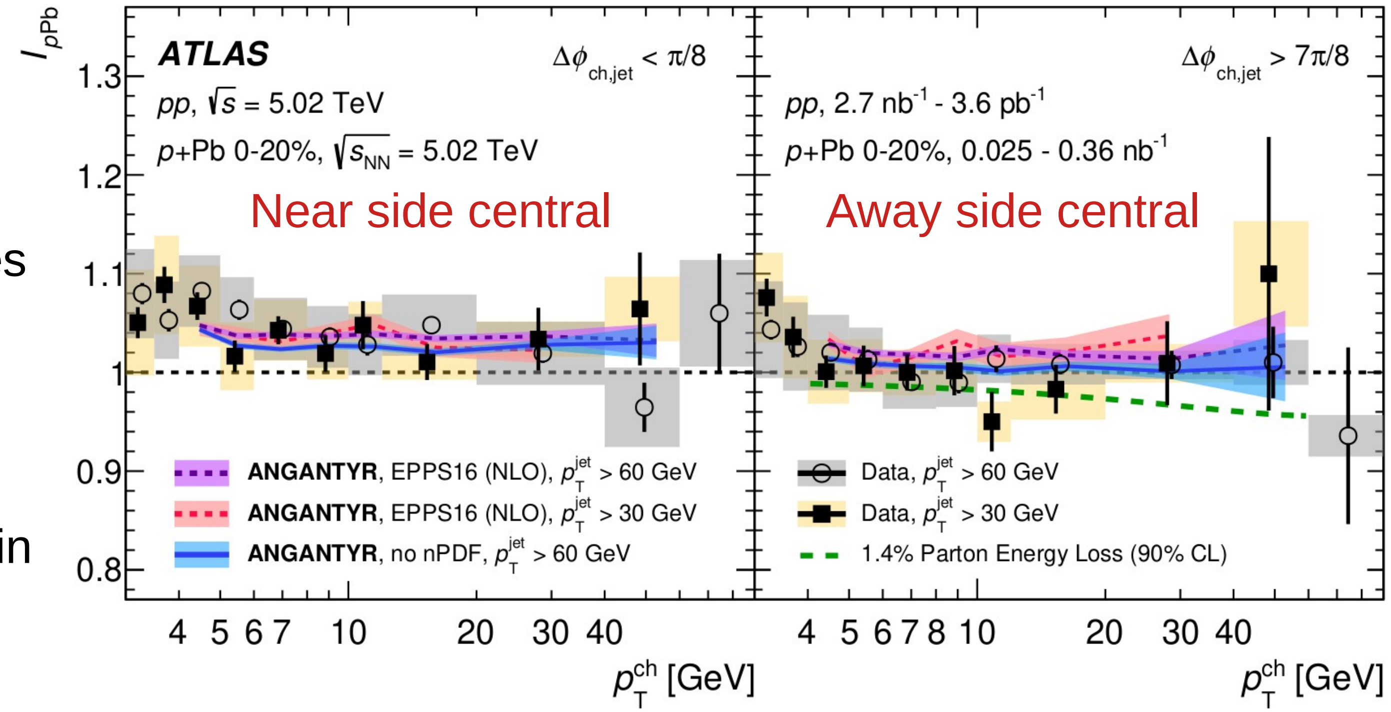
Constraints on jet quenching in centrality-dependent p-Pb

ATLAS, Phys. Rev. Lett. 131 (2023) 072301

ANGANTYR

C. Bierlich at al. JHEP 10 (2018) 134

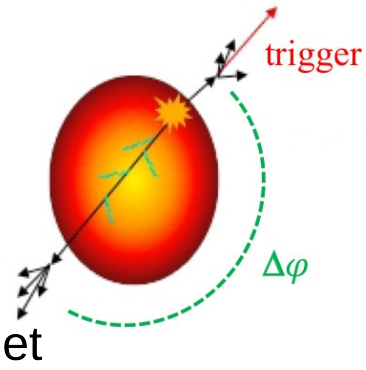
- PYTHIA based model does not account for QGP
- Reproduces data
- Nearside enhancement is not due to nPDFs & isospin & interaction with QGP



E-loss modeled with PYTHIA parton energy loss constrained to be 0.2 ± 0.5 % ⇒ less than 1.4% at the 90% CL

Search for jet quenching in high-multiplicity pp

ALICE, JHEP 05 (2024) 229



Observable: per trigger hadron normalized yield of correlated jets

$$\Delta_{\rm recoil}(\Delta\varphi) = \frac{1}{N_{\rm trig}}\frac{{\rm d}N_{\rm jet}}{{\rm d}\Delta\varphi}\bigg|_{{\rm TT}\{20,30\}\,\&\,p_{\rm T,jet}^{\rm ch}} - c_{\rm ref}\cdot\frac{1}{N_{\rm trig}}\frac{{\rm d}N_{\rm jet}}{{\rm d}\Delta\varphi}\bigg|_{{\rm TT}\{6,7\}\,\&\,p_{\rm T,jet}^{\rm ch}}$$

