Light-flavor hadron production
Adrian Nassirpour, for the ALICE Collaboration
Outline

• This presentation will cover:
  
  • Neutral meson yields as a function of $p_T$ and multiplicity
  
  • Light-flavor particle production as a function of Unweighted Transverse Spherocity
Light-flavor hadron production as a function of multiplicity

- Light-flavor hadrons: a key tool to study hadronization
- Main focus for this presentation:
  - Light-flavor yield vs. event multiplicity.

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    - Relative yield of strange hadrons to pions ($S/\pi$).

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Light-flavor hadron production as a function of multiplicity

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• Main focus for this presentation:
  • Light-flavor yield vs. event multiplicity.
    • Relative yield of strange hadrons to pions (S/π).
    • The average charged particle-multiplicity measured at midrapidity.
Light-flavor hadron production as a function of multiplicity

• Light-flavor hadrons: a key tool to study hadronization

• Main focus for this presentation:
  • Light-flavor yield vs. event multiplicity.

• In A-A systems, strangeness enhancement could be interpreted as a signature of the formation of a quark–gluon plasma (QGP).
  • Unresolved if this also applies to pp collisions.
Light-flavor hadron production as a function of multiplicity

• In this context, how can we improve our understanding of light-flavor hadron production?

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• Can these events be characterized by other properties than $<dN/d\eta>$ production?
Light-flavor hadron production as a function of multiplicity

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  • Can these events be characterized by other properties than $<dN/d\eta>$ production?

  • Do ALL light-flavor particles follow the same trend?
ALICE apparatus

A large range of subdetectors are utilized in the different measurements presented here:

- TPC
  - Track reconstruction + PID
- ITS
  - Track reconstruction + midrapidity multiplicity
- TOF
  - PID
ALICE apparatus

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  - **TPC**
    - Track reconstruction + PID
  - **ITS**
    - Track reconstruction + midrapidity multiplicity
  - **TOF**
    - PID
  - **PHOS**
    - Neutral meson yield
  - **EMCal**
    - Neutral meson yield
A large range of subdetectors are utilized in the different measurements presented here:

- **TPC**
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- **TOF**
  - PID

- **PHOS**
  - Neutral meson yield

- **EMCal**
  - Neutral meson yield

- **V0A/V0C**
  - Triggering + forward-rapidity multiplicity.
Outline

• This presentation will cover:
  
  • Neutral meson yields as a function of multiplicity

  • Light-flavor particle production as a function of Unweighted Transverse Spherocity
Neutral meson production: analysis details

- The $\eta$ and $\pi^0$ mesons are reconstructed by calculating invariant masses of photon pairs.
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- Final yield is extracted by combining subdetectors.
Neutral meson production: Results

• Indications of universal scaling as a function of collision energy.
  • $x_T = \frac{2p_T}{\sqrt{S}}$
Neutral meson production: results

- Indications of universal scaling as a function of collision energy.
  \[ x_T = \frac{2p_T}{\sqrt{s}} \]

- Measurements of \( \eta \) and \( \pi^0 \) as a function of forward multiplicity
Neutral meson production: results

- New results suggest that $\eta/\pi^0$ is independent of multiplicity as a function of $p_T$. 
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- $p_T$-differential $\eta$ production is not modified even in extremely large pp multiplicities.
Neutral meson production: results

- New results suggest that $\eta/\pi^0$ is independent of multiplicity as a function of $p_T$.
  - $p_T$-differential $\eta$ production is not modified even in extremely large pp multiplicities.
- $p_T$ integrated double-ratio presents a suppression of $\eta$ with increasing multiplicity.
Outline

• This presentation will cover:
  • Neutral meson yields as a function of multiplicity
  • Light-flavor particle production as a function of Unweighted Transverse Spherocity
Strangeness enhancement in different topologies: Transverse Spherocity $S_{0}^{p_T=1}$

- Categorize event into two types:
  - **Jetty**: Back-to-Back "jet-like" events
    - Particle production mainly driven by hard processes
  - **Isotropic**: Azimuthally isotropic events.
    - Particle production driven by multiple softer collisions.

$$S_{0}^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \sum_{i} \frac{|\vec{p}_{T,i} \times \hat{n}|}{N_{\text{trk}}} \right)$$
Strangeness enhancement in different topologies: Transverse Spherocity $S_0^{p_T=1}$

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- These categories are defined by the bottom/top 20% $S_0^{p_T=1}$ quantile.

\[
S_0^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \sum_i \frac{|\hat{p}_{T,i} \times \hat{n}|}{N_{trk}} \right)
\]

