Emergence of long-range angular correlations in low-multiplicity proton-proton collisions

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CERN LHC seminar
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Based on PRL. 132 (2024) 172302

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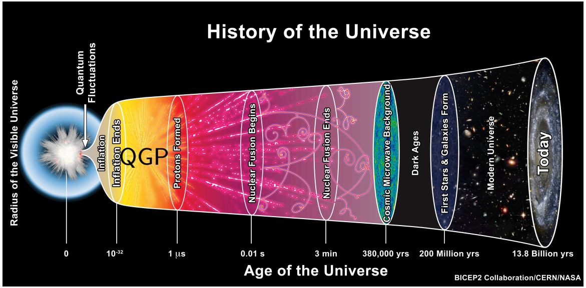
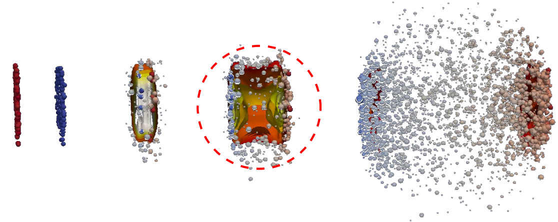
ALICE

Matter in early Universe

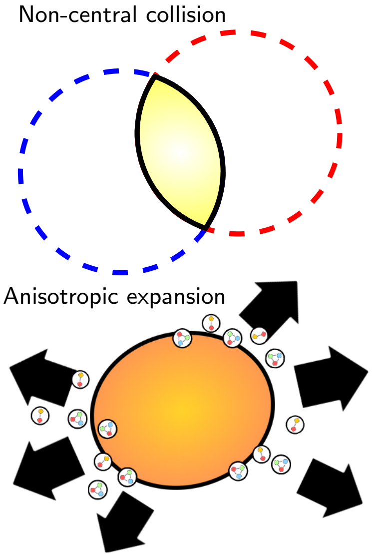




- Early Universe immediately after Big Bang: free quarks and gluons not confined to hadrons
- Can be created small nuclei-sized droplets at the LHC in heavy-ion collisions
- Study of this matter can improve the understanding on a strongly-interacting system as well as the conditions in early Universe

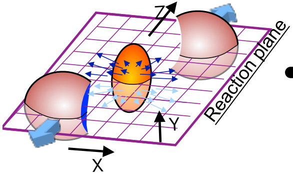
Observations on the heavy-ion systems (Pb–Pb, Au–Au, etc.)

- Strongly-interacting “medium” is formed in collisions according to several indicators (nuclear modification, jet quenching, strangeness enhancement, . . .)
- This medium is fluid-like, implied by the anisotropic momentum pattern of the hadronic products
- The anisotropic expansion is a result of “collective” behavior, and is very prominent in heavy-ion systems
- Collectivity allows the constraining of the medium dynamical properties through model comparisons and tuning

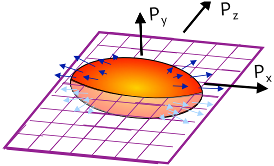


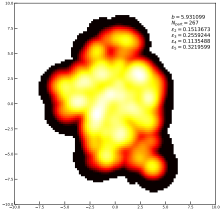
Origin of collectivity in heavy-ion theory

Initial stage:
Spatial anisotropy

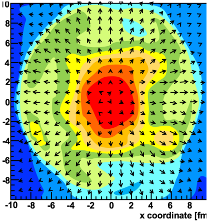


Medium stage:
Momentum anisotropy





Initial condition models

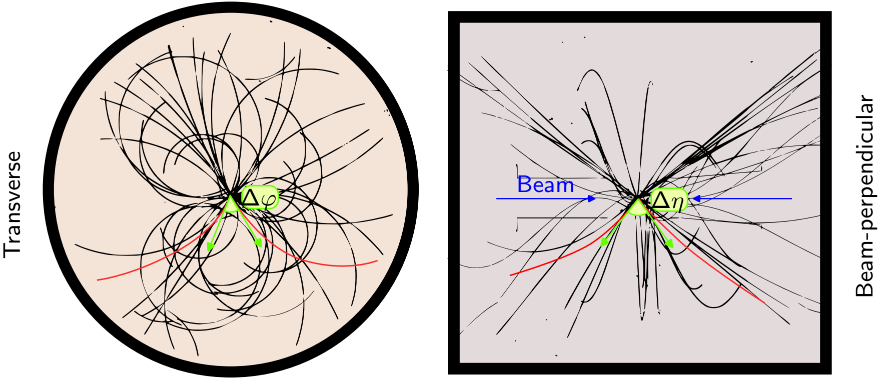


Relativistic hydrodynamics

- Hydrodynamics is a mainstream description of the medium
- The system undergoes a fluid-like expansion under the pressure gradients of the initial-state geometry.
- Successful description of wide range of experimental observables

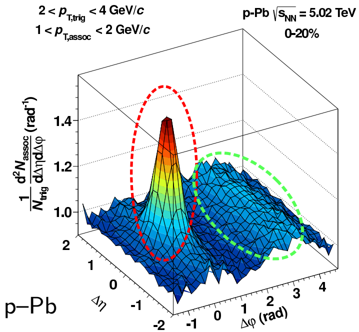
Two-particle correlations – experimental quantification of medium expansion

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

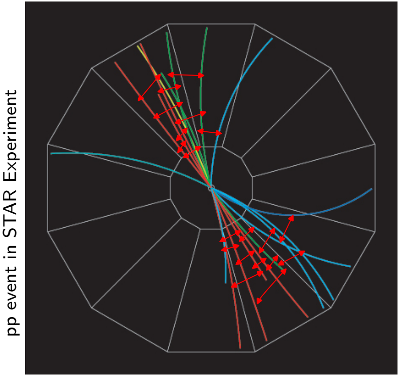


- **Two-particle correlations:** measurement of the polar angle $\Delta\varphi$ and pseudorapidity $\Delta\eta$ between all pairs of charged particles coming from the collision. What sort of correlations can be observed?

