Heavy quarks: where do we stand? What next?

E. Scomparin (INFN-Torino)

Quarkonia → Sensitive to the temperature of QGP

Probes the opacity of QGP → Open heavy quarks
The beginning of the story...

...28 years after the prediction of $J/\psi$ suppression by Matsui and Satz

...18 years after the prediction of radiative energy loss by the BDMPS group
... and the story goes on

...28 years after O beams were first accelerated in the SPS

...14 years after Au beams were first accelerated at RHIC

... and barely 3.5 years (!!!) after Pb beams first circulated inside the LHC
Are LHC results matching our expectations?

Definitely yes!
..and RHIC is keeping pace
Heavy quark energy loss...

- **Fundamental test** of our understanding of the energy loss mechanism, since $\Delta E$ depends on
  - Properties of the medium
  - Path length
- ..but should critically depend on the properties of the parton
  - Casimir factor
  - Quark mass (dead cone effect)

\[ \Delta E_{\text{quark}} < \Delta E_{\text{gluon}} \]
\[ \Delta E_b < \Delta E_c < \Delta E_{\text{light q}} \]

which should imply

\[ R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi) \]

S. Wicks, M. Gyulassy, JPG35 (2008) 054001
... and $v_2$

- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium $\rightarrow v_2(b) < v_2(c)$

- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium $\rightarrow$ Transported through the full system evolution

Can the unprecedented abundance of heavy quarks produced at the LHC bring to a (final ?) clarification of the picture?
Open heavy quark: charm

- Semi-leptonic decays → High-$p_T$ single leptons (pioneered at RHIC)

  Non-negligible background issues

- Direct reconstruction of the decay products (D-mesons)

  Needs Vertexing resolution
  Particle ID
  Topological cuts

\[ \text{D}^0 \rightarrow \text{K}^- \text{π}^+ \]
\[ \text{D}^+ \rightarrow \text{K}^- \text{π}^+ \text{π}^- \]
\[ \text{D}^{*+} \rightarrow \text{D}^0 \text{π}^+ \rightarrow \text{K}^- \text{π}^+ \text{π}^- \]
\[ \text{D}^{+s} \rightarrow \phi \text{π}^+ \rightarrow \text{K}^+ \text{K}^- \text{π}^+ \]
Open heavy quark: beauty

Non-prompt J/ψ

- Fraction of non-prompt J/ψ from simultaneous fit to $\mu^+\mu^-$ invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)
- Expected shapes from sidebands (background) +MC templates (signals)

b-jet measurements

- Jets are tagged by cutting on discriminating variables based on the flight distance of the secondary vertex → enrich the sample with b-jets
- b-quark contribution extracted using template fits to secondary vertex inv. mass distributions
Selected charm pp results

- Excellent testing ground for QCD calculations
- Good agreement between data and models at BOTH $\sqrt{s}=7$ and 2.76 TeV
- Confirmed by single-lepton studies

- D-hadron correlations
- Promising tool to investigate production mechanisms
- Gluon splitting $\rightarrow$ no away-side
- LO (also NLO) $\rightarrow$ Back-to-back
p-Pb results: CNM

- $R_{p\text{Pb}}$ for HFE (mid-rapidity) compatible with 1
- HFM (forward rapidity) to be shown at QM2014

- Absence of significant CNM effects
- Similarity to PHENIX not really expected (different shadowing)

- Direct measurements confirm $R_{p\text{Pb}} \sim 1$ (with smaller uncertainties!)
- Compatible D-meson production ratios between $pp$ and $p$-$Pb$ for all the measured states ($D^0, D^+, D_{s}^+, D^{*+}$)
p-Pb results: collective effects?

