9.11.2017 **EMMI2017**, *Torino*

Overview of exotica production at CMS

Latest results from the **Run I** data

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for the CMS collaboration

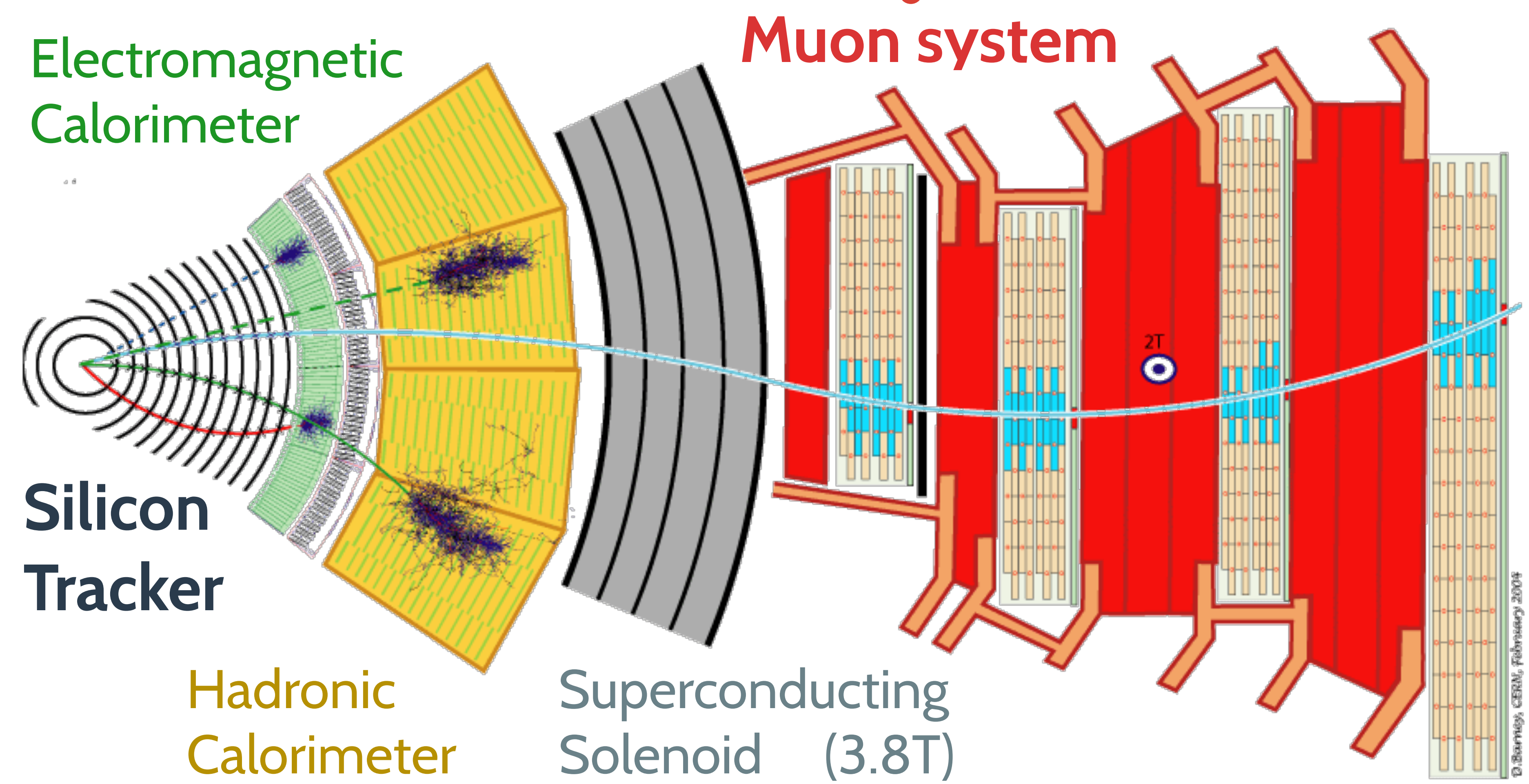
Outline

- **CMS experiment introduction**
- **Overview of main CMS results:**
  - **Y(4140)** *[7 TeV]*
  - **X(3872)** *[7 TeV]*
  - ***X_b partner of* X(3872)** *[8 TeV]*
  - **X(5568)** *[8 TeV]*

CMS experiment: detector

Compact Muon Solenoid: detector optimised for measuring muons

Combination of subdetectors to identify + measure particle properties



Precise track reconstruction:

- p_T resolution: $\boldsymbol{\Delta p_T/p_T \approx 1\%}$ (barrel)
- tracking efficiency: > **99%** (central)
- impact-parameter resolution: **down to 15 μm**

Excellent muon identification:

- wide rapidity coverage: $\boldsymbol{|\eta| < 2.4}$
- $m(\mu\mu)$ resolution: $\boldsymbol{\Delta m/m \approx 0.6\%}$
- fake rate: $\boldsymbol{\varepsilon(\mu \,|\, \pi, K, p) \leq 0.1\%}$

CMS experiment: data

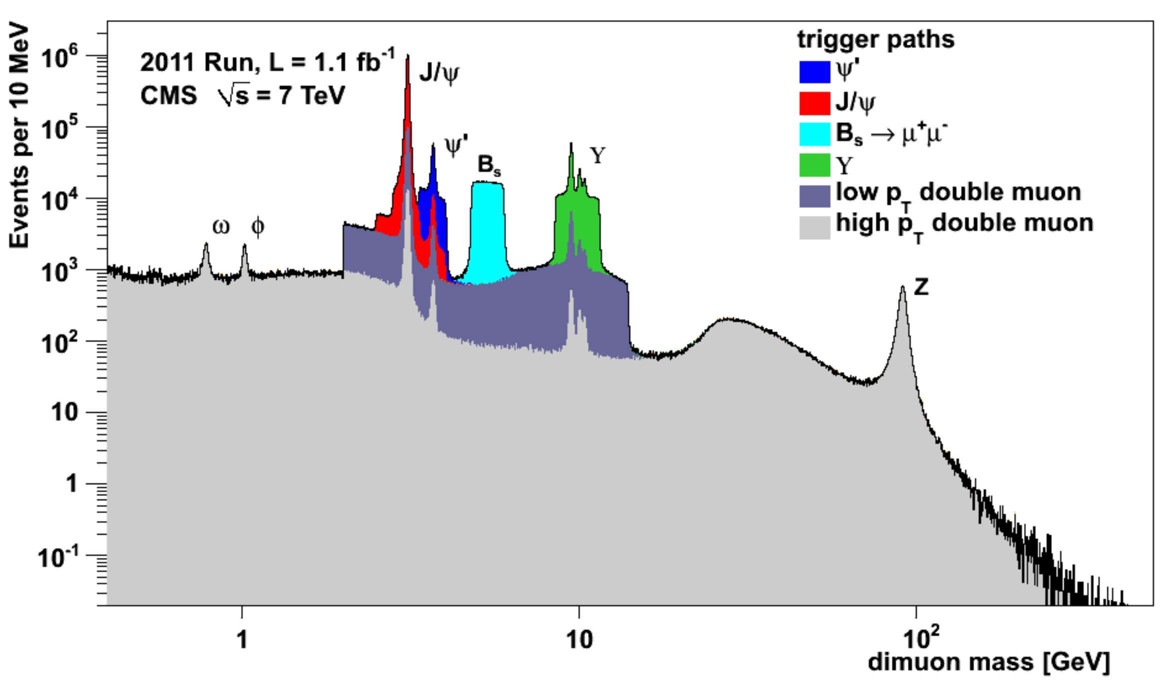
Collecting data from *pp* collisions at increasing centre-of-mass energies:

√s = 7 TeV	√s = 8 TeV	√s = 13 TeV
5 fb^{-1}	**20 fb^{-1}**	**80+ fb^{-1}**
(2011)	(2012)	(2015 →)

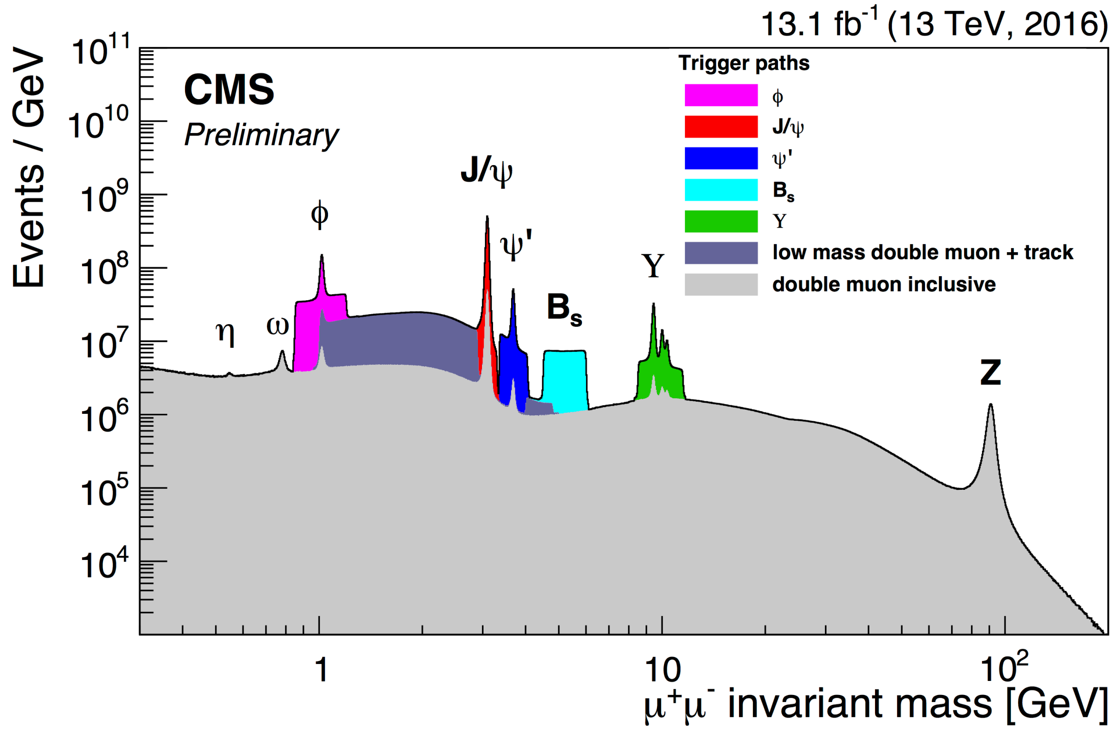
Dedicated set of triggers optimised for quarkonia states

