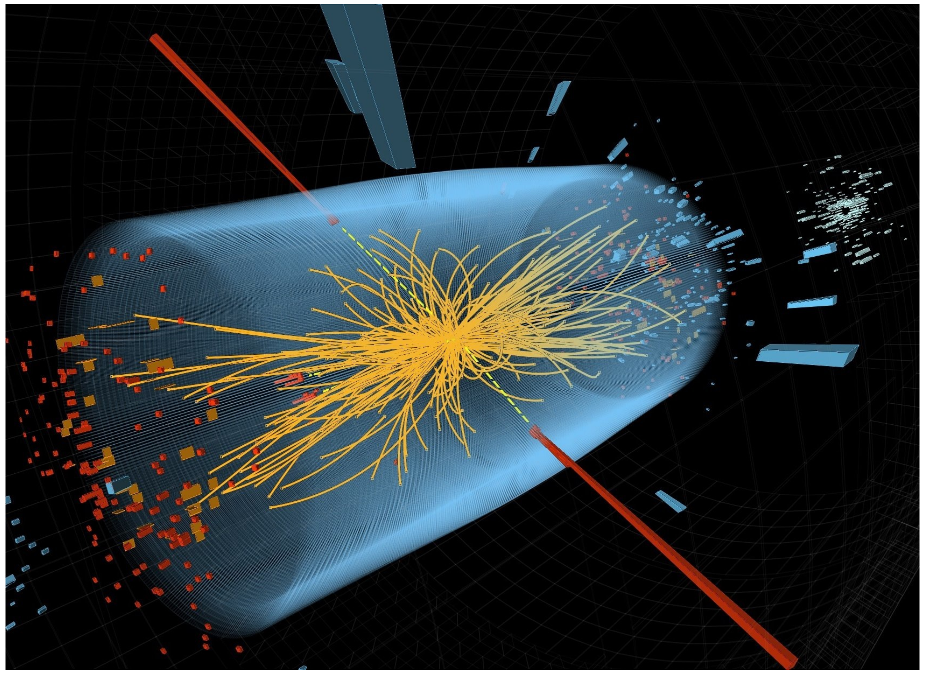
Search for the production of *two* Higgs bosons decaying to four bottom quarks

Souvik Das on behalf of the **CMS Collaboration**

US LUA 2014, 14 November 2014

An Experimentalist's Tool

"I think we got it", Rolf Heuer, 4 July 2012



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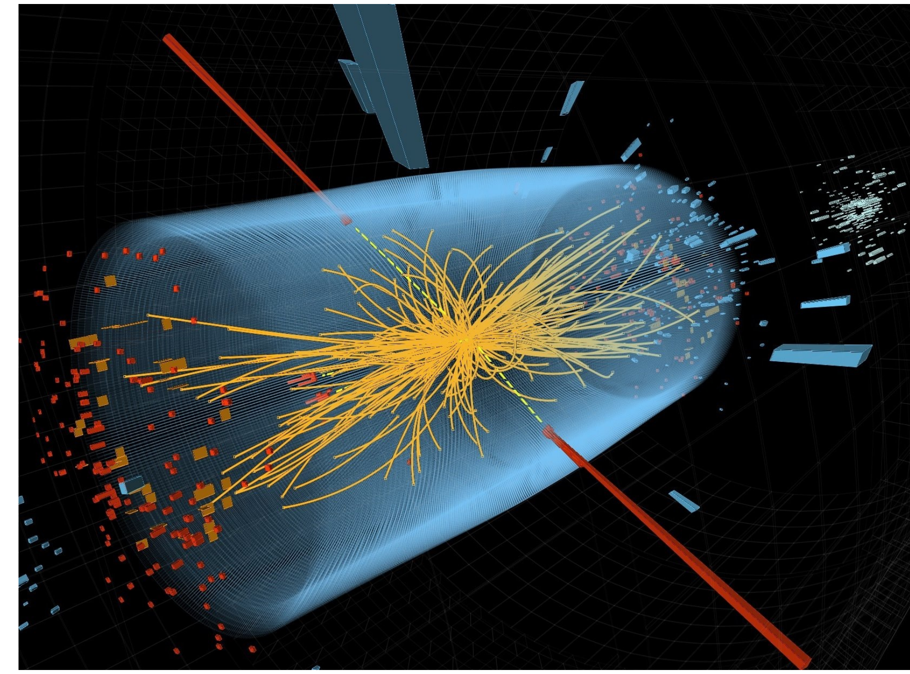

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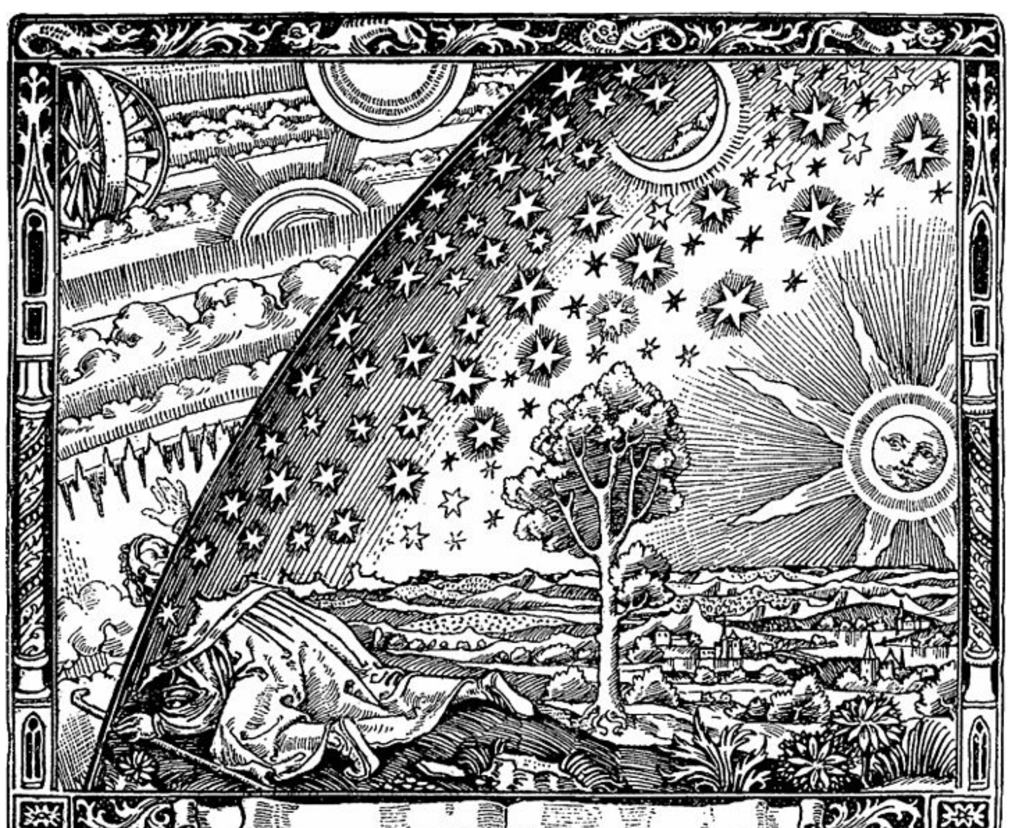


Higgs bosons may be **produced in pairs** by rare processes **Beyond the Standard Model**.

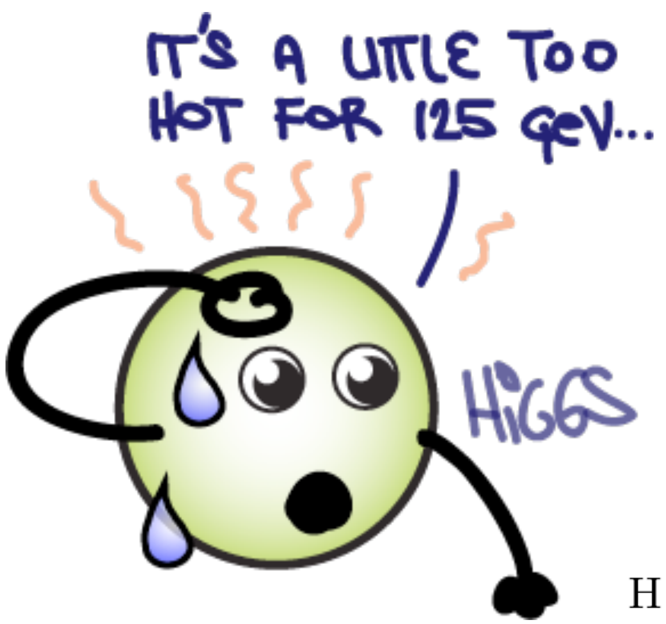
Higgs bosons now an **experimentalist's tool** to peer deeper

Searches underway at CMS.

- Multi-leptons and Photons Final State: $X \to HH \to (ll)(ll/\gamma)$
- 2 Photons and 2 b-jets Final State: $X \to HH \to (\gamma\gamma)(b\bar{b})$
- 4 b-jet Final State: $X \to HH \to (b\bar{b})(b\bar{b})$

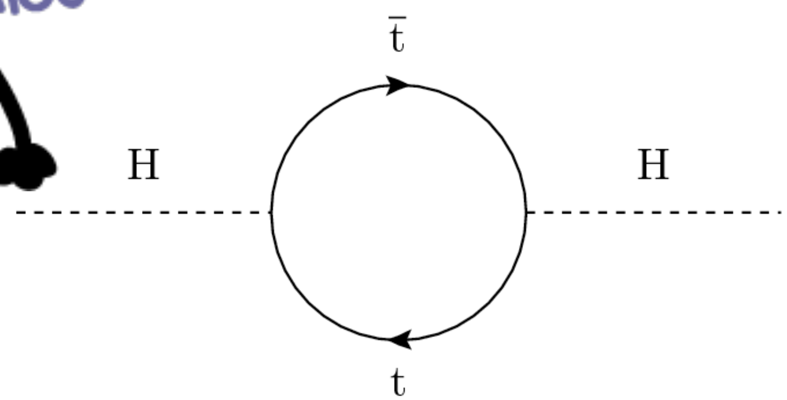
4 b-jet Final State most sensitive beyond m_X of 400 GeV

The Theorist's Dilemma and a Hypothesis



The Hierarchy Problem

The Higgs field's interactions with the ambient *quantum energy of the vacuum* should make its mass much heavier, closer to the Planck mass of 10^{19} GeV.



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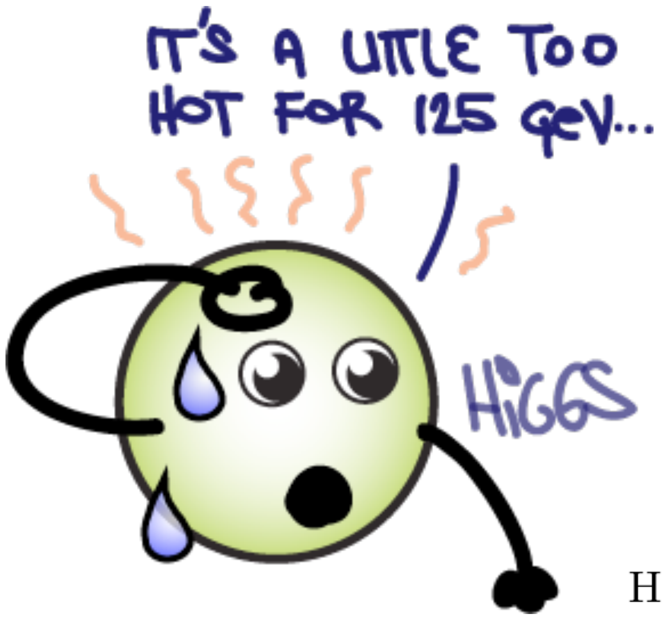

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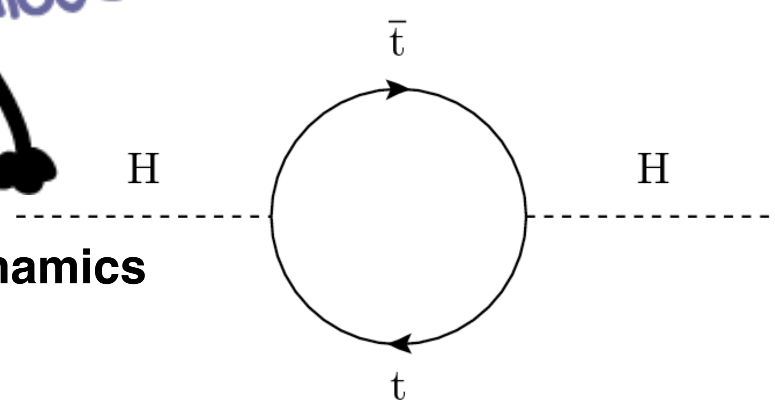

Like ice in a glass of warm water, it is unstable.

Thermodynamics

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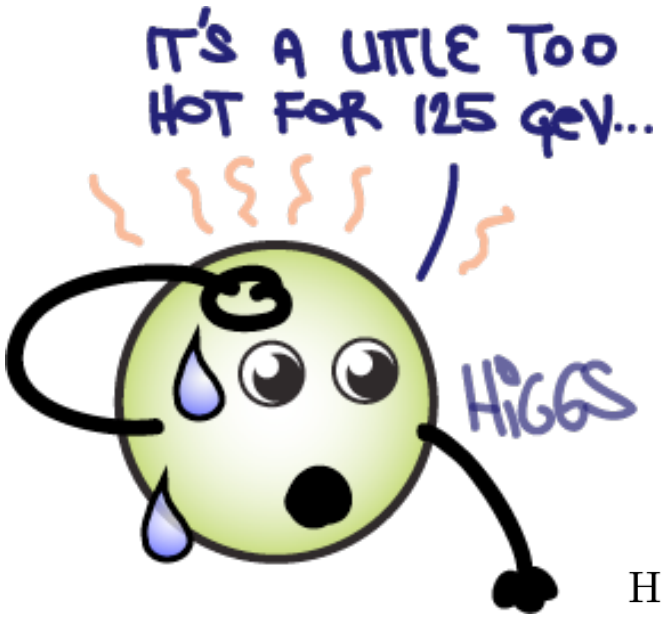

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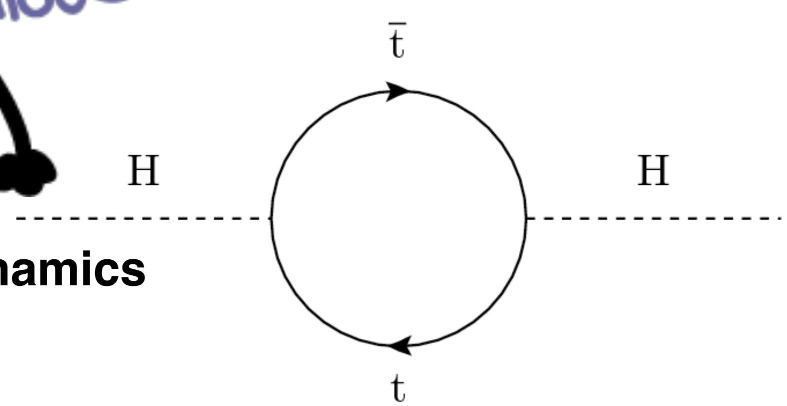

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What gives?

Thermodynamics

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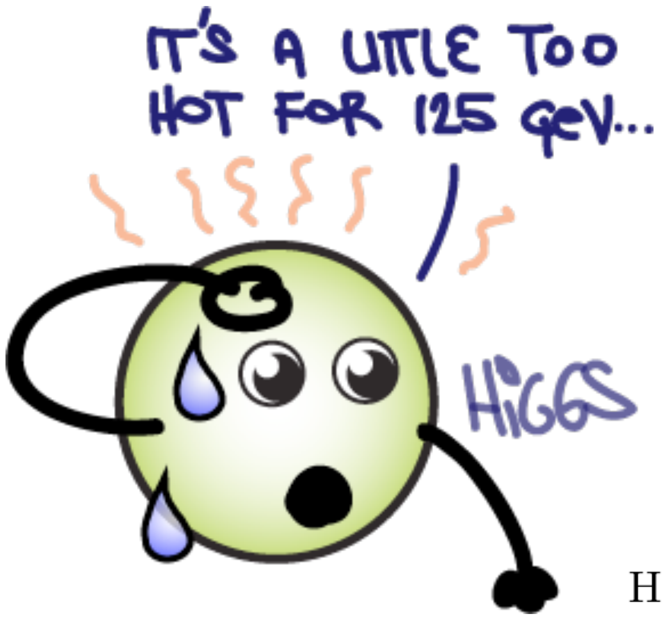

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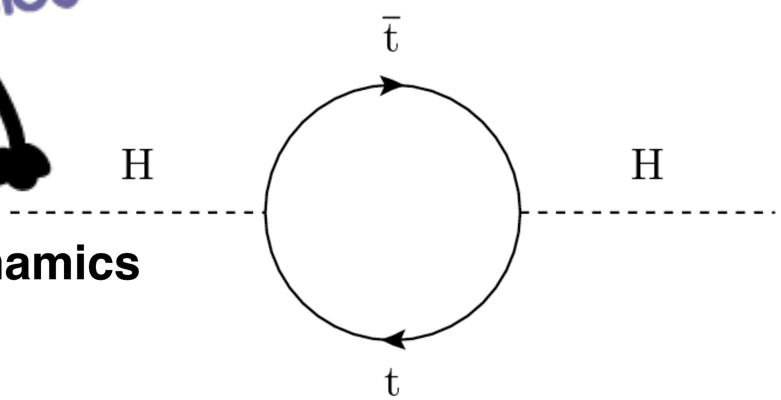

