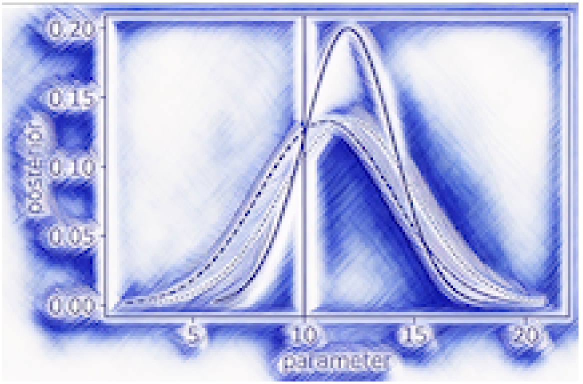


ALICE

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Emergence and quantification of collective effects across collision systems

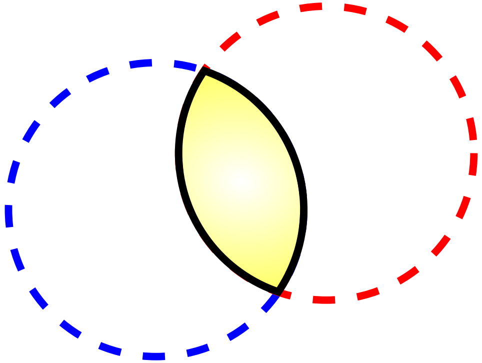
Precision Frontier of QCD Matter: Inference and Uncertainty Quantification. CCNU Wuhan 4.9.2025

Jasper Parkkila

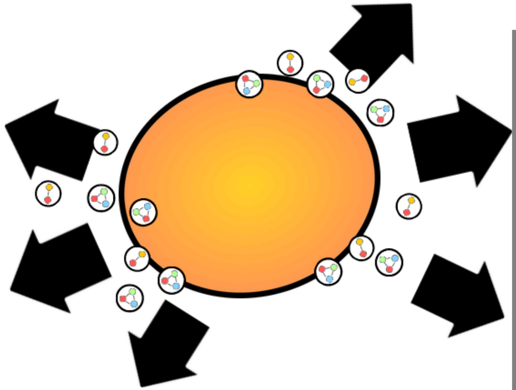
Talk ouline

1. Collective-like effects in heavy-ion collisions, theory and experiment
2. Transport properties from LHC and RHIC observables
3. Small system collective-like effects
4. Signatures of medium
4. Light-ion mid-point results

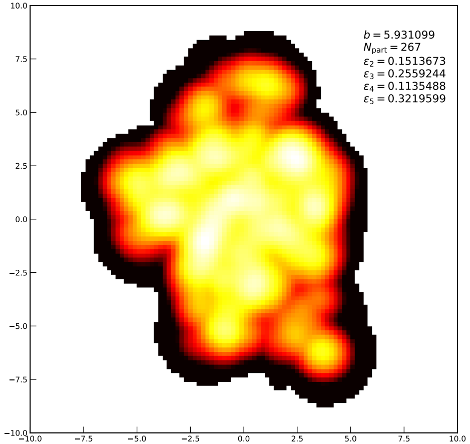
Origin of collectivity in experiment and theory



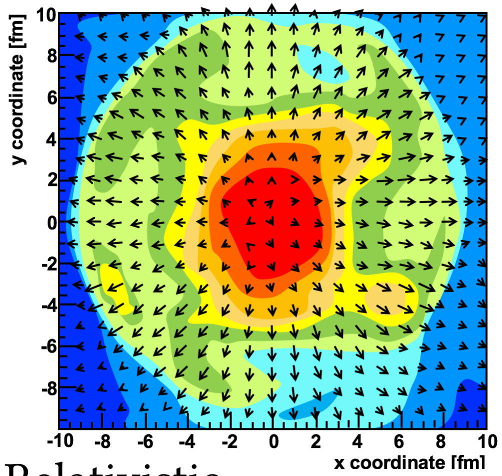
Spatial anisotropy



Momentum anisotropy



Initial condition models



Relativistic hydrodynamics

▹ Experiment

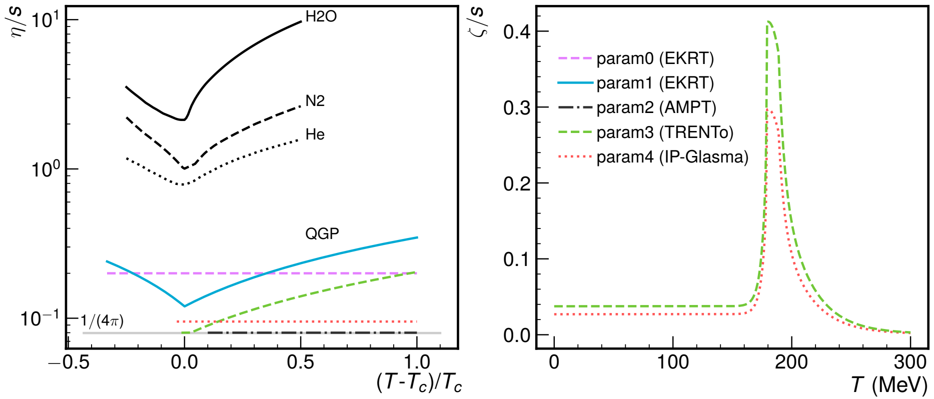
- Strongly-interacting **medium** is formed in collisions according to several experimental indicators
- This medium is fluid-like, implied by **anisotropic** particle momentum pattern of the hadronic products
- The anisotropic expansion is a result of **collective** behaviour, and is very prominent in heavy-ion system

▹ Theory

- Hydrodynamics is a mainstream description of the medium
- The system undergoes a fluid-like expansion under the pressure gradients of the initial stage geometry
- Successful description of wide range of experimental observables
- Medium properties characterized by shear and bulk resistance to evolution over time

$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}, \quad \sigma_{\mu}T^{\mu\nu} = 0$$

Transport properties of the hydrodynamic theory



- ▹ Specific shear viscosity

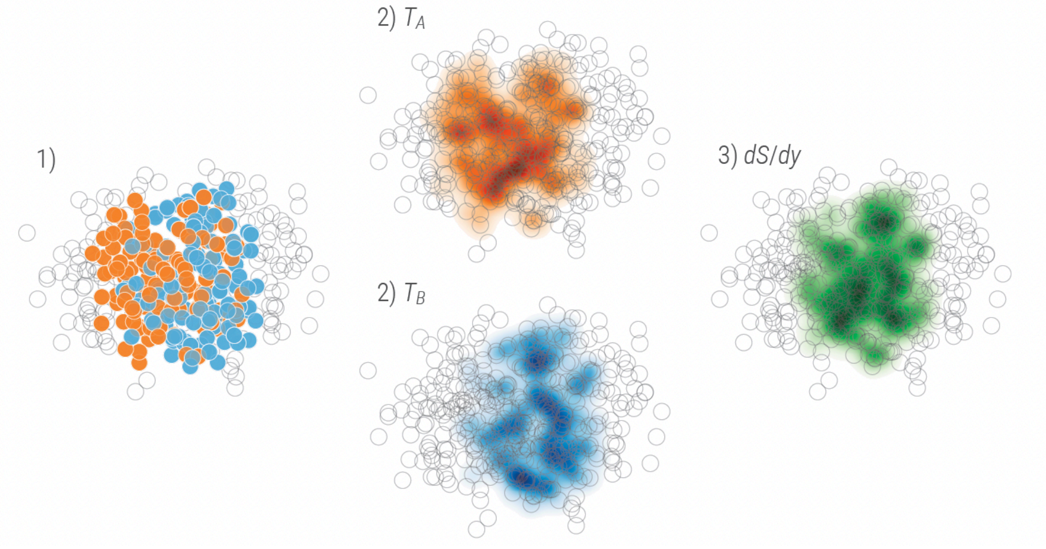
$$\frac{\eta}{s}(T) = \left(\frac{\eta}{s}\right)_{\text{min}} + \left(\frac{\eta}{s}\right)_{\text{slope}} (T - T_{\text{c}}) \left(\frac{T}{T_{\text{c}}}\right)^{(\eta/s)_{\text{crv}}}$$

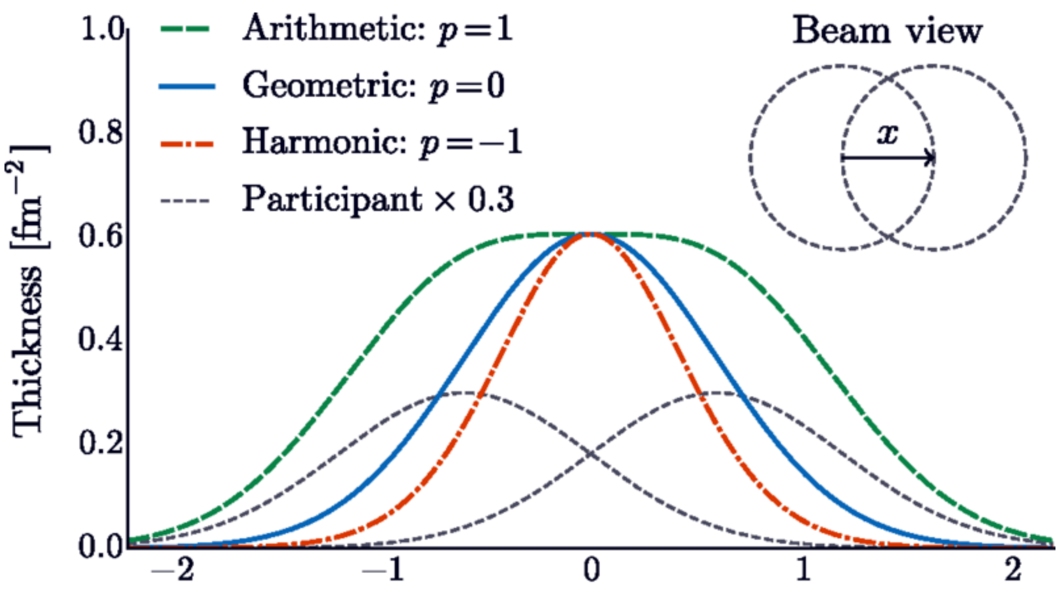
- ▹ Specific bulk viscosity

$$\frac{\zeta}{s}(T) = \frac{(\zeta/s)_{\text{max}}}{1 + \left(\frac{T - (\zeta/s)_{\text{T}_{\text{peak}}}}{(\zeta/s)_{\text{width}}}\right)^2}$$

Parameter	Description
T_{c}	Temperature of const. $\eta/s(T)$, $T < T_{\text{c}}$
$\eta/s(T_{\text{c}})$	Minimum $\eta/s(T)$
$(\eta/s)_{\text{slope}}$	Slope of $\eta/s(T)$ above T_{c}
$(\eta/s)_{\text{crv}}$	Curvature of $\eta/s(T)$ above T_{c}
$(\zeta/s)_{\text{T}_{\text{peak}}}$	Temperature of maximum $\zeta/s(T)$
$(\zeta/s)_{\text{max}}$	Maximum $\zeta/s(T)$
$(\zeta/s)_{\text{width}}$	Width of $\zeta/s(T)$ peak
T_{switch}	Switching / particlization temperature
$N(E)$	Overall normalization for collision energy E
p	Entropy deposition parameter
w	Nucleon width
σ_{k}	Std. dev. of nucleon multiplicity fluctuations
d^3_{min}	Minimum volume per nucleon
τ_{fs}	Free-streaming time

