Heavy flavour measurements with ALICE

- heavy ion collisions & QGP
- heavy flavours & QGP
- ALICE detector overview
- selected physics channels
The QCD phase diagram

- $\mu_B = 0$:
  - $T_c = 173 \pm 15$ MeV
  - $\varepsilon_c = 0.7 \pm 0.3$ GeV/fm$^3$
  - "crossover"-like transition
- $\mu_B > 0$:
  - large uncertainties
  - order of transition unknown
  - existence of a critical point
  - chiral sym. rest. coincides with deconf.
  - the QGP is not an ideal gas
  - $\mu_B \gg 0$: color superconductivity (not shown)

$T_c = (173 \pm 15)$ MeV
$\varepsilon_c \sim 0.7$ GeV/fm$^3$
Exploring the QCD phase diagram with heavy ion collisions

key parameters: bombarding energy, collision centrality, particle transverse momentum

pressure + heat $\Rightarrow$ QGP

$\text{pressure} + \text{heat} \Rightarrow \text{QGP}$

QGP

See the graph for the QCD phase diagram with key parameters and states such as early universe, hadron gas, quark-gluon plasma, and neutron stars.
- 4 main “distinct” phases
- strategy: use produced particles as probes of the medium
QGP signatures

- suppression of high-mass resonances
- strangeness enhancement
- modification of low-mass resonances
- photon production
- jet quenching

Hard probes:
- based on particles produced in the early stage

Soft probes:
- based on particles produced in the late stage

“direct” info from the medium

“non-direct” info from the medium
Heavy flavours in heavy ion collisions

- open heavy flavour quenching probe medium density
  - parton energy loss via medium-induced gluon radiation
  - proportional to $\varepsilon$, $L$ & $C_R$ with $C_R = 4/3(3)$ for $q(g)$
  - and to $m_Q$ (gluon radiation suppressed at $\Theta < m_Q/E_Q$)
    \[ \Delta E_g > \Delta E_c \sim q > \Delta E_b \text{ expected} \]

- quarkonia (final) yield probe medium temperature
  - debye screening suppresses $QQ$bar bound states
  - but non-correlated quarks can recombine in the QGP

- observable: nuclear modification factor

\[ R_{AA} = \frac{\text{Yield in } AA}{\text{Yield in } pp \times N_{\text{coll}}} \]

if no hot nuclear effects

average number of NN collision in an AA collision

Note: only effects in final state here, for effects in initial state, see M. Malek talk on Friday.
1975-2009: 34 years of heavy-ion collisions

BEVALAC (LBL) fixed target 1975-1986 \( \sqrt{s} < 2.4 \) GeV 2 experiments ~ 100 physicists

Saturne II (Saclay) fixed target 1978-1997 \( \sqrt{s} < 2.4 \) GeV 1 experiment ~ 30 physicists

SIS (GSI) fixed target 1989- \( \sqrt{s} < 2.7 \) GeV 4 experiments ~ 200 physicists

FAIR (GSI) fixed target 2014- \( \sqrt{s} < 9 \) GeV 1 experiment ~ 300 physicists

AGS (BNL) fixed target 1986-1998 \( \sqrt{s} < 5 \) GeV 4 experiments ~ 400 physicists

RHIC (BNL) collider 2000- \( \sqrt{s} < 200 \) GeV 4 experiments ~ 1000 physicists

SPS (CERN) fixed target 1986- \( \sqrt{s} < 20 \) GeV 7 experiments ~ 600 physicists

LHC (CERN) collider 2009- \( \sqrt{s} < 5500 \) GeV 3 experiments ~ 1000 physicists

Synchro... (JINR) fixed target 1971-1999 \( \sqrt{s} < 3 \) GeV x experiments ~ xxx physicists

NICA (JINR) collider 2013- \( \sqrt{s} < 9 \) GeV 1 experiment ~ xxx physicists

\( \sqrt{s} \) from ~2 GeV in 1975 to 5500 GeV in 2009
SPS & RHIC results on heavy flavours in 4 plots

• **SPS: J/ψ suppression in central PbPb**
  - debye screening not a unique scenario
  - models cannot reproduce data in InIn collisions

• **RHIC: J/ψ suppression in central AuAu**
  - large uncertainties in cold nuclear effects
  - larger suppression at forward angles?

