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LISHEP 2021

Experimental Measurement of Heavy Flavours at CMS

Session C

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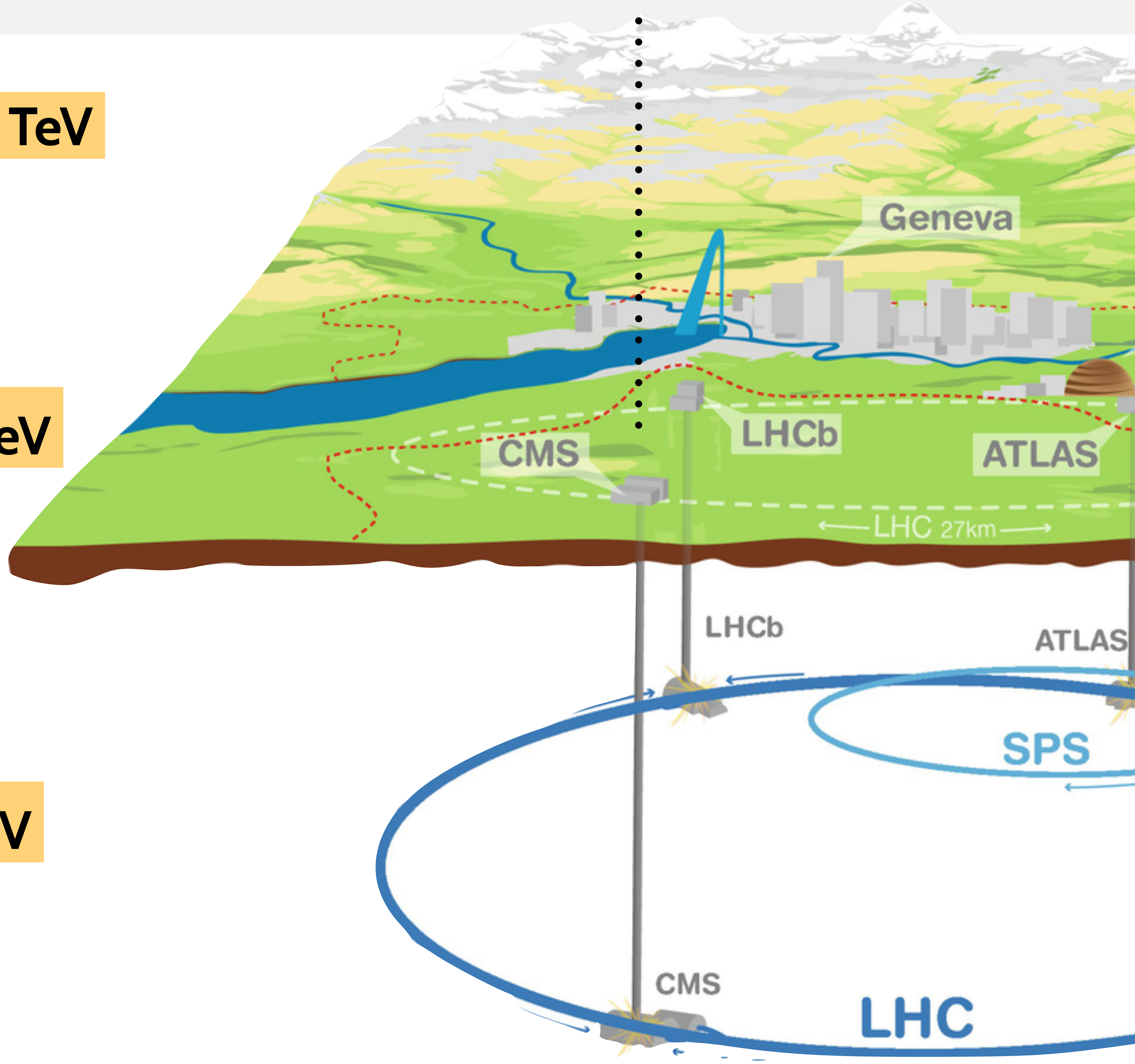
Outline: presented results

This talk presents an overview of the latest measurements in heavy-flavour physics by CMS

1. Observation of an excited *bsq* baryon decaying to $\Xi_b^- \pi^+ \pi^-$ **13 TeV**
2. Study of excited Λ_b^0 states decaying to $\Lambda_b^0 \pi^+ \pi^-$ **13 TeV**
3. Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross-section ratios **13 TeV**
4. Measurement of $2 \times \Upsilon(1S)$ production **13 TeV**
   + search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$
5. Study of event-activity dependence of $\Upsilon(nS)$ production **7 TeV**
6. Angular analysis of $B^+ \to K^*(892)^+ \mu^+ \mu^-$ **8 TeV**

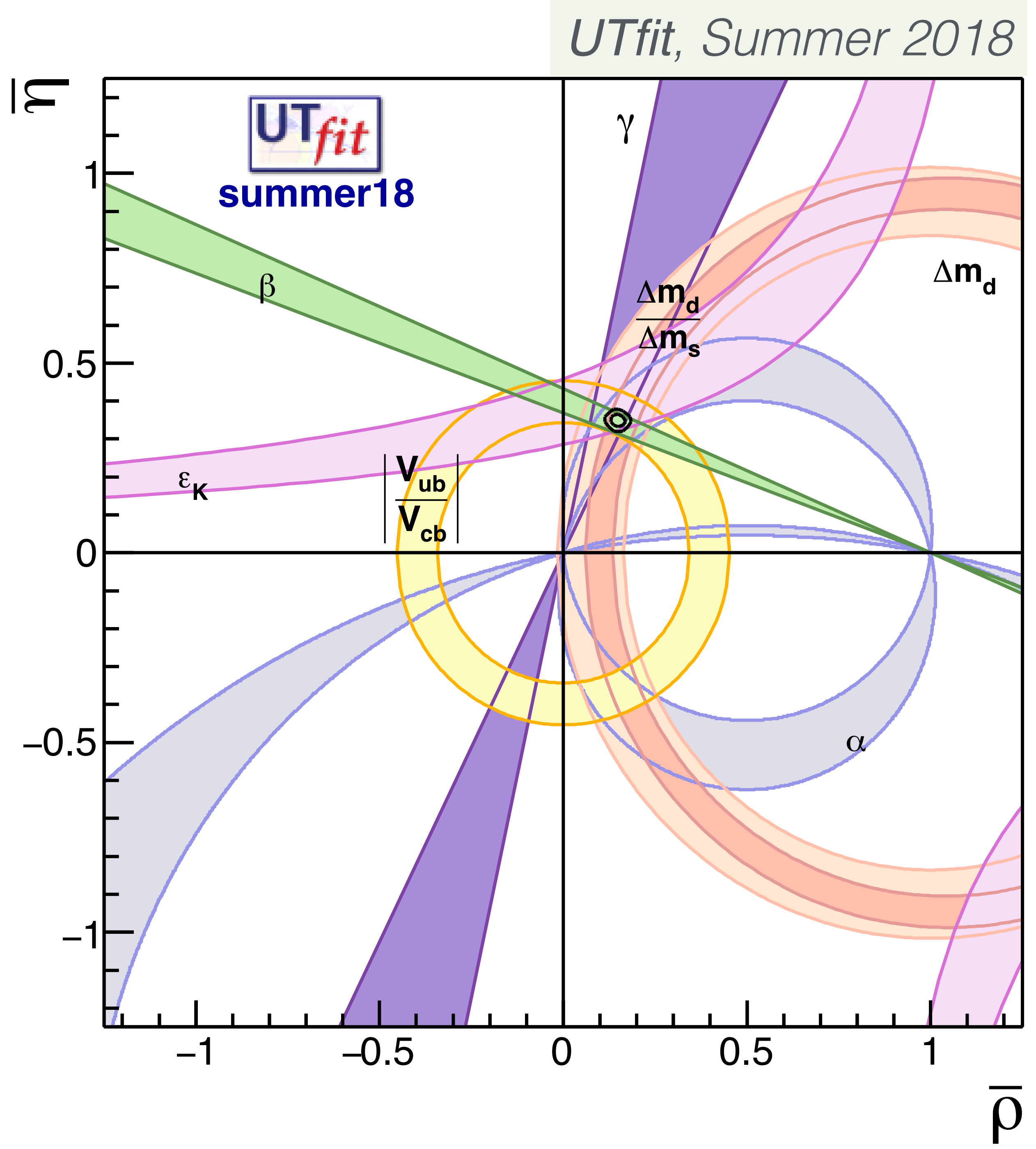


We know that the Standard Model is incomplete: dark matter, matter-antimatter asymmetry, neutrino masses, ...

↳ **hoping to eventually observe new (BSM) particles at increasing energies: no success so far**

Flavour physics is very precisely described by the CKM-matrix formalism ▶
with its parameters overconstrained by a myriad of experimental measurements

↳ **look for indirect effects of New Physics in low-energy processes**
e.g. slightest discrepancies from SM in c/b-hadron production and decays



Production of heavy-flavour hadrons at LHC described by factorisation theorem

proton PDFs ▶ **pQCD partonic xsection** ▶ **hadronisation**

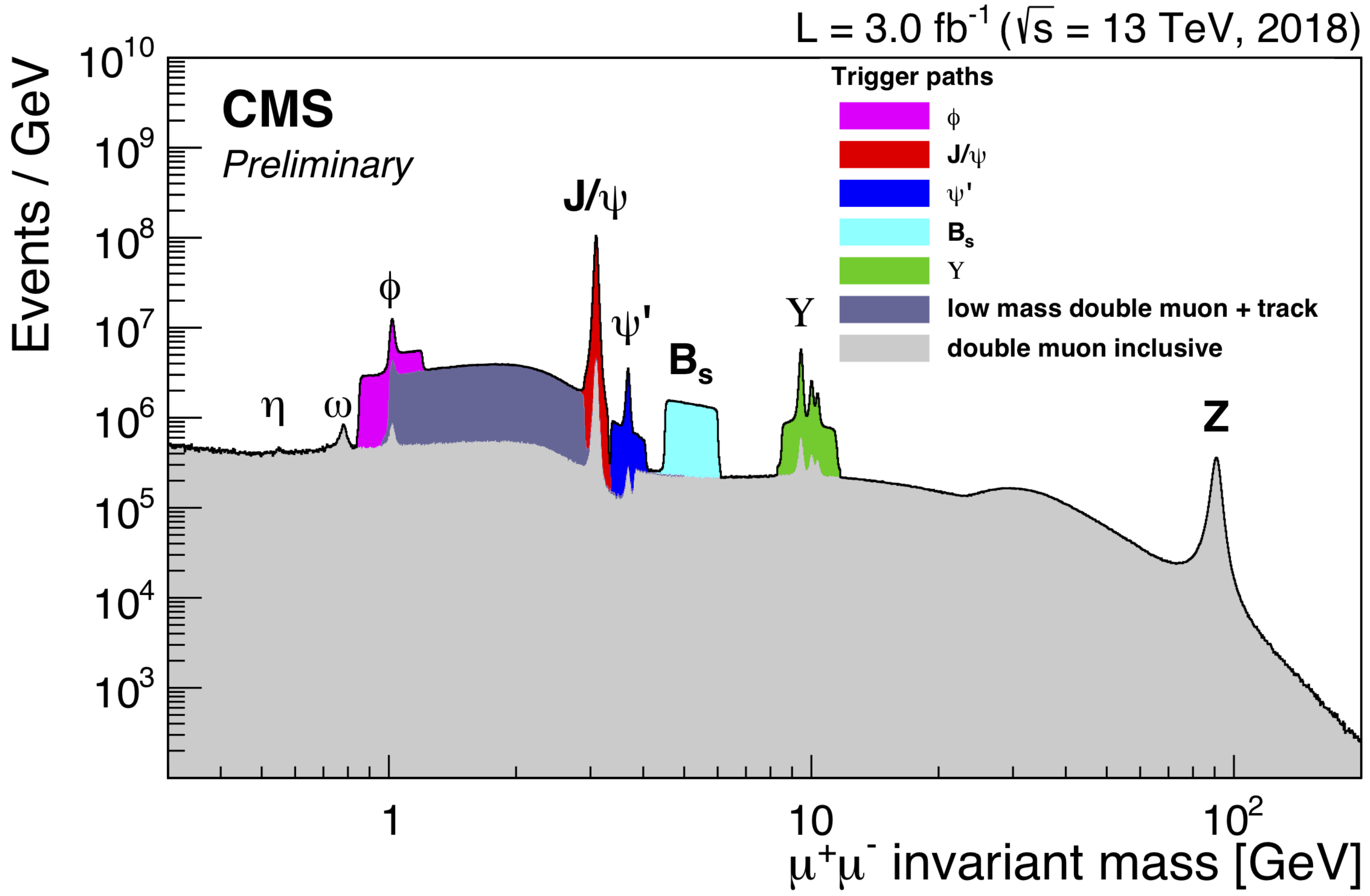
Measurement of bottom/charm-hadron production and their properties allows to validate pQCD predictions and different hadronisation models

