Higgs search in WW^* and ZZ^*

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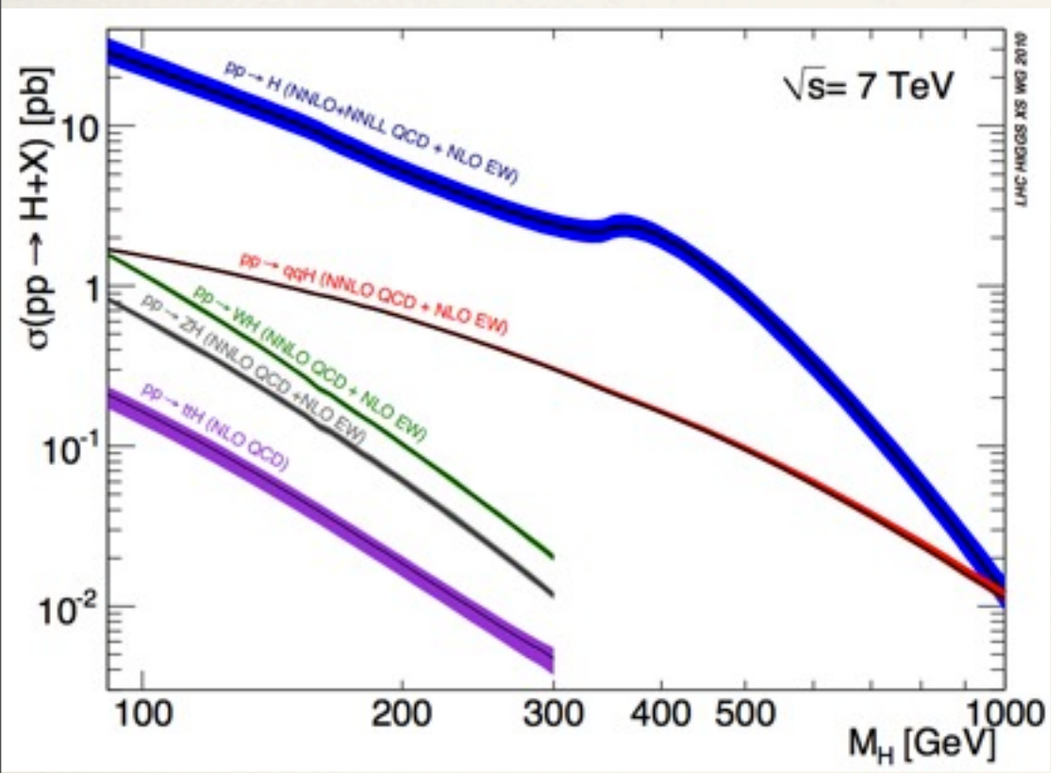
"La Sapienza" Università di Roma & INFN Roma1

July, 29 2011

Higgs production at LHC

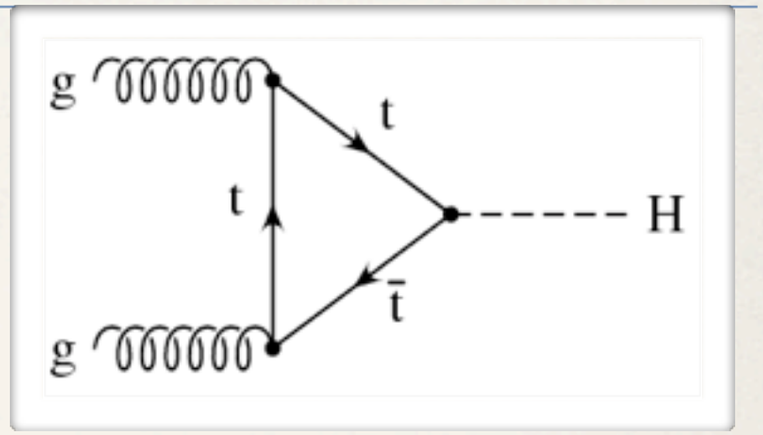


gg→H is the dominant production

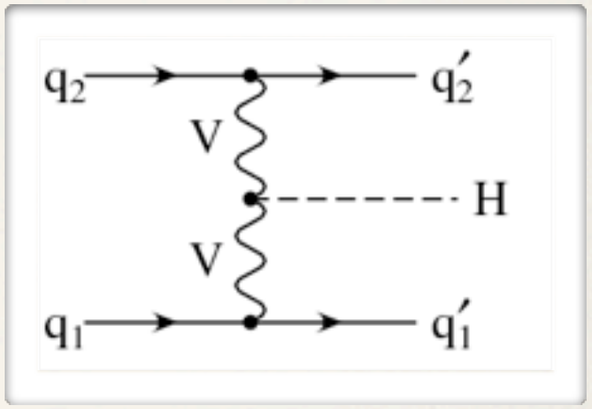
For mH>140 GeV:
gg→H cross section
> 15 times that at 2 TeV

decreasing cross section

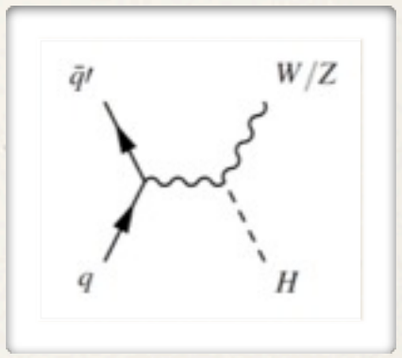
gluon fusion (gg→H)



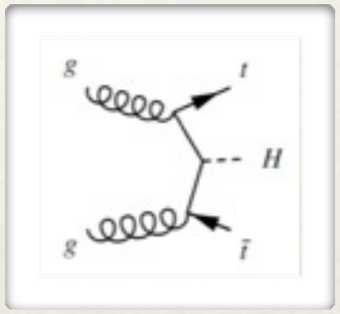
Vector Boson Fusion (qq→q′q′H)



W,Z Associated Prod. (qq→VH)

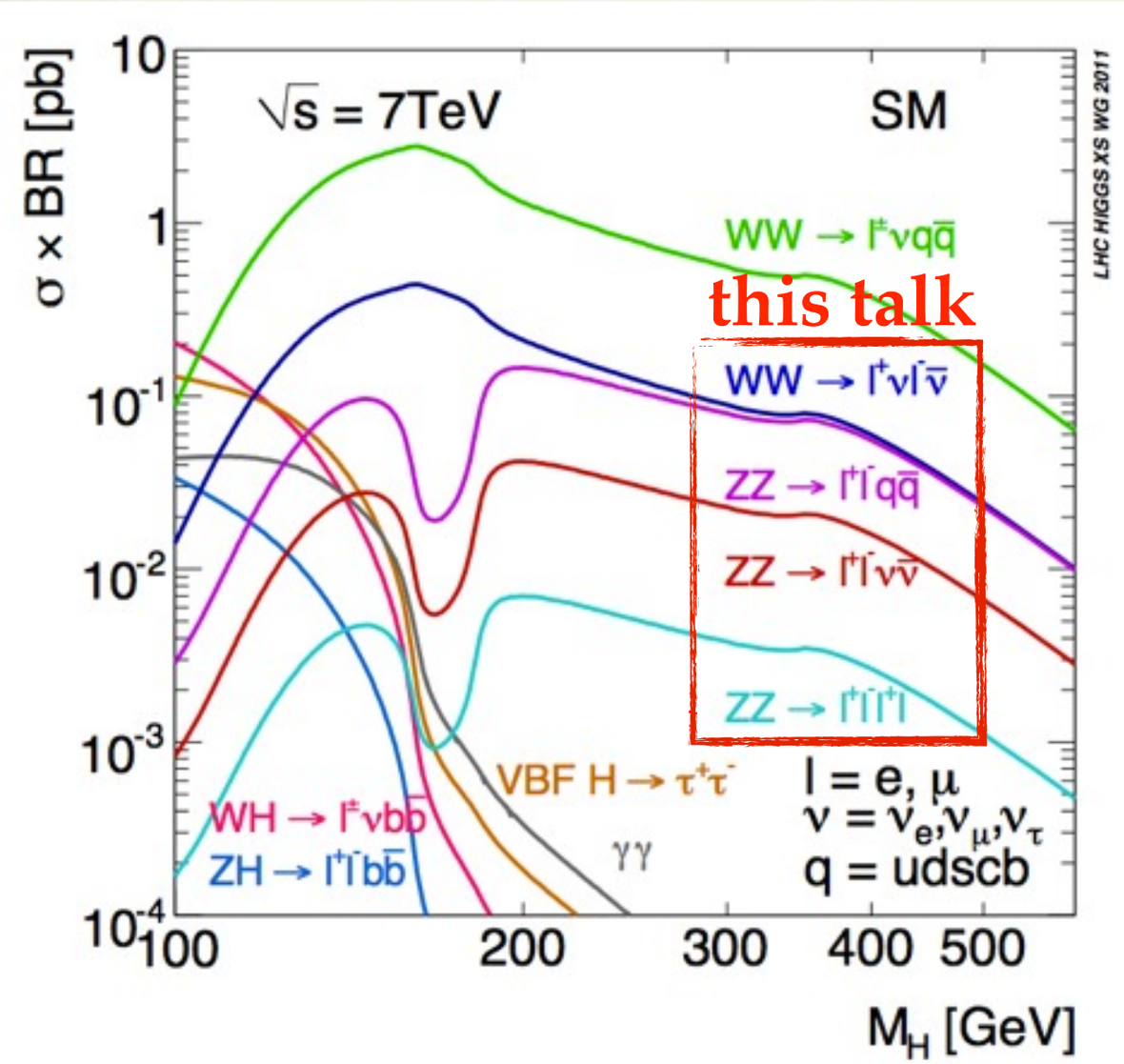


tt Associated Prod. (gg→ttH)

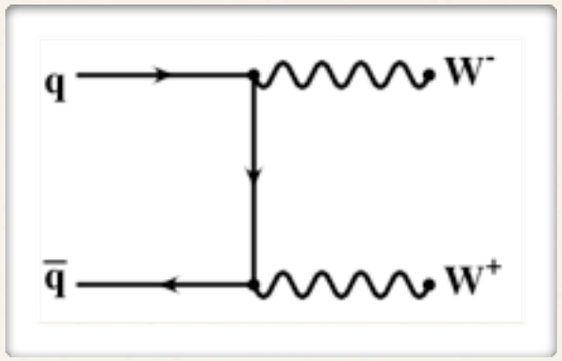


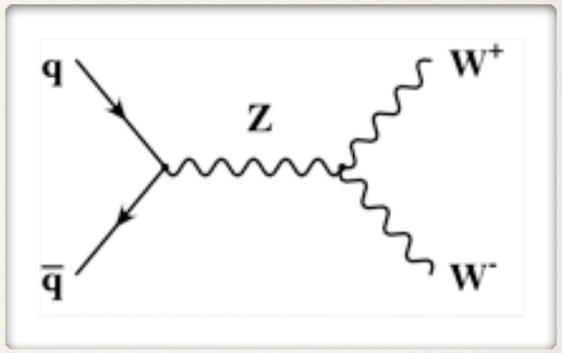
H→WW, ZZ decays

- **H→WW→2l2ν + 0,1,2 jets**: the leader mode for m_H=130 - 200 GeV
- **H→ZZ**: 3 final states studied: **llqq**, **2l2ν**, **4l**



Irreducible backgrounds (WW,ZZ):





originate from qq, which rises slowly in pp respect $p\bar{p}$

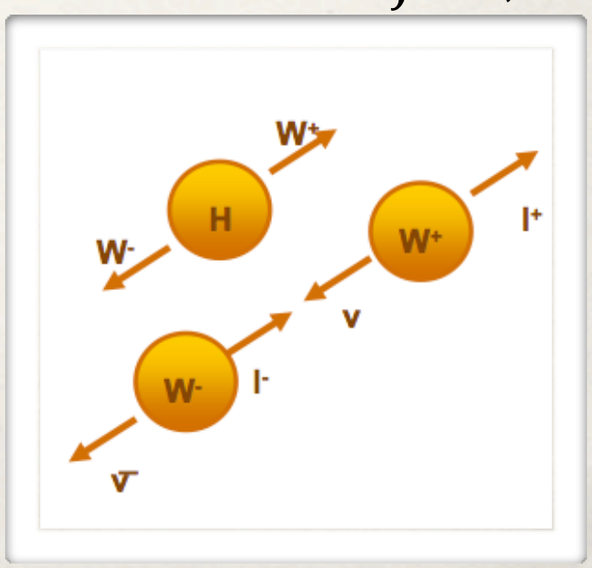
⇒ <u>better S/B wrt Tevatron</u>

Higgs→WW* search

CMS PAS HIG-11-003

$H \to WW^* \to 2l2\nu$ strategy

- The pioneer of Higgs hunting with o(1 fb^{-1}): combines large BR with a clean final state
  - maximal sensitivity at $m_H \approx 2m_W$
  - the price to pay: no mass peak ⇒ counting experiment with reduced m_H sensitivity
  - two opposite sign leptons (e,μ) with $p_T^{max(min)}$>20 (10) GeV (preserve sensitivity for m_H=120 GeV, higher thresholds for larger m_H)
  - large E_T^{miss} due to 2 undetected ν's
  - 0, 1 high p_T jets (dedicated selection for VBF production with 2 jets)
  - small lepton opening angle ($\Delta\phi_{ll}$) $H \to WW^*$ vs large angle $qq,gg \to WW^*$ due to spin correlations