Phenomelogical initial conditions





PRC. **C92** (2015) 011901

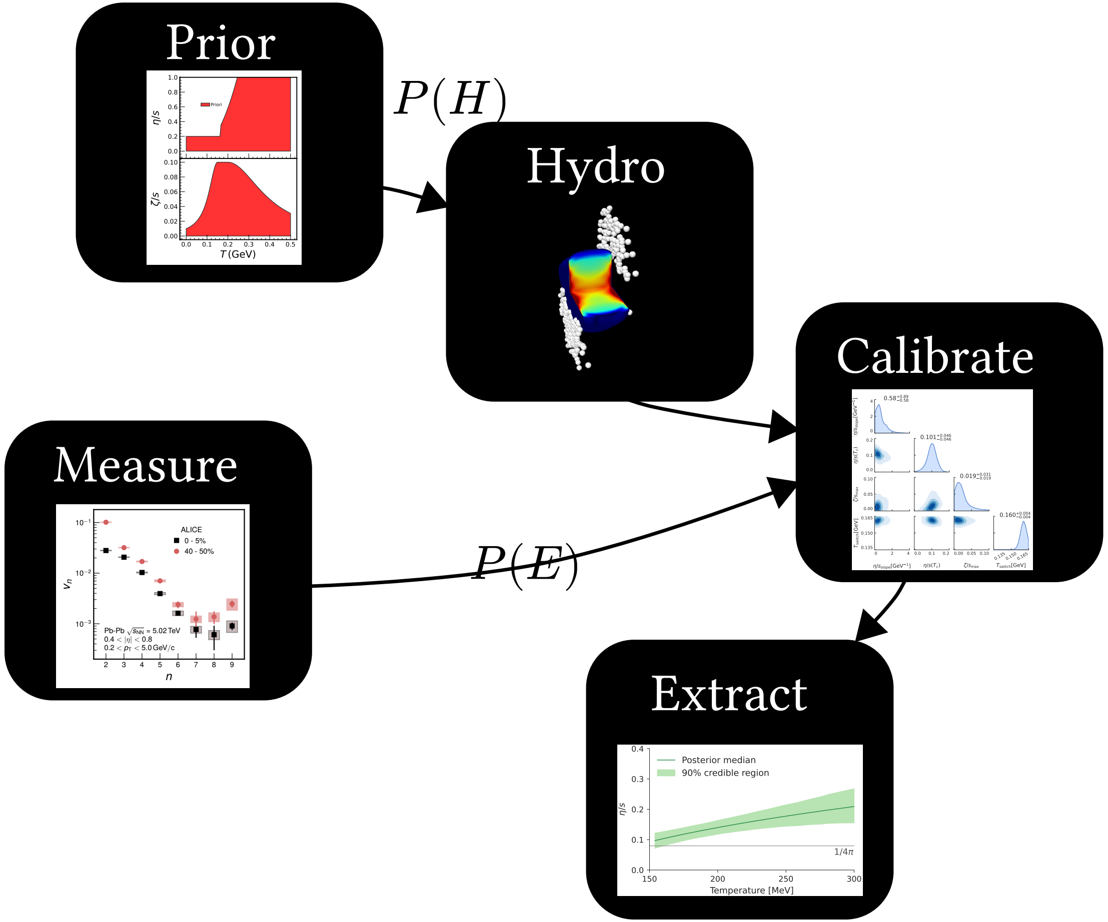
Parameter	Description
$N(E)$	Overall normalization for collision energy E
p	Entropy deposition parameter
w	Nucleon width
σ_{k}	Std. dev. of nucleon multiplicity fluctuations
d^3_{min}	Minimum volume per nucleon
τ_{fs}	Free-streaming time

$$\frac{\mathrm{d}E}{\mathrm{d}x_\perp\,\mathrm{d}\eta_s} = \mathrm{Norm} \times \left(\frac{T_{\mathrm{A}} + T_{\mathrm{B}}}{2}\right)^{1/p}$$

$$T_{\mathrm{A,B}} = \int \mathrm{d}z \rho_{\mathrm{A,B}}(x \pm b/2, y, z)$$

$$\rho_{\mathrm{nucleon}}(x) = \frac{1}{(2\pi w^2)^{3/2}} \exp(-|x|^2/2w^2)$$

Working principle of parameter estimation



Prior

$P(H)$

Hydro

Calibrate

Measure

$P(E)$

Extract

Bayes' theorem

$$P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E)}$$

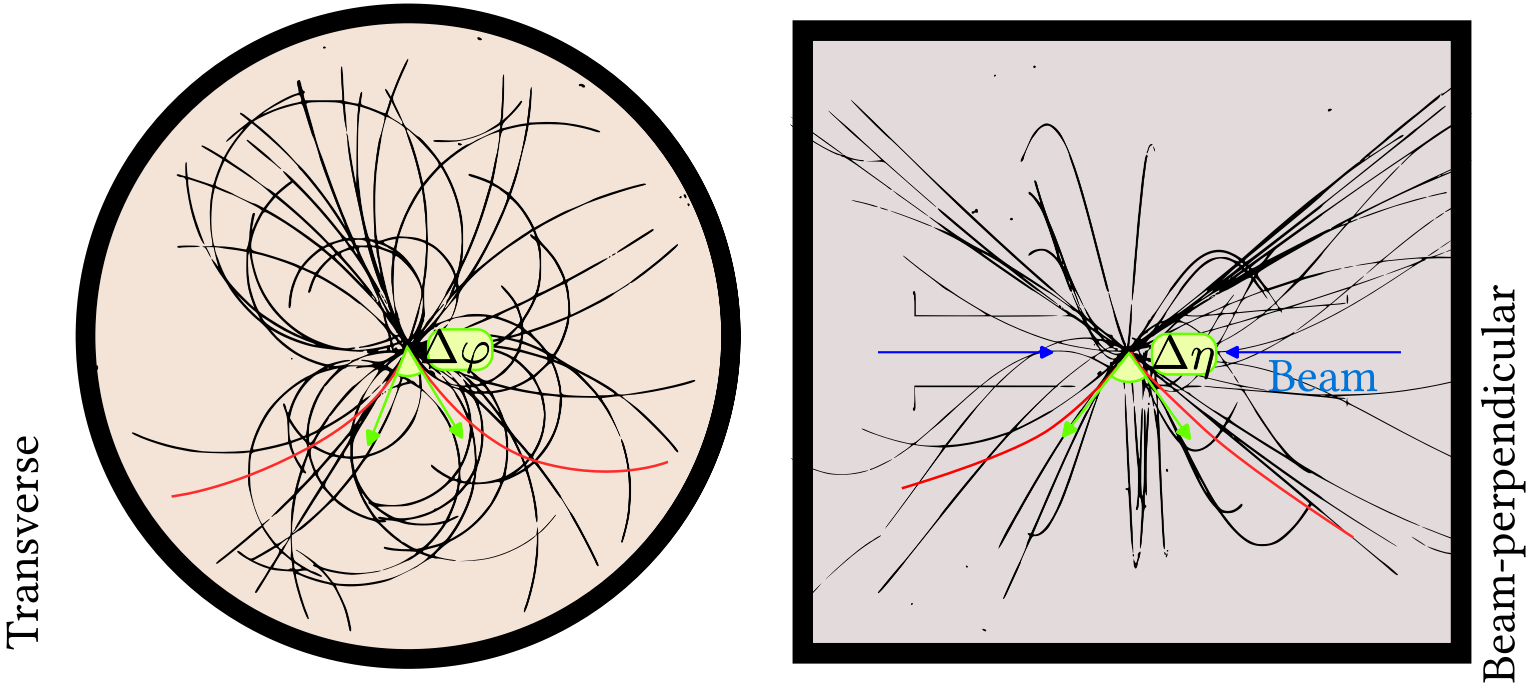
$$P(E) = \sum_{i=1}^{n} P(E|H_i)P(H_i)$$

Posterior: $P(H|E)$: prob. of H given E (experimental data)

- Find optimal set of model parameters that best reproduce the experimental data.
- Utilize constraints, such as flow observables, to help narrow down the $\eta/s(T)$ etc.
- Massive computational cost: need to probe the entire 14-parameter space with sufficient statistics

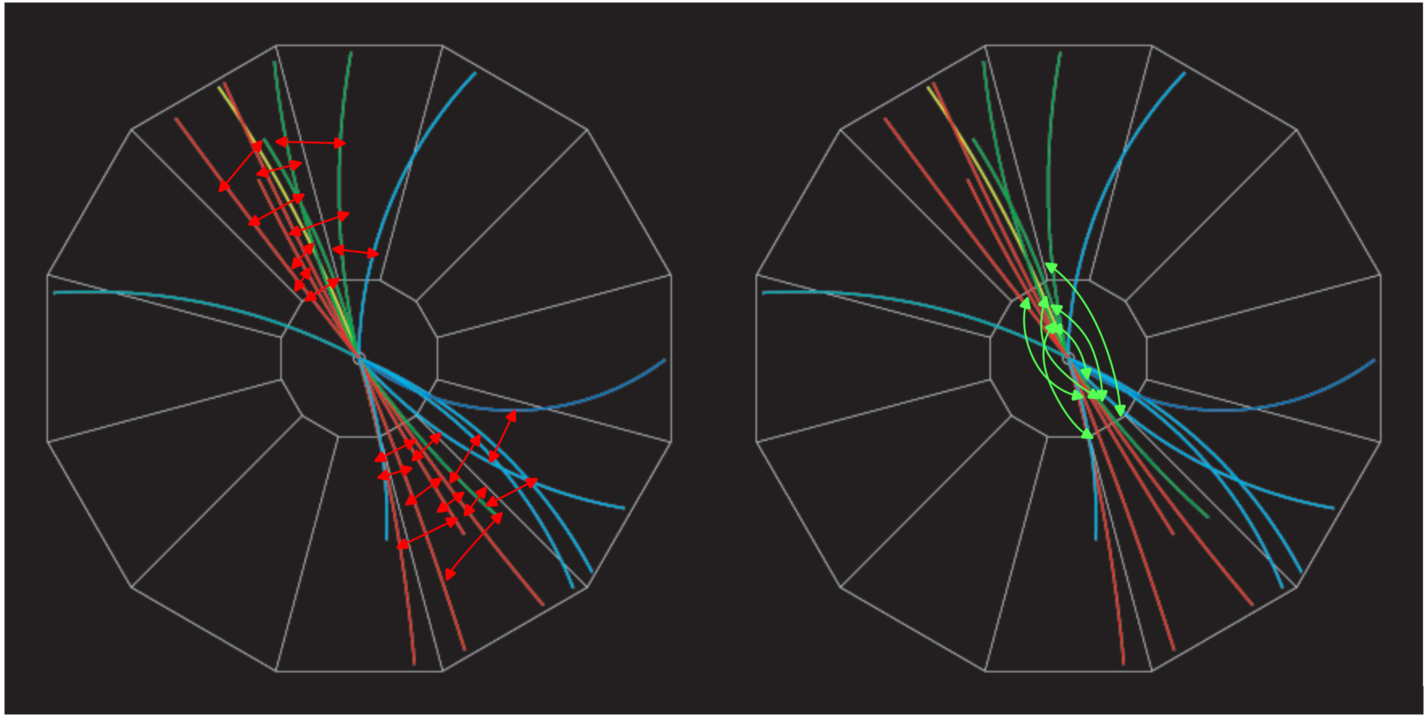
Experimental quantification

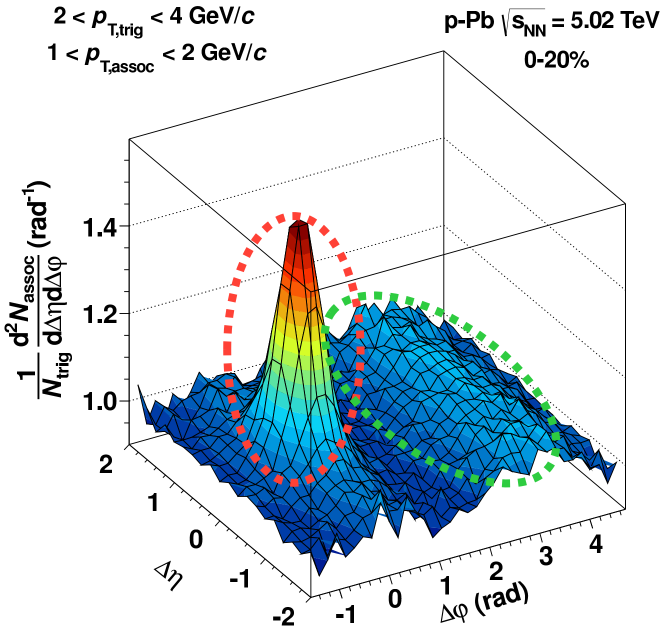
- Experimentally, only final-stage particles and their attributes can be measured
- How can the collective-like effects be experimentally quantified?



- **Two-particle azimuthal correlations**: measurement of the polar angle $\Delta\varphi$ and pseudorapidity $\Delta\eta$ between all pairs of charged particles coming from the collision. What sort of correlations can be observed?

