

# Quarkonium cross sections in pp collisions with CMS

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QCD@LHC  
Zürich  
22-26 August 2016



# Recent results on heavy quarks in pp collisions with CMS

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# Recent results

**CMS-PAS-BPH-15-005**

Quarkonium production cross sections in pp collisions at  $\sqrt{s} = 13$  TeV

**CMS-PAS-BPH-14-008**

Observation of  $\Upsilon(1S)$  pair production at CMS

**CMS-PAS-BPH-15-002**

Measurement of the  $\Lambda_b$  polarization and the angular parameters of the decay  
 $\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$

**CMS-PAS-BPH-16-002**

Search for the  $X(5568)$  state in  $B_s^0\pi^\pm$  decays

**CMS-PAS-BPH-15-004**

Measurement of  $B^+$  hadron production cross section in pp collisions at 13 TeV

**CMS-PAS-BPH-13-009** (sub. to PLB)

Observation of the decay  $B^+ \rightarrow \psi(2S)\phi(1020)K^+$  in  
pp collisions at  $\sqrt{s} = 8$  TeV



Red ruffed lemur  
All photos taken from Zoo Zürich

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# Quarkonium cross sections

- Double differential cross section times branching ratio

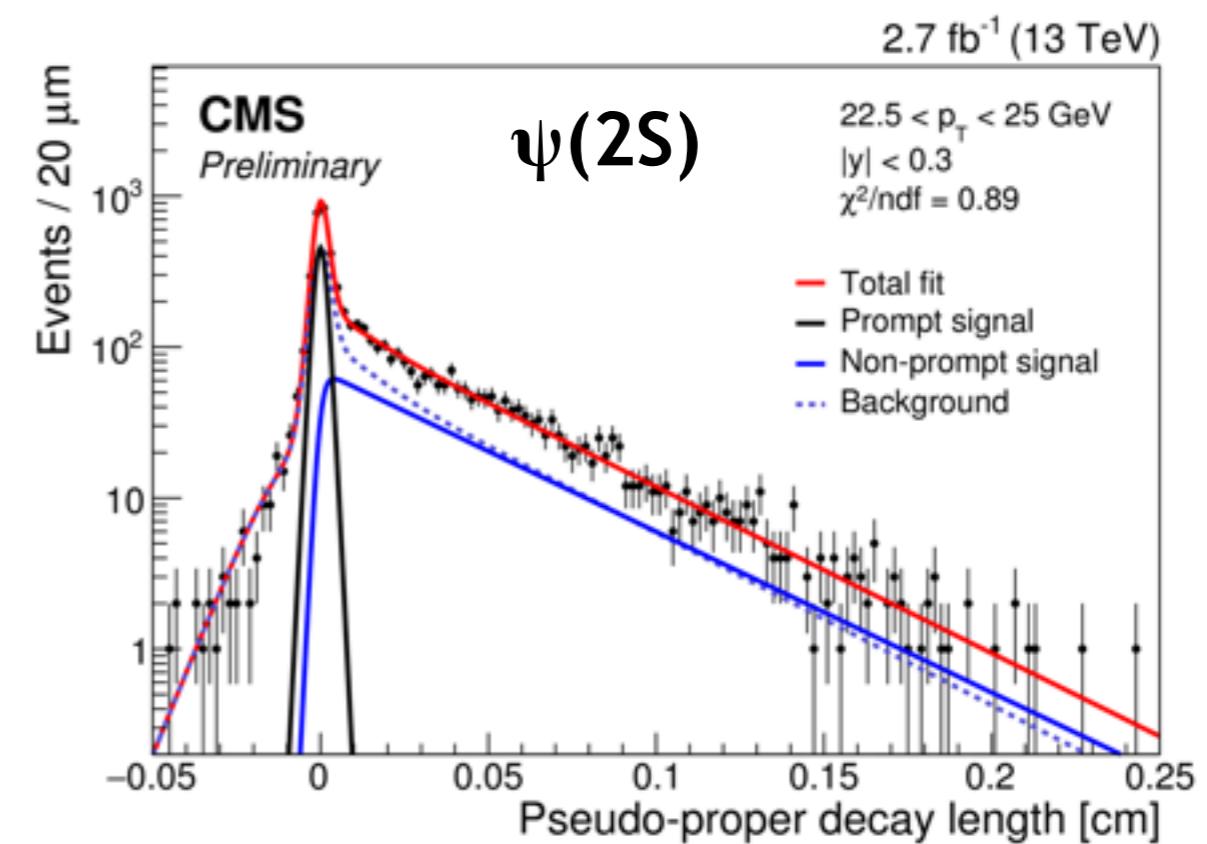
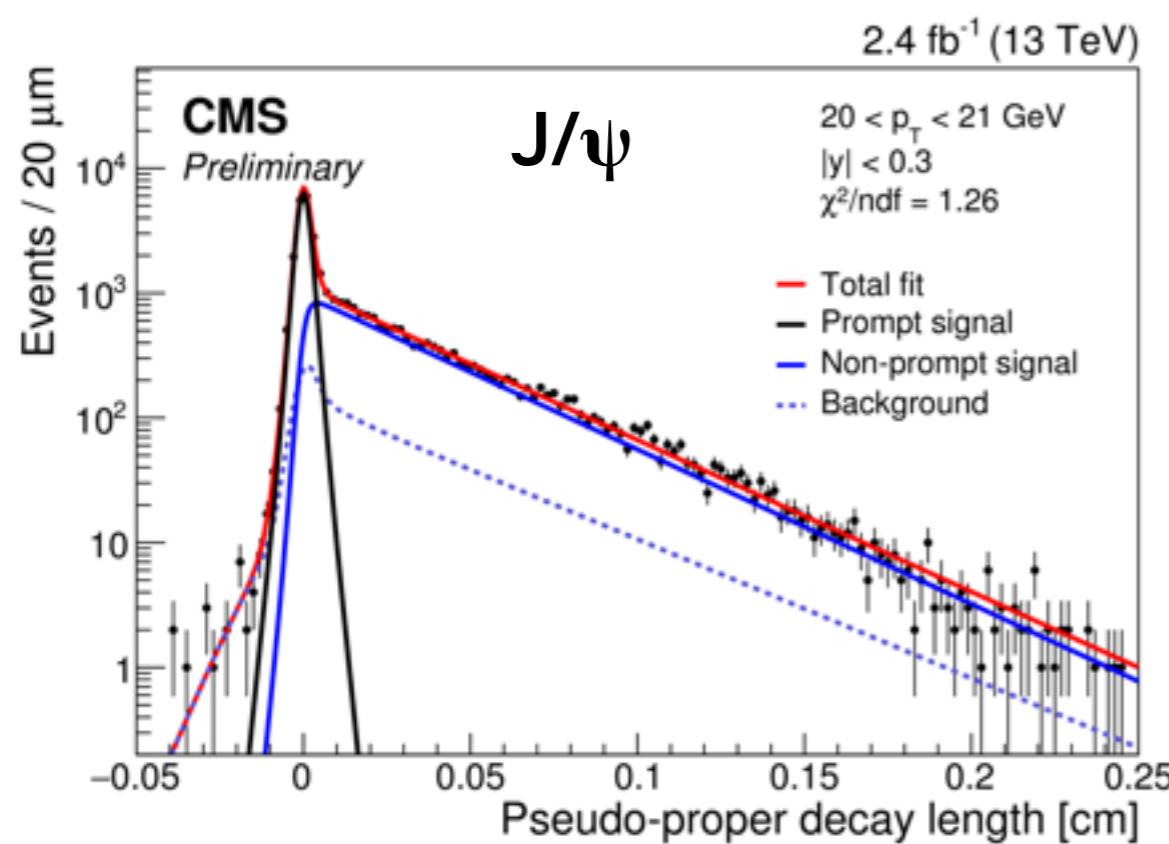
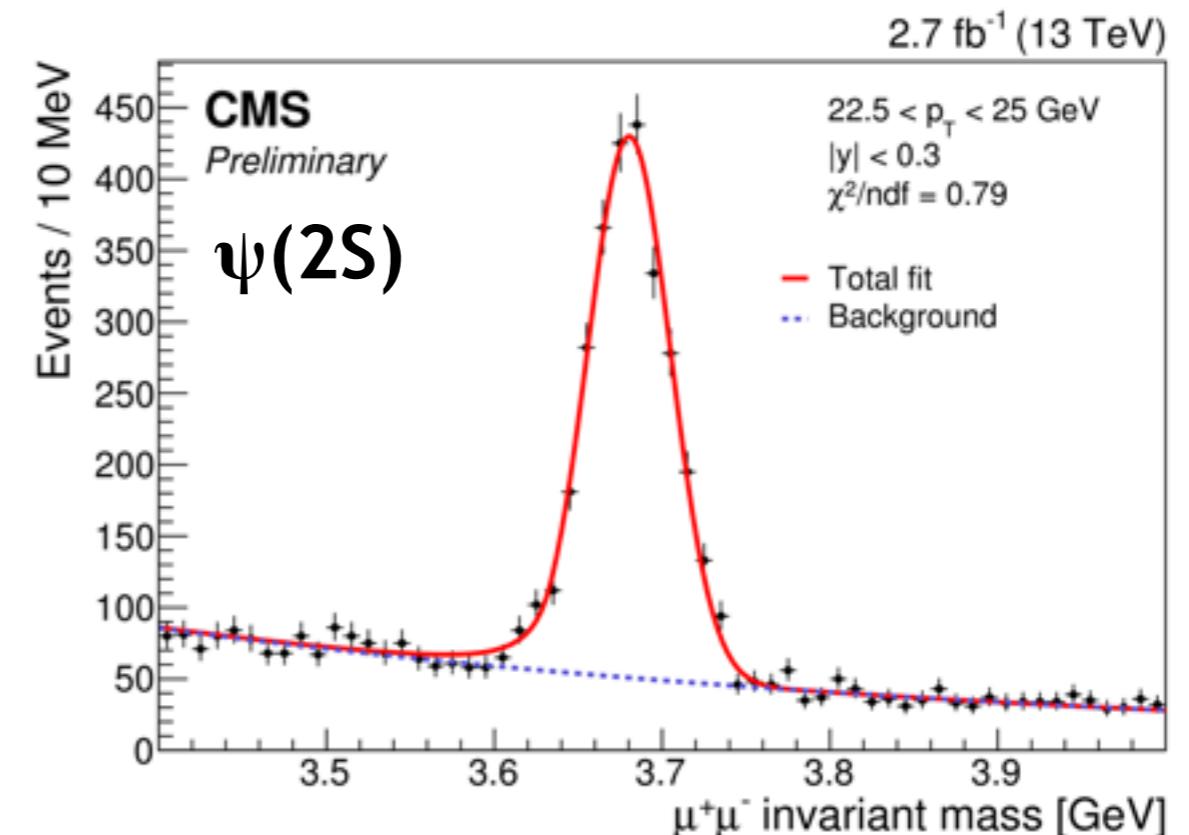
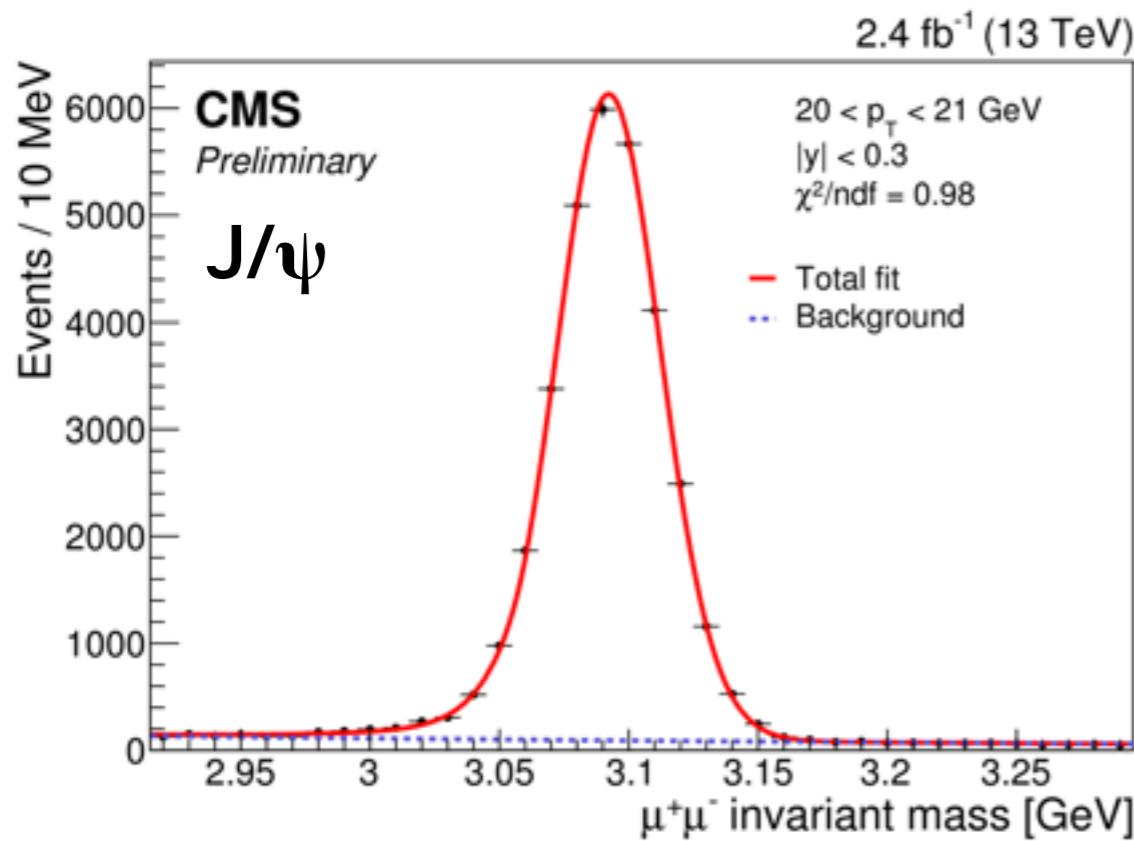
$$\frac{d^2\sigma(pp \rightarrow Q)}{dp_T dy} \times \mathcal{B}(Q \rightarrow \mu^+ \mu^-) = \frac{N(p_T, y)}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y \cdot \varepsilon(p_T, y) \cdot \mathcal{A}(p_T, y)}$$

- Signal yields  $N$  determined from unbinned maximum likelihood fits to dimuon mass and (in case of  $\psi(nS)$  states) pseudo-proper decay length distributions
- Integrated luminosity  $\mathcal{L} = 2.4 \text{ fb}^{-1}$  ( $J/\psi$ ) and  $2.7 \text{ fb}^{-1}$  collected in 2015 at  $\sqrt{s} = 13 \text{ TeV}$
- Acceptance  $\mathcal{A}$  calculated from simulations
- Single muon and dimuon efficiency  $\varepsilon$  obtained from data
- Bin widths  $\Delta p_T$ ,  $\Delta y$