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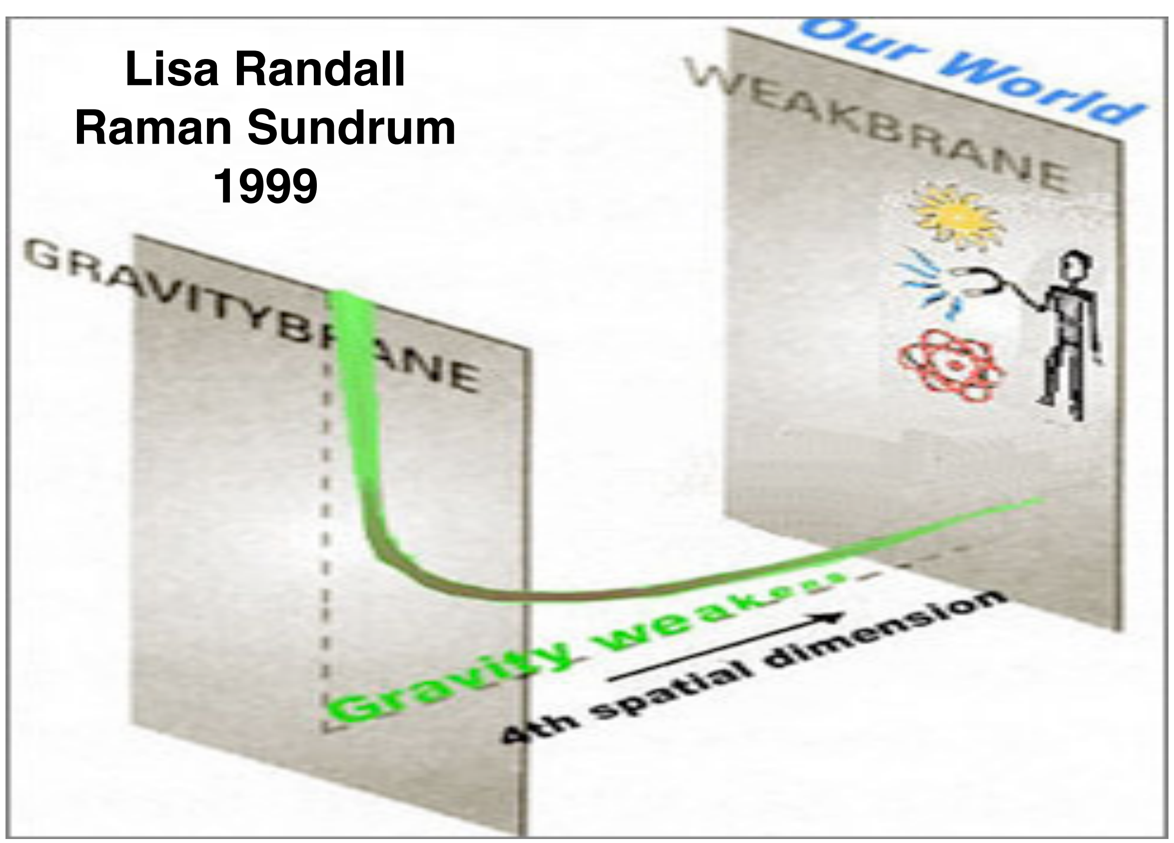
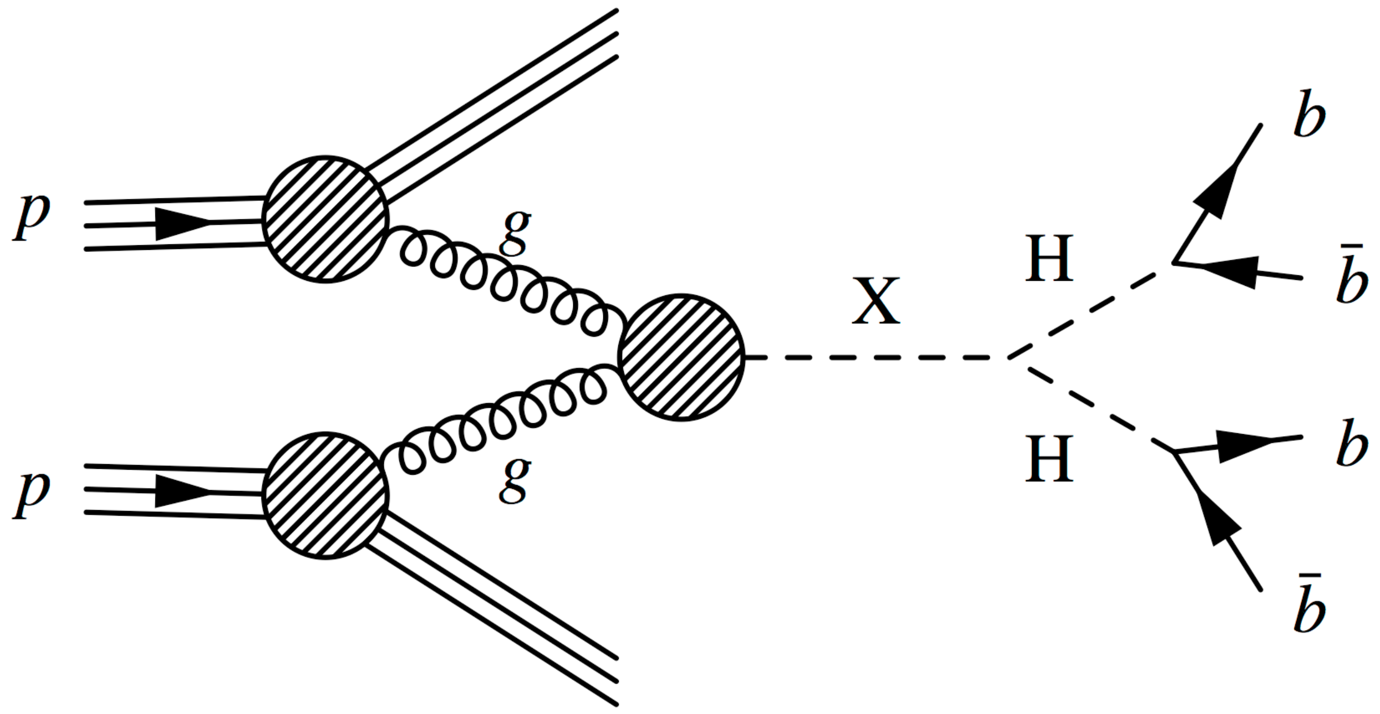


Warped Extra Dimension

- Perhaps we live in a 4D slice of a 5D world? Walking along the 5th dimension warps spacetime. We live on the "weak brane" where the wavefunction of the Higgs is localized, separated from the Planck brane
- This theory **predicts a spin 0 *radion*** that can decay into two Higgs bosons!
- By searching for resonances decaying to Higgs bosons, we exclude significant parameter space of this hypothesis

$H(b\bar{b})H(b\bar{b})$: The Challenge



A resonance, *X*, decaying to a pair of Standard Model Higgs bosons, decaying to 4 b-jets

- Signal would be buried under **copious 4-jet QCD multi-jet background**.
- We rely on:
  - A **trigger with b-tagging** (b-jet identification) algorithms
  - Our most powerful b-tagging algorithm for offline analysis (CMVA)
  - **Data-validated model** of the QCD multi-jet background
  - Good $\boldsymbol{m_{b\bar{b}}}$ **resolution**
- Data: L = 17.93 fb^{-1}. $\sqrt{s}$ = 8 TeV

$H(b\bar{b})H(b\bar{b})$: Search Strategy

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Trigger

- CMS data acquisition drinks from a fire-hose. Two levels of triggers used to bring 40 MHz collision rate to a few kHz.

- Require **2 b-jets** identified with a *Combined Secondary Vertex* algorithm to reject overwhelming background of QCD multi-jet events.

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Two mass regimes

- Low Mass Regime: 270 GeV $\leq$ mX $\leq$ 450 GeV
- High Mass Regime: 450 GeV $<$ mX $\leq$ 1100 GeV

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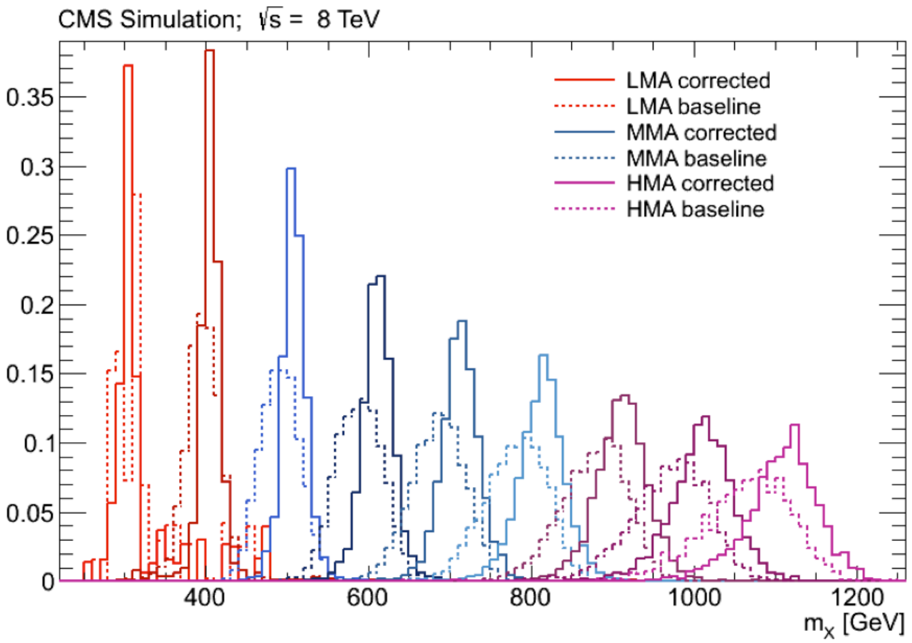

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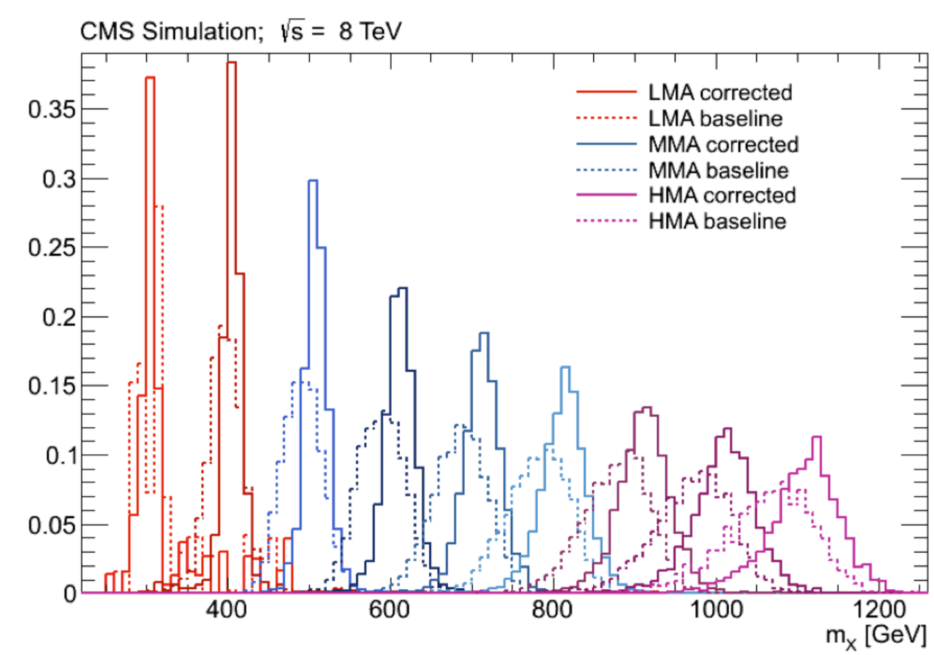
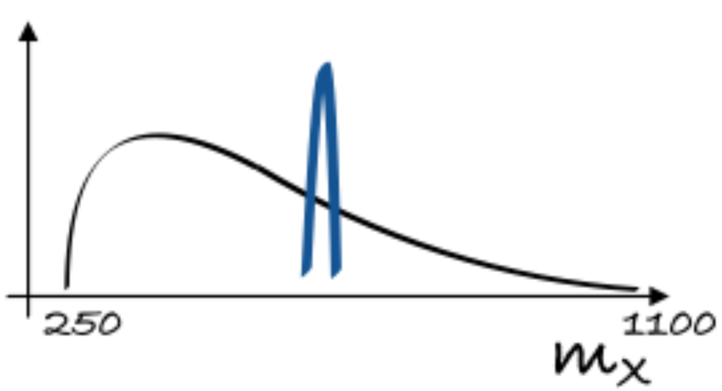


- **Kinematic constraint** on jet energies to the Higgs mass. Jet momenta varied within experimental resolutions
- Parametric form for **signal modeled from MC**



- Background decomposed into two components
  - **$t\bar{t}$ component**. Parametric form from MC
  - **QCD multi-jet component**. Form modeled from data sidebands, validated in several Control Regions

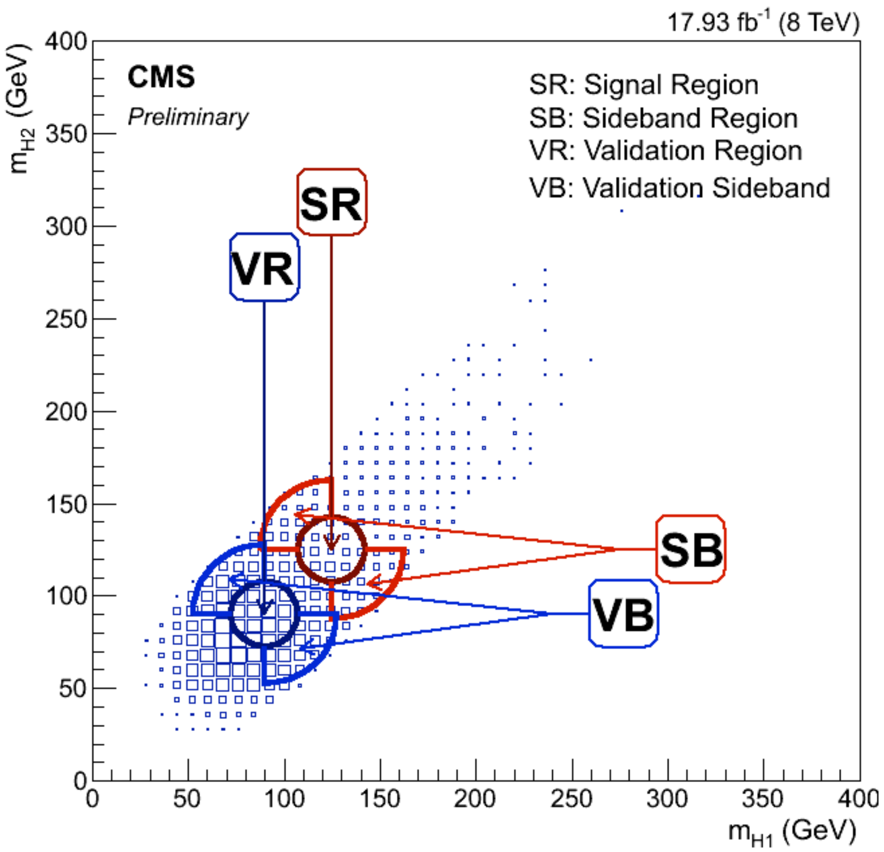
$H(b\bar{b})H(b\bar{b})$: QCD Background Modeling

All-hadronic final state **dominated by multi-jet QCD**. Cannot rely on MC. **Functional form** from studying data.

- Signal Region (SR) defined in (m_{H1}, m_{H2}) plane
  $\Delta m^2_{H1} + \Delta m^2_{H1} < (17.5\ \text{GeV})^2$
  where $\Delta m_{H1,2} = m_{H1,2} - 125$ GeV
  Blind Analysis.

- Sideband Region (SB) defined as
  $(35\ \text{GeV})^2 < \Delta m^2_{H1} + \Delta m^2_{H1} < (17.5\ \text{GeV})^2$
  and $\Delta m_{H1} \Delta m_{H2} < 0$

- Validation Region (VR) and Validation Region Sideband (VB) centered around (90 GeV, 90 GeV)



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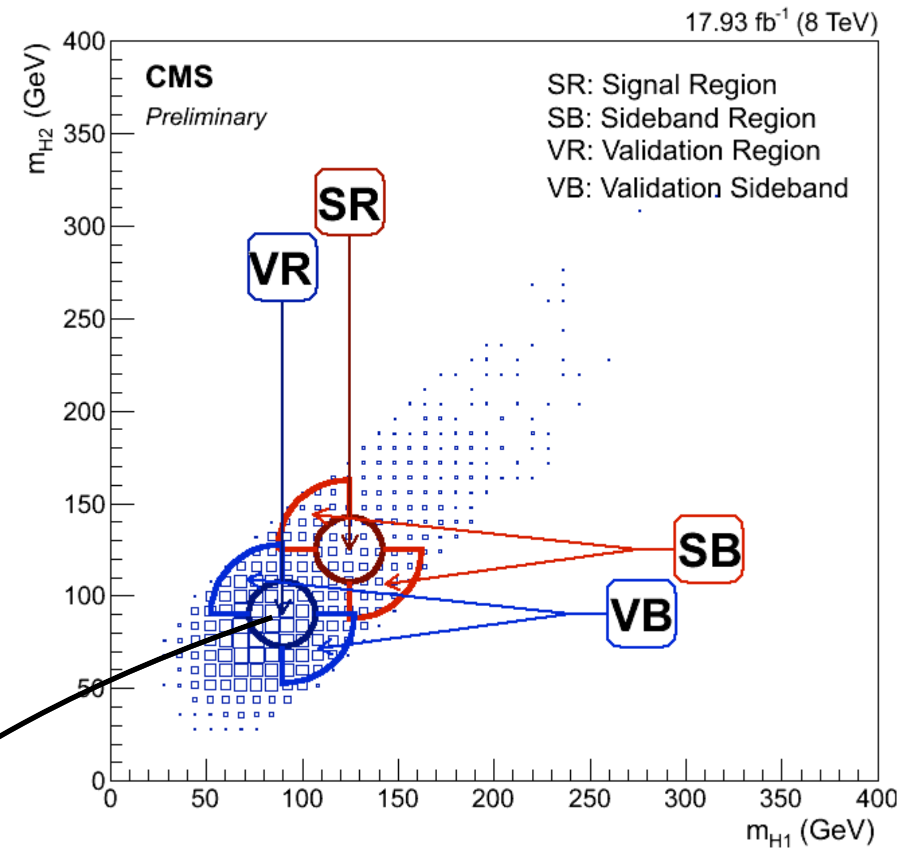
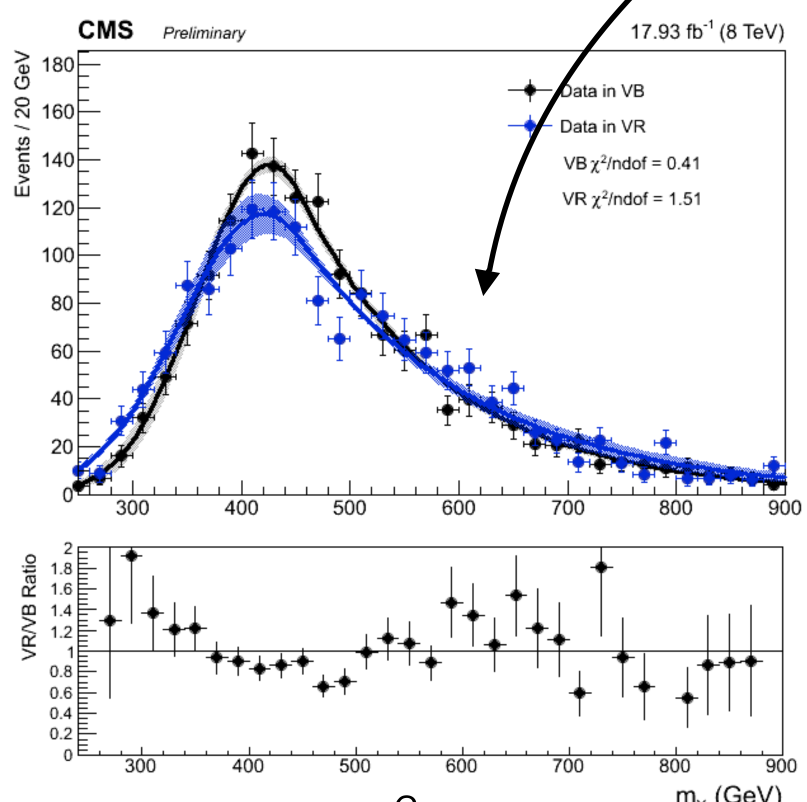


Functional forms tried

- Gaussian core differentiably continued to exponential tail
- Up to 7 orders of Bernstein polynomials

Bias due to choice of functional form included as systematic uncertainty.



