“ALICE et la physique des ions lourds”
A-A, p-A and pp

OPEN-PHO-EXP-2015-013
Outline

Part A - Introduction: QCD+QGP experimentation
Part B - Runs 1+2 status and outcome
Part C - Runs 3+4 preparation and physics perspectives
Part A – QCD+QGP experimentation
I.0 – Intro: QCD fundamental questions

- How does the complexity emerge from the dynamics of the strong interaction? *(phase diagram of nuclear matter)*

- Can one probe the fundamental symmetries of the QCD Lagrangian and study the QCD vacuum?

Symmetry Z3
deconfinement

Wuppertal-Budapest coll.,
*arXiv:1007.2580*

Chiral symmetry
dynamic mass of the quarks

*Weise, arXiv:1009.6201*

2 symmetries broken under normal conditions, but 2 symmetries whose *restoration* = accessible in the lab → uniqueness in HEP!
I.1 – Experimental intro: Bjorken scenario

Deconfinement + thermodynamics at ~equilibrium

→ Remark:
No such thing as a QGP-live vision!
but always, an observation based on remnants from the past ...

(NB: physics \( \sim 10^{-23} \) s
/electronic readout \( > 10^{-12} \) s)
At the same $\sqrt{s_{\text{NN}}}$, the *plain* question is:

$$(p+p) \times N \neq 1 \times (\text{Pb}+\text{Pb}) ?$$
1.3 – Exp^al intro: continuum of physics?

1. pp, Min. Bias
2. pp, High Multiplicity
3. p-Pb
4. Pb-Pb, low centrality
5. Pb-Pb, most central events

\[ \frac{dN_{\text{ch}}}{d\eta} \text{ in Cu-Cu at RHIC} \approx \frac{dN_{\text{ch}}}{d\eta} \text{ in pp 7 TeV high mult!} \]
I.4 – Exp al intro : $dN_{\text{ch}}/d\eta = f(\eta_{\text{LAB}})$

$\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

$\frac{dN_{\text{ch}}}{d\eta} \approx 1600$

in 0-5%

$\frac{dN_{\text{ch}}}{d\eta} \approx 600$

in 20-30%

$\frac{dN_{\text{ch}}}{d\eta} \approx 13$

in 80-90%

$\frac{dN_{\text{ch}}}{d\eta} \approx 4-5$

$\rightarrow i.e. N_{\text{ch,TOT}}(0-5\%) = f \frac{dN_{\text{ch}}(0-5\%)}{d\eta}$

$= 17170 \pm 770 \text{ ch. particles}$

(ALICE, arXiv:1509.07299)

$\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
II.1 – ALICE: the experiment and the collaboration

41 countries
178 institutes
≈1.5 x10³ members
II.2 – ALICE: ALICE campaigns in LHC runs 1+2

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

2009

2010

2011

2012

2013

2014

pp $\sqrt{s} = 0.9$ TeV

7 TeV

pp $\sqrt{s} = 2.76$ TeV

8 TeV

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

1 day, pilot run

LS1
II.2 – ALICE: ALICE campaigns in LHC runs 1+2

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>√s_{NN} (TeV)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>pp</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>pp</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>pp</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>pp</td>
<td>2.76</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb</td>
<td>5.02</td>
<td>1 day, pilot run</td>
</tr>
<tr>
<td>2014</td>
<td>Pb-Pb</td>
<td>5.02</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>pp</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>pp</td>
<td>5.02</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>pp</td>
<td>5.02</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>Pb-Pb</td>
<td>5.02</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>Xe-Xe</td>
<td>5.44</td>
<td></td>
</tr>
</tbody>
</table>

Note: √s = energy of the collision, √s_{NN} = energy per nucleon pair.
II.2 – ALICE: ALICE campaigns in LHC runs 1+2

ALICE objectives for Runs 1+2:

- 1 nb⁻¹ in Pb-Pb + “track-equivalent” $\mathcal{L}_{\text{int}}$ in pp
- pp campaigns at reference $\sqrt{s}$
- p-Pb campaigns
II.2 – ALICE: ALICE campaigns in LHC runs 1+2

ALICE objectives for Runs 1+2:
• 1 nb\(^{-1}\) in Pb-Pb + “track-equivalent” \(\mathcal{L}_{\text{int}}\) in pp
• pp campaigns at reference \(\sqrt{s}\)
• p-Pb campaigns

Remark (~for pp): delivered Vs. inspected Vs. recorded luminosity

\textit{e.g.} LHC-delivered \(\mathcal{L}_{\text{int}}\) pp for 2017 (\texttt{acc-stats.cern.ch/LHC}):  
CMS, ATLAS \approx 50 770 pb\(^{-1}\) Vs. LHCb \approx 1870 pb\(^{-1}\) Vs. ALICE \approx 17.7 pb\(^{-1}\)
II.2 – ALICE: ALICE campaigns in LHC runs 1+2

**ALICE objectives for Runs 1+2:**
- 1 nb\(^{-1}\) in Pb-Pb + “track-equivalent” \(L_{\text{int}}\) in pp
- pp campaigns at reference \(\sqrt{s}\)
- p-Pb campaigns

