Heavy-quark and quarkonia production in pp and heavy-ion collisions
Outlook

- Heavy quarks in pp collisions
  - Charmonium
  - Bottomonium
  - Open Charm/Beauty

- Heavy-Ion collisions
  - Charmonium $R_{AA}$
  - Heavy Quark energy loss
  - Elliptic Flow
  - $J/\psi$ in ultra-peripheral collisions
Heavy quarks in pp

- charm ($\approx 1.5$ GeV/c\(^2\))
- bottom ($\approx 5$ GeV/c\(^2\))
- top ($\approx 175$ GeV/c\(^2\))
- heavy quark pairs produced in hard partonic scattering

→ perturbative QCD

to get production cross sections, convolute three terms:

1. parton distribution function of incoming protons
2. partonic hard scattering cross sections (perturbative QCD)
3. hadronization into specific hadron → nonperturbative models
Heavy quarks in pp

- **Quarkonium production models**
  - **CSM**: $Q\bar{Q}$ pair in color-singlet state with same quantum numbers as quarkonium. $\rightarrow$ Successful at low energies, large corrections needed at higher, infrared divergences for $P$ (and higher)-wave quarkonia
  - **CEM**: $Q\bar{Q}$ pair evolves to quarkonium if invariant mass less than threshold for pair of open-flavor mesons. Probability for specific state energy and momentum independent. $\rightarrow$ Rough description of data
  - **NRQCD factorization**: most sound theoretically and most successful phenomenologically. Probability for $Q\bar{Q}$ to evolve to quarkonium as matrix elements of NRQCD operators (expansion in $\alpha_s$ and $v$) $\rightarrow$ many successes in describing data, remaining discrepancies
  - **Fragmentation functions**: convolution of parton production cross section and light-cone fragmentation functions.
Charmonium

S. Eidelman et al., Review of Particle Physics, Phys. Lett. B592:1+, 2004
J/ψ decay modes

- mass below threshold for production of two D mesons
- hadronic decay modes strongly suppressed due to OZI rule
- → narrow width: 93 keV/c²
- → electromagnetic decays become relevant
- BR J/ψ → e⁺e⁻/μ⁺μ⁻ : 6% each
**J/ψ in ALICE**

- dielectron channel at midrapidity
- dimuon channel at forward rapidity

**electron identification:**

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February 6, 2014  |  TU Darmstadt  |  Relativistische Schwerionenphysik  |  Steffen Weber  |  7
$J/\psi \rightarrow ee$

- mass spectrum of oppositely charged electrons
- background description
  - like-sign pairs
  - track rotation
  - event mixing
  - fitting

Counts per 40 MeV/c²

ALICE pp $\sqrt{s}=7$ TeV

Physics Letters B 704 (2011) 442–455
$J/\psi \to \mu\mu$

- mass spectrum of oppositely charged muons
- background description
  - like-sign pairs
  - track rotation
  - event mixing
  - fitting

![Graph showing mass spectrum of oppositely charged muons](Physics Letters B 704 (2011) 442–455)
Efficiencies and uncertainties

- take efficiencies into account to extract inclusive cross section
- systematic errors mainly due to unknown J/ψ polarization
Inclusive $J/\psi$ cross section
Sources of inclusive $J/\psi$

- **Prompt**
  - Direct production: 50-60%
  - Feed-down from heavier charmonia ($\psi(2s), \chi_c$): 30-40%

- **Non-prompt**
  - B meson decay: ~10%, $p_T$ dependent

  (numbers for LHC energies)
B mesons

- mesons with 1 b (anti-) quark and one light quark
- masses > 5280 MeV/c²
- weak decay to charmonium
- $c \tau \approx 450 - 500 \, \mu m$ → can be used to disentangle prompt from non-prompt J/ψ's
**J/ψ from B decay**

- for each J/ψ candidate:
  - find primary vertex and J/ψ decay vertex, connect by vector $\vec{L}$
  - project on $J/\psi$ $p_T$ → $L_{xy} = \frac{\vec{L} \cdot \vec{p_T}}{p_T}$

→ pseudoproper decay length $l_{J/\psi} = \frac{c \cdot L_{xy} \cdot m_{J/\psi}}{p_T}$

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**Graphs and Equations**

- $\chi^2/dof = 73/39$
- $ALICE \, pp, \sqrt{s} = 7 \, TeV$
- $p_T > 1.3 \, GeV/c$

- $\chi^2/dof = 27/44$
- $ALICE \, pp, \sqrt{s} = 7 \, TeV$
- $p_T > 1.3 \, GeV/c$