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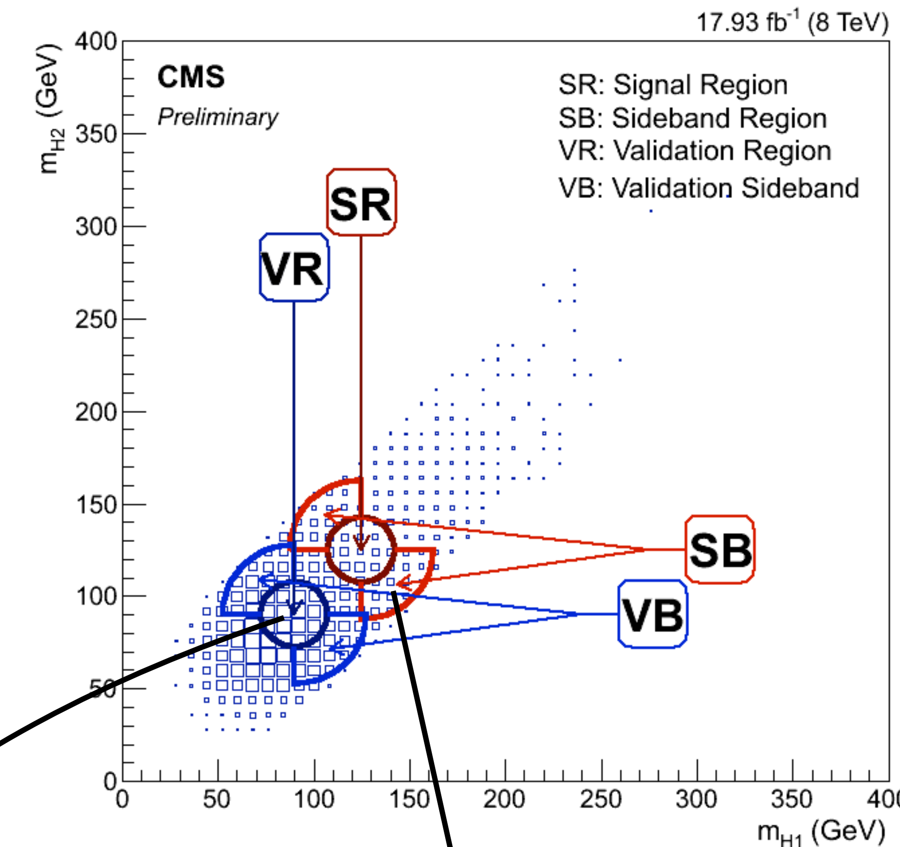

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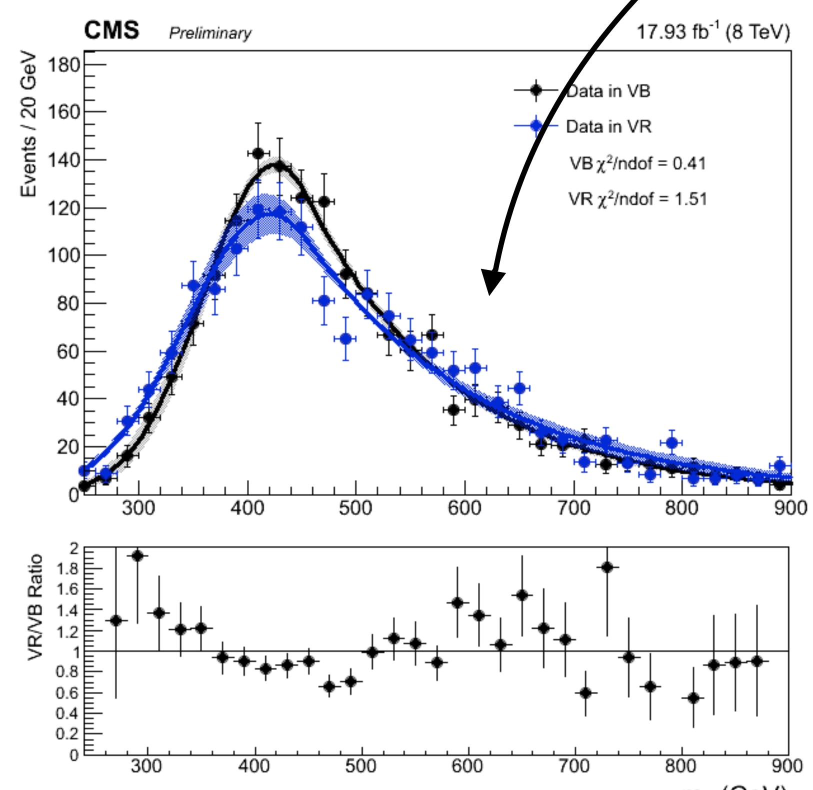

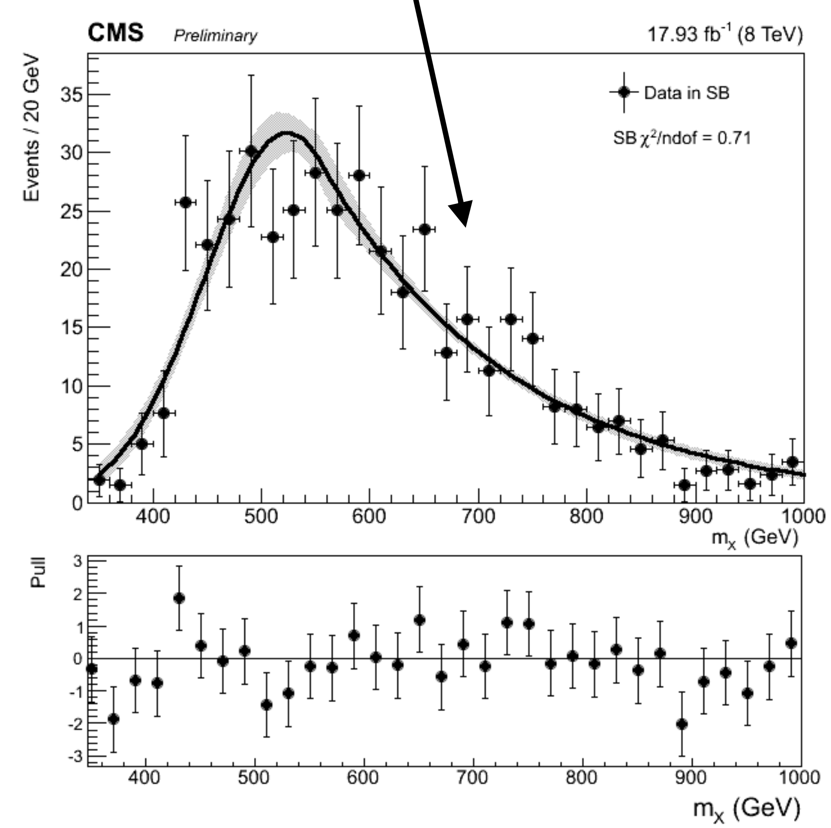

$H(b\bar{b})H(b\bar{b})$: Signal and $t\bar{t}$ Background

Event Selection Criteria

- 4 jets with $p_T > 40$ GeV, $|\eta| < 2.5$, CMVA $\epsilon = 70\%$
- **Low Mass Regime**:
  - HH candidates such that $|m_H - 125\ \text{GeV}| < 35$ GeV
  - 2 of these jets $p_T > 90$ GeV
- **High Mass Regime**:
  - HH candidates such that jets from a H have $\Delta R < 1.5$
  - If $m_X > 740$ GeV, H $p_T > 300$ GeV
- In case of multiple HH candidates, we choose the combination that minimizes $|m_{H1} - m_{H2}|$
- m_{HH} must fall within SR

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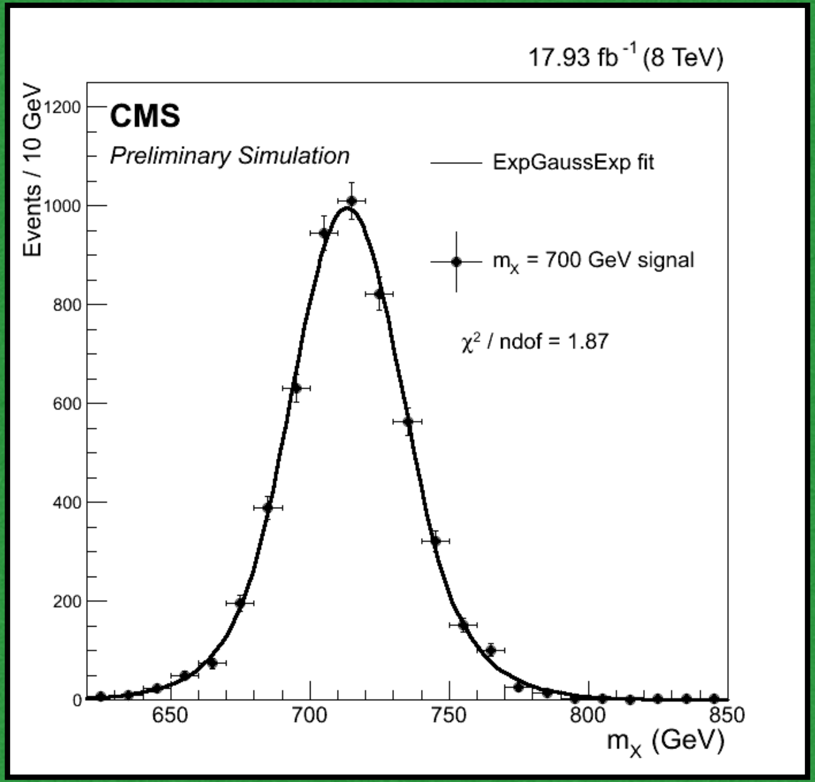
Signal Modeling

- Signal shape from simulation
- **Negligible natural width** 1 GeV
- Samples m_X = 270 GeV to 1100 GeV



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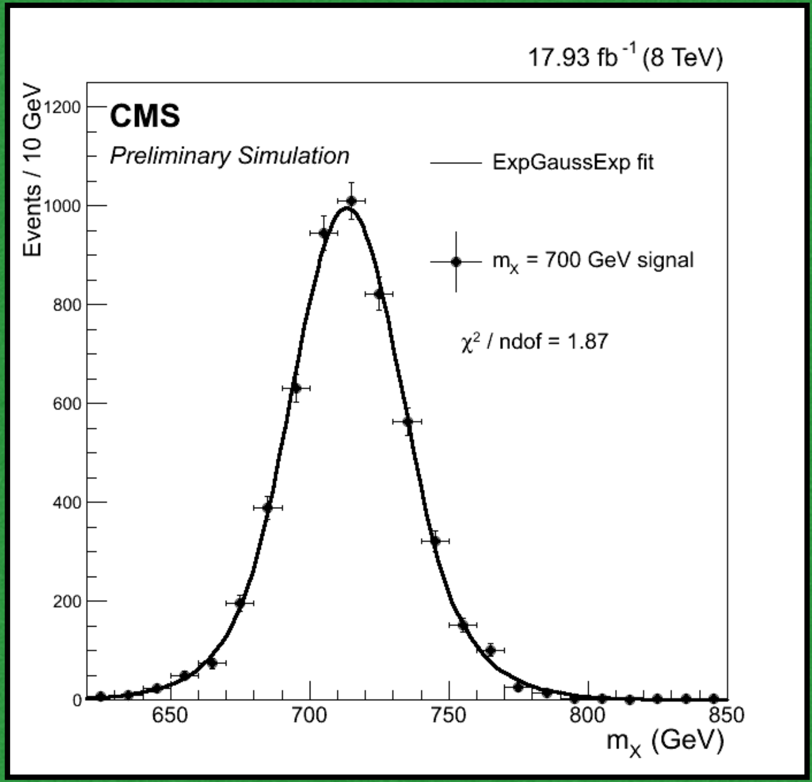
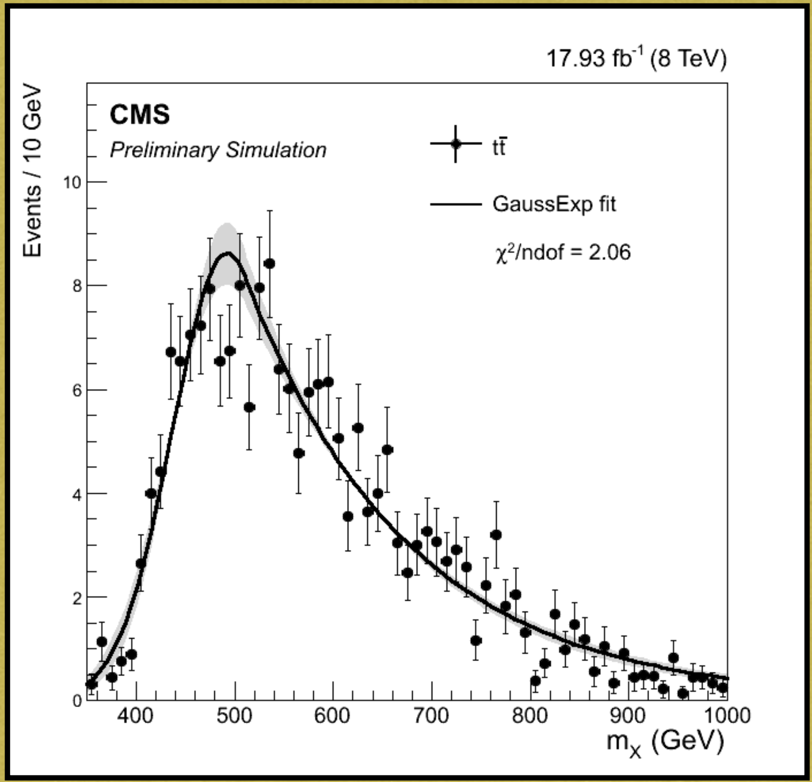
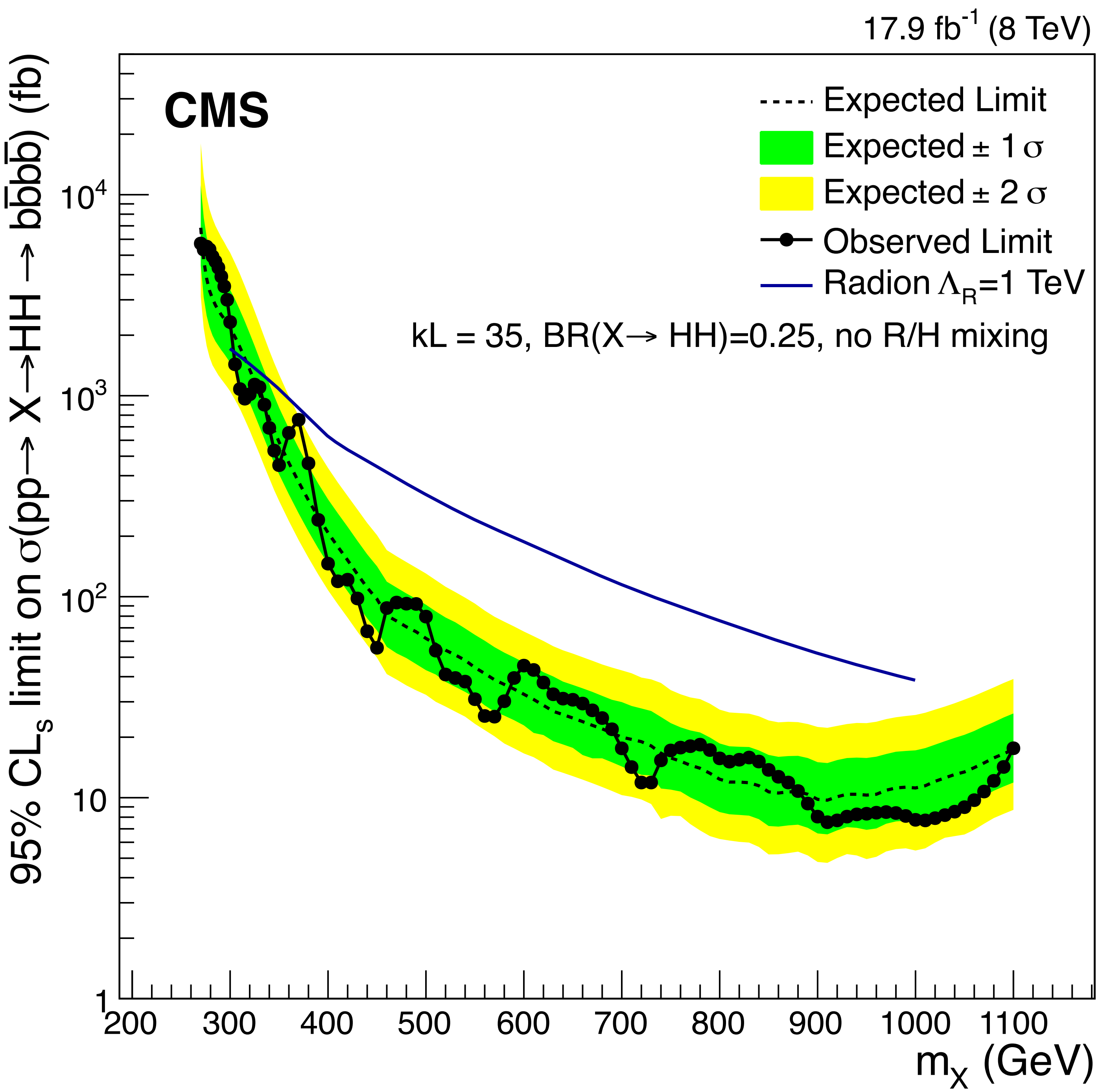


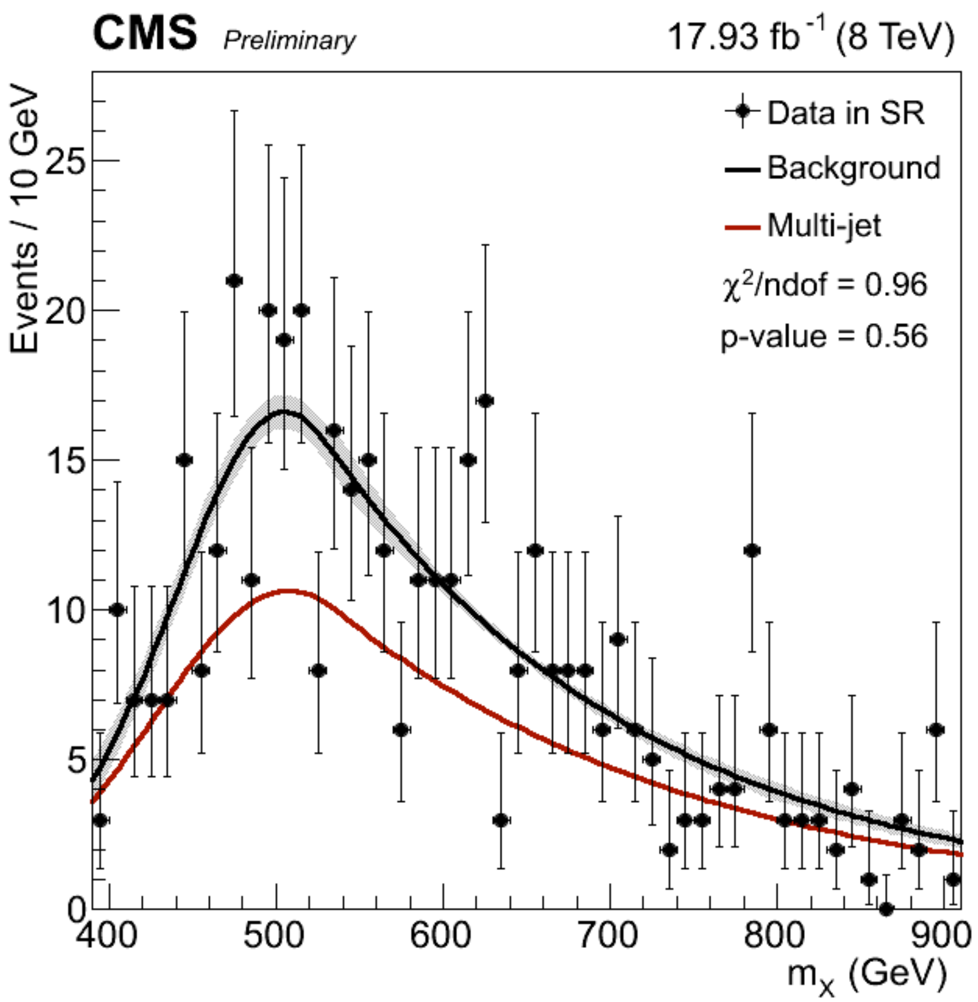
t$\bar{t}$ Modeling

- t$\bar{t}$ contributes **22% (27%)** of background in Low (High) mass regimes
- Modeled from simulation.



