Heavy flavour production and spectroscopy at LHCb

Lepton Photon 2023

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on behalf of the LHCb Collaboration

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Outline

1. **LHCb experiment**

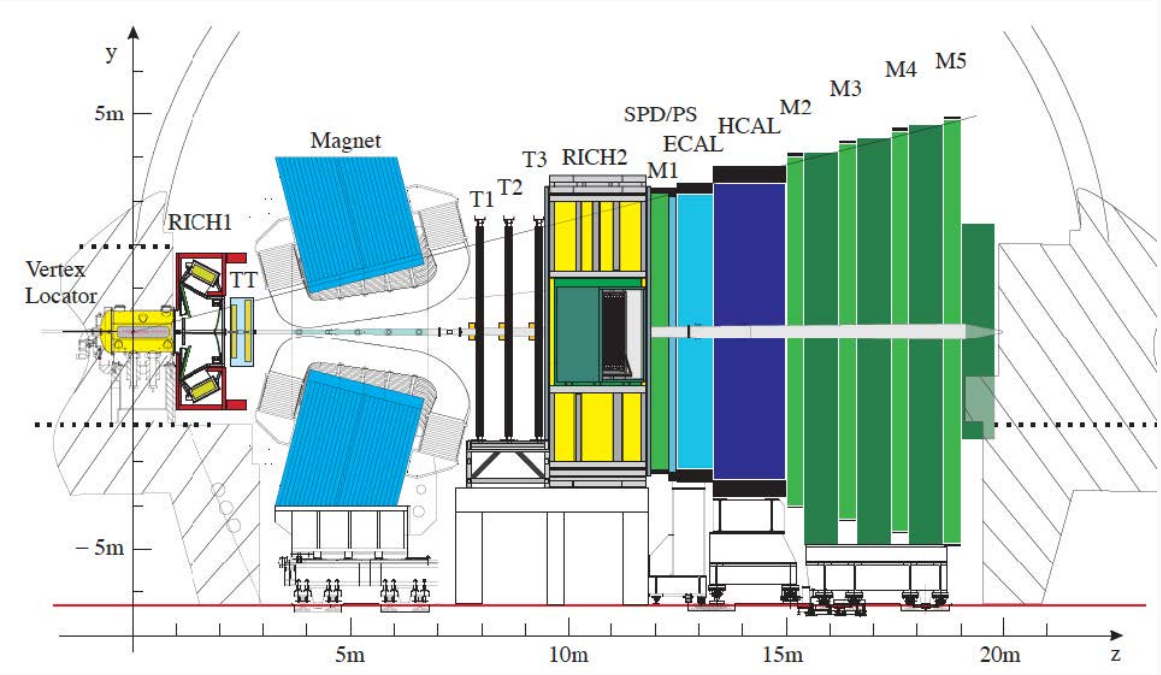
2. **Heavy flavour spectroscopy**
   - Observation of new Ω_c^0 states
   - Observation of new Ξ_b^0 states
   - Mass and production measurement of Ω_b^- and Ξ_b^-

3. **Heavy flavour production**
   - Measurement of $\Upsilon(nS)$ production
   - Associated production of prompt J/ψ and Υ mesons

4. **Summary**

LHCb experiment

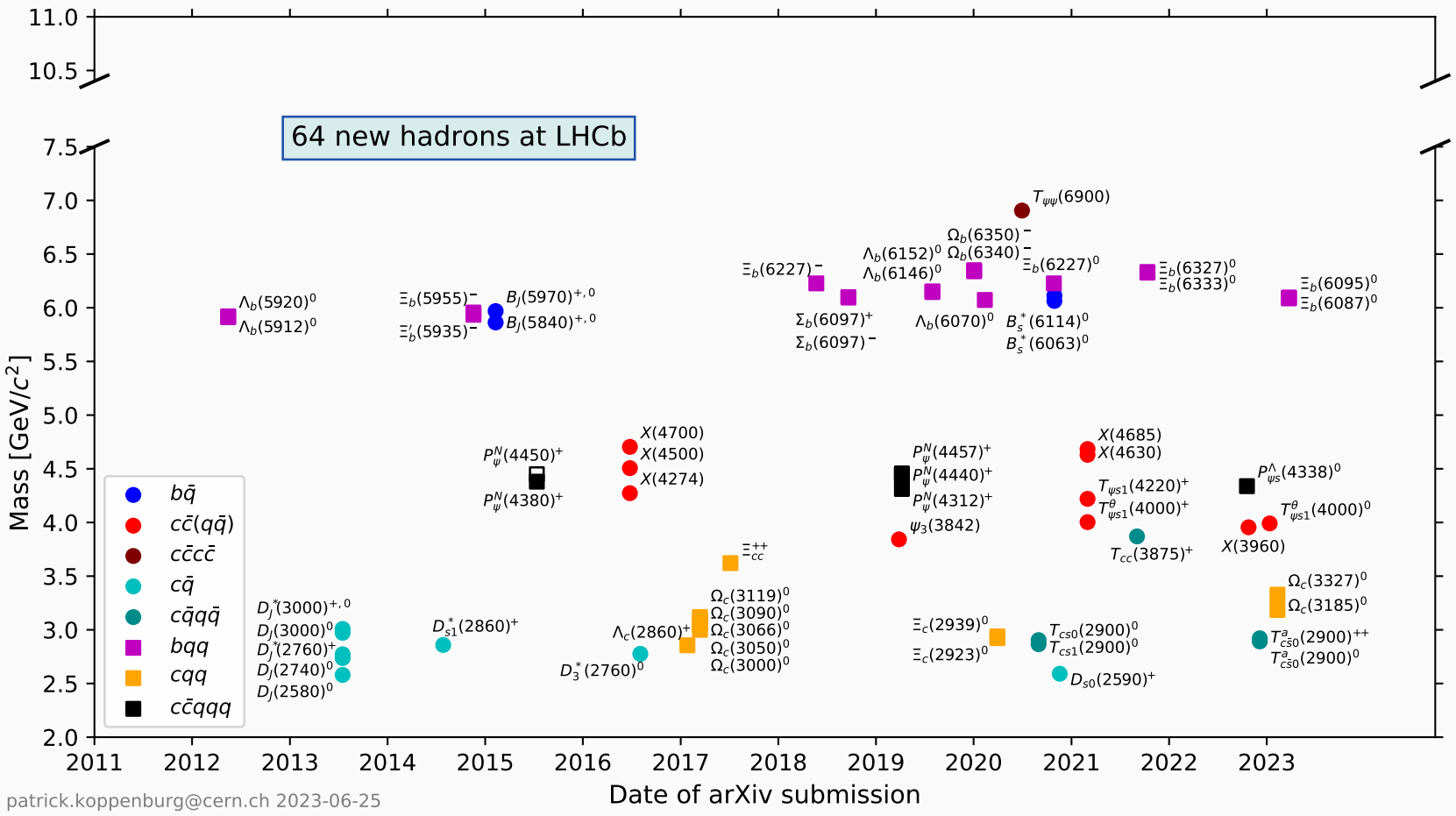
- A huge amount of *b*, *c* have been produced
  - $\sigma(pp \to c\bar{c}) \approx 35\,\mathrm{mb}@\sqrt{s} = 13\,\mathrm{TeV}$
  - $\sigma(pp \to b\bar{b}) \approx 0.5\,\mathrm{mb}@\sqrt{s} = 13\,\mathrm{TeV}$
  - Collected 9 fb^{-1} of data at 7, 8 and 13 TeV
- Excellent vertex and PID performance and precise tracking resolution
- Ideal place for spectroscopy study



