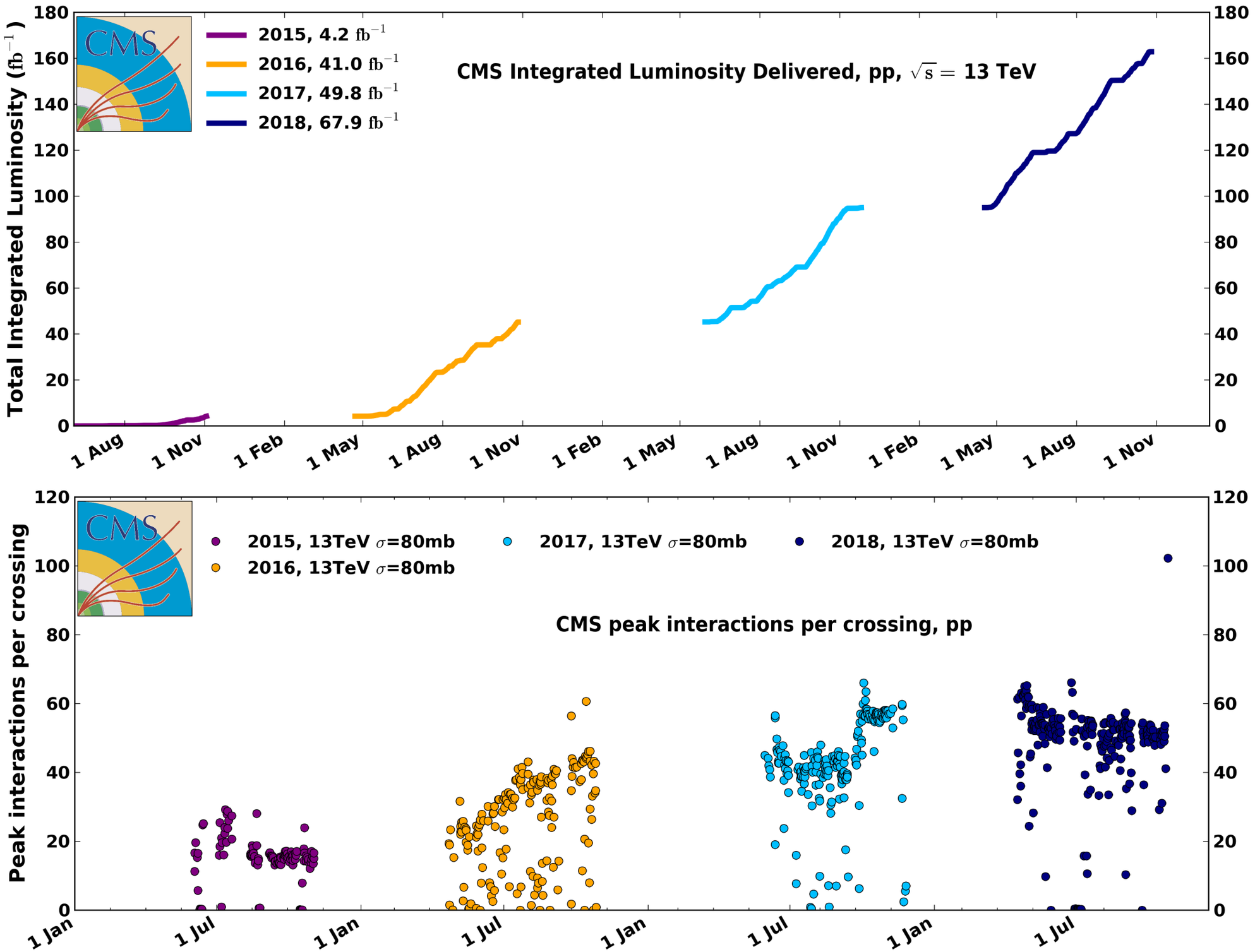
Higgs to WW Run 2 results at CMS

Jónatan Piedra, on behalf of the CMS Collaboration
IFCA (CSIC - Universidad de Cantabria)

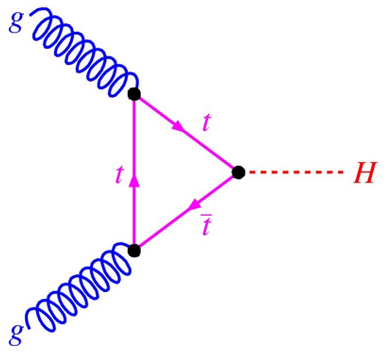
Higgs Couplings
30 September - 4 October, 2019, Oxford, UK