- Study of the correlation function between trigger particles (electrons from heavy-flavour hadron decay) and associated particles (charged hadrons)

- Double ridge structure observed also for HF e-h correlation as in h-h correlations

- For h-h correlations it has been described in terms of hydro or CGC

Difference of highest multiplicity event class (0-20% multiplicity) and lowest multiplicity event class (60-100%) (removes jet-like corr.)
Pb-Pb results (semi-leptonic)

- Results available up to $p_T = 18$ GeV/c (EMCAL)
- Clear suppression for central collisions in the studied $p_T$ range
- Stronger suppression for central collisions (hint)
- Good compatibility between mid- and forward rapidity results
- No separation D vs B
**Pb-Pb results (direct)**

- **D⁰, D⁺ and D*⁺⁺** $R_{AA}$ agree within uncertainties.

- Strong suppression of prompt D mesons in central collisions → up to a factor of 5 for $p_T \approx 10$ GeV/c.

- Comparison e, μ results vs direct D not straightforward (decay kinematics).

- High $p_T$: $p_T^e \approx 0.5 \cdot p_T^D$.

- Larger suppression for D than for e? B component may have larger $R_{AA}$. 
Charm(ed) and strange: $D_S R_{AA}$

- First measurement of $D_s^+$ in AA collisions
- Expectation: enhancement of the strange/non-strange $D$ meson yield at intermediate $p_T$ if charm hadronizes via recombination in the medium

- Strong $D_s^+$ suppression (similar as $D^0$, $D^+$ and $D^{*+}$) for $8 < p_T < 12$ GeV/c
- $R_{AA}$ seems to increase at low $p_T$
- Current data do not allow a conclusive comparison to other $D$ mesons within uncertainties
Comparison D vs π

- Test the mass ordering of energy loss
  - $\Delta E(q,g) > \Delta E(c)$? → Not evident, but...
    - Different quark spectrum
    - $D_s$ enhancement may bring down D
    - ....

- Different centrality dependence high vs low $p_T$ → might be due to D “pushed” from high $p_T
D-meson and HFE/HFM $v_2$

- **First** measurements of charm anisotropy in heavy-ion collisions

- Similar amount of $v_2$ for D-mesons and charged pions
- Similar $v_2$ values for HF decay muons and HF decay electrons (different $y$)
- All channels show positive $v_2$ ($>3 \sigma$ effect)

Information on the **initial azimuthal anisotropy** transferred to charm quarks
Open charm: model comparisons

- Simultaneous measurement/description of $v_2$ and $R_{AA}$
  - Understanding heavy quark transport coefficient of the medium

- Wealth of theory calculations
  - Main features correctly reproduced but....
  - In spite of the relatively large experimental uncertainties there are still difficulties in reproducing BOTH $R_{AA}$ and $v_2$
Charm vs beauty

- Comparing direct D results with non-prompt J/ψ
- Similar kinematic range
- In agreement with expectations $R_{AA}(B) > R_{AA}(D)$
- Nice qualitative agreement with models

- B-suppression stronger at large $p_T$ (still large uncertainties, though)
Clear suppression of b-jets

- $R_{AA}$ vs $p_T$ shows suppression up to very large $p_T$
- Trend vs centrality well visible

Central $b$-jet suppression consistent with that in inclusive jets

At large $p_T$ the effects related to quark mass become negligible
Results from STAR

- Significant low-\(p_T\) enhancement (confirmed in U-U at 193 A GeV)

- Could be due to a combination of various effects
  - High \(p_T\) quenching
  - Effect of low \(p_T\) radial flow
  - Shadowing

- Significant NPE \(v_2\) at low \(p_T\)
  - Coalescence with light quark?
  - Charm flow?

- Quite different low \(p_T\) behaviour for \(R_{AA}\) with respect to LHC energy
Comparisons LHC vs RHIC

- Qualitative agreement also for HFE
- Same model can reproduce results at the two energies
Results from PHENIX

- Detailed study of HFM in dAu collisions
- Clear enhancement beyond shadowing effects at $y<0$ (Au-going direction)
- Compatible with unity at $y>0$ (and also at mid-rapidity)

...still waiting for an explanation

From enhancement to suppression with increasing reaction volume
Open charm/beauty: short summary

