Prospectives for heavy-ion physics at LHCb in LHC Run 3-Run 4

Benjamin Audurier*, Laboratoire Leprince-Ringuet

Prospectives QGP France - Orsay - 11 Dec. 2019
The LHCb detector

- Track reconstruction **down to** $p_T = 0$
- Excellent $p_T$ and mass resolution.
- Excellent particle identification.
- Precision vertex reconstruction.

LHCb: single arm spectrometer **fully instrumented** in pseudo-rapidity range $2 < \eta < 5$
The LHCb detector

Can operate both in pp/pPb/PbPb and fixed-target!

Fixed-target mode: unique at LHC!
- Injecting gas in the LHCb VErtex LOcator (VELO) tank.
- Noble gas only: He, Ne, Ar
- Gas pressure: $10^{-7}$ to $10^{-6}$ mbar.
# List of publications

## Published papers

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<tr>
<th>TITLE</th>
<th>DOCUMENT NUMBER</th>
<th>JOURNAL</th>
<th>SUBMITTED ON</th>
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<tbody>
<tr>
<td>Prompt $\Lambda_c^+$ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV</td>
<td>PAPER-2018-021 arXiv:1809.01404 [PDF]</td>
<td>JHEP 02 (2019) 102</td>
<td>05 Sep 2018</td>
<td>23 [plot]</td>
</tr>
</tbody>
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## Conference notes

<table>
<thead>
<tr>
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<tr>
<td>Multiplicity-dependent modification of $p_T$ ($\psi(2S)$) and $\eta_c(1S)$ production in pp collisions at $\sqrt{s} = 8$ TeV</td>
<td>CONF-2019-005</td>
<td>14 Nov 2019</td>
<td></td>
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<tr>
<td>Study of prompt $D^0$ meson production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV at LHCb</td>
<td>CONF-2019-004</td>
<td>12 Nov 2019</td>
<td></td>
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<tr>
<td>Measurement of $Z$ production cross-sections in proton-lead collisions at $\sqrt{s_{NN}} = 8.16$ TeV</td>
<td>CONF-2019-003</td>
<td>12 Nov 2019</td>
<td></td>
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<tr>
<td>LHCb projections for proton-lead collisions during LHC Runs 3 and 4</td>
<td>CONF-2018-005</td>
<td>22 Nov 2018</td>
<td>1 [plot]</td>
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<tr>
<td>Study of coherent $J/\psi$ production in lead-lead collisions at $\sqrt{s_{NN}} = 5$ TeV with the LHCb experiment</td>
<td>CONF-2018-003</td>
<td>25 May 2018</td>
<td>16 [plot]</td>
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<tr>
<td>Prompt $\Lambda_c^+$ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV</td>
<td>CONF-2017-005</td>
<td>01 Sep 2017</td>
<td>7 [plot]</td>
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<tr>
<td>LHCb dimuon and charm mass distributions</td>
<td>CONF-2016-005</td>
<td>19 Jul 2016</td>
<td>2 [plot]</td>
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<tr>
<td>Reference pp cross-sections for $Y(1S)$ studies in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV and comparisons between ALICE and LHCb results</td>
<td>CONF-2014-003</td>
<td>08 Aug 2014</td>
<td>5 [plot]</td>
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<td>Reference pp cross-sections for $J/\psi$ studies in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV and comparisons between ALICE and LHCb results</td>
<td>CONF-2013-013</td>
<td>22 Dec 2013</td>
<td>20 [plot]</td>
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<tr>
<td>First analysis of the pPb pilot run data with LHCb</td>
<td>CONF-2012-034</td>
<td>03 Dec 2012</td>
<td>8 [plot]</td>
</tr>
</tbody>
</table>

- 12 papers
- 10 notes
- Link to all documents
Open and hidden charm production in pPb collisions

❖ Preliminary results for $D^0$ cross-section in pPb/Pbp collisions at $\sqrt{s_{NN}} = 8$ TeV up to $p_T = 16$ GeV/c.

❖ Improved statistics by factor 20 compared to previous LHCb results.

❖ Tension between data and nPDFs predictions. Additional effects required.

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Highlights of ongoing analysis ...

❖ $\chi_{c1}$ and $\chi_{c2}$ peaks observed in pPb/Pbp collisions with converted and non-converted photons.

Analysis ongoing, stay tuned!
Highlights of ongoing analysis ...

Compact tetraquark/pentaquark

Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)

Hadronic Molecules
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Hadrocharmonium/adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)
X(3872) : exotic state still not understood.

- Tetraquark / hadronic molecule / something else?
Highlights of ongoing analysis ...

