Exploring flow signals and jet modification in small systems with ALICE

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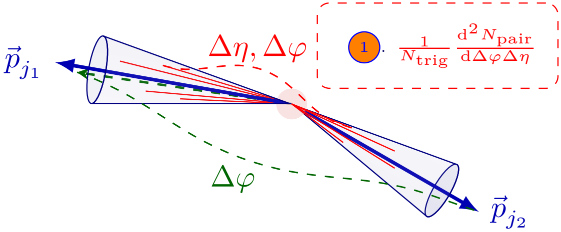
Lammi Research Station

CERN
UNIVERSITY OF JYVÄSKYLÄ
Centre of Excellence in Quark Matter
HELSINKI INSTITUTE OF PHYSICS

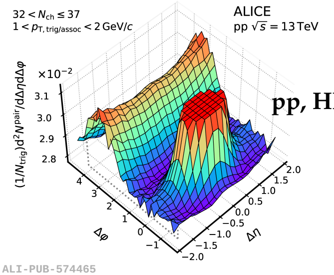
- Strong collectivity and jet quenching observed in larger systems $\rightarrow$ Formation of Quark Gluon Plasma
- Evidence of collectivity also observed in high-multiplicity pp and p–Pb
  ALICE, JHEP 05 (2021) 290, Phys. Lett. B 719 (2013) 29
- No evidence of jet quenching in small systems so far ALICE,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

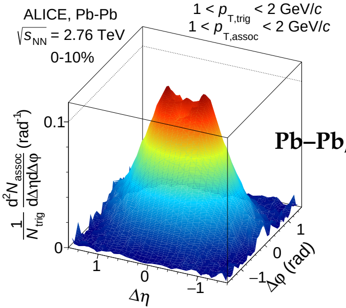


$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\Delta\varphi}(\Delta\eta, \Delta\varphi)$$



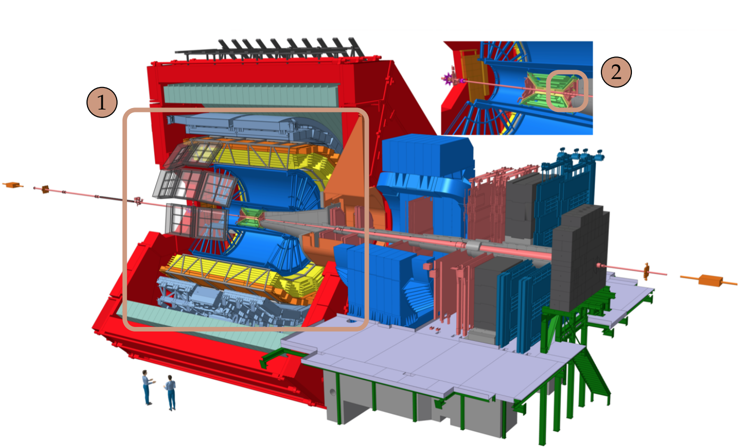
pp, HM, ridge

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

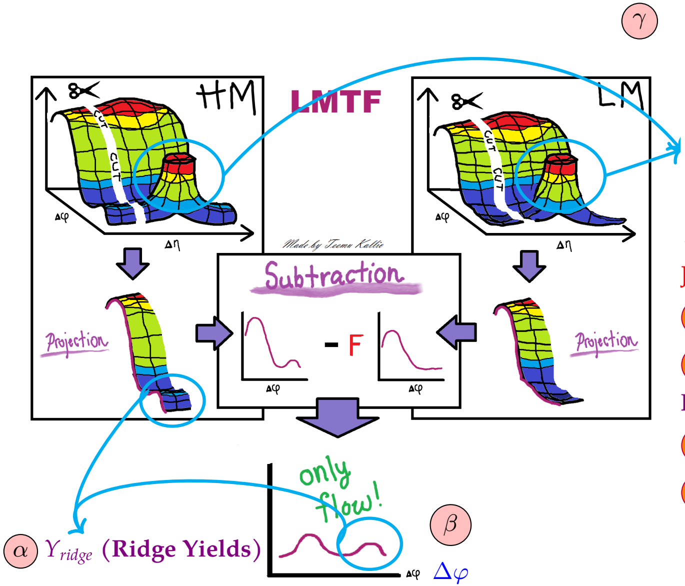
- pp, $\sqrt{s} = 13$ TeV, $N_{\text{ch}} \simeq 80$
- Pb–Pb, $\sqrt{s_{\text{NN}}} = 5.02$ TeV, $N_{\text{ch}} \simeq 3000$

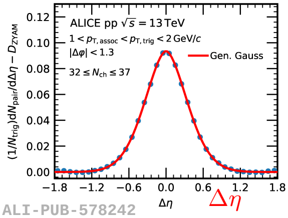
ALICE, Physics Letters B 845 (2023) 138110

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





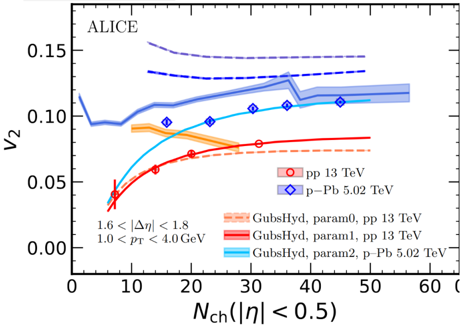
Jets, Short Range Correlation:

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

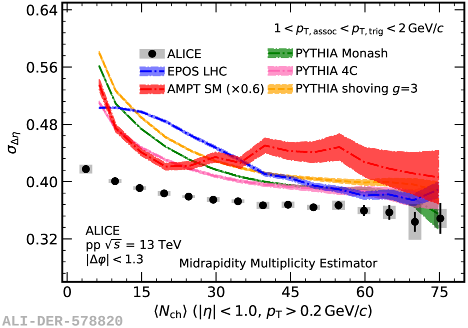
Flow, Long Range correlation

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

Phys. Rev. D 110, 034017 (2024)

- pp, $\sqrt{s} = 13.6$ TeV (Run 3, 2022 and 2023 combined)
- 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

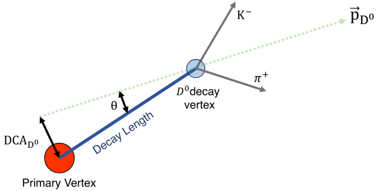
$$f(m_{D^0}) = \underbrace{a + bm_{D^0} + cm_{D^0}^2}_{\equiv B(m_{D^0})} + \underbrace{AG(m_{D^0}, M_{D^0}, \sigma)}_{\equiv S(m_{D^0})}$$

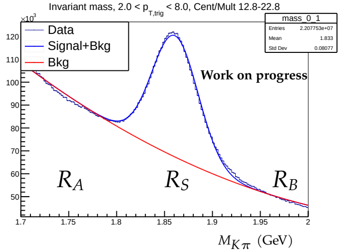
- Sideband regions, $\mathcal{R}_{\mathcal{A}} \in [1.7, 1.8]$ and $\mathcal{R}_{\mathcal{B}} \in [1.9, 2]$
- Signal region, $\mathcal{R}_{\mathcal{S}} \in [1.8, 1.9]$
- Extract $\alpha_{\mathcal{R}_{\mathcal{A}}}$ and $\alpha_{\mathcal{R}_{\mathcal{B}}}$ from the fit as,

$$\alpha_{\mathcal{R}_{\mathcal{A}}} = \frac{1}{2}\frac{B(m_{D^0})_{\mathcal{R}_{\mathcal{S}}}}{B(m_{D^0})_{\mathcal{R}_{\mathcal{A}}}}.$$

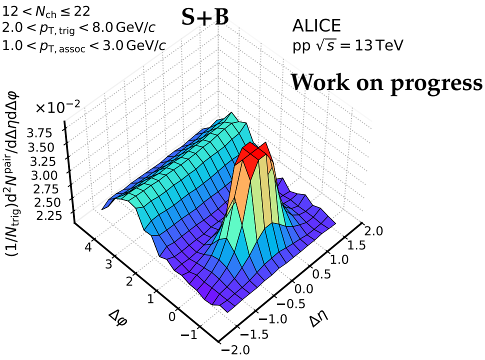
  Here $\frac{1}{2}$ comes due to two sides being involved.
- Subtract the sideband 2D correlation function as,

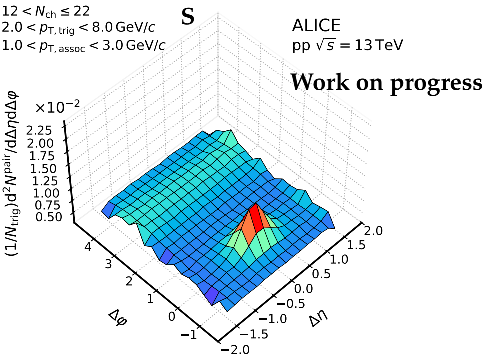
$$\left(\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\phi}\right)^{\mathcal{R}_{\mathcal{S}}} - \alpha_{\mathcal{R}_{\mathcal{A}}}\left(\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\phi}\right)^{\mathcal{R}_{\mathcal{A}}} - \alpha_{\mathcal{R}_{\mathcal{B}}}\left(\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\phi}\right)^{\mathcal{R}_{\mathcal{B}}}$$



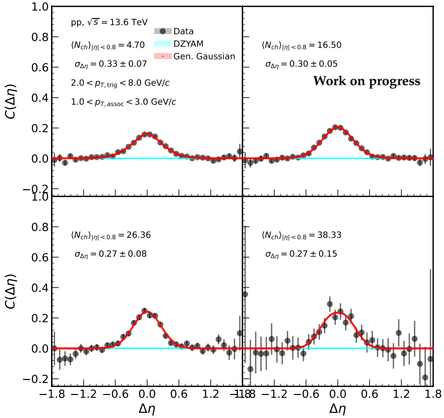


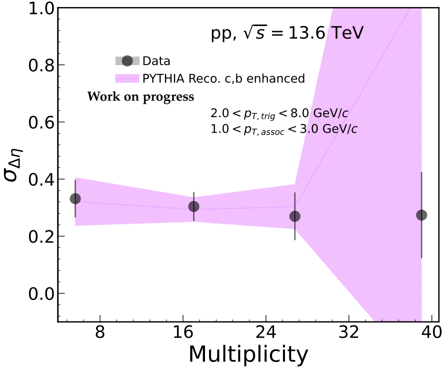
- The final correlation function is normalized by $N_{\mathcal{R}_{\mathcal{S}}}^{\mathrm{trig}} - \alpha_{\mathcal{R}_{\mathcal{A}}} N_{\mathcal{R}_{\mathcal{A}}}^{\mathrm{trig}} - \alpha_{\mathcal{R}_{\mathcal{B}}} N_{\mathcal{R}_{\mathcal{B}}}^{\mathrm{trig}}$.





