Collectivity of (non-) strange hadrons in high-multiplicity pp with CMS

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Newer CMS data to be discussed

- **HIN-16-010**: pp
  - $v_2$ and $v_3$ of charged particles vs event multiplicity
  - $v_2$ of $K_S^0$ and $\Lambda/\bar{\Lambda}$ vs event multiplicity and $p_T$
  - Multiparticle cumulant analysis for charged particles vs event multiplicity

- **HIN-15-006**: pp/pPb/PbPb
  - Spectra of $K_S^0$ and $\Lambda/\bar{\Lambda}$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
CMS detector

Inner tracker: charged particles
Also for $\gamma$ isolation, PF input to jets

EM and Hadron calorimeters: photons, jets
Also $E_{\text{had}}$ for $\gamma$ isolation

Muon HCAL ECAL Tracker

Region used

Photons

Region used

Other particles

$|\eta| < 2.4$

$|\eta| < 5.2$

$|\eta| < 3.0$

$|\eta| < 2.5$
s quark mass: Nature’s gift to Heavy Ion physics

- s quark mass
  - Largely responsible for the kaon mass falling between $\pi$ and proton $\Rightarrow$ PID with TOF or dE/dx.
  - Big enough that kaon decays in a “short” time
  - Small enough that it decays in a macroscopic distance (unlike, for example, B mesons)
  - It’s just right for particles like $K^0_s$ and $\Lambda/\bar{\Lambda}$ to decay in a “reasonable” distance and be “identified” because of their $V^0$ topology

- This last feature is exploited in the analysis shown in this talk
Correlations of pairs of charged particles emitted in heavy ion collisions were observed to show a very clear “ridge”, a significant near-side (small $\Delta \Phi$) long-range (large $\Delta \eta$) enhancement.

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Where we started...

- Correlations of pairs of charged particles emitted in heavy ion collisions were observed to show a very clear "ridge", a significant near-side (small $\Delta \Phi$) long-range (large $\Delta \eta$) enhancement.

- As well as a broad away-side (large $\Delta \Phi$) structure.
Recognizing the importance of fluctuations and triangular flow killed off the “Mach cone” and other distractions.

The “ridge” (and most of the away-side) result from hydrodynamic flow of a dense asymmetric medium.

Now being extensively studied to understand the detailed properties of the medium.
Then something strange (not the quark) happened!

- Ridge in pPb collisions!
- But only in events with a very high multiplicity.
- Who ordered that???
Then something strange (not the quark) happened!

- Ridge in pPb collisions!
- But only in events with a very high multiplicity.
- Who ordered that???

Many detailed studies followed to try to understand the nature and origin of these near-side (small $\Delta \Phi$) long-range (large $\Delta \eta$) correlations in “small” systems.
Ridge studies in pPb (now with strangeness)

PRL 115 (2015) 012301

Ntrk≥110

PLB 742 (2015) 200

Mass ordering (using strangeness)

v₃ Similar to Pb-Pb

PLB 724 (2013) 213

v₂{2} > v₂{4} ≈ v₂{6} ≈ v₂{8} ≈ v₂{∞}
What we learned for pPb ridge

- It is a collective effect
  > $v_2$ from multi-particle correlations all about equal

- Importance of fluctuations
  > $v_3$ about the same for pPb and PbPb

- Suggestion of hydrodynamic flow
  > Mass ordering of elliptic flow versus $p_T$ (but other models might also explain this feature)
But the strangest thing of all!

- Ridge in high mult pp!!
- First with charged particles in pp @ 7 TeV in 2010 (JHEP 09 (2010) 091).
- Now found for both charged and strange particles in pp @ 13 TeV (CMS-HIN-16-010).
But the strangest thing of all!

- Ridge in high mult pp!!
- First with charged particles in pp @ 7 TeV in 2010 (JHEP 09 (2010) 091).
- Now found for both charged and strange particles in pp @ 13 TeV (CMS-HIN-16-010).
- However, they are harder to study because here the away-side is dominated by the effects of jets
Spectra of particles in high-mult pp

Spectra qualitatively similar

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Spectra of particles in high-mult pp

Especially particle ratios

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But small differences in the details (Blast Wave fits shown)

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Correlations in high-mult pp collisions?

Need a robust procedure for removing the effect of jets on the away-side correlations!
Jet removal technique

CMS pp \( \sqrt{s} = 13 \) TeV

1 < \( p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \) GeV/c

Long range (|\( \Delta \eta \)| > 2)

Low mult

High mult

CMS HIN-16-010

Short range (|\( \Delta \eta \)| < 1) minus

Long range (|\( \Delta \eta \)| > 2)

Project long range (above) and short minus long range (below)
Jet removal technique

- Jet shape taken from low multiplicity data
  - Assume it doesn’t depend on multiplicity
- Shape is scaled by the yield in the jet peak
- Correction is applied to the $V_n$ after fitting
  - The only option for multi-particle cumulants
- Need to also scale by associated total multiplicity

\[
V^\text{sub}_{n\Delta} = V_{n\Delta} - V_{n\Delta}(10 \leq N^\text{offline}_{\text{trk}} < 20) \times \frac{N_{\text{assoc}}(10 \leq N^\text{offline}_{\text{trk}} < 20)}{N_{\text{assoc}}} \times \frac{Y_{\text{jet}}(10 \leq N^\text{offline}_{\text{trk}} < 20)}{Y_{\text{jet}}}
\]
Results: \( v_2 \) and \( v_3 \) in pp @ 5, 7, 13

