B^0_s to X(3872)ϕ decay and search for resonances in Y(1S)l$^+$l$^-$ at CMS

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Cécile Caillol, University of Wisconsin-Madison,
on behalf of the CMS Collaboration

Additional material in https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-17-005/index.html

B_S TO X(3872)Φ DECAY

Introduction

- **X(3872) discovered by Belle in 2003**
  - Mass close to $D^0 D^{*0}$ threshold
  - Natural width $\Gamma < 1.2$ MeV
  - Quantum numbers $J^{PC} = 1^{++}$ correspond to the charmonium state χ_{c1}

- **X(3872) nature still unclear to this day**
  - Several possible theoretical interpretations: tetraquark, molecule, mixture of those with a conventional charmonium state, …

- Before CMS measurement, **X(3872) had not been observed in B^0_s decays**, only from B^0, B^+ and Λ_b^0
  - Measurement of X(3872) production in B^0_s decays helps understanding properties, in particular dynamics of its formation in B hadron decays

What do we want to measure?

- We want to observe X(3782) production in B^0_s decays.

- Measuring the ratio to the equivalent $\psi(2S)$ production cancels most systematics:

$$R \equiv \frac{\mathcal{B}(B^0_s \to X(3872)\phi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B^0_s \to \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} \equiv \frac{N(B^0_s \to X(3872)\phi)}{N(B^0_s \to \psi(2S)\phi)} \times \frac{\epsilon_{B^0_s \to \psi(2S)\phi}}{\epsilon_{B^0_s \to X(3872)\phi}}$$

- Normalization and signal channels very similar → similar event selection, but different mass window

- N events extracted from 2D fits

Event selection

- **Trigger**: $\mu^+\mu^-$ with J/ψ mass constraint + displaced track

- 2 OS muons and 4 additional high-purity tracks

- B^0_s vertex fit probability > 7%

- $p_T(B^0_s)$ > 10 GeV

- $p_T(K)$ > 1.5 and 2.2 GeV

- $p_T(\pi)$ > 0.7 GeV

- Cos (2D B^0_s pointing angle to PV) > 0.999

- L_{xy}/σ_{Lxy} (B^0_s vtx → PV) > 15

- **In ψ(2S) channel**: m($\pi\pi$) > 0.45 GeV

- **In X channel**: m($\pi\pi$) > 0.7 GeV
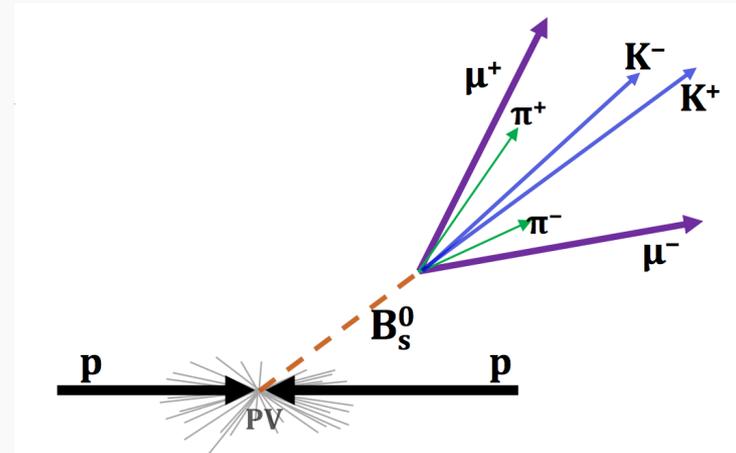
- **Track assignment**:
  - $3.60 < m(\mathrm{J}/\psi\,\pi^+\pi^-) < 3.95\,\mathrm{GeV}$
  - $1.00 < m(\mathrm{K}^+\mathrm{K}^-) < 1.04\,\mathrm{GeV}$
  - $5.32 < m(\mathrm{B}^0_s) < 5.42\,\mathrm{GeV}$

- **Selection efficiencies**:
  $\varepsilon_{\psi(2S)}/\varepsilon_{X(3872)} = 1.136 \pm 0.026$

