Search for a heavy boson decaying into $ZZ \to 2l2\nu$

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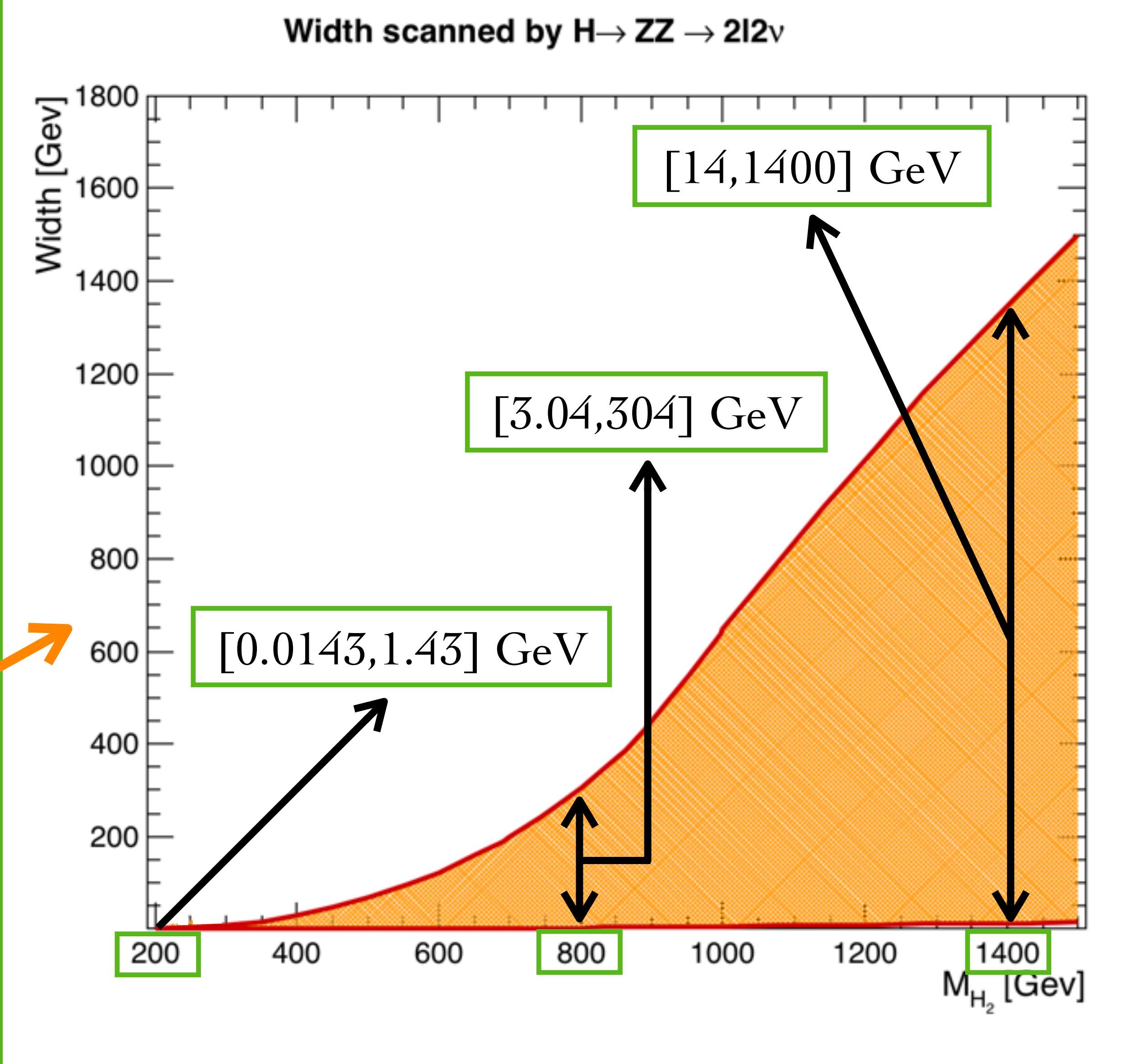
Higgs Hunting 2016, 01-09-2016

Goal of the Analysis

- ✦ Targeted decay chain: $X \rightarrow ZZ \rightarrow 2l2\nu$
- ✦ Analyzed 2.3 fb^{-1} of data collected by CMS
  - HIG-16-001
- ✦ Analysis looking for any kind of resonance
  - $M_H \in [200,1500]$ GeV
  - $\Gamma \in [1\%,100\%]\Gamma_{Heavy\_SM\_like}$
    - $\Gamma_{Heavy\_SM\_like}$ SM predicted width
      - Arxiv: 1307.1347 [YR3]



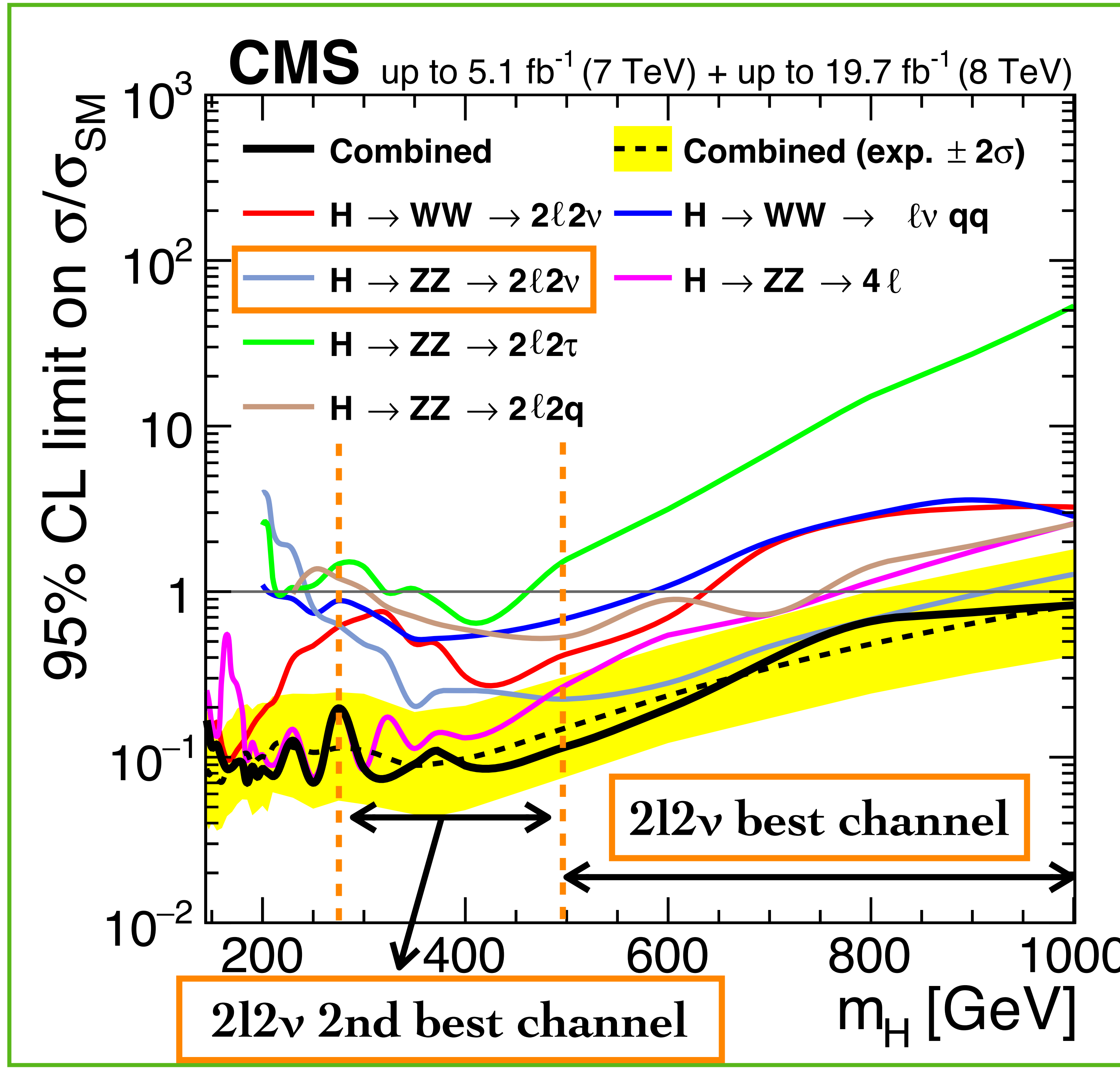
- ✦ **Search model independent**
  - Limits set only as function of mass and width
  - Interpretations
    - Electroweak Singlet Model (EWS)
    - Doublet Singlet Model (2HDM) (**NEW!!**)

Why $2l2\nu$?