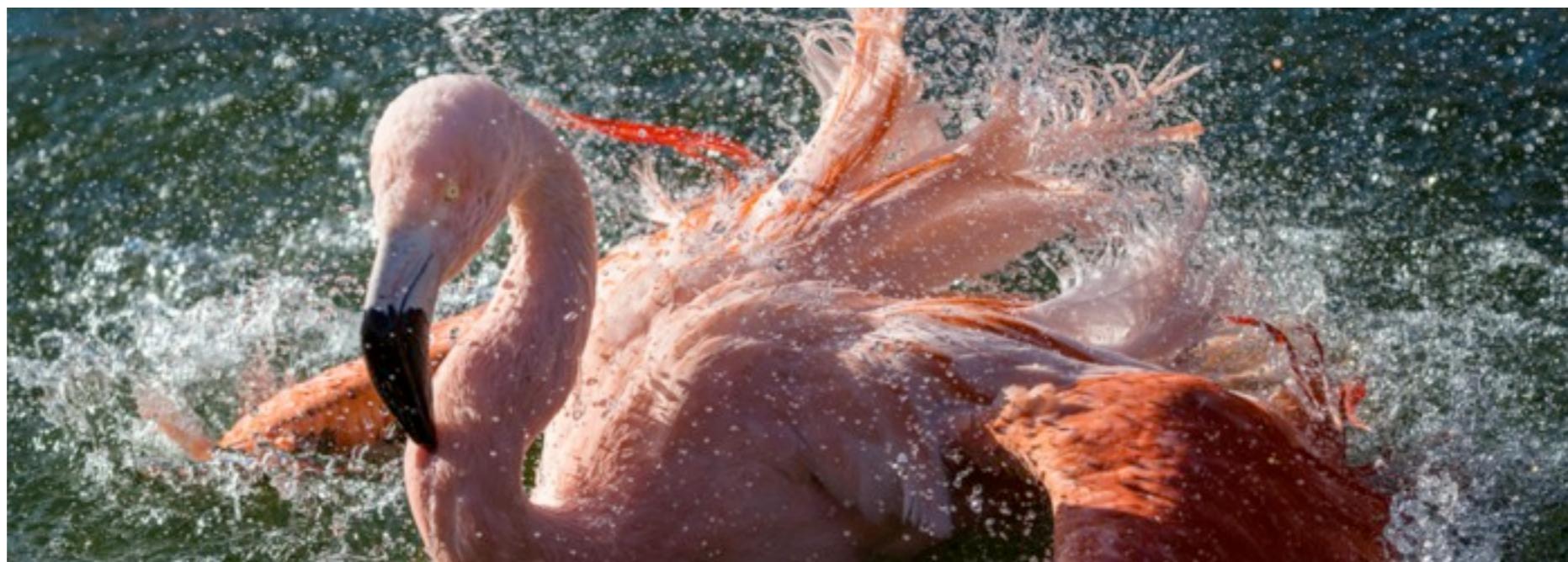
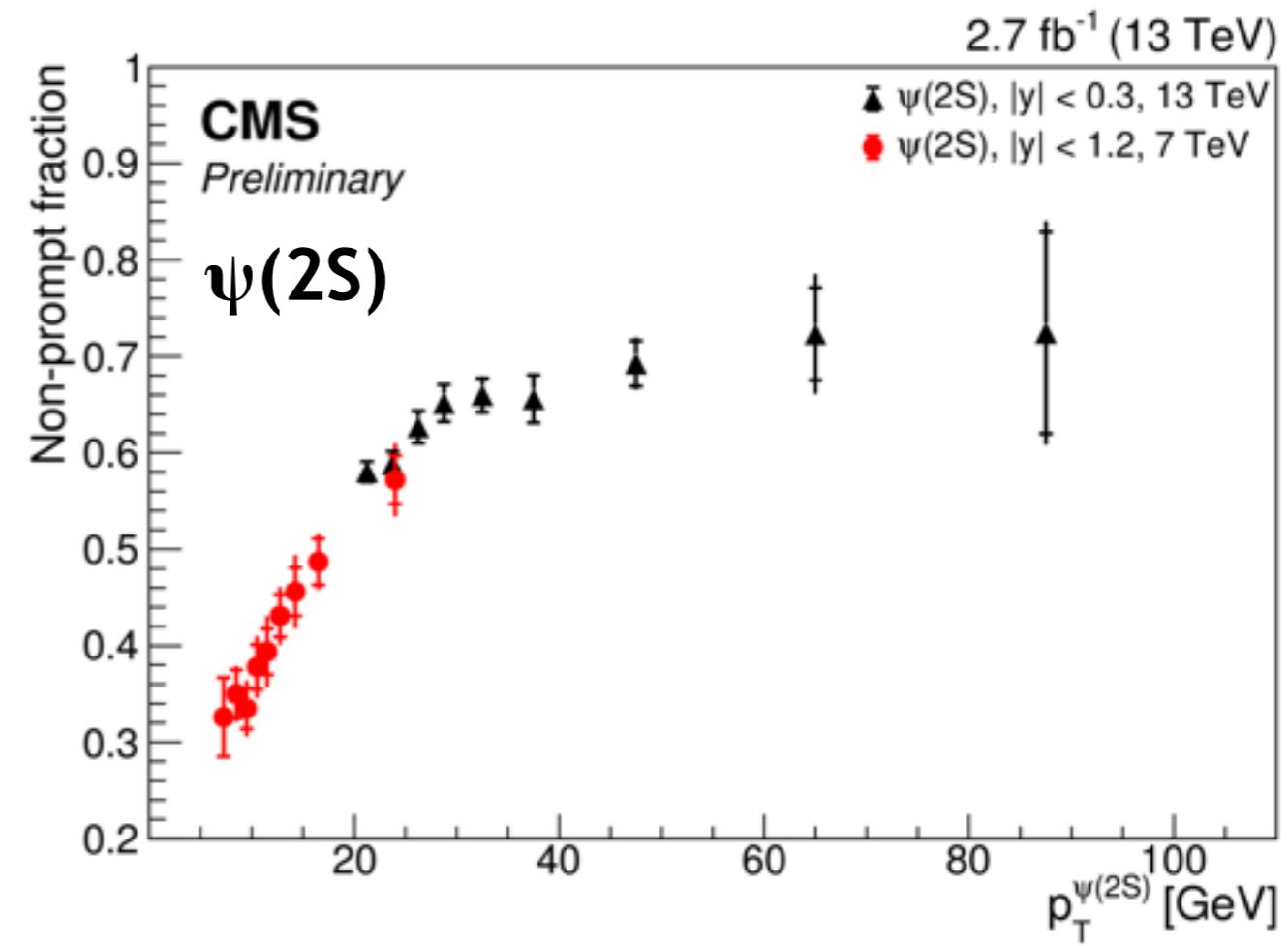
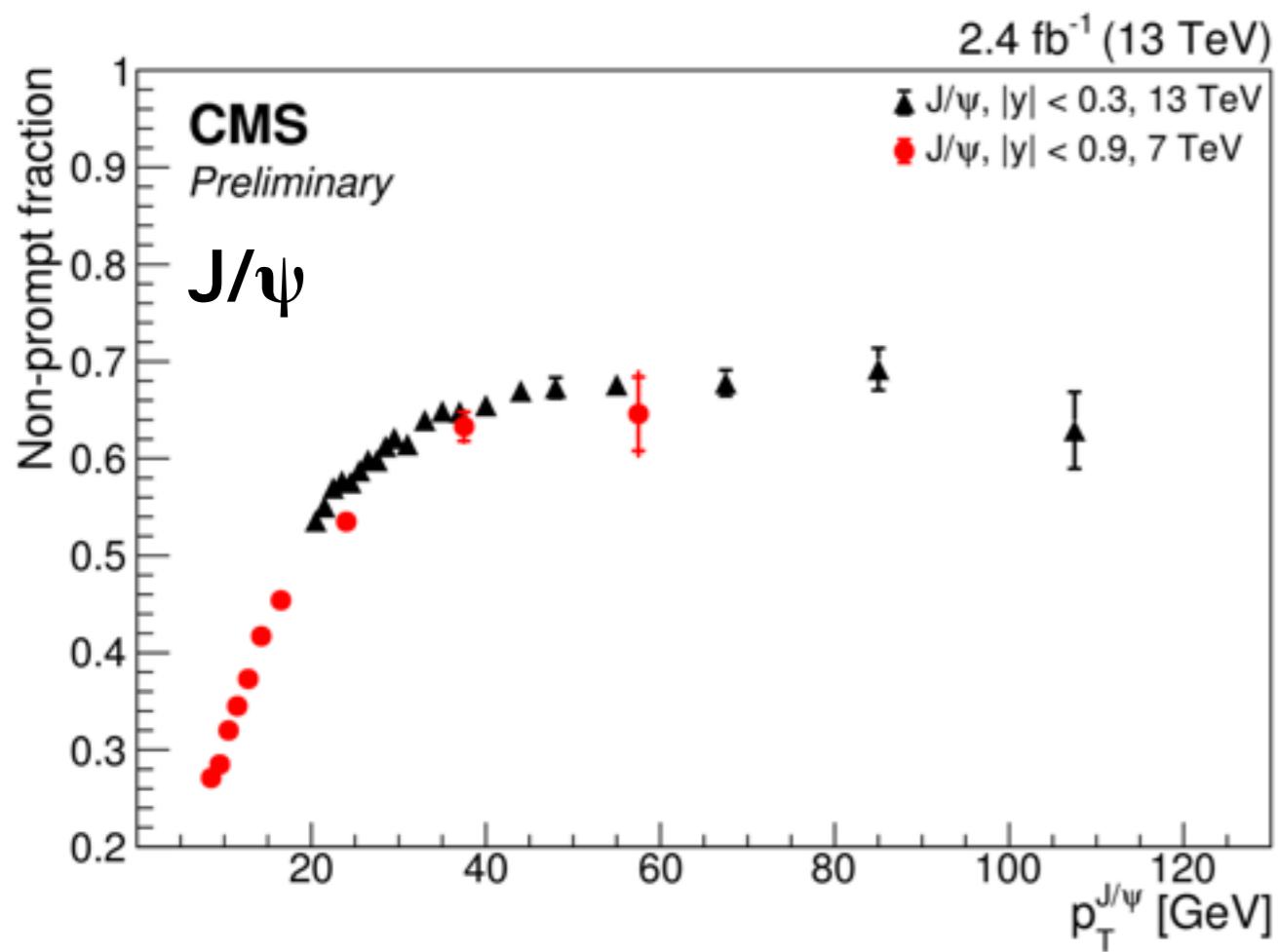


Tanagers

# $\psi(nS)$ distributions

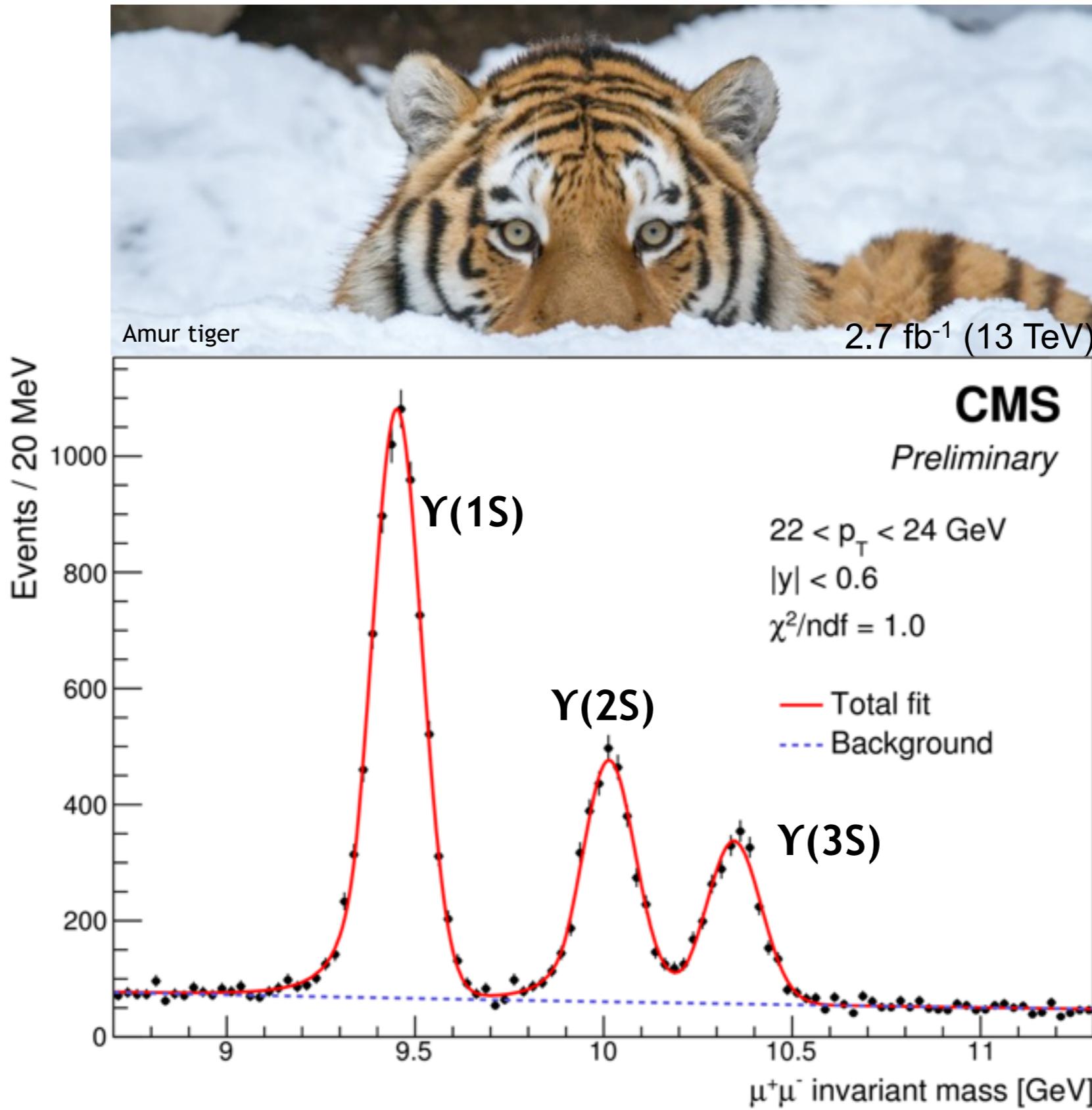


# Non prompt fractions



Flamingo

# $\Upsilon(nS)$ mass distribution



# Systematic uncertainties

- Determination of the signal yields - signal and background modeling
- Estimation of the non prompt fraction
- Acceptance and efficiencies
- Luminosity (not included)