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Signal extraction in ψ(2S) region

- 2D fit of **m(J/ψ π⁺π⁻)** [peaking at ψ(2S) mass for the signal] and **m(K⁺K⁻)** [peaking at φ mass for the signal] → **N(B⁰ₛ → ψ(2S)φ) = 15359 ± 171**

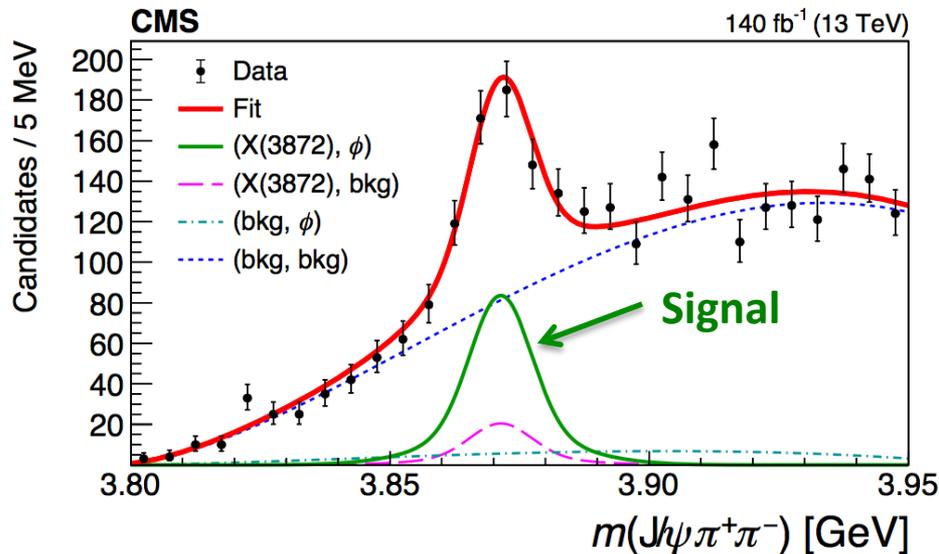- Floating parameters: all normalizations, background shapes, meson masses, ψ(2S) resolution
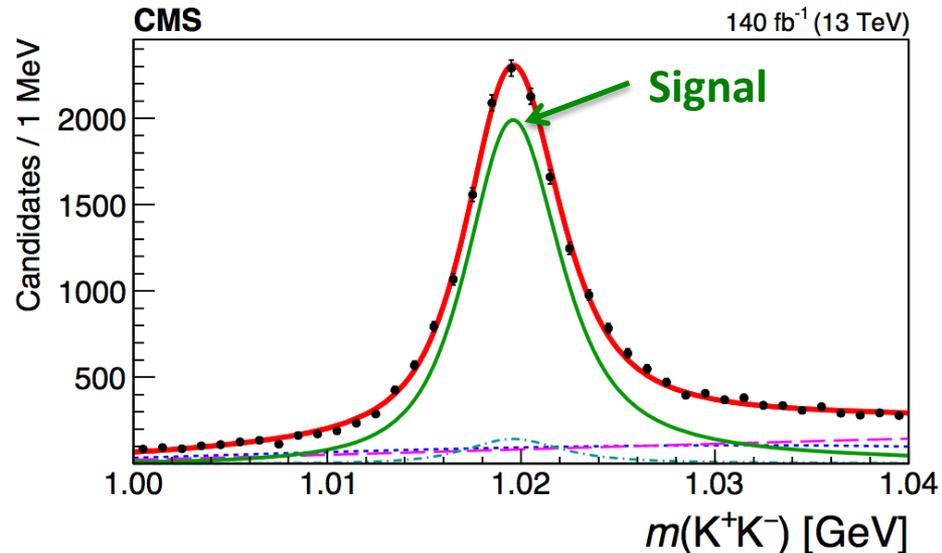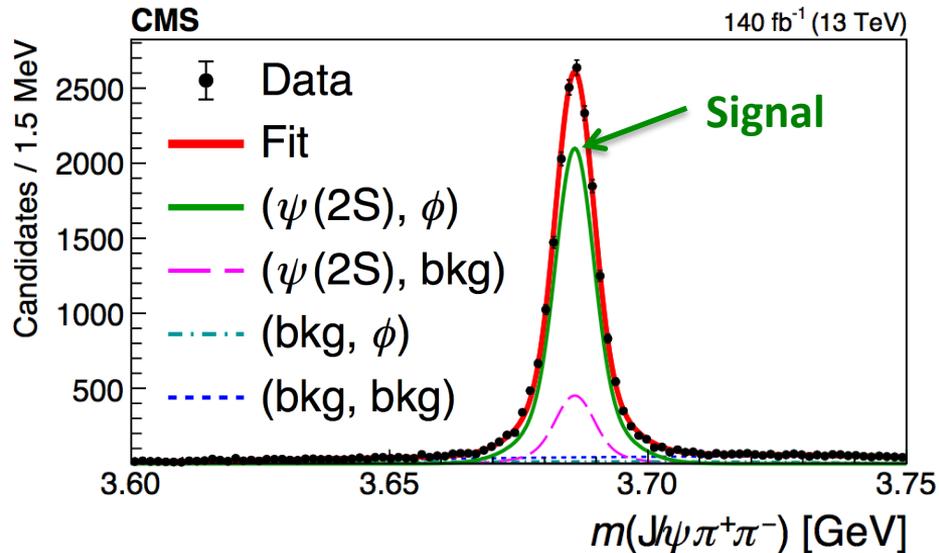
Signal extraction in X(3872) region