JINST 3 (2008) S08005, Int.J.Mod.Phys.A 30 (2015) 07,1530022

Hadron spectroscopy at the LHCb

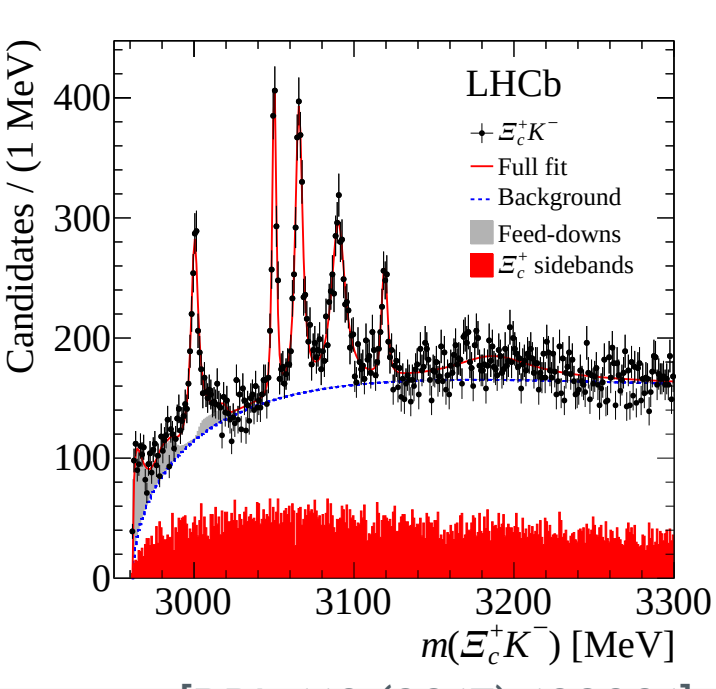
- 72 new hadrons discovered by LHC, 64 from LHCb



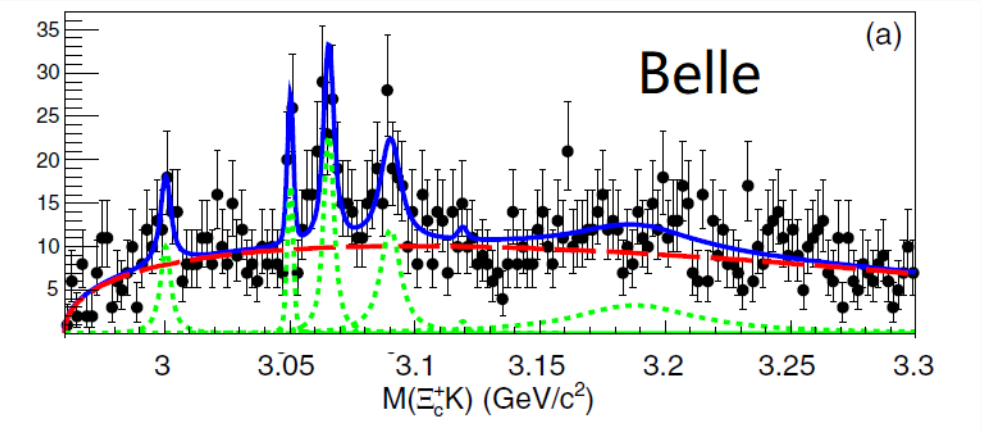
End of Run2

Excited $\Omega_c^0 \to \Xi_c^+ K^-$ states

- 5 new narrow states observed by LHCb in 2017 with its decays to $\Xi_c^+ K^-$
  - Broad structure was seen around 3188 MeV mass region
- 4 of them confirmed by Belle



[PRL 118 (2017) 182001]