Two-particle correlation: typical general features in $(\Delta\eta, \Delta\varphi)$





ALICE, PLB. **719** (2013) 29-41

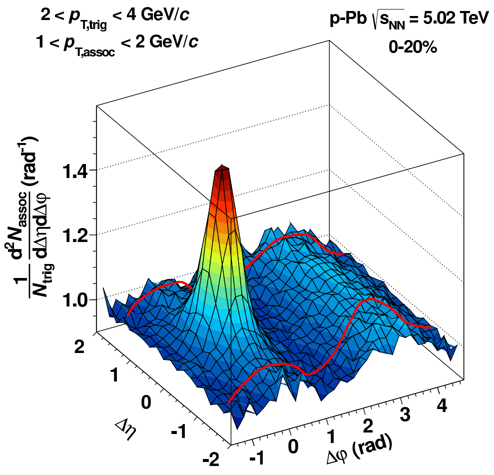
Particles from the same jet at low $\Delta\eta\Delta\varphi$ form the near-side peak

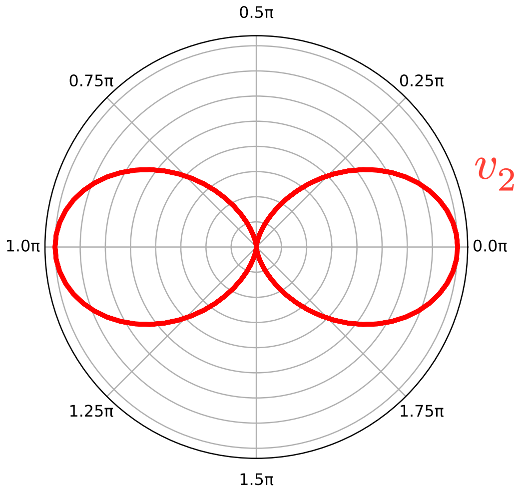
Particles from back-to-back jets at $\Delta\varphi \sim \pi$ form the away-side ridge

pp event in STAR experiment

Long-range correlations

- Collective-like effects manifest themselves as the double-ridge structure in the long-range correlations

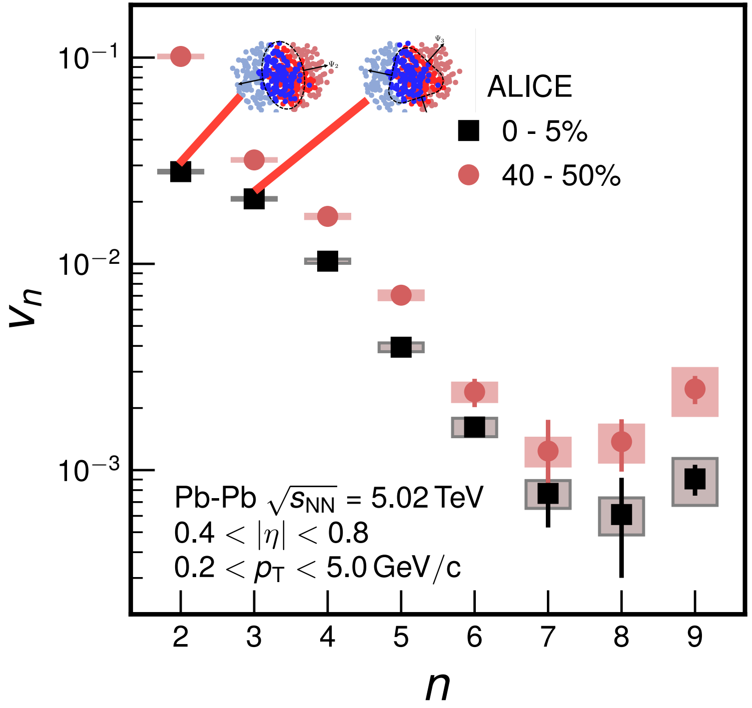




- The double-ridge emerges when a large *elliptic* harmonic component is present: characterizes the elliptic expansion

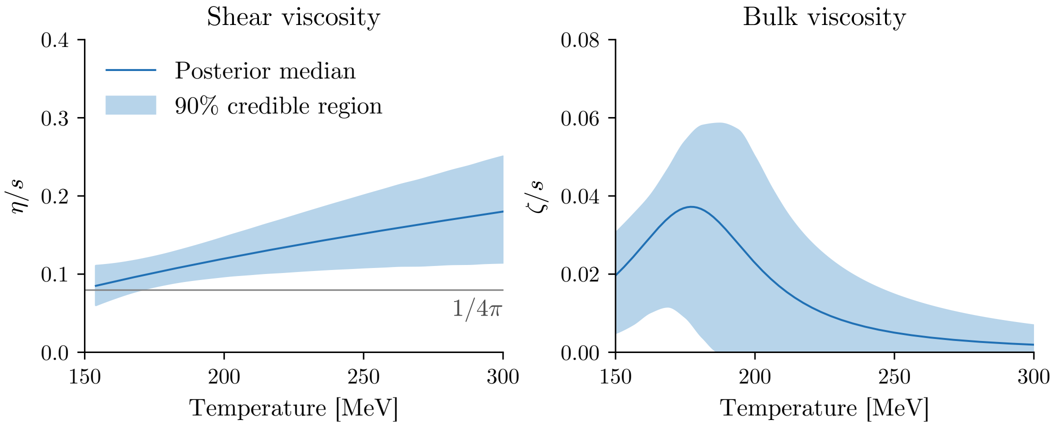
Modes of expansion are chacterized through the flow coefficients v_n:

$$\frac{dN}{d\Delta\varphi} \propto 1 + \sum_{n=1}^{\infty} v_n^2 \cos(\Delta\varphi).$$



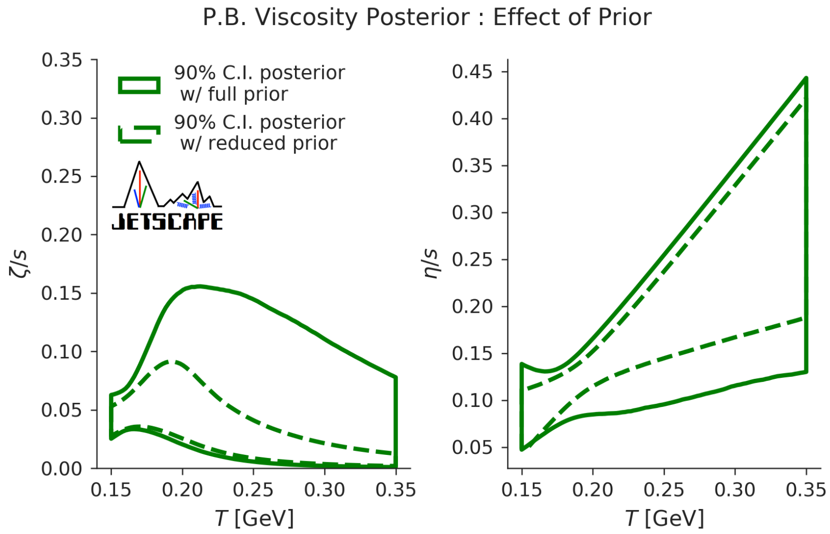
Bayesian parameter estimation

Duke Trento+VISH(2+1D)+UrQMD



Steffen A. Bass *et al.*, Nature Physics (2019)

JETSCAPE Trento+MUSIC+SMASH



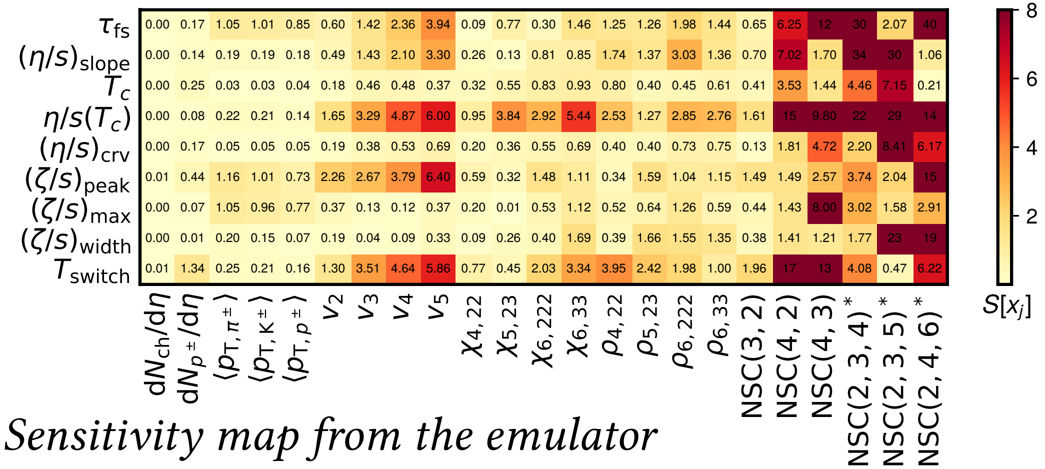
JETSCAPE Collaboration, PRC **103** (2021) 054904

- A number of studies done by 2021 utilizing mostly low-harmonic and 2.76 TeV observables
- Still rather large uncertainty for both $\eta/s(T)$ and $z\eta/s(T)$. Can uncertainty be improved?
- Duke and JETSCAPE provide open source setups for hydrodynamics and bayesian parameter estimation – good starting point phenomelogy work
- Started with JETSCAPE, soon move over to Duke setup

Our arsenal of observables from ALICE

Name	Symbol	Sensitivity-stochastic approach
(High harmonic) Flow coefficients	v_n	Average $\langle\eta/s\rangle$, $\langle\zeta/s\rangle$
Non-linear flow mode coefficients	$\chi_{n,mk}$	$\eta/s(T)$ at the freeze-out
Symmetry-plane correlations	$\rho_{n,mk}$	$\eta/s(T)$ temperature dependence
(Normalized) symmetric cumulants	(N)SC(k,l,m) $\langle v_m^2 v_n^2\rangle$	…
Asymmetric cumulants	AC$_{a,b}(k,l,m)$ $\langle v_m^{2\cdot a} v_n^{2\cdot b}\rangle$	…
N_{ch} spectra and avg. transverse momentum	$N_{p^\pm}/\,\mathrm{d}\eta$, $\langle p_{\mathrm{T}}\rangle$	T_{switch} and τ_{fs}