- 2D fit of $m(J/\psi\, \pi^+\pi^-)$ [peaking at X(3872) mass for the signal] and $m(K^+K^-)$ [peaking at ϕ mass for the signal] → **N(B^0_s → X(3872)ϕ) = 299 ± 39**

- More fit constraints because of limited number of events but fitted X mass compatible with the known mass

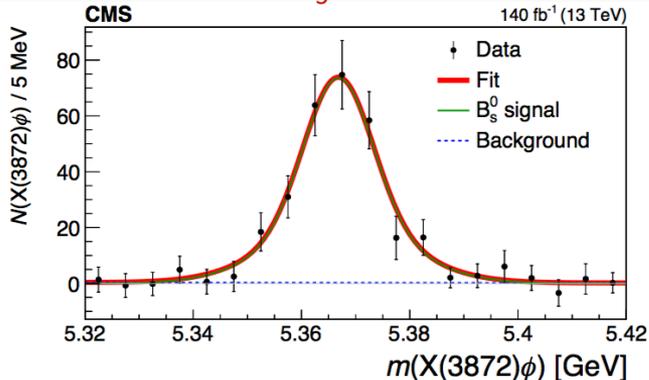**More than 6σ, first observation in B^0_s decays!**
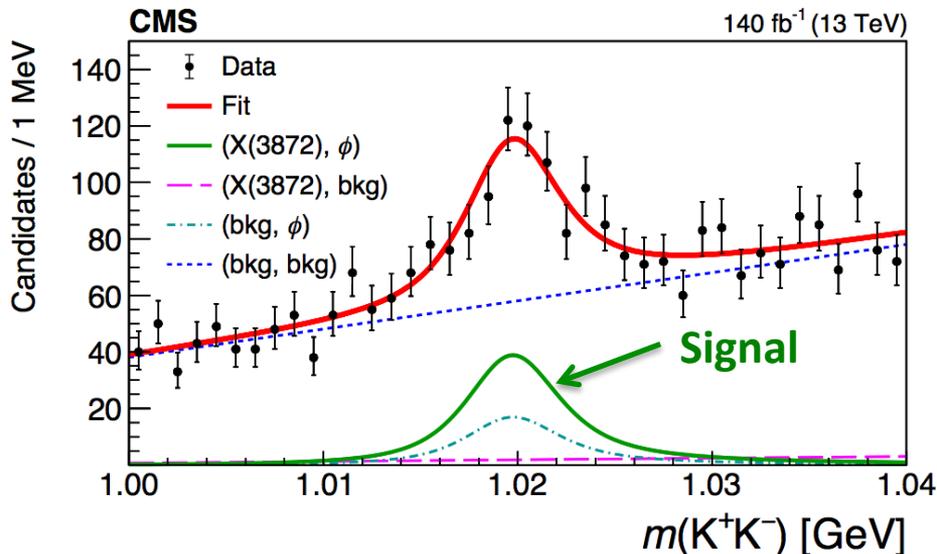
Systematic uncertainties

