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# Heavy-flavour production results with CMS

The latest of **8TeV** and **13TeV** results

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# Outline

- Motivation for heavy-flavour measurements
- Experimental setup
- Overview of the latest results by CMS:

1. **$B^+$ hadron production cross sections** 13 TeV
   CMS-PAS-BPH-15-004
2. **Quarkonium production cross sections** 13 TeV
   CMS-PAS-BPH-15-005
3. **Observation of Υ(1S) pair production** 8 TeV
   CMS-PAS-BPH-14-008

# Motivation

## Heavy-flavour production is an important process to study.

In view of the Standard Model measurements:

- advancements in b/c-hadron spectroscopy
- verification of *pQCD* and *effective field theory* predictions

In view of BSM searches:

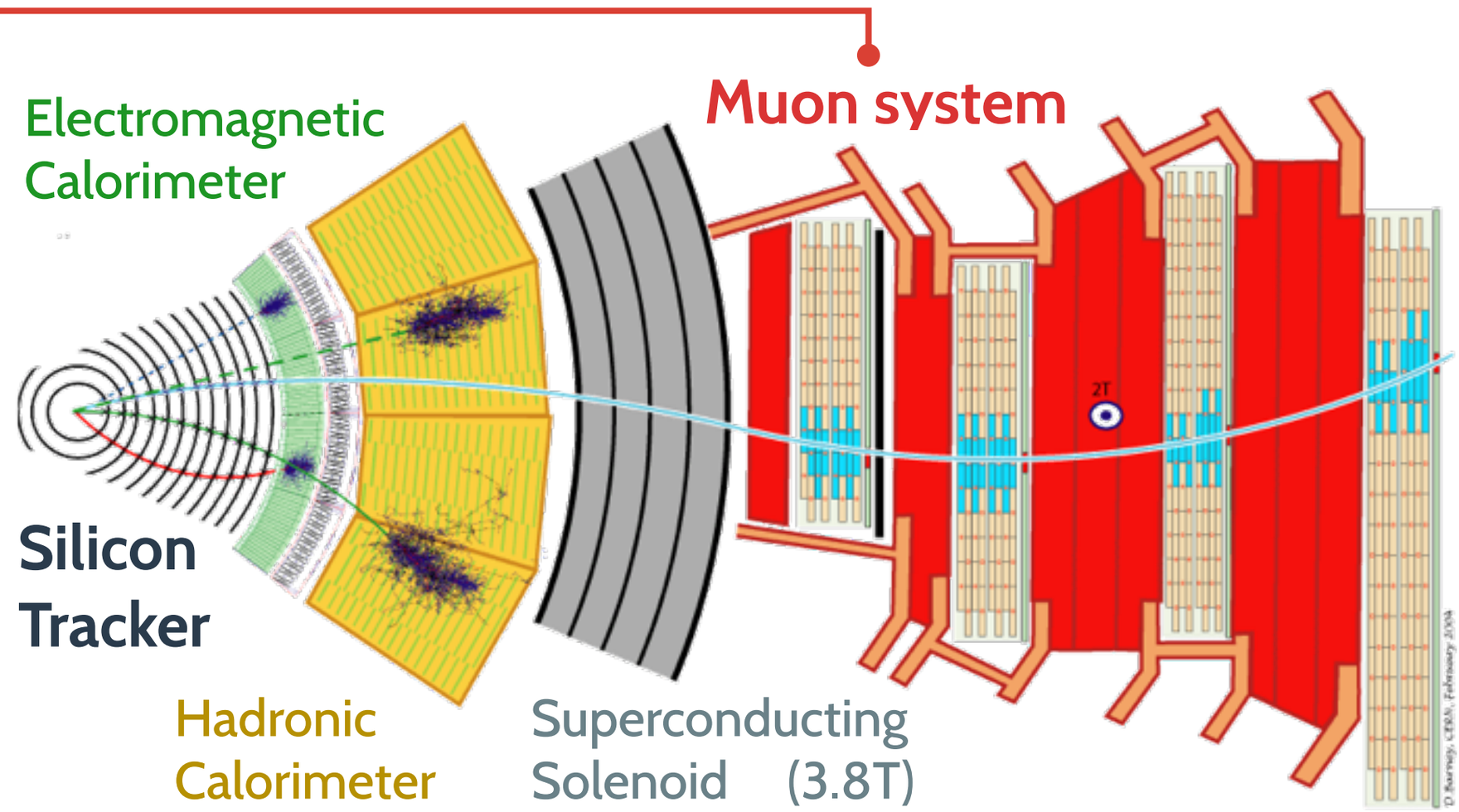
- CP-violation studies
- probing/constraining *new physics* scenarios