J.E. Parkkila, **et. al**, Phys. Lett. B **835** (2022) 137485

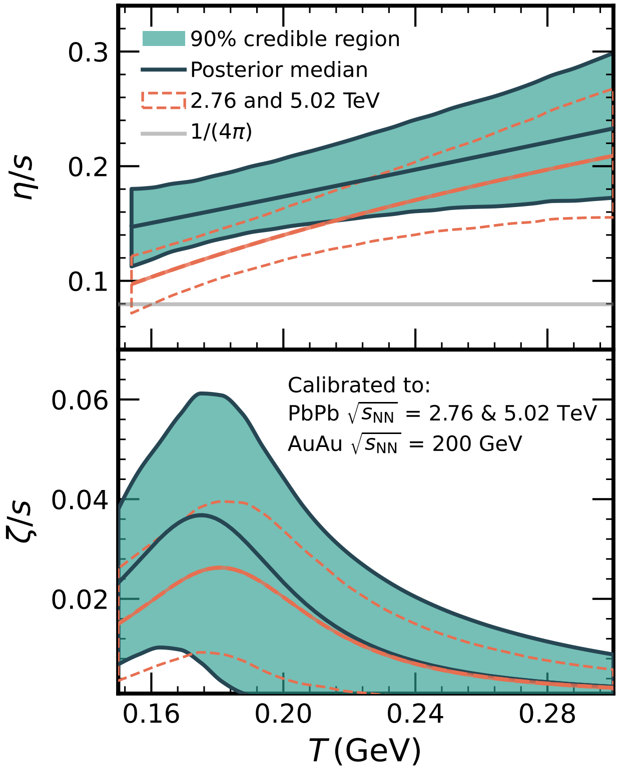


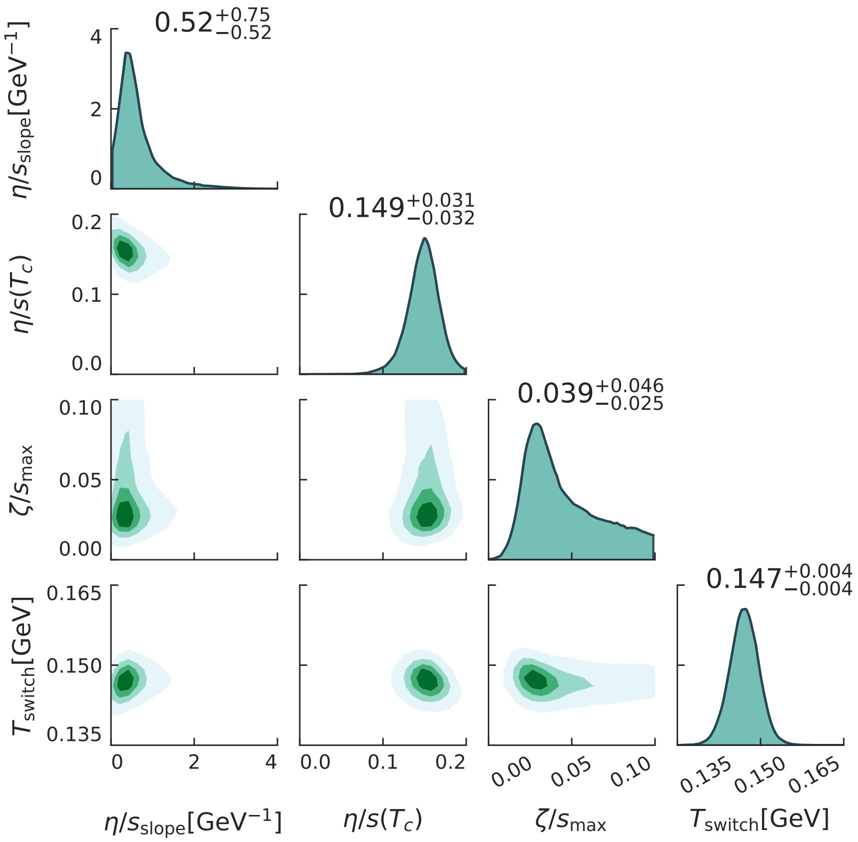
	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$	$\mathrm{d}N_{p^\pm}/\mathrm{d}\eta$	$\langle p_{\mathrm{T},\pi^\pm}\rangle$	$\langle p_{\mathrm{T},\mathrm{K}^\pm}\rangle$	$\langle p_{\mathrm{T},p^\pm}\rangle$	v_2	v_3	v_4	v_5	$\chi_{4,22}$	$\chi_{5,23}$	$\chi_{6,222}$	$\chi_{6,33}$	$\rho_{4,22}$	$\rho_{5,23}$	$\rho_{6,222}$	$\rho_{6,33}$	NSC(3, 2)	NSC(4, 2)	NSC(4, 3)	NSC(2, 3, 4)*	NSC(2, 3, 5)*	NSC(2, 4, 6)*
τ_{fs}	0.00	0.17	1.05	1.01	0.85	0.60	1.42	2.36	3.94	0.09	0.77	0.30	1.46	1.25	1.26	1.98	1.44	0.65	6.25	12	30	2.07	40
$(\eta/s)_{\mathrm{slope}}$	0.00	0.14	0.19	0.19	0.18	0.49	1.43	2.10	3.30	0.26	0.13	0.81	0.85	1.74	1.37	3.03	1.36	0.70	7.02	1.70	34	30	1.06
T_c	0.00	0.25	0.03	0.03	0.04	0.18	0.46	0.48	0.37	0.32	0.55	0.83	0.93	0.80	0.40	0.45	0.61	0.41	3.53	1.44	4.46	7.15	0.21
$\eta/s(T_c)$	0.00	0.08	0.22	0.21	0.14	1.65	3.29	4.87	6.00	0.95	3.84	2.92	5.44	2.53	1.27	2.85	2.76	1.61	15	9.80	22	29	14
$(\eta/s)_{\mathrm{crv}}$	0.00	0.17	0.05	0.05	0.05	0.19	0.38	0.53	0.69	0.20	0.36	0.55	0.69	0.40	0.40	0.73	0.75	0.13	1.81	4.72	2.20	8.41	6.17
$(\zeta/s)_{\mathrm{peak}}$	0.01	0.44	1.16	1.01	0.73	2.26	2.67	3.79	6.40	0.59	0.32	1.48	1.11	0.34	1.59	1.04	1.15	1.49	1.49	2.57	3.74	2.04	15
$(\zeta/s)_{\mathrm{max}}$	0.00	0.07	1.05	0.96	0.77	0.37	0.13	0.12	0.37	0.20	0.01	0.53	1.12	0.52	0.64	1.26	0.59	0.44	1.43	8.00	3.02	1.58	2.91
$(\zeta/s)_{\mathrm{width}}$	0.00	0.01	0.20	0.15	0.07	0.19	0.04	0.09	0.33	0.09	0.26	0.40	1.69	0.39	1.66	1.55	1.35	0.38	1.41	1.21	1.77	23	19
T_{switch}	0.01	1.34	0.25	0.21	0.16	1.30	3.51	4.64	5.86	0.77	0.45	2.03	3.34	3.95	2.42	1.98	1.00	1.96	17	13	4.08	0.47	6.22

Sensitivity map from the emulator

- More advanced multi-particle observables beyond the v_n present unique sensitivity to various stages of the evolution
- More sensitive observables have more constraining power
- Observables should be independent of from other

Parameter estimation using advanced azimuthal correlations





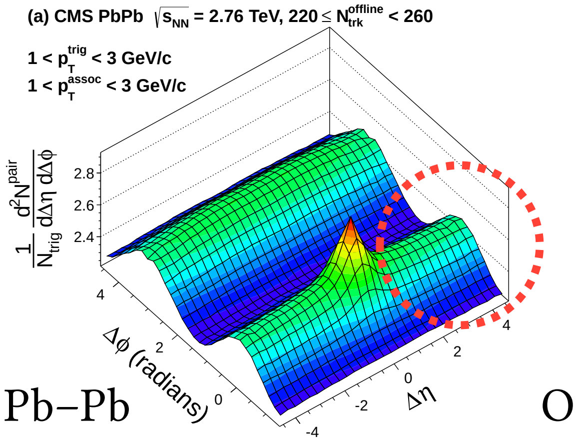
Our latest calibration includes data from LHC Pb–Pb at 5.02 + 2.76 TeV *and* RHIC Au–Au at 200 GeV.

- Parameters well constrained despite 3 collision systems and many observables
- Larger uncertainty than Pb–Pb alone (2022 study)
- Model limitations, choice of centrality etc.

- M. Virta, J.E. Parkkila, D.J. Kim, PRC. **111** (2025) 044903
- J.E. Parkkila, **et. al**, Phys. Lett. B **835** (2022) 137485

Collective-like effects in various collision systems

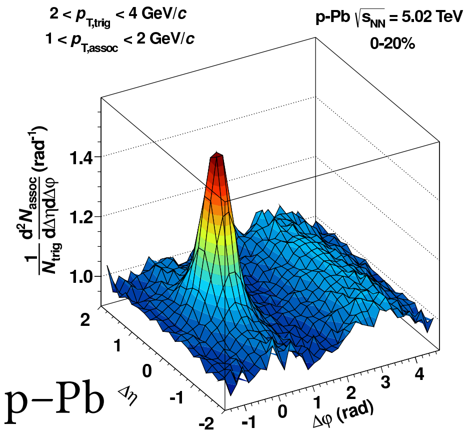
- This signal is present across various collision system sizes



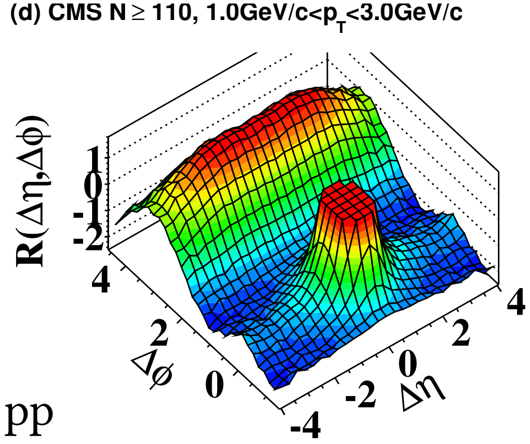
Pb–Pb

OO

❗ no public preliminary



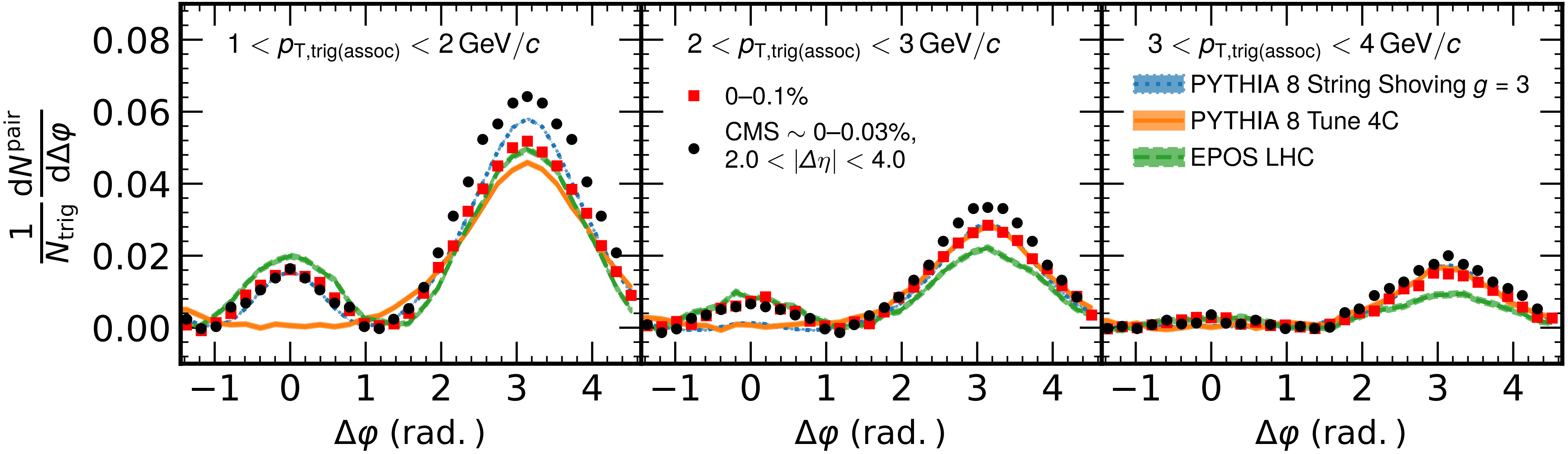
p–Pb



pp

- Long-range correlation emerges during the early stages
- In heavy-ion systems this is the medium response to initial stage geometry
- Light-ion: likely medium response
- p–Pb and pp: medium-like, but might be something else
- In small systems the origin is unclear (QGP? Multi-parton scattering? Ropes? Initial-stage effect?)

Long-range correlations in pp: basic findings



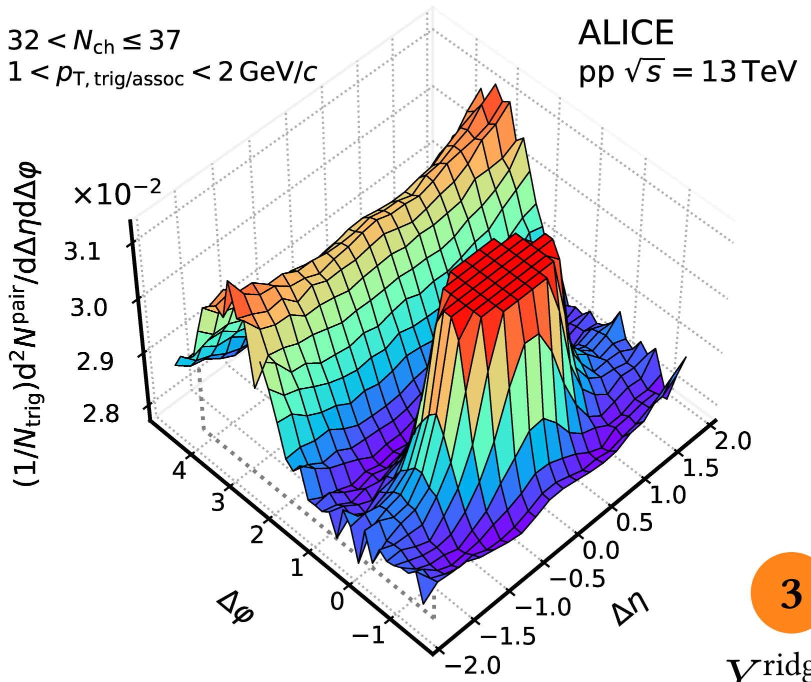
JHEP **05** (2021) 290

- Prominent long-range near-side ridge in high multiplicity ($N_{\rm ch} > 110$) collisions
- Small signal in minimum bias (0–100%)
- **How small can the system get and still exhibit these signals?**
- Several theoretical approaches with or without medium

