Future heavy ion facilities:

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on behalf of the HI Working Group of FCC-hh/Physics&Exp
Outline

- FCC Study activities and timeline
- Ions at the FCC: projected performance
- QGP studies
- nPDFs and gluon saturation
International FCC collaboration (CERN as host lab) to study:

- **pp-collider** (**FCC-hh**)  
  - main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV **pp** in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e⁺e⁻ collider** (**FCC-ee**), as potential first step
- **HE-LHC** with **FCC-hh** technology
- **p-e** (**FCC-he**) option, IP integration, e⁻ from ERL

<table>
<thead>
<tr>
<th></th>
<th>Pb-Pb</th>
<th>p-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FCC-hh</strong></td>
<td>39 TeV</td>
<td>63 TeV</td>
</tr>
<tr>
<td><strong>HE-LHC</strong></td>
<td>10.6 TeV</td>
<td>17 TeV</td>
</tr>
</tbody>
</table>
Timeline

2014: Study kickoff, formation of international collaboration
2018: CDR as input for European Strategy for Particle Physics Update
FCC-hh reference detector

- Detector concept; could be implemented in two experiments
- Central solenoid (4T) + two forward solenoids (4T)
- Si-tracker 400 m² surface |η|<6
- ECAL&HCAL |η|<6, granularity about x4 ATLAS/CMS
- Muon system à la ATLAS/CMS
FCC-hh reference detector

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Same detector for heavy ions?

- pp with pile-up of 1000 more challenging than Pb-Pb environment
- Excellent performance for hard probes also in HI collisions
- Coverage for forward measurements up to |η| = 6
- Operation with reduced field would give access to low-p_T observables
- Silicon timing layers for pile-up rejection could be used for hadron PID
FCC HI working group and documents

◆ Ions at FCC-hh Working Group:
  ➢ Sub-group of “FCC-h Physics, Experiments, Detectors”
  ➢ Machine studies: M. Schaumann, J. Jowett, E. Logothetis Agaliotis
  ➢ Twiki https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons

◆ Workshops/meetings 2013-17
  ➢ https://indico.cern.ch/event/331669/ and links therein


◆ Contribution to FCC CDR 2018
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- nPDFs and gluon saturation
HI luminosity projections

- Two scenarios considered for FCC: Baseline and Ultimate
  - reduced bunch spacing (50 ns) and $\beta^*$ (0.3 m)

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Baseline</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation mode</td>
<td>-</td>
<td>Pb–Pb</td>
<td>Pb–Pb</td>
</tr>
<tr>
<td>Number of Pb bunches</td>
<td>-</td>
<td>2760</td>
<td>5400</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>[ns]</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Peak luminosity (1 exp)</td>
<td>$[10^{27}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>80</td>
<td>320</td>
</tr>
<tr>
<td>Integrated luminosity (1 exp, 30 days)</td>
<td>$[\text{nb}^{-1}]$</td>
<td>35</td>
<td>110</td>
</tr>
</tbody>
</table>

Includes 50% operation efficiency

- >100 nb$^{-1}$/month in Pb-Pb in ultimate scenario: ~ 10x full LHC programme
- 15 1-month HI runs in tentative FCC-hh schedule $\Rightarrow$ ~150 x LHC programme
- HE-LHC, first estimate: x2 lumi than at LHC; further improvement with lighter nuclei (reduced BFPP), e.g. $L_{NN}$ for Xe-Xe at HE-LHC ~ 5x Pb-Pb at LHC
Outline

- FCC Study activities and timeline
- Ions at the FCC: projected performance
- QGP studies
  - Global properties and collective effects
  - Hard probes and jet quenching
- nPDFs and gluon saturation
Global properties at FCC (and HE-LHC)

**FCC wrt LHC:** \( dN_{\text{ch}}/d\eta \times 1.8 \)  
Volume \( x1.8 \)  
\( dE_T/d\eta \) (\& \( \varepsilon \)) \( x2.2 \)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Pb–Pb 2.76 TeV</th>
<th>Pb–Pb 5.5 TeV</th>
<th>Pb–Pb 10.6 TeV</th>
<th>Xe–Xe 11.5 TeV</th>
<th>Pb–Pb 39 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dN_{\text{ch}}/d\eta ) at ( \eta = 0 )</td>
<td>1600</td>
<td>2000</td>
<td>2400</td>
<td>1500</td>
<td>3600</td>
</tr>
<tr>
<td>( dE_T/d\eta ) at ( \eta = 0 )</td>
<td>1.7–2.0 TeV</td>
<td>2.3–2.6 TeV</td>
<td>3.1–3.4 TeV</td>
<td>( \approx 1.5 ) 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>7400 fm(^3)</td>
<td>4500 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>11.5 fm/c</td>
<td>10 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>22–24 GeV/fm(^3)</td>
<td>( \approx 15 ) GeV/fm(^3)</td>
<td>35–40 GeV/fm(^3)</td>
</tr>
</tbody>
</table>

- Xe–Xe at HE-LHC: similar “medium” as Pb-Pb 2.76 TeV, with ~5 times larger \( L_{\text{NN}} \) wrt Pb-Pb at 5.5 TeV → optimal scenario for HE-LHC?
Higher temperature: thermal charm?