Arxiv: 1504.00936

✦ Comparison between golden channels

- $ZZ_{2l2\nu}$ Vs ZZ_{4l}
  - $Bckg_{4l}$ (High mass) < $Bckg_{2l2\nu}$
  - $BR_{2l2\nu}$ > BR_{4l}
- $ZZ_{2l2\nu}$ Vs ZZ_{2l2q}
  - $BR_{2l2\nu}$ < BR_{2l2q}
  - $Bckg_{2l2q}$ (High mass) < $Bckg_{2l2\nu}$



✦ For high mass $ZZ \to 2l2\nu$ has the best sensitivity in di-boson channels

BSM Benchmark Models

✦ Electroweak Singlet Model (EWS) [Arxiv: 1307.3948, 1306.2329, 1406.1043, 1409.0005, 1412.0258, 1501.02234]

- Two scalar fields predicted: h, h_2
- Physical Parameters
  - $M_{h2} \in [200,1500]$ GeV
  - $\Gamma \in [1\%,100\%]\Gamma_{Heavy\_SM\_like} \longrightarrow C' \in [0.1,1]$
- No interference contributions with light Higgs and background taken into account
  - Small effects due to limited mass resolution in 2l2ν final state

$$C^2 + C'^2 = 1 \qquad \Gamma' = \Gamma_{SM}\frac{C'^2}{1 - B_{new}}$$

B_{new} : branching fraction of EWS to non-SM decay

✦ Doublet Singlet Model (2HDM) [Arxiv: 1106.0034, 1207.4835, 1507.04281]

- Five scalar fields predicted: h, H, A, H^+ and H^-
- Scan performed in decoupling region
  - $\cos(\alpha-\beta) = 0.1$
  - $M_H \in [200,600]$ GeV
  - $tg(\beta) \in [0,60]$
  - Limits as function of mass and tg(β) in both type-I and type-II scenario
  - ggH only
  - $\Gamma_{2HDM} < \Gamma_{SM}$
  - Re-interpretation of EWS limits in 2HDM framework

$$h_{SM} = h \cdot \sin(\alpha - \beta) - H \cdot \cos(\alpha - \beta)$$

Workflow of the Analysis

1. Trigger selection
    1. Double e/μ (P_T thrs: 23-17 e_1 - 12 e_2 GeV, 17 μ_1 - 8 μ_2 GeV)
    2. Single e/μ (P_T thrs: 23-22 GeV, 27-20 GeV)
2. Events categorization
    1. 0-jet
    2. >= 1-jet
    3. Vbf ($P_T > 30$ GeV, $\Delta\eta_{jj} > 4.0$, $M_{jj} > 500$ GeV, 0 central jets, central leptons)
3. Selection
    1. Exactly two leptons (e/μ), Tight Id and Iso
    2. $P_T^{lep} > 25$ GeV, $|\eta| < 2.5$ (e)/ 2.4 (μ)
    3. Z mass window constrain, $P_T^Z > 55$ GeV
    4. Veto cuts (third lepton, b-jet)
    5. $\Delta\phi$(jet,MET) > 0.5
    6. MET > 125 GeV
4. Performed statistical analysis using Transverse Mass (M_T) shape distribution

Irreducible Background

✦ IRREDUCIBLE

- MC prediction
  - ZZ
    - $qq \rightarrow ZZ \rightarrow 2l2\nu$ (**l = e, μ, τ**)
      - $EWK_{[NLO/LO]}$ k-Factors function of quarks flavor and Mandelstam variables
      - $QCD_{[NNLO/NLO]}$ k-Factors function of M_{ZZ}
    - $gg \rightarrow ZZ \rightarrow 2l2\nu$ (**l = e, μ**)
      - $QCD_{[NNLO/LO]}$ k-Factors function of M_{ZZ}
  - WZ
    - No EWK corrections applied (added 3% uncertainties account for no corr.)
  - ZVV

Instrumental MET Background

✦ INSTRUMENTAL MET

- Data-Driven
- MET in Drell-Yan is an instrumental effect
  - γ+j and Z+j affected similarly by detector features
  - γ and Z similar in SM (except for mass)
    - Reweight γ P_T to di-lepton P_T in data, faking Z mass
    - Reweighting done in analysis bins (ee/$\mu\mu$ and jet bins)
- Genuine MET subtracted from γ data using MC
  - $W+\gamma \rightarrow l\, \nu\, \gamma$
  - $W+j \rightarrow l\, \nu\, j$
  - $Z+\gamma \rightarrow \nu\, \nu\, \gamma$
  - $Z+j \rightarrow \nu\, \nu\, \gamma\, j$

Non Resonant Background

✦ Top/W/WW - Non Resonant Bckg

- Data-Driven
  - α computed
    - Inclusive category (α independent from jet category)
    - b-jet tag events (Drell-Yan suppressed region)
    - MET > 50 GeV (independent from MET cut)

Signal Region, bVeto	b Tag Region
$ll_{in} : M_{ll} = M_Z$	$ll_{out} : M_{ll} \neq M_Z$
$e\mu_{in} : M_{ll} = M_Z$	$e\mu_{out} : M_{ll} \neq M_Z$

