Heavy-ion physics studies for the
Future Circular Collider

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Outline

- Introduction: the FCC design study
- Ions at the FCC
- High-density QCD in the initial state: small-x and saturation
- High-density QCD in the final state: deconfinement and QGP
- High-multiplicity events in small systems (pp, pA)
- Connection with cosmic-ray physics
- Summary
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

• **pp-collider (FCC-hh)** → defining infrastructure requirements
  
  ~16 T ⇒ 100 TeV *pp* in 100 km
  ~20 T ⇒ 100 TeV *pp* in 80 km

• **e⁺e⁻ collider (FCC-ee)** as potential intermediate step

• **p-e (FCC-he)** option

• 80-100 km infrastructure in Geneva area
Ions at FCC: energies and luminosities

- Centre-of-mass energy per nucleon-nucleon collision:

\[ \sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \sqrt{s_{pp}} \quad \rightarrow \quad \sqrt{s_{PbPb}} = 39 \ \text{TeV} \]
\[ \sqrt{s_{pPb}} = 63 \ \text{TeV} \quad \text{for} \quad \sqrt{s_{pp}} = 100 \ \text{TeV} \]

- First (conservative) estimates of luminosity (in comparison with LHC): x5 larger \( L_{int} \) per month of running

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<tr>
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<tbody>
<tr>
<td>Pb–Pb peak ( \mathcal{L} ) (cm(^{-2})s(^{-1}))</td>
<td>10(^{27})</td>
<td>5 \times 10(^{27})</td>
<td>13 \times 10(^{27})</td>
</tr>
<tr>
<td>Pb–Pb ( L_{int} ) / month (nb(^{-1}))</td>
<td>0.8</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>p–Pb peak ( \mathcal{L} ) (cm(^{-2})s(^{-1}))</td>
<td>10(^{29})</td>
<td>t.b.d.</td>
<td>3.5 \times 10(^{30})</td>
</tr>
<tr>
<td>p–Pb ( L_{int} ) (nb(^{-1}))</td>
<td>80</td>
<td>t.b.d.</td>
<td>1000</td>
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- Possibility to increase \( L_{int} \) using nuclei with slightly smaller \( Z \)?
  - Some of the limiting factors (e.m. process) go with “large” powers of \( Z \)
- Could (optimistically) aim for programme of 100/nb (LHC x10)
High-density QCD in the initial state: Saturation at low $x$

- Explore new unknown regime of QCD: when gluons are numerous enough (low-$x$) & extended enough (low-$Q^2$) to overlap $\Rightarrow$ *Saturation, Non-linear PDF evolution*

Enhanced in nuclei: more gluons per unit transverse area

**Saturation scale:**

$$Q_S^2 \sim \frac{A g(x, Q_S^2)}{\pi A^{2/3}} \sim A^{1/3} g(x, Q_S^2) \sim A^{1/3} \frac{1}{x^\lambda} \sim A^{1/3} \left(\sqrt{s} \, e^y\right)^\lambda_{(\lambda \sim 0.3)}$$

Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

$\Rightarrow$ decrease $x$ (larger $\sqrt{s}$, larger $y$)

$\Rightarrow$ increase $A$
Kinematic coverage $Q^2$ vs. $x$: pA LHC
Kinematic coverage $Q^2$ vs. $x$: pA FCC
Kinematic coverage $Q^2$ vs. $x$: pA FCC

Goals:
- determine $Q^2_{\text{sat}}$
- test non-linear evolution

Perturbative probes ($J/\psi$, ...)

$y@LHC$  $y@FCC$

Charm  $>4$  $>2$
Kinematic coverage $Q^2$ vs. $x$: eA FCC

pA at FCC: unique access down to $x<10^{-6}$ with perturbative probes

eA at FCC: down to $x<10^{-5}$ with perturbative probes, but fully constrained parton kinematics

Perturbative probes ($J/\psi$, …)
\( \gamma \)-Pb physics at FCC (Pb-Pb)

- Sensitive to gluon density at very small \( x \): powerful handle on saturation region with perturbative probes
- E.g. exclusive Q-Qbar: \( x \sim \frac{m_{\text{QQ}}^2}{s^{\gamma \text{Pb}}} \), \( Q^2 \sim \frac{m_{\text{QQ}}^2}{4} \)

\[ \sqrt{s^{\gamma \text{Pb}}} \sim 7 \text{ TeV} \]
\[ \Rightarrow x \sim 10^{-7} \]

\~2 orders of magnitude below LHC!
Properties of QGP:
- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced (better tests of QGP transport)
- Initial temperature higher
- Equilibration times reduced

Hydrodynamic freeze-out curves
(S. Flörchinger)
QGP studies at the FCC: global properties

