Searching for QGP signals in small systems at the LHC

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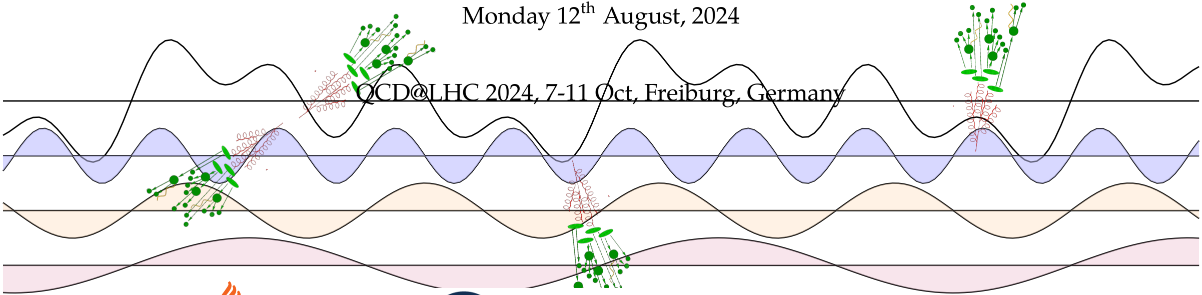
Monday 12th August, 2024



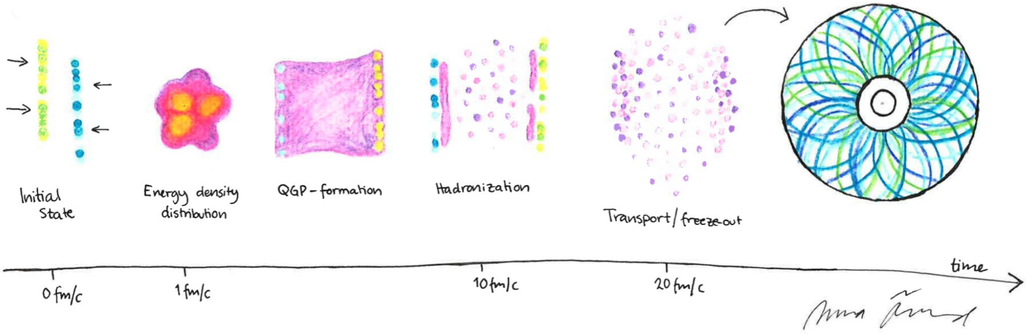
QCD@LHC 2024, 7-11 Oct, Freiburg, Germany

UNIVERSITY OF JYVÄSKYLÄ

Centre of Excellence in Quark Matter

HELSINKI INSTITUTE OF PHYSICS

The different stages of Heavy-Ion collisions



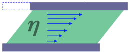
Credits to Anna Önnerstad

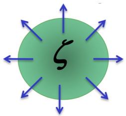
$T_{\mathrm{R}}ENTo$ | $VISH(2+1D)$ | $UrQMD$

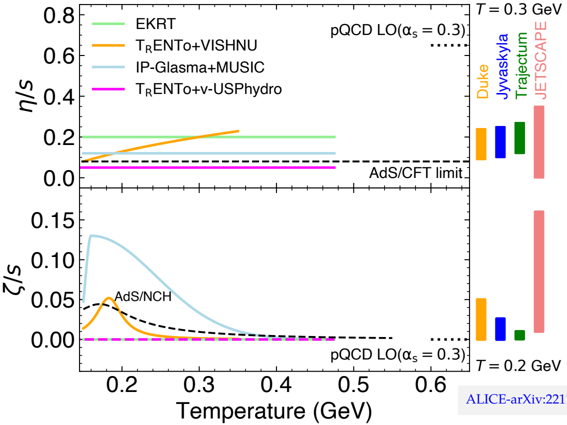
$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (P + \Pi)\Delta_{\mu\nu} + \pi^{\mu\nu}, \qquad \delta_{\mu}T^{\mu\nu} = 0$$

Constraining the QCP parameters is not our ultimate goal, but to understand the underlying physics in each stage and how to combine them.

based on https://github.com/Duke-QCD

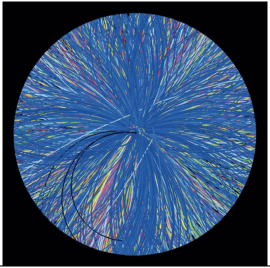


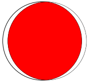


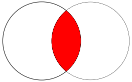


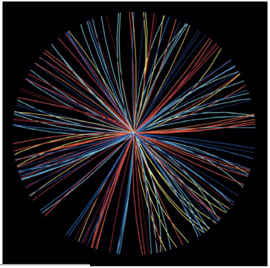
ALICE-arXiv:2211.04384, Jyvaskyla-PRC 104 (2021) 054904

- "The ALICE experiment - A journey through QCD(White paper)", arXiv:2211.04384 submitted to EPJC on Nov 9th 2022.
- 328 pages, 123 captioned figures, Published: 14 August 2024, Eur. Phys. J. C 84, 813 (2024)

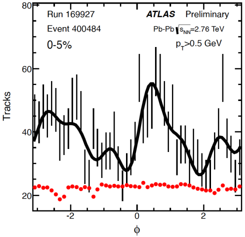








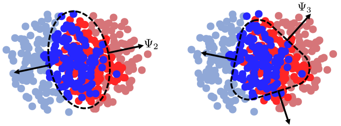
Obs	Description
$dN/d\eta$	Particle yields, $\pi^{\pm}$,$K^{\pm}$, proton...
$\langle p_T \rangle$	Mean transverse momentum, $\pi^{\pm}$,$K^{\pm}$, proton...
v_n	Anisotropic flow (v_n) from φ
...	..



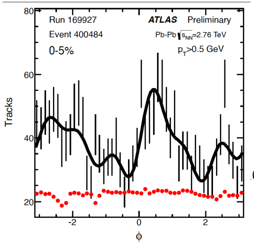
$$P(\varphi) \propto \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

every event: collision geometry changes → system(medium) size varies

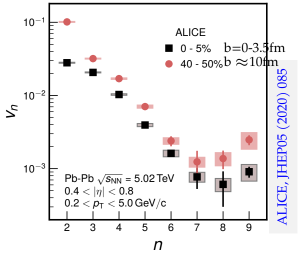
Higher Flow Harmonics Seen by All Experiments



Credits to M. Lesch

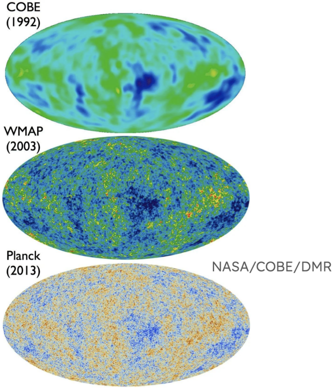


.00-1000 part..



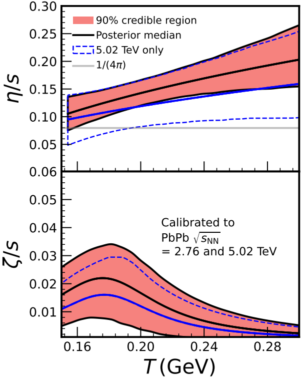
$$P(\varphi) \propto \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

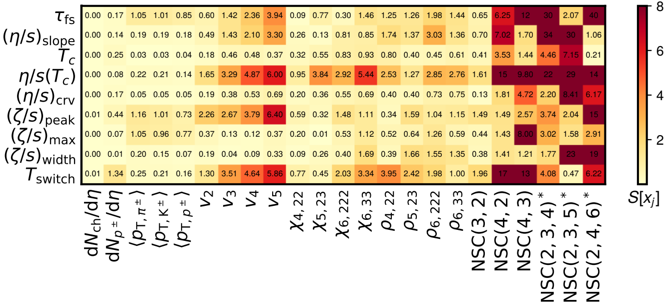
$$V_n \equiv v_n\{\Psi_n\} e^{in(\Psi_n - \phi)}$$



- Sensitive to initial state geometry and properties of the expanding QGP (viscosity(η/s), equation of state)
- Like measurements of early universe sound harmonics

Result: Jyvaskyla (2022) – combined collision energy analysis (2.76 + 5.02 TeV)





- Together with two collision energies and added observable, the uncertainty has reduced!
- More independent and sensitive observable!

