Measurements of $\Lambda_c$ and $X(3872)$ production in PbPb for the studies of charm hadronization with CMS

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for the CMS Collaboration

29th International Conference on Ultrarelativistic Nucleus Nucleus Collisions
Kraków, Poland

April 7th, 2022

The MITHIG’s work is supported by US DOE-NP
In-medium Hadronization is Important

From quarks to hadrons

- Hadronization: Important ingredient to the phenomenology of the observed $R_{AA}$, $v_2$
- Heavy quarks: flavor conservation in QGP ($m_Q \gg T_{QGP}$)
  - Ideal probe of the in-medium hadronization mechanism
In-medium Hadronization is Complicated

**Fragmentation** (High-\(p_T\))

- Universality of fragmentation

**Coalescence** (Low-\(p_T\))

- Instantaneous assumption
  - Instantaneous coalescence model (ICM)
  - Resonance recombination model (RRM)
- Parameters (thermal quark \(m_q\), width parameter, global normalization, …)

We are not sure about:

QGP
In-medium Hadronization is Complicated

- \( H_{AA} = R_{AA}^{H}/R_{AA}^{Q} \) directly exhibits hadronization effects

- Dramatically different hadronization effects in the models using different mechanisms and ways of implementing coalescence

- Lead to poor constraints on hot medium interaction effects
Study Coalescence with Baryons

• Coalescence more significant for baryons with 3 valence quarks
• Baryon to meson ratio $\Lambda_c / D$ is essential to study hadronization
• $\Lambda_c$ Reconstruction: $\Lambda_c \rightarrow pK\pi$ (Branching ratio $\sim 6.2\%$)
Λ_c Signals

**pp**

![Graph for pp collisions showing the distribution of Λ_c signals.]

- **Data**: Measured values
- **Signal + Background**: Estimated values
- **Background**: Calculated values

**PbPb**

![Graph for PbPb collisions showing the distribution of Λ_c signals.]

- **Data**: Measured values
- **Signal + Background**: Estimated values
- **Background**: Calculated values

**Legend**

- **5 < p_T < 6 GeV/c**
- **|y| < 1**
- **Cent. 0-100%**

**CMS**

- **38 nb⁻¹ (5.02 TeV pp)**
- **44 µb⁻¹ (5.02 TeV PbPb)**

**References**

- CMS (2020) PLB 803 (2020) 135328
• PYTHIA8 underestimates $\Lambda_c/D^0$ in 5-20 GeV

$\Lambda_c$ in pp Collisions (1/4)
$\Lambda_c$ in pp Collisions (2/4)

- PYTHIA8 underestimates $\Lambda_c/D^0$ in 5-20 GeV
- Color reconnection enhances the ratio
  - String formation between other partons than leading color
  - Significant in pp due to MPI

PLB 803 (2020) 135328
\( \Lambda_c \) in pp Collisions (3/4)

- PYTHIA8 underestimates \( \Lambda_c/D^0 \) in 5-20 GeV
- Color reconnection enhances the ratio
  → String formation between other partons than leading color
  → Significant in pp due to MPI
- **Solid line**: Partonic coalescence in pp as well

![Graph showing the ratio of \( \Lambda_c^+/\Lambda_c^0 \) to \( D^0/D^+ \) versus p_T (GeV/c)]

PbPb 44 \( \mu b^{-1} \), pp 38 nb\(^{-1} \) (5.02 TeV)

Global uncertainty
pp: 20%

*PLB 803 (2020) 135328*
• PYTHIA8 underestimates $\Lambda_c/D^0$ in 5-20 GeV

• Color reconnection enhances the ratio
  $\rightarrow$ String formation between other partons than leading color
  $\rightarrow$ Significant in pp due to MPI

• Solid line: Partonic coalescence in pp as well

• Dashed line: SHM + Feed-down from more excited charm baryon states than PDG list predicted by Relativistic Quark Model (RQM)
• Comparable $\Lambda_c/D^0$ in PbPb and pp collisions in $10 < p_T < 20$ GeV
\[ \Lambda_c \] in PbPb Collisions (2/2)