$$N_{ll_{in}} = \alpha \cdot \left(N_{e\mu\ in} \right)$$

$$\frac{N_{ll_{out}}}{N_{e\mu_{out}}} = \alpha$$

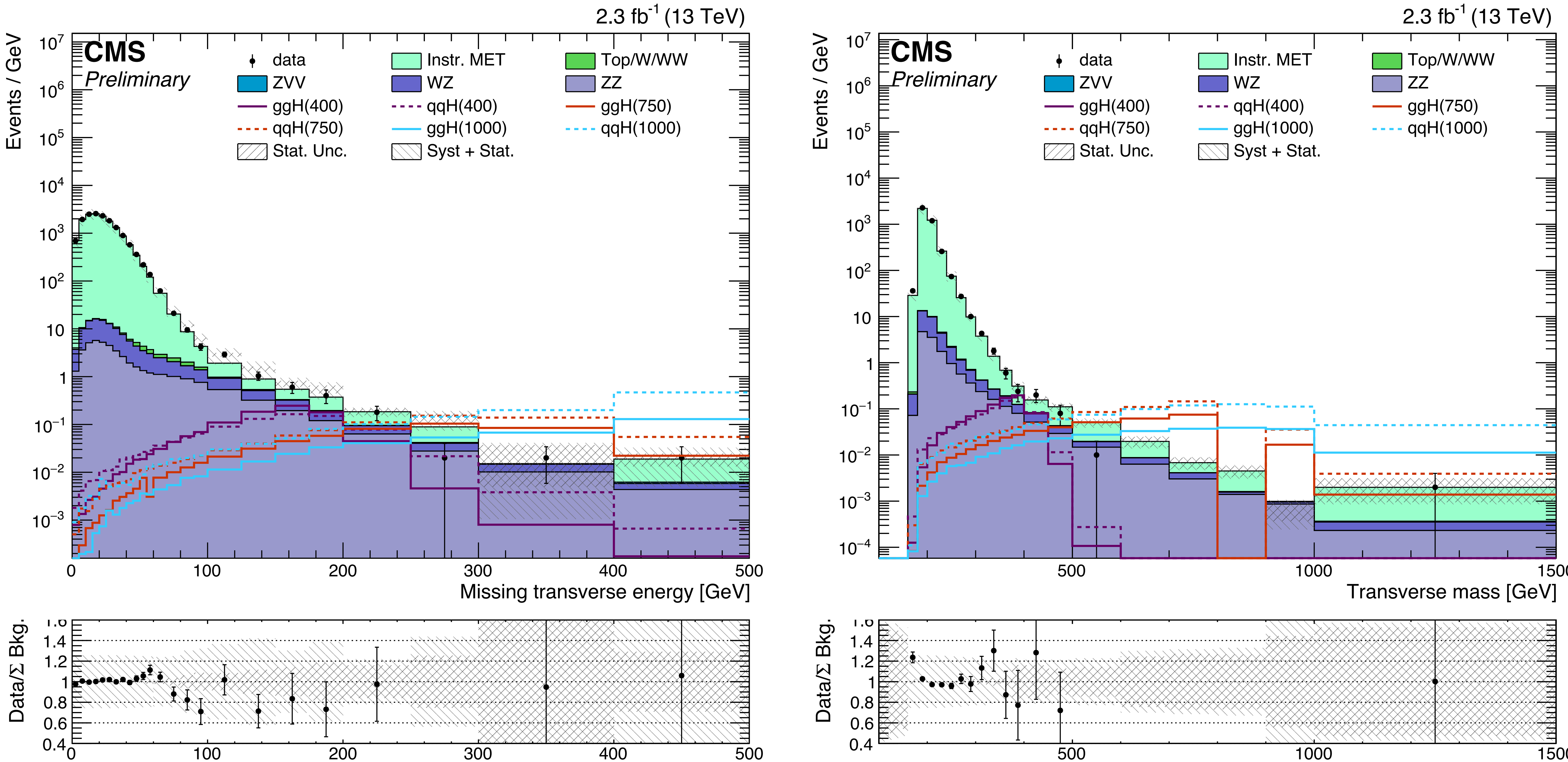
$$In \rightarrow |M_* - 91| < 15$$

$$Out \rightarrow M_* \in [40,70] \cup [110,120]$$

MET and Transverse Mass Shape

✦ Transverse Mass (M_T) and MET shape before MET cut

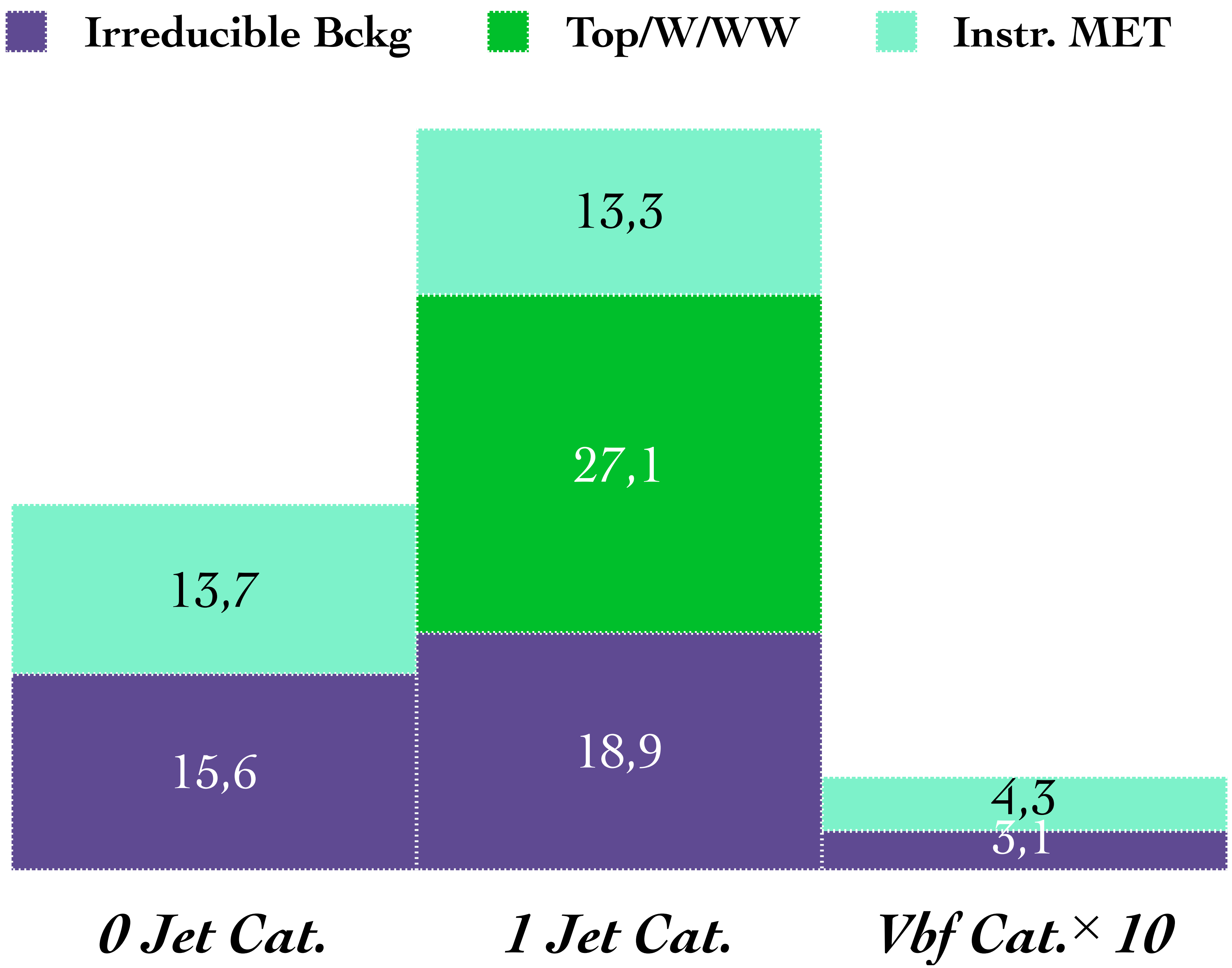
- Distributions inclusive in flavor and category



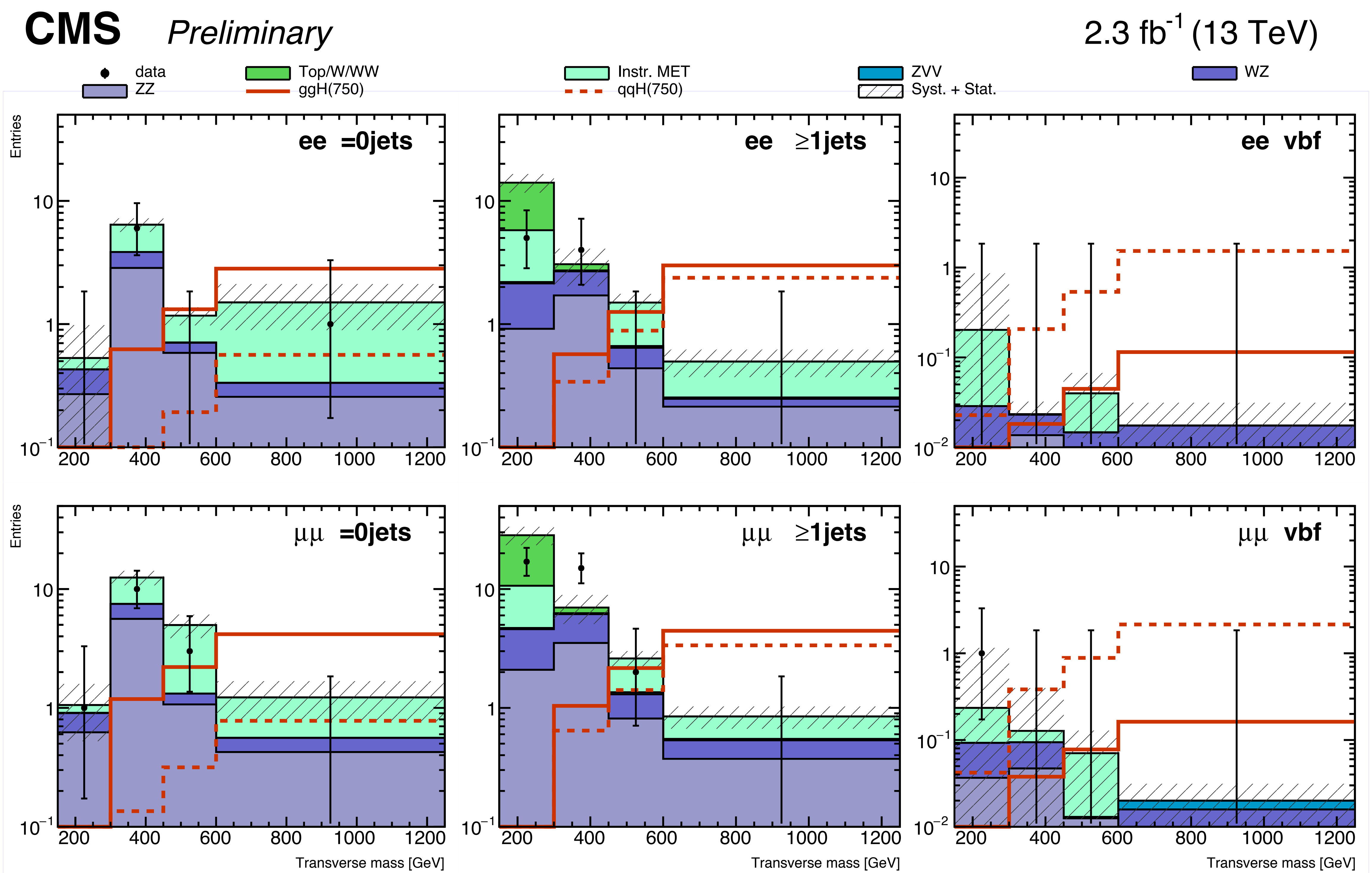
$$M_T^2 = \left(\sqrt{p_T(ll)^2 + M(ll)^2} + \sqrt{(E_T^{miss})^2 + M_Z^2}\right)^2 - \left(\vec{p}_T(ll) + (\vec{E}_T^{miss})\right)^2$$