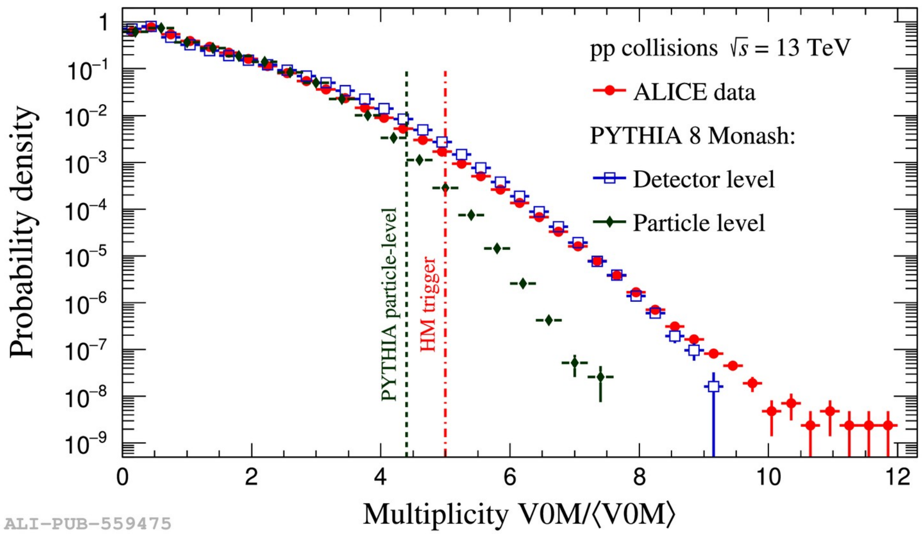
Yield of uncorrelated jets is subtracted in data-driven way

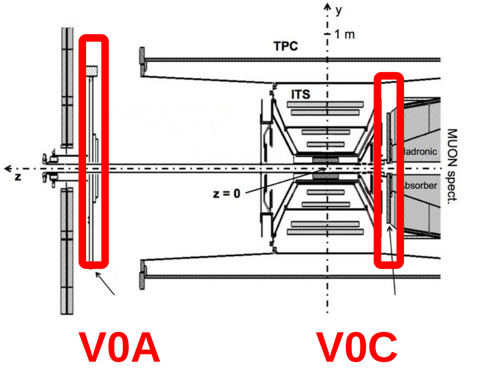
- Trigger:
  - Minimum bias (MB)
  - High multiplicity (HM)
- Event activity selection:

  V0M = V0A + V0C
- HM is 0.1% of MB cross sec.