$H \to WW^* \to 2l2\nu$: backgrounds

decreasing cross section

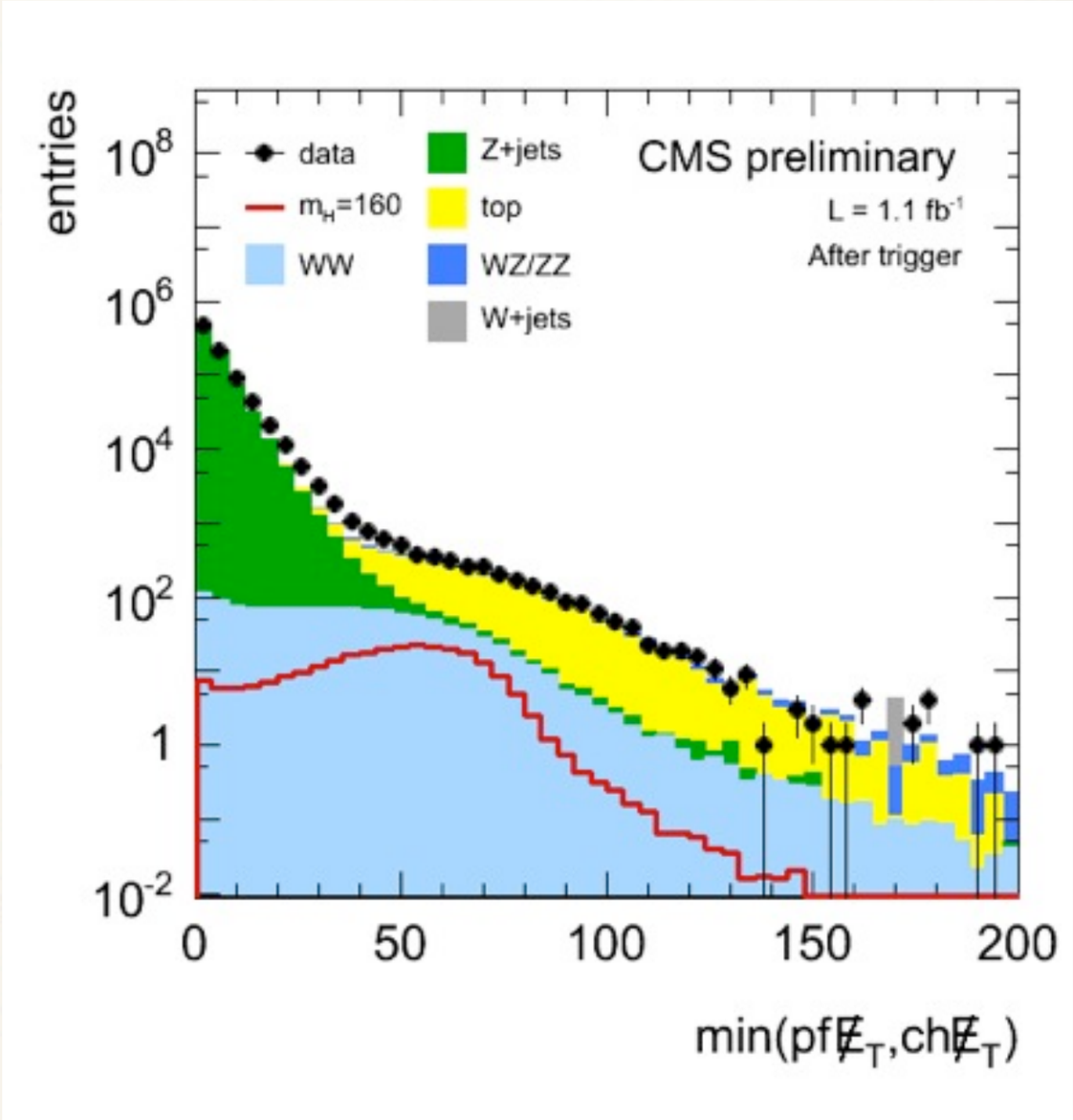
process	characteristic	rejection
W+jets (31000 pb)	lepton + fake lepton	2 well identified and isolated leptons
Z+jets (5000 pb)	Z peak, no real E_T^{miss}	✤ proj $E^T_{miss} > 40$ GeV(ee,μμ), 20 GeV (eμ) ✤ $\lvert m_{ll}-m_Z \rvert < 15$ GeV (ee, μμ), $m_{ll} > 12$ GeV (eμ)
tt (158 pb), tW (11 pb)	additional (b-)jets	✤ classify events in 0-,1-jet ✤ anti b-tagging
W,Z + γ (165 pb)	electron from γ coversion	✤ conversion veto
WW (43 pb)	non resonant	✤ small $\Delta\phi_{ll}$
WZ (18 pb), ZZ (6 pb)	Z peak	✤ $\lvert m_{ll}-m_Z \rvert < 15$ GeV (ee, μμ), $m_{ll} > 12$ GeV (eμ)

<u>relative importance after selection depends on m_H</u>

The pileup challenge on E_T^{miss}

$H \to WW^* \to 2l2\nu$
$1.1\ fb^{-1}$

- Pileup worsen E_T^{miss} resolution
- Two estimators considered:
  - **particle-flow E_T^{miss}**: charged + neutral component
  - **track E_T^{miss}**: only tracks consistent with nominal primary vertex ⇒ reduced PU dependency
  - **<u>take the min of the two</u>**



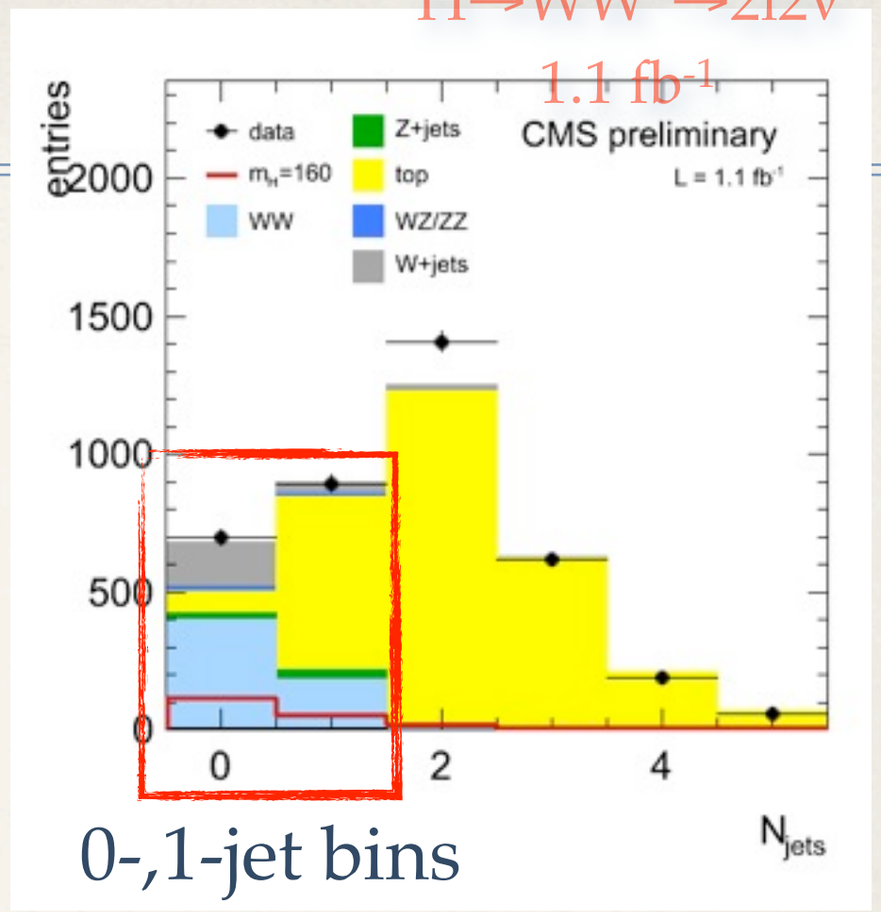
- Project along ll-system (Z→ττ rejection):

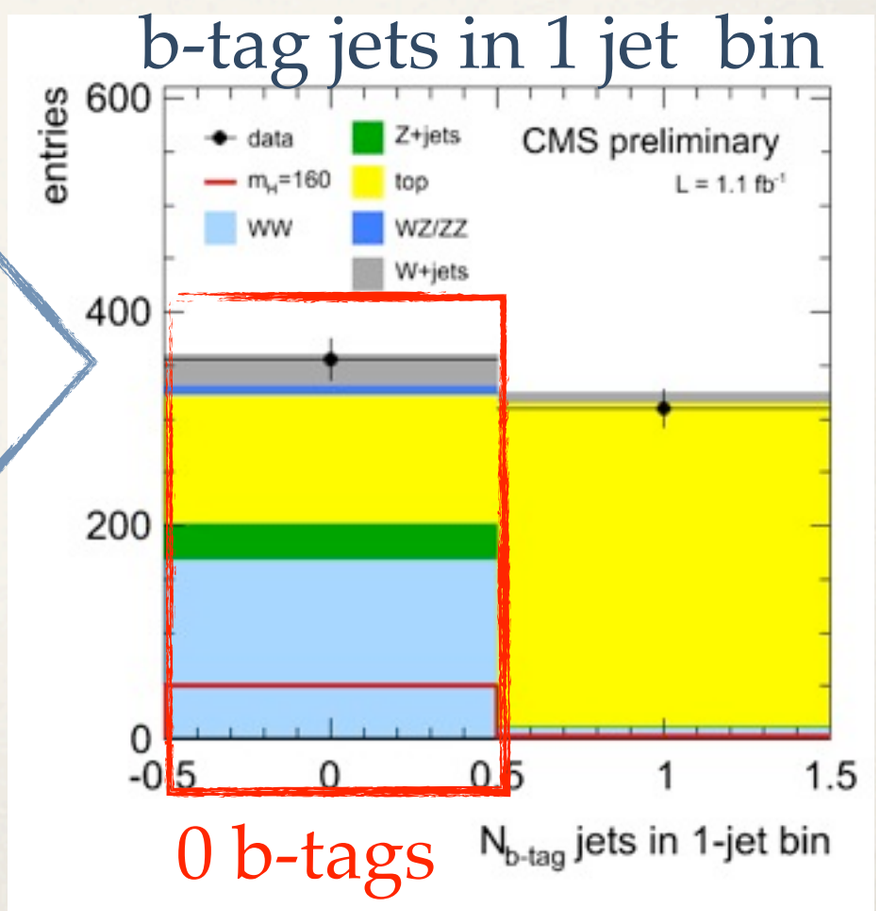
$$\mathrm{proj}E_T^{\mathrm{miss}} = \begin{cases} E_T^{\mathrm{miss}} & \text{if } \Delta\phi_{min} \geq \frac{\pi}{2}, \\ E_T^{\mathrm{miss}} \sin(\Delta\phi_{min}) & \text{if } \Delta\phi_{min} < \frac{\pi}{2} \end{cases}$$

$$\Delta\phi_{min} = min(\Delta\phi(\ell_1, E_T^{\mathrm{miss}}), \Delta\phi(\ell_2, E_T^{\mathrm{miss}}))$$

Jet multiplicity boxes

- Sample with 2 leptons, large E_T^{miss}, Z veto is dominated by W^+W^-, top and W+jets (low m_H-only)
- subdivide events by jet multiplicity (jet p_T>30 GeV, $|\eta|$<5)
  - <u>0-jet:</u> dominated by WW. Apply anti b-tagging on low p_T jets
  - <u>1-jet:</u> dominated by $t\bar{t}$+tW, apply anti b-tagging on all jets
  - <u>2-jets:</u> specific VBF selections (see A. Benaglia's talk)

