Future Facilities: LHC Plans

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for the ALICE, ATLAS, CMS and LHCb collaborations

Hard Probes 2020 (Online)  
June 5th
LHC timeline

- **LHC** injector upgrades:
  - interaction rate up to 50 kHz for PbPb
  - Run 2 <10 kHz for ALICE and up to 35 kHz CMS/ATLAS

- **ALICE** and **LHCb** major upgrades

- **CMS** and **ATLAS** upgrades
  - ALICE and LHCb additional upgrades

Run 3+4 main priority = large PbPb sample (13 nb\(^{-1}\)):
- x100 more statistics for MB for ALICE wrt Run2
- x10 more statistics ATLAS/CMS wrt Run2

\[ \mathcal{L}_{\text{Pb-Pb}} = -1.0 \text{ nb}^{-1} \]
\[ \mathcal{L}_{\text{Pb-Pb}} = 6.0 \text{ nb}^{-1} \]
\[ \mathcal{L}_{\text{Pb-Pb}} = 7.0 \text{ nb}^{-1} \]
Physics program highlights for Run3 and Run4

**ALICE:** rare probes at low $p_T$
- Heavy-flavour (charm and beauty)
- Charmonium
- Di-leptons from QGP radiation
- Light and hyper-nuclei

**LHCb:**
- Fixed target: nPDFs, phase transition scan, Generalised Parton Distributions
- PbPb: going to more central events
- Heavy flavors, quarkonia and exotic states in pPb and more central PbPb

**CMS and ATLAS:**
- Hard probes precise measurements at high $p_T$
- Heavy flavor at low $p_T$
- Rare exotic probes with UPC events for BSM
ALICE Upgrades for Run3

**Inner tracker system upgrade**
- CMOS monolithic active pixel sensors
- Higher granularity and reduced material budget

**Muon forward tracker**
- CMOS monolithic active pixel sensors
- Heavy-flavor vertex reconstruction

**TPC readout**
- GEM based read-out → operate TPC at 50 kHz without gating grid

**FOCAL (Run4) – TDR in preparation**
- Si sensors covering $3.4 < \eta < 5.8$
- Direct photons measurements

**Rare probes at low pT**

**O2 (online-offline) system**
LHCb Upgrades for Run3

**Tracker**
- UT Si-strip, granularity & coverage
- T Scintillating Fiber + SiPMs

**SMOG2**
- Fixed gas target
- Running in parallel with collider mode

**Vertex**
- New Si-pixel system

**PID**
- New photosensors in both RICH
- Modified optics in RICH1

Towards more central events (30-100%)
CMS Upgrades for Run4

Coverage extension

New tracker
- Si-Strip & Pixels increased granularity
- Extended coverage to $\eta \approx 3.8$

High Granularity Calorimeter Endcap
- 5D imaging: energy, time, x, y, z
- Si sensors/plastic scintillator tiles+SiPMs
- 6 millions Si channels

Muon systems
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$

MIP timing detector
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes
ATLAS Upgrades for Run4

**Coverage extension**

**Liquid Argon and Tile calorimeter**
- Increased granularity due to new electronics

**New tracker**
- Si-Strip & Pixels increased granularity
- Extended coverage to $\eta \approx 4$

**Muon systems**
- New electronics
- New inner barrel chambers

**High Granularity Timing Detector**
(TDR in preparation)
- Low Gain Avalanche Diodes $2.4 \leq \eta \leq 4$
ALICE Upgrades: Inner Tracking System

**ALPIDE Monolithic Active Pixel Sensor:**
- Detection efficiency > 99%
- Low fake-hit rate < 10^{-9} /pixel/event

**Commissioning:**
- Fake-rate is stable over time
- Very good uniformity

**Excellent tracking down to very low p_T**

**10m² active silicon area, 12.5x10^9 pixels**

Marco Van Leeuwen’s talk (4 Jun 2020, 11:15)

**Inner barrel replacement:**
- Truly cylindrical detector using thinned, wafer-sized sensors

Tracking efficiency >95% at p_T = 500 MeV/c
Precise determination of production vertex and tracking:

- single $\mu$ offset at primary vertex
- secondary vertices: prompt vs non-prompt J/$\psi$

Identification of forward prompt J/$\psi$

920 silicon pixel sensors (0.4 m$^2$) on 280 ladders of 2 to 5 sensors each

10 Half-disks — 2 detection planes each

MFT doses
- $< 300$ krad
- $< 2 \times 10^{12}$ 1 MeV $n_{eq}/cm^2$

Bottom half MFT already assembled and installed on surface at CERN
ALICE : TPC readout

50 kHz PbPb → continuous readout → Gas Electron Multiplier readout instead of Wire gating grid

Combination of standard and large pitch GEM foils:

New GEM readout:

- Result of intensive R&D
- Highly optimized HV configuration to keep Ion Back-Flow (IBF) < 1%
- Preserves momentum resolution for TPC+ITS combined tracks
- Preserves particle identification via dE/dx

[AlICE-TDR-016]

LHCb: Tracking system

VELO: in Run3 will not be saturated in central PbPb
Upgrade:
- Silicon pixel detector, 55x55 μm² pixels
- Closest pixels at 5.1 mm from the beam line

SciFi: saturate in the most central PbPb (0-30%)
Upgrade:
- 11000 km of ∅250 mm scintillating fibers with SiPM
- SiPM cooled down to -40° to reduce the dark current

Run5: no saturation expected after the MIGHTY tracking detector installation

Plateau: sign of saturation
Upgrade of the SMOG target by adding the **storage cell**:

- Increase the gaz density by factor 100, keeping the same gas flow
- Possibility to run in parallel with pp collisions and inject non noble gaz

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**Cold nuclear matter effects with higher precision**

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**20 cm long, with 5 mm radius around the beam, 30 cm away from IP made of two retractable halves**

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*Samuel Belin’s talk (4 Jun 2020, 10:55)*

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### Integrated luminosity

<table>
<thead>
<tr>
<th></th>
<th>SMOG released result</th>
<th>SMOG largest sample</th>
<th>SMOG2 example</th>
</tr>
</thead>
<tbody>
<tr>
<td>pHe@87 GeV</td>
<td>~7.6 nb(^{-1})</td>
<td>~100 nb(^{-1})</td>
<td>~45 pb(^{-1})</td>
</tr>
<tr>
<td>pNe@69 GeV</td>
<td>7%</td>
<td>6 - 7%</td>
<td>2 - 3 %</td>
</tr>
<tr>
<td>pAr@115 GeV</td>
<td>15k</td>
<td>150k</td>
<td>150M</td>
</tr>
<tr>
<td></td>
<td>100k</td>
<td>15M</td>
<td>1.5M</td>
</tr>
<tr>
<td></td>
<td>1k</td>
<td>1k</td>
<td>7k</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>9k</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9k</td>
<td></td>
</tr>
</tbody>
</table>
LHCb: new physics opportunities with SMOG2

QGP and phase transition

Hadronic physics: Generalised Parton Distributions

Rapidity scan at 72 GeV can complement the RHIC beam energy scan

nuclear PDFs and Generalized Parton Distributions at large Bjorken-x
CMS and ATLAS: tracking systems

ATLAS and CMS:

- Si-sensors: 3D inner pixel layer, thinner, granularity x4 to 6
- Pixel coverage extension to $\eta \approx 4$

$B_0/B_s$ separation in pp collisions (CMS)

Tracking reconstruction efficiency (ATLAS)

- ~20% for $|\eta|<1$ and ~30% for $|\eta|\sim 2$ improvement

50% improvement in mass resolution, same improvement is expected in PbPb $\rightarrow$ Y(3S) observation?
CMS and ATLAS: precise ToF MIP

