Overview of CMS and ATLAS results

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Heavy ion collisions

Different collision systems, different information

- **PbPb**: hot medium effects (quark-gluon plasma)
- **pPb**: cold nuclear effects (initial state, nuclear absorption, energy loss)
- **pp**: reference (“nucleons in vacuum”) at the same $\sqrt{s}$

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>$\sqrt{s_{NN}}$ [TeV]</th>
<th>Luminosity (CMS)</th>
<th>Lumi. $\times A^{(2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>PbPb</td>
<td>2.76</td>
<td>150 $\mu$b$^{-1}$</td>
<td>6.5 pb$^{-1}$</td>
</tr>
<tr>
<td>2013</td>
<td>pPb</td>
<td>5.02</td>
<td>30 nb$^{-1}$</td>
<td>6.2 pb$^{-1}$</td>
</tr>
<tr>
<td>2013</td>
<td>pp</td>
<td>2.76</td>
<td>5 pb$^{-1}$</td>
<td>5 pb$^{-1}$</td>
</tr>
<tr>
<td>2015</td>
<td>pp</td>
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<td>30 pb$^{-1}$</td>
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</tr>
<tr>
<td>2015</td>
<td>PbPb</td>
<td>5.02</td>
<td>400 $\mu$b$^{-1}$</td>
<td>17 pb$^{-1}$</td>
</tr>
<tr>
<td>2016</td>
<td>pPb</td>
<td>8.16</td>
<td>170 nb$^{-1}$</td>
<td>35 pb$^{-1}$</td>
</tr>
<tr>
<td>2017</td>
<td>XeXe</td>
<td>5.44</td>
<td>3.4 $\mu$b$^{-1}$</td>
<td>0.058 pb$^{-1}$</td>
</tr>
<tr>
<td>2017</td>
<td>pp</td>
<td>5.02</td>
<td>320 pb$^{-1}$</td>
<td>320 pb$^{-1}$</td>
</tr>
<tr>
<td>2018</td>
<td>PbPb</td>
<td>5.02</td>
<td>1.8 nb$^{-1}$</td>
<td>78 pb$^{-1}$</td>
</tr>
</tbody>
</table>

Run2: higher $\sqrt{s_{NN}}$, larger datasets
Isolated photons in pPb

- Nuclear modification factor of photons
- Sensitive to nuclear PDFs and initial state energy loss
  - Also modification because of different quark content (up / down) in the nucleus

- The data disfavour a large amount of energy loss
- Constraints on nPDFs
Dijets in pPb

- Saturation at low $x_{\text{Pb}}$ ($10^{-4}–10^{-3}$)?
- No broadening of azimuthal angular correlations for dijets in pPb
Dijets in pPb

- Saturation at low $x_{Pb}$ ($10^{-4} - 10^{-3}$)?
  - No broadening of azimuthal angular correlations for dijets in pPb
- Strong constraints on gluon nPDFs: shadowing, anti-shadowing, EMC
  - dijet $\eta \leftrightarrow x_{Pb}$
  - $p_T \leftrightarrow$ scale $Q^2$
  - imperfect modelling in pp $\rightarrow$ data-driven pp reference

**ATLAS**

- $c_{12} [\text{rad}]$

**CMS**

- $p_{T} [\text{GeV}]$

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**ATLAS-CMS overview**

LHCb-HI 2019 4 / 26
Forward jets in pPb

Forward: $-6.6 < \eta < -5.2$: $x_{Pb} \approx 10^{-6}$

Saturation models do not describe the data

None of the models describe pPb / Pbp well
Photonuclear jets in pPb

- Selecting $\gamma$Pb interactions using ZDC + rapidity gaps
- Comparison with PYTHIA ($\gamma$ spectrum reweighted to STARLIGHT)
- Sensitivity to nPDF
W bosons are sensitive to isospin effects (up vs down quarks)

- \( \eta_{CM} < 0 \) (Pb-going, large \( x_{Pb} \)): data agrees with both PDF and nPDF
  - slight anti-shadowing at \( x_{Pb} \approx 10^{-1} \)
- \( \eta_{CM} > 0 \) (p-going, small \( x_{Pb} \)): data favors nPDF
  - significant shadowing at \( x_{Pb} \approx 10^{-3} \)
  - consistent with EPPS16, exclude CT14 (free nucleon PDF)
Electroweak bosons in PbPb