- based on muons and tracks

[CMS BPH Public Results](#)



[CMS-DP-2016-059](#)



Y(4140) observation

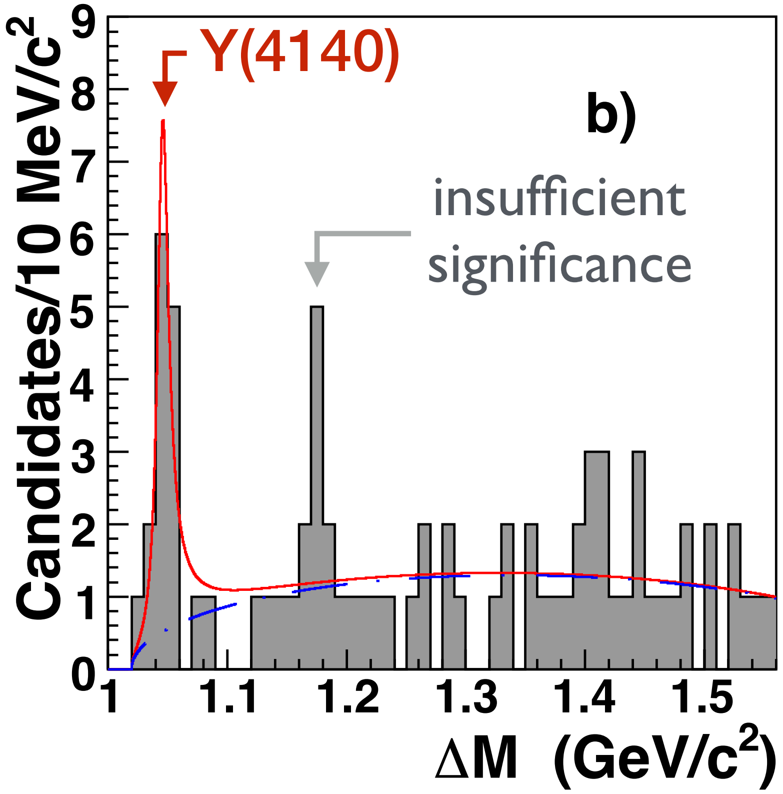
Phys. Lett. B 734 (2014) 261-281

- **exotic meson candidate**
- **first observed by CDF in 2009**
- **CMS analysed peaking structures in the $J/\psi\phi$ mass spectrum from $B^\pm \to J/\psi\phi K^\pm$ decays**

Y(4140): introduction

CDF reported a 3.8σ evidence for a narrow peak in $m(J/\psi\phi)$ spectrum from $B^+ \to J/\psi\phi K^+$ decays: $m = 4143.0 \pm 3.1\ \mathrm{MeV}/c^2$ [2009]

Phys.Rev.Lett.102:242002



m(μ⁺μ⁻K⁺K⁻) – m(μ⁺μ⁻)

- Search by Belle did not confirm it [2010]
- Same peak observed by CDF at >5σ: [2011]
  - $m = 4143.4 \pm 3.1\ \mathrm{MeV}/c^2$
- No evidence by LHCb measurement: [2012]
  - upper limit 2.4σ away from the CDF result

Proposed interpretations:

- $cs\bar{c}\bar{s}$ tetraquark;
- threshold kinematic effect;
- hybrid charmonium;
- $D_s^* \bar{D}_s^*$ molecule – *molecular strange partner of* Y(3940);

Y(4140): analysis method

Same $m(J/\psi\phi)$ spectrum from $B^{\pm} \to J/\psi\phi K^{\pm}$ decays studied by CMS
to further investigate this peaking structure [2014]

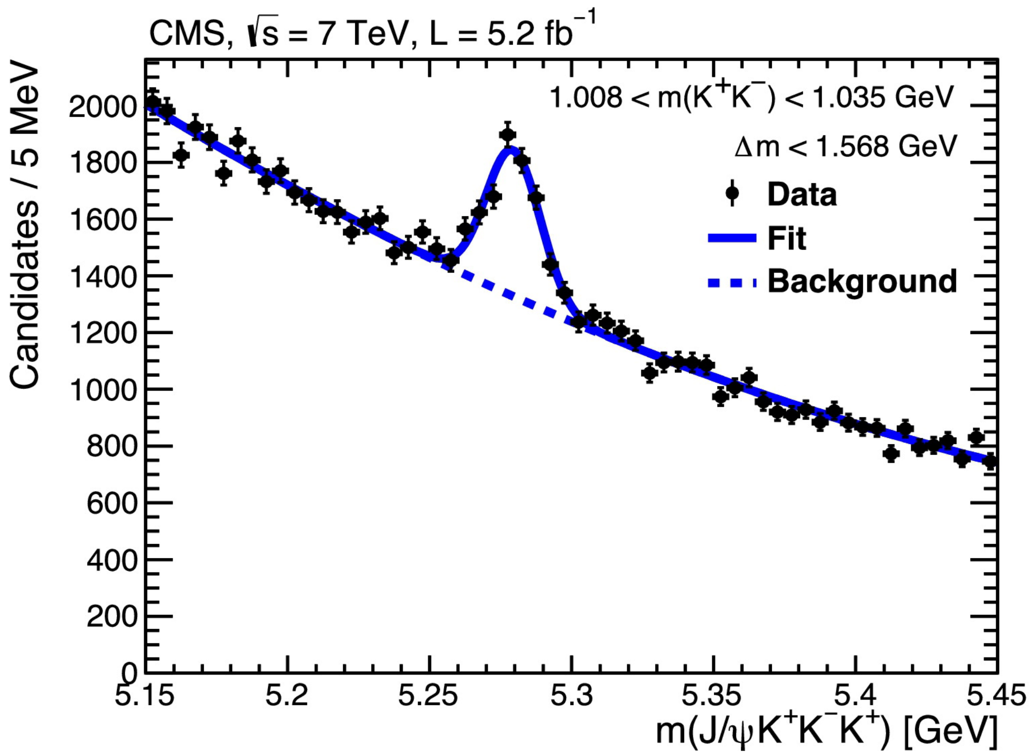
Using 5.2 fb^{-1} of *pp* collisions at $\sqrt{s}$ = 7 TeV

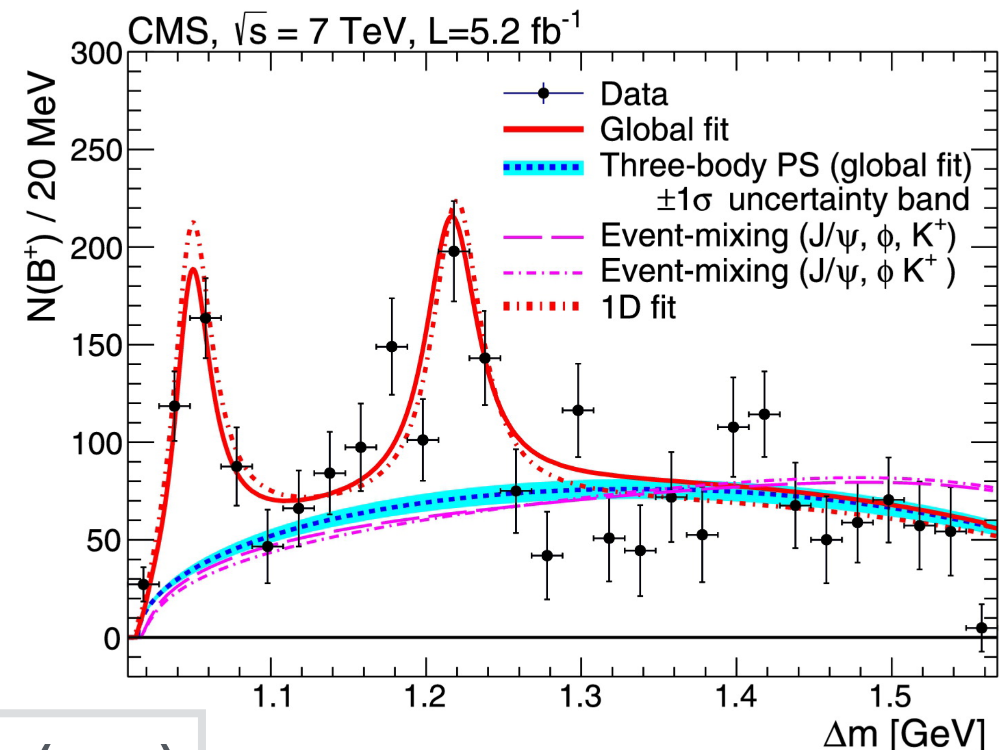
Selecting events with ≥2 muons ($J/\psi \to \mu\mu$) + ≥3 tracks ($K^{\pm}$, $\phi \to K^{+}K^{-}$)

