New opportunities in HI physics at HL-LHC with a MIP Timing Detector at CMS

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on behalf of the CMS Collaboration

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Ultra-relativistic Nucleus-Nucleus Collisions
• Successful HI program at LHC: Pb-Pb, Xe-Xe and p-Pb, with all 4 main LHC experiments participating.

• By the end of Run 3+4, we expect an increase of 5-7x HI data.

• CMS major upgrade for High Luminosity LHC will bring new opportunities for the HI programme.
CMS Phase 2 upgrades for HL-LHC

- Trigger / HLT / DAQ
- Barrel Calorimeters
- New Endcap Calorimeters
- Muon Systems
- New Tracker
- New MIP Timing Detector
CMS Phase 2 upgrades for HL-LHC

- **Trigger / HLT / DAQ**
- **Muon Systems**
  - Radiation tolerance
  - High granularity
- **Barrel Calorimeters**
  - Replace FE/BE electronics
- **New Endcap Calorimeters**
- **New Tracker**
- **New MIP Timing Detector**
CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ

Barrel Calorimeters

Muon Systems
• $|\eta| < 2.4 \rightarrow |\eta| < 3.0$

New Endcap Calorimeters

New Tracker
• Radiation tolerance
• High granularity
• $|\eta| < 2.4 \rightarrow |\eta| < 4.0$

New MIP Timing Detector
CMS Phase 2 upgrades for HL-LHC

**Trigger / HLT / DAQ**
- Track info. in L1
- L1/HLT rate x7.5
- DAQ: 6 $\rightarrow$ 60 GB/s

**Muon Systems**

**Barrel Calorimeters**

**New Endcap Calorimeters**

**New Tracker**

**New MIP Timing Detector**
CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ

Barrel Calorimeters

New Endcap Calorimeters

Muon Systems

New Tracker

New MIP Timing Detector
- Precision timing
- $|\eta| < 3.0$
Conceptual design
CMS MIP Timing Detector (MTD)

• One barrel section (BTL) and two end-cap disks (ETL).
• Coverage for tracks: $p > 0.7$ GeV at $|\eta| < 3.0$, and time resolution: $\sim 30$ ps
• Installation planned for HL-LHC: 2022 for BTL and 2024 for ETL.
Barrel Timing Layer (BTL)

Design:

- 72 trays covering a surface of \(\sim 38 \text{ m}^2\)
- Material budget: < 0.4 \(X_0\)
- Rapidity coverage: \(|\eta| < 1.5\)
- Timing resolution: \(\sim 30 \text{ ps}\)

Sensors:

- **L(Y)SO:Ce crystal** bars as scintillator:
  - Excellent radiation tolerance, high signal and fast response time.
- **Silicon Photomultipliers** as detectors:
  - Compact, fast and insensitive to magnetic fields.
Endcap Timing Layer (ETL)

Design:

- 2 disks covering a surface of ~14 m²
- Material budget: < 0.2 $X_0$
- Rapidity coverage: $1.6 < |\eta| < 3.0$
- x10 higher radiation level than BTL
- Timing resolution: ~ 30-50 ps

Sensors:

- **Ultra fast silicon detectors:**
  - Low gain avalanche diodes optimised for precision timing.
Applications and performance
Applications of CMS MTD

- Time compatibility for track-vertex association:
  - Suppress impact of pile-up in pp collisions.

- 4D vertex reconstruction:
  - Improved reconstruction of displaced products (B decays) or long-lived particles (BSM).

- Measurement of velocity of low $p_T$ hadrons:
  - Particle identification via Time-of-Flight (TOF) of charged hadrons ($\pi$, K, p) down to $p = 0.8$ GeV.

![CMS Simulation](image1.png)

![CMS Simulation](image2.png)
• Clear identification of π/K up to p ~ 2.5 GeV and p/K up to p ~ 5 GeV.
• Hermetic coverage over |η| < 3
TOF-PID comparison with ALICE and STAR

- Competitive momentum coverage compared to ALICE and STAR
- Unique wider rapidity coverage

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\eta$ coverage</th>
<th>$L$ at $\eta = 0$ (m)</th>
<th>$\sigma_T$ (ps)</th>
<th>$L/\sigma_T \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 3.0$</td>
<td>1.16</td>
</tr>
<tr>
<td>ALICE</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 0.9$</td>
<td>3.7</td>
</tr>
<tr>
<td>STAR</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 0.9$</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Physics impact
Heavy quark dynamics in QGP

- CMS will be able to study c- and b-hadrons over 6 units of rapidity (|η| < 3) with MTD.
- Measurements of the production yield and correlation will constrain the 3D HF dynamics in QGP.
CMS HL upgrades + MTD provides a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.
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Universal scaling of elliptic flow

• MTD will allow to derive the $v_2$ of charm baryons and to measure precisely the $N_q$-scaling of $v_2$ in the charm quark sector:

$$v_2(\Lambda_c) = \frac{3}{2} v_2(D^0)?$$
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Origin of collectivity in small systems

CMS Preliminary

$\text{pPb} \, 186 \, \text{nb}^{-1} \,(8.16 \, \text{TeV})$

- Collect more data by triggering on high MIP-multiplicity with MTD.
- Reduce the HF background using TOF-PID, allowing to measure $v_2$ down to very low $p_T$ for a variety of HF hadrons in small systems.