  5 < V0M / ⟨V0M⟩ < 9

  ⟨V0M⟩ = average in MB



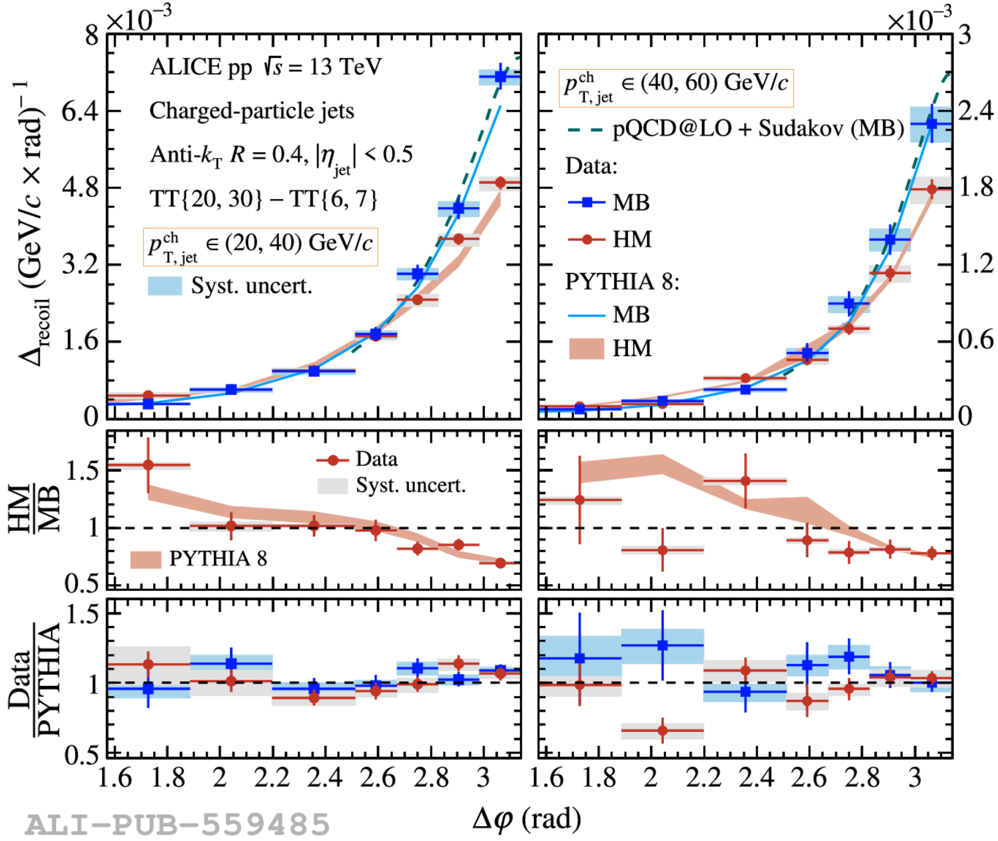


2.8 < η < 5.1

-3.7 < η < -1.7

Search for jet quenching in high-multiplicity pp

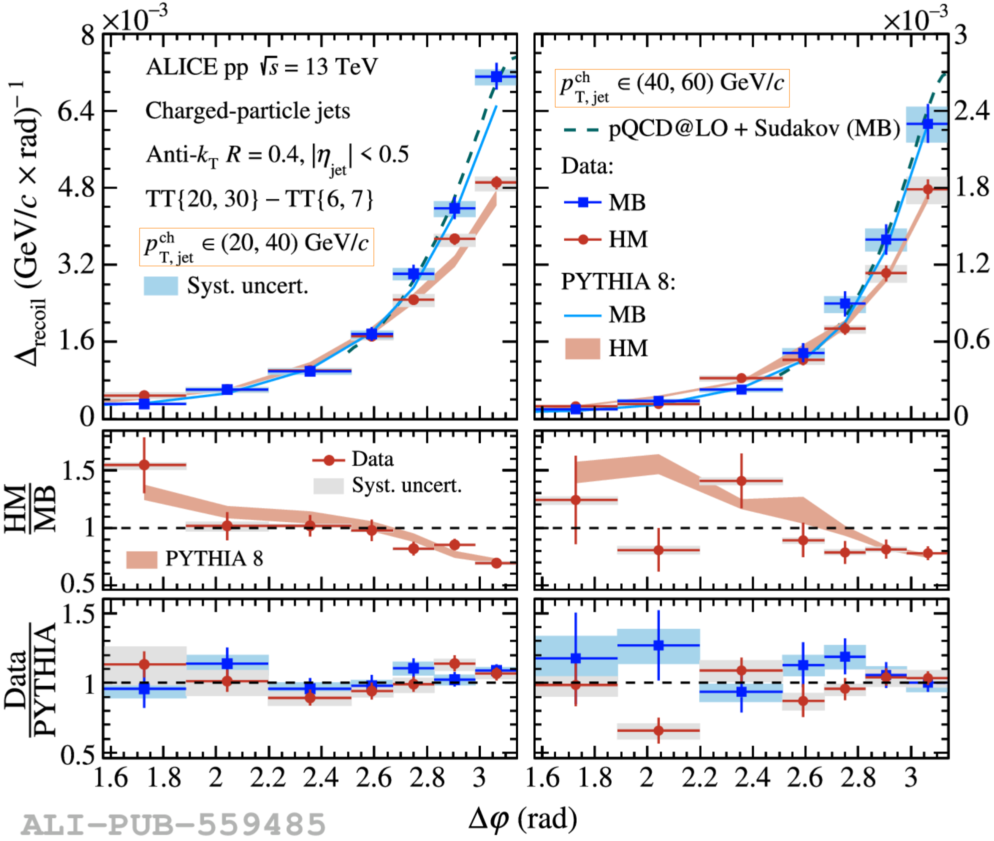
ALICE, JHEP 05 (2024) 229

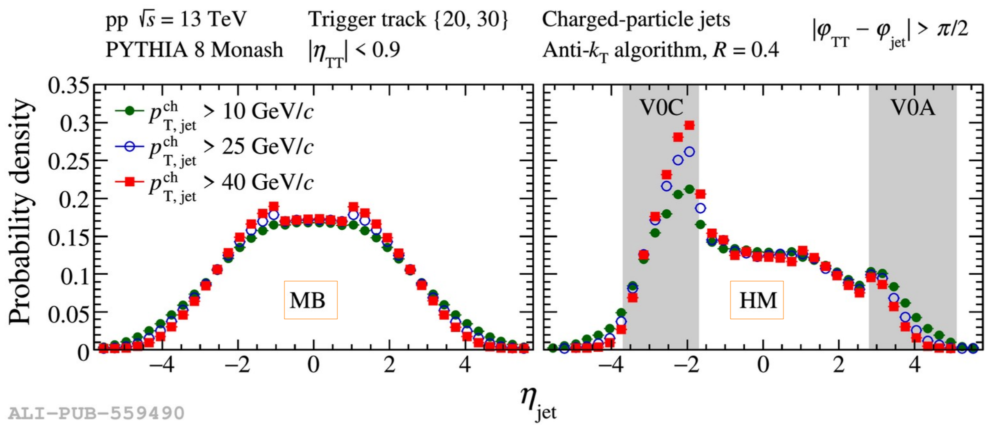


- Suppression of back to back correlation in HM w.r.t. MB
- Reproduced by PYTHIA

Search for jet quenching in high-multiplicity pp

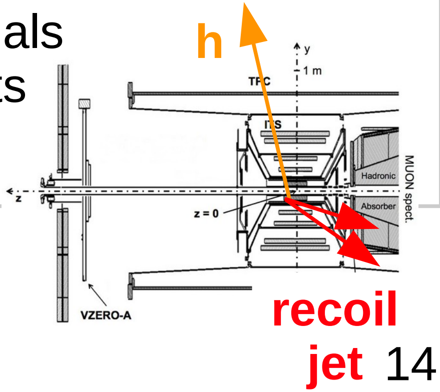
ALICE, JHEP 05 (2024) 229





Lesson learned from PYTHIA :