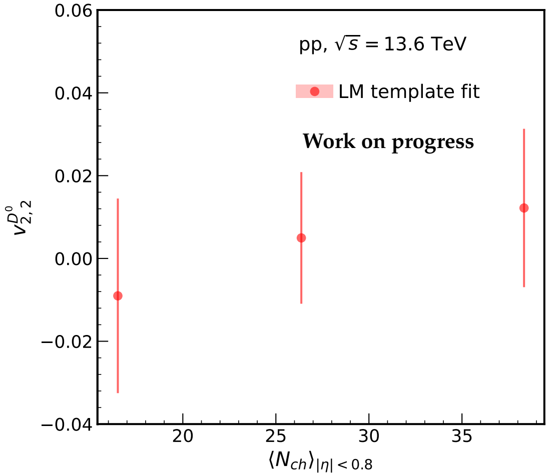
- Clear jet peak visible before background subtraction
- Substantial reduction after sideband subtraction
- Room for S/B, and candidate selection efficiency improvements





- Fitted with the generalized Gaussian function

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



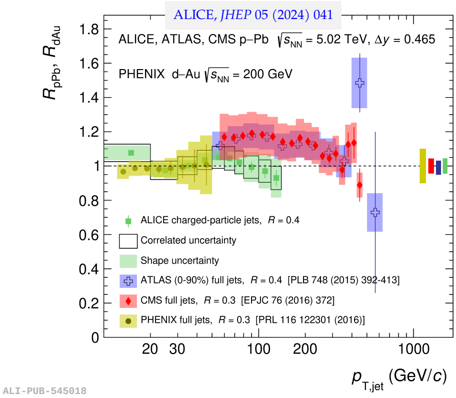
- Low-multiplicity template fit for h-h and D^0-h flow extraction using Run 3 data
- Increasing trend with increasing multiplicity for both h-h and D^0-h flow

Many thanks to **Maxim** and **DJ** for working on the h-h correlations

- **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 (Run 3)
- Jet shape variation with multiplicity for D^0-h correlation is studied
- Finite flow signal for D^0 meson expected after flow factorization

Thank you for your attention!

Min.Bias

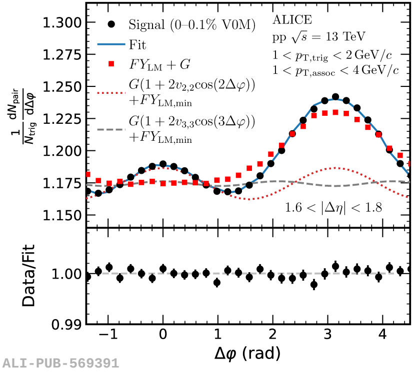


- Evidence of collectivity observed in HM pp and p–Pb ALICE, JHEP 05 (2021) 290, Phys. Lett. B 719 (2013) 29
- No sign of jet quenching in small systems
- Strong collective behaviour associated with QGP formation in large systems