J.E. Parkkila, A. Onnerstad, M. Virta, S.F. Taghavi, C. Mordasini, A. Bilandzic, D.J. Kim, Phys. Lett. B 835 (2022) 137485

The precision measurements of observable, reflecting mostly non-linear responses, are crucial

New and Independent information!

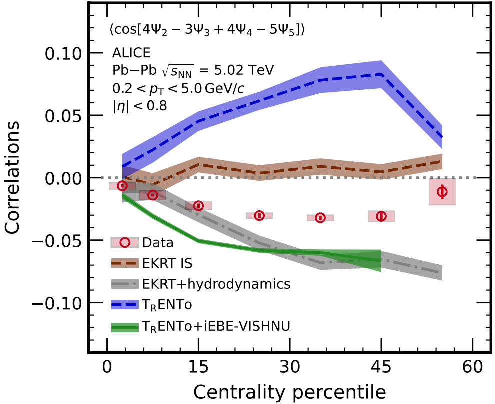
$$V_n \equiv v_n\{\Psi_n\} e^{in(\Psi_n - \phi)}$$

1 Symmetric cumulants	$\langle v_m^2 v_n^2 \rangle_c$, $\langle v_k^2 v_l^2 v_m^2 \rangle_c$, "SC$(m,n)$"	additonal information
2 Non-linear flow modes	relations of flow obs, "$\chi_{n,kl}$"	decomposition
3 Asymmetric cumulants	$\langle v_m^{2\cdot a} v_n^{2\cdot b} \rangle_c$, "AC$_{a,b}(m,n)$"	new moments
4 Symmetric plane Corr.	$\langle \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle$	independent
5 Small systems	v_n only from 2PC	jets are dominant

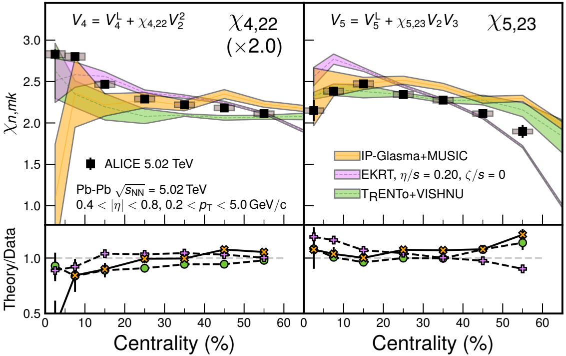
- Thanks to the higher order flow measurements! ALICE, Phys.Rev.Lett.116 (2016) 132302, JHEP05 (2020) 085
- Thank you: Flow Fluctuation! ALICE, JHEP 07(2018) 103, 2018

Non-linear hydrodynamic response is very clear for large systems

ALICE, arXiv:2409.04238

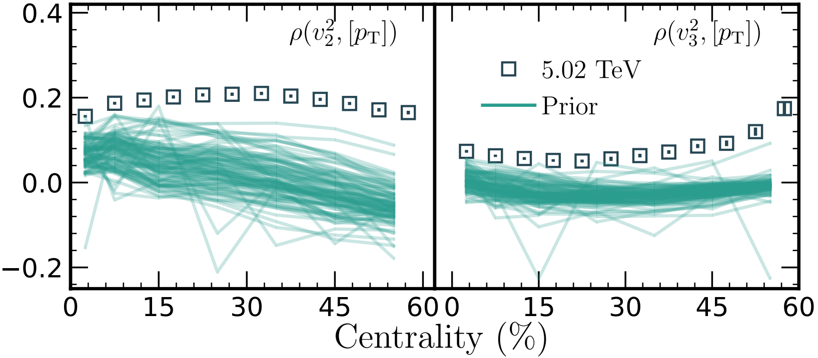


ALICE, JHEP05 (2020) 085



- Clear non-linear hydrodynamic response from a specific observable!
- 25 correlators, including 16 new ones
- First measurement of correlations between five different symmetry planes in 2024

- The nonlinear response is quantified as additional observable!
- $V_4 = V_4^L + \chi_{4,22} V_2 V_2$
- $V_5 = V_5^L + \chi_{5,32} V_2 V_3$

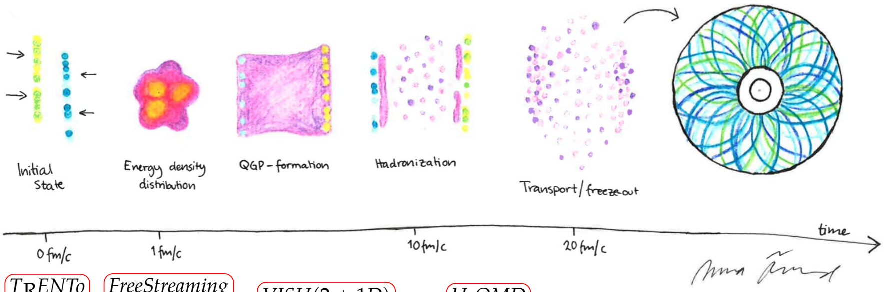


$v_n^2, [p_T]$ correlation

$$\rho(v_2^2, [p_T]) = \frac{\langle (v_2^2 - \langle v_2^2 \rangle)\,([p_T] - \langle [p_T] \rangle) \rangle}{\sqrt{\langle (v_2^2 - \langle v_2^2 \rangle)^2 \rangle \langle ([p_T] - \langle [p_T] \rangle)^2 \rangle}}$$

- Clear centrality dependence
- Gains negative values - what is going on?

ALICE, Phys. Lett. B 834 (2022) 137393



Credits to Anna Önnerstad

TRENTo
EKRT
IPGlasma
MCGlauber
AMPT

FreeStreaming
KøMPøST
Gauge/Gravity

VISH(2 + 1D)
MUSIC

UrQMD
SMASH

Even though our standard model of heay-ion collisions are well establised

- Need to improve our understanding of earlier dynamics before Hydrodynamics (τ_{hydro})
- Need to work through model dependent Bayesian analysis with cautions
- This would help us to understand model to data uncertainties.

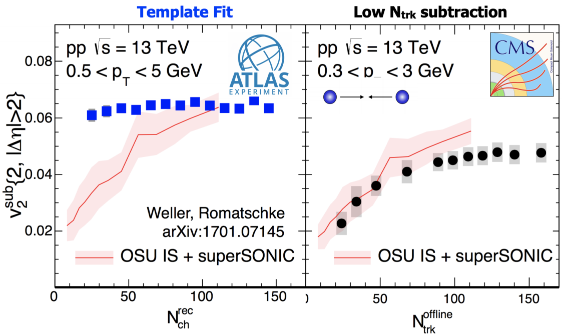
Even if likelihood and posterior are explicitly given

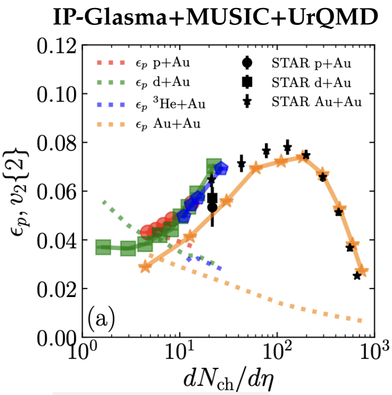
- Likelihood can be costly to evaluate
- **Evidence can be hard to compute** Jeffrey et al., arXiv:2305.11241

$$P(\theta|d,M) = \frac{P(d|\theta,M)P(\theta|M)}{\boxed{P(d|M)}},$$

$$\boxed{P(d|M)} = \int P(d|\theta,M)P(\theta|M)d\theta$$

- Strong collective behaviour associated with QGP formation in large systems
- Collectivity also observed in small systems (e.g., ALICE, JHEP 05 (2021) 290, Phys. Lett. B 719 (2013) 29-41)
- **Key Questions:**
  1. **How to measure collective flow correctly in small systems?**
  2. **How to probe the creation of QGP in small systems?**
  3. **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]
    $\rightarrow$ Definitive suggestion on extracting flow signals in small systems
  - Experimental verification: ALICE, JHEP 03 (2024) 092 [A. Önnerstad, J.E. Parkkila, D.J. Kim]
    $\rightarrow$ Non-flow subtraction and hydro limits
  - Model developments





B. Schenke et. al. PLB.2020.135322

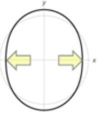
- Flow extraction in small systems with different methods leads to different results, can we find the correct method?
- Viscosity effect is clearly seen in the hydro calculations from $N_{\rm ch}$ dependence
- Can we set the lower limit of event multiplicity on flow signal both for pp and p–Pb?