*Varying φ natural width and m(K⁺K⁻)
resolution within uncertainties*

Testing alternative fit models

Little non-B⁰ₛ contamination

Source	Uncertainty (%)
$m(\mathrm{K^+K^-})$ signal model	< 0.1
$m(\mathrm{K^+K^-})$ background model	2.5
$m(\mathrm{J}/\psi\,\pi^+\pi^-)$ signal model	5.3
$m(\mathrm{J}/\psi\,\pi^+\pi^-)$ background model	4.3
Non-B_s^0 background	1.2
Simulated sample size	2.2
Total	7.7

CMS   140 fb⁻¹ (13 TeV)

- Data
- Fit
- B⁰ₛ signal
- Background

$N(X(3872)\phi)$ / 5 MeV

$m(X(3872)\phi)$ [GeV]

Statistical uncertainty dominates R measurement

Results (1)

$$R \equiv \frac{\mathcal{B}(B_s^0 \to X(3872)\phi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29\,(\text{stat}) \pm 0.17\,(\text{syst}))\%$$

Multiplying R by the known B($B^0_s \to \psi(2S)\phi$) and B($\psi(2S) \to J/\psi\,\pi^+\pi^-$):

$$\mathcal{B}(B_s^0 \to X(3872)\phi)\,\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) = (4.14 \pm 0.54\,(\text{stat}) \pm 0.32\,(\text{syst}) \pm 0.46\,(\mathcal{B})) \times 10^{-6}$$
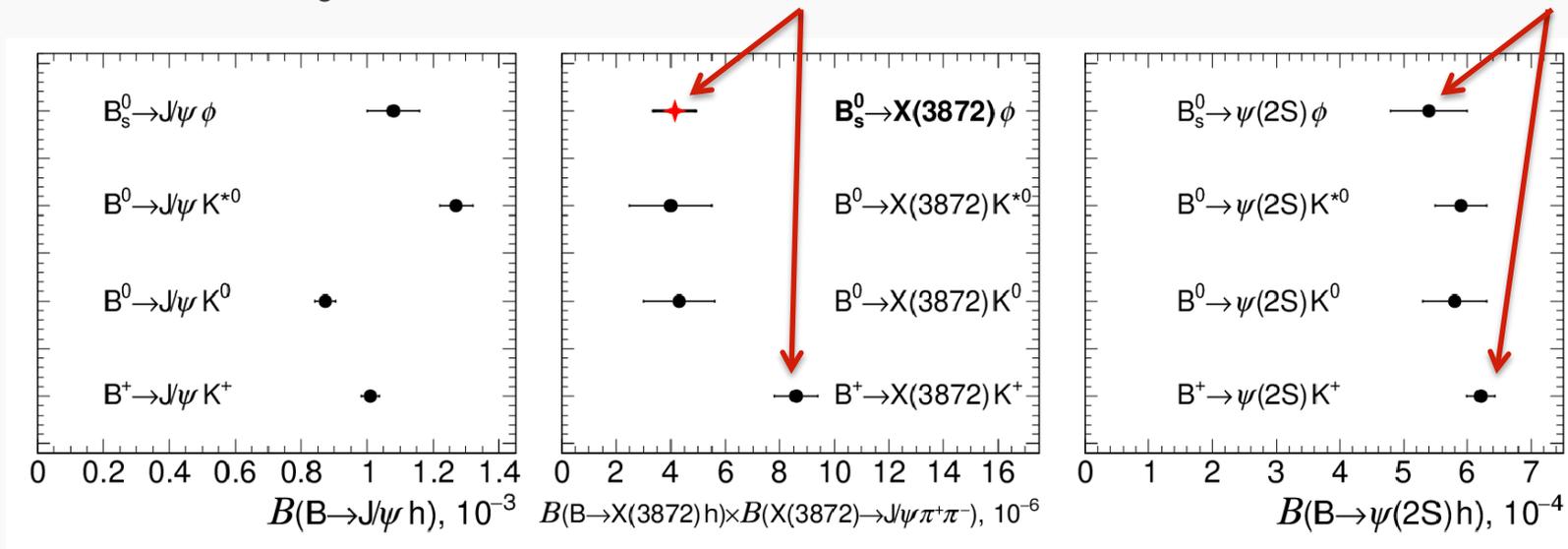
LHCb confirmed the ratio in arXiv:2011.01867:

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}$$

Results (2)

$$\frac{\mathcal{B}(B_s^0 \rightarrow X(3872)\phi)}{\mathcal{B}(B^+ \rightarrow X(3872)K^+)} = 0.482 \pm 0.063\,(\text{stat}) \pm 0.037\,(\text{syst}) \pm 0.070\,(\mathcal{B})$$

Measured value for B_s^0 consistent with B^0 but twice as high for B^+, unlike in decays with $\psi(2S)$:

Could be explained within tetraquark model of X(3872) (arXiv:2005.08764)

SEARCH FOR RESONANCES IN Y(1S)L⁺L⁻

Introduction

- Mass region between ~10 GeV and Z peak not explored much at the LHC

- Could hide resonances like tetraquarks, or BSM states

- A tetraquark made of 4 b quarks would have mass around 18 GeV and could decay to an onshell Y(1S) and 2 leptons → we study the four muon final state because low-p_T muons can be reconstructed with CMS

- The analysis is extended to a more generic resonance search using the 4 muon spectrum in a larger mass range than for the tetraquark hypothesis

Methodology

- Looking for a narrow signal resonance over a smooth background in the distribution of:

$$\widetilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)}$$

- Improved signal resolution compared to $m_{4\mu}$ distribution

- Signal modeled with the sum of 2 Gaussians with the same mean

- 2 background components with different shapes:
  - $\Upsilon(1S)\Upsilon(1S)$ with a steep rising edge around $m_{4\mu} = 2\ m_{\Upsilon(1S)}$
  - Combinatorial background with a smooth shape with trends dictated by event selection

Event selection

- 4 medium ID muons with p_T > 2.5 GeV
- Trigger with 3 muons: 2 with 8.5 < mass < 11.4 GeV and vtx. prob. > 0.005, and another one on top
- Vertex probability of the four muons is > 0.05
- Events with any 2 OS pairs of muons with mass below 4 GeV are rejected
- The 4 muons have a total charge of zero
- No alternative OS muon pairing has mass compatible with a J/ψ within 2σ;

Pairing:

- The 2 muons passing the Y filter of the trigger are paired together
- If more than 2 muons associated to the filter, the OS pair with mass closest to the Y(1S) mass is chosen
- The mass of the dimuon pair associated to the Y(1S) candidate is required to be compatible with a Y(1S) meson within 2σ

Y(1S)Y(1S) background estimation

- Normalization estimated from 2D fit to $m_{\mu1\mu2}$ vs $m_{\mu3\mu4}$
  - 74 ± 13 events

