The LHC is a heavy quarkonium factory!

ATLAS, CMS, LHCb and ALICE reported many studies of (prompt) quarkonium production

How do those measurements compare to each other? Are there inconsistencies among the experimental results?
Executive summary

• Many measurements made at 7 TeV (2010+2011 data) and a few at 8 TeV (2012)
  • S-wave and P-wave cross sections and/or cross section ratios
  • $\chi_c$ and $\chi_b$ feed-down fractions to S-wave states
  • Polarizations of five S-wave states (charmonia and bottomonia)

• Much still to come
  • Many analyses of 2011 and 2012 data still ongoing or not even started...
  • Run II (13 TeV) will provide many more measurements
  • Availability of results limited by manpower, not by “statistics”

• In general, good agreement between measurements made by several experiments
Many papers contributed to the preparation of this talk, from LHC and Tevatron experiments.
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$\gamma(nS)$ cross sections

- Measured in the $p_T$ range from 0 to 100 GeV
- No hint of significant discrepancies between measurements

- The curves represent fits to the function $N \cdot p_T \cdot \left[ 1 + \frac{1}{\beta - 2} \cdot \frac{p_T^2}{\gamma} \right]^{-\beta}$

![Graphs showing $\gamma(1S)$ and $\gamma(3S)$ cross sections for $s = 7$ TeV](image-url)
Prompt J/ψ cross sections

- Measured in the $p_T$ range from 0 to 120 GeV
- No hint of significant discrepancies between measurements
Prompt $\psi(2S)$ cross sections

- Measured in the $p_T$ range from 0 to 100 GeV

- Comparing CMS and ATLAS *preliminary* results showed a problem at high-$p_T$
  The ATLAS points were corrected in the final publication
  → Shows that these comparisons are *very* useful 😊

prompt $\psi(2S)$
\[ \sqrt{s} = 7 \text{ TeV} \]
All together now: 7 different quarkonia

- Mid-rapidity cross sections for seven quarkonia have identical $p_T/M$ shapes, for $p_T/M > 3$
- Interesting empirical observation

ATLAS and CMS will soon have $J/\psi$ and $\psi(2S)$ differential cross sections up to $p_T/M \sim 30$!

All 12 (!) curves have identical shapes

Fitted to the CMS $J/\psi$ data for $p_T/M > 3$

Global $\chi^2$/ndf = 91/85; $P = 30\%$
Disclaimer

For some measurements, the several experiments use a different binning in $p_T$ or $y$; small corrections (intra/extrapolations) were applied to improve the comparisons.

To make the ratio of two distributions measured with different $p_T$ bins, we first fit each distribution and then show the ratio of the functions.

→ Such “harmless manipulations” are identified by the “sticker”

The same label identifies figures showing “derived variables”...

The LHC collaborations are not responsible for these “derivations” 😊
S-wave quarkonium cross sections vs. rapidity

- All experiments measured cross sections in the bin $8 < p_T < 15 \text{ GeV}$ (or very similar)
  → Allows us to see how the cross sections change with rapidity and state
- At first sight, reasonable overlap between ATLAS, CMS and LHCb...
  but looking more closely we see significant differences (given the tiny uncertainties)

\begin{align*}
\text{ALICE} & : 5.6 \text{ nb}^{-1} \\
\text{CMS} & : 37, 36 \text{ pb}^{-1} \\
\text{ATLAS} & : 2.2 \text{ pb}^{-1}, 1.8 \text{ fb}^{-1} \\
\text{LHCb} & : 5.2, 36, 25 \text{ pb}^{-1}
\end{align*}

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ 8 < p_T < 15 \text{ GeV} \]

ATLAS $\Upsilon(nS)$ : cross sections seem to increase with rapidity

Other states and experiments show a decrease

Slightly different $p_T$ bins implied interpolations
Changes of $p_T$ with rapidity

- The shape of the $p_T$ distributions changes with rapidity
  - Interesting to see the average $p_T^2$ versus rapidity
    Sensitive to the low-$p_T$ reach of the data...

$\sqrt{s} = 7$ TeV

Y(1S):
- ATLAS, CMS and LHCb compatible;
- striking drop at forward-rapidity

J/$\psi$:
- ALICE forward $y$ is inclusive
- others are prompt;
- flatter trend vs. $y$ than Upsilons
Cross section ratios: bottomonium

- The nS/1S cross section ratios increase steeply with $p_T$ up to around 40 GeV
  → At higher $p_T$ the increase seems to slow down and the trend might flatten out...
  → More high-$p_T$ data needed to clarify the observations

- The ATLAS 3S/1S ratio is systematically lower than the LHCb and CMS trends...
Cross section ratios: charmonium

- The 2S/1S cross section ratio increases steeply with $p_T$ up to around 20 GeV
  → At higher $p_T$ we see some tendency for saturation... but the errors are very large
  → More measurements needed to clarify the high-$p_T$ trend

- ATLAS and CMS are working on improved measurements; should be available “soon”

### Derived

Different $p_T$ bins for the 1S and 2S states
→ ratio of fitted functions

ALICE measures *inclusive* ratio...
but the low-$p_T$ b-hadron fraction is small and identical
for the 1S and 2S states