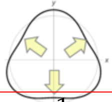
SP: $$\frac{dN}{d\phi} \propto \left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \psi_n))\right)$$

2P: $$\frac{dN^{pairs}}{d\Delta\phi} \propto \left(1 + \sum_{n=1}^{\infty} 2v_{n\Delta} \cos(n(\phi_1 - \phi_2))\right)$$

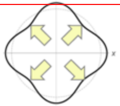
2P: $$v_{n\Delta} = v_n^2 = \langle \cos\left[n\left(\phi_i - \phi_j\right)\right]\rangle$$

Harmonic shapes





$$\sigma_\nu \sim \frac{1}{\sqrt{N}} \frac{1}{M^{k/2}} \frac{1}{\nu^{k-1}}$$



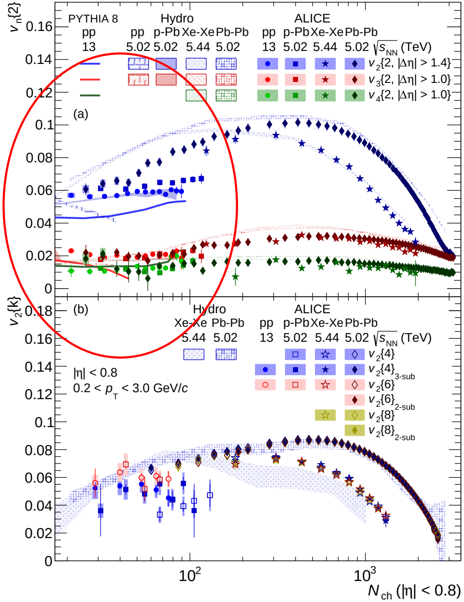
Phys. Rev. C 105, 014905

Single particle and two-particle correlations

SP:

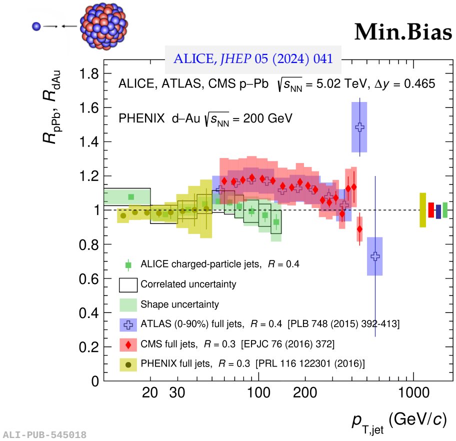
2P:

- work for the large systems because $N_{flow} >> N_{jets}$, negligible non-flow contribution
- e.g, cumulants from PbPb to pp, Phys. Rev. Lett. 123, 142301 (2019), caution for the smaller systems and peripheral collisions in larger systems

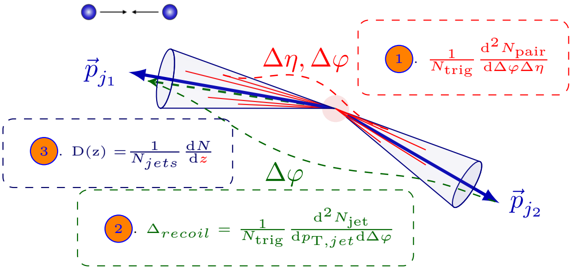


ALICE, PRL 123, 142301 (2019)

- Famous results including from large to small systems
- However, the measurements need to be revisited due to the remaining non-flow contributions.
- **New methods are needed to extract flow signals in small systems, understanding QCD kinematics!**

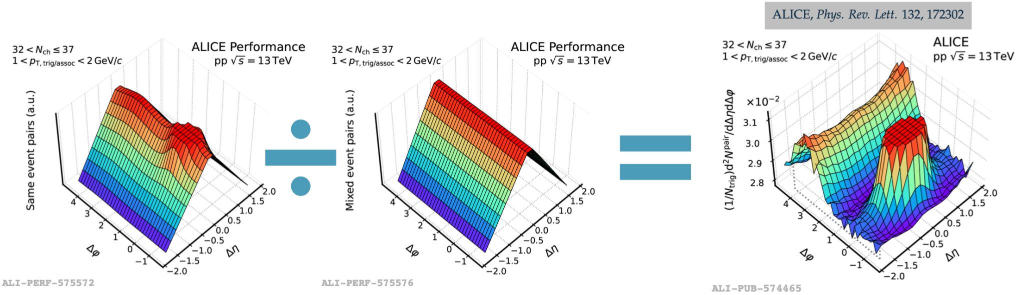


- Even though flow signatures are observed
- No sign of jet quenching in small systems



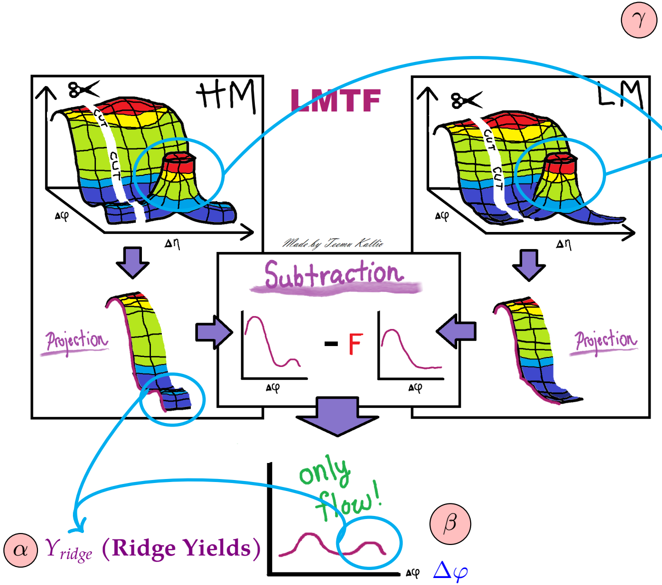
What about pp collisions at $\sqrt{s} = 13$ TeV : **Multiplicity dep.**?