- X(3872) : exotic state still not understood.
  - Tetraquark / hadronic molecule / something else ?
- \(X(3872) / \psi(2S)\) ratio versus \(N_{\text{tracks}}\) measured in pp collisions at \(\sqrt{s} = 8\) TeV.
  - No significant variation is observed for the non-prompt component.
  - Hint of a relative suppression with event activity for prompt component.

\[ \begin{align*}
\text{LHCb preliminary pp } \sqrt{s} &= 8 \text{ TeV} \\
\end{align*} \]
Highlights of ongoing analysis …

❖ X(3872) : exotic state still not understood.
   - Tetraquark / hadronic molecule / something else ?

❖ X(3872) /ψ(2S) ratio versus N_{tracks} measured in pp collisions at √s = 8 TeV.
   - No significant variation is observed for the non-prompt component.
   - Hint of a relative suppression with event activity for prompt component.

❖ Baseline for a future pPb analysis !
LHCb physics program

- Large variety of samples to study!
- **Two new samples**: PbNe at $\sqrt{s_{NN}} = 68.6$ GeV and PbPb at $\sqrt{s_{NN}} = 5.02$ TeV.

~ 20 times 2015 luminosity
Status in nucleus-nucleus collisions
Studies in PbPb limited to 60% less central collisions.
Status in nucleus-nucleus collisions

Studies in PbPb limited to 60% less central collisions.

LHCb preliminary \( \sqrt{s_{NN}} = 5 \text{ TeV} \)

PbPb \( 60\% < \text{centrality} < 90\% \)
\( p_T^{\text{jet}} < 15 \text{ GeV/c} \)
\( 2.0 < y_{\text{jet}} < 4.5 \)

LHCb preliminary \( \sqrt{s_{NN}} = 5 \text{ TeV} \)

\( \Lambda_c \text{ signal} \approx 600 \Lambda_c \text{ background} \)

\( \approx 15k J/\psi \)

2018 data

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Status in nucleus-nucleus collisions

Studies in PbPb limited to 60% less central collisions.

Analysis ongoing, stay tuned!

~15k J/ψ

~600 Λ_c

~700 J/ψ
### The future: Precision era

**Upgrade 1a**  
**LS2**  
**Run 3**

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>3 weeks</td>
<td>3.9 $\text{pb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>O–O, p–O</td>
<td>1 week</td>
<td>250 $\mu\text{b}^{-1}$ and 200 $\mu\text{b}^{-1}$</td>
</tr>
<tr>
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<td>p–Pb 8.8 TeV, pp 8.8 TeV</td>
<td>3 weeks</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>1.5 $\text{pb}^{-1}$ (ALICE), 100 $\text{pb}^{-1}$ (ATLAS, CMS, LHCb)</td>
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**Upgrade 1b**  
**LS3**  
**Run 4**

<table>
<thead>
<tr>
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<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
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</thead>
<tbody>
<tr>
<td>2027</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>5 weeks</td>
<td>3.8 $\text{nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>O–O, p–O</td>
<td>1 week</td>
<td>300 $\text{pb}^{-1}$ (ATLAS, CMS), 25 $\text{pb}^{-1}$ (LHCb)</td>
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<tr>
<td>2028</td>
<td>p–Pb 8.8 TeV, pp 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 $\text{pb}^{-1}$ (ATLAS, CMS), 0.3 $\text{pb}^{-1}$ (ALICE, LHCb)</td>
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<td></td>
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</tbody>
</table>

**Upgrade 2**  
**LS4**

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2029</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>4 weeks</td>
<td>3 $\text{nb}^{-1}$</td>
</tr>
</tbody>
</table>

**Run-5**  
Intermediate AA pp reference  
11 weeks  
1 week  
e.g. Ar–Ar 3–9 $\text{pb}^{-1}$ (optimal species to be defined)
LHCb is well placed for a **decisive contribution** to Heavy-ion Physics in Run 3 and Run 4.

### The future: Precision era

<table>
<thead>
<tr>
<th>Upgrade</th>
<th>LS</th>
<th>Year</th>
<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
<th>$L_{int}$</th>
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</thead>
<tbody>
<tr>
<td>1a</td>
<td>LS2</td>
<td>2021</td>
<td>Pb–Pb 5.5 TeV</td>
<td>3 weeks</td>
<td>2.3 nb$^{-1}$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>pp 5.5 TeV</td>
<td>1 week</td>
<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
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<tr>
<td>1b</td>
<td>LS3</td>
<td>2022</td>
<td>Pb–Pb 5.5 TeV</td>
<td>5 weeks</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>O–O, p–O</td>
<td>1 week</td>
<td>500 $\mu$b$^{-1}$ and 200 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>LS4</td>
<td>2023</td>
<td>p–Pb 8.8 TeV</td>
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<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
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<td></td>
<td></td>
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<td>few days</td>
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<td></td>
<td></td>
<td></td>
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<td>1 week</td>
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</table>
The future : Precision era