# Experimental setup: CMS

**Compact Muon Solenoid:** perfect detector for measuring muons

**Muons** – main experimentally measured signature in HF physics

Combination of subdetectors to identify + measure **muon properties**




$|\eta| < 2.4$

$\sigma_{\mu\mu}$: 0.6% - 1.5%

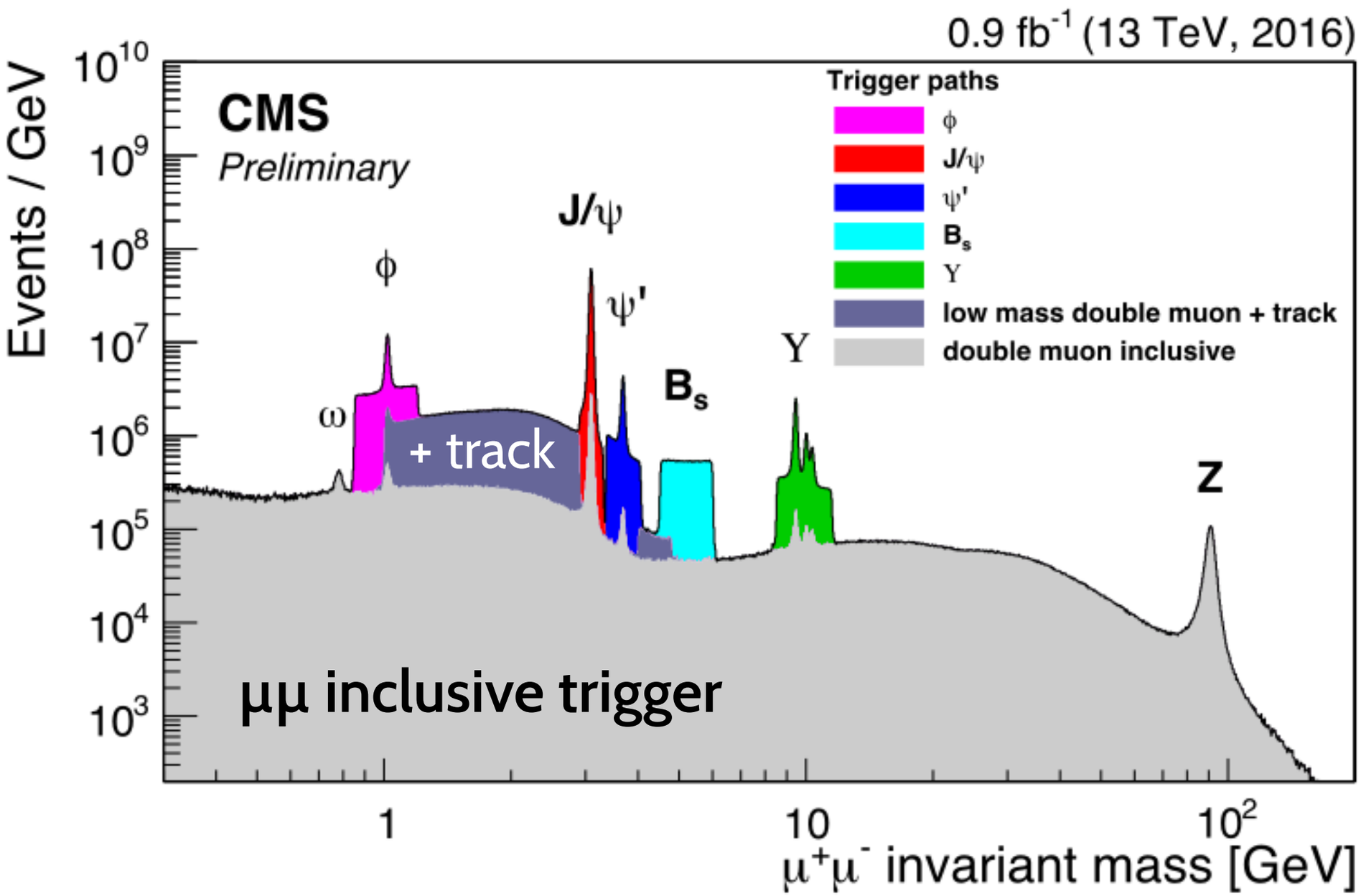
**Run1 data:** ~ 20.7 $fb^{-1}$

**Run2 data:** varies among analyses

# Experimental setup: triggers

**Dedicated triggers:** optimised for different analyses

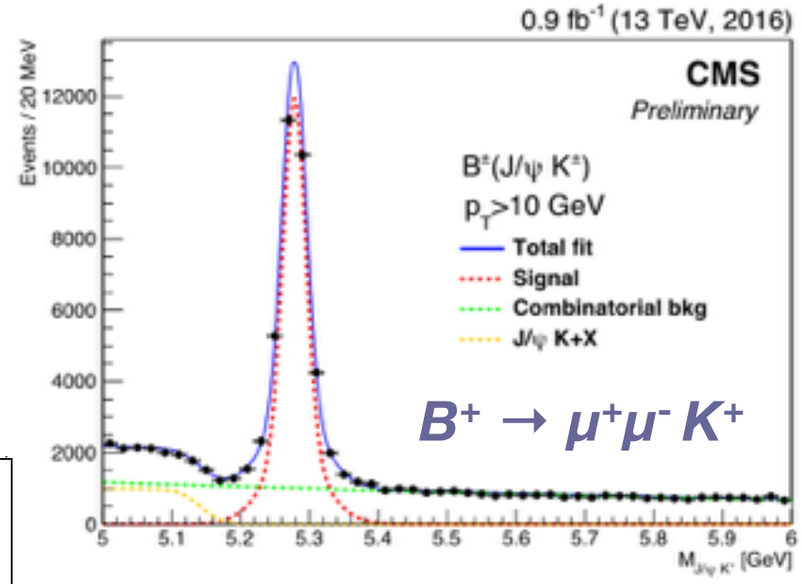
CERN-CMS-DP-2016-016

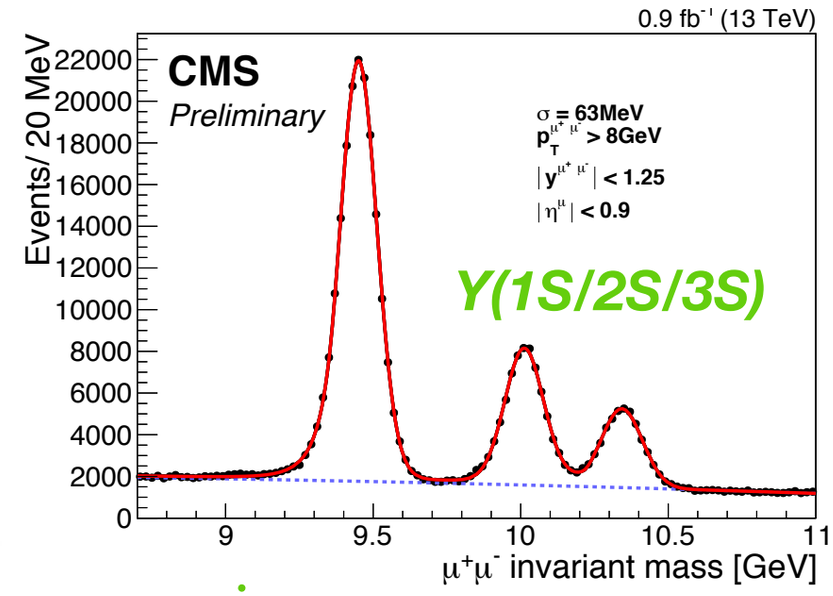


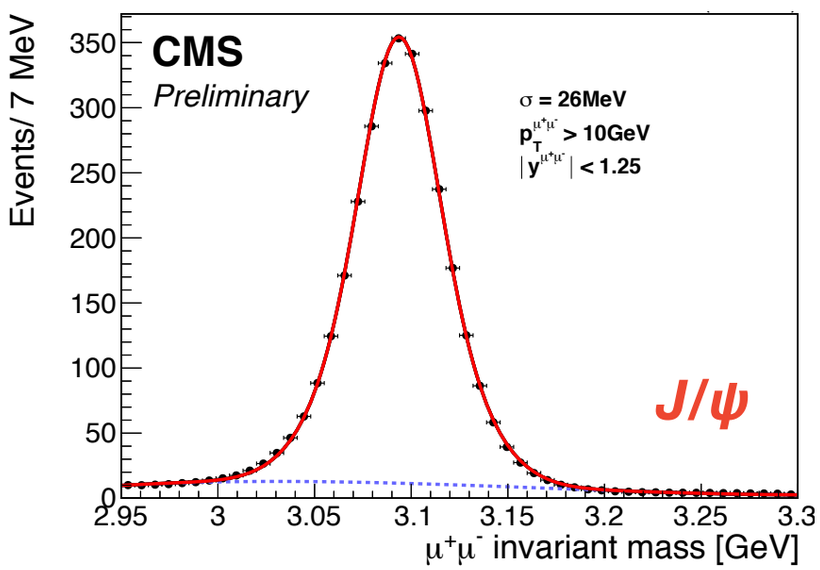
# Experimental setup: resonant peaks

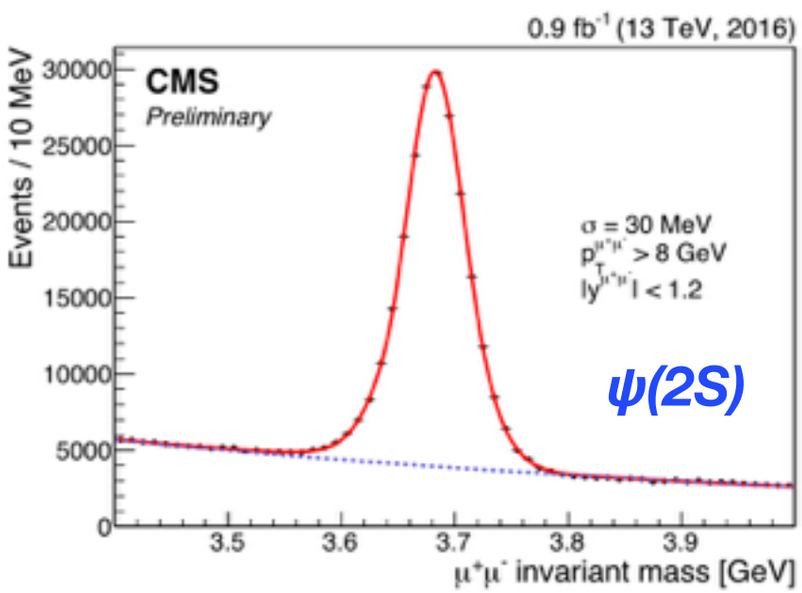
## Using 2016 data

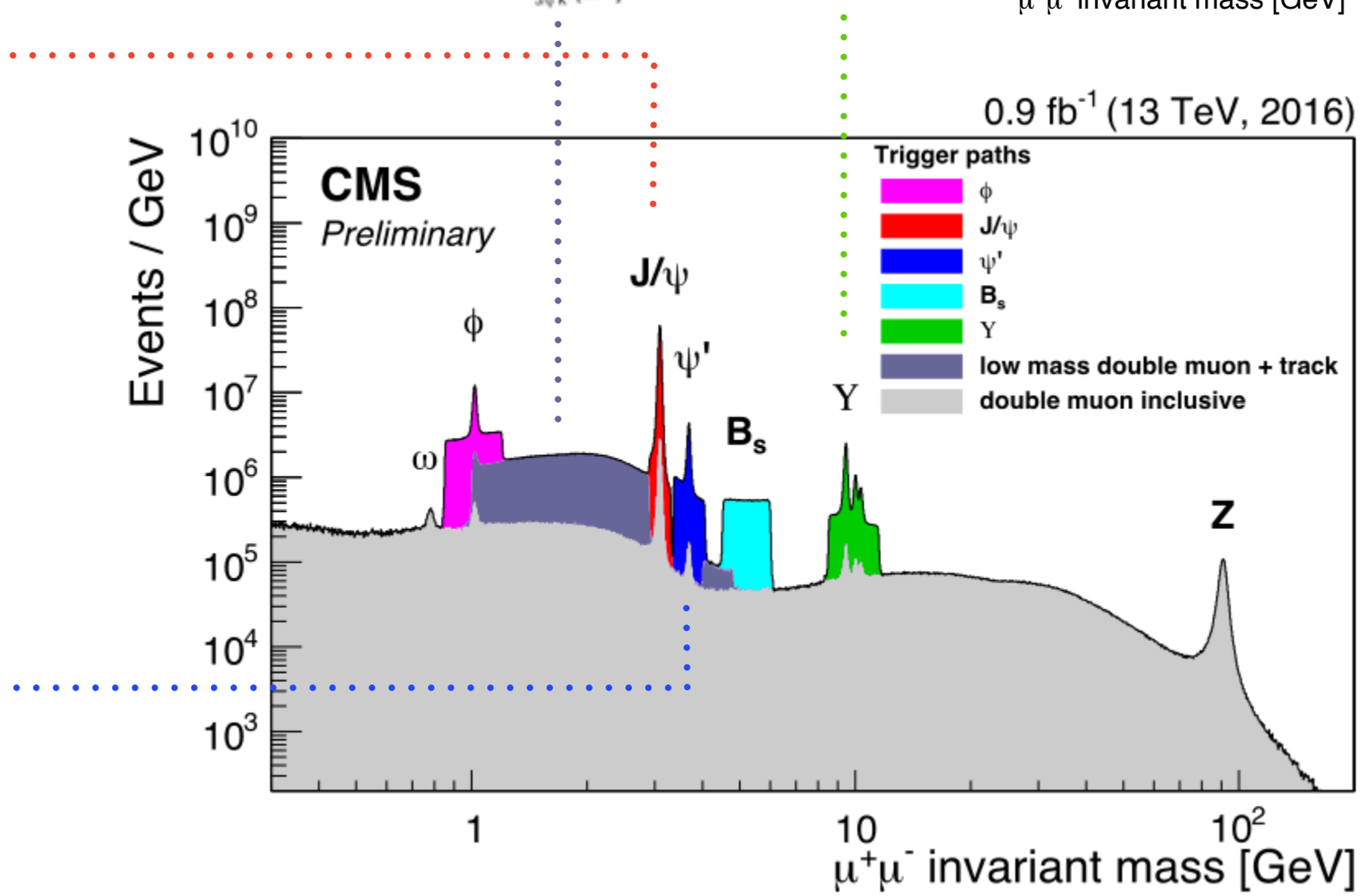
CERN-CMS-DP-2016-016



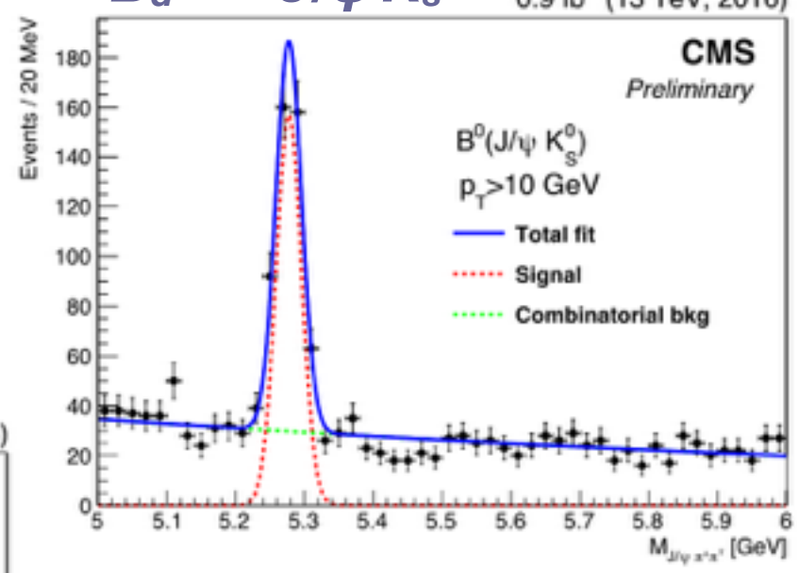



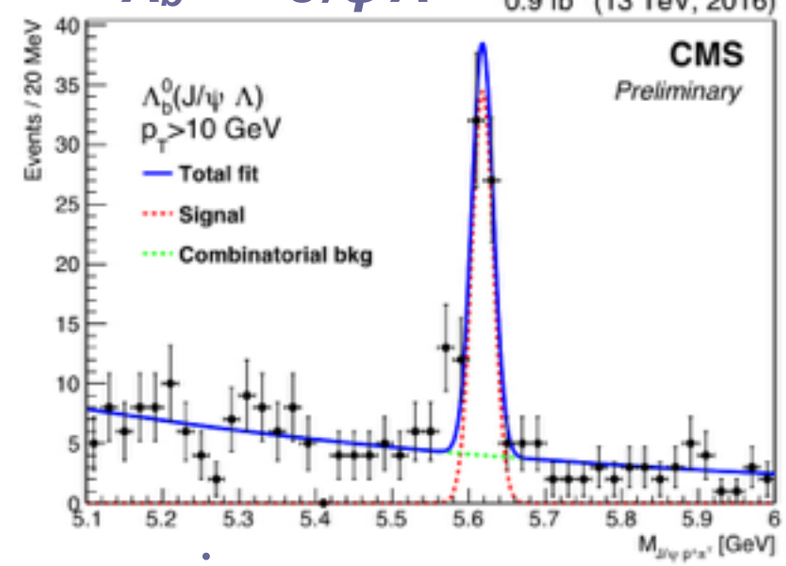
# Experimental setup: resonant peaks

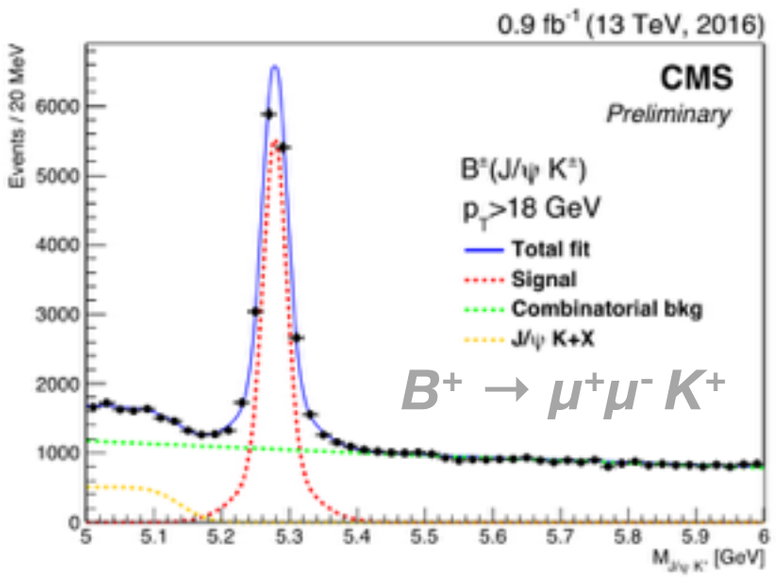
**Using 2016 data**
CERN-CMS-DP-2016-016

