High-momentum particle identification with HMPID

Search for the origins of $p/\pi$ ratio

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Measurement of $p/\pi$ ratios and why it is so interesting?

- The $p/\pi$ ratio is a source of experimental surprises ever since we are able to measure it in various systems $e^+ + e^-$, Heavy-Ion and recently, as I will show and discuss in this presentation, proton-proton collisions.
- It’s measurement poses an experimental as well as theoretical challenge.
- It inspires new experimental approaches and theoretical ideas.
Outline

1. $p/\pi$ ratio in history
   - Measurements at RHIC
   - Measurements at LHC
   - Theoretical understanding of the ratio

2. $p/\pi$ ratio in proton-proton collision measured with HMPID
   - The HMPID detector
   - Proton and pion spectra and the $p/\pi$ ratio with HMPID

3. $p/\pi$ ratio from 2-particle correlation
   - Correlation measurement
   - Per-trigger yields of protons and pions in jet and bulk $p/\pi$ ratio in jet and bulk

4. Understanding the $p/\pi$ ratio and future measurements
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4. Understanding the $p/\pi$ ratio and future measurements
p/π ratio at RHIC


‘baryon puzzle’

- central AuAu collisions
  - ratio **anomalously high** ∼ 1 between 2 − 5 GeV/c
  - strong dependence with momentum with a **peak**
- peripheral AuAu collisions and dAu
  - similar values
  - not such a strong $p_T$ dependence
Quark coalescence

- *Phys. Rev. Lett. 90, 202303(nucl-th/0301087)*
  - R. J. Fries, B. Mueller, C. Nonaka, and S. A. Bass
  - ‘emission of hadrons with transverse momentum up to about 5 GeV/c in central relativistic heavy ion collisions is dominated by recombination’

- *Phys. Rev. Lett. 90, 202302(nucl-th/0301093)*
  - V. Greco, C. M. Ko, and P. Levai
  - ‘Coalescence of minijet partons with the partons from the quark-gluon plasma formed in relativistic heavy ion collisions is suggested as the mechanism for production of hadrons with intermediate transverse momentum’
**p/π** ratio at RHIC: \( v_2 \) measurements

\[ \frac{p}{π} \text{ ratio at RHIC: } v_2 \text{ measurements} \]

\[ \text{Phys. Rev. C 72 (2005) 14904} \]

\[ \begin{align*}
\text{Hydro model} & : \\
\pi & : \quad \text{dashed line} \\
K & : \quad \text{dotted line} \\
P & : \quad \text{solid line} \\
\Lambda & : \quad \text{solid line (blue)}
\end{align*} \]

\[ \begin{align*}
\text{PHENIX Data} & : \\
\pi^+ + \pi^- & : \quad \text{diamonds} \\
K^+ + K^- & : \quad \text{downward triangles} \\
p + p & : \quad \text{green circles}
\end{align*} \]

\[ \begin{align*}
\text{STAR Data} & : \\
h^+ + h^- & : \quad \text{stars} \\
K_S^0 & : \quad \text{red triangles} \\
\Lambda + \Lambda & : \quad \text{blue circles}
\end{align*} \]

\[ \begin{align*}
\text{p}_T < 2 \text{ GeV/c} & : \\
\text{mass ordering, Hydro OK} & : \\
\text{p}_T > 2 \text{ GeV/c} & : \\
\text{mass ordering breaks} \\
\text{baryon/meson splitting} & : \\
\end{align*} \]

**Quark coalescence and elliptic flow**

- **Phys. Rev. Lett. 91, 092301(nucl-th/0302014)**
- D. Molnar and S. A. Voloshin
- ‘quark coalescence enhances hadron elliptic flow at large \( p_T \)’
Number of quark ($n_q$) scaling

- Supports the idea of coalescence enhancing flow
**p/π** ratio at RHIC: number of quark scaling


