Heavy-Flavour Measurements at the LHC

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OUTLINE

- Why Heavy flavours in heavy-ion physics
- Heavy-flavour observables
- Overview of heavy-flavour measurements
  - in pp, p-Pb, Pb-Pb collisions
- Summary
Deconfined QCD matter and its probes

- Heavy-ion (HI) collisions at LHC energies
  - Deconfined QCD matter (Quark-Gluon Plasma phase) is expected (lifetime ~ O(10 fm/c))

- Hard (large $Q^2$, large mass scale) probes are produced at the beginning of the collisions → probe the whole evolution of the collisions

**Hard processes:**
- Charm, Beauty, W, Z, photons, Jets

**Tomographic probes**
What’s special about heavy quarks

- Heavy quarks
  - Large mass ($m_q \gg \Lambda_{QCD}$)
    - hard probes even at low $p_T$
    - produced in the early stages of the HI collision with short formation time;
      \[ t_{charm} \sim \frac{1}{m_c} \sim 0.1 \text{ fm/c} \ll \tau_{QGP} \sim O(10 \text{ fm/c}) \]
  - Interactions with QGP don’t change flavour identity
  - Uniqueness of heavy quarks: cannot be destroyed/created in the medium
    - traverse the medium interacting with its constituents
      - natural probe of the hot medium created in HI interactions

<table>
<thead>
<tr>
<th></th>
<th>Pole mass $M$</th>
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<tbody>
<tr>
<td>Charm</td>
<td>$\sim 1.3\text{–}1.7 \text{ GeV}$</td>
</tr>
<tr>
<td>Bottom</td>
<td>$\sim 4.5\text{–}5 \text{ GeV}$</td>
</tr>
<tr>
<td>Top</td>
<td>$173.1 \pm 0.6 \pm 1.1 \text{ GeV (?)}$</td>
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PDG; TevEWWG
Heavy quarks as medium probes

q: colour triplet
  \textbf{u,d,s}: m \approx 0, \text{ } C_R = 4/3
  (difficult to tag at LHC)

\textbf{g}: colour octet
  \textbf{g}: m = 0, \text{ } C_R = 3
  > E loss, dominant at LHC

\textbf{Q}: colour triplet
  \textbf{c}: m \approx 1.5 \text{ GeV}, \text{ } C_R = 4/3
  small m, tagged by D’s
  \textbf{b}: m \approx 5 \text{ GeV}, \text{ } C_R = 4/3
  large mass \rightarrow \text{ dead cone}
  \rightarrow < E loss

Parton Energy Loss by
\rightarrow \text{ medium-induced gluon radiation}
\rightarrow \text{ collisions with medium constituents}
\Delta E(\varepsilon_{\text{medium}}; C_R, m, L)

\textbf{Prediction:} \quad \Delta E_g > \Delta E_{c \approx q} > \Delta E_b

\text{Might translate into a hierarchy of nuclear modification factors}
R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}?

Collectivity in the QGP
- in general: initial spatial asymmetry
  \rightarrow \text{azimuthal asymmetry of particle emission in momentum space}
- heavy quarks participate in collectivity of the medium in case of sufficient re-scattering
  \rightarrow \text{approach to thermalization}
- high $p_T$: path-length dependence of energy loss introduces azimuthal asymmetry as well
Heavy-flavour Observables: measure decay products

Heavy-flavor hadrons decay via weak interaction: lifetimes $c\tau \sim$ few 100 $\mu$m

Full reconstruction of D-meson hadronic decays

$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+$
$D_s^+ \rightarrow K^- K^+ \pi^+$

Semi-leptonic decays (c,b)

HF jets
Correlations with HF

Non-prompt $J/\psi$

Exclusive B meson decays

b-jet reconstruction
Heavy flavours

Results in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV

Baseline for AA and p-A collisions
Test perturbative QCD calculations
Heavy-flavour cross section measured in various channels

- pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization) compatible with data
  

- Similar conclusion at $\sqrt{s} = 2.76$ TeV
• Statistical separation of $e^\pm$ from charm and beauty decays using displaced secondary vertex and electron-hadron angular correlation

• Relative contributions of charm and beauty decays as well as beauty decay electron cross section reproduced by pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization), similar conclusion at $\sqrt{s} = 7$ TeV