- Abundant heavy flavour production at the LHC
  - Allow for precision measurements
- Can separate charm and beauty (vertex detectors!)
  - Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
  - $R_{AA}^{beauty} > R_{AA}^{light}$ at low $p_T$, effect vanishing at very high $p_T$
  - $R_{AA}^{charm}$ vs. $R_{AA}^{light}$ comparison more delicate
- Indication ($3\sigma$) for non-zero charm elliptic flow at low $p_T$
- Hadrochemistry of D meson species: first intriguing result on $D_s$
Charmonia/bottomonia

- Three main issues/problems
  - Two competing mechanisms
    - Color screening $\rightarrow$ suppression
    - (Re-)combination $\rightarrow$ enhancement
  - Sequential suppression
    - Charmonium $\rightarrow$ J/$\psi$, $\chi_c$, $\psi(2S)$
    - Bottomonium $\rightarrow$ $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_b$
    - Relying on theory for connection with temperature
  - Cold nuclear matter effects
    - Very effective at all energies
    - Description/understanding of underlying mechanisms difficult
    - Extrapolation pA $\rightarrow$ AA
      - “model-”dependent
The legacy: SPS and RHIC

- SPS: first evidence of anomalous suppression (i.e., beyond CNM expectations) in Pb-Pb at $\sqrt{s} = 17$ GeV

- RHIC: suppression, strongly depending on rapidity, in Au-Au at $\sqrt{s} = 200$ GeV

- Weaker suppression at $y=0$: evidence for re-combination?

A. Adare et al. (PHENIX) PRC84(2011) 054912
Did we reach a consensus on the role played by recombination at RHIC? One should in principle observe:

- $J/\psi$ elliptic flow

  $\rightarrow J/\psi$ should inherit the heavy quark flow

- $J/\psi$ $p_T$ distribution

  $\rightarrow$ should be softer ($<p_T^2>$) wrt pp

Evidence not compelling

Could weaker suppression at $y=0$ be due to other effects (CNM, for example)?
Questions for LHC

1) Evidence for charmonia (re)combination: now or never!

Do we see enhancement vs centrality?
Do we see $J/\psi$ flow?
Do we see softer $p_T$ distributions?

2) A detailed study of bottomonium suppression

Do we see sequential suppression?
(as recombination does not play a role)
ALICE, focus on low-$p_T$ $J/\psi$

- **Electron analysis**: background subtracted with event mixing → Signal extraction by event counting

- **Muon analysis**: fit to the invariant mass spectra → signal extraction by integrating the Crystal Ball line shape

Centrality: 0 - 80
SE/ME fit range: 3.2 - 4.0
$\chi^2$/NDF = 1.0803
Sig. range: [2.92,3.16]

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
$2.5 < y_{J/\psi} < 4$

$N_{J/\psi} = 39502 \pm 815$
$\sigma_{J/\psi} = 75.1 \pm 1.6$ MeV/c$^2$
S/B (3$\sigma$) = 0.212 ± 0.004
J/$\psi$, ALICE probes the low $p_T$

- Even at the LHC, NO rise of $J/\psi$ yield for central events, but....
- Compare with PHENIX
  - Stronger centrality dependence at lower energy
  - Systematically larger $R_{AA}$ values for central events in ALICE

Is this the expected signature for (re)combination?
The \( p_T \) signature

- Expect smaller suppression for low-\( p_T \) J/\( \psi \) \( \rightarrow \) observed!

- The trend is different \( \text{wrt} \) the one observed at lower energies, where an increase of the \( \langle p_T \rangle \) with centrality was obtained.

- Fair agreement with transport models and statistical model.
CNM effects are not negligible!