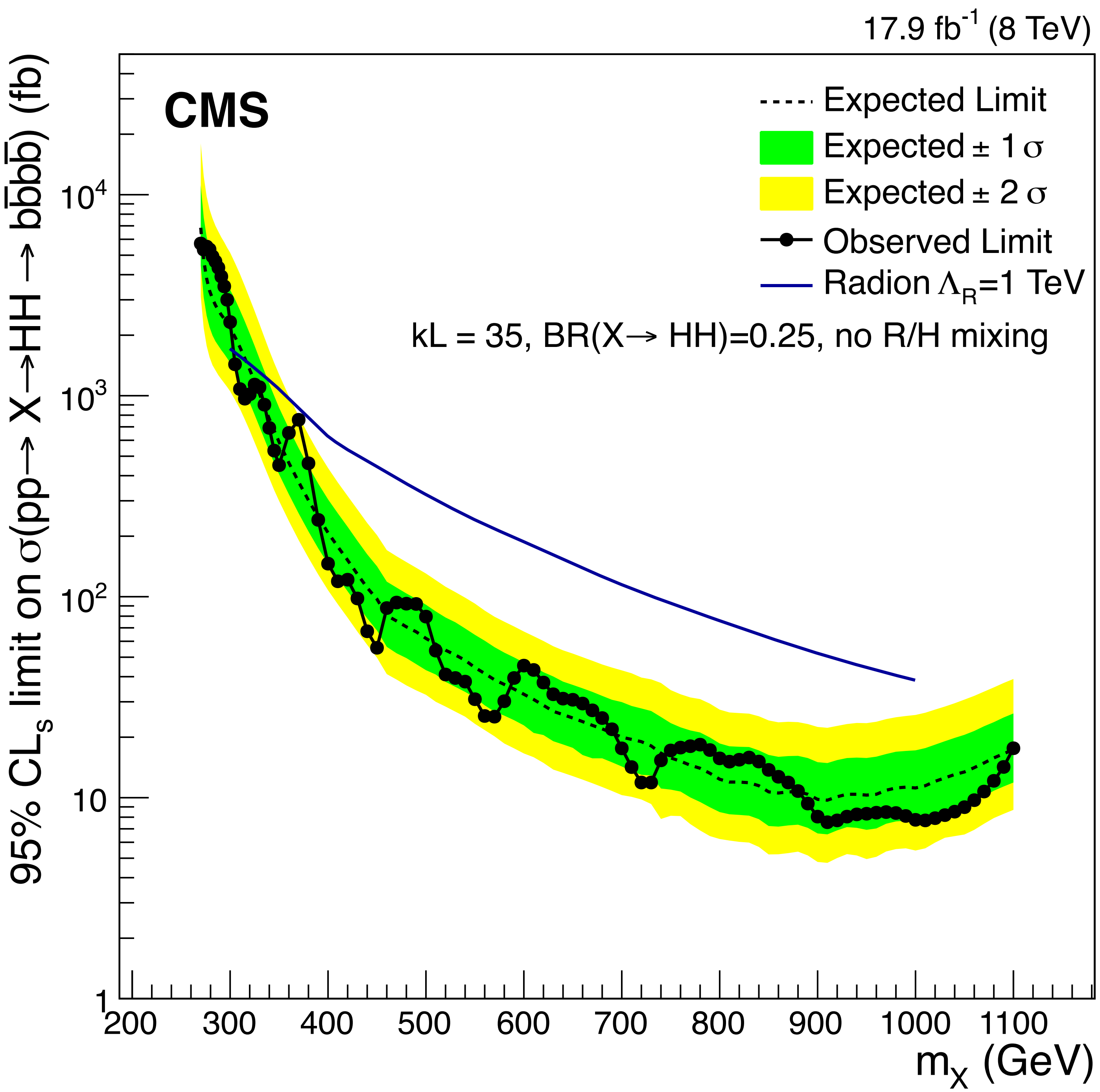
H(b$\bar{b}$)H(b$\bar{b}$): Results

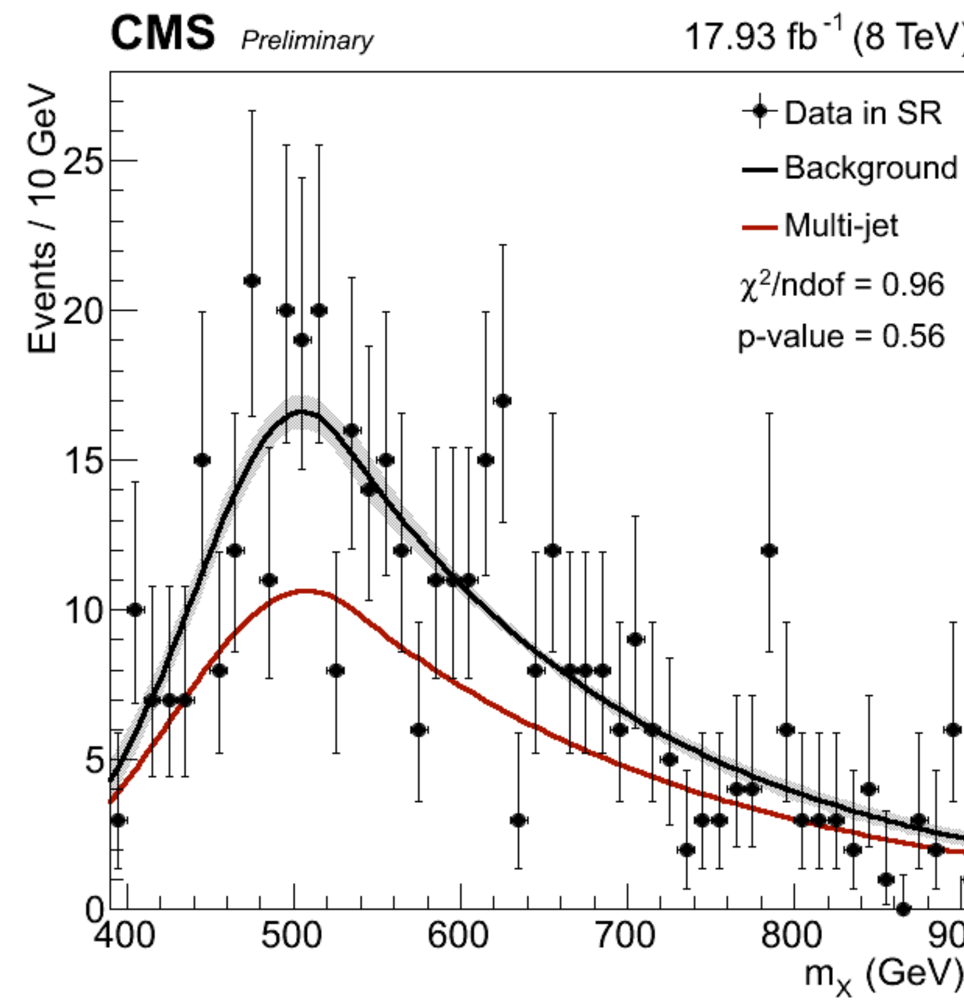




Unblinded data in the High Mass Regime fitted to the background-only hypothesis

H(bb̄)H(bb̄): Results



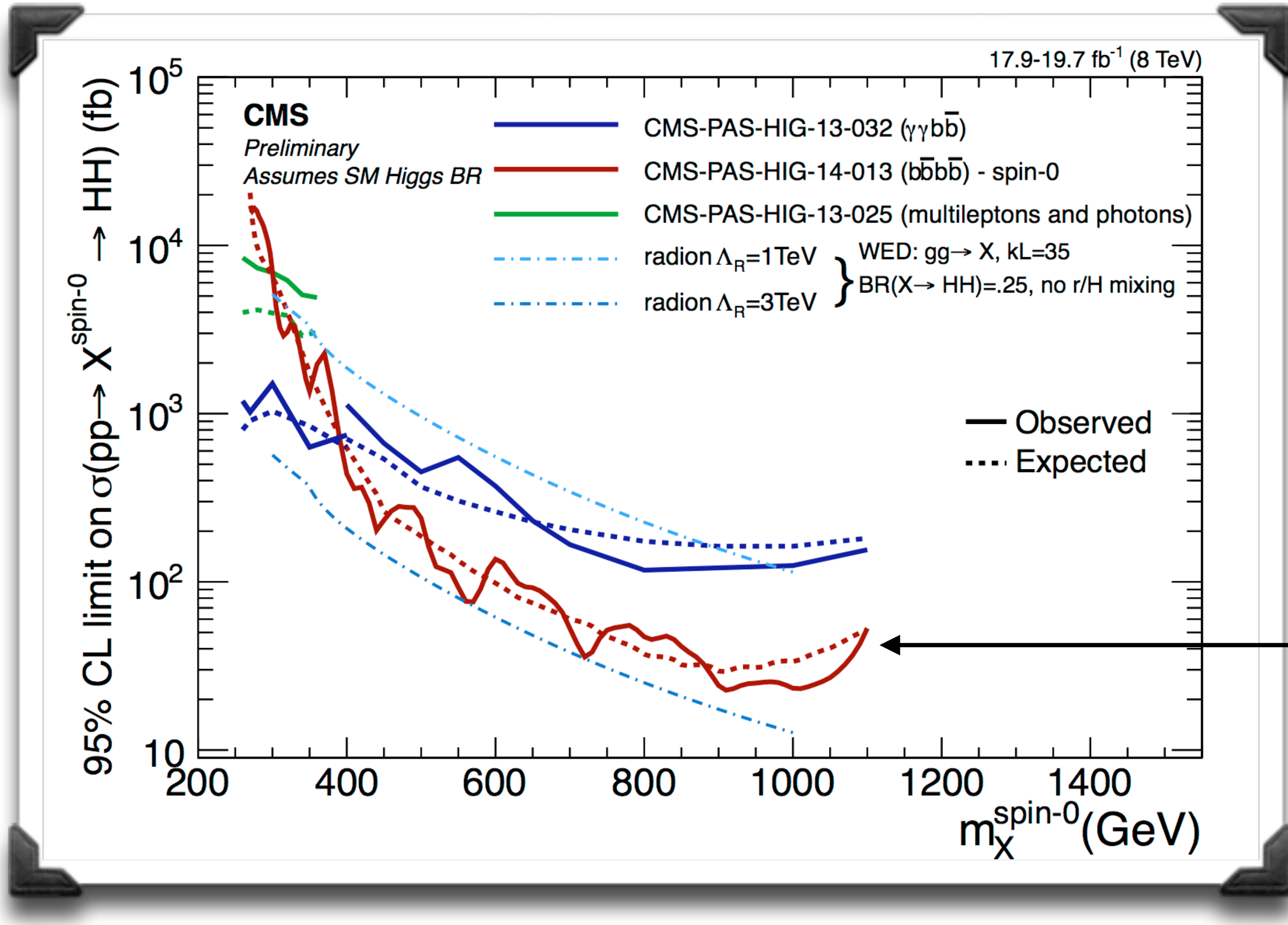


Unblinded data in the High Mass Regime fitted to the background-only hypothesis

Search for a narrow width resonance with mass between 270 GeV and 1.1 TeV decaying to pairs of Higgs bosons conducted by CMS. **No statistically significant excess** over backgrounds observed.

The **radion** of the Warped Extra Dimension hypothesis, in given parameter space, is **excluded at 95% CL**

Combined two-Higgs Results and Conclusions



The reach of our analysis

- H(bb̄)H(bb̄) Physics Analysis Summary and public twiki are online
- H(γγ)H(bb̄) and H(bb̄)H(bb̄) sensitivities cross. **Complementary searches**
- Resonant searches **constrain Beyond the Standard Model Physics**

Analyses gearing up for Run II data

BACKUP

$H(b\bar{b})H(b\bar{b})$: CSV tagger

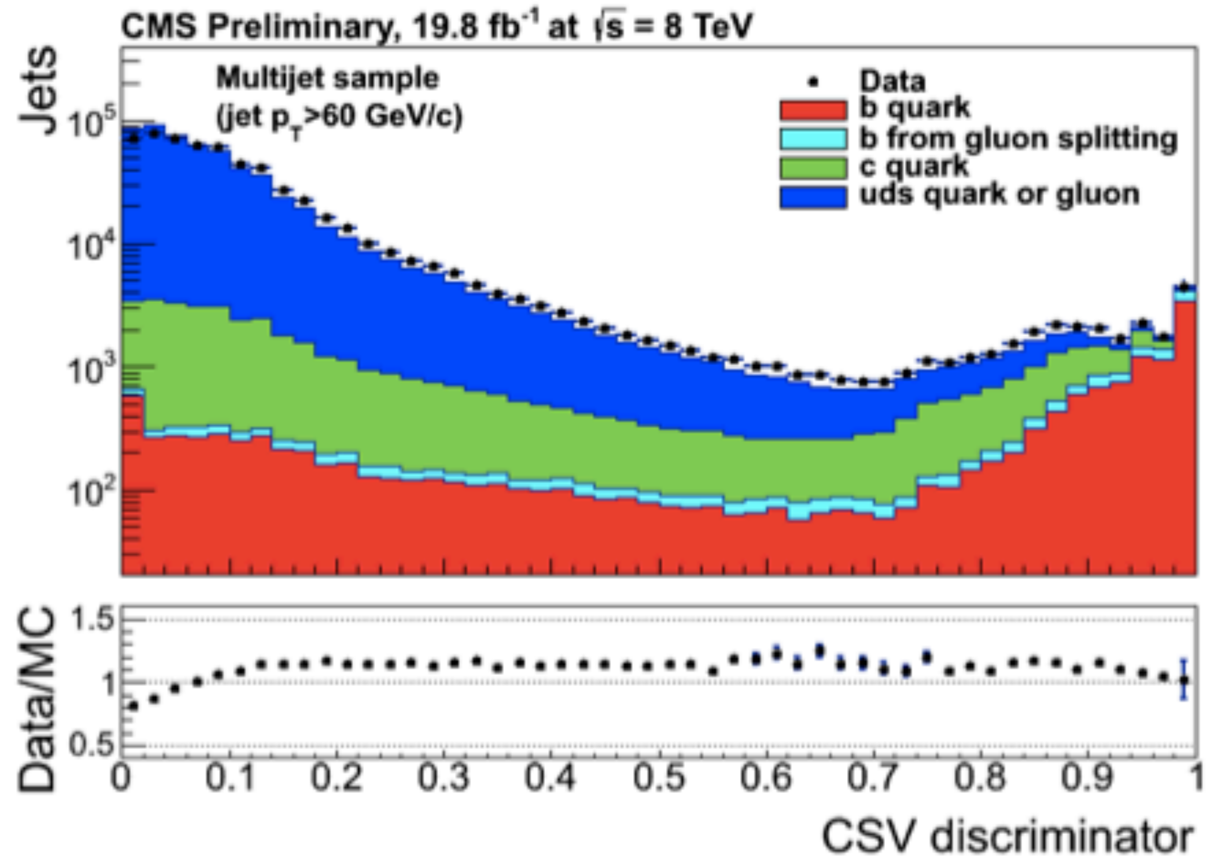
- The Combined Secondary Vertex through multivariate technique combines

