Physics with ions at the Future Circular Collider

FCC week 2019
Brussels, 28th June 2019

David d'Enterria
(for the FCC-ions team)

CERN

M. Schaumann: Ions at FCC-hh: https://indico.cern.ch/event/727555/contributions/3452761/
**Unique fundamental physics with heavy-ions**

- **Central heavy-ion collisions:**
  1) ONLY way known to experimentally study the thermodynamics & phase transitions of a non-Abelian quantum-field theory. Collective ✔ QCD, ✗ EWK in the lab.

- **Ultra-peripheral heavy-ion collisions:**
  2) Unique SM & BSM studies via photon-photon collisions: light-by-light, axion-like particles, magn. monopoles, Higgs,...

- **QGP = Least viscous fluid known.** Test-bed for string theory applications via AdS/CFT duality.

- **Understand early Universe “bath” (~1 μs):** WIMP decoupling, axion mass, imprints on gravitational wave spectrum?...

**Note:** Likely, no other place in Universe produces Pb-Pb collisions at multi-TeV c.m. energies (heaviest cosmic-rays colls.: Fe-Air up to $\sqrt{s_{\text{max}}} \approx 400$ TeV).
Heavy-ion collisions at the FCC-hh

- CM energy $\sqrt{s} = 100$ TeV for pp means: $\sqrt{s_{NN}} = \sqrt{s}\sqrt{Z_1 Z_2/A_1 A_2}$ for A-A colls.

  PbPb: $\sqrt{s_{NN}} = 39$ TeV, $L_{\text{int}} = 110$ nb$^{-1}$/month
  pPb: $\sqrt{s_{NN}} = 63$ TeV, $L_{\text{int}} = 29$ pb$^{-1}$/month

- Huge increase in pQCD cross sections (yields) to probe QGP:
  - Charm: $\times 4$ (40) LHC
  - Bottom: $\times 6$ (60) LHC
  - 100-GeV jets: $\times 30$ (300) LHC
  - W: $\times 7$ (70) LHC
  - Z: $\times 7$ (70) LHC
  - Top: $\times 80$ (800) LHC
  - Higgs: $\times 20$ (200) LHC
PbPb(39 TeV): Bulk QGP properties

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Pb–Pb 2.76 TeV</th>
<th>Pb–Pb 5.5 TeV</th>
<th>Pb–Pb 39 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dN_{ch}}{d\eta}$ at $\eta = 0$</td>
<td>1600</td>
<td>2000</td>
<td>3600</td>
</tr>
<tr>
<td>Total $N_{ch}$</td>
<td>17000</td>
<td>23000</td>
<td>50000</td>
</tr>
<tr>
<td>$\frac{dE_T}{d\eta}$ at $\eta = 0$</td>
<td>1.8–2.0 TeV</td>
<td>2.3–2.6 TeV</td>
<td>5.2–5.8 TeV</td>
</tr>
<tr>
<td>Homogeneity volume</td>
<td>5000 fm$^3$</td>
<td>6200 fm$^3$</td>
<td>11000 fm$^3$</td>
</tr>
<tr>
<td>Decoupling time</td>
<td>10 fm/c</td>
<td>11 fm/c</td>
<td>13 fm/c</td>
</tr>
<tr>
<td>$\varepsilon$ at $\tau = 1$ fm/c</td>
<td>12–13 GeV/fm$^3$</td>
<td>16–17 GeV/fm$^3$</td>
<td>35–40 GeV/fm$^3$</td>
</tr>
</tbody>
</table>

Fig. 2: Left: space-time profile at freeze-out from hydrodynamical calculations for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and 39 TeV. Right: time evolution of the QGP temperature as estimated on the basis of the Bjorken relation and the Stefan-Boltzmann equation (see text for details).

x2–2.5 larger particle & energy densities (~40 GeV/fm$^3$) than LHC
PbPb(39 TeV): Thermalized charm in QGP

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium from $gg \rightarrow c\bar{c}$, $q\bar{q} \rightarrow c\bar{c}$ + NLO ... (~500 $c\bar{c}$ pairs!)