ALICE Simulation
PYTHIA 8.212 (Monash 2013)

pp $\sqrt{s} = 7$ TeV
$|\Delta \eta| < 0.8$, $N_{ch} \geq 15$

Spherocity classes
(More than two charged particles $|\eta| < 0.8$, $p_T \geq 0.15$ GeV/c)

- 0-10% 50-60%
- 10-20% 60-70%
- 20-30% 70-80%
- 30-40% 80-90%
- 40-50% 90-100%
Multiplicity triggers for $S_0^{p_T=1}$ analysis

Multiplicity (0-10%) for spectra is measured in two rapidity regions

- Forward rapidity:
  \[ 2.8 < \eta < 5.1, \quad -3.7 < \eta < -1.7 \]
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Multiplicity (0-10%) for spectra is measured in two rapidity regions:

- **Forward rapidity:** $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$
- **Midrapidity:** $|\eta| < 0.8$

### Forward Estimator

- ALICE Preliminary
- $p_{p}, |\eta| < 0.8$
- $N_{ch} \geq 10$, $p_{T} \geq 0.15$ (GeV/c), $|\eta| < 0.8$
  - VOM I-III
  - $S_{0}^{p_{T}=1}$-integrated
  - Jetty ($S_{0}^{p_{T}=1} < 0.6$)
  - Isotropic ($S_{0}^{p_{T}=1} > 0.823$)

### Midrapidity Estimator

- ALICE Preliminary
- $p_{p}, |\eta| < 0.8$
- $N_{ch} \geq 10$, $p_{T} \geq 0.15$ (GeV/c), $|\eta| < 0.8$
  - $S_{0}^{p_{T}=1}$-integrated
  - Jetty ($S_{0}^{p_{T}=1} < 0.625$)
  - Isotropic ($S_{0}^{p_{T}=1} > 0.833$)
Multiplicity triggers for $S_0^{p_T=1}$ analysis

Multiplicity (0-10%) for spectra is measured in two rapidity regions:

- Forward rapidity: $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$
- Midrapidity: $|\eta| < 0.8$

Forward Estimator

Midrapidity Estimator
\[ p \rightarrow \pi \text{ ratios as functions of } S_0^{p_T=1} \]

**Forward Estimator**

2.8 < \eta < 5.1 , -3.7 < \eta < -1.7

**ALICE Preliminary**

pp, \( \sqrt{s} = 13 \text{ TeV} \)

**VQM I-III**

\( N_{p_{\text{p}}}, p_{\text{p}} > 0.15 \text{ (GeV/c), } |\eta| < 0.8 \)

- **\( S_{0}^{\pi^-} \)-integrated**
- **Isotropic** (\( S_{0}^{\pi^-} > 0.023 \))
- **Jetty** (\( S_{0}^{\pi^-} < 0.06 \))
- **PYTHIA8 (Monash 2013)**
- **EPOS-LHC**

**JETTY** : RED

**ISOTROPIC** : BLUE

p-to-\( \pi \) : shift of protons from low (high) \( p_T \) to high (low) \( p_T \) for isotropic (jetty) events.

Normally associated with increase (decrease) of radial flow in large systems.
p-to-π ratios as functions of $S_0^{pT=1}$

**Forward Estimator**

$2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$

**Midrapidity Estimator**

$|\eta| < 0.8$

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$|\eta| < 0.8$

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p-to-π: shift of protons from low (high) $p_T$ to high (low) $p_T$ for isotropic (jetty) events.

Normally associated with increase (decrease) of radial flow in large systems.

Likely competing effects between radial flow and hardening due to jet fragmentation.

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**K-to-π ratios as functions of $S_0^{p_T=1}$**

**Forward Estimator**

$2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$

**Midrapidity Estimator**

$|\eta| < 0.8$

---

**JETTY : RED**

**ISOTROPIC : BLUE**

K-to-π ratio showcases a clean separation between the kaon production in Isotropic and Jetty events

Generators describe the double-ratio quite well.
E-to-π ratios as functions of $S_0^{p_T=1}$

Midrapidity results suggest that one can enhance or suppress the strangeness enhancement by selecting on $S_0^{p_T=1}$

Generators describe the double-ratio quite well, except for some tension at low $p_T$, but not the $p_T$ evolution
$\phi$-to-$\pi$ ratios as functions of $S_0^{p_T=1}$

Forward Estimator
$2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$

Midrapidity Estimator
$|\eta| < 0.8$

Unlike the K and $\Xi$, the $\phi$ does not show a difference for jetty and isotropic events.