LHCb is well placed for a decisive contribution to Heavy-ion Physics in Run 3 and Run 4

- **Best placed for pp and pPb collisions at forward rapidity down to low-p_T**
  - In pPb: $L_{pPb} \sim 30 \text{ nb}^{-1}$ in Run 2 ($\sim 1M J/\psi \rightarrow L_{pPb} \sim 300 \text{ nb}^{-1}$ in Run 3 and $\sim 300 \text{ nb}^{-1}$ Run 4
- **Well placed** (less limited) in PbPb collisions at forward
  - See next slides.
- **Full physics program in fixed-target.**
Run 3 prospects for heavy-ion physics with LHCb

**EPPS16 nPDF prediction at NLO**

- **Drell-Yan production in pPb collisions.**
  - Forward rapidity: access shadowing region.
  - Backward rapidity: access to EMC effect.

- Other studies in this document:
  - $D_0$-$\overline{D}_0$ correlations.
  - B$^+$ meson productions.

- Projections show valuable inputs for nPDF fit with limited data taking periods.

**Luminosity:**
- pPb: 500 nb$^{-1}$ (4 weeks)
- pp: 104 pb$^{-1}$ (much shorter time)
LHCb Upgrade 1a
LHCb detector: season 3 (2021)

- Upgrade based on pp collision requirements:
  - Collision rate at 40 MHz.
  - Pile-up factor $\mu \approx 5$

- Replace the entire tracking system.

- Full software trigger.
  - Remove L0 triggers.
  - Read out the full detector at 40 MHz.

New Tracking system:
- Silicon upstream detector (UT)
- Scintillating tracking fibre (SciFi)

New pixel VELO

New RICH optics and photodetectors

New electronics for muon and calorimeter systems
Tracking system: Scintillating fibre tracker (SciFi)

- ~10000 km of scintillating fibres arranged in 6 layers with silicon photo-multipliers (SiPM) readout.
- 3 stations.
- 4 detection layers per station arranges in x-u-v-x configuration per stations.
- 10 modules of 2x4 mats.
Run 3 prospects for heavy-ion physics with LHCb
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Run 3 prospects for heavy-ion physics with LHCb

- **No significant saturation** of the new LHCb detectors **up to 30%!**
- Two proposals for a new tracker (see next slides):
  - In 2024 → reach event more central collisions!
  - In 2030 → no more limitations!
SMOG 2 (TDR): Standalone gas storage cell covering $z \in [-500;-300]$ mm:

- Up to x100 higher gas density with same gas flow of current SMOG.
- Gas feed system measures the gas density with few % accuracy.
- Possibility to run in parallel of pp collisions and inject non noble Gaz.

Installation due in December 2019, to be operational from the start of LHC Run 3.

<table>
<thead>
<tr>
<th>Int. Lumi.</th>
<th>80 pb⁻¹</th>
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</thead>
<tbody>
<tr>
<td>Sys.error of $J/\Psi$ xsection</td>
<td>~3%</td>
</tr>
<tr>
<td>$J/\Psi$ yield</td>
<td>28 M</td>
</tr>
<tr>
<td>$D^0$ yield</td>
<td>280 M</td>
</tr>
<tr>
<td>$\Lambda_c$ yield</td>
<td>2.8 M</td>
</tr>
<tr>
<td>$\Psi'$ yield</td>
<td>280 k</td>
</tr>
<tr>
<td>$Y(1S)$ yield</td>
<td>24 k</td>
</tr>
<tr>
<td>$DY \mu^+\mu^-$ yield</td>
<td>24 k</td>
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Run 3 prospects for SMOG2 with LHCb
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Rapidity scan
Run 3 prospects for SMOG2 with LHCb

Rapidity scan at 72 GeV with FT@LHCb can complement the RHIC beam energy scan.

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Run 3 prospects for SMOG2 with LHCb

Rapidity scan

Deep in the hadronic structure

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Deep in the hadronic structure

One of the objectives: 3D pictures in impact parameter space.
Run 3 prospects for SMOG2 with LHCb

Rapidity scan

- Rapidity scan at 72 GeV with FT@LHCb can complement the RHIC beam energy scan.

Deep in the hadronic structure

- SMOG2@LHCb could probe nuclear PDFs, TMDs, GPDs at large Bjorken-x.

One of the objectives: 3D pictures in impact parameter space.
LHCb Upgrade 1b and 2

Upgrade I:
- $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Pile-up = 5

Upgrade II:
- $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Pile-up = 42
Phase II in a nutshell

Sub detectors considering timing:
- Before the magnet:
  - VELO, RICH1
- After the magnet:
  - TORCH, RICH2, ECAL
Magnet Tracking Station

- 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.