LHCb values include global uncertainties on each point...
From cross section ratios to feed-down fractions (1)

- We have derived the “1S from nS feed-down fractions” from the cross section ratios
  - correcting for the ratios of branching fractions
  - scaling the nS $p_T$ by the mass ratio $M(1S) / M(nS)$

- Method validated using $2S \rightarrow 1S \pi \pi$ results, available from ATLAS both vs. 1S and 2S $p_T$

The derived results agree very well with those measured directly by ATLAS
From cross section ratios to feed-down fractions (2)

- Applying the method to the bottomonium family, we see that:
  - a fraction between 7% and 15% of the $\Upsilon(1S)$ is produced from $\Upsilon(2S)$ decays while the $\Upsilon(3S)$ feed-down contribution is less than 2.5%
  - the S-wave feed-down “contamination” increases with $p_T$

![Graphs showing fraction of $\Upsilon(1S)$ from $\Upsilon(2S)$ and $\Upsilon(3S)$ decays versus $p_T(\Upsilon(1S))$]
From cross section ratios to feed-down fractions (3)

- LHCb recently reported measurements of the $nP \rightarrow mS$ feed-down fractions:
  - the biggest $\Upsilon(1S)$ feed-down contribution comes from the $\chi_b(1P)$
  - at around 30 GeV, more than half of the $\Upsilon(1S)$ mesons result from feed-down
  - the $\Upsilon(2S)$ gets contributions from $\Upsilon(3S)$, $\chi_b(2P)$ and $\chi_b(3P)$ decays
  - the $\Upsilon(3S)$ feed-down from $\chi_b(3P)$ decays is $37\pm7\%$ (in $25 < p_T < 40$ GeV)

Important inputs to interpret the $\Upsilon(nS)$ suppression seen in p-Pb and Pb-Pb collisions
From cross section ratios to feed-down fractions (4)

- The same method can be applied to the charmonium family:
  - the biggest $J/\psi$ feed-down fraction is from $\chi_c$ decays
  - the LHCb and ATLAS points are very well aligned...
  - while the low $p_T$ CDF points seem to be outliers...

![Graph showing prompt $J/\psi$ feed-down as a function of $p_T^{J/\psi}$ with various data points and labels.](image)
$\chi_{c2} / \chi_{c1}$ cross section ratios

- Measurements using photon conversions are well aligned with each other

- LHCb results with ECAL and conversions are quite different, for $p_T < 8$ GeV
  → Is there an experimental problem? Or is this a physics (phase space) effect?

\[ \chi_{c1, \text{unpolarized}} \pm 6.0\% \text{ BF uncertainty} \]
\( \chi_{c2} / \chi_{c1} \) cross section ratios

- Results depend on the polarizations assumed for the two states (acceptance correction)
  - If both states have helicity = 0, the LHCb results with ECAL and conversions *agree well*
  - If they have extreme polarizations (±1, ±2), the spread of the measurements increases

→ Important to measure the polarizations of the \( \chi_{c1} \) and \( \chi_{c2} \) mesons
$\chi_{b2}/\chi_{b1}$ cross section ratios

- The corresponding ratio in the bottomonium family is also seemingly flat.
- LHCb and CMS results agree well, within the large uncertainties.
Quarkonium polarization

S-wave polarizations are measured from the dimuon angular decay distributions

\[
\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi
\]

\[
\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}
\]

The frame-invariant \(\tilde{\lambda}\) is useful to detect systematic biases:

\(\tilde{\lambda}(HX)\) and \(\tilde{\lambda}(CS)\) must be identical

\[
\tilde{\lambda} = +1
\]

\[
\tilde{\lambda} = -1
\]
Quarkonium polarization: $\Upsilon(nS)$ from CDF run 2

• The $\tilde{\lambda}$ values reported by CDF for the $\Upsilon(nS)$ polarizations show systematic biases not covered by the uncertainties

• The lowest $p_T \Upsilon(3S)$ value is $\tilde{\lambda} >> 1$

• Note: $\tilde{\lambda}$ is not frame invariant for background
Quarkonium polarization: $\psi(2S)$ in LHCb

- The polarizations measured by LHCb for $p_T < 10$ GeV cluster at around $\tilde{\lambda} = -0.25$

- But the highest $p_T$ bin shows values that systematically decrease with rapidity…
  An “edge effect” in the acceptance calculations? Or is this a physics (phase space) effect?
Quarkonium polarization: $\psi(2S)$ in LHCb and CMS

- The polarizations measured by LHCb and CMS still suffer from large uncertainties...
  - We cannot say that there are significant discrepancies
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More results from quarkonium @ LHC can be found at:
ALICE: http://aliceinfo.cern.ch/ArtSubmission/publications
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
LHCb: http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/bq.php
\( \chi_{c1} \) and \( \chi_{c2} \) cross sections

So far, only ATLAS measured the \( \chi_{c1} \) and \( \chi_{c2} \) cross sections

A challenging result, given the very low photon conversion and reconstruction efficiencies