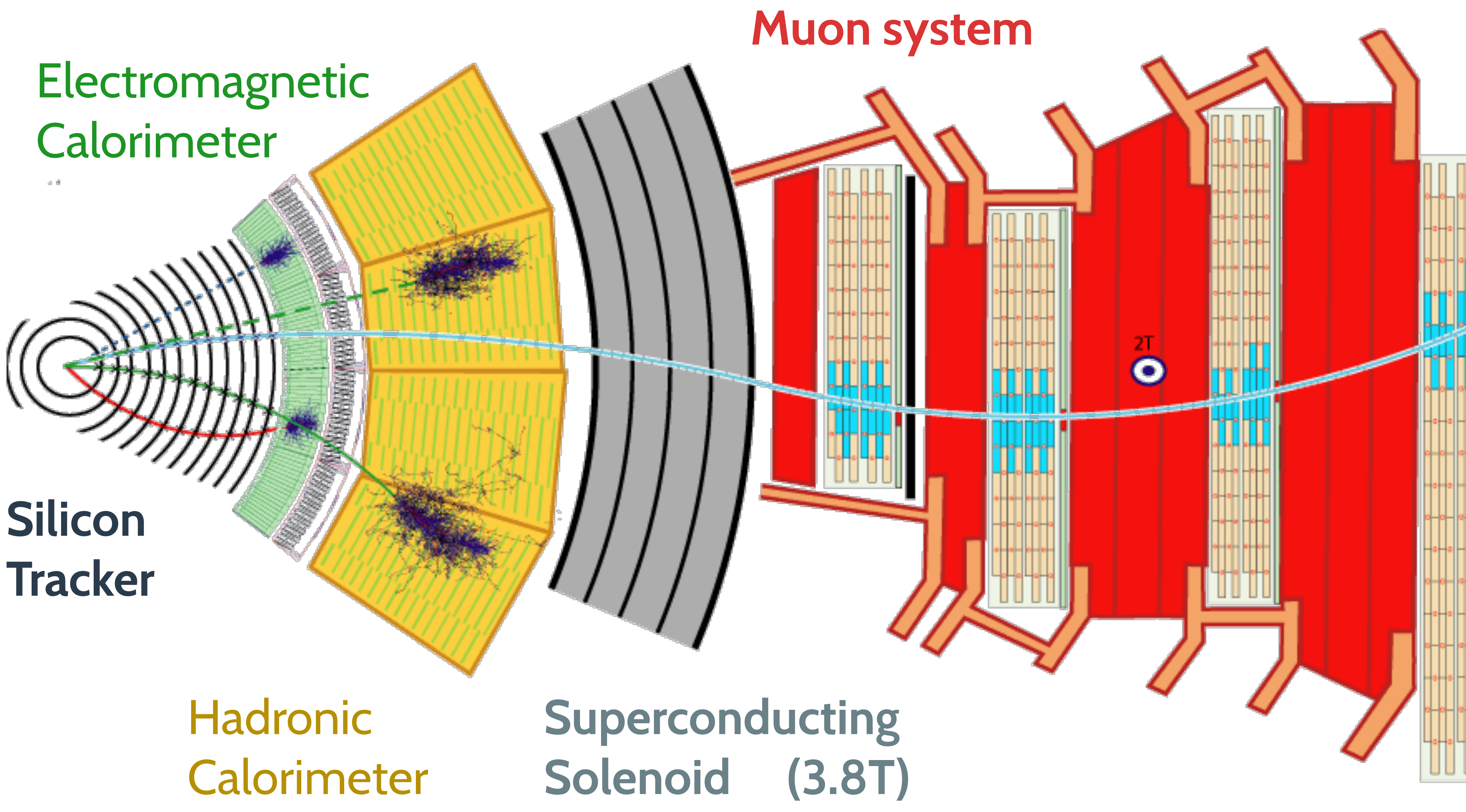
↳ **translates into improved modelling of low-energy and exotic processes**
which are beneficial for describing the flavour content in many other measurements

CMS experiment: the detector

CMS detector is perfectly suited for studying b/c hadrons

- **many decay channels with muons in the final state**
  easy to detect and trigger on
- **great muon identification capabilities** ▶
  $|\eta| \leq 2.4 \quad p_T \geq 2$ GeV
- **plenty of pp collision data collected over the years**
  up to 20 fb^{-1} (Run 1) + up to 143 fb-1 (Run 2)





A set of triggers with good coverage of heavy-flavour physics

- inclusive μμ or μ+track triggers
- dedicated triggers for specific μμ resonances
- more generic triggers with tracks

- $J/\psi \to \mu^+\mu^-$
- $\Xi^- \to \Lambda\pi^-$
- $\Lambda \to p\pi^-$

final states

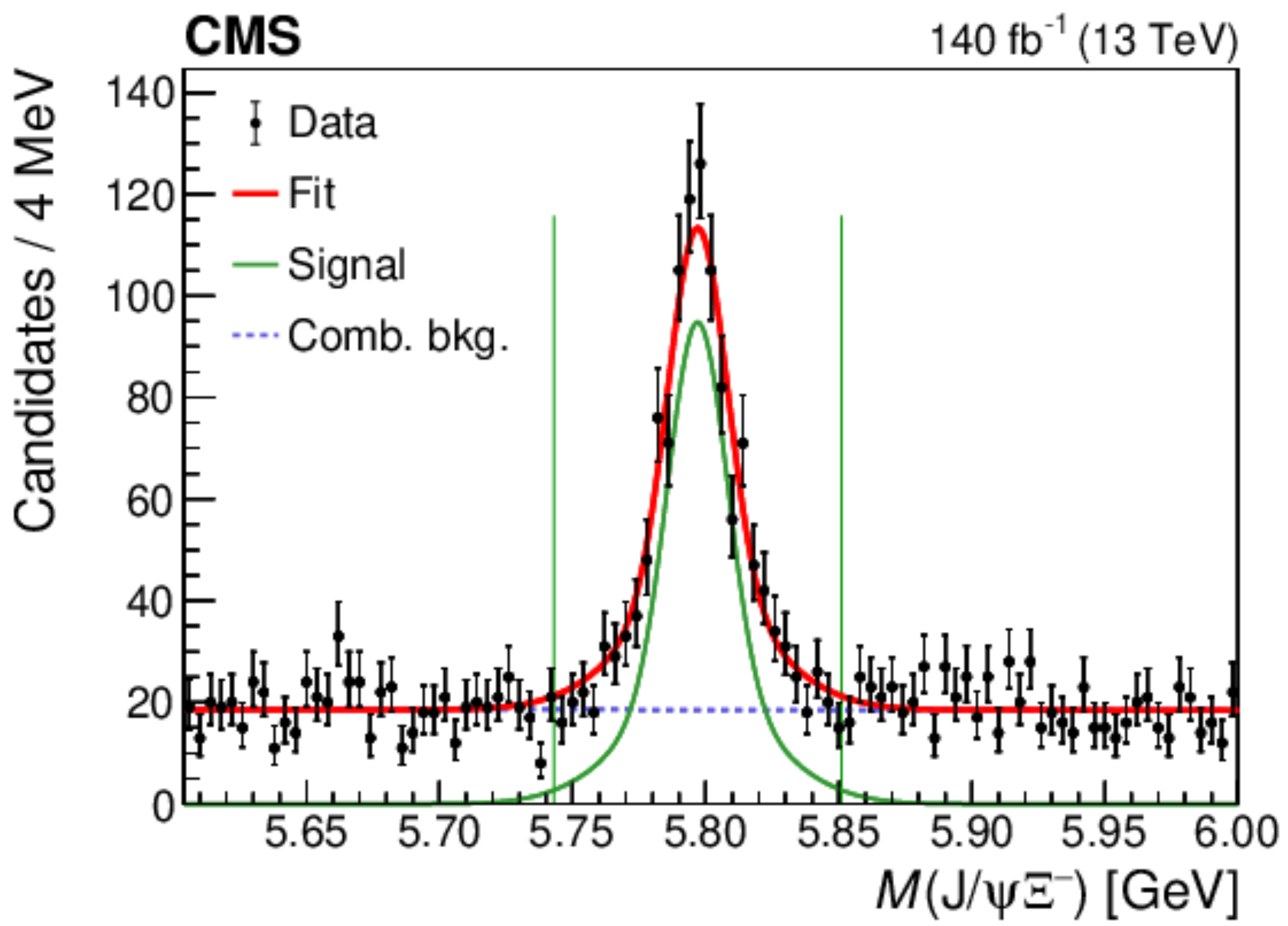
Observation of a new excited state of a beauty-strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$
using 140 fb^{-1} at $\sqrt{s}$ = 13 TeV (2016-2018)

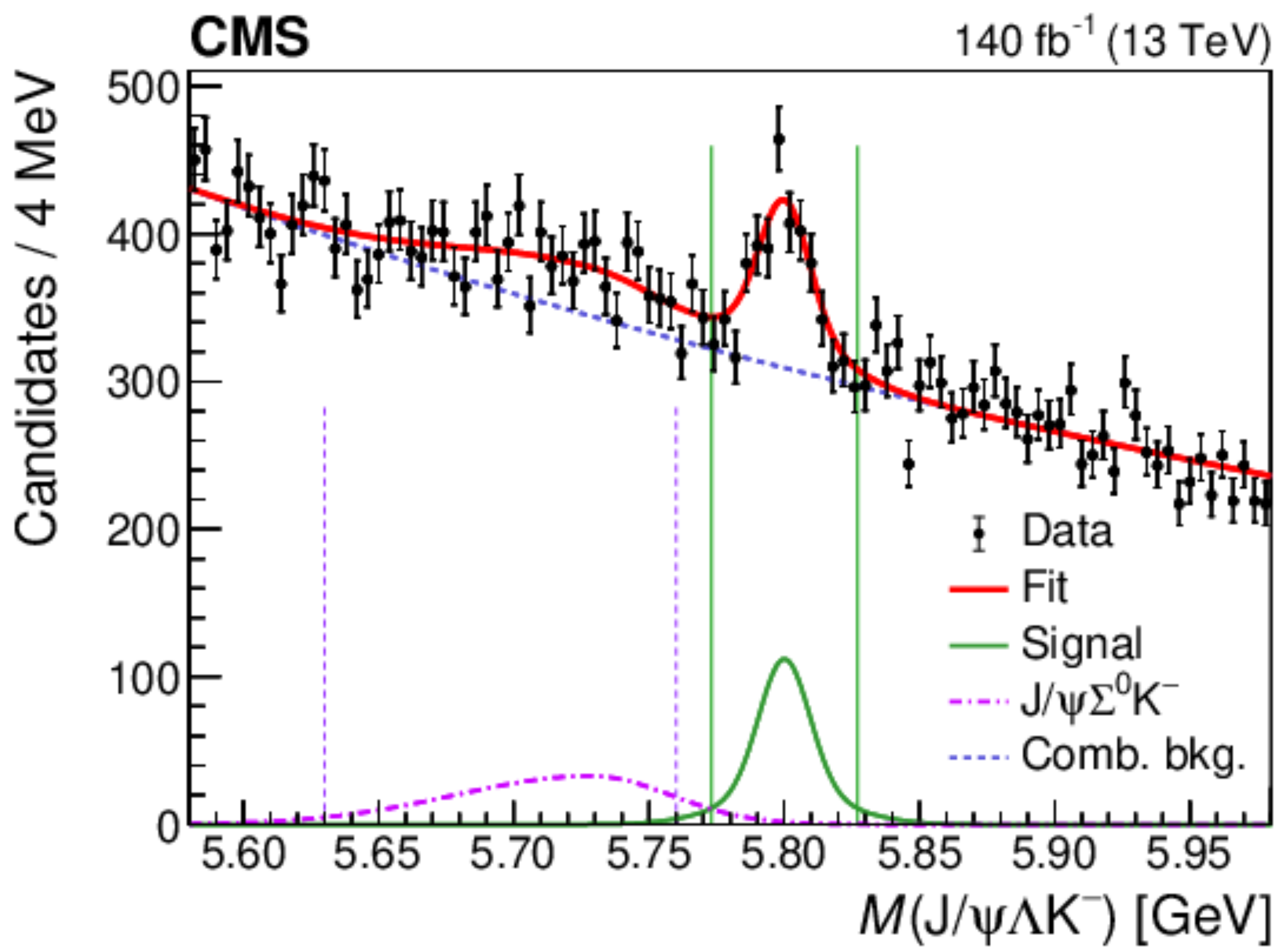
2 decay channels of the ground state considered: $\Xi_b^- \to J/\psi\, \Xi^-$ + $\Xi_b^- \to J/\psi\, \Lambda K^-$

also including $\Xi_b^- \to J/\psi\, \Sigma^0 K^- \to J/\psi\, \Lambda\, \gamma\, K^-$ undetected (too soft)