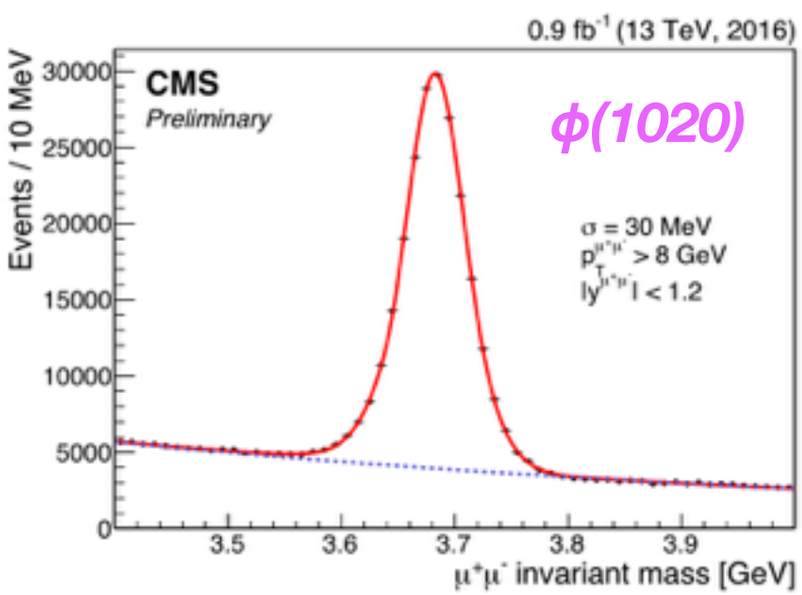
$B_d^0 \to J/\psi K_s^0$

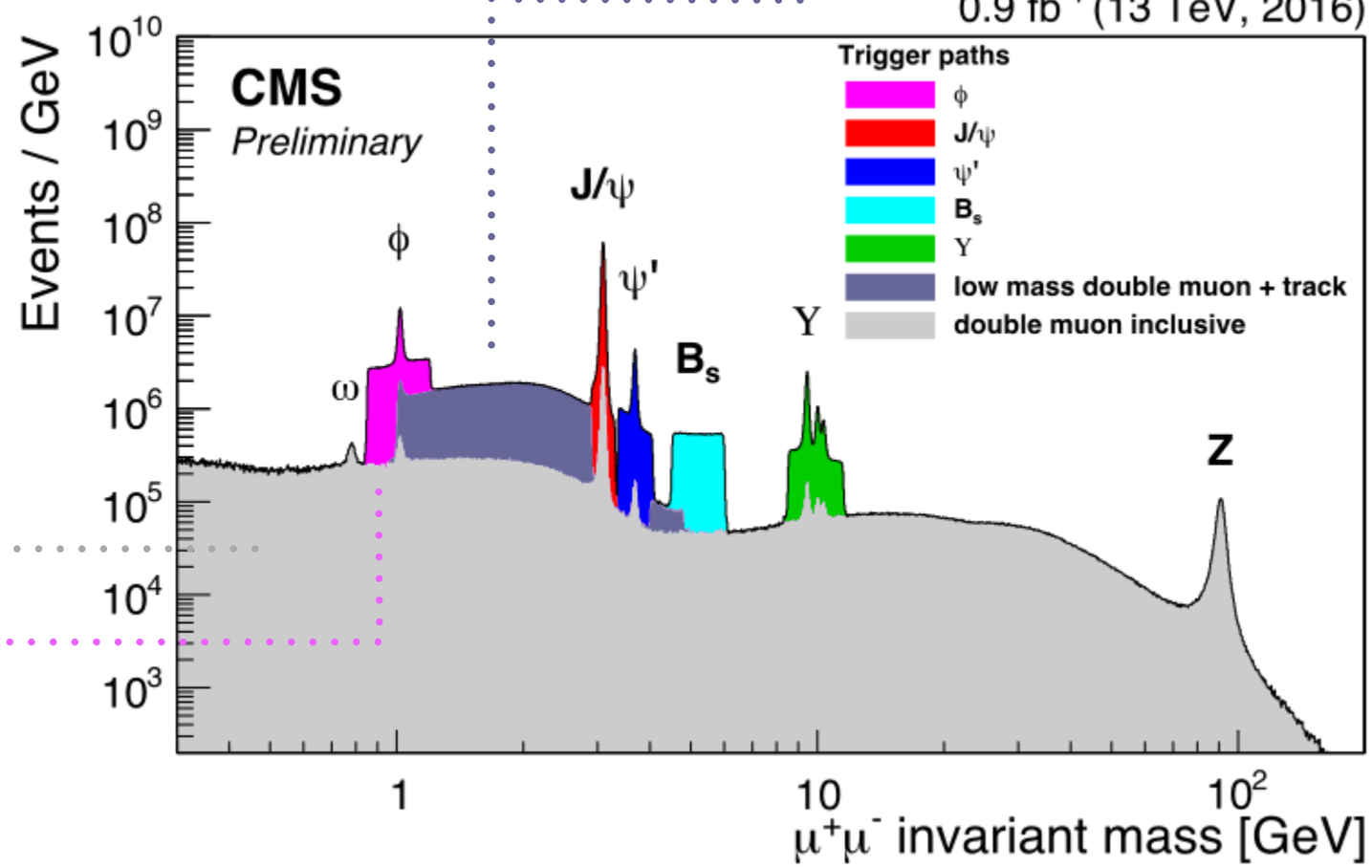



$\Lambda_b^0 \to J/\psi \Lambda^0$



# $B^+$ CROSS SECTION

CMS-PAS-BPH-15-004

- probing b-hadron production at higher energies wrt to Run1 measurements
- important test of QCD

# $B^+$ production: selection

13 TeV

Using data with 50 ns bunch spacing: $\mathcal{L}$: ~50.8 $pb^{-1}$

Exclusive decay channel: $B^+ \rightarrow J/\psi\, K^+ \rightarrow \mu^+\mu^-\, K^+$

Candidate selection:

Displaced triggered dimuon vertex

- L1: 2 × $|\eta|^\mu < 1.6$ OR ≥1 × $|p_T|^\mu > 10$ GeV
- HLT: 2 × $|\eta|^\mu < 2.4$ AND $|p_T|^\mu > 4$ GeV
- $2.9 < m_{\mu\mu} < 3.3$ GeV

$J/\psi$ candidate: $\mu\mu$ pair with $|p_T| > 10$ GeV

$K^+$ candidate: track with $|p_T| > 1$ GeV

# $B^+$ production: cross-section

13 TeV

**Differential measurement:** as function of Q (Q = $p_T$ or |y| of $B^+$)

signal yield in bin ΔQ

$$\frac{d\sigma(pp \to B^+X)}{dQ} = \frac{N_{\mathrm{sig}}}{2\mathcal{A}\epsilon \cdot \mathcal{B}\mathcal{L} \cdot \Delta Q}$$

result for a single charge

acceptance × efficiency

bin width

*A: from $B^+$ MC simulations*

*ϵ: data-driven from inclusive $J/\psi \to \mu\mu$*

BR( $B^+ \to J/\psi\, K^+$ ) × BR( $J/\psi \to \mu\mu$ )