Backgrounds Contamination

- Expected Yields obtained for 2.3 fb^{-1}
- After final MET Cut of 125 GeV (no M_T cut applied)
- For precise numbers and errors check backup slides



Final Transverse Mass Shape



- ✦ Signal Cross Section 1 pb for every mass point
- ✦ No Evidence of excess in data → proceed to set limits

Systematics on the Yield

✦ Theoretical Uncertainties

- Factorization and Renormalization scale (<10%), Pdf (<13%) and α_S (<11%)
- QCD scale in jet bins: <64% for 0-jet cat., <10% in 1-jet cat., <10% in Vbf.
- Signal Shape: <1%

✦ Instrumental Systematics

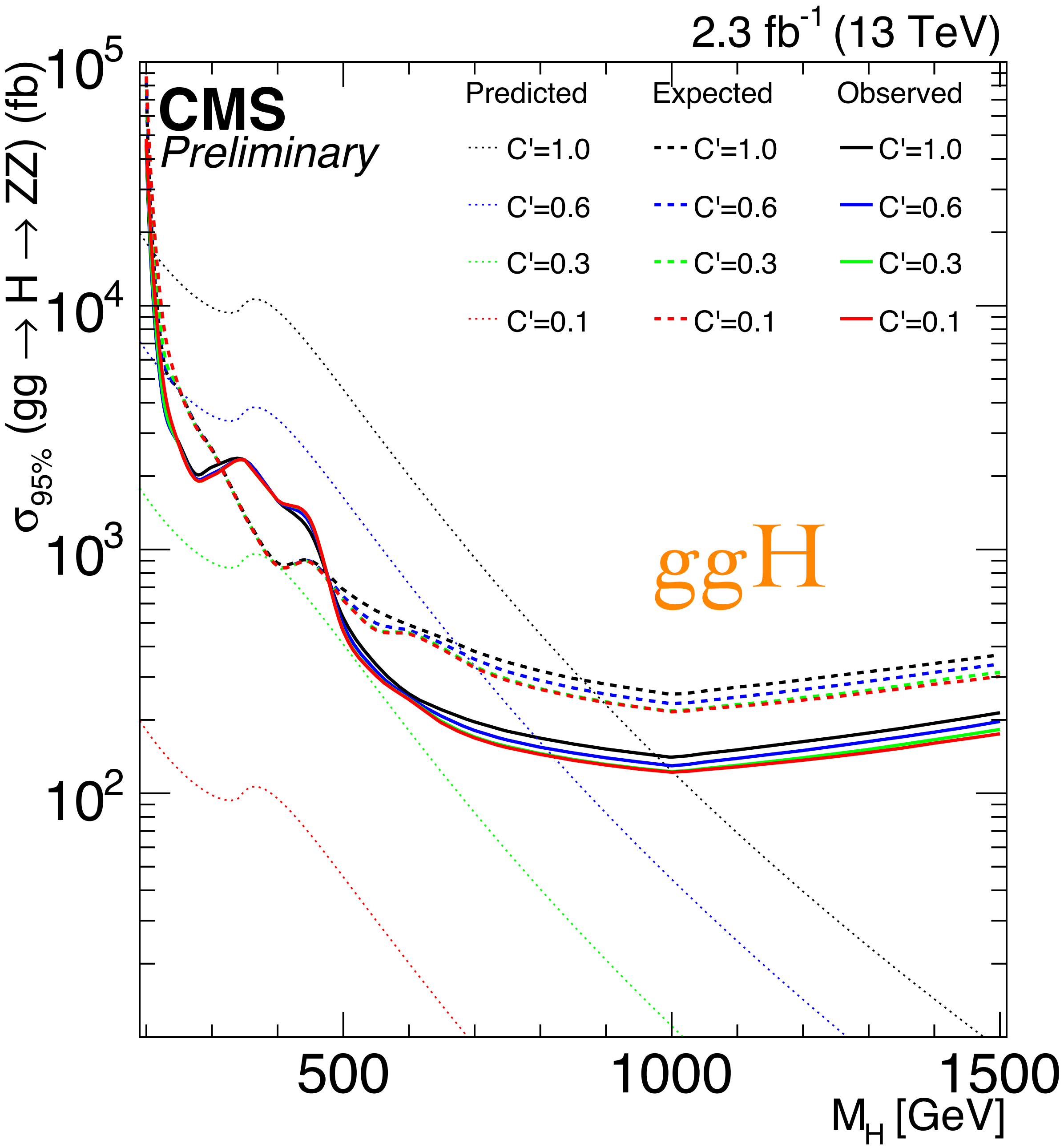
- Luminosity: 2.7%
- Lepton Eff. (Trigger+Id): 5% Ele, 4.2% Mu
- Lep Veto: <4.5%
- PileUp: <2%
- Jet Resolution Energy Scale: <10%
- Jet Energy Scale: <10%