- Shape taken from simulation:
  - Nominal: mixture from SPS and DPS productions
 - SPS and DPS-only models considered as alternative models as shape uncertainties
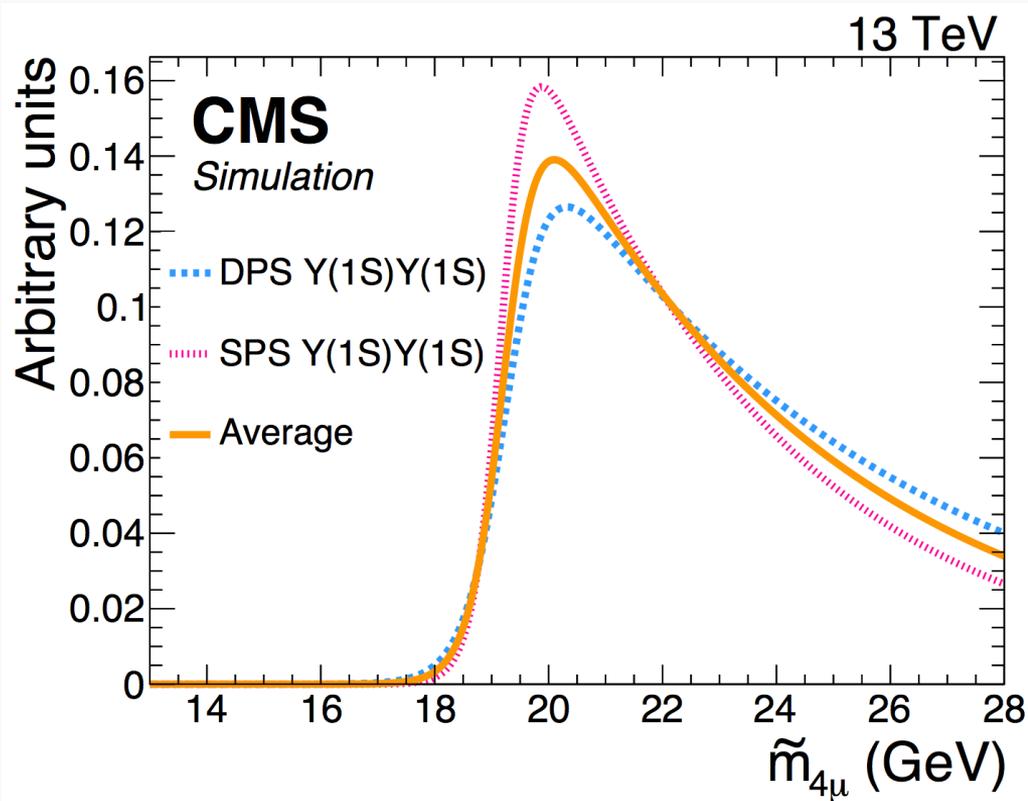
Combinatorial background estimation

- Combinatorial background modeled with generic smooth functions:
  - Chebychev polynomials
  - Sums of polynomials with Gaussian or Breit-Wigner functions

- All parameters (function coefficients and normalization) floating in the fit

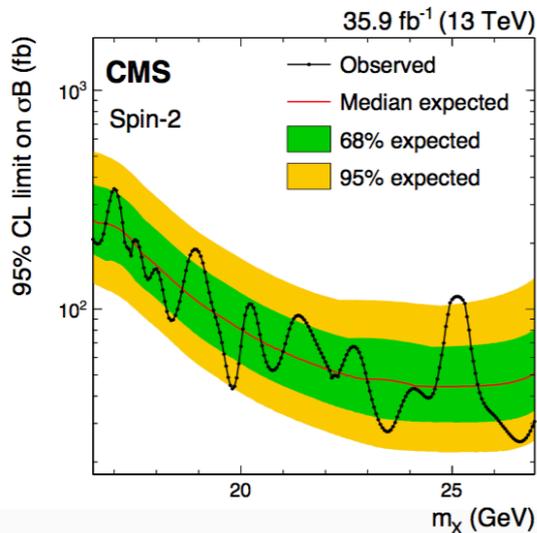- Function description verified in signal-free control region with looser vertex probability condition