- $p_T(J/\psi) > 7$ GeV; $p_T(K^{\pm}) > 1$ GeV;
- B^{+} transverse decay length > 3σ;

Invariant-mass spectrum within ±3σ around the *B*⁺ mass:

fitted by a gaussian (—) and a 2nd order polynomial (- - -) to obtain *B*⁺ yield





$m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

Fitting m(*J/ψ*φ*K*) to extract B⁺ signal yield in every Δm = 20 MeV bin

Fitting Δm distribution to extract the two structures yield

- S-wave Breit-Wigner (BW) convoluted with mass resolution; [signal]
- 3-body Phase Spase Shape (PS); [background]

Y(4140): results

Properties of the lower-mass resonance determined from the fit:

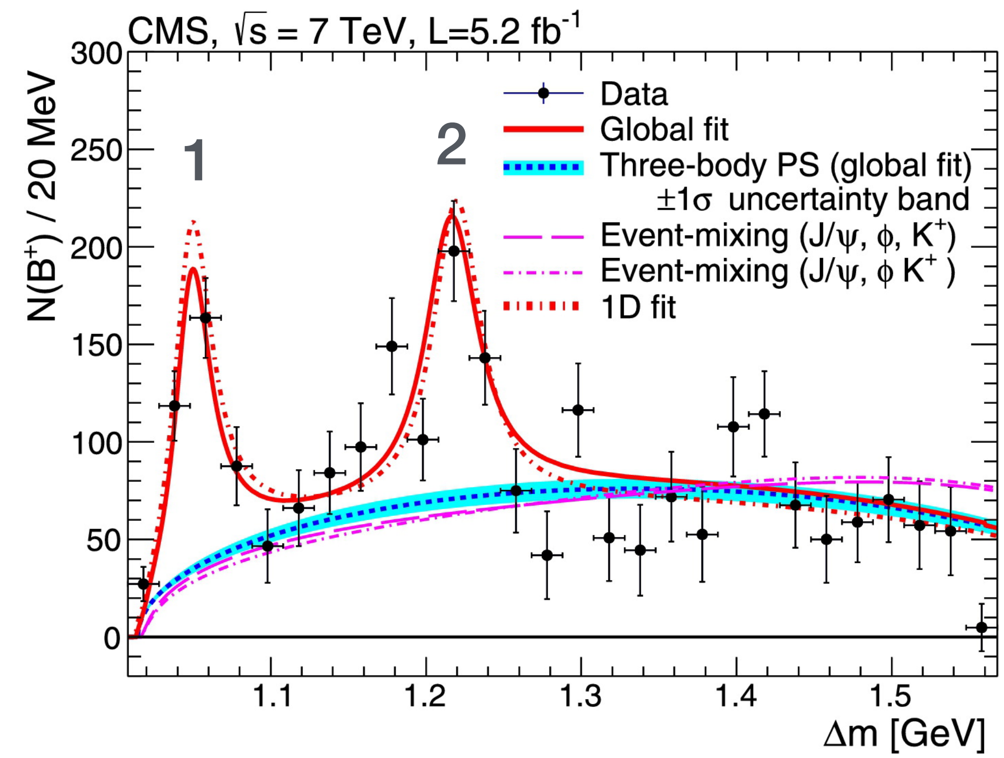
$\mathbf{m_1 = 4148.0} \pm 2.4^{stat.} \pm 6.3^{syst.}$ **MeV/c²** $\mathbf{\Gamma_1 = 28}\ ^{+15}_{-11}{}^{stat} \pm 19^{syst}$ **MeV**

Significance of the first peak > 5σ

Mass and width consistent with the Y(4140) values reported by CDF

BR relative to $B^+ \to J/\psi\phi K^+$: $0.1 \pm 30\%^{stat}$

- consistent with the CDF result and upper limit by LHCb



Evidence for a second mass peak:

- $\mathbf{m_2 = 4313.8} \pm 5.3^{stat} \pm 7.3^{syst}$ **MeV/c²** $\mathbf{\Gamma_2 = 38}\ ^{+30}_{-15}{}^{stat} \pm 16^{syst}$ **MeV**

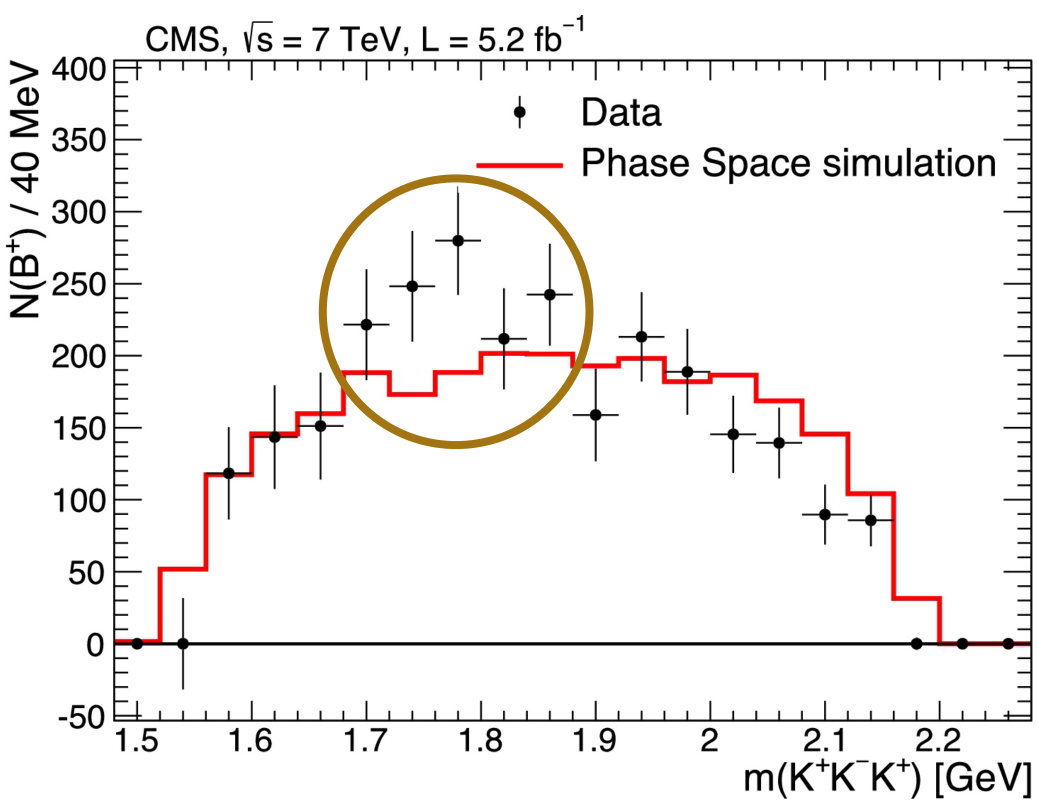
Conventional charmonium mesons would have larger widths at these mass values → must be something exotic

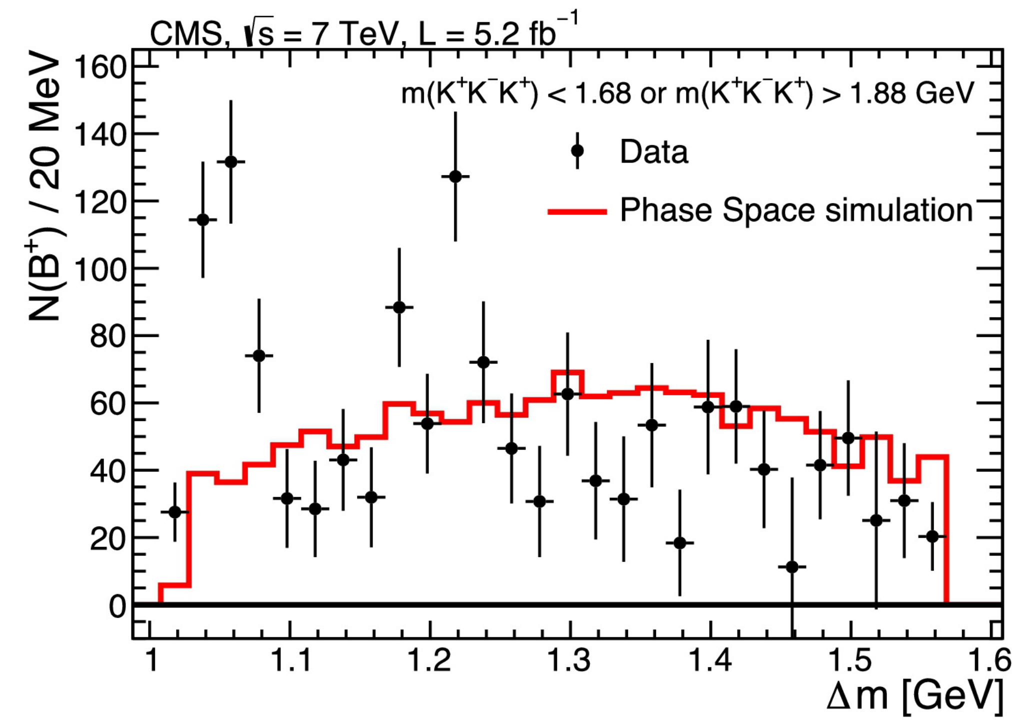
Y(4140): reflection studies

Possibility of presence of two-body resonances was further investigated:
fitting m($J/\psi\phi K$) in intervals of m($K^+K^-K^+$) = 40 MeV