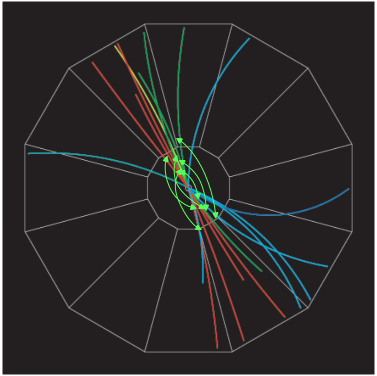
Two-particle correlations – typical features



ALICE, PLB 719 (2013) 29-41



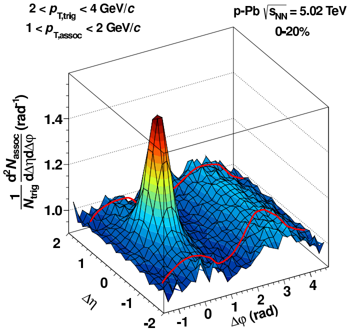
Particles from the same jet at low $\Delta\eta\Delta\varphi$ form the near-side peak

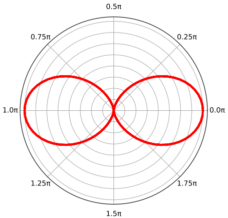


Particles from back-to-back jets at $\Delta\varphi \sim \pi$ form the away-side peak

Long-range correlations

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

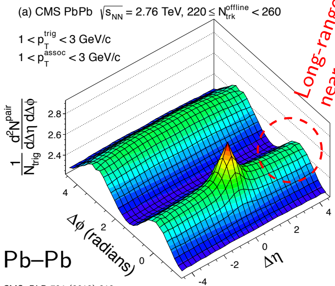




- The double-ridge emerges when a large *elliptic* harmonic component is present: characterizes the elliptic expansion

Long-range correlations across collision systems of varying size

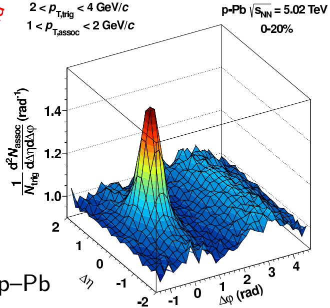
- This signal is present across various collision system sizes



Long-range near-side yield

Pb–Pb

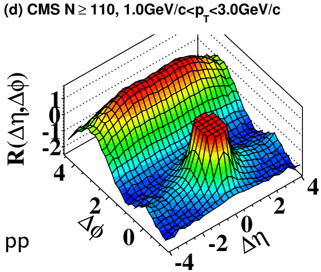
CMS, PLB 724 (2013) 213



p–Pb

ALICE, PLB 719 (2013) 29-41

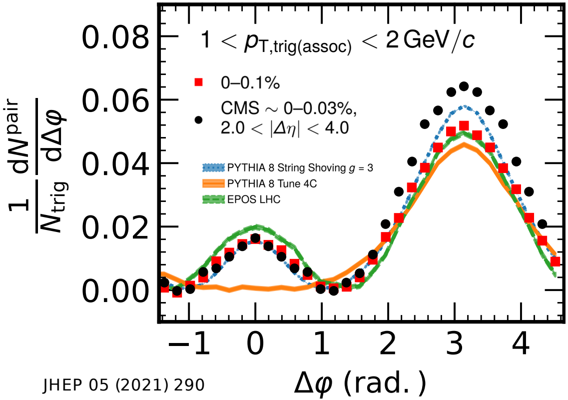
CMS, JHEP 09 (2010) 091



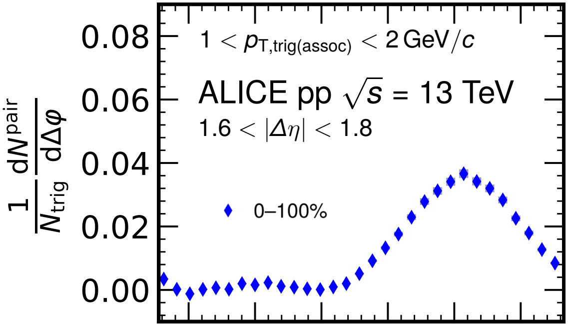
pp

- Long-range correlation emerges during the early stages
- In heavy-ion systems medium response to initial conditions
- **In pp unclear (QGP? Multi-parton scattering? PYTHIA ropes? Initial-stage effect?)**

Long-range correlations in pp – basic facts



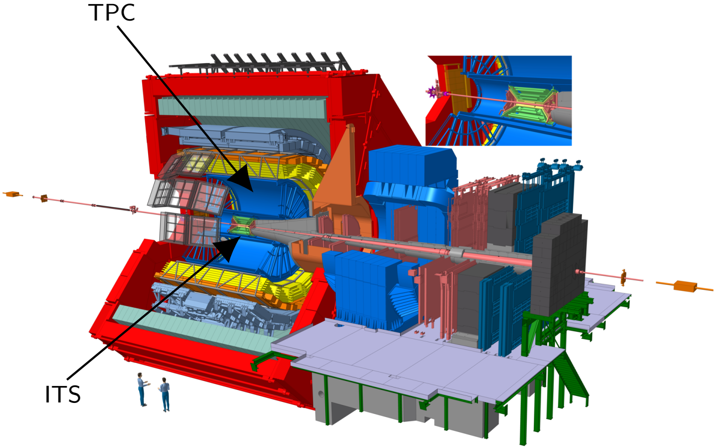
JHEP 05 (2021) 290



$$\int_{1.6<|\Delta\eta|<1.8}\left(\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi}\right)\frac{1}{\delta_{\Delta\eta}}\mathrm{d}\Delta\eta$$

- Prominent long-range near-side ridge in high multiplicity ($N_{\mathrm{ch}} > 110$) 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

Analysis details and selection criteria



The ALICE detector in Run 2.