Number of quark \((n_q)\) scaling

- Supports the idea of coalescence enhancing flow

What happens at LHC?
$p/\pi$ ratio at the LHC

PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

- $p/\pi$ ratio continues to show anomalous behavior at the LHC
- it’s value is strongly momentum dependent
- also the peripheral collisions show a peak (smaller)
- let’s look at the $v_2$
$p/\pi$ ratio at the LHC: $v_2$ origins

**JHEP 1506 (2015) 190**

<table>
<thead>
<tr>
<th>$p_T$ &lt; 3 GeV/$c$</th>
<th>mass ordering</th>
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ALICE
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
$|\eta| < 0.8$
and $|y| < 0.5$

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<tr>
<td>$K^0_s$</td>
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<tr>
<td>$p+\bar{p}$</td>
</tr>
<tr>
<td>$\phi$</td>
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<tr>
<td>$\Lambda+\bar{\Lambda}$</td>
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</tr>
<tr>
<td>$\Omega^++\bar{\Omega}^-$</td>
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$\nu_2$ origins

\[ v_2^{\text{SP}}(|\eta| > 0.9) \]

\( \text{ALI-PUB-82451} \)
$p/\pi$ ratio at the LHC: $v_2$ origins

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ALICE
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
$|\eta| < 0.8$
and $|y| < 0.5$

Particle species
$\pm\pi, K, p, \bar{p}, \phi, \Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}, \Omega, \bar{\Omega}$

violation of $n_q$ scaling
$p/\pi$ ratio at the LHC: $v_2$ origins

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ALICE
Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76$ TeV

$|n| < 0.8$
and $|y| < 0.5$

violation of $n_q$ scaling
$\sim 20\%$

mass ordering restored
Correlation measurement:

Is the $p/\pi$ ratio connected to jet-fragmentation? possibility to separate hard jet from underlying event

anomalous ratio associated with bulk
Current understanding of the ratio measured in Heavy-Ion collisions

- LHC measurements suggest a **mass ordering rather than number of quark scaling** that was observed at RHIC
- the anomalous ratio is connected with **physics of the ‘bulk’**
- the ‘bulk’ particle production is associated with soft physics described by *hydrodynamical models*
- coalescence questioned
Current understanding of the ratio measured in Heavy-Ion collisions

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*What is happening in proton-proton collisions?*
The HMPID detector

- Part of ALICE detector system
- \(|\eta| < 0.5, \ 0 < \varphi < 1/3\pi, \ \sim 7\% \ of \ ALICE \ acceptance\)
- Ring Imaging CHerenkov (RICH) detector
- if \(v(\text{particle}, n) > c(n)\) light-cone is emitted around it’s path

\[
\cos \Theta_{ch} = \frac{1}{\beta n}
\]

\((n\text{-refractive index})\)

Ring size \((\Theta_{ch})\) together with momentum information from tracking detectors provides \textit{PID}
Particle identification with HMPID: $n_{\sigma}$ variable

$\Theta_{ch}^{rec}$ distributed around $\Theta_{ch}^{th}(i = \{\pi, K, p\})$

$$n_{\sigma}(m_i) = \frac{\Theta_{ch}^{rec} - \Theta_{ch}^{th}(i)}{\sigma_i}, \quad i = \{\pi, K, p\}$$

possibility to identify track-by-track ($|n_{\sigma}(m_i)| < 2$)

Separation capability: $\pi/K$: $p_T < 3$ GeV/c, $K/p$: $p_T < 5$ GeV/c
Particle identification with HMPID: $n_\sigma$ vs $p_T$

proton well separated

$\pi$ and $K$ ‘stripes’: merging

projection of $n_\sigma(m_\pi)$

MC truth $\pi, K$ show clear overlap
Particle identification with HMPID: $n_\sigma$ vs $p_T$