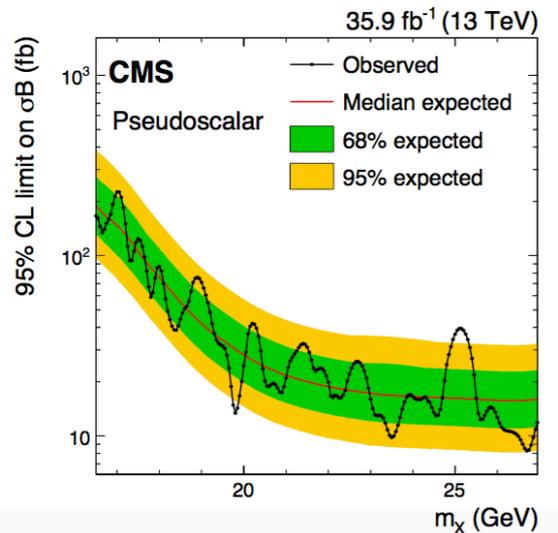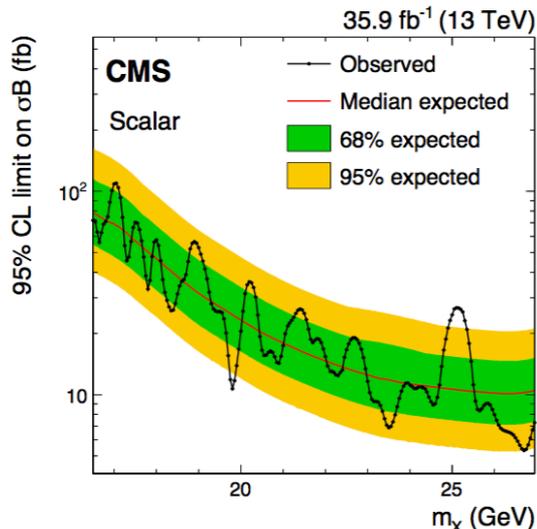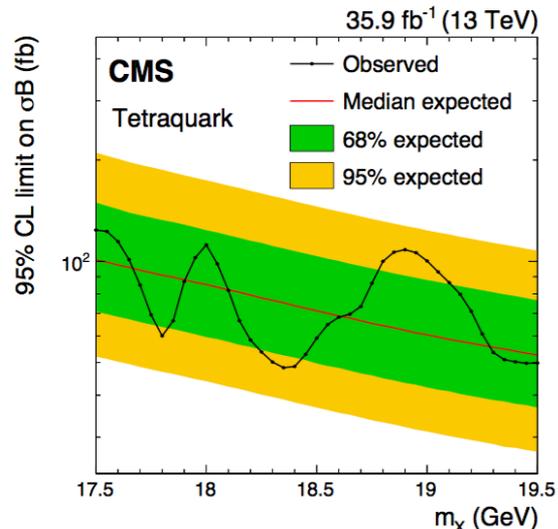
$10^{-10} < vtx\ probability < 10^{-3}$
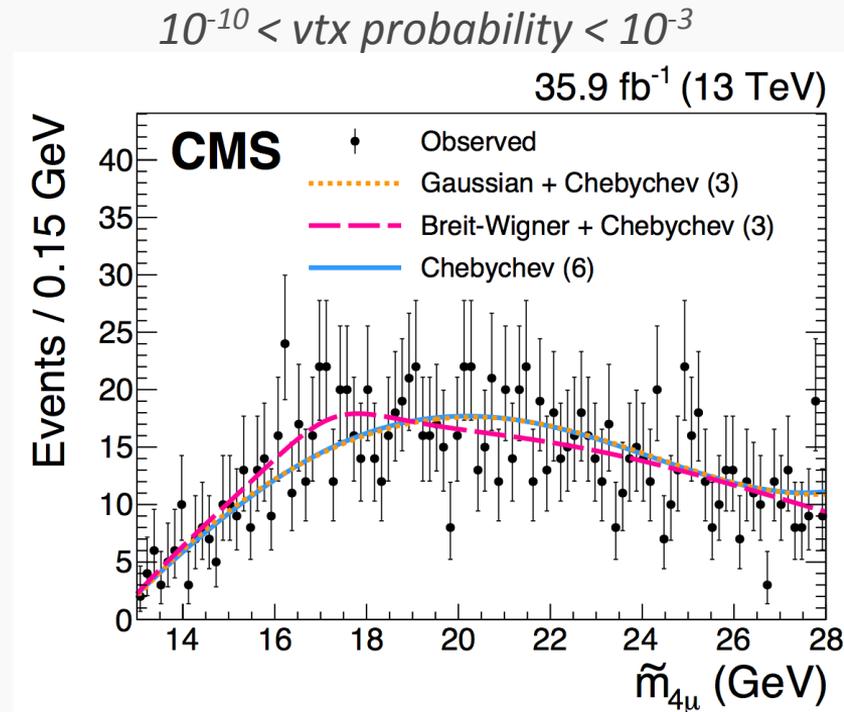
Looking at the data...

