Nuclear collisions at the Future Circular Collider

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Contents:

1. The FCC(-AA):
   - Motivation.
   - Site.
   - Parameters.
   - Detector.

2. Physics case:
   - Global observables.
   - Hard probes.
   - Small x.

3. Summary and outlook.

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC.

- 4 HI dedicated workshops, last one at CERN 09.14: https://indico.cern.ch/event/331669/;
- Workshop, ECT* 03.15: https://indico.cern.ch/event/382529/;
- FCC Week 2015, Washington DC, Mar. 2015: http://indico.cern.ch/event/340703/timetable/#all.detailed;
Motivation:

- Big machines take long time to come from first idea to reality e.g. >20 years for the LHC, so it is time to start thinking of another high-energy machine after the LHC.
Motivation:

LHC roadmap: according to MTP 2016-2020 V1

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<tbody>
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<td>LHC</td>
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<td>LS 2</td>
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<tr>
<td>Run 2</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
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<td>Q1</td>
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<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
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<td>PHASE 1</td>
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<tr>
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<td>Q4</td>
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<tr>
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<td>Q4</td>
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<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
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<td>PHASE 2</td>
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<th>2032</th>
<th>2033</th>
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<th>2035</th>
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<tr>
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<td>LS 4</td>
<td>Run 5</td>
<td>LS 5</td>
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<tr>
<td>LS 4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
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<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Run 5</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<tr>
<td>LS 5</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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Motivation:

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC.
Motivation:

LHC roadmap: according to MTP 2016-2020 V2

<table>
<thead>
<tr>
<th>Year</th>
<th>LS2 starting in 2019</th>
<th>=&gt; 24 months + 3 months BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>LS3 LHC: starting in 2024</td>
<td>=&gt; 30 months + 3 months BC</td>
</tr>
<tr>
<td></td>
<td>Injectors: in 2025</td>
<td>=&gt; 13 months + 3 months BC</td>
</tr>
</tbody>
</table>

Goal of HI program: 10-15 nb⁻¹ in Run3+4.

Frederick Bordry to the SPC and FC, June 2015

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC.
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
  - $\sim 16$ T $\Rightarrow$ $100$ TeV $pp$ in $100$ km
  - $\sim 20$ T $\Rightarrow$ $100$ TeV $pp$ in $80$ km

- **$e^+e^-$ collider (**FCC-ee**) as potential intermediate step
  - $120$-$350$ GeV
- **$p$-$e$ (**FCC-he**) option
- **$80$-$100$ km infrastructure in Geneva area**
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- **pp-collider (FCC-hh)**
  - defining infrastructure requirements
  - \( \sim 16 \text{ T} \Rightarrow 100 \text{ TeV} \text{ pp in } 100 \text{ km} \)
  - \( \sim 20 \text{ T} \Rightarrow 100 \text{ TeV} \text{ pp in } 80 \text{ km} \)

- **e^+e^- collider (FCC-ee)** as potential intermediate step
  - 120-350 GeV
- **p-e (FCC-he)** option
- **80-100 km infrastructure in Geneva area**

\[ pp: \sqrt{s}=100 \text{ TeV} \]
\[ \text{PbPb}: \sqrt{s}=39.4 \text{ TeV/nucleon} \]
\[ \text{pPb}: \sqrt{s}=62.8 \text{ TeV/nucleon} \]
Site: 93 km option (Lebrun in Washington DC)

- **pp**: $\sqrt{s} = 100$ TeV
- **PbPb**: $\sqrt{s} = 39.4$ TeV/nucleon
- **pPb**: $\sqrt{s} = 62.8$ TeV/nucleon

Alignment Profile:
- Surface
- Lake
- Molasse
- Calcaire
- Alignment
- Shaft

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
Site:

100 km option (Lebrun in Washington DC)
Accelerator parameters: 

**Heavy Ion Pre-Accelerator Chain**

The requirements and performance of the pre-accelerator chain for FCC are under studied.

*Straw-man assumption to estimate (conservative) beam parameters and luminosity: LHC, as it is today, but cycling to 3.3 Z TeV, is assumed to be the injector for FCC-hh.*

Baseline: Inject one LHC beam into 1/4 FCC, no waiting.

Present heavy-ion pre-injectors:

- HI source
- LINAC 3
- LEIR

2014/09/22

M. Schaumann, Workshop on Ions at the FCC, CERN
Accelerator parameters:

Conservative filling scheme!!!