3.5 < $p_T$ < 4.0 GeV/c

Area in the triangle
Impossible to separate $\pi$ from $K$
Reject all tracks in that area $\rightarrow$ severe loss of efficiency
Extending the pion identification: exclusion cut

Solution

Not only look how close is the $\Theta_{ch}^{rec}$ to $\Theta_{ch}^{th}(\pi)$

Also how far it is from $\Theta_{ch}^{th}(K)$

Look at $n_\sigma(m_K)$

Efficiency remains high

Contamination from Kaons low ($< 10\%$)
Proton and pion spectra with HMPID

HMPID track-by-track ($HMP_{tbt}$)

results compared to statistical analyses

results consistent within 5%
Proton and pion spectra with HMPID

Relativistic rise in TPC (rTPC)

large systematic errors, jumps at $\approx 3$ GeV/c
possibility to improve precision utilizing $HMP_{tbt}$
$p/\pi$ ratio with HMPID

Ratio **not described by Pythia** Monte Carlo generator

*Similar behavior to Heavy-Ion*

Shows $p_T$ dependence with **peak** at $\sim 3$ GeV/$c$
Correlation measurement

Analysis set-up

**Unidentified trigger** correlated with **pions** and **protons** identified with HMPID

**Trigger:** \( 4 < p_T < 10 \text{ GeV}/c, \ 0 < \varphi < 2\pi, \ |\eta| < 0.9 \)

**Associated:** \( p_T = \{1.5, 2.0, 2.5, 3.0, 4.0\}, \ 0 < \varphi < 1/3\pi, \ |\eta| < 0.5 \)

\[
S(\Delta\eta, \Delta\varphi):
\]
signal events

\[
B(\Delta\eta, \Delta\varphi):
\]
mixed event pair-efficiency
Correlation measurement: defining jet and bulk

\[ \Delta \phi \] distribution of yields

- Two peaks sitting on pedestal
- Peaks: jets fitted with 2-Gaus + constant
- Pedestal: bulk identified with constant from peak-fit
Per-trigger yields of protons and pions in jet and bulk

Jet and bulk contribute evenly to pion yield at $p_T > 2$ GeV/c

Difference for jet and bulk in proton yield contribution
$p/\pi$ ratio in jet and bulk

$p/\pi$ (Bulk)

**Higher** than $p/\pi$ (Jet)

**Agrees** with measurement obtained from spectra

protons emerge from bulk in a different way than from a jet

*Similar observations made in Heavy-Ion*
Towards understanding of the $p/\pi$ ratio

What we’ve measured so far

- RHIC measured **anomalous values of $p/\pi$ ratio** dependent on momentum
- Theory saw this as a proof of **collective behavior** in the early stages of Heavy-Ion collisions (elliptic flow and coalescence)
- LHC confirmed the behavior of the ratio
- **LHC** measured **violation of the number of quark scaling**
- Correlation measurements show, that **ratio** is connected with the **soft physics of the bulk** associated with collectivity
- *Measurements in proton-proton collisions show similar patterns to those observed in Heavy-Ion*
Towards understanding of the $p/\pi$ ratio

What to do next

- new theories talking about **collectivity in proton-proton collisions**
  - Hydrodynamics, CGC
- theories looking for flow boosting **mechanisms not connected to collectivity**
  - random parton escape mechanism (nucl-th/1502.05572)
  - L He, T Edmonds, Z-W Lin, F Liu, D Molnar, F Wang
- new experimental research
  - $\nu_2$ measurements in proton-proton collisions at various multiplicities
  - *soft and hard jets event tagging* (SP)
adding pQCD to hydrodynamical calculations brings the $v_2$ down
$n_\sigma(m_K), n_\sigma(m_p)$
using $S/\sqrt{S+B}$ ratio
looking for maximum in several $p_T$ bins
fit with $p_0 \times p_T/(p_1 - p_T)$
random escape mechanism

nucl-th/1502.05572

With only random escape w/o Hydro (thin lines) $v_2 \neq 0$