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JHEP 11 (2012) 065
J/ψ from B decay

- fit simultaneously mass spectrum and $l_{J/ψ}$ distribution by log-likelihood function

$$\ln L = \sum_{i=1}^{N} \ln F(l_{J/ψ}, m_{ll})$$

- contributions from signal and background

- signal $l_{J/ψ}$ shape:

$$F_{\text{Sig}}(l_{J/ψ}) = f_{B} \cdot F_{B}(l_{J/ψ}) + (1 - f_{B}) \cdot F_{p}(l_{J/ψ})$$

$F_{p}(l_{J/ψ})$ : resolution function

$F_{p}(l_{J/ψ})$ : res. fnc. + true $l_{J/ψ}$ distribution
J/ψ from B decay

- consistent results from different LHC experiments
- amount of J/ψ from B decay rises with transverse momentum
Prompt J/ψ cross section

- obtain prompt cross section
- comparison with models shows importance of color octet contributions
Higher charmonia states

\[ J^{PC} = 0^{-+} \quad 1^{-+} \quad 1^{++} \quad 1^{+-} \quad 2^{++} \]
\( \chi_{cJ} \)

- \( \text{BR } \chi_{c1} \rightarrow \gamma \ J/\psi : 35\% \)
- \( \text{BR } \chi_{c2} \rightarrow \gamma \ J/\psi : 20\% \)

- mass difference between \( J/\psi \) and \( \chi_{cJ} \): 500 MeV/c\(^2\)
  \( \rightarrow \) low momentum \( \gamma \)

- mass difference between \( \chi_{c1} \) and \( \chi_{c2} \): 45 MeV/c\(^2\)
  \( \rightarrow \) high momentum resolution necessary to distinguish states

- often used: conversion \( \gamma \rightarrow e^+e^- \)
$\chi_{cJ}$

ALICE Performance
pp @ $\sqrt{s} = 7$ TeV
10$^5$ May 2011

CMS
pp, $\sqrt{s} = 7$ TeV
$L = 4.6$ fb$^{-1}$

11 GeV/c $< p_T(J/\psi)$
13 GeV/c $> p_T(J/\psi)$

$\psi(2S)$

- $\text{BR } \psi(2S) \rightarrow J/\psi + \text{anything}: 60\%$

- $\text{BR } \psi(2S) \rightarrow J/\psi + \pi^+\pi^-: 34\%$

- Also $\psi(2S) \rightarrow e^+e^- / \mu^+\mu^- : 0.8\%$ each

![Graph showing data and fit for $e^+e^-$ and $\mu^+\mu^-$ events](image-url)
Bottomonium

THE BOTTOMONIUM SYSTEM

_mass (MeV)\n
9300
9500
9700
9900
10100
10300
10500
10700
10900
11100

$\eta_b (1S) \rightarrow \pi \pi$
$\pi \pi$
$\eta_b (2S) \rightarrow \pi \pi K K$
$\eta_b (3S) \rightarrow \pi \pi \pi$

$\gamma (1S) \rightarrow \eta$
$\gamma (2S) \rightarrow \pi \pi$
$\gamma (3S) \rightarrow \pi \pi \pi$
$\gamma (4S) \rightarrow \pi \pi \pi \pi$
$
\eta_b (2P) \rightarrow \pi \pi$
$\chi_{b0} (2P) \rightarrow \pi \pi$
$\chi_{b1} (2P) \rightarrow \pi \pi$

$\gamma (10860) \rightarrow \pi \pi$
$\gamma (11020) \rightarrow \pi \pi$

$\chi_{b0} (1P) \rightarrow \pi \pi$
$\chi_{b1} (1P) \rightarrow \pi \pi$
$\chi_{b2} (1P) \rightarrow \pi \pi$

$\chi_{b0} (3P) \rightarrow \pi \pi$

$J^{PC} = 0^- 1^- 1^+ 0^+ 1^+ 2^+ 2^-$

Thresholds:

$b, B^+, \bar{b} B^*$

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$\Upsilon(nS)$

- as for $J/\psi$, relatively large BR to dilepton channel: 
  $\sim 5\%$ for $\Upsilon(1S)$

- $\Upsilon(nS) \rightarrow \Upsilon(1S) + \pi^+\pi^-$

...
Open heavy flavor in pp
Semileptonic decays

- $D^+ = c \bar{d}$, $D^0 = c \bar{u}$,
  $\bar{D}^0 = \bar{c} u$, $D^- = \bar{c} d$
  $c \tau \approx 120 - 310 \mu m$