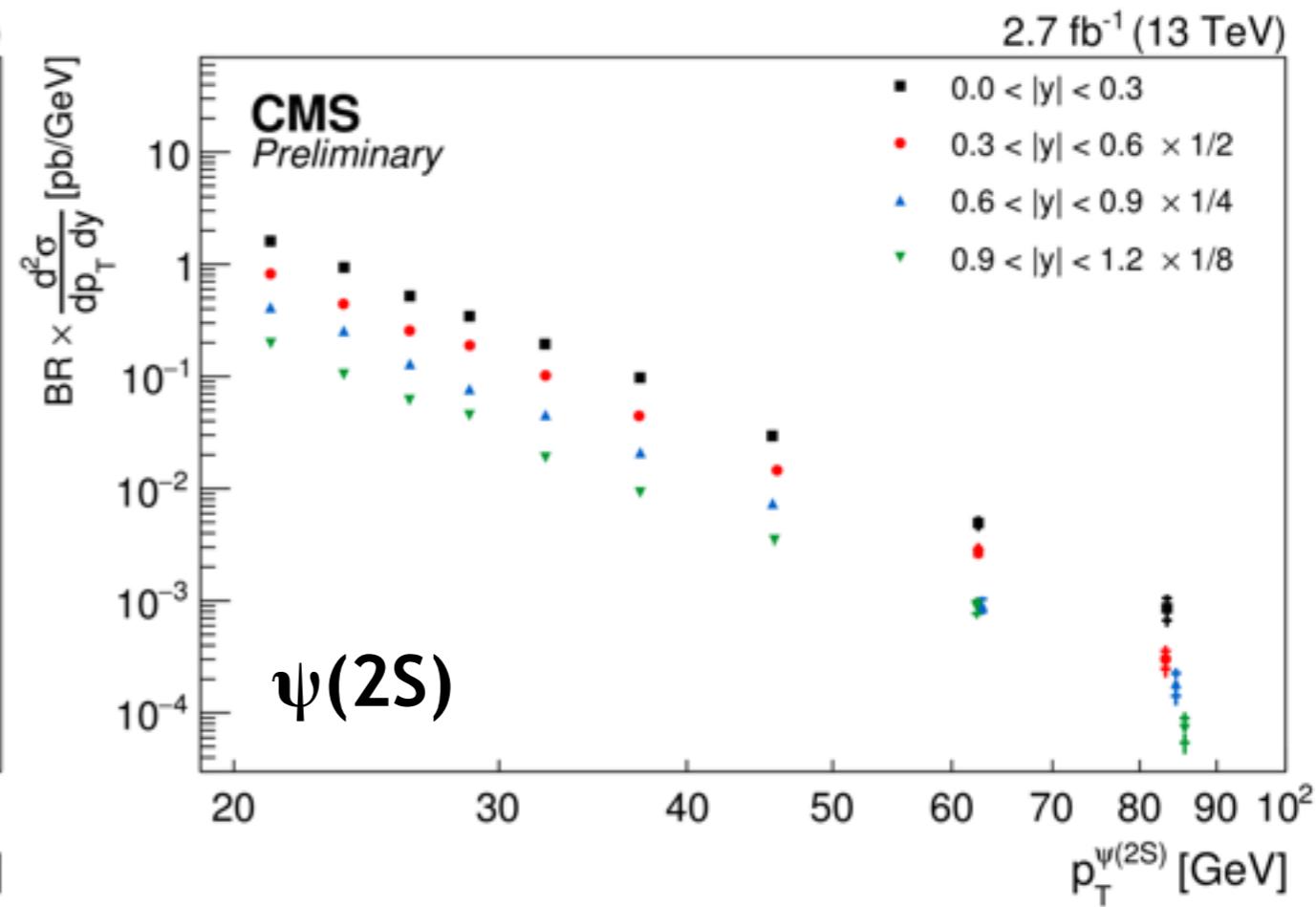
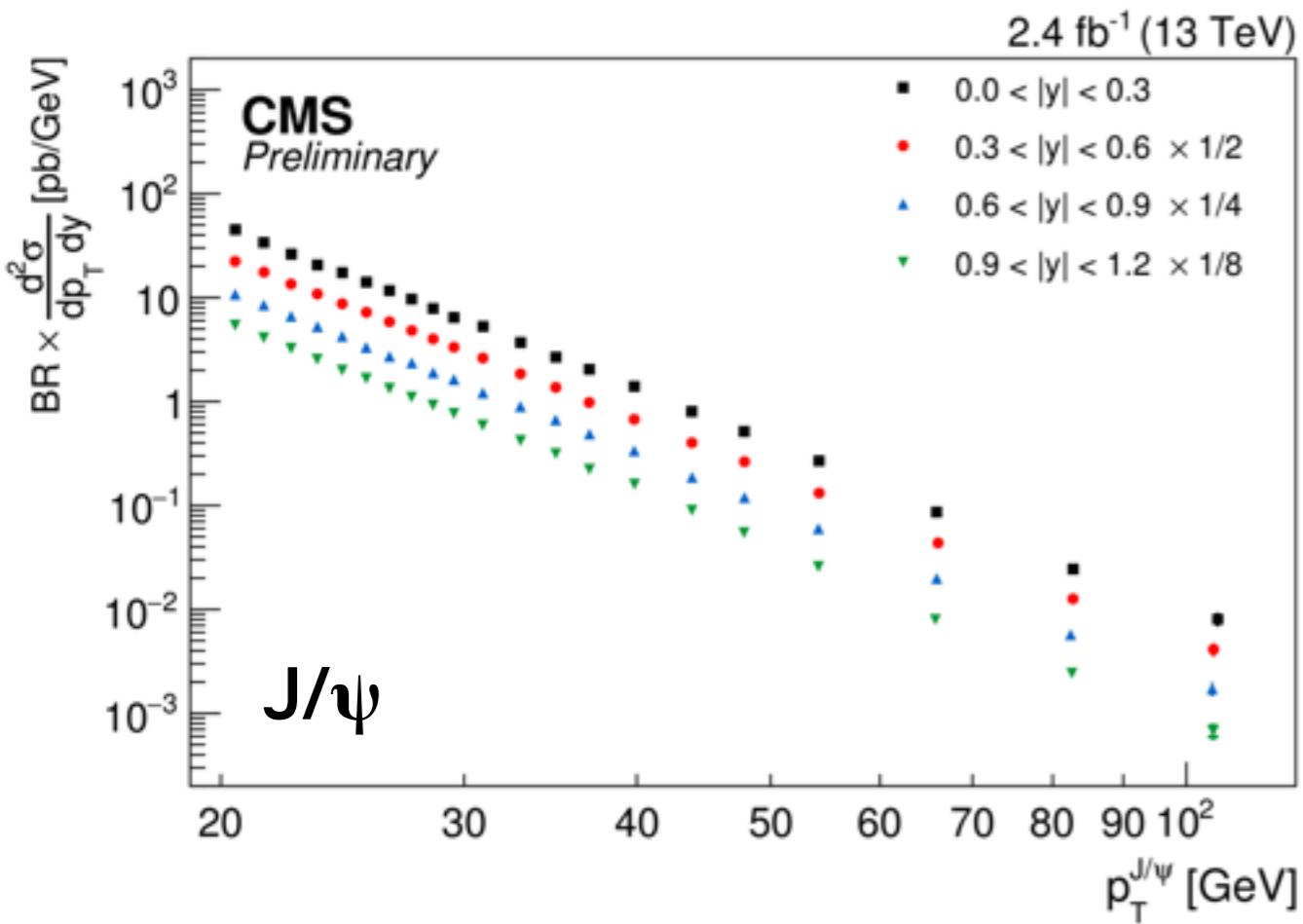


Young blackbuck with geese

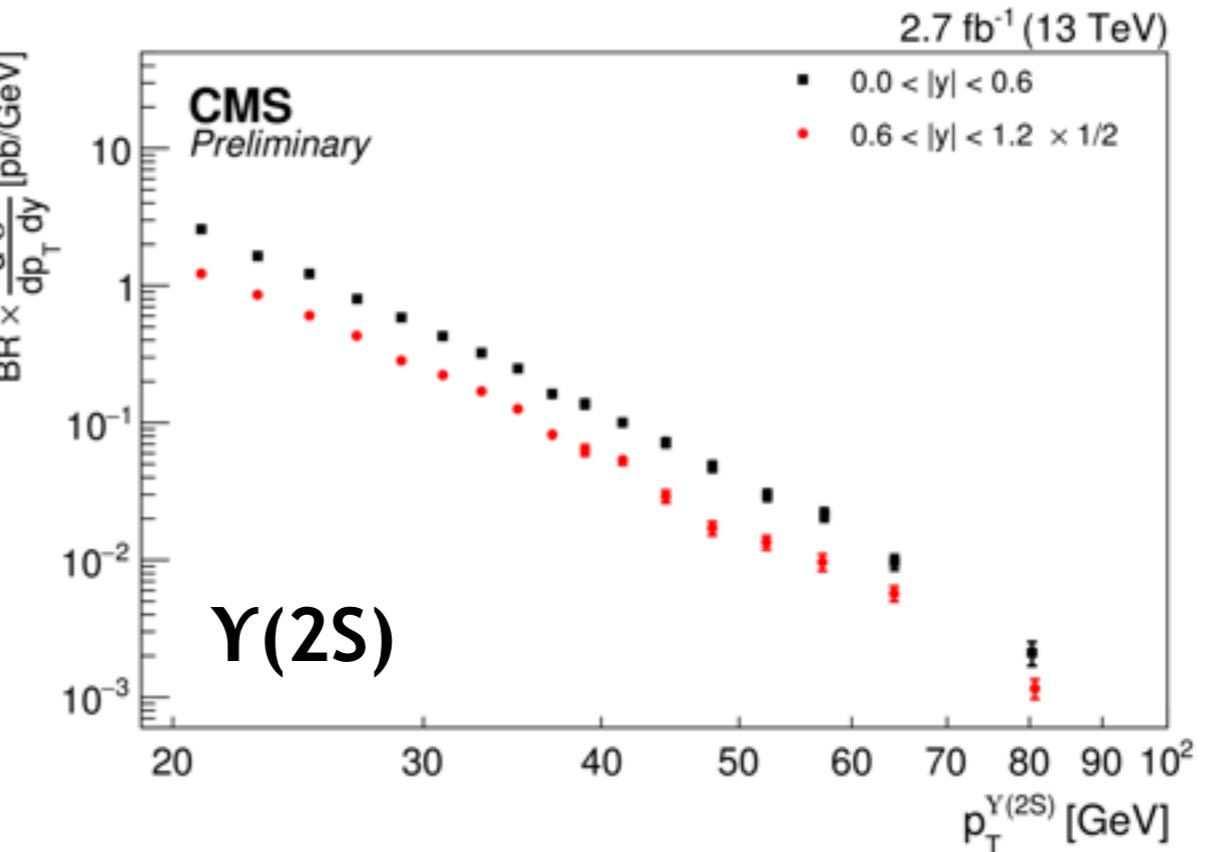
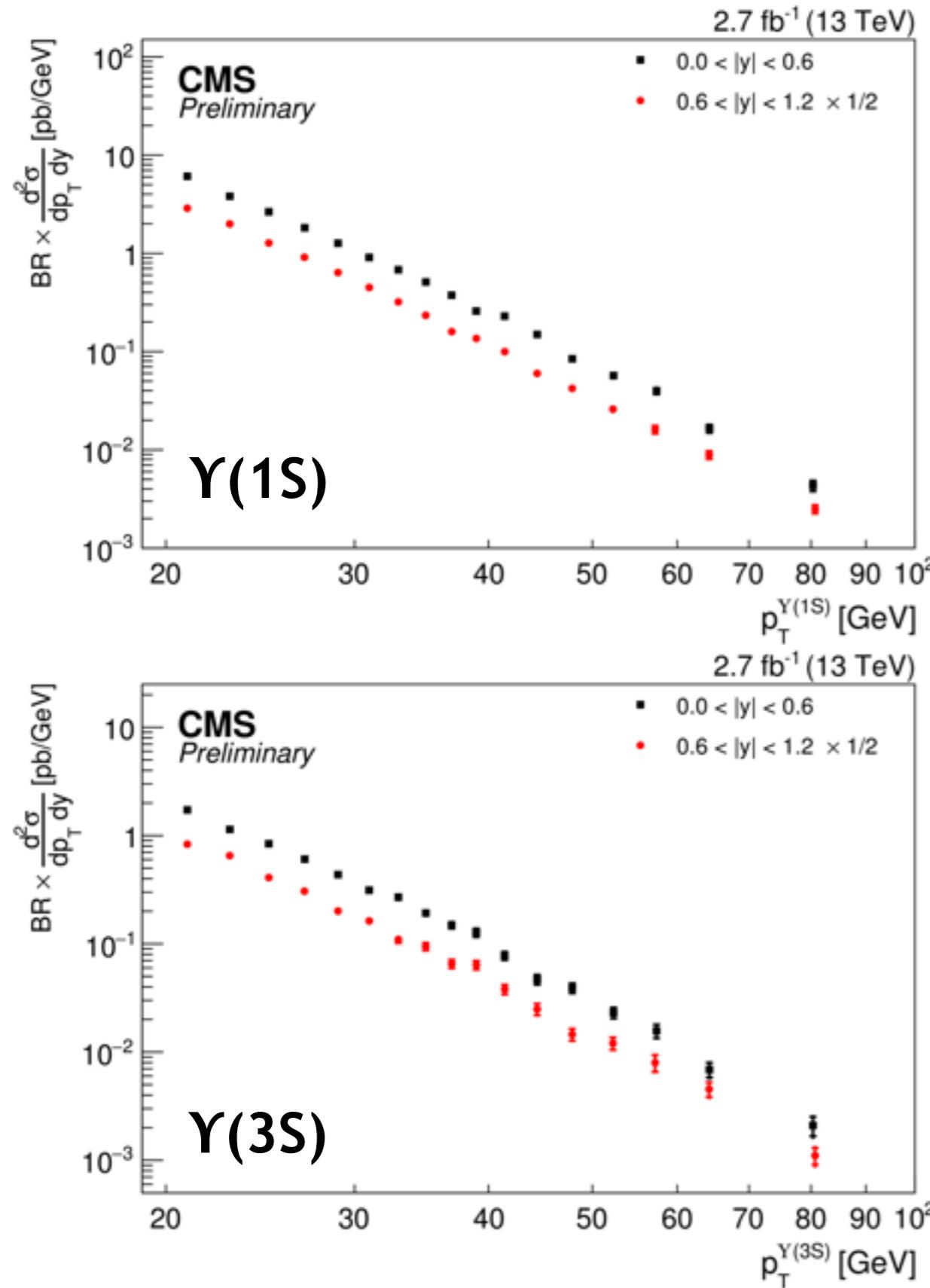
# Prompt $\psi(nS)$ cross sections