**Remark (~for pp):** delivered Vs. inspected Vs. recorded luminosity

e.g. LHC-delivered \(L_{\text{int}}\) pp for 2017 (acc-stats.cern.ch/LHC):
CMS, ATLAS \(\approx 50,770\) pb\(^{-1}\) Vs. LHCb \(\approx 1,870\) pb\(^{-1}\) Vs. ALICE \(\approx 17.7\) pb\(^{-1}\)

→ ALICE = physics at the event level ≠ physics for particles ~independently of the event
→ specific data taking strategy (campaign planning + \(L_{\text{instantaneous}}\) leveled at \(\approx 2.6 \times 10^{30}\) cm\(^{-2}\)s\(^{-1}\))...

\[ \mu_{\text{ALICE}} \leq 0.02 \quad // \quad \mu_{\text{CMS}} \mathcal{O}(40-60) \]
II.3 – ALICE: detector layout

ALICE in run 2 = 20 active sub-detectors of various kinds → 2 parts: i) forward $y$ + ii) $y \approx 0$

A side

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

C side

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD
II.4 – ALICE: ITS

- **Inner Tracking System = ITS**

  \[ | \eta_{\text{ITS}} | < 0.9 \text{ at least} / p_T^{\text{threshold}} \approx 50 \text{ MeV/c} \]

  - 2 layers = silicon pixels, SPD (hybrid pixels: 50 x 425 µm²)
  - 2 layers = silicon drift, SDD
  - 2 layers = silicon strips, SSD ←

  → **trigger** (SPD)
  → **vertexing, tracking** (SPD, SDD, SSD)
  → **PID (dE/dx)** (SDD, SSD)
II.5 – ALICE : EmCal+DCal

• **EmCal+DCal**

\[ \approx 20 \frac{x}{X_0} (\text{Pb layers + scintillator layers}) \]

\[ E \text{ or } p_T^{\text{threshold}} \approx 2 \text{ GeV}/c \]

- EmCal : \[ \Delta \phi = 107^\circ \]
- DCal : \[ \Delta \phi = 67^\circ \]

\[ + |\eta_{\text{EmCal}}| < 0.7 \]

\[ + 0.22 < |\eta_{\text{EmCal}}| < 0.7 \]

→ **trigger**

→ \[ e^+ + \text{direct } \gamma, \pi^0 \rightarrow \gamma\gamma, \eta \rightarrow \gamma\gamma, \ldots \]
• **VZERO or V0**

  \[ V0A = 2.8 < \eta < 5.1 \]
  \[ V0C = -3.7 < \eta < -1.7 \]

  forward arrays of scintillators

  → **event activity** : Online trigger (Min Bias + Pb-Pb centrality + high-mult. pp)
  
  Offline use = (Pb-Pb, p-Pb, pp)

  → **event selection** : physics vs beam-gas identification

  → **event charac.** : event plane + ref. flow vector (Pb-Pb)
II.7 – ALICE: $\mu$ spectrometer

- $\mu$ arm: $\mu$ tracking + $\mu$ trigger
  
  - $-4 < \eta_\mu < -2.5$
  
  dedicated dipole magnet (rigidity = 3 T.m)

  $\mu$ tracking: 5 stations of MWPC, beyond absorber
  $\mu$ trigger: 2 stations of RPC, beyond iron wall

  → $\mu\mu$ (low-mass vector mesons, quarkonia cc, bb, Z)
  
  → single $\mu$ (open heavy flavours, $W^\pm$)
III.1 – ALICE features: low $p_T$

**A)** Focus on low $p_T$ ($\leq 2\text{-}3$ GeV/$c$) and intermediate $p_T$ ($2\text{-}3 \leq p_T \leq 8\text{-}10$ GeV/$c$)

*NB:* X% of the particle production sit below $p_T \leq 0.5$ GeV/$c$, $\leq 2$ GeV/$c$, ...

To keep

1) large Acceptance x Efficiency, $Ax\varepsilon$
2) detection threshold at very low $p_T$
3) excellent $p_T$ resolution (ex: $\leq 1\text{-}2\%$ for $p_T \in [0.1\text{-}10]$ GeV/$c$)

- **Need 1)** → low event pile-up (in bunch + out-of-bunch) // readout speed // $\mathcal{L}_\text{inst}$
- **Need 2)** → moderate B field

- **Need 3)** → lowest possible material budget $x/X_0$

---

**2) low B field from L3 ($0.5$ T)**

![Image of L3 field](image)

*To be compared with CMS and ATLAS corresponding figures at $\gamma=0$*

---

For further details, see ALICE Performance, arXiv:1402.4476

---

Antonin.MAIRe@cern.ch – ALICE France / Conseil Sci. 2018
III.2 – ALICE features: passive PID at forward $y$

B) very good detector-PID capabilities over wide range of $p_T$

$y$ forward: $\mu^+\mu^-$

![Graph showing $dN/dM$ for muon pairs](image)

$pp \sqrt{s_{NN}} = 7$ TeV

$p_T^\mu > 1$ GeV/c

$M(\mu^+\mu^-)$ (GeV/c$^2$)
### III.2 – ALICE features: PID at $y \approx 0$

**B)** very good detector-PID capabilities over wide range of $p_T$

$\gamma$, $e^\pm$, $\pi^\pm$, $K^\pm$, $p$ + $^2$H, $^3$H, $^3$He, $^4$He ...