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>LHC Design</th>
<th>FCC Collision</th>
<th>FCC Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation mode</td>
<td>-</td>
<td>Pb-Pb</td>
<td>Pb-Pb</td>
<td>p-Pb</td>
</tr>
<tr>
<td>$\beta$-function at the IP</td>
<td>[m]</td>
<td>0.5</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Initial RMS beam size at IP</td>
<td>[\mu m]</td>
<td>15.9</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td><strong>Initial luminosity</strong></td>
<td>[Hz/mb]</td>
<td>1</td>
<td>2.6</td>
<td>213</td>
</tr>
<tr>
<td><strong>Peak luminosity</strong></td>
<td>[Hz/mb]</td>
<td>1</td>
<td>7.3</td>
<td>1192</td>
</tr>
<tr>
<td><strong>Integrated luminosity per fill</strong></td>
<td>[\mu b^{-1}]</td>
<td>&lt;15</td>
<td>57.8</td>
<td>21068</td>
</tr>
<tr>
<td><strong>Integrated luminosity per run</strong></td>
<td>[nb^{-1}]</td>
<td>-</td>
<td>8.3</td>
<td>1784</td>
</tr>
<tr>
<td>Initial bb tune shift per IP</td>
<td>[10^{-4}]</td>
<td>1.8</td>
<td>3.7</td>
<td>3.7</td>
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<tr>
<td>Total cross-section</td>
<td>[b]</td>
<td>515</td>
<td>597</td>
<td>2</td>
</tr>
<tr>
<td>Peak BFPP beam power</td>
<td>[W]</td>
<td>26</td>
<td>1705</td>
<td>0</td>
</tr>
<tr>
<td>Initial beam current lifetime</td>
<td>[h]</td>
<td>&lt;11.2 (2 exp.)</td>
<td>10.9</td>
<td>39.3</td>
</tr>
<tr>
<td>Luminosity lifetime ($L_0/c$)</td>
<td>[h]</td>
<td>&lt;5.6 (2 exp.)</td>
<td>6.2</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Schaumann, 1503.09107  

**Note:** the ALICE goal for Run 3+4 is 10-15 nb^{-1} in PbPb; in the 2013 pPb run got ~30 nb^{-1}.
Accelerator parameters:

First (conservative) estimates of luminosity (in comparison with LHC): >8 larger $L_{\text{int}}$ per month of running

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Pb–Pb peak $\mathcal{L}$ (cm$^{-2}$s$^{-1}$)</td>
<td>$(2-3\times)10^{27}$</td>
<td>$5 \times 10^{27}$</td>
<td>$13 \times 10^{27}$</td>
</tr>
<tr>
<td>Pb–Pb $L_{\text{int}}$ / month (nb$^{-1}$)</td>
<td>0.8(1)</td>
<td>1(1.5)</td>
<td>&gt;8</td>
</tr>
<tr>
<td>p–Pb peak $\mathcal{L}$ (cm$^{-2}$s$^{-1}$)</td>
<td>$(2-3\times)10^{29}$</td>
<td>t.b.d.</td>
<td>$3.5 \times 10^{30}$</td>
</tr>
<tr>
<td>p–Pb $L_{\text{int}}$ (nb$^{-1}$)</td>
<td>80</td>
<td>t.b.d.</td>
<td>&gt;1800</td>
</tr>
</tbody>
</table>

A. Dainese at ECT*

Could aim for programme of 100/nb (LHC x10)
Detector (pp/pA/AA):

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)

Solenoid: 5-6 m diameter, 5-6 T, 23 m long
+ massive Iron yoke for flux return (shielding) and muon tagging.

Dipoles: 10 Tm with return yoke placed at 18 m.
Practically no coupling between dipoles and solenoid.
They can be designed independently at first.

H. Ten Kate

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
Detector (pp/pA/AA):

**Option 2: Twin Solenoid + Dipoles**

---

**Twin Solenoid:** the original 6 T, 12 m \times 23 m solenoid + now with a shielding coil
{concept proposed for the 4\textsuperscript{th} detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

**Gain?**

+ **Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
+ **Very light:** 2 coils + structures, \(\approx 5\) kt, only \(\approx 4\%) of the option with iron yoke!
+ **Smaller:** outer diameter is less than with iron.

---

H. Ten Kate
Detector (pp/pA/AA):

Option 3: Toroids + Solenoid + Dipoles (ATLAS +)

- Air core Barrel Toroid with 7 x muon bending power $B L^2$.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m$^3$).
1. The FCC(-AA):
   • Motivation.
   • Site.
   • Parameters.
   • Detector.