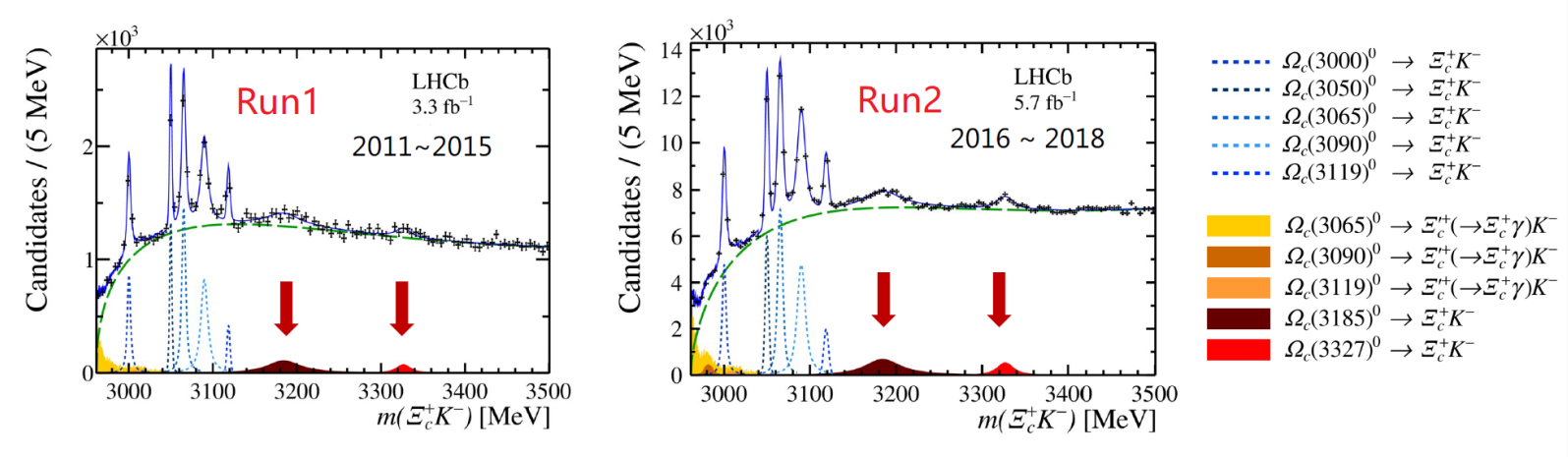
PRD 97 (2018) 051102

New excited $\Omega_c^0 \to \Xi_c^+ K^-$ states

arXiv:2302.04733

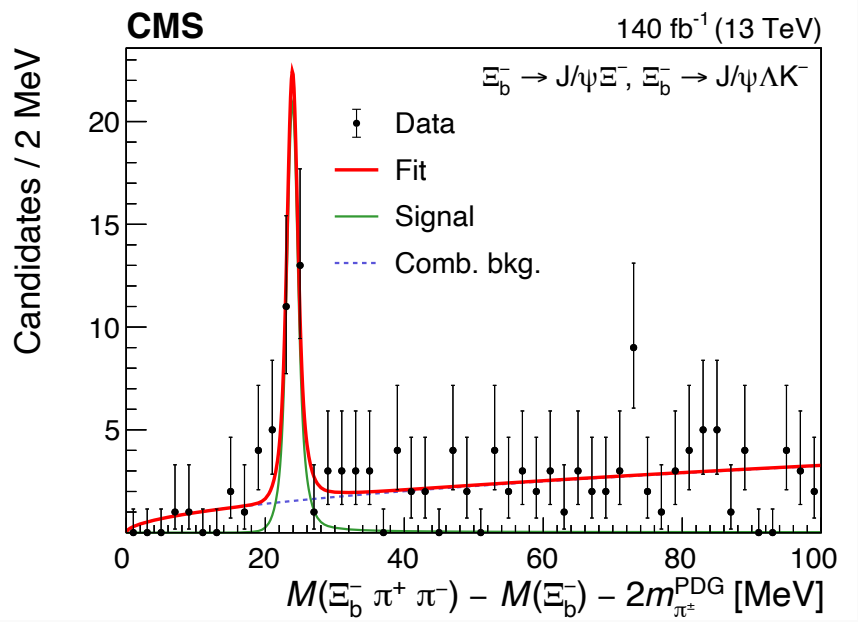
- Use full Run1+Run2 data [9 fb^{-1}]
- All previous states confirmed with improved masses and widths precision
- Two new states (near ΞD and ΞD^* thresholds)
  - $\Omega_c(3185)^0, \Omega_c(3327)^0$

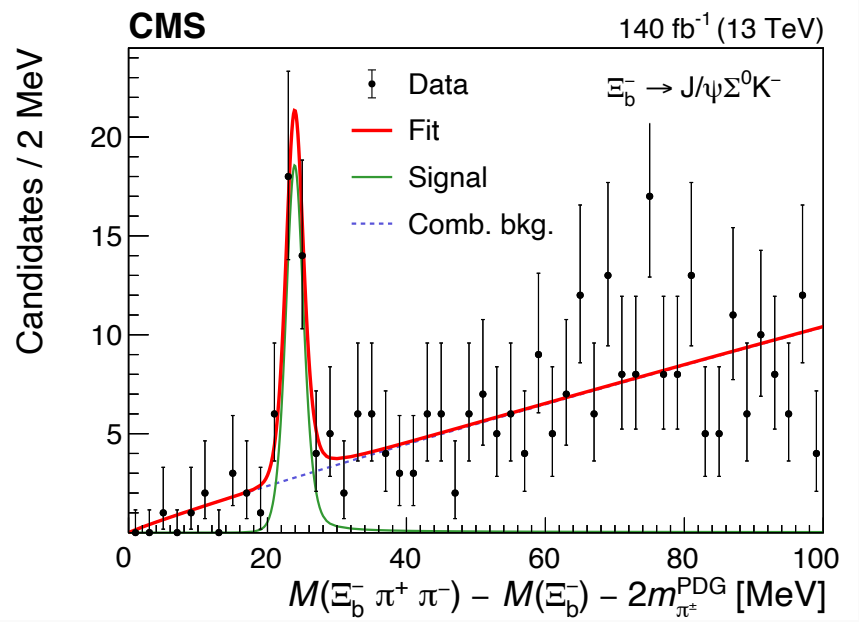
Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\,^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\,^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\,^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\,^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\,^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\,^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\,^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\,^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\,^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\,^{+0.90}_{-1.05}$
		< 2.5 MeV, 95% C.L.
new $\Omega_c(3185)^0$	$3185.1 \pm 1.7\,^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\,^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\,^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\,^{+13}_{-1}$



Excited Ξ_b^- states

- $\Xi_b(6100)^-$ observed by CMS in $m(\Xi_b^-\pi^+\pi^-)$ PRL 126 (2021) 252003
- Two channels used to reconstruct Ξ_b^-
  - Mass : $M(\Xi_b(6100)^-) = 6100.3 \pm 0.2\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) \pm 0.6\,(\Xi_b^-)\,\mathrm{MeV}$
  - Width : $\Gamma(\Xi_b(6100)^-) < 1.9\,\mathrm{MeV@CL95\%}$



