CMS Studies in Heavy Flavour Production

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on behalf of the
CMS Collaboration

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Summary

- In this talk: general review of the CMS measurements of heavy flavor production published recently

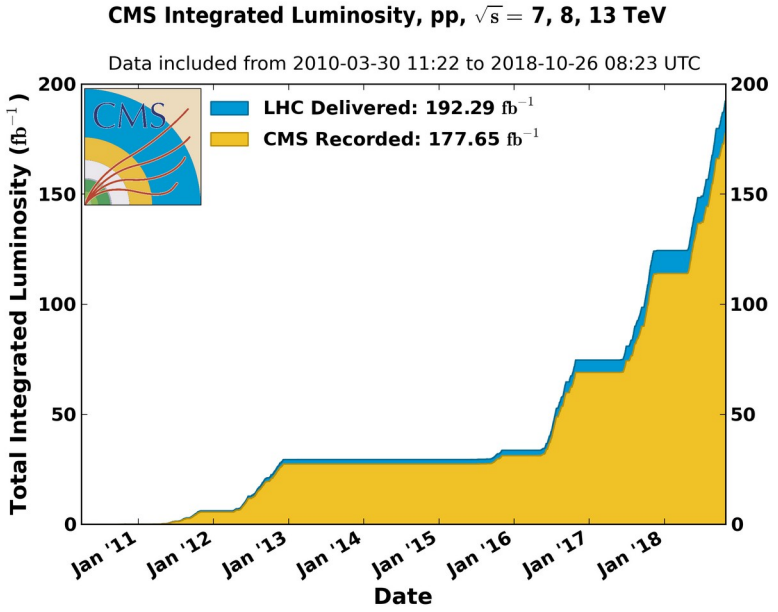
Outline

- **Open heavy flavour production**
- **Heavy quarkonia production**

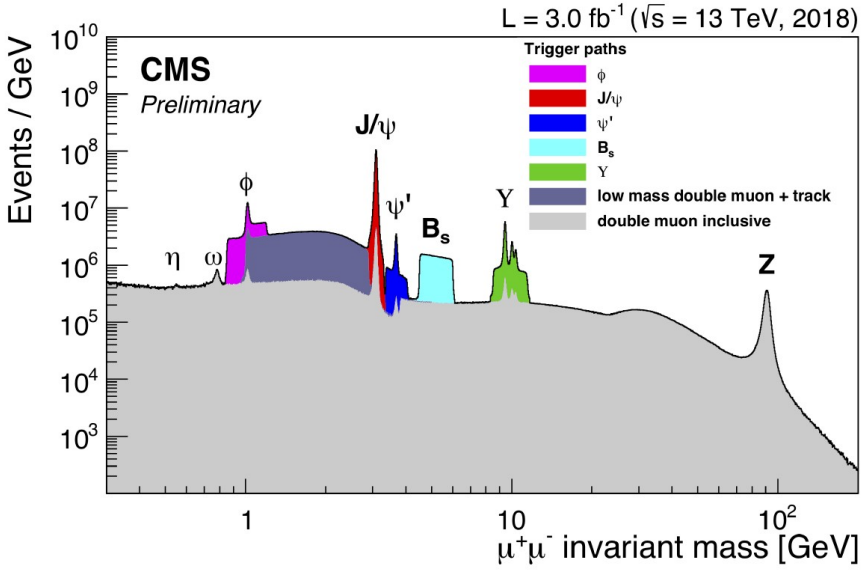
- Disclaimer: Some (small) overlap with other more specific talks

Data taking summary and performance

- Analyses shown in this talk use CMS data taken between 2011 and 2018
- Integrated luminosity good for physics:
  - Run 1: **~5/fb @ 7 TeV**
    ~20/fb @ 8 TeV
  - Run 2: **~140/fb @ 13 TeV**
- Data taking stopped since the end of 2018 due to LHC LS2, to resume in 2021



- HF physics mostly studied through **final states containing muons**
- Several single- and multi-muon triggers to cover a wide range of processes
- HF reconstruction mainly relying on tracking and muon subdetectors
  - $\Delta p_T/p_T$~O(1-5%) for low-momentum tracks
  - Vertex and IP resolution O(10-100μm)

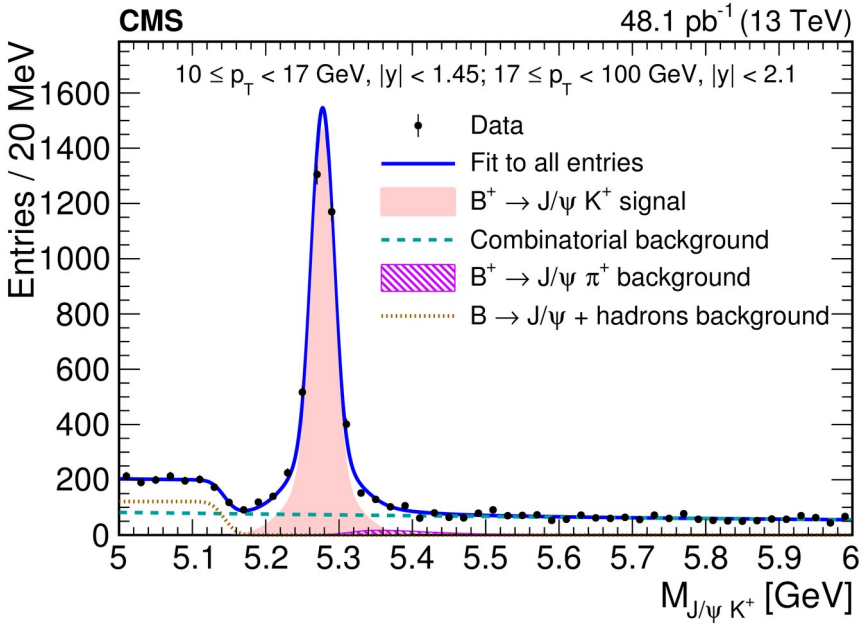


Open heavy flavour production

B^+ cross section at 13 TeV

- CMS measured the B^+ cross section in pp collisions at 13 TeV using 48.1/pb of data
- $\mathbf{B^+ \to J/\psi(\to \mu^+\mu^-)K^+}$ decay mode
- Considered the fiducial phase space

