Exploring flow signals and jet modification in small systems at the LHC

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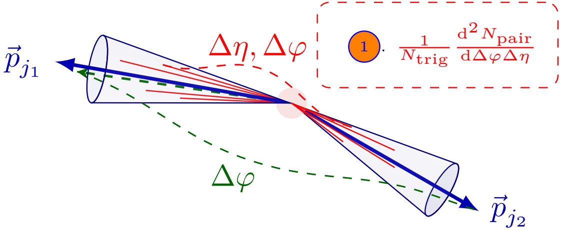
Wednesday 15th January, 2025

10th Asian Triangle Heavy-Ion Conference 2025
Berhampur, Odisha, India

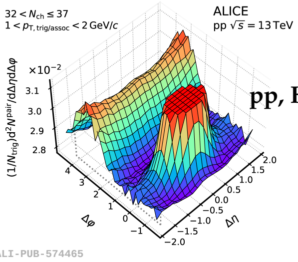
- Strong collectivity and jet quenching observed in larger systems → Formation of Quark-Gluon Plasma
- Evidence of collectivity also observed in high-multiplicity pp and p–Pb collisions
  ALICE, JHEP 05 (2021) 290, Phys. Lett. B 719 (2013) 29
- No evidence of jet quenching in small systems so far ALICE, *JHEP* 05 (2024) 041

Key Questions still remain:

1. **How to measure collective flow in small systems while jets are dominant?**
2. **Possible observables for jet quenching in small systems?**

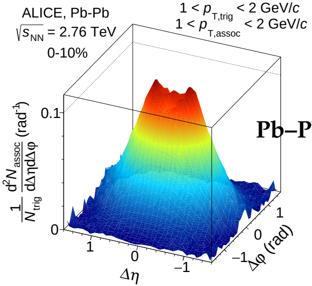


$$\frac{1}{N_{\rm trig}} \frac{d^2 N_{\rm pair}}{d\Delta\eta\Delta\varphi}(\Delta\eta, \Delta\varphi)$$



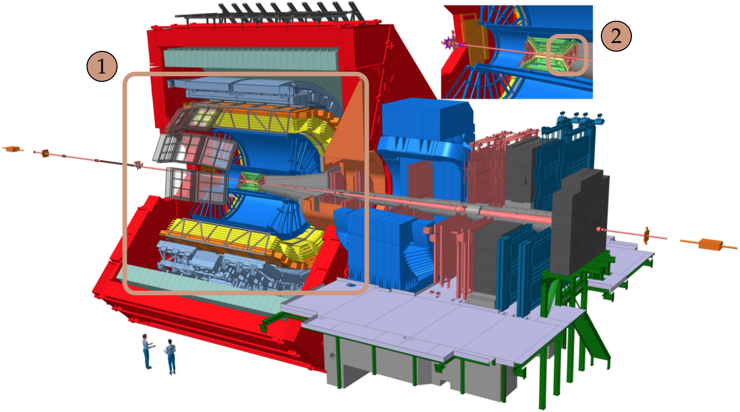
pp, HM, ridge

ALICE, *Phys. Rev. Lett.* 132, 172302



Pb–Pb, Broadening

ALICE, *Phys. Rev. Lett.* 119 (2017) 102301



More about ALICE
ALICE, *Eur. Phys. J. C* 84, 813 (2024)

1 Midrapidity Multiplicity Estimator ($|\eta| < 0.8$)

- Event activity estimated with tracks
- Directly translates to $\langle N_{ch} \rangle$ with unfolding

ALICE, *JHEP03* (2024) 092

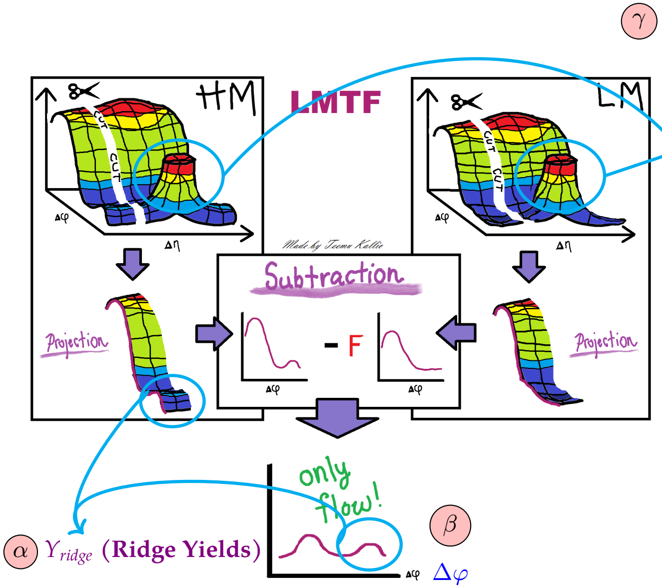
- pp, $\sqrt{s} = 13$ TeV, $N_{\mathrm{ch}} \simeq 80$
- Pb–Pb, $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, $N_{\mathrm{ch}} \simeq 3000$