More data, more pileup

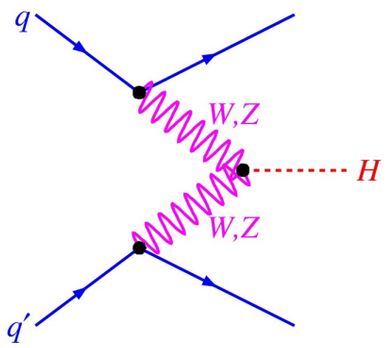


Higgs production at the LHC

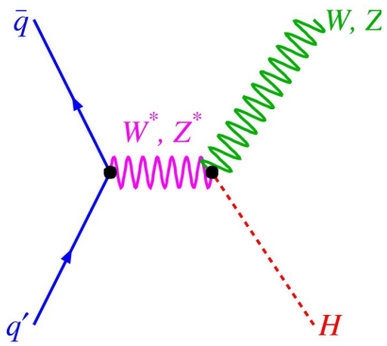
ggH
87%



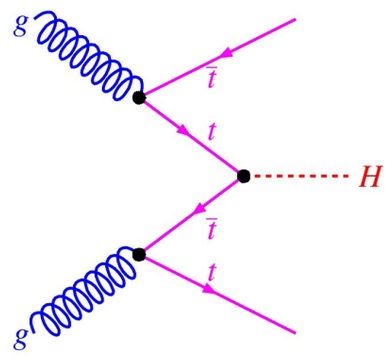
VBF
6.8%

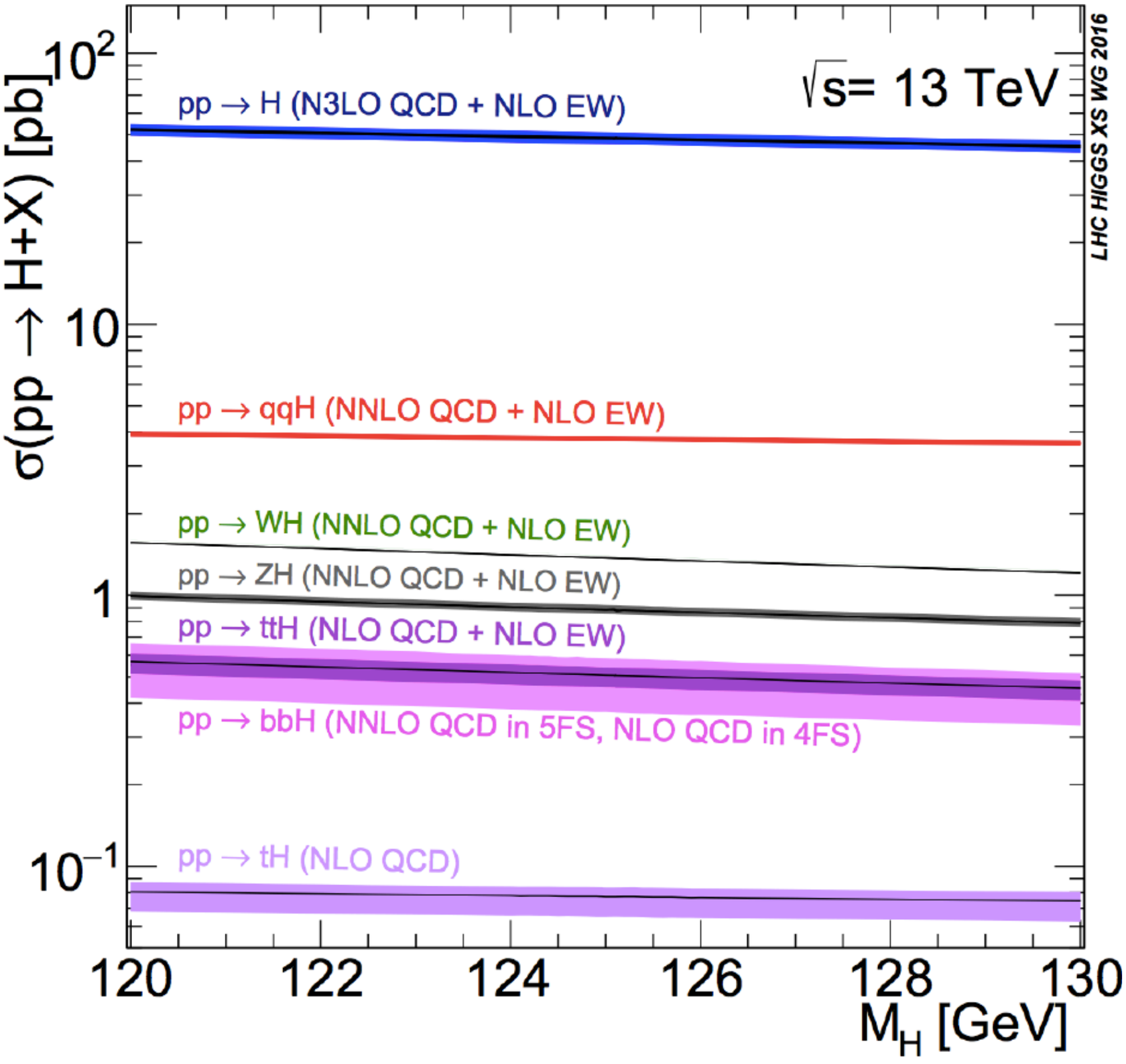


VH
4.1%

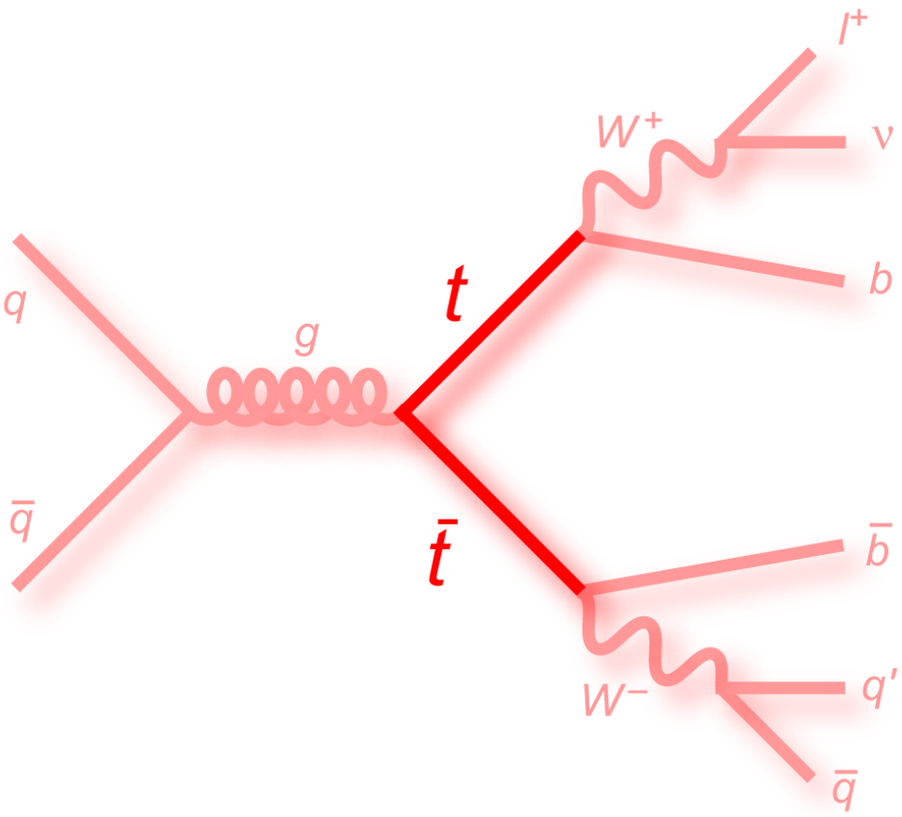


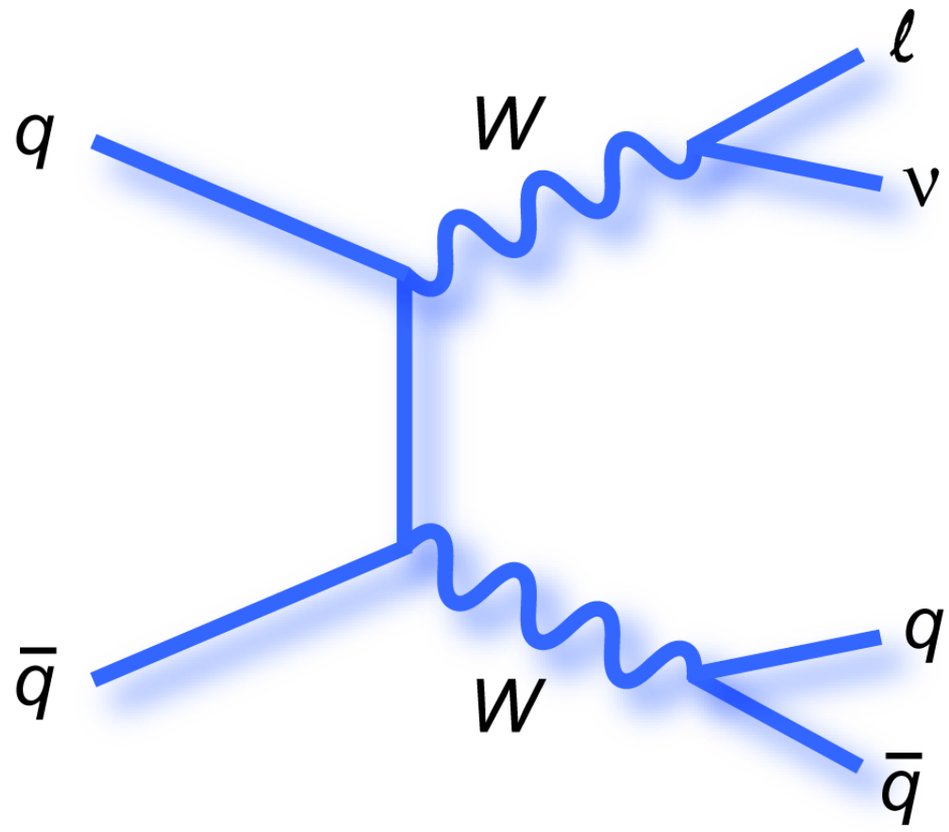
ttH
0.9%

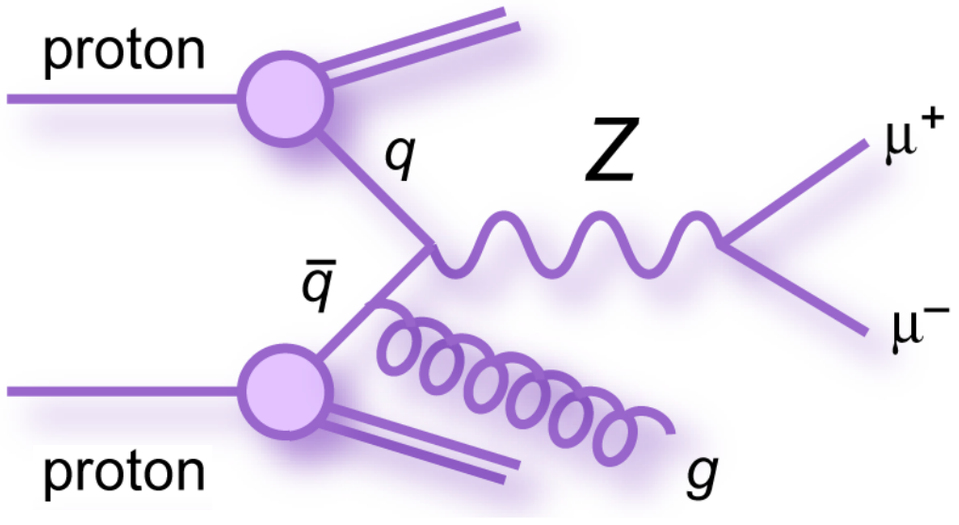




Main backgrounds







Also processes (such as W+jets) with ***jets or leptons faking leptons coming from a W or a Z boson***

Results covered in this talk

HIG-16-042	Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at 13 TeV	**February 2019** Phys. Lett. B 791 (2019) 96
HIG-17-033	Search for a heavy Higgs boson decaying to a pair of W bosons in pp collisions at 13 TeV	**March 2019**
HIG-19-002	Measurement of Higgs differential production cross section in the leptonic WW decay mode at 13 TeV	**October 2019**

NEW FOR HC 2019

Related results covered in other talks

October 1st @ 9:30	Measurements of Higgs couplings to gauge bosons at CMS and ATLAS **Piergiulio Lenzi**
October 1st @14:40	Measurements of ttH and tH production at ATLAS and CMS **Peter Onyisi**
October 1st @17:15	Prospects for Higgs boson measurements at the HL-LHC **Nicola De Filippis**

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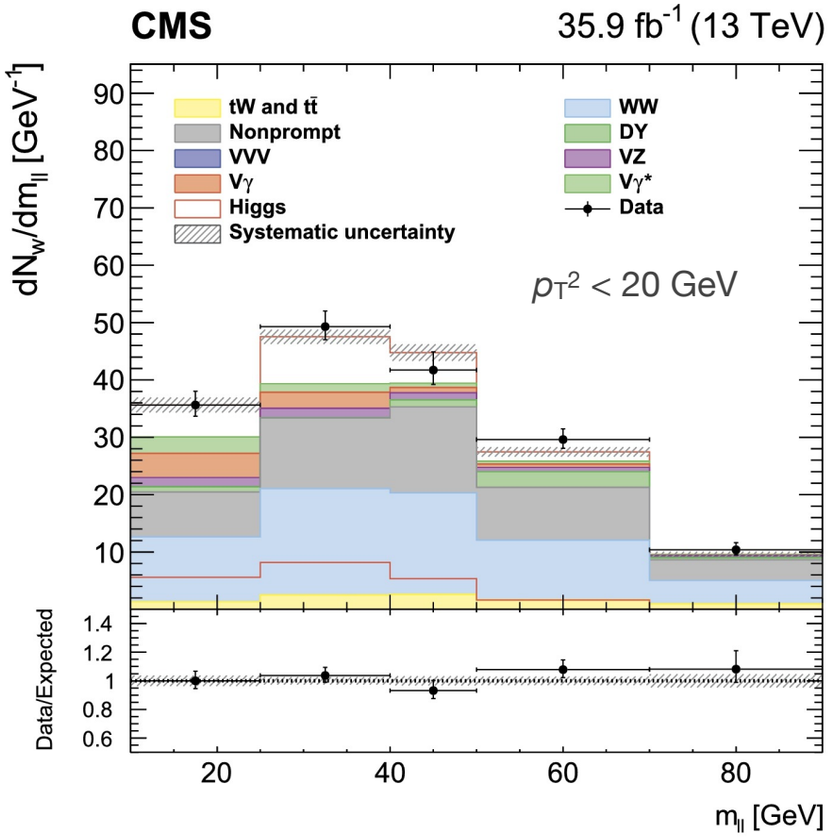
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell\ell} p_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos \Delta\phi(\ell\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})]}$$

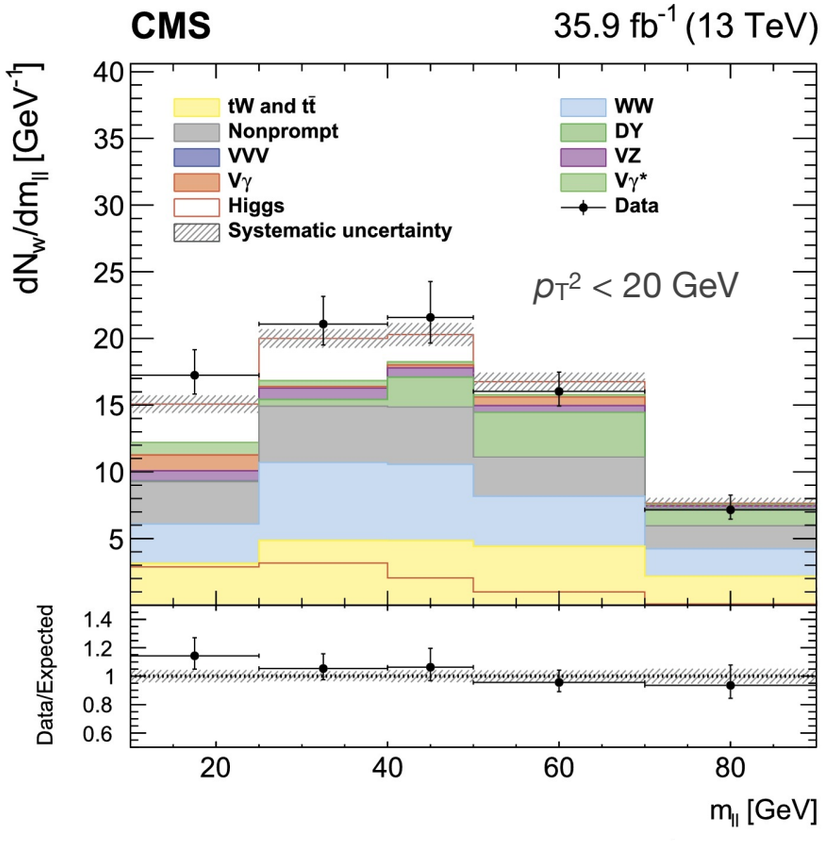
Events are split in 30 categories

category		subcategories	expected	observed ± total uncertainty	signal extraction
ggH DF	17	0-jet (x8) 1-jet (x8) 2-jet (x1)	509 313 103	677 ± 31 398 ± 19 130 ± 16	$m_{\ell\ell}$ vs m_{T} shape
2-jet VBF DF	2	$400 < m_{jj} < 700$ GeV $m_{jj} > 700$ GeV	31	40 ± 3	$m_{\ell\ell}$ shape
2-jet VH DF	1	eμ	20	25 ± 3	$m_{\ell\ell}$ shape
ggH SF	6	0-jet (x4) 1-jet (x2)	240 93	337 ± 24 108 ± 13	event count
3-lepton WH	2	$\mu^{\mp}\mu^{\pm}e^{\mp}$ / $e^{\mp}e^{\pm}\mu^{\mp}$ $\mu^{\pm}\mu^{\pm}e^{\mp}$ / $e^{\pm}e^{\pm}\mu^{\mp}$	5.6	7.4 ± 0.7	min $\Delta R_{\ell\ell}$ shape
4-lepton ZH	2	SF + Z DF + Z	2.7	3.5 ± 0.3	event count