- As function of  $p_T$  for four rapidity ranges up to  $|y| = 1.2$



# $\Upsilon(nS)$ cross sections



- As function of  $p_T$  for two ranges of rapidity

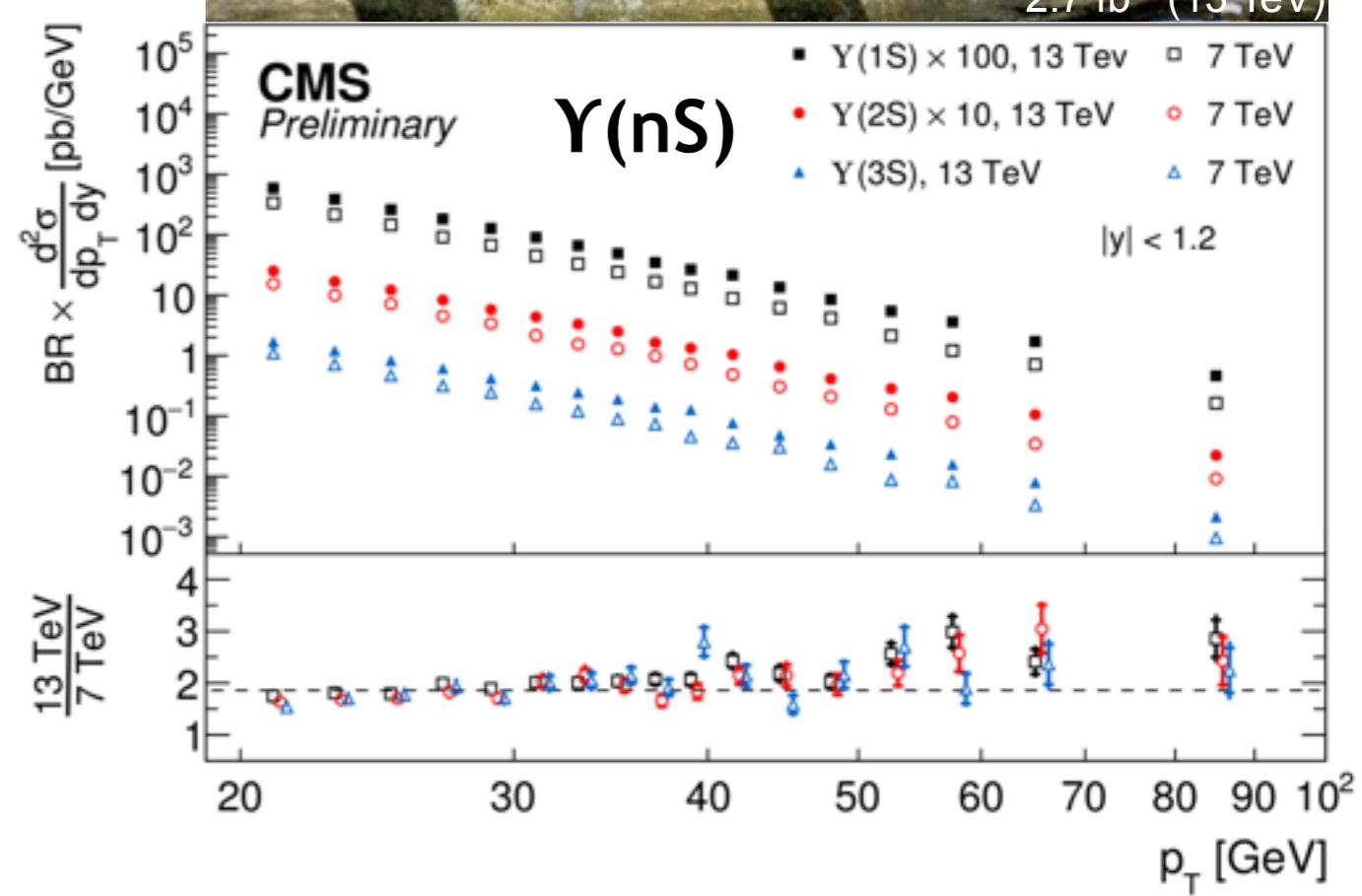
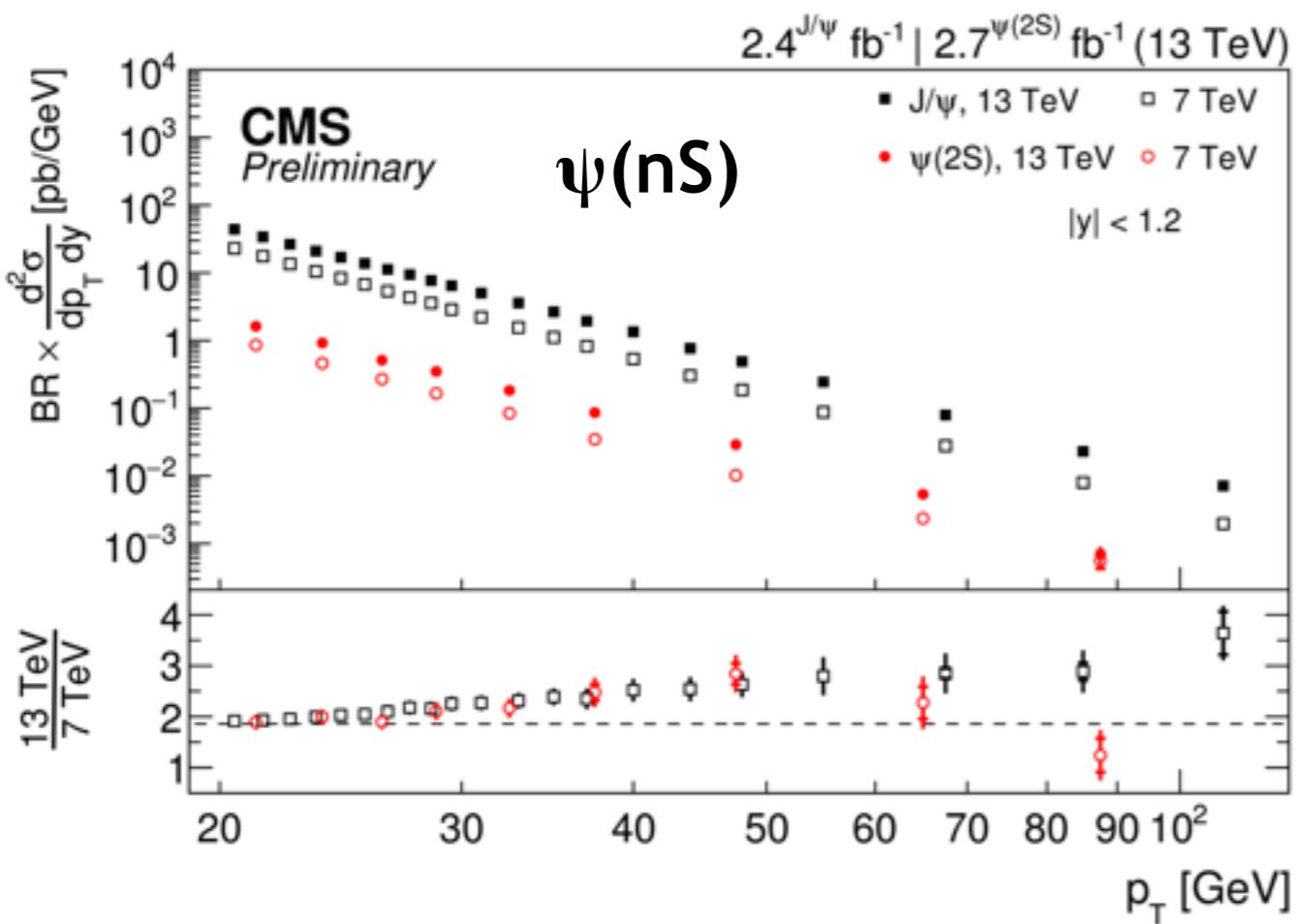
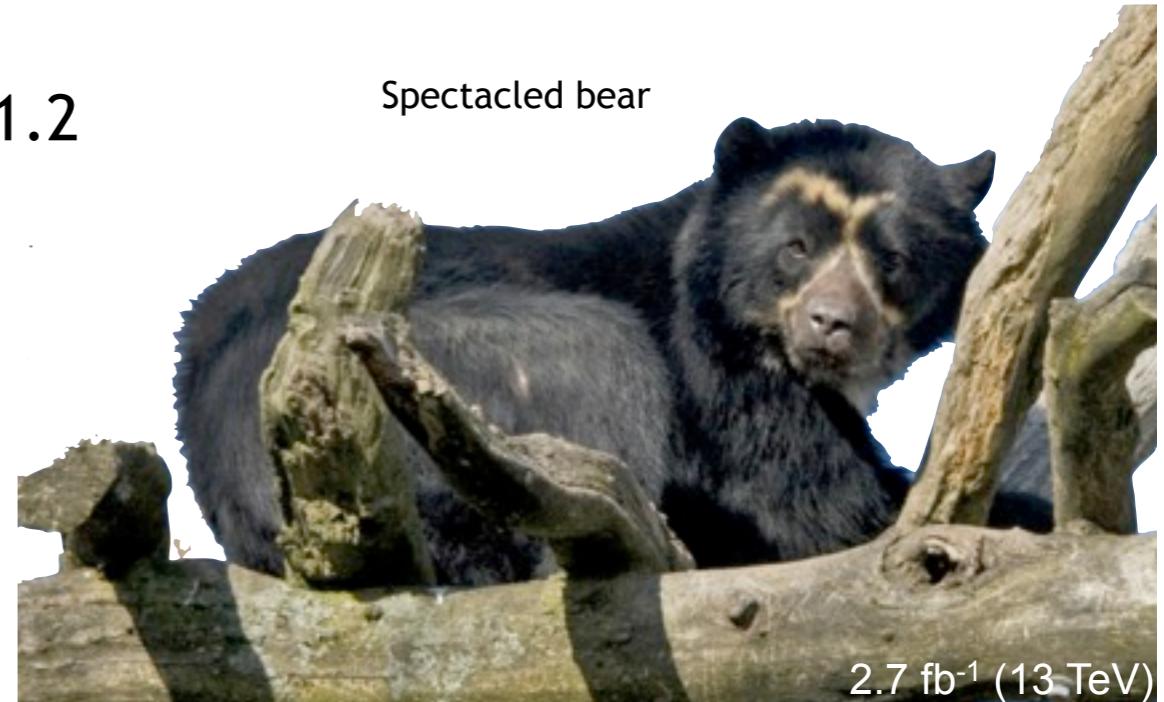


Hypnotoad

# Comparison of 13 TeV to 7 TeV

- Results for rapidity-integrated range,  $|y| < 1.2$
- Cross sections at 13 TeV are 2-3 times larger than the corresponding 7 TeV cross sections

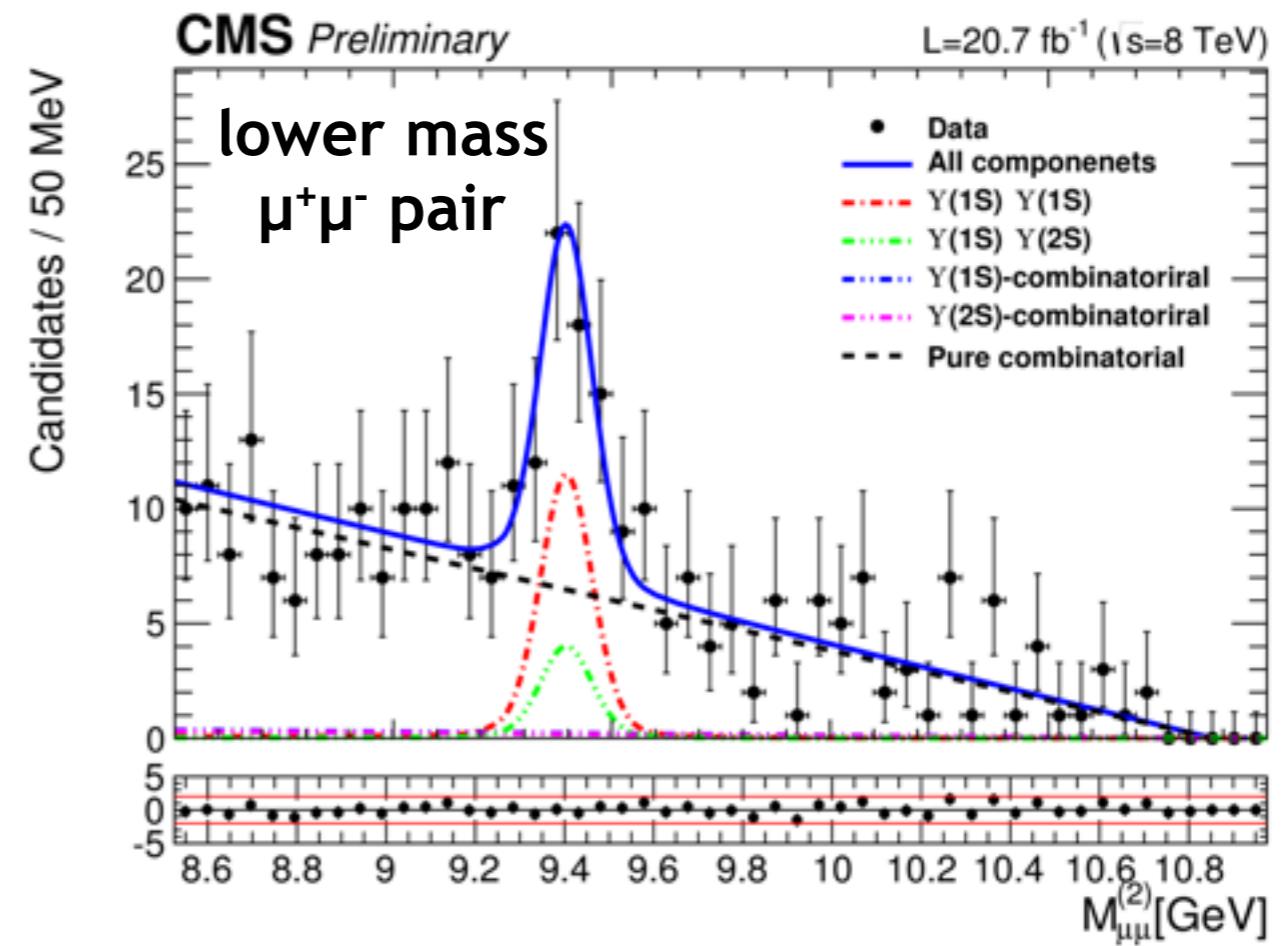
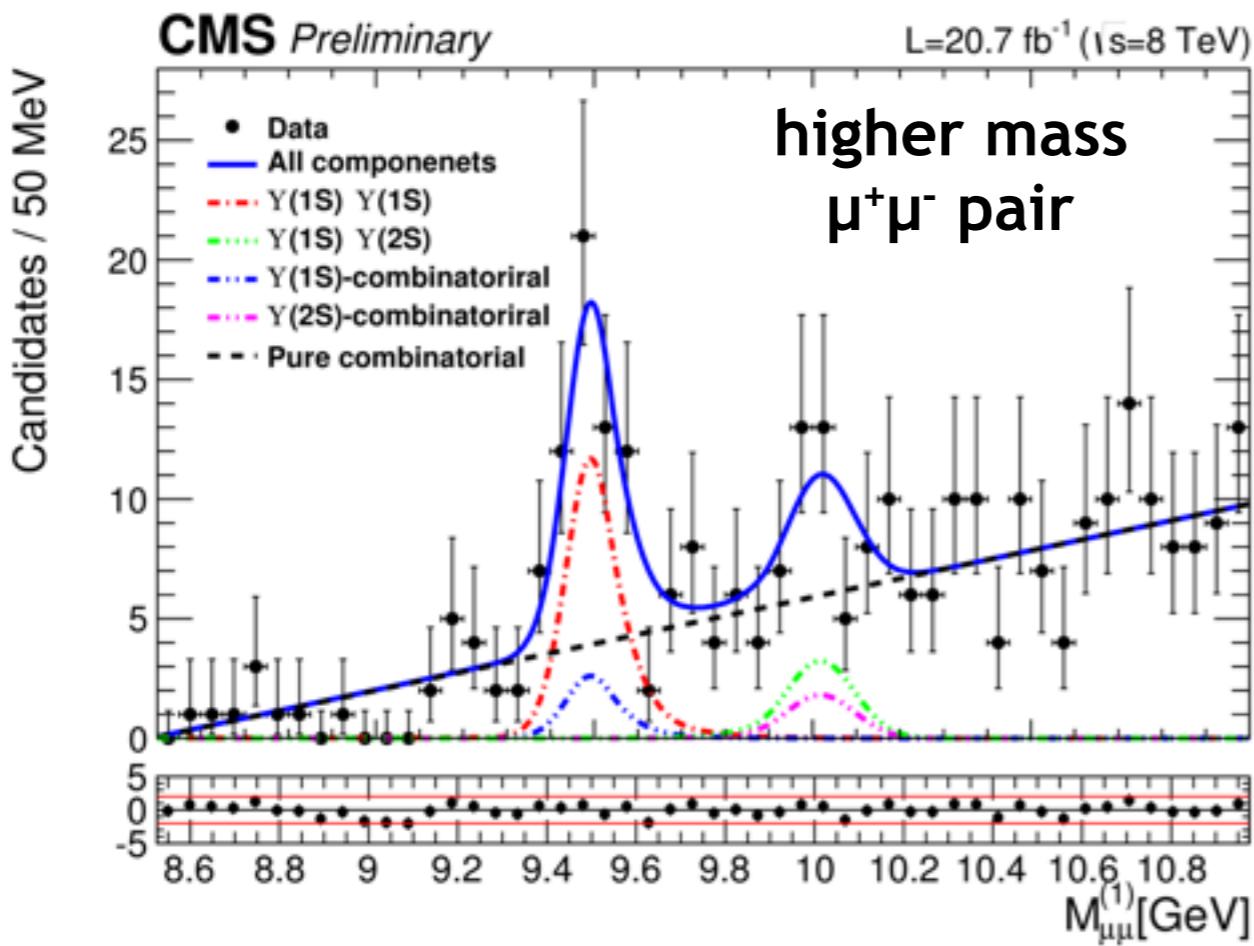
Spectacled bear



# $\Upsilon(1S)$ pair production



- First observation of  $\Upsilon(1S)$  pair production with  $9.2\sigma$
- Dataset taken at  $\sqrt{s} = 8$  TeV corresponding to  $\mathcal{L} = 20.7 \text{ fb}^{-1}$
- $\Upsilon$  candidates are reconstructed via their  $\mu^+\mu^-$  decay
- $38 \pm 7$   $\Upsilon(1S)$  pairs are observed for  $p_T^\Upsilon < 50$  GeV,  $|y^\Upsilon| < 2$



# $\Upsilon(1S)$ pair production cross section

- Systematic uncertainties

- Determination of the yield
- Detector simulation
- Acceptance
- Efficiencies
- Luminosity (2.5%)