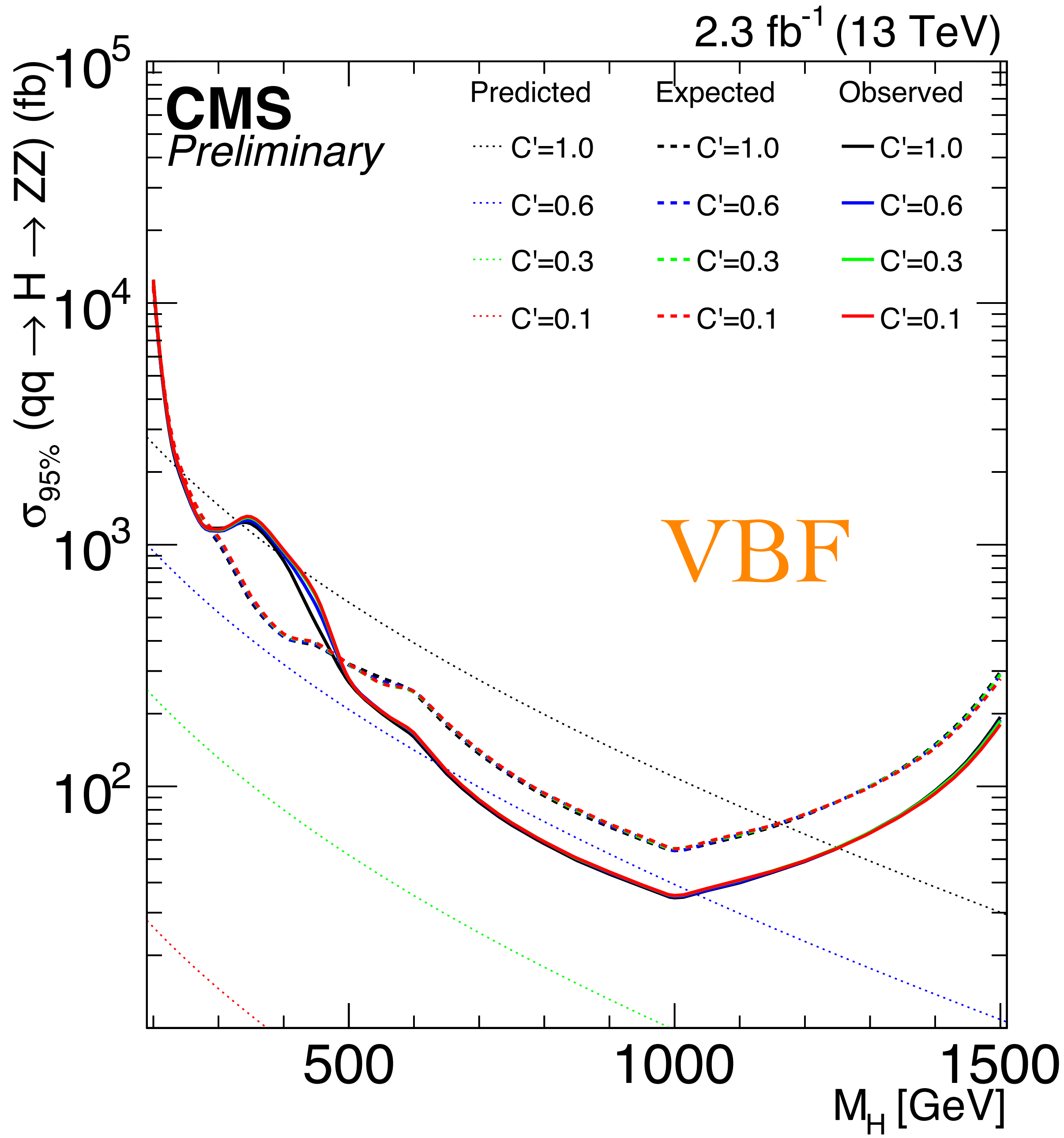
✦ Data-Driven Method

- Non Resonant Bckg: Systematic (20%), Stat. (<20% or Garwood 1.8 events)
- Instrumental Met: Systematic (25%), Stat. (<50%)

Results

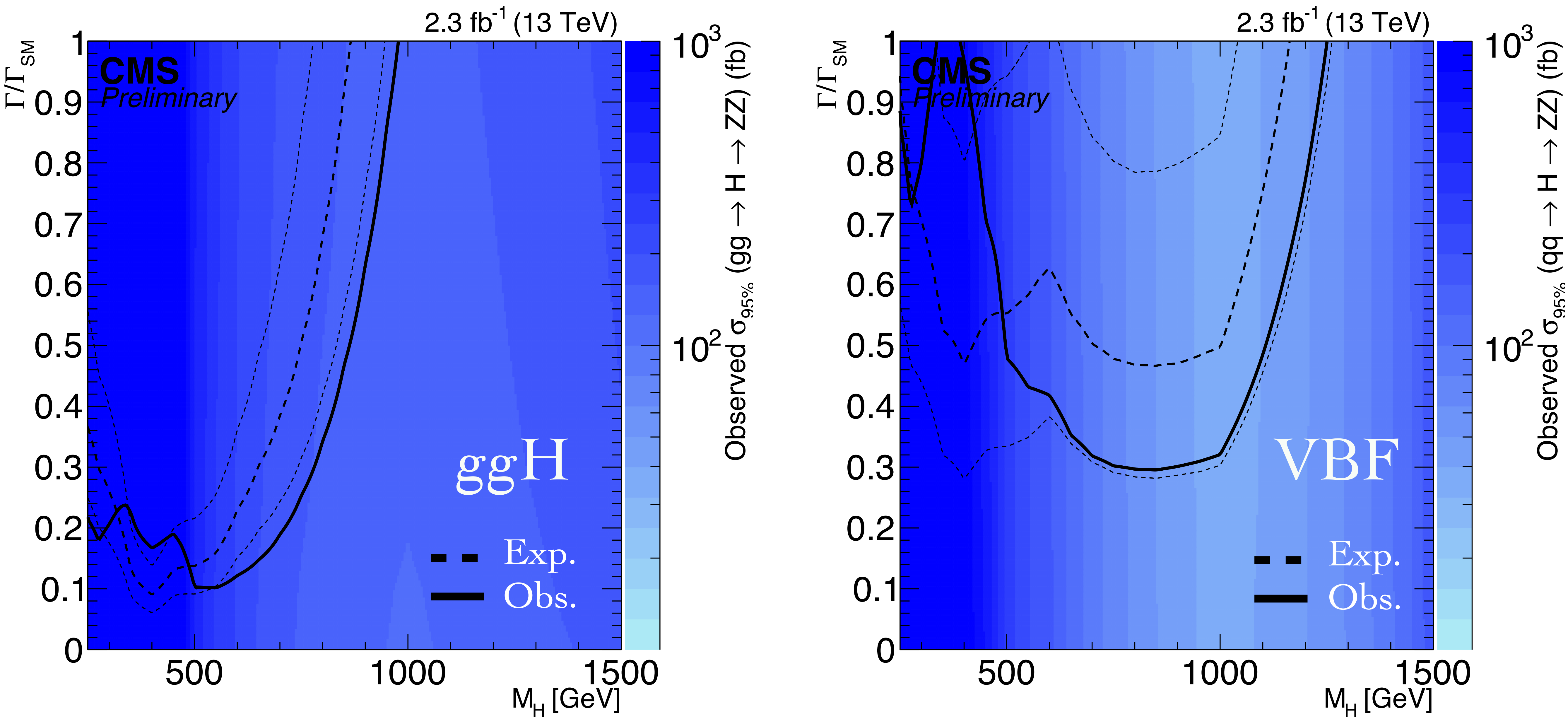
Limits on Heavy Scalar Boson in EWS Model





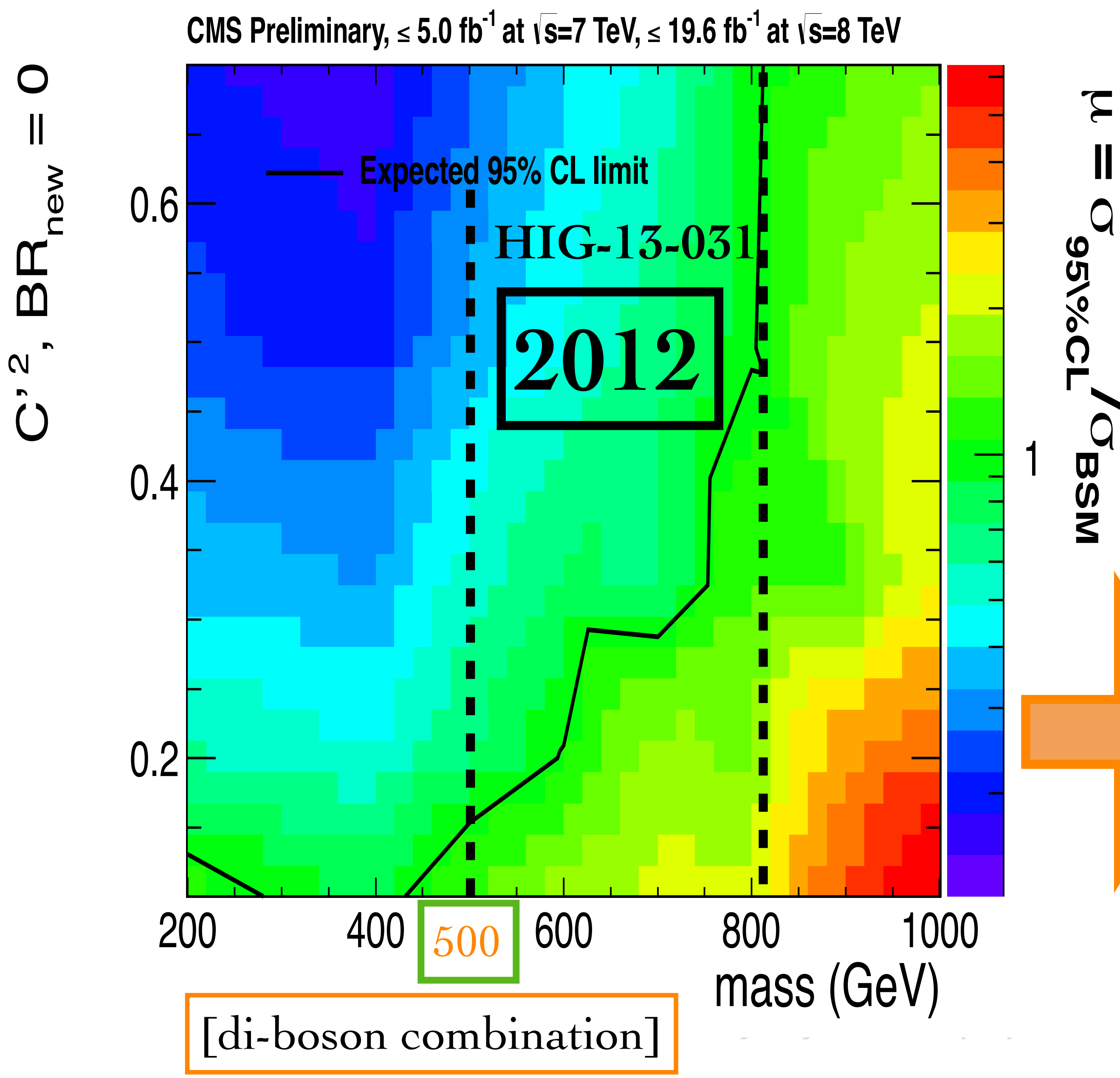
- ✦ SM ratio between ggH and VBF production rates assumed
- ✦ Small dependence of cross-section limit with width (M_T and MET resolution)