Events and detectors:

- pp $\sqrt{s} = 13\,\mathrm{TeV}$ recorded in 2017–2018
- 1.3 billion MB events
- TPC+ITS for tracking

Charged tracks and multiplicity:

- Multiplicity estimation: accepted tracks in $|\eta| < 1.0$, $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$
- Trigger and associated particles* $1.0 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$, $|\eta| < 1.0$
- "Long-range" definition $1.4 < |\Delta\eta| < 1.8$

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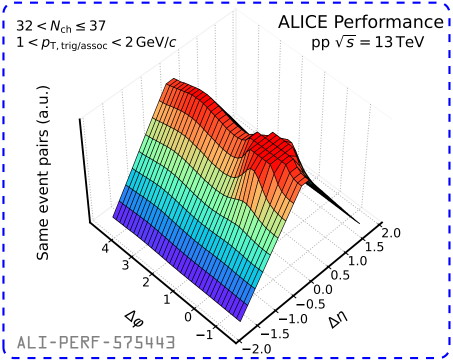
* In a two-particle correlation particle 1 "trigger" and particle 2 "associated".

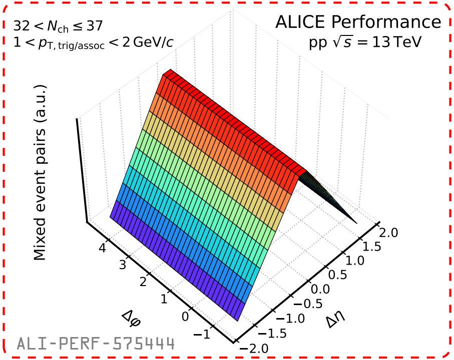
Analysis strategy for associated yield

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

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

same: correlations of particles from same event

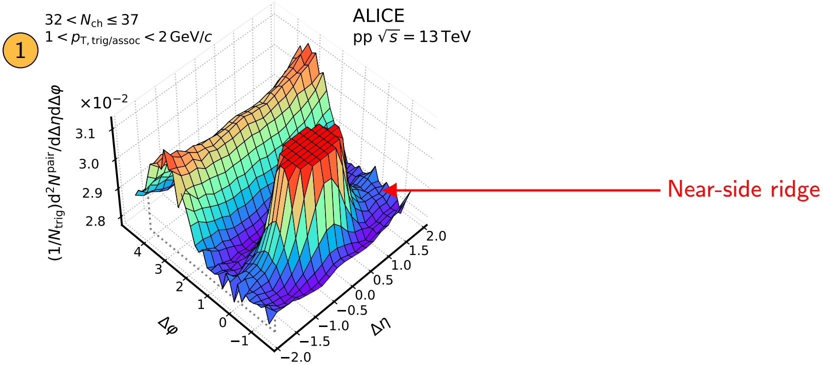




mixed: correlations of particles from different events

Long-range $\Delta\varphi$-correlations in low multiplicity

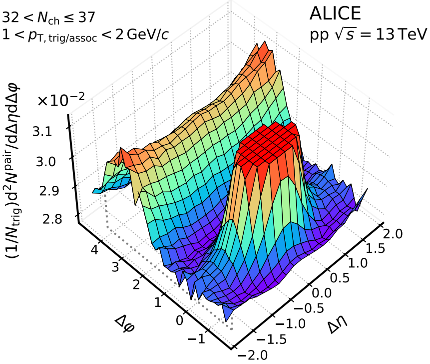
- Near-side ridge clearly visible in high-multiplicity events.



Long-range $\Delta\varphi$-correlations in low multiplicity

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

①

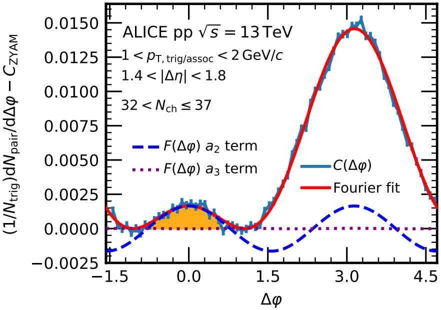


$\int \mathrm{d}\Delta\eta$

$1.4 < |\Delta\eta| < 1.8$

②

$$\int \left(\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi} \right) \frac{1}{\delta_{\Delta\eta}} \mathrm{d}\Delta\eta - C_{\mathrm{ZYAM}}$$



PRL. 132 (2024) 172302

Find the ZYAM* and $|\Delta\varphi_{\min}|$ by fitting $F(\Delta\varphi) = A(1 + 2\sum_{n=1}^{3} v_n^{2,\mathrm{cent}} \cos(n\Delta\varphi)) + C_{\mathrm{ZYAM}}$ to the signal.