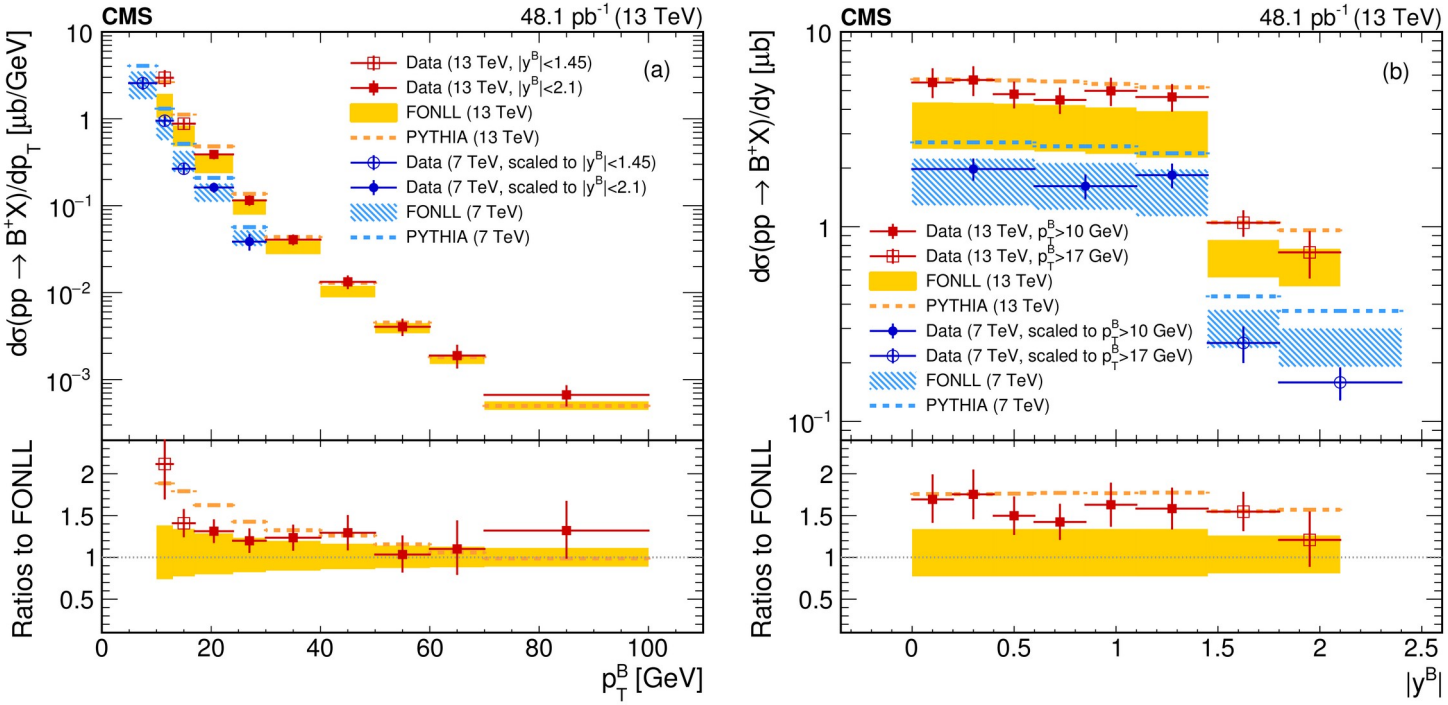
  $\mathbf{|y(B^+)| < 1.45}$ for $\mathbf{10 \le p_T(B^+) < 17\ GeV}$, and
  $\mathbf{|y(B^+)| < 2.1}$ for $\mathbf{17 \le p_T(B^+) < 100\ GeV}$
- Main backgrounds: **combinatorial dimuons**, $\mathbf{B^+ \to J/\psi\pi^+}$, and $\mathbf{B^+ \to J/\psi}$ + **hadrons** decays



Systematic sources	Relative uncertainties (%)
Muon trigger, identification, and reconstruction	6.0–14
Detector alignment	2.8
B^+ vertex reconstruction	1.4
Size of simulated samples	0.5–3.9
Track reconstruction efficiency	3.9
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ branching fraction	3.1
Model in likelihood fits	1.0–6.4
Bin-to-bin migration	0.4–3.7
B^+ kinematic distributions	0.4–11
Parton distribution functions	0.1–0.7
B^+ lifetime	0.3
Total (excluding the integrated luminosity)	9.1–16
Integrated luminosity	2.3

- Main systematic uncertainties from
  - Muon trigger, identification, and reconstruction
  - Likelihood fit model
  - Kinematic distributions of B^+ events in simulation
- **Analysis is not statistically-limited**