- T evolution from hydrodynamic simulation
- Large secondary production of charm pairs in the medium \( gg \rightarrow c\bar{c}, q\bar{q} \rightarrow c\bar{c} \)
- Up to 50-100% “enhancement” wrt primary charm
- Sensitive to QGP properties: T vs \( \tau \), and \( \tau_0 \)

900 MeV at \( \tau = 0.2 \) fm/c
650 MeV at \( \tau = 0.5 \) fm/c

C.M. Ko, Y. Liu, JPG43 (2016) no. 12, 125108
K. Zhou et al., PLB758 (2016) 434
Quarkonia: large $\psi$ enhancement? full Y melting?

- Large charm yield from hard scattering + thermal production would lead to $J/\psi$ enhancement ($R_{AA} >> 1$)
  - $J/\psi$ yield could be sensitive to secondary/thermal charm production
- $Y(1S)$ would melt when $T > 350$ MeV, may be reached only at FCC
- However, large $b\bar{b}$ yields (~20 pairs in central Pb-Pb) could lead to regeneration in the bottomonium sector ($Y R_{AA} > 1$)

A. Andronic, et al., based on JPG38 (2011) 124081

G. Aarts et al, JHEP 07 (2014) 097
New hard probes at FCC energy: top events

- Increase of $\sqrt{s}$ and $L_{\text{int}}$/month by $\sim x30$ at FCC will enable new ways to probe the QGP
- Top cross section increases by $x80$ from 5.5 TeV to 39 TeV
  - Kinematic simulation study: $3 \times 10^5 \, \ell \ell \nu \nu$ per run in the baseline scenario (35/nb)
  - Top $p_T$ distribution up to $\sim 2$ TeV/c

D. d'Enterria, et al. PLB746 (2015) 64
Boosted color singlets from top events

\[ \bar{t}t \rightarrow b\bar{b} + q\bar{q} + \ell + \nu \]

This \( q\bar{q} \) is produced as a color singlet and it “sees” the QGP with a time delay \( \tau_{\text{tot}} \) of up to several \( \text{fm}/c \) given by the boost of the top and of the W.

The rest of the final state

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

is used to tag the event topology.

- Boosted-top events can therefore be used to address two novel studies in the sector of parton energy loss:
  1. Time-evolution of QGP opacity \( \rightarrow \text{at which time } \tau_{\text{m}} \text{ does the quenching "stop"?} \)
  2. Role of color coherence in parton energy loss

Apolinario, Mihano, Salam, Salgado, PRL120 (2018) 23, 232301
Boosted color singlets from top events

- Energy loss of the $q\bar{q}$ pair $\rightarrow$ shift of reconstructed W mass
- Shift vs. top $p_T$ probes the time-evolution of the QGP density
- A first glimpse at LHC? (possibly with lighter ions)
- Scan entire QGP lifetime at FCC, and up to 6-7 fm/c at HE-LHC

Apolinario, Milhano, Salam, Salgado, PRL120 (2018) 23, 232301
Probing the QGP with Higgs bosons at FCC?

- Higgs lifetime $\tau \approx 50\text{ fm/c} > \text{QGP lifetime} \approx 10\text{ fm/c}$
- Strong interaction with QGP induces decay to $gg$ depleting its decay channels to $\gamma\gamma$ and $ZZ^*$
- Detailed calculation of “absorption” cross section in 2D+1 hydro medium with different EoSs

$\Rightarrow$ suppression by 15% at $p_T<50\text{ GeV/c}$

$\Rightarrow$ see talk by C. Loizides

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- First estimate of significance with FCC reference detector: $\sim 5$ ($10$) $\sigma$ in one Pb-Pb month with baseline (ultimate) $L_{int}$

$\rightarrow$ Promising!

