Heavy ions: flavour production

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Outline

- The Quark-Gluon Plasma
- Heavy-ion collisions
- Flavour production
  - Strangeness
  - Open heavy-flavour
  - Quarkonium
- Summary

Many results not included here for time reasons, apologies!

Strange, charm, and beauty quarks are all produced anew in the collision → reflect the amount of energy available.
Quark-Gluon Plasma

Ordinary nuclear matter
Pressure

Heat

QGP

Deconfined quarks and gluons
Partonic number of degrees of freedom

Predicted by lattice QCD
hep-lat/0106019

GSI
Dense and hot nuclear matter: why?

Status of matter in first instants of our universe 10^{-6} seconds
QGP in the laboratory

Produced in the collisions of **heavy ions** at **high energies**

(Au, Pb ...)

$\sqrt{s_{NN}}$ few GeV at AGS, GSI, SPS
up to 200 GeV at RHIC
2.76 TeV at LHC

UrQMD

PHENIX, STAR
Heavy ions at the LHC

Pb – Pb collisions
\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
2010–2011: \( \sim 0.1 \text{ nb}^{-1} \)
Heavy ions at the LHC

Pb – Pb collisions
$\sqrt{s_{NN}} = 2.76$ TeV
2010–2011: $\sim 0.1$ nb$^{-1}$

p – Pb collisions
$\sqrt{s_{NN}} = 5.02$ TeV
(2012–)2013: $\sim 30$ nb$^{-1}$
LHC experiments: 1 highlight each

ALICE:
Excellent particle identification

Pb-Pb, 2011 run, $\sqrt{s_{NN}} = 2.76$ TeV

negative particles

\[ m^2 / z^2 \, (GeV^2/c^4) \]

$\bar{p}$, $\bar{d}$, $\bar{t}$, He, $^3$He

offline trigger

TPC ionization signal (a.u.)

$p / Z \, (GeV/c)$

Candidates (0.2 ps)