Excluding excess region **from the plot** →

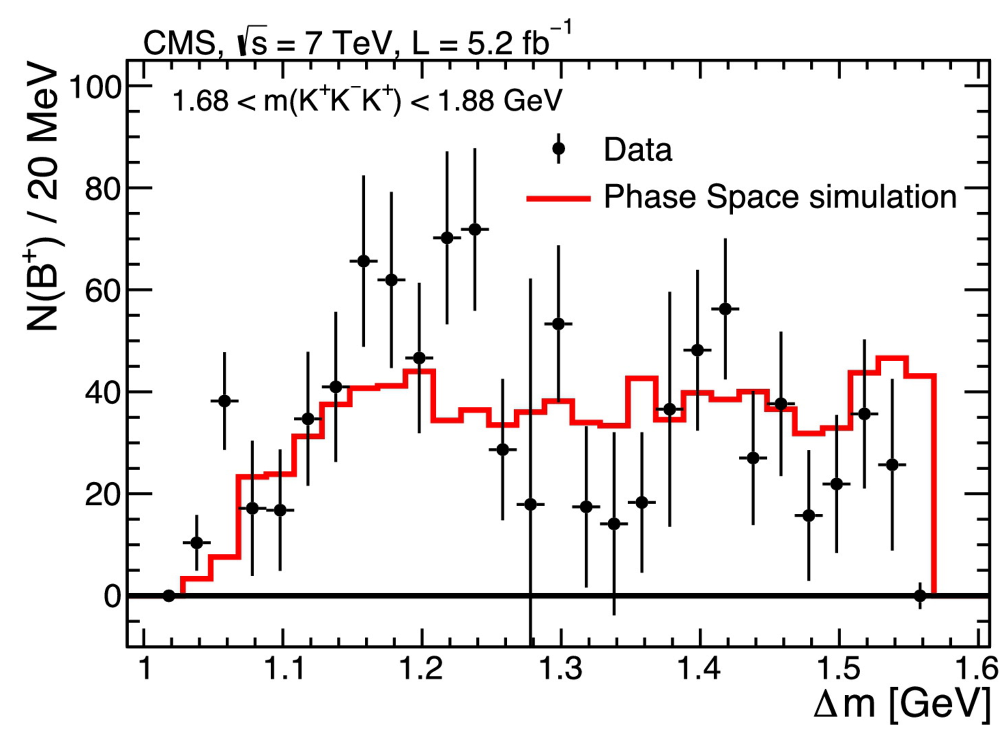
- Y(4140) not affected by ϕK^+ resonances





Using only excess region **in the plot** →

- second peak can be affected by ϕK^+ resonances



Y(4140): conclusions

Y(4140) structure found by CDF also confirmed by CMS

- measured mass and width consistent with CDF results
- relative BR consistent with CDF results and LHCb upper limit
- statistical significance of the second peak can't be determined reliably due to possible reflections from two-body decays
- further studies, including full amplitude analysis, needed to understand the nature of the peaking structures
- Run-II data will help a lot in extracting pure sample of B^+ with sufficient statistics

X(3872) differential cross section

J. High Energy Phys. 04 (2013) 154

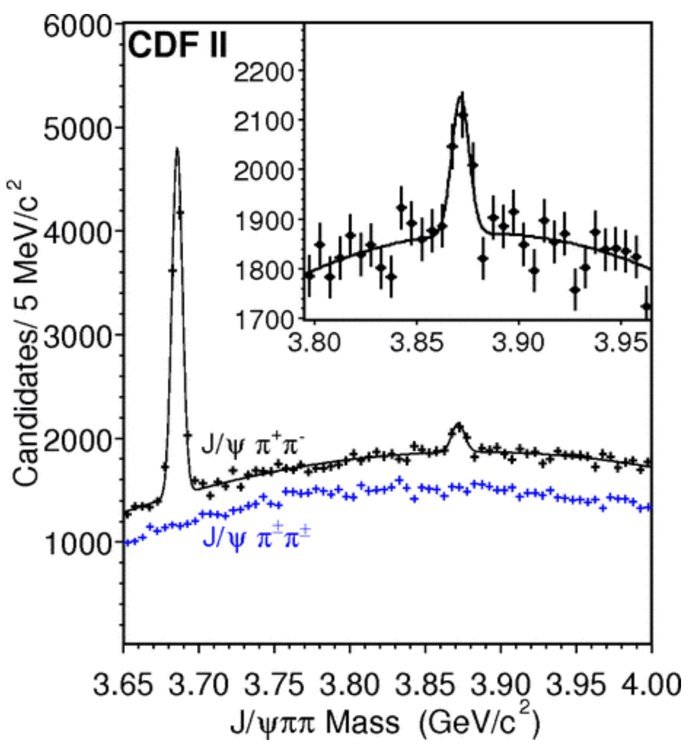
- **first exotic charmonium candidate**
- **discovered by Belle in 2003**
  - still no clear understanding of its nature
- **CMS analysed decays into $J/\psi\pi^+\pi^-$ ($J/\psi \rightarrow \mu^+\mu^-$) to study it further**

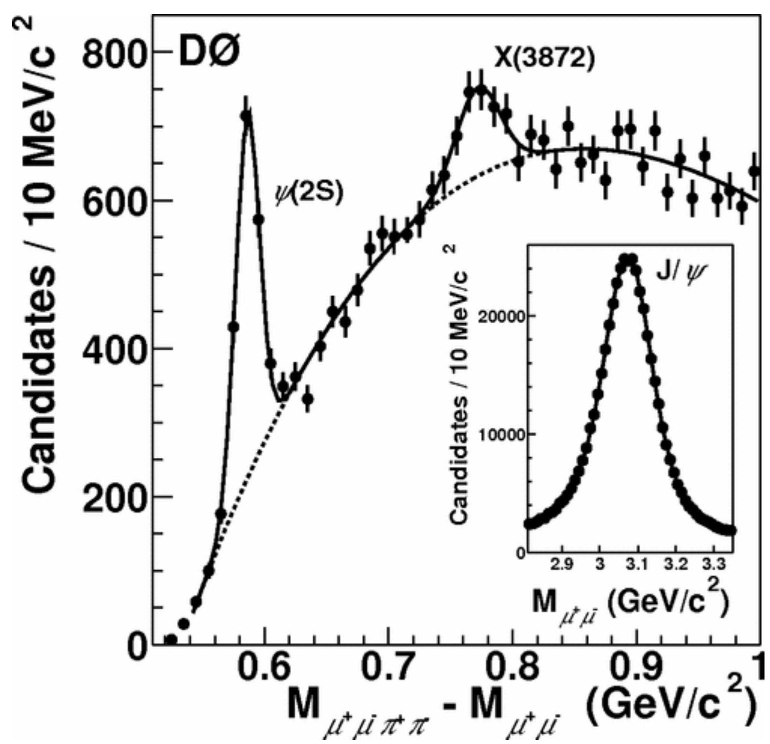
X(3872): introduction

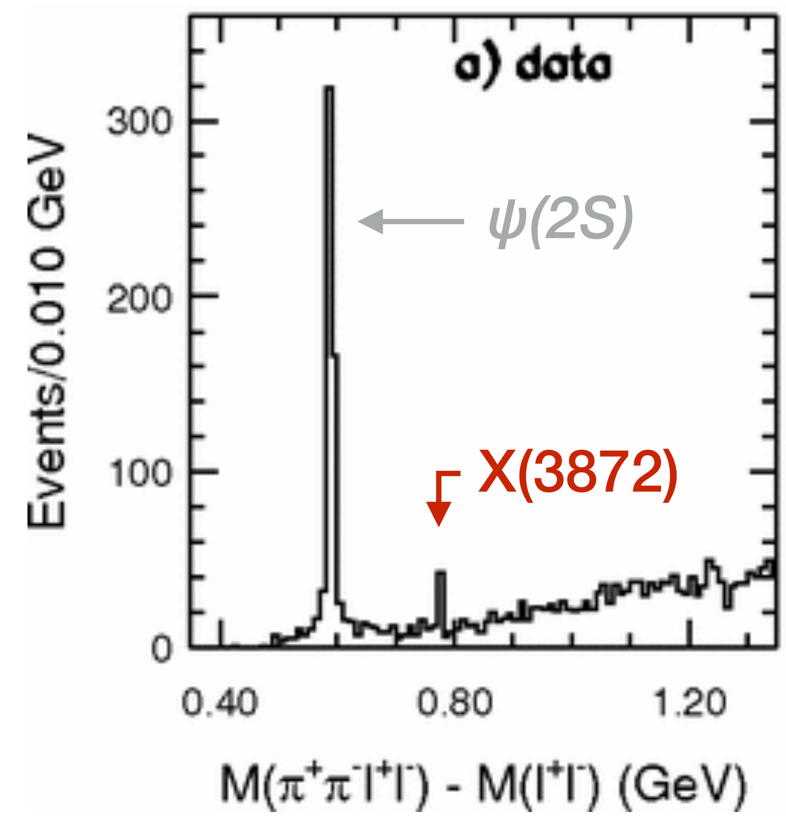
Belle reported a 10σ observation of a narrow peak in $m(J/\psi\pi^+\pi^-)$ spectrum from $B^\pm \to K^\pm J/\psi\pi^+\pi^-$ decays: **m = 3872.0 ± 0.8 MeV/c²** [2003]