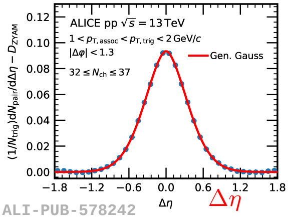
1. hadron-hadron correlations? (**This analysis**)
2. hadron-jet correlations? (di-jets: *JHEP* 05 (2024) 229)
3. intra-jet correlations? (Intra-jet: arXiv:2311.13322)



$$\frac{1}{N^*_{\mathrm{trig}}(z)}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\Delta\varphi}(\Delta\eta,\Delta\varphi,z) = \frac{1}{N^*_{\mathrm{trig}}(z)}\frac{N^{*,\mathrm{same}}_{\mathrm{pair}}(\Delta\eta,\Delta\varphi,z)}{N^{*,\mathrm{mixed}}_{\mathrm{pair}}(\Delta\eta,\Delta\varphi,z)}N^{*,\mathrm{mixed}}_{\mathrm{pair}}(0,0,z),$$
$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\Delta\varphi}(\Delta\eta,\Delta\varphi) = \frac{1}{\sum_z N^*_{\mathrm{trig}}(z)}\sum_z N^*_{\mathrm{trig}}(z)\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\Delta\varphi}(\Delta\eta,\Delta\varphi,z) \tag{1}$$

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta} = \int_{|\Delta\varphi|<1.3}\left(\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi}\right)\frac{1}{\delta_{\Delta\varphi}}\mathrm{d}\Delta\varphi - D_{\mathrm{ZYAM}}. \tag{2}$$



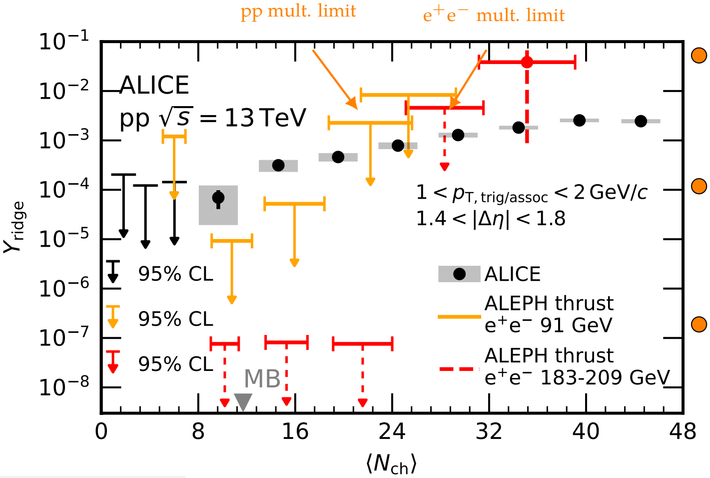


Jets, Short Range Correlation:

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

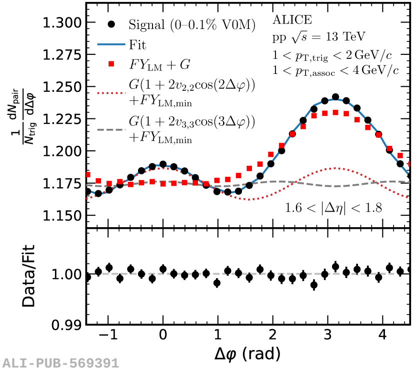
Flow, Long Range correlation

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



- pp collision exhibits larger yield $Y^{pp}_{ridge} \gtrsim Y^{e^+e^-}_{ridge}$
  - 5σ (best) at 91 GeV
  - 6.3σ (best) at 183–209 GeV
- **A comparison to e^+e^- can provide insight to what processes might or do not contribute to the yield**
  - PRL 123, 212002 (2019)
  - arXiv:2312.05084 (2023)
- **A reference point-like collision can also help understand the magnitude of initial stage effects**

ALICE, PRL. 132 (2024) 172302

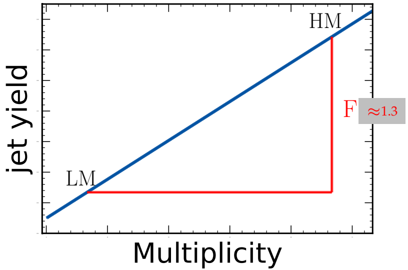


ALICE, *JHEP03* (2024) 092

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

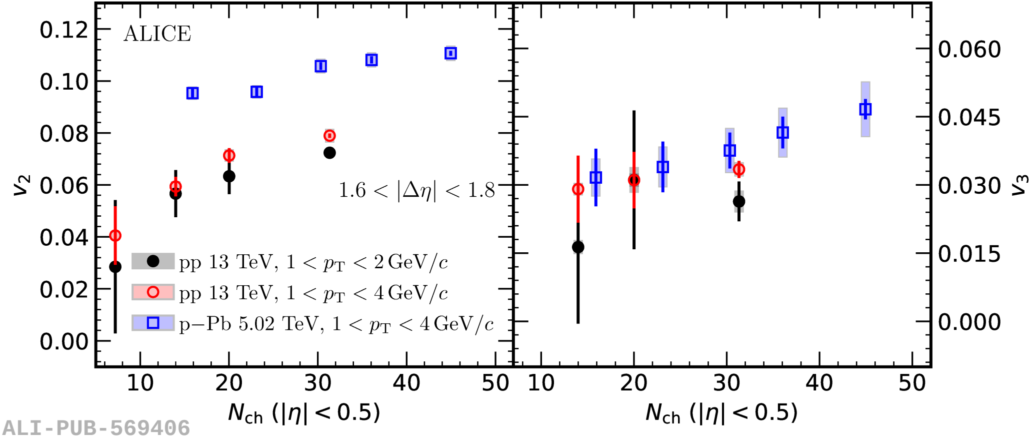
1. No ridge or flow in **Near-Side** in the LM-template
2. No **Away-side** jet shape modifications in HM events

Jet yield is 30% stronger in HM compared to LM



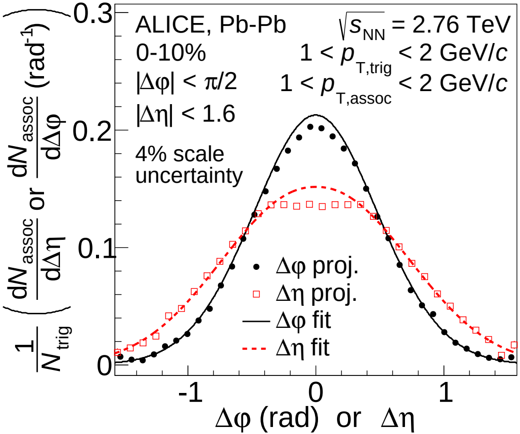
- **$\Delta\eta$ can be measured (weak η-dependence, flow) and can be used as a proxy for away-side.**

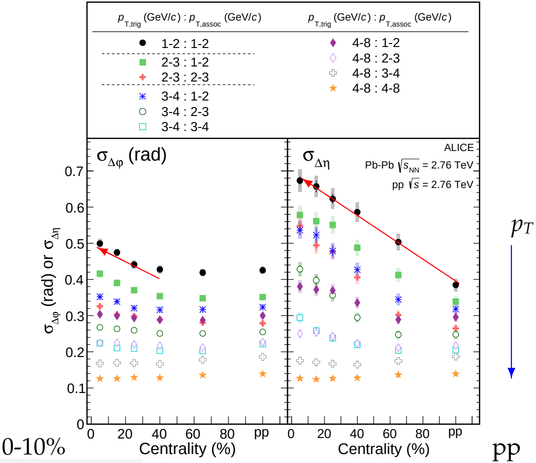
1. Because $\Delta\eta$ and $\Delta\varphi$ symmetry in jets.
2. Because $\Delta\varphi$ **width can't be measured because of the existence of the flow.**



- v_n increases with increasing multiplicity for both collision systems and p_T-ranges.
- v_2 in p–Pb is higher than in pp collisions but similar for v_3
- Note that the integrated flow measurements are for $p_T > 1$ GeV/c because of wider jet widths for lower-p_T

ALICE, JHEP 03 (2024) 092

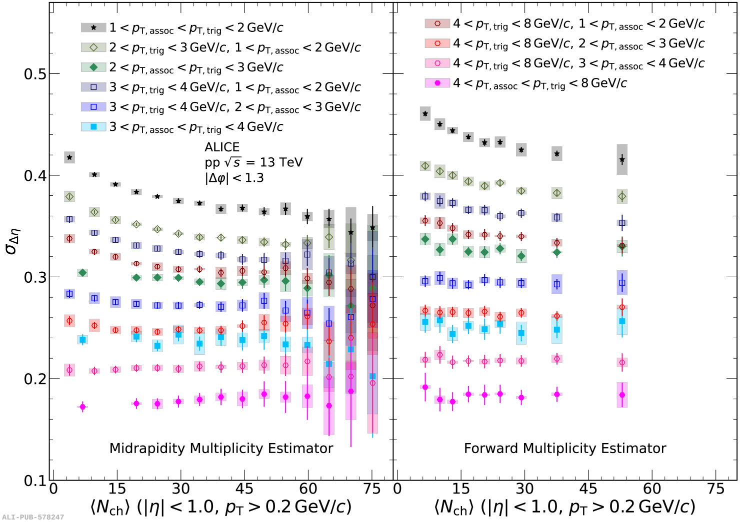




ALICE, *Phys. Rev. Lett.* 119 (2017) 102301

- **Broadening** of the jet fragmentation peak in various kinematic regions observed in HI collisions
- Abnormal and wider in $\Delta\eta$ direction than $\Delta\varphi$