$2.5 < y < 4.5$

$P_{T, < 15}$

$0.1 < 0.2$

$100 < 150$

$0.3 < 0.5$

$200 < 250$

$0.5 < 0.7$

$300 < 350$

$0.7 < 0.9$

$400 < 450$

$0.9 < 1.1$

$500 < 550$

$1.1 < 1.3$

$600 < 650$

$1.3 < 1.5$

$700 < 750$

$1.5 < 1.7$

$800 < 850$

$1.7 < 1.9$

$900 < 950$

$1.9 < 2.1$

$1000 < 1050$

$2.1 < 2.3$

$100 < 150$

$2.3 < 2.5$

$150 < 200$

$2.5 < 2.7$

$200 < 250$

$2.7 < 2.9$

$250 < 300$

$2.9 < 3.1$

$300 < 350$

$3.1 < 3.3$

$350 < 400$

$3.3 < 3.5$

$400 < 450$

$3.5 < 3.7$

$450 < 500$

$3.7 < 3.9$

$500 < 550$

$3.9 < 4.1$

$550 < 600$

$4.1 < 4.3$

$600 < 650$

$4.3 < 4.5$

$650 < 700$

$4.5 < 4.7$

$700 < 750$

$4.7 < 4.9$

$750 < 800$

$4.9 < 5.1$

$800 < 850$

$5.1 < 5.3$

$850 < 900$

$5.3 < 5.5$

$900 < 950$

$5.5 < 5.7$

$950 < 1000$

$5.7 < 5.9$

$1000 < 1050$

$5.9 < 6.1$

$1050 < 1100$

$6.1 < 6.3$

$1100 < 1150$

$6.3 < 6.5$

$1150 < 1200$

$6.5 < 6.7$

$1200 < 1250$

$6.7 < 6.9$

$1250 < 1300$

$6.9 < 7.1$

$1300 < 1350$

$7.1 < 7.3$

$1350 < 1400$

$7.3 < 7.5$

$1400 < 1450$

$7.5 < 7.7$

$1450 < 1500$

$7.7 < 7.9$

$1500 < 1550$

$7.9 < 8.1$

$1550 < 1600$

$8.1 < 8.3$

$1600 < 1650$

$8.3 < 8.5$

$1650 < 1700$

$8.5 < 8.7$

$1700 < 1750$

$8.7 < 8.9$

$1750 < 1800$

$8.9 < 9.1$

$1800 < 1850$

$9.1 < 9.3$

$1850 < 1900$

$9.3 < 9.5$

$1900 < 1950$

$9.5 < 9.7$

$1950 < 2000$

$9.7 < 10.0$

$2000 < 2050$

$10.0 < 10.1$

$2050 < 2100$

$10.1 < 10.2$

$2100 < 2150$

$10.2 < 10.3$

$2150 < 2200$

$10.3 < 10.4$

$2200 < 2250$

$10.4 < 10.5$

$2250 < 2300$

$10.5 < 10.6$

$2300 < 2350$

$10.6 < 10.7$

$2350 < 2400$

$10.7 < 10.8$

$2400 < 2450$

$10.8 < 10.9$

$2450 < 2500$

$10.9 < 11.0$

$2500 < 2550$

$11.0 < 11.1$

$2550 < 2600$

$11.1 < 11.2$

$2600 < 2650$

$11.2 < 11.3$

$2650 < 2700$

$11.3 < 11.4$

$2700 < 2750$

$11.4 < 11.5$

$2750 < 2800$

$11.5 < 11.6$

$2800 < 2850$

$11.6 < 11.7$

$2850 < 2900$

$11.7 < 11.8$

$2900 < 2950$

$11.8 < 12.0$

$2950 < 3000$
LHC experiments: 1 highlight each

ATLAS:
Excellent jet reconstruction
LHC experiments: 1 highlight each

CMS: Outstanding dimuons
LHC experiments: 1 highlight each

LHCb: Master of beauty
Results presented today

- Strangeness production: $K^0_s$, $\Lambda$, $\Xi$, $\Omega$, ($^3\Lambda\mathrm{H}$)
  - Thermal fits. Baryon “anomaly”
  - Open heavy-flavour production: $D$, $B$
    - Parton energy loss in the medium
    - Heavy-quark thermalization
  - Quarkonia production: $J/\psi$, $\Upsilon$
    - Melting in the medium, (re)generation

proton - proton
Reference system, normalization

proton - Pb
Cold nuclear matter, initial-state effects (shadowing, gluon saturation)
Central collisions → high number of participants  
→ high multiplicity

Peripheral collisions → low number of participants  
→ low multiplicity

E.g. measure by VZERO scintillators +  
reproduced by Glauber model fit

Centrality: percentile of total hadronic cross section

peripheral  
central
Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
Strangeness production: particle yields

\[ K^0_S, \Lambda, \Xi, \Omega: \text{topological reconstruction + particle identification} \]

Strange quark: light enough to be produced thermally in the QGP

Measured yields consistent with thermal production?
The baryon “anomaly”

p/π and Λ/K⁰_s ratios enhanced in intermediate p_T region (seen at RHIC). Coalescence?

Very similar at the LHC. Peak p_T increases slightly

Integrated ratio is unchanged → suggests particle redistribution in p_T

Effect of radial flow
The baryon “anomaly” vs RHIC and theory

$p/\pi$ and $\Lambda/K^0_S$ ratios enhanced in intermediate $p_T$ region (seen at RHIC). Coalescence?

Very similar at the LHC. Peak $p_T$ increases slightly

Integrated ratio is unchanged $\rightarrow$ suggests particle redistribution in $p_T$

Effect of radial flow
$K^0_S$ and $\Lambda$ in p-Pb collisions

**Spectra in multiplicity bins**

$\Lambda/K^0_S$ ratio

Very intriguing results from the proton-Pb data! At high multiplicities, behaviour found which recalls hydro-type models → see correlation results in the next talk!
Medium tomography: heavy flavours

Infer properties of the deconfined medium from the interaction of “probes” with it:
- Energy loss in medium, suppression
- Transport coefficients
- Collective phenomena

Heavy quarks are ideal probes:
they are produced in high-$Q^2$ processes
in the initial stage of the collision
→ present from the early time of the medium,
  the highest density phase
→ exposed to the medium evolution