- Higher precision and wider kinematic analysis is ongoing with latest dataset
  - 2017 pp: 3 < \( p_T \) < 30 GeV
  - 2018 PbPb: 6 < \( p_T \) < 40 GeV

**Figure:**

- CMS Collaboration
- Data points for \( |y| < 1 \)
- Global uncertainty: pp: 20%, PbPb: 31%

**Data Points:**

- 2015 PbPb
- 2017 pp: 3 - 30 GeV
- 2018 PbPb: 6 - 40 GeV

**Legend:**

- PbPb 44 \( \mu b^{-1} \), pp 38 nb\(^{-1} \) (5.02\, TeV)
- Data: Cent. 0-100%

**References:**

- PLB 803 (2020) 135328
Study Coalescence with Exotic Hadrons

How about one more quark? $\rightarrow X(3872)$
X(3872) in Heavy-ion Collisions

Not that simple: the inner structure of X(3872) affects its production in HIC

Tightly bound
Small radius

Compact four quark state

Loosely bound
Large radius

D-\bar{D}^* hadron molecule

Tetraquark

r_{4q} \approx r_{cc} \approx 0.3 \text{ fm}

\bar{u} \bar{c}

\bar{D}^* \bar{c}

\bar{D} \bar{u}

r_{\text{mol}} \text{ as large as } 5 \text{ fm}
X(3872) in HIC (1/2): Coalescence

- Coalescence with particles in HIC $\rightarrow$ Enhance X(3872)

Coalescence probability depends on X(3872) inner structure
X(3872) in HIC (2/2): Breakup

- Breakup by comoving particles $\Rightarrow$ Suppress X(3872)
- Coalescence with particles in HIC $\Rightarrow$ Enhance X(3872)

Dissociation probability depends on X(3872) inner structure
Proton-proton collisions

$LHCb$

$pp\ \sqrt{s} = 8\ TeV$

$p_T > 5\ GeV/c$

$X(3872)/\psi(2S)$

PRL 126 (2021) 092001

X(3872) in High-Multiplicity pp Collisions
X(3872) in High-Multiplicity pp Collisions

- Breakup by comoving particles $\rightarrow$ Suppress X(3872)

- Destroyed by comoving particles due to smaller binding energy than $\psi(2S)$?

PRL 126 (2021) 092001
X(3872) in Heavy-ion Collisions

- Breakup by comoving particles $\Rightarrow$ Suppress X(3872)

Proton-proton collisions

Heavy-ion collisions

Even higher multiplicity

LHCb

$pp \sqrt{s} = 8$ TeV
$p_T > 5$ GeV/c

PbPb

Breakup by comoving particles

PRL 126 (2021) 092001
X(3872) in Heavy-ion Collisions

- Breakup by comoving particles $\Rightarrow$ Suppress X(3872)
- Coalescence with particles in HIC $\Rightarrow$ Enhance X(3872)

![Graph showing the ratio of X(3872) to ψ(2S) in PbPb collisions](image)

- LHCb
- $pp$, $\sqrt{s} = 8$ TeV
- $p_T > 5$ GeV/c

$\frac{BR_{X(3872)}(3872) \rightarrow J/\psi \pi^+ \pi^-}{BR_{\psi(2S)}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}$

PRL 126 (2021) 092001

Jing Wang (MIT), CMS Charm Hadronization, Quark Matter (Kraków, Poland), 2022.4.7
X(3872) Signals

- First evidence of X(3872) production in heavy ion collisions!
  - Statistical significance \(~ 4.2\sigma\)

After BDT cut

CMS Inclusive

\[ \sigma_{X(3872)} = 4.7 \text{ MeV/c}^2 \]

1.7 nb\(^{-1}\) (PbPb 5.02 TeV)

\[ 15 < p_T < 50 \text{ GeV/c} \]

\[ \sqrt{s} < 1.6, \text{ Cent. 0-90\%} \]

\[ m_{J/\psi \pi \pi} (\text{GeV/c}^2) \]

1.7 nb\(^{-1}\) (PbPb 5.02 TeV)