- Up to 50-100% “enhancement” wrt primary charm
- Sensitive to QGP properties: $T$ vs $\tau$, and $\tau_0$ (active $ndof$ in QCD EoS)

$\times 3$ larger charm-anticharm densities than at the LHC

K. Zhou et al., arXiv:1602.01667
C.M. Ko, Y. Liu, arXiv:1604.01207
FCC (T₀~1GeV) can probe QGP temperature through \( \Upsilon(1S) \) “melting” expected by lattice-QCD at \( T = 4–5 \ T_c \).

Melting compensated by \( b\bar{b} \) recombination? Density of bottom pairs large enough for \( \Upsilon(1S) \) recombination?

[A. Andronic, et al., JPG38 (2011) 124081]

[G. Aarts et al, JHEP 07 (2014) 097]
PbPb(39 TeV): Boosted-top quark in QGP

- Top-quark decays ($\tau \sim 0.1$ fm/c) before hadronization into $W + b$. But, boosted $t \rightarrow W \rightarrow qq'$ traverses QGP:

  $t \rightarrow b + 2$jets (66%)  
  $\text{ttbar} \rightarrow b\bar{b} + 2$jets + $1\ell$ + MET($\nu$) (45%)

→ Colour reconnection of decay $b,q,q'$?
→ Enhanced gluon radiation in QGP?
→ Boosted $t$-tbar = Color-singlets probe medium opacity at diff. time scales:

- Reconstructed $m_W(qq)$ vs $p_T(t)$ provides space-time QGP tomography:

![Graph showing reconstructed $m_W(qq)$ vs $p_T(t)$](image)
**PbPb(39 TeV): H→γ γ in the QGP**

Analysis based on NNLO MCFM cross sections. Pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

**Pb-Pb @ 39 TeV (L_{int} = 110 nb⁻¹)**

- **Higgs boson (τ~50 fm) final-state interaction in QGP?**

- **S/√B~5.7σ observation in just 1ˢᵗ month**

**PbPb(39 TeV): H→γ γ in the QGP**

Analysis based on NNLO MCFM cross sections. Pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

**Pb-Pb @ 39 TeV (L_{int} = 110 nb⁻¹)**

- **Higgs boson (τ~50 fm) final-state interaction in QGP?**

- **S/√B~5.7σ observation in just 1ˢᵗ month**

**PbPb(39 TeV): H→γ γ in the QGP**

Analysis based on NNLO MCFM cross sections. Pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

**Pb-Pb @ 39 TeV (L_{int} = 110 nb⁻¹)**

- **Higgs boson (τ~50 fm) final-state interaction in QGP?**

- **S/√B~5.7σ observation in just 1ˢᵗ month**
PbPb(39 TeV): $H \rightarrow \gamma \gamma$ in the QGP

Analysis based on NNLO MCFM cross sections. Pseudo-data for $H(\gamma\gamma)$ and $\gamma\gamma$ backgrounds after typical CMS/ATLAS cuts.

- Pb-Pb @ 39 TeV ($L_{int} = 110 \text{ nb}^{-1}$)
- Higgs boson ($\tau \sim 50 \text{ fm}$) final-state interaction in QGP?
- $S/\sqrt{B} \sim 5.7\sigma$ observation in just 1st month
- Negligible modification of Higgs decay width in QGP $\sim (T/m_H)^4 \sim 10^{-6}$...

\[ \delta \Gamma_{H \rightarrow gg} = -\Gamma_{H \rightarrow gg}^{\text{vac}} \frac{T^4}{M_H^4} \frac{112\pi^3}{45} \left( 8 - n_f \right) \]

for $H$-decay in the plasma rest frame.

[DdE, arXiv:1701.08047]
[MCFM, NNLO
PDF: CT10, nPDF=EPS09]
[Ghiglieri & Wiedemann, arXiv:1901.04503]
**pPb(63 TeV): Nuclear parton distrib. functions**

- **Huge nPDF kinematical reach:** $Q^2 \sim 2 - 4 \cdot 10^8 \text{ GeV}^2$, $x \sim 1 - 10^{-7}$

- **Unknown nuclear gluon at x<10^{-4}** (saturation?)