- B similar
  $c \tau \approx 450 - 500 \mu m$

- measurement: either electrons
  from semileptonic decays:
  measure inclusive electron
  spectrum, subtract electrons
  from other sources
Open heavy flavor in pp
Semileptonic decays

- $D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $D^- = c\bar{d}$, $\tau \approx 120 - 310 \mu m$
- $B$ similar, $\tau \approx 450 - 500 \mu m$

- Measurement: either electrons from **semileptonic decays**: measure inclusive electron spectrum, subtract electrons from other sources

- Agreement with FONLL calculations
**b and c**

- use impact parameter to disentangle feed-down from beauty

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![Graph](image.png)

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b and c

- use impact parameter to disentangle feed-down from beauty

- high resolution in ALICE:

JHEP 1201 (2012) 128

Open heavy flavor in pp 
Hadronic decays

- measurement: or reconstruction of decay products from hadronic decays
- require minimum impact parameter to reduce background
Total charm cross section

- divide cross section for measured D mesons by fragmentation ratio to obtain total charm cross section
**B meson reconstruction**

\[ B_s^0 \rightarrow J/\psi \phi , \text{ BR } \sim 10^{-3} \]

- indirect search for physics beyond the standard model
- probes CP violation

\[ B_s^0 \rightarrow \mu \mu , \text{ BR } \sim 10^{-9} \]

*Phys. Rev. D84 (2011) 052008*

*Phys. Rev. Lett. 111 (2013) 101804*
Heavy quarks in heavy-ion collisions

- heavy quarks are produced early on in the collision \( (m_c \gg T_c \rightarrow \text{thermal production strongly suppressed}) \)

- maintain their identity throughout all stages of the collision

- \( \rightarrow \) ideal probe for the medium created in the collision
Charmonium suppression

- Quantified by nuclear modification factor:

\[
R_{AA} = \frac{d^2 N_{AA}/dp_T dy}{\langle N_{coll} \rangle d^2 N_{pp}/dp_T dy}
\]

- compare yield in heavy-ion and proton-proton collisions

- hard probes \( \rightarrow \) scale by mean number of collisions for given centrality \( \rightarrow \) Glauber Monte Carlo calculations

Charmonia melting & (re)combination

- potential between $c$ and $\bar{c}$ quark is screened by free color charges in QGP → “melting” of charmonia states with increasing $T$
- at higher (LHC) energies, $c\bar{c}$ are abundantly produced → (re)combination to charmonia at phase boundary (Statistical Hadronization Model) or continuous creation and dissociation during hot phase (transport models)

Start of collision → Development of quark-gluon plasma → Hadronization

Nature 448, 302-309

SPS + RHIC

- agreeing results
- BUT: at RHIC less suppression at midrapidity → hint for (re)combination?


ALICE measurements

- $J/\psi \rightarrow ee$
- reminder: in pp: $S/B \sim 1$
ALICE measurements

- $J/\psi \rightarrow \mu \mu$
- reminder: in pp: $S/B \sim 2-3$

![Graph showing ALICE measurements](image_url)
\( J/\psi \) \( R_{AA} \) at LHC energies

- less suppression in central collisions and at low \( p_T \) than at RHIC
J/ψ $R_{AA}$ at LHC energies: models

- data reasonably well described by models
- models based on very different physical assumptions perform comparably well in describing the data
Higher charmonia states

- different models make different predictions for $R_{AA}$ of higher mass charmonia with respect to $J/\psi$
- measurements can help to discriminate between competing models
Heavy quark energy loss

- smaller loss expected than for light quarks → dead cone effect: gluon radiation suppressed at \( \theta_0 < m/E \)

- measurements in favor of this assumptions

(Caution: different \( p_T \) and \( y \) ranges)
Elliptic flow

- anisotropic (almond shaped) overlap region in non-central collisions → (interaction in medium) → momentum anisotropy

- non-zero elliptic flow seen in both charmonium and open charm
J/ψ in ultra-peripheral collisions

- impact parameter larger than size of nuclei
- strong electromagnetic field between heavy-ion nuclei
- exclusive vector meson production: exchange of two gluons with no net color transfer
- either coherent: photon couples to whole nucleus or incoherent: photon couples to single nucleon

**J/ψ in ultra-peripheral collisions**

- select event with $\leq 10$ tracks
- two tracks compatible with being dilepton pair
**J/ψ in ultra-peripheral collisions**