15 < \(p_T\) < 50 GeV/c

\[ \sqrt{s} < 1.6, \text{ Cent. 0-90\%} \]

\[ \sigma_{X(3872)} = 4.7 \text{ MeV/c}^2 \]

PRL 128 (2022) 032001
$X(3872)/\psi(2S)$ Ratio in PbPb

\[
\frac{\rho_{\text{PbPb}}}{\rho_{\text{pp}}} = \frac{N_{X(3872)}}{N_{\psi(2S)}}
\]

- $X(3872)$ to $\psi(2S)$ ratio
  \[\rho_{\text{PbPb}} = 1.08 \pm 0.49 \text{ (stat.)} \pm 0.52 \text{ (syst.)}\]

PRL 128 (2022) 032001
X(3872)/ψ(2S) Ratio in PbPb

- Indication of $\rho$ enhancement in PbPb w.r.t to pp
- Better precision needed to draw conclusion

$\rho_{pp,PbPb}^{(X(3872)\to J/\psi\pi\pi)} = \frac{N_{X(3872)}^{(PbPb)}}{N_{\psi(2S)}^{(PbPb)}}$

CMS

Prompt

$|y| < 1.6, 0-90\%$

- $pp$ (7 TeV)
  $|y| < 1.2$ (CMS)
- $pp$ (8 TeV)
  $|y| < 0.75$ (ATLAS)

PRL 128 (2022) 032001
Callback

- Breakup by comoving particles $\rightarrow$ Suppress $X(3872)$
- Coalescence with particles in HIC $\rightarrow$ Enhance $X(3872)$

$\sigma_{X(3872)} / \sigma_{\psi(2S)}$ vs. $N_{\text{VELO tracks}}$

- LHCb
  - $pp$ $\sqrt{s} = 8$ TeV
  - $p_T > 5$ GeV/c

$X(3872)/\psi(2S)$

- Prompt

PRL 126 (2021) 092001
X(3872)/ψ(2S) Ratio in PbPb

Coalescence seems to play important role in PbPb

$$\rho_{\text{PbPb}} = 1.08 \pm 0.49\text{ (stat.)} \pm 0.52\text{ (syst.)}$$

PRL 126 (2021) 092001
X(3872)/ψ(2S) Ratio in Different Systems

Coalescence seems to play important role in PbPb

$\rho_{\text{PbPb}} = 1.08 \pm 0.49 \text{ (stat.)} \pm 0.52 \text{ (syst.)}$

LHCb

$pp \sqrt{s} = 8 \text{ TeV}$

$p_T > 5 \text{ GeV/c}$

$X(3872)/\psi(2S)$

Coalescence with particles in LHC

PRL 126 (2021) 092001

Breakup by comoving particles

ρ\text{PbPb} = 1.08 ± 0.49 (stat.) ± 0.52 (syst.)
Theoretical calculation (I)

X(3872) production vs. centrality

- Higher multiplicity: Large system
- Lower multiplicity: Smaller system

Breakup

Coalescence
Theoretical calculation (II)

X(3872) production vs. centrality

**AMPT model**

- **Instantaneous coalescence model (ICM)**
  - **Molecule**: decrease at peripheral
    - Higher coalescence rate in large system
  - **Tetraquark**: relatively flat vs. centrality
    - Decreasing numbers of available $c\bar{c}$ vs. increasing chances of small spatial separation

- **Pb–Pb @ 2.76 TeV**
  - $X_{3872}$
  - Molecular
  - Tetraquark

Higher multiplicity

- Large system

Lower multiplicity

- Smaller system

**PRL 126 (2021) 012301**
TAMU model \( \text{EPJA 57 (2021) 122} \)

- Thermal-rate equation framework, focusing on hadronic phase
- Yield (molecule) \(<\) Yield (tetraquark)
  - Tetraquark: Mostly produced in hadronization in QGP transition region
  - Molecule: Regeneration in hadronic medium stage dominates
- Different from ICM

\[
\text{Yield (molecule)} < \text{Yield (tetraquark)}
\]

\[
\Rightarrow \text{Tetraquark: Mostly produced in hadronization in QGP transition region}
\]