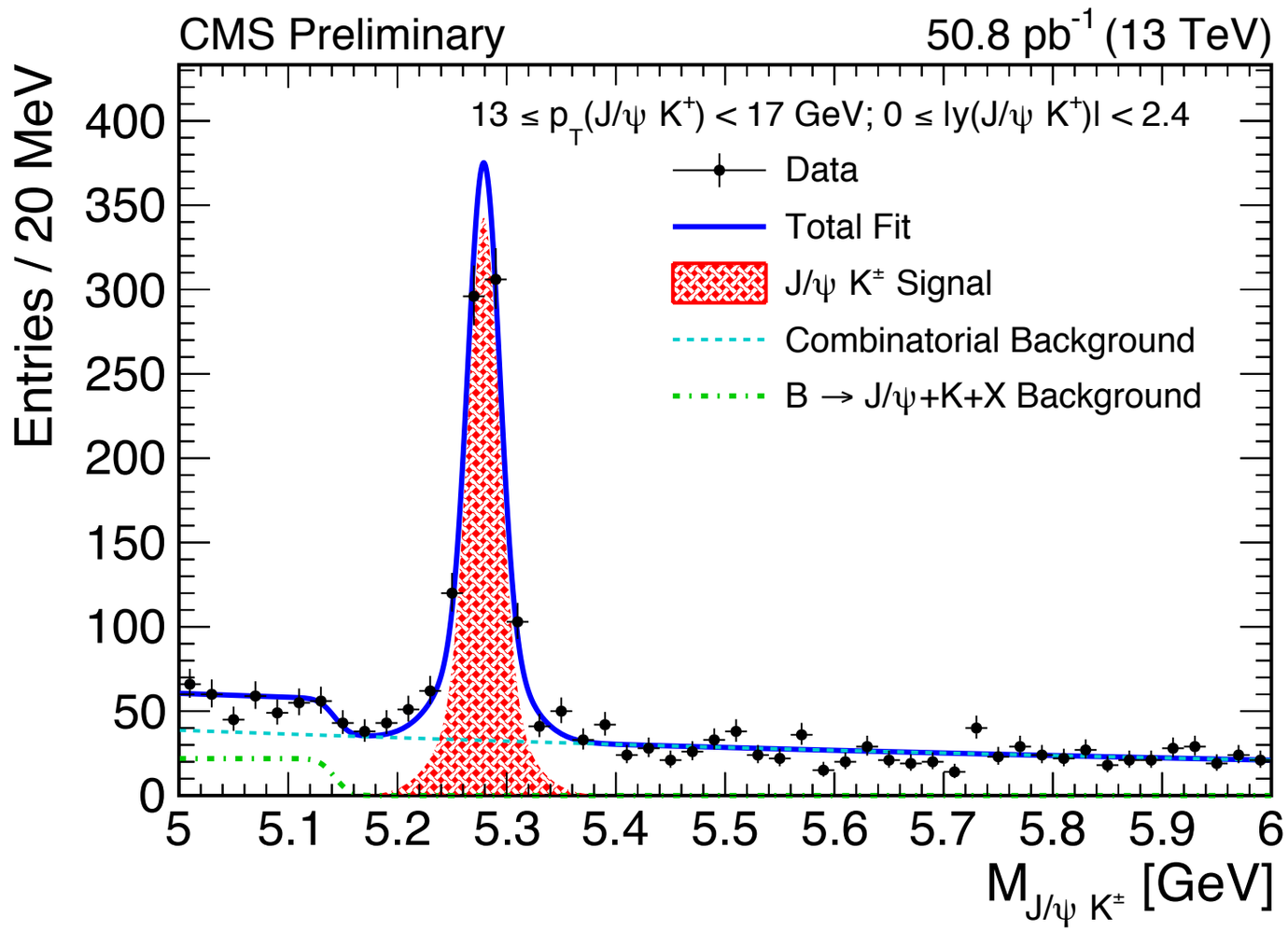
# $B^+$ production: signal yields

13 TeV

**Signal yields:** extracted from invariant mass of $B^+$ candidates

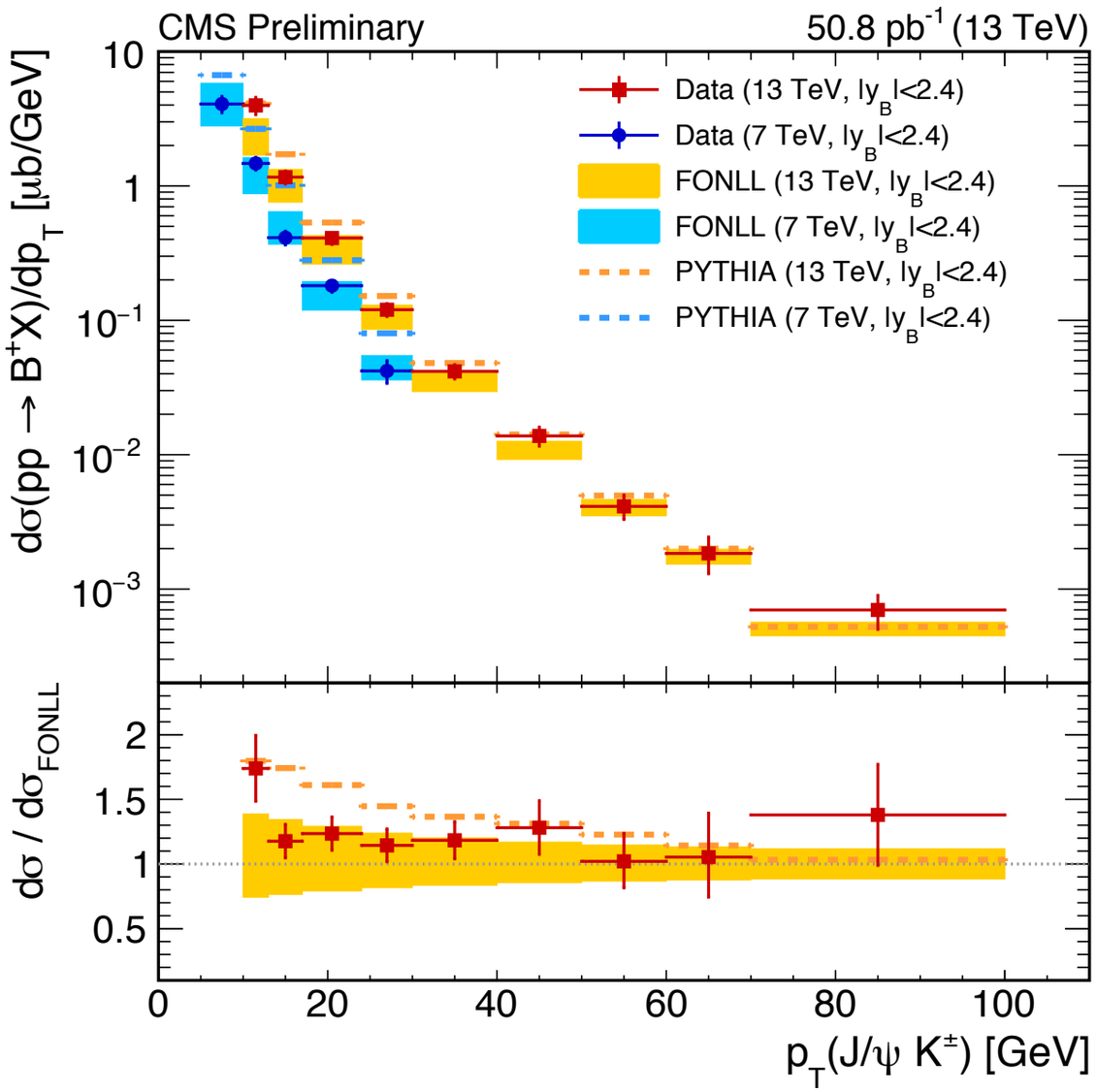
**Extended unbinned likelihood fit in each bin of the measurement**

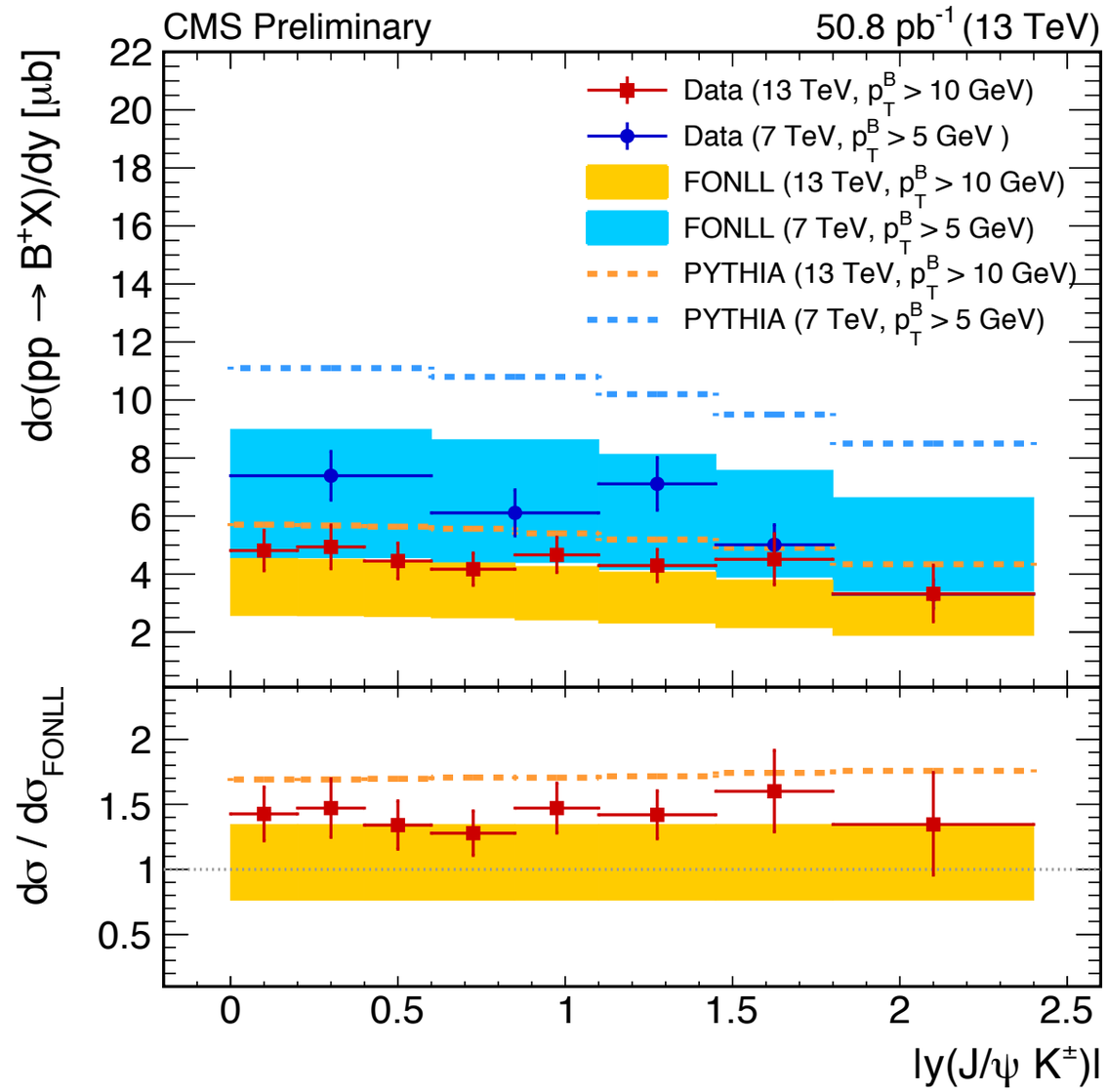
- **signal component**
  double gaussian
- **combinatorial bkg.**
  exponential function
- **misreconstructed bkg.**
  error function



# $B^+$ production: results

## Comparison of Data, MC and FONLL calculations at 7 TeV and 13 TeV




**Theory predictions in reasonable agreement with the measurement**

**Improved precision of FONLL predictions at 13 TeV**

# QUARKONIUM CROSS SECTION

CMS-PAS-BPH-15-005

- testing the factorisation hypothesis of NRQCD
- extending the $p_T$ reach of the previous measurement using Run1 data

# Quarkonium production: selection

13 TeV

Using data with 25 ns bunch spacing: $\mathcal{L}$: ~2.7 fb$^{-1}$

5 S-wave charmonium states: ***J/ψ*** ***ψ(2S)*** ***Υ(1/2/3S)***

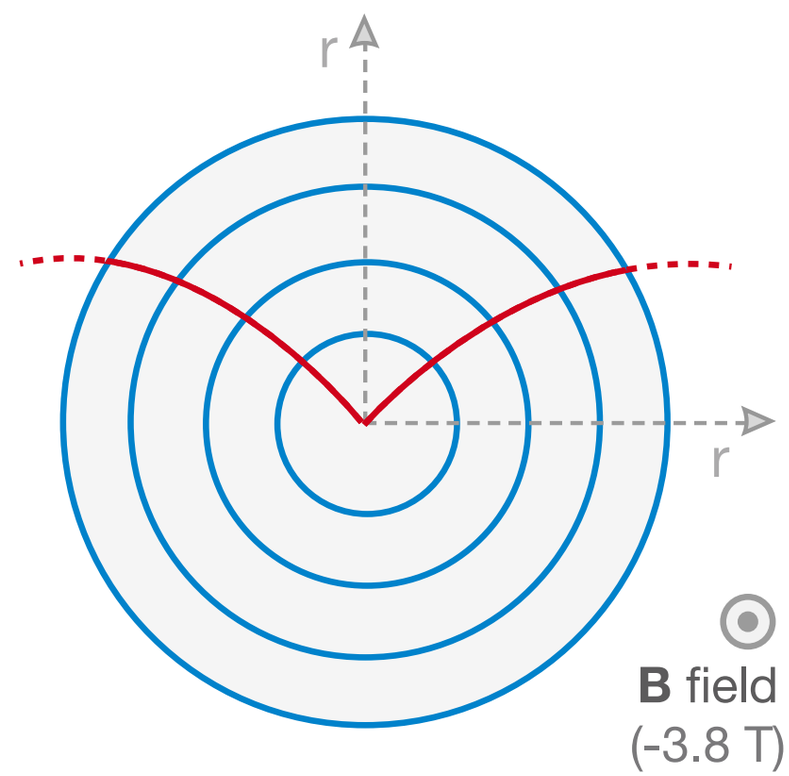
Candidate selection:

High-$p_T$ $\mu\mu$ pair in central rapidity

- L1: $2 \times |\eta|^{\mu} < 1.6$
- HLT: $|p_T|^{\mu\mu} > 10$ GeV [***J/ψ***]
  $|p_T|^{\mu\mu} > 8$ GeV [***ψ(2S), Υ(nS)***]
- specific $m_{\mu\mu}$ windows for each state