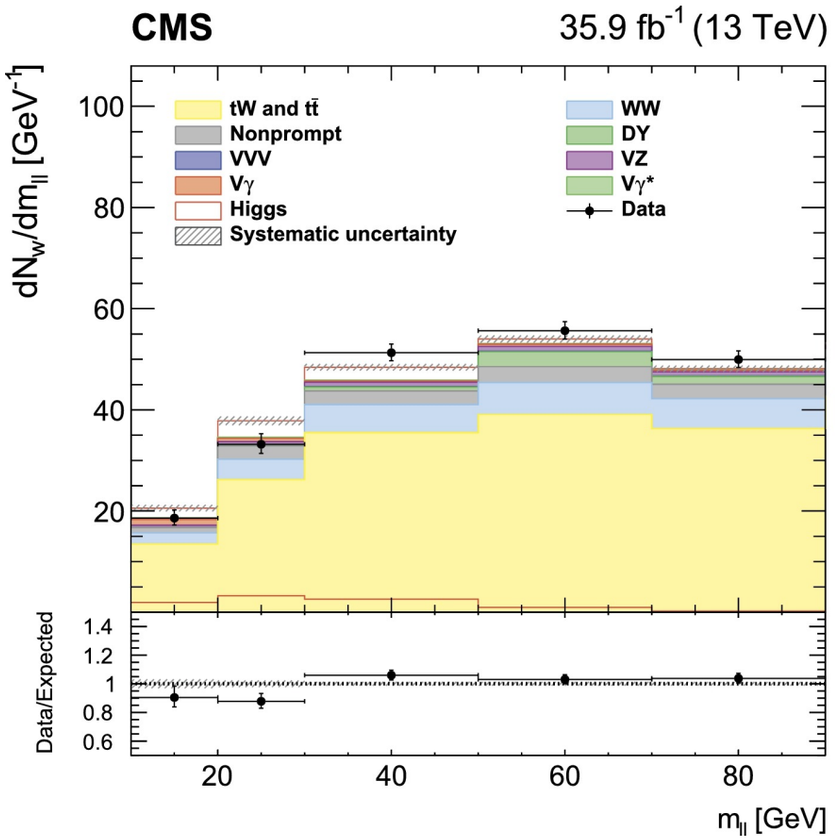
ggH 0j eμ



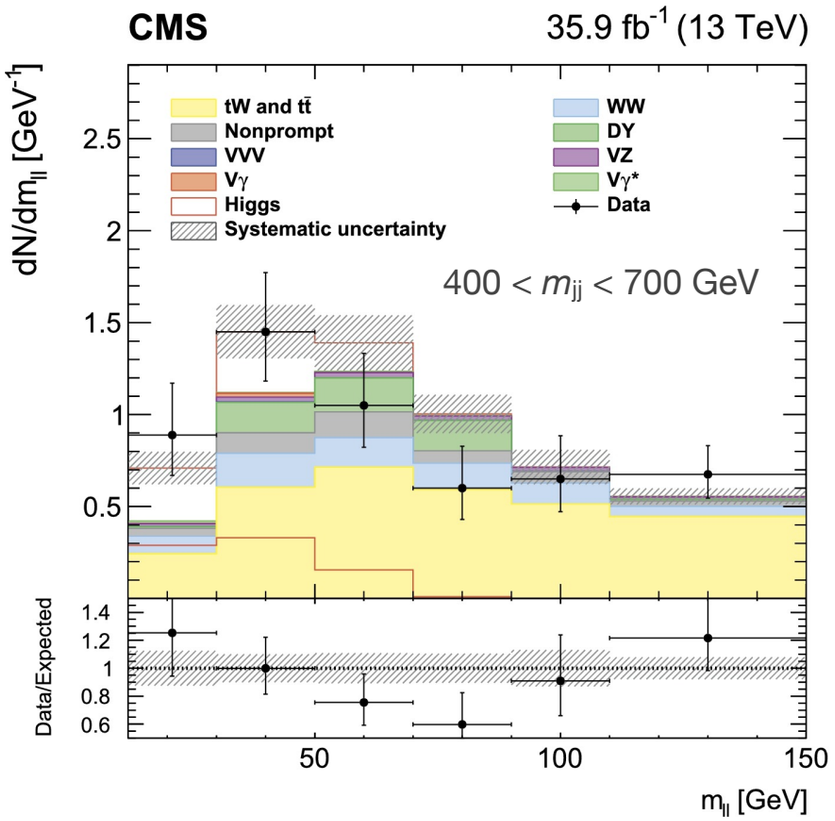
ggH 1j eμ



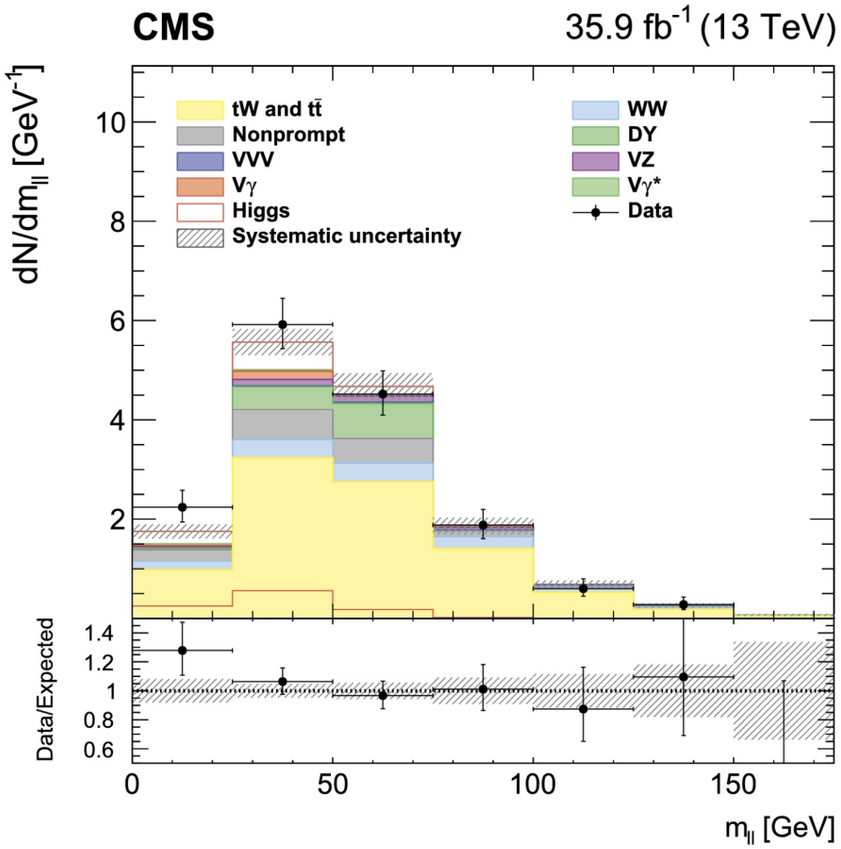
ggH 2j eμ



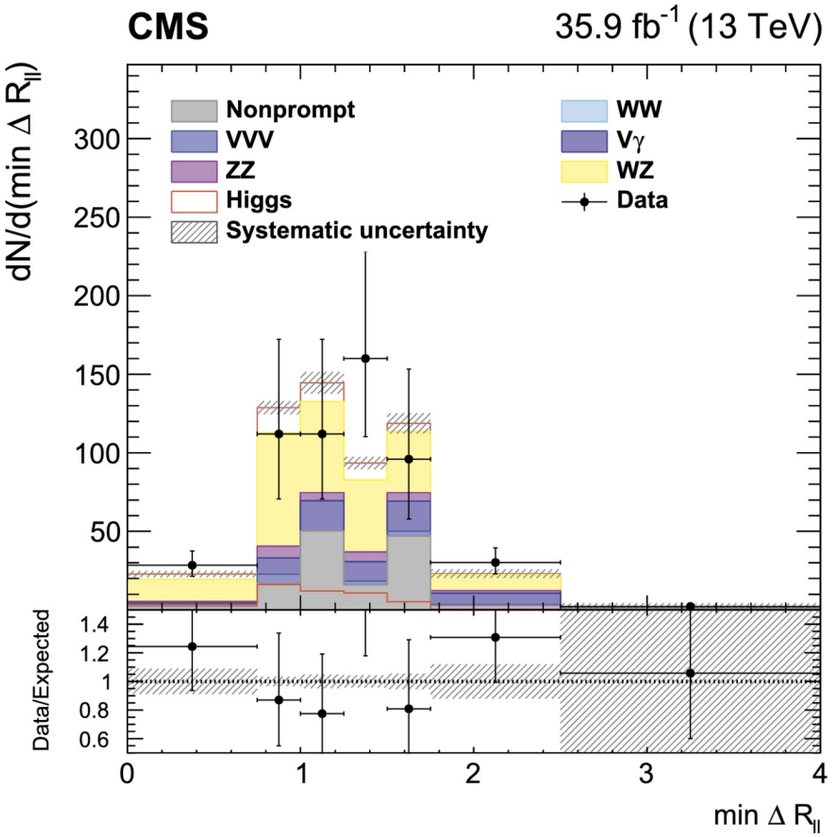
2j VBF eμ



2j VH



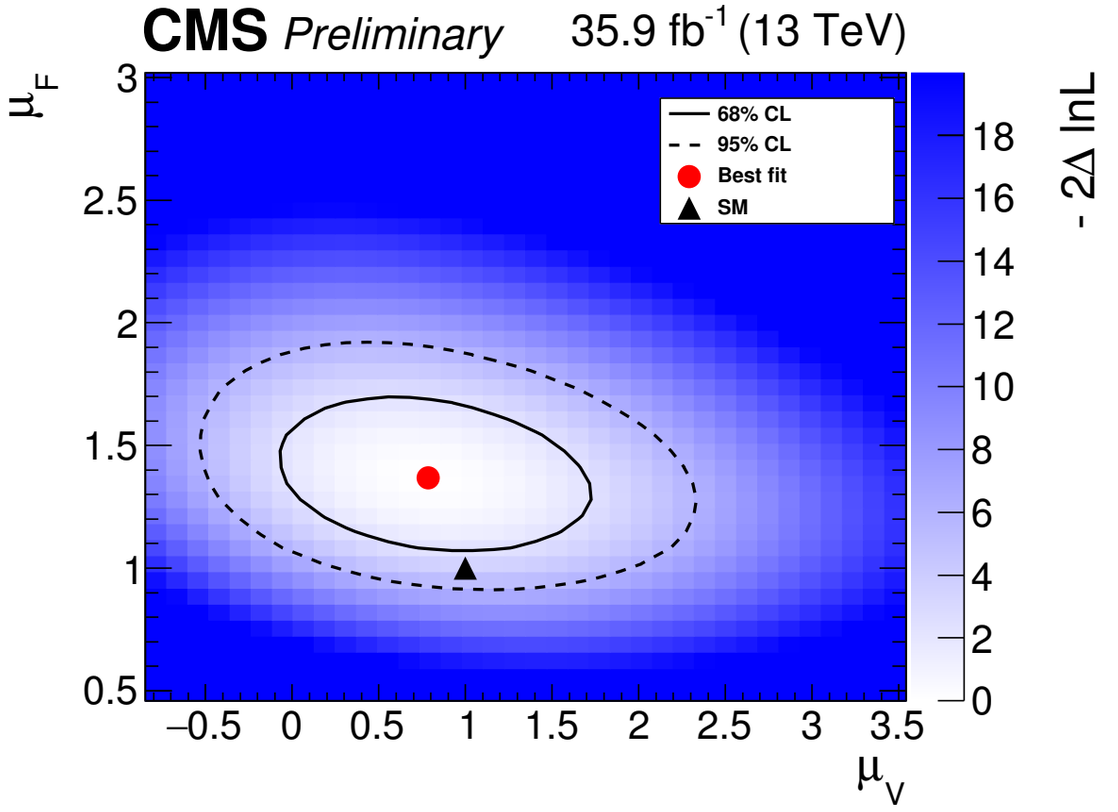
WH

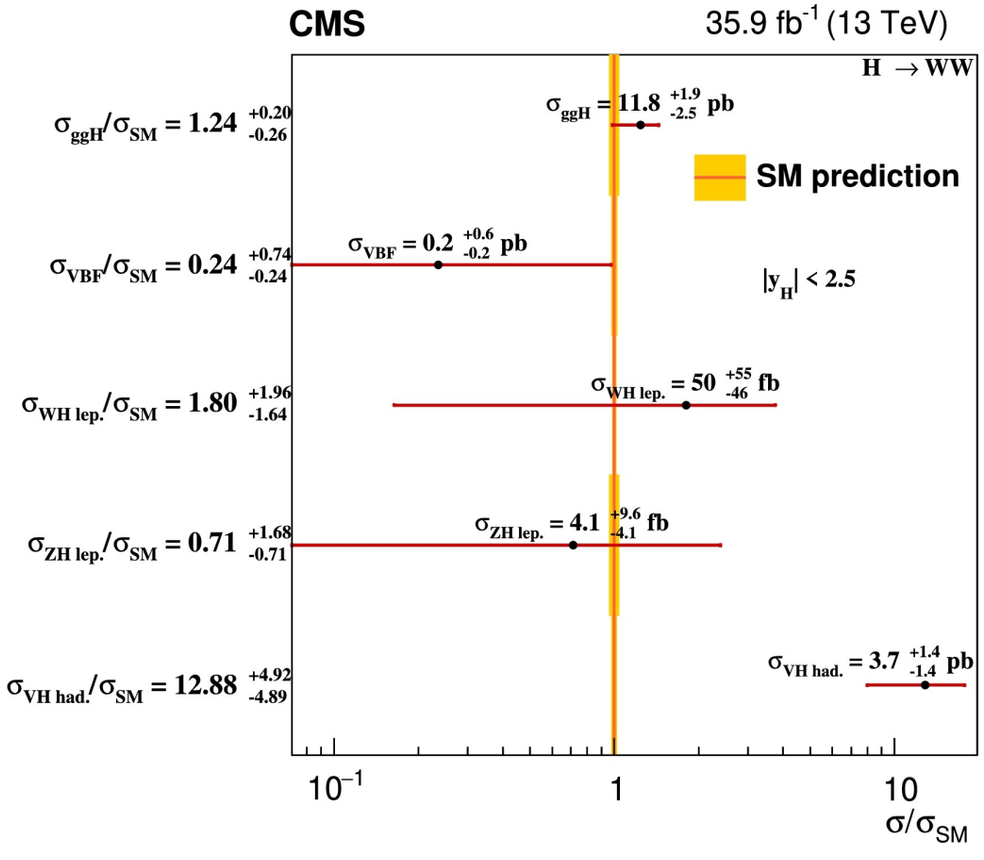


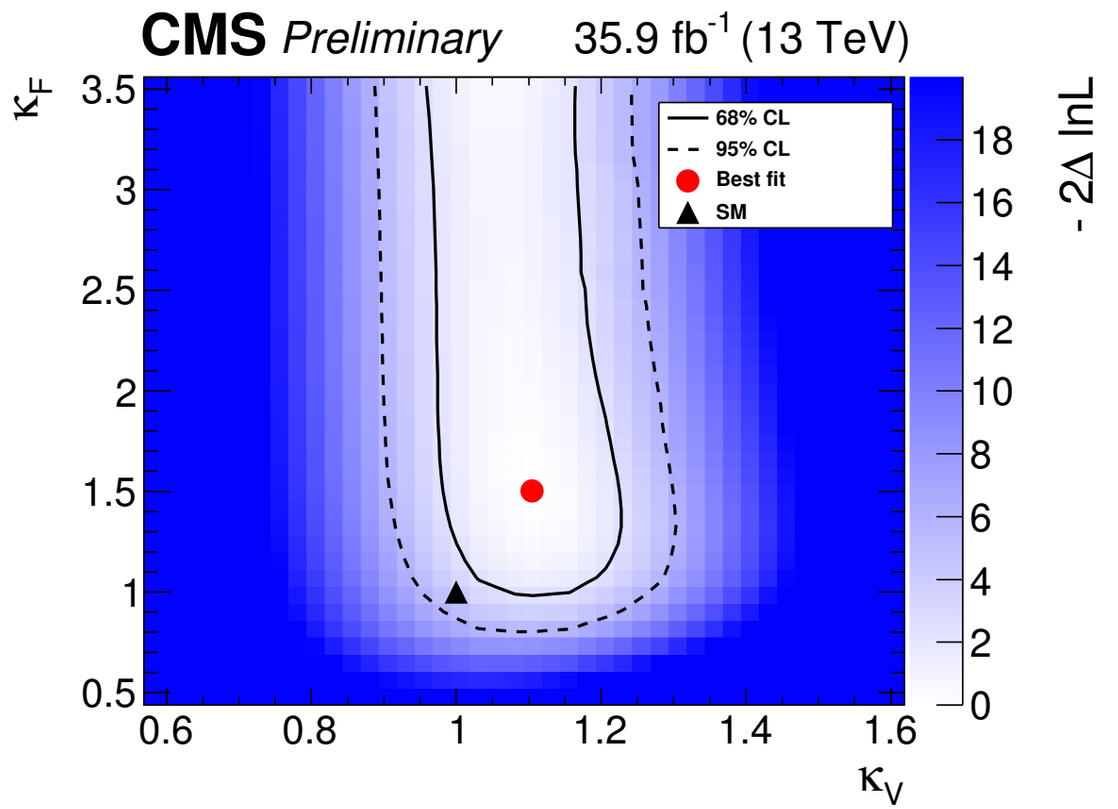
Signal strength measurements

$$\sigma/\sigma_{\mathrm{SM}} = \mu = 1.28^{+0.18}_{-0.17}$$

Signal strengths measured by a simultaneous likelihood fit on all signal (30) and background (12) regions. **The observed (expected) significance is 9.1 (7.1)**