• **RHIC: charm quenching ~ light hadron quenching**
  - non-photonic electron vs. hadron $R_{AA}$
  - a challenge for models
  - experiments disagree on charm x-section
Heavy ion collisions & QGP @ LHC

The biggest step in energy in the history of heavy-ion collisions

<table>
<thead>
<tr>
<th>machine</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>17</td>
<td>200</td>
<td>5500</td>
</tr>
<tr>
<td>$N_{ch}$</td>
<td>1000</td>
<td>4000</td>
<td>50 000</td>
</tr>
<tr>
<td>$\tau^0_{QGP}$ (fm/c)</td>
<td>1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>$T/T_c (\tau^0_{QGP})$</td>
<td>1.1</td>
<td>1.9</td>
<td>3.0-4.2</td>
</tr>
<tr>
<td>$\varepsilon[1\text{ fm/c}]$ (GeV/fm$^3$)</td>
<td>3</td>
<td>5</td>
<td>15-60</td>
</tr>
<tr>
<td>$\tau_{QGP}$ (fm/c)</td>
<td>$\leq 2$</td>
<td>2-4</td>
<td>$\geq 10$</td>
</tr>
<tr>
<td>$\tau_f$ (fm/c)</td>
<td>$\sim 10$</td>
<td>20-30</td>
<td>30-40</td>
</tr>
<tr>
<td>$V_f$ (fm$^3$)</td>
<td>$\sim 10^3$</td>
<td>$\sim 10^4$</td>
<td>$\sim 10^5$</td>
</tr>
<tr>
<td>$\mu_B$ (MeV)</td>
<td>250</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>

Processes: soft $\rightarrow$ semi-hard $\rightarrow$ hard

$\varepsilon$, vol. & $\tau$ QGP $\times 10^4$ from SPS(RHIC) to LHC

"...the LHC will become the ideal facility for a systematic exploration and quantitative confirmation of the insights obtained at RHIC, aided by the plentiful abundance of hard probes."

B. Müller, hep-ph/0410115

Heavy-flavour x-sections @ LHC

\begin{align*}
\sigma_c(LHC) &= \sigma_c(RHIC) \times 10 \\
\sigma_b(LHC) &= \sigma_b(RHIC) \times 100 \\
\sigma_W(LHC) &= \sigma_\gamma(RHIC) \times 10 \\
\sigma_Z(LHC) &= \sigma_\gamma(RHIC)
\end{align*}
A closer look at heavy-quark cross-section

- NLO predictions for pp @ LHC: a factor ~ 2 uncertainty
- $\sigma(14 \text{ TeV}) / \sigma(5.5 \text{ TeV}) \sim 10\%$
  $\rightarrow$ measuring $\sigma(c,b)$ in pp @ 14TeV is top priority

Quarkonia suppression @ LHC

Quarkonium dissociation temperatures

- whether $J/\psi$ melts or not @ RHIC it will be strongly either suppressed or regenerated @ LHC
- use $\Upsilon(2S)$ to unravel $J/\psi$ sup. vs. reco. $\Upsilon$ reco. is small: L. Grandchamp et al., PRC 73 (2006) 064906
- $\Upsilon(1S)$ melts significantly only at LHC
- additional suppression by hard gluons
- relevance of quarkonium ratios vs. $p_t$
Charmonium regeneration @ LHC

1. peculiar centrality dependence
2. predictions strongly depend on $\sigma_{cc}$
3. (re-)dissociation by comovers
4. regeneration $\rightarrow$ smaller $<p_t^2>$

note: $N(B \rightarrow J/\psi) / N(\text{direct } J/\psi) \sim 20\%$ in $4\pi$

Heavy quark quenching @ LHC: new ratios

\[ \Delta E_g > \Delta E_{q=c} > \Delta E_b \Rightarrow R^h_{AA} < R^D_{AA} < R^B_{AA} \]

\[ R^{D(B)/h} = \frac{R^D_{AA}}{R^h_{AA}} \]

\[ R^{B/D}_{AA} = \frac{R^B_{AA}}{R^D_{AA}} \]

- \( R^{D/h} \) probes color charge dep. of \( \Delta E \)
- \( R^{B/h} \) probes mass dep. of \( \Delta E \)

\[ \text{mesons} \]

- isolate mass dep. of \( \Delta E \)
- sensitivity disappears at large \( p_t \)
- lower sensitivity to qhat

Heavy ions @ LHC

CMS

ALICE

ATLAS

Excited QCD09, Zakopane, 09/02/09
ALICE (A Large Ion Collider Experiment)

7(4) SPS(RHIC) experiments in one
18 sub-detectors
10000 tons
16 x 26 m
150 MCH

1000 members
109 institutes
31 countries
Heavy flavours with ALICE

ITS, TPC, TRD, ToF (|η|<0.9)
(dia-)electrons: J/ψ, ψ', Υ, Υ', Υ'', open charm, open bottom, W⁺,

muon spectrometer (-2.5<η<-4)
(dia-)muons: J/ψ, ψ', Υ, Υ', Υ'', open charm, open bottom, W⁺, Z⁰

ITS, TPC, TRD, ToF (|η|<0.9)
hadrons: D⁰, D⁺,…

electron-muon coincidences: open charm & bottom

no 2nd vertex
2nd vertex
Selected physics channels

- Quarkonia
- B from single leptons
- $D^0 \rightarrow K\pi$
- Heavy flavour quenching