Heavy-flavour production cross sections

- Calculation based on pQCD (ex. FONLL) describes consistently energy dependence of total cross sections
- Charm (beauty) x~10 (~100) from RHIC (200 GeV) to LHC
- Precision measurement required for quarkonia reference!
More on production mechanism: Multiplicity dependence of heavy-flavour production

Particle production in pp collisions at the LHC shows a better agreement with models including Multi-Parton Interactions (MPIs)

For heavy flavours:

- LHCb: double charm production agrees better with models including double parton scattering
  

**MPIs** involving only light quarks and gluons, or for heavy-flavour production?

- D-meson, non-prompt J/ψ yields increase with charged-particle multiplicity → presence of MPIs and contribution on the harder scale?
More on production mechanism: 
Multiplicity dependence of heavy-flavour production

Particle production in pp collisions at the LHC shows a better agreement with models including Multi-Parton Interactions (MPIs) 


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**MPIs** involving only light quarks and gluons, or for heavy-flavour production?

Same behavior for open and hidden charm production → this behaviour is most likely related to the c̅c and b̅b production processes, but not significantly influenced by hadronisation!
Heavy flavours
Results in p-Pb collisions

Cold nuclear matter effects

- Modification of the parton distribution functions inside nucleus
- $k_T$ broadening via collisions inside the nucleus
- Energy loss in cold nuclear matter...

\[ \frac{dN_{PbPb}^D}{dp_T} = PDF(x_1)PDF(x_2) \times \frac{d\hat{\sigma}^c}{dp_T} \times P(\Delta E) \times D_{c\rightarrow D}(z) \]

Nuclear modification factor

\[ R_{AA} = \frac{dN_{AA}}{dp_T} \times \frac{dN_{coll}}{dN_{pp}} / \frac{dN_{coll}}{d\sigma_{pp}} = \frac{dN_{AA}}{dp_T} / \frac{dN_{coll}}{d\sigma_{pp}} \]

Binary scaling based on the Glauber Model

- $R_{AA} = 1$: binary scaling
- $R_{AA} \neq 1$: medium effect

$y_{CMS} = 0.465$ in the p-beam direction

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Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

- $R_{p\text{Pb}}$ measured in various channels

- $R_{p\text{Pb}}$ consistent with unity within uncertainties

ALICE

- $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening

Full reconstruction of D-meson hadronic decays

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+$
- $D_s^+ \rightarrow K^- K^+ \pi^+$

- $\tau$ ~ few 100 $\mu$m! measure decay products

- Heavy-flavor hadrons decay via weak interaction:

- HF jets

- Correlations with HF

- How to measure open heavy flavor?
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties

ALICE
- $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, [arXiv:1308.1258]
  pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening [PRC 75(2007)064906]
- $c,b\rightarrow e$ & $b\rightarrow e$ (mid rapidity)

Semi-leptonic decays (c,b)

Primary vertex
---
$B,D$

rec. track
---
e,µ

ALICE Preliminary
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

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**ALICE**
- $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, \(\text{arXiv:1308.1257}\)
- pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening \((\text{PRC 75(2007)064906})\)
- $c,b\rightarrow e$ & $b\rightarrow e$ (mid rapidity)
- $c,b\rightarrow \mu$ (forward, backward rapidity)

Semi-leptonic decays ($c,b$)
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

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- $D^0$, $D^+$, $D^{++}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening

**CMS**
- $c,b\rightarrow e$ & $b\rightarrow e$ (mid rapidity)
- $c,b\rightarrow \mu$ (forward, backward rapidity)
- $B^+$, $B^0$, $B_s$ (mid rapidity): FONLL expectation as a pp reference

**Figure 3:** D-meson production in p–Pb collisions at 20% most central and in the 40-80% Pb–Pb collisions at 5.02 TeV. As a consequence, the suppression observed in central Pb–Pb collisions is predominantly induced by final-state effects, e.g. the ch."
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties

**ALICE**
- $D^0$, $D^+$, $D^{++}$ mesons (mid rapidity): can be described by CGC calculations, [arXiv:1308.7476](https://arxiv.org/abs/1308.7476);
pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening ([PRC 75(2007)064906](https://journals.aps.org/prc/abstract/10.1103/PhysRevC.75.064906))
- $c,b \rightarrow e$ (mid rapidity)
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**CMS**
- $B^+$, $B^0$, $B_s$ (mid rapidity): FONLL expectation as a pp reference