The biggest uncertainties are ggH theoretical uncertainty and electrons reco+ID

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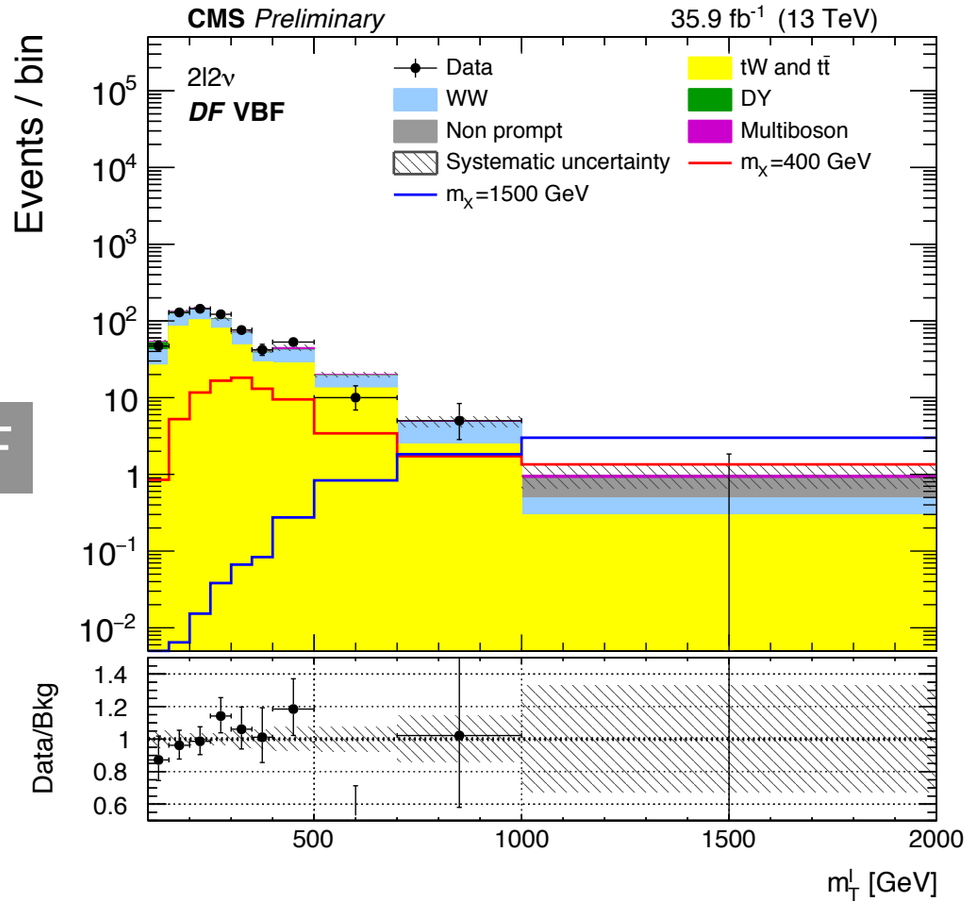
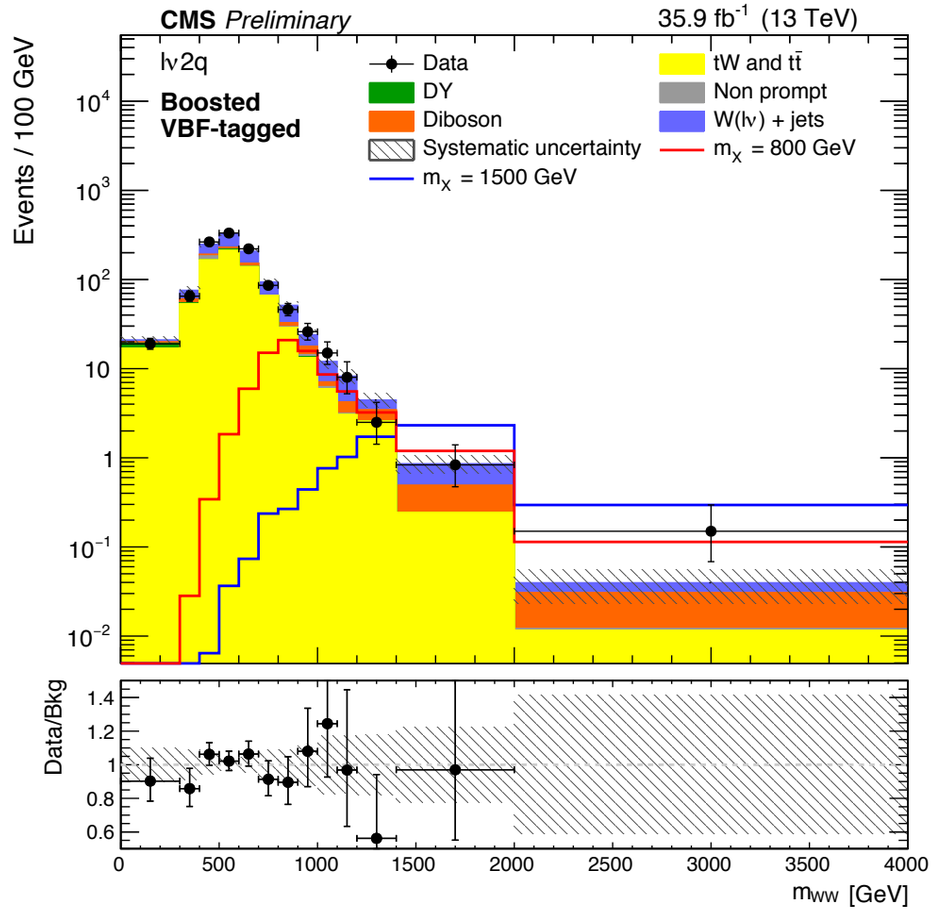
Squeezing events to find a high mass Higgs boson

visible mass $m_T^I = \sqrt{(p_{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\ell\ell} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2}$

Final state topology	**lnln**		**lnqq**	
	em	**ee, mm**	**boosted**	**resolved**
Discriminant	**visible mass**		WW invariant mass m_{WW}	
Categories	0j, 1j, 2j VBF-fail, 2j VBF	2j VBF	VBF ggF (VBF-fail and "MELA" > 0.5) untagged (ggF-fail)	
Lepton *pt*	> 25, 20 GeV	> 20, 20 GeV	> 30 GeV	
MET	> 20 GeV	> 50 GeV	> 40 GeV	> 30 GeV
b-tagged jets	no 20 GeV b-tagged jets		no 20 GeV b-tagged jets	
Additional requirements	m_{ll} > 50 GeV	m_{ll} > 120 GeV	65 < m_J < 105 GeV pt_W / m_{WW} > 0.4	65 < m_{jj} < 105 GeV pt_W / m_{WW} > 0.35
	pt_{ll} > 30 GeV $m_T{}^I$ > 100 GeV m_T > 60 GeV			$m_T{}^W$ > 50 GeV m_T > 60 GeV
Main backgrounds	WW and top *both with floating normalization*		W+jets and top *both with floating normalization*	