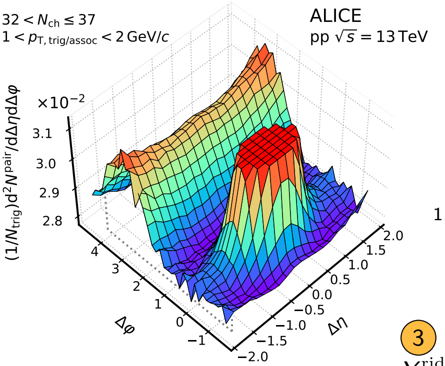
- Measured in $1.4 < |\Delta\eta| < 1.8$ to suppress short-range nonflow correlations
- $p_{\mathrm{T}} > 1.0\,\mathrm{GeV}/c$ (*trig* and *assoc*) to avoid near-side jet broadening into $|\Delta\eta| > 1.4$

* Zero-Yield-At-Minimum

Long-range $\Delta\varphi$-correlations in low multiplicity

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

①

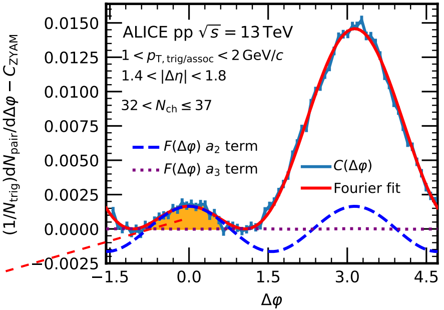


$\int \mathrm{d}\Delta\eta$

$1.4 < |\Delta\eta| < 1.8$

②

$$\int \left(\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi} \right) \frac{1}{\delta_{\Delta\eta}} \mathrm{d}\Delta\eta - C_{\mathrm{ZYAM}}$$



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③

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

Find the ZYAM* and $|\Delta\varphi_{\min}|$ by fitting $F(\Delta\varphi) = A(1 + 2\sum_{n=1}^{3} v_n^{2,\mathrm{cent}} \cos(n\Delta\varphi)) + C_{\mathrm{ZYAM}}$ to the signal.

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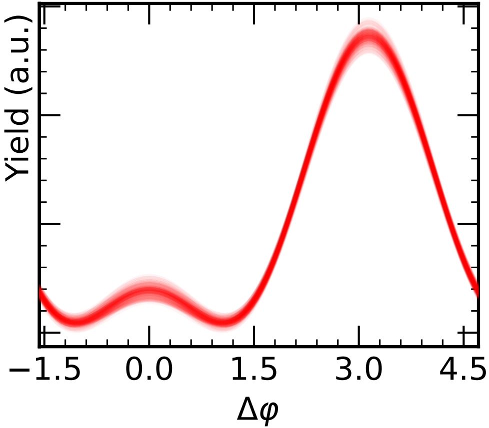
* Zero-Yield-At-Minimum

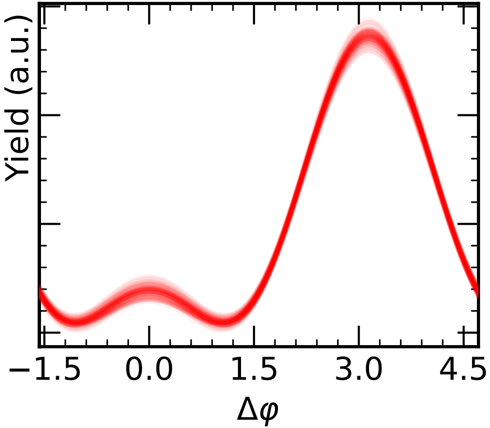
Precision uncertainty



Variant fits on the $Y(\Delta\varphi)$ (sketch)

- Method simple until one goes to very small signals
- Uncertainties evaluated using tailored bootstrapping method
- Upper-limits for non-gaussian yield-distributions
- Limits for feasible compatibility analysis with other results

Precision uncertainty



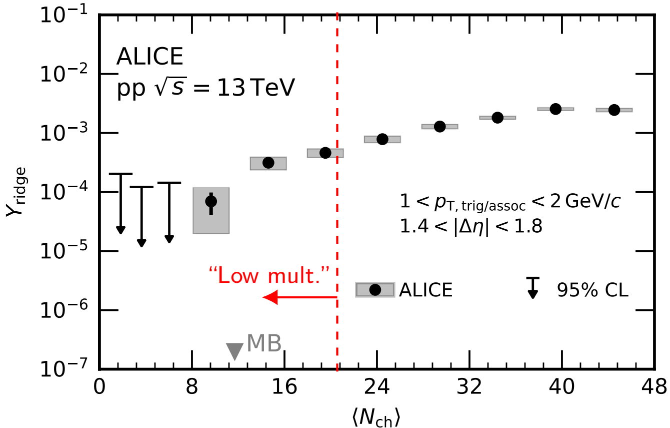
Variant fits on the $Y(\Delta\varphi)$ (sketch)

Bootstrapping strategies:

- Statistics evaluation: Gaussian-distributed relative offset to each bin of $Y(\Delta\varphi)$
- Combined evaluation: add a fixed Gaussian-distributed error based on the ratio between variant and default configuration
- Per-systematic evaluation: combine one configuration with statistics. Subtract statistics-only for pure systematic contribution

Configuration	Contribution
$\lvert z_{\mathrm{vtx}}\rvert < 10\,\mathrm{cm}$	$< 5\%$
Long-range $1.5 < \lvert\Delta\eta\rvert$	3–22%
Tracking mode	3–10%
Residual acceptance	$\sim 4\%$
Integration limit	5–25%