with help of:

- SDD+SSD
- TPC
- TRD
- EMCal/DCal

+ topological reconstruction
III.3 – ALICE features: systematism

Comprehensive and systematic measurements in pp, p-Pb and Pb-Pb
→ ALICE role for QGP+QCD at LHC

(heavy-)flavour physics:

\[ \begin{align*}
&u,d,s,c,b \ (t) \ \leftrightarrow \ \pi^+ \pi^0 \ K^+ \ K^0_S \ \ldots \ \ p \ \Lambda \ \Xi^- \ \Omega^- \ \ldots \ \eta(547) \ \omega(782) \ K^0(892) \ \phi(1020) \ \Sigma^+(1385) \ \Lambda(1520) \ \Xi^0(1530) \\
&d \ t \ ^3\mathrm{He} \ ^4\mathrm{He} \ ^3\Lambda\ ^\Lambda\ H \ \ldots \ \\
&D^0 \ D^+ \ D^{*+} \ D_S \ \ldots \ J/\psi \ \chi_{\mathrm{C}} \ \psi(2S) \ \ldots \ \Lambda^+_c \ \Xi^-_c \\
&\text{heavy-flavour} \ (\mu^\pm, e^\pm) \\
&\ldots \ \Upsilon(1S,2S,3S) \\
&\gamma \ W^\pm \ Z \ + \ \text{anti-particles.}
\end{align*} \]
III.3 – ALICE features: systematism

Comprehensive and systematic measurements in pp, p-Pb and Pb-Pb

→ ALICE role for QGP+QCD at LHC

(heavy-)flavour physics:

\[ u,d,s,c,b (t) \leftrightarrow \pi^+ \pi^0 K^+ K_S^0 \ldots p \Lambda \Xi^- \Omega^- \ldots \]
\[ \eta(547) \omega(782) K^0(892) \phi(1020) \Sigma^+(1385) \Lambda(1520) \Xi^0(1530) \]
\[ d t ^3\text{He} ^4\text{He} ^3\Lambda \text{H} \ldots \]
\[ D^0 D^+ D^{*-} D_S \ldots J/\psi \chi_{\text{Ci}} \psi(2S) \ldots \Lambda_c^+ \Xi_c \]

heavy-flavour (\( \mu^\pm, e^\pm \))

... \( Y(1S,2S,3S) \)

\[ \gamma W^\pm Z \] + anti-particles.

→ ALICE publications

\[ \geq 200 \text{ submitted/published papers} \quad \text{(in date: 2 Feb. 2018)} \]

Among which:

• 6 \((500+ \text{ citations}) / 11 \ldots 45 \ldots 45 \ldots \) / ...

Average citations \( \approx 102.5/\text{article} \quad \text{(in date: 7 Feb. 2018)} \)

→ INSPIRE:find on ALICE and ac 100+
III.4 – ALICE features: computing

ALICE (in 2018)
- 64 sites (Tier-0, Tier-1, Tier-2)
  - for tape storage (T0+T2 $\approx$ 90 PB)
  - for disk storage (T0+T1+T2 $\approx$ 90 PB)
  - for CPU ($\approx$3x $350.10^3$ HEP-Spec06)

Use cases (CPU+Storage):
1/ Offline detector calibration
2/ Event reconstruction:
   - real data:
     $\mathcal{O}$(1-2 min) / Pb-Pb 0-5% event
     $\mathcal{O}$(1-2 s) / pp Min Bias
   - MC (gen+transport Geant3,4):
     $\approx$70%
     $\mathcal{O}$(10 min) / Pb-Pb 0-5% event
     $\mathcal{O}$(10 s) / pp Min Bias
3/ Analysis LEGO train on data & MC

ALICE-France:
Tier-1: CC-in2p3
+ Tier-2: 5 sites (IPHC, GRIF, LPC, LPSC, Subatech)
→ Pledge: $\mathcal{O}$(10%) of the whole ALICE Grid
III.5 – ALICE features: Human Resources

In Run 2:

ALICE Collaboration: $\mathcal{O}(1100)$ authors (Feb. 2018)
628 total M&O-A (Sept. 2017)

ALICE France
- 25 CNRS (+7 CEA)
- 11 University staff,
- 13 PhD Students
+ 22.97 FTE IR+Technicians In2p3 (info basis ≠ NSIP 2017...)

→ Construction/operation:
- V0 (among which project leader)
- $\mu$Trk+$\mu$Trg (among which project leader)
- ITS-Si Strips SSD
- Em/DCal
- Data Preparation Group DPG (calibration, Quality Assu.)
- Computing

→ Scientific management in runs 1+2:
- Deputy spokespersons
- Editorial Board members
- Conference Committee members
- Management Board

→ Phys Coordination:
- Physics Working Group convenors
- Physics Analysis Group convenors
- Analysis/Internal Review Committees
Part B – run 1+2 outcome
IV.1 – Runs 1+2: defining usual observables

1. $p_T$ spectra:

$$\frac{1}{N_{\text{evt}}} \frac{d^2 N}{dp_T dy} = f(p_T)$$

measured in pp, pA, AA

2. Yields:

$$\frac{1}{N_{\text{evt}}} dN/dy$$

3. $R_{AA}(p_T) = \frac{\left(\frac{1}{N_{\text{evt}}^{AA}}\right) \frac{d^2 N^{AA}}{dp_T dy}}{\langle N_{\text{coll}} \rangle \left(\frac{1}{N_{\text{evt}}^{pp}}\right) \frac{d^2 N^{pp}}{dp_T dy}}$$

"$1 \times (\text{Pb-Pb}) \neq n \times (\text{pp})$?"