- **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

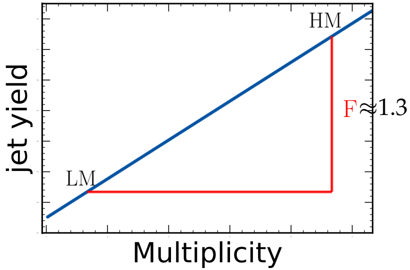


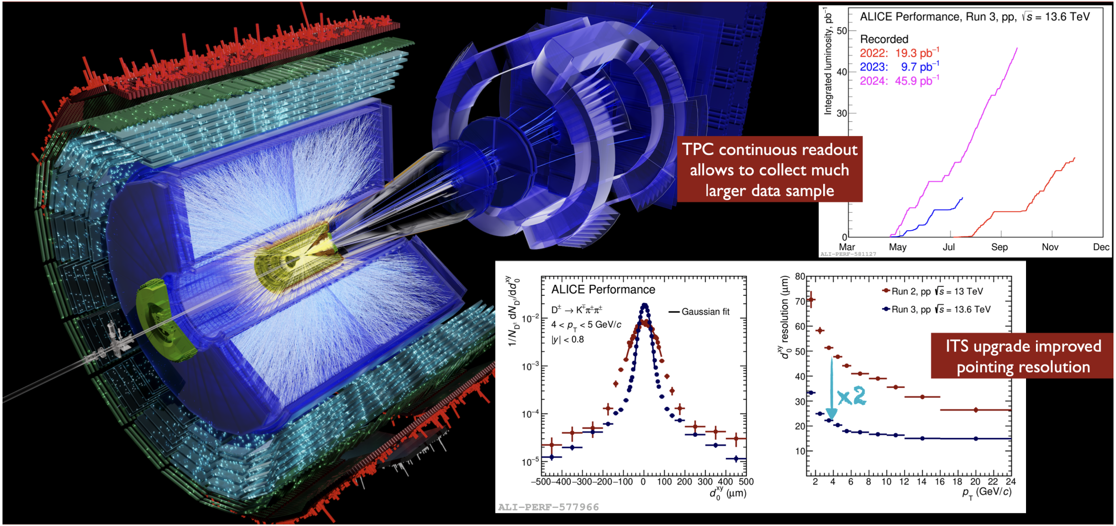
ALICE, *JHEP03* (2024) 092

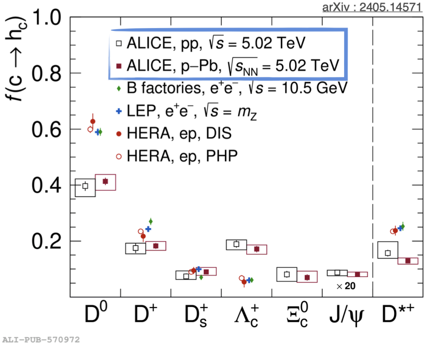
$$Y_{HM}(\Delta\varphi) = G(1 + 2v_{2,2}\cos(2\Delta\varphi) + 2v_{3,3}\cos(3\Delta\varphi)) + FY_{LM}(\Delta\varphi)$$

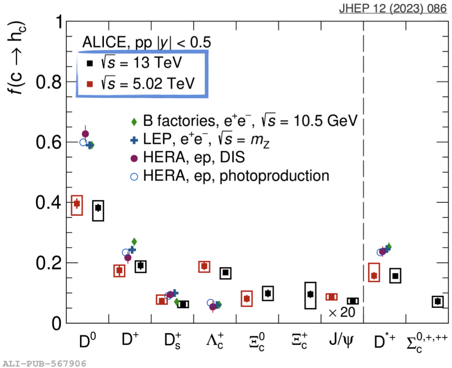
1. No ridge or flow in **Near-Side** in the LM-template
2. No **Away-side** jet shape modifications in HM events

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





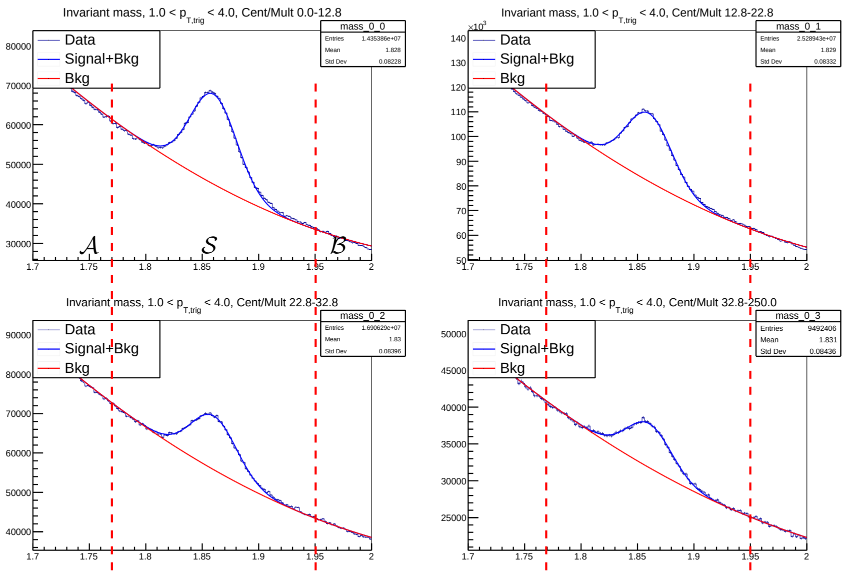
Fragmentation fractions in pp and p–Pb collisions are consistent with each other

↓

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

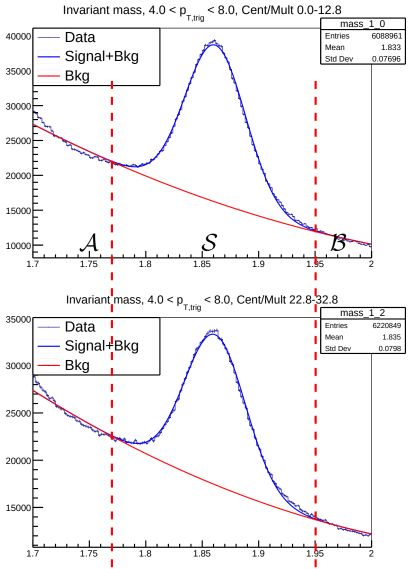
Fragmentation fractions do not show energy dependence within the uncertainties

Mass fits $1 < p_T < 4\,\mathrm{GeV}/c$ in multiplicity bins



- Fit the invariant mass distributions with pol2 background + Gaussian signal
- For sideband method, regions $\mathcal{A}, \mathcal{S}, \mathcal{B}$ are picked by eye for now
- Sideband regions (subject to improvements)
  - $\mathcal{A} \in [1.66, 1.77]$
  - $\mathcal{S} \in [1.77, 1.95]$
  - $\mathcal{B} \in [1.95, 2.1]$

Mass fits $4 < p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$ in multiplicity bins