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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:

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

Saturation affects process with $Q^2 < \text{few} \times Q_s^2$

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

→ See talk by M. Klein for complementarity with FCC-he
Searching for saturation with forward di-jet measurements in p-Pb

- Saturation effects $\rightarrow$ azimuthal decorrelation of di-jets
- Focus on di-jets with rapidity 3-5: small-x partons in the Pb
- Decorrelation $k_T$ would be of the order of $Q_s$ (~ few GeV)

C. Marquet et al., based on JHEP 1612 (2016) 034
Constraining nuclear PDFs with top

- Within collinear factorisation, nuclear effects (including high-density effects at small-x) described using nuclear modifications to the proton PDFs:

- Top production measurements at FCC in p-Pb and in Pb-Pb can reduce by a factor ~2 the present uncertainty on the nPDFs at $Q = m_{\text{top}}$, in particular at $x > 0.1$ (EMC region)

D. d’Enterria et al., PLB746 (2015) 64
Summary

◆ Pb-Pb at FCC: 39 TeV; $L_{\text{int}}$ projections $>100x$ LHC programme

◆ Unique studies of the Quark-Gluon Plasma
  - Larger temperature $\rightarrow$ thermal production of charm, Y(1S) melting
  - Larger $\sqrt{s}$ and $L_{\text{int}}$ $\rightarrow$ new hard observables, e.g. top, Higgs, to characterize the QGP

◆ Unique studies of high-density initial state
  - Access to saturation region (down to $x<10^{-6}$) with perturbative probes, e.g. forward-$y$ di-jets
  - Access to [small-$x$, large-$Q^2$] region with top, W, Z

◆ Unique contributions to other sectors of HEP (see Extra Slides)
  - $\gamma\gamma$ collisions (search for axion-like particles, see new limits presented by CMS)
  - Fixed-target collisions with extracted beams or internal gas targets
  - Input to collision models for ultra-high-energy cosmic rays
EXTRA SLIDES
Photon-induced collisions

- Nuclei generate strong EM fields from coherent emission of Z=82 p's
- Photon-induced collisions can occur when two nuclei cross without interacting hadronically

- Huge photon fluxes:
  - $\sigma(\gamma\text{-Pb}) \sim Z^2$ ($\sim 10^4$ for Pb) larger than in pp
  - $\sigma(\gamma\text{-}\gamma) \sim Z^4$ ($\sim 5\cdot10^7$ for Pb-Pb) larger than in pp

- Maximum c.m.s. energies for Pb-Pb at FCC:

  $$\sqrt{s_{\gamma\gamma}} = W_{\gamma\gamma} \sim 1.2 \text{ TeV} \quad \sqrt{s_{\gamma\text{Pb}}} \sim 7 \text{ TeV}$$
γγ physics at FCC (Pb-Pb)

- Effective luminosity $dL_{\text{eff}}/dW_{\gamma\gamma}$ for $\gamma\gamma$ processes from LHC to FCC: $10^2$ at low masses, $10^4$ for Higgs, $10^5$ for ZZ production.

- Unique tests for EW sectors of the SM.

- $\gamma\gamma \rightarrow \gamma\gamma$ process has potential sensitivity to New Physics.

$N_X = \int \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} W_{\gamma\gamma} \sigma_X (W_{\gamma\gamma})$

E.g. $N_{\text{higgs}} > 100$ counts/month:

Fixed-target collisions with FCC beams

- Fixed-target collisions with FCC (or LHC) p or Pb beams could be realized with either:
  - Beam extraction, fast (magnet) or slow (bent crystals technique)
  - Internal gas detectors, à la LHCb-SMOG

<table>
<thead>
<tr>
<th>Nucleon–Nucleon c.m.s. energy ($\sqrt{s_{NN}} = \sqrt{2E_b m_N}$) [GeV]</th>
<th>p@LHC</th>
<th>Pb@LHC</th>
<th>p@FCC</th>
<th>Pb@FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta y_{c.m.s.}^{lab} = \ln(\gamma_{c.m.s.}^{lab} + \sqrt{(\gamma_{c.m.s.}^{lab})^2 - 1})$</td>
<td>4.80</td>
<td>4.33</td>
<td>5.79</td>
<td>5.32</td>
</tr>
</tbody>
</table>

- Luminosity and physics opportunities for LHC case are discussed in detail in the context of the AFTER@LHC proposal

- Heavy ion studies:
  - c.m.s. energy similar to RHIC energies
  - much larger luminosity and access to (very) backward rapidity region would enable unique and high-precision studies, e.g. related to quarkonium production and its cold and hot nuclear matter effects

Thermal charm production?

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium
  
  $gg \rightarrow c\bar{c}$, $q\bar{q} \rightarrow c\bar{c}$ + higher orders

- Up to 50-100% “enhancement” wrt primary charm
- Sensitive to QGP properties: $T$ vs $\tau$, and $\tau_0$

K. Zhou et al., PLB758 (2016) 434
C.M. Ko, Y. Liu, JPG43 (2016) no. 12, 125108
An interesting physics case for top: boosted color singlets in the QGP

2) Testing the role of color coherence

$q$-$\bar{q}$ 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**

Armesto, Casalderrey, Iancu, Ma, Mehtar-Tani, Salgado, Tywoniuk 2010-2014
FCC pA and AA probe ankle-energy and provides strong constraints for hadronic Monte Carlos for UHECR (p,Fe+Air)