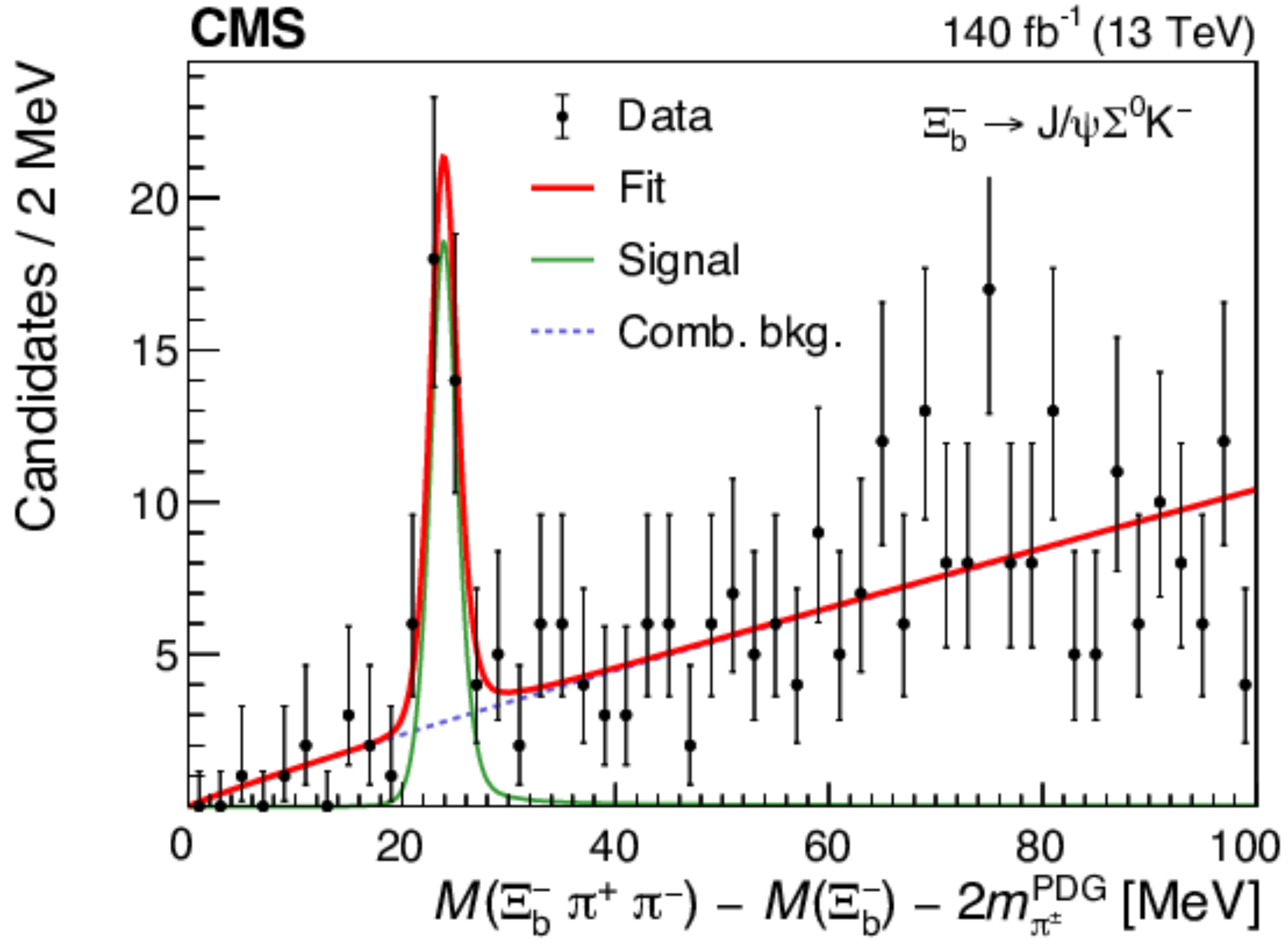
like in the LHCb measurement
[Phys. Lett. B 772 (2017) 265]

Reconstructing Λ/Ξ^- candidates: within ±10/9.5 MeV from the PDG value





+ $\pi^+ \pi^-$



$M = 6100.3 \pm 0.2^{stat} \pm 0.1^{syst} \pm 0.6^{\Xi_b^-}$ MeV with stat. significance: 6.2σ

Decay sequence suggests that it is a beauty partner of Ξ_c^-

$\Delta M = 24.14 \pm 0.22^{stat}$ MeV

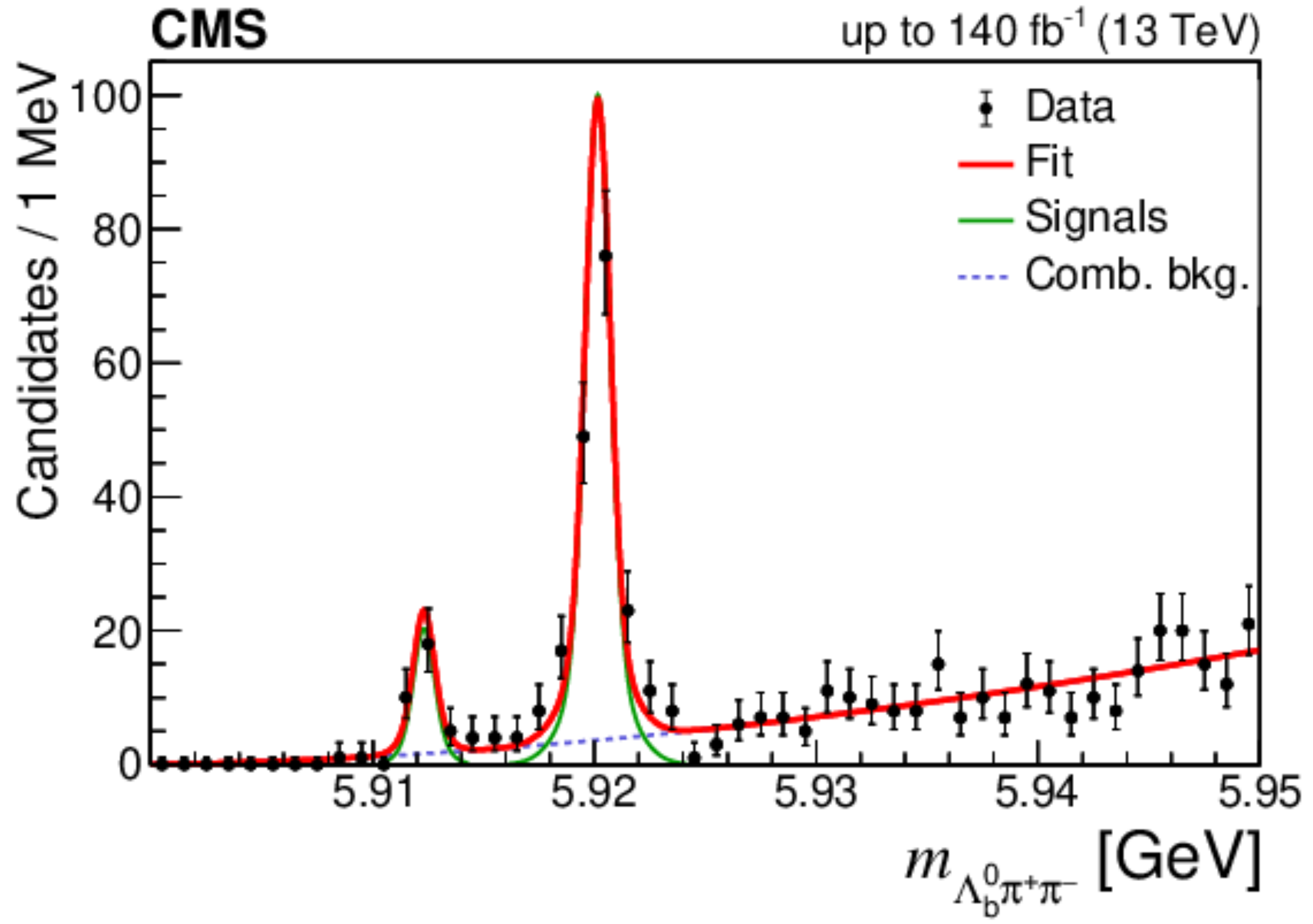
↳ insensitive to the lost γ

Excited $\Lambda_b^0 \to \Lambda_b^0 \pi^+ \pi^-$

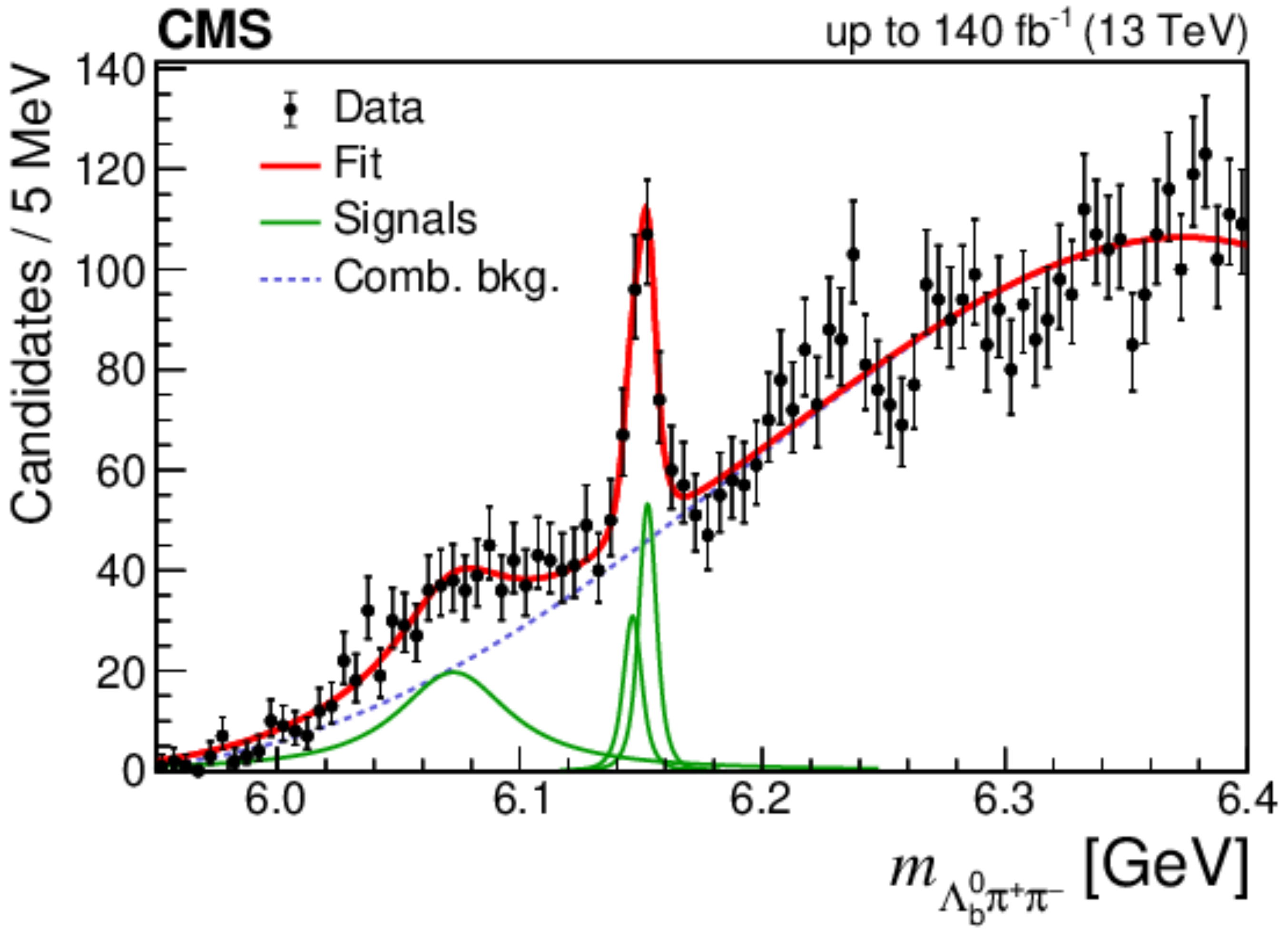
Using the same data to search for an excited Λ_b^0 state in the range $5.9 \leq m \leq 6.4$ GeV