γ: Multiplicity dependence of $\sigma_{\Delta\eta}$ in pp 13 TeV: width comparison



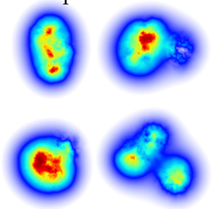
ALICE, arXiv:2409.04501

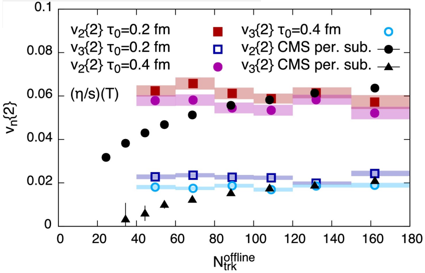
- Multiplicity dependence decreases for higher p_T and higher multiplicity
- V0M results have broader jets and weaker multiplicity dependence across almost all p_T-bins
- Clear ordering in the magnitude → narrower peaks towards higher p_T

- **Initial state effects:** CGC + fluctuation
  K. Dusling *et. al* PRD 87 5 (2013) 05150, A. Bzdak *et. al* PRC 87 6, (2013) 064906
- **Final state effects:** Hydrodynamics
  R. D. Weller *et. al* PLB 774 (2017) 351–356, W. Zhao *et. al* PLB 780 (2018) 495–500
- **Hybrid models:** How quantitatively they interplay? Relative contributions?
  M. Greif *et. al* PRD 96 9, (2017) 091504, H. Mäntysaari *et. al* PLB 772 (2017) 681–686

Alternatively, MC-based models?

Fluctuating gluon density in a proton

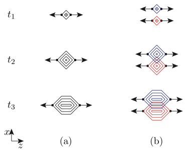




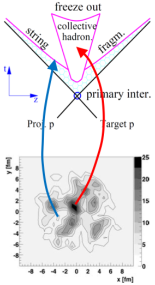
p + Pb 5.02TeV, CMS per. sub, $0.3 < p_T < 3\ GeV/c$

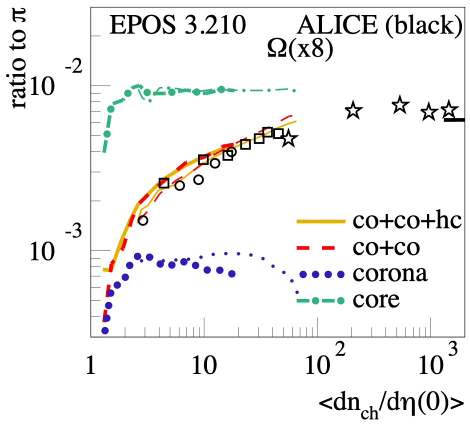
H. Mäntysaari et al., PLB 772 (2017) 681-686

- **PYTHIA 8 String Shoving**: Pushing the strings resulting in transverse pressure
  C. Bierlich *et. al* PLB 779 (2018) 58-63 → strings produced from hard scatterings are also affected by the repulsive force, which then leads to observed long-range correlation even in low-multiplicity events L, Lönnblad (Thurs)

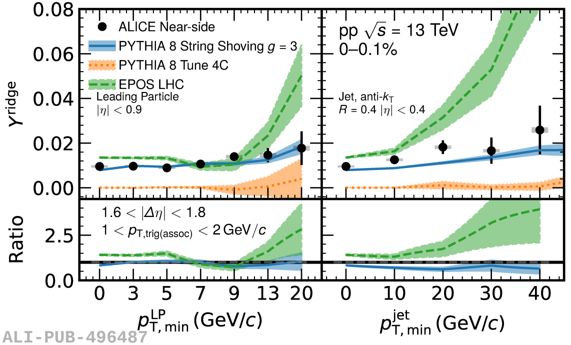


- **AMPT String Melting**: soft and hard partonic and hadronic interactions, Zi-Wei *et al.* → parton cross section value of 3 mb, fluid-like (hydrodynamic) excitations for Pb–Pb collisions and particle-like (or non-hydrodynamic) excitations for pp or p–Pb
- **Core vs. corona**
  - **EPOS LHC**: Parameterized hydrodynamic evolution in core
    T. Pierog *et. al* PRC 92, 034906 T. Pierog (Tues)
  - **DCCI2**: Equilibrium and non-equilibrium (e.g.,Y. Kanakubo et al., *Phys. Rev. C* 106, 054908, 2022))
  - **MC-EKRT**:Refining/improving both QCD and initial condition models (e.g., M. Kuha et al., arXiv:2406.17592))



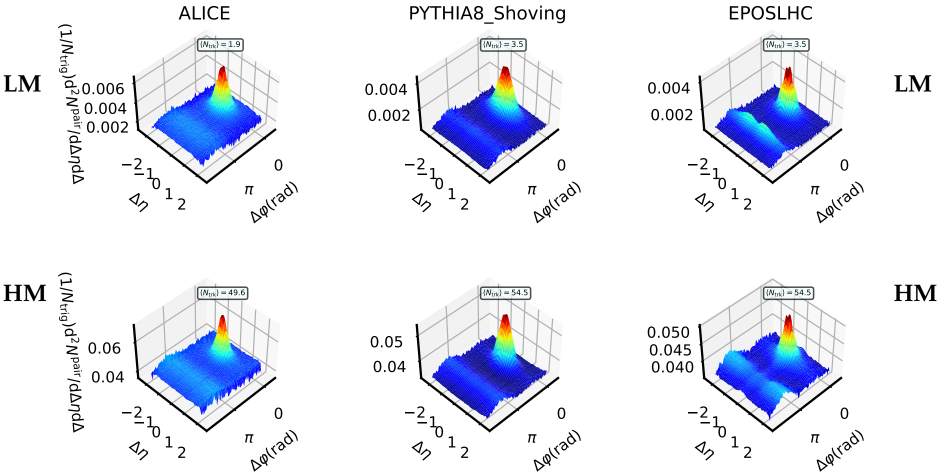


- Core(high density) - QGP formation, thermal hadronization
- Corona(low density) - jets, hadronization in vacuum
- Increasing multiplicity corresponds to increaseing N_{Pom} → Increasing Q_s → harder Pomerons → harder strings → strong increase of $< p_T >$



ALICE, JHEP 05 (2021) 290

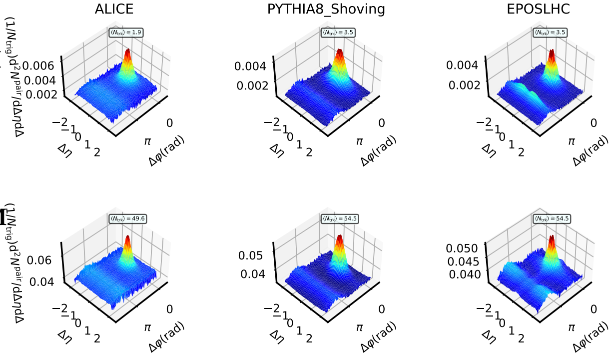
$1 < p_{\mathrm{T,trig}} < 2 \otimes 1 < p_{\mathrm{T,assoc}} < 2\ \mathrm{GeV}/c$



$$1 < p_{\mathrm{T,trig}} < 2 \otimes 1 < p_{\mathrm{T,assoc}} < 2\ \mathrm{GeV}/c$$