CMS-PAS-HIN-19-009

Initial-state collectivity (initial color fields)
Final-state collectivity: (“geometry” + rescatterings)

Small systems (pp, pA, dA, etc.)
Large systems (PbPb, AuAu)

Probes:

- Heavy (b, c, J/ψ)
- Light (π, K, p, Λ, Ξ, Ω, ...)

"geometry" "Pre-equilibrium"
Origin of collectivity in small systems

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Heavy (b, c, J/$\psi$)
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CMS-PAS-HIN-19-009
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- Collect more data by triggering on high MIP-multiplicity with MTD.
- Reduce the HF background using TOF-PID, allowing to measure $v_2$ down to very low $p_T$ for a variety of HF hadrons in small systems.
• Light (d, $^3$He, t) and hyper ($^3$He, $^3$H) nuclei can be identified over a wide kinematic range via TOF using MTD.

• Also provide insights for dark matter searches and astrophysics.
Light (hyper-) nuclei production

- Light (d, $^3$He, t) and hyper ($^3\Lambda$He, $^3\Lambda$H) nuclei can be identified over a wide kinematic range via TOF using MTD.
- Also provide insights for dark matter searches and astrophysics.
SUMMARY

CMS will add a new precise MIP timing detector for HL-LHC
For more details check: CERN-LHCC-2017-027

MTD will bring a completely new capability to CMS: particle identification via time-of-flight

High impact on CMS Heavy Ion physics program:
• Heavy quark dynamics in QGP → D $p_T > 0$ GeV and $\Lambda_C$ $p_T > 3$ GeV
• QGP response to parton energy loss
• Universal scaling of elliptic flow
• Origin of collectivity in small systems
• Light (hyper-) nuclei physics
• …. among other topics
Thank you for your attention!
Acknowledgement
BACKUP
• LYSO:Ce crystal bar size: 3 x 3 x 50 mm³ and time resolution: ~30 ps.
• LYSO:Ce optimal due to their high light yield (40k photons/MeV), fast scintillation rise time (<100 ps) and short decay time (~40 ns). Also, the light wavelength (420 nm) matches the sensitive range of SiPMs.
Ultra Fast Silicon Detector

- LGAD sensor pixel size: 1.3 x 1.3 mm\(^2\) and time resolution: 30-50 ps.
- Extra \(p\)-type implant near the \(n\)-electrode generates a large electric field, resulting in an electron-avalanche effect that offers a gain factor of 10-30.
- Additional gain allows to extract signals with thinner pixels (depths of 30-50 \(\mu m\)), resulting in: low noise, large slew-rate and fast rising pulse.
Impact of radiation damage

- **BTL**: Radiation damage leads to worse time resolution up to 60 ps by the end of Run 4. Dominated by the dark count rate (DCR) noise of SiPMs.
- **ETL**: The UFSD is also affected by radiation dose, however the time resolution can be recovered by increasing the bias voltage.
• Can be studied experimentally by measuring the higher cumulants of net strangeness or baryon number ($\kappa_n$).

• The PID capabilities of MTD allows to measure the net kaon and proton cumulants in a **wide rapidity range**, directly testing the lattice QCD calculations at LHC energies.
### Preliminary proposal of future HI runs

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Pb–Pb 5.5 TeV</td>
<td>3 weeks</td>
<td>$2.3 \text{ nb}^{-1}$</td>
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<td></td>
<td>pp 5.5 TeV</td>
<td>1 week</td>
<td>$3 \text{ pb}^{-1}$ (ALICE), 300 $\text{ pb}^{-1}$ (ATLAS, CMS), 25 $\text{ pb}^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2022</td>
<td>Pb–Pb 5.5 TeV</td>
<td>5 weeks</td>
<td>$3.9 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>O–O, p–O</td>
<td>1 week</td>
<td>$500 \mu\text{b}^{-1}$ and 200 $\mu\text{b}^{-1}$</td>
</tr>
<tr>
<td>2023</td>
<td>p–Pb 8.8 TeV</td>
<td>3 weeks</td>
<td>$0.6 \text{ pb}^{-1}$ (ATLAS, CMS), 0.3 $\text{ pb}^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td>pp 8.8 TeV</td>
<td>few days</td>
<td>$1.5 \text{ pb}^{-1}$ (ALICE), 100 $\text{ pb}^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2027</td>
<td>Pb–Pb 5.5 TeV</td>
<td>5 weeks</td>
<td>$3.8 \text{ nb}^{-1}$</td>
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<td>2028</td>
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<td>few days</td>
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</tr>
<tr>
<td>2029</td>
<td>Pb–Pb 5.5 TeV</td>
<td>4 weeks</td>
<td>$3 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td>Run-5</td>
<td>Intermediate AA</td>
<td>11 weeks</td>
<td>e.g. Ar–Ar 3–9 $\text{ pb}^{-1}$ (optimal species to be defined)</td>
</tr>
<tr>
<td></td>
<td>pp reference</td>
<td>1 week</td>
<td></td>
</tr>
</tbody>
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CERN-LPCC-2018-07
CMS Detector

Muon acceptance: $|\eta| < 2.4$

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Dashed Green: Neutral Hadron (e.g., Neutron)
- Blue dots: Photon

Transverse slice through CMS
- 4T
- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid

Iron return yoke interspersed with Muon chambers