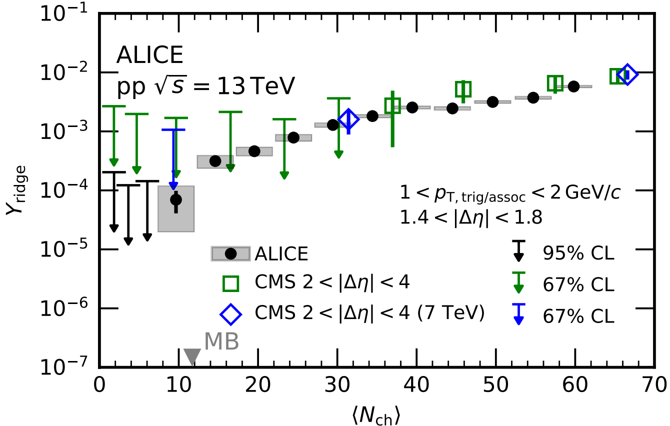
Ridge yield: precision measurement down to very low multiplicity in pp



PRL. 132 (2024) 172302

- Near-exponential increase of yield toward higher multiplicities
- Non-zero yield even in very low multiplicity collisions
- The lowest bins are presented as 95% confidence limit

Ridge yield: comparison with CMS results, PRL 116, 172302 (2016)



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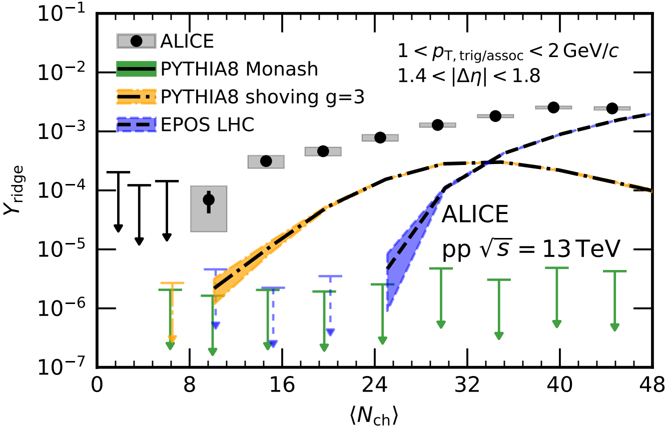
- Conversion of CMS multiplicity to ALICE using PYTHIA (factor = 0.59 × 1.15)
  - $p_{\mathrm{T,min}} \to 0.0\,\mathrm{GeV}/c$
  - $|\eta_{\mathrm{max}}| \to 4.0$
  - CMS efficiency for multiplicity
- CMS data points in agreement (PRL 116, 172302 (2016))
- Improved uncertainty in the low multiplicity region: towards quantitative constraints!

Models overview

Model	Physics	Observations	Refs
PYTHIA8 Monash	Jets only (2013)	No soft partonic or hadronic interactions	T. Sjöstrand *et al.*, pythia.org
PYTHIA8 String Shoving	Jets and Flow	Uses strings to simulate soft interactions	C. Bierlich *et al.* PLB 779 (2018) 58-63
EPOS4	Jets and Flow	Uses core (hydrodynamic expansion) and corona (hadrons from string decays)	K. Werner *et al.* PRC 92 (2015) 034906
AMPT String Melting	Jets and Flow	Uses soft and hard partonic and hadronic interactions	Zi-Wei *et al.* PRC 72 064901

Ridge yield: model comparisons



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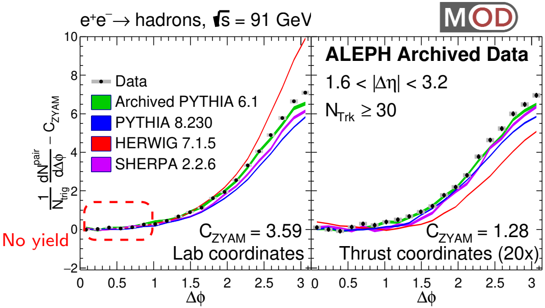
- Models use $2 < |\Delta\eta| < 4$ due to wide jet fragmentation peak
- Monash: no yield (expected)
- String shoving: yield is produced in lower multiplicities, but too small in magnitude
- EPOS: yield reproduced in high multiplicities, no yield in low multiplicities
- **All models underestimate the ridge yield**

Interpretation by comparison to e^+e^-

Non-trivial interpretation of pp results due to intricate structure.

- Study the simpler processes involved in e^+e^- annihilations (point-like collision: no uncertainties on initial geometry or parton distribution function description)
- e^+e^- do not exhibit yield within the given confidence levels



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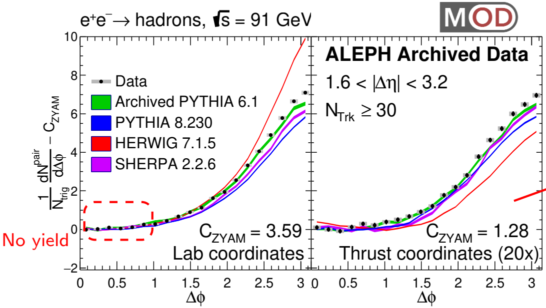
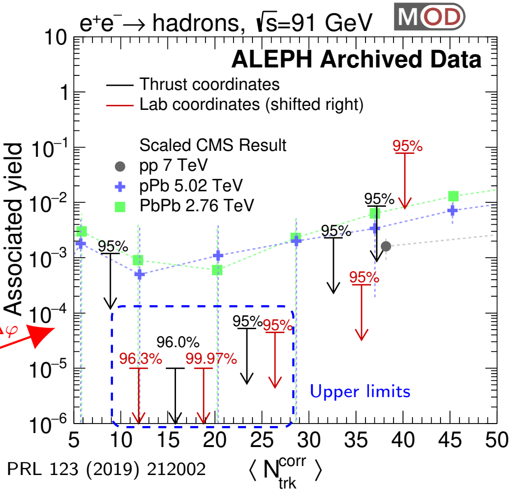