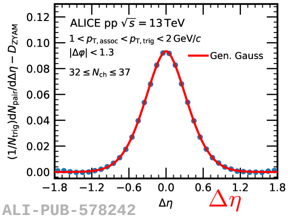
ALICE, Physics Letters B 845 (2023) 138110

2 Forward Multiplicity Estimator

- Run 2, V0M, $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$
- **Run 3, FT0M**, $3.5 < \eta < 4.9$ and $-3.3 < \eta < -2.1$
- Measures centrality percentiles

ALICE, *Eur. Phys. J. C* 81, 630





Jets, Short Range Correlation:

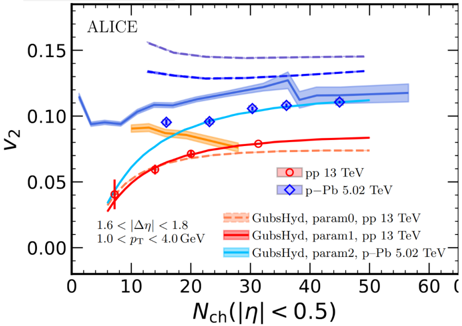
1. Project to $\Delta\eta$ for $|\Delta\varphi| < 1.3$
2. Evaluate jet yields and shapes

Flow, Long Range correlation

1. Project to $\Delta\varphi$ for $1.6 < |\Delta\eta| < 1.8$
2. Subtract LM from HM with a template fit $\rightarrow$ flow magnitudes(v_2 and v_3)

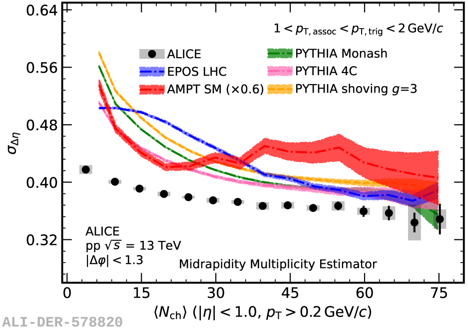
ALICE, JHEP 03 (2024) 092

Anna Önnerstad



ALICE, arXiv:2409.04501

Maxim Virta



- Finite elliptic flow measured in small systems
- Jet shape modification as a function of multiplicity and p_T
- PYTHIA: Only jets, AMPT and EPOS: Jets+Flow
- Second assumption for the LM-template fit got broken
- Instead of broadening as a signature of jet quenching expected from larger system, we found narrowing in HM events, this is represented in PYTHIA → Disentangle QCD bias to QGP effects in small systems

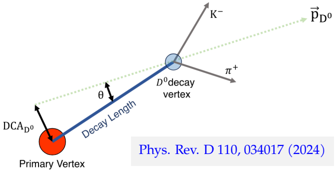
- **Observation:**
  - Universal behavior of charm fragmentation function breaks in *pp* compared to e^+e^- (e.g. arXiv:2105.06335)
- **Measurement Challenge:**
  - Most measurements include underlying event (UE) contributions
  - This complicates direct comparison with models
  - Large jet contamination makes traditional methods ineffective
- **Solution: Two-particle Correlation Method**
  - Currently the only viable technique to extract flow signals:
    - Effectively removes UE contributions
    - Successfully handles large jet contamination (LM-template)
  - Enables direct comparison with models without UE activities
  - Provides cleaner test of fragmentation universality

- pp, $\sqrt{s} = 13.6$ TeV (PYTHIA8, Monash)
- Mid-rapidity multiplicity, *i.e.*, $|\eta| < 0.8$, $p_{\mathrm{T}} > 0.2$ GeV$/c$
- $2.0 < p_{\mathrm{T,trig}}^{D^0} < 8.0$ GeV$/c$, $1.0 < p_{\mathrm{T,assoc}} < 3.0$ GeV$/c$, $|\eta| < 0.8$
- Fit the invariant mass distribution with signal+background