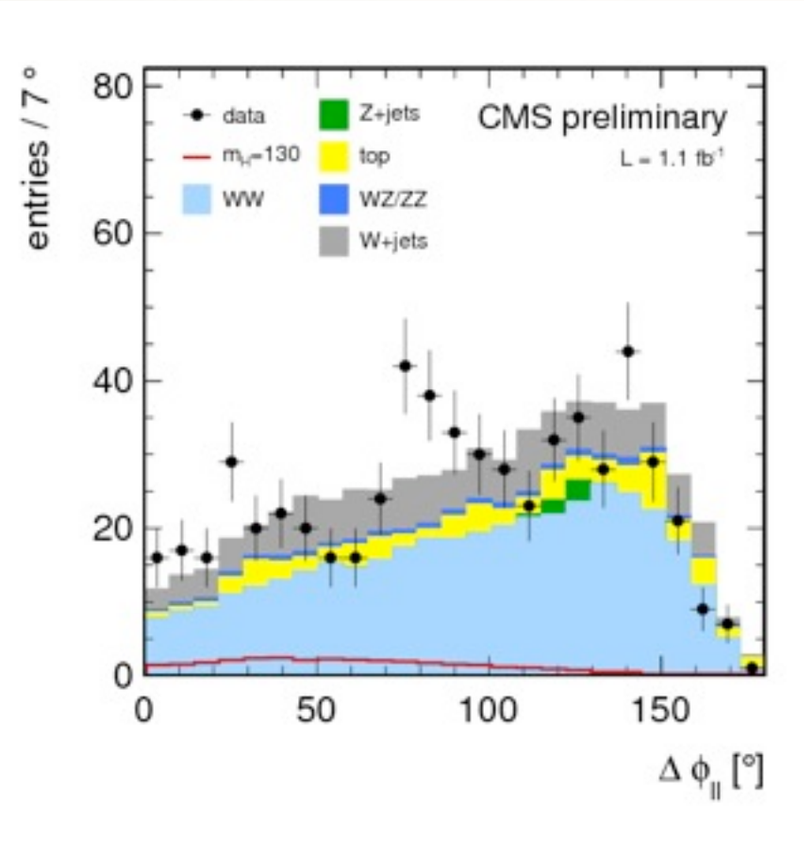




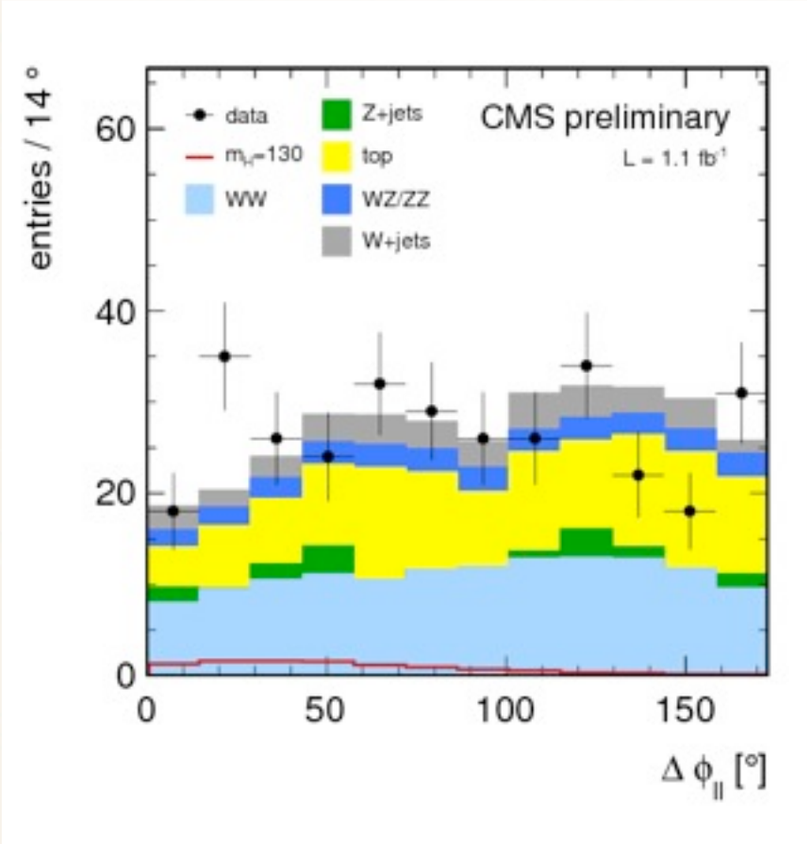
W^+W^- + 0, 1, 2 jets

$H \to WW^* \to 2l2\nu$
1.1 fb^{-1}

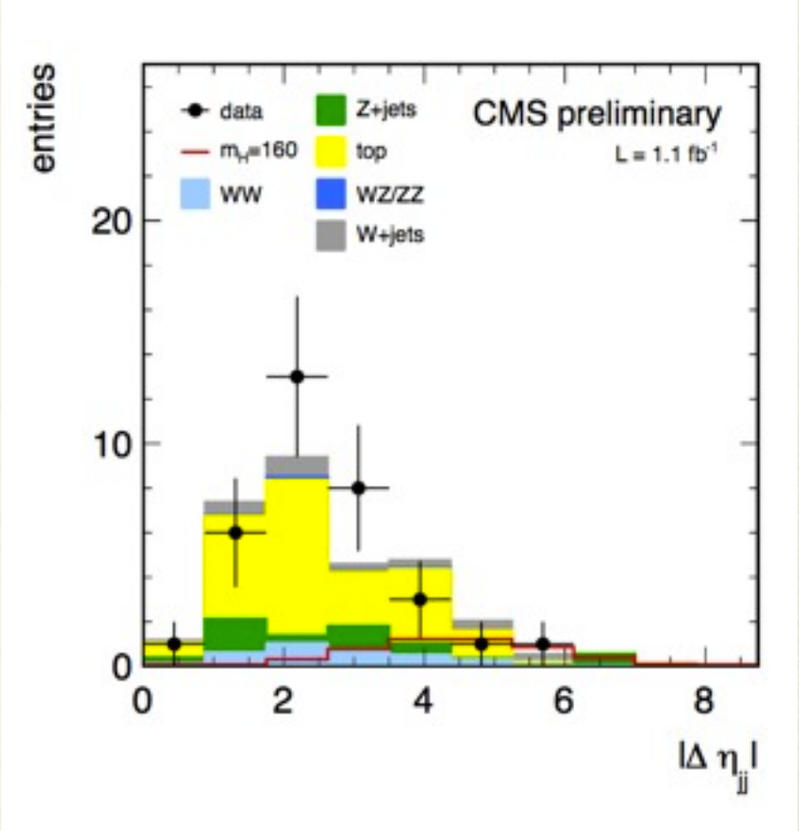
$\Delta\phi_{ll}$, 0-jet



$\Delta\phi_{ll}$, 1-jet



$\Delta\eta_{jj}$, 2-jet



	data	all bkg.	$qq \to W^+W^-$	$gg \to W^+W^-$	$t\bar{t} + tW$	$W + \gamma$
0-jet	626	568.6 ± 52.2	349.7 ± 30.3	17.2 ± 1.6	63.8 ± 15.9	8.7 ± 1.7
1-jet	334	316.0 ± 24.7	101.4 ± 9.3	5.9 ± 0.5	141.1 ± 14.1	2.4 ± 0.8
2-jet	175	164.6 ± 18.0	22.1 ± 2.0	1.1 ± 0.1	99.3 ± 9.9	1.1 ± 0.5

	WZ/ZZ not in $Z/\gamma^* \to \ell^+\ell^-$	$Z/\gamma^* \to \ell^+\ell^- + WZ + ZZ$	$Z/\gamma^* \to \tau^+\tau^-$	W + jets
0-jet	8.5 ± 0.9	12.2 ± 5.3	1.6 ± 0.4	106.9 ± 38.9
1-jet	7.2 ± 0.8	10.5 ± 11.5	10.6 ± 1.2	36.9 ± 13.8
2-jet	1.5 ± 0.2	19.2 ± 13.5	3.9 ± 0.7	16.4 ± 6.4

pp→WW cross section

- With this selected sample, in the 0-jet bin, the WW cross section is measured
- 626 events selected on data, with 201.7 ± 42.4 background events
- total W^+W^- signal efficiency $\varepsilon = (6.69 \pm 0.51)\%$

$$\sigma(pp \to WW + X) = 55.3 \pm 3.3(\text{stat.}) \pm 6.9(\text{syst.}) \pm 3.3(\text{lumi.})pb$$

- consistent with $\sigma^{th.}(\text{NLO}) = 43 \pm 2$ pb at 1σ level

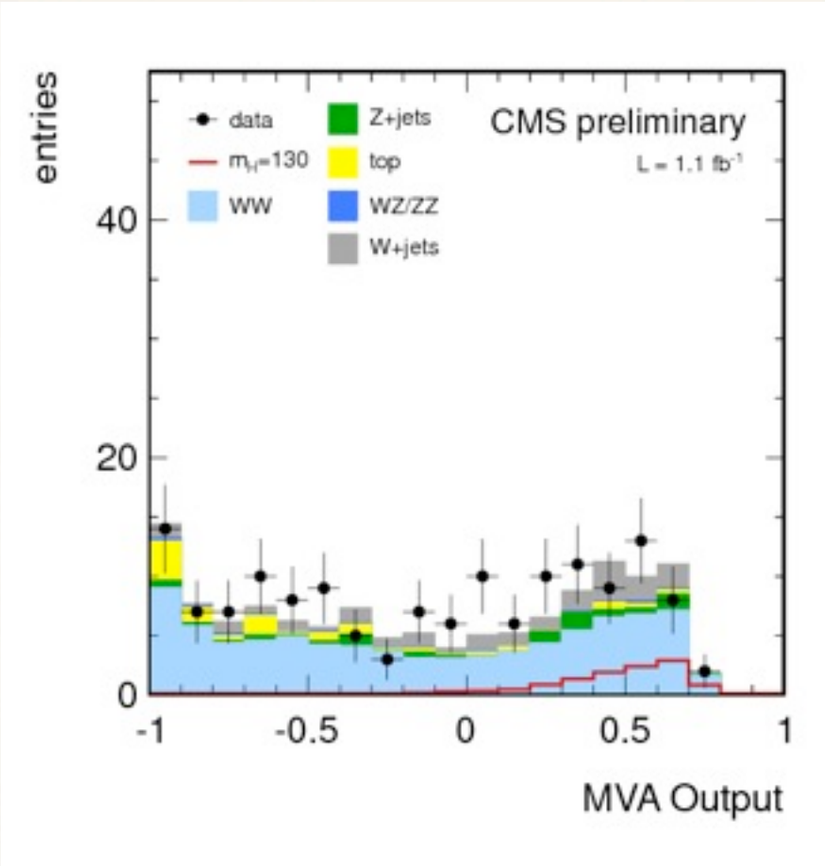
CMS PAS EWK-11-010 (measurement of WW, WZ,ZZ cross sections)

Higgs cut-based/MVA selection

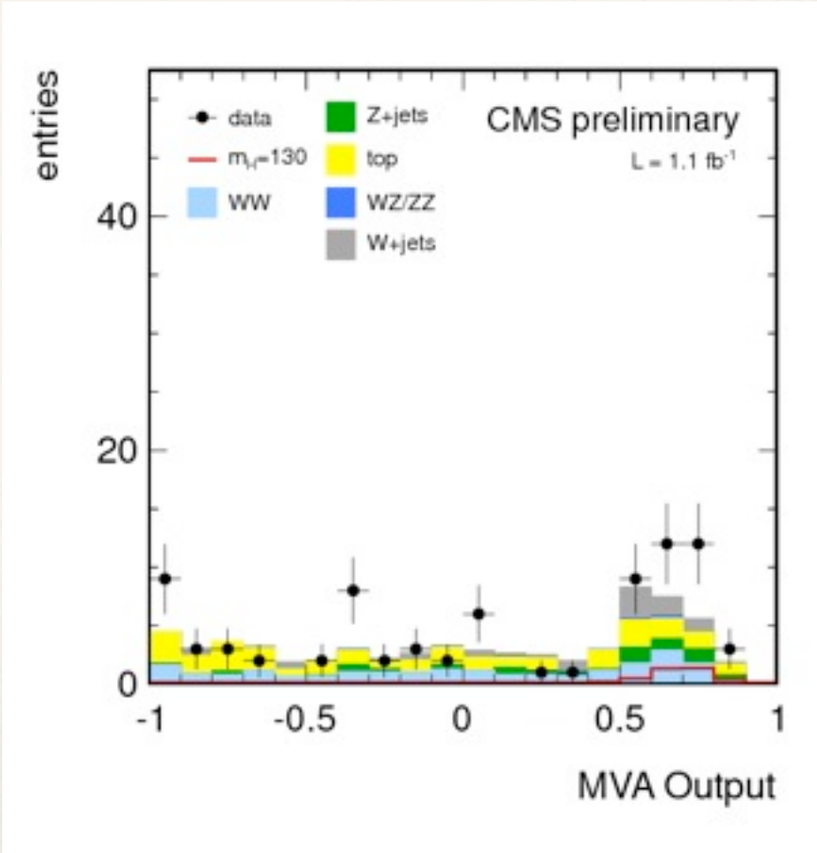
$H \rightarrow WW^* \rightarrow 2l2\nu$
$1.1\ fb^{-1}$

- m_H-dependent cuts are applied on: p_T^{min}, p_T^{max}, m_{ll}, $\Delta\phi_{ll}$, m_T and count after subtracting backgrounds (estimated from data):
  - W+jets (from fake-rate prediction), top (from b-tagged sample), Z+jets (events under Z-peak extrapolation), WW (high m_{ll} region)
- or a BDT is trained with above variables, plus some other (ΔR_{ll},lepton flavor)
  - (binned) BDT output distribution used to extract signal