- Extrapolation to 39 TeV: increase wrt LHC 5.5 TeV

\[ \frac{dN_{\text{ch}}}{d\eta} \times 1.8 \]

Volume \( \times 1.8 \)

\[ \frac{dE_T}{d\eta} \times 2.2 \]

<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_{\text{ch}}}{d\eta} ) at ( \eta = 0 )</td>
<td>1600</td>
<td>2000</td>
<td>3600</td>
</tr>
<tr>
<td>Total ( N_{\text{ch}} )</td>
<td>17000</td>
<td>23000</td>
<td>50000</td>
</tr>
<tr>
<td>( \frac{dE_T}{d\eta} ) at ( \eta = 0 )</td>
<td>2 TeV</td>
<td>2.6 TeV</td>
<td>5.8 TeV</td>
</tr>
<tr>
<td>BE homogeneity volume</td>
<td>5000 fm³</td>
<td>6200 fm³</td>
<td>11000 fm³</td>
</tr>
<tr>
<td>BE decoupling time</td>
<td>10 fm/c</td>
<td>11 fm/c</td>
<td>13 fm/c</td>
</tr>
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QGP studies at the FCC: temperature

- Energy density with Bjorken formula:
  \[ \varepsilon(\tau) = \frac{E}{V(\tau)} = \frac{1}{c \tau \pi R_A^2} \frac{dE_T}{d\eta} \]

- Temperature from S-B equation:
  \[ T(\tau) = \sqrt[4]{\varepsilon(\tau) \frac{30}{\pi^2 n_{d.o.f.}}} \]

- 20% larger for the same time
  - E.g. 360 MeV at 1 fm/c

- Initial time (QGP formation time)?
  - Usually \(\sim 0.1\) fm/c for LHC
  - Could be smaller at FCC

- Significantly larger initial temperature? Could reach close to 1 GeV?
Secondary/thermal charm?

- Expect abundant production of $c\bar{c}$ pairs in the medium
- Calculations for LHC 5.5 TeV: + 15-45% wrt hard scattering
  - At 39 TeV could become comparable with initial production
- Should show up as “thermalized” component at 1-2 GeV
- Secondary charm yield very sensitive to the initial temperature and to the temperature evolution
- If charm is produced abundantly during the equilibration of the medium, the additional d.o.f. should have impact on the equation of state

\[ P/T^4 \sim \varepsilon/T^4 \propto n_{d.o.f} \]

J. Uphoff et al. PRC82 (2010)

\[ g+u+d+s+c \]

S. Borsanyi et al., arXiv:1204.0995
Y(1S) melting at the FCC

- Sequential quarkonium melting (according to binding energy), one of the most direct probes of deconfinement
- Indication of sequential melting at LHC
- Y(1S) $R_{AA} \sim 0.5$: consistent with suppression of higher states only?
- Y(1S) expected to melt at $\sim 350$ MeV

May not melt at LHC

Full quarkonium melting at FCC?

Digal, Petrecki, Satz PRD64(2001) confirmed by recent calculations, e.g. Miao, Mócsy, Petreczky, NPA (2011)
A new set of Hard Probes

- LHC heavy-ion programme shows that it is possible to reconstruct HEP-like observables in HI collisions
  - Jets, b-jets, Z⁰, W, γ-jet correlations …
- Large $\sqrt{s}$ and $\mathcal{L}$ of the FCC will make new probes abundantly available, for the study of the interaction mechanisms, of the medium density and its time evolution

![](http://mcfm.fnal.gov)

- Larger increases for larger masses:
  - 80x for top
  - 20x for $Z^0 + 1\text{ Jet}(p_T > 50\text{ GeV})$
  - 8x for beauty or $Z^0$
Example: Top quarks

- $t\bar{t}$ decay channels:
  - 10% $b\bar{b} + \ell\ell + \mathcal{E}_T$ “observation channel”
  - 44% $b\bar{b} + \ell + 2\text{ jets} + \mathcal{E}_T$
  - 46% $b\bar{b} + 4\text{ jets}$

- Estimate for observation channel in CMS (CMS PAS-FTR-2013-025)
  - ~500 events for 10 nb$^{-1}$ Pb-Pb 5.5 TeV (LHC Runs-3-4)
- FCC: with 100 nb$^{-1}$, x800 more wrt HL-LHC
  - FCC with CMS-like setup, ~4x10$^{5}$ for “observation channel”
    - could be 4-5x more in the other channels (but higher background)
High-multiplicity events in small systems

- One of the most interesting findings from LHC Run-1: similarity of long-range correlations (ridge) in high-mult pp, pPb as in Pb-Pb collisions
- Similar mechanism? Collectivity in small high-density systems? Initial or final state collectivity?

Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity
High-multiplicity events in small systems

- One of the most interesting findings from LHC Run-1: similarity of long-range correlations (ridge) in high-multiplicity pp, pPb, as in Pb-Pb collisions.
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Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity.
FCC pA and AA probe ankle-energy and provides strong constraints for hadronic Monte Carlos for UHECR (p,Fe+Air)
Summary

- Discussions started on opportunities with heavy ions, within the FCC design study

- Saturation physics in pA, eA and γA
  - Higher energy and large nuclei → unique access to saturation region (down to $x<10^{-6}$) with perturbative probes

- QGP physics
  - Larger initial temperature and volume entail potentially unique aspects, e.g. thermal production of charm
  - Larger $\sqrt{s}$ and $L_{\text{int}}$ give access to new hard observables, e.g. top or $Z + N$-jets

- Also: benefit for UHECR studies

- New inputs and ideas are most welcome!
Timeline of future HI running at the LHC

- Run 2 (LS1→LS2): Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}} \sim 5.1$ TeV
- LS2: major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS, LHC collimator upgrades
- Run 3 + Run 4: Pb-Pb >10/nb, at $\sqrt{s_{NN}} \sim 5.5$ TeV
- pp reference and p-Pb in both Runs 2 and 3-4

Experiments request/goal:
HI-HL-LHC Programme

- **Jets**: characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, $\gamma$/Z-jet at very high $p_T$ (focus of ATLAS and CMS)
  - Flavour-dependent in-medium fragmentation functions (focus of ALICE)

- **Heavy flavour**: characterization of mass dependence of energy loss, HQ in-medium thermalization and hadronization, as a probe of the medium transport properties
  - Low-$p_T$ production and elliptic flow of several HF hadron species (focus of ALICE)
  - B and b-jets (focus of ATLAS and CMS)

- **Quarkonium**: precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-$p_T$ charmonia and elliptic flow (focus of ALICE)
  - Multi-differential studies of $\Upsilon$ states (focus of ATLAS and CMS)

- **Low-mass di-leptons**: thermal radiation $\gamma$ ($\rightarrow e^+e^-$) to map temperature during system evolution; modification of $\rho$ meson spectral function as a probe of the chiral symmetry restoration
  - (Very) low-$p_T$ and low-mass di-electrons and di-muons (ALICE)
For illustration: Drell-Yan in p-Pb at LHC

Pseudo-data (CMS acceptance)

Plan: perform similar studies to assess sensitivity of FCC

Armesto et al., 1309.5371
Hydro simulation at FCC

• Hydro-simulation (b=0, \(\eta/s = 1/4\pi\), \(dN_{\text{ch}}/dy = 3600\) @ FCC) without initial fluctuations.
• In the simulation, the difference between FHC and LHC results from adjusting the initial temperature in the same geometry such that the final charged multiplicity increases to 3600 (instead of 1600 at LHC).
• The arrows along the curves indicate the direction and strength of flow.
QGP studies at the FCC: energy density

- Energy density with Bjorken formula

\[ \varepsilon(\tau) = \frac{E}{V(\tau)} = \frac{1}{c \tau} \frac{dE_T}{d\eta} \]

- x2.2 larger for the same time
  - E.g. 35 GeV/fm³ at 1 fm/c

- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC

- Significantly larger initial energy density?
An interesting physics case: boosted color singlets in the medium

Basic idea: the QCD medium does not affect colored objects smaller than its resolving power $\Lambda$

$\rightarrow$ q-qbar with small opening angle; seen as color-singlet by the medium, no interaction expected

Medium induces decoherence, opening angle increases $\rightarrow$ energy loss of color-octet’s in the medium

$\rightarrow$ Boosted color singlet states can be used to probe the medium opacity / density at different time scales

Armesto, Casalderrey, Iancu, Ma, Mehtar-Tani, Salgado, Tywoniuk 2010-2014
An interesting physics case: boosted color singlets in the medium

First estimation of the timescales for boosted objects in the medium

\[ t\bar{t} \rightarrow b\bar{b} + \ell + 2 \text{ jets} + E_T \]

A tool to probe timescale of medium evolution?
Top quark projection (FCC)

- ttbar cross section x80 from 5.5 to 39 TeV
- With $L_{\text{int}}=100/nb$, x800 top wrt 10/nb@LHC5.5
  → With a detector similar to CMS, we have $\sim 4 \times 10^5$ in the “observation (cleanest) channel”

- Top cross section drops by 2 (3.5) orders of magnitude at $p_T = 0.5 (1) \text{ TeV}$
  → few $10^3$ with $p_T > 0.5 \text{ TeV}$
  → few $10^2$ with $p_T > 1 \text{ TeV}$

M. Mangano, FHC informal meeting Nov 2013