- Suppression at backward + central rapidity
- No suppression (enhancement?) at forward rapidity
- Fair agreement with models (shadowing + energy loss)
- (Rough) extrapolation of CNM effects to Pb-Pb → evidence for hot matter effects!
CMS, focus on high $p_T$

- Muons need to overcome the magnetic field and energy loss in the absorber

- Minimum total momentum $p \sim 3-5$ GeV/c to reach the muon stations

- Limits $J/\psi$ acceptance
  - Midrapidity: $p_T > 6.5$ GeV/c
  - Forward rapidity: $p_T > 3$ GeV/c

..but not the $\gamma$ one ($p_T > 0$ everywhere)
Striking difference with respect to ALICE
- No saturation of the suppression vs centrality
- Factor 5 suppression for central events
- No significant $p_T$ dependence from 6.5 GeV/c onwards
- (Re)generation processes expected to be negligible
High $p_T$ $J/\psi$: comparison CMS vs STAR

- Opposite behaviour when compared to low-$p_T$ results

- Suppression is stronger at LHC energy (by a factor ~3 compared to RHIC for central events)

- Negligible (re)generation effects expected here
- Is the suppression for central events ($R_{AA} \sim 0.2$) compatible with a full suppression of all charmonia (excluding corona)?
Non-zero $v_2$ for $J/\psi$ at the LHC

- The contribution of $J/\psi$ from (re)combination should lead to a significant elliptic flow signal at LHC energy.

- A significant $v_2$ signal is observed by BOTH ALICE and CMS.
- The signal remains visible even in the region where the contribution of (re)generation should be negligible.
- Due to path length dependence of energy loss? Expected for $J/\psi$?
- In contrast to these observations STAR measures $v_2=0$.
Finally, the $\Upsilon$

- LHC is really the machine for studying bottomonium in AA collisions (and CMS the best suited experiment to do that!)

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(2S)/\Upsilon(1S)}|_{PbPb} = 0.14 \pm 0.05 \pm 0.01$$

$$N_{\Upsilon(3S)/\Upsilon(1S)}|_{PbPb} < 0.07$$
First accurate determination of $\Upsilon$ suppression

- Suppression increases with centrality

- First determination of $\Upsilon(2S)$
  $R_{AA}$: already suppressed in peripheral collisions

- $\Upsilon(1S)$ (see also ALICE)
  compatible with only feed-down suppression?

  → Probably yes, also taking into account the normalization uncertainty

Compatible with STAR (1S+2S+3S) (but large uncorrelated errors): expected?
Is $\Upsilon(1S)$ dissociation threshold still beyond LHC reach? → Full energy
Start to investigate the kinematic dependence of the suppression

- Suppression concentrated at low $p_T$
  (opposite than for $J/\psi$, no recombination here!)
- Suppression extends to large rapidity (puzzling $y$-dependence?)
Hints from theory

Theory is on the data! Fair agreement, but....

- One model has no CNM, no regeneration
- The other one has both CNM and regeneration (which would be responsible for all $\Upsilon(2S)$ in central events)

Still too early to claim a satisfactory understanding?
Do not forget CNM...

- Also in the \( \gamma \) sector, the influence of CNM is not negligible

With respect to 1S, the 2S and 3S states are more suppressed than in pp... but less than in Pb-Pb \( \rightarrow \) confirm Pb-Pb suppression as hot matter effect

As a function of event activity, loosely related to centrality in pPb (and surely not in pp!) “smooth” behaviour: to be understood!
RHIC: energy scan

- System size and energy dependence of $R_{AA}$

- No appreciable dependence on both energy and system size

- Not trivial! Requires
  - counterbalancing of suppression + regeneration effects over a large $\sqrt{s}$-region (note however large global systematics)
  - Warning: CNM effects (shadowing) expected to vary with $\sqrt{s}$
Interesting effect as a function of rapidity

Stronger suppression for $J/\psi$ than for open charm at backward and central rapidity $\rightarrow$ where ccbar spends more time in CNM

Evidence for $J/\psi$ break-up? Maybe, but
- Backward rapidity open charm results not compatible with shadowing
- Same $p_T$ comparison between open and closed charm is questionable

More generally: comparison open vs closed heavy quarks very interesting

Still difficult for A-A: meaningful comparison requires
Quarkonia – where are we?