Only μμ flying away from each other

$\Delta\varphi < 0$ $\Delta\varphi = \varphi(\mu+) - \varphi(\mu-)$




$-\pi < \Delta\varphi < \pi$

# Quarkonium production: cross section 13 TeV

**Double-differential measurement:** as function of $p_T$ and $|y|$

signal yield in a 2D bin

maximum likelihood fit to $m_{\mu\mu}$ spectra

$$\mathcal{B}(Q \to \mu^+\mu^-) \times \frac{d^2\sigma^Q}{dp_{\mathrm{T}}dy} = \frac{N^Q(p_{\mathrm{T}}, |y|)}{\mathcal{L} \cdot \Delta p_{\mathrm{T}} \Delta y} \cdot \langle \frac{1}{\epsilon(p_{\mathrm{T}}, |y|)\mathcal{A}(p_{\mathrm{T}}, |y|)} \rangle$$

bin width

average inverse acceptance × efficiency

***J/ψ***

***ψ(2S)***

***Υ(1S)***

***Υ(2S)***

***Υ(3S)***

***A:*** *from MC simulations*

***ϵ:*** *data-driven using Tag&Probe*

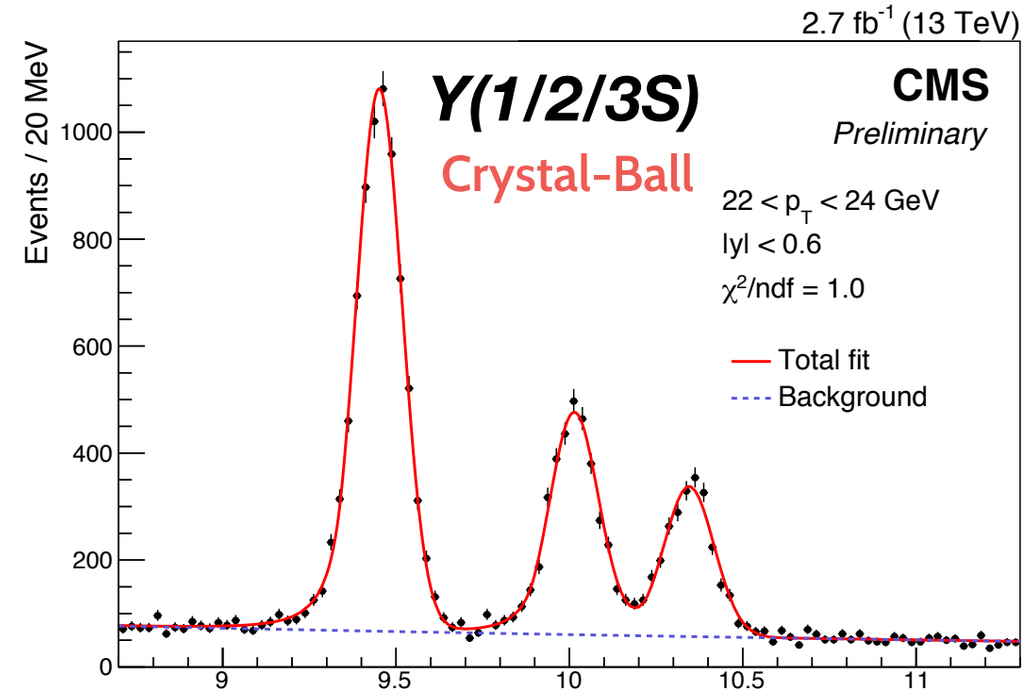
$\epsilon_{\mu\mu} = \epsilon_{\mu 1} \cdot \epsilon_{\mu 2} \cdot \rho$ ← *for high-$p_T$ μμ correlations*

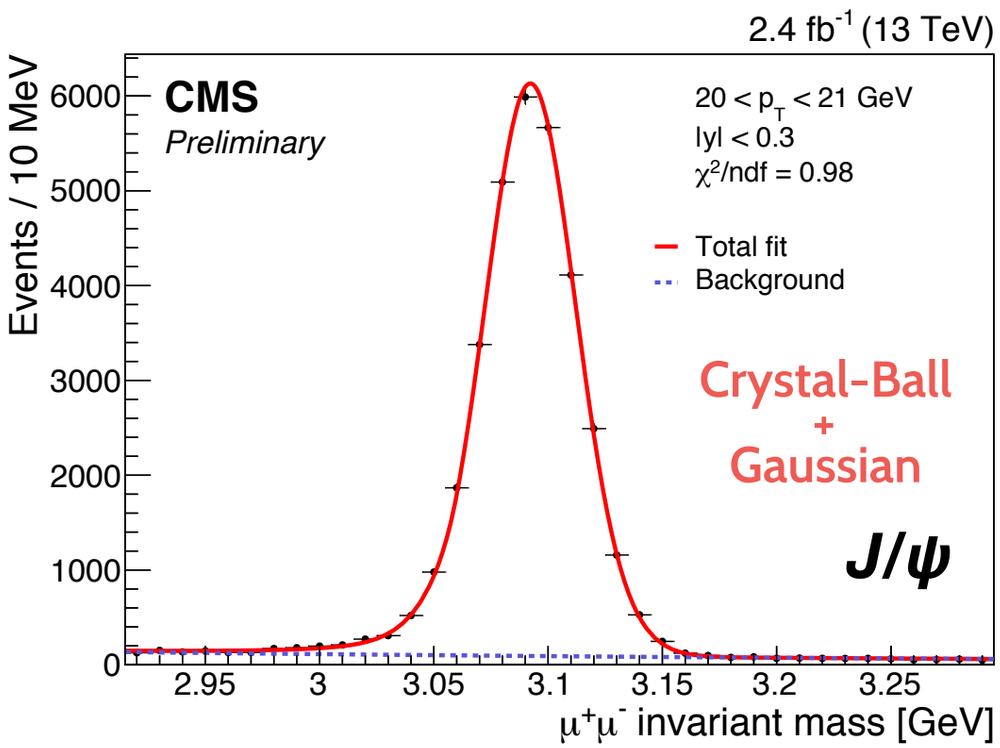
# Quarkonium production: signal yields 13 TeV

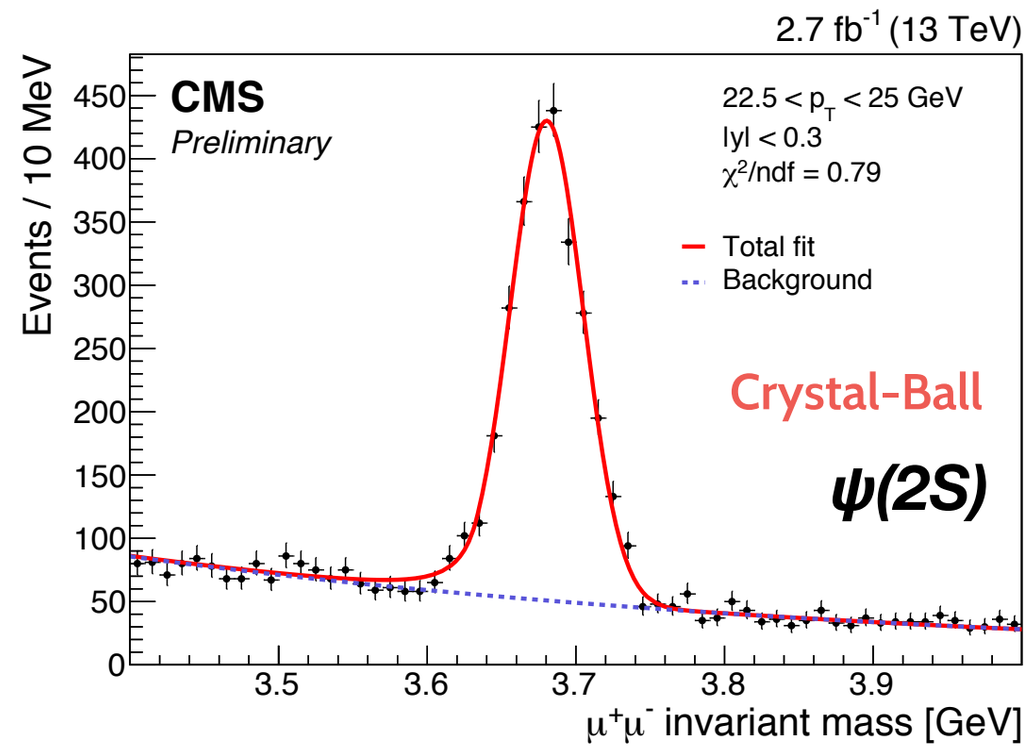
**Signal yields:** extracted from invariant mass of meson candidates