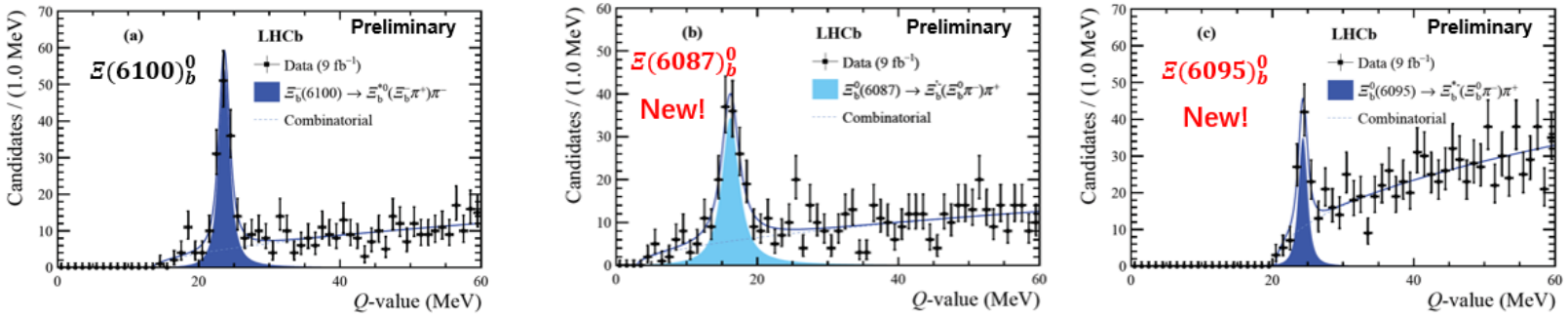


New excited Ξ_b^0 states

LHCb-PAPER-2023-008 (In preparation)

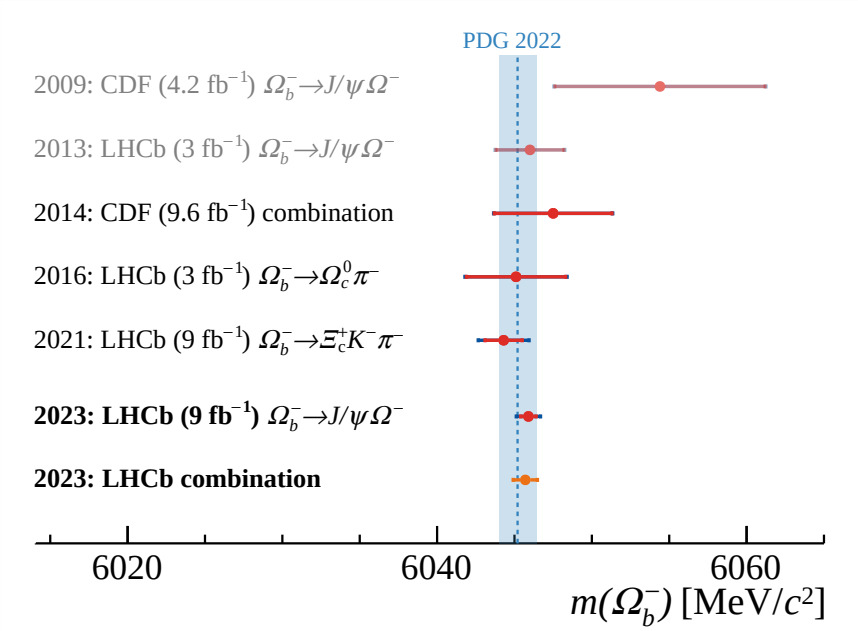
- Search for new $\Xi_b^{**-/0}$ states in $m(\Xi_b^{-/0}\pi^+\pi^-)$ with Run1+Run2 data
  - $\Xi_b^{-/0} \to \Xi_c^{0/+}\pi^-$ and $\Xi_c^{0/+}\pi^-\pi^+\pi^-$ (max. 9 tracks!)
- Two new states observed
  - $\Xi_b(6087)^0 \to \Xi_b^{'-}(\to \Xi_b^0\pi^-)\pi^+$
  - $\Xi_b(6095)^0 \to \Xi_b^{*-}(\to \Xi_b^0\pi^-)\pi^+$
- One state observed by CMS is confirmed
  - $\Xi_b(6100)^- \to \Xi_b^{*0}(\to \Xi_b^-\pi^+)\pi^-$
- Best measurement on known $\Xi_b^{'-}$ and Ξ_b^{*-} states