- Two main mechanisms at play
  1) Suppression in a deconfined medium
  2) Re-generation (for charmonium only!) at high $\sqrt{s}$
  
  can qualitatively explain the main features of the results

- ALICE is fully exploiting the physics potential in the charmonium sector
  (optimal coverage at low $p_T$ and reaching 8-10 GeV/c)
  
  - $R_{AA} \rightarrow$ weak centrality dependence at all $y$, larger than at RHIC
  - Less suppression at low $p_T$ with respect to high $p_T$
  - CNM effects non-negligible but cannot explain Pb-Pb observations

- CMS is fully exploiting the physics potential in the bottomonium sector
  (excellent resolution, all $p_T$ coverage)
  
  - Clear ordering of the suppression of the three $\Upsilon$ states with their binding energy $\rightarrow$ as expected from sequential melting
  - $\Upsilon(1S)$ suppression consistent with excited state suppression (50% feed-down)
Conclusions

**LHC:** first round of observations EXTREMELY fruitful

- Many (most) of the heavy-quark/quarkonia related observables were investigated, no showstoppers, *first physics* extracted

- Many (most) of the heavy-quark/quarkonia related observables would benefit from more data to *sharpen the conclusions*
  - full energy run, 2015-2017
  - upgrades, 2018 onwards

**RHIC:** still a *main actor*, with upgraded detectors

**Lower energies:** SPS, FAIR

- Serious experimental challenge
- High-$\mu_B$ region of the phase diagram unexplored for what concerns heavy quark/quarkonia below 158 GeV/c
Backup
LHC, 3 factories for heavy quark in Pb-Pb
ATLAS open heavy flavours

- ATLAS measures muons from HF in $|\eta|<1.05$, $4<p_T<14$ GeV/c
- No pp at 2.76 TeV reference available, use $R_{CP}$ rather than $R_{AA}$

HF yield through fit of templates for discriminant variable C

- $R_{CP}$ subject to statistical fluctuations $\rightarrow$ use $R_{PC}$ too!
- $\sim$flat vs $p_T$ up to 14 GeV/c, different from inclusive $R_{CP}$!

If $\sim$no suppression for 60-80% $\rightarrow$ central $\sim$ forward suppression
The new frontier: b-jet tagging

- Jets are tagged by cutting on discriminating variables based on the flight distance of the secondary vertex → enrich the sample with b-jets

- b-quark contribution extracted using template fits to secondary vertex invariant mass distributions

\[ b\text{-fraction} \sim \text{constant vs both } p_T \text{ and centrality} \]
Beauty vs light: high vs low $p_T$

- Low $p_T$: different suppression for beauty and light flavours, but:
  - Different centrality
  - Decay kinematics

- High $p_T$: similar suppression for light flavour and b-tagged jets

Fill the gap!
PHENIX, b vs c

- Charm and bottom contributions in electron from heavy-quark decay is measured directly from the electron DCA distribution (VTX).

- Bottom fraction in pp consistent with published data (from e-h correlations) and with FONLL.

Look forward to forthcoming Au-Au results!
Data vs models: HFE

Simultaneous description of heavy-flavor electrons $R_{AA}$ and $v_2$  

Challenge for theoretical models
Intermezzo: multiplicity dependence of D and J/ψ yields

- Should help to explore the role of multi-parton interactions in pp collisions

- The \( \sim \)linear increase of the yields with charged multiplicities and the similar behaviour for D and J/ψ are remarkable....

...but need to be explained!
PHENIX – new systems/energies

- New system (Cu-Au) at old energy: Cu-going finally different! (probably not a CNM effect)
- A challenge to theory
- SPS went the other way round (from S-U to Pb-Pb...)

- Old system (Au-Au) at new energy: still a balancing of suppression and regeneration?
- Theory seems to say so....
First study of a charmonium excited state at collider energy → Seems contradicting our previous knowledge

- $p_T$ dependence of $R_{dAu}$
- Increase vs $p_T$ at central/forward $y$  
  → Reminds SPS observation
- But different behaviour at backward rapidity
- Not easy to reproduce in models!

Overall picture still not clear!
Bottomonium: the “clean” probe
- 3 states with very different binding energies
- No complications from recombination

But not that easy at RHIC!

...and this has been split into 3 centrality bins....

Compatible with 3S melting and 2S partial melting