LHC: large production cross section
In-medium parton energy loss

- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium constituents

- Depends on:
  - Colour charge \( \Delta E_{\text{gluon}} > \Delta E_q \rightarrow \) heavy to light hadrons
  - Parton mass \( \Delta E_c > \Delta E_b \rightarrow \) charm and beauty

Quantifier: the **nuclear modification factor**

\[
R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{\text{coll}}} \]

as function of \( p_T \) and centrality
Nuclear modification factor

No medium effect  $\rightarrow$  $R_{AA} \approx 1$
Medium effect  $\rightarrow$  medium “slows” down particles  $\rightarrow$  $R_{AA} < 1$

- No modification for vector bosons: $\gamma$, $W^\pm$, $Z^0$
- Strong suppression for charged hadrons, still significant at 100 GeV/c!
- Look at charm and beauty

ALICE: (Pb-Pb) PLB720 (2013) 52, (p-Pb) PRL 110, 082302 (2013)
Heavy-flavour reconstruction

- **Vertexing**: impact parameter resolution (similar for all experiments)
  \[\sim 60 \, \mu\text{m at 1 GeV/c}\]

- **Particle identification**

- **Invariant mass analysis**

\[D^0 \rightarrow K^- \pi^+\]
\[D^+ \rightarrow K^- \pi^+ \pi^+\]
\[D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+\]
\[D^+_{s} \rightarrow \Phi \pi^+ \rightarrow K^- K^+ \pi^+\]

**JHEP 1209 (2012) 112**

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Charm: D mesons

$D^0, D^+, D^{*+}, D_s^+$

$R_{AA}$ Nuclear modification factor vs $p_T$ and collision centrality

Charm mesons exhibit strong suppression

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Semi-leptonic decays

c, b → lepton + X  inclusive measurements
Low $p_T$: background subtraction needed
Above 4-5 GeV/c: beauty dominant

Significant suppression of both charm and beauty
Beauty: $B \to J/\psi X$

Exclusive beauty component

The method: pseudo-proper decay length

Nuclear modification factor as function of centrality and $p_T$

Strong suppression of beauty

CMS PAS HIN-12-014

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Charged, charm, and beauty

Comparison of suppression for: light → charm → beauty

Clear difference between charm and beauty

More statistics needed to extract mass and colour charge dependence
Charged, charm, and beauty

Comparison of suppression for: light $\rightarrow$ charm $\rightarrow$ beauty

Clear difference between charm and beauty

More statistics needed to extract mass and colour charge dependence

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Comparison to theory

Comparison of measured $R_{AA}$ with theoretical models → from the experimental result to the description of the medium and its properties

Important to further understand how the parton energy loss depends on mass and colour charge
proton-Pb results: 2013 run

proton-Pb: control experiment for Pb-Pb
Expectation about initial state effects: shadowing, no energy loss

- Nuclear modification factor compatible with unity and well described by pQCD+EPS09 predictions
  JHEP 0904 (2009) 065
- Pb-Pb suppression is a final state effect
proton-Pb results: 2013 run

proton-Pb: control experiment for Pb-Pb

Pb-Pb suppression is not a cold nuclear matter effect. It is a final state effect

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Quarkonium

QQ states

\{ cc \quad J/\psi, \psi', \chi_c \\
\quad b\bar{b} \quad Y(1S), Y(2S), Y(3S), \chi_b \}

Excellent probes of the medium:

- With increasing temperature, the maximum size up to which quarkonium states are bound decreases
- The melting of the quarkonium states should follow a sequence defined by their size
- Thermometer of the QGP!

Colour screening in the medium

Probe of deconfinement!