  Track information

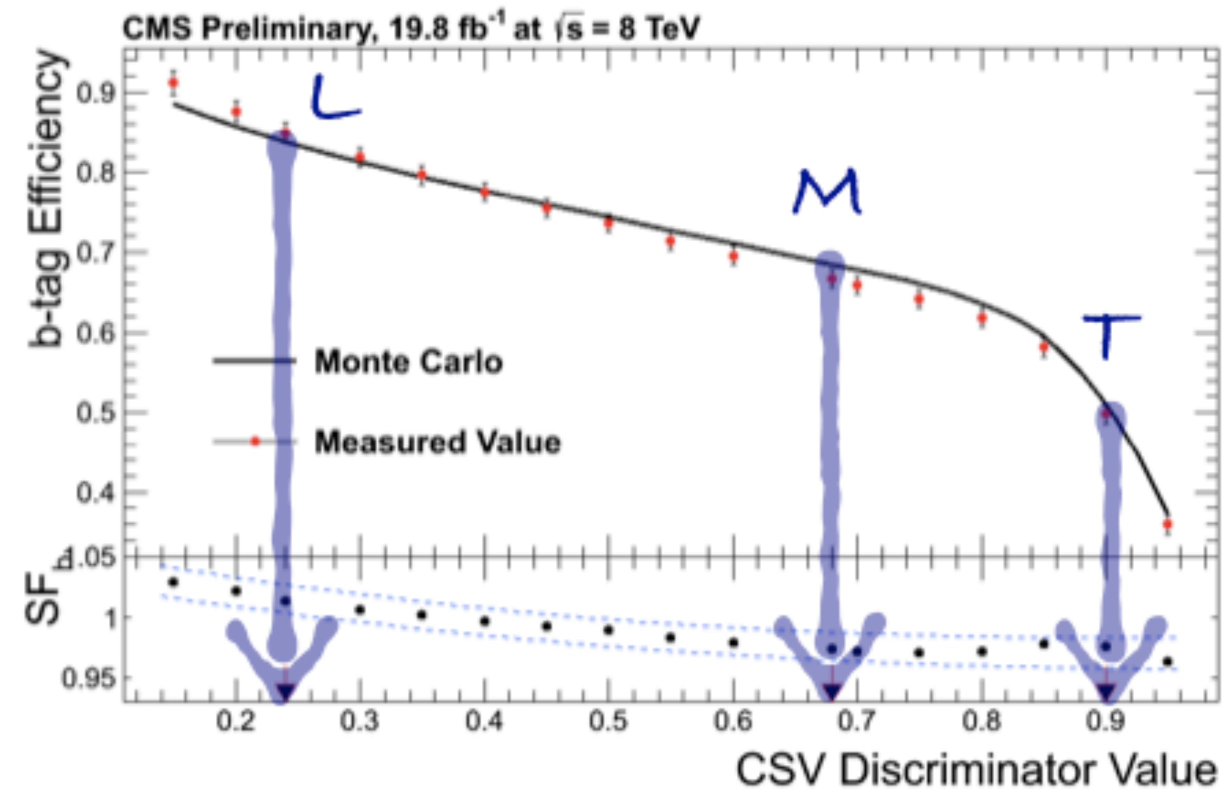
  - 3D IP significance of the most energetic tracks

  Vertex information

  - if available or pseudo vertex from displaced tracks



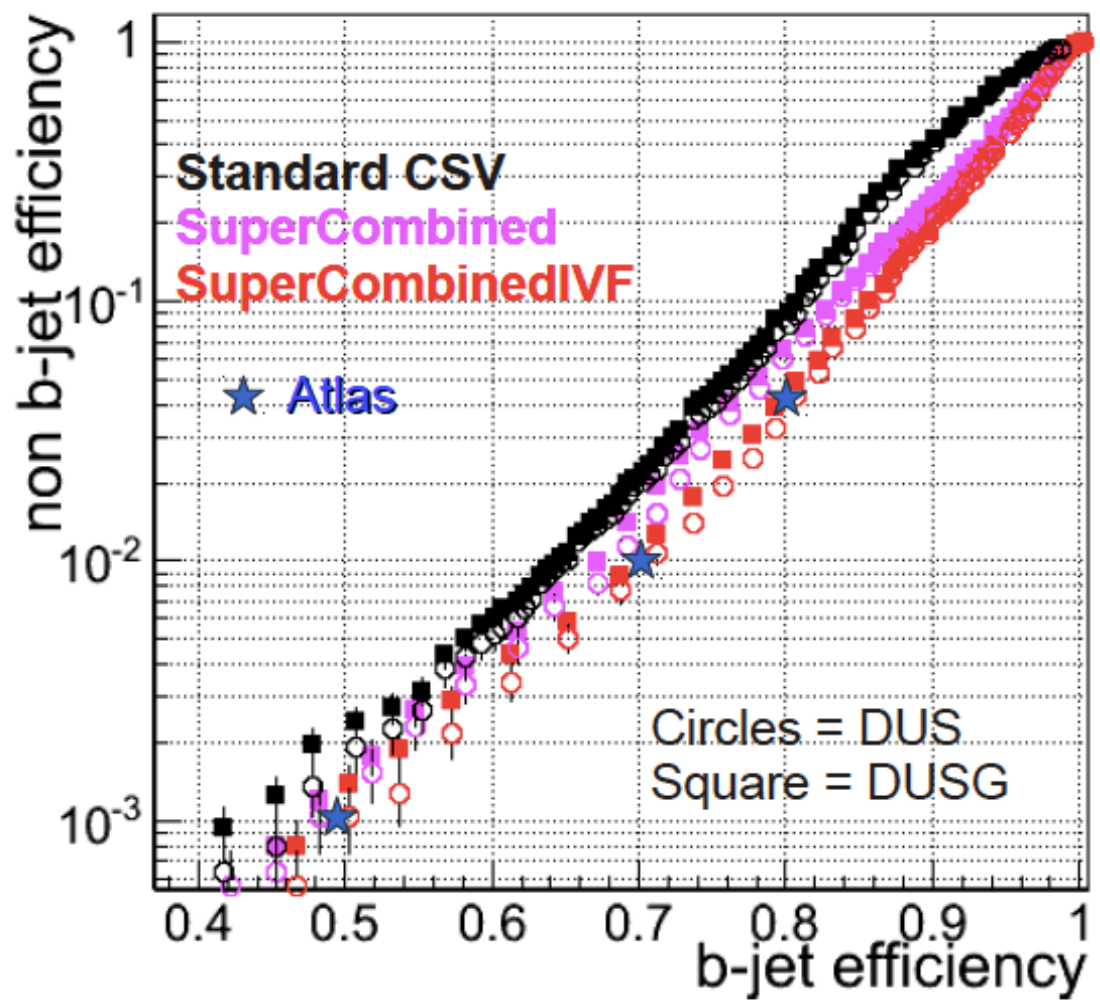
	b	c	light [%]
L	85	32	10
M	70	15	1
T	50	6	0.1



H($b\bar{b}$)H($b\bar{b}$): Combined MVA tagger

The CMVA tagger combines features from different b-taggers:

- Jet Probability for IP
- CSV for combining SV information
- Soft leptons information when available
- Inclusive Vertex Finder to determine Secondary Vertices

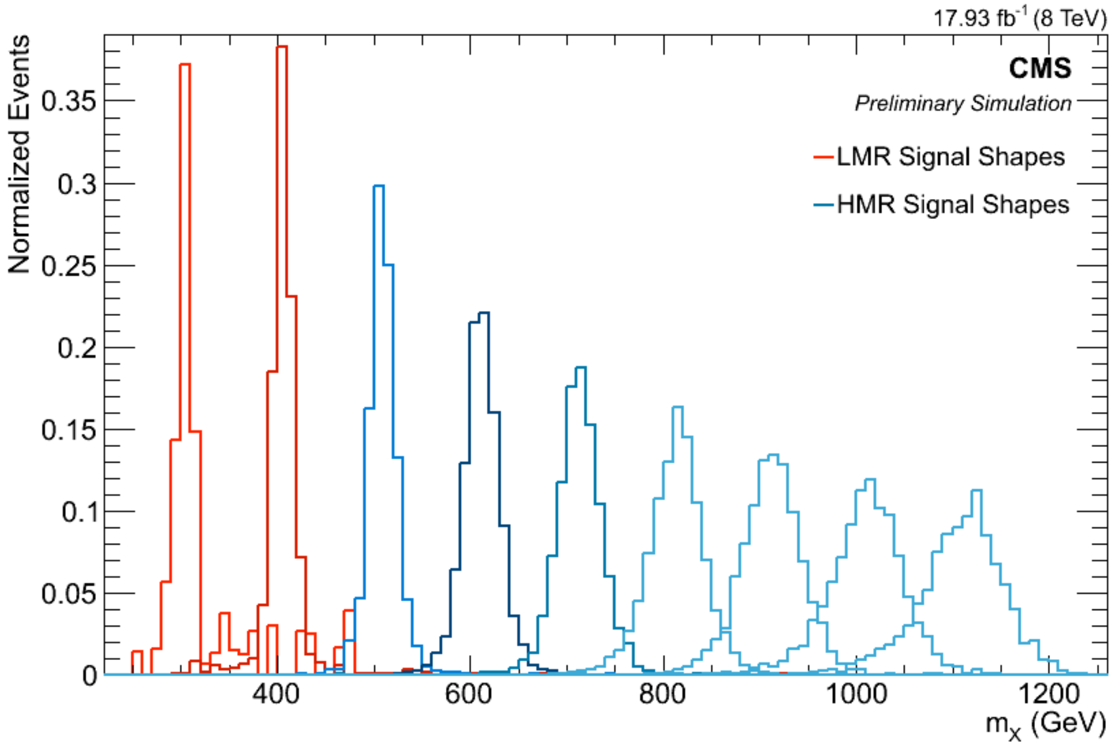


- **2x better fake rejection at 70% efficiency**

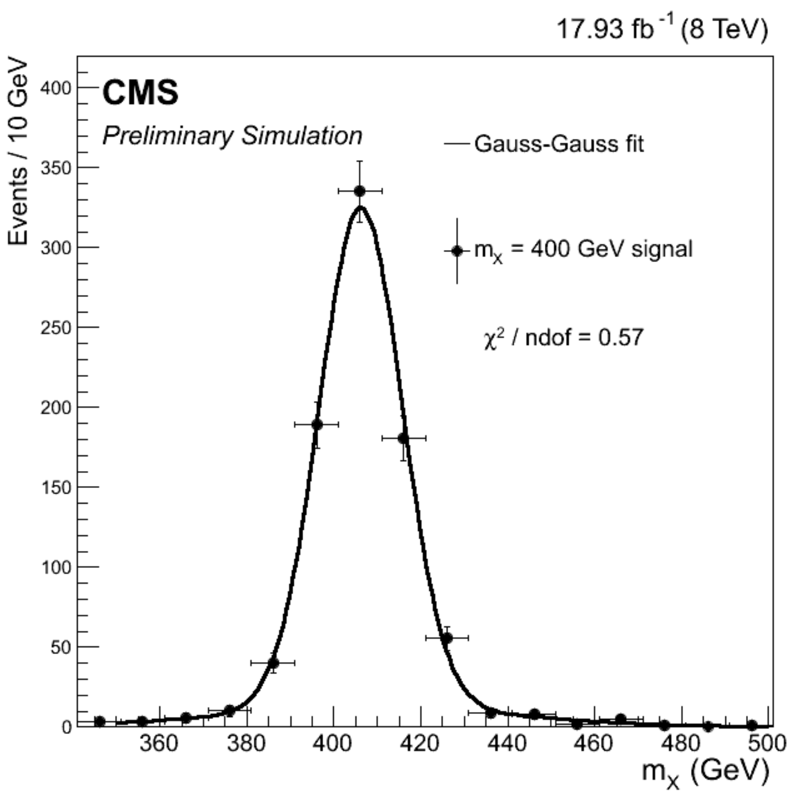
- CMVA SF for MC computed as a correction to CSV SF, determined in a $t\bar{t}$ enriched region of data

- ±1σ variations of this scale factors propagates to a 12.7% systematic uncertainty on the signal efficiency

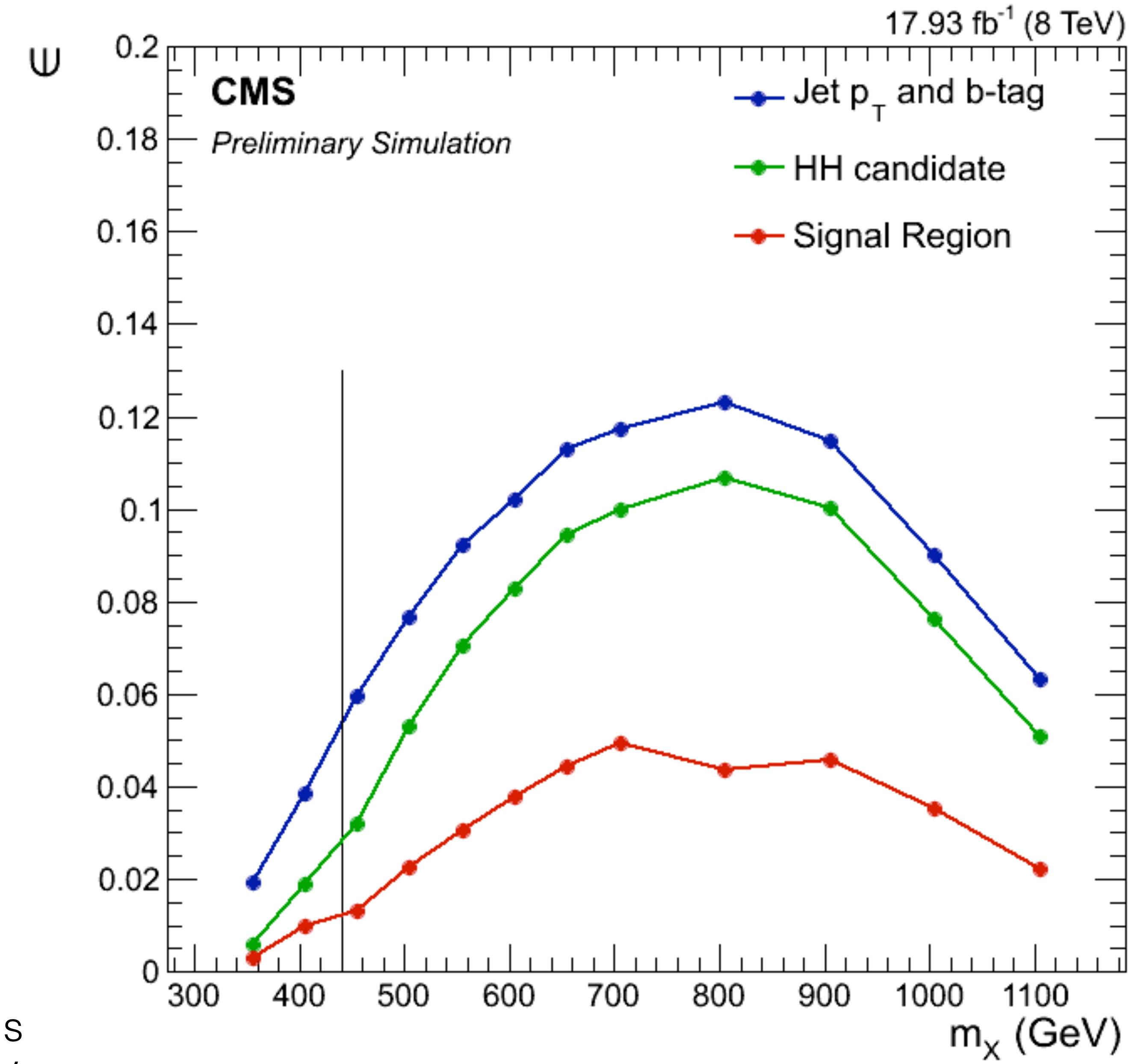
$H(b\bar{b})H(b\bar{b})$: Signal Modeling and Efficiencies



The m_X distribution of signal events after the event selection criteria for each of mass hypothesis. Momenta of b-jets have been corrected by the kinematic constraint to m_H

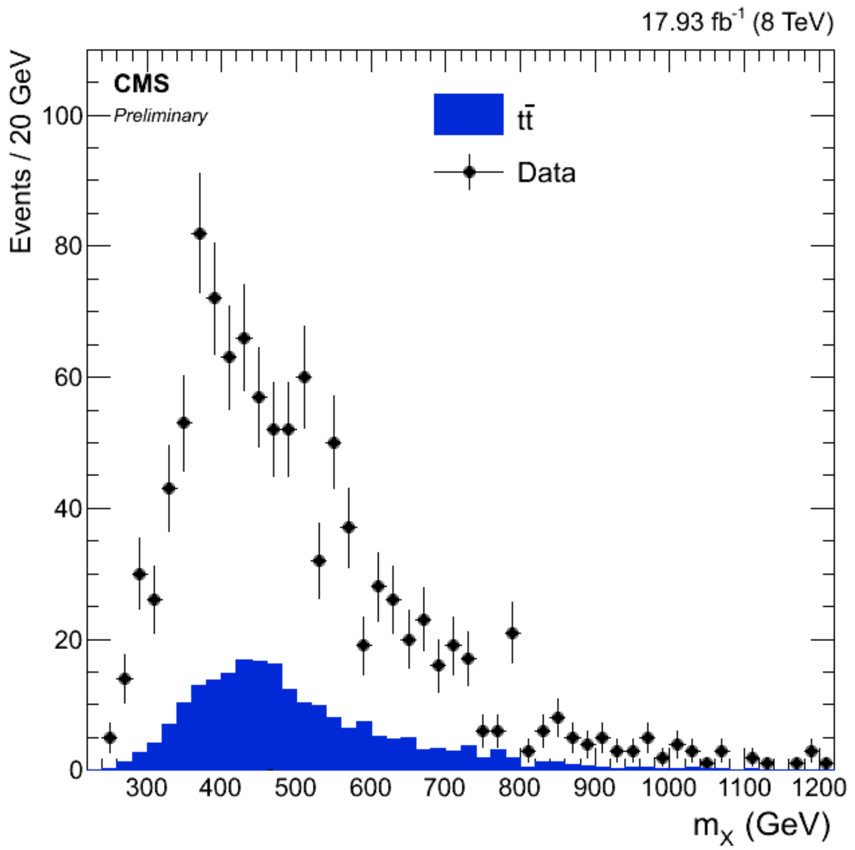


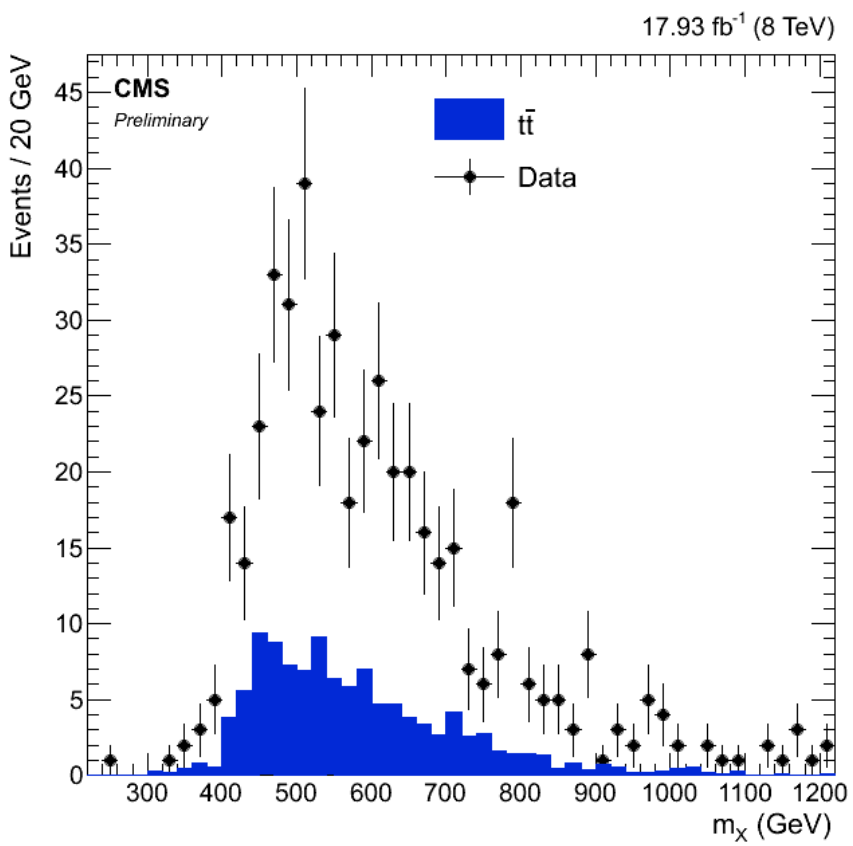
The sum of two Gaussians fitted to the mX= 400 GeV distribution of simulated signal events after the event selection criteria for the Low Mass Regime.



