open heavy flavor production in ALICE
and its connection to quarkonium production

- $\sqrt{s} = 7$ and 2.76 TeV pp data:
  - measurement of hadronic decays of charmed hadrons
  - extraction of total charm cross section
  - measurement of electrons and muons from semi-leptonic decays of heavy flavor hadrons
- $\sqrt{s_{NN}} = 2.76$ TeV PbPb collisions:
  - open charm and beauty from hadronic decays
  - and from heavy flavor electrons and muons
- perspectives

EMMI Workshop  'Quarkonia in Deconfined Matter'
Acitrezza, September 29, 2011
why open heavy flavor?

- cross section in pp interesting in its own right, can be computed in pQCD
  - in PbPb collisions
    - cross section and gluon shadowing, probes nuclear gluon distributions
    - heavy quark energy loss in hot QGP and thermalization via $R_{AA}$ and elliptic flow?
    - do spectra exhibit radia flow?
- reference for quarkonia
best reference for charmonia?

- **NA38/NA50**: Drell-Yan
  - has several disadvantages: large stat. error, completely diff. production mechanism

- as a consequence proposal by H. Satz, K. Sridhar, PRD50 (1994) 3557 to use **open charm instead**
  much smoother $\sqrt{s}$ dependence

- for statistical hadronization model **open charm** is the only physical reference, only free parameter for prediction for yield of charmonia (J.S., P. Braun-Munzinger, PLB490 (2000) 196)
  - but due to quadratic dependence strong sensitivity to uncertainty in charm cross section

- need really accurate open charm measurement to have predictive power!

- $R_{AA}$ not the holy grail either, since shadowing enters, still need open charm
production of charm quarks at LHC energies

pair production

and higher orders...

gluon splitting

flavor excitation
production of charm in pQCD

Calculations of cross section and spectra in pQCD
FONLL Cacciari, Frixione, Mangano, Nason, Ridolfi, JHEP 0407 (2004) 033
and priv. comm.

significant uncertainties due to charm mass (used range 1.3 – 1.7 GeV and fragmentation and renormalisation scales ($\mu_F$ and $\mu_R$ 0.5 – 2)
less in FONLL (see talk by Ramona Vogt for details)

fragmentation of charm quarks into hadrons

<table>
<thead>
<tr>
<th></th>
<th>LEP data</th>
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<tbody>
<tr>
<td></td>
<td>stat. ⊕ syst. br.</td>
</tr>
<tr>
<td>$f(c \to D^{*+})$</td>
<td>0.235 ± 0.007</td>
</tr>
<tr>
<td>$f(c \to D^+)</td>
<td>0.222 ± 0.010</td>
</tr>
<tr>
<td>$f(c \to D_s^+)</td>
<td>0.087 ± 0.009</td>
</tr>
<tr>
<td>$f(b \to D^{*\pm})$</td>
<td>0.175 ± 0.020</td>
</tr>
<tr>
<td>$f(b \to D^{\pm})$</td>
<td>0.227 ± 0.016</td>
</tr>
<tr>
<td>$f(b \to D_s^{\pm})$</td>
<td>0.140 ± 0.016</td>
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</table>

thermal population very similar, see below
measurement of open charm via hadronic decays

\[ D^0 \rightarrow K^- + \pi^+ \]
\[ \text{BR} = 0.0389 \pm 0.0005 \]

\[ D^+ \rightarrow K^- + \pi^+ + \pi^+ \]
\[ \text{BR} = 0.094 \pm 0.004 \]

\[ D^{*+} \rightarrow D^0 + \pi^+ \]
\[ \text{BR} = 0.677 \pm 0.005 \]
measurement of charm and beauty via semi-leptonic decays

\[
\begin{align*}
D^+ &\rightarrow e^+/\mu^+ + \text{anything} \\
& \quad \text{BR} = 0.161 \pm 0.003 \\
D^0 &\rightarrow e^+/\mu^+ + \text{anything} \\
& \quad \text{BR} = 0.065 \pm 0.001 \\
D_s^+ &\rightarrow e^+/\mu^+ + \text{anything} \\
& \quad \text{BR} = 0.065 \pm 0.004 \\
B^+ &\rightarrow e^+/\mu^+ + \text{anything} \\
& \quad \text{BR} = 0.110 \pm 0.003 \\
B^0 &\rightarrow e^+/\mu^+ + \text{anything} \\
& \quad \text{BR} = 0.103 \pm 0.003 \\
B_s^0 &\rightarrow e^+/\mu^+ + D_s^- + \text{anything} \\
& \quad \text{BR} = 0.079 \pm 0.024 \\
B &\rightarrow J/\psi + \text{anything} \\
& \quad \text{BR} = \mathcal{O}(10^{-3})
\end{align*}
\]
open heavy flavor measurements in ALICE

rely on good tracking and vertexing performance and good particle identification (PID)
tracking performance – ITS system