B^+ cross section at 13 TeV

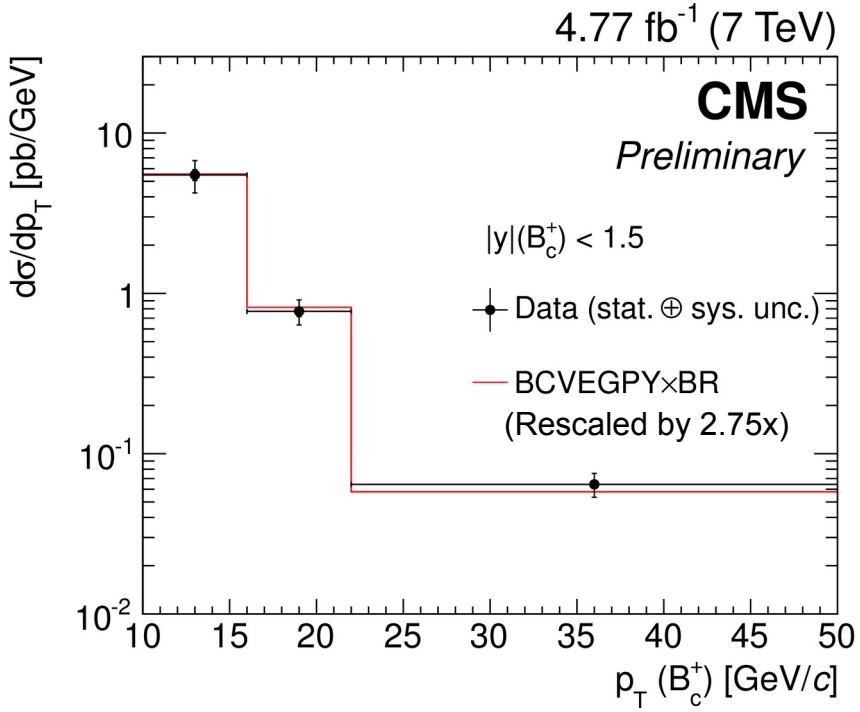


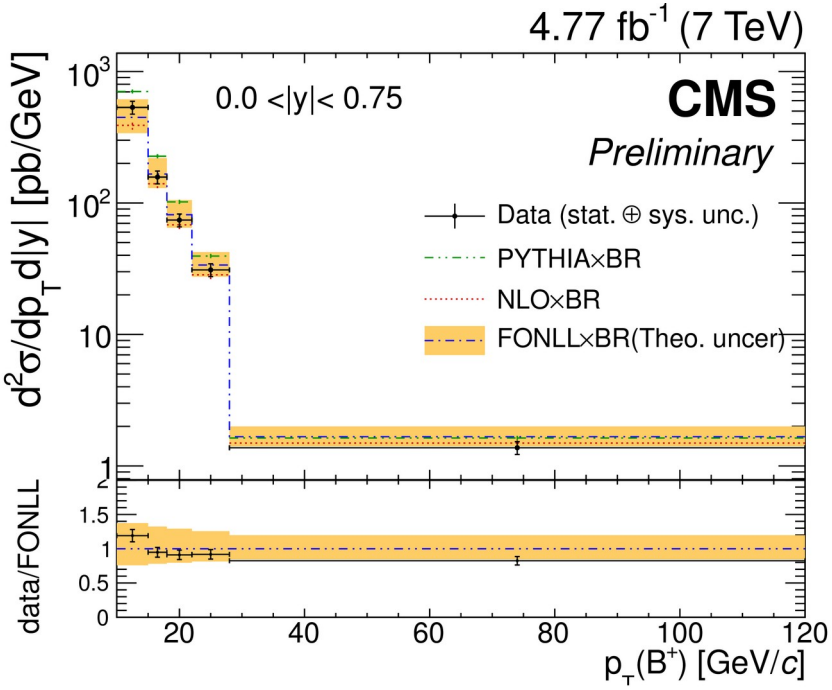
- Cross section given in **bins of $p_T(B^+)$ and $|y(B^+)|$**
- **13 TeV results** compared to **FONLL predictions** and with **PYTHIA**
  - Data compatible with FONLL at high p_T, while they favour higher cross sections at low p_T
  - **Previous CMS** (PRL 106 (2011) 112001, shown above) **and ATLAS measurements at 7 TeV** (JHEP 10 (2013) 042) have a better data-theory agreement at low p_T
- **Total cross section** in the fiducial region at 13 TeV measured from the sum over all bins

$$\sigma(pp \to B^+X) = 15.3 \pm 0.4(stat) \pm 2.1\,(syst) \pm 0.4(lumi)\ pb$$

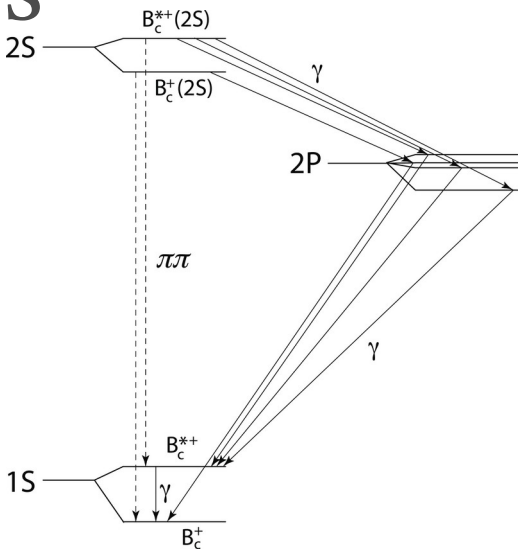
B_c and B^+ cross sections at 7 TeV

- CMS measured the B_c^+ and B^+ cross sections at 7 TeV, using 4.77 fb^{-1} of Run 1 pp data
- Mesons reconstructed through their $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ decays
- Inclusive $\sigma \times$BRs:
  - **$B_c^+ \to J/\psi\pi^+$: σ = 40.8 ± 4.7 (stat) ± 2.8 (syst) pb [$p_T(B_c^+)$ > 10 GeV and $|y(B_c^+)|$ < 1.5]**
  - **$B^+ \to J/\psi K^+$: σ = 5851 ± 37 (stat) ± 446 (syst) pb [$p_T(B^+)$ > 10 GeV and $|y(B^+)|$ < 1.5]**
- B_c shape in agreement with BCVEGPY prediction, normalization off by a factor ~2.75
- B^+ measurement consistent with predictions from PYTHIA, NLO, and FONLL





Observation of two excited B_c^+ states

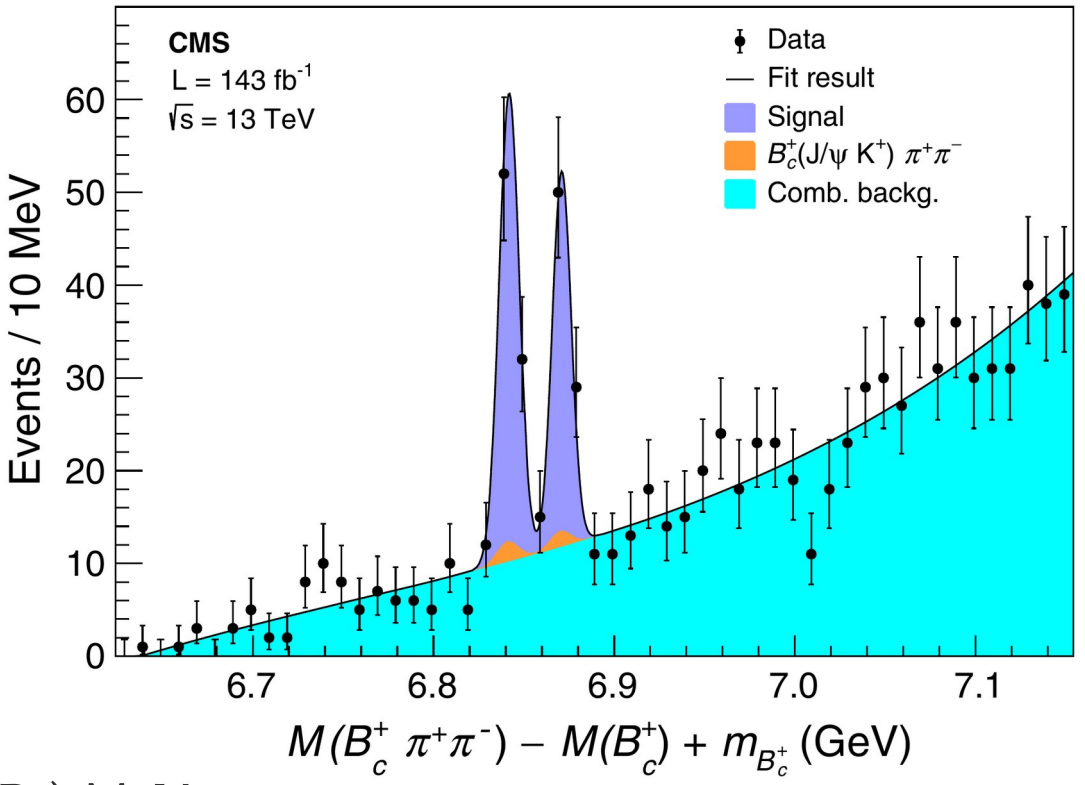


More details in yesterday's talk by L. Cristella

- CMS resolved for the first time the $B_c(2S)$ doublet, using 143 fb^{-1} of 13 TeV data collected in the LHC Run 2
  - These states had first been seen by ATLAS as a single wide enhancement (PRL 113 (2014) 212004)
- The B_c excited states are reconstructed in the $B_c\pi^+\pi^-$ decay channel
  - Soft photon from $B_c^* \longrightarrow B_c\gamma$ decay not reconstructed
- The two peaks are resolved with >5σ significance
- The mass split is measured to be:

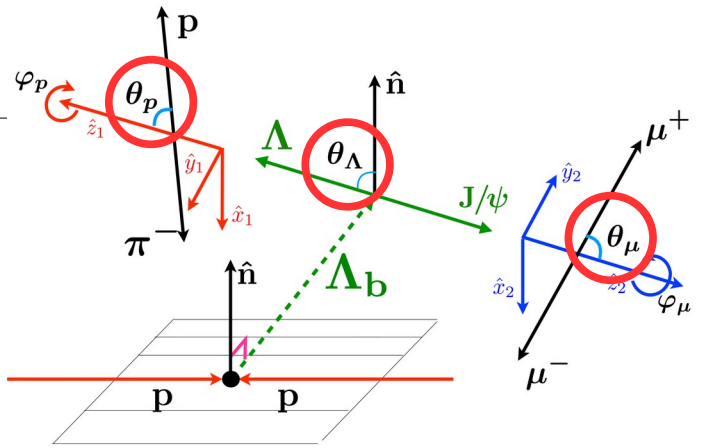
  $\Delta M = 29.1 \pm 1.5(stat) \pm 0.7(syst)$ MeV
- The $B_c(2S)$ mass is measured to be:

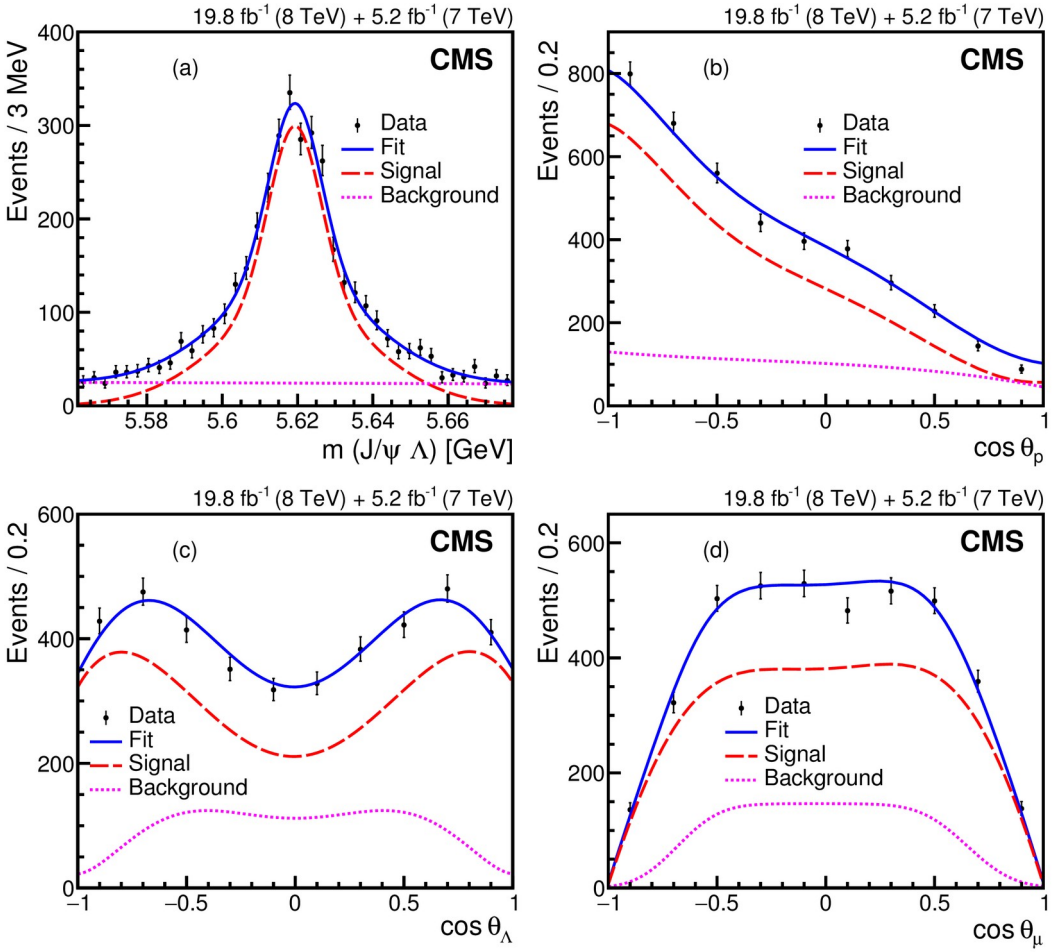
  $M = 6871.0 \pm 1.2(stat) \pm 0.8(syst) \pm 0.8(B_c)$ MeV



Λ_b polarization at 7 and 8 TeV

- The polarization parameters of Λ_b baryons were measured by CMS on 7 and 8 TeV data
  - $\Lambda_b \to J/\psi(\to\mu^+\mu^-)\,\Lambda(\to p\pi^-)$ decay used
- The decay can be described as a function of the **helicity amplitudes** $T_{\lambda_1\lambda_2}$ (λ_i are the helicities of J/ψ and Λ particles)
- Measured parameters depending on $T_{\lambda_1\lambda_2}$:
  - **P** $\Longrightarrow$ Λ_b polarization
  - α_1 $\Longrightarrow$ Asymmetry in $\Lambda_b \to J/\psi\Lambda$ decay
  - α_2 $\Longrightarrow$ Longitudinal Λ polarization
  - γ_0 $\Longrightarrow$ Depending on J/ψ polarization
- Parameters measured through a fit to the invatiant mass **m(J/ψ Λ)** and the three angles θ_Λ, θ_p, θ_μ
- **Analysis is statistically-limited**, main systematics from **reconstruction bias** (evaluated in MC by comparing input and measured values)





Λ_b polarization at 7 and 8 TeV

- The four parameters are measured to be

$$P = 0.00 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}),$$
$$\alpha_1 = 0.14 \pm 0.14(\text{stat}) \pm 0.10(\text{syst}),$$
$$\alpha_2 = -1.11 \pm 0.04(\text{stat}) \pm 0.05(\text{syst}),$$
$$\gamma_0 = -0.27 \pm 0.08(\text{stat}) \pm 0.11(\text{syst}),$$

- They correspond to the helicity amplitudes

$$|T_{++}|^2 = 0.05 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}),$$
$$|T_{+0}|^2 = -0.10 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}),$$
$$|T_{-0}|^2 = 0.51 \pm 0.03(\text{stat}) \pm 0.04(\text{syst}),$$
$$|T_{--}|^2 = 0.52 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}).$$

- Consistent with previous measurements by LHCb (PLB 724 (2013) 27) and ATLAS (PRD 89 (2014) 092009)
- **Inconsistent (at >5σ) with HQET**, but **consistent with predictions from PQCD and quark model techniques**