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  - $\mathcal{A} \in [1.66, 1.77]$
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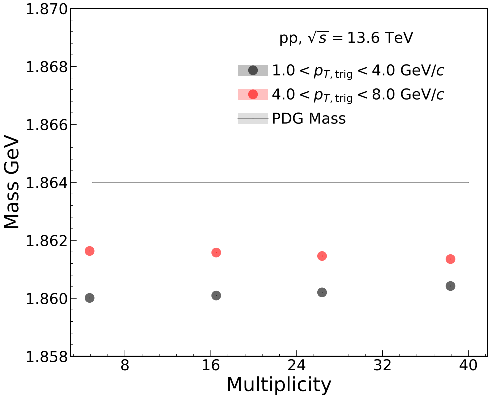
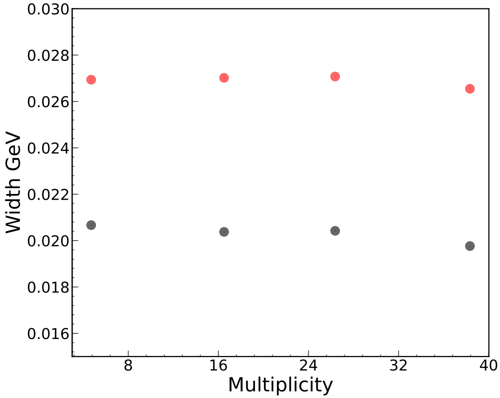
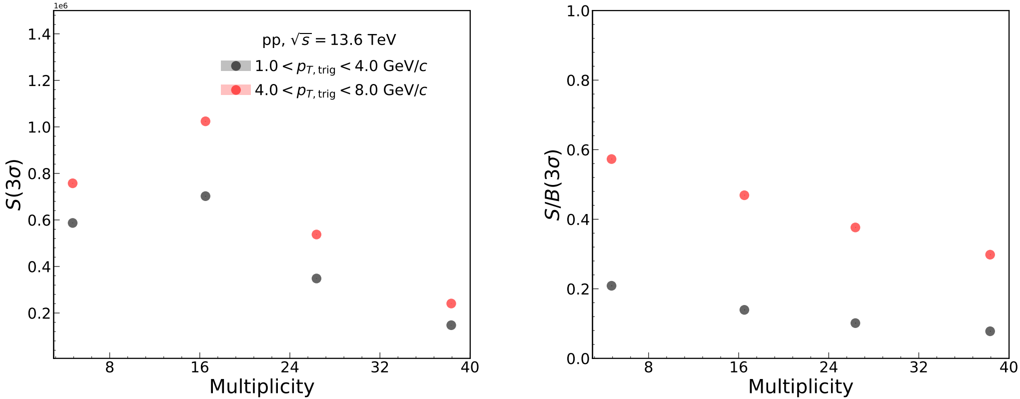
Signal Extraction (I)





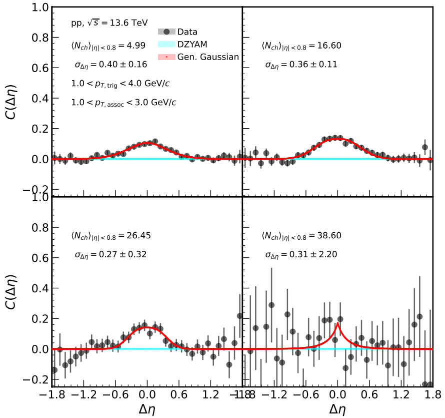
- D^0 mass and width values are mostly stable across multiplicity bins, higher values for higher p_T
- Extracted D^0 mass is still way below the PDG mass, overestimated in Run 2 ($\simeq 1.868$ GeV)[1]
- Run 3 has slightly wider width for D^0, it was $\simeq 0.017$ GeV in Run 2[1]

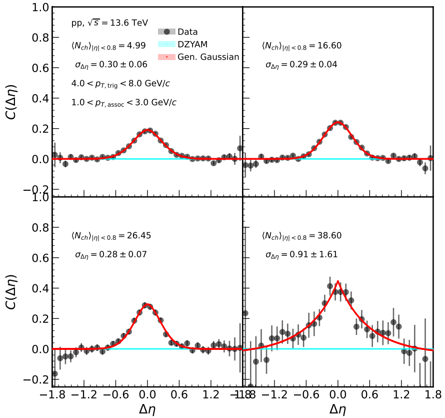
[1] pp, $\sqrt{s} = 13$ TeV, Physics Letters B 829 (2022) 137065, https://alice-notes.web.cern.ch/system/files/notes/analysis/993



- $S/B(3\sigma)$ values are smaller compared to Run 2 ($\simeq$ 0.6 to 1.4)[1]
- $S/B(3\sigma)$ decreases with increasing multiplicity, same behavior in Run 2[1]
- $S/B(3\sigma)$ improves at higher p_{T}, same behavior in Run 2[1]

[1] pp, $\sqrt{s}$ = 13 TeV, Physics Letters B 829 (2022) 137065, https://alice-notes.web.cern.ch/system/files/notes/analysis/993





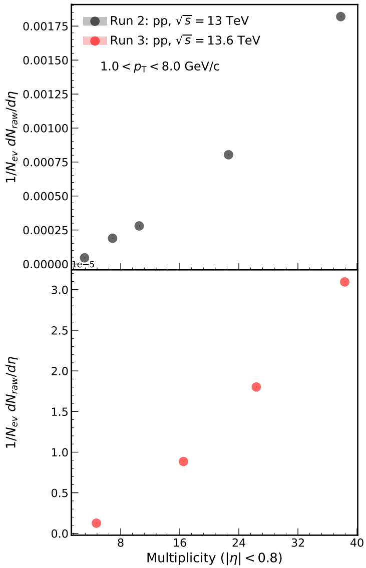
- Fitted with the generalized Gaussian function