Notes:

$R_{AA} = 1$, if no visible change in AA ...

e.g. direct photons, $W^\pm, Z^0$

$R_{AA} > 1$, if enhancement in the AA system

e.g. strange baryons $\Lambda, \Xi, \Omega$ at low momenta ($p_T < 3 \text{ GeV}/c$)

$R_{AA} < 1$, if suppression in the AA system

e.g. $h^+, \pi, K, p, \Lambda, D, J/\psi$ at mid/high $p_T$ ($p_T > 3-5 \text{ GeV}/c$)
IV.2 – Runs 1+2: defining usual observables

The 2+2 interleaved families of essential QGP observables:

I. relativistic hydrodynamics of the fireball
   \( p_T \leq 2-3 \text{ GeV/c} \)
   explosive emission, isotropic in azimuth
   (radial flow)

II. in-medium energy losses:
   jet quenching, attenuation of high-\( p_T \) particles \( p_T \geq 6-8 \text{ GeV/c} \)
   + azimuthal modulations
   (anisotropic flow, \( v_n = f[m^0, p_T, \text{centrality}] \) )

A. via light flavour \((u,d,s)\)
B. via heavy flavours \((c,b)\) : open or hidden

→ In the following: sample of major ALICE(-France) results...
V.1 – Runs 1+2: \( u, d, s \)

\[
\int_{p_T} d^2N/dp_T dy = dN/dy \rightarrow 14 \text{ differential measurements}
\]

+ comparison to Statistical Hadronisation Model = thermo-statistical model

**ALICE, arXiv:1710.07531**

**ALICE, arXiv:1506.07287**

**ALICE, arXiv:1307.5530**

---

\( p_T \)-integrated yields

\[
\int_{p_T} d^2N/dp_T dy = dN/dy
\]

\[\Lambda\]

\[\phi\]

\[K^0\]

\[\pi^+ K^-\]

\[K^+ K^-\]

\[d, \bar{d}\]

\[\text{ALICE, 0-10\% Pb-Pb, } \sqrt{s_{NN}} = 2.76 \text{ TeV}\]

**ALICE, arXiv:1710.07531**

**ALICE, arXiv:1506.07287**

**ALICE, arXiv:1307.5530**
V.2 – Runs 1+2: s, strangeness enhancement, pp to AA

1/ Strangeness enhancement↗ with strangeness content

2/ Consistent pattern between
Pb-Pb
p-Pb
pp (!) for a given multiplicity

3/ Comparison with models:
Models missing (largely) the data
**V.3 – Runs 1+2: hydrodynamics, \(v_n(PID)\)**

1. **\(v_2(PID)\) Pb-Pb**

2. **\(v_n(PID)\) Pb-Pb**

3. **\(v_2(PID)\) p-Pb**

\(v_n(PID)\) Pb-Pb

\[ v_2, v_3, v_4, v_5 = f(p_T, \text{centrality}) \text{ for } \pi, K, p \]

**ALICE, arXiv:1405.4632**

**ALICE, arXiv:1307.3237**

**ALICE, arXiv:1606.06057**

“mass ordering” of \(v_2\) with \(m_0\) in Pb-Pb but also in p-Pb...
V.4 – Runs 1+2: **c**, hidden with *inclusive J/ψ, ψ(2S)**

\(J/ψ(1S)\) (\(c\bar{c}\), \(m_{PDG} = 3.096\) GeV/\(c^2\))

\(ψ(2S)\) (\(c\bar{c}\), \(m_{PDG} = 3.686\) GeV/\(c^2\))

ALICE, arXiv:1311.0214 + Prelim

\(ALICE,\ arXiv:1709.05260\)

\(+\ ALICE\ arXiv:1709.06807\)

\(\psi(2S)\) p-Pb Vs. pp

\[\psi(2S)\] p-Pb Vs. pp

1. \(v_2(J/ψ) \neq 0\) but also \(v_2(J/ψ) \neq 0\)
V.5 – Runs 1+2 : c (+b), open with prompt $D^0$, $D^+$, $D^{*+}$, $D_s$, ...

1. Heavy-Flavour $\mu$

   $R_{AA} + v_2$

2. $R_{pPb}(D) \approx 1$, while $R_{PbPb}(D) << 1$

3. $v_2(D) \neq 0$

   charm, sensitive to hydrodynamics!
V.6 – Runs 1+2: high-$p_T$ and jets ...

1/ ALICE’s say wrt CMS,ATLAS: “lowest high-$p_T$”, i.e. jet $\in [-10\sim 100 \text{ GeV}]$ + its soft components

_FJKPPL 2017, Young investigator award_
V.6 – Runs 1+2: high-$p_T$ and jets ...

2/ ALICE’s say wrt CMS, ATLAS: intra-jet PID, PID+jet

2.1/ Jet hadro-chemistry $\pi$, $K$, $p$ (e.g. with TPC)
but also $K^0$s, $\Lambda$, ..., $D$, ...