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Upsilon suppression and melting

PRL 109, 222301 (2012)
Upsilon at the LHC

PRL 109, 222301 (2012)
arXiv: 1201.5069v2

ALICE Preliminary

CMS

L_{int} = 150 \mu b^{-1}; |y| < 2.4

\gamma(1S)

\gamma(2S)

\gamma(3S), 95% upper limit

1S
Flat in rapidity

2S

3S

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J/ψ production: results

Forward rapidity ($\mu^+\mu^-$)  \hspace{1cm} p_T>0  \hspace{1cm} Mid rapidity ($e^+e^-$)

- Shown as function of collision centrality
- ALICE compared to RHIC, PHENIX result (lower energy density)
- Higher yield at the LHC !!
J/ψ production: models

can be explained by regeneration in the QGP or by statistical hadronization → signature of deconfinement

Start of collision  Development of quark-gluon plasma  Hadronization

Low (RHIC) energy

High (LHC) energy
J/ψ production: models

(Re-)generation of J/ψ from deconfined charm quarks in the medium

Still missing ingredients to estimate quantitatively the final state effects:

- Cold Nuclear Matter effects: nuclear absorption likely to be negligible
- Shadowing
- Charm production cross section
- Beauty feed-down (order of ~ 10%)

\[ p-Pb \text{ run!} \]
The J/ψ in p-Pb

- Nuclear absorption expected to be small at the LHC
- Large gluon shadowing expected, with large uncertainties
- Initial energy loss? Or gluon saturation?
The J/ψ in p-Pb

- Nuclear absorption expected to be small at the LHC
- Large gluon shadowing expected, with large uncertainties
- Initial energy loss? Or gluon saturation?
- Large (pp) uncertainties → no discrimination yet between shadowing and shadowing+energy loss
- Color Glass Condensate (CGC) calculation disfavoured by data
Upsilon(1S) in p-Pb

Also Upsilon(1S) is measured in pPb for cold nuclear matter effects:

\[ \Upsilon(1s) \]
Summary

- High quality data from the excellent heavy-ion LHC periods
- First characterization of the hot QGP, *unprecedented conditions*
- A wealth of results from ALICE, ATLAS, CMS (Pb-Pb) and LHCb (p-Pb)
- … has given plenty of experimental input to theorists!

Flavour production

- Strangeness: thermodynamical view
- Open heavy flavour: medium properties investigation, parton energy loss
- Quarkonia: melting and (re)generation

Fascinating exploration of strongly interacting matter
Heavy-ion parallel sessions: 18-19 July

- P. Christiansen “Identified charged pion, kaon, and proton production in pp and Pb-Pb collisions at the LHC energies measured with ALICE”
- F. Jing “Particle production in p-Pb and Pb-p collisions at the LHC with LHCb”
- K. Krajczar “Measurements of hadron production in pPb collisions in CMS”
- R. Preghenella “Transverse momentum distribution of charged particles and identified hadrons in p-Pb collisions at the LHC with ALICE”
- A. Grelli “Heavy flavour production in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV with the ALICE detector”
- D. Tlustý “Open charm hadron production in pp and Au+Au collisions at STAR”
- O. Hajkova “The measurement of non-photonic electrons in STAR”
- H. van Hees “Heavy quarks in heavy-ion collisions”
- C. Bianchin “Prospects for heavy-flavour measurements in Pb-Pb collisions at the LHC with the new ALICE inner tracker”
- A. Kalweit “Measurement of anti- and hyper-matter production with the ALICE experiment”
- E. Frąciacom “Hadronic resonance production in pp and Pb-Pb collisions at LHC with the ALICE experiment”
- M. Marchisone “Quarkonia production in Pb-Pb and pp collisions at forward rapidity with the ALICE experiment”
- F. Arleo “Heavy-quarkonium suppression in p-A collisions from parton energy loss in cold QCD matter”
- E. Atomssa “Recent results from the PHENIX experiment”
SPARES
Phase diagram

RHIC, LHC:
very high temperature
low baryochemical potential
(~pressure in the water phase diagram)

RHIC
Beam energy scan

FAIR, NICA:
lower temperature
high baryochemical potential

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Integrated luminosities at LHC

LHC in 2011 reached amazing interaction rates, beating its own expectations!