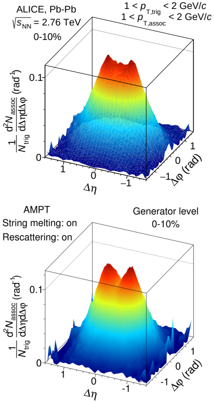
LM

HM



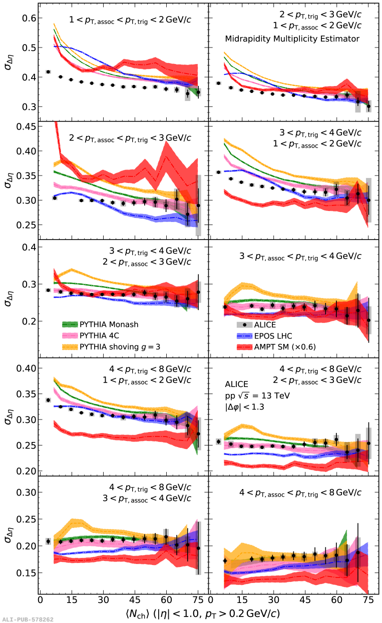
LM

HM



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

Model comparisons: Near-side width $\sigma_{\Delta\eta}$



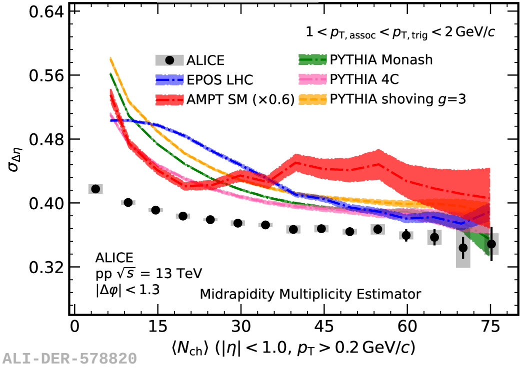
ALICE, arXiv:2409.04501

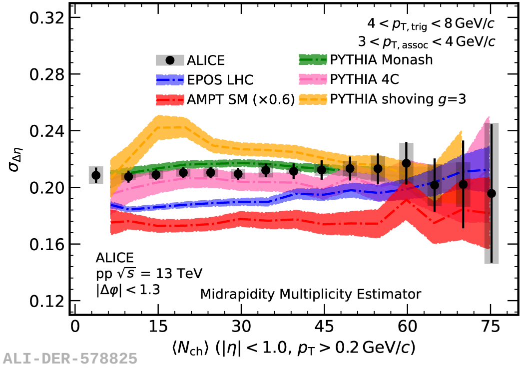
Too many p_T-intervals?

Let's zoom in!

Model comparisons: Near-side width $\sigma_{\Delta\eta}$, Summary

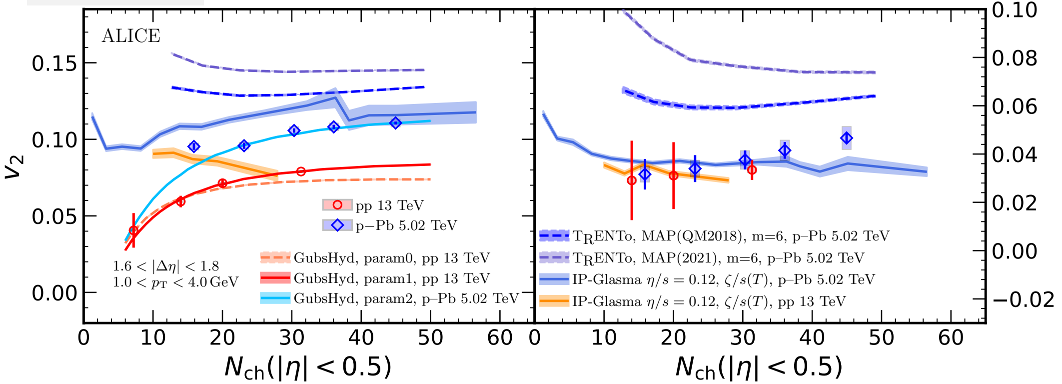
ALICE, arXiv:2409.04501





- Models overestimate for the lower-p_{T} but better description for higher-p_{T}
- Trend is captured by most models
- The multiplicity dependence is weaker for higher-p_{T}
- Non-trivial p_{T} and multiplicity dependence in the models which contains "Jets" + "Flow"
- Be careful for your interpretation, introduced biases while producing flow (e.g, EPOS and PYTHIA8-Shoving)
- Not trivial to extract flow from some models (see S. Ji et al., PRC **108**, 034909 (18.09.2023))

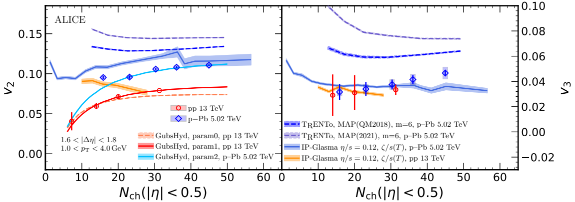
ALICE, JHEP 03 (2024) 092



- Excellent test for developments of the models for small systems, including MC-based models.

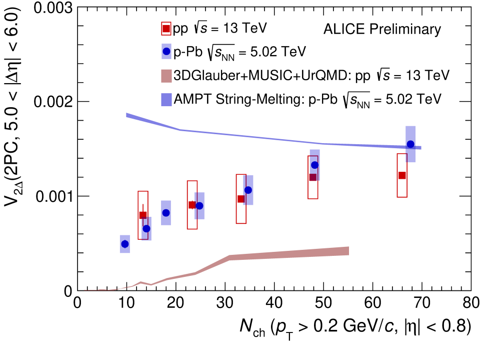
[1] S.F. Taghavi, PRC **104**, 054906 (2021) [2] J.E. Parkkila *et al.*, PLB **835**, 137485 (2022) [3] B. Schenke *et al.* PRC **102**, 044905 (2020)

CERN Courier, Nov 2023



ALICE, JHEP 03 (2024) 092

- Only verified with ALICE acceptance for $|\eta| < 0.9$ and $p_{\mathrm{T}} > 1.0$ GeV/c.
- Large η acceptance → potential multi-jet contributions biasing the flow signal.
- **This explains why other results, which require careful verification, are not presented.**
- Latest small system review paper (arXiv:2407.07484)



- Test with larger η acceptance using FMD
- Models fail to describe the data in the forward region
- Currently only $V_{2\Delta}$ available; need to test different combinations and study potential multi-jet contributions

Success:

- More Beam energies and new sensitive flow data $\rightarrow$ better understanding of QCD matter
- Small systems: improving the measurements(exp) + sub-nucleon structure(theory)

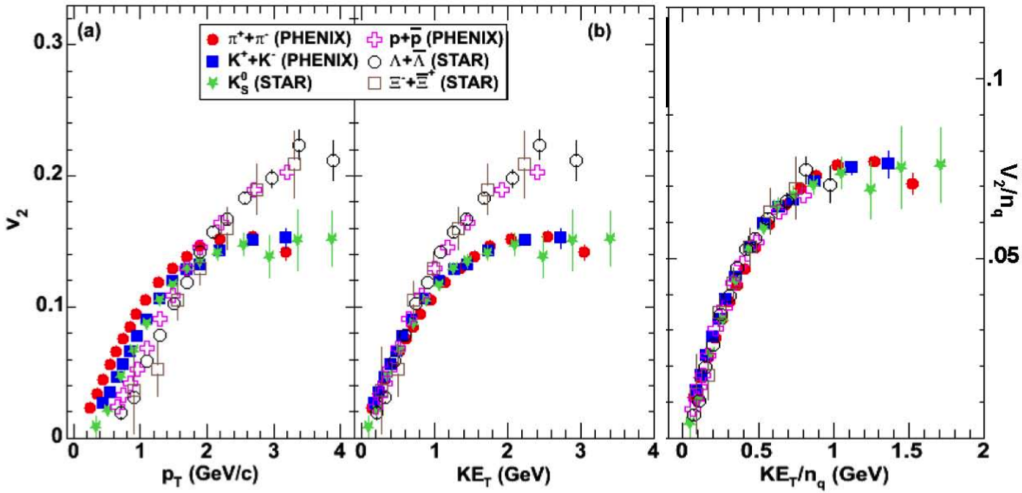
Challenges:

- Large systems
  - Challenging initial state models (e.g, Trento)
    - $\rho(v_2^2, [p_T])$ challenges initial state modelling
    - 10% difference for v_2 (5.02 TeV) and still lacking for NSC(4,2) ...
- Small systems
  - Better understanding on the flow extraction method (but still limited because of jet kinematic biases)
  - Need more insights from theory $\rightarrow$ better understanding of large systems!
  - Disentangling QCD biases to find QGP effects in small systems
    - Core vs. corona contributions (e.g.,Y. Kanakubo et al., *Phys. Rev. C* 106, 054908, 2022))
    - Refining/improving both QCD and initial condition models (e.g., M. Kuha et al., arXiv:2406.17592))

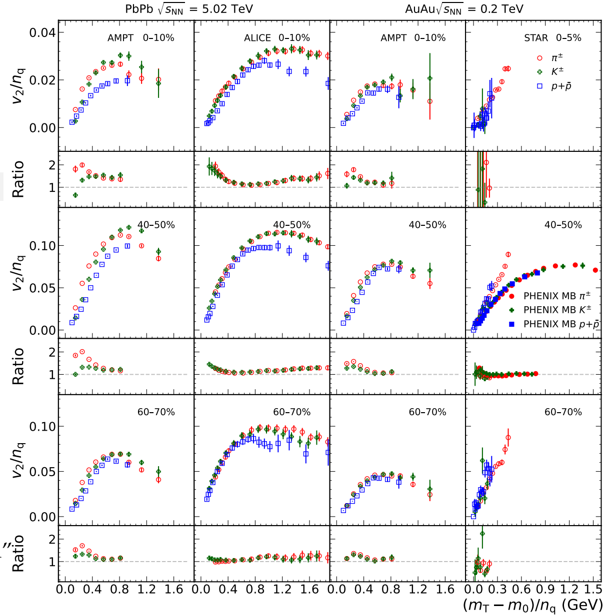
Thank you for your attention!

Remarks

"The study of Heavy Ion (HI) collisions involves a sophisticated modelling process across various stages within a multidimensional parameter space. To gain a comprehensive understanding of the physics involved and to effectively constrain the model parameters, it is imperative to supply as much independent information as possible. This is crucial due to the lever arm existing between these stages, ensuring that the modelling remains robust and sensitive to nuanced details." – D.J. Kim

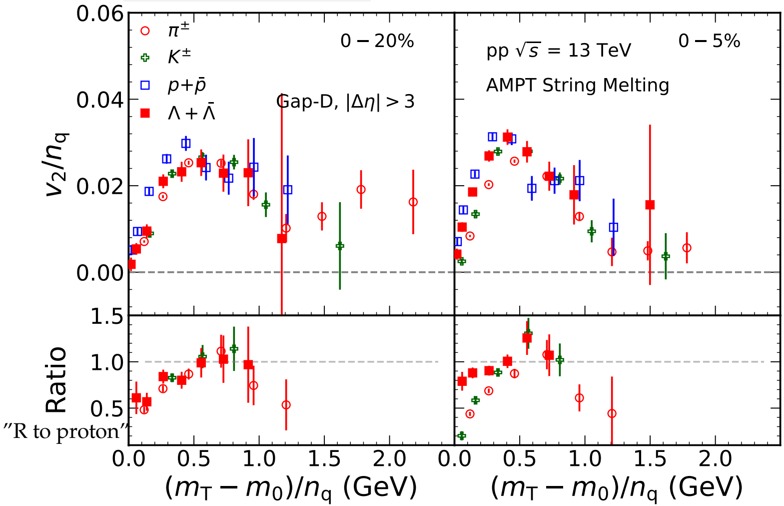

(a)
(b)
$\pi^++\pi^-$ (PHENIX)
K^++K^- (PHENIX)
K^0_S (STAR)
$p+\bar{p}$ (PHENIX)
$\Lambda+\bar{\Lambda}$ (STAR)
$\Xi^-+\bar{\Xi}^+$ (STAR)
v_2
0.3
0.2
0.1
0
p_T (GeV/c)
KE_T (GeV)
KE_T/n_q (GeV)
v_2/n_q
.1
.05
0
0.5
1
1.5
2
3
4

S. Ji et. al, PRC **108**, 034909 (18.09.2023)



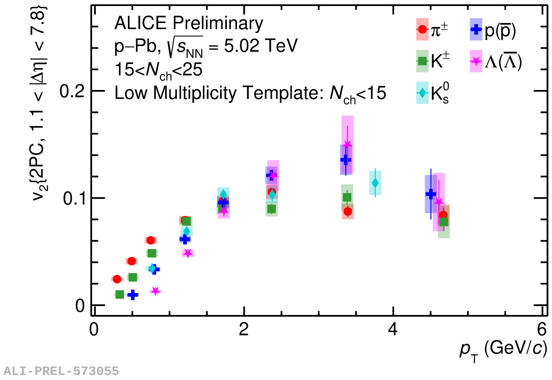
"Ratio to proton"

S. Ji et. al, PRC **108**, 034909 (18.09.2023)

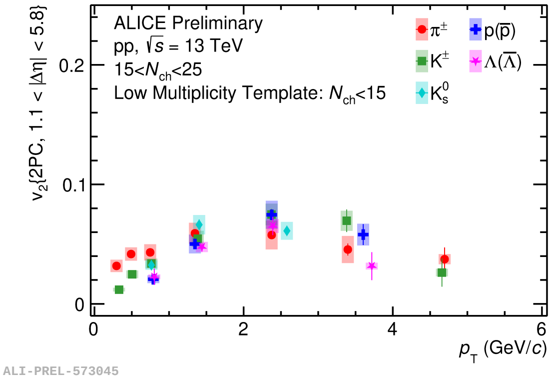


- Very different quark number scaling between small and large systems in AMPT
- Avoid over-interpretation of this scaling both in small and large systems.

pPb 5.02 TeV

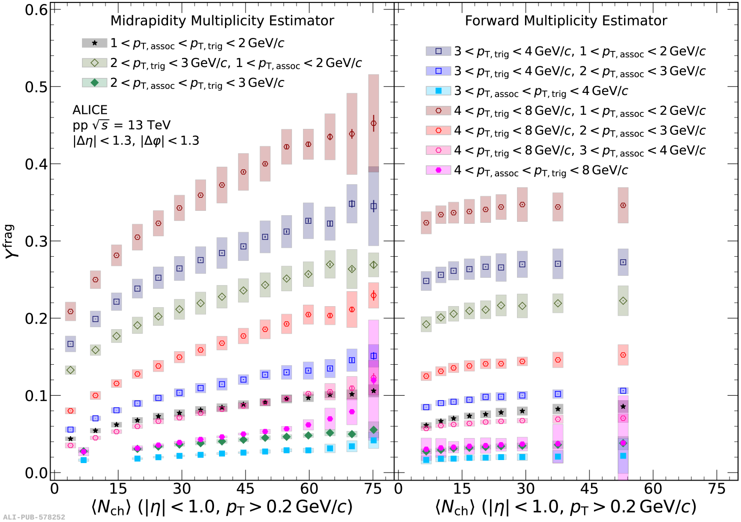


pp 13 TeV



Stay tuned for the final results!