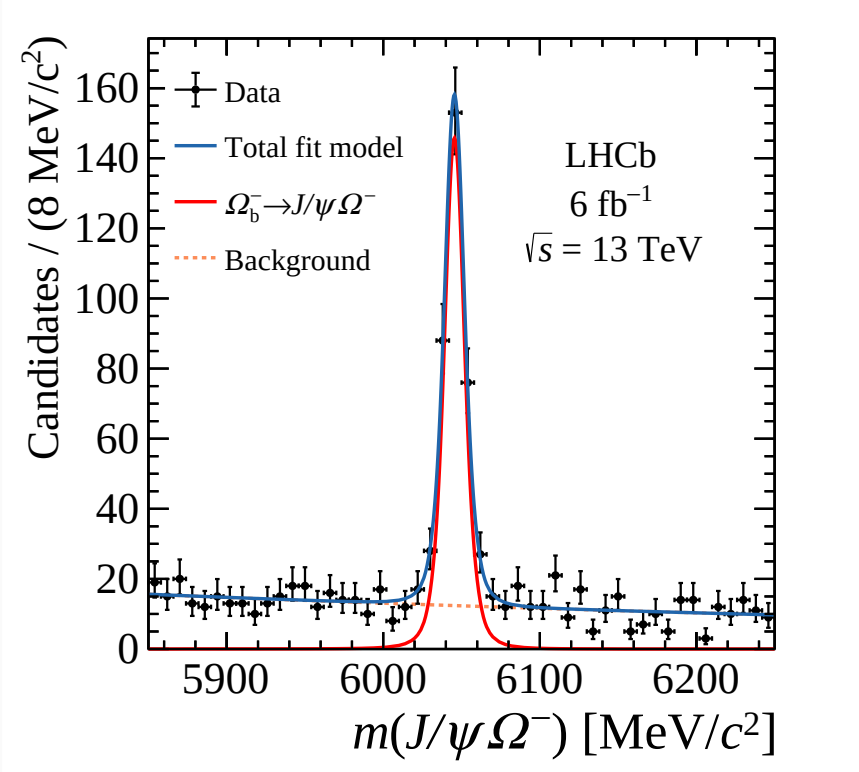
		Value [MeV]
	$Q_0\ [\Xi_b(6100)^-]$	$23.60 \pm 0.11 \pm 0.02$
	$\Gamma\ [\Xi_b(6100)^-]$	$0.94 \pm 0.30 \pm 0.08$
	$m_0\ [\Xi_b(6100)^-]$	$6099.74 \pm 0.11 \pm 0.02\ \pm 0.6\ (\Xi_b^-)$
New	$Q_0\ [\Xi_b(6087)^0]$	$16.20 \pm 0.20 \pm 0.06$
	$\Gamma\ [\Xi_b(6087)^0]$	$2.43 \pm 0.51 \pm 0.10$
	$m_0\ [\Xi_b(6087)^0]$	$6087.24 \pm 0.20 \pm 0.06\ \pm 0.5\ (\Xi_b^0)$
	$Q_0\ [\Xi_b(6095)^0]$	$24.32 \pm 0.15 \pm 0.03$
	$\Gamma\ [\Xi_b(6095)^0]$	$0.50 \pm 0.33 \pm 0.11$
	$m_0\ [\Xi_b(6095)^0]$	$6095.36 \pm 0.15 \pm 0.03\ \pm 0.5\ (\Xi_b^0)$



Mass and production measurement of Ω_b^- and Ξ_b^- arXiv:2305.15329

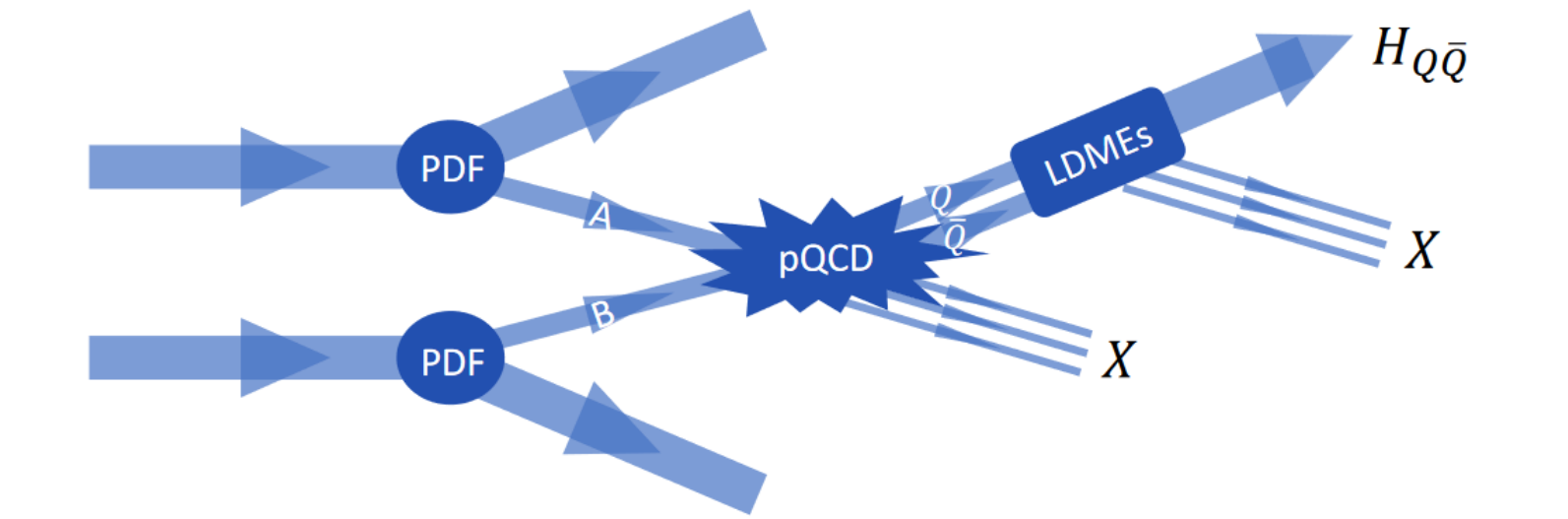
- Ω_b^- and Ξ_b^- can only decay weakly and experimental knowledge was limited
- Measurement the mass difference and production ratio with full Run1+Run2 data
  - $m(\Omega_b^-) - m(\Xi_b^-) = 248.54 \pm 0.51\,(\mathrm{stat}) \pm 0.38\,(\mathrm{syst})\ \mathrm{MeV}/c^2$
  - $\frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)} = 0.120 \pm 0.008\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})$





Quarkonium production

- Factoriza in two scales of production
  - Quark pair formation : Short distance, perturbative
  - Hadronization : Long distance, non-perturbative
- Various of theoretical approaches non has successfully described all experimental observables
  - Color singlet model (CSM) : Difficult to predict production cross-sections at high energies
  - Non-relavitistic QCD (NRQCD) : Relies heavily on the universality of non-perturbative long-distance matrix elements (LDMEs)
- Critical need for experimental input that can advance the understanding of quarkonium production and its applications