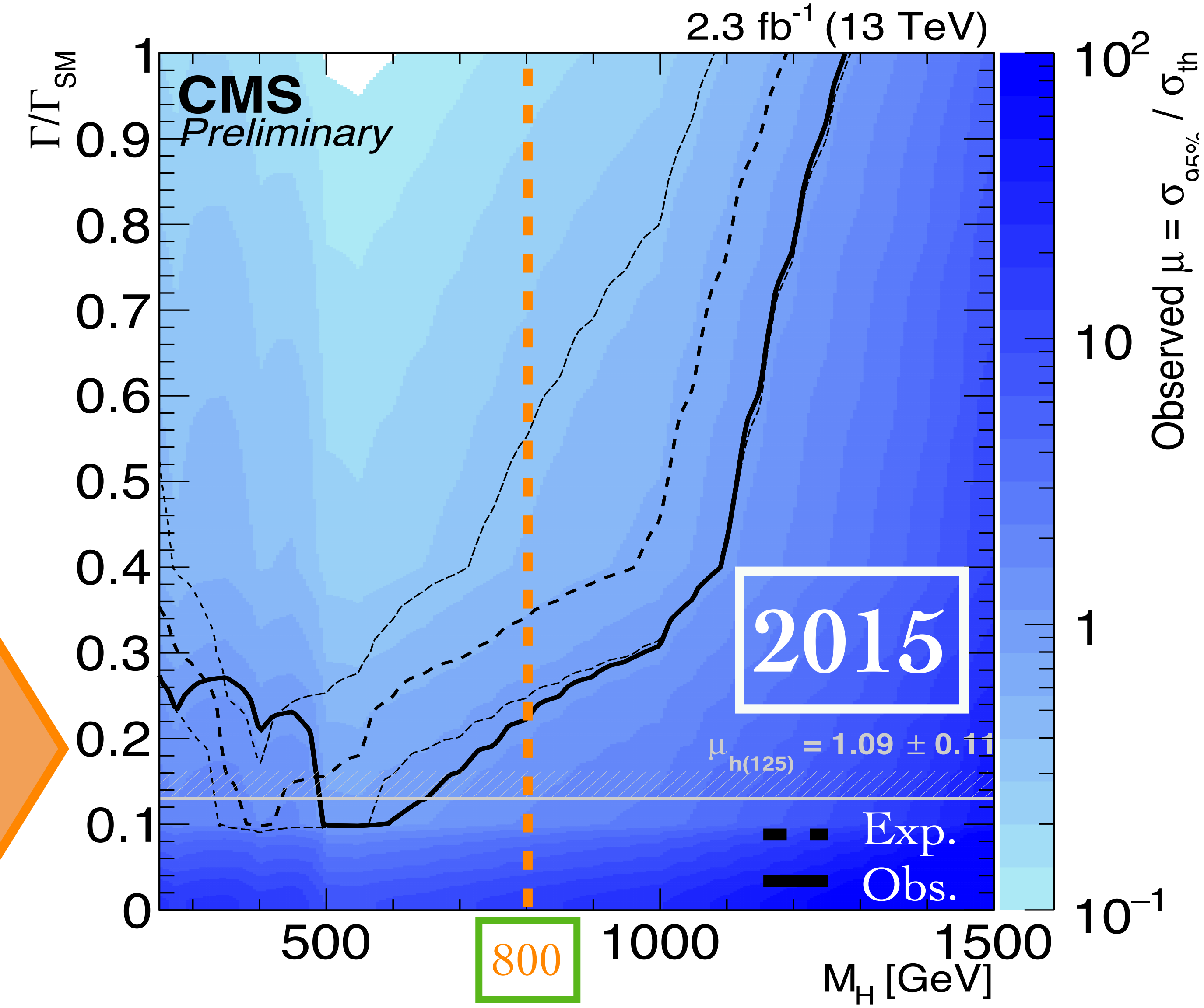
Limits on Heavy Scalar Boson in EWS Model



✦ 2D results model independent

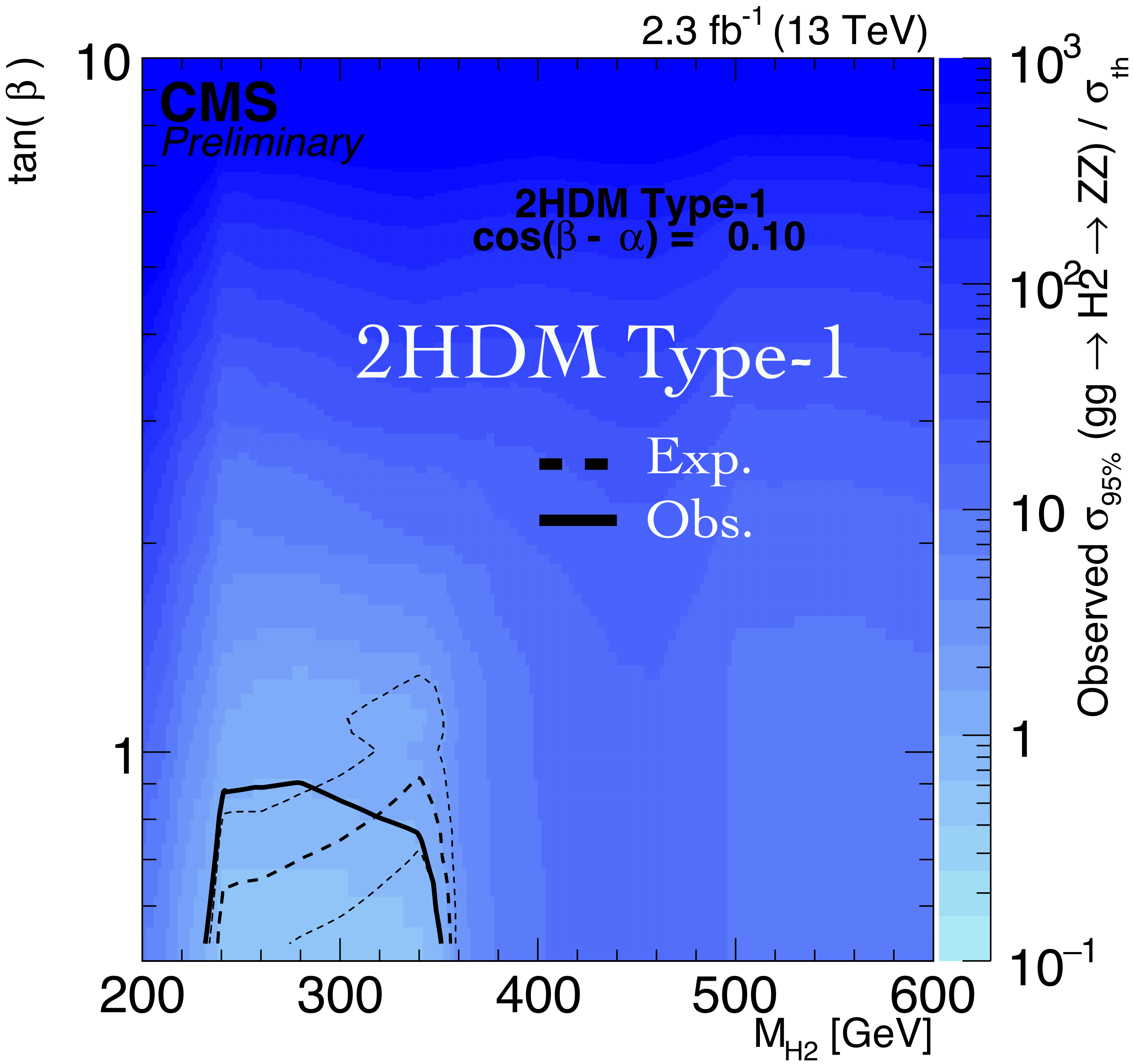
Limits on Heavy Scalar Boson in EWS Model