- Designed for pile-up mitigation

**ATLAS HGTD**: $2.4 < \eta < 4.0$; TDR in preparation

**CMS MTD**: hermetic up to $\eta = 3$ → PID of protons up to $p_T \approx 5$ GeV; pions and kaons up to $p_T \approx 2.5$ GeV

| Experiment | $|\eta|$ coverage | $L$ at $\eta = 0$ (m) | $\sigma_T$ (ps) | $L/\sigma_T \times 100$ |
|------------|------------------|----------------------|----------------|------------------------|
| CMS        | $|\eta| < 3.0$     | 1.16                 | 30             | 3.9                    |
| ALICE      | $|\eta| < 0.9$    | 3.7                  | 56             | 6.6                    |
| STAR       | $|\eta| < 0.9$    | 2.2                  | 80             | 2.2                    |

CMS MTD to probe charm hadronization effects:

- Precision in mid-rapidity is significantly improved → competitive to ALICE (including Phase2 upgrades)
- Gives insights into the forward region → complimentary to ALICE

Geonhee Oh's talk
(4 Jun 2020, 11:35)
CMS and ALICE: High Granularity Calorimeter

**CMS HGCal** = ECAL and HCAL in the endcaps

Completely new type of calorimeters, based on Si-sensors with 6 millions channels

**ALICE FOCAL** design: similar to CMS HGCal one (rapidity range 3.4-5.8) → direct photon measurement at low $p_T$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>Improvement in pp: up to 25%</th>
</tr>
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<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
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</table>

5% accuracy ($p_T > 5$ GeV) on the direct photon measurement

Gluon density in protons and Pb nuclei at $x \sim 10^{-5}$:
gluon saturation and non-linear effects in the gluon density may become apparent

Estimated saturation scale for Pb
Estimated saturation scale for proton
<table>
<thead>
<tr>
<th>LHC experiments: Trigger, DAQ and Computing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run3+4 statistics goals</td>
</tr>
</tbody>
</table>
| ALICE | 100B MB events | New Online-Offline system:  
  • data readout, compression, processing, data volume reduction > an order magnitude |
| LHCb | pPb/Pbp: x20 more statistics | New Fast Interaction Trigger Detector (instead of T0 and V0)  
Continuous readout |
| CMS and ATLAS | • x10 more statistics for triggerable probes  
• Large MB sample | In Run4: L1 and HLT read-out rates x10 wrt Run2  
SMOG2: simultaneous runs with collision mode |
Summary

- **ALICE and LHCb upgrades** for Run3 are already in the commissioning phase
- **CMS and ATLAS upgrades** are in the R&D and production phase, to be installed for Run4
- Higher LHC luminosity and enhanced readout capabilities of all detectors → **very high statistics**

High precision measurements of the QGP properties with standard candles and new rare probes

And many more topics to explore:

- Extension of “small systems” program: pPb, OO (and pO) run, pp 14 TeV low-PU run …
- Hadronic physics with SMOG2
- BSM searches in PbPb UPC collisions
- ...

Thanks to: M. van Leeuwen, J. Klein, S. Panebianco and M. Winn (ALICE), I. Cali and M. Nguyen (CMS), B. Audurier (LHCb)
Additional slides ahead …
## Proposal for future luminosity at LHC from WG5

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{\text{NN}}}$</th>
<th>Time</th>
<th>$L_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>3 weeks</td>
<td>2.3 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2022</td>
<td>Pb–Pb 5.5 TeV, O–O, p–O</td>
<td>5 weeks</td>
<td>3.9 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>500 µb$^{-1}$ and 200 µb$^{-1}$</td>
</tr>
<tr>
<td>2023</td>
<td>p–Pb 8.8 TeV, pp 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>1.5 pb$^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2027</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>5 weeks</td>
<td>3.8 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2028</td>
<td>p–Pb 8.8 TeV, pp 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>1.5 pb$^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2029</td>
<td>Pb–Pb 5.5 TeV</td>
<td>4 weeks</td>
<td>3 nb$^{-1}$</td>
</tr>
<tr>
<td>Run-5</td>
<td>Intermediate AA, pp reference</td>
<td>11 weeks</td>
<td>e.g. Ar–Ar 3–9 pb$^{-1}$ (optimal species to be defined)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td></td>
</tr>
</tbody>
</table>

CERN-LPCC-2018-07
ALICE: ALPIDE (ALICE Pixel Detector)