\[
\Rightarrow \text{Molecule: Regeneration in hadronic medium stage dominates}
\]

\[
\text{TAMU model}
\]

\[
\text{Thermal-rate equation framework, focusing on hadronic phase}
\]

\[
\text{Yield (molecule)} < \text{Yield (tetraquark)}
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\[
\Rightarrow \text{Tetraquark: Mostly produced in hadronization in QGP transition region}
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\Rightarrow \text{Molecule: Regeneration in hadronic medium stage dominates}
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\[
\text{Different from ICM}
\]

\[
\text{TAMU model}
\]

\[
\text{Thermal-rate equation framework, focusing on hadronic phase}
\]

\[
\text{Yield (molecule)} < \text{Yield (tetraquark)}
\]

\[
\Rightarrow \text{Tetraquark: Mostly produced in hadronization in QGP transition region}
\]

\[
\Rightarrow \text{Molecule: Regeneration in hadronic medium stage dominates}
\]

\[
\text{Different from ICM}
\]
Summary

- Study charm in-medium hadronization by baryons and exotic hadrons in CMS

- $\Lambda_c$ measured in pp and PbPb collisions
  - PYTHIA8 underestimates $\Lambda_c/D^0$ in pp
  - CR, coalescence and feed-down from more excited baryons can enhance $\Lambda_c/D^0$ in pp
  - Analysis using larger dataset is ongoing

- First evidence of $X(3872)$ in heavy-ion collisions
  - Indication of strong coalescence in PbPb
  - Discriminate nature of exotic hadrons
Thanks for your attention!
Back up

Thanks for your attention!
## Heavy-ion data in CMS

<table>
<thead>
<tr>
<th>Run</th>
<th>Collision</th>
<th>Energy</th>
<th>Lumi</th>
<th>Scale to pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>0.17 nb⁻¹</td>
<td>7.5 pb⁻¹</td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb</td>
<td>5.02 TeV</td>
<td>0.035 pb⁻¹</td>
<td>7.4 pb⁻¹</td>
</tr>
<tr>
<td>2015</td>
<td>p-p</td>
<td>5.02 TeV</td>
<td>28 pb⁻¹</td>
<td>28 pb⁻¹</td>
</tr>
<tr>
<td>2015</td>
<td>Pb-Pb</td>
<td>5.02 TeV</td>
<td>0.55 nb⁻¹</td>
<td>24 pb⁻¹</td>
</tr>
<tr>
<td>2016</td>
<td>p-Pb</td>
<td>8.16 TeV</td>
<td>0.18 pb⁻¹</td>
<td>38 pb⁻¹</td>
</tr>
<tr>
<td>2017</td>
<td>Xe+Xe</td>
<td>5.44 TeV</td>
<td>6.0 µb⁻¹</td>
<td>0.1 pb⁻¹</td>
</tr>
<tr>
<td>2017</td>
<td>p-p</td>
<td>5.02 TeV</td>
<td>316 pb⁻¹</td>
<td>316 pb⁻¹</td>
</tr>
<tr>
<td>2018</td>
<td>Pb-Pb</td>
<td>5.02 TeV</td>
<td>1.7 nb⁻¹</td>
<td>74 pb⁻¹</td>
</tr>
<tr>
<td>Run 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td>p-p</td>
<td>5.5 / 8.8 TeV</td>
<td>300 / 100 pb⁻¹</td>
<td>300 / 100 pb⁻¹</td>
</tr>
<tr>
<td>~</td>
<td>Pb-Pb</td>
<td>5.5 TeV</td>
<td>6.2 nb⁻¹</td>
<td>268 pb⁻¹</td>
</tr>
<tr>
<td>2024</td>
<td>p-Pb</td>
<td>8.8 TeV</td>
<td>0.6 pb⁻¹</td>
<td>126 pb⁻¹</td>
</tr>
<tr>
<td></td>
<td>O-O / p-O</td>
<td>7 / 9.9 TeV</td>
<td>0.5 / 0.2 nb⁻¹</td>
<td></td>
</tr>
<tr>
<td>Run 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2027</td>
<td>p-p</td>
<td>5.5 / 8.8 TeV</td>
<td>300 / 100 pb⁻¹</td>
<td>300 / 100 pb⁻¹</td>
</tr>
<tr>
<td>~</td>
<td>Pb-Pb</td>
<td>5.5 TeV</td>
<td>6.8 nb⁻¹</td>
<td>294 pb⁻¹</td>
</tr>
<tr>
<td>2029</td>
<td>p-Pb</td>
<td>8.8 TeV</td>
<td>0.6 pb⁻¹</td>
<td>126 pb⁻¹</td>
</tr>
</tbody>
</table>
\( \Lambda_c \) in PbPb Collisions: Theoretical Model