Consistency with b-jet measurement
**Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV**

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties

**Described by pQCD models including cold nuclear matter effects**

**Cold nuclear matter effects are small at high $p_T$!**

- $c,b \to e$ & $b \to e$ (forward, backward rapidity)
- $B^+, B^0, B_s$ (mid rapidity): FONLL expectation as a pp reference
Heavy flavours

Results in Pb-Pb collisions

Peripheral from 100%

Centrality

Central to 0%

Dense/hot partonic medium effect

Nuclear modification factor

\[ R_{AA} = \frac{dN_{AA}}{d\sigma_{pp}} \frac{d\sigma_{pp}}{dT} = \frac{dN_{AA}}{d\sigma_{pp}} \frac{d\sigma_{pp}}{dT} \]

Binary scaling based on the Glauber Model
\[ R_{AA} = 1: \text{binary scaling} \]
\[ R_{AA} \neq 1: \text{medium effect} \]

Anisotropic flow: \( v_2 \)

\[ \frac{dN}{d\varphi} = \frac{N_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos[2(\varphi - \Psi_{RP})] + ...) \]

Initial spatial anisotropy via re-scatterings momentum anisotropy of particle emission

The anisotropy is quantified via a Fourier expansion in azimuthal angle (\( \varphi \)) with respect to the reaction plane (\( \Psi_{RP} \))
D-meson $R_{AA}$ in p-Pb and Pb-Pb

- p-Pb results indicate that the suppression observed in Pb-Pb comes from strong interaction of charm quarks with the medium.
- $D_s^+$ suppressed by a factor $\sim 3$ for $8 < p_T < 12$ GeV/c.
- More statistics needed at low $p_T$ where an enhancement of $D_s^+/D$ due to coalescence is predicted.

Kuznetsova, Rafelski EPJ C 51 (2007) 113
He et al. PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149

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D-meson $R_{AA}$ in p-Pb and Pb-Pb

Cold nuclear matter effects are small ($R_{pPb} \sim 1$)

Suppression due to dense/hot partonic medium effect!

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Heavy-flavour decay lepton $R_{AA}$

- Significant suppression at high $p_T$ in central Pb-Pb collisions w.r.t. binary scaled pp collisions
  - HF decay electrons ($|y| < 0.6$) and muons ($2.5 < y < 4$) $R_{AA}$ are similar
  - Less suppression in more peripheral collisions
Heavy-flavour decay lepton $R_{AA}$

**0-50% non-prompt J/ψ $R_{AA}$**

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

- Alberico W. M. *et al.*
- Vitev I. *et al.*
- Aichelin J. *et al.*
- WHDG
- He M. *et al.*
- AdS/CFT
- LatQCD
- HTL

0-20% CMS (|y|<2.4)
0-50% ALICE (|y|<0.8)

**0-20% electrons from beauty decays $R_{AA}$**

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV, 0-20% centrality

- $b (\rightarrow c) \rightarrow e, |y| < 0.8$
- syst. uncertainty
- normalization uncertainty

**ALICE Preliminary**

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  - Less suppression in more peripheral collisions
  - $R_{AA}$ of non-prompt J/ψ, electrons from beauty decays shows

**hint of suppression**
Heavy-flavour decay lepton $R_{AA}$

Cold nuclear matter effects are small ($R_{pPb} \sim 1$)

Suppression due to dense/hot partonic medium effect!

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b-Jet $R_{AA}$

- Evidence of b-jet suppression in PbPb collisions
- Suppression favors pQCD model with stronger jet-medium coupling

CMS

CMS HIN-12-003
PRL 113, 132301 (2014)
Cold nuclear matter effects are small ($R_{pPb} \sim 1$)

Suppression due to dense/hot partonic medium effect!

- Evidence of $b$-jet suppression in PbPb collisions
- Suppression favors pQCD model with stronger jet-medium coupling
Color charge dependence?: D-meson $R_{AA}$ vs. $\pi^\pm$

$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$ could be reflected in $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

- D-meson and $\pi$ $R_{AA}$ are compatible within uncertainties
- Agreement with models including energy loss hierarchy: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c)$, different shapes of the parton $p_T$ distributions, different fragmentation functions, soft production mechanisms for low-$p_T$ $\pi$
- Measurement not yet conclusive $\rightarrow$ precision measurement required!