2.2/ jet-like correlations ($\text{PID-h}^\pm$)
$= ([\pi^\pm, \pi^0, K^\pm, p, ... \gamma ... ]-h^\pm)$

$\sigma$ isolated $\gamma$

arXiv:1511.02766
V.7 – Runs 1+2: constraining nPDF (initial state)

1. $W^\pm, Z$

Ultra-peripheral AA collisions → photo-production

- Ultra-peripheral AA collisions
- Photo-production

**Schéma de Guillermo Contreras**

$J/\psi + \psi(2S)$

**ALICE, arXiv:1508.05076**

**ALICE, arXiv:1209.3715**

**ALICE, arXiv:1611.03002**
V.8 – Runs 1+2: bottom line

→ early 2018, where are we?

Runs 1+2 not yet finished (pp+Pb-Pb 2018 still to come), but the situation is rather clear

1/ Hydrodynamics = already into a precision era!
   (tremendous improvements over the last years, both in theory and experiments)
   But, no worry, still some way ahead...

2/ in-medium energy loss = not yet there but...
   LHC = the place to be for hard probes!
   i) drop of $\sigma_{\text{inclusive jet}} \approx 1/p_T^8$ at RHIC Vs. $1/p_T^4$ at LHC...
      = nature makes it easier for high $\sqrt{s}$
   ii) detectors suited for that (see at least ATLAS, CMS)

3/ the real new thing: AA-like signs at high $\sqrt{s}$ in small systems like pp, p-Pb
V.9 – Runs 1+2: some open questions left

**Initial state**
- What is the fundamental nature of the initial state?
  Can hard probes reveal it?

**Equilibration**
- Which mechanisms drive a (quantal QCD system) into a (high-T ~equilibrated medium)?
- such an equilibration, possible in small systems?
- or are there elementary QCD mechanisms that mimic the observed collective behaviour?

**Chiral symmetry**
- Can we prove directly that chiral symmetry is (partially) restored?

**In-medium dynamics**
- What does the apparent collective behaviour of c+b tell us?
- What is the fundamental nature of degrees of freedom
  relevant for QCD at finite T (partons, quasi-particles, ...)?

**Hadronisation**
- Which processes do create hadrons, flavour by flavour?

Ultimately, which precision do we need to reach in our measurements?
For comparison/test of QGP fundamental properties calculable from first principles
(Equation of state, viscousity, transport coefficient, ...)

→ Runs 3+4!
Part C – run 3+4 preparation and perspectives
VI.1 – Beyond LS2: ALICE campaigns in LHC run 3+4

Consequence: **50 kHz in Pb-Pb** // ~200 kHz in pp, p-Pb

→ preserve ALICE features (PID, material budget, µ arm, ...)
+ improve tracking precision (ITS, MFT)
+ improve data rate (pile-up challenge)

→ specific data taking strategy:
  - “triggerless” readout (small S/S+B → ~no online trigger)
  - **Readout+recorded: 50 kHz** Min Bias Pb-Pb
    + a few 100 kHz pp, p-Pb collisions
    Runs 3+4 = 100x Run 2
  - no more 8-month/year of pp data taking...

ALICE pp campaign = $\mathcal{O}(\text{weeks})$
(main limit: computing capacity)
VI.2 – Beyond LS2: TDRs for run 3+4 detectors
VI.3 – Beyond LS2: tracking perf. $y \approx 0$ + forward $y$

**Fig 7.12**

TDR ITS Upgrade - CERN-LHCC-2013-024

**Fig 6.15 + 6.16**

TDR MFT - CERN-LHCC-2015-001

- $\mu$ tracks: MFT+ $\mu$ spectrometer

- ITS stand-alone

- $y \approx 0$

- **forward $y$**

- $\sim x6$ in $z$

- $\sim x5$ in $z$

- $\sim x3$ in $xy$

- Current ITS
  - IB: $X/X_0 = 0.3\%$; OB: $X/X_0 = 0.8\%$
  - IB: $X/X_0 = 0.3\%$; OB: $X/X_0 = 1.0\%$
  - IB: $X/X_0 = 0.3\%$; OB: $X/X_0 = 1.2\%$

- Transverse Momentum, $p_T$ (GeV/c)

- Correct Matching Rate

- $p_T$ (GeV/c)

- Resolution in $\varphi$

- Resolution in $z$

- $\sigma$ (µm)

- $c_x$ (µm)

- $x/X_0 = 1\%$
  - $x/X_0 = 0.8\%$
  - $x/X_0 = 0.6\%$

- $\mu$ tracks: MFT + $\mu$ spectrometer

- $y \approx 0$

- **forward $y$**
VII.1 – Upgrade: ITS+MFT chip, ALPIDE

Here, **ALPIDE**: 0.18-μm CMOS technology by TowerJazz

- **chip**: 1.5 x 3 cm²
- **pixel size**: 29 x 27 μm²
- **silicon thickness**: 50 μm / 100 μm
- **spatial resol°/layer**: ~5 μm
- **power density**: < 50 mW/cm²
- **event-time resol°**: ~2-5 μs
- **detection efficiency**: >99%
- **fake-hit rate**: << 10⁻⁶ /event/pixel
- **NIEL radiation tolerance**: >1.7 x 10¹³ 1MeV n eq/cm²
- **TID radiation tolerance**: >2.7 Mrad