PbPb @ 5.02 TeV (0-20%)

TAMU model
- Uncertainty: variation of reaction rate width
• Higher precision and wider kinematic analysis is ongoing with latest dataset
  ➔ 2017 pp: 3-4 GeV ~ 6.6σ
  ➔ 2018 PbPb: 6-8 GeV ~ 5σ
A Brief Intro to X(3872)

• 2003: X(3872), aka $\chi_{c1}(3872)$, discovered by Belle

• Today: Internal structure is still under debate
  Possible interpretations:
  ➡ Tetraquark: Compact four quark state
  ➡ D-\Dbar* hadron molecule: $X(3872) \approx D(1875)\Dbar^*(2007)$
  ➡ Hybrid: mixed molecule-charmonium state

• All interpretations can explain measured mass/decay width
  ⇒ Any way to distinguish these models?
X(3872) Reconstruction

- X(3872) and ψ(2S) fully reconstructed with hadronic decay chain $J/\psi(\mu\mu)\pi\pi$
- Di-muon trigger sample in PbPb collisions at 5 TeV collected by CMS

![Diagram of X(3872) and ψ(2S) decay chains](image)

- Much higher background

- Boosted Decision Tree method is used to optimize the kinematic selections

![Graph of $M_{J/\psi,\pi^+\pi^-}$ vs Candidates/(1 MeV/c^2)](image)
Combinatorial Background Suppression

- Kinematic variables have discrimination power between signal and background, but not very effective

- 5 variables
  - Secondary vertex probability
  - $\pi p_T$ imbalance
  - Slow $\pi p_{T2}$
  - Opening angle between $J/\psi$ and $\pi$: $\Delta R_1$, $\Delta R_2$

- Additional cut on $Q = m_{\mu\mu\pi} - m_{\mu\mu} - m_{\pi\pi}$
Separate Nonprompt Component

- **Inclusive:**
  - ✔ **Prompt** $c$-quark fragmentation
  - ✗ **Nonprompt** $b$-hadron decays

- $l_{xy}$
  - Pseudo-proper decay length
  - Separate nonprompt with $l_{xy}$

\[
l_{xy} = \frac{L_{xy} \cdot m}{|p_T|}
\]
b-enrich Method

- **Inclusive:**
  - ✔ **Prompt** $c$-quark fragmentation
  - ✗ **Nonprompt** $b$-hadron decays

- **b-enriched sample:**
  - Pure nonprompt in $l_{xy} > 0.1$ mm
b-enrich Method

- **Inclusive**:
  - ✔ Prompt $c$-quark fragmentation
  - ✗ Nonprompt $b$-hadron decays

- **b-enriched sample**:
  - ➡ Pure nonprompt in $l_{xy} > 0.1\text{ mm}$
  - ➡ Cross-check with $l_{xy}$ template fit

![Graph showing CMS inclusive data and b-enriched (l$_{xy}$ > 0.1 mm) data with fits and pull values.](image-url)

PRL 128 (2022) 032001
Result: $X(3872)$ in PbPb

\[
R_{AA} = \frac{N_{pp} X(3872)}{N_{pp} X(3872)} = \frac{\rho_{PbPb}}{\rho_{pp}} \cdot \frac{N_{PbPb} \psi(2S)}{N_{pp} \psi(2S)}
\]