- **W,Z:** Ultraprecise shadowing at $x \sim 10^{-3}$

- **top(l^+l^-):** Antishadow & EMC at $x > 0.1$
pPb(63 TeV): Nuclear parton distrib. functions

- Huge nPDF kinematical reach: $Q^2 \sim 2 - 4 \cdot 10^8$ GeV$^2$, $x \sim 1 \times 10^{-7}$

- DGLAP breakdown below $x < 10^{-4}$ (CCG?)

- W,Z: Ultraprecise shadowing at $x \sim 10^{-3}$

- Top(l+ l-): Antishadow & EMC at $x > 0.1$
Huge $\gamma\gamma$ luminosities in AA thanks to collective action of $Z=82$ charges:

$$\sigma_{\text{PbPb} \to \gamma\gamma \to H} \approx Z^4 \times \sigma_{\text{pp} \to H} = 5 \times 10^7 \times \sigma_{\text{pp} \to \gamma\gamma \to H}$$

Large eff. lumi up to $\sqrt{s_{\gamma\gamma}} \sim 1$ TeV

Ultraperipheral interactions: Nuclei survive.

Unique SM & BSM $\gamma-\gamma$ processes accessible without pileup:
**PbPb(39 TeV): SM & BSM via γγ collisions**

- **Huge γγ luminosities** in AA thanks to collective action of Z=82 charges:
  \[ \sigma_{PbPb \rightarrow \gamma\gamma \rightarrow H} \approx Z^4 \times \sigma_{pp \rightarrow H} = 5 \cdot 10^7 \times \sigma_{pp \rightarrow \gamma\gamma \rightarrow H} \]

- **Large eff. lumi up to** \( \sqrt{s_{\gamma\gamma}} \sim 1 \text{ TeV} \)

**Ultraperipheral interactions:** Nuclei survive.

- **Unique SM & BSM γ–γ processes accessible without pileup** (e.g. ALPs):

---

**FCC**

**LHC**
## PbPb(39 TeV): Higgs boson via $\gamma-\gamma \rightarrow H \rightarrow bb$

### Expected exclusive Higgs over $bb$ background after cuts:

<table>
<thead>
<tr>
<th>System</th>
<th>$\mathcal{L}_{AB}$ (cm$^{-2}$ s$^{-1}$)</th>
<th>$\Delta t$ (s)</th>
<th>$\langle N_{\text{pileup}} \rangle$</th>
<th>$N_{\text{Higgs}}$ total ($H \rightarrow b\bar{b}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$ (14 TeV)</td>
<td>$10^{34}$</td>
<td>$10^7$</td>
<td>25</td>
<td>77 (55)</td>
</tr>
<tr>
<td>$pPb$ (8.8 TeV)</td>
<td>$1.5 \cdot 10^{29}$</td>
<td>$10^6$</td>
<td>0.05</td>
<td>0.050 (0.035)</td>
</tr>
<tr>
<td>PbPb (5.5 TeV)</td>
<td>$5 \cdot 10^{26}$</td>
<td>$10^6$</td>
<td>$5 \cdot 10^{-4}$</td>
<td>0.009 (0.007)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System at $\sqrt{s}_{NN} = 39$ TeV</th>
<th>Cross section after $p_T^j$, $\cos \theta_{jj}$, $m_{jj}$ cuts</th>
<th>Visible cross section ($N_{\text{evts}}$ ($L_{\text{int}} = 110$ nb$^{-1}$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \gamma \rightarrow H \rightarrow b\bar{b}$</td>
<td>1.02 nb (0.50 nb)</td>
<td>0.19 nb</td>
</tr>
<tr>
<td>$\gamma \gamma \rightarrow b\bar{b}$ [m$_{b\bar{b}}$=100–150 GeV]</td>
<td>24.3 nb (11.9 nb)</td>
<td>0.23 nb</td>
</tr>
<tr>
<td>$\gamma \gamma \rightarrow c\bar{c}$ [m$_{c\bar{c}}$=100–150 GeV]</td>
<td>525 nb (1.31 nb)</td>
<td>0.02 nb</td>
</tr>
<tr>
<td>$\gamma \gamma \rightarrow q\bar{q}$ [m$_{q\bar{q}}$=100–150 GeV]</td>
<td>590 nb (0.13 nb)</td>
<td>0.002 nb</td>
</tr>
</tbody>
</table>