“published” results only
Quarkonia: expected statistics in muon channel

1 LHC year = 7 months pp (10^7s, 3·10^{30}cm^{-2}s^{-1}) + 1 month AA (10^6s, 5·10^{26}cm^{-2}s^{-1})

<table>
<thead>
<tr>
<th>PbPb MB 5.5 TeV</th>
<th>( J/\psi )</th>
<th>( \psi' )</th>
<th>( \Upsilon )</th>
<th>( \Upsilon' )</th>
<th>( \Upsilon'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (( \times 10^3 ))</td>
<td>681.4</td>
<td>18.92</td>
<td>6.33</td>
<td>1.8</td>
<td>1.02</td>
</tr>
<tr>
<td>S/B</td>
<td>0.33</td>
<td>0.02</td>
<td>2.46</td>
<td>1.03</td>
<td>0.74</td>
</tr>
<tr>
<td>S/\sqrt{S+B}</td>
<td>413</td>
<td>19.53</td>
<td>67.14</td>
<td>30.19</td>
<td>20.85</td>
</tr>
<tr>
<td>pp 14 TeV</td>
<td>( S (\times 10^3) )</td>
<td>4670</td>
<td>122</td>
<td>44.7</td>
<td>11.4</td>
</tr>
<tr>
<td>S/B</td>
<td>12.6</td>
<td>0.55</td>
<td>5.8</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>S/\sqrt{S+B}</td>
<td>2081</td>
<td>209</td>
<td>195</td>
<td>86</td>
<td>62</td>
</tr>
</tbody>
</table>

- from PbPb MB to pp, a factor ~ 10 more stat.
  - \( J/\psi \): large stat., good significance
  - \( \psi' \): small S/B
  - \( \Upsilon \): good stat., S/B > 1, good significance
  - \( \Upsilon' \): good stat., S/B > 1, good significance
  - \( \Upsilon'' \): low statistics

- similar expected statistics in the electron channel

Observables with bottomonia

suppression 1: $T_C = 270$ MeV, $T_D/T_C = 4.0 (1.4)$ for $Y(Y')$

suppression 2: $T_C = 190$ MeV, $T_D/T_C = 2.9 (1.1)$ for $Y(Y')$

• statistics: one month PbPb @ 5.5 TeV

• large sensitivity to dissociation temperatures and medium size

More with quarkonia

polarization

- pp: test production mechanisms
- AA: probe QGP formation

\[ \gamma(\alpha_{gen} - \alpha_{rec}) \text{ vs. } p_t \]

pp @ 14 TeV

- pp @ 14 TeV: J/ψ & \( \Upsilon \) pol. vs. \( p_t \)
- PbPb @ 5.5TeV: J/ψ pol. vs. centrality, \( \Upsilon \) pol. needs 2-3 runs

dN/dy in pp

- probe gluon distribution at low x

R. Analdi, E. Scomparin, D. Stocco
### Open charm & bottom: accessible channels

#### Charm: exclusive hadronic channels
- $D^0 \rightarrow K\pi$ (tested in pp & PbPb)
- $D^+ \rightarrow K\pi\pi$ (tested in pp & PbPb)
- $D^{\pm}_s \rightarrow KK\pi$ (under study)
- $D^* \rightarrow D^0\pi$ (under study)
- $D^0 \rightarrow K\pi\pi\pi$ (under study)
- $\Lambda_c \rightarrow pK\pi$ (under study)

#### Charm & bottom: semi-inclusive leptonic channels
- $c \rightarrow l + X$ (à la CDF & D0)
- $b \rightarrow l + X$ (à la CDF & D0)
- $b \rightarrow J/\psi + X$ (à la CDF & D0)
- $b\bar{b} \rightarrow J/\psi + l$ (under study)
- $b\bar{b} \rightarrow 3\mu$ (should work in pp)
- $b\bar{b} \rightarrow l^+l^-l^+l^-$ (Bchain & BBdiff)
- $b\bar{b} \rightarrow l^l^l^-l^+l^+$ (Bchain & B osc.)