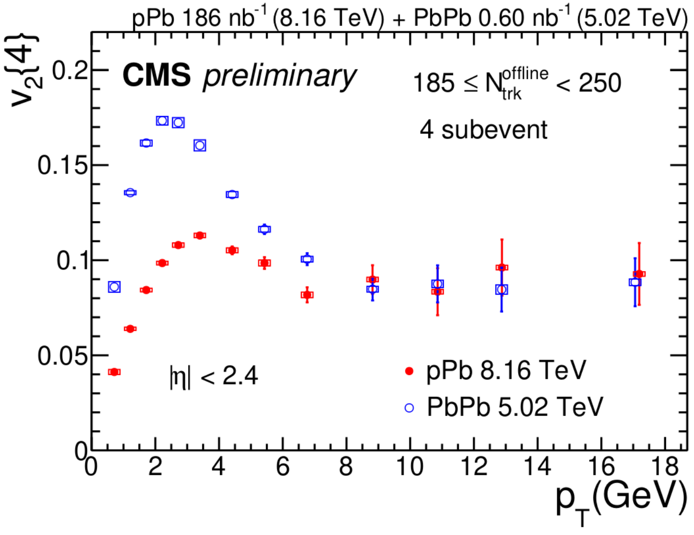
- HM trigger enhances probability to have a high-p_T jet in V0C
- Small jet quenching signals can be masked by effects coming from trigger

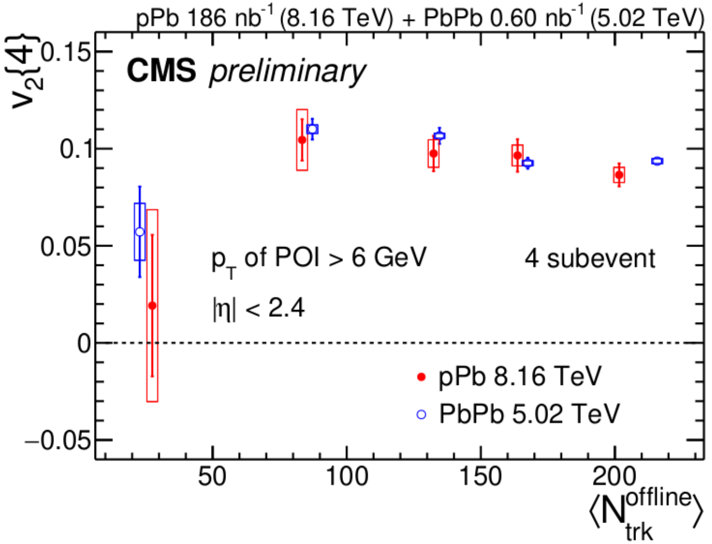


- Suppression of back to back correlation in HM w.r.t. MB
- Reproduced by PYTHIA

Summary

- Jet quenching in small collision systems not seen yet - likely to be a small effect
- Jet quenching signatures can be created by event selection biases
  - picking up fluctuations in particle wavefunction when imposing event activity bias
  - NLO processes with multi-jet topology in final state
- We need to understand origin of high-p_T track v_2



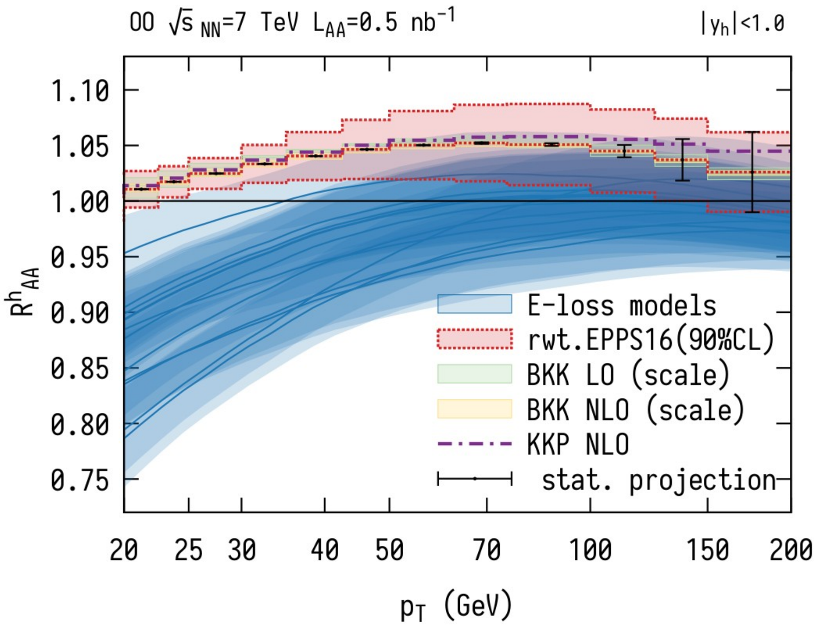


CMS-PAS-HIN-23-002

Outlook

OO $\sqrt{s_{NN}}$ = 6.37 TeV run at the LHC in 2025 minimum bias should provide sufficient precision

$$R_{\mathrm{AA}}^{\mathrm{min.bias}} = \frac{1}{A^2} \cdot \frac{\mathrm{d}^2\sigma_{\mathrm{pA}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