### 5σ significance in first PbPb (pPb) month (year):

### Measurement of H-$\gamma$ coupling not based on decay but s-channel prod.

### Total Higgs width via:

$$\Gamma_{\text{H}} = \Gamma(H \rightarrow \gamma\gamma)/B(H \rightarrow \gamma\gamma)$$
PbPb(39 TeV): BSM searches (e.g. magnetic monopoles)

Magnetic fields produced in peripheral heavy-ion collisions are the strongest known in the universe, $\sim 7.5 \text{GeV}^2$ at LHC energies.

Magnetic monopoles:
- Explain charge quantization.
- Predicted by GUT/string theory.

't Hooft-Polyakov magn. monopoles not accesible in p-p, $e^+e^-$ collisions (pair prod. expon. suppressed), but x-section $\sigma \sim \exp(-m^2/(gB))$:

Unique FCC mass bounds $m > 1$ TeV

[D. d'Enterria (CERN)]

Unique heavy-ion physics at FCC

Unparalleled physics possibilities at \( \times 7 \) & \( \times 10 \) larger \( \sqrt{s} \) & \( L_{\text{int}} \) than LHC:

- Energy densities: \(~40 \text{ GeV/fm}^3\)
- \(~500\) charm pairs in QGP
- Top quark = Parton rad. “chrono-fmeter” & high-x gluon nPDF probe

Higgs in QGP & \( \gamma-\gamma \)

BSM via \( \gamma-\gamma \) colls.

- Gluon saturation down to \( x \sim 10^{-7} \)
- \( Y(1S) \) melt.+recomb.?
- ALPs, Monopoles,...
Back-up slides
t-tbar total x-sections in p-p, p-Pb, Pb-Pb

- **Pb-Pb:**
  - LHC(5.5 TeV) = 3.4 μb
  - FCC(39 TeV) = 300 μb
- **p-Pb:**
  - LHC(8.8 TeV) = 59 nb
  - FCC(63 TeV) = 3.2 μb
- **p-p (reference):**
  - LHC(5.5 TeV) = 75 pb
  - LHC(8.8 TeV) = 270 pb
  - FCC(39 TeV) = 6.5 nb
  - FCC(63 TeV) = 15 nb

nPDF anti-shadowing increases $\sigma_{tt}$ by +(2-8)%

$\rightarrow$ Cross-sections increase by $\times 55-85$ from LHC to FCC

[DdE, K.Krajczaár, H.Paukkunen
PLB746 (2015) 64-72]
Differential top-pair $p_T$ distributions

- LHC: $p_T$ reach up to $\sim 500$ GeV
- FCC: $p_T$ reach up to $\sim 2$ TeV
Higgs total $x$-sections in p-p, p-Pb, Pb-Pb

- Pb-Pb:
  - LHC(5.5 TeV) = 500 nb
  - FCC(39 TeV) = 12 $\mu$b

- p-Pb:
  - LHC(8.8 TeV) = 6 nb
  - FCC(63 TeV) = 120 nb

- p-p (reference):
  - LHC(5.5 TeV) = 12 pb
  - LHC(8.8 TeV) = 27 pb
  - FCC(39 TeV) = 270 pb
  - FCC(63 TeV) = 490 pb