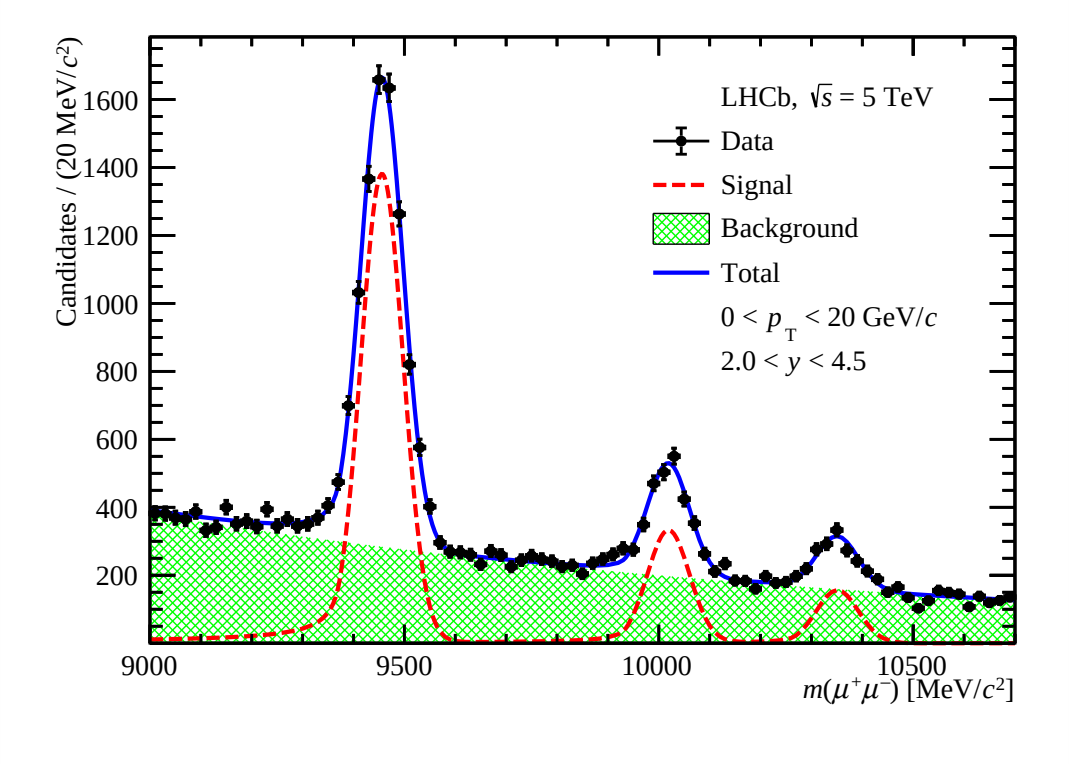


Measurement of $\Upsilon(nS)$ production

arXiv:2212.12664

- Use 2015 *pp* collision data at $\sqrt{s} = 5\,\mathrm{TeV}$ [$9.1\,\mathrm{pb}^{-1}$]
- With $\Upsilon(nS) \to \mu^+\mu^-$ decay
- Measurement the double-differential cross-section in kinematic range of $0 < p_\mathrm{T} < 20\,\mathrm{GeV}/c$, $2 < y < 4.5$

$$\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-) \times \frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}y} = \frac{N(\Upsilon(nS) \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_\mathrm{tot} \times \Delta p_T \times \Delta y},$$



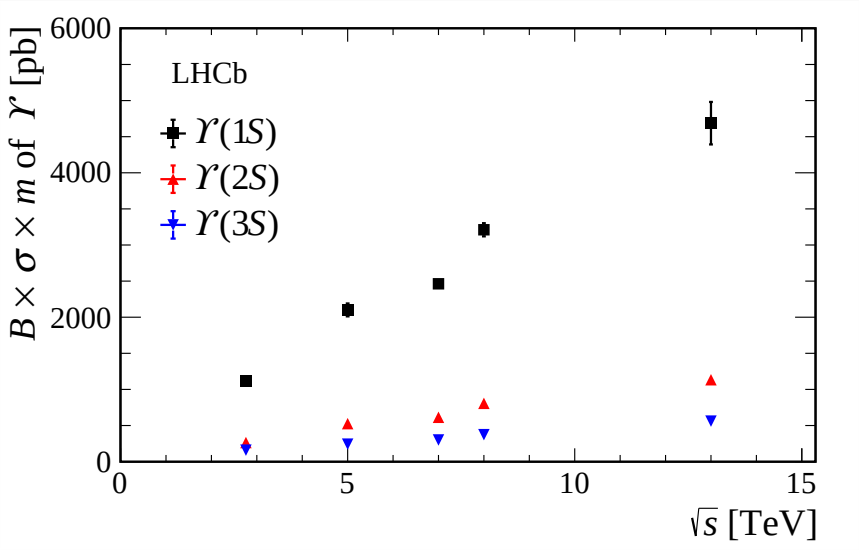
Measurement of $\Upsilon(nS)$ production

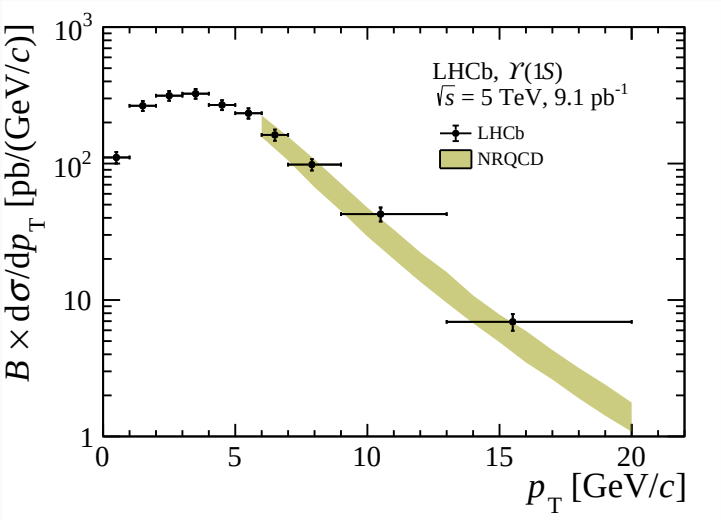
arXiv:2212.12664

- Result of integrated cross-sections of $\Upsilon(nS)$ with improved precision (factor of two)

$$\begin{aligned}
\sigma(\Upsilon(1S)) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) &= 2101 \pm 33 \pm 83\,\mathrm{pb} \\
\sigma(\Upsilon(2S)) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) &= 526 \pm 20 \pm 21\,\mathrm{pb} \\
\sigma(\Upsilon(3S)) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) &= 242 \pm 16 \pm 10\,\mathrm{pb}
\end{aligned}$$