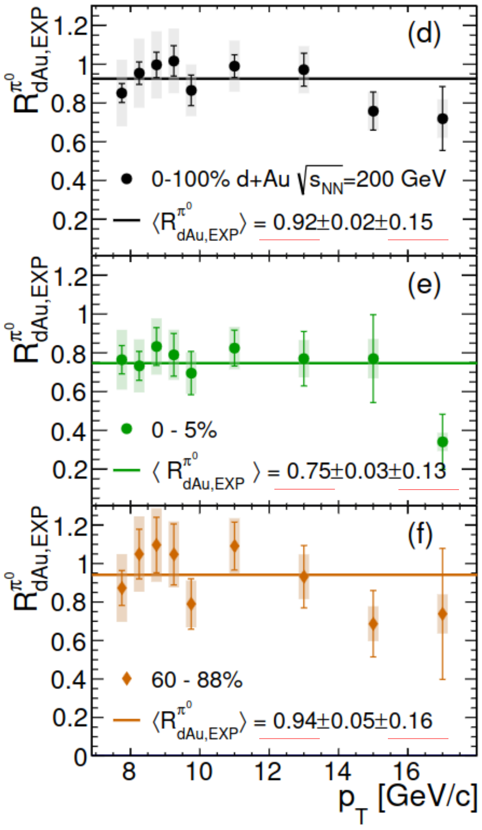


Huss et al., Phys. Rev. Lett. 126, 192301 (2021)

Backup

Disentangling centrality bias and final-state effect in d-Au

PHENIX, arXiv:2303.12899



Avoid usage of Glauber N_{coll} based on γ^{dir}:

$$R^{\gamma^{dir}}_{dAu} = 1 \Rightarrow \quad N^{EXP}_{coll}(p_T) = \frac{Y^{\gamma^{dir}}_{dAu}(p_T)}{Y^{\gamma^{dir}}_{pp}(p_T)}$$

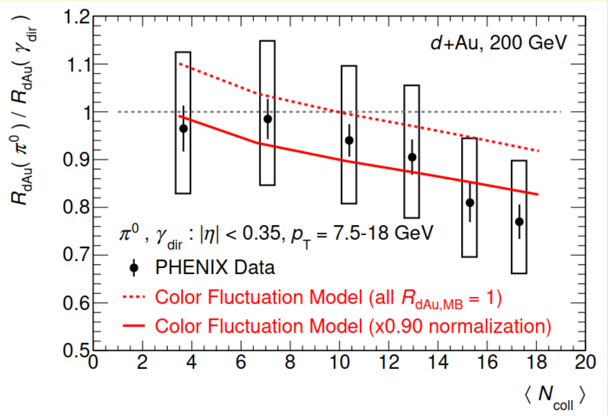
$$R^{\pi^0}_{dAu,EXP} = \frac{Y^{\pi^0}_{dAu}}{N^{EXP}_{coll}\; Y^{\pi^0}_{pp}} = \frac{Y^{\pi^0}_{dAu}/Y^{\pi^0}_{pp}}{Y^{\gamma^{dir}}_{dAu}/Y^{\gamma^{dir}}_{pp}}$$

Cent.	$N^{Glauber}_{coll}$	N^{EXP}_{coll}
MB	7.6 ± 0.4	7.6 ± 1.2
0-5%	18.1±1.2	17.3±2.9
60-88%	3.2 ± 0.2	3.7 ± 0.6

D. Perepelitsa, arXiv:2404.17660

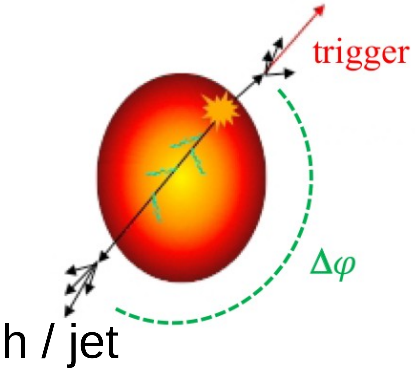
Partons producing γ^{dir} and π^0 have different x ⇒ different color fluctuations

Phys. Rev. D 98 (2018), 071502(R)



Semi-inclusive measurements

$$\frac{1}{N_{\mathrm{trig}}^{AA}}\frac{\mathrm{d}^2 N_{\mathrm{h/jet}}^{AA}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T,trig}}} = \frac{1}{\sigma^{AA\rightarrow\mathrm{trig}+X}}\frac{\mathrm{d}^2\sigma^{AA\rightarrow\mathrm{trig}+\mathrm{h/jet}+X}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T,trig}}}$$

