CMS Heavy Ion Physics

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- Hadronic Collisions
  - Quarkonia Production
  - Jet Collisions
- Coherent Interactions
Why HI at LHC
Jurgen Shukraft, Quark Matter 2001

Pb+Pb, central collisions (b=0)

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>RHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dN_{ch}/dy$</td>
<td>500</td>
<td>800</td>
<td>3000</td>
</tr>
<tr>
<td>$V_f(Km^3)$</td>
<td>1</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>$\varepsilon (GeV/Km^3)$</td>
<td>2.5</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>$\tau_{QGP} (fm/c)$</td>
<td>1</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>$\tau_0 (fm/c)$</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Bigger
Hotter
Longer

Before

After

Pb+Pb, central collisions (b=0)
J/ψ Melting

NA50 Collaboration, CERN

L(fm): Average distance travel by the J/ψ inside nuclear matter.


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Quarkonia Acceptance in CMS $\mu$–Chambers

**$\psi$ at CMS**
- CMS: $\psi$ mainly $p_T > 5$ GeV with barrel, due to $\mu$ cutoff.
- ALICE: $\eta > 2.5$ with $\mu$
- ATLAS (if they do HI) lower acceptance due to higher $\mu$ $p_T$ cutoff.

**Upsilon at CMS**
- Full Detector
- Barrel

$\psi$ acceptance:
- $10\%$

$\Upsilon$ acceptance:
- $20\%$

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Quarkonia Reconstruction

- **Essential sub-detectors:**
  - Tracking devices
  - Muon system

- **Pessimistic assumptions for background estimates:**
  - $dN_{ch}/dy=8000$ (most generators < 5500)
  - $<p_t>_{\pi}=0.48$ GeV/c (HIJING 0.39 GeV/c)
  - $<p_t>_{K}=0.67$ GeV/c

- **Special Heavy Ion Tracking Algorithm**
  - Significant Muon background from $\pi$ and $K$ decays
**J/Ψ Signal**

1 month running at top Luminosity:
J/Ψ's detected and reconstructed in the Barrel:

### Pb-Pb

- **# events/25 MeV/c²**
- **Ψ/cont. = 1.0**
- **L = 10^{27} cm² s⁻¹**

### Ca-Ca

- **# events/25 MeV/c²**
- **Ψ/cont. = 9.7**
- **L = 2.5 \times 10^{29} cm² s⁻¹**

**Ca-Ca**

- **# \textit{J/Ψ}**
  - Pb-Pb: 2.2 \times 10^5
  - Ca-Ca: \textbf{9.7}

**S/B**

- Pb-Pb: 1.0
- Ca-Ca: 9.7

ALICE: ~2K events with μs

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Upsilon in Pb-Pb

1 month: 22000 $\Upsilon$ and 7500 $\Upsilon'$ detected in the barrel

L = $10^{27}$ cm$^{-2}$ s$^{-1}$

Upsilon/cont. = 1.6

Total

Decay-Decay

Decay-b

b-b

Decay-c

c-c

Opposite-sign di-muon Invariant Mass (GeV/c$^2$)

Background contributions

Combinatorial background subtracted after reconstruction

# Events/25 MeV/c$^2$

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Upsilon in Ca-Ca

L = 2.5 $10^{29}$ cm$^{-2}$s$^{-1}$

Upsilon/cont. = 9.4

- 1 month:
  - 340000 $\Upsilon$
  - 115000 $\Upsilon'$
  - Only barrel used.
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Upsilon' / Upsilon ratio as a Thermometer
(Ramona Vogt)
Quarkonia Reference

- At SPS, $J/\Psi$ is compared to Drell-Yan.
- At LHC Drell-Yan contribution is negligible.
- $Z^0$ proposed as reference to $\Upsilon$ production.
  - $\Delta M_Z > M_\Upsilon$
  - Different production mechanisms:
    - $Z_0$: antiquark-quark, quark-gluon and antiquark-gluon.
    - $\Upsilon$: gluon-gluon.
- Cross check di-muon reconstruction algorithm.
Jet Quenching