- $\Upsilon(1S)$ cross-section as function of p_{T} well describe by NRQCD ($p_{\mathrm{T}} > 5\,\mathrm{GeV}/c$)

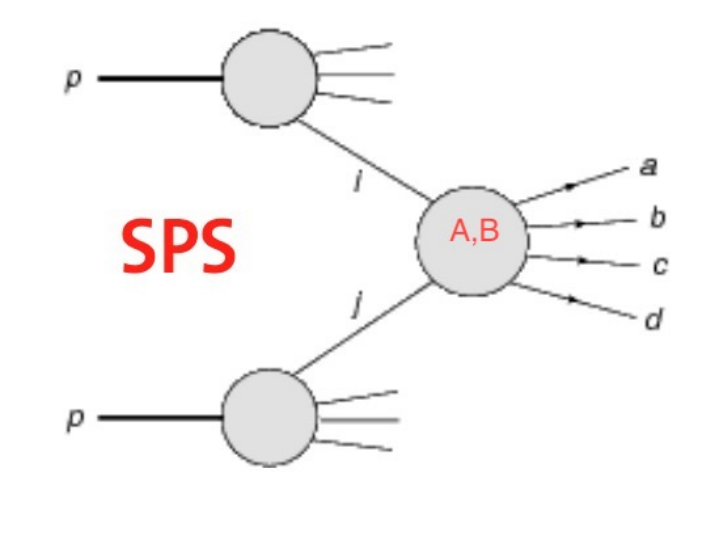


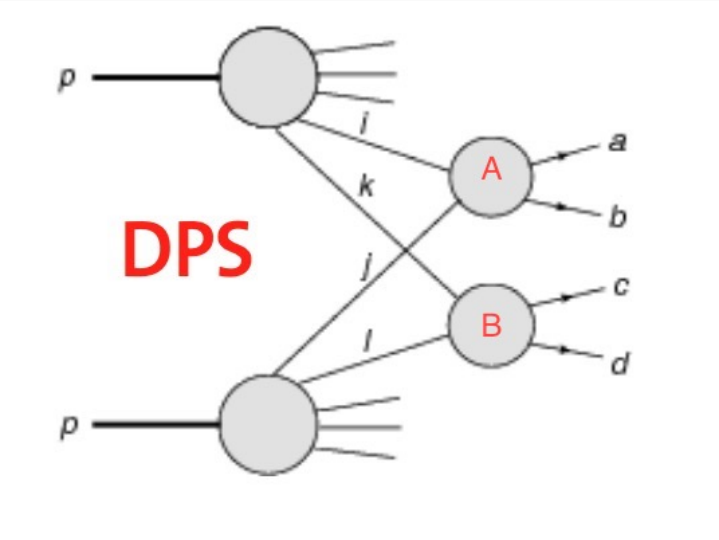


Quarkonium pair production

- Two production mechanism : Single parton scattering (SPS), Double parton scattering (DPS)
  - SPS: test various of production models
  - DPS: test the "pocket formula" Phys. Rev. D57 (1998) 503
    - assume no correlations between two partons and transverse and longitudinal components are factorisable

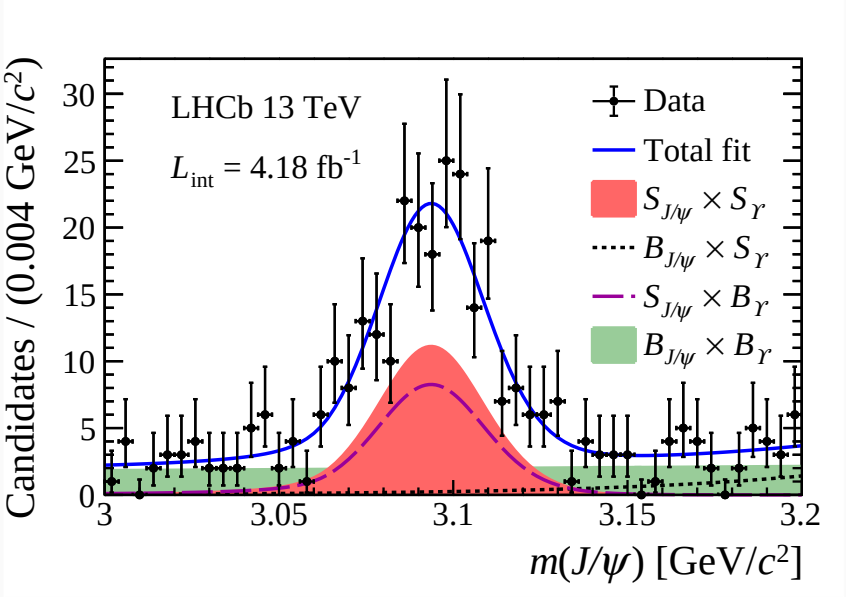
$$\sigma_{DPS}^{pp\to AB} = \frac{m}{2}\frac{\sigma_{SPS}^{pp\to A}\sigma_{SPS}^{pp\to B}}{\sigma_{eff,DPS}}$$