- Data systematically higher than nPDF models
- Peripheral data: smaller experimental uncertainties than Glauber

- Non-flat centrality dependence
  - Not captured by different Glauber parameters
  - Not captured by neutron skin model
  - Opposite trend compared to HG-Pythia (selection bias, reproduces hadron $R_{AA}$)

- Then... what??

\[ \begin{align*}
\langle T_{AA} \rangle & \equiv \frac{1}{N_{\text{evt}}} \sum_{\text{evt}} \frac{dN}{d|\eta|} \\
\text{Data} & \quad \text{CT14} \\
\text{EPPS16} & \\
\text{nCTEQ15} & \\
\text{Pred.} & \\
\text{Data} & \quad \text{HG-Pythia (isospin corrected)}
\end{align*} \]
Electroweak bosons in PbPb

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![Graph showing the data systematically higher than nPDF models](arXiv:1907.10414)

![Graph showing peripheral data with smaller experimental uncertainties than Glauber](arXiv:1907.10414)

![Graph showing non-flat centrality dependence](arXiv:1907.10414)
Top quarks in pPb

First top quark observation in heavy ion collisions!

- $\ell + \text{jets}$ channel (electron and muon)
- Fitting the $W \rightarrow jj$ mass in the different b-jet and lepton flavour categories
- Measurement in agreement with pQCD + nPDF expectations
Quarkonia in pPb

**pPb: nPDF, energy loss, final state interactions?** (excited states vs ground states)

- $p_T$ and $y$ dependent suppression of all 5 $S$-wave quarkonium states
- Excited states are more suppressed than the ground state
- Event activity dependence?

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**Figure:**
- **Top Left:** $R_{pPb}$ vs $p_T$ for ATLAS and CMS, with CMS data showing $p_{T_p} < 10$ GeV/c.
- **Top Center:** CMS data for prompt $\psi(2S)$ with $6.5 < p_T < 10$ GeV/c.
- **Top Right:** CMS data for prompt $J/\psi$ with various $|y|$.
Quarkonia: puzzles in small systems

- Prompt $J/\psi$ fragmentation not well modeled in PYTHIA

![Graph showing data and PYTHIA predictions for $J/\psi$ production in pp collisions.](image)
Quarkonia: puzzles in small systems

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- Sensitivity to LDMEs
Quarkonia: puzzles in small systems

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- Sensitivity to LDMEs
- Υ(nS) vs multiplicity: several studies
  - Similar trend in pp, pPb, PbPb
Quarkonia: puzzles in small systems

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  - Similar trend in pp, pPb, PbPb
  - Not related to local track multiplicity
  - No dependence of polarisation
Quarkonia flow in pPb and PbPb

Non-zero $v_2$ in PbPb... but also in pPb!

**ATLAS**
- ATLAS, Prompt J/$\psi$, 5.02 TeV, $|y| < 2$, 0 - 60%
- ALICE, Inclusive J/$\psi$, 5.02 TeV, 2.5 < $y$ < 4, 20 - 40%
- CMS, Prompt J/$\psi$, 2.76 TeV, 1.6 < $|y|$ < 2.4, 10 - 60%
- CMS, Prompt J/$\psi$, 2.76 TeV, $|y|$ < 2.4, 10 - 60%

**CMS**
- Prompt J/$\psi$,
- $K_S^0$,
- $\Lambda$,
- $185 \leq N_{\text{offline}} \leq 250$
Charmonia in PbPb

PbPb: sequential melting (color screening) in the QGP, regeneration at low $p_T$, jet quenching at high $p_T$?