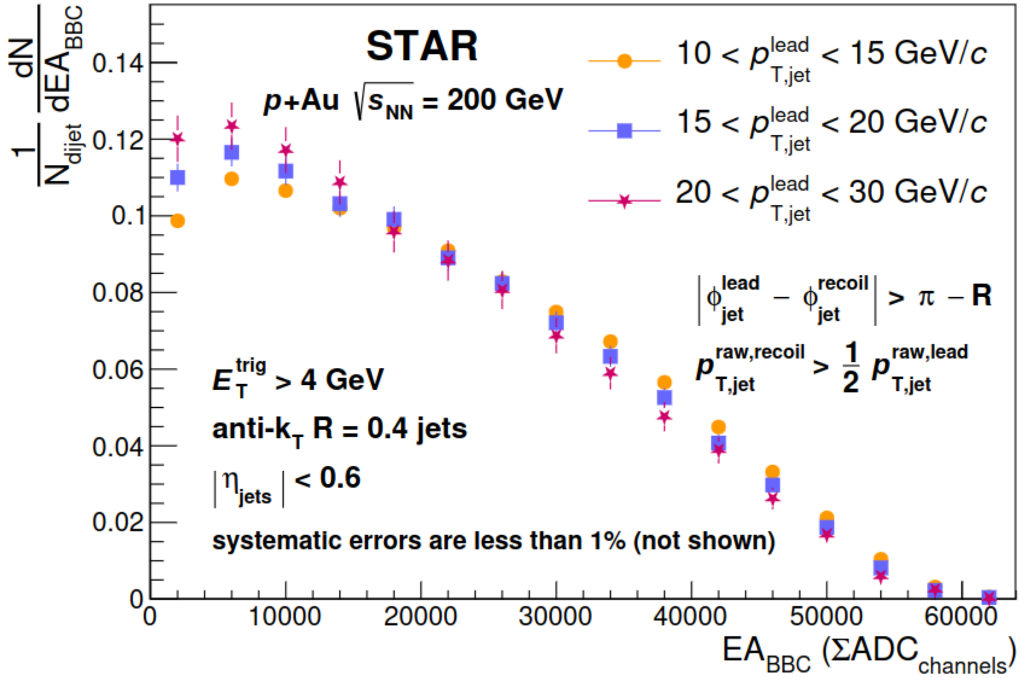


in case of no nuclear effects

$$= \frac{\langle T_{AA}\rangle}{\langle T_{AA}\rangle}\cdot\frac{1}{\sigma^{\mathrm{pp}\rightarrow\mathrm{trig}+X}}\frac{\mathrm{d}^2\sigma^{\mathrm{pp}\rightarrow\mathrm{trig}+\mathrm{h/jet}+X}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T,trig}}} = \frac{1}{N_{\mathrm{trig}}^{\mathrm{pp}}}\frac{\mathrm{d}^2 N_{\mathrm{h/jet}}^{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T,trig}}}$$

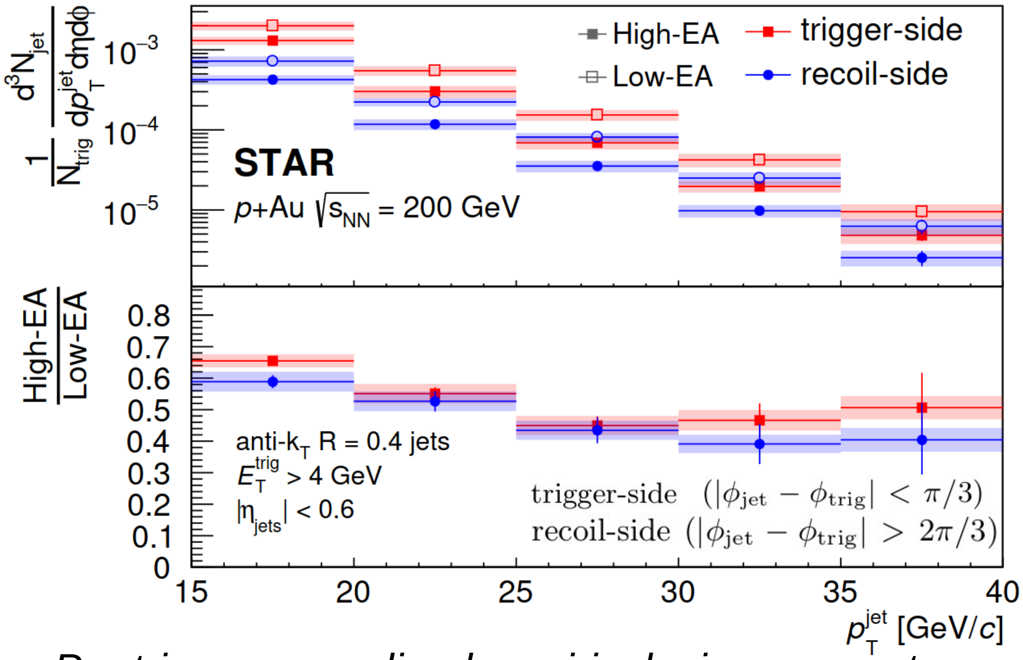
Correlations of event activity with hard and soft processes in p-Au

STAR, arXiv:2404.08784v1



Event activity in events having dijet in TPC BBC in Au direction: $-5 < \eta_{BBC} < -3.4$

Anticorrelation between average Q^2 of hard scattering in midrapidity and forward EA