Phys. Rev. Lett. 91, 262001

Confirmed by CDF and DØ a year after [2004]







Currently available hypotheses: charmonium state, loosely bound molecular state or a tetraquark

Theoretical predictions of differential cross sections of prompt X(3872) production are available *(calculated in the NRQCD framework)*

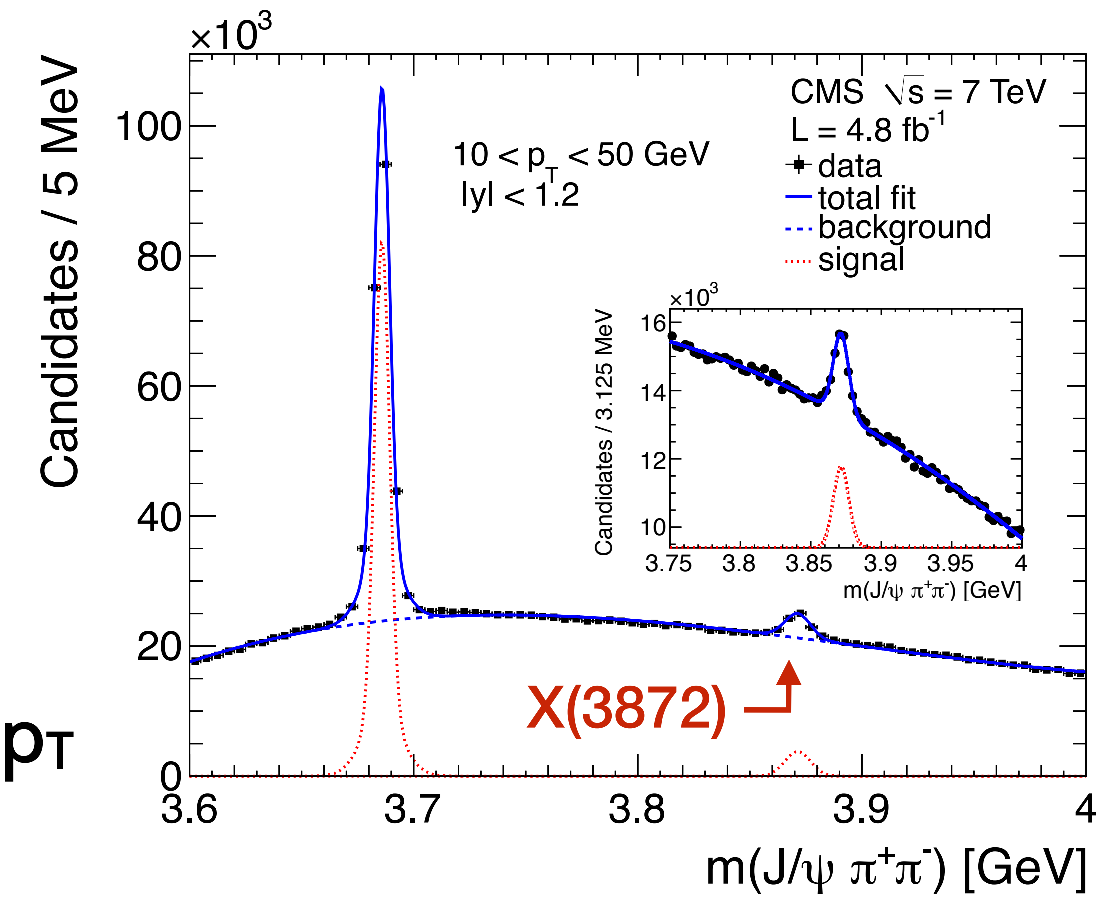
X(3872): analysis overview

CMS detector well suited for measurement of the $\mu^+\mu^-\pi^+\pi^-$ final state

Using 4.8 fb^{-1} of *pp* collisions at $\sqrt{s}$ = 7 TeV → ~12K reconstructed events

Kinematic region:

- 10 < p_T < 50 GeV; |y| < 1.2;
- $\Delta R(J/\psi, \pi) < 0.55$ to reduce combinatorial background



Measured several aspects of the process:

1. X(3872) / *ψ(2S)* cross-section ratio vs p_T
2. non-prompt fraction vs p_T
3. $\pi^+\pi^-$ invariant mass distribution

+ prompt X(3872) cross section vs p_T

- using (1), (2) and **σ(ψ**(*2S*)**)** measured earlier

X(3872): cross-section ratio

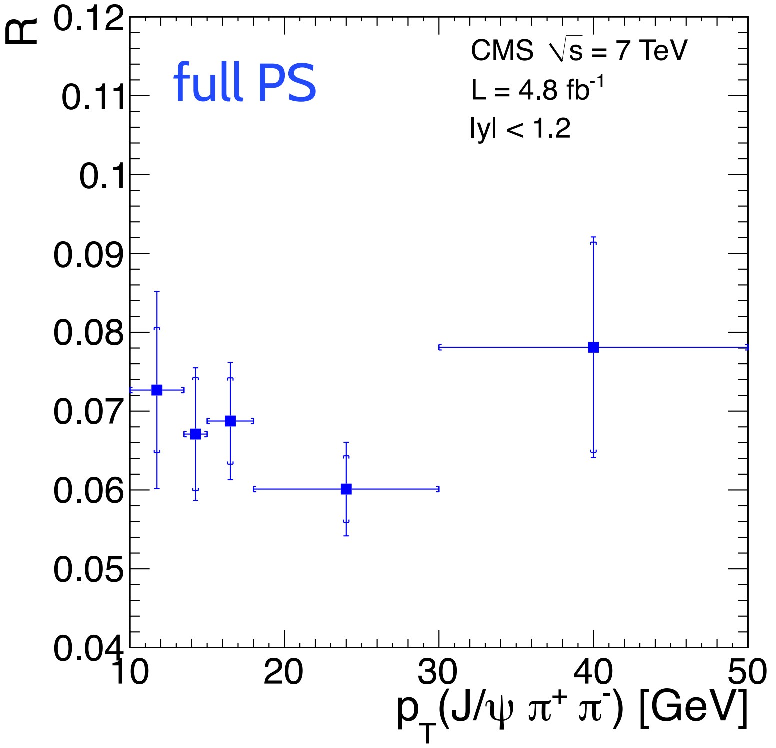
Ratio allows to avoid many systematic uncertainties:

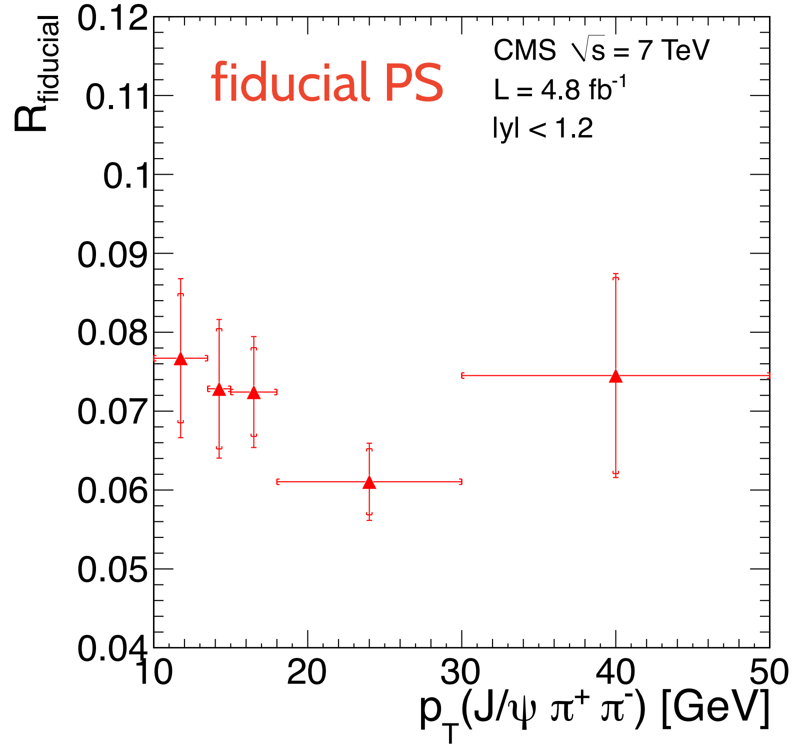
$$R = \frac{\sigma(\mathrm{pp} \to \mathrm{X}(3872) + \mathrm{anything}) \cdot \mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \psi(2\mathrm{S}) + \mathrm{anything}) \cdot \mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-)} = \frac{N_{\mathrm{X}(3872)} \cdot A_{\psi(2\mathrm{S})} \cdot \epsilon_{\psi(2\mathrm{S})}}{N_{\psi(2\mathrm{S})} \cdot A_{\mathrm{X}(3872)} \cdot \epsilon_{\mathrm{X}(3872)}}$$