Results using different estimators are consistent within uncertainties.
Multiplicity triggers for $S_0^{p_T=1}$ analysis

Multiplicity (0-10%) for spectra is measured in two rapidity regions:

- Forward Rapidity: $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$
- Midrapidity: $|\eta| < 0.8$

**Takeaway messages:**

- The HM events are not a direct average of the Isotropic and Jetty event classes.
- Instead, HM events are more similar to Isotropic events.
- This indicates that HM events are dominated by soft processes.
Outlook on low-multiplicity studies

• Run 3 analyses can be utilized to measure extremely low multiplicities:
  
  • \(< dN/d\eta >\)
Outlook on low-multiplicity studies

- Run 3 analyses can be utilized to measure extremely low multiplicities:
  - $< dN/d\eta >$
  - Neutral mesons
Outlook on low-multiplicity studies

- Run 3 analyses can be utilized to measure extremely low multiplicities:
  - \(< dN/d\eta >\)
  - Neutral mesons
  - Strangeness
- Analyses currently ongoing!
Summary

Neutral meson production as a function of multiplicity:
- No significant multiplicity dependence of $\eta/\pi^0$ as a function of $p_T$
- Integrated $\eta/\pi^0$ yields hint towards suppression of $\eta$ at larger multiplicities

Particle Production as a function of Unweighted Transverse Spherocity:
- $S_0^{p_T=1}$ can be used to select strangeness enhanced/suppressed events
- $S_0^{p_T=1}$ can select different physics depending on the $\eta$ region
- The results suggest that high-multiplicity events are primarily dominated by soft processes.

Outlook:
- Comprehensive paper on $S_0^{p_T=1}$ under review, expected publication in the near future
- Run 3/4 will allow for differential low-multiplicity measurements

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BACKUP
The $\eta$ and $\pi^0$ mesons are reconstructed by combining photon pairs.
  - Final yield is extracted by combining subdetectors.

Measurements up to high-$p_T$ (>50 GeV/c) using merged EMCal clusters.
  - Ensures a high $\pi^0$ purity (>70%)
New results suggest that $\eta/\pi^0$ is independent of multiplicity as a function of $p_T$.

- $p_T$-differential $\eta$ production is not modified even in extremely large pp multiplicities.

- Double-ratio hints towards a very small effect.
  - Qualitatively well described by PYTHIA
  - Small tension at 3-5 GeV/c, could contain interesting physics.
Jet Pt Evolution

ALICE Preliminary, pp, $\sqrt{s} = 5.02$ TeV
MC data

- **inclusive**
- **inside charged jet**

anti-$k_T$, $R = 0.4$, $E > 10$ GeV/c
Jet Pt Evolution

pp \( \sqrt{s} = 7 \) TeV
ALICE Preliminary
- 5-10 GeV/c
- 10-15 GeV/c
- 15-20 GeV/c

anti-\( k_T \)
\( R=0.4; |\eta|^{\text{jet}} < 0.5 \)
\( p_T^{\text{track}} > 0.15 \) GeV/c
\( |\eta|^{\text{track}} < 0.9 \)

\( \frac{K^+ + K^-}{\pi^+ + \pi^-} \)

Scaled to 5-10 GeV/c

ALI-PREL-68753

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Unweighed Transverse Spherocity $S_{O}^{p_{T}=1}$

- $S_{O}^{p_{T}=1}$ is measured as $S_{O}$, but only considers the angular component.

\[
S_{O} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_{i} |p_{T} \times \hat{n}|}{\Sigma_{i} p_{T_{i}}} \right)^2
\]

\[
S_{O}^{p_{T}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_{i} |\hat{p}_{T} \times \hat{n}|}{N_{\text{trk}}} \right)^2
\]

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Unweighed Transverse Spherocity $S_{o}^{p_{T}=1}$

- $S_{o}^{p_{T}=1}$ is measured as $S_{o}$, but only considers the angular component.

$$S_{o} = \frac{\pi^2}{4} \min \left( \frac{\Sigma_i |p_{T} \times \hat{n}|}{\Sigma_i p_{T_i}} \right)^2$$

$$\rightarrow \quad S_{o}^{p_{T}=1} = \frac{\pi^2}{4} \min \left( \frac{\Sigma_i |\hat{p}_{T} \times \hat{n}|}{N_{trk}} \right)^2$$

$S_{o,1}$ and $S_{o,2}$ will describe two completely different topologies!

$S_{o,1}^{p_{T}=1}$ and $S_{o,2}^{p_{T}=1}$ will describe two similar topologies.
Identified Vs Unidentified Hadrons

- There is a non-trivial difference in the $S_0$ measurement for Identified and Unidentified hadrons

\[ S_0 = \frac{\pi^2}{4} \min \left( \frac{\sum_i |p_T \times \hat{n}|}{\sum_i p_T} \right)^2 \]

- Primary Unidentified hadrons enter both the yield extraction and $S_0$
- This also applies to $\pi/K/P$
- **But this does NOT apply to $\Xi$!**
- $\phi$ enters twice! ($K^+ K^-$)

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