0-jet, same flavor leptons



1-jet, same flavor leptons



Systematic uncertainties

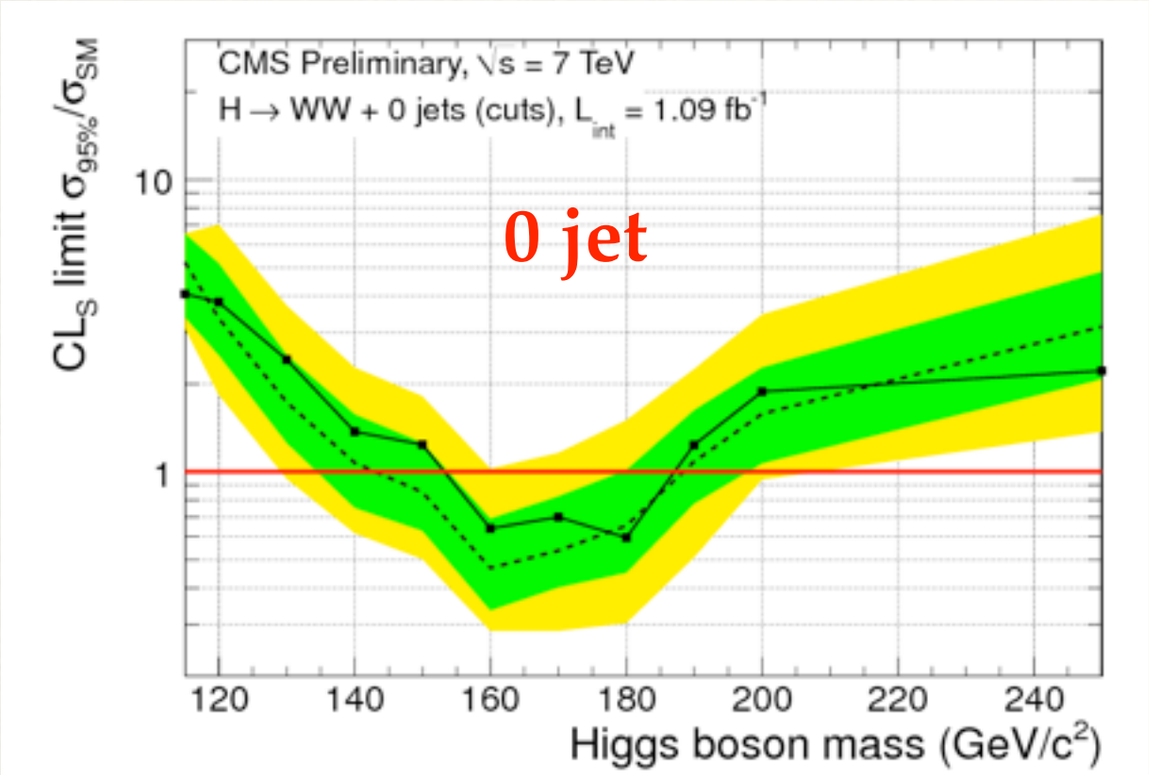
$H \to WW^* \to 2l2\nu$
1.1 fb^{-1}

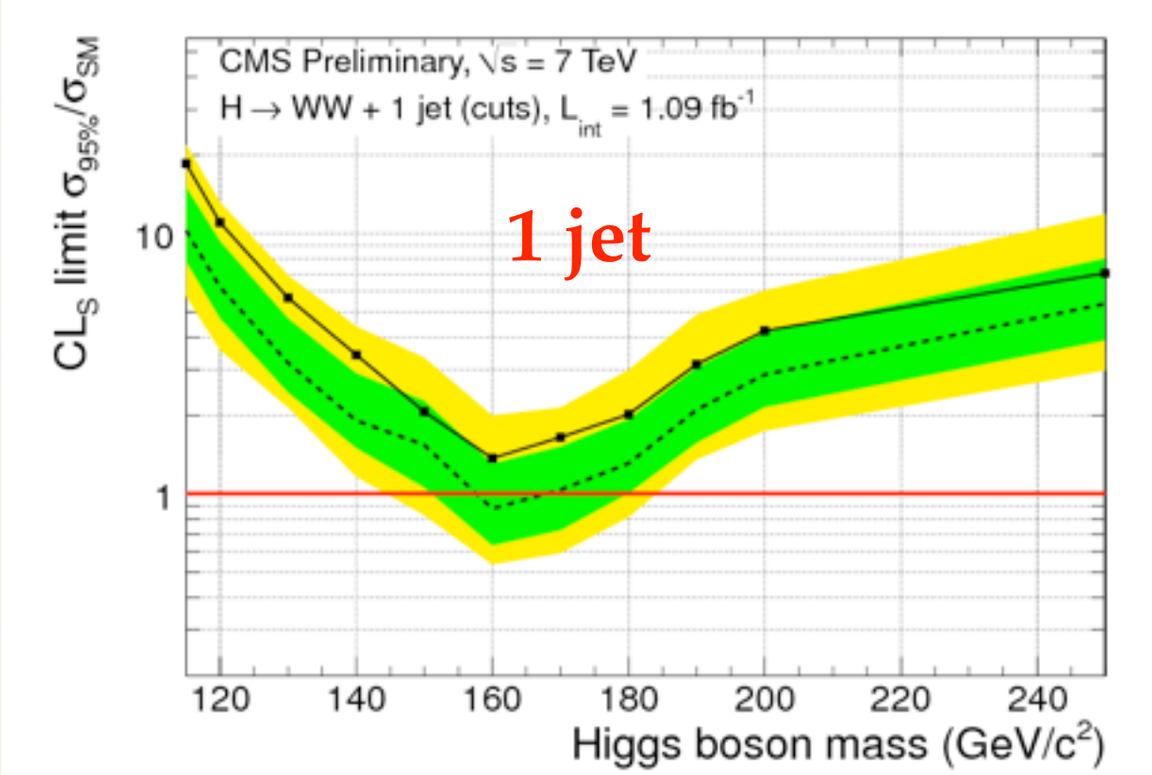
- Largest systematics from background estimation
  - W+jets: ≈40% (do not improve with statistics)
  - Drell-Yan: 60%
  - Top: 25%
  - WW: 15-30%
  - lepton efficiency (momentum scale) 2%, 1.5%

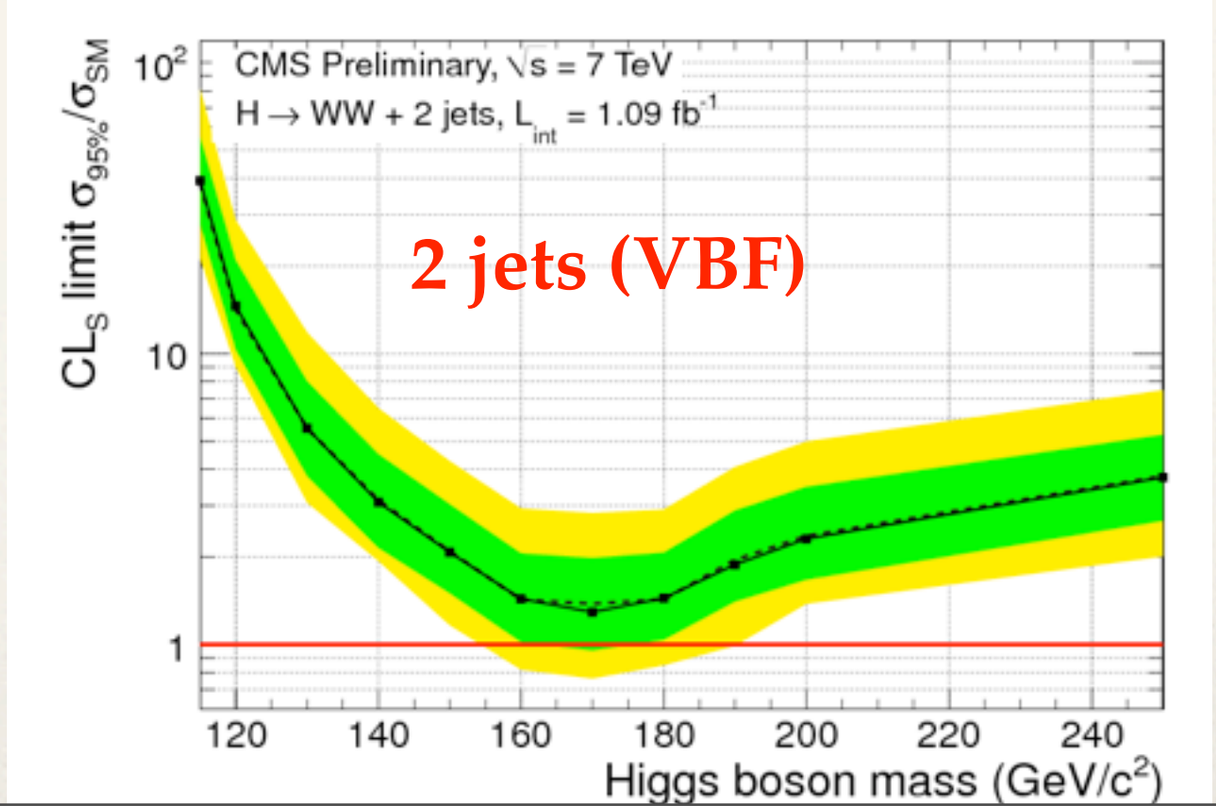
} improve with stat.

- Theory Higgs cross section: 15%, which includes jet bin uncertainty: 7, 10, 20% between 0-,1-,2-jet bins.
  - 0-jet efficiency estimated with Z+jets events
- Luminosity: 6%