**Extended unbinned likelihood fit in each bin of the measurement**

- **background**
  exponential function

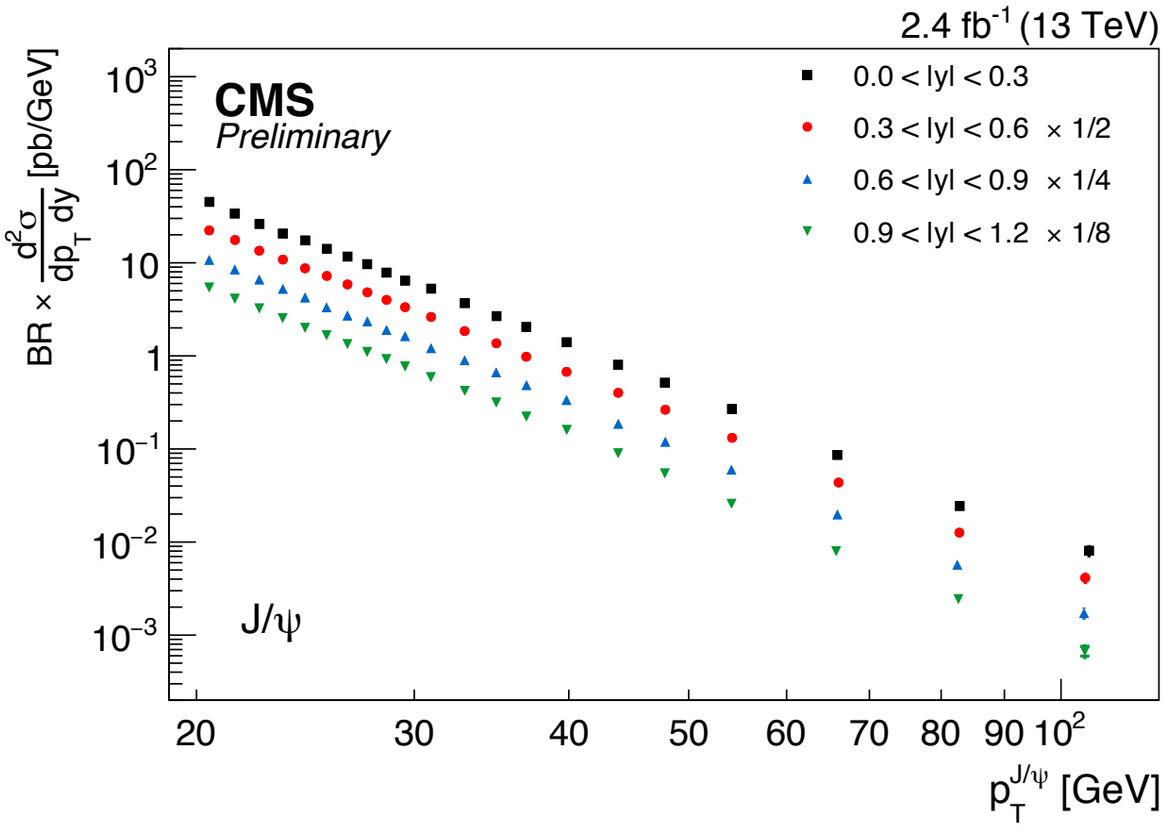


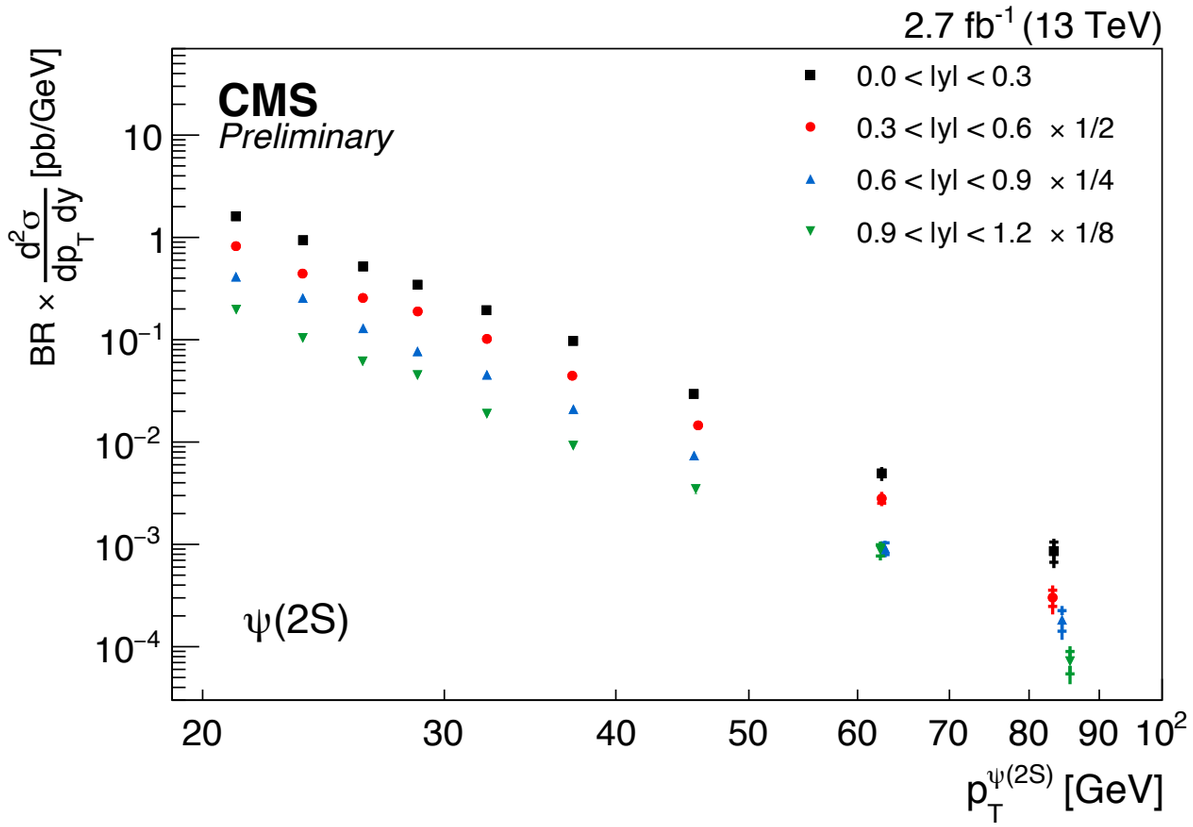



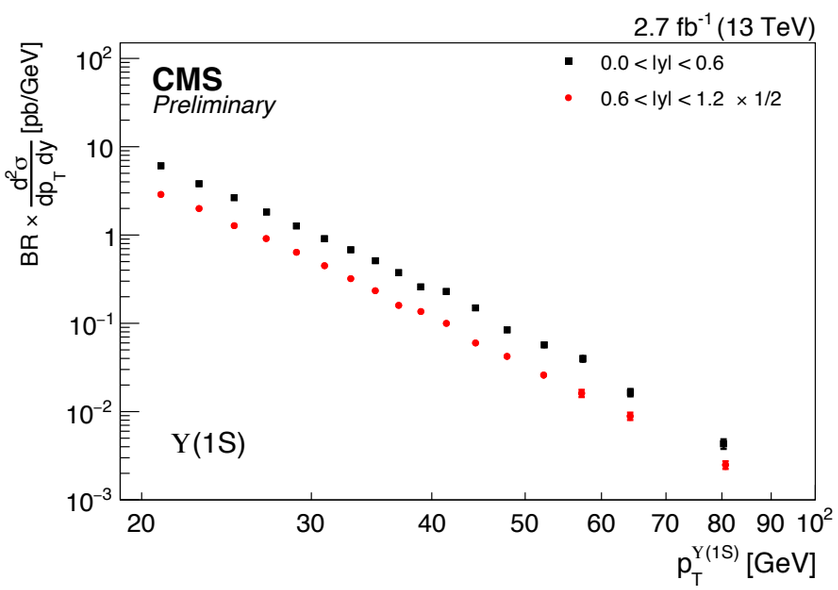



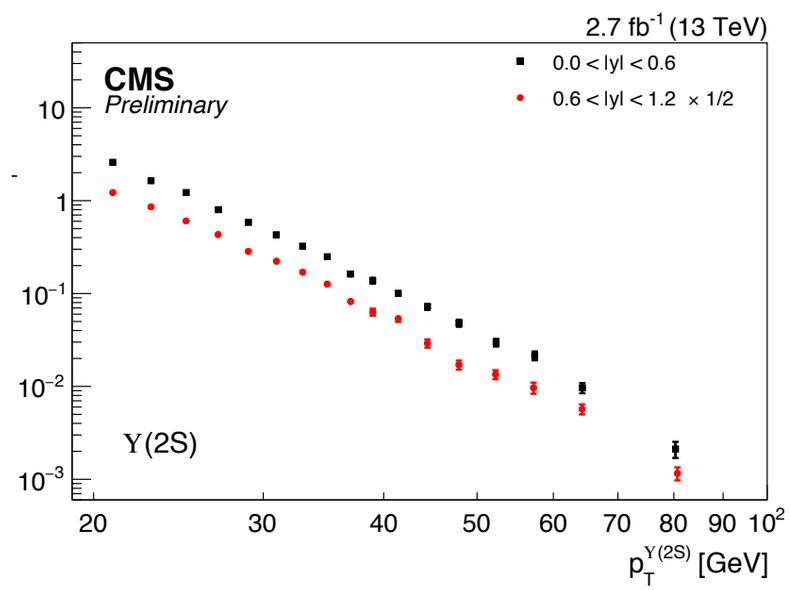