**NB**: no more dE/dx information, unlike current SDD, SSD...

CMOS R&D (IPHC, CEA)
VII.2 – Upgrade : ITS characteristics

**ITS Runs 1+2**

- 3 technologies: pixels, drifts, strips
  - 6 layers
    - $x/X_0$ (per layer) $\geq 1.1\%$
  - $x/X_0$ (ITS) $\sim 7.4\%$

**ITS upgrade Runs 3+4**

- Beam pipe: $R_{\text{current}} = 2.9\,\text{cm}$
- Beam pipe: $R_{\text{upgrade}} = 1.72\,\text{cm}$
  - $R_{\text{avg}}$ (ulTS, Layer 0) $= 2.4\,\text{cm}$
  - $R_{\text{inner}} = 2.4 / 3.2 / 4.0$
  - $R_{\text{outer}} = 19.6 / 24.5 / 34.4 / 39.3$

- Single technology: CMOS (ALPIDE)
  - 7 layers
    - IB, Layer 0,1,2: $x/X_0$ (per layer) $\sim 0.3\%$
    - OB, Layer 3,4,5,6: $x/X_0$ (per layer) $\sim 0.8\%$
  - $x/X_0$ (ITS) $\sim 6.9\%$

$x/X_0$ (per layer): Ratio of the ionization loss in a gas to the ionization loss in vacuum.

R_{\text{inner}} and R_{\text{outer}}: Radial distances from the axis of the beam pipe.
VII.3 – Upgrade: ITS+MFT

ITS+MFT commonalities

• both equipped with ALPIDE chips

• mechanical structure and services bound together

• Removal possibility during annual shut down

A first difference

• ITS = 9.4 m² = industrial production (73% of active surface for the last 2 layers)

• MFT = 0.4 m² = 5% of ITS surface but further complexity in layout of ladders
VII.4 – Upgrade: MFT

MFT = vertexing ahead of μ spectrometer
-3.6 < \( \eta \) < -2.5

(NB: in front of absorber, no sensitive magnetic field)

Components:
5 disks split into 2 halves
each disk = 2 sides of detection

280 ladders out of 920 silicon sensors (2 to 5 chips/ladder)
0.6 % \( x/X^0 \) per disk

NB: MFT doses \( \mathcal{O}(700 \text{ krad}) \) over 10 years of operation,
~same ballpark as ITS inner layer
VII.5 – Upgrade: ALICE-France commitments

+ Read-out: firmware of Common Readout Unit CRU (LPSC)
VII.5 – Upgrade: ALICE-France commitments

**LPSC:**
- assembly tool

**IPHC:**
- module assembly
  - ~400 modules /~2500
    - (2x7 chips glued, bonded on flexible circuit)
- Coordination WG tracking/simul°/phys perf.

Total cost:
- **12.8 MCHF**

In2p3:
- **800 k€**
VII.5 – Upgrade : ALICE-France commitments

- Project leader
- Full detector construction → 8 out of 9 WG led by In2p3/CEA staff
- Coordination WG tracking/simulation/physics performance

Total cost:
- MFT: 3.35 MCHF
- In2p3: 1.37 M€
VII.5 – Upgrade: ALICE-France commitments

- **µID** LPC + Subatech
  - Front-End (FEERIC)
  - the whole Read-out electronics
    - 250 cards

- **µTrk** IPNO (+ CEA)
  - the whole Read-out electronics
    - 20 000 cards DualSampa

Total cost:
- 1.596 MCHF **µTrk**
- 677 kCHF **µID**

*In2p3*:
- 646 k€ **µTrk**
- 430 k€ **µID**
VII.5 – Upgrade: ALICE-France commitments

LPSC: • assembly tool
    • module assembly
    ~400 modules /~2500
    (2x7 chips glued, bonded on flexible circuit)
    • Coordination WG
    tracking/simul°/phys perf.

IPHC: • module assembly
    • Project leader
    • Full detector construction
    → 8 out of 9 WG led
      by In2p3/CEA staff
    • Coordination WG
    tracking/simul°/phys perf.

IPNO (+ CEA)
• the whole Read-out electronics
  = 20 000 cards DualSampa

In2p3:

Total cost: 12.8 MCHF

Total cost: 3.35 MCHF

Total cost: 1.596 MCHF

μID LPC + Subatech
• Front-End (FEERIC)
• the whole Read-out electronics
  = 250 cards

μTrk IPNO (+ CEA)
• the whole Read-out electronics
  = 20 000 cards DualSampa

IPNO:

IPNL/cc:

Subatech:

LPSC:

IPHC:

CEA:

μID:

μTrk:
### VIII.1 – Run-3+4 physics: (fwd y) physics-case summary

**Prompt/non-prompt J/ψ**

<table>
<thead>
<tr>
<th>Observable</th>
<th>MUON only</th>
<th>MUON + MFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive $J/\psi R_{AA}$</td>
<td>$p_T^{\min}$ (GeV/c)</td>
<td>uncertainty</td>
</tr>
<tr>
<td>$\psi' R_{AA}$</td>
<td>0</td>
<td>5% at 1 GeV/c</td>
</tr>
<tr>
<td>Prompt $J/\psi R_{AA}$</td>
<td>0</td>
<td>30% at 1 GeV/c</td>
</tr>
<tr>
<td>$J/\psi$ from $b$-hadrons</td>
<td>not accessible</td>
<td>not accessible</td>
</tr>
</tbody>
</table>