X(3872) and ψ*(2S)* assumed to be unpolarised

Acceptance corrections depend on assumptions about the angular distribution of the final-state muons and pions

- this effect is minimised in fiducial cross sections
  (kinematic requirement on muons, dimuons and pions in the phase-space definition)





Average ratio:

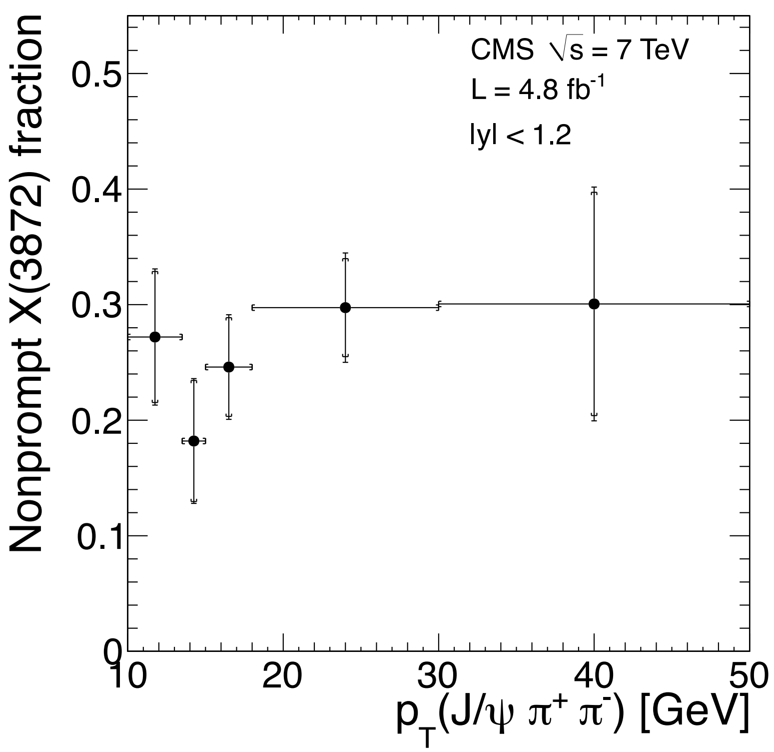
$R = 0.0656 \pm 0.0029 \pm 0.0065$

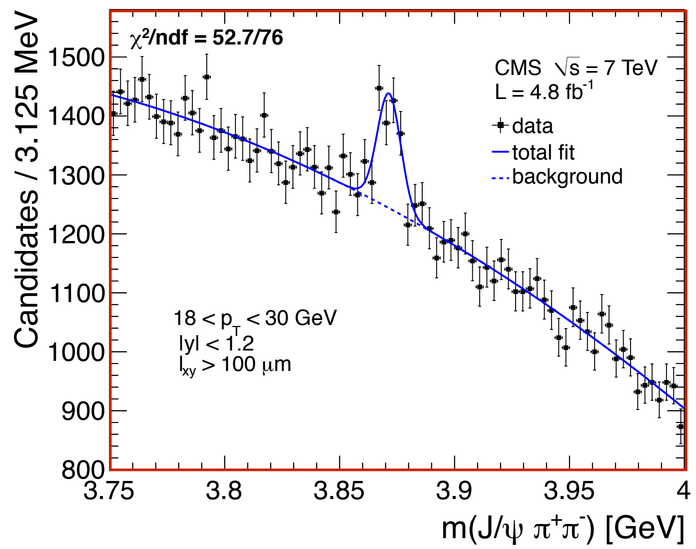
$R = 0.0694 \pm 0.0029 \pm 0.0036$

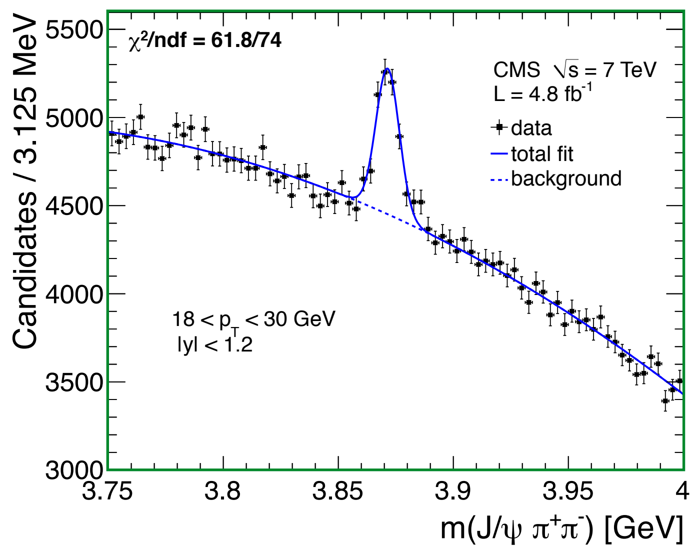
No significant p_T dependence

X(3872) can be produced from B-hadron decays *(non-prompt production)*

- **non-prompt fraction based on "pseudo-proper" decay length *(l_{xy})*** for selection of sample enriched in non-prompt candidates
  - $l_{xy} > 100$ μm: efficiency: 80%; prompt contribution: 0.1%;
- **determined from the ratio:** # non-prompt / # total







Average non-prompt fraction:

$0.263 \pm 0.023^{stat} \pm 0.016^{syst}$

No significant p_T dependence observed

X(3872): absolute cross-section

Absolute prompt cross section is determined as a function of p_T
using results of the previous measurement [JHEP02 (2012) 011]

$$\sigma^{\rm prompt}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\rm prompt}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

this measurement

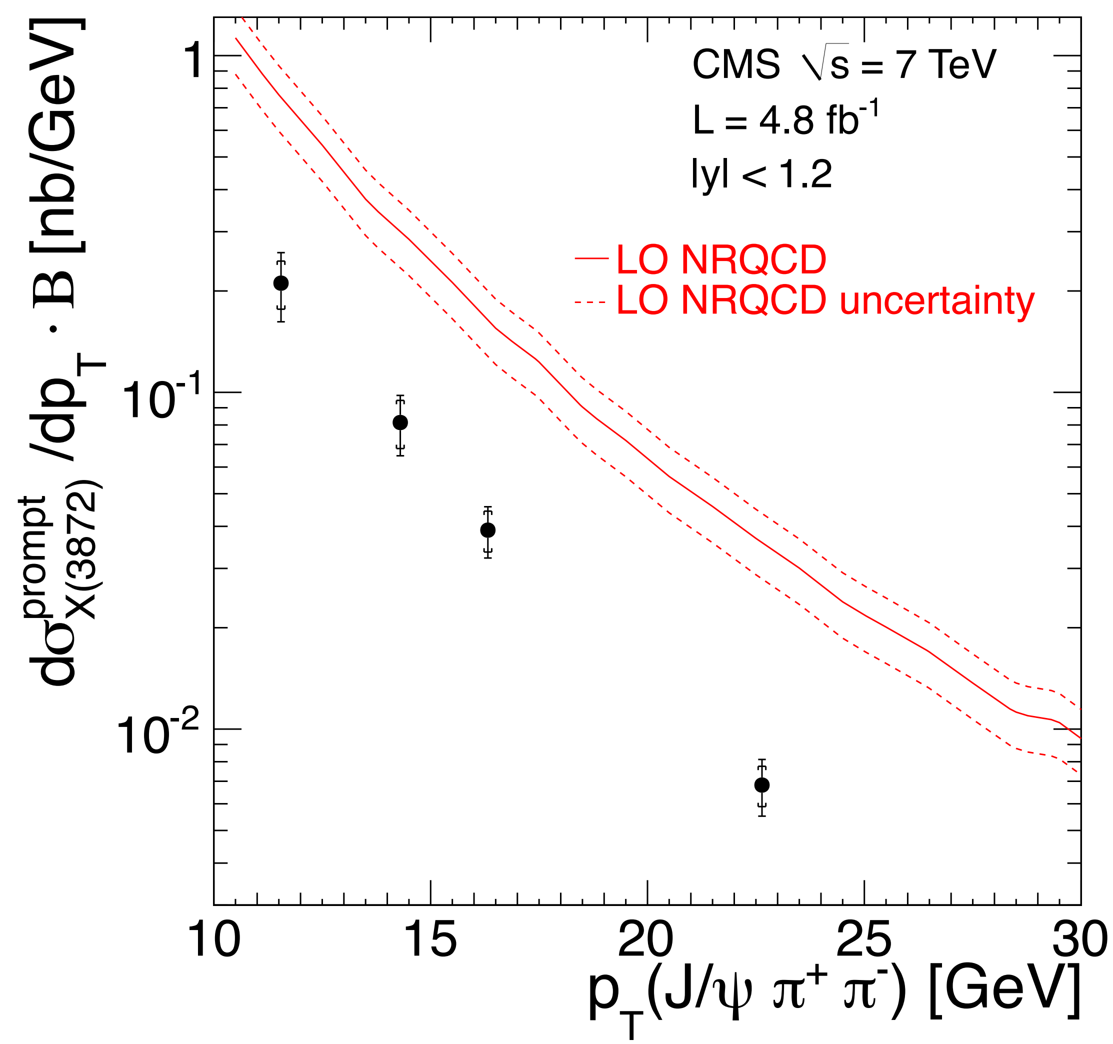
PDG

Measured cross section compared to NRQCD prediction [Phys.Rev.D81:114018]