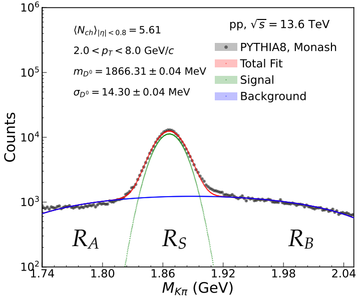
$$f(m_{D^0}) = \underbrace{a + bm_{D^0} + cm_{D^0}^2}_{\equiv B(m_{D^0})} + \underbrace{AG(m_{D^0}, M_{D^0}, \sigma)}_{\equiv S(m_{D^0})}$$

- Sideband regions, $\mathcal{R_A}, \mathcal{R_B} \in [\pm 4\sigma, \pm 8\sigma]$
- Signal region, $\mathcal{R_S} \in [-2\sigma, 2\sigma]$
- Extract the relative background $\alpha_{\mathcal{R_A}}$ and $\alpha_{\mathcal{R_B}}$ from the fit
- Subtract the sideband 2D correlation function as,

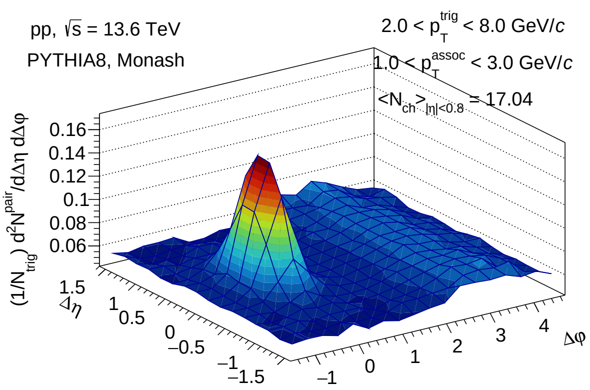
$$\left(\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\phi}\right)^{\mathcal{R_S}} - \alpha_{\mathcal{R_A}}\left(\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\phi}\right)^{\mathcal{R_A}} - \alpha_{\mathcal{R_B}}\left(\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\phi}\right)^{\mathcal{R_B}}$$

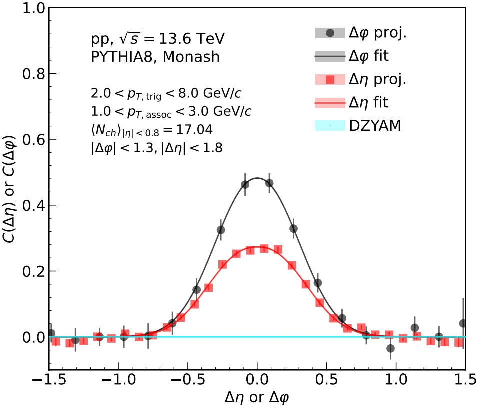


Phys. Rev. D 110, 034017 (2024)



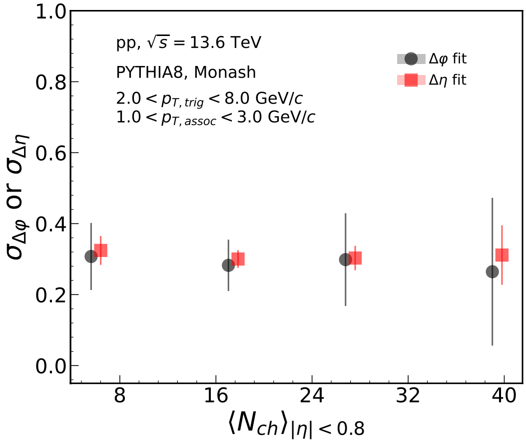
- The final correlation function is normalized by $N_{\mathcal{R_S}}^{\mathrm{trig}} - \alpha_{\mathcal{R_A}} N_{\mathcal{R_A}}^{\mathrm{trig}} - \alpha_{\mathcal{R_B}} N_{\mathcal{R_B}}^{\mathrm{trig}}$.