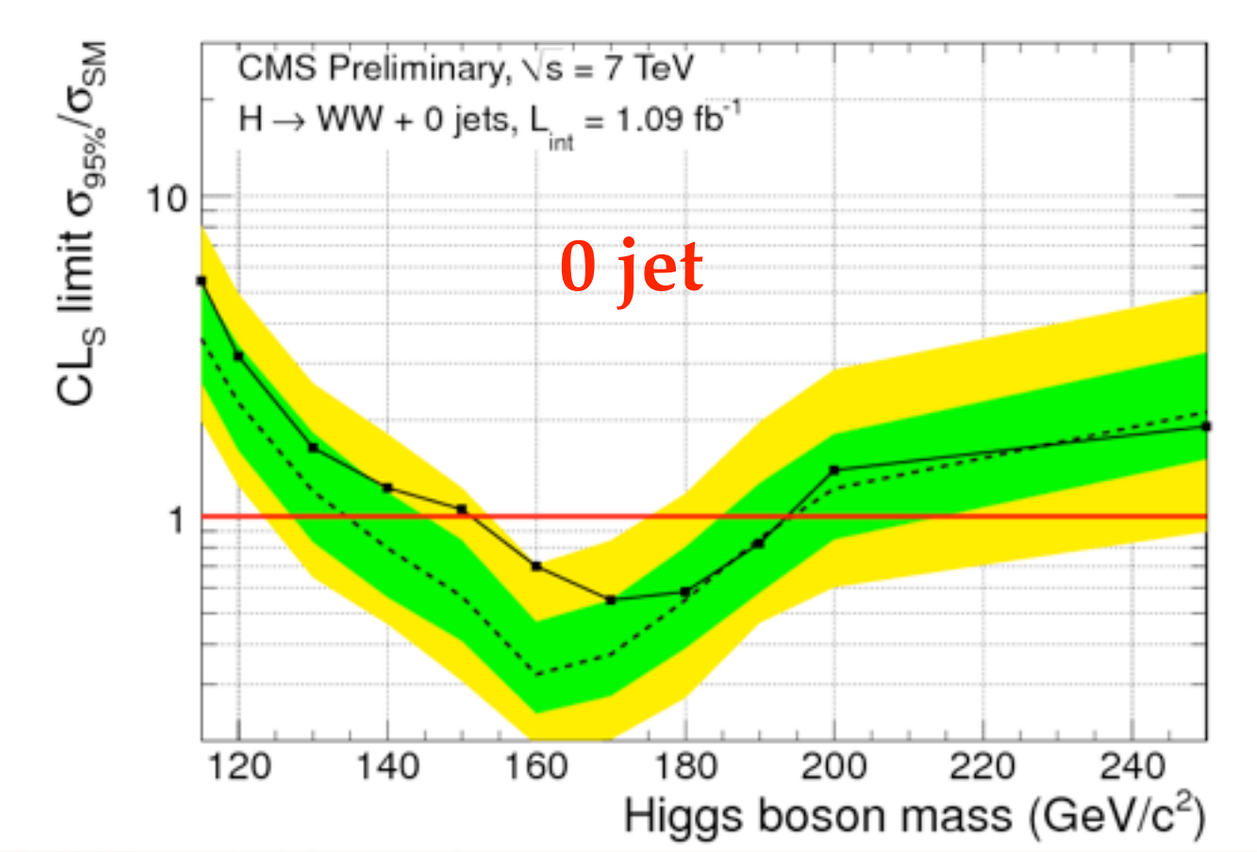
H→WW* cut based limits/jet bin

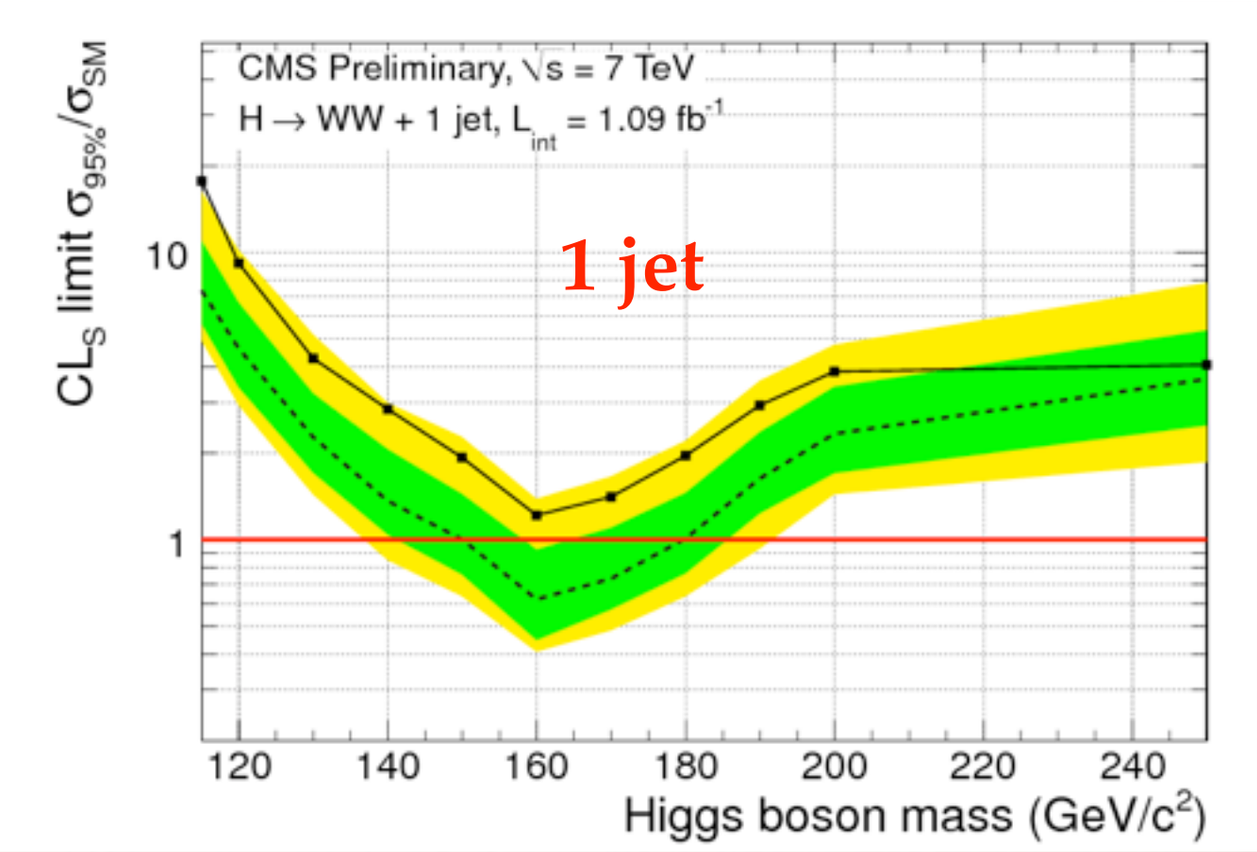






H→WW* MVA limits/jet bin





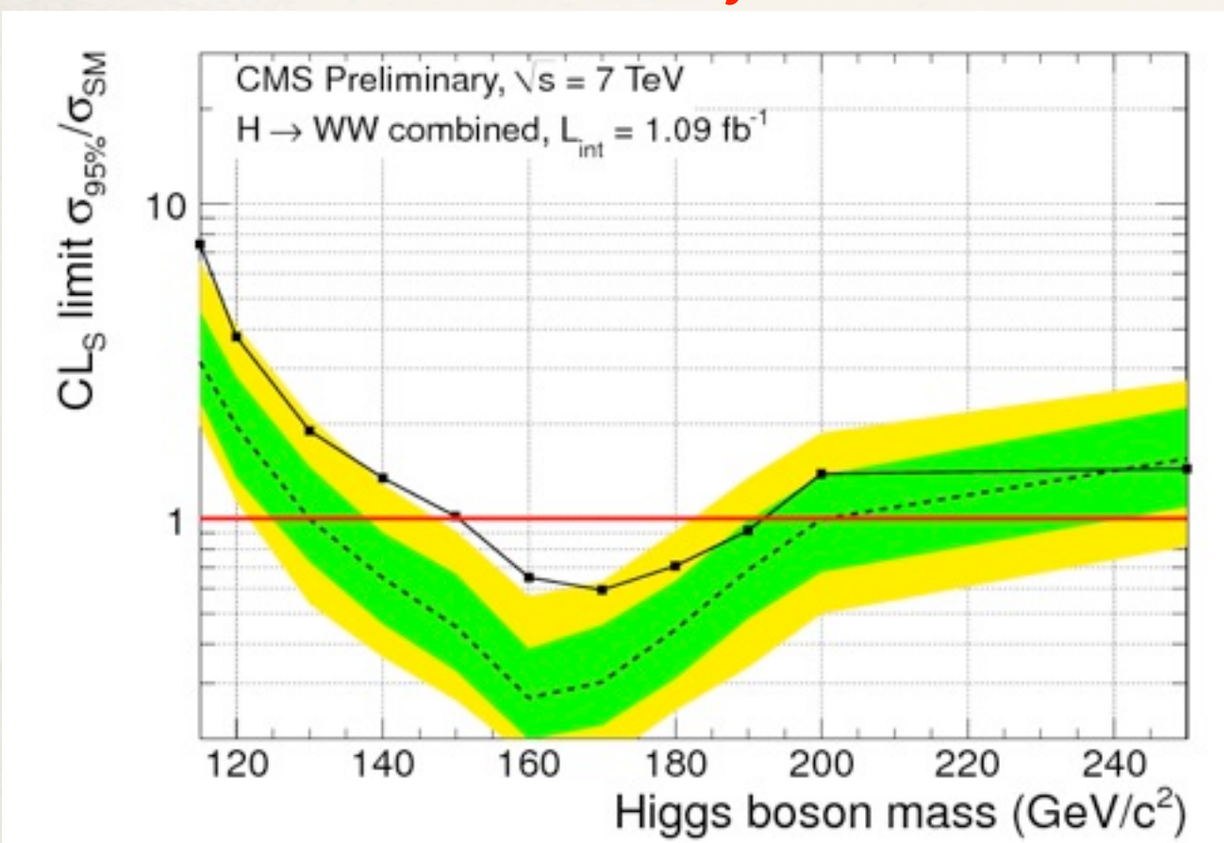
- for the 2 jet bin only cut-based analysis has been performed

H→WW* exclusion limit

H→WW*→2l2ν
1.1 fb^{-1}

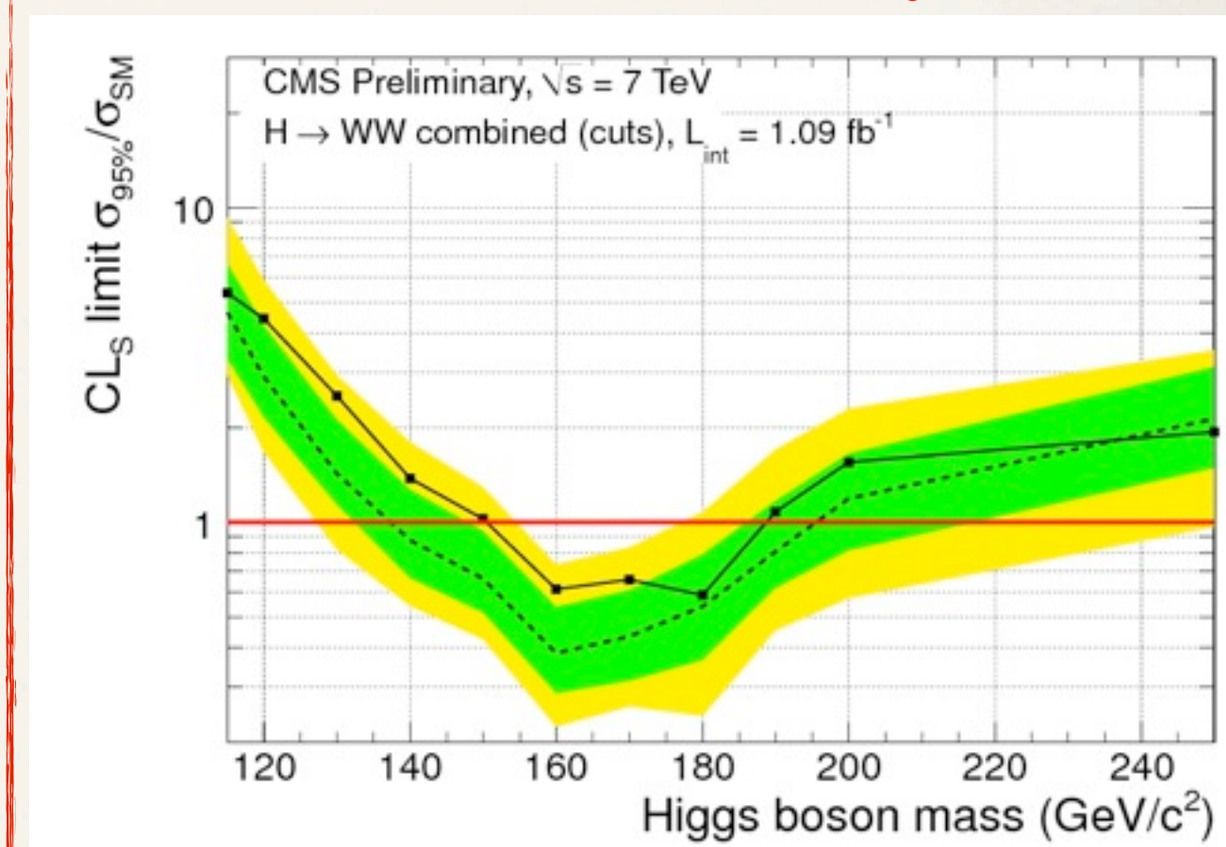
- Analysis performed in m_H=115 - 600 GeV, sensitivity with 1 fb^{-1} in m_H=130 - 200 GeV. Limits with CLs (95% C.L.)

MVA analysis



Exp.: [130 - 200] GeV
Obs.: [150 - 193] GeV

cut-based analysis



Exp.: [135 - 190] GeV
Obs.: [150 - 190] GeV

- one single channel, one single experiment, competitive with Tevatron

Higgs→ZZ* search

CMS PAS HIG-11-005 (ZZ→2l2ν)

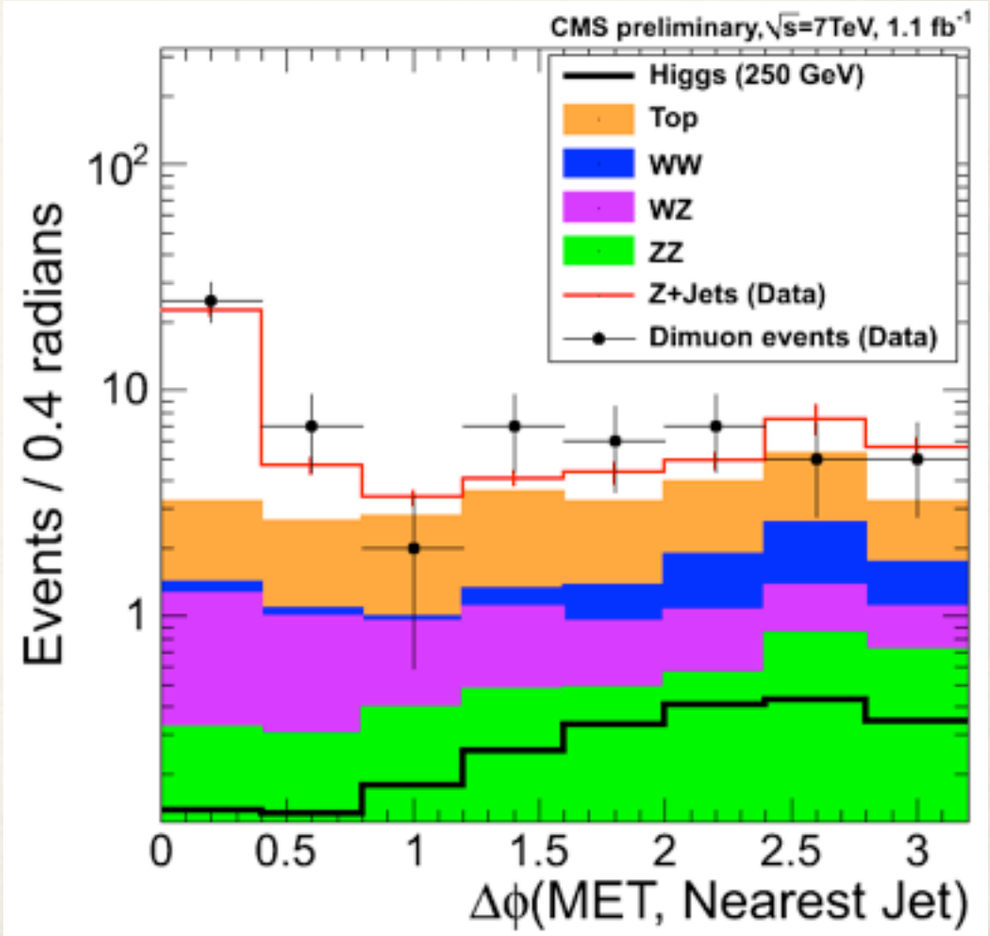
CMS PAS HIG-11-006 (ZZ→2l2q)

CMS PAS HIG-11-004 (ZZ→4l)

H→ZZ→2l2ν: strategy

H→ZZ*→2l2ν
1.1 fb^{-1}

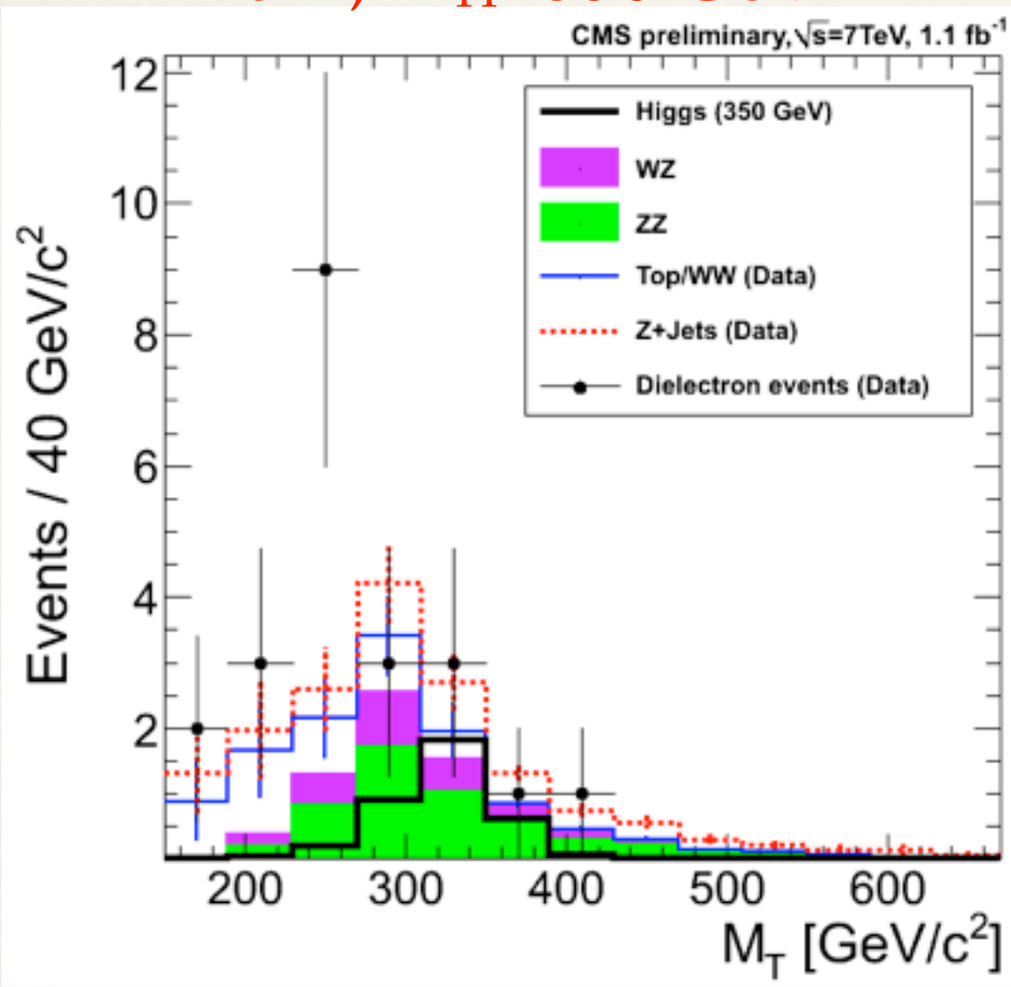
- Large yield: BR(ZZ→2l2ν)≈6 BR(ZZ→4l) for m_H=[250 - 600] GeV
- Same final state as WW: 2 leptons + large E_T^{miss}
  - Same problematics: no mass peak, large backgrounds
- Selection:
  - two opposite sign same flavor leptons (p_T>20 GeV)
  - large E_T^{miss}
  - large E_T^{miss} - jet separation ($\Delta\phi_{MET,Jet}$): fake E_T^{miss} in Z+jets is aligned with a mis-measured jet
  - large transverse mass (m_T)