**Heavy-Flavour μ**

<table>
<thead>
<tr>
<th>Observable</th>
<th>MUON only</th>
<th>MUON + MFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open charm in single μ</td>
<td>1</td>
<td>7% at 1 GeV/c</td>
</tr>
<tr>
<td>Open beauty in single μ</td>
<td>2</td>
<td>10% at 2 GeV/c</td>
</tr>
<tr>
<td>Open HF in single μ</td>
<td>4</td>
<td>30% at 4 GeV/c</td>
</tr>
<tr>
<td>no c/b separation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Low-mass μμ**

<table>
<thead>
<tr>
<th>Observable</th>
<th>MUON only</th>
<th>MUON + MFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low mass spectral func. and QGP radiation</td>
<td>not accessible</td>
<td>1–2</td>
</tr>
</tbody>
</table>

*Tab 1*

*Loi MFT*

- CERN-LHCC-2013-014
VIII.2 – Run-3+4 physics: (fwd y) physics-case examples

Fig 6.21 + 6.19
TDR MFT
- CERN-LHCC-2015-001

prompt vs non-prompt
J/ψ and HFµ

LoI MFT
- CERN-LHCC-2013-014

ψ(2S) pp scenario
2.5<y<4.0 and p_T>0

Low-mass µµ

Raw signal( ψ(2S) )
**VIII.3 – Run-3+4 physics**: 

- (x ≈ 0) example, D in Pb-Pb

i.e. Significance for \( \mathcal{L}_{\text{int}} = 10 \text{ nb}^{-1} = 8.10^{9} \text{ evts} : \)

- \( \approx 50 \text{ for } p_T < 1 \text{ GeV/c}, \approx 10^{3} \text{ at high } p_T \ldots \)
- \( \approx 100 \text{ for } D^{*+}, \approx 50 \text{ for } D_{S}^{+} \)

**NB:**

- Better control on systematics
- Ease signal extraction (S/B, \( p_T \) resolution.)
- Bigger data sample to play with
- Feed-down correction more straightforward

Rejection of combinatorial background:

\( \approx 5-10x (\approx 2x \text{ for } D_{S}^{+}) \)
VIII.4 – Run-3+4 physics : \((y \approx 0)\) example, \(B^+\) in Pb-Pb

**Hypotheses:**

- ITSu+TPC tracking
- TPC PID for \(e^\pm\) / TPC+TOF for \(K^+\)

\(NB:\) Stat uncert. \(\Leftrightarrow 8\times10^9\) events, \(10\ \text{nb}^{-1}\)
### VIII.5 – Run-3+4 physics: \((y \approx 0)\) physics-case summary table

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current, 0.1 nb(^{-1})</th>
<th>Upgrade, 10 nb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(p_T^{\text{min}}) (GeV/c)</td>
<td>statistical uncertainty</td>
</tr>
<tr>
<td>Heavy Flavour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D) meson (R_{AA})</td>
<td>1</td>
<td>10 %</td>
</tr>
<tr>
<td>(D_s) meson (R_{AA})</td>
<td>4</td>
<td>15 %</td>
</tr>
<tr>
<td>(D) meson from B (R_{AA})</td>
<td>3</td>
<td>30 %</td>
</tr>
<tr>
<td>(J/\psi) from B (R_{AA})</td>
<td>1.5</td>
<td>15 % ((p_T\text{-int.}))</td>
</tr>
<tr>
<td>(B^+) yield</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>(\Lambda_c^+) (R_{AA})</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>(\Lambda_c/D^0) ratio</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>(\Lambda_b) yield</td>
<td>not accessible</td>
<td>7</td>
</tr>
<tr>
<td>(D) meson (v_2) ((v_2 = 0.2))</td>
<td>1</td>
<td>10 %</td>
</tr>
<tr>
<td>(D_s) meson (v_2) ((v_2 = 0.2))</td>
<td>not accessible</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>(D) from B (v_2) ((v_2 = 0.05))</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>(J/\psi) from B (v_2) ((v_2 = 0.05))</td>
<td>not accessible</td>
<td>1</td>
</tr>
<tr>
<td>(\Lambda_c) (v_2) ((v_2 = 0.15))</td>
<td>not accessible</td>
<td>3</td>
</tr>
<tr>
<td>Dielectrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (intermediate mass)</td>
<td>not accessible</td>
<td>10 %</td>
</tr>
<tr>
<td>Elliptic flow ((v_2 = 0.1)) [4]</td>
<td>not accessible</td>
<td>10 %</td>
</tr>
<tr>
<td>Low-mass spectral function [4]</td>
<td>not accessible</td>
<td>0.3</td>
</tr>
<tr>
<td>Hypernuclei</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^3\text{H}) yield</td>
<td>2</td>
<td>18 %</td>
</tr>
</tbody>
</table>

- Run I+II
  \(\approx 1\) nb\(^{-1}\) MB Pb-Pb delivered
  \(\rightarrow 0.1\) nb\(^{-1}\) recorded