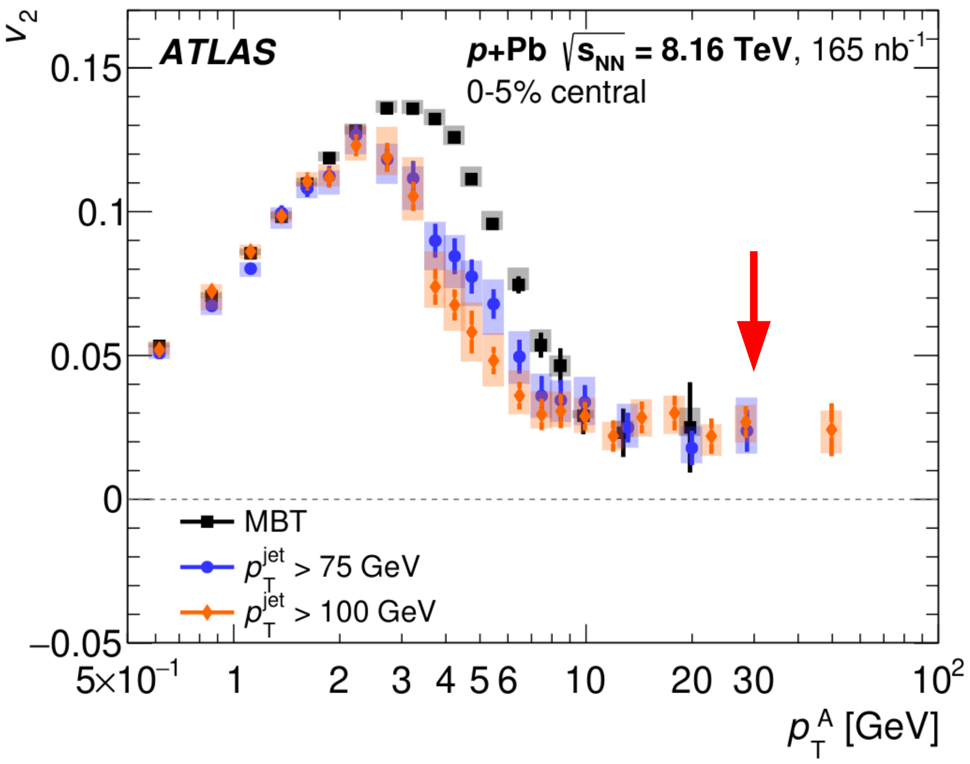


Per trigger normalized semi-inclusive p_T spectrum of jets in coincidence with a calo trigger $E^{trig} > 4$ GeV

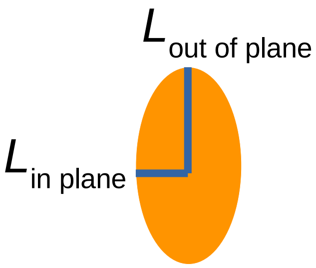
- suppression in ratios is not due to jet quenching EA selection biases abundance of Q^2 proceses
- EA bias does not impact dijet acoplanarity and dijet momentum imbalance

Flow of high-p_T particles in p-Pb from ATLAS

ATLAS, Eur. Phys. J. C 80 (2020) 73



Asymmetric collision zone



Radiative energy loss of partons

$$\Delta E \propto \hat{q} L^2$$

BDMPS, Nucl. Phys. B483 (1997) 291

Measurement of the sensitivity of two-particle correlations in pp collisions to the presence of hard scatterings by ATLAS

ATLAS, Phys. Rev. Lett 131 (2023) 162301

Correlation classes:

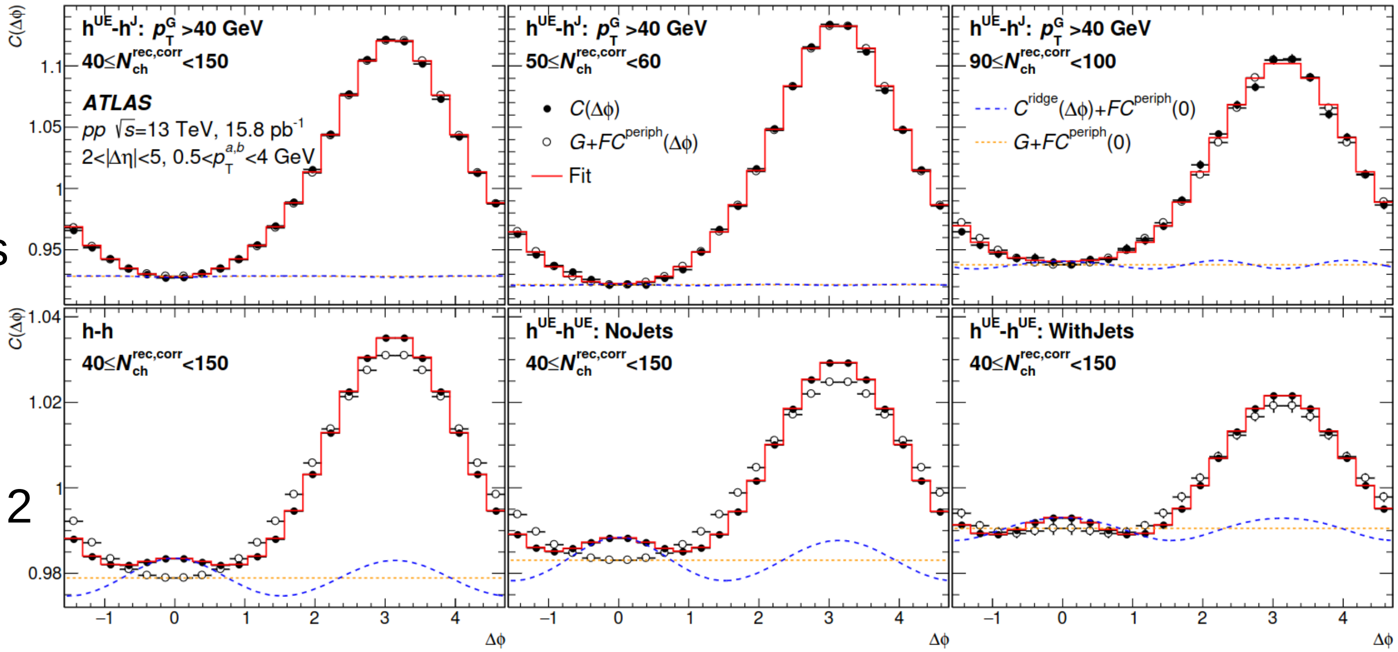
- h - h
- h^{UE} - h^{UE} in all events
- h^{UE} - h^{UE} in events w/o jets
- h^{UE} - h^{UE} in events with jets
- h^{UE} - h^{Jet}