γ: Multiplicity dependence of jet fragmentation yields: magnitude comparison

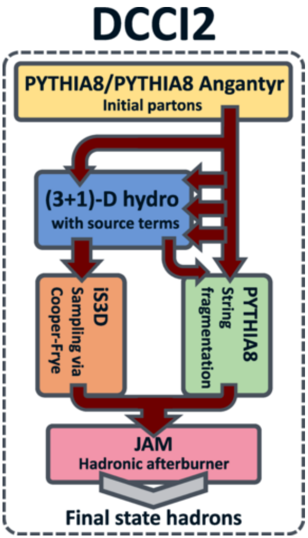


ALICE, arXiv:2409.04501

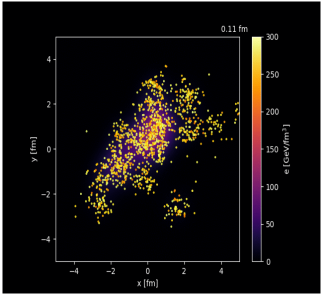
- Evaluate jet fragmentation yield:

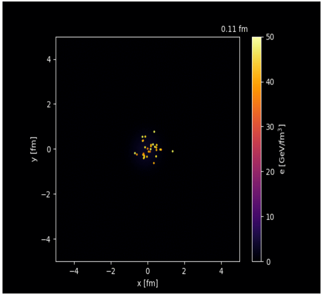
$$Y^{\mathrm{frag}} = \int_{|\Delta\eta|} \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}N}{\mathrm{d}\Delta\eta} \mathrm{d}\Delta\eta.$$

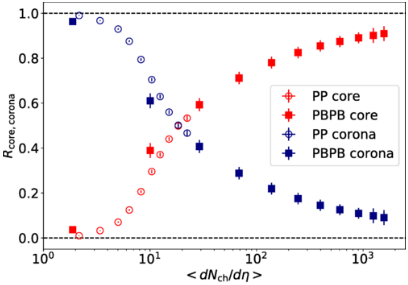
- Largest jet yields for $1 < p_{\mathrm{T,assoc}} < 2$ GeV/c bins
- Smallest yields for symmetric trig-assoc bins
- $F = 1.3$ (~ 2.2) for forward-rapidity (mid-rapidity) in low-p_{T}

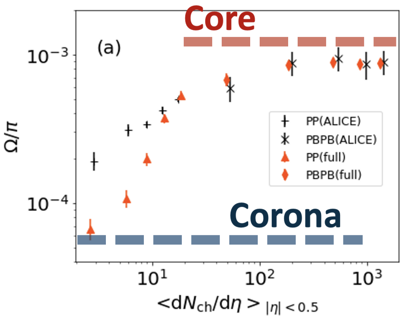


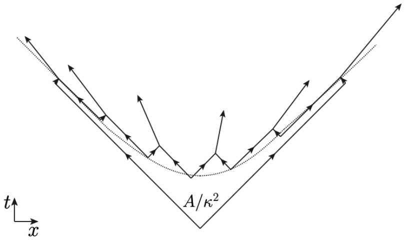
Y. Kanakubo et al., Phys.Rev.C 105 (2022) 2, 024905







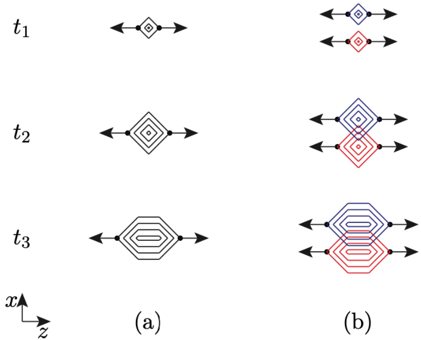




$$f(z) = N z^a \exp(-b\, m^2/z). \qquad (3)$$

$$\langle \tau^2 \rangle = \frac{1+a}{b\,\kappa^2}, \qquad (4)$$

where κ is the tension of the string. With values $a = 0.68$, $b = 0.98$ GeV^{-2} (PYTHIA default), and $\kappa = 0.9 - 1$ GeV/fm, the typical breaking time around 2 fm $\rightarrow$ the string breaks typically when the original quark and antiquark are about 4 fm apart.



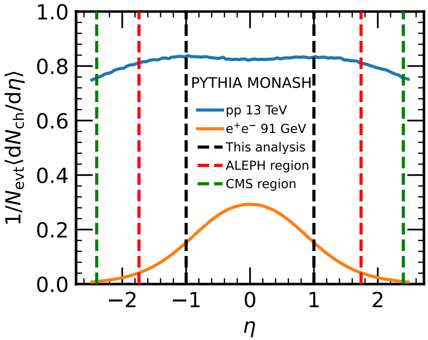
Interactions between strings by overlapping flux tubes; The repulsion gives the flux tubes a transverse velocity,"shoving"

- Reproduces the pp ridge with suitable choice of g parameter.

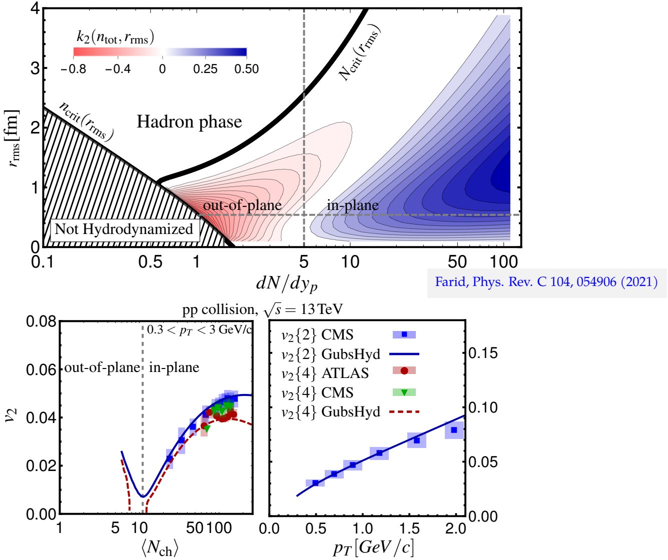
$$f(r_\perp) = \frac{dE}{dr_\perp} = \frac{g\kappa r_\perp}{2R^2} exp(\frac{-r_\perp^2}{2R^2}) \qquad (5)$$

- Estimate the limits of uncertainty on the conversion of the multipicity
- Target: multiplicity defined by accepted particles within $|\eta| < 1.0$, $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$
- Conversion between different systems and experiments is done using PYTHIA
  1. Simulate pp at $\sqrt{s} = 13\,\mathrm{TeV}$ in both experimental acceptances. Multiplicity ratio to obtain factor 1
  2. Simulate e^+e^- at $\sqrt{s} = 91\,\mathrm{GeV}$ in both experimental acceptances. Multiplicity ratio to obtain factor 2

Experiment	$\|\eta_{\max}\|$	$p_{\mathrm{T,min}}$	$\sqrt{s}$
ALICE pp	1.0	0.2	13 TeV
ALEPH e^+e^-	1.738	0.2	91 GeV



Method	Experiment	Corr. factor
PYTHIA	ALEPH pp 13 TeV	0.57
	ALEPH e^+e^- 91 GeV	0.78
Flat $dN/d\eta$	ALEPH	0.63



$k_2(n_{tot}, r_{rms})$
−0.8 −0.4 0 0.25 0.50
Hadron phase
$N_{crit}(r_{rms})$
$n_{crit}(r_{rms})$
out-of-plane
in-plane
Not Hydrodynamized
r_{rms}[fm]
dN/dy_p
Farid, Phys. Rev. C 104, 054906 (2021)
pp collision, $\sqrt{s} = 13$ TeV
$0.3 < p_T < 3$ GeV/c
out-of-plane
in-plane
v_2
$\langle N_{ch} \rangle$
$v_2\{2\}$ CMS
$v_2\{2\}$ GubsHyd
$v_2\{4\}$ ATLAS
$v_2\{4\}$ CMS
$v_2\{4\}$ GubsHyd
$p_T\,[GeV/c]$