Extended acceptance
Extended coverage
MIGHTY Tracker

- MIGHTY tracker: biggest silicon tracker built by LHCb.
  - Upgrade 1b: Inner Tracker + Scifi.
    - DMAPs technology for silicon sensors.
  - Upgrade II: New mighty silicon tracker covering larger area.
    - Rebuild of SciFi + reuse IT.
- Hybrid technology detector, many challenges!
- First estimations show no limitation in centrality reach with the complete MIGHTY.
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- **LHCb has greatly contribute to heavy-ion physics.**
  - Precise measurements in the **heavy-flavour sector** in pPb and fixed-target.
  - Limitations of the current detector to the 70% most peripheral PbPb collisions.
  - No limitation in **Pb-SMOG** collisions.
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❖ **LHCb physics program is expanding.**
  - Many ongoing analysis in pPb collisions.
  - Two new datasets to explore: PbPb at $\sqrt{s_{NN}} = 5$ TeV and PbNe at $\sqrt{s_{NN}} = 86$ GeV.
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❖ **LHCb’s future is bright and full of opportunities!**
  - **New detector** with **new tracking/PID system** driven by pp physics.
  - **Improved fixed-target program with SMOG2.**
  - **Better performances expected** for Run 3 in high-multiplicity collisions.
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Extended capabilities of the detector = expansion of the physics program!
Back-up
Open and hidden beauty production in pPb collisions

- Relative production of upsilon states to test cold (hot ?) nuclear matter effects in pPb collisions.
- Relative $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ suppression measured in pPb and PbP at $\sqrt{s_{NN}} = 8$ TeV down to zero $p_T$.
- Good agreement between data and predictions when including co-movers effects.
- Beauty mesons and baryon measured in pPb/Pbp collisions at $\sqrt{s_{NN}} = 8$ TeV.
- Extensive studies show good agreement between data and model predictions.
Fixed-target results

**Antiproton in pHe at $\sqrt{s_{NN}} = 110$ GeV**

- Antiproton cross-sections in pHe: key to constrain dark matter search in cosmic flux.
  - Data constrain extrapolations from pp to pHe cross-sections.
  - Data constrain empirical parameterization for scaling violation of cross-sections.

**Charm in pHe at $\sqrt{s_{NN}} = 86.6$ GeV**

- Open-charm production in fixed-target LHCb acceptance: access to **anti-shadowing** and **intrinsic charm** content in the nucleons.
- **Precise** $J/\psi$ and $D^0$ measurements in pHe.
- **Good agreement** between data and theory with **no strong intrinsic charm** contribution observed.

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Tracking system: Vertex Locator (VELO)

- Silicon pixel detector, 41 M 55 x 55 $\mu$m$^2$ pixels.
- Closest pixels at 5.1 mm from the beam line.
- Aluminium foil to protect the Velo without interfering with the beam.
- Sensors to be kept $<-20^\circ$C
- **Total data rate**: 2.8 Tb/s
Tracking in LHCb

- Many types of tracks in LHCb, the most important ones are
  - Long tracks.
  - Downstream tracks

- Tracking steps:
  - Finding a track: Forward Tracking algorithm.
    - Combine VELO seeds with hits in the T-stations
    - Match VELO tracks and seeds from T-stations
  - Fitting a track: Kalman filter.
TORCH is a large area time of flight detector that is designed to provide PID in the GeV/c momentum range

- Considered for use in Upgrade Ib.
- 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.
- Test-beam ongoing
- Good separation between between $\pi/K/p$ is possible in 2-10 GeV/c range.
Upgrade II VELO faces significant mechanical challenges

- huge impact on the design and R&D.

Track timing will be crucial

- PV timing and associations, displaced track trigger etc.

- Difficult question to address that will impact the design.

- Other issues: cooling, radiations …

Typical B meson flight time ~15ps

Two-technology concept

\[ \sigma_z(\text{lumi region}) \approx 45 \text{ mm} \]
\[ \sigma_t(\text{lumi region}) \approx 190 \text{ ps} \]
Trigger scheme

**L0 Hardware Trigger:** 1 MHz readout, high Energy signatures
- 450 kHz $h^\pm$
- 50 kHz $\mu/\nu$
- 150 kHz $e/\gamma$

**Software High Level Trigger**
- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers
- 12.5 kHz (0.6 GB/s) to storage

**Software High Level Trigger**
- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections
- Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers
- 2-5 GB/s to storage

**Partial event reconstruction**
- Data preparation for tracking
- Track reconstruction
- Efficient event selection to reduce the rate to between 500 - 1000 kHz

**Full event reconstruction**
- Best tracking performance, add PID information
- Offline quality selections
- Physics analysis on output of the trigger

Re use the Run II strategy
Real Time Analysis (RTA)