**Pb – Pb 2010**

- 2010 HI RUN (3.5 Z TeV/beam)
- DELIMINARY (±10% scale)
- ATLAS
- ALICE
- CMS

**Pb – Pb 2011**

- LHC 2011 HI RUN (3.5 Z TeV/beam)
- ATLAS 167.6 µb⁻¹
- CMS 149.7 µb⁻¹
- ALICE 143.6 µb⁻¹

0.01 nb⁻¹ (2010)

0.1 nb⁻¹ (2011)

6 kHz Pb-Pb!
AA collisions at ultra-relativistic energies

Thermalization: equilibrium is established (t < 1 fm/c)

Expansion and cooling: (t < 10-15 fm/c)

Chemical freeze-out (particle yields)
Kinetic freeze-out (particle spectra)

Compress a very large amount of energy in a very small volume → “fireball” of hot matter, temperature O(10^{12} K)
- \( \sim 10^5 \times T \) at the center of the sun
- \( \sim T \) of the early universe (\( \mu \)s after Big Bang)
ATLAS: A Toroidal LHC ApparatuS

Total weight : 7000 T
Overall diameter : 25 m
Overall length : 44 m
Magnetic field : 2 Tesla
ALICE: A Large Ion Collider Experiment

Central barrel $|\eta| < 0.9$
L3 magnet: 0.5 T

Inner Tracking System

Time Projection Chamber

Time Of Flight

Transition Radiation Detector

Electromagnetic Calorimeter

Muon spectrometer $-4 < \eta < -2.5$

Total weight: 16000 T
Overall diameter: 16 m
Overall length: 26 m
Magnetic field: 0.5 Tesla

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CMS: Compact Muon Solenoid

- Total weight: 12500 T
- Overall diameter: 15.0 m
- Overall length: 21.5 m
- Magnetic field: 4 Tesla

Diagram showing the CMS detector with labels for Tracker, Crystal ECAL, Preshower, Superconducting Magnet, HCal, Feet, Forward Calorimeter, and Muon Chambers.
ALICE: particle identification 1

**Time Projection Chamber**

- **TPC dE/dx (a.u.)**
- **pp @ √s = 7 TeV**
- **ALICE Performance**
- **2011-05-18**

**Inner Tracking System**

**Time of Flight**

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ALICE: particle identification 2

Transition Radiation Detector

e/π separation Trigger

Electromagnetic Calorimeter: E/p
ALICE: strange hadrons

Single-Strange

\[ K_S^0 \rightarrow \pi^+ + \pi^- \] (B.R. 69.2%)
\[ \Lambda \rightarrow p + \pi^- \] (B.R. 63.9%)
\[ \bar{\Lambda} \rightarrow \bar{p} + \pi^+ \] (B.R. 63.9%)

Secondary Strange

\[ d \bar{s} - s \bar{d} \over \sqrt{2} \]

Multi-Strange

\[ \Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^- \] (B.R. 63.9%)
\[ \Xi^+ \rightarrow \bar{\Lambda} + \pi^+ \rightarrow \bar{p} + \pi^+ + \pi^+ \] (B.R. 63.9%)
\[ \Omega^- \rightarrow \Lambda + K^- \rightarrow p + \pi^- + K^- \] (B.R. 43.3%)
\[ \Omega^+ \rightarrow \bar{\Lambda} + K^+ \rightarrow \bar{p} + \pi^+ + K^+ \] (B.R. 43.3%)

Weak Decays:
Possible identification over a large range of transverse momentum

Detection in the mid-rapidity (|y| < 0.5) range

Cascade Decay Topology

- Silicon Pixel (4cm, 7cm)
- Silicon Drift (15cm, 24cm)
- Silicon Strip (39cm, 44cm)
- TPC (> 85cm)

Track based selections:
- Topological selection
- TPC dE/dx selection
- Competing decay rejection
Thermal hadronization model

Fit includes full variety of measured particles:

- Global fit gives a freeze-out temperature of 156 MeV, lower than predictions (~164 MeV). It misses multi-strange.

- Excluding protons → better fit gives 158 MeV, and describes well Ξ, Ω.

- K* not used in the fit, resonances can interact with hadronic medium in final state.

**Unique chemical freeze-out temperature does not describe p, Λ, Ξ, Ω**

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Hyper-matter

- Hyper-triton

- Search for exotic states: upper limit for $\Lambda n$ and $H$-dibaryon
Charged particle $R_{AA}$

0-5% most central coll.
- Minimum at $p_T$
  $\sim 6$-7 GeV/c
- Then a slow increase for higher $p_T$
- Still a significant suppression at 100 GeV/c !!

