Heavy Flavor production@CMS

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Heavy quark production

• Measurements and observations provide important tests of QCD and give insight into particle production at colliders

• Hadronization challenging to understand, measurements needed

• Few puzzles: e.g. conciliate cross-section and polarisation results, color singlet vs color octet contributions, single vs multiple particle interaction contributions

• LHC provides access to wide kinematic range, from low to high $p_T$, different collision energies (2.76, 5, 7, 8, 13TeV) and environments (pp, pA, AA) — all of which are explored by CMS

• Form baseline or background for other physics studies at the LHC

• Topics discussed: production of open and hidden beauty and charm
dimuons

- provide robust and clean experimental signature (baseline final states)
  - HF → μμX
- flexible trigger
  - muon pairs selected at hardware level, further requirements added at HLT, to allow low $p_T$ thresholds
- good muon identification
  - fakes at permil level
- precise track/vertex reco
  - mass resolution & displaced vertices

[CMS DP-2018/036], [CMS-CR-2012-216]
quarkonium production

Charmonia

- differential cross sections of all 5 S-wave states measured at 13 TeV
  - 2-3 times larger than a 7 TeV, slowly increasing with $p_T$
- $p_T$ dependencies of the x-sections well described by NRQCD
  - high $p_T$ reach, beyond 100 GeV
- $Y(nS)$ ratios increase with $p_T$
- results contribute to consolidate underlying hypothesis of QCD and constrain theory parameters

Bottomonia

[PLB 780 (2018) 251]
The $\chi_b(3P)$ was the first new state found at the LHC.

Test effects of open-beauty states on bottomonium spectrum

$\sigma(\chi_b(2P))/\sigma(\chi_b(1P)) = 0.85 \pm 0.07 \text{(stat + syst)} \pm 0.08 \text{ (BF)}$

$\chi_b(1P) \rightarrow \gamma$

$\chi_b(2P) \rightarrow \gamma$

$\chi_b(3P) \rightarrow \gamma$

$\chi_b(nP) \rightarrow Y(mS) \gamma$

observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

- the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states
- used pp data at 13 TeV collected in 2015 + 2016 + 2017
  ‣ totalling 80 fb$^{-1}$ (2.7 + 35.2 + 42.1 fb$^{-1}$)
- the photon is reconstructed via pair conversion in tracker
  ‣ the reduced $\chi \rightarrow e^+e^-$ reconstruction efficiency (<1%) required the large dataset
- measured mass difference between the $J=1$ and $J=2$ states
  ‣ $M[\chi_{b2}(3P)] - M[\chi_{b1}(3P)] = 10.60 \pm 0.64$ (stat) $\pm 0.17$ (syst) MeV

\[ M(\chi_{b1}(3P)) = 10\,513.42 \pm 0.41 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ MeV} \]
\[ M(\chi_{b2}(3P)) = 10\,524.02 \pm 0.57 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ MeV} \]

- photon energy scale calibrated through a $\chi_{c1} \rightarrow J/\Psi \gamma$ sample
- tested with $\chi_b(1P,2P)$ states

[arXiv:1805.11192]
associated production: double quarkonia

- measurements of associated production give further insight into hadroproduction mechanisms
- allow to study contributions from multi-particle interactions and search for new resonances

$$\sigma(pp\rightarrow Y(1S)Y(1S)) = 68.8 \pm 12.7 \text{ stat} \pm 7.4 \text{ syst} \pm 2.8 \text{ BR pb}$$

first observation of this process
associated production: quarkonia in jets

- measure fraction of jet momentum taken by J/ψ, 
  - for prompt and non-prompt components, extracted with 2D (m,t) fit
- but jet activity accompanying prompt J/ψ is found to be much underestimated in simulation 
  - indicating they are less isolated than suggested by production models
- fraction of J/ψ produced in jets is also under-predicted
- these results may shed also light into the polarisation puzzle
quarkonium production at 5TeV

- sequential state suppression in ion collisions: 1S > 2S > 3S

\[ R_{AA} = \frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} \]
open charm production

- the differential cross section in pp collisions, measured from 0 to 100 GeV, lie in agreement with theory prediction

- D mesons are suppressed in PbPb collisions relative to pp collisions. The suppression factor displays a $p_T$ dependence. At intermediate $p_T$ open charm appears to be less suppressed than light hadrons, and more suppressed than B hadrons (accessed via displaced J/ψ)

[arXiv:1708.04962]
open beauty production

• b-hadron cross sections measured at different pp collision energies

• B\(^+\) cross sections in good agreement with FONNL prediction, although discrepancies at low p\(T\)

• B\(c\) cross sections shape in good agreement with prediction, normalisation is off by a factor \(\sim 3\)
B production in AA collisions

- First direct reconstruction of B mesons in heavy ion collisions

- Significant suppression of B yields in PbPb compared to pp
- Hint of smaller $B_s$ suppression relative to $B^+$, consistent with strangeness enhancement
- (indications of strangeness enhancement have been reported by ALICE in the charm sector)
... and in pA collisions

- B mesons as novel probes of the QGP
  - For characterising hot and cold matter effects, and flavor dependence of energy loss in media
Λ_b polarisation

- study the angular distributions in the decay \( \Lambda_b \to J/\psi \Lambda \to \mu \mu \rho \pi \)
  
  - extract the Λ_b polarisation and the parity-violating decay asymmetry \( \alpha \)

Based on about 6000 Λ_b decays, the polarization parameters are found to be:

\[
P = 0.00 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)}
\]

\[
\alpha_1 = 0.14 \pm 0.14 \text{ (stat)} \pm 0.10 \text{ (syst)}
\]

Results are in agreement with LHCb and ATLAS

[PRD 97 (2018) 072010]
study of P-wave $B_s$ mesons

- observed the $B_{s2}^* \rightarrow B^0 K^0_S$ decay
- measured relative branching fractions

\[
\frac{B(B_{s2}^* \rightarrow B^0 K^0_S)}{B(B_{s1} \rightarrow B^+ K^-)} \quad \frac{B(B_{s1} \rightarrow B^0 K^0_S)}{B(B_{s2} \rightarrow B^+ K^-)} \quad \frac{B(B_{s2} \rightarrow B^0 K^0_S)}{B(B_{s1} \rightarrow B^+ K^-)} \quad \frac{B(B_{s2} \rightarrow B^0 K^0_S)}{B(B_{s1} \rightarrow B^+ K^-)}
\]

- measured mass differences $M(B^*)-M(B)$
- measured $B_{s2}^*$ natural width
- precision on pair with LHCb and CDF
- good agreement also with theory predictions
summary

- while CMS is a multi-purpose detector, not designed for dedicated heavy flavor studies, it delivers complementary and unique results
  - covering central-rapidity, high-\(p_T\) kinematic region
- reported measurements of charm and beauty production
  - at different collision energies and collision systems
- these heavy flavour production results aim at facilitating
  - an improved understanding of the QCD hadroproduction mechanisms, through dedicated measurements of cross sections and polarizations
  - an improved understanding of the properties of the media created in ion collisions, through a variety of exclusively reconstructed heavy flavor states, as novel probes of the medium and of the flavor dependence of energy loss
  - the exploration of rarer processes, and the pursuit of new physics effects though heavy flavor decays
- see also CMS reports in tracks: Heavy ions; Quark & lepton flavor physics