- Measure $\rho = N_{X(3872)} / N_{\psi(2S)}$ to cancel some uncert.
  ➡ $\rho_{PbPb} > \rho_{pp}$ does not mean $X(3872)$ enhanced in PbPb compared to pp
  ➡ $\psi(2S)$ as reference modified in PbPb

```
arXiv:2102.13048
```
Result: X(3872) in PbPb

\[ R_{AA}^{X(3872)} = \frac{N_{PbPb}^{X(3872)}}{N_{pp}^{X(3872)}} = \frac{\rho_{PbPb}}{\rho_{pp}} \cdot R_{AA}^{\psi(2S)} \approx 1.08 \]

PbPb 368 \mu b^{-1}, pp 28.0 pb^{-1} (5.02 TeV)

CMS


Prompt \psi(2S)

\[ R_{AA}^{\psi(2S)} \approx 0.1 \]

CMS

1.7 nb^{-1} (PbPb 5.02 TeV)

\[ \rho_{PbPb}^{PbPb} = 1.08 \]

\[ \rho_{PbPb} \approx 0.1 \]
pp vs. Theoretical Models

Prompt $X(3872)/\psi(2S)$ vs. multiplicity in pp

- Comparison to comover interaction model supports tetraquark interpretation
Theoretical calculations for PbPb (IV)

- AMPT transport model
- TAMU transport model

- Both models predict yields increasing vs. multiplicity
- Strong effect from coalescence

$N_{\text{High-multiplicity}} > N_{\text{Low-multiplicity}}$

$N_{\text{Low-multiplicity}} < N_{\text{High-multiplicity}}$

Jing Wang (MIT), CMS Charm Hadronization, Quark Matter (Kraków, Poland), 2022.4.7
Theoretical calculations for PbPb (V)

AMPT transport model

TAMU transport model

\[ N_{\text{Molecule}} > N_{\text{Tetraquark}} \]

\[ N_{\text{Molecule}} < N_{\text{Tetraquark}} \]

• Disagreement between theoretical models

PRL 126 (2021) 012301

arXiv:2006.09945
Have Some Fun with Heavy Flavors!

Heavy Flavor Measurement Compilation Tool

Observable: RAA $\pm$ vs. $p_T$ $\pm$

X-axis range: 0 0 - 40 0 Log x

Y-axis range: 0 0 - 1.5 0 Log y

Clear all Random color Checked only

e.g. open, baryon, lepton

- Prompt $D^0$ AuAu 200 GeV STAR 0-10% $|y| < 1$
- Prompt $D^0$ AuAu 200 GeV STAR 10-40% $|y| < 1$
- Prompt $D^0$ AuAu 200 GeV STAR 40-80% $|y| < 1$
- Prompt $D^0$ PbPb 5.02 TeV ALICE 0-10% $|y| < 0.5$
- Prompt $D^0$ PbPb 5.02 TeV ALICE 10-40% $|y| < 0.5$
- Prompt $D^0$ PbPb 5.02 TeV ALICE 40-80% $|y| < 0.5$
- Prompt $D^0$ PbPb 5.02 TeV CMS 0-100% $|y| < 1$
- Prompt $D^0$ PbPb 5.02 TeV CMS 10-100% $|y| < 1$

https://boundino.github.io/hinHFplot/
CMS Phase-2 upgrades for HL-LHC

Table 1: Main features of CMS detector at present and Phase 2 upgrades.

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>CMS present</th>
<th>CMS Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Tracker</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>Low-granularity</td>
<td>High-granularity end-cap with silicon sensors</td>
</tr>
<tr>
<td>Muon detector</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>L1 trigger bandwidth</td>
<td>30 kHz for PbPb, 100 kHz for pp and pPb</td>
<td>750 kHz (pass through all PbPb events)</td>
</tr>
<tr>
<td>DAQ throughput</td>
<td>6 GB/s</td>
<td>60 GB/s</td>
</tr>
<tr>
<td>Time-of-flight for Particle ID</td>
<td>N/A</td>
<td><strong>MTD for charged hadron</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>**PID over $</td>
</tr>
</tbody>
</table>