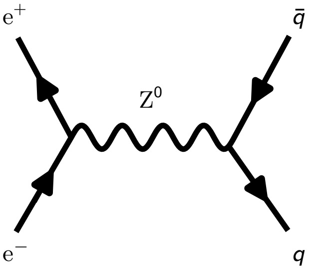


PRL 123 (2019) 212002

- **Would we get similarly small values in pp as in e^+e^- or are the two systems intrinsically different?**

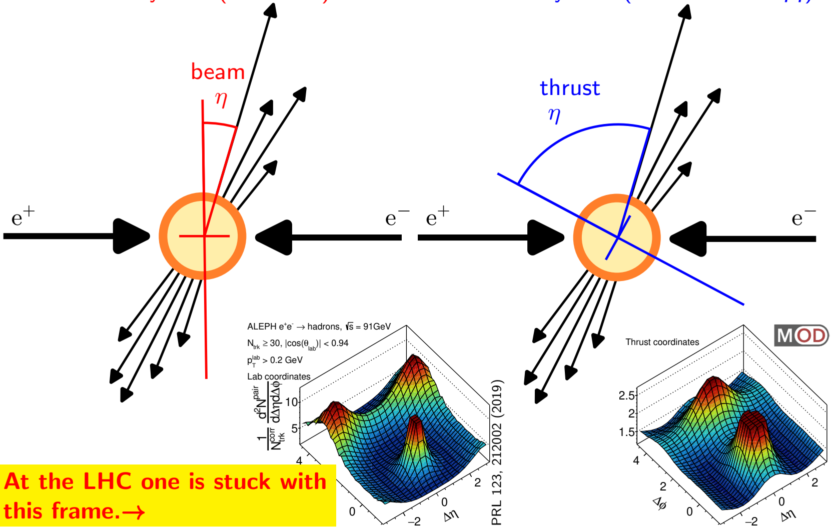
Main mechanism in e^+e^-, thrust vs beam axis

A decay of a Z-boson . . .



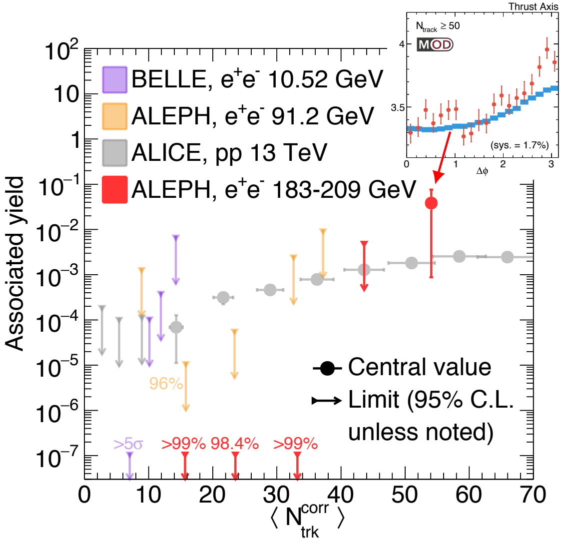
. . . is a candidate for origin of potential long-range correlations in e^+e^--collisions.

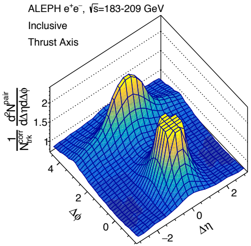
Lab coordinate system (also LHC) Thrust coordinate system (boosted $Z \rightarrow q\bar{q}$)



At the LHC one is stuck with this frame.→

Latest e^+e^- insights

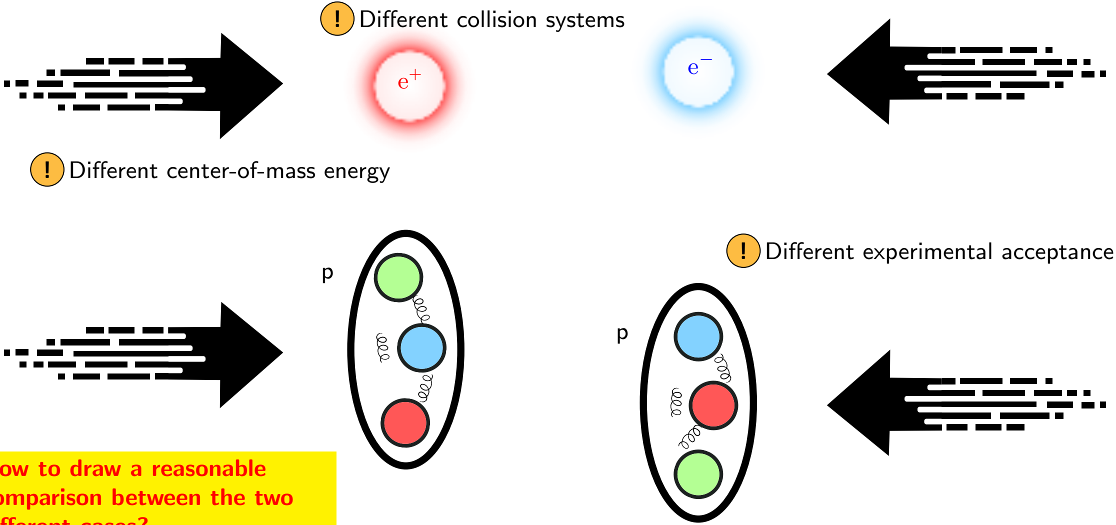




arXiv:2312.05084 (2023)