The selection efficiency for X to $H(b\bar{b})H(b\bar{b})$ signal events at different stages of the event selection for each mass hypothesis. The vertical lines represents the transition from the Low Mass Regime and the High Mass Regime as evaluated to optimize the expected significance.

$H(b\bar{b})H(b\bar{b})$: Background Composition



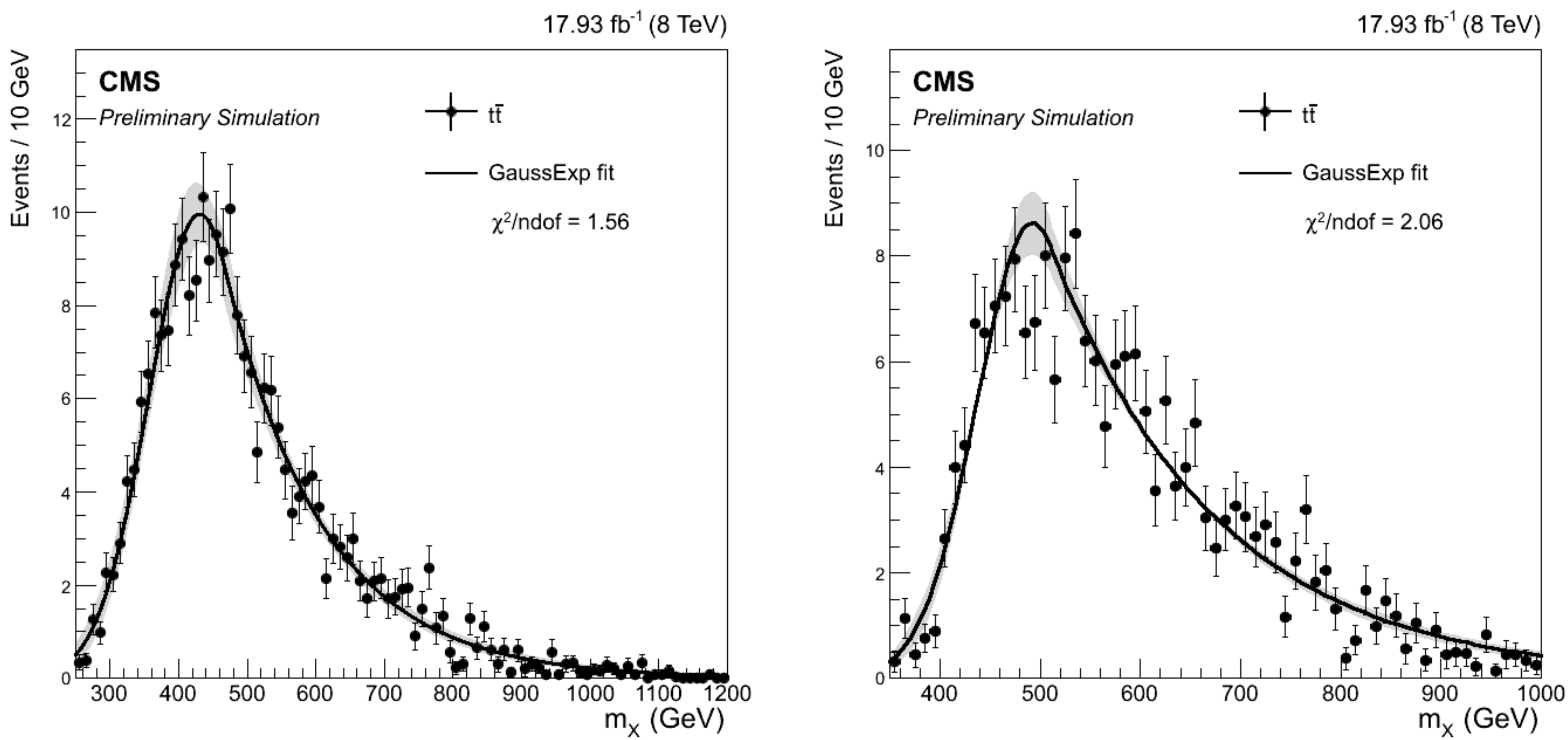


	LMR (%)	MMR & HMR (%)
Z + jets	< 0.1	< 0.04
ZZ	0.003	0.003
ZH	< 0.001	< 0.004
$t\bar{t}$	22	27

The contribution of Z+jets, ZZ, ZH and $t\bar{t}$ to the background after all selection criteria. The remainder of the background comes from QCD multi-jet events

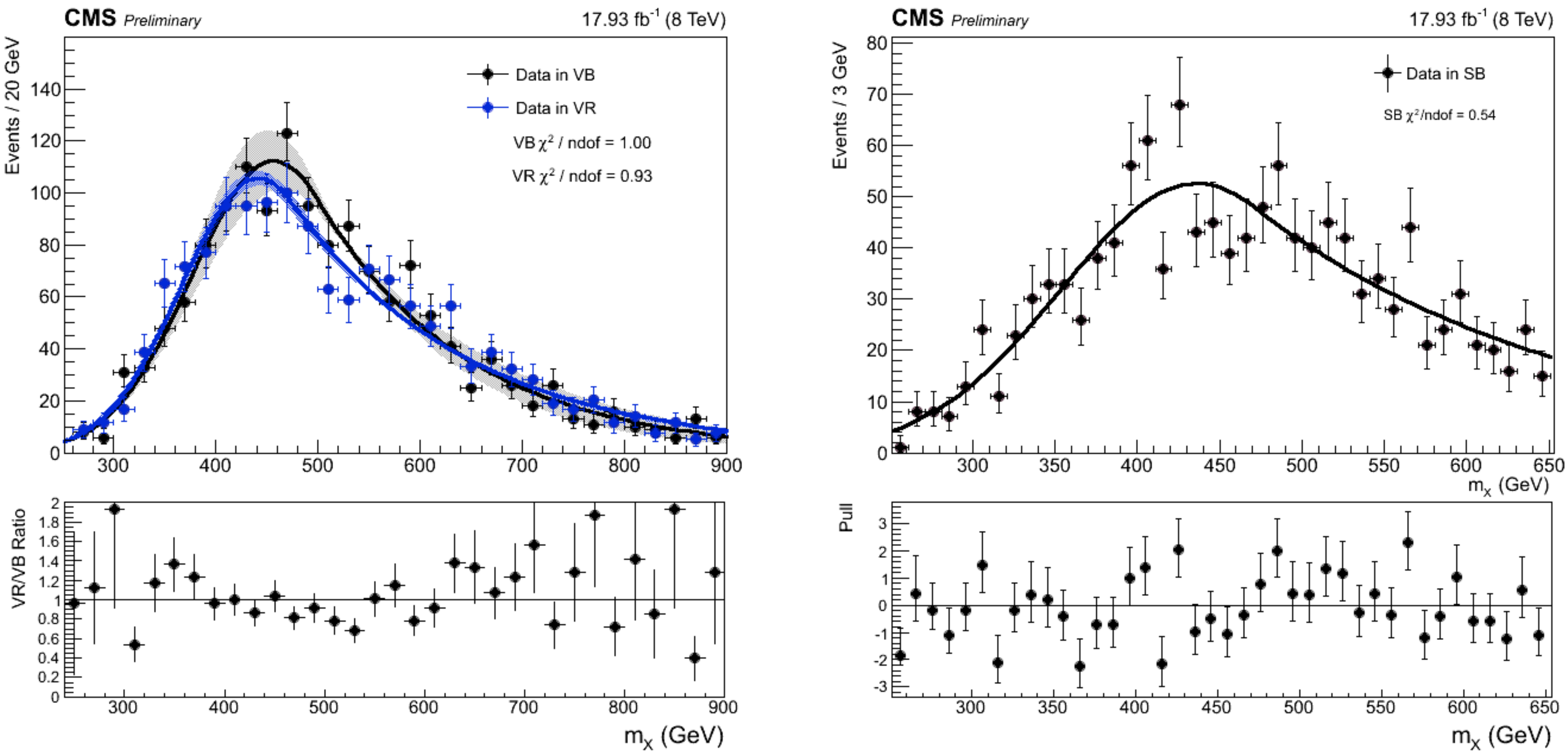
The $t\bar{t}$ composition of the data events in the SR region for the Low Mass Region (top) and the High Mass Region (bottom) as estimated in simulation. All event weights to correct for data/MC differences in pile-up, trigger and b-tagging efficiencies have been applied. Momenta of b-jets have been corrected by the kinematic constraint to m_H.

$H(b\bar{b})H(b\bar{b})$: $t\bar{t}$ Modeling



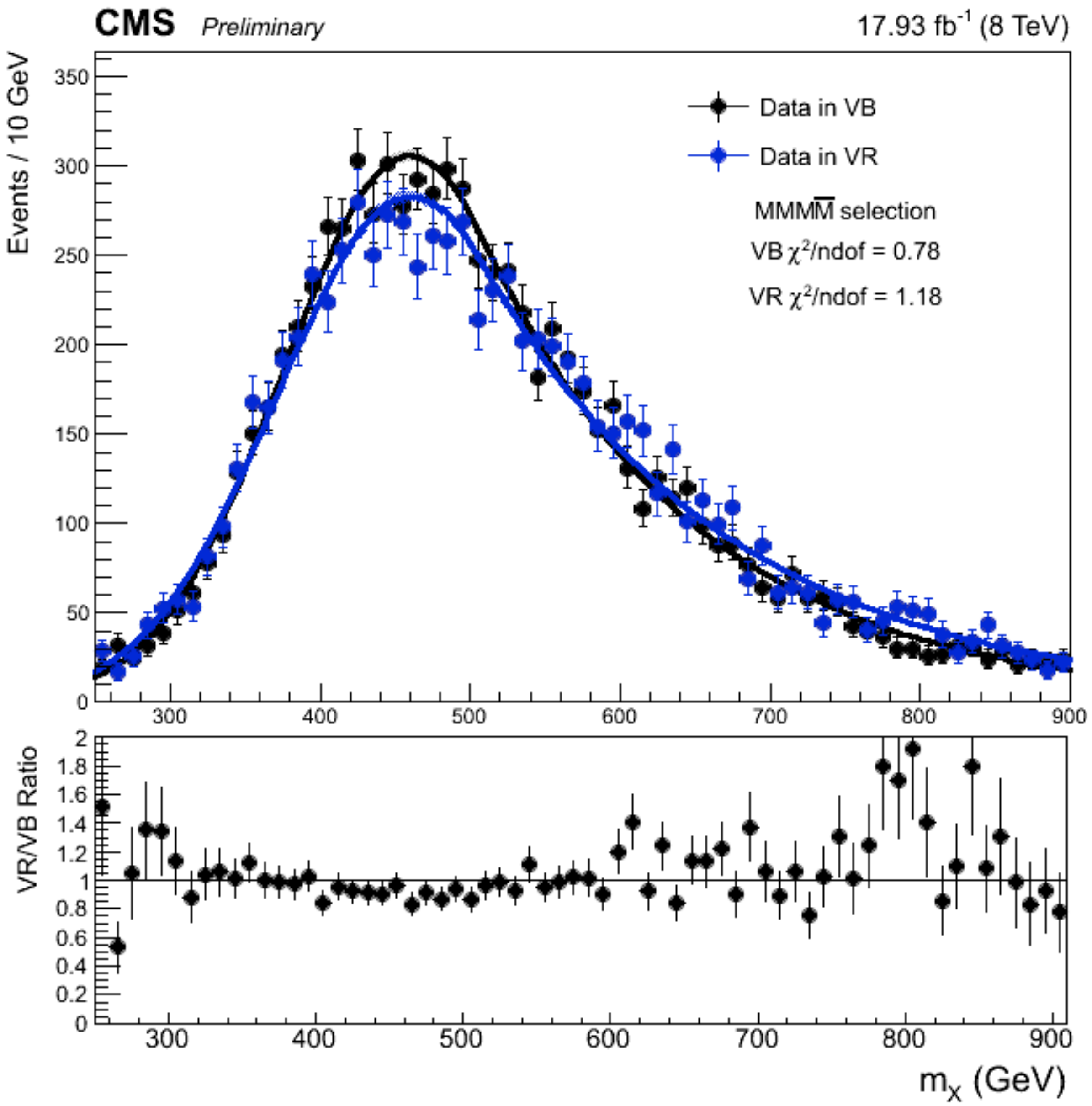
The m_X of simulated ttbar events after the event selection criteria for the Low Mass Region (left) and High Mass Region (right). The distributions are fitted to the GaussExp function

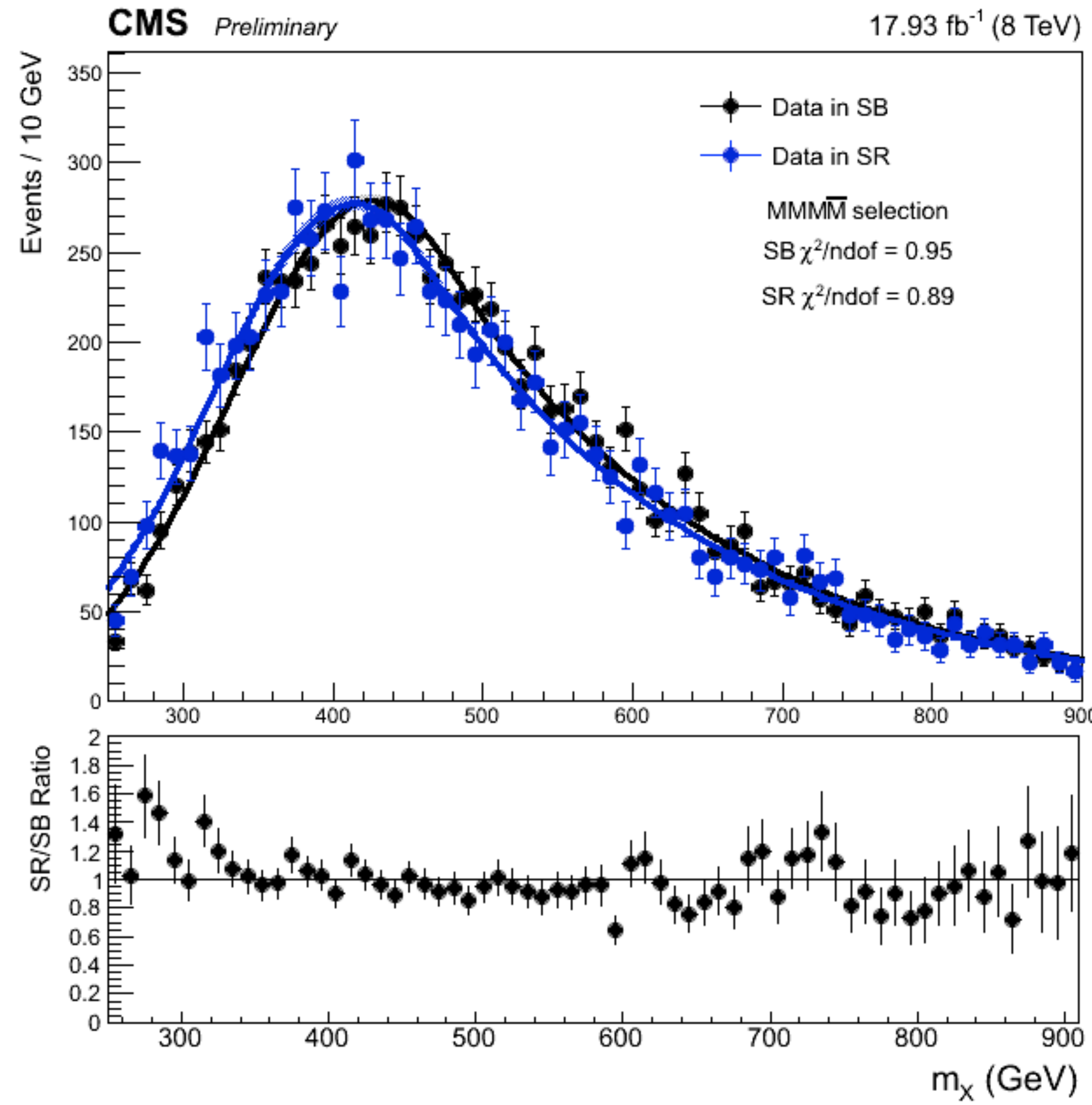
$H(b\bar{b})H(b\bar{b})$: QCD Multi-jet Modeling



Low Mass Region: The m_X distributions of the QCD multi-jet component of the background in the Validation Region & Sideband (VR & VB) on the left and the Signal Region Sideband (SB) of LMR. The distributions are fitted to the GaussExp function.