After careful alignment of Silicon Pixel Detectors, expected vertex and impact parameter resolution already nearly reached.
measured TPC stand-alone momentum resolution

tracking cosmic rays in magnetic field resolution from two halves of a cosmic ray track: already at this stage 7% at 10 GeV/c
ALICE has PID over large momentum range

EMCAL adds electron/pion separation via shower shape
excellent PID with TPC
dE/dx resolution 5%
close to theoretical limit
ALICE PID performance 2 – time-of-flight (TOF)

\[ \sigma_{\text{TOF}} = \sigma / \sqrt{2} = 88 \text{ ps} \]
ALICE PID performance 3 – energy loss in ITS
Transition Radiation Detector

- Electron/pion discrimination
- Electron trigger
  (high pT, particle ID)

**Graph:**

- Pion Rejection Factor: 23
- Electron Efficiency: 0.89
- $p = 2.0$ GeV/c
- 6 Tracklets

**Legend:**

- Red: without TRD
- Blue: with TRD

**ALICE Performance**
10/03/2011
$pp, \sqrt{s} = 7$ TeV

[Diagram showing TPC dE/dx - $<dE/dx>_{\text{electron}}$ with counts on the y-axis and TPC dE/dx values on the x-axis.]

- Johanna Stachel
- Ruprecht-Karls-Universität Heidelberg
**D^0, D^±, D_s^± and D^{*±} in 7 TeV pp data**

**D^±, D^0, D_s^±, D^{*±}**

reconstructed in ALICE central barrel tracking ITS/TPC sec vertexing ITS PID TPC/TOF

Λ_c anal. just starting
D meson spectra in pp collisions

currrent analysis with 1/3 of 2010 statistics: spectra from 2 to 12 GeV/c expect to cover open charm for $p_t = 1 - 20$ GeV/c with full statistics

data also available for 2.76 TeV for D+, D0, D*+
population of various D states

in good agreement with systematics observed in e+e-, ep, and pp
errors will be reduced in future
in fact fragmentation very close to thermal
(except quarkonia)

5-flavor: use population of the 5 quark flavors following weak isospin

Andronic, Beutler, Braun-Munzinger, Redlich, Stachel., PLB678 (2009) 350
Measurements agree well with state of the art pQCD calculations.

spectra measured between 2 and 12 GeV/c can use good agreement with pQCD in measured range to extrapolate to charm production in full phase space.
from measured D-meson spectra to a total charm cross section

ALICE: D⁰, D⁺, D*⁺⁺-
2 < \( p_t \) < 12 GeV corresponds to about 40% of full spectrum
|y| < 0.5  about 12% of rapidity distribution of FONLL

ATLAS: D⁻, D*⁺⁺, Ds⁺-
\( p_t > 3.5 \) GeV/c corresponds to 1/7 of full spectrum
|\( \eta \)| < 2.1

ATLAS-CONF-2011-017
systematic errors of total charm cross section

in addition to statistical and systematic error of the measured D-meson spectra and error in luminosity measurement
theoretical error due to PDF, c-mass and pQCD scales enters via extrapolation

example:
present preliminary ALICE data

\[ \sigma^{\text{vis}}(D^0) = 206 \pm 20(\text{stat.})^{+25}_{-48}(\text{syst.}) \pm 14(\text{lum.}) \pm 3(\text{br.}) \mu b \]

– extrapolation factor is \( 1/(0.4 \times 0.12) = 20.7 \)

from FONLL

<table>
<thead>
<tr>
<th>D^0 central:</th>
<th>19.507</th>
</tr>
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<tbody>
<tr>
<td>Scales:</td>
<td>+5.600 -2.719</td>
</tr>
<tr>
<td>Mass:</td>
<td>+0.109 -0.618</td>
</tr>
<tr>
<td>PDF:</td>
<td>+0.780 -1.03</td>
</tr>
<tr>
<td>Overall:</td>
<td>+5.655 -2.973</td>
</tr>
</tbody>
</table>

+ 17 %
- 26 %

this will improve
(has already)

+ 29 %
- 15 %

best way to improve: increase measured fraction (lower p_t)
a first try at the total ccbar cross section in pp collisions