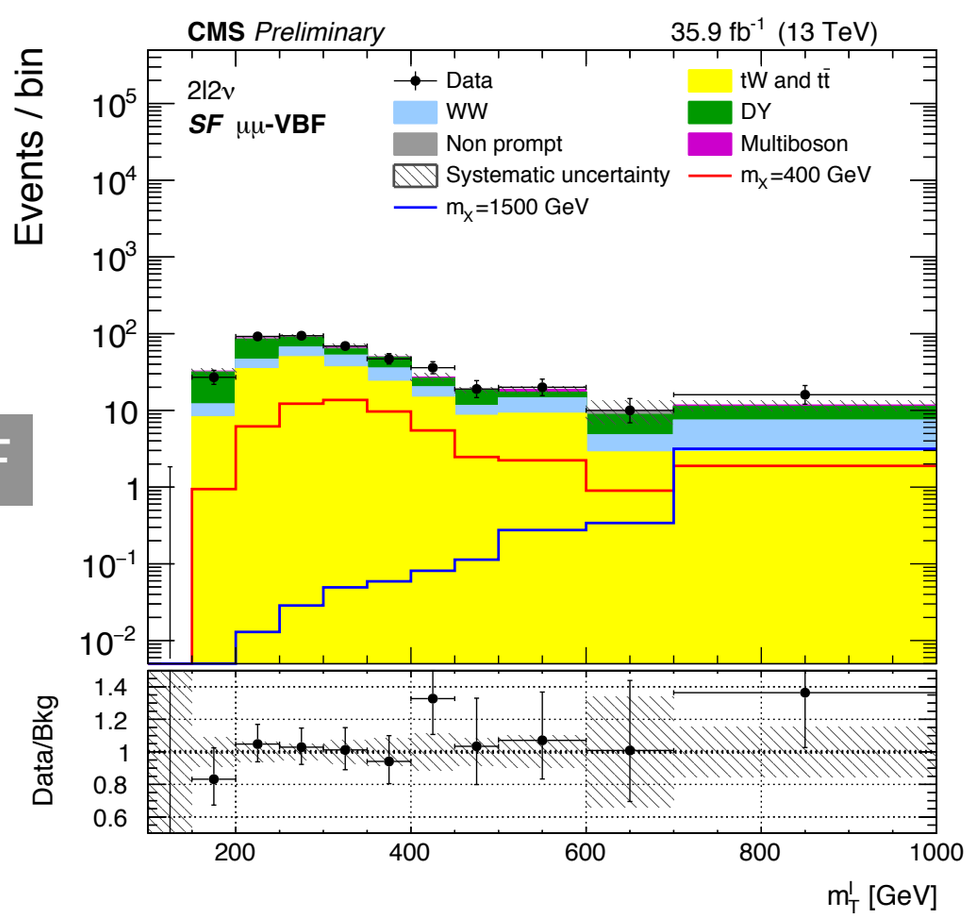
eμ VBF

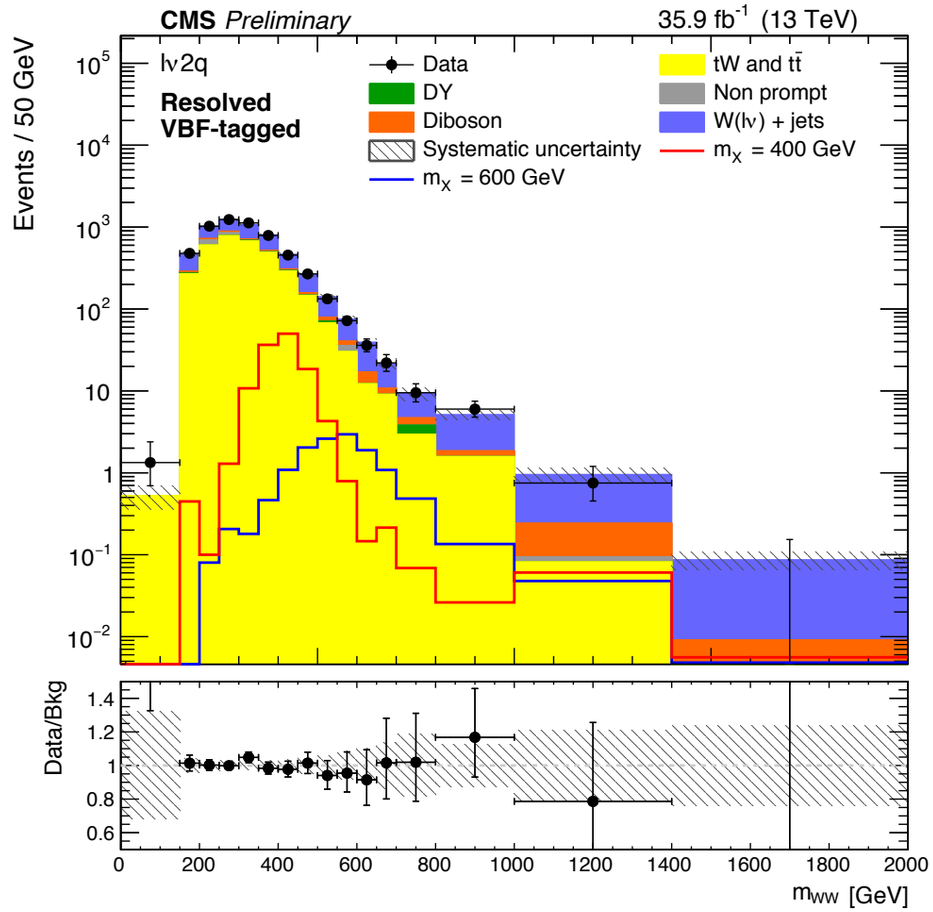




BOOSTED VBF

μμ VBF

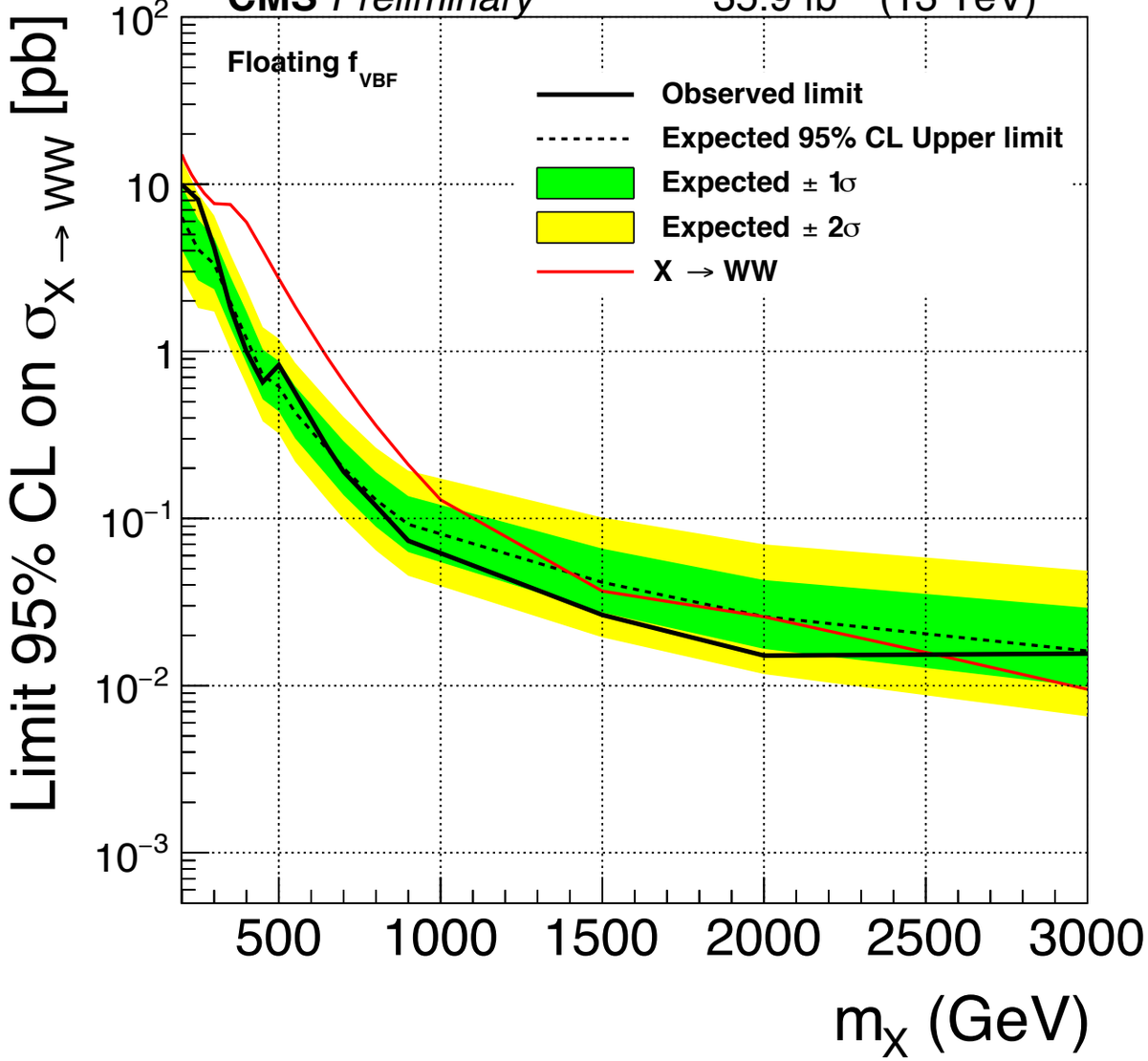


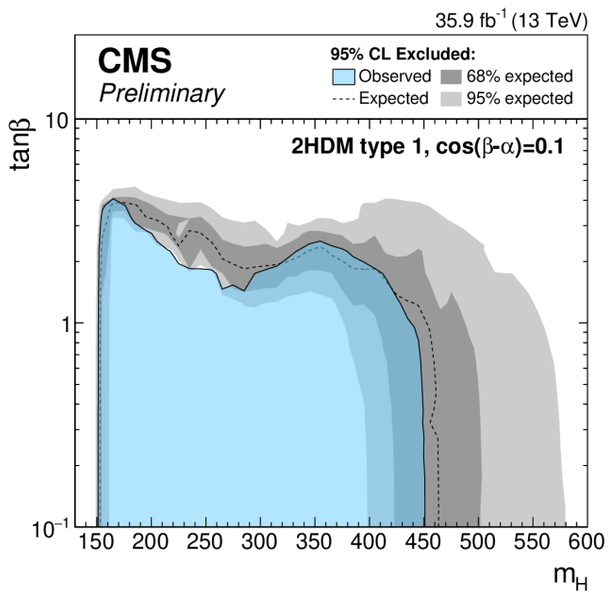


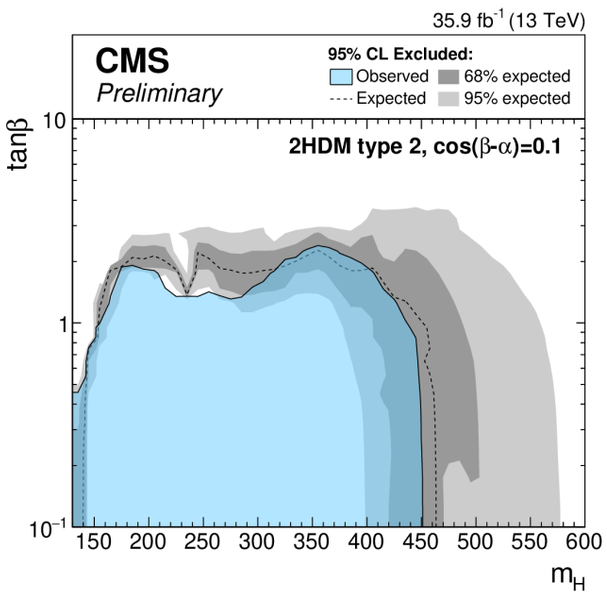
RESOLVED VBF

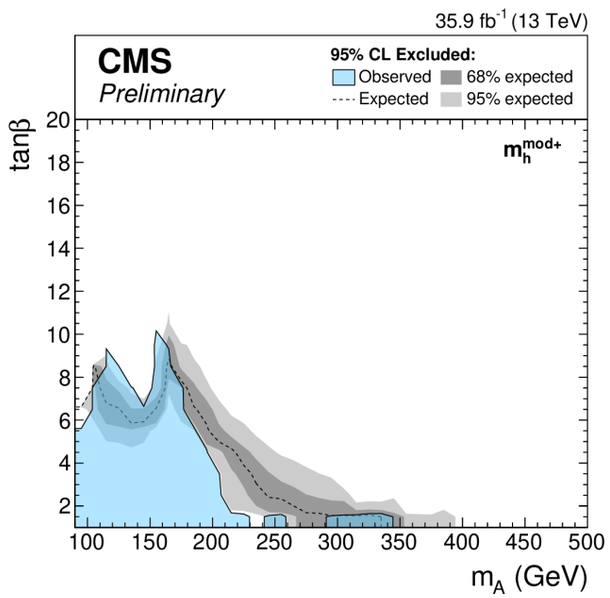
Limits

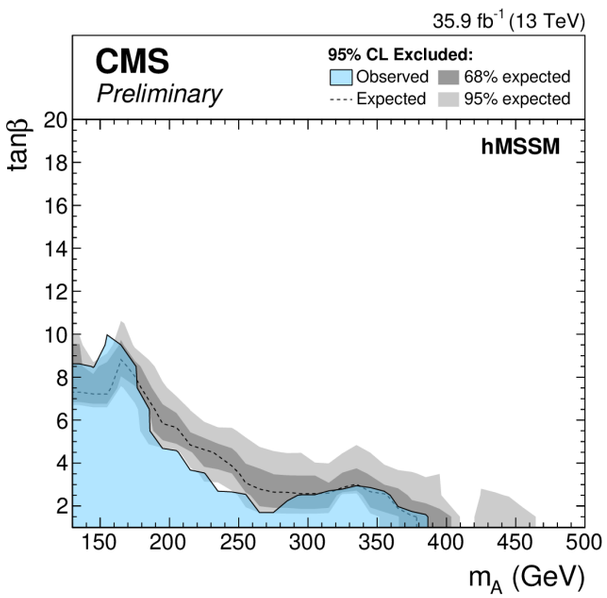
Limits set on σ_X for different VBF fractions, tanβ-m_H in 2HDM models, and tanβ-m_A in hMSSM











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σ(Higgs pt) *sensitive to possible SM deviations of the light quarks Yukawa couplings*

Analysis **strategy**

Differential distributions are measured for pt(H) and N_{jets}

In every pt(H) or N_{jets} bin a 2D fit of the $m_{\ell\ell}$ vs. m_{T} shape is performed

The top and DY backgrounds are normalized in their control regions for each pt(H) and N_{jets} bin

Selection	Requirements	Note
Preselection	leading two leptons have opposite sign and different flavour, $p_{\text{T}}^{\ell_1} > 25\,\text{GeV}$, $p_{\text{T}}^{\ell_2} > 13\,\text{GeV}$, $\lvert\eta\rvert < 2.5$ (2.4) for e (μ), $p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$, $p_{\text{T}}^{\ell\ell} > 30\,\text{GeV}$, no additional leptons with $p_{\text{T}} > 10\,\text{GeV}$	
Signal region	$m^{\ell\ell} > 12\,\text{GeV}$, $m_{\text{T}}^{\text{H}} > 60\,\text{GeV}$, $m_{\text{T}}^{\ell_2} > 30\,\text{GeV}$, no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$	Binned by p_{T}^{H} or N_{jet} and categorized by lepton properties
$\text{t}\bar{\text{t}}$ control region	$m^{\ell\ell} > 50\,\text{GeV}$, $m_{\text{T}}^{\ell_2} > 30\,\text{GeV}$, at least one b-tagged jet with $p_{\text{T}} > 20\,\text{GeV}$ if $N_{\text{jet}} = 0$, else $p_{\text{T}} > 30\,\text{GeV}$	Binned by p_{T}^{H} or N_{jet}
$\tau^+\tau^-$ control region	$40 < m^{\ell\ell} < 80\,\text{GeV}$, $m_{\text{T}}^{\text{H}} < 60\,\text{GeV}$, no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$	Binned by p_{T}^{H} or N_{jet}

Signal model and fit

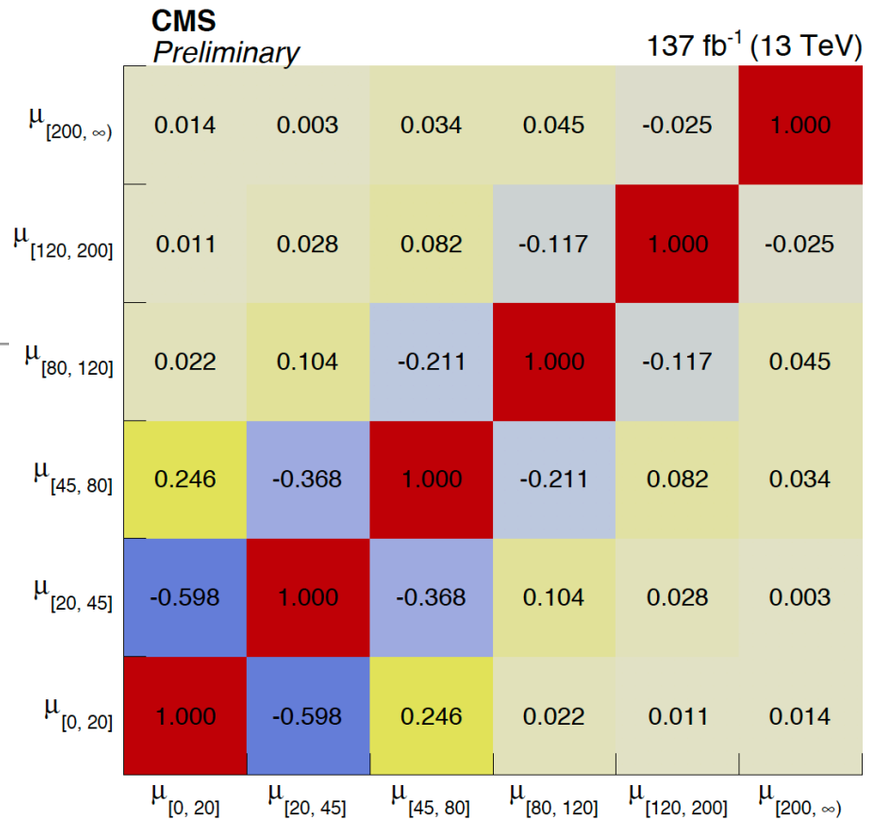
Each signal event is classified as fiducial or nonfiducial, with the **fiducial definition very close to the analysis signal region**