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Quark mass dependence?: D-meson $R_{AA}$ vs. non-prompt $J/\psi$

$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$ could be reflected in $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

- **ALICE prompt D mesons & CMS non-prompt $J/\psi$:**
  - B and D mesons $<p_T> \sim 10$ GeV/c, slightly different rapidity ranges

- **Clear indication of $R_{AA}^{B<\downarrow J/\psi} > R_{AA}^{D}$**

  consequence of mass differences of c and b quarks

---

pQCD model including mass-dependent rad+coll energy loss predict a difference

Similar pattern from other calculations

(e.g. BAMPS, WHDG, Vitev et al.)
Azimuthal anisotropy of heavy flavours

**D mesons**


- **HF decay muons**

  - Similar to electrons
  - Positive $v_2$ for D mesons and leptons from heavy-flavor hadron decays
  - Similar $v_2$ for D mesons and charged-particles
  - Hint for increasing flow from central to semi-central collisions
  - Confirmation of significant interaction of charm quarks with the medium
Azimuthal anisotropy of heavy flavours

D mesons


HF decay muons

ALICE

Heavy quarks participate in collective motion of the medium with sufficient re-scatterings

- Positive $v_2$ for D mesons and leptons from heavy-flavor hadron decays
- Similar $v_2$ for D mesons and charged-particles
- Hint for increasing flow from central to semi-central collisions
- Confirmation of significant interaction of charm quarks with the medium
**$R_{AA}$ and $v_2$: Comparison with models**

- Simultaneous reproduction of $R_{AA}$ and $v_2$ challenging for models

⇒ provide understanding of heavy-quark energy loss mechanism, the degree of thermalization of heavy-quarks within the medium

- Task to us: Precision measurements! → reduction of stat. and sys. uncertainties of data


Summary and Outlook

**Summary**

- pp data are described by perturbative QCD ⇒ Heavy flavours are a calibrated probe
- Pb-Pb data:
  - Hints of a stronger suppression for charm than for beauty at intermediate/high $p_T$.
  - No strong conclusions drawn yet from the comparison of D-meson and pion $R_{AA}$, given the current uncertainties
  - Positive flow of charm hadrons and heavy-flavour decay leptons ⇒ participating in collectivity of the medium with sufficient re-scatterings
- p-Pb data:
  - Results consistent with pQCD + shadowing ⇒ the observed suppression in Pb-Pb collisions is due to a dense/hot partonic medium effect

**Outlook**

- High precision, more statistics, extended $p_T$ coverage (high and low $p_T$)
- Smaller uncertainties and new differential measurements will help to
  - constrain model calculations quantitatively
  - address open questions concerning the flavour dependence of parton energy loss, their path-length dependence, thermalization of charm and beauty, heavy-flavour jet pair asymmetries and angular correlations, heavy-flavour jet fragmentation functions/subjet structure, coalescence including heavy quarks ...

LHC run II, III, IV data will answer to the open questions
Thank you for your attention!
ALICE detectors: D mesons

\[ D^0 \rightarrow K^- \pi^+ \]
\[ D^+ \rightarrow K^- \pi^+ \pi^+ \]
\[ D^{*+} \rightarrow D^0 \pi^+ \]
\[ D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+ \]

\(|\eta| < 0.9\]

ITS: tracking, vertexing
TPC: tracking, PID
TOF: K-ID
ALICE detectors: Heavy-flavour decay electrons

- **D → e+X, BR ~ 10%**
- **B → e+X, BR ~ 11%**
- **|η| < 0.9**
- **ITS**: tracking, vertexing, PID
- **TPC**: tracking, PID
- **TOF, EMCal, TRD**: e-ID
ALICE detectors: Heavy-flavour decay muons

-4 < \( \eta < -2.5 \)

\( \mu^- \) ID via tracks in the muon spectrometer matched with the trigger system

- \( D \rightarrow \mu^+X, \text{BR} \sim 10\% \)
- \( B \rightarrow \mu^+X, \text{BR} \sim 11\% \)
CMS detectors