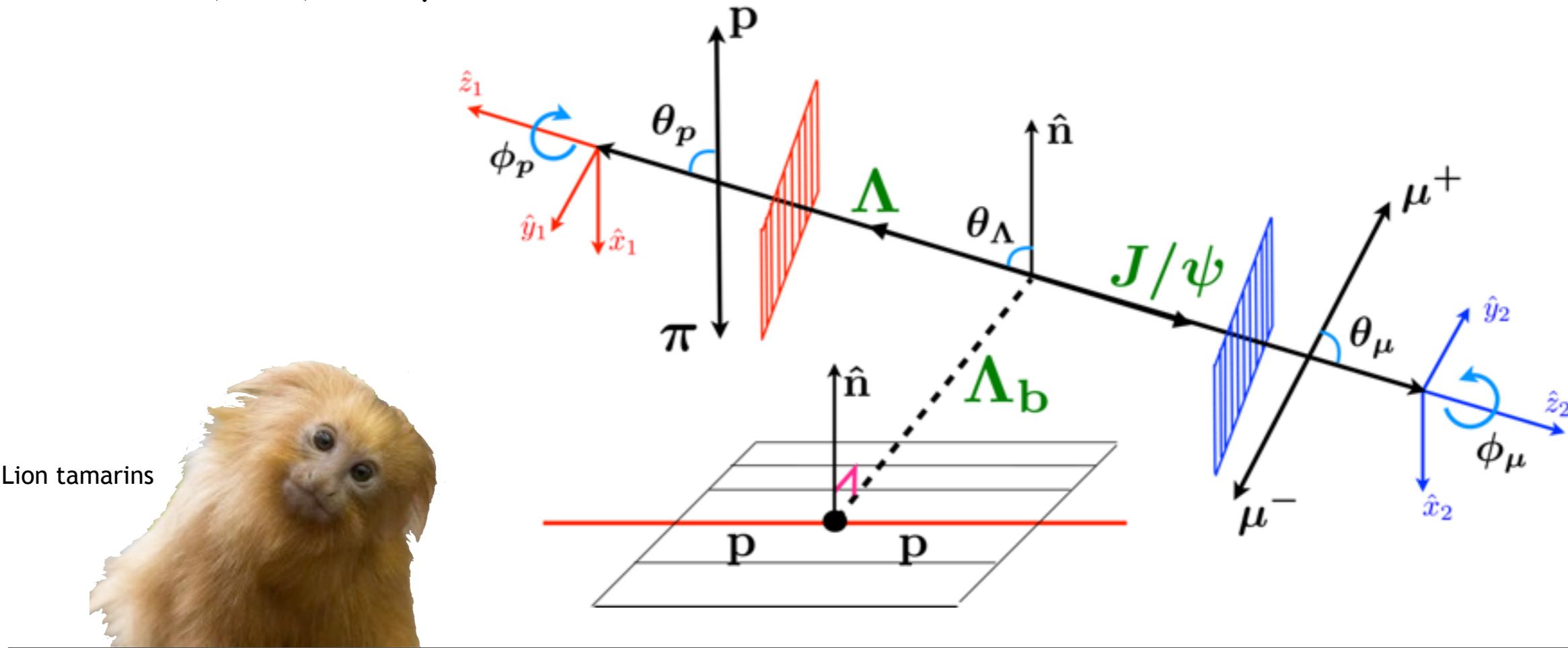
- Total cross section assuming isotropic decays

$$\sigma_T = 68.8 \pm 12.7(\text{stat.}) \pm 7.4 \text{ (syst.)} \pm 2.8 \text{ (BR)} \text{ pb}^{-1}$$

- Polarization changes cross section ranging from -38% to +36%

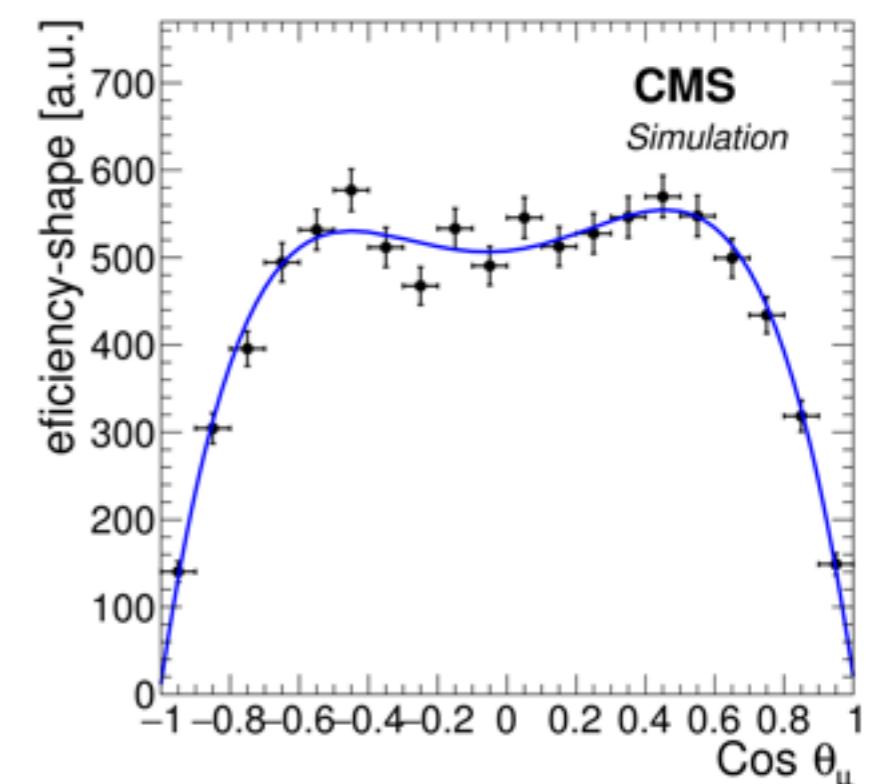
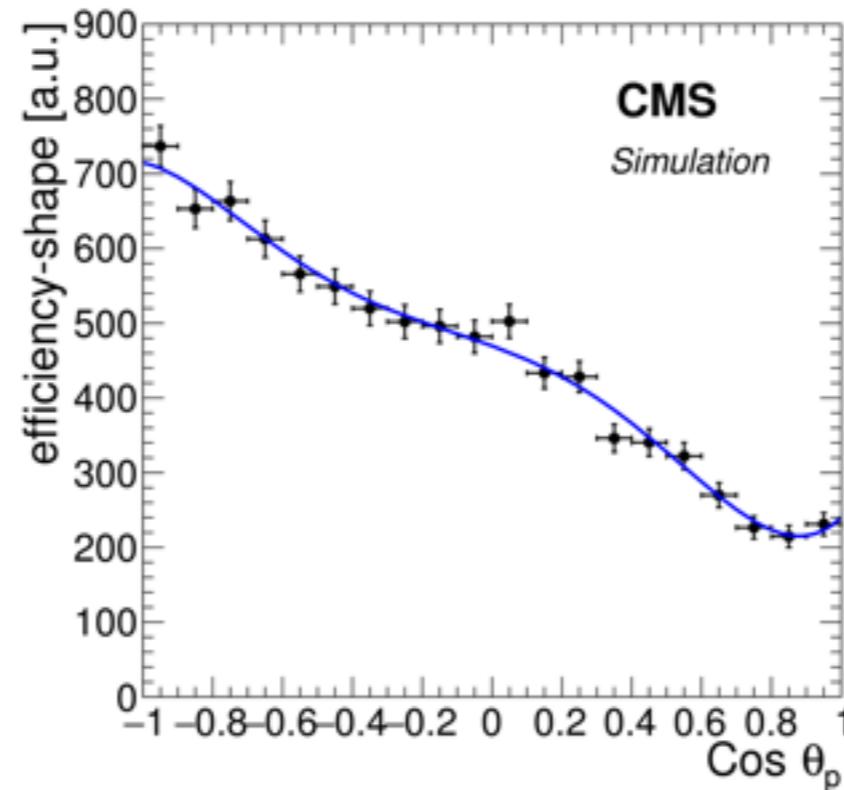
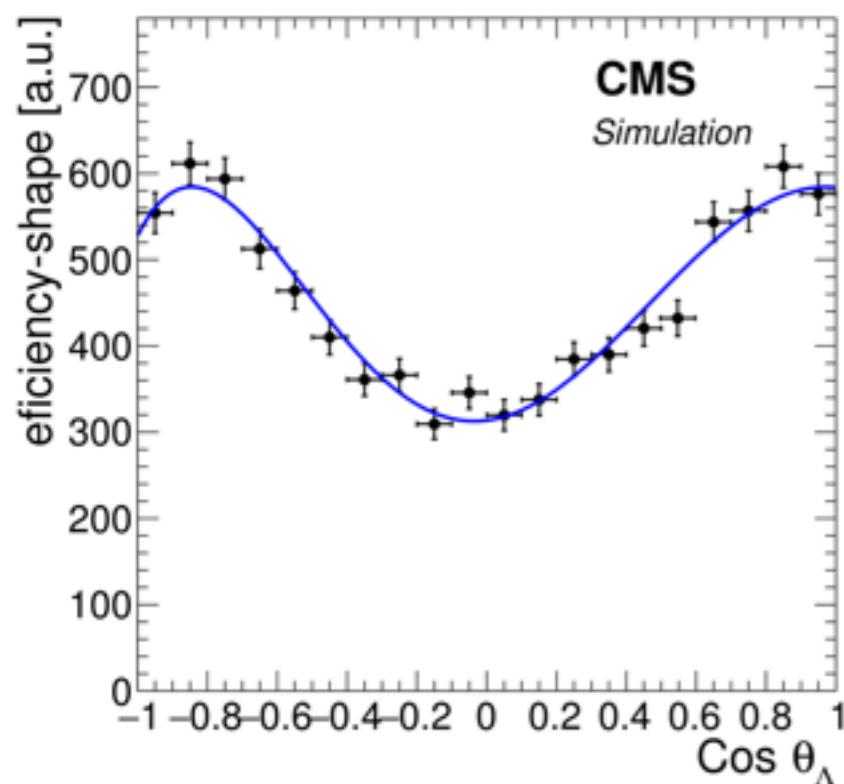
# Angular analysis of $\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$

- Data taken at  $\sqrt{s} = 7$  TeV ( $\mathcal{L} = 5.28 \text{ fb}^{-1}$ ) and 8 TeV ( $\mathcal{L} = 19.7 \text{ fb}^{-1}$ )
- About 6000  $\Lambda_b$  candidates with  $p_T > 10$  GeV reconstructed via their decay to  $J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$
- Angular distributions of  $\Lambda_b$  studied assuming CP conservation and a uniform detector acceptance over  $\phi_p$  and  $\phi_\mu$
- Measurement of  $\Lambda_b$  polarization  $P$  and the angular decay parameters  $\alpha_1$  ( $= -\alpha_b$ ),  $\alpha_2$ ,  $\gamma_0$



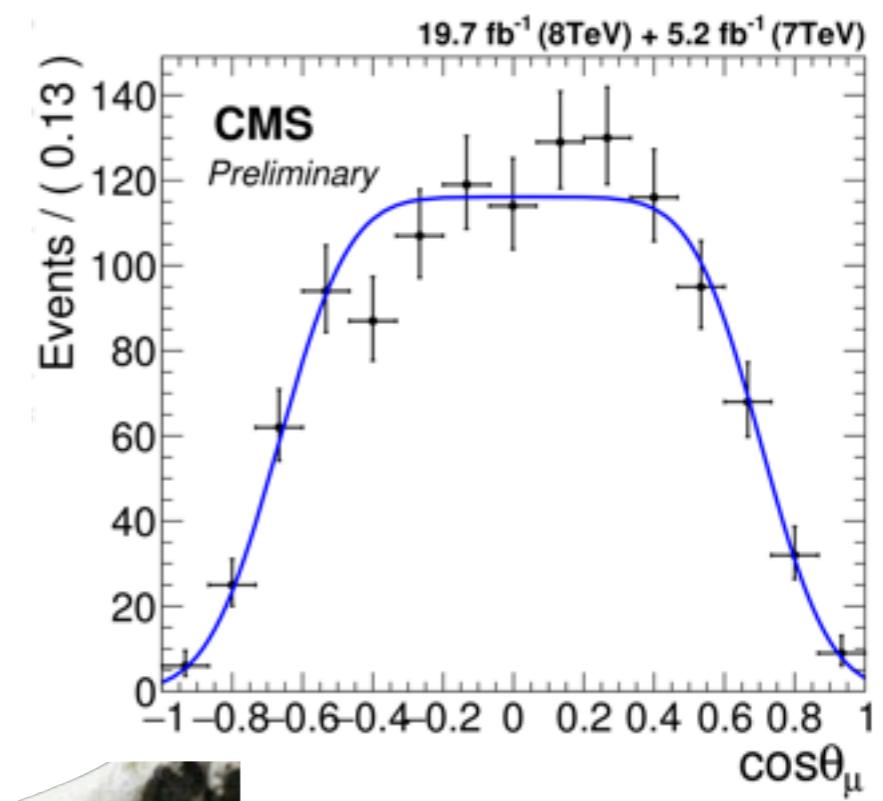
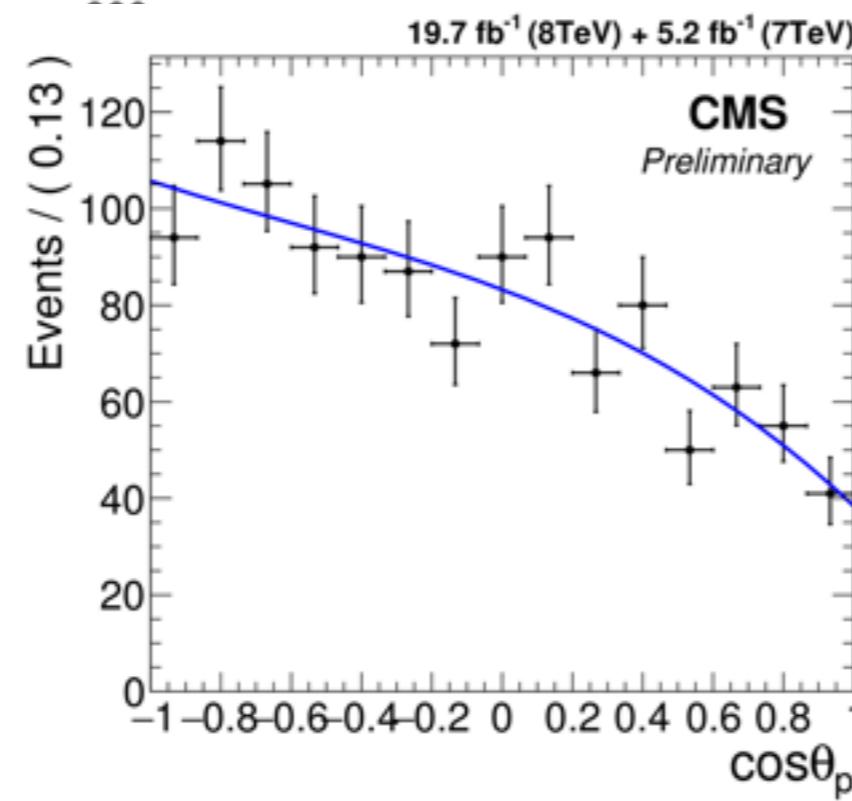
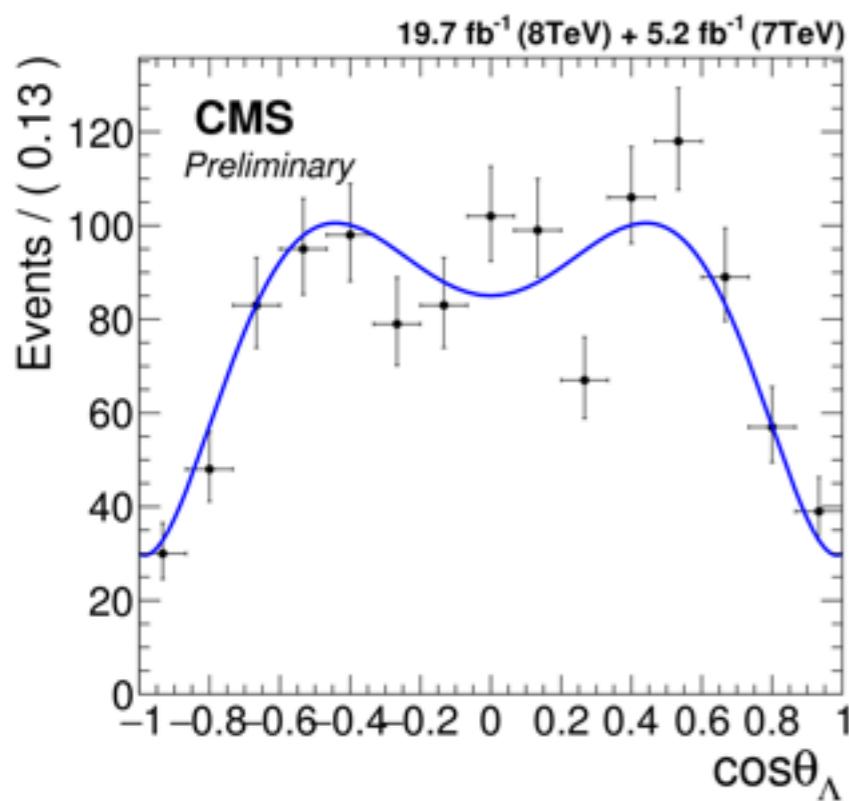
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- Angular efficiency for signal events obtained from simulations