- Looking for a narrow signal resonance on top of a smoother background

- No large excess seen over the mass range

- Largest local significance: 2.4σ for a mass of 25.1 GeV
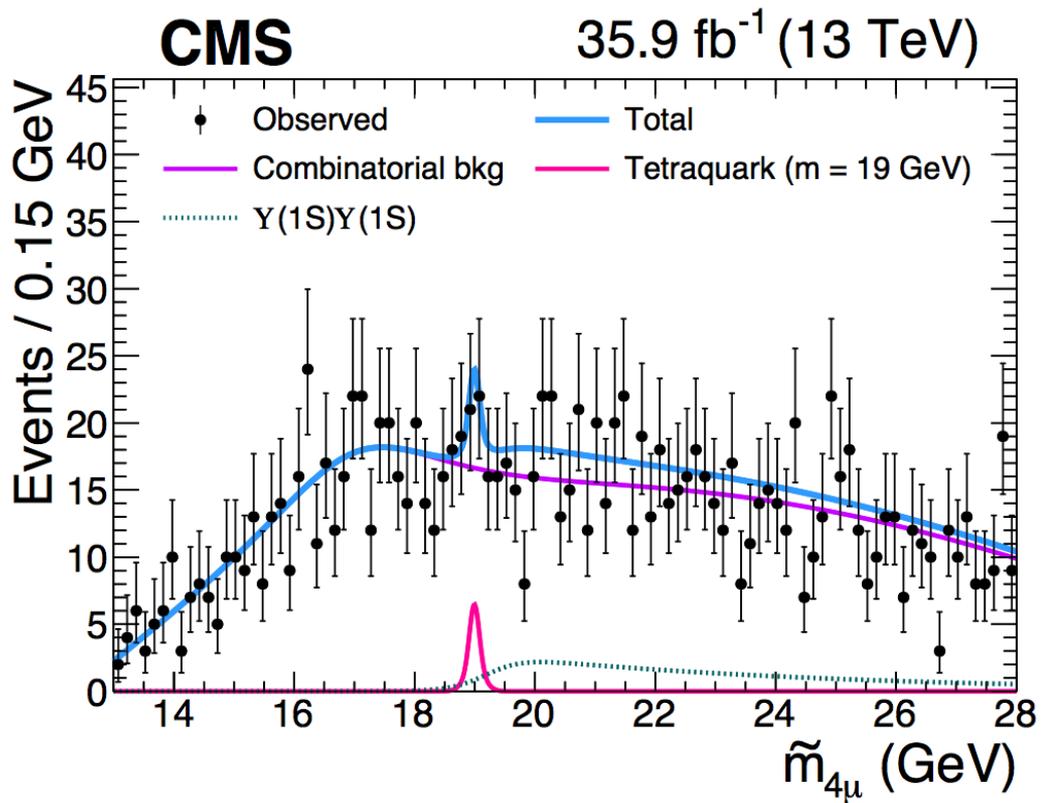
Limits

- Limits set in the context of 4 signal model hypotheses:
  - Tetraquark
  - Scalar
  - Pseudoscalar
  - Spin-2

- No significant excess with respect to bkg-only hypothesis