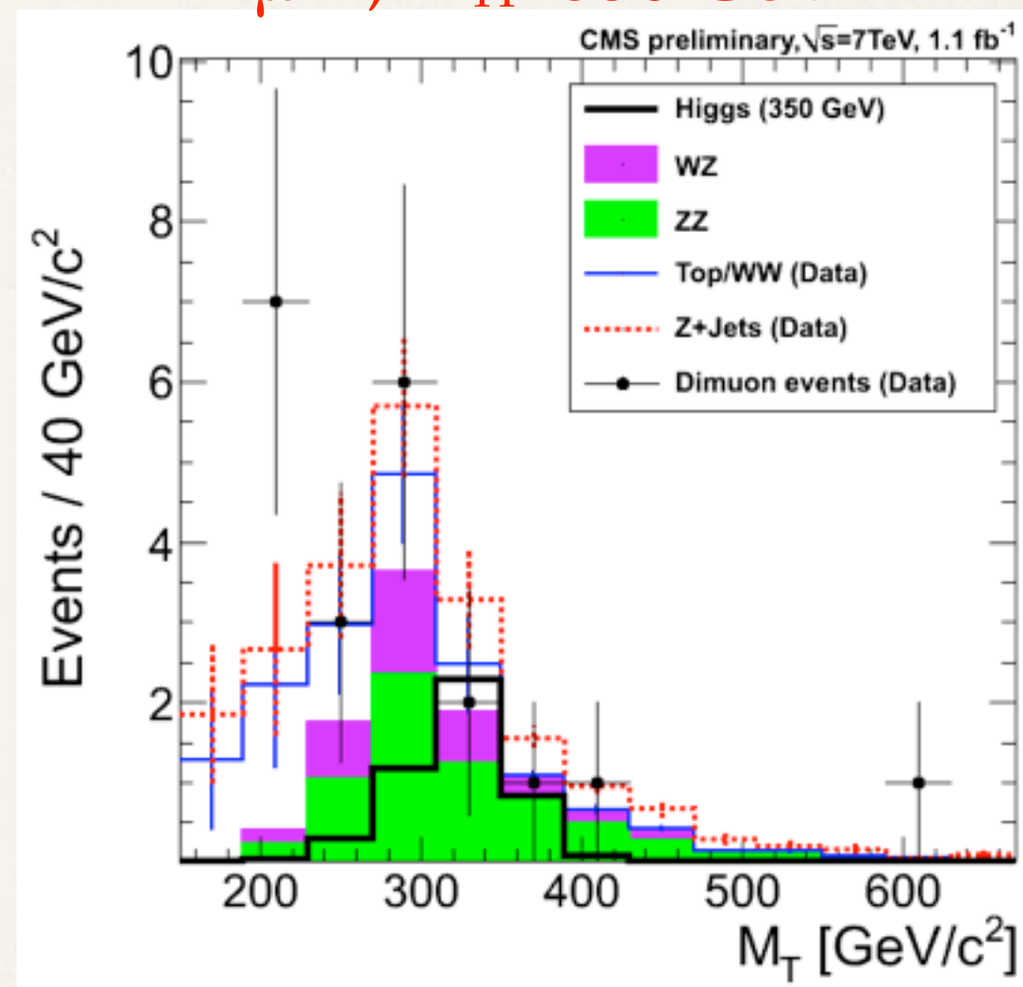
Expected and observed events

$H \to ZZ^* \to 2l2\nu$
1.1 fb^{-1}

2e2ν, m_H=350 GeV



2μ2ν, m_H=350 GeV



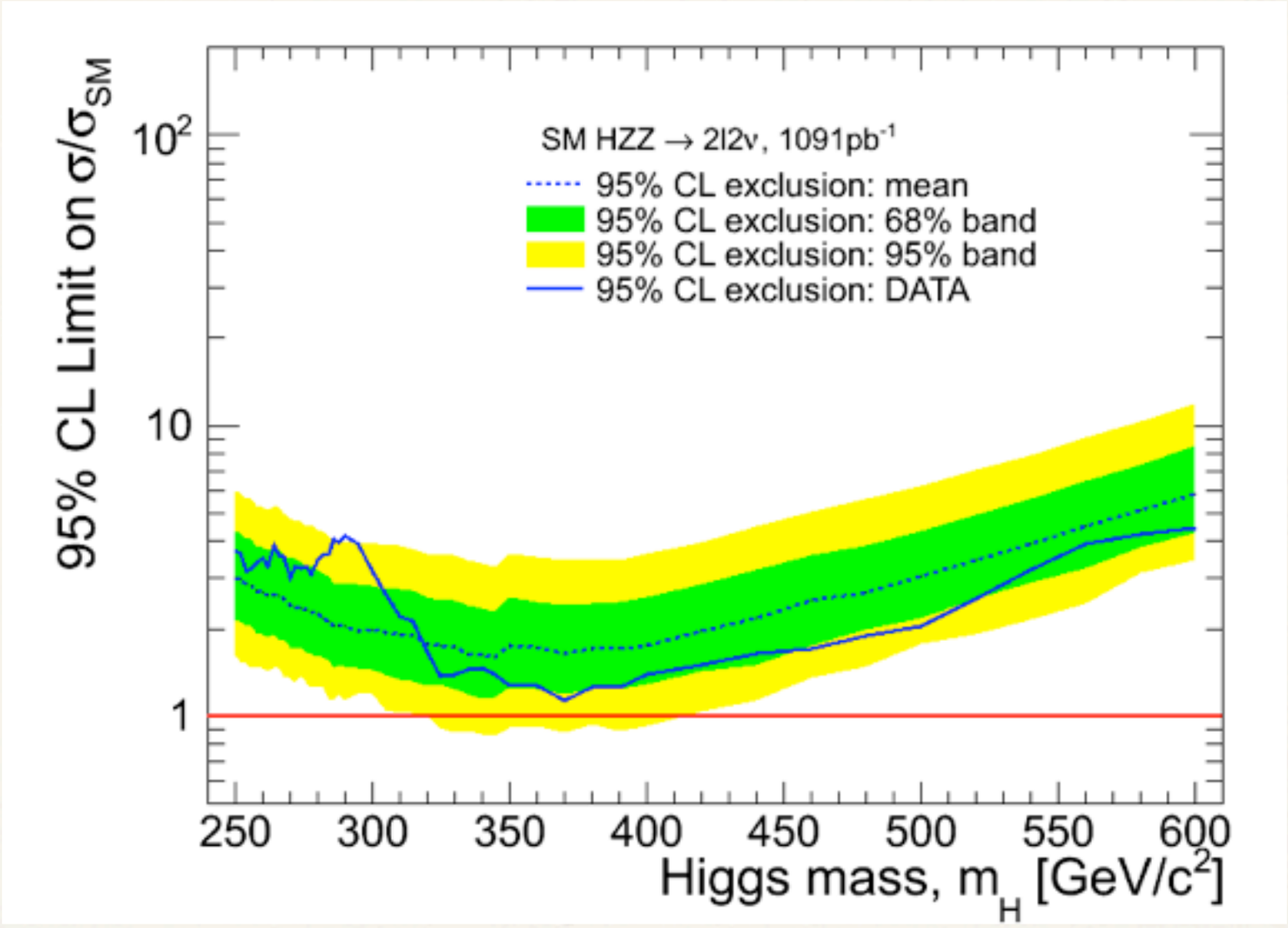
Channel	ZZ	WZ	Top/WW/W+Jets	Z+Jets	Total	mH(350)	Data
$\mu\mu$	$5.2 \pm 0.1 \pm 0.5$	$2.5 \pm 0.1 \pm 0.3$	2 ± 1.2	3.5 ± 1.8	13 ± 2	3.9 ± 0.6	11
ee	$4.2 \pm 0.1 \pm 0.4$	$1.8 \pm 0.1 \pm 0.2$	1.3 ± 0.8	3.2 ± 1.7	11 ± 3	3.2 ± 0.5	8

- Main backgrounds: Z+jets (estimated with γ+jets), ZZ (MC), top+WW (estimated with eμ events)

Exclusion limits

$H \to ZZ^* \to 2l2\nu$
$1.1\ fb^{-1}$

- Close to Standard Model sensitivity in m_H = [300 - 500] GeV



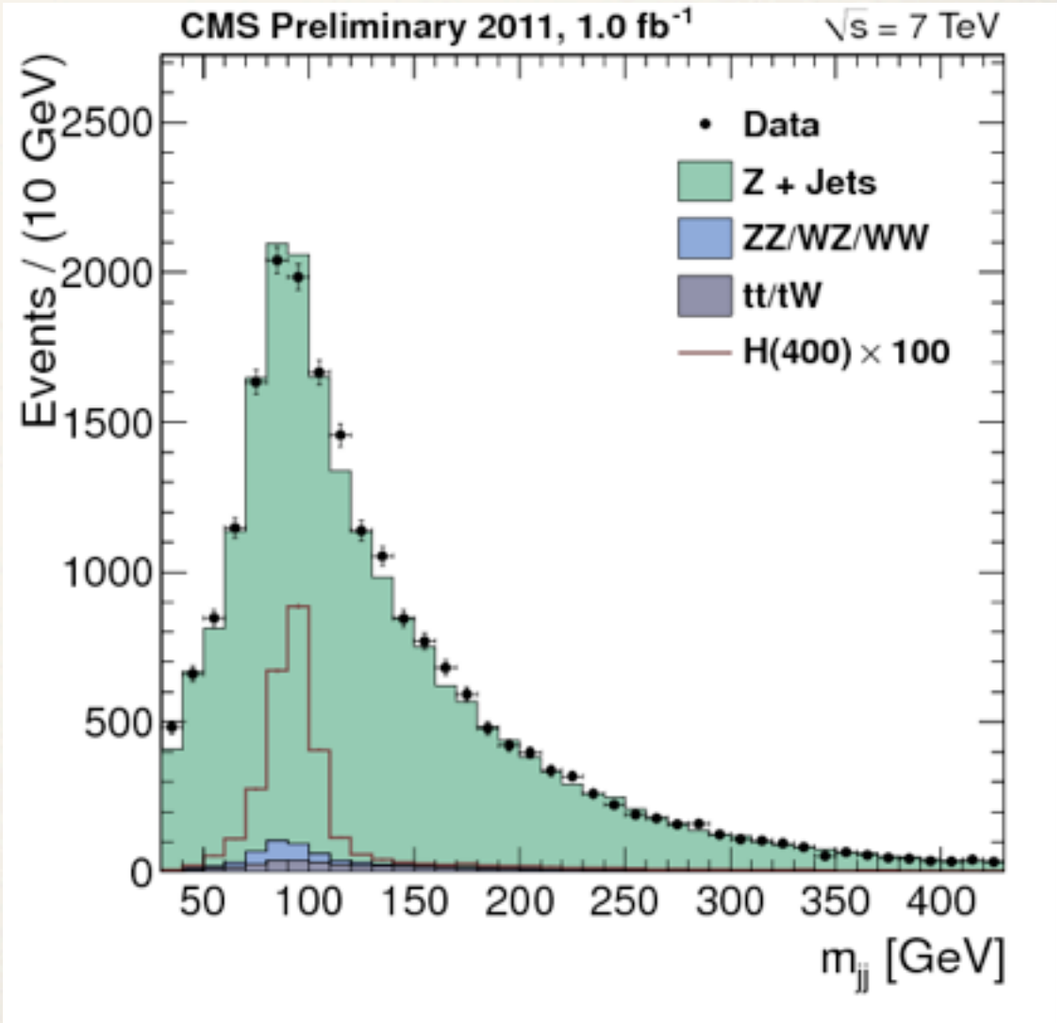
- with 4-th generation of (heavy) quarks, enhanced cross section:
  - ⇒ m_H=[250 - 550] GeV is excluded @95% C.L.

H→ZZ→2l2q: strategy

H→ZZ*→2l2q
1.1 fb^{-1}

- Large Yields: BR(Z→qq)=70%
- Closed kinematics: full event reconstruction
- Price to pay:
  - large backgrounds (Z+jets)
  - limited mass resolution due to jets
- Selection:
  - 2 opposite sign, same flavor leptons (p_T>20,40 GeV), 2 jets (p_T>30 GeV)
  - m_{ll}, m_{jj} close to Z peak

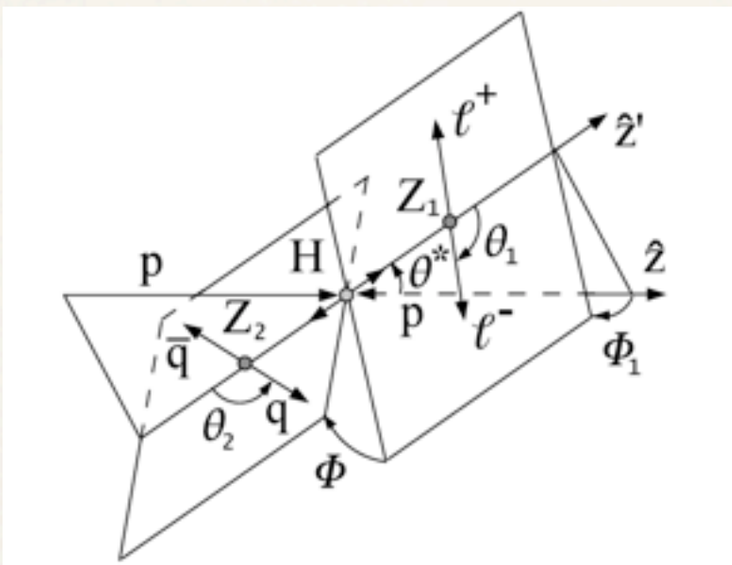
di-jet mass

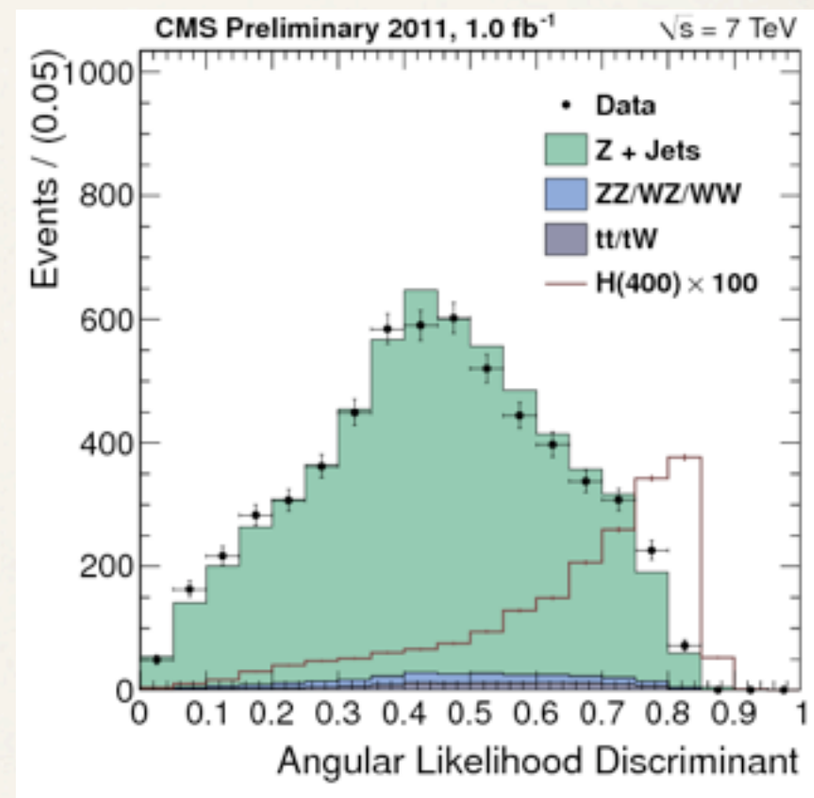


Angular analysis & jet composition

$H \to ZZ^* \to 2l2\nu$
$1.1\ fb^{-1}$

- 5 angles define the kinematics of scalar H→ZZ→llqq: used in a likelihood discriminant
  - advantage: little correlation with m_{lljj}, possibility to measure Z+jets background from mass sidebands