2 narrow states near the kinematic threshold observed by LHCb in 2012 + 2 higher-mass states in 2019

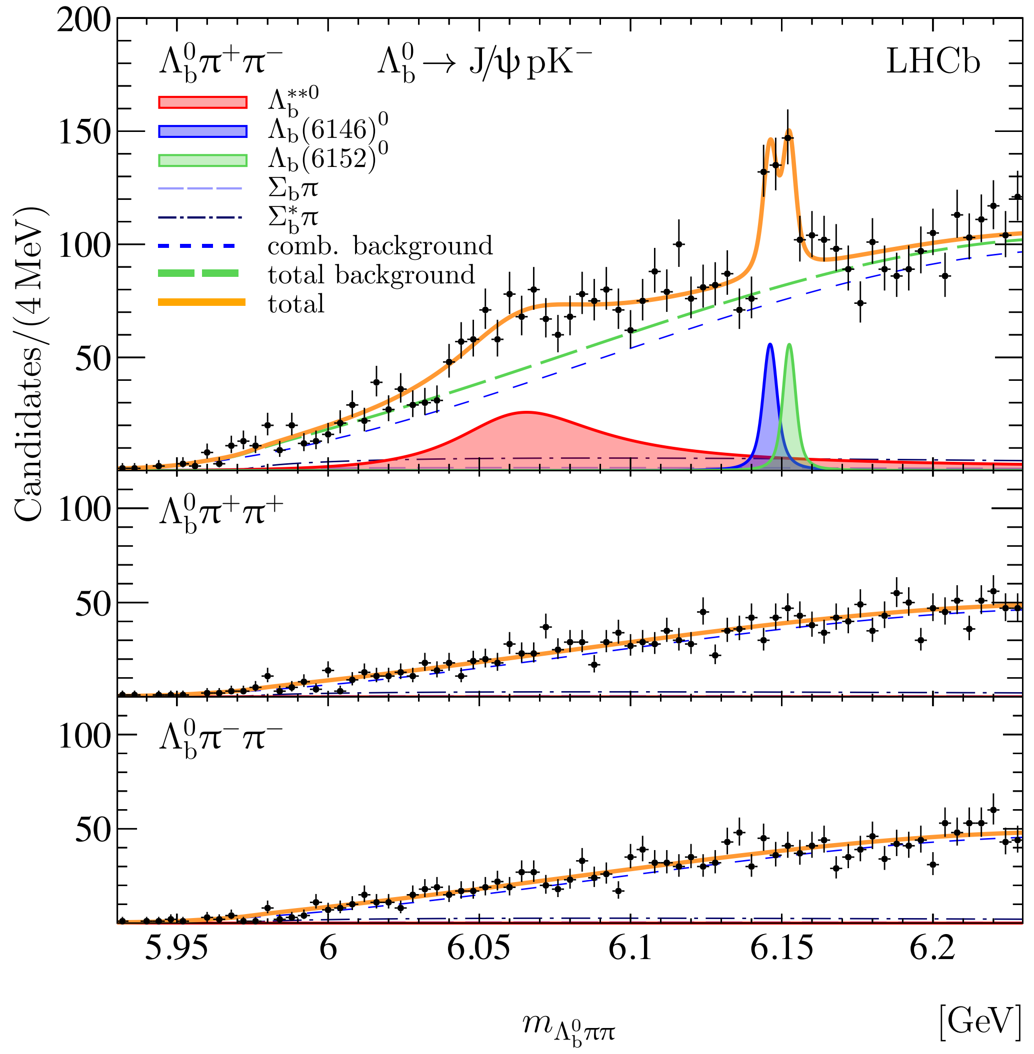
2 decay channels of the ground state considered: $\Lambda_b^0 \to J/\psi\, \Lambda^0$ + $\Lambda_b^0 \to \psi(2S)\, \Lambda^0$



$$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\mathrm{MeV}$$
$$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\,\mathrm{MeV}$$



$$M(\Lambda_b(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\mathrm{MeV}$$
$$M(\Lambda_b(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\mathrm{MeV}$$



- $J/\psi \to \mu^+\mu^-$
- $\psi(2S) \to \mu^+\mu^-$
- $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$
- $\Lambda^0 \to p\pi^-$

final states

+ 2 opposite sign $\pi^\pm$
$p_T > 0.35$ GeV

+ new broad resonance at 6073 ± 5^{stat} MeV later confirmed by LHCb

Masses of the observed resonances consistent with the results from LHCb

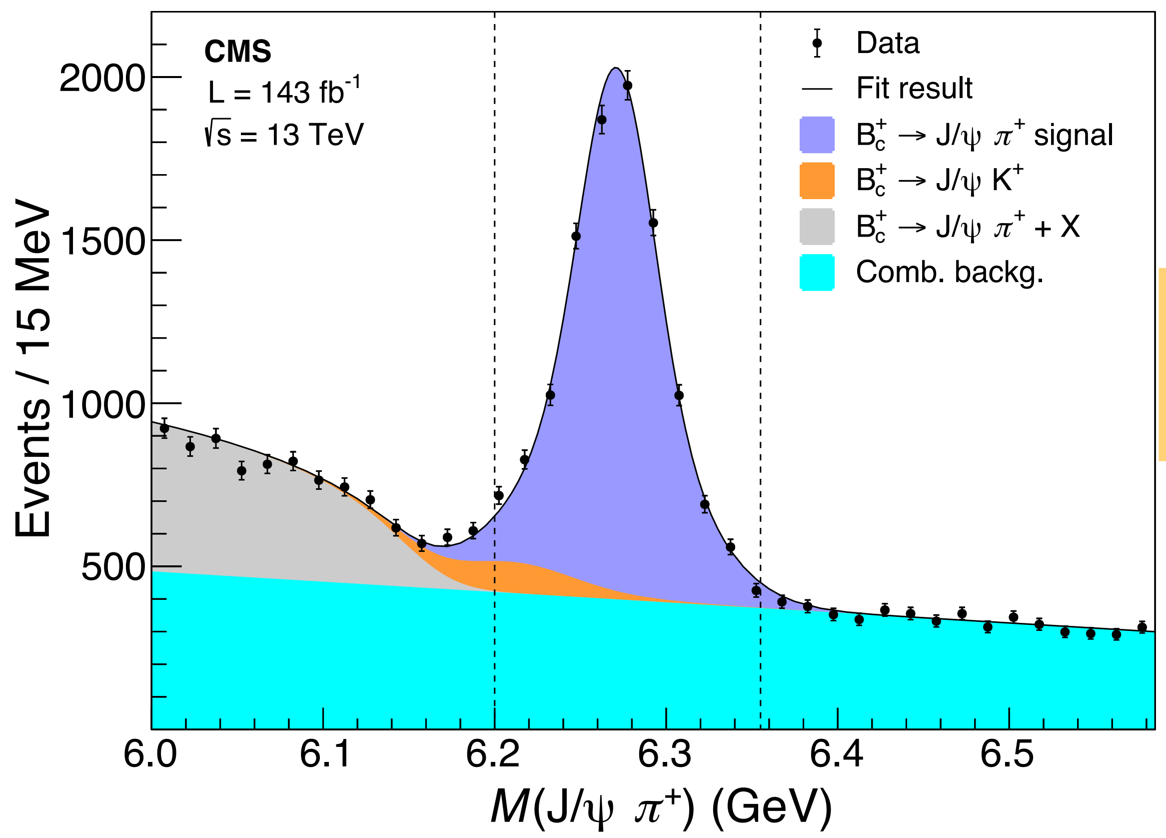
$B_c(2S)^+$ + $B_c^*(2S)^+$ cross-section ratios

Phys. Rev. D **102** (2020) 092007

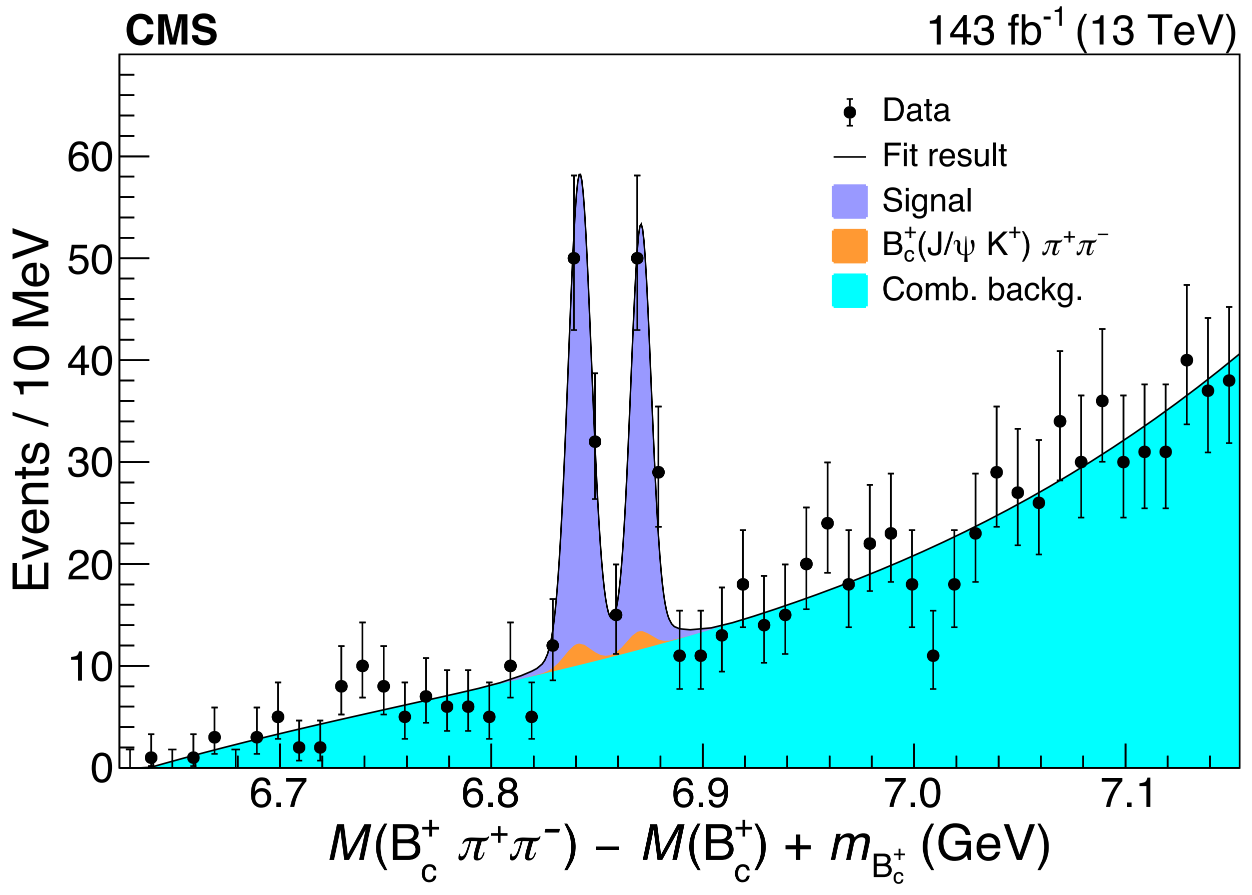
Measuring cross-section ratios of $B_c(2S)^+/B_c^+$ + $B_c^*(2S)^+/B_c^+$ with the same dataset (143 fb^{-1} at $\sqrt{s}$ = 13 TeV)