# Quarkonium production: results

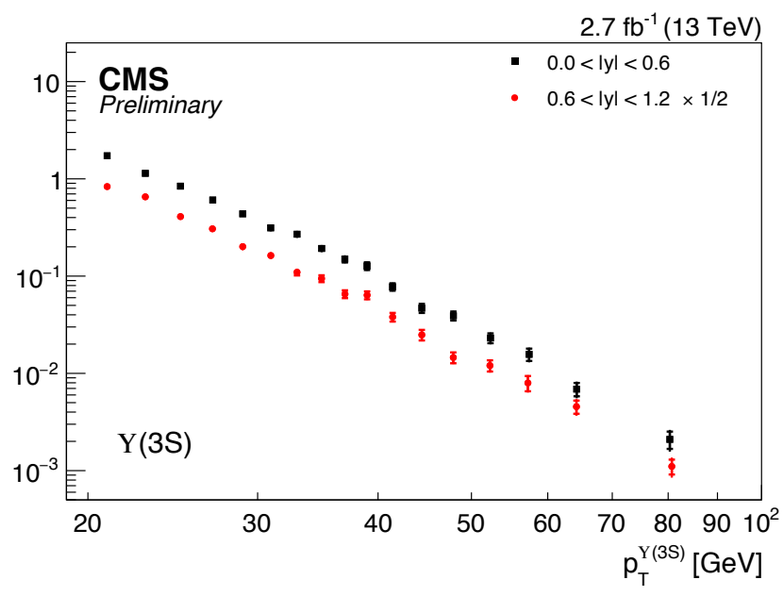
13 TeV



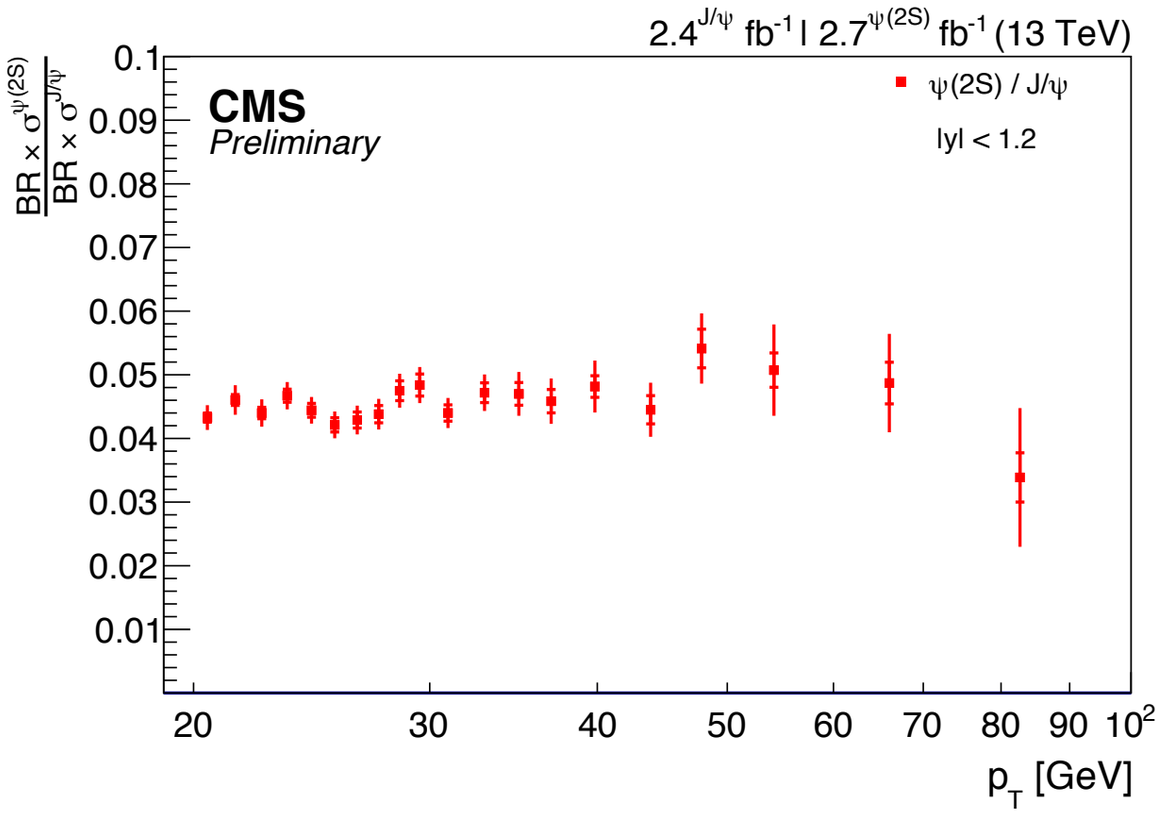



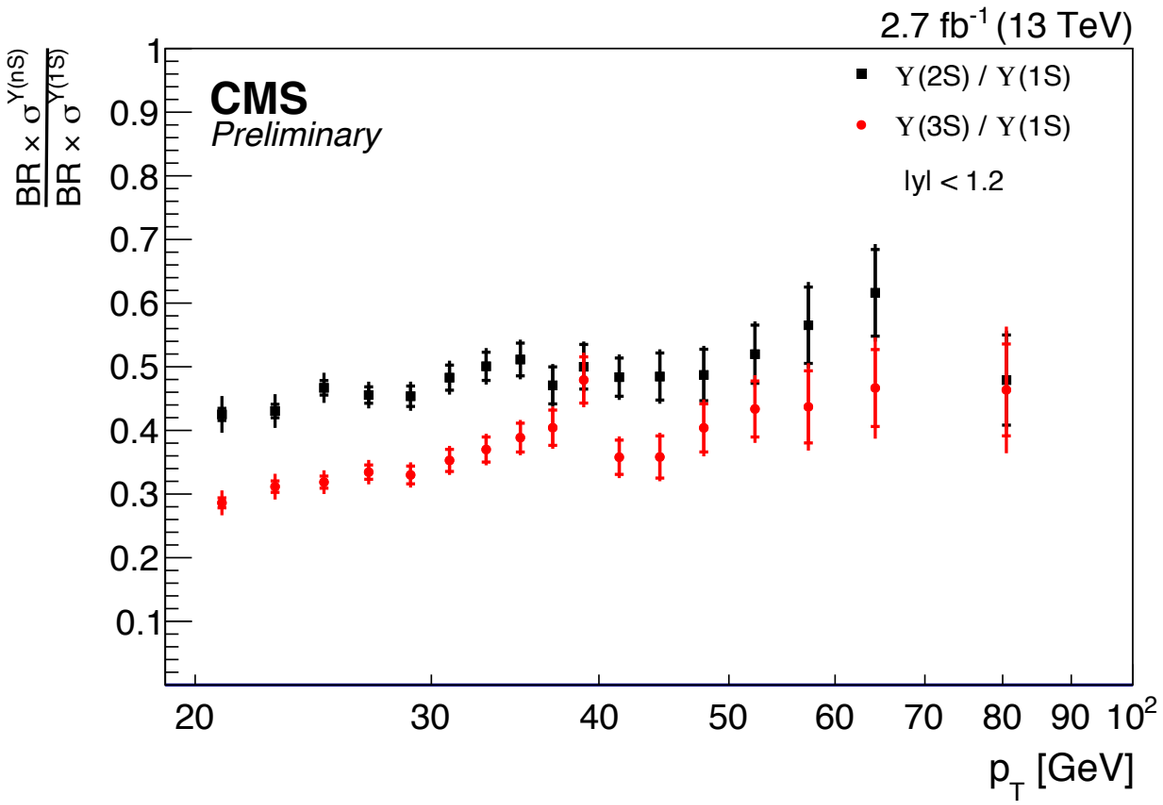




**Shapes consistent across rapidity regions**

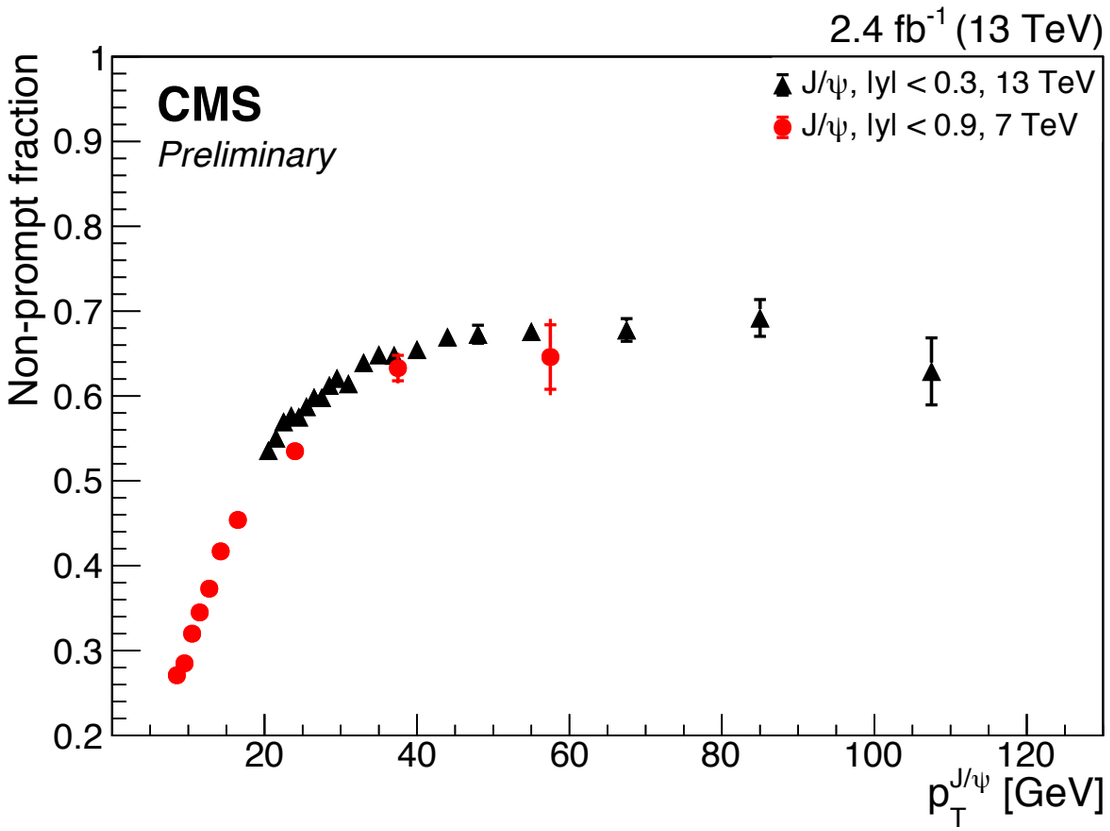
## Radial excitations relative to ground states