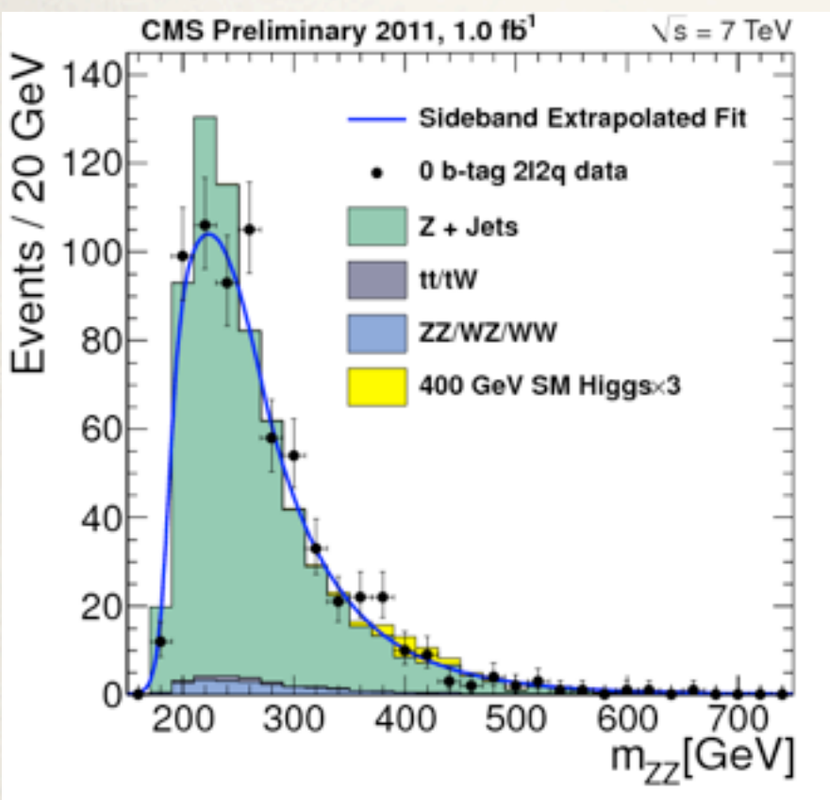
- Signal Z→qq: 2 jets from quarks (light + b,c): use b-tag & g/q discriminator
  - main bkg: 2 jets from gluons

2l2jet invariant mass

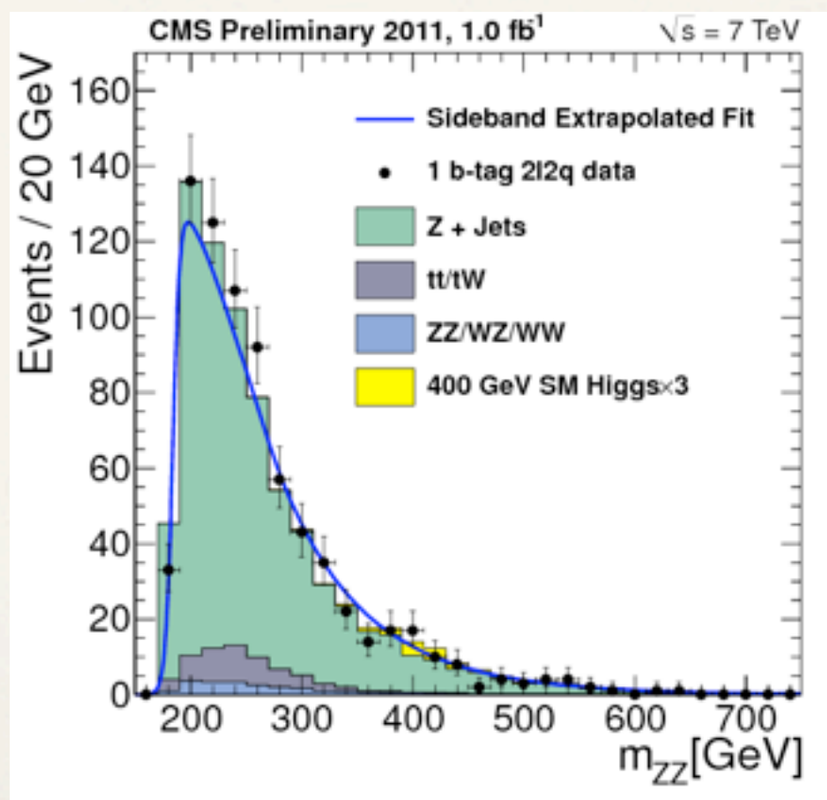
$H \rightarrow ZZ^* \rightarrow 2l2\nu$
$1.1\ fb^{-1}$

- Full distribution of m_{ZZ} used to extract the signal (default) OR cut-and count
- Background modeled from m_{jj} sidebands: $(60<m_{jj}<75\ GeV) \cup (105<m_{jj}<130\ GeV)$
- $e\mu jj$ used also as control sample (Z+jets free)

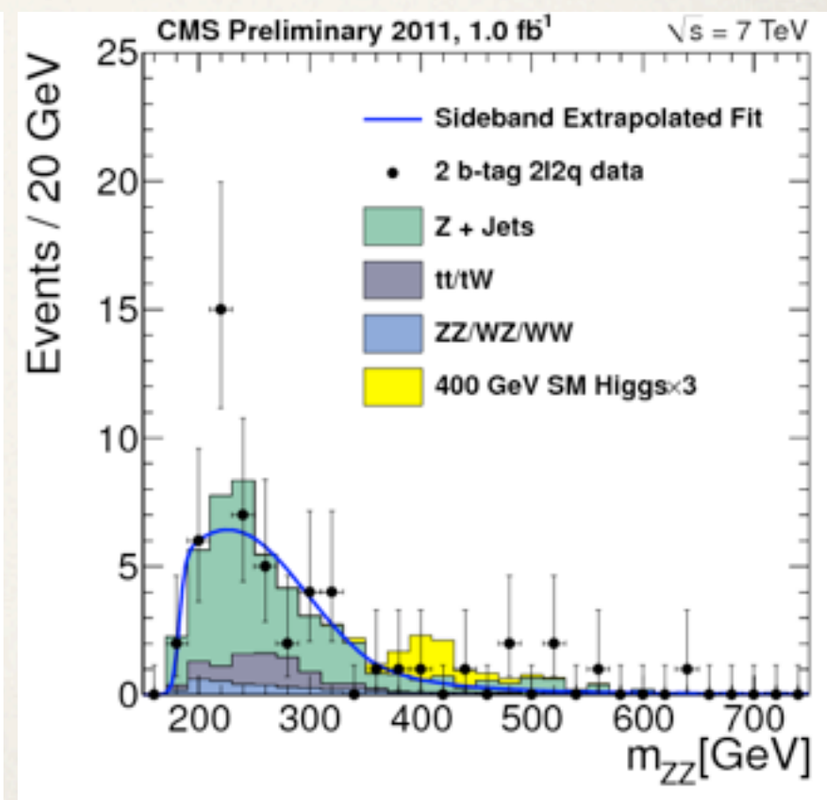
0 b-tag



1 b-tag



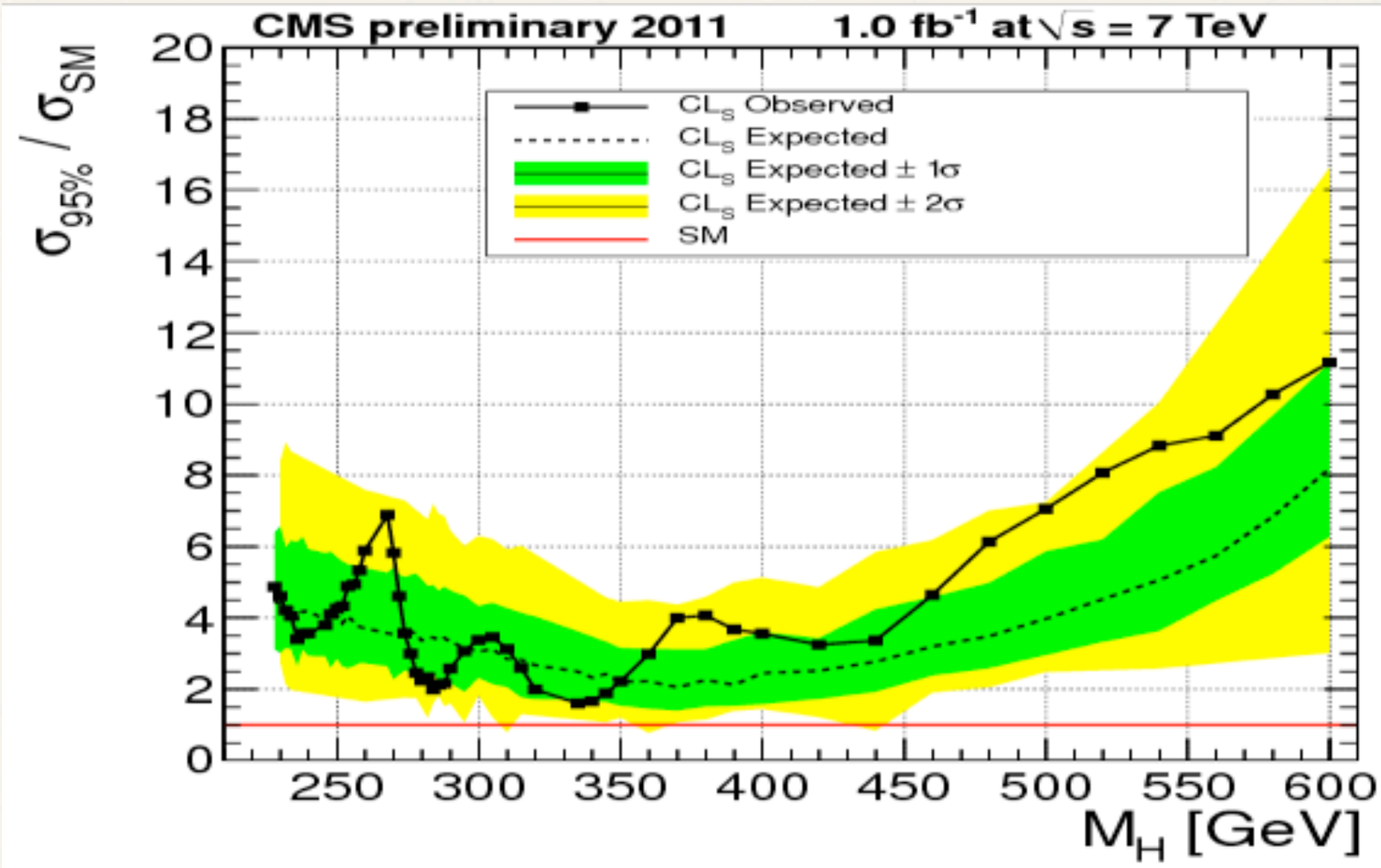
2 b-tags



Exclusion limits

$H \to ZZ^* \to 2l2\nu$
$1.1\ fb^{-1}$

- Best sensitivity with the fit to m_{ZZ} distribution. Including shape systematics estimated in m_{jj} sidebands



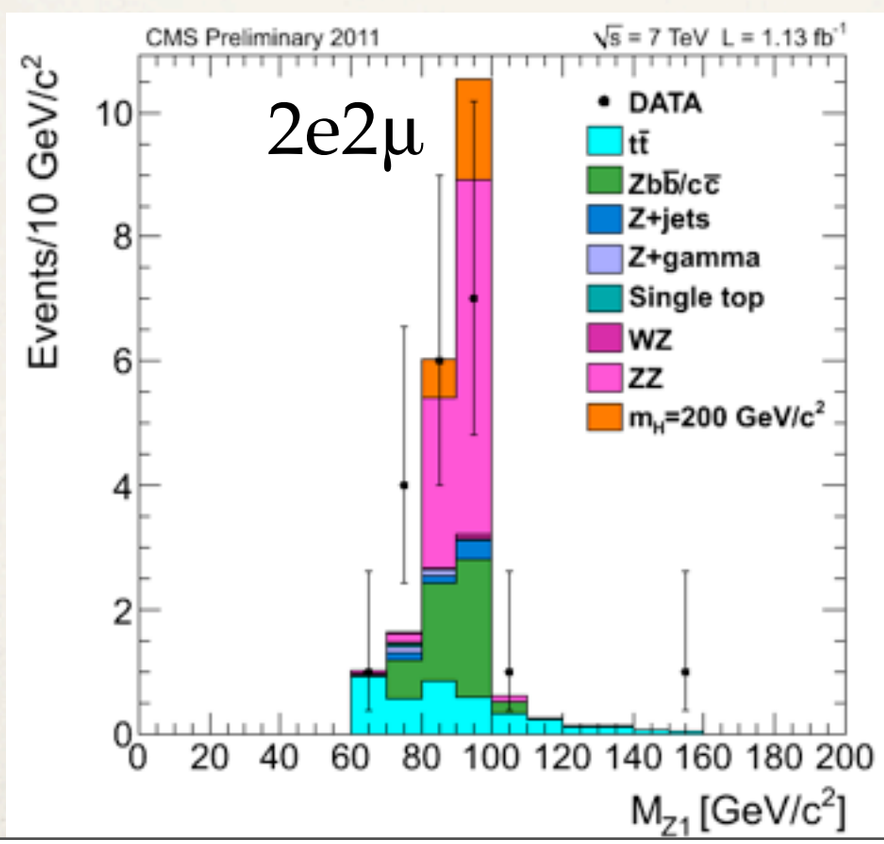
- reaching sensitivity to SM Higgs around 350 GeV.
- With 4th fermion generation, exclude m_H = [226 - 445] GeV