The two $b\bar{c}$ excited states observed earlier by CMS ▶
decaying through cascades of γ and $\pi^+\pi^-$: $\Gamma \sim O(100\ \text{KeV})$

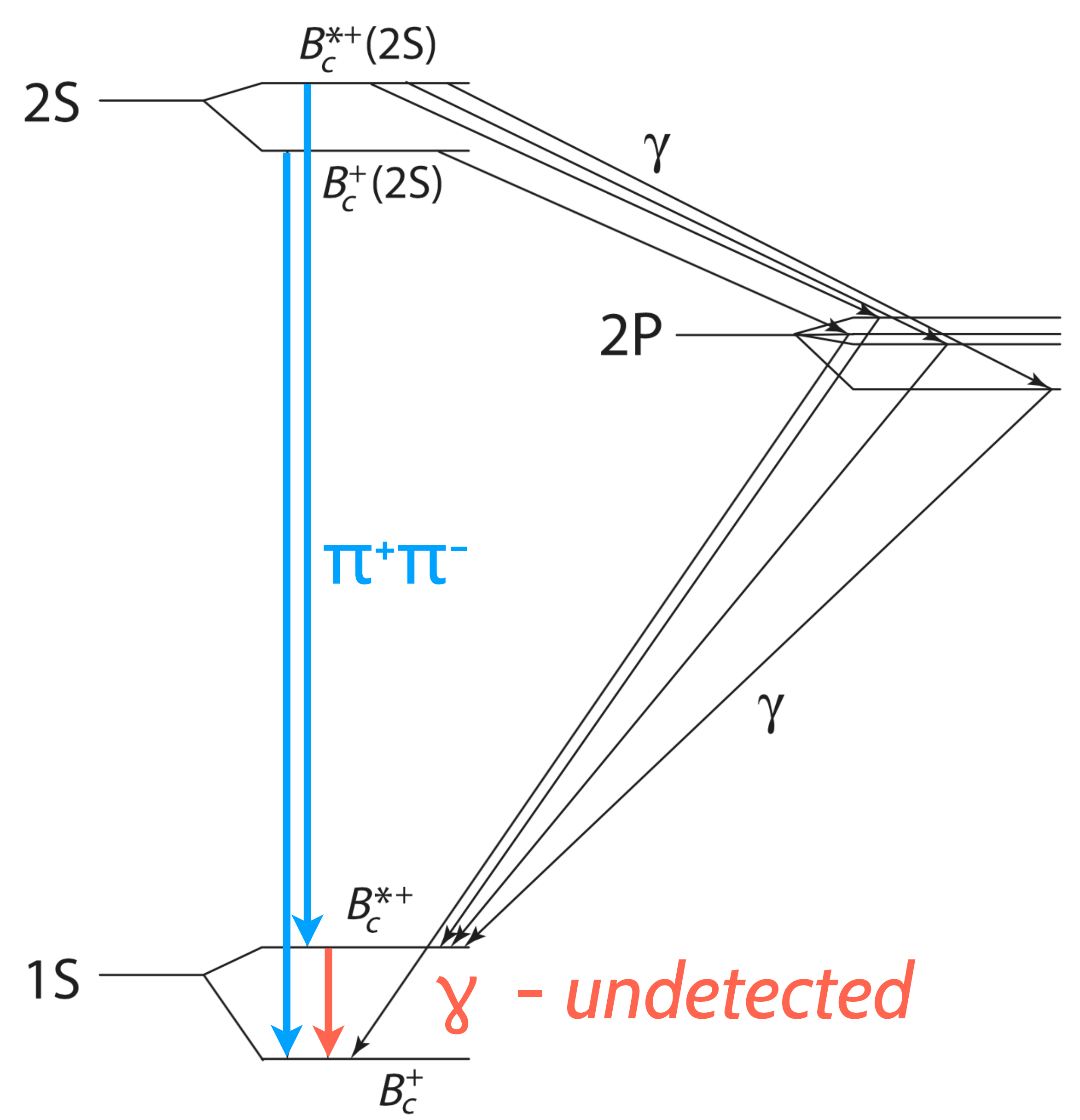
B_c^+ phase space: $p_T > 15$ GeV $|y| < 2.4$



+ $\pi^+\pi^-$



PRL **122** (2019) 132001



- $B_c(2S)^+ \to B_c^+ \pi^+\pi^-$
- $B_c^*(2S)^+ \to B_c^{*+} \pi^+\pi^-$
- $B_c^+ \to J/\psi\ \pi^+$
- $J/\psi \to \mu^+\mu^-$

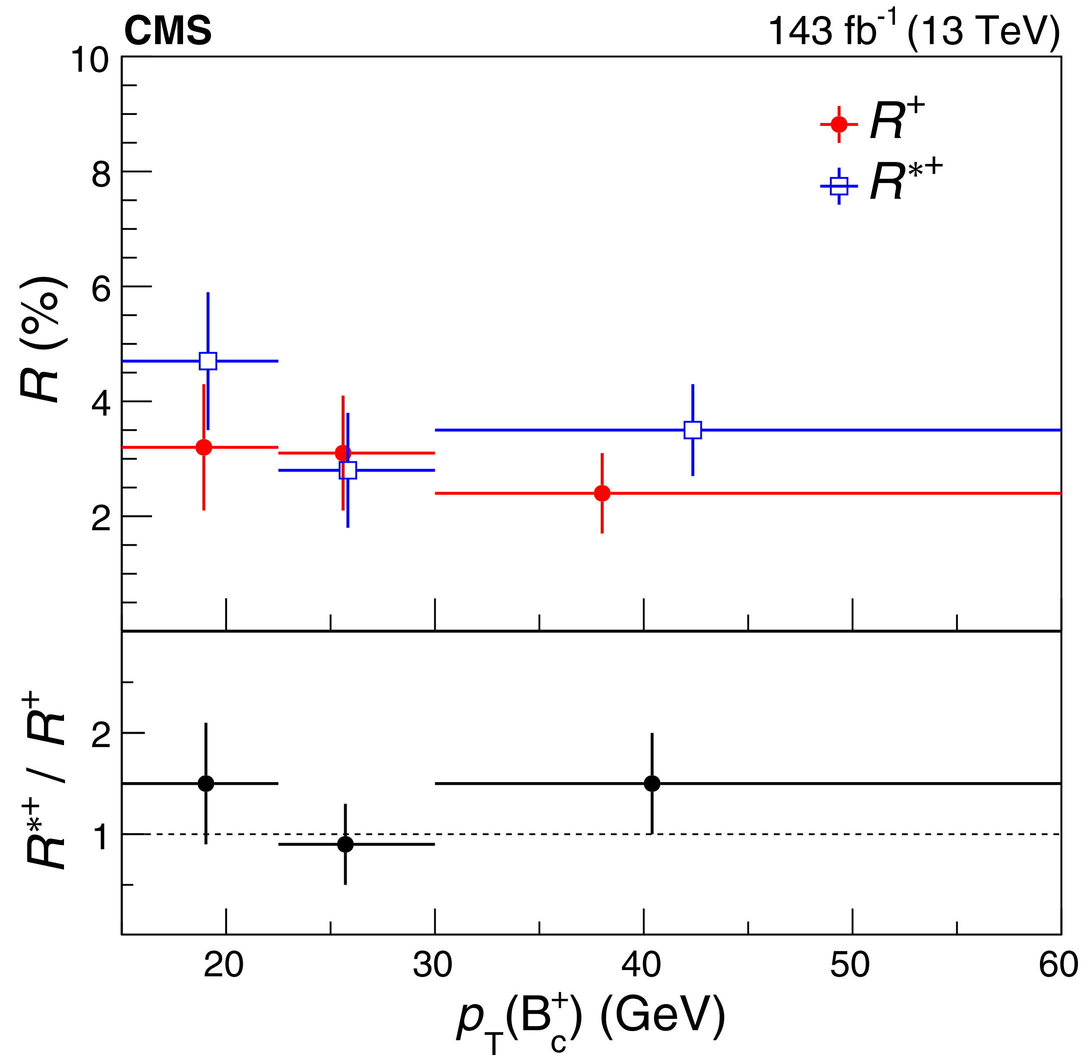
final states

Reconstruction efficiencies evaluated with MC simulations to calculate the ratios
(common $J/\psi \to \mu^+\mu^-$ trigger efficiency cancels out)

$$R^+ \equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-) = \frac{N(B_c(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)}$$

$$R^{*+} \equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-) = \frac{N(B_c^*(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)}$$

$$R^+ = (3.47 \pm 0.63(\text{stat}) \pm 0.33(\text{syst}))\%$$
$$R^{*+} = (4.69 \pm 0.71(\text{stat}) \pm 0.56(\text{syst}))\%$$
$$R^{*+}/R^+ = 1.35 \pm 0.32(\text{stat}) \pm 0.09(\text{syst}).$$