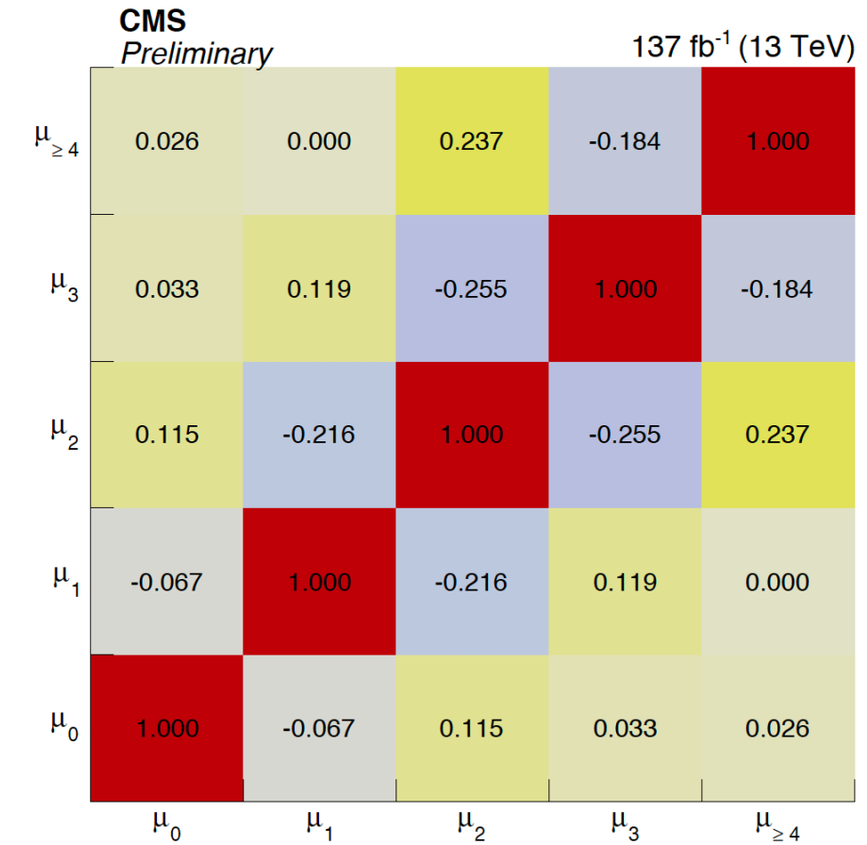
Leptons are “dressed” with nearby photons

The fiducial component of each gen-level bin **is extracted from a regularized fit**

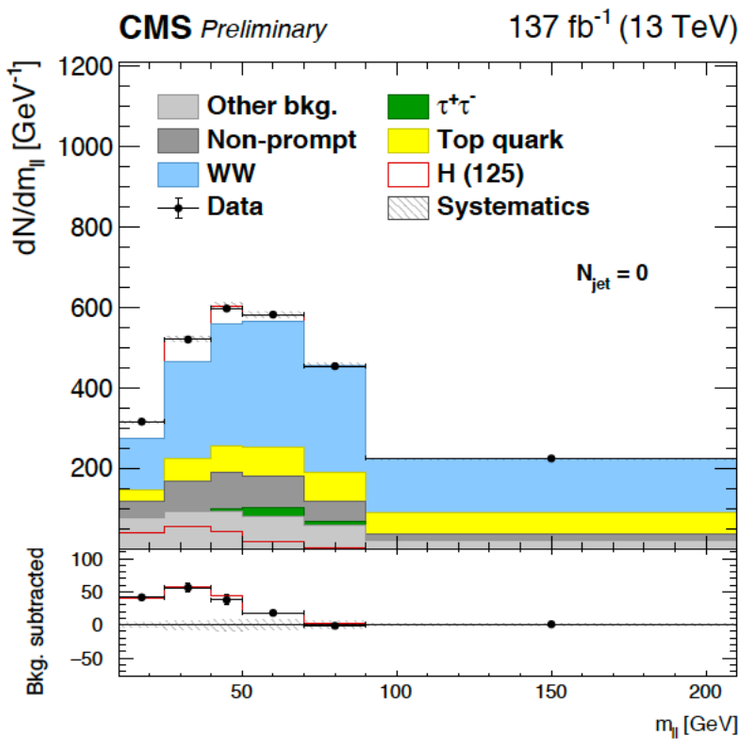
Lepton origin	Direct decay product of $H \to WW$
Lepton flavor and charge	Different flavor, opposite charge
Leading lepton p_T	$p_T^{\ell_1} > 25\,\text{GeV}$
Trailing lepton p_T	$p_T^{\ell_2} > 13\,\text{GeV}$
Pseudorapidity of the leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{\ell\ell} > 12\,\text{GeV}$
Dilepton transverse momentum	$p_T^{\ell\ell} > 30\,\text{GeV}$
Transverse mass of trailing lepton	$m_T^{\ell_2} > 30\,\text{GeV}$
Higgs transverse mass	$m_T^{H} > 60\,\text{GeV}$

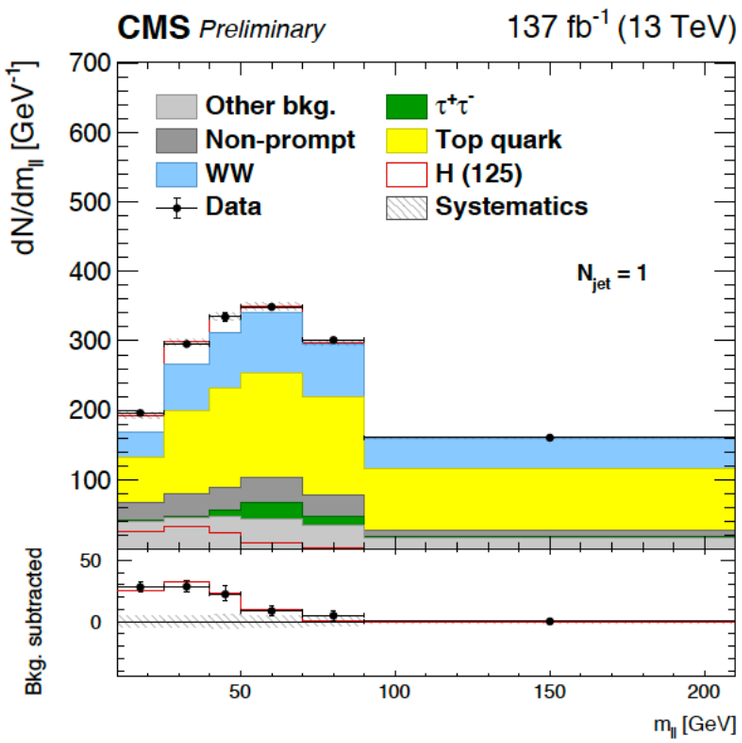
FIDUCIAL REGION DEFINITION

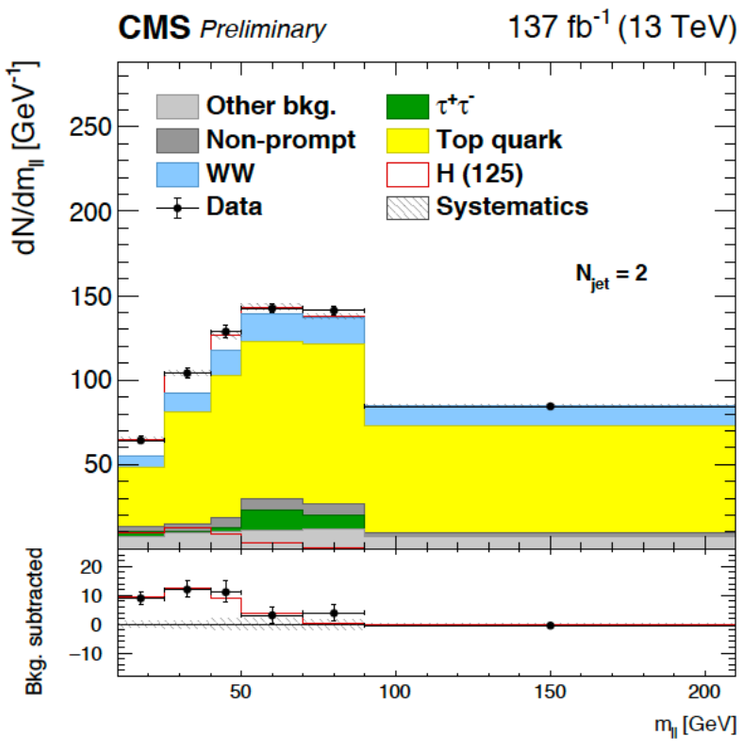


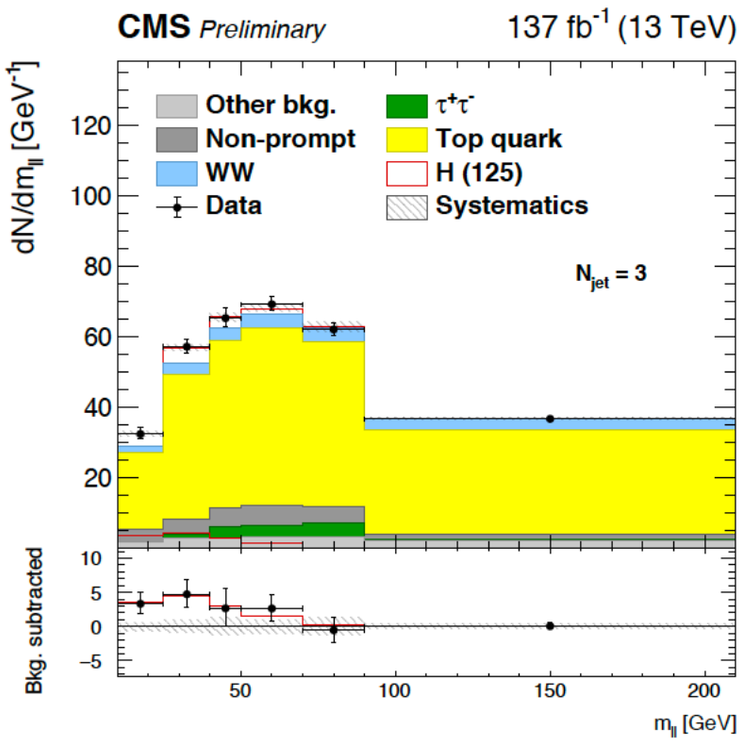


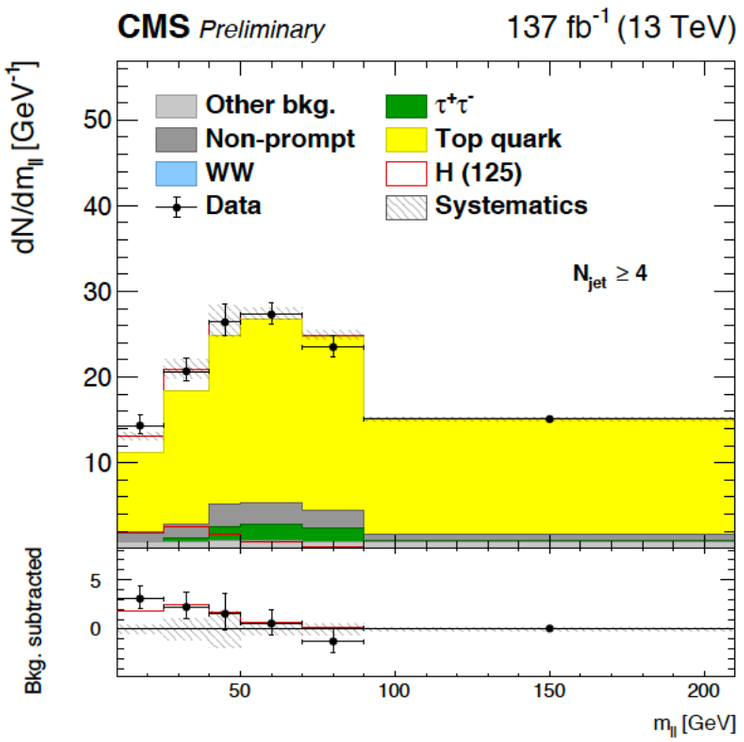
Postfit m_{ll} distributions for the different jet bins