**Champion, E.** (CERN)

**ATLAS-CMS overview**
Charmonia in PbPb

**PbPb**: sequential melting (color screening) in the QGP, regeneration at low $p_T$, jet quenching at high $p_T$?

### Graphs

**Graph 1:**
- **Title**: R$_{AA}$ vs $N_{part}$
- **Data**: PbPb 368 (<30%) / 464 (>30%) μb$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV)
- **Y-axis**: 0 to 1.4
- **X-axis**: 0 to 400
- **Legend**:
  - Prompt J/$\psi$
  - Prompt $\psi$(2S)

**Graph 2:**
- **Title**: Prompt J/$\psi$ vs $p_T$ (GeV/c)
- **Data**: PbPb 368 μb$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV)
- **Y-axis**: 0 to 1.4
- **X-axis**: 0 to 50
- **Legend**:
  - $\sqrt{s_{NN}} = 5.02$ TeV
  - $\sqrt{s_{NN}} = 2.76$ TeV

**Note:**
- |y| < 1.6
- $6.5 < p_T < 30$ GeV/c
- $|y| < 2.4$
- Cent. 0-100%
Bottomonia in PbPb

- No sign of $\Upsilon(3S)$ in PbPb data (2015)
- Agree with models with melting + with or without $\Upsilon$ regenerations
- No rise at high $p_T$

![Graph showing $R_{AA}$ vs $N_{\text{part}}$ for PbPb 368/464 $\mu$b$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV) and $R_{AA}$ vs $p_T$ for PbPb 368 $\mu$b$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV).]
Open heavy flavour in pPb

- Charm ($D^0$, $D^*$)
- pPb: flavour independence of energy loss at high $p_T$?
- PbPb: charm flows!
- pPb: no large $D^0$ or $D^*$ forward/backward asymmetry

PRL 120 (2018) 202301
Open beauty in PbPb

- High $p_T$: similar suppression for beauty as charm and light
- Medium $p_T$: smaller suppression
Open beauty in PbPb

- High $p_T$: similar suppression for beauty as charm and light
- Medium $p_T$: smaller suppression
- Hint for nonzero $v_2$ for nonprompt $J/\psi$

ATLAS
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \ 0.42 \text{ nb}^{-1} \]
Non-prompt $J/\psi, |y| < 2, 0\% - 60\%$

EPJC 78 (2018) 784

CMS
27.4 pb$^{-1}$ (5.02 TeV pp) + 530 $\mu$b$^{-1}$ (5.02 TeV PbPb)

Global uncertainty

CUJET
EPOS2+MC@sHQ
TAMU
PHSD

Global uncertainty

PRL 123 (2019) 022001

ATLAS-CMS overview
Open beauty in PbPb

- High $p_T$: similar suppression for beauty as charm and light
- Medium $p_T$: smaller suppression
- Hint for nonzero $v_2$ for nonprompt $J/\psi$
- $B_s$ vs $B^+$: hint for strangeness enhancement?

ATLAS

Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV, 0.42 nb$^{-1}$
Non-prompt $J/\psi$, $|y| < 2$, 0 - 60%

CMS

$D^0$ from b hadrons $|y|<1$
$B^\pm$ $|y|<2.4$
$J/\psi$ from b hadrons:
$|y|<2.4$
Global uncertainty

27.4 pb$^{-1}$ (5.02 TeV pp) + 530 µb$^{-1}$ (5.02 TeV PbPb)

ATLAS-CMS overview
EPJC 78 (2018) 784
PLB 796 (2019) 168

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C_{c} in PbPb

Charm quark hadronisation in the QGP

- indication of suppression in PbPb for $p_{T} > 10\text{GeV}$
- Higher suppression in central events
- Similar $\Lambda_{c}/D^{0}$ ratio in pp and PbPb: no significant contribution from coalescence for $p_{T} > 10\text{GeV}$

![Graph showing the ratio of $\Lambda_{c}^{+} + \Lambda_{c}^{-}$ in PbPb compared to pp](image-url)

![Graph showing the ratio $(\Lambda_{c}^{+} + \Lambda_{c}^{-})/(D_{+}^{0} / D_{-}^{0})$ in PbPb compared to pp](image-url)
Suppression of charged particles in $^{129}$Xe data at 5.44 TeV (2017): $R_{AA}$

XeXe: smaller suppression than PbPb at the same centrality

Slightly greater suppression in XeXe at the same $N_{\text{part}}$
Suppression of jets in PbPb collisions

Nuclear modification factor: increases to high $p_T$ and from central to peripheral

$R_{AA}$

**ATLAS** anti-$k_t$ $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV

<table>
<thead>
<tr>
<th>$y$</th>
<th>$p_T$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10%</td>
<td>40 - 900</td>
</tr>
<tr>
<td>20 - 30%</td>
<td>40 - 900</td>
</tr>
<tr>
<td>40 - 50%</td>
<td>40 - 900</td>
</tr>
<tr>
<td>60 - 70%</td>
<td>40 - 900</td>
</tr>
</tbody>
</table>