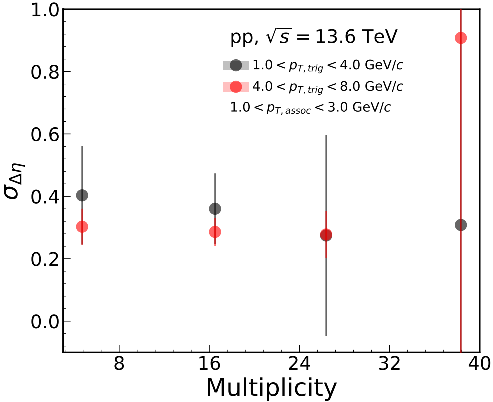
$$A + \frac{\beta}{2\alpha\Gamma(1/\beta)} \exp\left[-\left(\frac{|x|}{\alpha}\right)^{\beta}\right], \sigma = \sqrt{\frac{\alpha^2\Gamma(3/\beta)}{\Gamma(1/\beta)}}$$

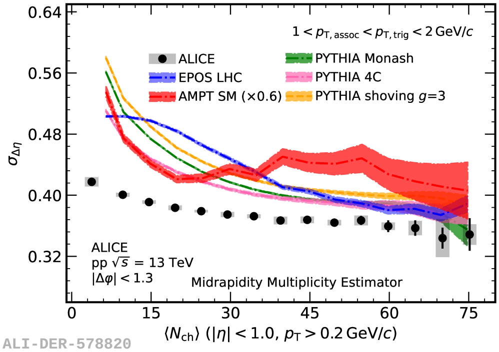
Raw Yield

p_T (GeV/c)	S (Run 2)[1]	S (Run 3)[2]
[1.0, 4.0]	35426	1785252
[4.0, 8.0]	24554	2559588
Total	59980	4344840
# MB events	1.710×10^9	734×10^9
Signal/event	3.50×10^{-5}	5.92×10^{-6}

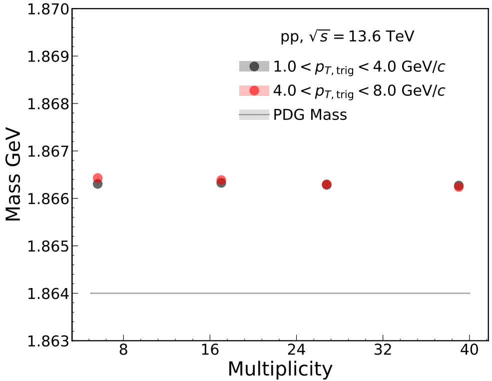
[1] pp, $\sqrt{s}$ = 13 TeV, Physics Letters B 829 (2022) 137065, https://alice-notes.web.cern.ch/system/files/notes/analysis/993 [2] pp, $\sqrt{s}$ = 13.6 TeV, This Analysis

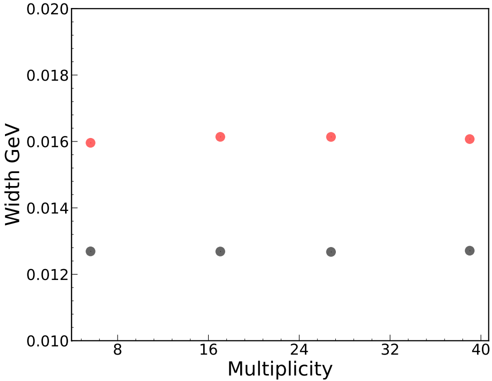






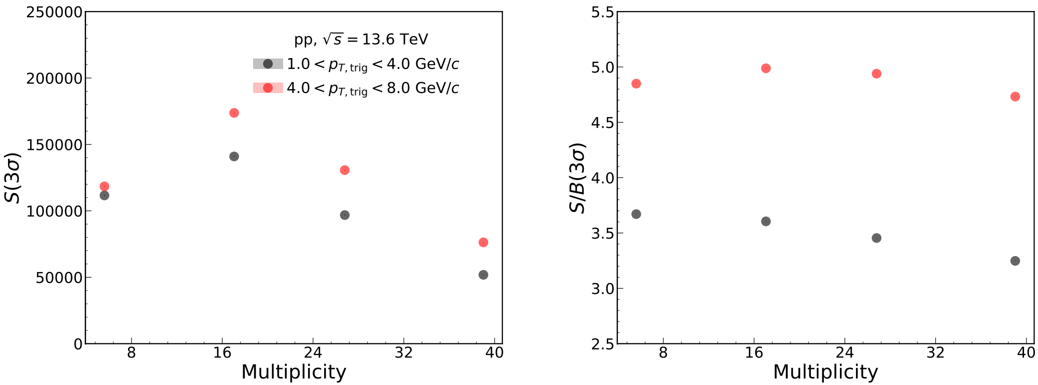
- Modification of jet shape with multiplicity
- Similar width and decreasing trend compared to h-h results (ALICE, arXiv:2409.04501)
- This effect should be considered in the LM-template fit since 2nd assumption is broken.