- good agreement with ATLAS and LHCb
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
electrons from semileptonic decays of charm and beauty hadrons

- **TOF:** ±3σ around expectation for electrons
  → remove K and p at low momenta
- **TRD:** use the energy deposit + TR for electron only
  cut fixed at 80% electron efficiency
  → suppress pions
  (not yet used in Pb-Pb analysis)
- **TPC:** lower cut in the middle of dE/dx distribution
  50% electron efficiency
  → Remove further pion contamination

- **pp:** $0.5 < p_T < 10$ GeV/c
  → less than 5% hadron contamination
- **Pb-Pb:** $1.5 < p_T < 6$ GeV/c
  → less than 10% hadron contamination
Inclusive electron spectrum

electron ID with TOF-TRD-TPC

Cocktail of known background e

- $\gamma$ conversion in the detector material
- $\pi^0$, $\eta$, $\eta'$ Dalitz-decays
- $\rho$, $\omega$, $\phi$ decays
- $J/\psi$, $Y$ decays
- Direct $\gamma$, $\gamma^*$ (based on NLO, W. Vogelsang)

- measured $\pi^0$ as input
- heavier mesons: $m_{\pi}$ scaling
- $J/\psi$, $Y$: ALICE and CMS measurements
- ratio Conversions/Dalitz: from the known material budget
D, B \rightarrow e + X

inclusive electrons - cocktail = D, B \rightarrow e + X

D mesons + decay kinematics

D \rightarrow e + X

measurement of D, B \rightarrow e + X from 0.8 to 10 GeV/c (TPC+TOF+TRD)

well described by FONLL calculations

large b mass and cτ of 500 μm combined with good impact parameter resolution allow cut on impact parameter in transverse plane $d_0$

subtraction of remaining background
$B \rightarrow e + X$

- Measurement of beauty electrons for $1.4 - 6.8 \text{ GeV/c}$
- Heavy flavor electrons – charm from D mesons
- Excellent agreement of 2 methods to determine electrons from B-decays
- Good agreement with FONLL calc.
Electrons from beauty relative to electrons from charm
in acceptance -4 < \eta < -2.5
background from decays of primary pion and kaon before absorber
    from decay of secondary pion and kaon in absorber
    from punch-through through absorber
    reduced by cuts and remaining background subtracted
data corrected for efficiency and acceptance
systematic error contains beyond
    correction uncertainties the error of
    background subtraction alignment
    and overall cross section error
for $p_t = 2$-10 GeV integrated yield of semi-leptonic muon data/FONLL = 1.24 
starts to constrain scales - see talk by Ramona Vogt
Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
R\textsubscript{AA} for D mesons in PbPb collisions

with increasing centrality significant suppression observed for D\textsuperscript{0}
and with somewhat larger errors but in good agreement also for D\textsuperscript{\pm} and D\textsuperscript{*}

how much of it is due to gluon shadowing in nuclear collisions?
no measurement yet estimates show: at small p\textsubscript{t} this could account for data, at p\textsubscript{t} > 5 GeV/c genuine hot medium effects
suppression of D mesons relative to pions

comparable
Inclusive electron spectrum as function of centrality

PID with TOF and TPC systematic error ±35% dominated by PID

cocktail similar as for pp: systematic error ±25%
ratio inclusive electrons to decay cocktail

in PbPb a hint for an electron excess at low $p_T$, increasing with centrality
thermal radiation? (measured by PHENIX in central collisions)
thermal charm production? See talk by Krzysztof Redlich
$R_{AA}$ for electrons from charm and beauty decays

- for central collisions significant suppression of heavy flavor electrons (dominate beyond 3.5 GeV/c)
- separation into charm and beauty to come
open heavy flavour suppression vs centrality

D mesons

all measures of open charm and beauty indicate significant energy loss of heavy quarks in central nuclear collisions
elliptic flow of D mesons

event plane from charged particle tracks in the TPC

SP: scalar product method

D^0 \rightarrow K\pi \text{ in 2 bins in and out of plane background subtraction with side-band method}

looking forward to more statistics with 2011 data
summary

Open charm measured in pp via hadronic D decays and semi-leptonic electron and muon decays at 7 and 2.76 TeV

Errors will still be reduced by adding more statistics and improving systematics

First measurement of b production via semi-electronic B decays J/psi from B just starting

Errors still too large to constrain J/psi to open charm ratio

In PbPb open charm and beauty are on the way, will benefit a lot from improved luminosity of 2011 run