2015 data: Pb+Pb 0.49 nb$^{-1}$, $pp$ 25 pb$^{-1}$

$\langle T_{AA} \rangle$ and luminosity uncer.
Further understanding of jet quenching

- Jet-hadron correlations in PbPb: fewer high $p_T$ and more low $p_T$ hadrons at large angles
- Enhanced dijet asymmetry in PbPb compared to pp
**Flavour dependence of jet modification in PbPb**

- **Photon-tagged jets:**
  - different modification in central events (enhanced quark jet fraction)
  - impact of the different $p_T$ spectrum?
- **b-jet pairs:**
  - enhanced contribution of primary $b$ quarks
  - compatible behaviour of light and $b$ jets

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**Graphs:**

- **JHEP 03 (2018) 181**
  - Inclusive dijets
  - $\langle x \rangle$ vs $\langle N_{part} \rangle$
  - CMS
  - Data
  - $p_T = 80-126$ GeV
  - $p_T = 63-144$ GeV
  - $\gamma$-tagged jets 5.02 TeV
  - inclusive jets 2.76 TeV

- **CMS**
  - $\langle x \rangle$ vs $\langle N_{part} \rangle$
  - Inclusive dijets
  - $p_T = 80-126$ GeV
  - $p_T = 63-144$ GeV

- **25.8 pb$^{-1}$ (5.02 TeV pp) + 404 $\mu$b$^{-1}$ (5.02 TeV PbPb)**
  - $\langle x \rangle$ vs $\langle N_{part} \rangle$
  - CMS
  - $\gamma$-tagged jets
  - Inclusive dijets
  - $b$ dijets
Jet substructure

- Probing the jet substructure and the medium modification of the parton shower evolution: splitting functions, groomed jet mass
Ultra-peripheral collisions

Very strong EM fields in PbPb collisions: $\gamma\gamma$ collider!

- $\Upsilon(1S)$ photoproduction in pPb collisions: bridging the gap in $W_{\gamma p}$ between HERA and LHCb
- Photon-induced processes also in non-UPC events
Light-by-light scattering

- Precise measurement with 2018 PbPb data
- Interpretation in terms of limits on axion-like particle models

PRL 123 (2019) 052001

ATLAS

\[ \text{Pb+Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

ATLAS

- Data 2018, 1.7 nb⁻¹
- Signal (\(\gamma\gamma \rightarrow \gamma\gamma\))
- CEP gg \(\rightarrow \gamma\gamma\)
- \(\gamma\gamma \rightarrow ee\)
- Sys. unc.

CMS

- Beam dumps
- \(e^+e^- \rightarrow 2\gamma\) (OPAL)
- \(pp \rightarrow 2\gamma\) (CMS)
- \(e^+e^- \rightarrow 3\gamma\) (OPAL)
- \(pp \rightarrow 3\gamma\) (ATLAS)

PLB 797 (2019) 134826

- \(1/\Lambda (\text{GeV}^{-1}) \equiv g_{a\gamma, a\tilde{F}}\)
- \(m_a (\text{GeV})\)

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ATLAS-CMS overview

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Collectivity

- Higher flow in Z-tagged events?
- Flow in small systems:
  - how to subtract non-flow?
  - HF $\mu \nu_2$ in pp
  - event-by-event correlations in $(\nu_n, \nu_m)$

![Graphs showing flow distributions](arXiv:1906.08290)

![Graphs showing flow distributions](arXiv:1909.01650)

![Graphs showing flow distributions](arXiv:2018.092301)

![Graphs showing flow distributions](arXiv:2019.06290)
Completing the picture of QCD in a dense (and hot) medium

- Initial state, fluctuations, hydrodynamics, parton interactions, flavour dependence, time evolution...
- Access to new processes (t\bar{t}, \gamma\gamma \rightarrow \gamma\gamma, ...)
- Many results not shown
- Results starting to appear with the very large 2018 PbPb dataset (1.7 nb\textsuperscript{-1})

More results

- ATLAS results
- CMS results: heavy ions (papers, preliminary), forward physics (papers, preliminary)