Ridge-yield as quantification for collective-like effects

- Near-side ridge clearly visible in high-multiplicity events

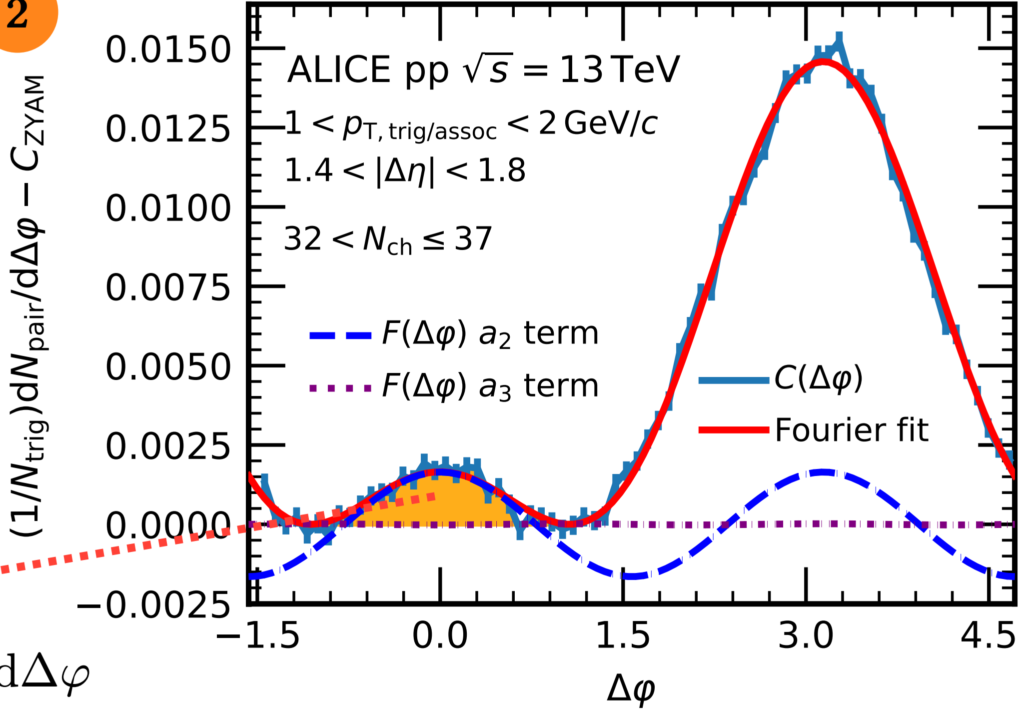
1



ALI-PUB-574465

$\int \mathrm{d}\Delta\eta$ ➜

2

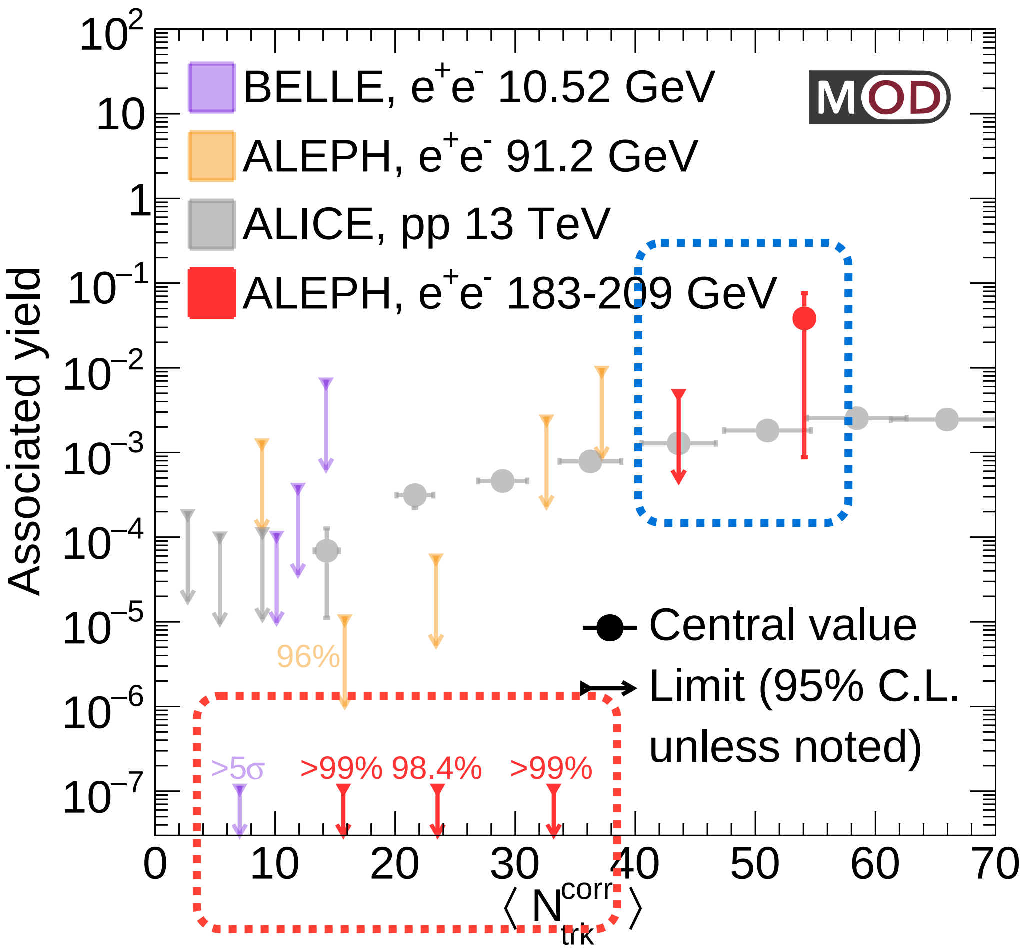


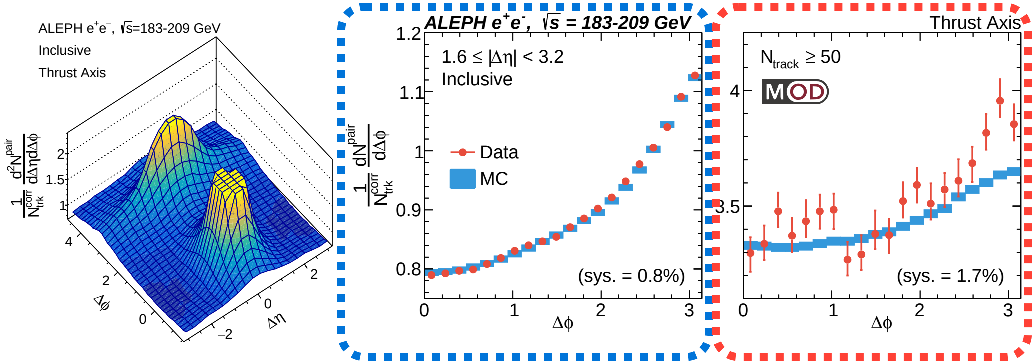
3

$Y^{\mathrm{ridge}} = \int \mathrm{d}\Delta\varphi$

- Find the baseline and $|\Delta\varphi_{\mathrm{min}}|$ by fitting $F(\Delta\varphi) = A\left(1 + 2\sum_{n=1}^{3} v_n^{2,\mathrm{cent}} \cos(n\Delta\varphi)\right) + C_{\mathrm{ZYAM}}$ to the signal
- Measured in $1.4 < |\Delta\eta| < 1.8$ to suppress the short-range non-flow correlations
- $p_{\mathrm{T}} > 1.0$ GeV$/c$ (*trig* and *assoc*) to avoid near-side jet broadening into $|\Delta\eta| > 1.4$

Ridge yield in e^+e^- collisions

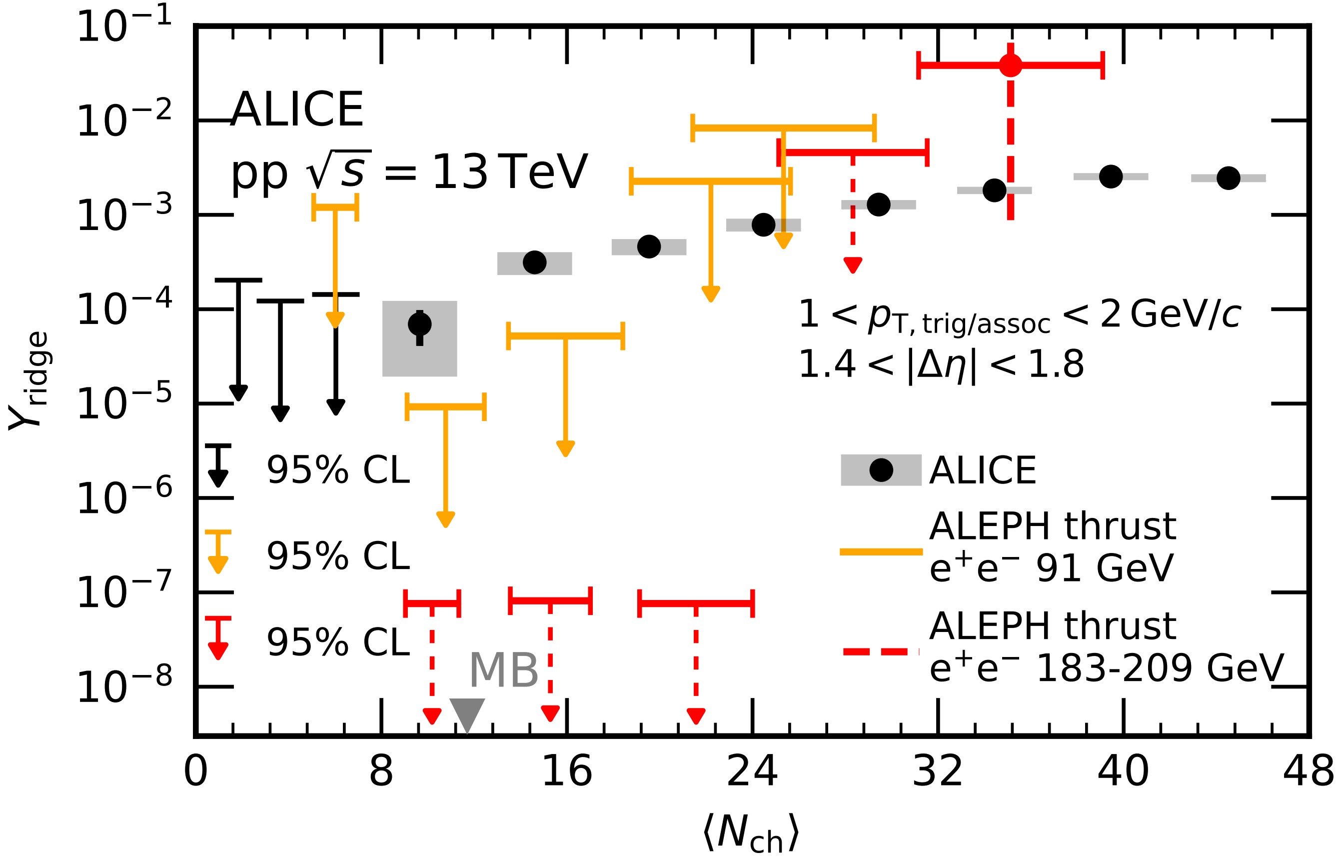




pp system details are intricate. Study the simpler processes involved in e^+e^- annihilations (point-like collision: no uncertainties on initial geometry or parton distribution function description)

- No yield in the lowest multiplicities $N_{\mathrm{ch}} < 10$
- Would we get similarly small values in pp as in e^+e^- or are the two systems intrinsically different?

Ridge yield in low-multiplicity pp

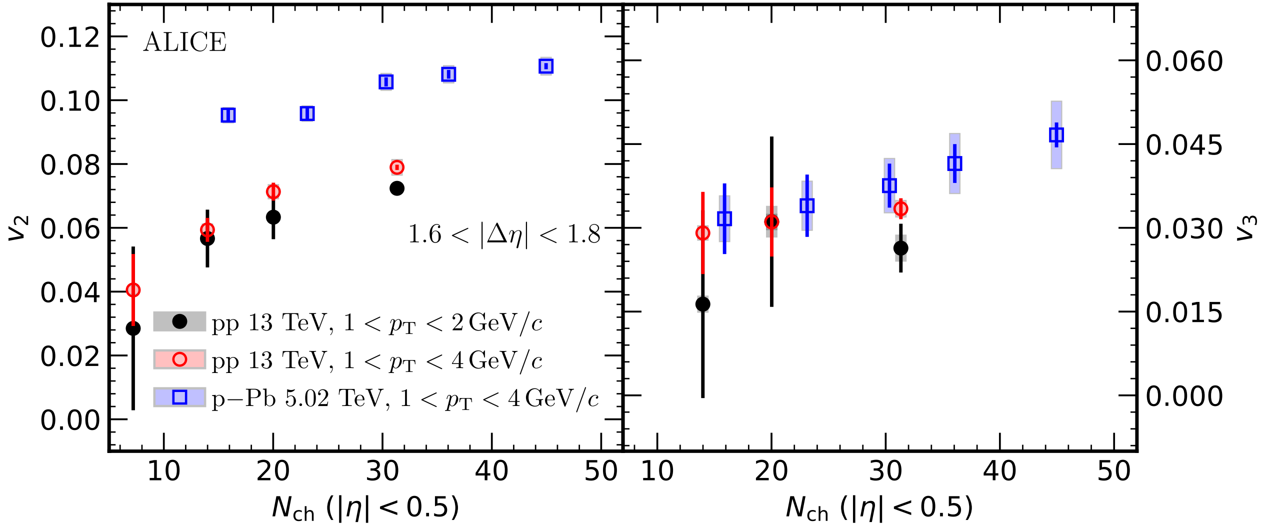


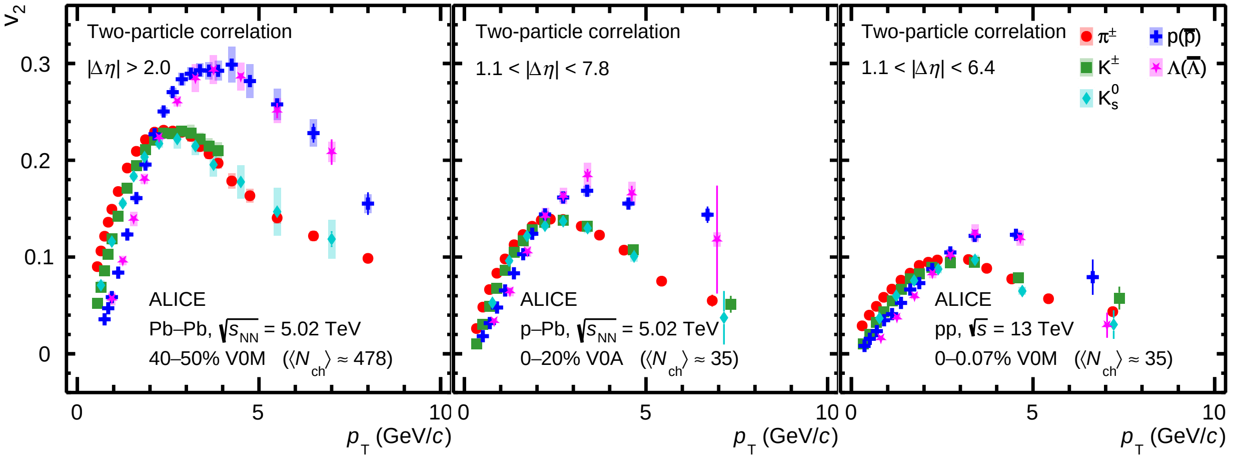
- Non-zero yield even in very low multiplicity collisions (95% C.L)
- First quantitative constraints of yield in smallest hadronic collisions
- 5–6σ larger yield in pp compared to e^+e^- collisions
- A comparison to e^+e^- can provide insight to what processes might or do not contribute to the yield
- A reference point-like collision can also help understand the magnitude of initial stage effects