- Developed for the ALICE upgrade (ITS and MFT)
- 130,000 pixels/cm²
- Max. particle rate: ~ 100 MHz/cm²
- Spatial resolution: ~ 5 μm
- Thickness: 50 μm for the inner layers
- Fake-hit rate: < 10⁻⁹/pixel/event

10 m² active silicon area, 12.5×10⁹ pixels

Improves vertex and tracking precision, faster readout:

- Closer to IP: 39 mm → 22 mm
- Pseudorapidity coverage: -1.0 ≤ η ≤ 1.0 → -1.4 ≤ η ≤ 1.4
- Thinner: for innermost layers ~ 1.14% X₀ → ~0.35% X₀
- Smaller pixels: 50 × 425 μm² → 27 × 29 μm²
- Granularity: 20 ch/cm³ → 2000 pixels/cm³
- Readout rate: 1 kHz → 100 kHz
ALICE : Gas Electron Multiplier for TPC readout

Today’s readout-electronics for gaseous detectors aren’t sensitive to \( \sim \) single electrons

\[ \rightarrow \text{Primary ionisation needs to be amplified} \]
\[ \rightarrow \text{Increase the kinetic energy of primary electrons until they further ionise the gas} \]
\[ \rightarrow \text{Transport the electrons into a region with high electric field to provide the electrons with enough kinetic energy to create electron multiplication} \]

Requirements for TPC readout :

- Nominal gain = 2000
- Ion backflow < 1%
- Energy resolution : \( \sigma_E/E < 12\% \) for \( ^{55}\text{Fe} \)
- Stable operations
ALICE: data flow

Reading out PbPb collisions at rates of 50kHz, sampling the pp and pPb at up to 200kHz. The resulting data throughput from the detector: > 1TB/s for PbPb events.

- **Detector**: Front-end electronics send data according to time intervals and/or trigger over ~ 8100 read-out links.
- Local aggregation of data from up to 48 optical links per **First Level Processor** in Timeframes; Local reconstruction and calibration.
- **Switching Network**: Physical transportation of timeframe data.
- **Event processing node**: Aggregation of all sub-timeframes and global reconstruction of the full Timeframe data sample.
- Intermediate/permanent **storage** of pre-processed and compressed data.
ALICE : Fast Integration Trigger (FV0, FT0, FDD)

Upgrade of the existing T0 and V0 and AD detectors:

- Luminosity leveling
- Identification of diffractive processes
- Fast Interaction Trigger with latency < 425 ns:
  - Online vertex determination
  - Minimum bias and centrality selection
  - Rejection of beam/gas events
  - Veto for ultra peripheral collisions
- Multiplicity → Centrality and Event Plane
- Collision time for Time-Of-Flight particle ID
ALICE: ITS3

- Smaller beam pipe diameter
- Sensor thickness 20 - 40 μm (0.02 - 0.04% $\chi_0$)
- Total material up to r~4 cm reduced by a factor of 3
- Material homogeneously distributed
  → essentially zero systematic error from material distribution
- Plug-in replacement of the current Inner Barrel

- Pointing resolution x2 better
- Improved tracking efficiency for low momenta

Improved physics performance for heavy-flavour baryons and low-mass dielectrons
ALICE : FOCAL

FoCal: forward electromagnetic and hadronic calorimeters

→ FoCal-E: high-granularity Si-W sampling calorimeter for the measurement of direct $\gamma$ and $\pi^0$

→ FoCal-H: Pb-Sc sampling calorimeter for photon isolation and jets

Main challenge: separate $\gamma$ and $\pi^0$ at high energy

• two photon separation from $\pi^0$ decay $\sim 2$ mm
• needs small Molière radius and high granularity readout
• Si-W calorimeter with effective granularity $\sim 1$ mm$^2$

Timeline: TDR end of 2021
ALICE : FOCAL

FoCal: forward electromagnetic and hadronic calorimeters

→ **FoCal-E**: high-granularity Si-W sampling calorimeter for the measurement of direct $\gamma$ and $\pi^0$