Phys. Lett. B **808** (2020) 135578

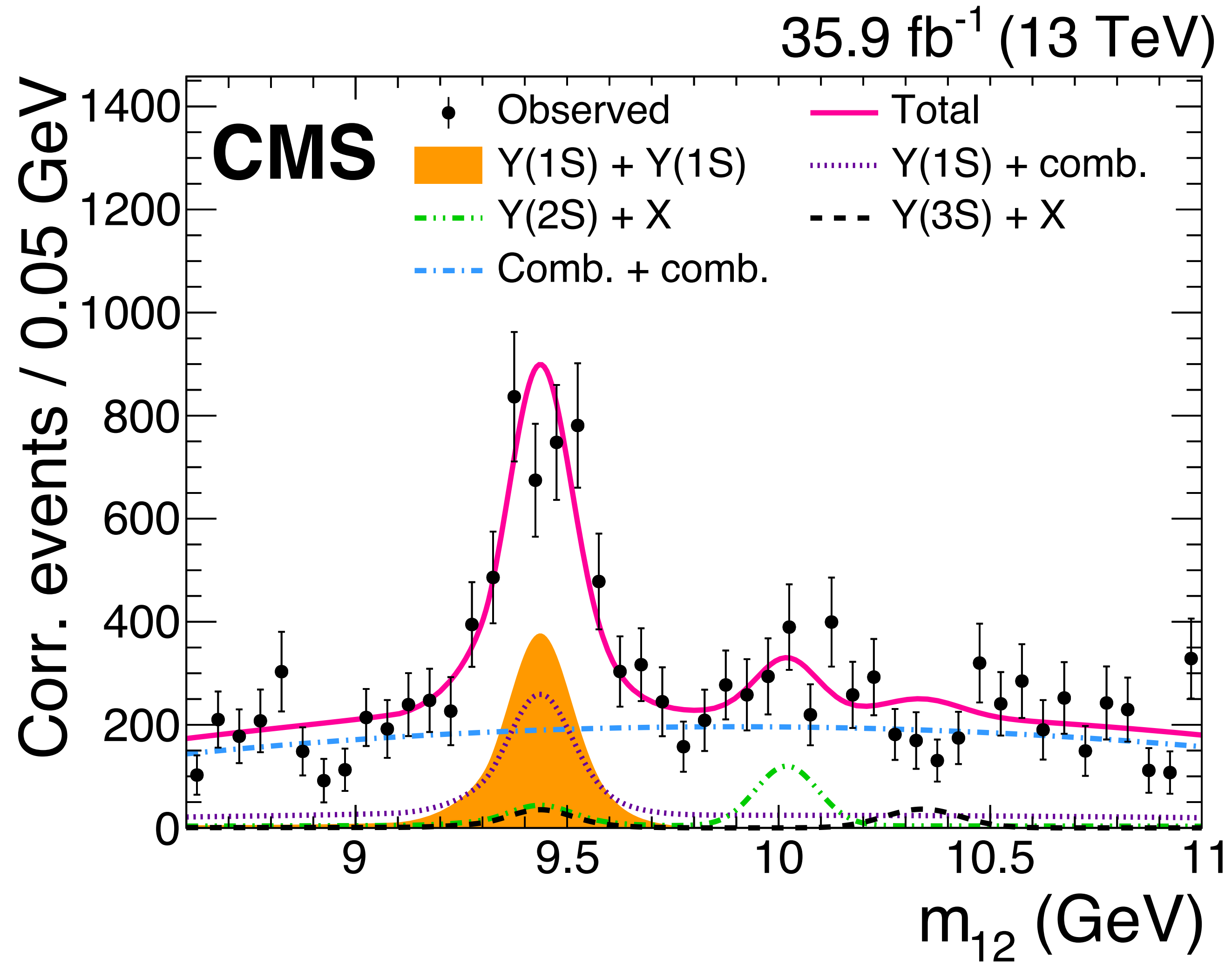
- ϒ(1S) → $\mu^+\mu^-$

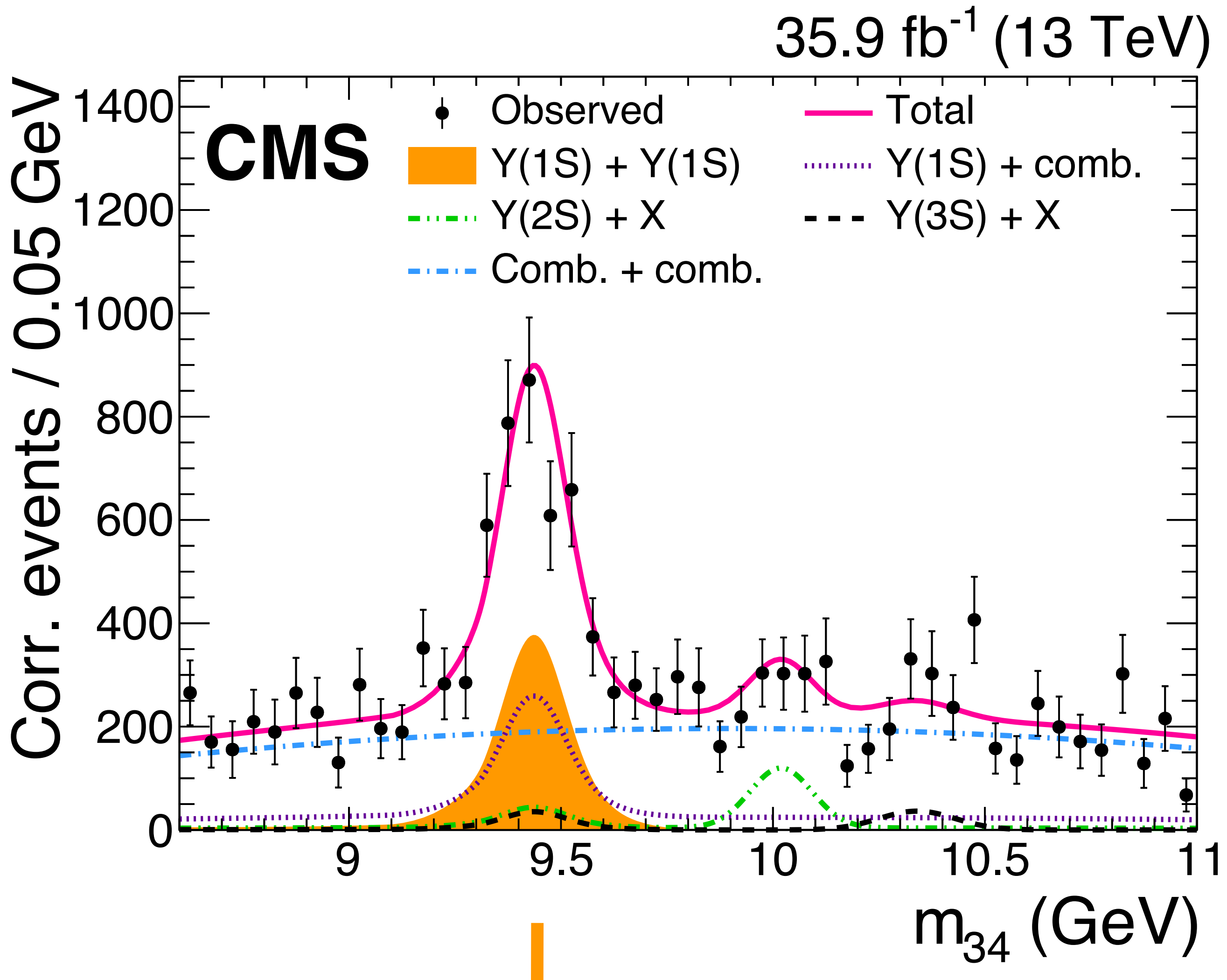
final states

Measuring cross-section of ϒ(1S) pair production in the fiducial region |y| < 2.0
with 4 muons in the final state: **BR(ϒ(1S) → $\mu^+\mu^-$)** = 2.48 ± 0.05 %

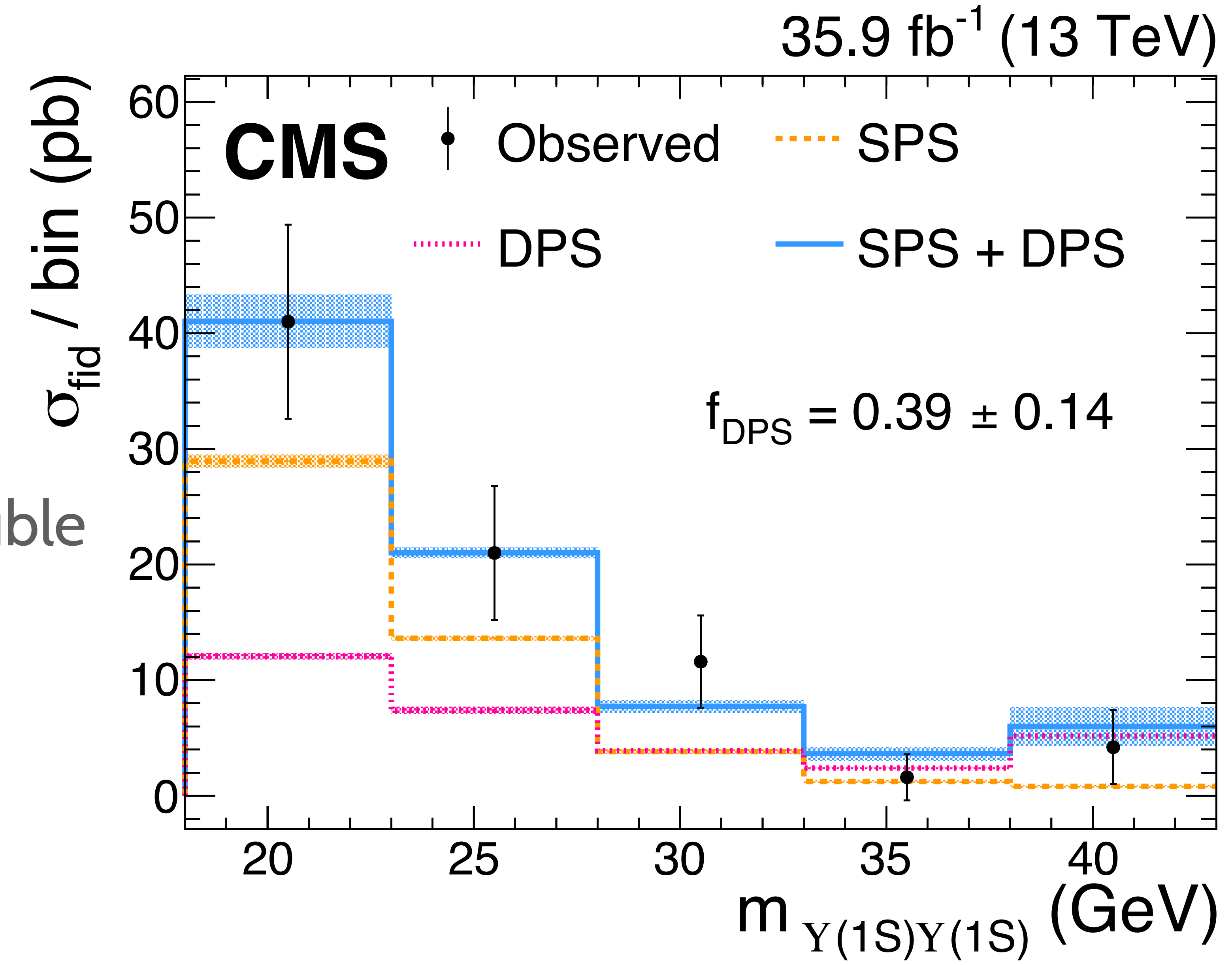
Using 35.9 fb^{-1} at √s = 13 TeV (2016) in the kinematic region not accessible to LHCb
following the previous observation by CMS at √s = 8 TeV ▶ JHEP **05** (2017) 013

Number of events extracted from the 2D unbinned maximum likelihood fit to the two $m_{\mu\mu}$ spectra
applying acceptance + efficiency corrections on event-by-event basis: 1740 ± 240 events





Single / Double Parton Scattering



$$\sigma_{\text{fid}} = 79 \pm 11\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(\mathcal{B})\;\;\text{pb}$$