PRL. **132** (2024) 172302

Flow in pp

JHEP 03 (2024) 092

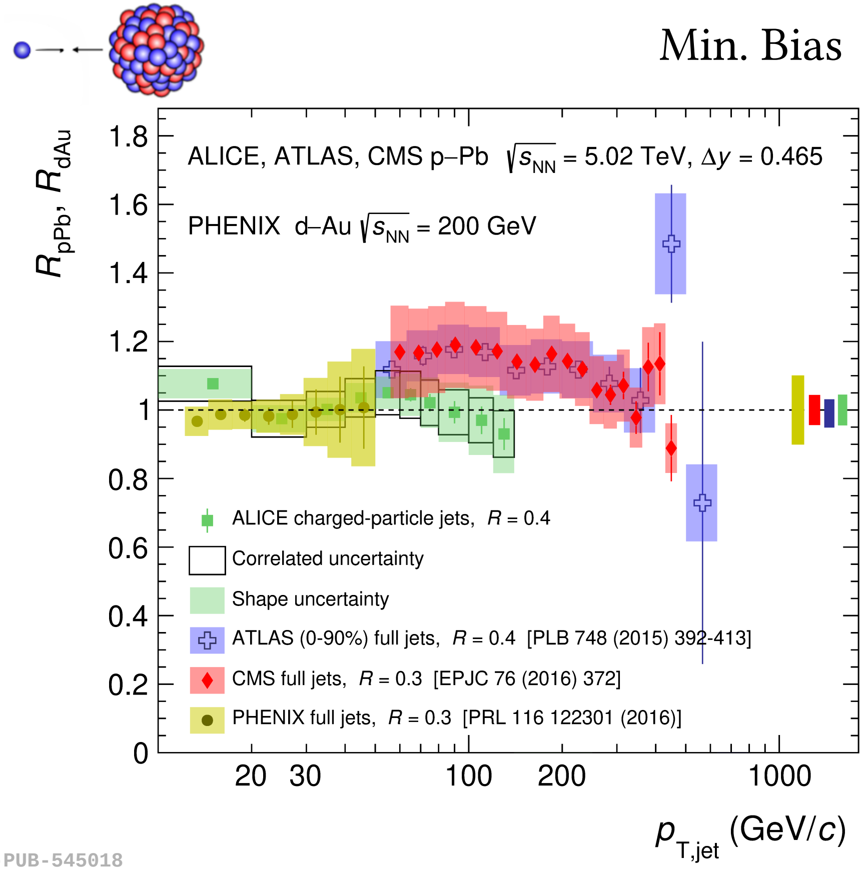




arXiv:2411.09323

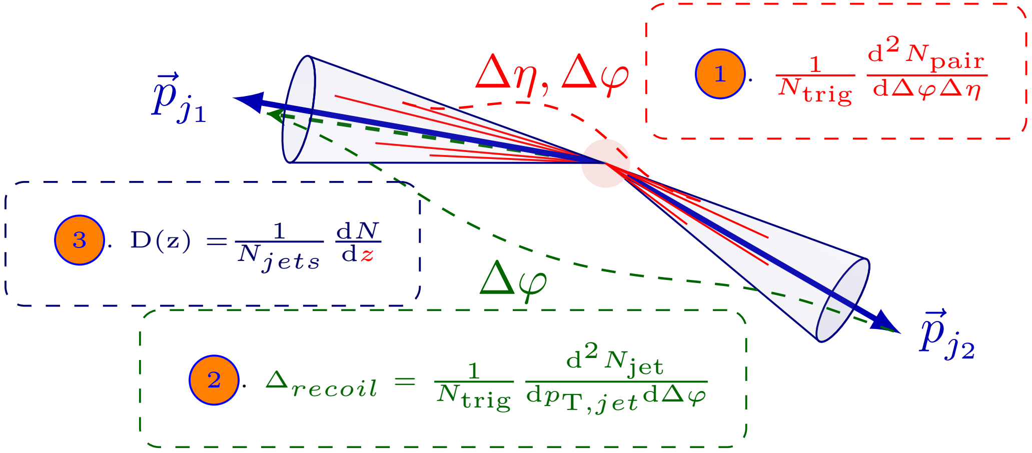
- Significant flow v_2 and v_3 measured in pp and pPb
- Even mass ordering is observed
- Evident that everything from small to large systems flows

Search for jet quenching effects in small systems



ALI-PUB-545018

- Even though flow signatures are observed, no sign of jet quenching in small systems (ALICE, JHEP **05** (2024) 041)



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

③. $D(z)=\frac{1}{N_{jets}}\frac{{\rm d}N}{{\rm d}z}$

②. $\Delta_{recoil}=\frac{1}{N_{\rm trig}}\frac{{\rm d}^2N_{\rm jet}}{{\rm d}p_{{\rm T},jet}{\rm d}\Delta\varphi}$

How about multiplicity dependence in pp collisions?

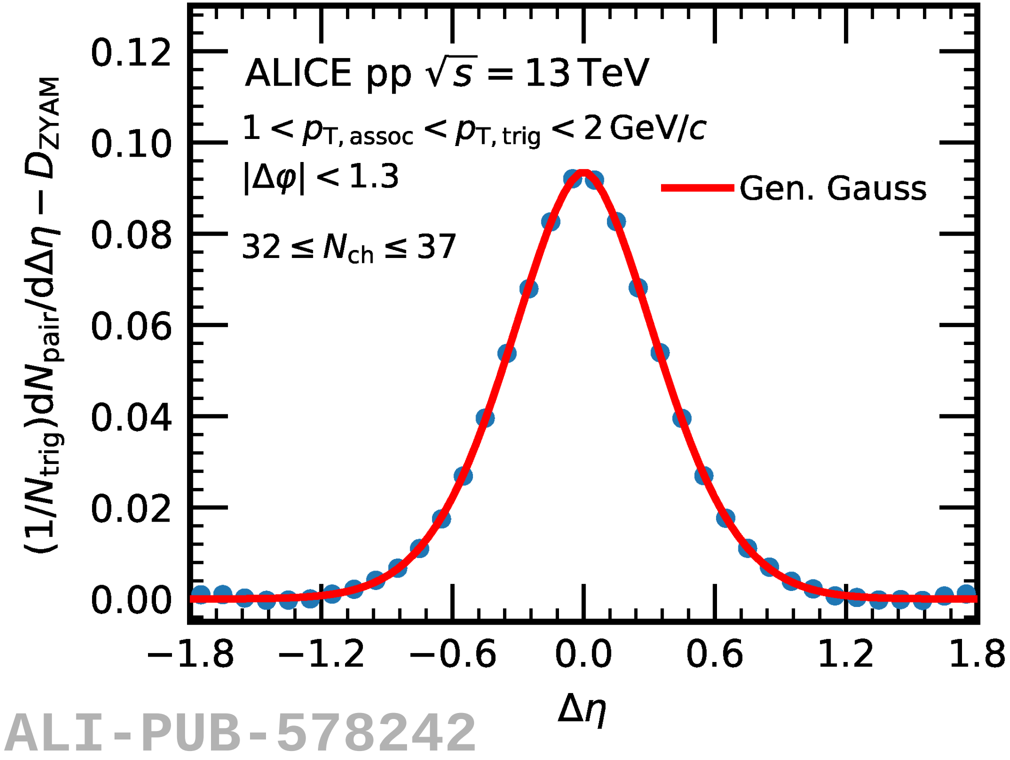
1. hadron-hadron correlations? (presented today)
2. hadron-jet correlations (JHEP **05** (2024) 229)
3. intra-jet correlations (Eur.Phys.J **C84** (2024) 1079)

▹ Multiplicity dependence of di-hadron correlations

Robust test against Pb–Pb reference

Quantification of jet modification

Aim to quantify the modification of the jet correlation shape over various multiplicity bins.



Fit a generalized Gaussian over $\Delta\eta$-projection of the correlation function over $\Delta\varphi \in [-1.3, 1.3]$.

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

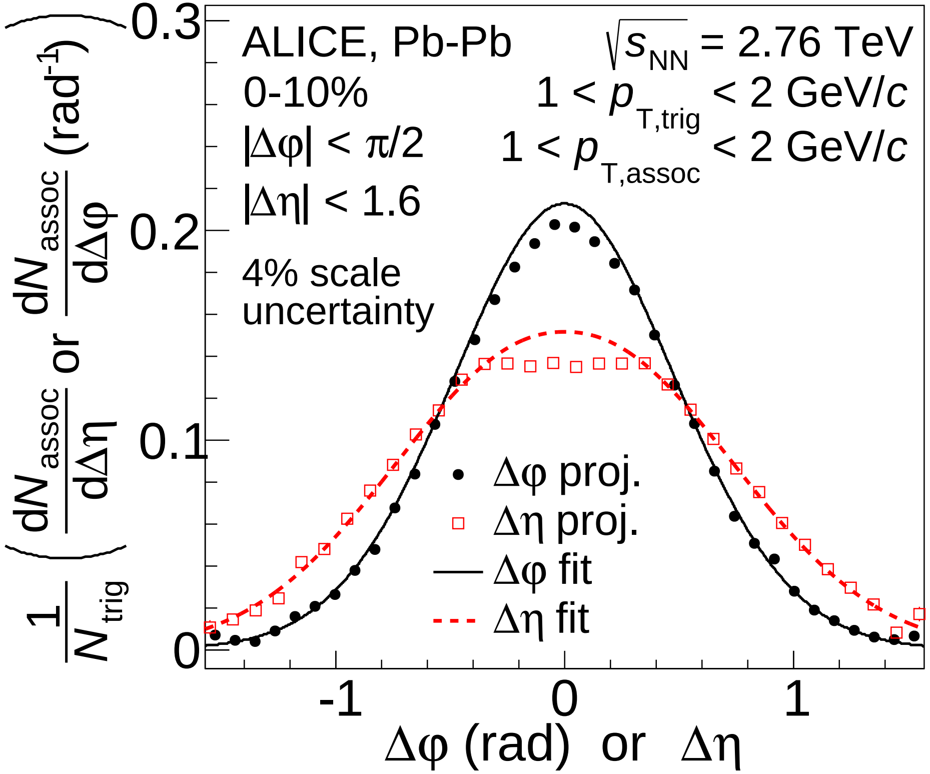
where

$$\sigma = \sqrt{\frac{\alpha^2\Gamma(3/\beta)}{\Gamma(1/\beta)}}$$

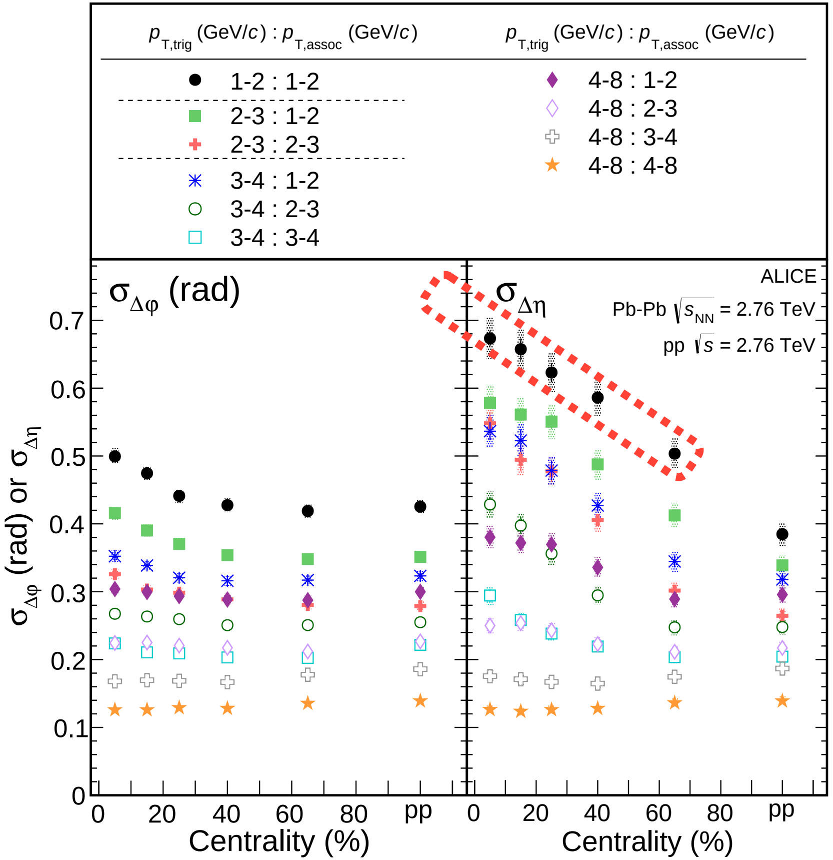
Broadening

Greater $\sigma_{\Delta\eta}$ toward larger (higher multiplicity) collisions. This can signal the presence of jet quenching, and therefore, likely medium.