Quarkonium production

J/ψ production from jet fragmentation

- J/ψ production in jets can be used to probe LDME contributions to jet fragmentation
- Studied by CMS on 19.1 fb^{-1} of 8 TeV pp collisions
  - 4 different LDMEs studied: $^1S_0^{(8)}$, $^3S_1^{(8)}$, $^3S_1^{(1)}$, **and** $^3P_j^{(8)}$
- Measurement conducted in different bins of the J/ψ energy fraction z:

$$\mathbf{z \equiv E(J/\psi) \,/\, E(jet)}$$

- **Using $\Xi(E_1, z_1)$ as sensitive variable:**

$$\Xi(E_1, z_1) \equiv \frac{N(E_1, z_1)}{\int_{0.3}^{0.8} N(E_1, z) dz} \equiv \frac{d\tilde{\sigma}}{dE dz}\Big|_{E_1, z_1}$$

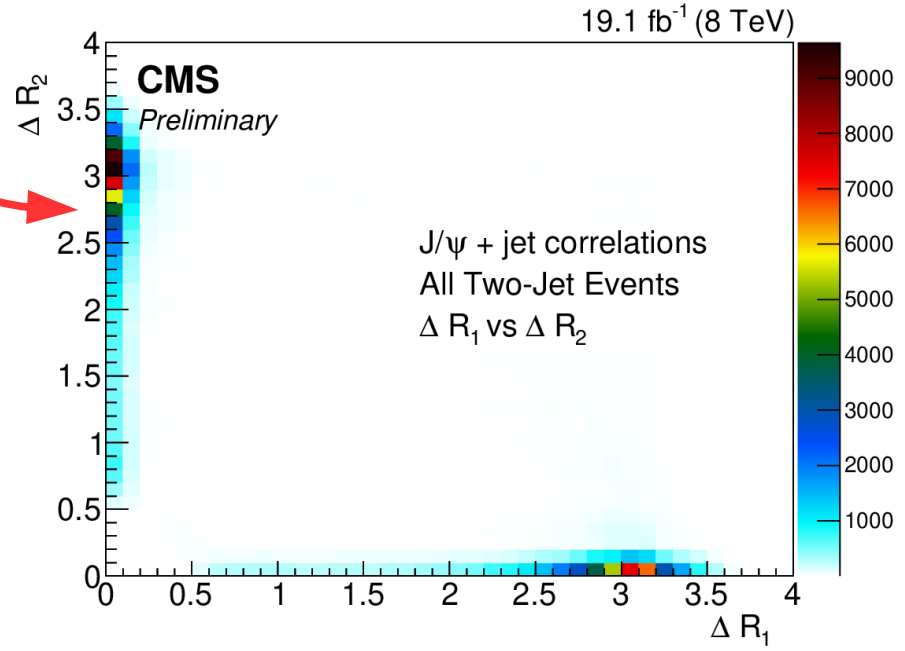
  - $N(E_1, z_1)$ is the number of events in a z interval $\Delta_z = \pm 0.025$
  - Last term is the sum of the contributions from the 4 LDMEs to the differential cross section

⟹ If just one LDME dominates at a given z value, then it will give a good description of the the jet energy dependence in data.
⟹ Otherwise it is unlikely that any single LDME will be a good match for data.

J/ψ production from jet fragmentation

$$\Xi(E_1, z_1) \equiv \frac{N(E_1, z_1)}{\int_{0.3}^{0.8} N(E_1, z) dz} \equiv \frac{d\tilde{\sigma}}{dE dz}\Big|_{E_1, z_1}$$

- J/ψ mesons are matched to jets in ΔR
- Both 1-jet and 2-jet events analyzed
- Data corrected for efficiencies and unfolded with D'Agostini method
- Main systematics coming from efficiencies and from the J/ψ – jet association
- 3 z bins considered:
  - **0.40 < z < 0.45**
  - **0.50 < z < 0.55**
  - **0.60 < z < 0.65**



- Theory using the fragmenting jet approach (FJF, **JHEP 1411 (2014) 003**) with 2 sets of LDMEs:
  - Bodwin, Chung, Kim, Lee (BCKL) **PRL 113 (2014) 022001**
  - Butenshoen and Kniehl (BK) **MPL A 28 (2013) 1350027**

J/ψ production from jet fragmentation

- **0.40 < z < 0.45:** tables show χ^2 (χ^2 probabilities)
  - The only acceptable match to data is **BCKL $^1S_0^{(8)}$**
  - See plots on the right

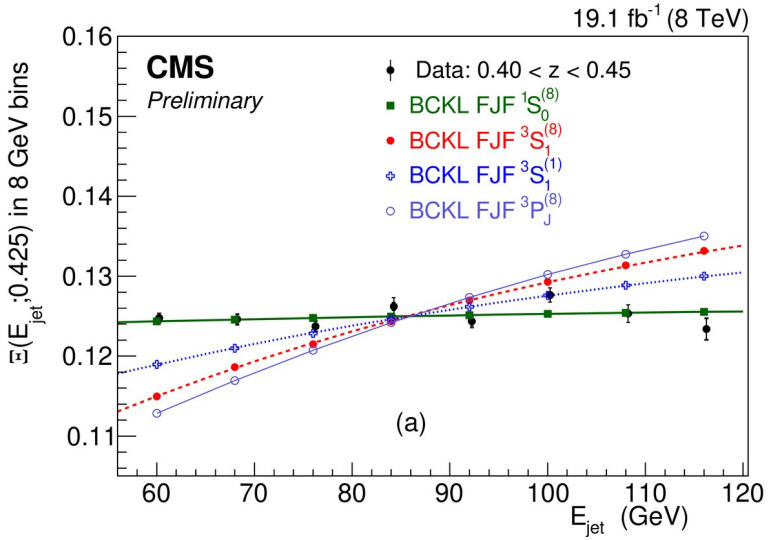
	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
BCKL	14.2 (0.048)	810 (10^{-170})	163(10^{-32})	675 (10^{-141})
BK	278 (10^{-55})	42 (10^{-6})	29 (1.4×10^{-4})	122 (10^{-23})

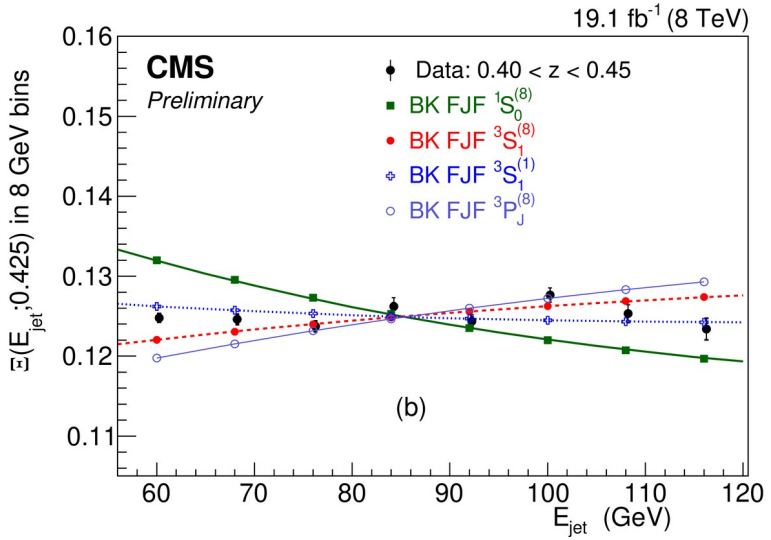
- **0.50 < z < 0.55:**
  - **BCKL $^1S_0^{(8)}$** and **BK $^3S_1^{(1)}$** give equally good matches