→ **FoCal-H**: Pb-Sc sampling calorimeter for photon isolation and jets

**Deep-Inelastic Scattering (DIS):**

- Classical PDF method
- Not sensitive to gluons at LO
- Gluons from NLO

**Photon production in hadronic collisions:**

- **Sensitive to gluons at LO**
Next generation HI detector

- EoI for a “all silicon” detector to be installed during LS4, input to the European Strategy Update
- Increase rate capabilities: factor 50 wrt to ALICE Run 4
- Tracker: ~10 tracking barrel layers based on MAPS
- TOF PID – few barrel layers instrumented with silicon sensors: $\sigma_\tau < 30$ ps
- High-granularity shower pixel detector for e/\gamma identification

Physics: from EM probes at ultra-low $p_T$ to precision physics in charm and beauty sector
LHCb: MIGHTY silicon tracker starting from Run4

Composed of a silicon central region (Inner Tracker and Middle Tracker) and an outside part with SciFi

New Upstream Tracker for Run3 (based on Si strip sensors)

Upgrade Ib: Inner Tracker + Scifi

Upgrade II: New mighty silicon tracker covering larger area.
LHCb : Magnet Tracking Station for Run4

Proposal for tracking station inside the magnet:

- Triangular Extruded Scintillating Bars
- Increase coverage of low-\(p_T\) tracks.
- Physics motivations: access to converted photons.

Proposing the installation of a small prototype inside the magnet during LS3.
LHCb : Time of Reflected Cerenkov Light Rich (TORCH)

Wall of 18 elements in front of RICH2:

- Exploit prompt production of Cherenkov light in a quartz radiator plate to provide a fast timing signal.
- **Aim for a resolution of 10-15 ps per track**
- A large-scale prototype has been developed

Good separation between pion/K/p is possible in 2-10 GeV/c range
CMS: tracker upgrade

Material budget:
- Fewer layers
- Lighter materials
- Optimized service routing
- New geometry

Radiation level:
- $1000 \text{ fb}^{-1}$ limit → $3000 \text{ fb}^{-1}$ limit

Number of channels:
- 10 million → 200 million

Forward coverage:
- $|\eta| < 2.5$ → $|\eta| < 4$
CMS : HGCAL

Sampling calorimeter consists of:

- 28 layers Si-based EM compartment (CE-E), ~25X₀ and ~1.3λ
- 22 layers hadronic compartment (CE-H): Si-based + Scintillator tiles, ~8.5λ

- ~620 m² Si sensors in ~30k channels
- **6M Si channels of 0.5/1 cm² cell size**
- ~400 m² of scintillators in 4k boards
- ~240k scintillators channels, 4-30 cm² cell size
- Operating temperature: -35 C
## CMS : Trigger and DAQ upgrade

<table>
<thead>
<tr>
<th>CMS detector</th>
<th>LHC Run-2</th>
<th>HL-LHC Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak $\langle PU \rangle$</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>L1 accept rate (maximum)</td>
<td>100 kHz</td>
<td>500 kHz</td>
</tr>
<tr>
<td>Event Size</td>
<td>2.0 MB $^a$</td>
<td>5.7 MB $^b$</td>
</tr>
<tr>
<td>Event Network throughput</td>
<td>1.6 Tb/s</td>
<td>23 Tb/s</td>
</tr>
<tr>
<td>Event Network buffer (60 seconds)</td>
<td>12 TB</td>
<td>171 TB</td>
</tr>
<tr>
<td>HLT accept rate</td>
<td>1 kHz</td>
<td>5 kHz</td>
</tr>
<tr>
<td>HLT computing power $^c$</td>
<td>0.5 MHS06</td>
<td>4.5 MHS06</td>
</tr>
<tr>
<td>Storage throughput</td>
<td>2.5 GB/s</td>
<td>31 GB/s</td>
</tr>
<tr>
<td>Storage capacity needed (1 day)</td>
<td>0.2 PB</td>
<td>2.7 PB</td>
</tr>
</tbody>
</table>

$^a$ Design value.

$^b$ Obtained by scaling the Event Size at $\langle PU \rangle = 200$ with pile-up (140/200), except for sub-detectors with fixed size readout.

$^c$ Does not include Data Quality Monitoring.

[CMS-TDR-018]