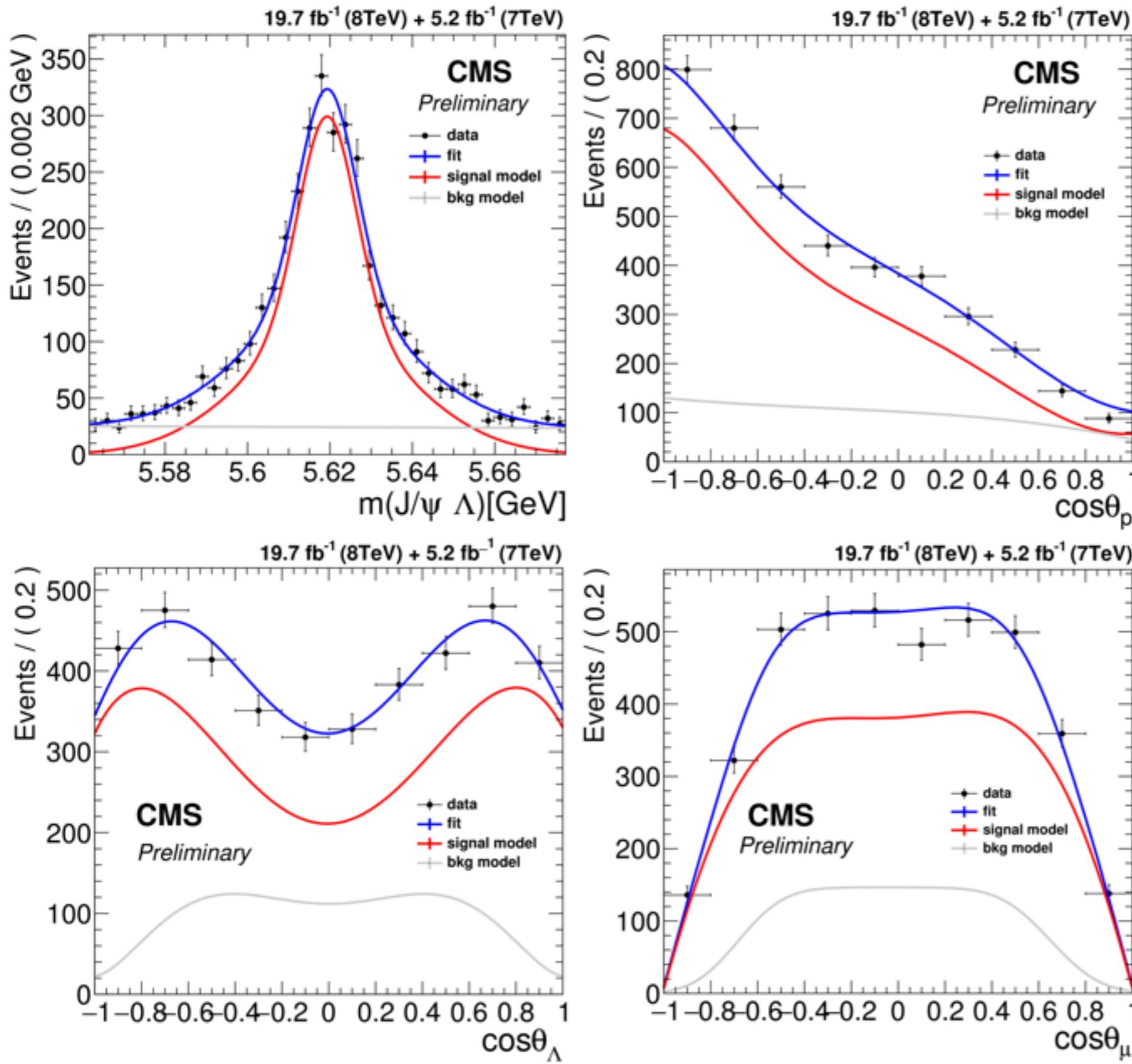


# Angular analysis of $\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$

- Angular efficiency for signal events obtained from simulations
- Angular background distributions modeled from  $\Lambda_b$  sidebands



# $\Lambda_b$ distributions



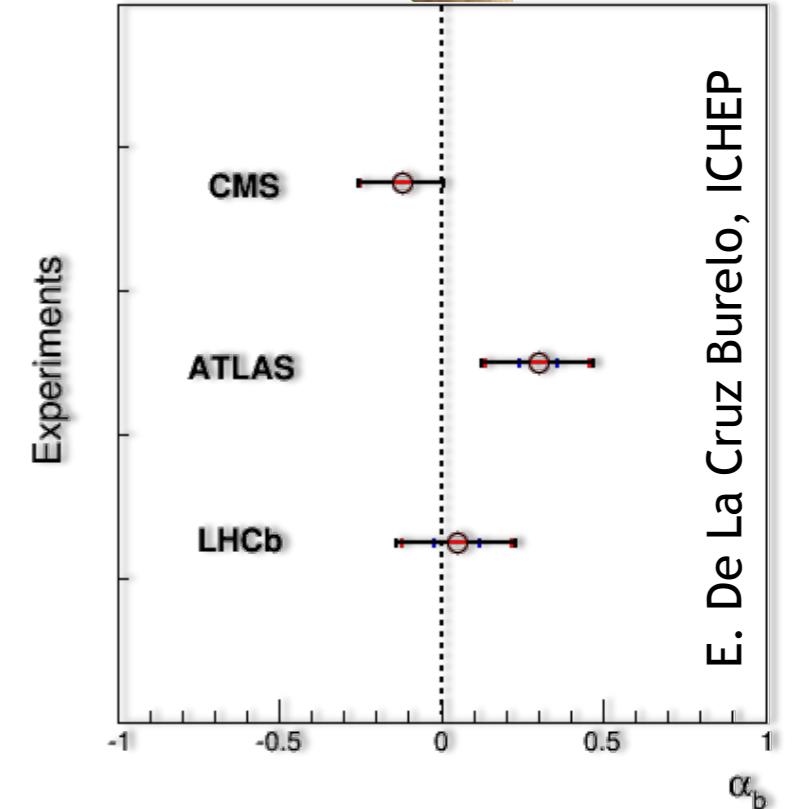
- Unbinned maximum likelihood fit to the invariant mass and angular distributions ( $\cos\theta_\Lambda$ ,  $\cos\theta_p$ ,  $\cos\theta_\mu$ ) is performed in signal enriched mass range
- Parameters for angular background, efficiency shapes and mass distributions are fixed from previous fits



Frilled-neck lizard

# $\Lambda_b$ polarization and decay parameters

- Systematic uncertainties
  - Signal and background mass model
  - Background angular model
  - Angular efficiency
  - Angular resolution
  - Azimuthal efficiency
  - Asymmetry parameter  $\alpha_\Lambda$  (fixed to  $0.642 \pm 0.013$ )
  - Reweighting procedure of simulations
  - Fit and reconstruction bias
- Measured values



$$P = 0.00 \pm 0.006 \text{ (stat.)} \pm 0.002 \text{ (syst.)}$$

$$\alpha_1 = -\alpha_b = 0.12 \pm 0.13 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

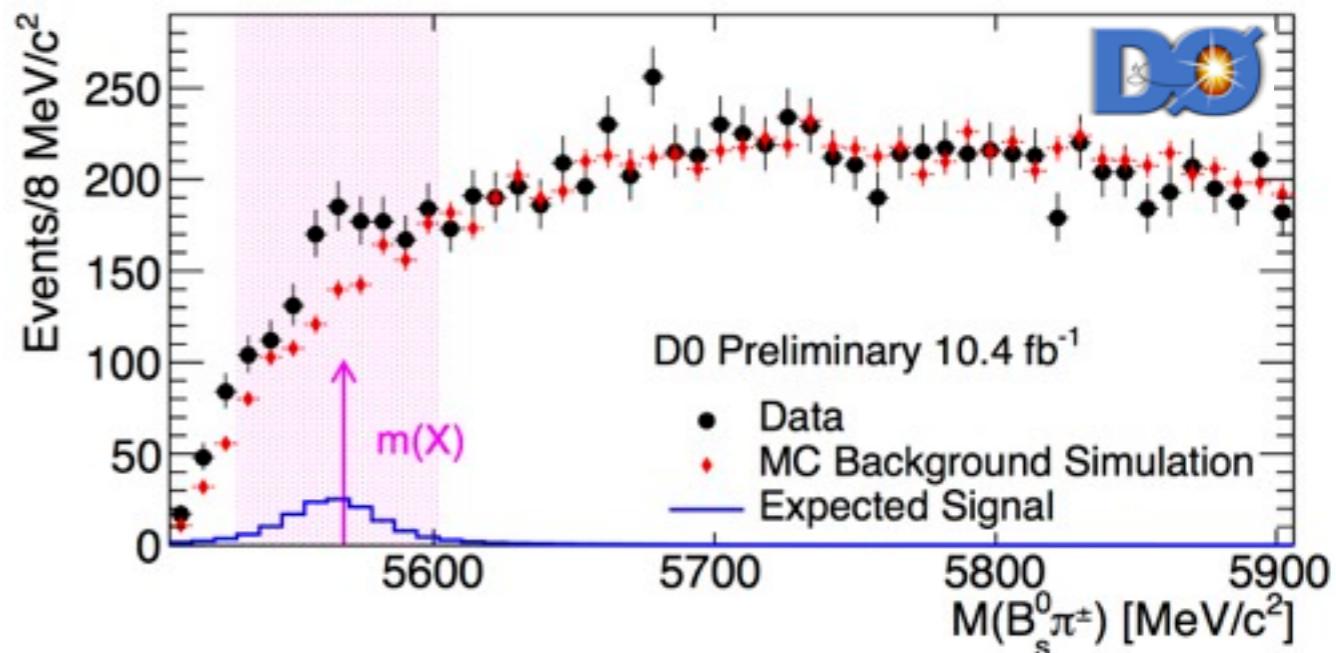
$$\alpha_2 = -0.93 \pm 0.04 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$$

$$\gamma_0 = -0.46 \pm 0.07 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$$

# Search for X(5568) in $B_s^0\pi^\pm$ decays

DØ Note 6488-CONF

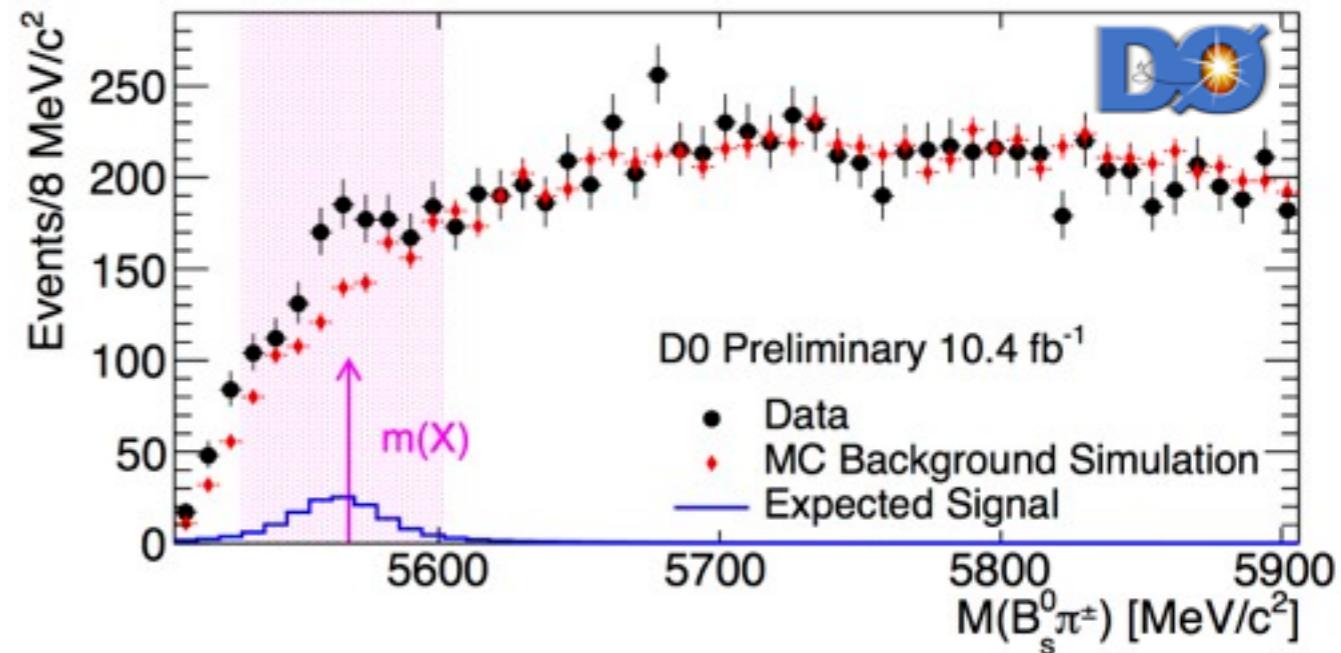
- DØ observed a narrow structure at  $m = 5.567 \text{ GeV}$  in the  $B_s^0\pi^\pm$  spectrum



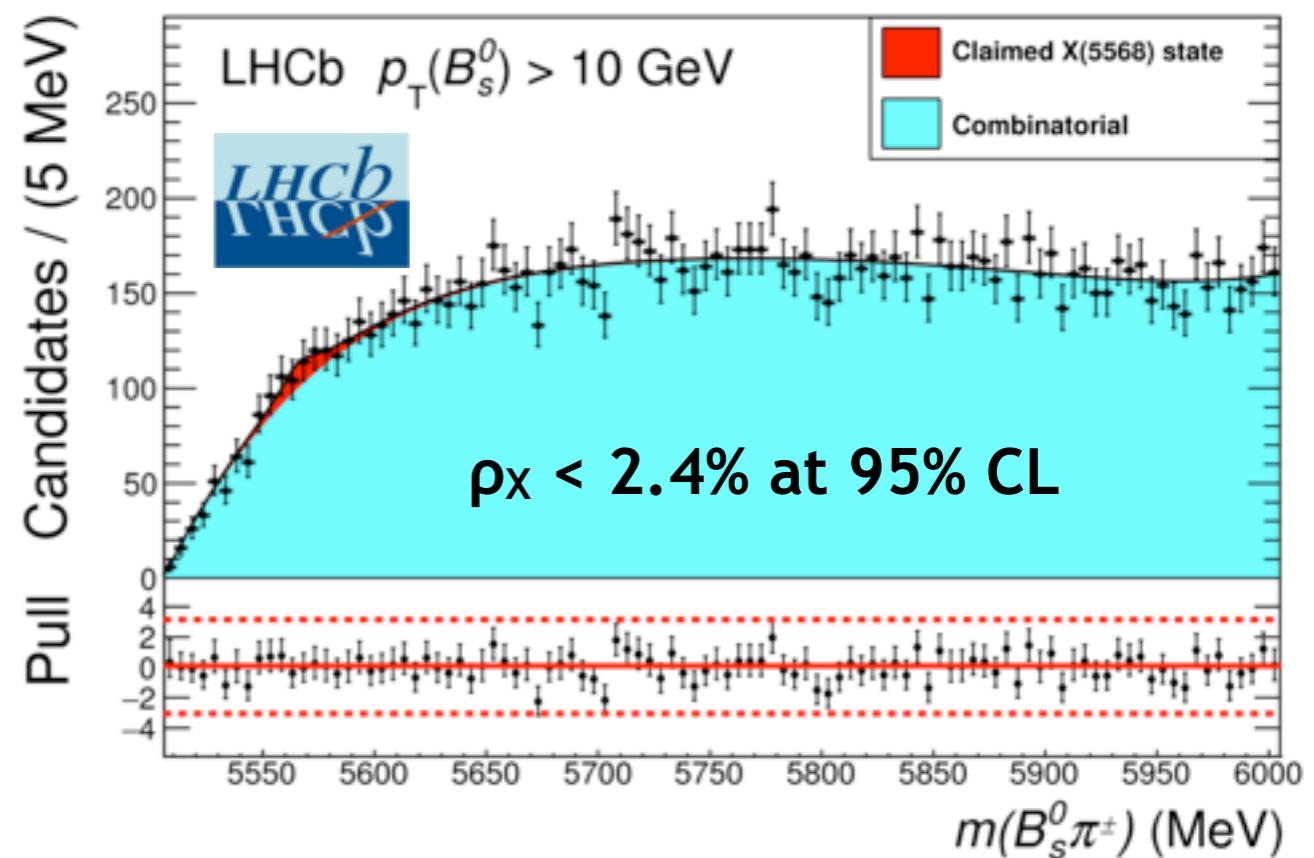
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- LHCb found no significant excess and set an upper limit  $\rho_X$  on the production rate of X(5568)