	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
BCKL	10.2 (0.18)	54 (10^{-9})	22 (2.4×10^{-3})	88 (10^{-16})
BK	22 (2.4×10^{-3})	19 (8.2×10^{-3})	10 (0.19)	36 (10^{-5})

- **0.60 < z < 0.65:**
  - Again, **BCKL $^1S_0^{(8)}$** and **BK $^3S_1^{(1)}$** give good matches

	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
BCKL	14.3 (0.046)	83 (10^{-15})	21 (3.8×10^{-3})	501 (10^{-104})
BK	50(10^{-8})	28 (2.0×10^{-4})	17 (0.017)	328 (10^{-66})

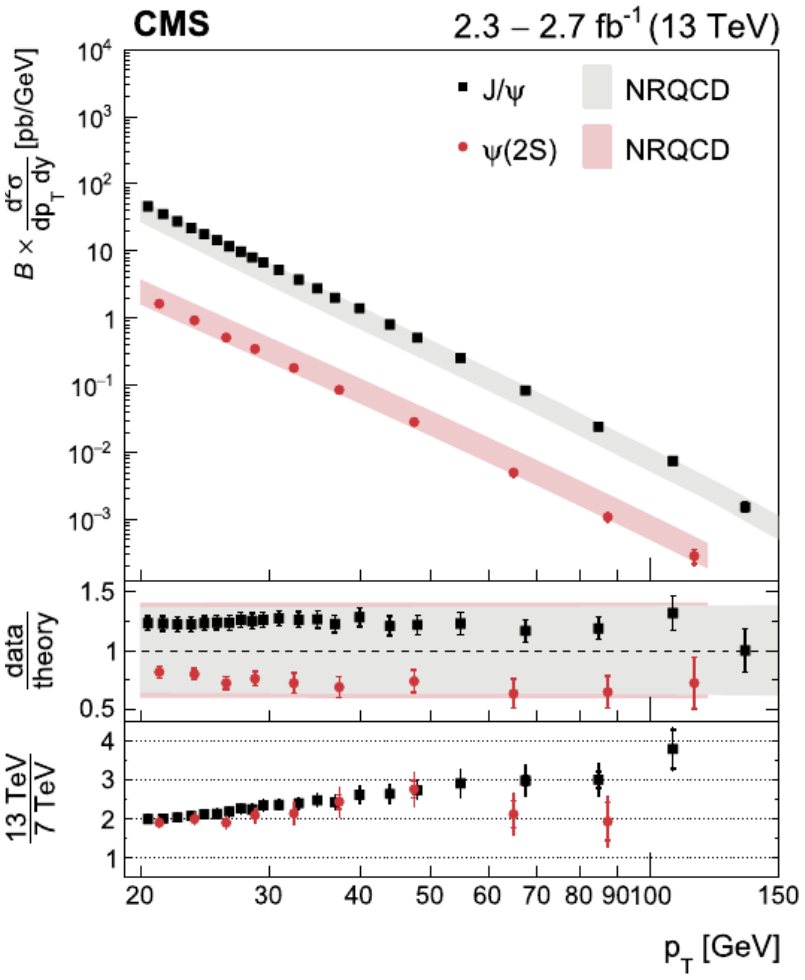




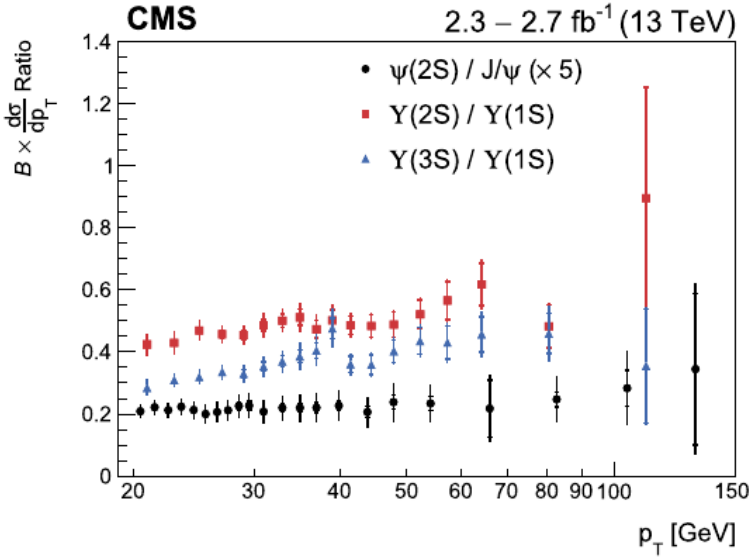
- **Terms $^3S_1^{(8)}$ and $^3P_j^{(8)}$ are disfavored at all z**
- **$^3S_1^{(1)}$ implies a significant transferse polarization, not observed in data**
- **FJF method allows to discriminate between BCKL and BK LDMEs**

Quarkonium production at central rapidity

- Production of J/ψ, ψ(2S) and Υ(nS) for |y|<1.2 studied by CMS on 2.3-2.7 fb^{-1} of 13 TeV data



- Single- and double-differential cross sections times branching fractions measured
- **Results in reasonable agreement with NRQCD predictions within uncertainties**
  - Confirms what seen for J/ψ and ψ(2S) at 7 and 8 TeV by ATLAS (**Eur. Phys. J. C (2016) 76**)