Broadening of jets in Pb–Pb collisions

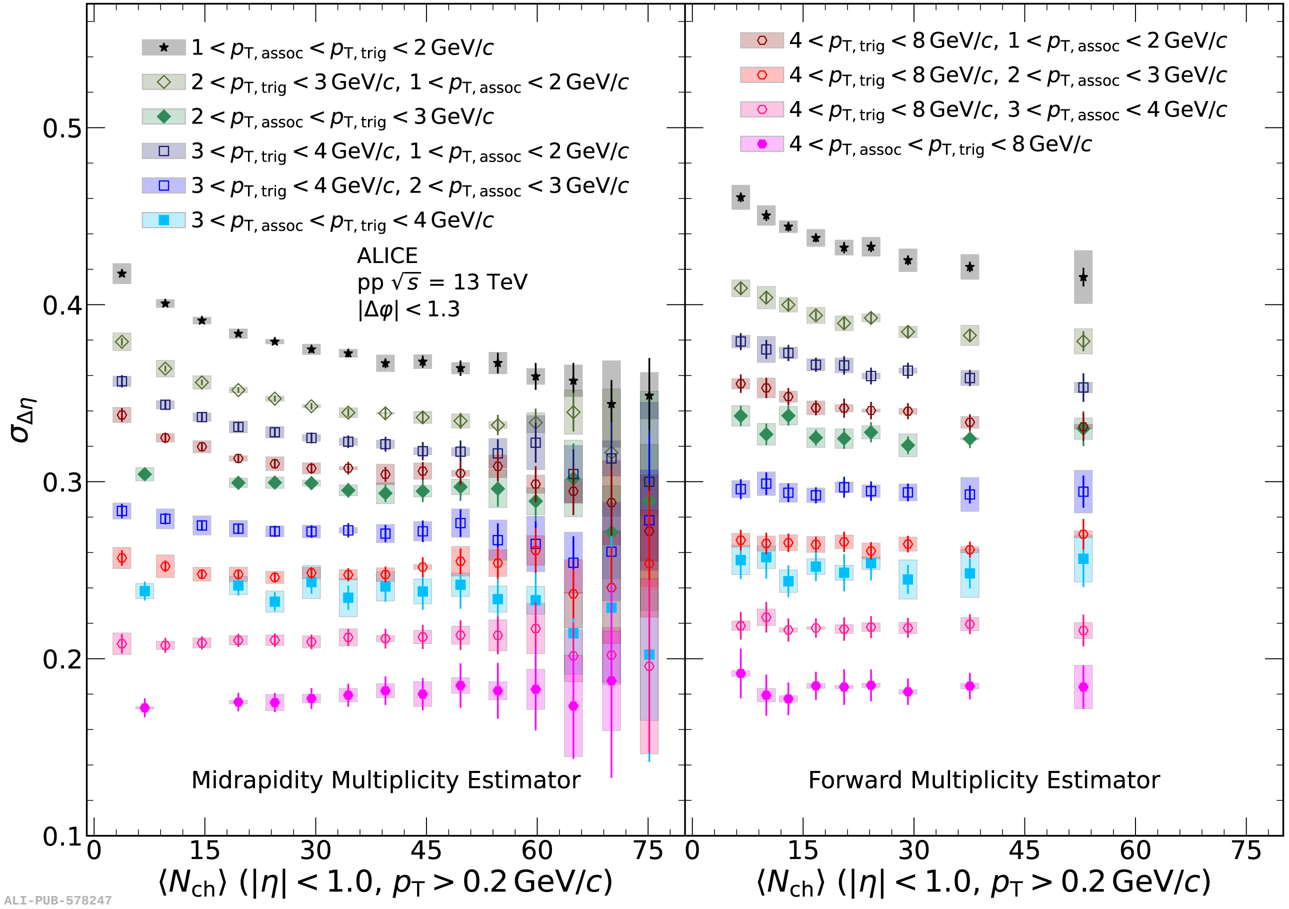


ALICE, Phys.Rev.Lett **119** (2017) 102301



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

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



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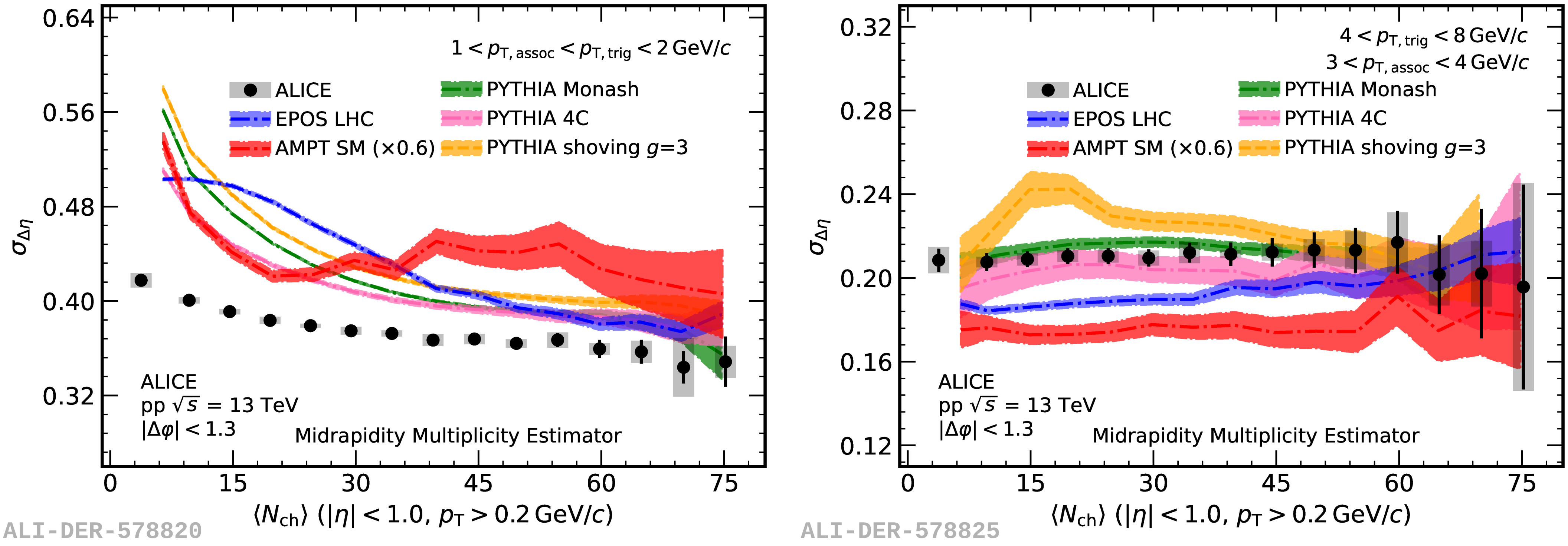
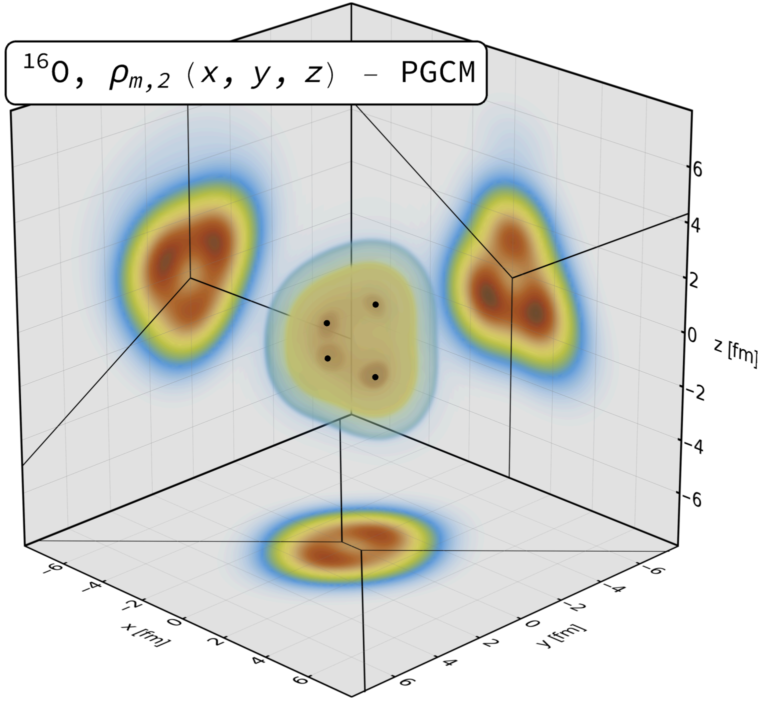
- Multiplicity dependence decreases for higher p_{T} and higher multiplicity
  - But could it be because of multiplicity estimator bias?
- Forward multiplicity estimator results have broader jets and weaker multiplicity dependence across almost all p_{T}-bins
- Clear ordering in the magnitude → narrower peaks towards higher p_{T}
- No signs of jet quenching in pp

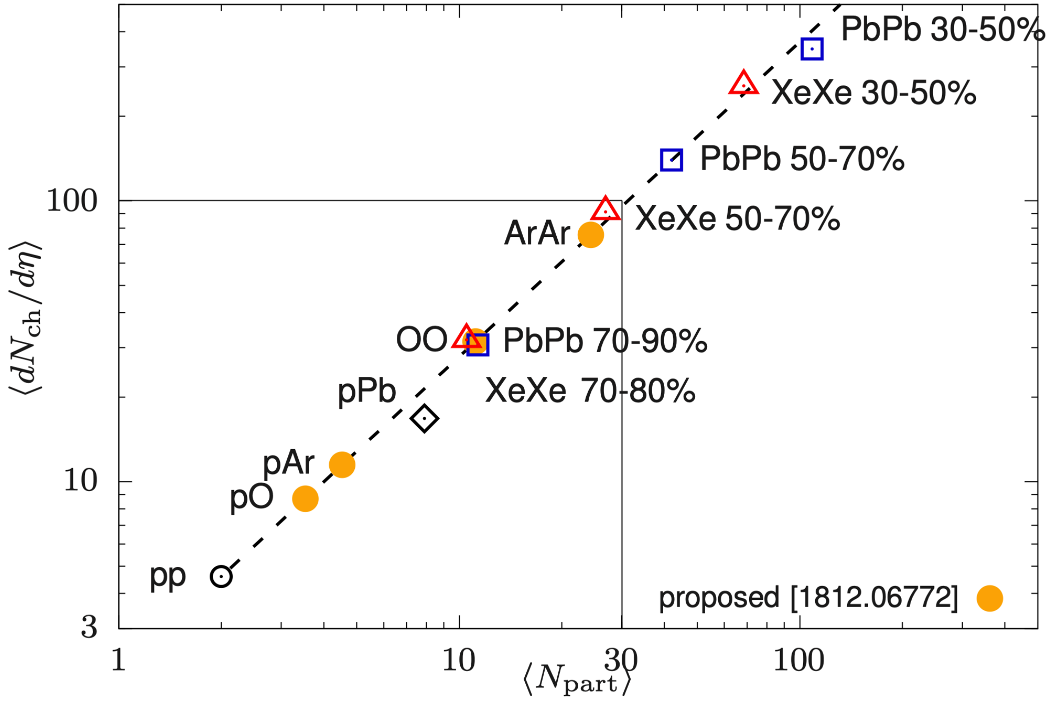
Model comparisons in pp



- Models overestimate for the lower-$p_{\rm T}$ but better description for higher-$p_{\rm T}$
- Trend is captured by most models
- The multiplicity dependence is weaker for higher-$p_{\rm T}$
- Non-trivial $p_{\rm T}$ and multiplicity dependence in the models which contains “Jets” + “Flow”
- Caution with 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** (2023) 034909)

Jet quenching in light-ion systems: OO?





Mazeliauskas talk at Initial State 2021

Expect p–Pb and OO fall into transition region $\tau_{\mathrm{Hydro}}/R \approx 1$ where system is expected to encounter final state interactions, but is also out-of-equilibrium for a significant part of its lifetime. No hint in p–Pb but a sweet spot to oberve jet quenching signal in OO.