- shape described reasonably well
- absolute value overestimated by 3σ

Integrated cross section also measured:

$\sigma^{\rm prompt} = 1.06 \pm 0.11^{\rm stat} \pm 0.15^{\rm syst}$ nb



X_b search

PLB 727 (2013) 57

- **beauty partner of X(3782)**
  - search motivated by observations of X(3782)
- **CMS analysed final states with $Y(1S)\pi^+\pi^-$ ($Y(1S) \rightarrow \mu^+\mu^-$) to look for X_b signature**
- **using 20.7 fb^{-1} of *pp* collisions at $\sqrt{s}$ = 8 TeV**

X_b: introduction

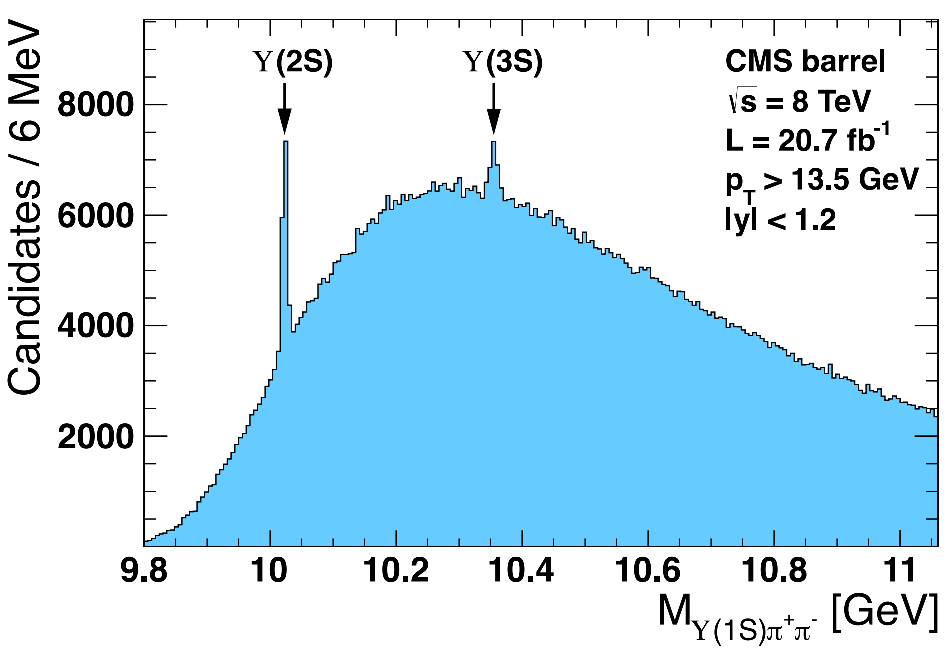
In analogy to X(3872), X_b is expected to exist with 10 < m(X_b) < 11 GeV and decay to *Υ(1S)π⁺π⁻* with a sizable rate

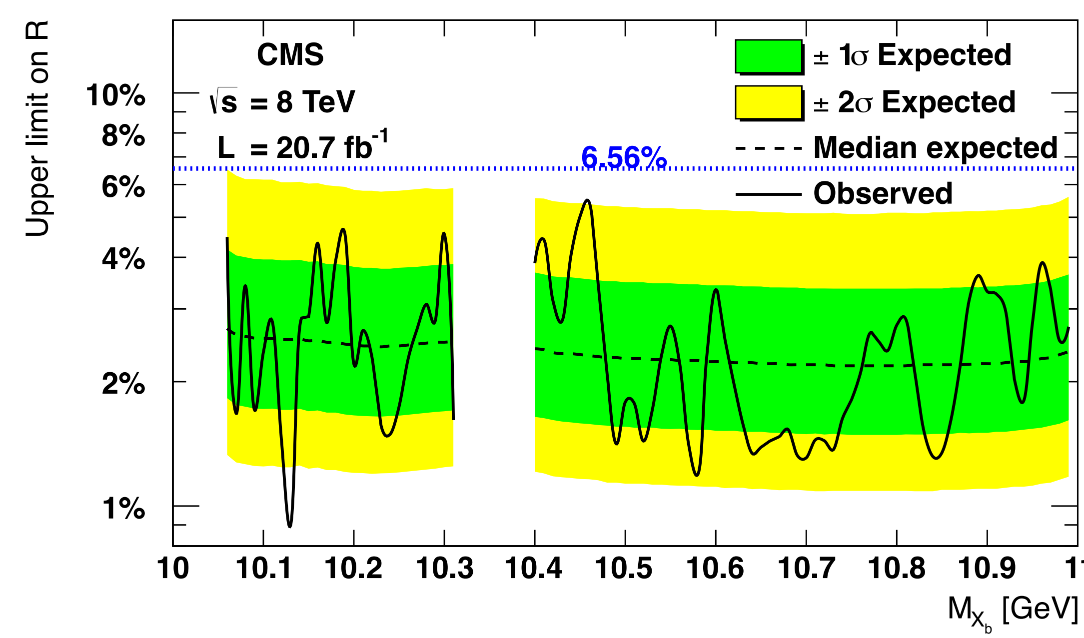
Analysis strategy:

- look for a peak in the m(*Υ(1S)$\pi^+\pi^-$*) spectrum within 10 - 11 GeV, other than *Υ(2S)* or *Υ(3S)*

No significant excess observed:

- setting upper limit on **R** = X_b / *Υ(2S)* cross-section ratio





Observed upper limit on R: 0.9 - 5.4 % at 95% CL depending on m(X_b)

X(5568) search

CMS-PAS-BPH-16-002

- **tetraquark candidate**
- **observed by DØ last year** [Phys. Rev. Lel. 117, 022003]
- **CMS prepared a preliminary result of the search for $B_s\pi^{\pm}$ candidates using B_s decays to $J/\psi\phi$**

DØ reported an evidence for a narrow peak in m($B_s\pi^\pm$) spectrum

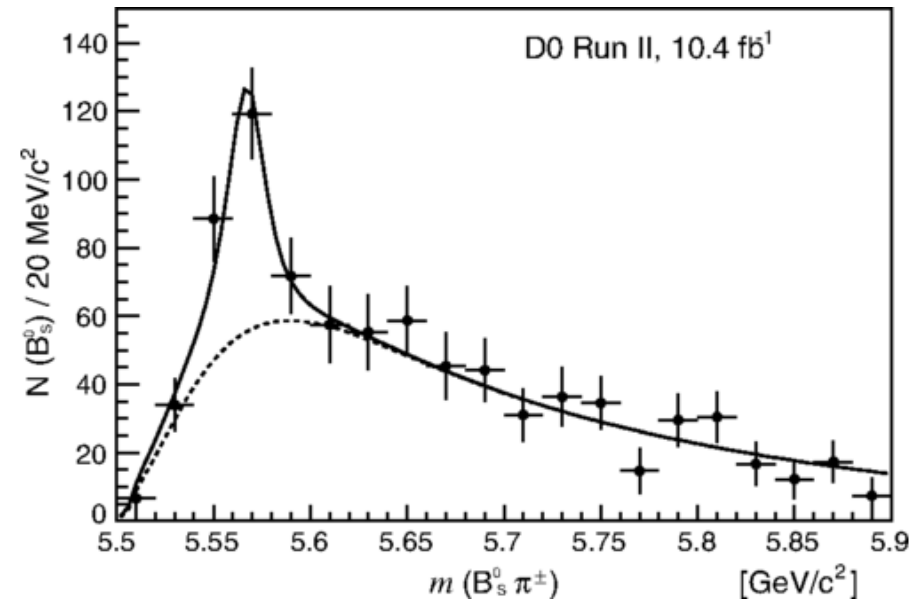
m = **5567.8** $\pm 2.9^{stat}\ {}^{+0.9}_{-1.9}{}^{syst}$ **MeV/c²** Γ = **21.9** $\pm 6.4^{stat}\ {}^{+5.0}_{-2.5}{}^{syst}$ **MeV**