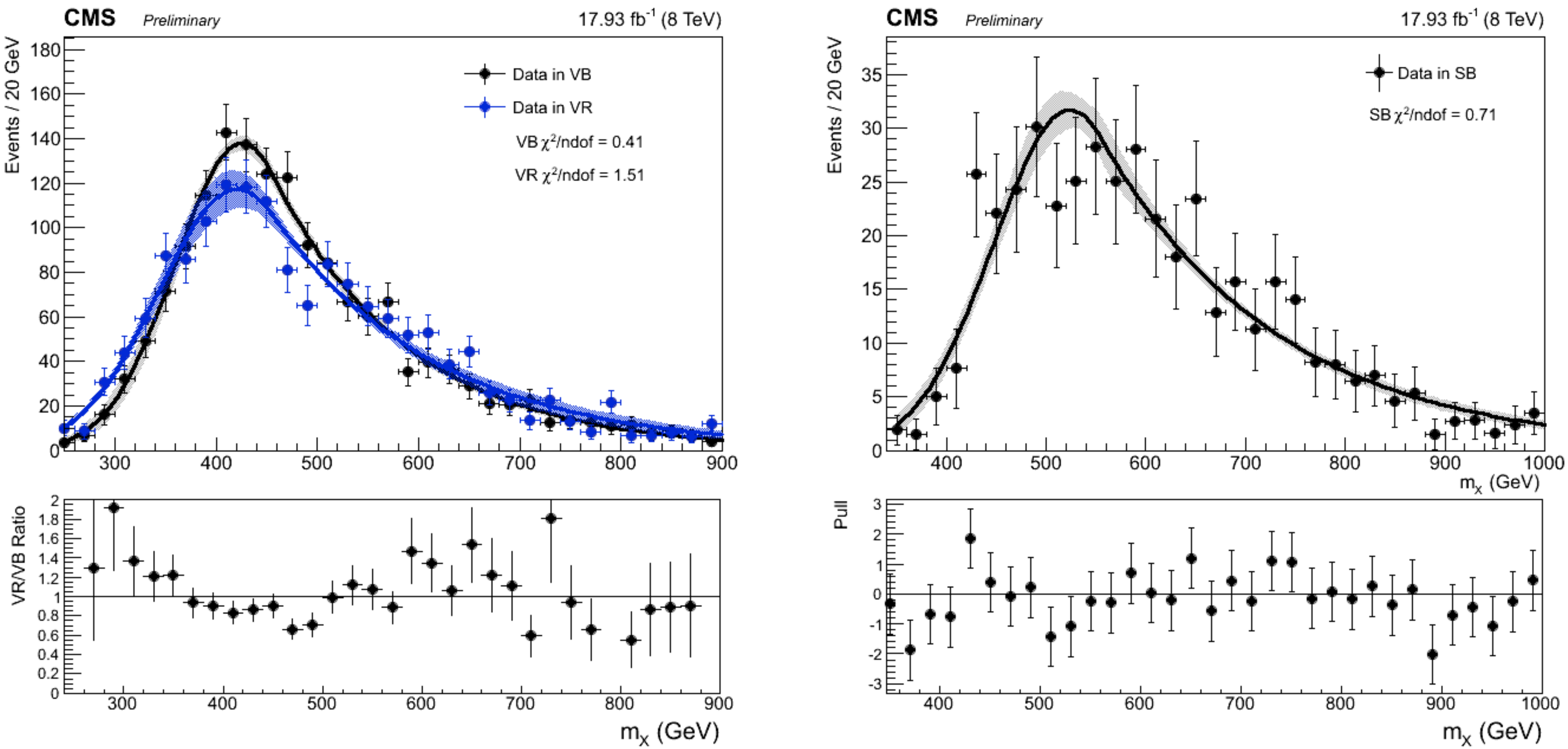
H(b$\bar{b}$)H(b$\bar{b}$): QCD Multi-jet Modeling





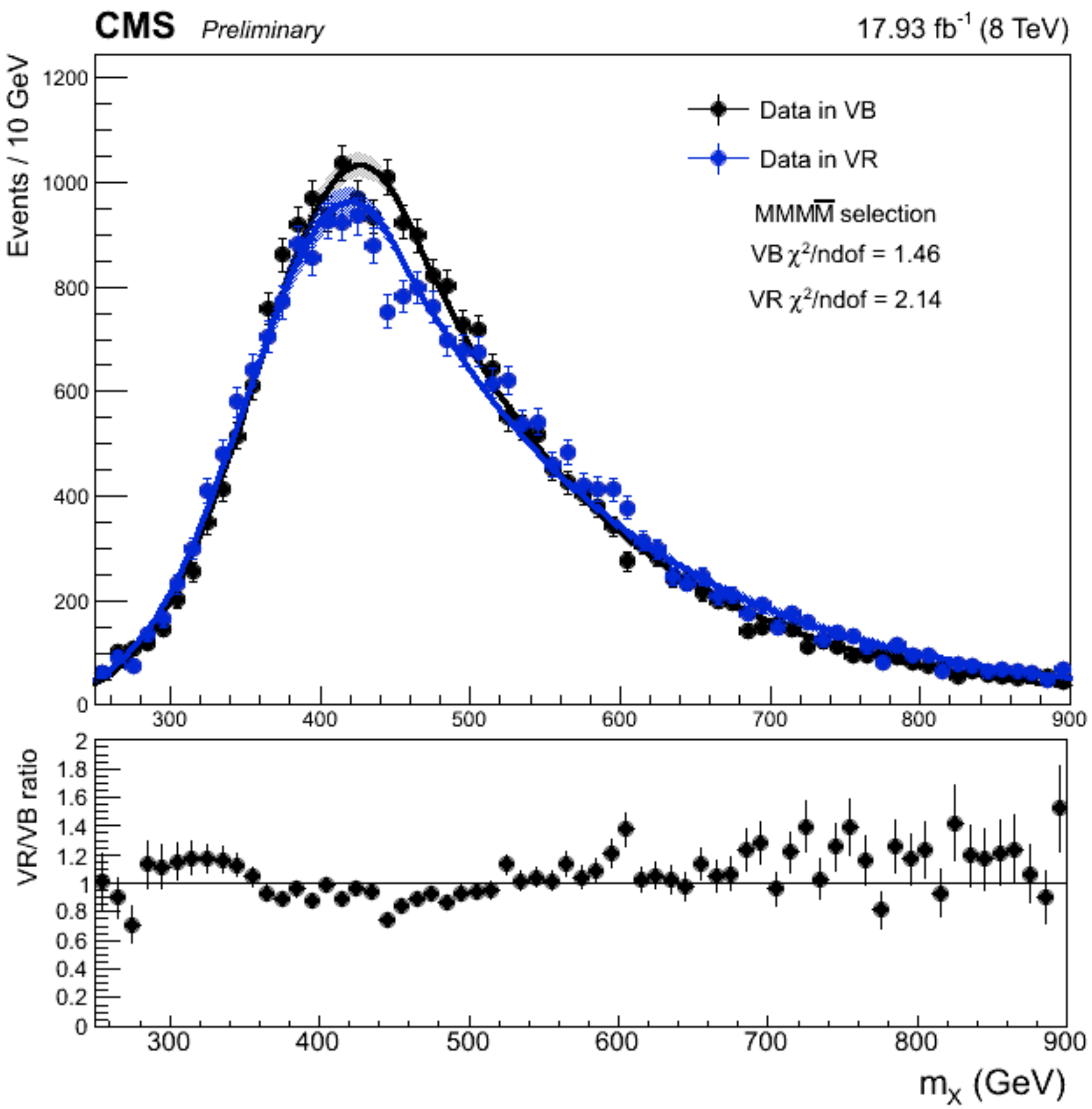
Low Mass Region, anti-btag Control Region: The m_X distributions of the QCD multi-jet component of the background in the Validation Region & Sideband (VR & VB) on the left and the Signal Region Sideband (SB) of LMR. The distributions are fitted to the GaussExp function.

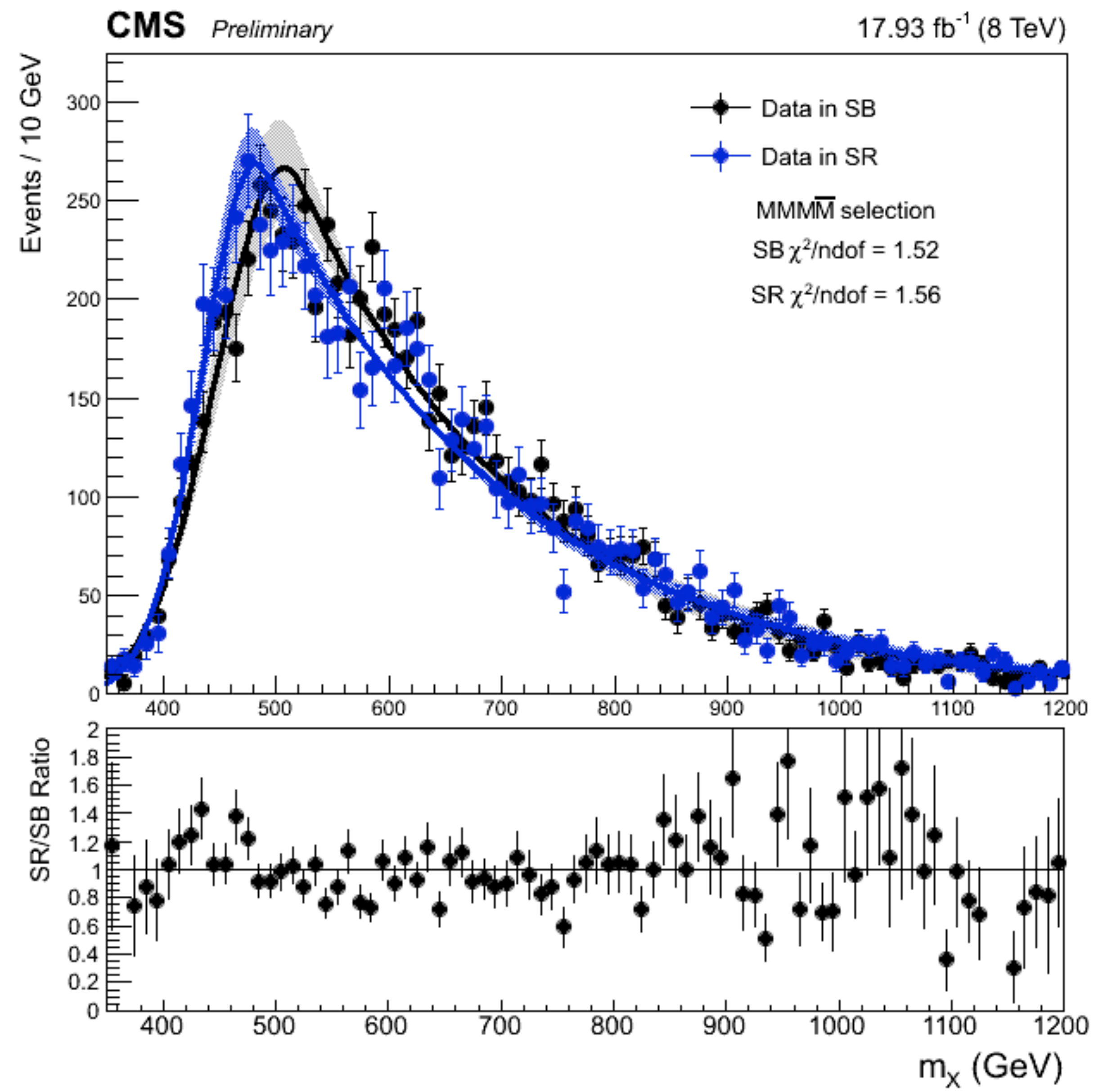
H(b$\bar{b}$)H(b$\bar{b}$): QCD Multi-jet Modeling



Medium Mass Region: The m_X distributions of the QCD multi-jet component of the background in the Validation Region & Sideband (VR & VB) on the left and the Signal Region Sideband (SB) of LMR. The distributions are fitted to the GaussExp function.

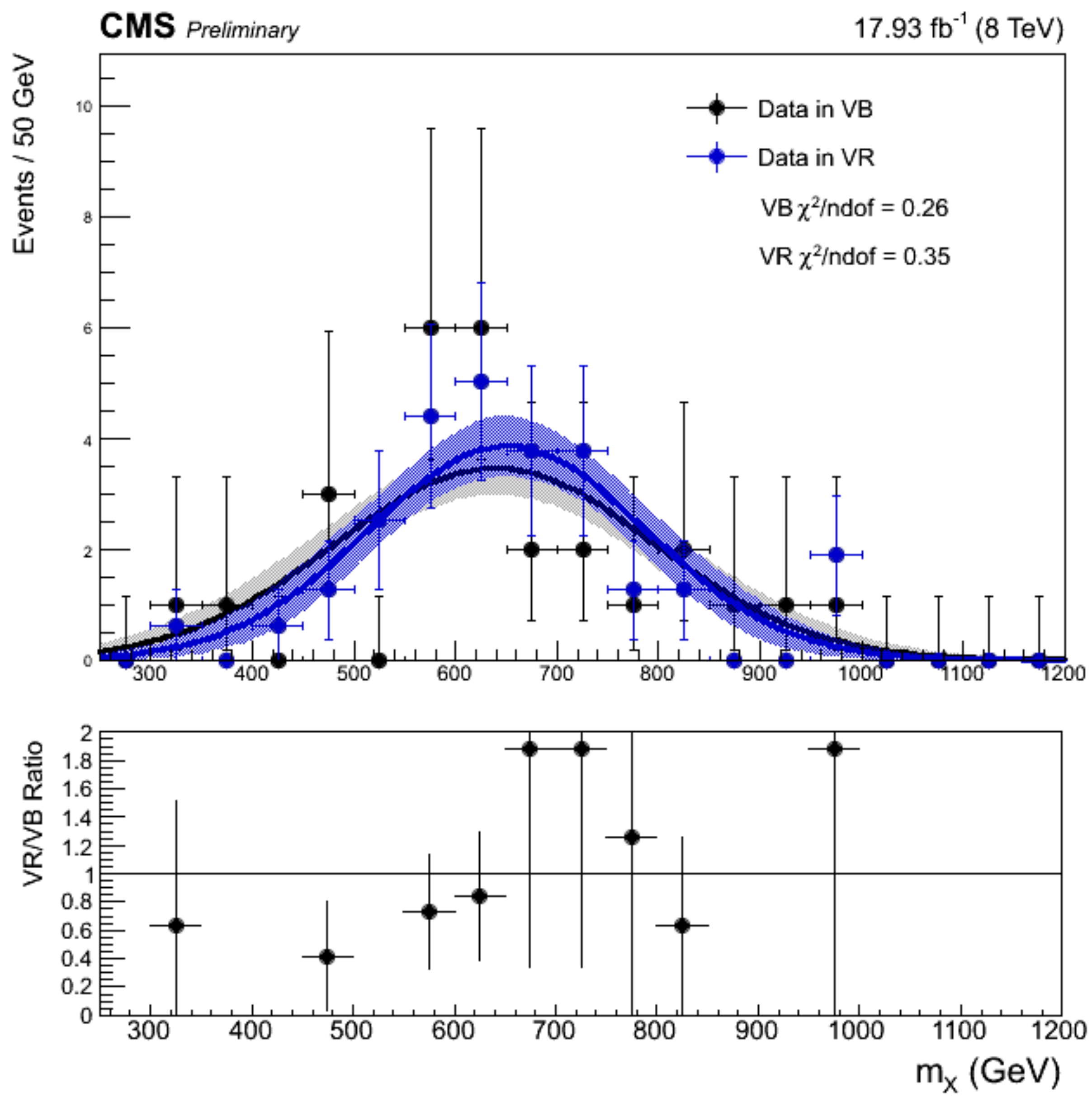
H(b$\bar{b}$)H(b$\bar{b}$): QCD Multi-jet Modeling

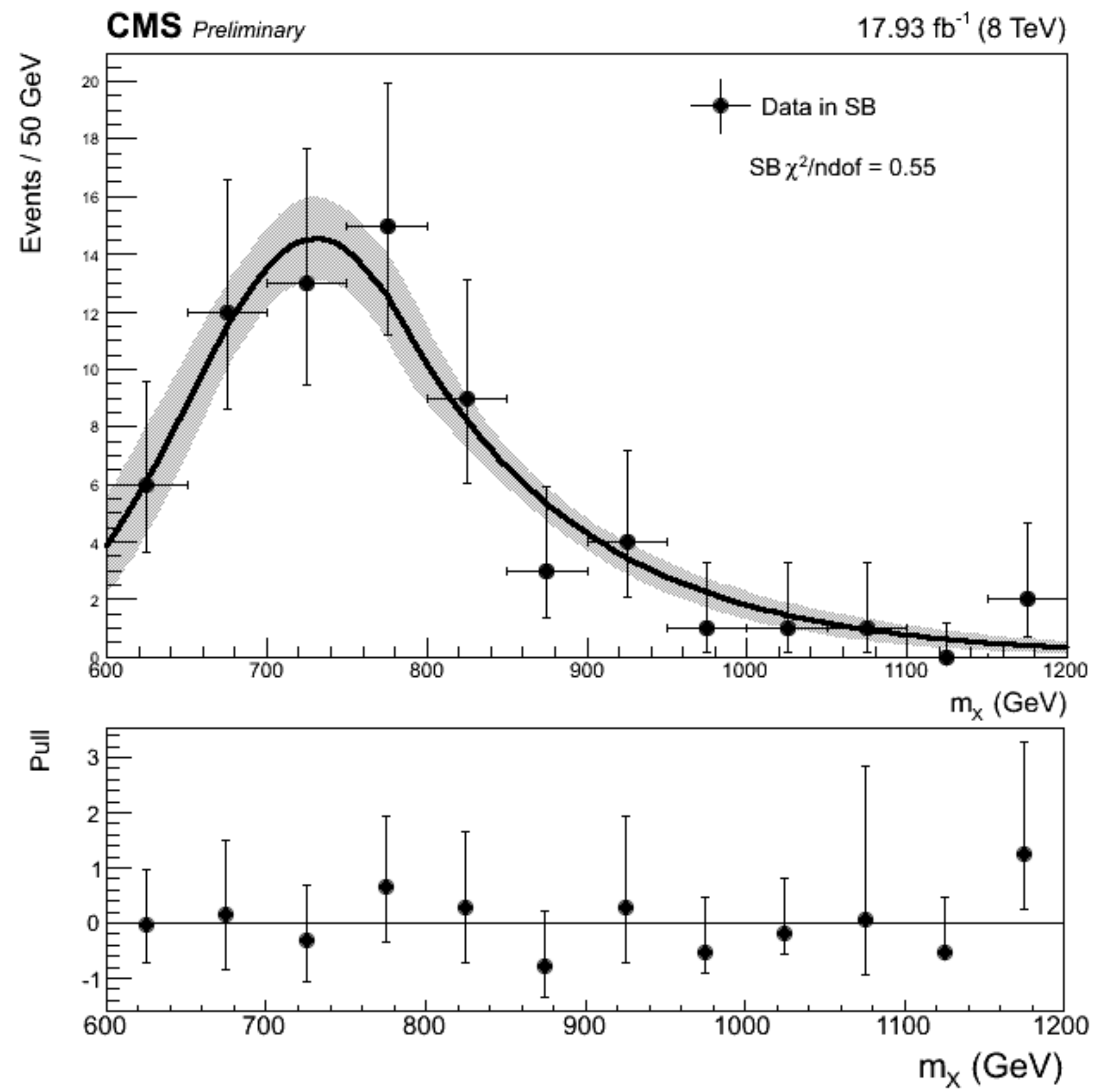




Medium Mass Region, anti-btag Control Region: The m_X distributions of the QCD multi-jet component of the background in the Validation Region & Sideband (VR & VB) on the left and the Signal Region Sideband (SB) of LMR. The distributions are fitted to the GaussExp function.