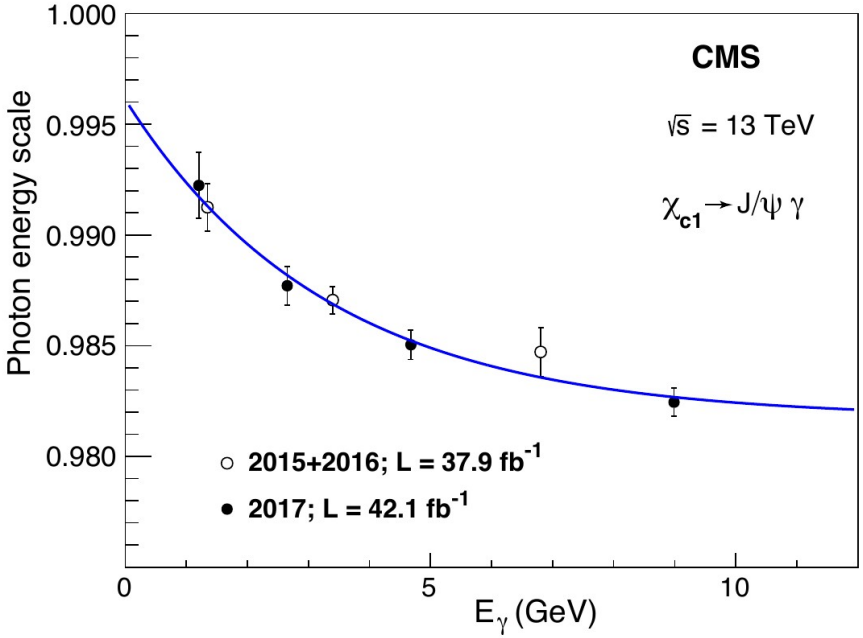
- Ratios of ψ(2S)/J/ψ, of Υ(2S,3S)/Υ(1S), and of 13/7 TeV cross sections also given
  - **Slight increase with p_T observed for both ratios**

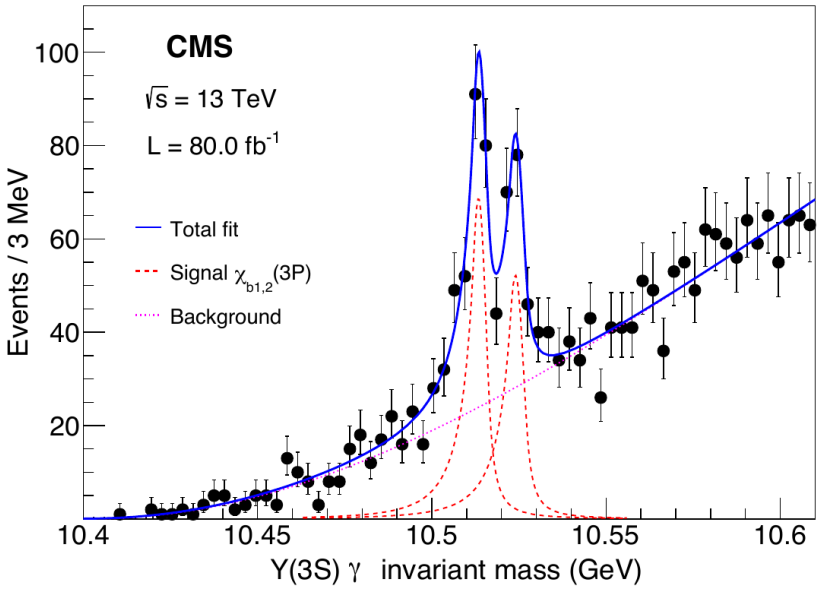
References for the 13/7 TeV ratios from **PRL 114 (2015) 191802** and **PLB 749 (2015) 14**

Observation of $\chi_{b1,2}(3P)$ mass split

- $\chi_b(3P)$ state first discovered by ATLAS (**PRL 108 (2012) 152001**), seen also by D0 and LHCb
- Analyzing **80 fb^{-1}** of LHC Run 2 data
  CMS observed for the first time **the split in the $\chi_{b1}(3P)$-$\chi_{b2}(3P)$ doublet** and measured the masses of the two states
- $\chi_b(3P)$ reconstructed in $\Upsilon(3S)+\gamma$ mode, with γ converting inside the CMS tracker
- Photon energy scale calibrated with high-yield $\chi_{c1} \longrightarrow J/\psi+\gamma$ decays
- Results

  M_1 = 10 513.42±0.41(stat)±0.18(syst) MeV
  M_2 = 10 524.02±0.57(stat)±0.18(syst) MeV
  ΔM = 10.60±0.64(stat)±0.17(syst) MeV
- **Significantly constrains theoretical predictions**, which give mass splits in the range [–2, 18] GeV





Summary and conclusions

- Even if CMS has not been taking data for almost 1 year, new results on heavy favour production are still being published
- Measurements are based on newer 13 TeV Run-2 data as well as on 7 and 8 TeV Run-1 data
- Older data relatively more important for production measurements since they cover different $\sqrt{s}$ points

- Among the newer CMS results are:
- The first observation of the **mass splits of the $B_c(2S)$ and of the $\chi_{b1,2}(3P)$ doublets**
- A study of **J/ψ production inside jets** shedding light on the fragmentation process
- Cross section measurements for **quarkonia at 13 TeV** and for **open beauty at 7 and 13 TeV**
- A measurement of the **Λ_b polarization** at 7 and 8 TeV

- **More analyses in the pipeline with the data currently on tape, while we wait for the LHC Run 3 to start in 2021!**