Medium so dense that pQCD still not restored around 100 GeV/c !!

Models!
Electrons from heavy-flavour hadron decays
Production cross section of charm + beauty $\rightarrow$ electron + X

Test of pQCD
ALICE specialties: proton-proton

\[ J/\psi (c\bar{c}) \rightarrow e^+e^-, \mu^+\mu^- \]
\[ p_T > 0 \text{ GeV/c} \]

Production yield as a function of charged particle multiplicity

LINEAR INCREASE!

Remains a puzzle!

Charm: D mesons ALICE

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

\[ R_{AA} \]

Strong suppression

JHEP 1209 (2012) 112
Charm: D mesons STAR

D° in Au+Au collisions, 200 GeV

Charm cross section scaling with number of binary collisions

Au+Au → D° + X @ 200 GeV y10+y11

- 0-80%
- He 0-80%
- Gossiaux 0-80%

STAR Preliminary

He: arXiv:1204.4442
Initial state effects: nuclear shadowing (reducing the parton distribution functions) cannot explain suppression above 6 GeV/c
Charm: D mesons and theory (2)

Parton energy loss models:
1) radiative + collisional (inelastic + elastic)
2) radiative + D dissociation

\[ R_{AA} (\text{prompt D}) \]

\[ p_T \text{ reach extended with 2011 statistics} \]
Charm: D mesons

Also for charm compare in and out of plane:
Charm flow

Elliptic flow of D mesons compatible with that of charged hadrons

→ indication of charm thermalization in the medium!
Beauty jets

- Jets tagged by their secondary vertices
- Template fits to the secondary vertex mass distribution

CMS PAS HIN-12-003

\[
\int L \, dt = 150 \, \mu b^{-1}
\]

PbPb Data

Pythia+Hydjet

Syst. uncertainty

\[
80 < \text{Jet } p_T < 100 \text{ GeV/c}
\]

\[
50-100\% \quad 20-50\% \quad 0-20\%
\]

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

**b-jet \( R_{AA} = \)** inclusive jet \( R_{AA} \) * double ratio

\[\begin{array}{c}
\text{CMS preliminary} \\
\text{0.06} \\
\text{0.05} \\
\text{0.04} \\
\text{0.03} \\
\text{0.02} \\
\text{0.01} \\
0 \\
\end{array}\]

\[\begin{array}{c}
\text{b-jet fraction} \\
\text{50-100\%} \\
\text{20-50\%} \\
\text{0-20\%} \\
\end{array}\]

\[\begin{array}{c}
\text{N_{part}} \\
0 \\
50 \\
100 \\
150 \\
200 \\
250 \\
300 \\
350 \\
400 \\
\end{array}\]

\[\begin{array}{c}
\text{jet } p_T (\text{GeV}) \\
100 \\
150 \\
200 \\
250 \\
300 \\
\end{array}\]

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Quarkonium: sequential melting

- The color-screening is stronger at higher temperatures
- $\lambda_D$ is the maximum size of a bound state to survive in the medium
  - It decreases when the temperature increases
- Different quarkonium states have different sizes

→ the melting of the resonances should follow a sequence defined by their size
→ thermometer of the QGP!
Upsilon suppression and melting

PRL 109, 222301 (2012)

$\Upsilon(1s)$

\[ R_{\pi} < 1.4 \]

\[ R_{pA} < 1.4 \]

\[ ALICE: L_{int} = 69 \mu b^{-1}, \ 2.5 < y < 4 \]

\[ CMS: L_{int} = 150 \mu b^{-1}, \ |y| < 2.4 \]

\[ ALICE: L_{int} = 69 \mu b^{-1}, \ 0\%-90\% \]

\[ CMS: L_{int} = 150 \mu b^{-1}, \ 0\%-100\% \]

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J/ψ $R_{AA}$ versus $p_T$

- Stronger suppression at high $p_T$
- $p_T$ dependence stronger for central collisions
- (re)generation contribution at low $p_T$
  → interesting region for the characterization of QGP