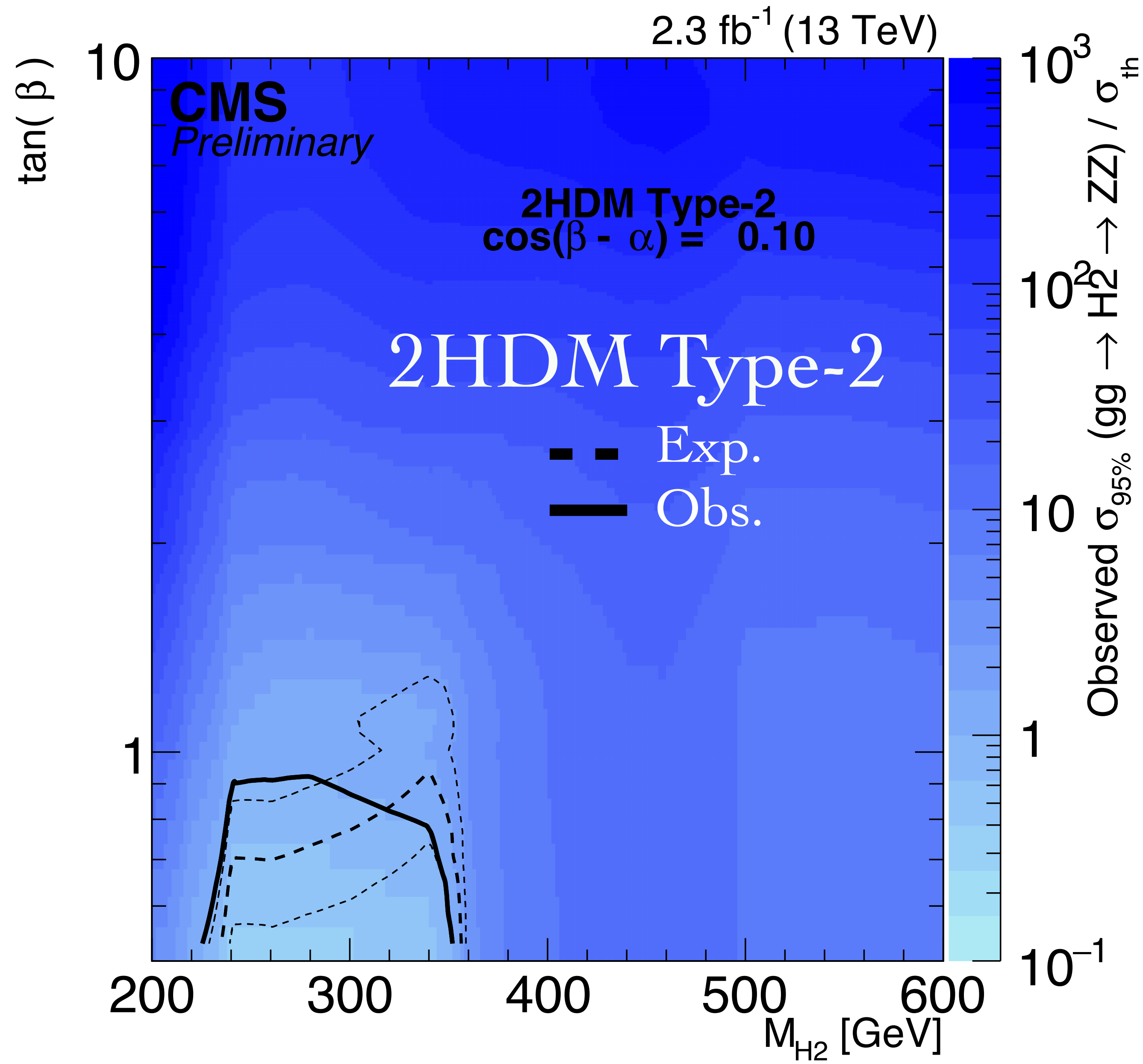




- ✦ ggH+VBF combined limit on Signal Strength-μ
- ✦ SM ratio between ggH and VBF production rates assumed
- ✦ Phase Space excluded bigger then Run I

Limits on Heavy Scalar Boson in 2HDM Model





- ✦ EWK singlet model results reinterpreted for 2HDM model
- ✦ Limits set only for gluon fusion

Conclusions

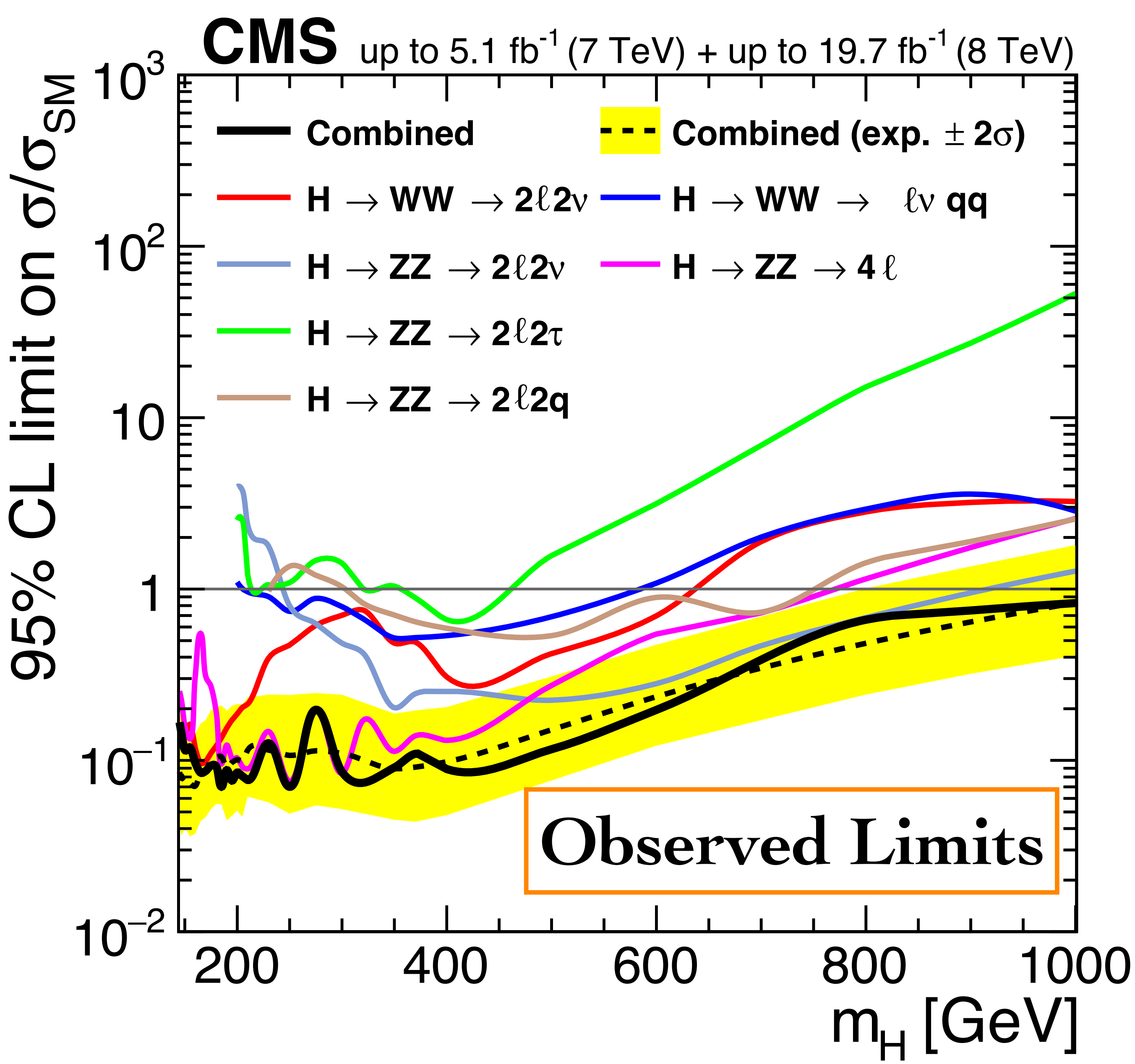
- ✦ Results for $ZZ \rightarrow 2l2\nu$ using 2.3 fb^{-1} of data were presented
  - HIG-16-001
- ✦ Results model independent
  - Limits set only as function of mass and width
    - Extended exclusion region for EWS
    - New results for 2HDM model
- ✦ These and more results can be found here
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-001/index.html
- ✦ Stay tuned with the latest 2016 data!!!