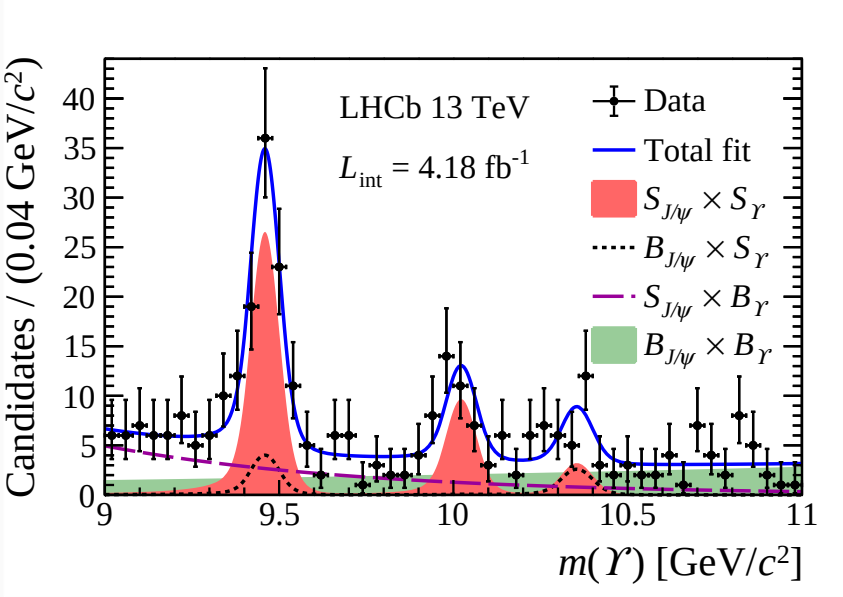




Associated production of prompt J/ψ and Υ arXiv:2305.15580

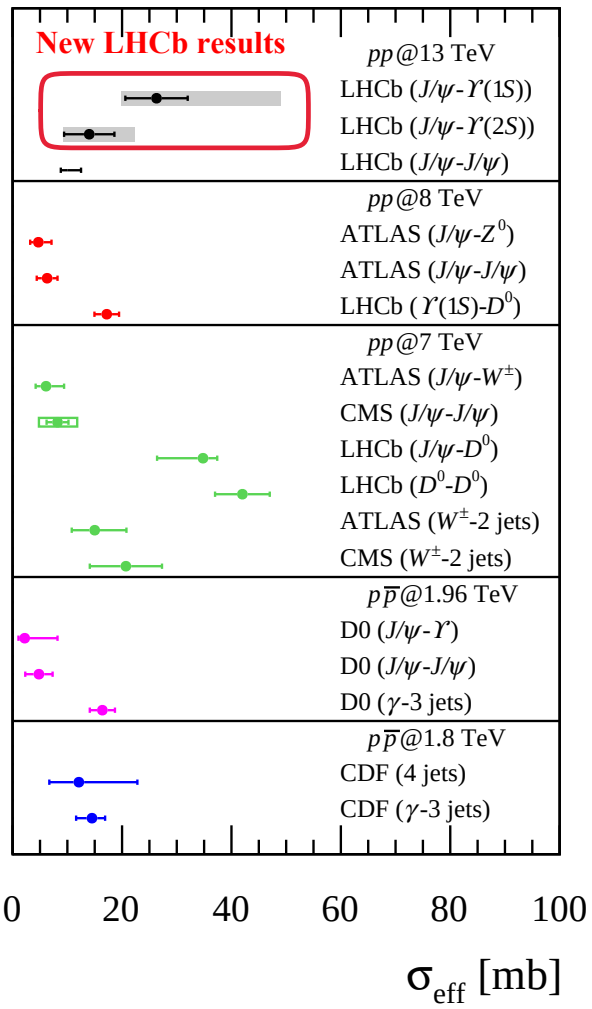
- Use 2016-2018 *pp* collision data at $\sqrt{s} = 13\,\mathrm{TeV}$ [4.2 fb^{-1}]
- With $\Upsilon(nS) \to \mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ decay
- Measure production in kinematic range:
  - $2 < y < 4.5$
  - $0 < p_{\mathrm{T}}(J/\psi) < 10\,\mathrm{GeV}/c$
  - $0 < p_{\mathrm{T}}(\Upsilon) < 30\,\mathrm{GeV}/c$
- 2D fit on $J/\psi - \Upsilon$ mass distribution to extract the signal yields
- Significance:
  - $J/\psi - \Upsilon(1S) : 7.9\sigma$
  - $J/\psi - \Upsilon(2S) : 4.9\sigma$





Associated production of prompt J/ψ and Υ arXiv:2305.15580

- Cross-section:
  - $\sigma(J/\psi - \Upsilon(1S)) =$ $133 \pm 22\,(\mathrm{stat}) \pm 7\,(\mathrm{syst}) \pm 3(\mathcal{B})\,\mathrm{pb}$
  - $\sigma(J/\psi - \Upsilon(2S)) =$ $76 \pm 21\,(\mathrm{stat}) \pm 4\,(\mathrm{syst}) \pm 7(\mathcal{B})\,\mathrm{pb}$
- $\sigma_{eff}(J/\psi - \Upsilon) = \frac{\sigma(J/\psi)\sigma(\Upsilon)}{\sigma_{DPS}(J/\psi - \Upsilon)}$
  - Substract the SPS contribution based on NRQCD to get σ_{DPS} Phys. Rev. Lett. 117 (2016) 062001
    - $\sigma_{SPS}(J/\psi - \Upsilon(1S)) = 20^{+52}_{-15}\,\mathrm{pb}$
    - $\sigma_{SPS}(J/\psi - \Upsilon(2S)) = 8^{+22}_{-6}\,\mathrm{pb}$
  - $\sigma_{eff}(J/\psi - \Upsilon(1S)) =$ $26 \pm 5\,(\mathrm{stat}) \pm 2\,(\mathrm{syst})^{+22}_{-3}(th.)\,\mathrm{mb}$
  - $\sigma_{eff}(J/\psi - \Upsilon(2S)) =$ $14 \pm 5\,(\mathrm{stat}) \pm 1\,(\mathrm{syst})^{+7}_{-1}(th.)$
- σ_{eff} compatible with measurements using hadroproduction of other particle



Summary

- A lot of important results in heavy flavor sector:
  - First observation of two new excited Ω_c^0 states near ΞD and ΞD^* thresholds
  - First observation of $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$
  - Most precise measurement of mass difference and production ratio of Ω_b^- and Ξ_b^-
  - Cross-sections of Υ mesons measured with improved precision
  - First measurement of prompt $J/\psi - \Upsilon$ associated production, effective cross-section was found compatible with other hadroproduction measurements
- Run3 approaching $\int \mathcal{L} dt = 23\ \text{fb}^{-1}$ (3 times more)
- More results are expected in the near future

Thanks!