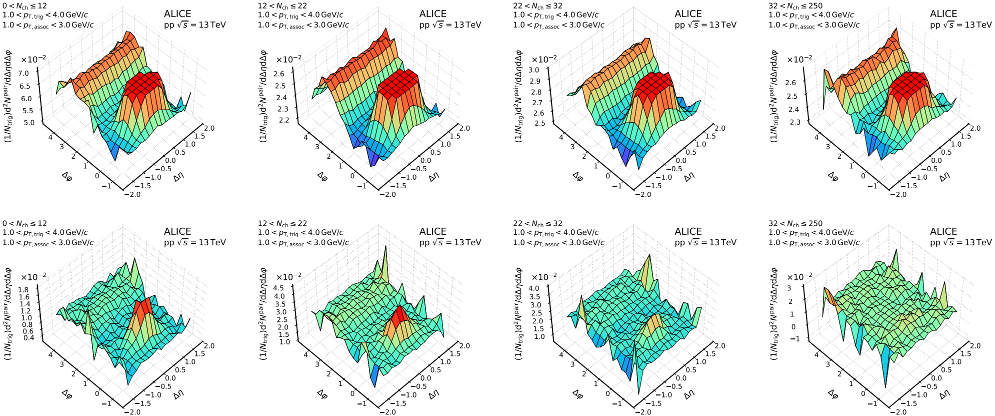
- LHC24g6: MC with D resonances PYTHIA (monash), gap trigger 5
- HF Derived data: HF_LHC24g6_All, 4.92×10^8 events
- D^0 mass and width values are mostly stable across multiplicity bins, higher values for higher p_{T}
- Extracted D^0 mass is above the PDG mass, higher than data ($\simeq 1.862$ GeV)
- Narrower width compared to data

Signal Extraction MC (II)



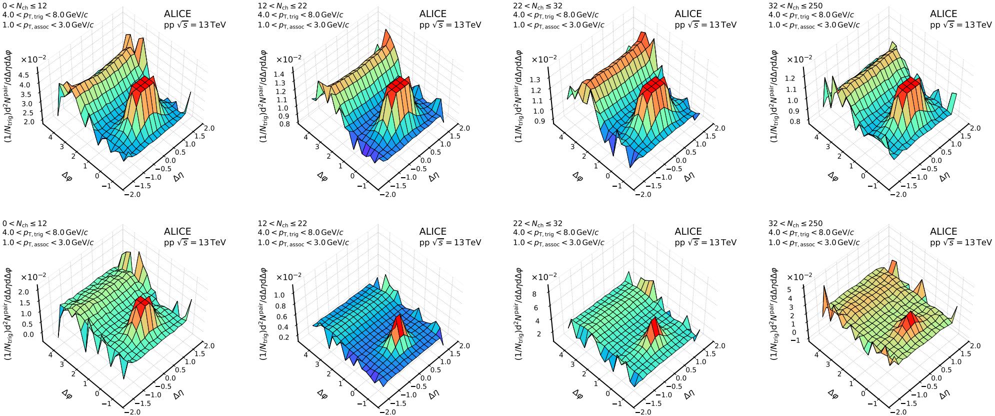
- Better S/B(3σ) compared to data ($\simeq$ 0.15 to 0.6)
- S/B(3σ) decreases with increasing multiplicity, same behavior in data
- S/B(3σ) improves at higher $p_{\rm T}$, same behavior in data

Correlation function $1 < p_{\mathrm{T}} < 4\,\mathrm{GeV}/c$ (before/after background subtraction)



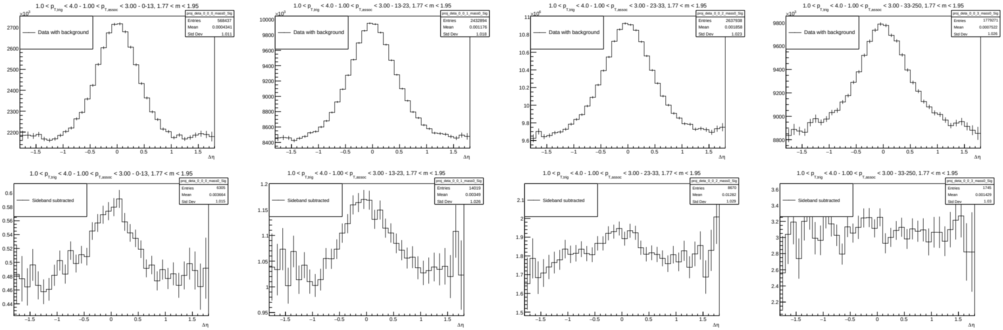
- Correlation functions before the subtraction feature a clearly visible near- and away-side jet fragmentation
- This peak is largest in mid-multiplicity and narrowing toward higher multiplicities
- After the background subtraction, the jet fragmentation is mostly gone.

Correlation function $4 < p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$ (before/after background subtraction)



- Correlation functions before the subtraction feature a clearly visible near- and away-side jet fragmentation
- This peak is largest in mid-multiplicity and narrowing toward higher multiplicities
- After the background subtraction, the jet fragmentation is mostly gone.