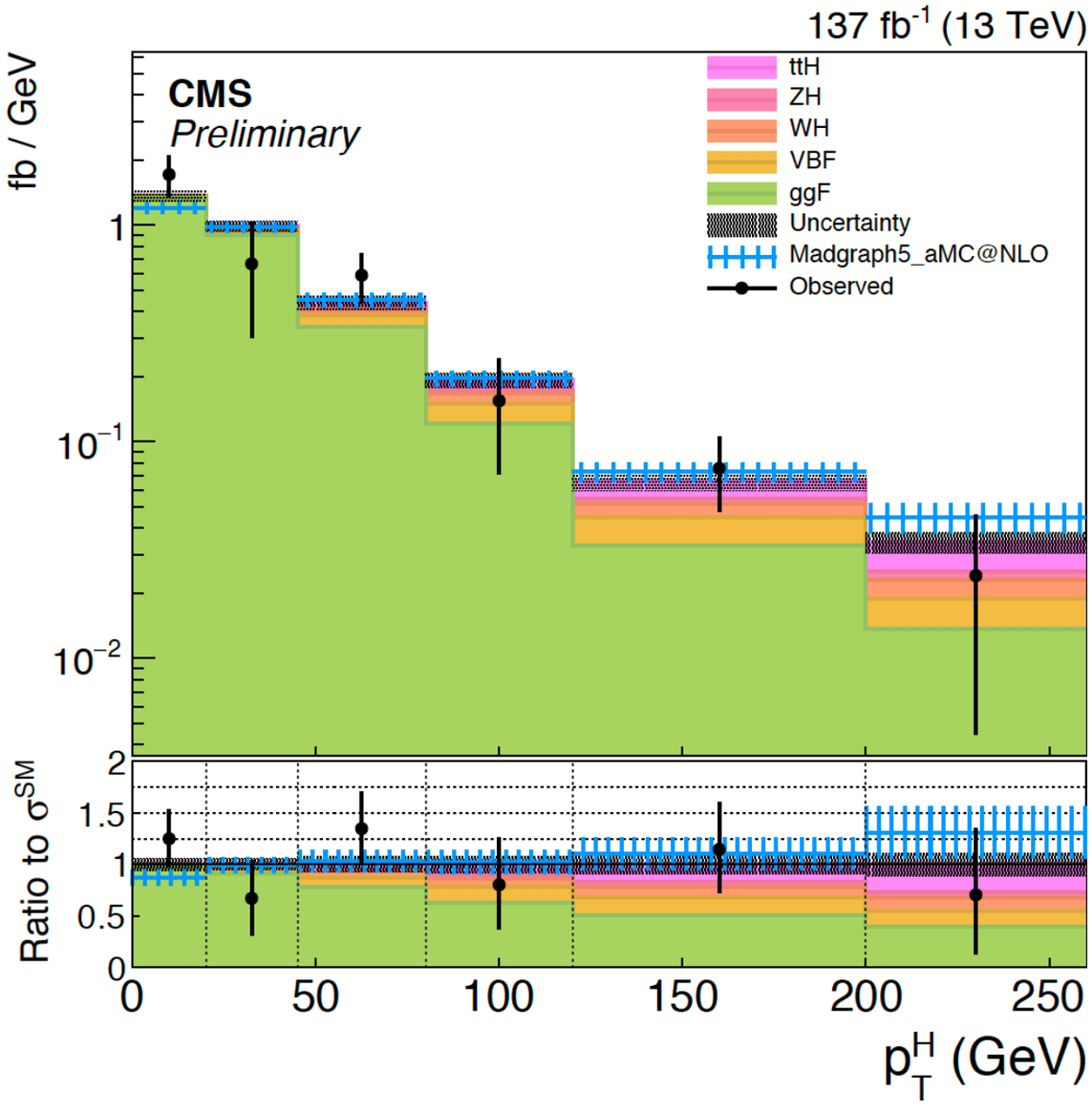


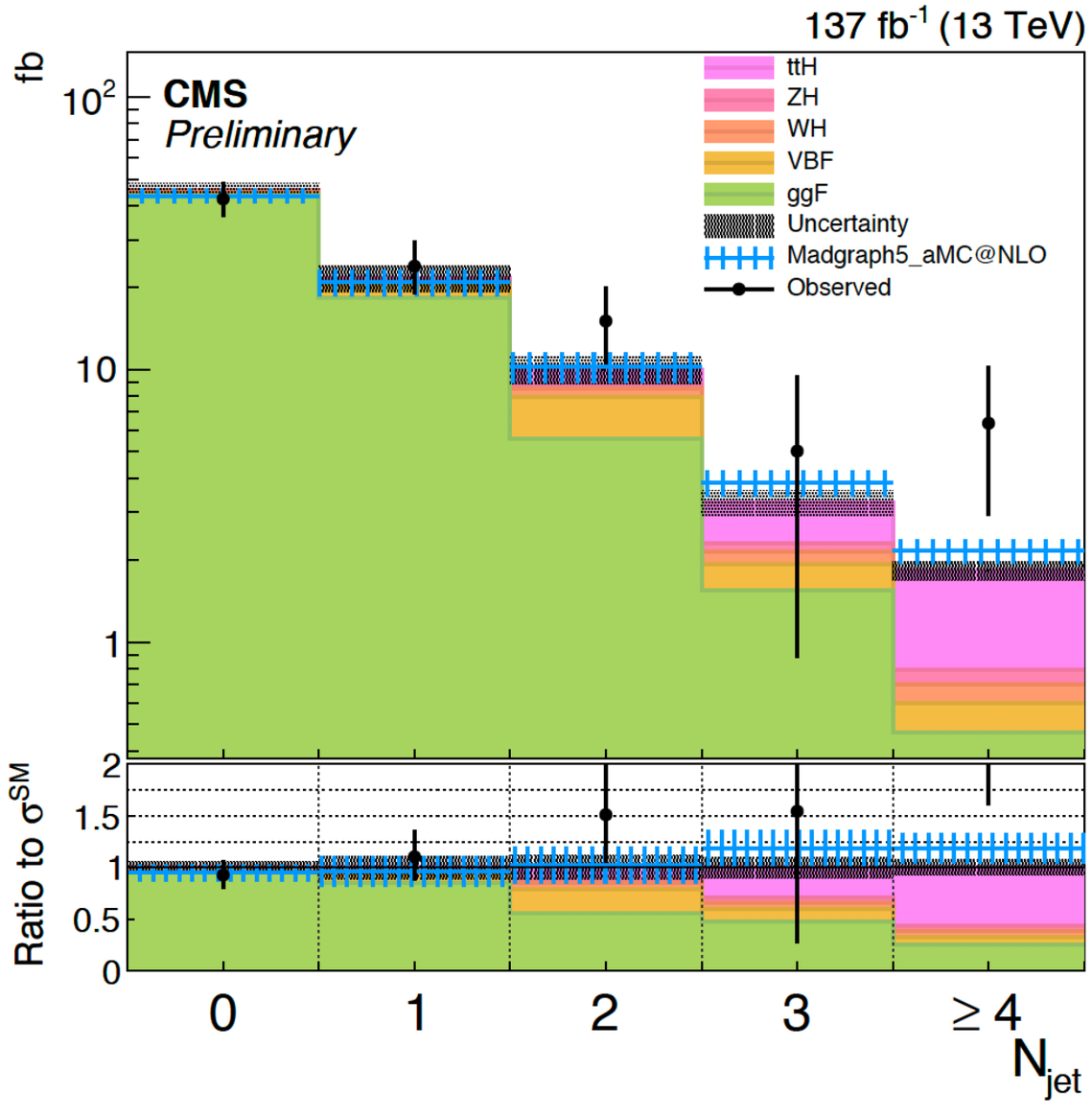




$$\sigma^{\mathrm{SM}} = 82.5 \pm 4.2\,\mathrm{fb}$$

Full Run 2 differential and fiducial results





$$\mu^{\mathrm{fid}} = 1.03^{+0.12}_{-0.11}\ \left(^{+0.05}_{-0.05}\,(\mathrm{stat.})\ ^{+0.08}_{-0.07}\,(\mathrm{theo.})\ ^{+0.03}_{-0.03}\,(\mathrm{lumi.})\ ^{+0.07}_{-0.07}\,(\mathrm{exp.})\right)$$

$$\sigma^{\mathrm{fid}} = 85.0^{+9.9}_{-9.3}\,\mathrm{fb}$$

Conclusions

Run 2 HWW results have been shown, **from its first observation at CMS to its differential cross section**

$$\sigma/\sigma_{\mathrm{SM}} = \mu = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})^{+0.10}_{-0.07}\,(\mathrm{theo})$$

$$\mu^{\mathrm{fid}} = 1.03^{+0.12}_{-0.11}\ \left(^{+0.05}_{-0.05}\,(\mathrm{stat.})\ ^{+0.08}_{-0.07}\,(\mathrm{theo.})\ ^{+0.03}_{-0.03}\,(\mathrm{lumi.})\ ^{+0.07}_{-0.07}\,(\mathrm{exp.})\right)$$

$$\sigma^{\mathrm{fid}} = 85.0^{+9.9}_{-9.3}\,\mathrm{fb}$$

Signal strengths have been measured for several production modes

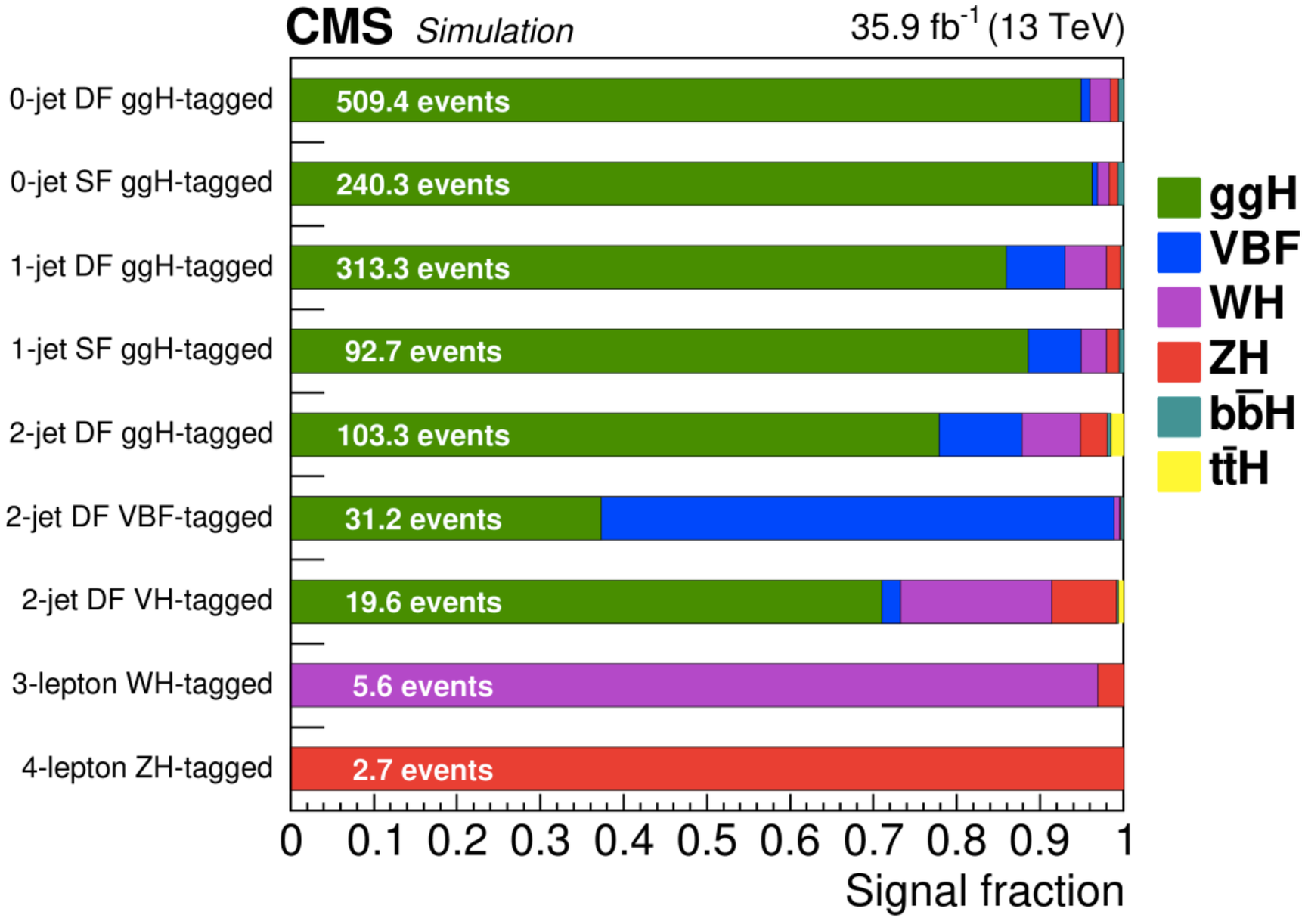
New limits have been set on a SM-like heavy Higgs boson, and in the Higgs mass vs. tanβ for 2HDM and MSSM scenarios

Backup slides

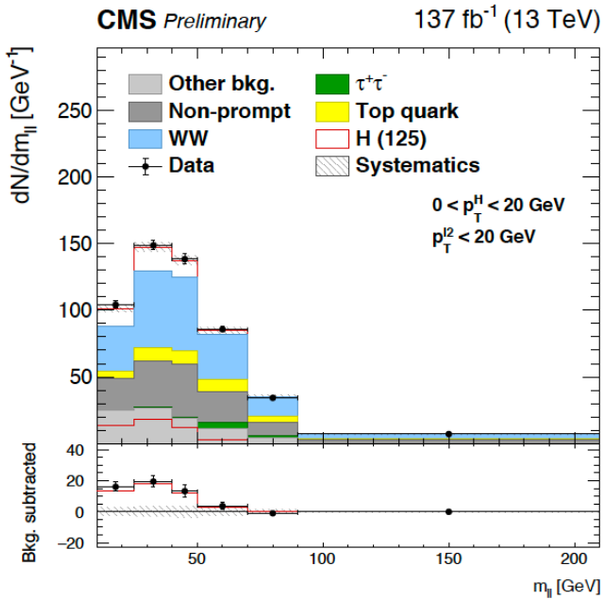
Expected relative fractions

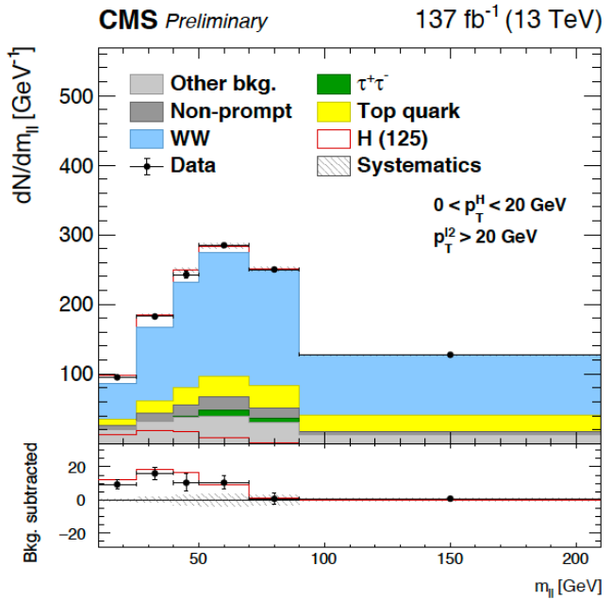
The 0-jet ggH categories (750 expected events) are very clean