DØ Note 6488-CONF



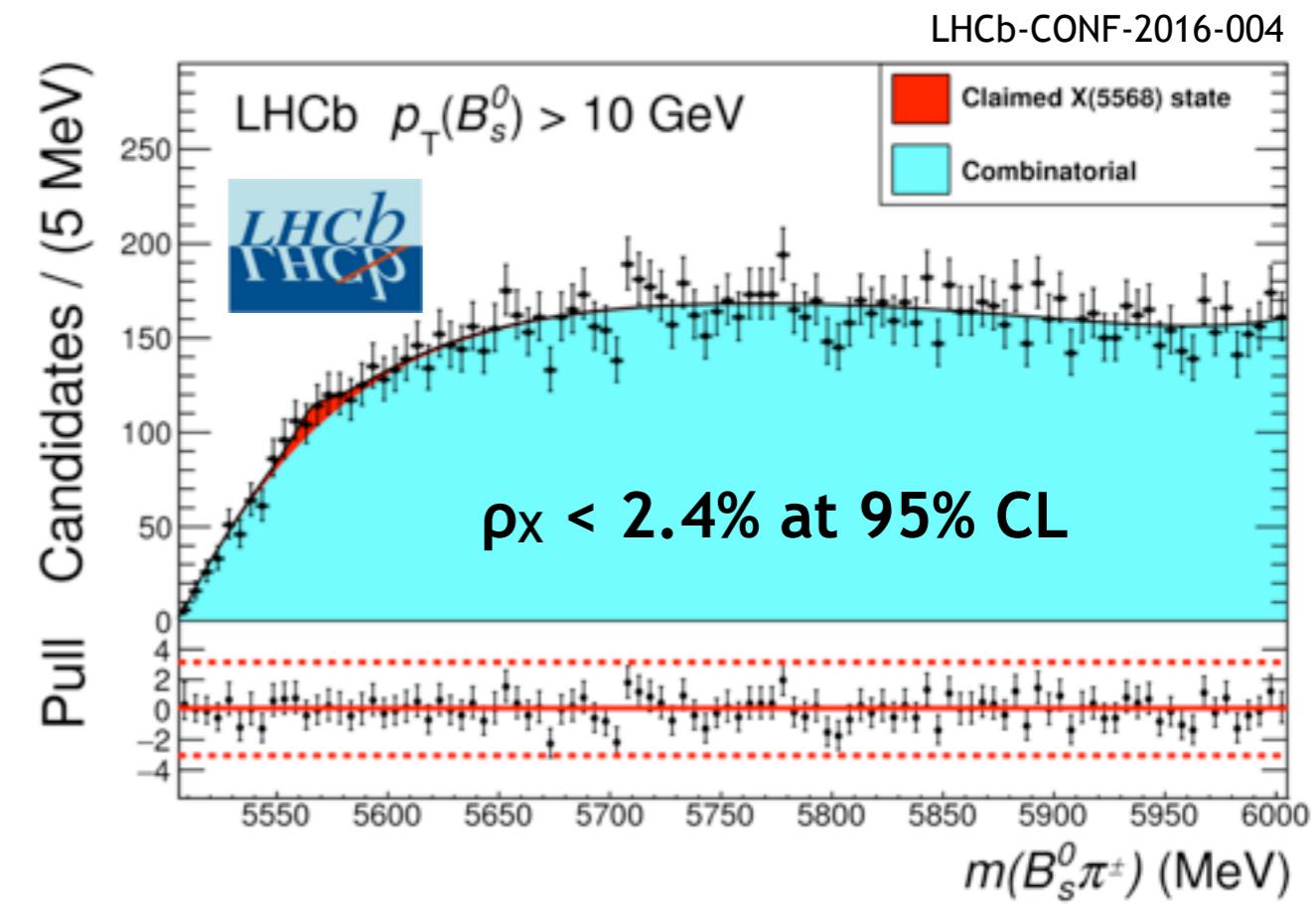
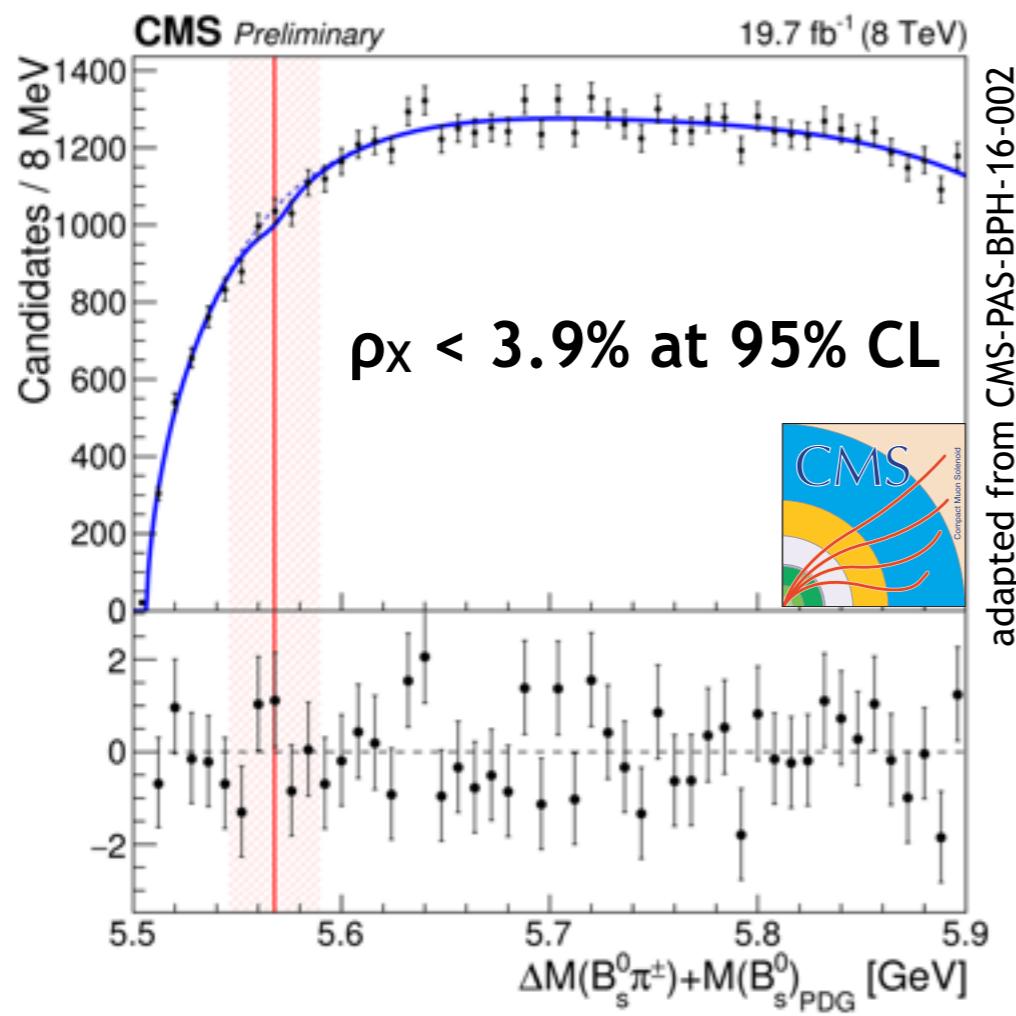
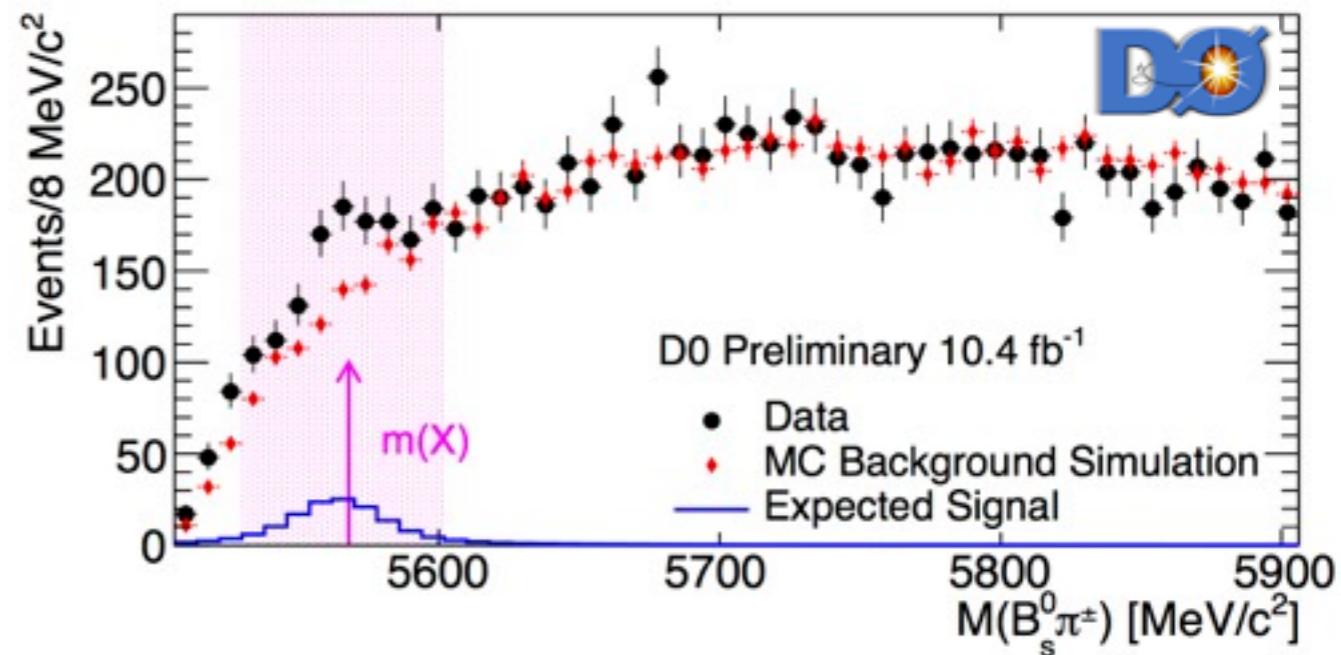
LHCb-CONF-2016-004



# Search for X(5568) in $B_s^0\pi^\pm$ decays

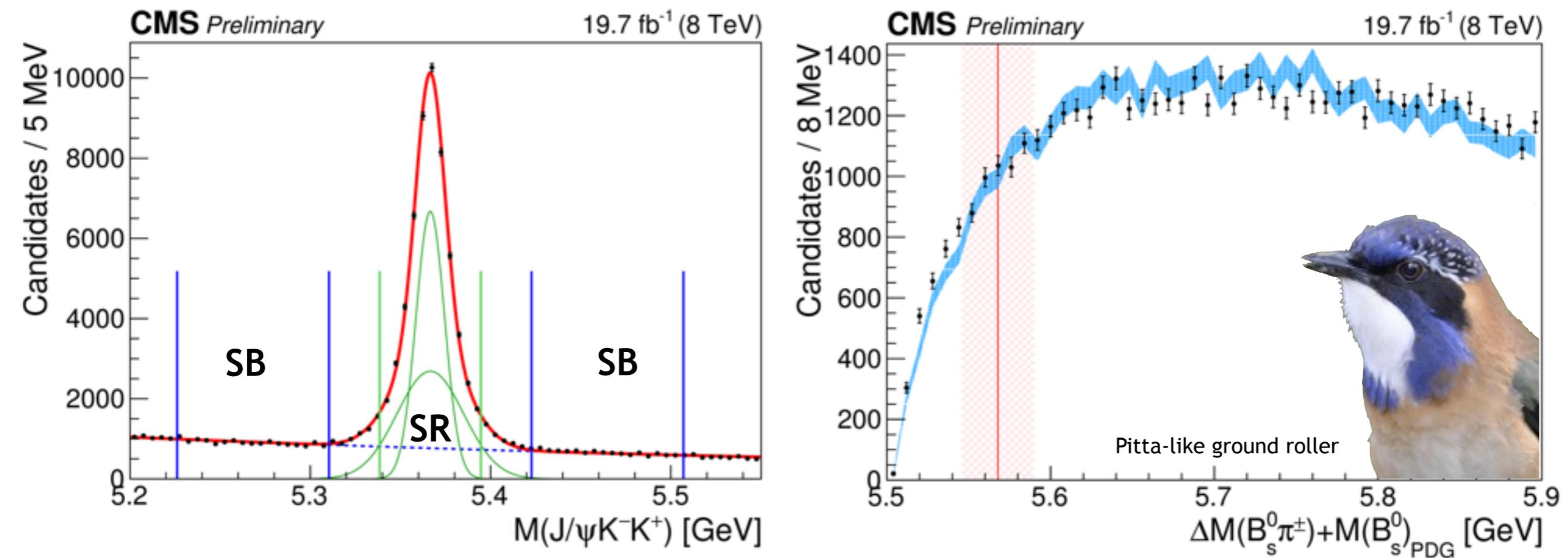
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- LHCb found no significant excess and set an upper limit  $\rho_X$  on the production rate of X(5568)
- CMS also does not see any signal and sets an upper limit

DØ Note 6488-CONF



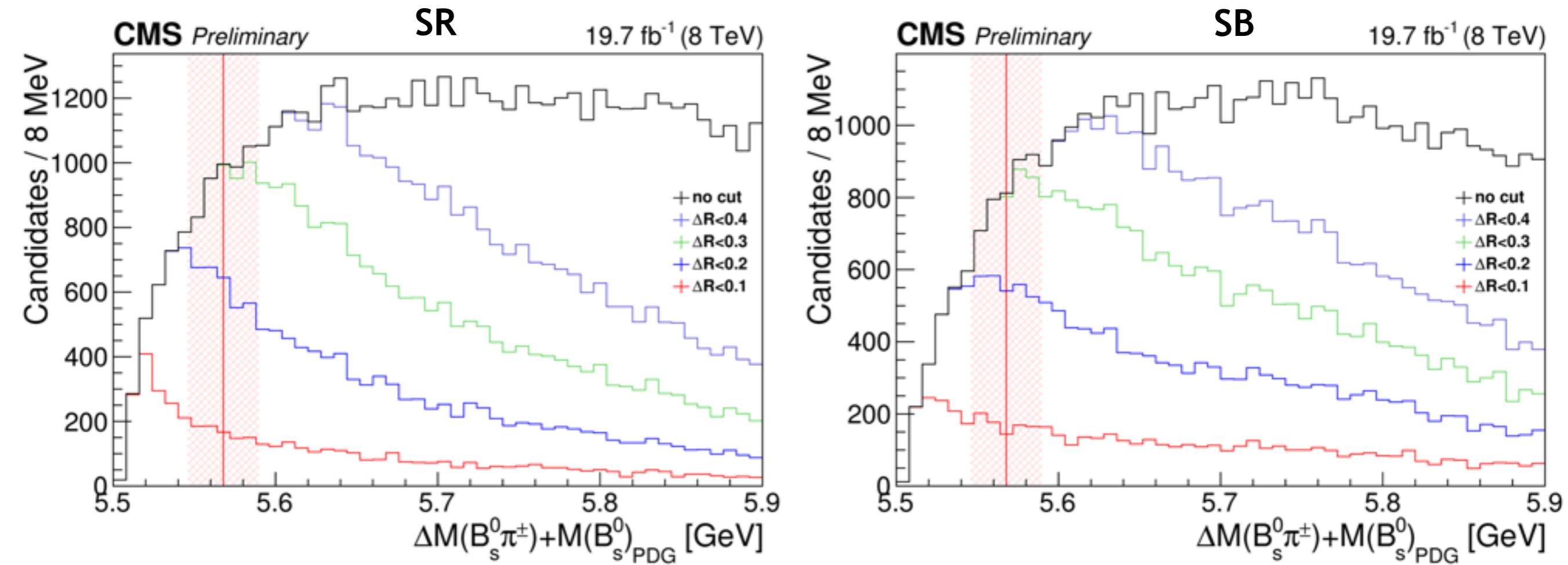
# Search for X(5568) in $B_s^0\pi^\pm$ decays