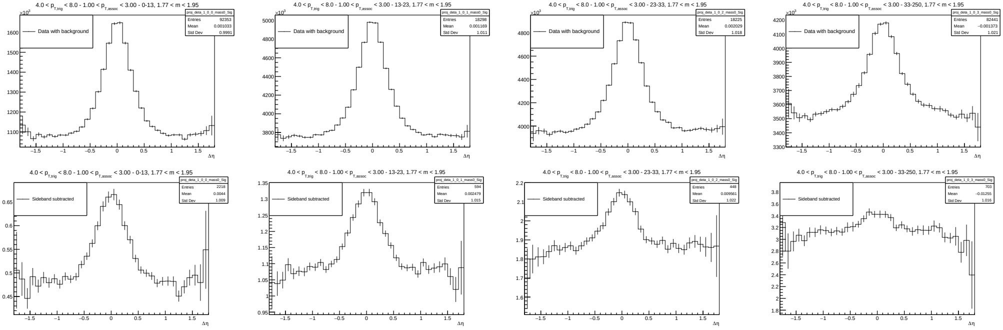
SHORT-RANGE CORRELATION $1 < p_{\mathrm{T}} < 4\,\mathrm{GeV}/c$ (SIGNAL REGION, BEFORE AND AFTER SIDEBAND)



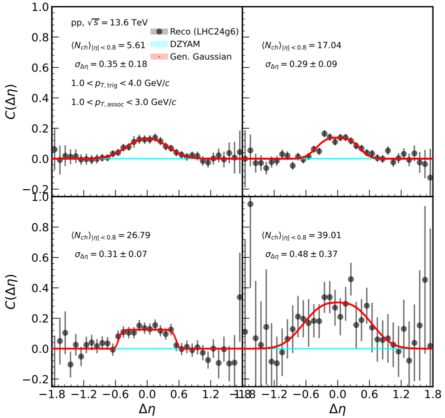
- $|\Delta\phi| < 1.3$
- The jet fragmentation peak is clearly visible in plots before the sideband subtraction
- Peak visible also in after the subtraction, particularly in lower multiplicity bins

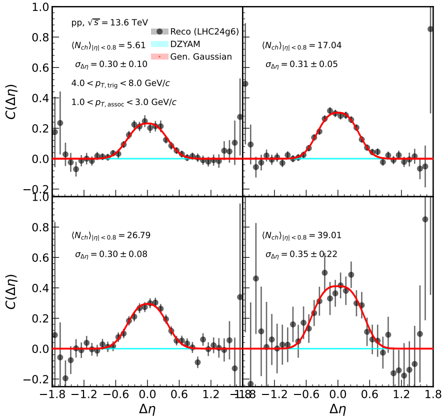
making a figure to put the subtracted terms on top panel

Short-range correlation $4 < p_T < 8\,\mathrm{GeV}/c$ (signal region, before and after sideband)



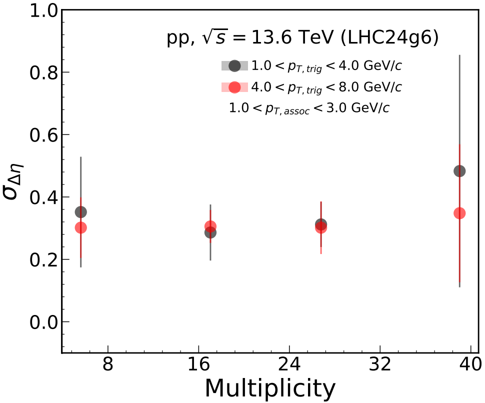
- $|\Delta\phi| < 1.3$
- Similar trends in higher p_T, although the peak is more visible also after subtraction

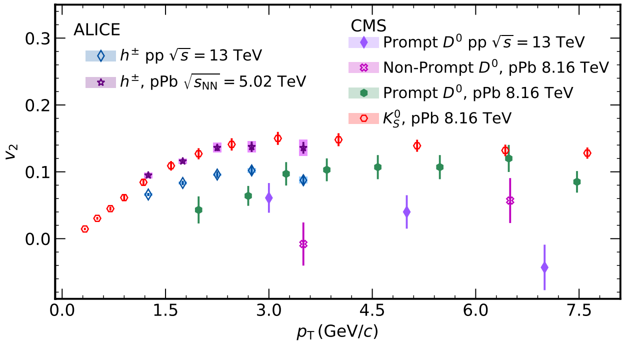




- Fitted with the generalized Gaussian function

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


pp, $\sqrt{s}$ = 13.6 TeV (LHC24g6)
$1.0 < p_{T,trig} < 4.0$ GeV/c
$4.0 < p_{T,trig} < 8.0$ GeV/c
$1.0 < p_{T,assoc} < 3.0$ GeV/c
$\sigma_{\Delta\eta}$
1.0
0.8
0.6
0.4
0.2
0.0
8
16
24
32
40
Multiplicity



CMS, PLB 813 (2021) 136036

ALICE, JHEP 03 (2024) 092

Exp.	η multi-jet	$\Delta\eta$	p_T width	Multiplicity
ALICE	$\lvert\eta\rvert < 0.9$	[1.6,1.8]	$p_T > 1.0$ GeV/c	$2.8 < \eta < 5.1$+$1.7 < -\eta < 3.7$
ATLAS	$\lvert\eta\rvert < 2.5$	[2.0,4.0]	$p_T > 0.4$ GeV/c	$\lvert\eta\rvert < 2.5$, $p_T > 0.3$ GeV/c raw
CMS	$\lvert\eta\rvert < 2.5$	[2.0,5.0]	$p_T > 0.1$ GeV/c	$\lvert\eta\rvert < 2.4$, $p_T > 0.4$ GeV/c raw

- Even though not possible to make an apple-to-apple comparison
- Low p_T results seem to agree (ALICE, only for intermediate ranges, due to non-flow, but CMS still largely contaminated for higher p_T)
- Run3 pp will allow us to study things further both including D-mesons and $h^{\pm}$