- Run III
  \(\approx 10\) nb\(^{-1}\) MB Pb-Pb delivered
  \(\rightarrow 10\) nb\(^{-1}\) recorded

*TDR ITS Upgrade*

- *CERN-LHCC-2013-024*

Tab 8.6
**VIII.6 – Run-3+4 physics: high-multiplicity pp**

Beware: Possible caveats in pp extrapolation

Multiplicity dependence extension
- further for Ξ, Ω?
- further for J/ψ?
- further for D mesons?
- + a 1st time for light nuclei produced d, t, $^3$He, $^3$H

**HL-LHC Wkshop**

From: J. F. Grosse-Oetringhaus

pp, p-Pb, Pb-Pb at a same $N_{ch}$

pp 5.5 TeV

**Graphical representation**

- $P(N_{ch})$ vs $N_{ch}$ for pp, p-Pb, Pb-Pb at a same $N_{ch}$
- Possible caveats in pp extrapolation
- Multiplicity dependence extension
- Further for Ξ, Ω, J/ψ, D mesons
- First time for light nuclei produced d, t, $^3$He, $^3$H
Wrap-up (1) : Heavy-Ion standard model

- « QCD at finite temperature » :
  → Extension of Standard Model
  
  i) How does sol N-body dynamics emerge from elementary QCD interaction
  
  ii) How it further evolves...

- Ongoing effort pursued over the next decade :
  → detailed++ understanding of QCD dynamics, from AA to pp
  
  → Systematic characterisation, towards textbook measurements ("precision era" for Runs 3+4)

0. Initial partonic State (CGC ?)

1. Partonic equilibration (glasma phase)

2. Relativistic slightly-viscous hydrodynamic evolution
   = bulk dynamics + hard probe response
   = space-time, flavour, momentum dependences...

3. Hadronisation (LQCD)

4. Hadronic transport

Deconfined phase

Chemical freeze-out

Kinetic freeze-out

 Hadron gas

Free particles

MADAI.us
Wrap-up (2) : particles of interest through LHC runs

(heavy-)flavour physics : \( u,d,s,c,b \ (t) \) behaviour wrt collectivity

Means : a full span of multi-differential analyses, in small (pp, p-Pb) and large (Pb-Pb) systems
\[
d^2N_{\text{PID}}/dp_Tdy = f(\text{event activity}) + n_{\text{PID}} + \text{azimuthal correlations} + ...
\]

ALICE reach in Runs 1+2

\( \pi^+ \pi^0 K^+ K_S^0 \ldots \ p \Delta \Xi^- \Omega^- \ldots \)
\( \eta(547) \ \omega(782) \ K^0(892) \ \phi(1020) \ \Sigma^+(1385) \ \Lambda(1520) \ \Xi^0(1530) \)
\( d \ t \ ^3\text{He} \ ^4\text{He} \ ^3\Lambda\ \text{H} \ldots \)
\( \{D^0 \ D^+ \ D^{**} \ D_S^0\} \ldots \ \psi(2S) \ \chi_{\text{C}} \ Y(1S,2S,3S) \)
\( W^\pm \ Z \)

ALICE reach in Runs 3+4

\( \pi^+ \pi^0 K^+ K_S^0 \ldots \ p \Delta \Xi^- \Omega^- \ldots \)
\( \eta(547) \ \omega(782) \ K^0(892) \ \phi(1020) \ \Sigma^+(1385) \ \Lambda(1520) \ \Xi^0(1530) \)
\( d \ t \ ^3\text{He} \ ^4\text{He} \ ^3\Lambda\ \text{H} \ldots \)
\( \{D^0 \ D^+ \ D^{**} \ D_S^0\} \ldots \ \psi(2S) \ \chi_{\text{C}} \ Y(1S,2S,3S) \)
\( W^\pm \ Z \)

Colour conventions :

- ■ : investigations for large parts already explored or in full swing
- ■ : tackled but further precision needed/expected
- ■ : missing (limited by statistics or detector capabilities)

\underline{Underlined} : with French contributions
Wrap-up (3) : ALICE(-France) take in that matter

ALICE in the characterisation of “QCD at finite temperature”:

1/ low + intermediate $p_T$ focus
2/ PID
3/ systematism of the measurements,
   complete panel of measurements, accessible and competitive
\[ \forall y \quad \rightarrow \text{ALICE} : |y| < 0.9-1.2 \text{ and } (\mu) \text{ forward } (-4/-3.6 < y < -2.5) \]
\[ \forall p_T \quad \rightarrow \text{ALICE} : p_T \geq 0 \text{ GeV/c} \]
\[ \forall \text{system} \quad \rightarrow \text{ALICE} : \text{pp, p-Pb, ... , Pb-Pb} \]
\[ \forall \text{event activity} \quad \rightarrow \text{ALICE} : \text{pp, p-Pb, ... / Pb-Pb : 100-90% } \rightarrow \text{0.5-0% centrality} \]

ALICE-France in that enterprise:

1/ past and future hardware/software commitments and responsibilities
   e.g. (ITS, MFT, $\mu$ arm, EmCal/DCal) construction, read-out, operation, calibration, tracking ...
2/ physics analyses on various + complementary fronts
   to elaborate a same and consistent global understanding