- New results of e^+e^- long-range correlations: BELLE, ALEPH
- BELLE: no yield at the lowest multiplicities $N_{\mathrm{ch}} \lesssim 10$
- ALEPH: Consistent observations in low multiplicity: no yield
- Hint of long-range correlations in e^+e^- at higher multiplicity, currently 1.02σ signal

How to compare pp collisions to e^+e^- collisions from the ALEPH archived data?



! Different collision systems

! Different center-of-mass energy

! Different experimental acceptance

How to draw a reasonable comparison between the two different cases?

Conversion of ALEPH multiplicity

- Estimate the limits of uncertainty on the conversion of the multiplicity
- Target: multiplicity defined by accepted particles within $|\eta| < 1.0$, $p_T > 0.2\,\mathrm{GeV}/c$

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

Conversion of ALEPH multiplicity

- Estimate the limits of uncertainty on the conversion of the multiplicity
- Target: multiplicity defined by accepted particles within $|\eta| < 1.0$, $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$
- Multiplicity 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 α_{A}
  2. Simulate $\mathrm{e^+e^-}$ at $\sqrt{s} = 91\,\mathrm{GeV}$ in both experimental acceptances. Multiplicity ratio to obtain α_{B}

$$\alpha_{\mathrm{A}} = \frac{N_{\mathrm{ch,pp}}^{\mathrm{ALICE}}}{N_{\mathrm{ch,pp}}^{\mathrm{ALEPH}}} \qquad \alpha_{\mathrm{B}} = \frac{N_{\mathrm{ch,e^+e^-}}^{\mathrm{ALICE}}}{N_{\mathrm{ch,e^+e^-}}^{\mathrm{ALEPH}}}$$

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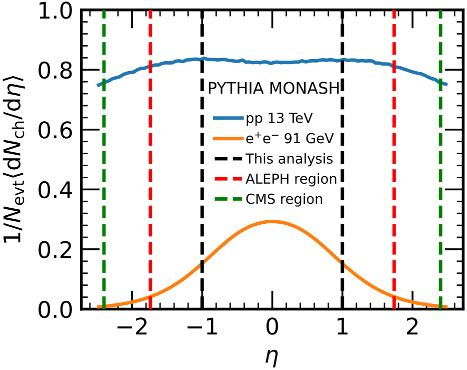

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  1. Simulate pp at $\sqrt{s} = 13\,\mathrm{TeV}$ in both experimental acceptances. Multiplicity ratio to obtain α_A
  2. Simulate e^+e^- at $\sqrt{s} = 91\,\mathrm{GeV}$ in both experimental acceptances. Multiplicity ratio to obtain α_B

Experiment	$\lvert\eta_{max}\rvert$	$p_{T,min}$	$\sqrt{s}$
ALICE pp	1.0	0.2	13 TeV
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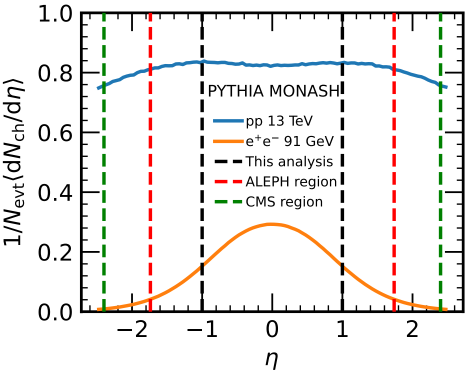
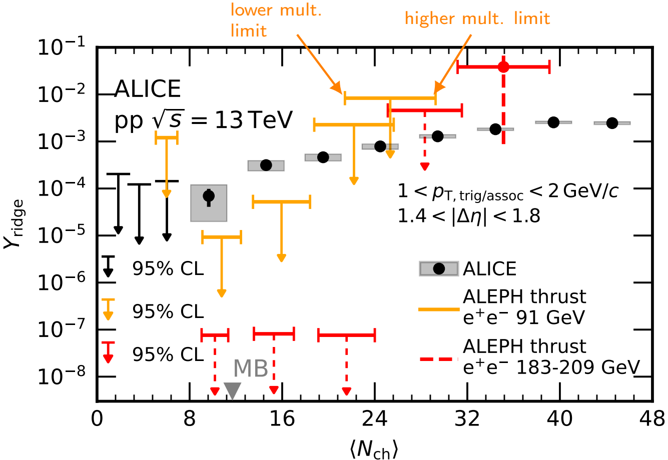


Method	Experiment	Corr. factor $\alpha_{A/B}$
PYTHIA	ALEPH pp 13 TeV	0.57 (A)
	ALEPH e^+e^- 91 GeV	0.78 (B)
Flat $dN/d\eta$	ALEPH	0.63

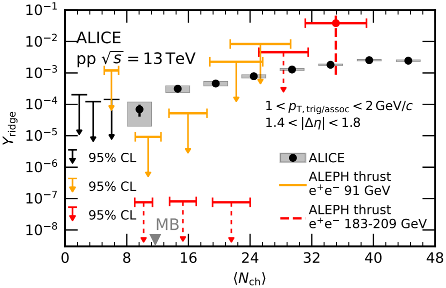
Ridge yield in low multiplicity pp: comparison to ALEPH archived data e^+e^-