Centrality dependent jet-shape modification in OO

❗ No public preliminary

Jet-shape modification in OO – comparison to Pb–Pb

❗ No public preliminary

Jet-shape modification in OO - comparison to pp reference

❗ No public preliminary

Summary

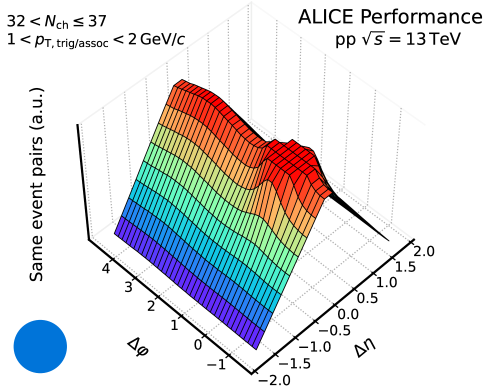
- QGP is created in heavy-ion collisions at the LHC and its evolution governed by relativistic hydrodynamics
- Higher harmonic and independent advanced multi-particle correlations can improve the parameter estimation outcomes
- Flow-like signals are measured even in the smallest collision systems
- However, no jet quenching signals observed in pp

Backup

Two-particle correlations: experimental representation

Two-particle correlation function between trigger and associated particles ($p_{\mathrm{T,trig}} > p_{\mathrm{T,assoc}}$)

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



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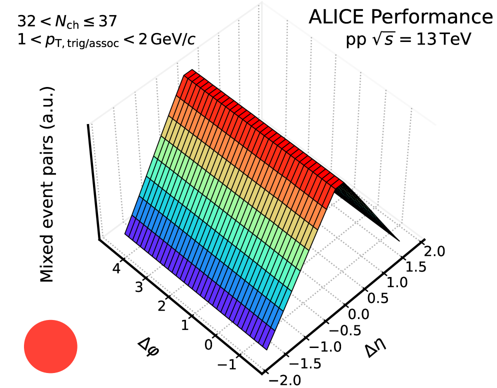

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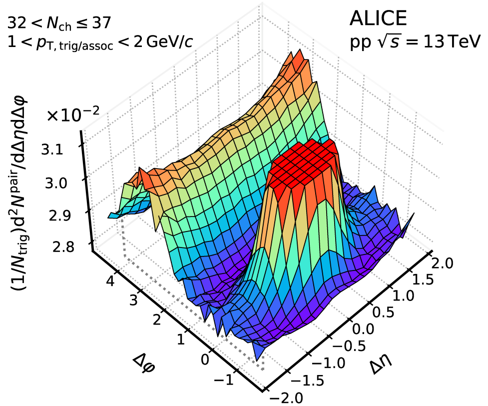

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Same- and Mixed-event correlation function, and the corrected outcome.

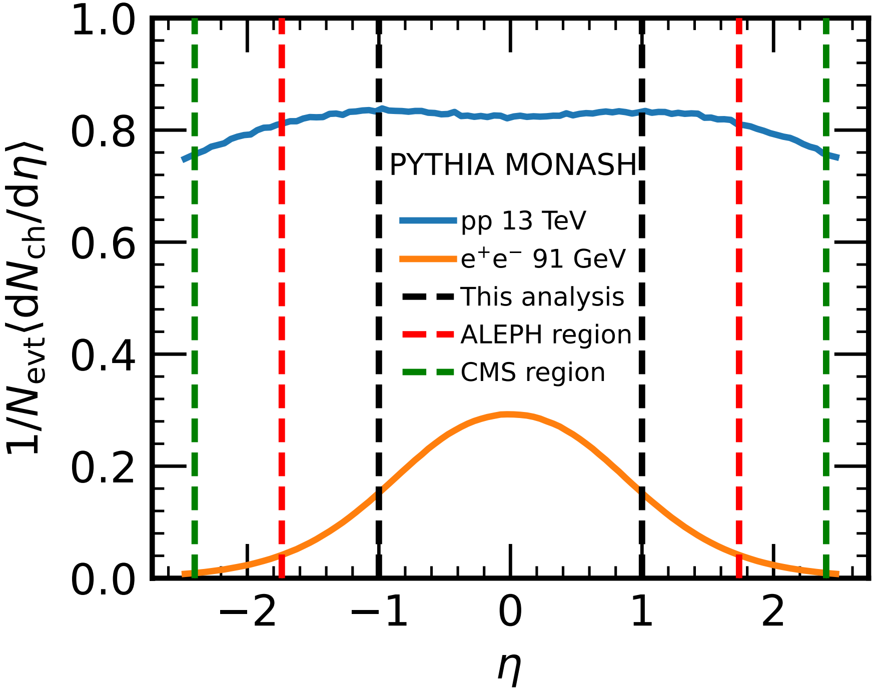
The two-particle correlation method is used to study azimuthal angle distributions of the emitted charged particles, and in turn probe collective-like effects and jet fragmentation interplay with potential medium.

Conversion of ALEPH multiplicity

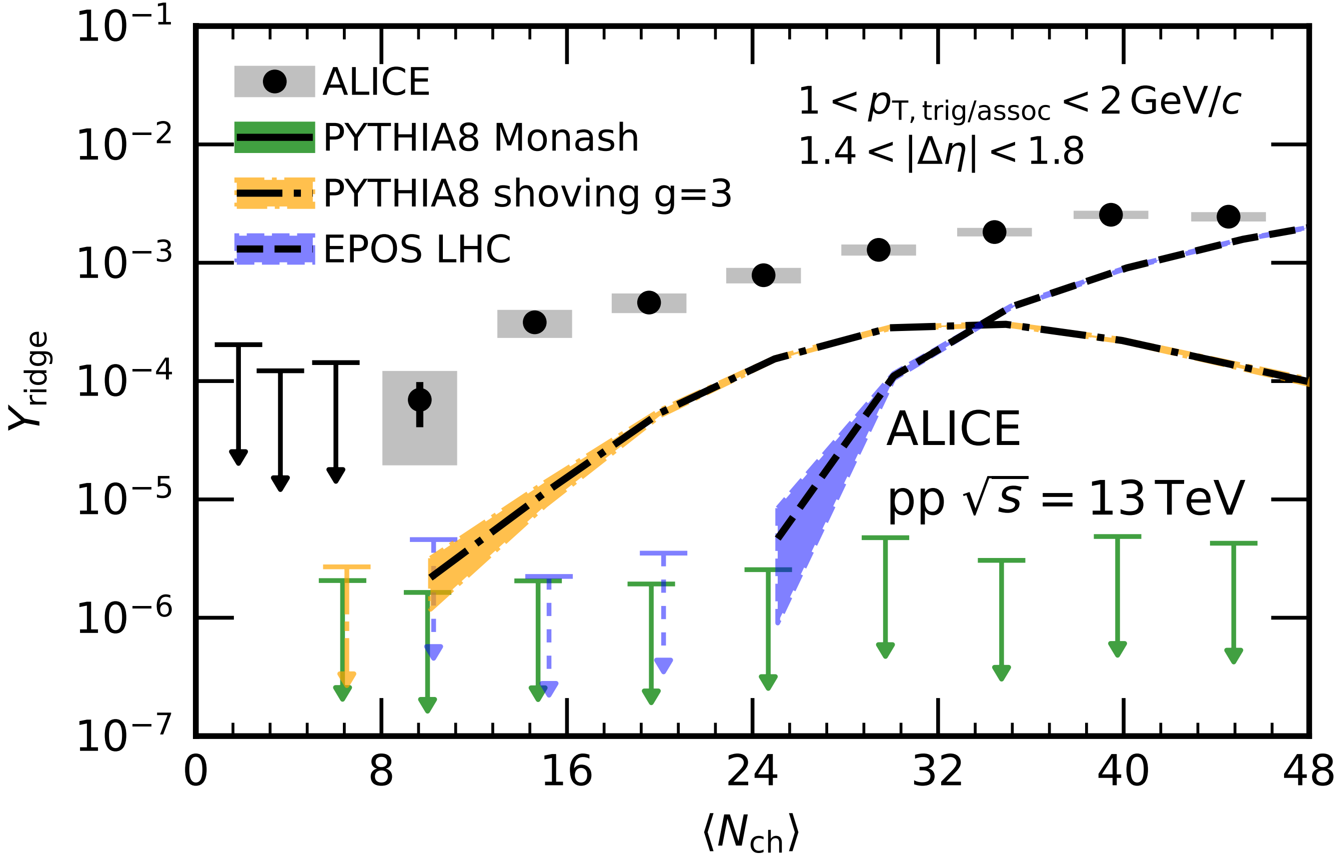
- Estimate the limits of uncertainty on the conversion of the multiplicity
- Target: multiplicity defined by accepted particles within $|\eta| < 1.0$, $p_{\mathrm{T}} > 0.2\frac{\mathrm{GeV}}{c}$
- Multiplicity conversion between different systems and experiments is done using PYTHIA
  1. Simulate pp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

Method	Experiment	Corr. factor $\alpha_{\mathrm{A/B}}$
PYTHIA	ALEPH pp 13 TeV, ALEPH $e^{+}e^{-}$ 91 GeV	0.57 (A) 0.78 (B)
Flat $\mathrm{d}N/\mathrm{d}\eta$	ALEPH	0.63

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



Low multiplicity pp ridge yield model comparisons



- No ridge from Monash, as expected
- Models with collectivity mechanisms underestimate the ridge yield
- Model ridge yield calculated at large $2 < |\Delta\eta| < 4$ to avoid the over-estimated jet fragmentation width

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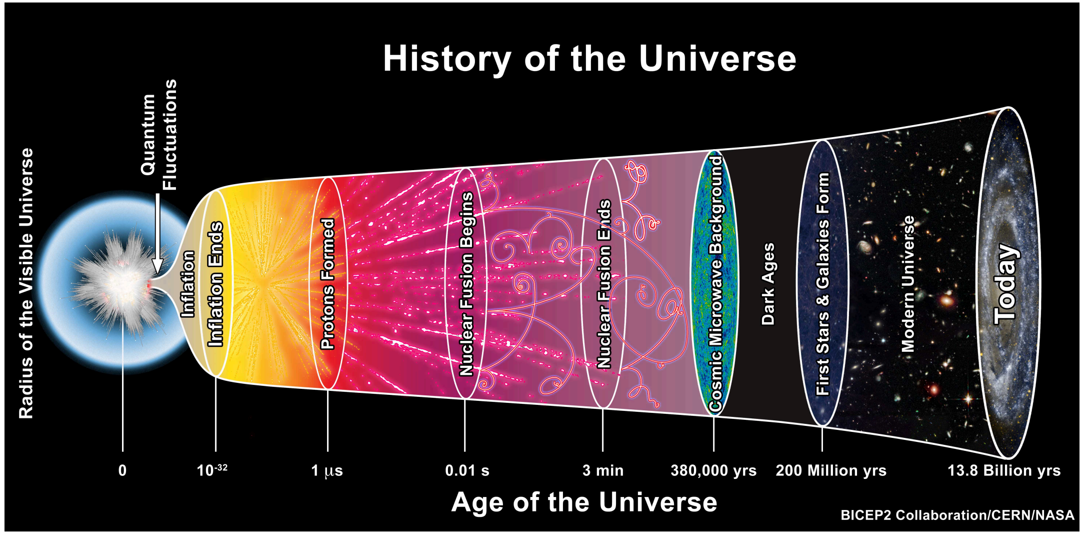
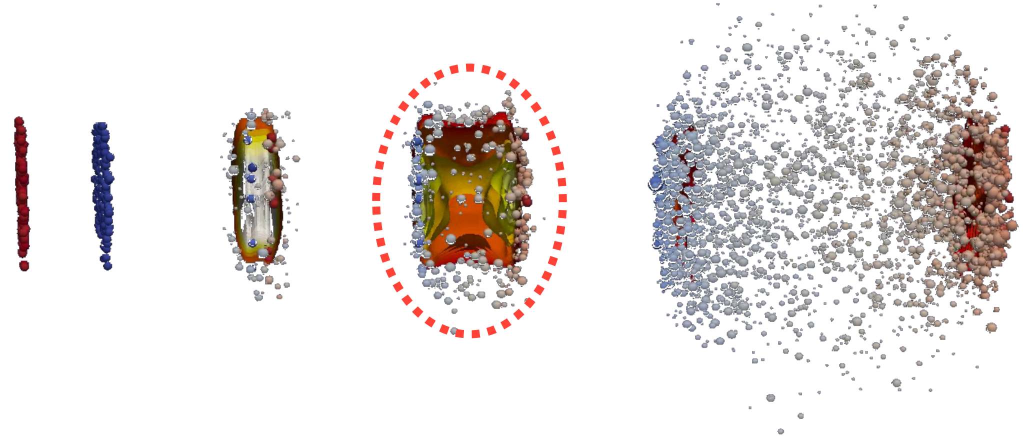
Matter in early universe



BICEP2 Collaboration/CERN/NASA



- Early Universe immediately after Big Bang: free quarks and gluons not confined to hadrons
- Can be created small nuclei-sized droplets at the LHC in heavy-ion collisions
- Study of this matter can improve the understanding on a strongly-interacting system as well as the conditions in early Universe