- Sideband subtracted D^0-hadron correlation function from PYTHIA8
- $\Delta\varphi$ projection for $|\Delta\eta| < 1.8$, and $\Delta\eta$ projection for $|\Delta\varphi| < 1.3$
- Fitted with generalized Gaussian function:

$$A + \frac{\beta}{2\alpha\Gamma(1/\beta)} \exp\left[-\left(\frac{|x|}{\alpha}\right)^{\beta}\right], \sigma = \sqrt{\frac{\alpha^2\Gamma(3/\beta)}{\Gamma(1/\beta)}}$$



- Fitted with the generalized Gaussian function

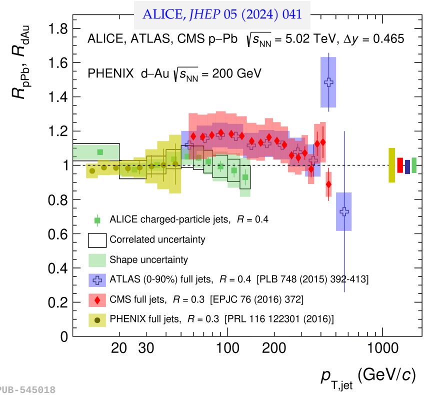
$$A+\frac{\beta}{2\alpha\Gamma(1/\beta)}\exp\left[-\left(\frac{|x|}{\alpha}\right)^{\beta}\right], \sigma=\sqrt{\frac{\alpha^2\Gamma(3/\beta)}{\Gamma(1/\beta)}}$$

- The widths of the jet fragmentation peak extracted from $\Delta\varphi$ and $\Delta\eta$ projections
- Within uncertainty, both $\sigma_{\Delta\varphi}$ and $\sigma_{\Delta\eta}$ are quite comparable in magnitude, no multiplicity dependence unlike light-flavor case
- Broadening of the jet fragmentation peak with increasing multiplicity is associated with jet quenching in HI collisions

- **Finite flow signal down to the low multiplicity** $\langle N_{\mathrm{ch}} \rangle \simeq 10$ (Better understanding of the flow extraction) and **Jet shape from Light-flavor sector** in small systems $\rightarrow$ more insight from theory needed
- D^0-hadron correlation measurement in pp, $\sqrt{s} = 13.6$ TeV
- Very little to no variation in D^0-hadron jet shape vs. multiplicity in pp collisions
- Experimental measurements ongoing including D^0 flow in pp collisions in Run 3

Thank you for your attention!

Min.Bias

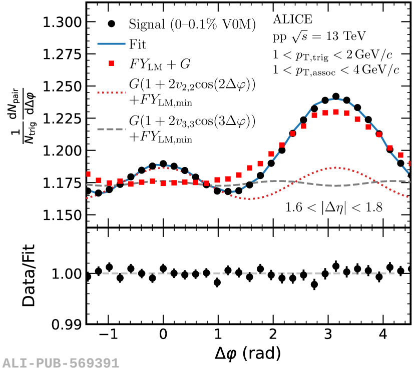


- Evidence of collectivity observed in HM pp and p–Pb ALICE, JHEP 05 (2021) 290, Phys. Lett. B 719 (2013) 29
- No sign of jet quenching in small systems
- Strong collective behaviour associated with QGP formation in large systems

- **Key Questions:**
  1. **How to measure collective flow correctly in small systems?**
  2. **How to probe the creation of QGP in small systems? → How can we best utilize experimental data and model approaches?**
- **Challenges: Flow measurements biased by non-flow effects, jets**

Recent Solutions:

- Latest development: PRC **108**, 034909 (2023), [S. Ji, T. Kallio, M. Virta, D.J. Kim]
  → Definitive suggestion on extracting flow signals in small systems
- Experimental verification: ALICE, JHEP 03 (2024) 092 [A. Önnerstad, J.E. Parkkila, D.J. Kim]
  → Non-flow subtraction was validated and hydro limits