PRL. 132 (2024) 172302

- pp collision exhibits larger yield $Y^{\mathrm{pp}}_{\mathrm{ridge}} \gtrsim Y^{e^+e^-}_{\mathrm{ridge}}$
  - 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**

Summary



- Precise measurement of near-side ridge yield in 13 TeV pp collisions down to very low multiplicity
- pp Y^{ridge} larger than $\mathrm{e}^+\mathrm{e}^-$ at 91 GeV by $\gtrsim 5\sigma$ and at 183-209 GeV $\gtrsim 6.3\sigma$
- **First quantitative comparison between the near-side yield of $\mathrm{e}^+\mathrm{e}^-$ and pp collisions**
- Identify the underlying mechanisms responsible for the emergence of near-side yield in pp

The findings constrain the origin of collective-like effects in small hadronic collisions.

- Further precision measurements in Run3 enable a broad range of kinematic cuts, investigations on identified particles and measurements transverse to the jet propagation

Backup

Backup

Analysis strategy for associated yield

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

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

$$\frac{1}{N_{\mathrm{trig}}}\frac{d^2N_{\mathrm{pair}}}{d\Delta\eta\Delta\varphi} = \sum_{z}\dots$$

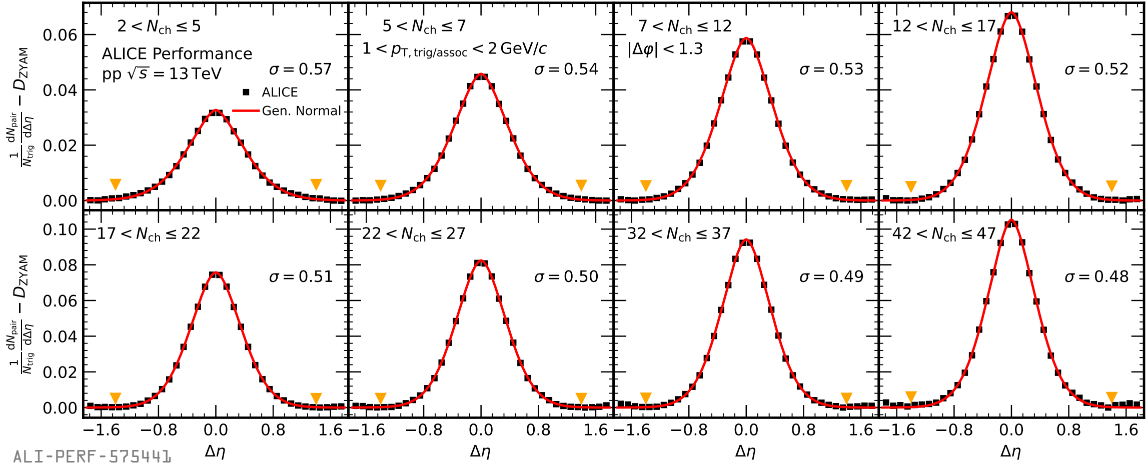
- Per-trigger yield. Measure over region $1.4 < |\Delta\eta| < 1.8$ at $p_{\mathrm{T}} > 1, \mathrm{GeV}/c$ i.e. outside the jet contributions:

$$Y(\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{pair}}}{\mathrm{d}\Delta\varphi} = \int_{1.4<|\Delta\eta|<1.8}\left(\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi}\right)\frac{1}{\delta_{\Delta\eta}}\mathrm{d}\Delta\eta - C_{\mathrm{ZYAM}}.$$

- Ridge-yield, obtained by integrating the near-side peak (main observable in this analysis):

$$Y^{\mathrm{ridge}} = \int_{|\Delta\varphi|<|\Delta\varphi_{\mathrm{min}}|}\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{pair}}}{\mathrm{d}\Delta\varphi}\mathrm{d}\Delta\varphi$$

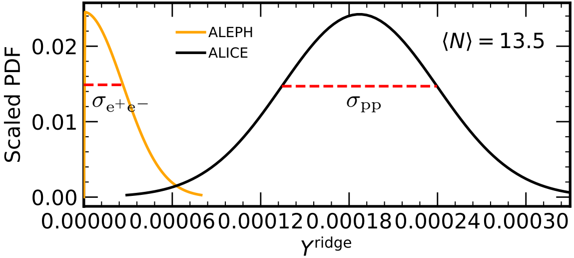
Near-side jet fragmentation peak



- Long-range minumum $\Delta\eta = 1.4$ (at ▼) not affected by the jet-fragmentation peak.

Estimation of uncertainty and compatibility with ALEPH points

- Need a strategy to evaluate the uncertainty for very small low multiplicity signals
- The conversion limits approach entails two estimates of compatibility ($N\sigma$) between pp and $\mathrm{e^+e^-}$
- Evaluation of compatibility needs a sufficiently conservative approach
- Underlying ALEPH Y_{ridge} distributions unknown to us



- Bootstrapping strategy to evaluate the uncertainty: multiple evaluations of Y_{ridge} by variating the underlying $Y(\Delta\varphi)$
- Systematic uncertainty included in the bootstrapping method
- Compatibility: interpolate ALICE results points at the ALEPH conversion limits
- Assume a conservative half-gaussian distribution for the ALEPH Y_{ridge}
- Consider entire range of ALEPH points to estimate the probability that the ALEPH and ALICE results overlap (p-value) → $N\sigma$