- New **MIP Timing Detector (MTD) for TOF-PID!**
- Unique PID up to $|\eta| = 3$

Precision determination of the arrival time of the signal
CMS MIP Timing Detector (MTD)

- Large acceptance
  - Barrel Timing Layer (BTL): $|\eta| < 1.5$
  - End-cap Timing Layer (ETL): $1.6 < |\eta| < 3$
- Serve as TOF detector for hadron particle identification
- Time resolution 30-40 ps

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$r$ (m)</th>
<th>$\sigma_T$ (ps)</th>
<th>$r/\sigma_T$ ($\times100$) (m $\times$ ps$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR-TOF</td>
<td>2.2</td>
<td>80</td>
<td>2.75</td>
</tr>
<tr>
<td>ALICE-TOF</td>
<td>3.7</td>
<td>56</td>
<td>6.6</td>
</tr>
<tr>
<td>CMS-MTD</td>
<td>1.16</td>
<td>30</td>
<td>3.87</td>
</tr>
</tbody>
</table>
CMS MIP Timing Detector (MTD)

Separation Power vs. kinematic phase space

- CMS MTD brings complementarity and uniqueness in PID

CMS MTD ($|\eta| < 3$) vs. ALICE: mid-rapidity ($|\eta| < 0.9$)
LHCb: forward ($2 < \eta < 5$)
MTD Impact on HF hadron reconstruction

- Significant improvement of signal to background ratio with PID information from MTD

**Without MTD**

**CMS 1 year of Run 4**

**With MTD**

CERN-LHCC-2019-003
MTD Impact on HF hadron reconstruction

\[ \Lambda_c \rightarrow pK\pi \]

- More significant improvement for \( \Lambda_c \) (3 daughters) with PID information from MTD
- Enable new probes e.g. \( B^+ \rightarrow D\pi \rightarrow K\pi\pi \)

\[ D^0 \rightarrow K\pi \]

\[ \Lambda_c \] BKG rejection with MTD, \( \sigma_T=30 \) ps

\[ D^0 \] BKG rejection with MTD, \( \sigma_T=30 \) ps
\( \Lambda_c \) Azimuthal Anisotropy \( v_2 \)

- High-precision measurements of \( D^0 \) \( v_2 \) down to 0 \( p_T \) with MTD
- MTD allows measurements of \( \Lambda_c \) \( v_2 \) down to 1 GeV
- Test of the \( n_q \) scaling universalness in the charm sector

(CERN-LHCC-2019-003)
Wide Rapidity Coverage of $\Lambda_{c}/D^0$ (PbPb)

- Unique capability of CMS due to the large inner tracker and MTD acceptance
- Capability to access low $p_T$ (down to 0) \(\Rightarrow\) Total charm cross-section
- Except for Langevin+CLVisc, other models shown assume boost invariant in the longitudinal direction
  \(\Rightarrow\) Provide the strongest constraint on the heavy quark hadronization mechanism

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Jing Wang (MIT), Future Opportunities with CMS, HF Workshop (ECT*, Trento)
CMS Phase-2 Upgrades

HL-LHC: CMS will be the most comprehensive QGP detector

<table>
<thead>
<tr>
<th></th>
<th>Wide-coverage Tracking</th>
<th>Precision Vertexing</th>
<th>Full Calorimetry</th>
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</table>

- High precision production and flow in large and small systems with detector upgrade and HL-LHC
  ➤ Hot and cold nuclear matter effects, wider kinematics and more differential

- New MTD leads to unprecedented precision of D mesons and Λ_c down to 0 p_T
  ➤ Also enable new observables (photon-D correlation, D-Ā correlation)

- Wide rapidity coverage (|η| < 4) provides new access to study of longitudinal dynamics
  ➤ Full 3+1D heavy quark dynamics in QGP medium
Charm Meson $v_2$ in PbPb

- Observe non-zero $D^0$ $v_2$
- Smaller $D^0$ $v_2$ than light flavor hadrons
  ➡ Charm quarks not fully thermalized
  ➡ Still remember their own properties

$v_2$ for different flavors

PbPb (5.02 TeV)

PLB 816 (2021) 136253
JHEP 1809 (2018) 006