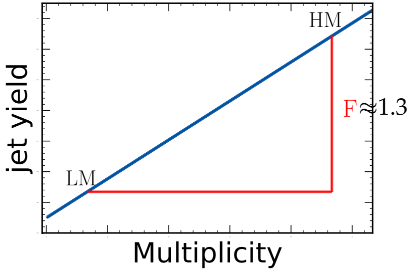


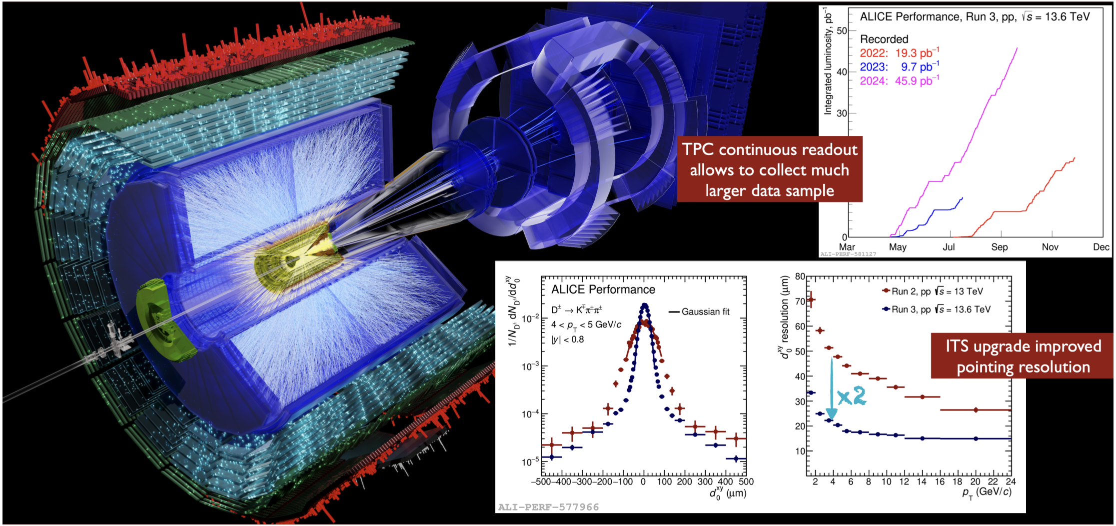
ALICE, *JHEP03* (2024) 092

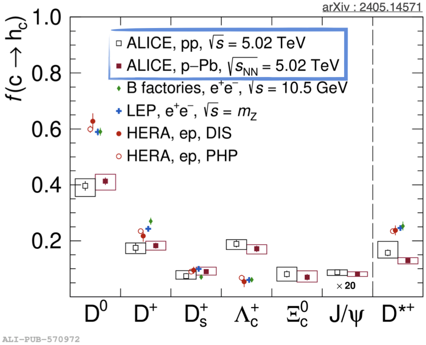
$$Y_{\mathrm{HM}}(\Delta\varphi) = G(1 + 2v_{2,2}\cos(2\Delta\varphi) + 2v_{3,3}\cos(3\Delta\varphi)) + FY_{\mathrm{LM}}(\Delta\varphi)$$

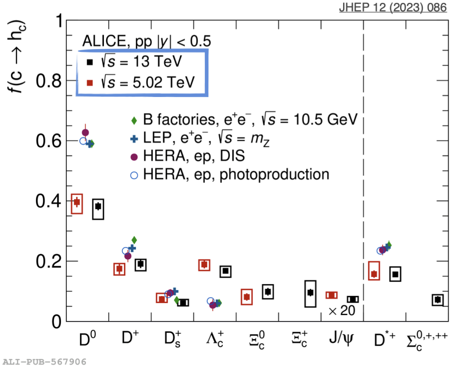
1. No ridge or flow in **Near-Side** in the LM-template
2. No **Away-side** jet shape modifications in HM events

Jet yield is 30% stronger in HM compared to LM




ALICE Performance, Run 3, pp, $\sqrt{s}$ = 13.6 TeV
Recorded
2022: 19.3 pb^{-1}
2023: 9.7 pb^{-1}
2024: 45.9 pb^{-1}
Integrated luminosity, pb^{-1}
Mar
May
Jul
Sep
Nov
Dec
ALI-PERF-581127
TPC continuous readout allows to collect much larger data sample
ALICE Performance
$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$
$4 < p_T < 5$ GeV/c
$|y| < 0.8$
Gaussian fit
$1/N_{D^{\pm}}\, dN_{D^{\pm}}/dd_0^{xy}$
d_0^{xy} (μm)
ALI-PERF-577966
Run 2, pp $\sqrt{s}$ = 13 TeV
Run 3, pp $\sqrt{s}$ = 13.6 TeV
d_0^{xy} resolution (μm)
p_T (GeV/c)
x2
ITS upgrade improved pointing resolution





Fragmentation fractions in pp and p–Pb collisions are consistent with each other

↓

No modification of charm hadronization process due to different hadronic collision system size

Fragmentation fractions do not show energy dependence within the uncertainties