#### More exotic (and more challenging):
- $QQ\bar{Q}\bar{Q} \rightarrow e\mu$, $b \rightarrow > 5$ prongs, $\Lambda_b \rightarrow J/\psi + X$, etc
B-hadron cross-section from single leptons

First step: extract $N_i \leftarrow B$

w/o 2$^{\text{nd}}$ vertex: unfold lepton $dN/dp_t$ via combined fit large statistics constrains fit

with 2$^{\text{nd}}$ vertex: cut on dca & subtract remaining background large purity of lepton sample

$$B \rightarrow \mu \mu \mu \mu + X$$

**pp @ 14 TeV**

$B \rightarrow \mu + X$

- $2.1 \cdot 10^{12}$ pp evts (1 year)
- $p_t > 2 \text{ GeV/c}$
- $1.7 \cdot 10^8 \mu^\pm$ from $B$

**PbPb @ 5.5 TeV**

$B \rightarrow e + X$

- $10^7$ PbPb (5%) evts (1 month)
- $p_t > 2 \text{ GeV/c}$, $200 < d_0 < 600 \mu \text{m}$
- 80,000 $e^\pm$ from $B$, $S/(S+B) = 80\%$

B-hadron cross-section from single leptons

Second step: correct for efficiency, acceptance & decay kinematics

\[ \sigma^B (p_t^B > p_t^{\text{min}}) = \frac{N_{l \leftrightarrow B}}{\int L \, dt} \times \frac{1}{\varepsilon} \times \sigma^B (p_t^B > p_t^{\text{min}}) \]

- total number of $l \leftrightarrow B$
- integrated luminosity
- lepton global detection efficiency

B-hadron cross-section from single leptons

Third step: the inclusive differential B-hadron cross-section

- method widely used (UA1, CDF, D0)
- large \( p_T \) reach (~ 80% of the total cross-section is reconstructed)
- large \( \eta \) reach (central and forward regions)
- (very) small statistical errors, systematics ~ 10-15%
- allows to get B-hadron \( R_{AA}(p_T) \) (and D-hadron \( R_{AA}(p_T) \) simultaneously)

**Hadronic charm**

\[ D^0 \rightarrow K \pi (3.8\%) \]
\[ c\tau = 123 \mu m \]

- \( S \approx 13000 \)
- \( S/B \approx 10\% \)
- \( S/\sqrt{(S+B)} \approx 40 \)

**Graph:**

- Events vs. Invariant Mass [GeV]
- Cos(\( \Theta_{pointing} \)) > 0.98
- \( d_0^K \times d_0^{\pi} < -40000 \mu \text{m}^2 \)
- Increase S/B by 10^3

**Background:**

- Assumes \( dN/d\eta = 6000 @ \eta = 0 \)

**In Summary:**

- \( 10^7 \) central PbPb (5%)
- \( S \sim 13000 \)
- \( S/B \sim 10\% \)
- \( S/\sqrt{(S+B)} \sim 40 \)

Philippe.Crochet@clermont.in2p3.fr
Excited QCD09, Zakopane, 09/02/09
Hadronic charm differential x-section

The most precise measurement of the total charm x-section in pp collisions @ LHC

The table below summarizes the conditions and results of the measurements:

<table>
<thead>
<tr>
<th>System</th>
<th>pp</th>
<th>pPb</th>
<th>PbPb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>14</td>
<td>8.8</td>
<td>5.5</td>
</tr>
<tr>
<td>Trig</td>
<td>MB</td>
<td>MB</td>
<td>CC</td>
</tr>
<tr>
<td>$N_{\text{evt}}$</td>
<td>$10^9$</td>
<td>$10^8$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Time (months)</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$p_t^{\text{min}}$ (GeV/c)</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>$E_{\text{stat}}$ (%)</td>
<td>3</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>$E_{\text{syst}}$ (%)</td>
<td>14</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

The graph shows the differential cross-section for $D^0 \rightarrow K^-\pi^+$ in various collision systems, with indications of the $p_t$ and $\sqrt{s}$ for each condition.
Testing QCD with hadronic charm in pp collisions @ 14 TeV

$m_c, \mu_F/\mu_0, \mu_R/\mu_0, \text{PDF}

Expected experimental errors are much smaller than theoretical uncertainties

bars: quadratic sum of statistical & systematic errors

"Theory/Data"

Heavy quark quenching: traditional ratios

1 nominal year: $10^7$ central Pb-Pb events, $10^9$ pp events
statistics: bars, systematics: bands

\[
R_{AA}^D = \frac{1}{N_{coll}} \times \frac{dN_{AA}^D}{dp_t} / \frac{dN_{pp}^D}{dp_t}
\]

\[
R_{AA}^e = \frac{1}{N_{coll}} \times \frac{dN_{AA}^e}{dp_t} / \frac{dN_{pp}^e}{dp_t}
\]

sensitivity to shadowing for $p_t \lesssim 7$ GeV/c & to energy loss for $p_t \gtrsim 7$ GeV/c

Heavy quark quenching: more ratios

1 nominal year: $10^7$ central Pb-Pb events, $10^9$ pp events
statistics: bars, systematics: bands

\[
R_{D/h} = \frac{R_{AA}^D}{R_{AA}^h}
\]

\[
R_{B/D} = \frac{R_{AA}^{e, from B}}{R_{AA}^{e, from D}}
\]

sensitivity to color charge dependence

sensitivity to mass dependence

Waiting for data… first collisions expected in August 09

PbPb @ 5.5 TeV in ALICE