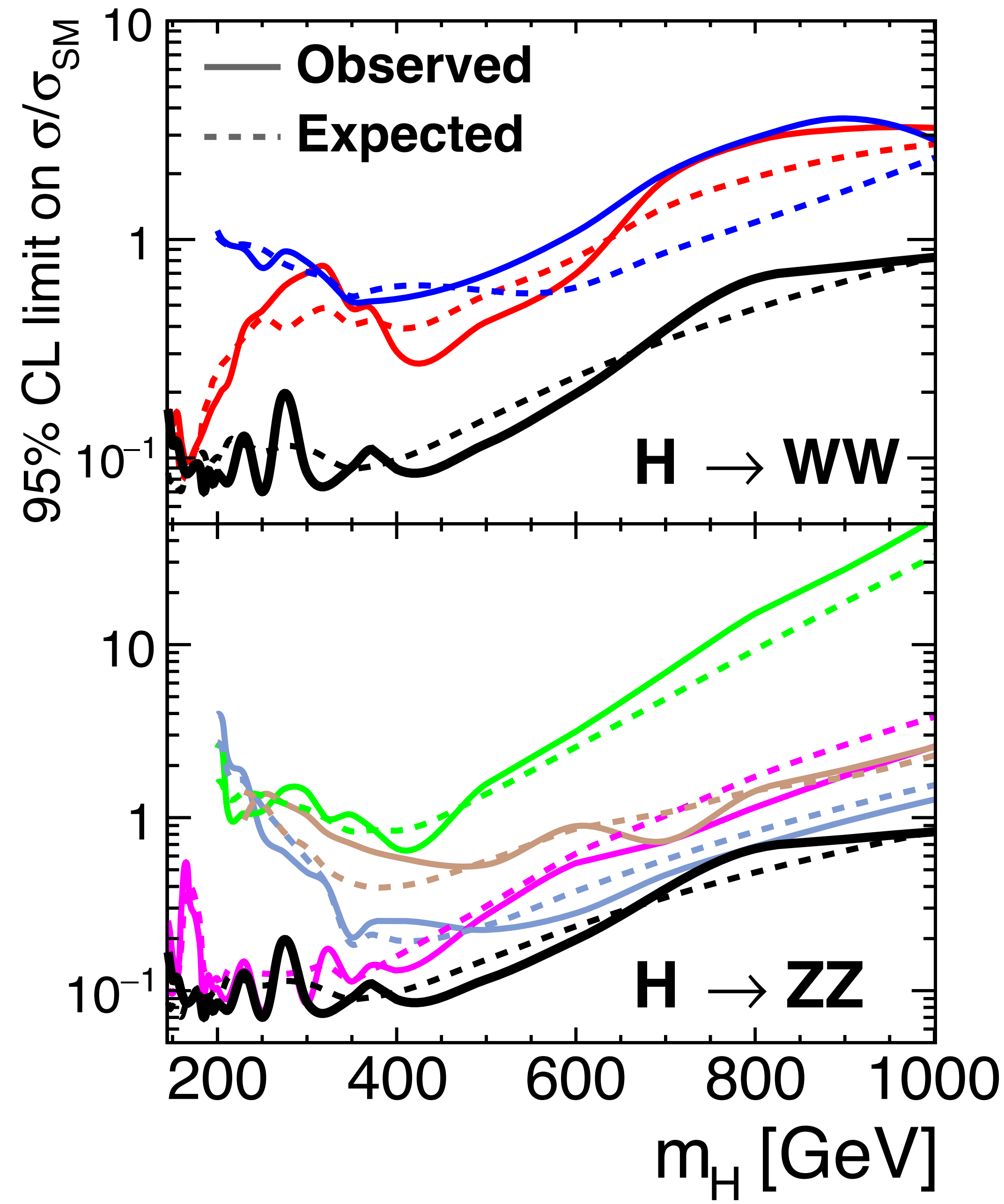
Thanks!

BackUp

Why $2l2\nu$

✦ Results from the di-boson combinations of Run I





Arxiv: 1504.00936

BSM Benchmark models

✦ Definition of the phase space in 2HDM

Parameter	Value
m_h	125.09 GeV
m_A	$m_H + 100$ GeV
m_{H^+}	$m_H + 100$ GeV
$\cos(\beta - \alpha)$	0.1
m_{12}^2	$\max(1 - \tan\beta^{-2}, 0) \cdot \frac{1}{2}\sin(2\beta)(m_A^2 + \lambda_5 v^2)$
m_H	scanned
$\tan\beta$	scanned

Backgrounds Contamination

- ✦ Expected Yields obtained for 2.3 fb^{-1}
- ✦ After final MET Cut of 125 GeV (no M_T cuts applied)

channel	Inc.	$=0jets$	$\geq 1jets$	vbf
ZZ	21.88 ± 0.10	11.69 ± 0.07	10.06 ± 0.07	0.133 ± 0.009
WZ	12.4 ± 0.4	3.9 ± 0.2	8.3 ± 0.3	0.17 ± 0.05
ZVV	0.47 ± 0.05	0.038 ± 0.008	0.42 ± 0.05	0.005 ± 0.004
Instr. MET	$27.5 \pm 2.6 \pm 3.5$	$13.7 \pm 1.4 \pm 2.6$	$13.3 \pm 2.2 \pm 2.4$	$0.43 \pm 0.16 \pm 0.08$
Top/W/WW	$27.1 \pm 4.4 \pm 3.8$	< 0.74	$27.1 \pm 4.2 \pm 4.1$	< 1.132
total	$89.3 \pm 5.1 \pm 5.4$	$29.3 \pm 1.6 \pm 2.6$	$59.2 \pm 4.7 \pm 4.7$	$0.74 \pm 1.14 \pm 0.08$
data	65	21	43	1
ggH(400)	17.83 ± 0.08	10.54 ± 0.06	7.09 ± 0.05	0.209 ± 0.009
qqH(400)	1.548 ± 0.010	0.161 ± 0.003	0.877 ± 0.007	0.510 ± 0.005
ggH(750)	25.4 ± 0.1	12.36 ± 0.08	12.60 ± 0.08	0.46 ± 0.01
qqH(750)	16.95 ± 0.10	2.06 ± 0.03	9.12 ± 0.07	5.76 ± 0.06
ggH(800)	25.6 ± 0.1	12.14 ± 0.07	12.96 ± 0.08	0.49 ± 0.01
qqH(800)	23.8 ± 0.1	2.94 ± 0.05	12.8 ± 0.1	8.09 ± 0.08
ggH(1000)	26.25 ± 0.10	11.26 ± 0.07	14.41 ± 0.07	0.58 ± 0.01
qqH(1000)	73.8 ± 0.4	9.4 ± 0.1	39.4 ± 0.3	25.0 ± 0.2
ggH(1500)	15.4 ± 0.2	5.8 ± 0.1	9.2 ± 0.1	0.34 ± 0.03
qqH(1500)	45.5 ± 1.1	6.7 ± 0.4	24.5 ± 0.8	14.3 ± 0.6

Systematics on the Yield

Source	Uncertainty [%]
Luminosity	2.7
Simulations	
PDF, gluon-gluon initial state	4
PDF, quark-quark initial state	10
QCD scale, gluon-gluon initial state (ggH)	10
QCD scale, quark-quark initial state (VBF)	10
QCD scale, gluon-gluon initial state (ggZZ)	20
QCD scale, quark-quark initial state (qqVV)	5.8–8.5
Higgs boson line shape	10–30
Signal cross-section	4.5
Data-driven corrections	
Anti b-tagging	1–3
Lepton identification and isolation	4-5
Jet energy scale	4-10
Pile-up effects, $E_{\mathrm{T}}^{\mathrm{miss}}$	1-2
Background estimation	
Non-resonant background	20
Z+jets	25 (syst.) $\pm$ 10-50 (stat.)