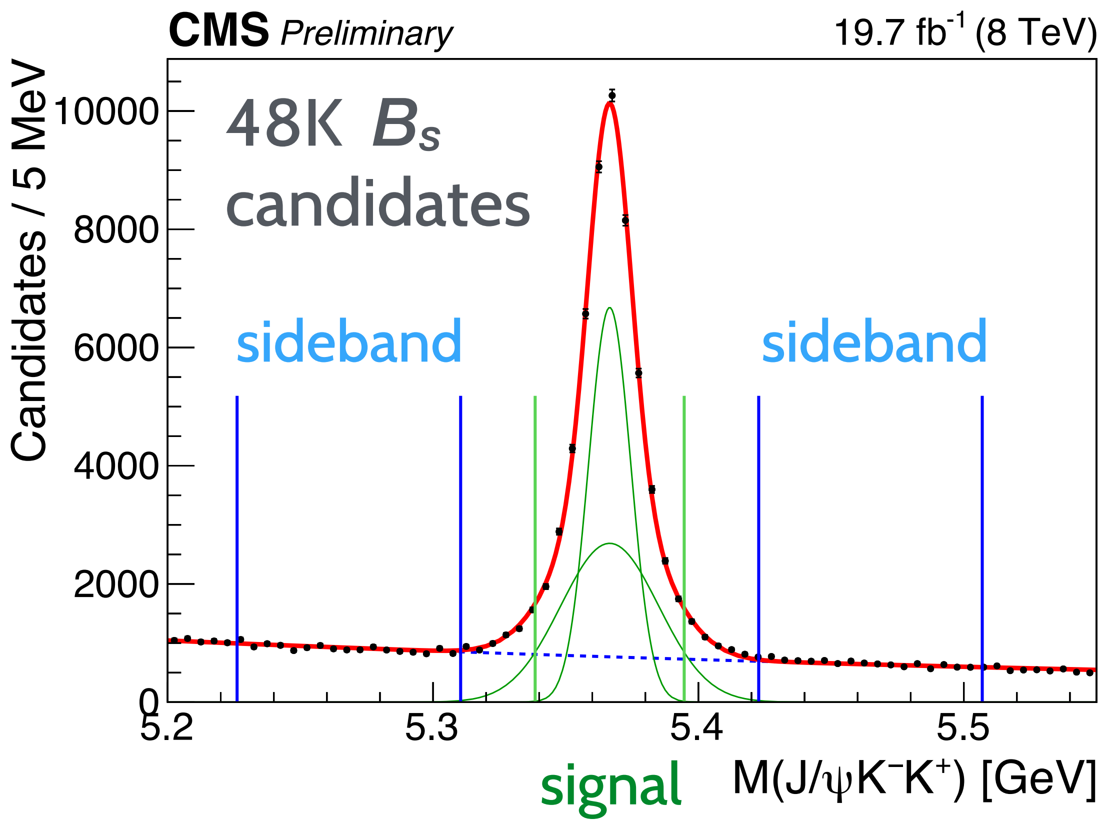
Not confirmed by LHCb search [2016]

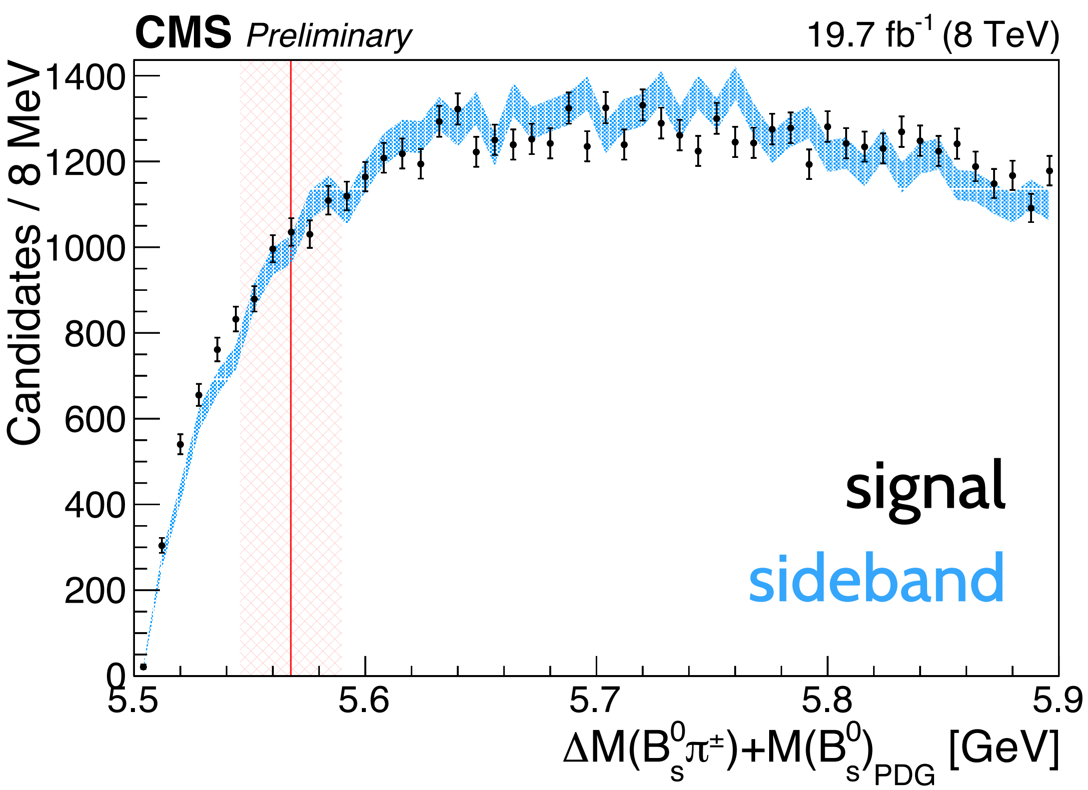
CMS performed a search in the final state:

X(5568) → $B_s\pi^\pm$ → $J/\psi\phi\pi^\pm$ → $\mu^+\mu^-K^+K^-\pi^\pm$

Signal and sideband regions look the same







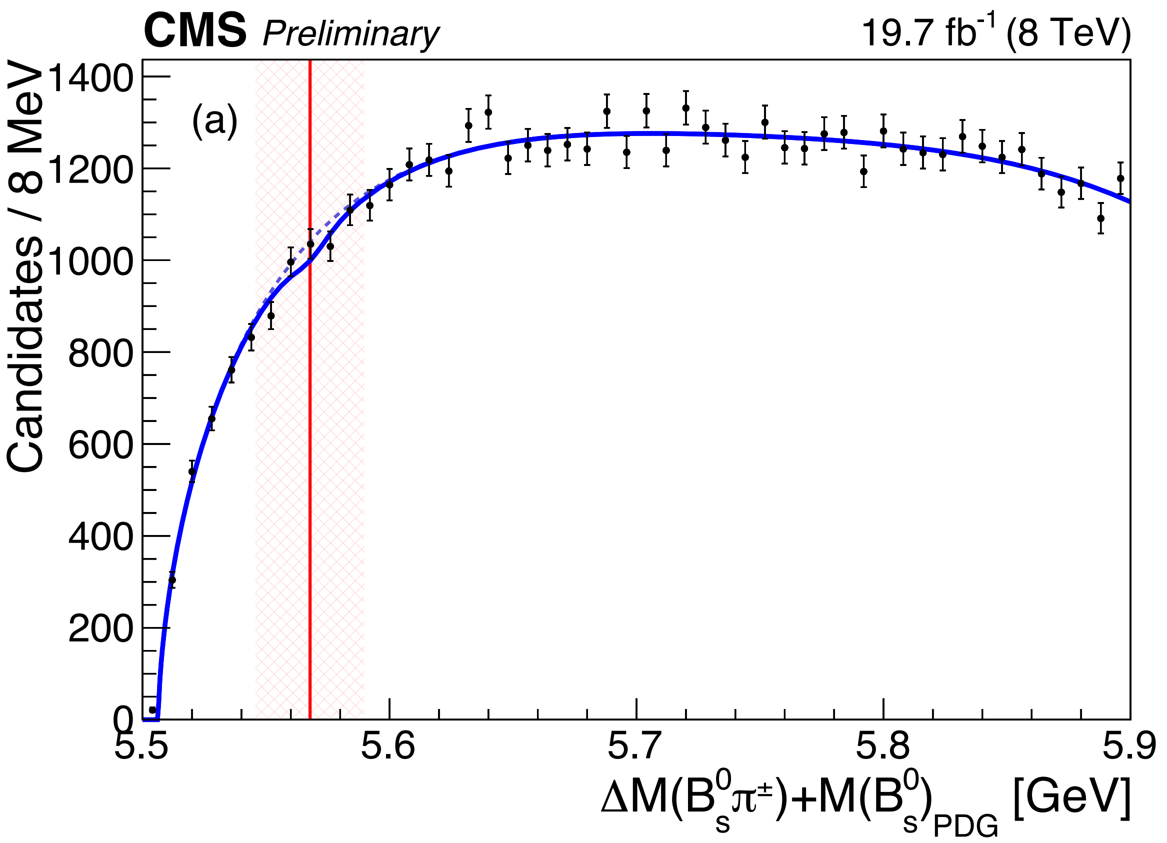
X(5568): upper limit

Upper limit on the relative production rate (ρ_X) wrt. to B_s is evaluated

$$\rho_X \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to \mathrm{B_s^0}\pi^\pm)}{\sigma(pp \to \mathrm{B_s^0} + \text{anything})} = \frac{N_{X(5568)}}{N_{\mathrm{B_s^0}}} \frac{\epsilon_{\mathrm{B_s^0}}}{\epsilon_{X(5568)}}$$

Unbinned extended ML fit performed to set the upper limit on X(5568) yield:

$\rho_{X(5568)} < 3.9\%$ at 95% C.L.



No evidence for X(5568) found by CMS

This is in disagreement with DØ result:

$\rho_{X(5568)} = 8.6 \pm 1.9^{stat} \pm 1.4^{syst}$ %

Summary

- CMS is perfectly suitable for heavy-flavor physics
- Important contributions to studies of exotic states made by CMS:
  - observation of Y(4140)
  - measurement of X(3872) differential cross section
  - search for X_b partner of X(3872)
  - search for X(5568)
- Not all searches resulted in observed particles, but Run-II data is bringing a lot of opportunities

Thank you

for attention