- Large $p_T$ quarks affected by hot hadronic media
- Jets at RHIC buried in low $p_T$ background
- Look at particle $p_T$ spectrum
Jets at LHC are Easy for High Multiplicity PbPb

Jet quenching

- monojet/dijet enhancement
- \( \text{jet} - Z^0 \rightarrow \mu\mu \text{ or } \text{jet} - \gamma \)

\[ dN_{\text{ch}}/dy = 8000 \]

Jet Finding

- \( 100 \text{ GeV } E_T \)
- \( \varepsilon \approx 100\% \)
- \( \sigma(E_T)/E_T = 11.6\% \)

\[ \text{Pt}(Z) = \text{Et(Jet)} = 100 \text{ GeV} \]
Balancing Photons and Jets

- $E_T^{\text{jet}} \gamma > 120$ GeV in the barrel
- 1 month:
  - ▲ 900 events for Pb-Pb
  - ▲ $10^4$ events for Ca-Ca

2 weeks at
$L = 10^{27}$ cm$^{-2}$s$^{-1}$

$2\text{ weeks at}$

$\gamma/\pi^0 - E_T^{\text{Jet}}$ (GeV)
Ultra Peripheral Collisions
(Coherent Interactions)

A \rightarrow \gamma \text{ or } P \rightarrow \gamma \text{ or } P \rightarrow A

- Low $p_T$
- Low Energy
  - ▲ CERN SPS
  - ▲ RHIC
  - ▲ CERN LHC

$p_T < 1/R \approx 50$ MeV
$E_{CM}^{Max} < \sqrt{s}/R$
- $E_{CM}^{Max} = 0.5$ GeV
- $E_{CM}^{Max} = 6$ GeV • Detected
- $E_{CM}^{Max} = 160$ GeV
STAR Ultra-Peripheral Event  
(DNP 2000)  
\[ \text{AuAu} \rightarrow \gamma P \ (\gamma \text{Au}) \rightarrow \rho \rightarrow \pi \pi \] 
Trigger: Low multiplicity and zero energy at Zero Degree Calorimeter (ZDC)
**γγ Physics**

- Mainly studied at $e^+e^-$ colliders. Typically $\pi^0 < m_{\gamma\gamma} < \eta_c$. $\sigma_{\text{tot}}$ up to 70 GeV by LEP.

- Non perturbative QED, coupling $Z^2$.

- **New Physics:**
  - ▲ Standard Model H production marginal for HI
  - ▲ Any exotic particle coupling to $\gamma\gamma$.
  - ▲ Supersymmetric Higgs for some areas of parameters space.

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**$e^+e^-$ Cross Sections**

<table>
<thead>
<tr>
<th>$E_{\text{thr}}$ (GeV)</th>
<th>$\sigma$ (Pb+Pb) (barn)</th>
<th>$\sigma$ (Ca+Ca) (barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1,500</td>
<td>5.5</td>
</tr>
<tr>
<td>1.0</td>
<td>500</td>
<td>1.8</td>
</tr>
<tr>
<td>5.0</td>
<td>30</td>
<td>0.1</td>
</tr>
</tbody>
</table>

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Ultra-Peripheral Collisions

\[ \gamma \gamma \text{ Cross Sections} \]

Meson or lepton/quark pair

\[ \sigma_{AA}(M) \text{ (barn)} \]

\[ \sigma_{AA}(M) \text{ (barn/GeV)} \]

\[ \text{events/sec} \]

\[ \text{events/year} \]

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Light quark: Difficult at CMS because of low $p_T$, challenge for triggering, unless a multiplicity trigger is used.