On the other hand the 2-jet DF VH category (20 events) is quite “ggH-contaminated”



Split 0- and 1-jet DF ggH in 8 categories ⇒ 15% improvement in expected significance


CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
0 < pTH < 20 GeV
pTl2 < 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]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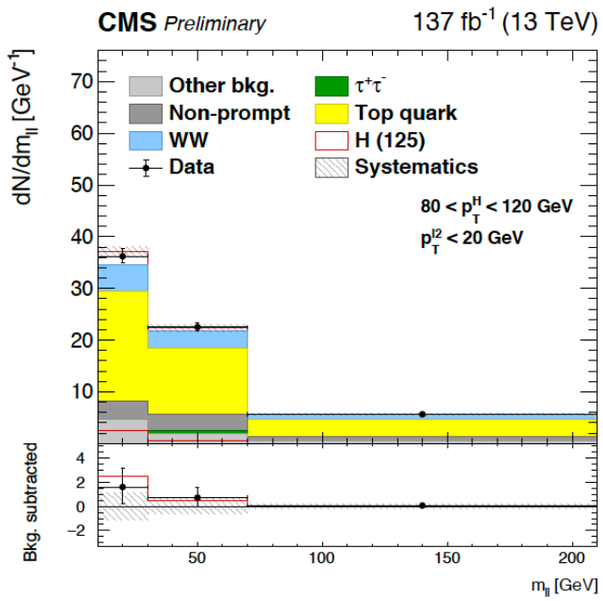
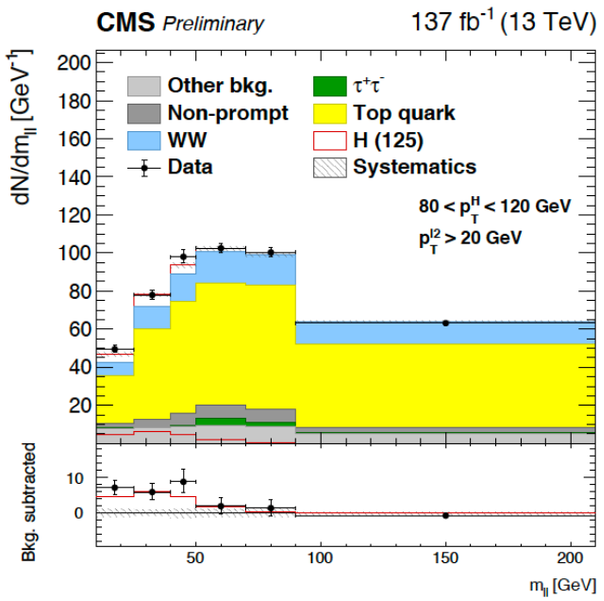
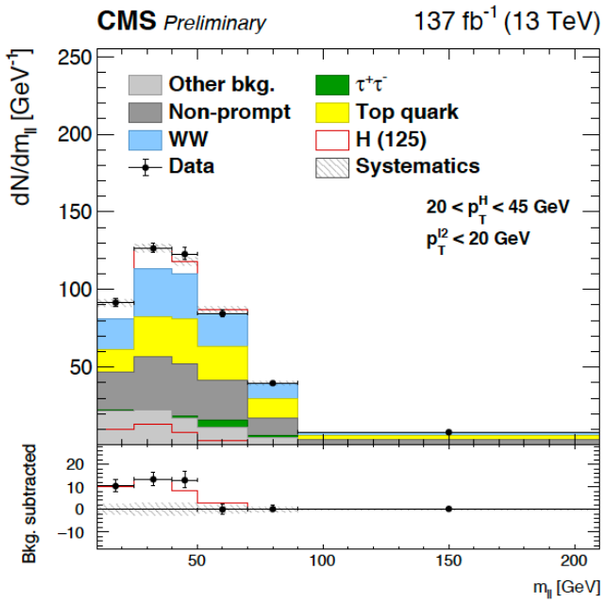
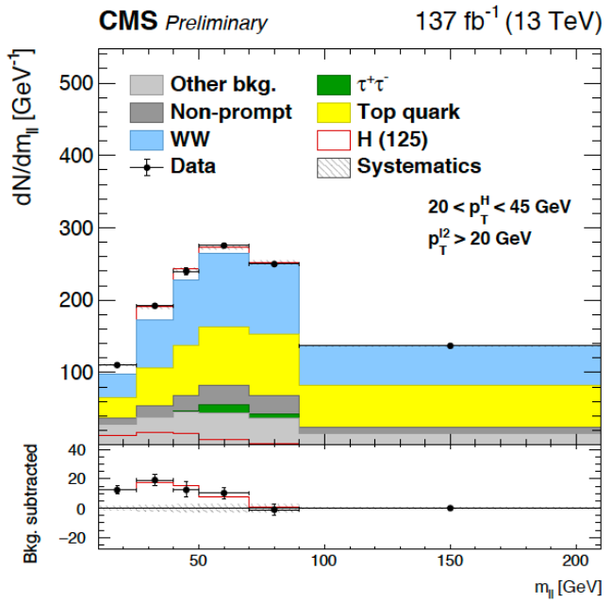
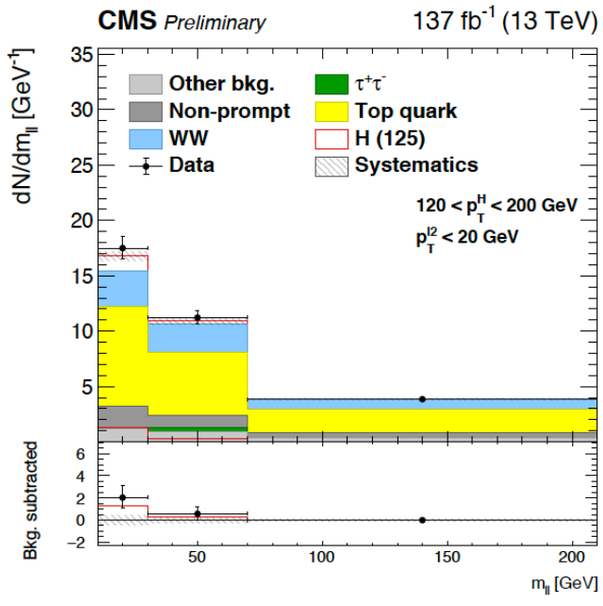
0 < pTH < 20 GeV
pTl2 > 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]

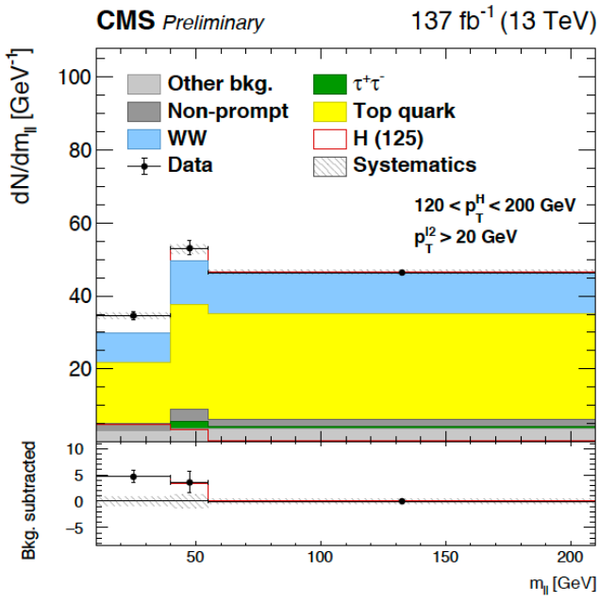

CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
80 < pTH < 120 GeV
pTl2 < 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]

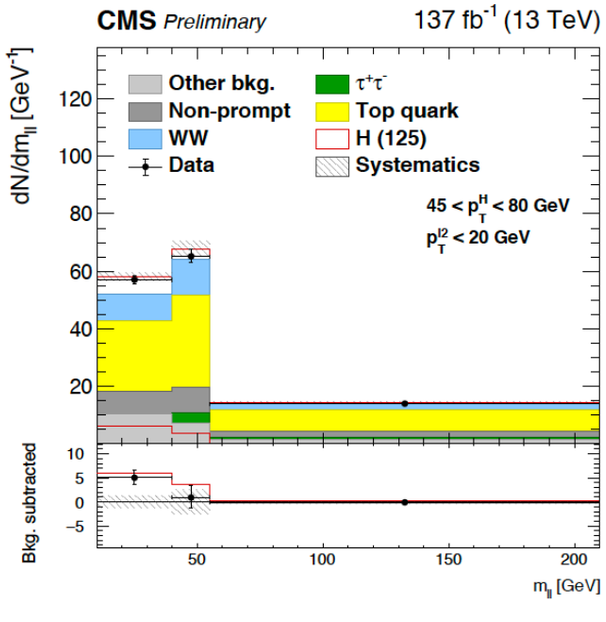

CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
80 < pTH < 120 GeV
pTl2 > 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]

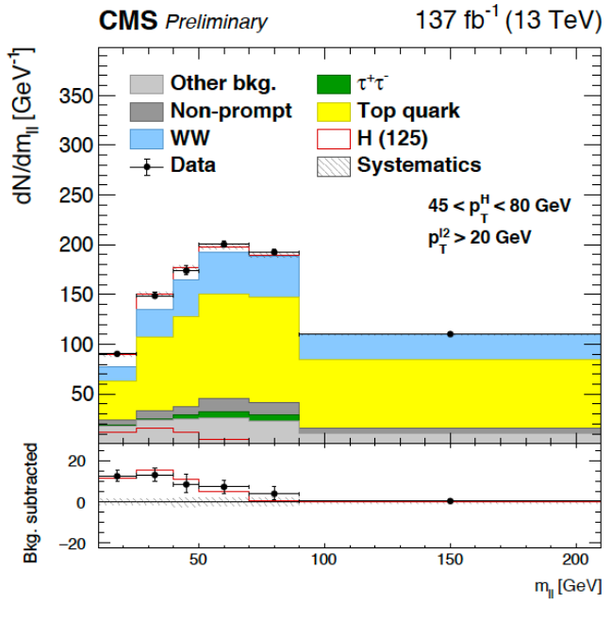

CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
20 < pTH < 45 GeV
pTl2 < 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]

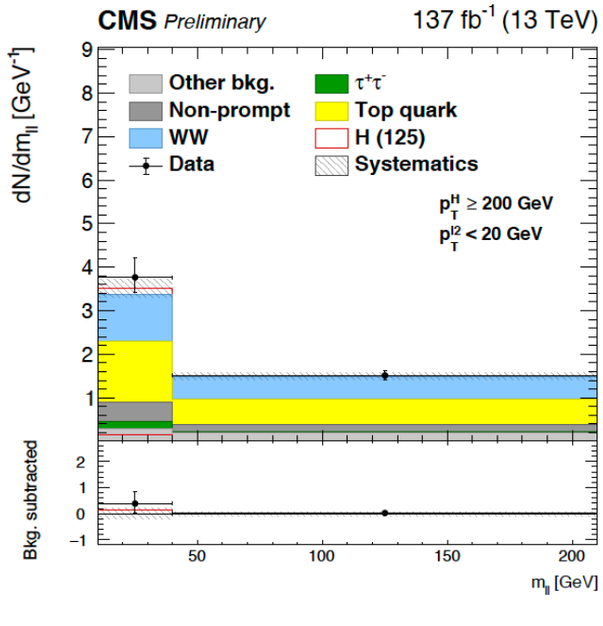

CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
20 < pTH < 45 GeV
pTl2 > 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]

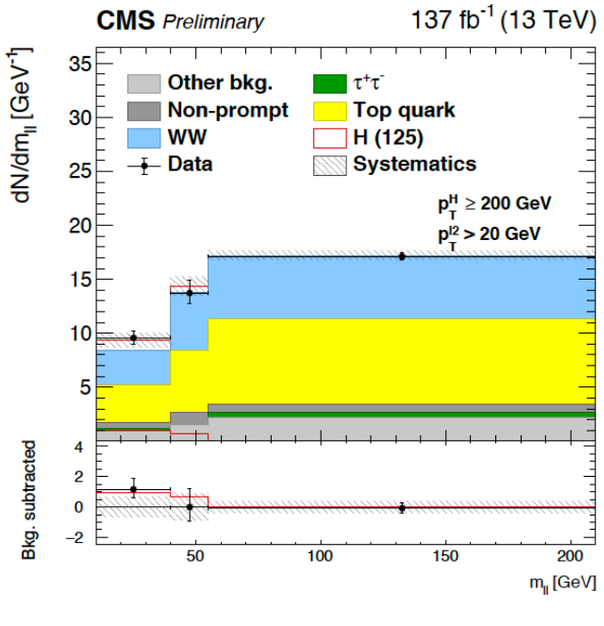

CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
120 < pTH < 200 GeV
pTl2 < 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]


CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
120 < pTH < 200 GeV
pTl2 > 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]


CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
45 < pTH < 80 GeV
pTl2 < 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]


CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
45 < pTH < 80 GeV
pTl2 > 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]


CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
pTH ≥ 200 GeV
pTl2 < 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]


CMS Preliminary
137 fb-1 (13 TeV)
Other bkg.
Non-prompt
WW
Data
τ+τ-
Top quark
H (125)
Systematics
pTH ≥ 200 GeV
pTl2 > 20 GeV
dN/dmll [GeV-1]
Bkg. subtracted
mll [GeV]