2. Physics case:
   • Global observables.
   • Hard probes.
   • Small x.

3. Summary and outlook.

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Global properties:

- Using data-driven extrapolations from lower energies to the LHC:

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

\[ \text{Volume} \times 1.8 \]

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

<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>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>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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</table>

A. Dainese at QM2014

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
Using data-driven extrapolations from lower energies to the LHC:

A. Dainese at QM2014

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N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
Global properties:

- Using data-driven extrapolations from lower energies to the LHC:

  - The medium:
    - Is larger;
    - Lives longer;
    - Reaches higher T’s;
    - Equilibrates faster.

  ⇒ larger opportunities to see collective effects.

A. Dainese at QM2014
Charm:

- Charm becomes an active flavour.
- It can be abundantly produced secondary interactions.

Ko, NLO

Uphoff at ECT*, LO

- Large increase: thermal production may overcome shadowing.

Zhou at ECT*, NLO

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
Correlations:

- Higher multiplicity may profit collective flow studies e.g. $T$ dependence of $\eta/s$.
- Much larger multiplicity in pp would help to understand the eventual onset of collectivity in pp and pA: flow-like features, ridge, $<p_T>$,...
Hard probes: yields

- Hard probes are much abundantly produced.

- This could make possible the use of top, abundant EWB+jet events,…

- New temperature and density range may affect hard probes: $\Upsilon$ melting, bbar regeneration,…

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
Hard probes: nPDFs

- Top could be used to constrain the nuclear glue as done now in pp collisions at the LHC. d'Enterria, Krajczac, Paukkunen, 1501.05879, Hessian reweighting

\[ \int \mathcal{L} = 10 \text{ nb}^{-1} (1 \text{ pb}^{-1}) \text{ in PbPb (pPb)} \]

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\mathcal{L}_{\text{int}}$ (nb$^{-1}$)</th>
<th>Number of top+antitop quarks $t\bar{t} \rightarrow b \bar{b} l\ell\nu\nu$</th>
<th>Number of top+antitop quarks $tW \rightarrow b \ell\ell\nu\nu$</th>
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</thead>
<tbody>
<tr>
<td>Pb-Pb</td>
<td>5.5</td>
<td>1</td>
<td>90</td>
<td>3</td>
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<tr>
<td>p-Pb</td>
<td>8.8</td>
<td>0.2</td>
<td>300</td>
<td>10</td>
</tr>
<tr>
<td>Pb-Pb</td>
<td>39.0</td>
<td>5</td>
<td>47000</td>
<td>1300</td>
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<tr>
<td>p-Pb</td>
<td>63.0</td>
<td>1</td>
<td>100000</td>
<td>2600</td>
</tr>
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![Graph showing the range for Z/W⁺ at the LHC and the FCC](image)
Hard probes: boosted tops

- Use boosted tops to probe the time scales in the medium and the energy loss mechanism.

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

yields 5 times those of the previous channel

Apolinario at ECT*,
\[ t_{coh} \sim 1 \quad \text{fm/c for} \]
\[ P_{T_{top}} \sim 800 \quad \text{GeV}. \]
Hard probes: boosted tops

- Use boosted tops to probe the time scales in the medium and the energy loss mechanism.

Apolinario at ECT*, $t_{coh} \sim 1$ fm/c for $P_{T_{top}} \sim 800$ GeV.
Small $x$ (I):

- Test whether (perturbative) saturation lies in the accessible kinematic region, and understand how it works.
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Small $x$ (II):

- Correlations (among hadrons, jets and $\gamma$'s) become available at sizeable transverse momenta.

- Exclusive VM production in UPCs will explore new regions of the kinematic plane.

N. Armesto, 29.09.2015 - Nuclear collisions at the FCC
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Summary and outlook:

● **Summary:** FCC-AA provides an extension of the pA/AA program to higher energies leading to
  - Hotter, longer-lived medium with larger opportunities to observe collectivity from small to large systems.
  - New degrees of freedom may become active.
  - Access to a large perturbative domain at small x: saturation.
  - Larger rates of harder probes, with new possibilities.
  - Tests of interaction models of wider interest (e.g. for UHE cosmic rays).

● **Outlook:**
  - Organisation: collaboration established, with FCC-hh, FCC-ee and FCC-he groups.
  - Initial physics document to be produced for next spring.
  - Synergy with the parallel Chinese effort highly desirable.

*Visit the web pages: everybody is more than welcome to join!!!*

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N. Armesto, 29.09.2015 - Nuclear collisions at the FCC

Thanks a lot for your attention!!!
Backup:
Hard probes: quarkonium

- $\Upsilon$ may melt at the FCC: pushing the thermometer to higher values.

- Recombination, enhanced by thermal charm production, will play a dominant role for ccbar states: $R_{AA}$, $v_2$, $D/\pi$, bbbar states?

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