- Data taken at  $\sqrt{s} = 8$  TeV corresponding to an integrated luminosity of  $\mathcal{L} = 19.7 \text{ fb}^{-1}$
- About 48 000  $B_s^0$  signal events are observed decaying to  $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- Reconstruction procedure is verified using  $B_{1,2}^{(*)+} \rightarrow B^{(*)0}\pi^\pm$
- No excess events in the  $B_s^0$  signal region (SR) w.r.t. the sidebands (SB)



# Search for X(5568) in $B_s^0\pi^\pm$ decays

- No significant structure found in fits to the  $B_s^0\pi^\pm$  mass spectrum
  - Including an X(5568) component
  - Using different kinematic selection requirements, background modeling, fit regions and quality criteria
- Events in  $B_s^0$  signal and sideband region are investigated with  $\Delta R$  requirement used by DØ

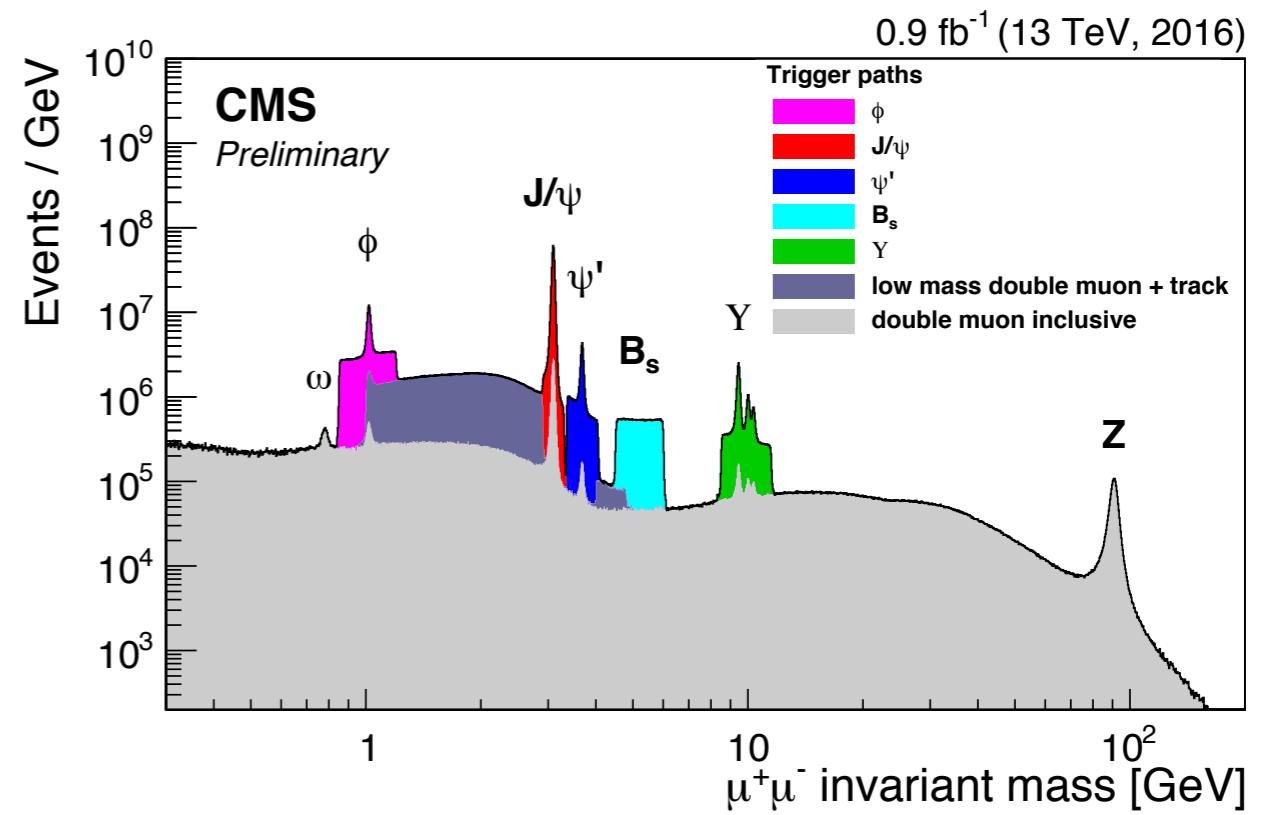


# Summary and outlook

- Recent results on quarkonia and heavy quarks have been presented
  - Search for the X(5568) state in  $B_s^0\pi^\pm$  decays at  $\sqrt{s} = 8$  TeV
  - Measurement of the  $\Lambda_b$  polarization and the angular parameters of the decay  $\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$  at  $\sqrt{s} = 7$  and 8 TeV
  - Observation of  $\Upsilon(1S)$  pair production at  $\sqrt{s} = 8$  TeV
  - Quarkonium production cross sections in pp collisions at  $\sqrt{s} = 13$  TeV
- All measurements can be found at  
<http://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html>
- 2016 data taking is commencing very well



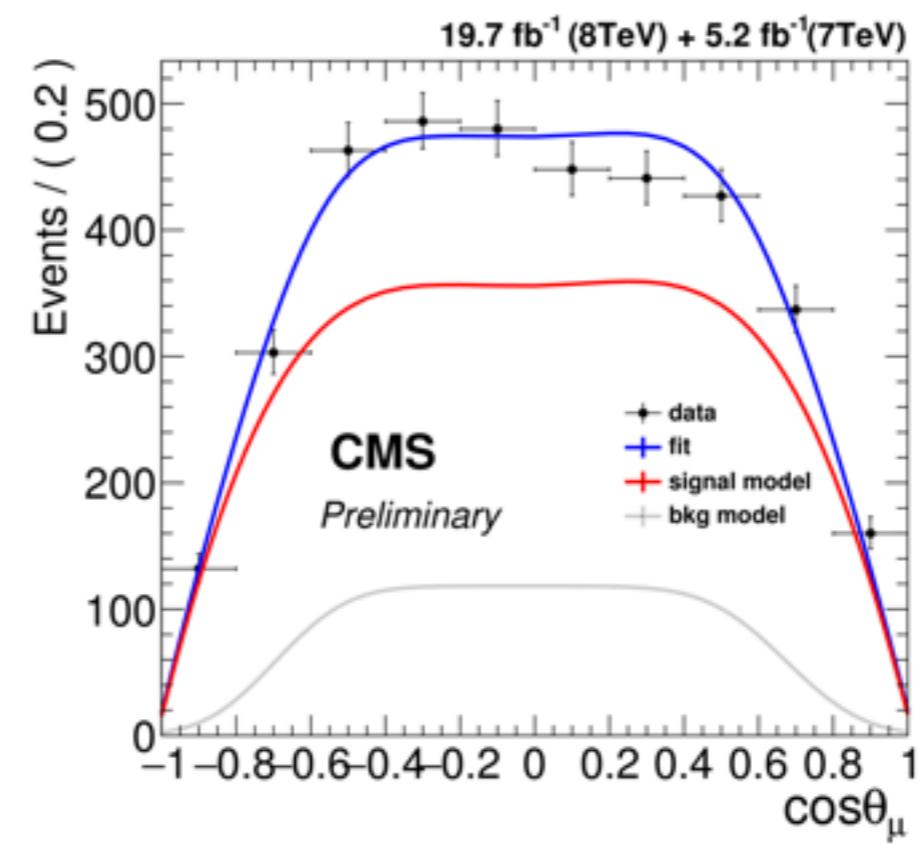
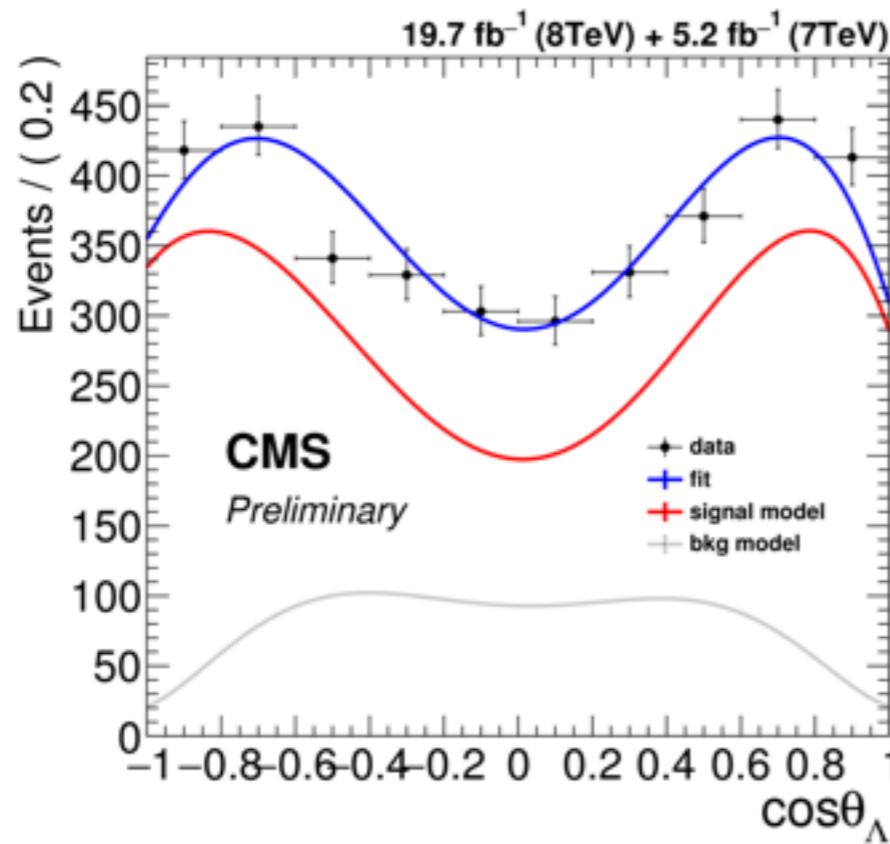
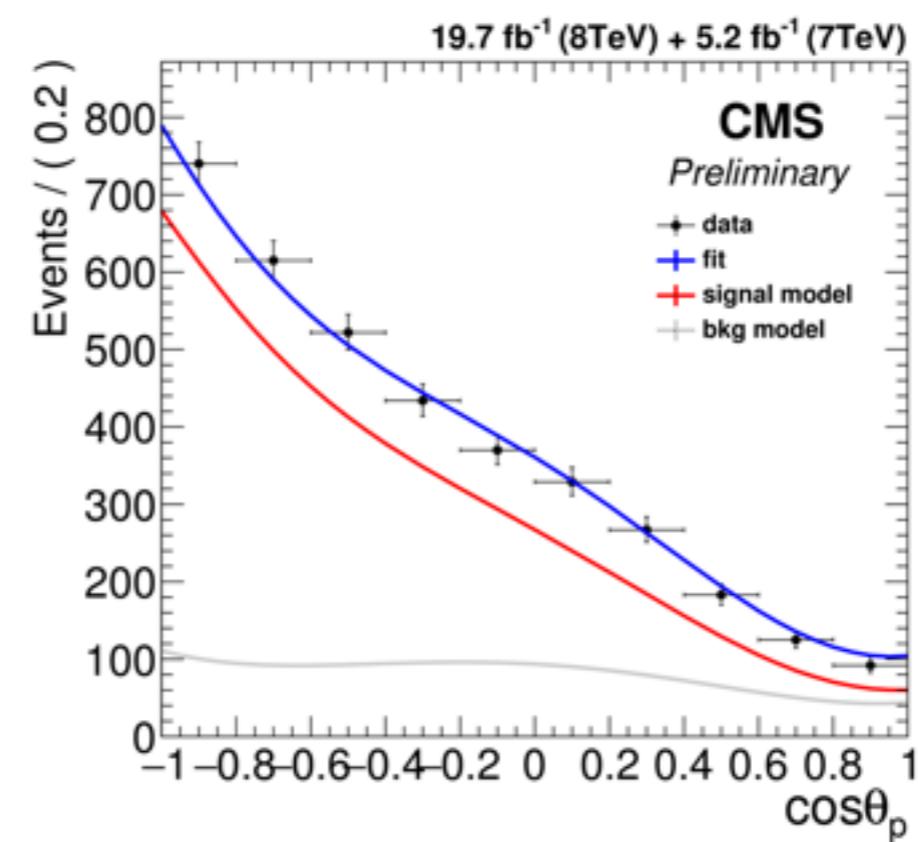
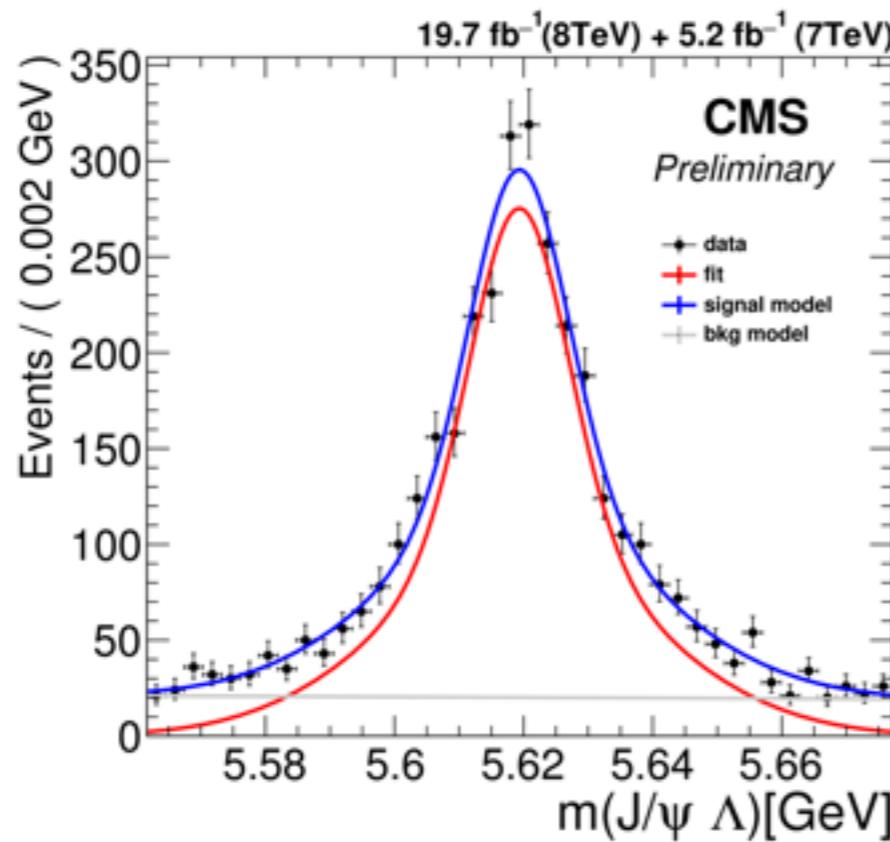
Burrowing owls



A photograph of three Red-ruffed Lemurs (Varecia rubra) in a dense forest setting. Two lemurs are perched on a large, textured tree trunk; one is facing left and the other is facing right. A third lemur is sitting on the ground in front of the trunk, looking towards the camera. The lemurs have distinctive black faces and orange-brown bodies. Large, bright green fern fronds frame the scene, creating a lush, tropical atmosphere.

**BACKUP**

# $\bar{\Lambda}$ distributions



# Search for X(5568) in $B_s^0\pi^\pm$ decays

- Reconstruction procedure is verified using  $B_{1,2}^{(*)+} \rightarrow B^{(*)0}\pi^\pm$ 
  - Similar decay topology
  - Requirement on the invariant mass  $M(K^+K^-)$  removed
  - Broad contribution of  $B^0 \rightarrow J/\psi K^+\pi^-$