<table>
<thead>
<tr>
<th>State</th>
<th>Mass, MeV</th>
<th>$\Gamma_{\gamma\gamma}$, keV</th>
<th>$\sigma(AA \to AA + X)$, PbPb</th>
<th>$\sigma(AA \to AA + X)$, CaCa</th>
<th>Events for $10^6$ sec, PbPb</th>
<th>Events for $10^6$ sec, CaCa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta'$</td>
<td>958</td>
<td>4.2</td>
<td>22 mb</td>
<td>125 $\mu$b</td>
<td>$2.2 \times 10^3$</td>
<td>$5.0 \times 10^3$</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>2981</td>
<td>7.5</td>
<td>590 $\mu$b</td>
<td>3.8 $\mu$b</td>
<td>$5.9 \times 10^4$</td>
<td>$1.5 \times 10^7$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>3415</td>
<td>3.3</td>
<td>160 $\mu$b</td>
<td>1.0 $\mu$b</td>
<td>$1.6 \times 10^4$</td>
<td>$4.0 \times 10^6$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>3556</td>
<td>0.8</td>
<td>160 $\mu$b</td>
<td>1.0 $\mu$b</td>
<td>$1.6 \times 10^4$</td>
<td>$4.0 \times 10^6$</td>
</tr>
<tr>
<td>$\gamma\gamma \to X$</td>
<td>2950</td>
<td>–</td>
<td>1.4 mb</td>
<td>9.0 $\mu$b</td>
<td>$1.4 \times 10^5$</td>
<td>$3.6 \times 10^7$</td>
</tr>
<tr>
<td>$\eta_b$</td>
<td>9366</td>
<td>0.43</td>
<td>370 nb</td>
<td>3.0 nb</td>
<td>37</td>
<td>12000</td>
</tr>
<tr>
<td>$\chi_{b0}$</td>
<td>9860</td>
<td>$2.5 \times 10^{-2}$</td>
<td>18 nb</td>
<td>0.14 nb</td>
<td>2</td>
<td>560</td>
</tr>
<tr>
<td>$\chi_{b1}$</td>
<td>9913</td>
<td>$6.7 \times 10^{-3}$</td>
<td>23 nb</td>
<td>0.19 nb</td>
<td>2</td>
<td>760</td>
</tr>
<tr>
<td>$\gamma\gamma \to X$</td>
<td>9400</td>
<td>–</td>
<td>140 $\mu$b</td>
<td>1.0 $\mu$b</td>
<td>$1.4 \times 10^4$</td>
<td>$4.0 \times 10^6$</td>
</tr>
</tbody>
</table>

Heavy quark spectroscopy. Very large numbers expected.
Photon Nucleus ($\gamma A$)

- $\gamma p$ studied in HERA: $W_{\gamma p} < 200$ GeV
- $\gamma A$ at LHC: $W_{\gamma p} < 900$ GeV
- Vector meson production: $\gamma p (A) \rightarrow V p (A)$, $V=\rho, \omega, \phi, J/\Psi$
  - Very large rates, for example $>10^4$ Hz $\phi$ in Ca-Ca
  - Interface QCD and hadronic physics
  - LHC will be a meson factory. Competitive with other meson factories like $\phi$ factory at Frascatti (CP, QM tests, etc).
  - Can CMS trigger on these events. Clean events with only a few tracks.
Conclusions

- CMS is provides unique tools to study Heavy Ion Collisions at LHC.
- Some physics topics:
  - Quarkonium production: \( \Upsilon \) and J/\( \Psi \) families.
  - Jet quenching.
  - Ultra-Peripheral collisions.
Addendum: Tracking

- Developed for \( dN^\text{ch}/dy = 8000 \) and \( dN^0/\text{dy} = 4000 \).
- Track only particles with tracks in \( \mu \) detector.
- Use \( \mu \)-chambers tracks as seeds.
- Use only tracking detector providing 3D space points.

Detector Pitch \( \mu \)m

- MSGC 200
- MSGC 240
- Silicon 147

Occupancy (%)

Radius of MSGC layer (cm)
Interference

- **Nuclei can emit or scatter** pair
  - two indistinguishable possibilities

- **Amplitudes add**
  - Vector meson has negative parity
    - $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
    - Destructive interference when $p_T << 1/b$