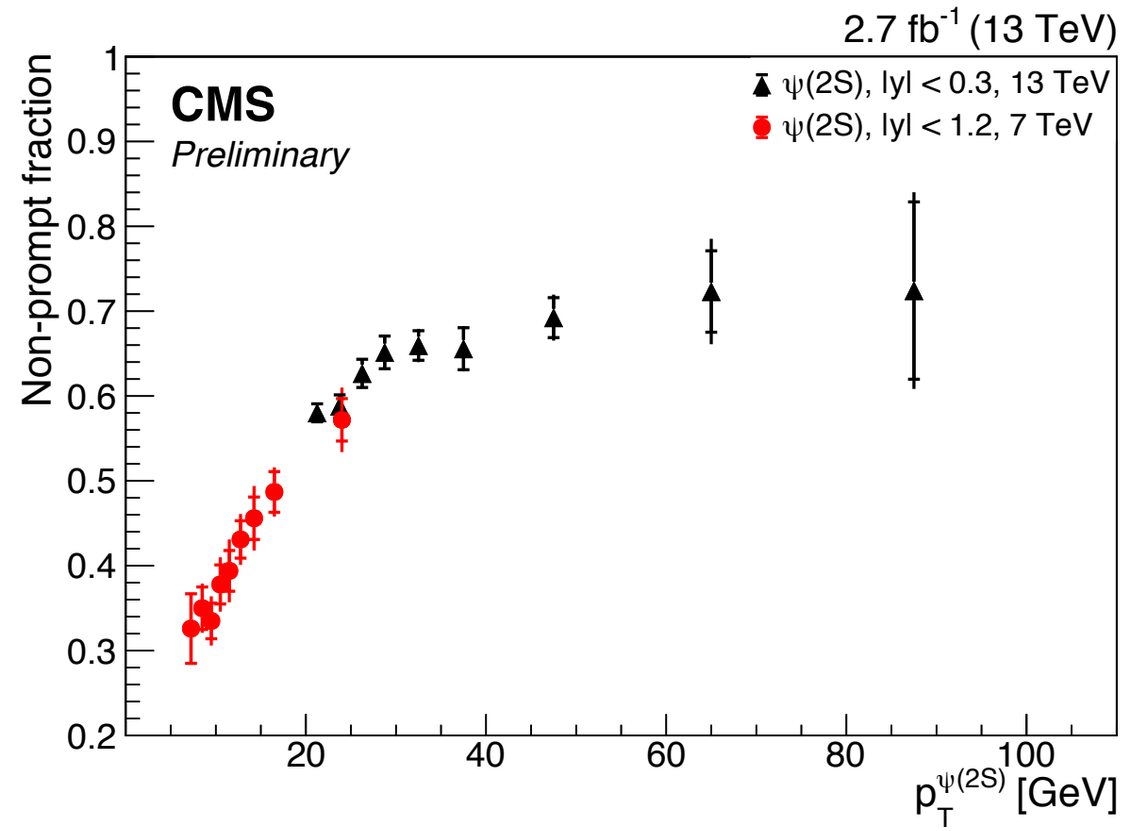


# Quarkonium production: results

## Charmonium non-prompt fraction: 13 TeV vs 7 TeV

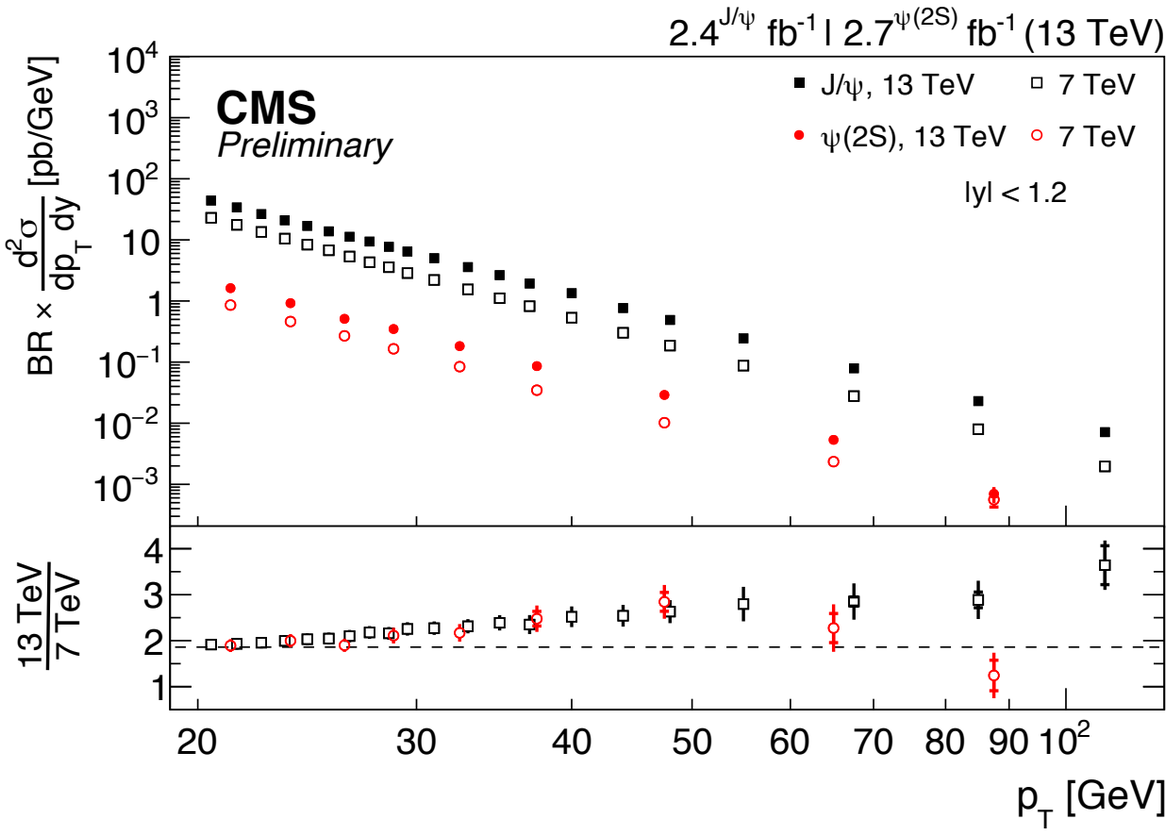


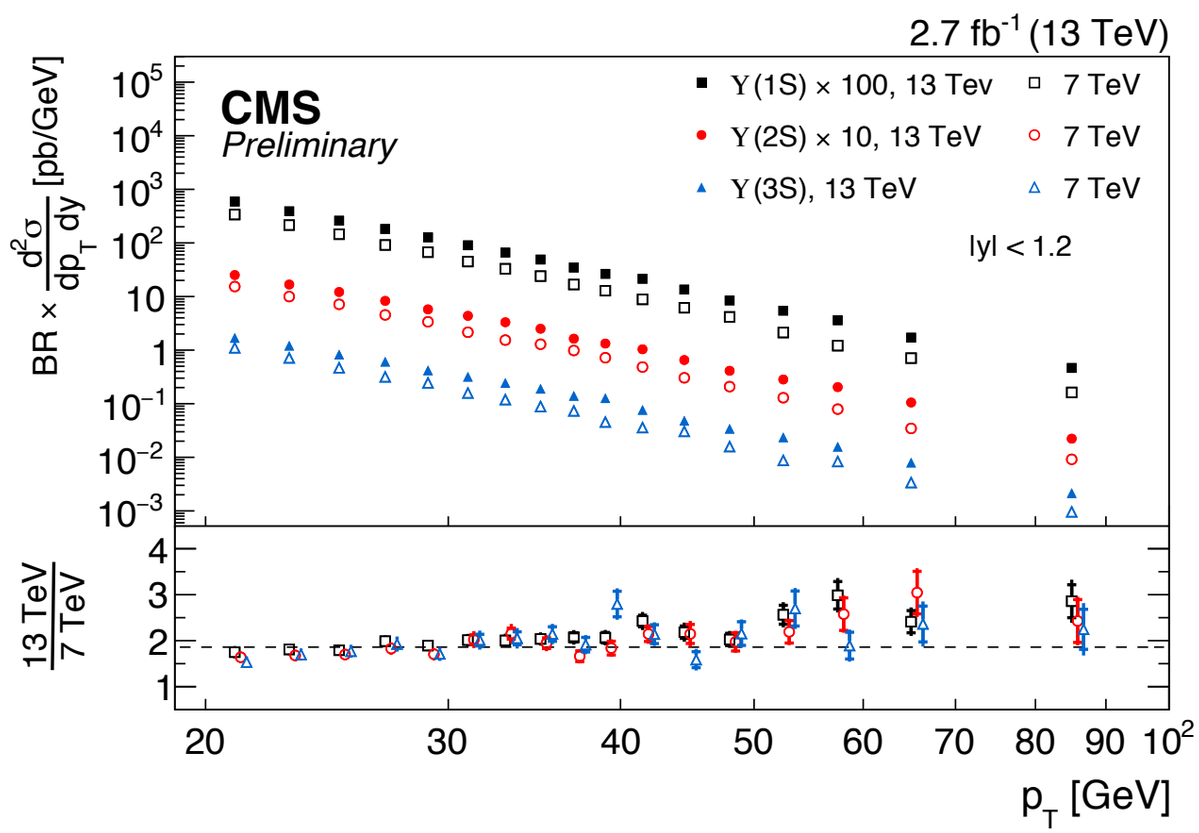




**$p_T$ reach significantly extended with the 13 TeV measurement**

# Charmonium production: results

## Comparison of the measurements at 7 TeV and 13 TeV




**Same $p_T$ dependence in Run1 and Run2**

**Increase of cross-section consistent with expectations from the PDF evolution**

# Y(1S) PAIR OBSERVATION

CMS-PAS-BPH-14-008

- never observed before (evidence by DØ)
- first step in searches for tetra-quarks
- important test of QCD predictions

# Υ(1S)-pair observation: selection

8 TeV

Using data from Run1: $\mathcal{L}$: ~20.7 fb$^{-1}$

Searching for: $2 \times$ ***Υ(1S) → μμ***

Candidate selection:

≥4 muons

- HLT: ≥1 pair with $8.5 < m_{\mu\mu} < 11$ GeV
- total 0 electric charge
- oppositely charged → kinematic fit

Υ(1S) candidate:

$|y| < 2.0$ $p_T < 50$ GeV

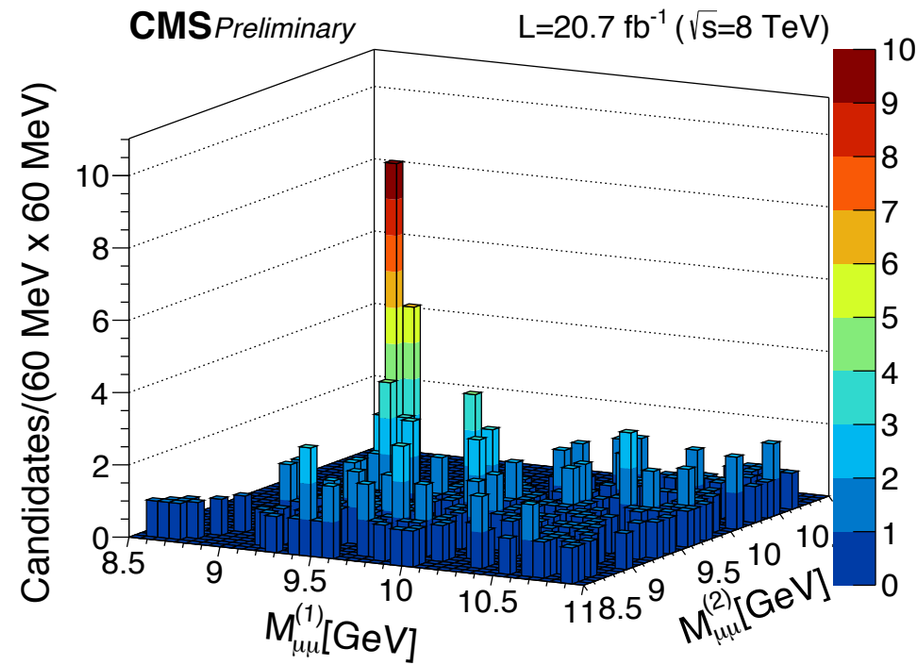
# Υ(1S)-pair observation: signal extraction

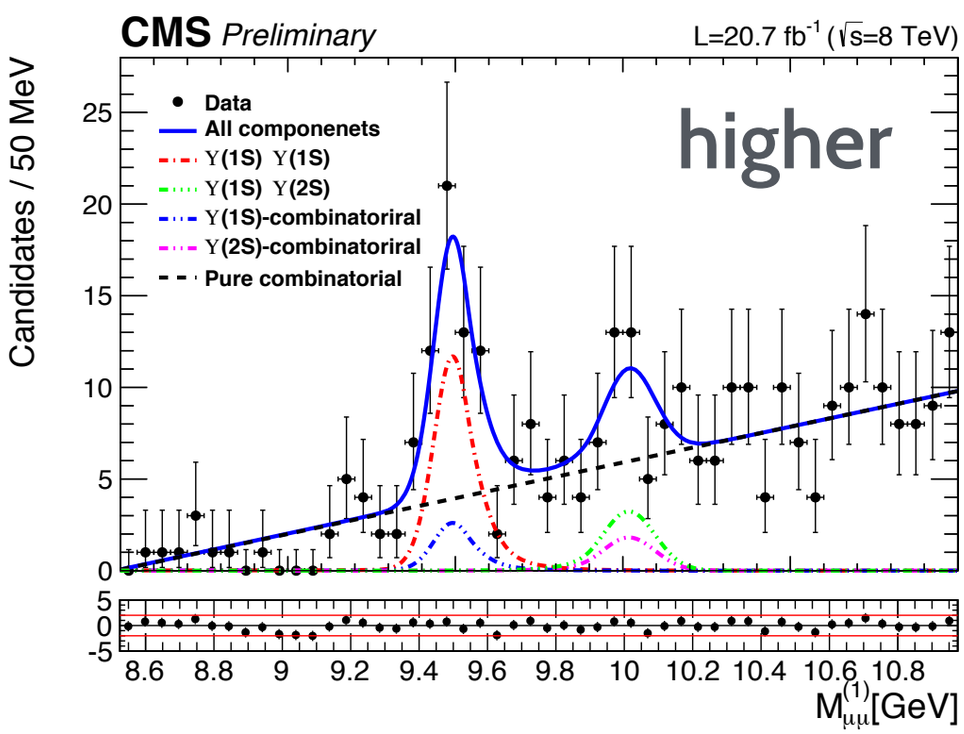
8 TeV

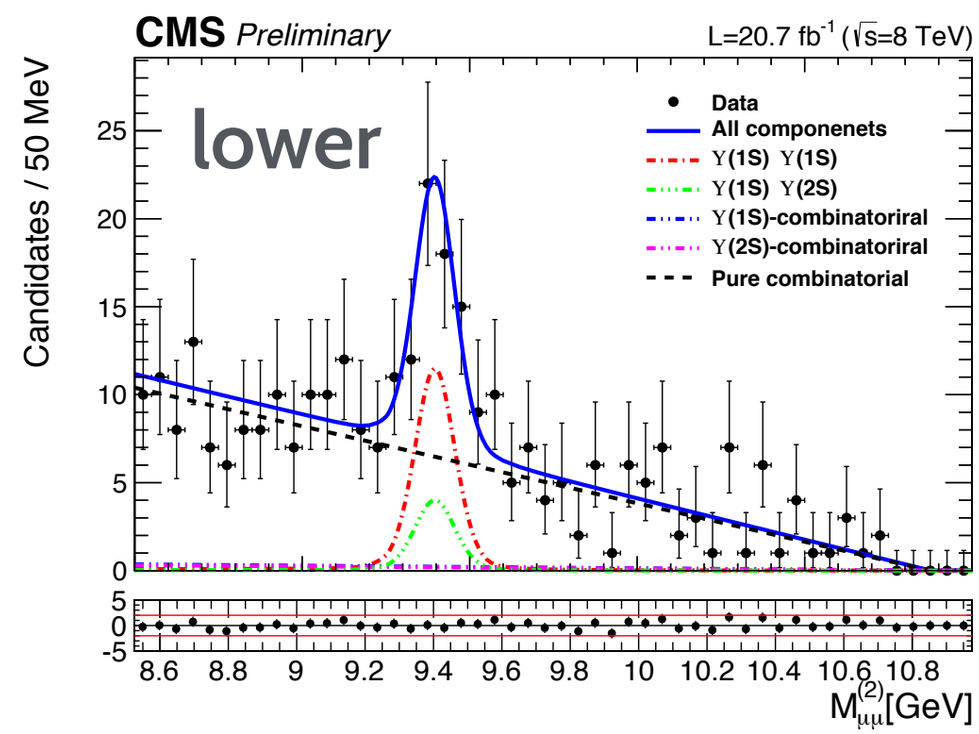
**Two discriminating variables:** higher $m_{\mu\mu}$ lower $m_{\mu\mu}$

**2D unbinned likelihood fit over the integrated |y| region**

- **signal**: 2 × Crystal-Ball
- **combinatorial bkg.**
  1st order Chebyshev Polynomial



# Υ(1S)-pair observation: results

8 TeV

**Inclusive cross-section measured:** $|y| < 2.0$ $p_T < 50$ GeV

**Signal yield:** 38 ± 7 events

average inverse acceptance × efficiency

$$\sigma = \frac{N_{\mathrm{sig}}}{\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)^2 \cdot \mathcal{L}} \cdot \left\langle \frac{1}{\epsilon(p_{\mathrm{T}}, |y|)\mathcal{A}(p_{\mathrm{T}}, |y|)} \right\rangle$$

**Total cross section:** $68.8 \pm 12.7^{\mathrm{stat}} \pm 7.4^{\mathrm{syst}} \pm 2.8^{\mathrm{BR}}$ pb

assuming isotropic *Υ(1S) → μμ* decays

**Expected to change by up to +36% (longitudinal) or -38% (transverse)** in case of extreme polarisation scenarios

# Summary

## Differential $B^+$ cross section measured at 13 TeV

- extended $p_T$ reach up to 100 GeV
- reasonable agreement with FONLL and Pythia8 predictions

## Double-differential quarkonia cross sections at 13 TeV

- consistent with 7 TeV results
- awaiting comparison to theoretical predictions

## First observation of double Υ(1S) production at 8 TeV

- inclusive cross section measured (statistics limited)
- first step in search for tetra-quarks

**Presented measurements constitute an important input for improving our understanding of QCD**

# Thank you

for attention