Inner tracker: charged particles, vertex, isolation

EM and Hadron calorimeters
photon, isolation, jet reco

Track impact parameter resolution
- 100 μm @ 1 GeV/c
- 20 μm @ 20 GeV/c
More differential information:
Heavy flavour correlations

Heavy flavour jet properties

Near Side

in Pb-Pb

Path length dependence

Away side

trigger hadron

• D-hadron correlations in pp show good agreement with expectations from Pythia (different tunes)
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

- non-prompt J/ψ:
  - at forward, modest suppression
  - at backward, consistent with unity within uncertainties

CMS Preliminary 34.6 nb⁻¹ (pPb 5.02 TeV)

- nPDF depleted compared to proton PDF at low x
  - Characterized by forward/backward asymmetry

 CMS PAS HIN-14-009

\[ R_{FB} = \frac{N_{fit\, forward}}{N_{fit\, backward}} \cdot \frac{A_{backward} \cdot \varepsilon_{backward}}{A_{forward} \cdot \varepsilon_{forward}} \]

\[ R_{pPb} = \frac{N_{pPb}}{N_{pp}} \frac{A_{pPb}}{A_{pp}} \]

**Figure 5:** Pb → pPb

**Figure 6:** shows the forward-backward production ratio as a function of the transverse momentum at backward, consistent with unity within uncertainties at forward, modest suppression.

**Figure 7:** shows the forward-backward production ratio from CMS, J/ψ from b, LHCb, pT < 14 GeV/c. The measurement is performed as a function of the transverse momentum at backward, consistent with unity within uncertainties at forward, modest suppression.

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The double ridge also observed in heavy-flavour sector!
The mechanism (CGC? Hydro?) that generates it affects also HF
Color charge dependence?: D-meson $R_{AA}$ vs. $\pi^\pm$

Calculation by M. Djordjevic
(rad+coll energy loss) can describe both $R_{AA}$

Shows strong colour charge effect in partonic $R_{AA}$ (g vs. light and c)

$R_{AA} (D) = R_{AA} (\text{charm})$

$R_{AA} (\text{light quarks}) = R_{AA} (\text{charm})$

Distortion by fragmentation!

$R_{AA} (h^{\pm}) = R_{AA} (D)$

Colour charge effect plays!

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Figure 11: III TAMU elastic [44]. This is a heavy-flavour transport mode

*\[v_2, 30-50\% \text{ centrality} \quad (\text{0-7.5\% centrality})\]

Summary analysis of soft collisions with a perturbative connection that transfers momentum from the medium described by relativistic diffusion of heavy-flavour hadrons

**Various observables provide constraints for the models**
**Outlook**

**Status: Heavy Flavor Tracker**

**Heavy Flavor Tracker (HFT)**
- **Physics goal:** Precision measurement of heavy quark hadron production in heavy ion collisions
- All 3 sub-detectors (PXL, IST, SSD) were completed, installed prior to Run14
- PXL – heart of the HFT: state-of-art detector, MAPS technology, first time used at a collider experiment
- **Integration time ~ 160μs**
- Taking data with STAR detector system, on track towards the physics goal
- With survey and preliminary alignment, Kaons at 750 MeV/c: DCA < 60μm

**Precision measurements**
- p_T~0 using D^0 and B-decay J/ψ

**PHENIX Silicon Vertex Tracking System**

**MINERvA**
- **Input values from BAMPS model:** C. Greiner et al. arXiv:1205.4945
- Charm v^2 down to p_T~0 using D^0 and B-decay J/ψ
- Beauty v^2 down to p_T~0 using B-decay D^0

**Conclusion and Outlook**
- TDR approved by RB on 12th March 2014
  - Detector layout and important technological aspects defined
  - Integration and installation aspects studied in detail
  - Detailed Monte Carlo simulations verified the detector and physics performances
- **Integration, commissioning at surface:**
  - 2016: Completion of R & D
  - 2017: Production, construction, tests
  - 2018: High lumi Pb-Pb with upgraded ALICE
  - 2020: High lumi Pb-Pb with upgraded ALICE

**Upgrade**
- Pb-Pb, √sNN = 5.5 TeV
- Centrality 30-50%
- 1.6×10^{10} events
- D^0 → Kπ^+
- Input values from ALICE Upgrade (ALICE, CERN-LHCC-2013-024)
- ALICE, CERN-LHCC-2013-024