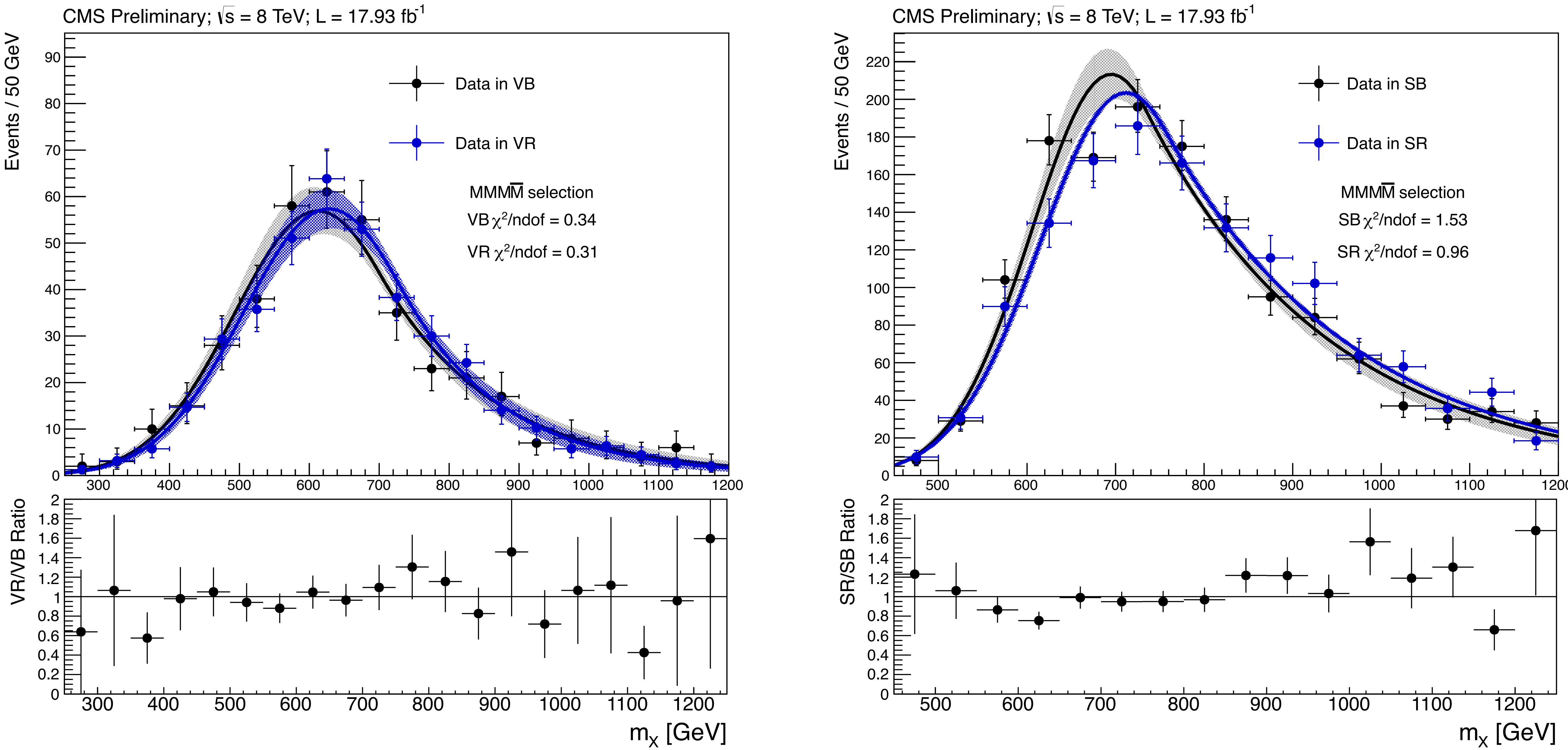
H(b$\bar{b}$)H(b$\bar{b}$): QCD Multi-jet Modeling





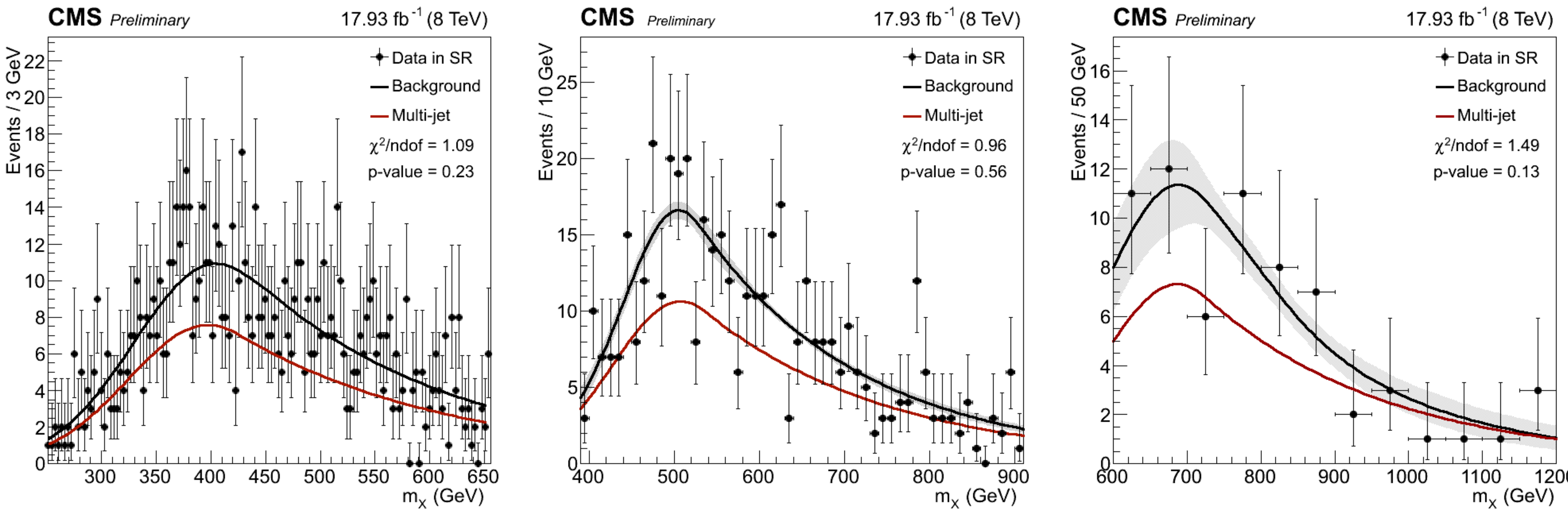
High Mass Region: The m_X distributions of the QCD multi-jet component of the background in the Validation Region & Sideband (VR & VB) on the left and the Signal Region Sideband (SB) of LMR. The distributions are fitted to the GaussExp function.

H(b$\bar{b}$)H(b$\bar{b}$): QCD Multi-jet Modeling



High Mass Region, anti-btag Control Region: The m_X distributions of the QCD multi-jet component of the background in the Validation Region & Sideband (VR & VB) on the left and the Signal Region Sideband (SB) of LMR. The distributions are fitted to the GaussExp function.

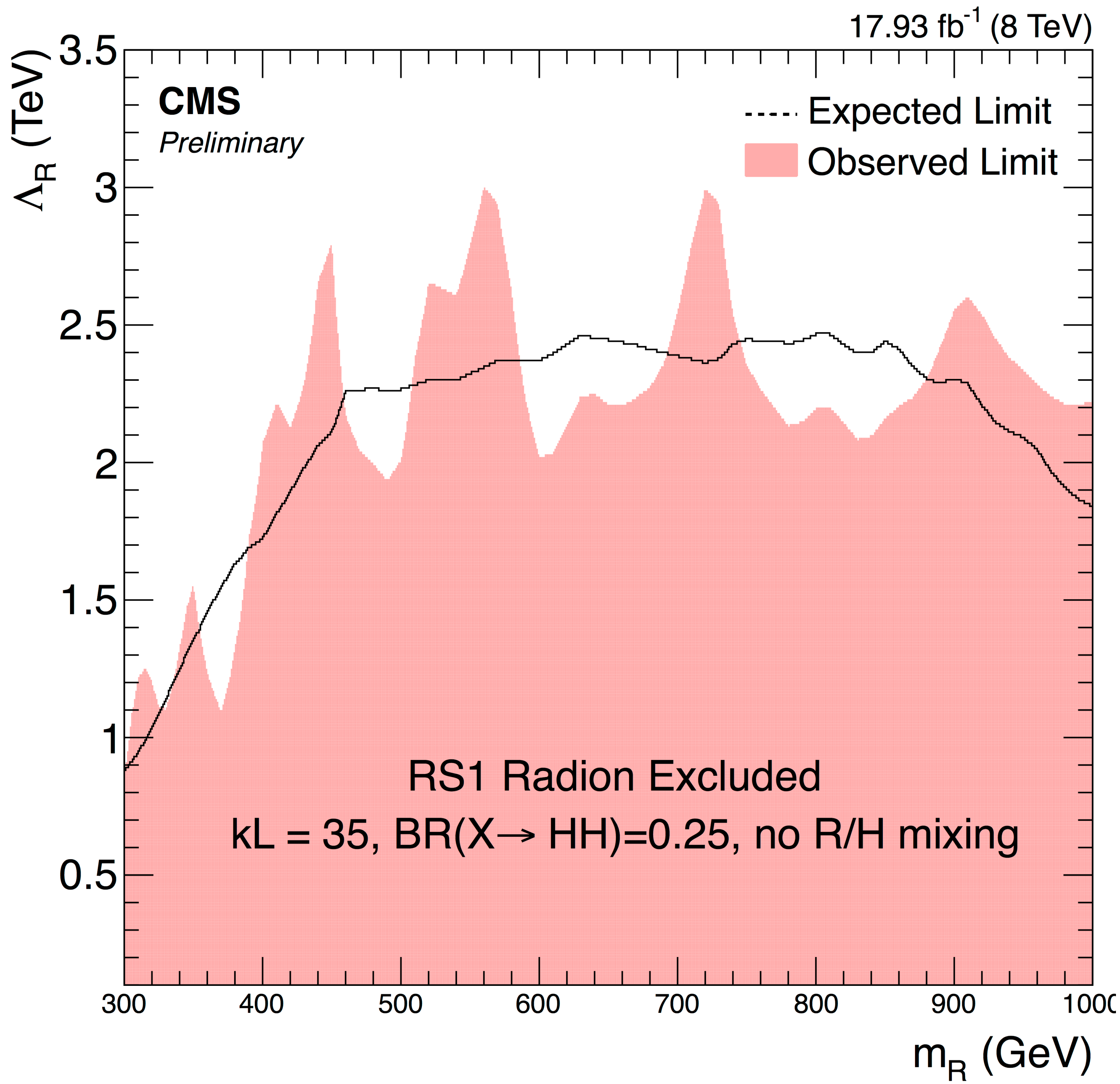
H(b$\bar{b}$)H(b$\bar{b}$): Unblinded Data



- Background-only fit shown to data in LMR, MMR and HMR. Red curve is the QCD multi-jet contribution. Black curve is QCD multi-jet + tt background.
- Shaded region corresponds to 1σ variation of parameterized fit. Number of degrees of freedom corresponds to the number of fit parameters subtracted from the number of bins in histogram

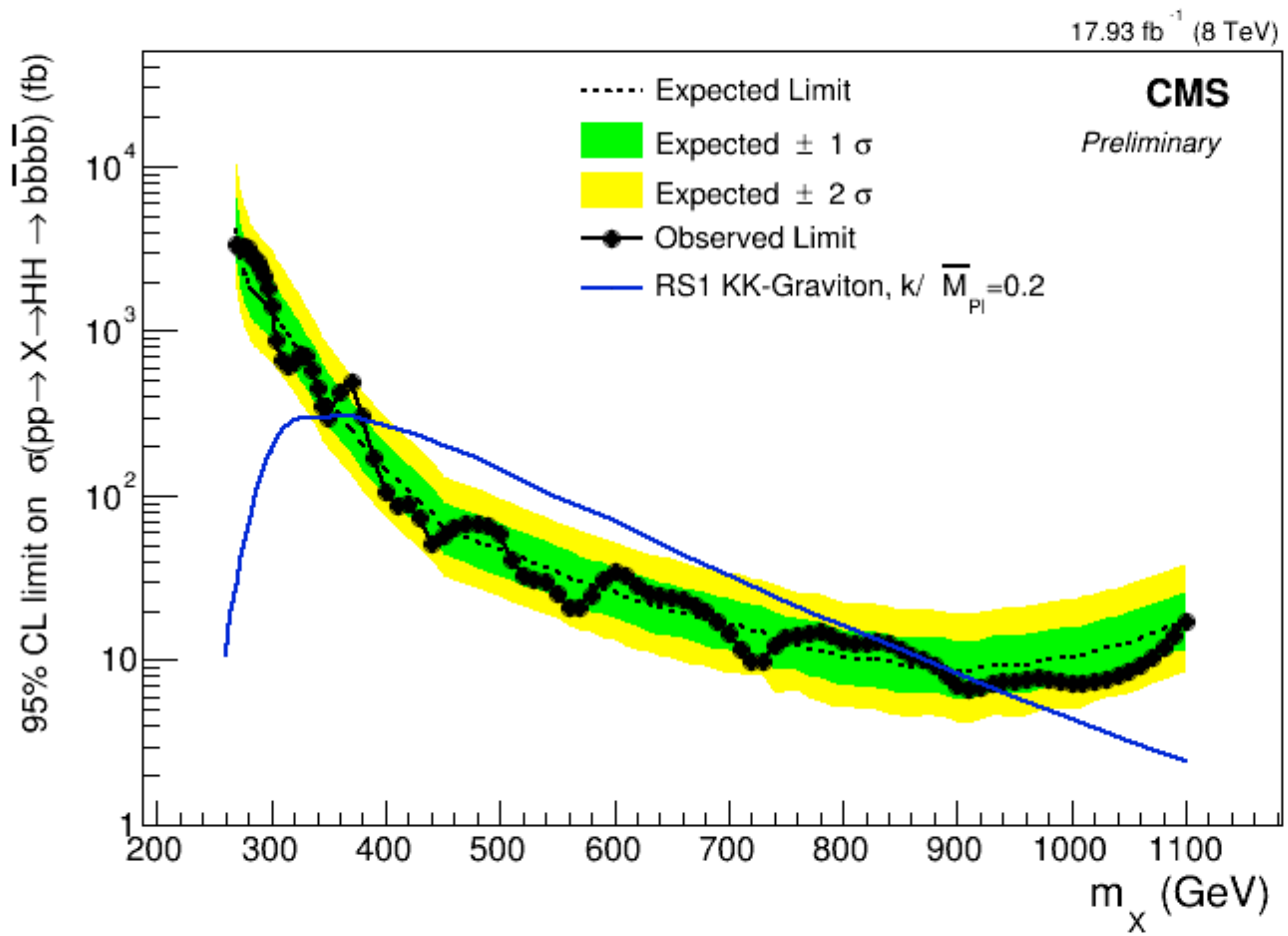
No clear deviation from background-only hypothesis. Compute upper limits.

H(b$\bar{b}$)H(b$\bar{b}$): Radion Exclusion



Cross sections of the radion assume *k*-factor for top-loop in gluon-fusion production of R to be identical to that of Higgs production. Also, Br(R→HH) = 0.25

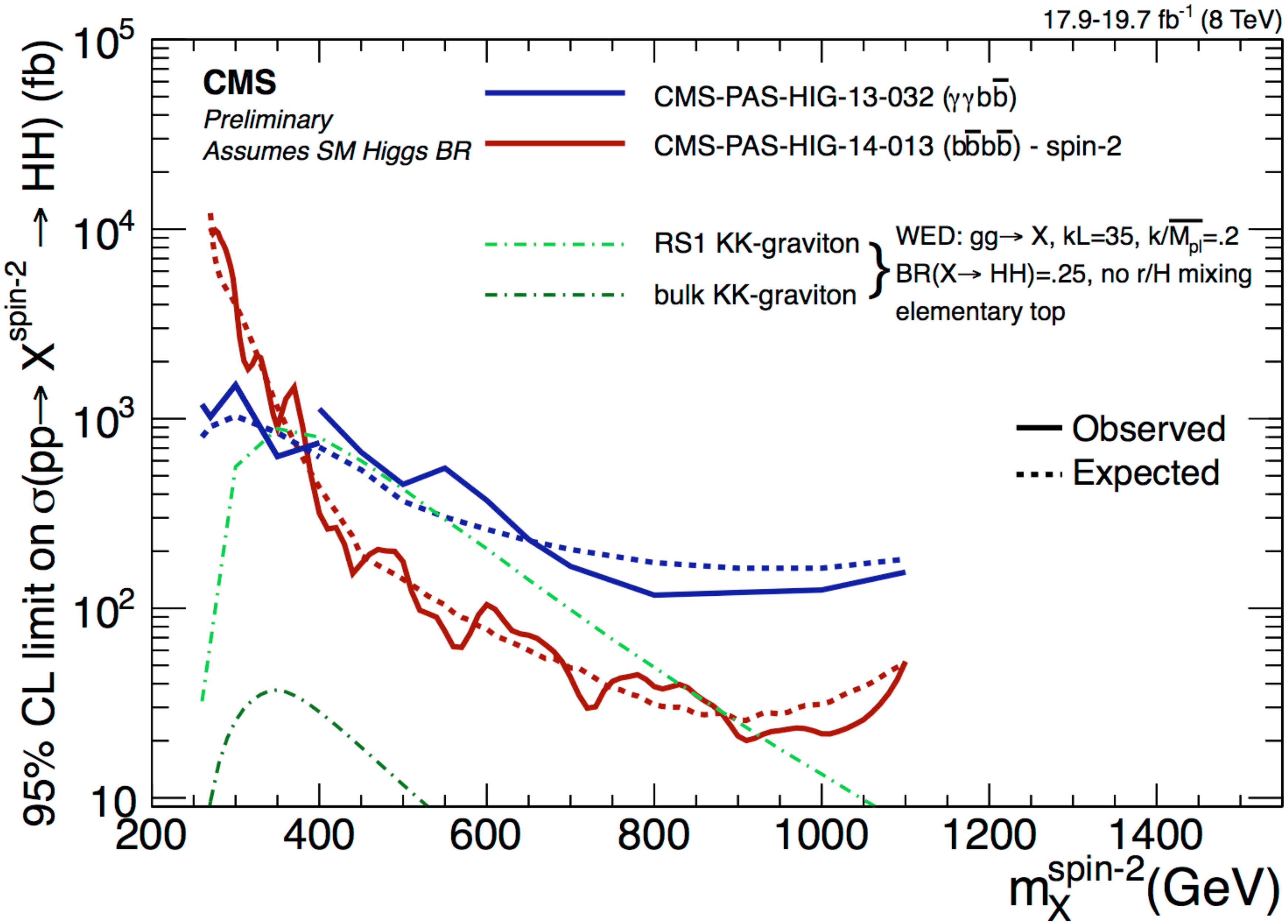
$H(b\bar{b})H(b\bar{b})$: Graviton Exclusion



The results are interpreted as upper limit on the production cross section for a spin-2 particle. Signal efficiency is larger than for the spin-0 hypothesis. This results in the exclusion of a smaller cross section. The observed and expected upper limits on the cross section for a spin-2 X to H(bb)H(bb) at 95% confidence level using data corresponding to an integrated luminosity of 17.93/fb at sqrt{s} = 8 TeV using the asymptotic CLs method are shown. Theoretical cross sections for the RS1 KK-Graviton decaying to four b-jets via Higgs bosons are overlaid.

WED scenario: kL = 35, k/M_{Pl}=0.2

CMS double-Higgs: Graviton Exclusion



The expected and observed upper limit of spin-2 X to HH production at 95% CLs provided by combining the searches performed by the CMS experiment looking at the $b\bar{b}b\bar{b}$ (HIG-14-013), $b\bar{b}gg$ (HIG-13-032) final states.

WED scenario: kL = 35, k/M_{Pl}=0.2