→ Cross-sections increase by about $\times 20$ from LHC to FCC

[DDdE, arXiv:1701.08047]
### $H \rightarrow \gamma \gamma$ counts after cuts

Analysis based on NNLO MCFM v.8.0
pseudo-data for \(H(\gamma\gamma)\) plus \(\gamma\gamma\) backgrounds after typical CMS/ATLAS cuts

<table>
<thead>
<tr>
<th>System</th>
<th>(\sqrt{s_{NN}}) (TeV)</th>
<th>(L_{\text{int}}) (fb(^{-1}))</th>
<th>(H \rightarrow \gamma \gamma \rightarrow ZZ^*(4\ell))</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbPb</td>
<td>5.5</td>
<td>10</td>
<td>(\sigma_{\text{tot}} = 500) (\text{nb}) (\text{yields} = 6) (\text{yields} = 0.3)</td>
</tr>
<tr>
<td>pPb</td>
<td>8.8</td>
<td>1</td>
<td>(\sigma_{\text{tot}} = 6.0) (\text{nb}) (\text{yields} = 7) (\text{yields} = 0.4)</td>
</tr>
<tr>
<td>PbPb</td>
<td>39</td>
<td>33</td>
<td>(\sigma_{\text{tot}} = 11.5) (\mu)(\text{b}) (\text{yields} = 450) (\text{yields} = 25)</td>
</tr>
<tr>
<td>pPb</td>
<td>63</td>
<td>8</td>
<td>(\sigma_{\text{tot}} = 115) (\text{nb}) (\text{yields} = 950) (\text{yields} = 50)</td>
</tr>
</tbody>
</table>

- **LHC** (nominal \(L_{\text{int}}\)): \(\sim 2\) Higgs bosons/month in Pb-Pb
- **HE-LHC** (nominal \(L_{\text{int}}\)): \(\sim 10\) Higgs bosons/month in Pb-Pb
- **FCC** (nominal \(L_{\text{int}}\)): \(\sim 500\) H bosons/month in Pb-Pb
EPS09 nuclear PDFs modify slightly x-sections wrt. pp PDFs:

Higgs boson cross sections
MCFM, NNLO (ggF+VBF+VH)
PDF=CT10, nPDF=EPS09

Uncertainties from 30 EPS09 eigenvalues

LHC: Small antishadowing: $R_{AA} \sim 1.07$, $R_{pA} \sim 1.03$

FCC: Mild shadowing: $R_{AA} \sim R_{pA} \sim 0.97$
**H → γ γ observation in Pb-Pb (LHC, FCC)**

- **Pb-Pb @ 5.5 TeV (L_{int} = 10 nb^{-1})**
  - LHC (5.5 TeV, 10 nb^{-1}):
    - Nomin. lumi: S/√B~0.36 (0.5, adding 4l)
    - L_{int} = 500 nb^{-1}: 3σ evidence
    - 4.2σ combined with H(4l)

- **Pb-Pb @ 5.5 TeV (L_{int} = 500 nb^{-1})**
  - FCC (39 TeV, 33 nb^{-1}):
    - Nominal lumi: S/√B~5.2σ observation

- **Pb-Pb @ 39 TeV (L_{int} = 33 nb^{-1})**

**HL-LHC??**
H→γγγ observation in p-Pb (LHC, FCC)

→ LHC (8.8 TeV, 1 pb⁻¹):
Nominal lumi: $S/\sqrt{B} \sim 0.4$ (0.6, adding 4l)
$L_{int} = 40$ pb⁻¹: 3σ evidence
4.2σ combined with H(4l)

→ FCC (63 TeV, 8 pb⁻¹):
Nominal lumi: $S/\sqrt{B} \sim 7.7\sigma$ observation

p-Pb @ 8.8 TeV ($L_{int} = 1$ pb⁻¹)

p-Pb @ 8.8 TeV ($L_{int} = 40$ pb⁻¹)

p-Pb @ 63 TeV ($L_{int} = 8$ pb⁻¹)
pPb(63 TeV): Triple-hard scatterings

- Kinematical reach at FCC down to $x \sim 10^{-7}$ ($10^{-4}$ with W,Z at $y \sim 0$)