- allows investigation of gluon distribution at Bjorken-x around $10^{-3}$
- model predictions wide spread, mainly differ in how they treat nuclear effects (gluon shadowing)
Summary and Conclusion

- Heavy quarks are important tool
  - in pp to test pQCD
  - in heavy-ion collisions to investigate deconfined medium

- Charmonium no longer “thermometer” for QGP, but it remains an important probe
  - either for medium itself (transport models),
  - or for phase transition (statistical hadronization model)

- Ultra-peripheral collisions can be used to investigate gluon distributions in nuclei
Backup
NLO corrections

Real Emission Diagrams

Virtual Emission Diagrams

CERN-TH/97-328
Charmonia melting

- potential between c and \( \bar{c} \) quark is screened by presence of free color charge in QGP

\[
V(r, T=0) = \sigma r - \frac{\alpha_{\text{eff}}}{r} \quad \Rightarrow \quad V(r, T \gg T_c) = \frac{\alpha_{\text{eff}}}{r} \exp\left[-\frac{r}{\lambda_D(T)}\right]
\]

- “melting”, if screening length smaller than size of hadron
Sequential suppression

- Charmonia states have different radii, they melt at different temperatures

- their feed-down to $J/\psi$ vanishes
  → stepwise decline of $J/\psi$ yield
  → thermometer for the QGP
SPS

- NA38, NA50, NA51, NA60: fixed target experiments \( \sqrt{S_{NN}} \approx 20 \text{GeV} \)

- Agreement between NA50 and NA60 in common region

- “Anomalous suppression” beyond cold nuclear matter effects

- Compatible with melting of \( \chi_c \) and \( \psi(2S) \), i.e. sequential suppression scenario
Higher energies: (Re)combination

- at higher energies, \( c\bar{c} \) pairs are abundantly produced \( \rightarrow \) can recombine to charmonia

<table>
<thead>
<tr>
<th></th>
<th>most central AA</th>
<th>SPS (20GeV)</th>
<th>RHIC (200GeV)</th>
<th>LHC (2.76TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{cc} )/event</td>
<td>~0.2</td>
<td>~10</td>
<td>~60</td>
<td></td>
</tr>
</tbody>
</table>

**Statistical hadronization:**

- no charmonia production before QGP
- \( c,\bar{c} \) quarks distributed to hadrons according to thermal model at hadronization

**alternative:** continuous destruction and recreation of charmonia in QGP

- Low (RHIC) energy
- High (LHC) energy

Start of collision
Development of quark-gluon plasma
Hadronization
$R_{AA}$ vs. $p_T$

- $R_{AA}$ $p_T$ dependence very different from RHIC
- at low $p_T$ suppression is significantly reduced
LHC: expectation

- another order of magnitude increase in $\sqrt{S_{NN}}$ → further suppression or (re)combination?

- different detectors cover different kinetic regions → complementary measurements
Open heavy flavor in Heavy-Ion collisions

- do heavy quarks take part in collective motion in deconfined stage → elliptic flow
Elliptic Flow

\( E \frac{d^3 N}{d^3 p} = \frac{1}{2 \pi} \frac{d^2 N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2 \nu_n \cos \left[ n (\phi - \psi_R) \right] \right) \)

\( \nu_1 \) directed flow

\( \nu_2 \) elliptic flow
Ultra-peripheral

**Graphs:**

1. 
Pb+Pb → Pb+Pb+J/ψ (\(|y| < 0.9\))
   - Opposite sign muon pairs
   - Like sign muon pairs
   - \(N_{\mu\bar{\mu}} = 91 \pm 15\)
   - \(m_{\mu\bar{\mu}} = 3.085 \pm 0.007\) GeV/c²
   - \(\sigma_{\mu\bar{\mu}} = 83 \pm 6\) MeV/c²

2. 
Pb+Pb → Pb+Pb+J/ψ (\(|y| < 0.9\))
   - Opposite sign electron pairs
   - Like sign electron pairs
   - \(N_{e+e^-} = 61 \pm 14\)
   - \(m_{e+e^-} = 3.089 \pm 0.007\) GeV/c²
   - \(\sigma_{e+e^-} = 86.8 \pm 1.4\) MeV/c²

**Equation:**
Pb+Pb → Pb+Pb+J/ψ (\(|y| < 0.9\))

\[\sqrt{s_{NN}} = 2.76\text{ TeV}\]

**Graphs:**

- **Starlight**
- **LM-flPset**
- **RSZ-LTA**