Backup

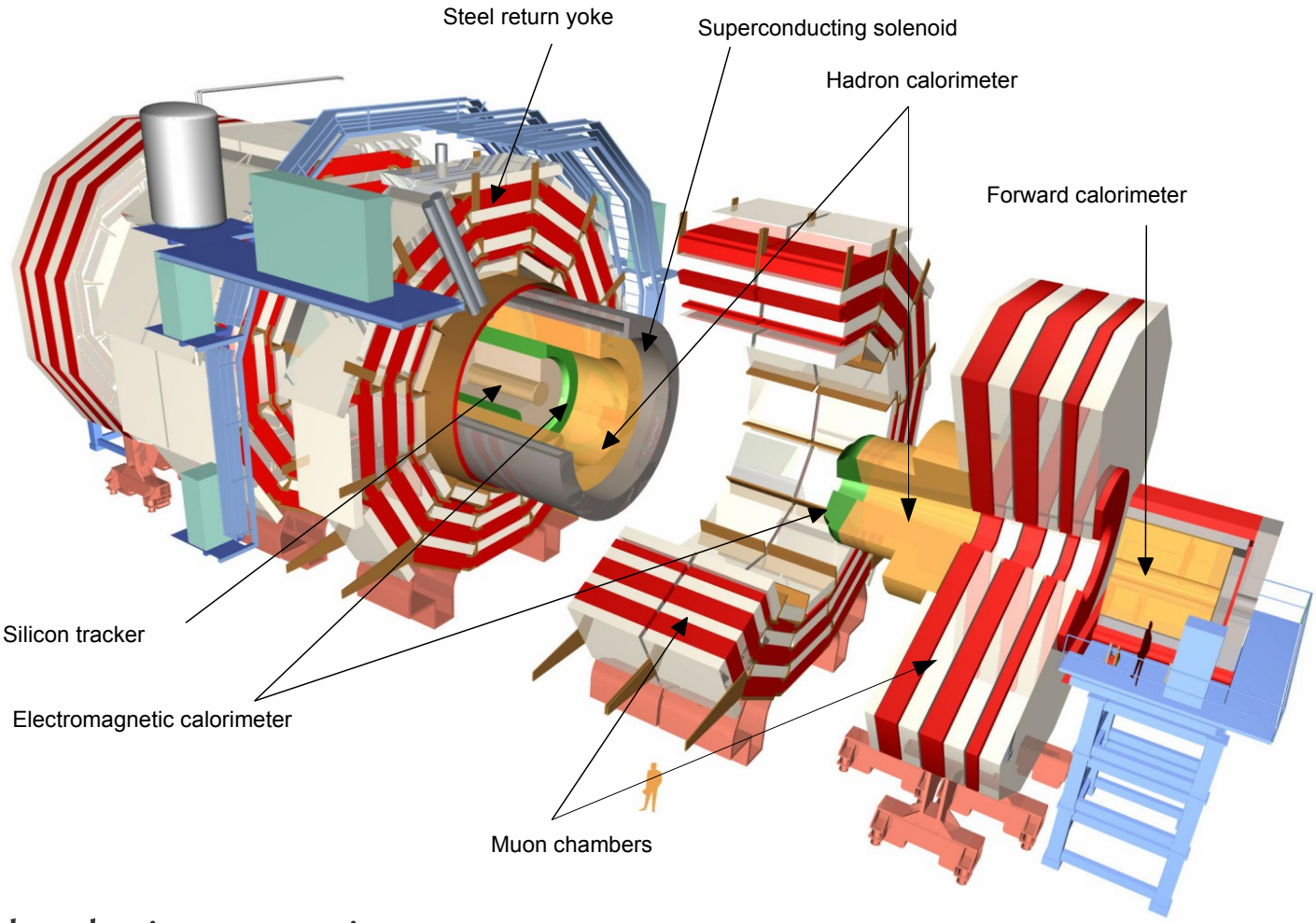
CMS detector

- General-purpose LHC experiment, conducting a wide range of measurements and searches

- General design, inside out:
  - Inner tracker
  - Calorimeters
  - Muon stations

- Solenoidal magnetic field (3.8 T)

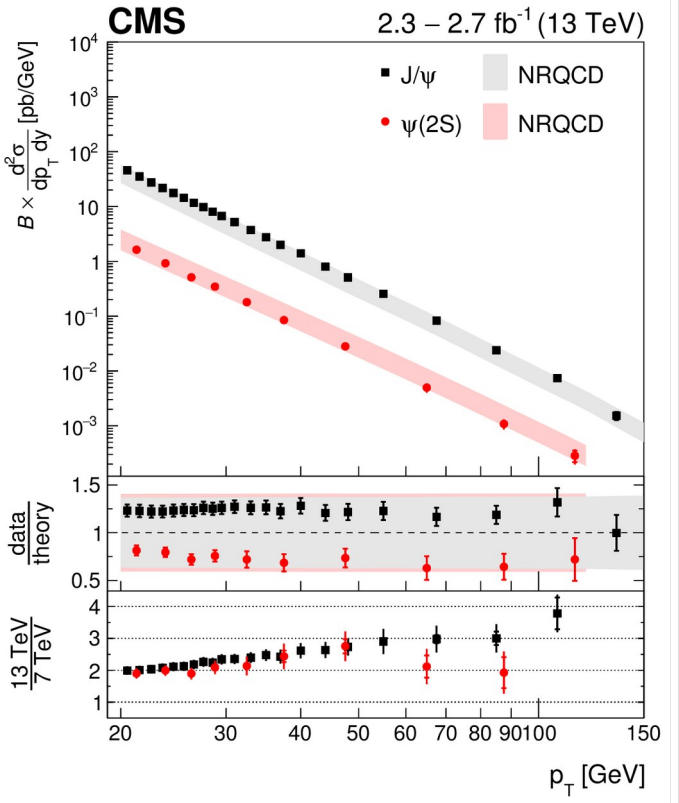
- Charged particle tracking for $|\eta|<2.4$, calorimetry up to $|\eta|\sim5$

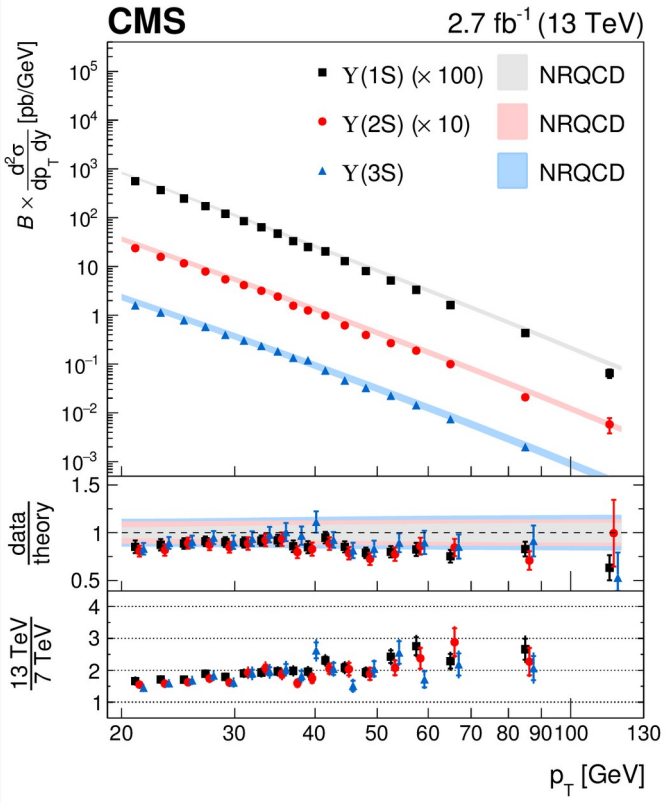


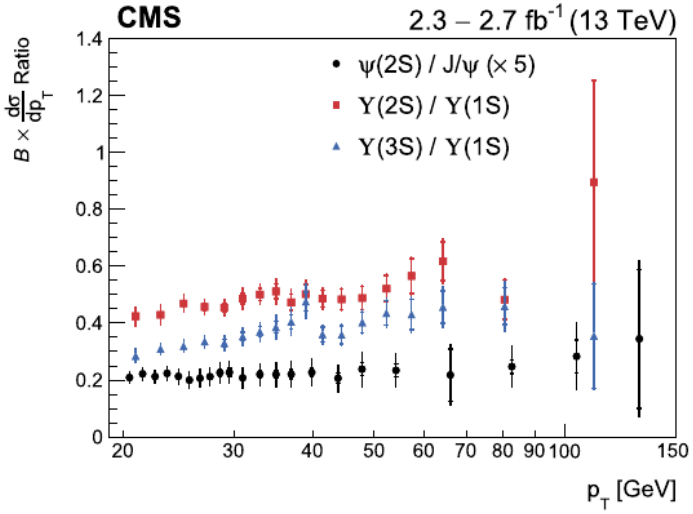
- Highly-configurable multi-level triggers saving to disk O(500-1000)Hz of events for offline analysis

Quarkonium production at central rapidity

- **Results in reasonable agreement with NRQCD predictions within uncertainties**







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