h^{UE}: $0.5 < p_T < 4$ GeV

Nonflow suppression: $|\Delta\eta| > 2$

Groomed jet p_T:

$$p_T^G = \left| \sum_{\text{constituents}} \boldsymbol{p}_T^{>4\text{ GeV}} \right|$$

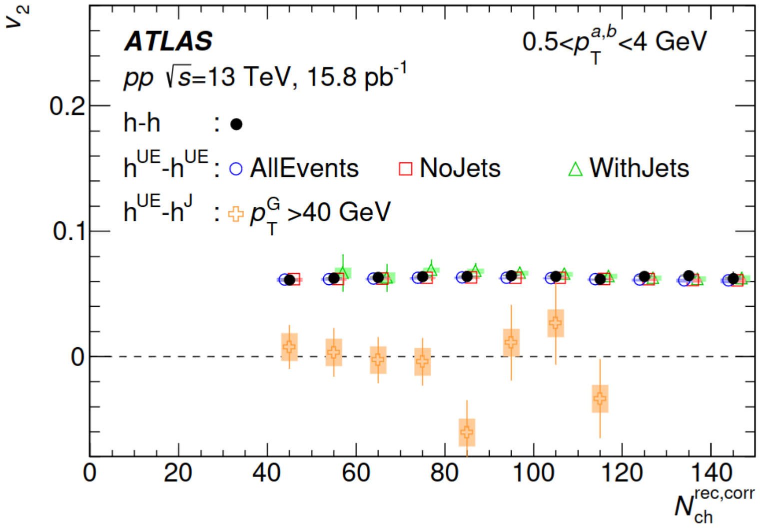


$$C(\Delta\phi) = FC^{\text{periph}}(\Delta\phi) + G\left(1 + 2\sum_{n=2} v_{n,n}\cos(n\Delta\phi)\right)$$

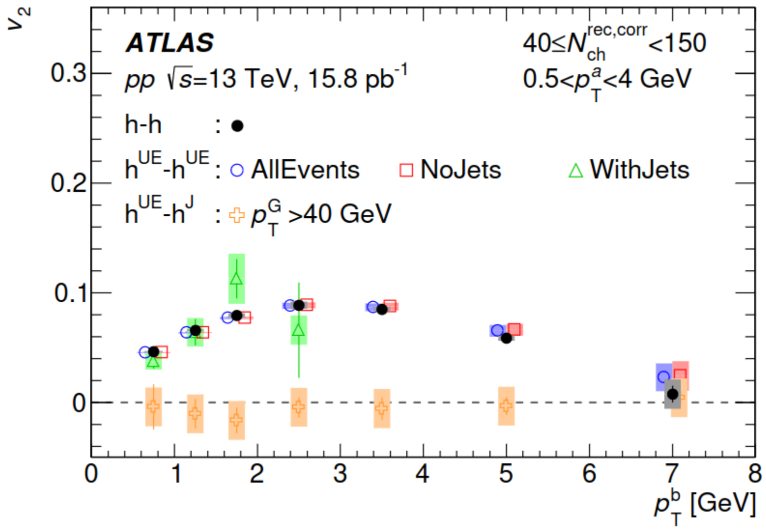
Measurement of the sensitivity of two-particle correlations in pp collisions to the presence of hard scatterings by ATLAS

ATLAS, Phys. Rev. Lett 131 (2023) 162301

v_2 vs multiplicity of UE tracks



v_2 vs hadron p_T



$$v_n(p_{\mathrm{T}}^{\mathrm{b}}) = v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{b}}) / \sqrt{v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{a}})}$$

Particles associated with jets do not exhibit any significant azimuthal correlations with UE

Summary and outlook

- Jet quenching in small collision systems not seen yet - likely to be a small effect
- Jet quenching signatures can be created by event selection biases

  - picking up fluctuations in particle wavefunction when imposing event activity bias

  - NLO processes with multi jet topology in final state

- OO $\sqrt{s_{NN}}$ = 6.37 TeV run at the LHC in 2025 minimum bias should provide sufficient precision

$$R_{AA}^{\text{min.bias}} = \frac{1}{A^2} \cdot \frac{\mathrm{d}^2\sigma_{\mathrm{pA}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}^{h,j}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

Huss et al., Phys. Rev. Lett. 126, 192301 (2021)