+ *effect of polarisation [-60%; +25%]*

No statistically significant ϒ(1S)+ϒ(1S) resonance observed

Υ(nS) vs event activity

JHEP **2011** (2020) 001

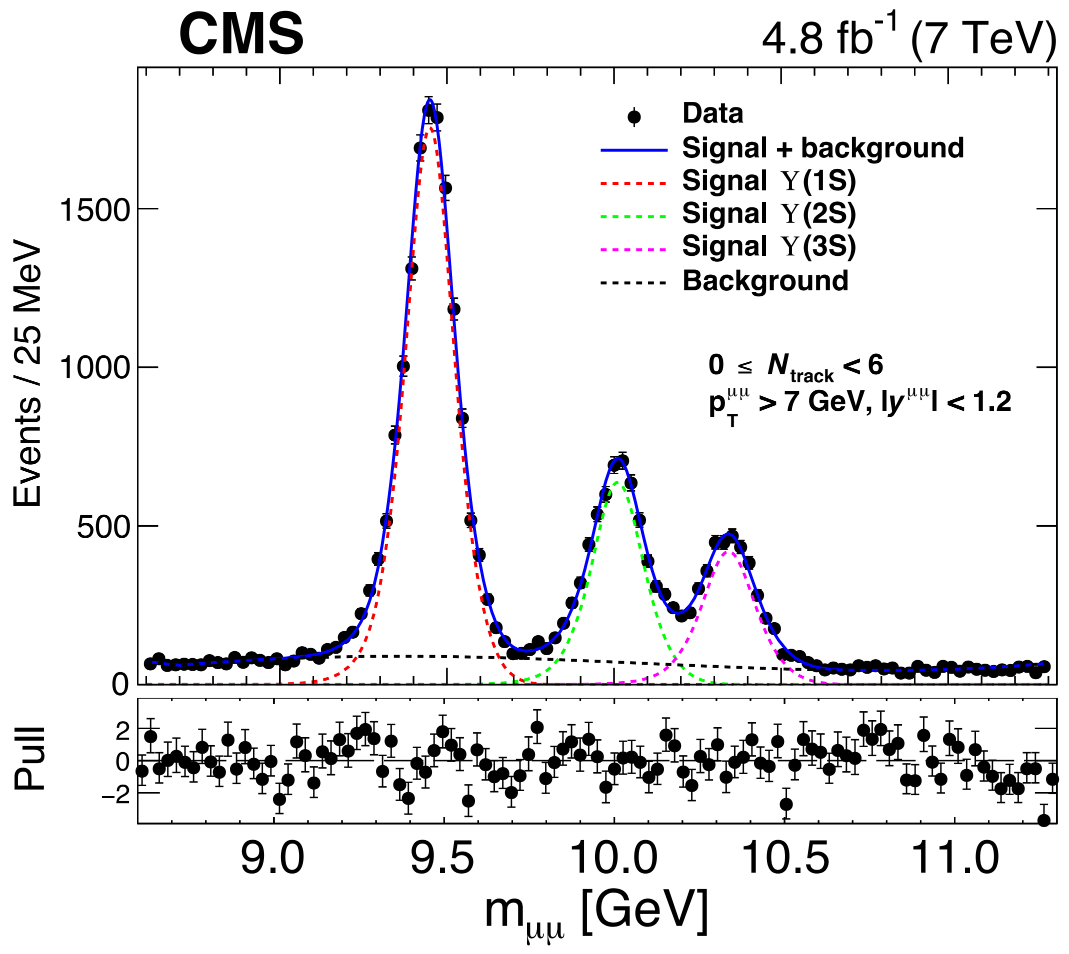
- Υ(nS) → $\mu^+\mu^-$

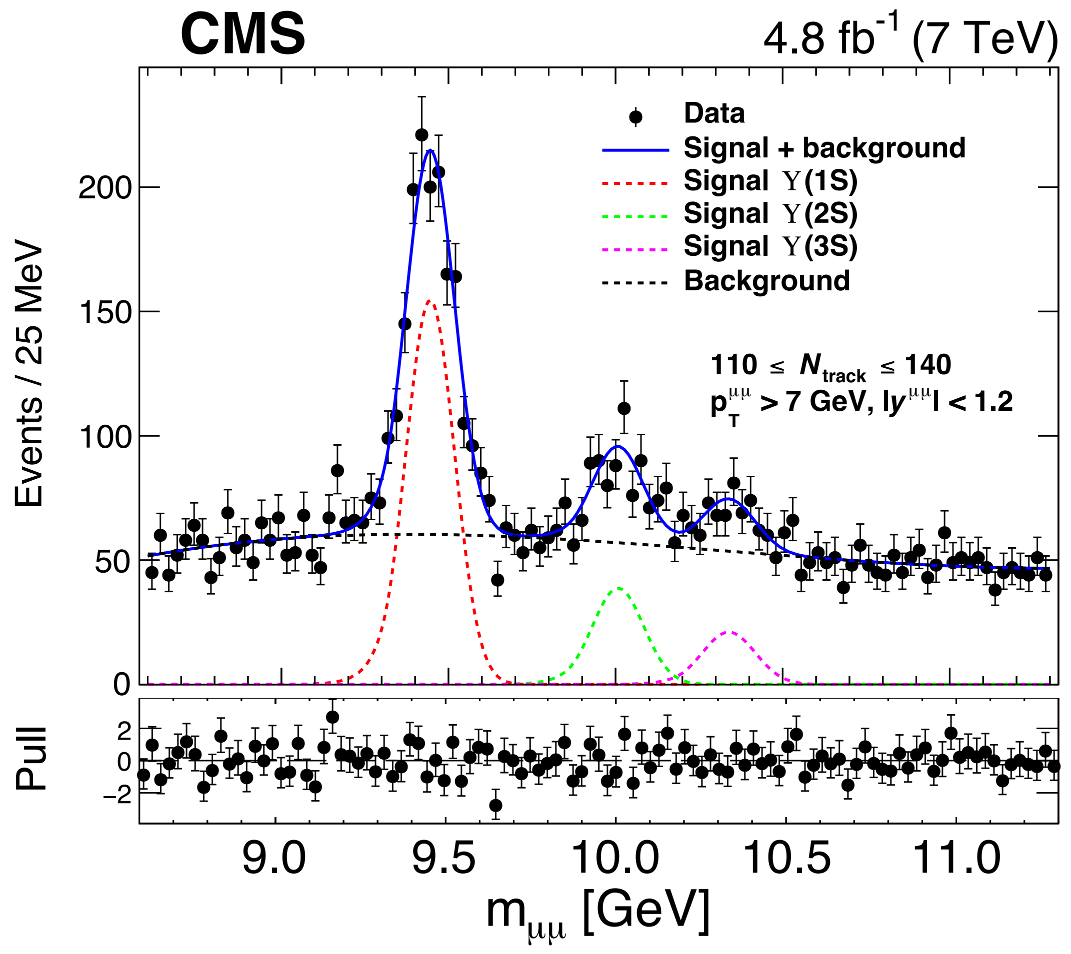
final states

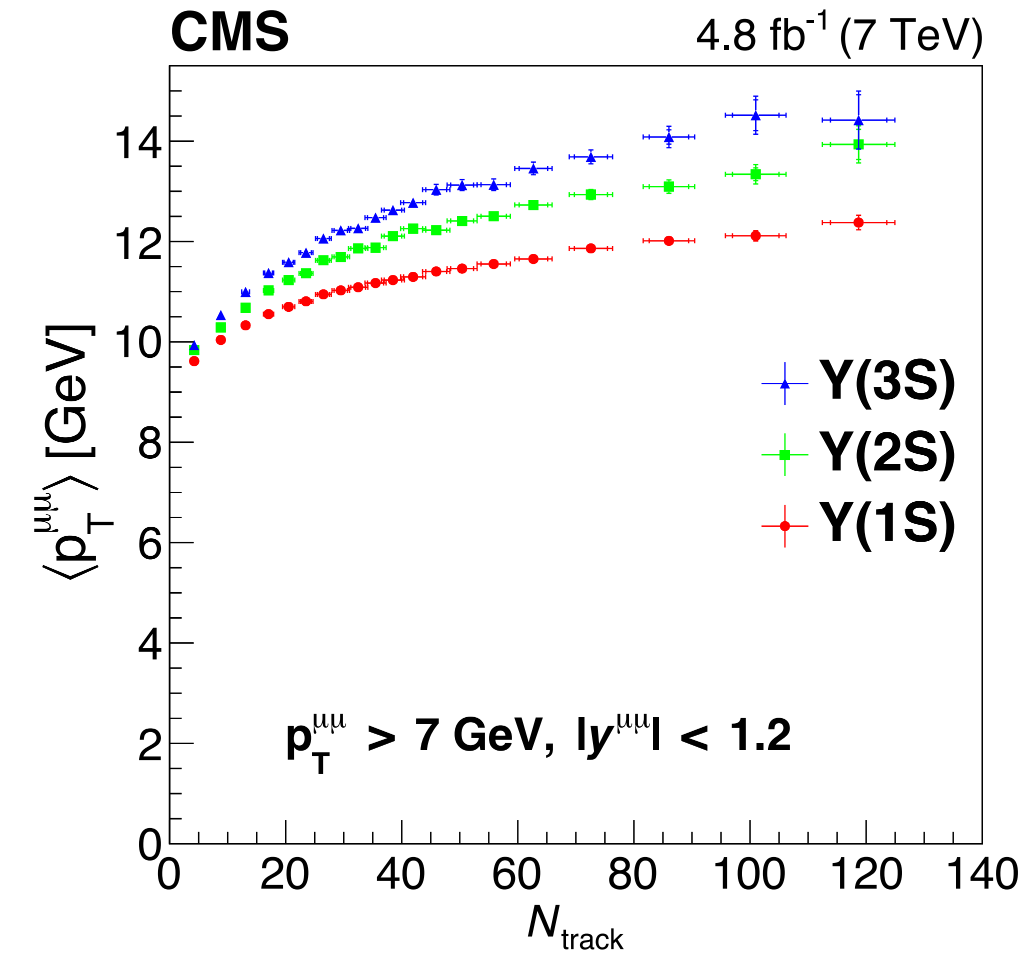
Investigating the effect of Underlying Event (UE) on the quarkonium production
e.g. fragmentation of soft gluons or decays of higher-mass states

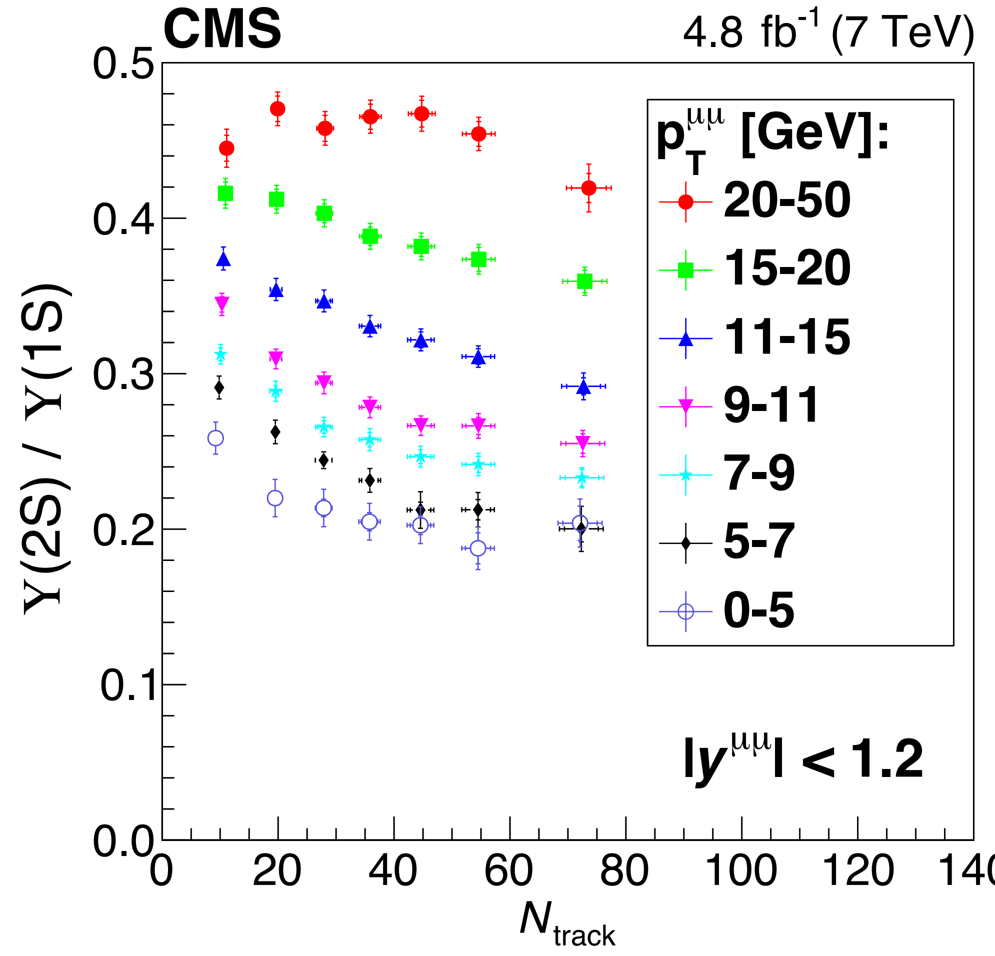
More apparent in heavy-ion collisions with very high particle density
↳ looking at quarkonium yields vs multiplicity of charged particles $p_T > 0.4$ GeV; $|\eta| < 2.4$

Using $\sqrt{s}$ = 7 TeV data (2011) with $|y_{\mu\mu}| < 1.2$ and increasing $p_T(\mu^+\mu^-)$ thresholds
0 GeV (0.3 fb^{-1}), **5 GeV** (1.9 fb^{-1}), **7 GeV** (4.8 fb^{-1}) due to the increasing luminosity