- **\( v_2 \):**
  - No energy dependence
  - Qualitatively similar shape for pp, p-Pb, and Pb-Pb

- **\( v_3 \):**
  - No energy dependence
  - Slightly different from p-Pb and Pb-Pb at higher mult
  - Difference in initial state fluctuations?
Results: $v_2$ versus $p_T$ for $K^0_S$ and $\Lambda$

Clear mass splitting observed up to about 2 GeV/c
Results: Multi-particle correlations in pp

- Cumulant method for multi-particle correlations
- Find that: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$
- Collectivity!
Qualitatively similar results seen in high-mult pp and pPb, as well as peripheral PbPb
Conclusions

Can you tell the difference between a very high mult pp, a high mult pPb, and a peripheral PbPb, all at same multiplicity?
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Can you tell the difference between a very high mult pp, a high mult pPb, and a peripheral PbPb, all at same multiplicity?

The answer so far is:

No (qualitatively)

but also

Yes (quantitatively in details)

Results relevant to many interesting questions

- Fluctuations in the initial state of the proton
- Onset of collectivity in small systems
CMS has many other recent flow results...

Flow at very high $p_T$ (>80 GeV/c) in PbPb

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
Conclusions

- Detailed properties of spectra and correlations in high-multiplicity p-p collisions at several energies
  - Spectra and yield ratios of particles similar to pPb and PbPb, but small differences in Blast Wave fits
  - Significant $v_2$ and $v_3$ at 5, 7, and 13 TeV
  - Qualitatively similar shape for $v_2$ in high-mult pp and p-Pb, as well as peripheral PbPb
  - $v_3$ values are even more similar for the three systems, especially at lower (but still high for pp) multiplicity
  - Mass ordering observed using strange particles
  - Evidence of collectivity: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$

- Provide insight to many different interesting questions
  - Fluctuations in the initial state of the proton
  - Onset of collectivity in small systems
Effect of ATLAS templates on $v_2$

$F$ scales up baseline in addition to jet peak

$$Y_{\text{templ}}(\Delta \phi) = F Y_{\text{periph}}(\Delta \phi) + Y_{\text{ridge}}(\Delta \phi)$$
Effect of ATLAS templates on $v_2$

$F$ times this number of particles are not allowed to "flow"
So, extracted $v_n$ are **larger**
In this case, $\sim(1.2/5.5)=22\%$

Much bigger effect at low mult

$$Y_{\text{templ}}(\Delta \phi) = F \cdot Y_{\text{periph}}(\Delta \phi) + Y_{\text{ridge}}(\Delta \phi)$$

$F$ scales up **baseline** in addition to jet peak

$$Y_{\text{ridge}}(\Delta \phi) = G \left(1 + 2v_{2,2} \cos(2\Delta \phi)\right)$$
- $V_n \Delta$ coefficients extracted using a Fourier fit

$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_n 2V_n \Delta \cos(n\Delta \phi) \right]$$

- Single $v_n$ coefficients are computed with:

$$v_n(p_T^{\text{trg}}) = \frac{V_n \Delta(p_T^{\text{trg}}, p_T^{\text{ref}})}{\sqrt{V_n \Delta(p_T^{\text{ref}}, p_T^{\text{ref}})}}, \quad n = 2, 3.$$ 

$$\langle\langle 2 \rangle\rangle \equiv \langle\langle e^{in(\phi_1 - \phi_2)} \rangle\rangle,$$

$$\langle\langle 4 \rangle\rangle \equiv \langle\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle\rangle,$$

$$\langle\langle 6 \rangle\rangle \equiv \langle\langle e^{in(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6)} \rangle\rangle$$

$$c_n \{4\} = \langle\langle 4 \rangle\rangle - 2 \times \langle\langle 2 \rangle\rangle^2,$$

$$c_n \{6\} = \langle\langle 6 \rangle\rangle - 9 \times \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \times \langle\langle 2 \rangle\rangle^3$$

$$v_2 \{4\} = \sqrt[4]{-c_n \{4\}},$$

$$v_2 \{6\} = \sqrt[6]{\frac{1}{4}c_n \{6\}}.$$
CMS pp $\sqrt{s} = 13$ TeV

$|\Delta\eta| > 2$

$V_{2}[t^m]|2 \rangle$

$0.00 \leq N_{\text{trk}} \leq 105$, $10 \leq N_{\text{trk}} \leq 150$, $20 \leq N_{\text{trk}} \leq 150$

$p_T$ (GeV/c)

$V_{2}[t^m]|2 \rangle/n_q$

$0.00 \leq KE_{\text{trk}}/n_q \leq 1.5$

Data/Fit

Polynomial fits to $K_S^0$
$v_2$ results on from ATLAS

A new method is used (template fit)
First measurement of $v_2$ in p-p

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