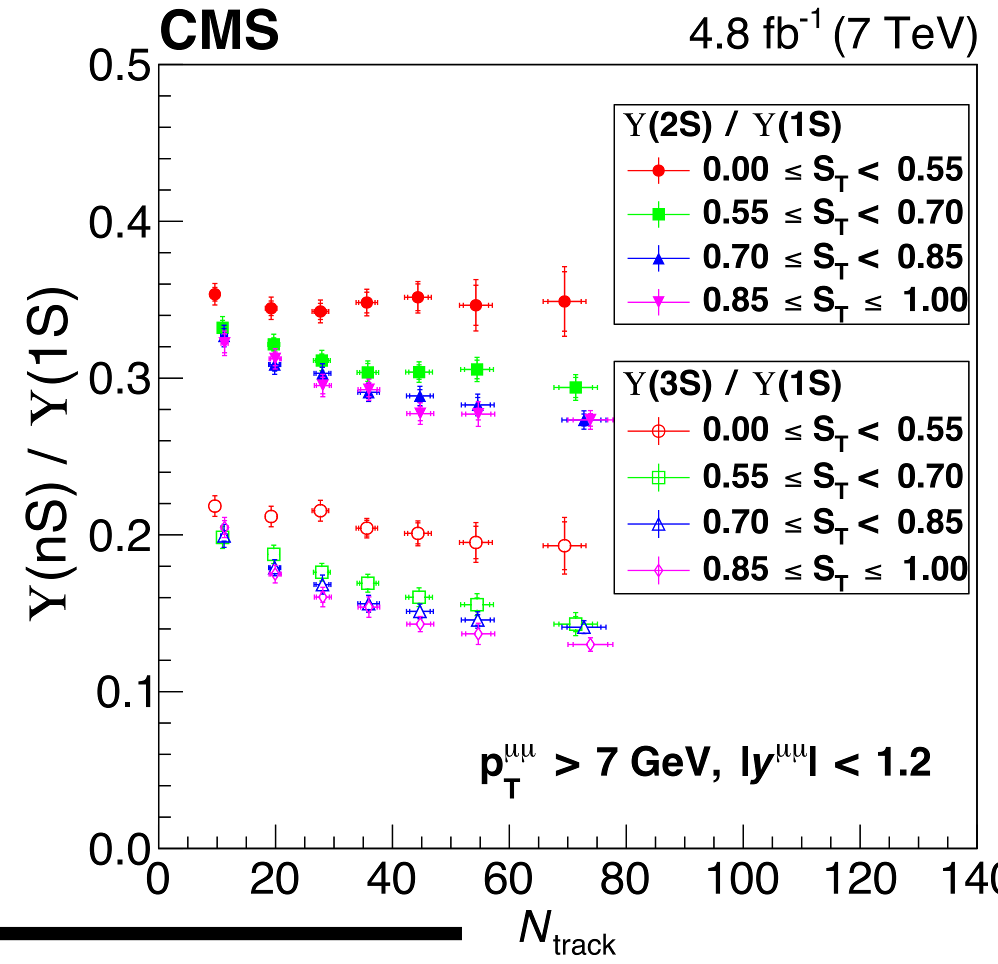


Confirmed previous observations in pp and p-Pb collisions

No multiplicity dependence in jet-like events: $0 < S_T < 0.55$
↳ UE likely responsible for the decrease in Υ(nS)/Υ(1S) ratios

+ sphericity dependence

$$S_{xy}^{T} = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$



Angular analysis of $B^+ \to K^{*+} \mu^+\mu^-$

- $K^{*+} \to K_S^0 \pi^+$
- $K_S^0 \to \pi^+\pi^-$

final states

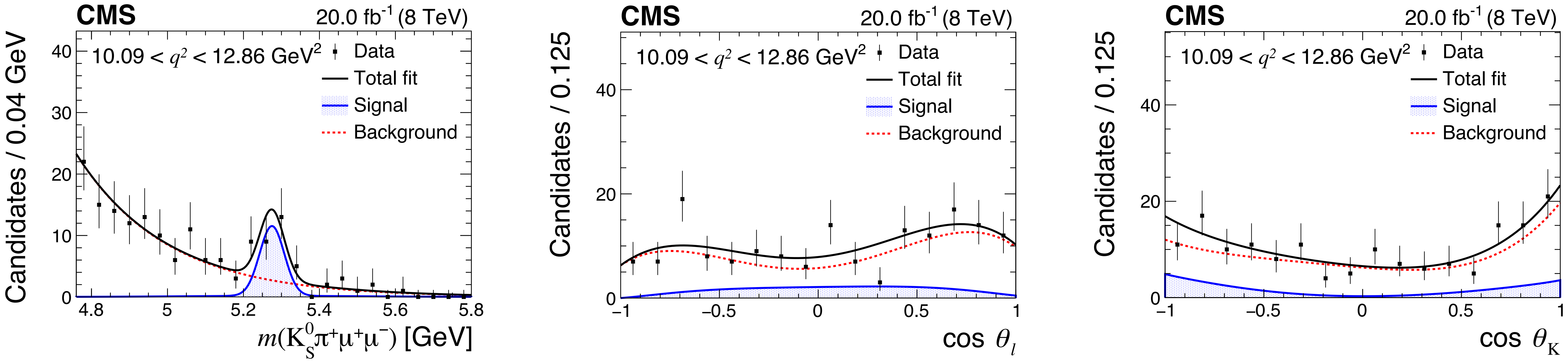
+ 2 × $\mu^\pm$ (OS)
$p_T > 3.5$ GeV

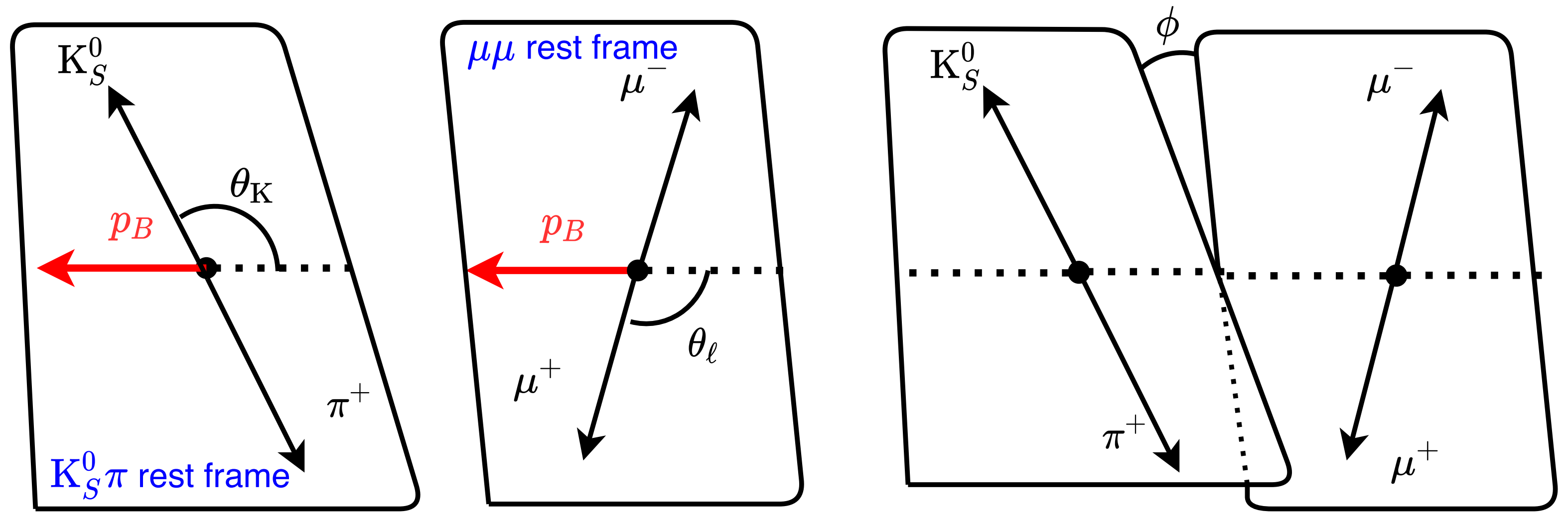
Good example of indirect search for New Physics: FCNC decay **b → s $\mu^+\mu^-$** in **$B^+ \to K^{*+} \mu^+\mu^-$**
↳ forbidden at tree level → loop-diagrams suppressed in SM, but enhanced in BSM models

Measuring forward-backward asymmetry (A_{FB}) + longitudinal polarisation (F_L)
using 20 fb^{-1} of pp collisions at $\sqrt{s}$ = 8 TeV

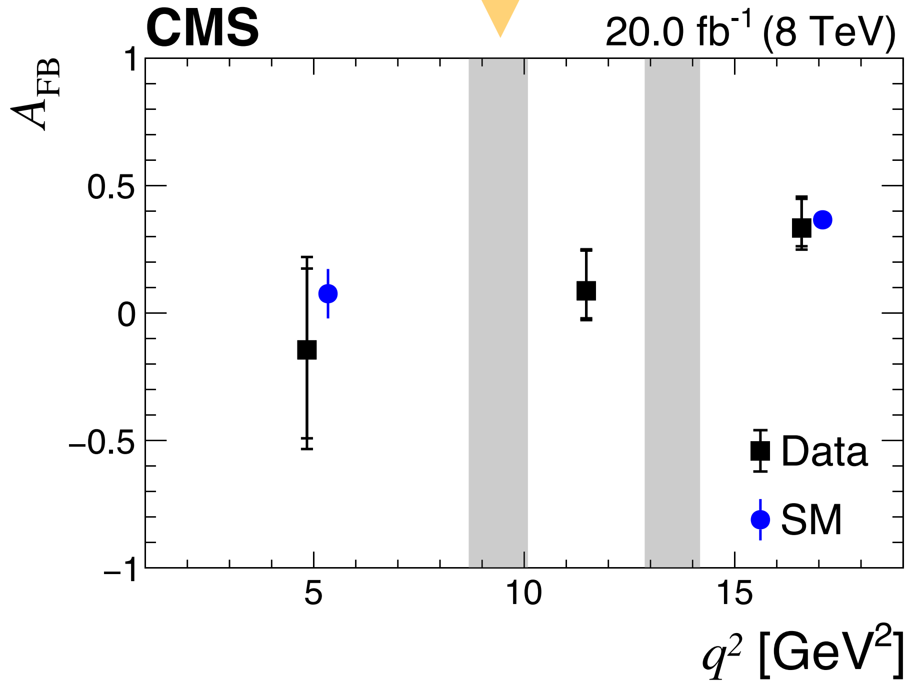
Suppressing charmonium contributions (J/ψ, ψ(2S)) by excluding bkg. rich q^2 regions
+ correlation of m and *q*
8.68 - 10.09 GeV² and 12.86 - 14.18 GeV²

Angular analysis performed in terms of three angles: θ_K | θ_L | ϕ
in three q^2 intervals: 1 - 8.68 GeV² | 10.09 - 12.86 GeV² | 14.18 - 19 GeV²

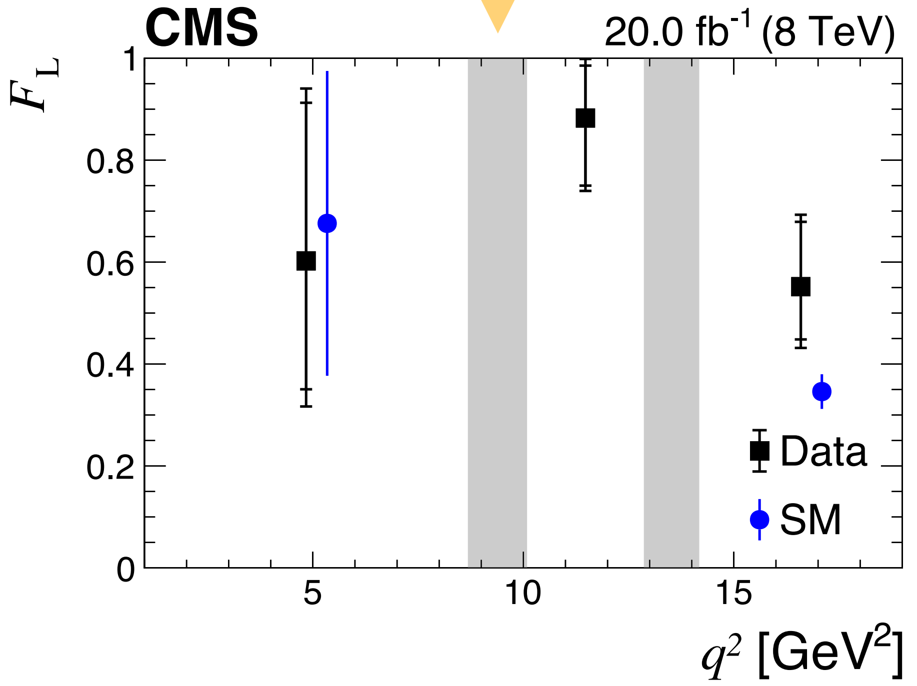




A_{FB}



F_L



↳ **3D maximum likelihood fit performed to extract A_{FB} and F_L**
all consistent with the Standard Model prediction so far

Summary

LHC provides a large phase space and high luminosity for studying heavy-flavour hadrons

CMS detector had very good tracking and muon-reconstruction capabilities
providing good sensitivity to a wide range of relevant final states

Great level of complementarity with other LHC experiments: LHCb, ALICE, ATLAS
exploring different kinematic regions, particle-density levels, etc.

Gradually reaching the level where factorisation approach is challenged
with universal fragmentation functions not being valid any more

Many recent measurements limited by statistics
expecting significant improvements in the future → HL-LHC

Many interesting things to study and to look forward in the Heavy-Flavour sector
for both experimentalists and theorists