$H \rightarrow ZZ^* \rightarrow 4l$

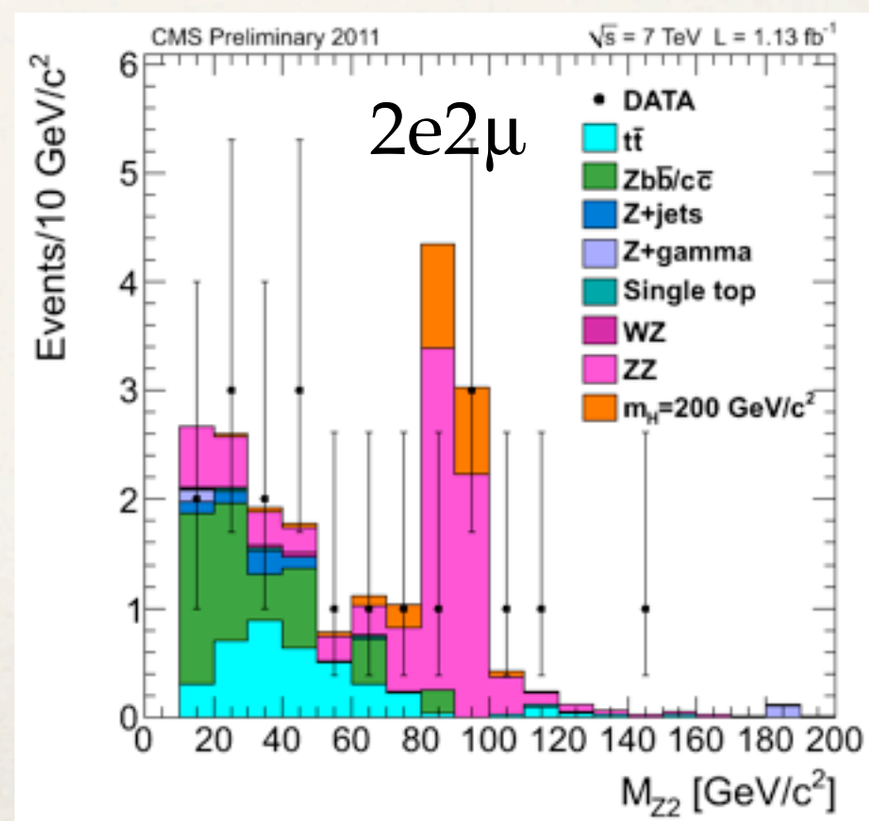
$H \rightarrow ZZ^* \rightarrow 4l$
$1.1\ fb^{-1}$

- Cleanest H mode, closed kinematics: high sensitivity to m_H
- small BR, low yields expected
- Two pair of opposite sign, same flavor leptons: $p_{T1,2} > 20,10$ GeV, $p_{T3,4} > 7(e),5(\mu)$: preserve efficiency for low mass Higgs
- Two Z bosons selection: 1 tight (on shell) + 1 loose (off shell)

Z1: m_{ll}>60 GeV



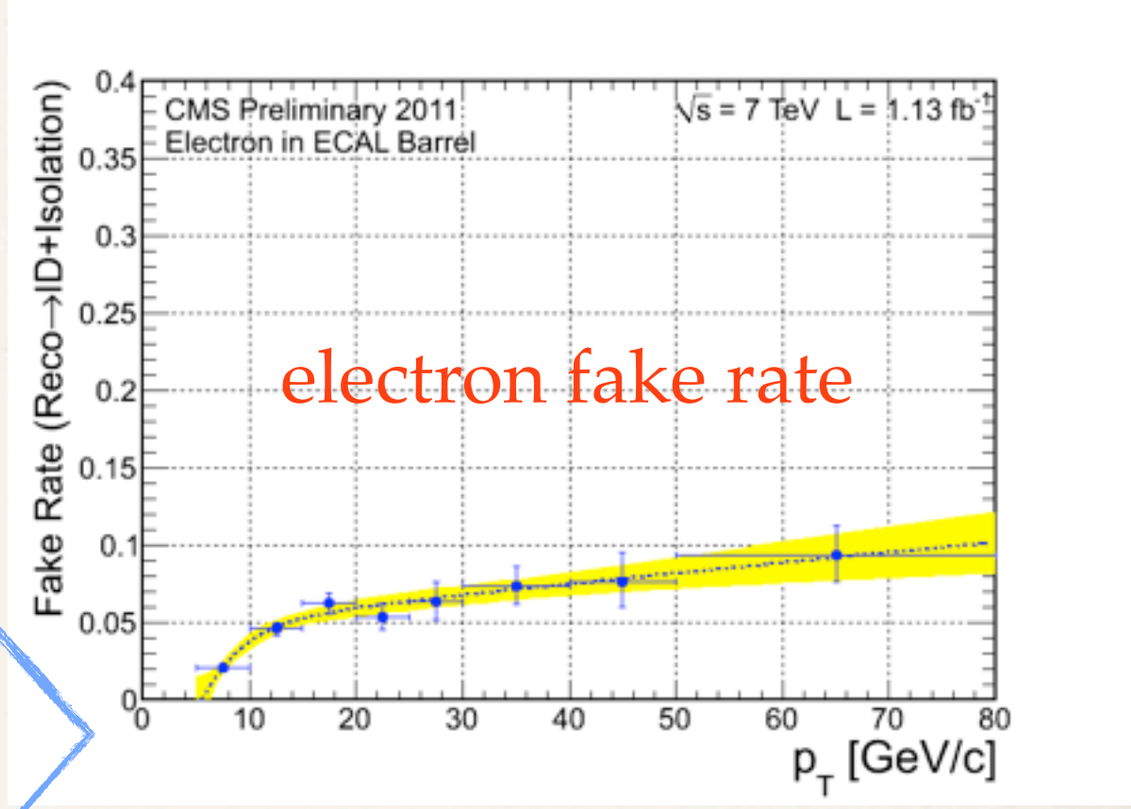
Z2: m_{ll}>20 GeV



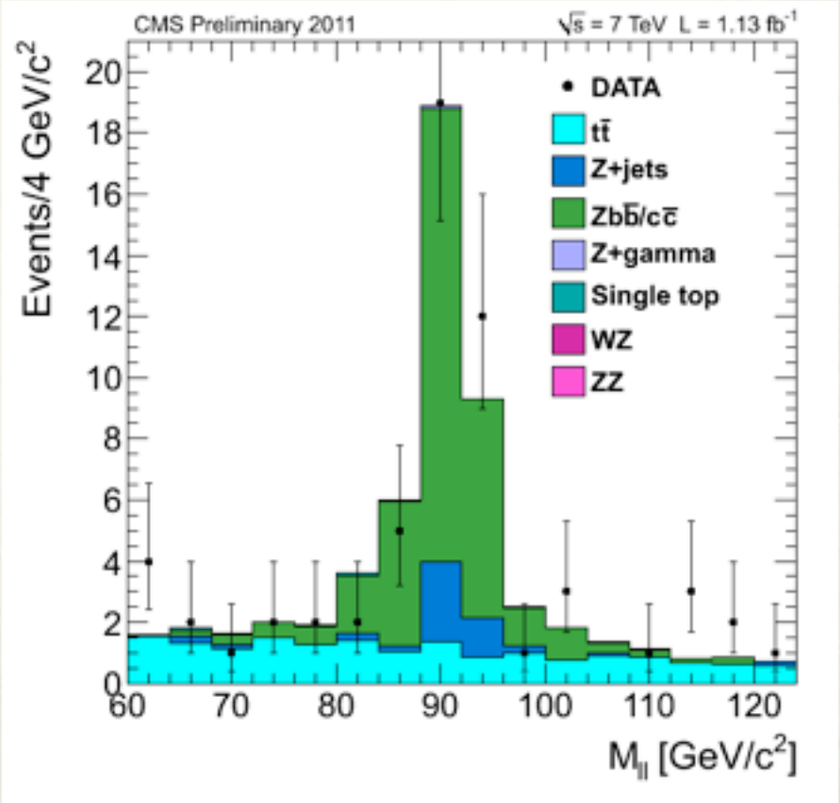
Backgrounds estimation

H→ZZ*→4l
1.1 fb^{-1}

- non resonant ZZ: scale factor data/MC obtained from single Z→ll, and corrected for ZZ phase space



- fake-lepton induced (Z+jets): apply fake-rate to Z + loosely identified leptons control sample

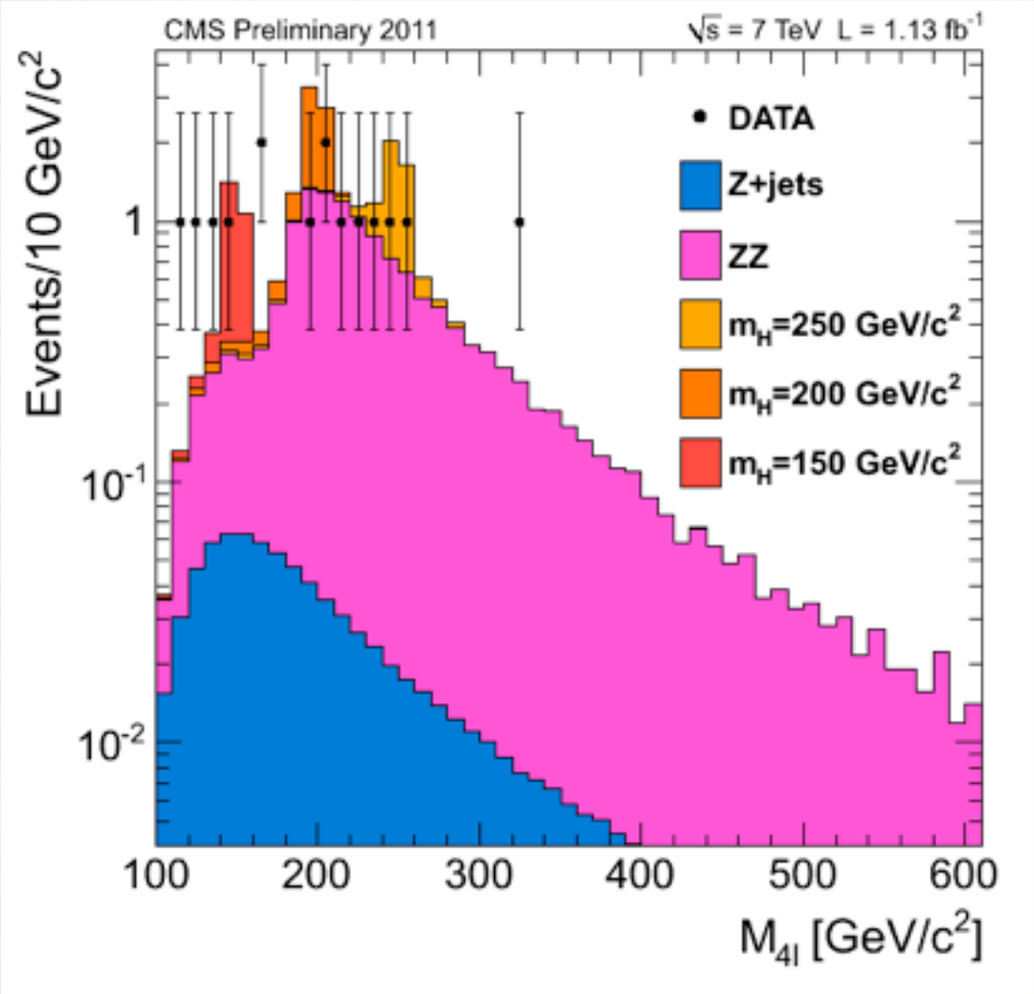


- Z→bb, tt: do not use flavor and charge requirement; require high impact parameter

4 leptons ZZ candidates

H→ZZ*→4l
1.1 fb^{-1}

- 15 events selected (3 in 4e, 6 in 4μ, 6 in 2e2μ)



	baseline		
	$4e$	4μ	$2e2\mu$
ZZ	2.76 ± 0.18	4.10 ± 0.27	6.72 ± 0.45
Z+jet	0.37 ± 0.07	0.06 ± 0.01	0.39 ± 0.07
$Zb\bar{b}/c\bar{c}, t\bar{t}$	0.01 ± 0.02	0.01 ± 0.01	0.02 ± 0.02
WZ	0.006 ± 0.006	0.006 ± 0.006	0.024 ± 0.012
All background	3.13 ± 0.19	4.17 ± 0.27	7.14 ± 0.46
$m_H = 150\,\mathrm{GeV}/c^2$	0.368 ± 0.007	0.637 ± 0.009	0.996 ± 0.011
$m_H = 200\,\mathrm{GeV}/c^2$	0.816 ± 0.011	1.161 ± 0.014	1.907 ± 0.018
$m_H = 250\,\mathrm{GeV}/c^2$	0.656 ± 0.009	0.885 ± 0.010	1.533 ± 0.013
Observed	3	6	6

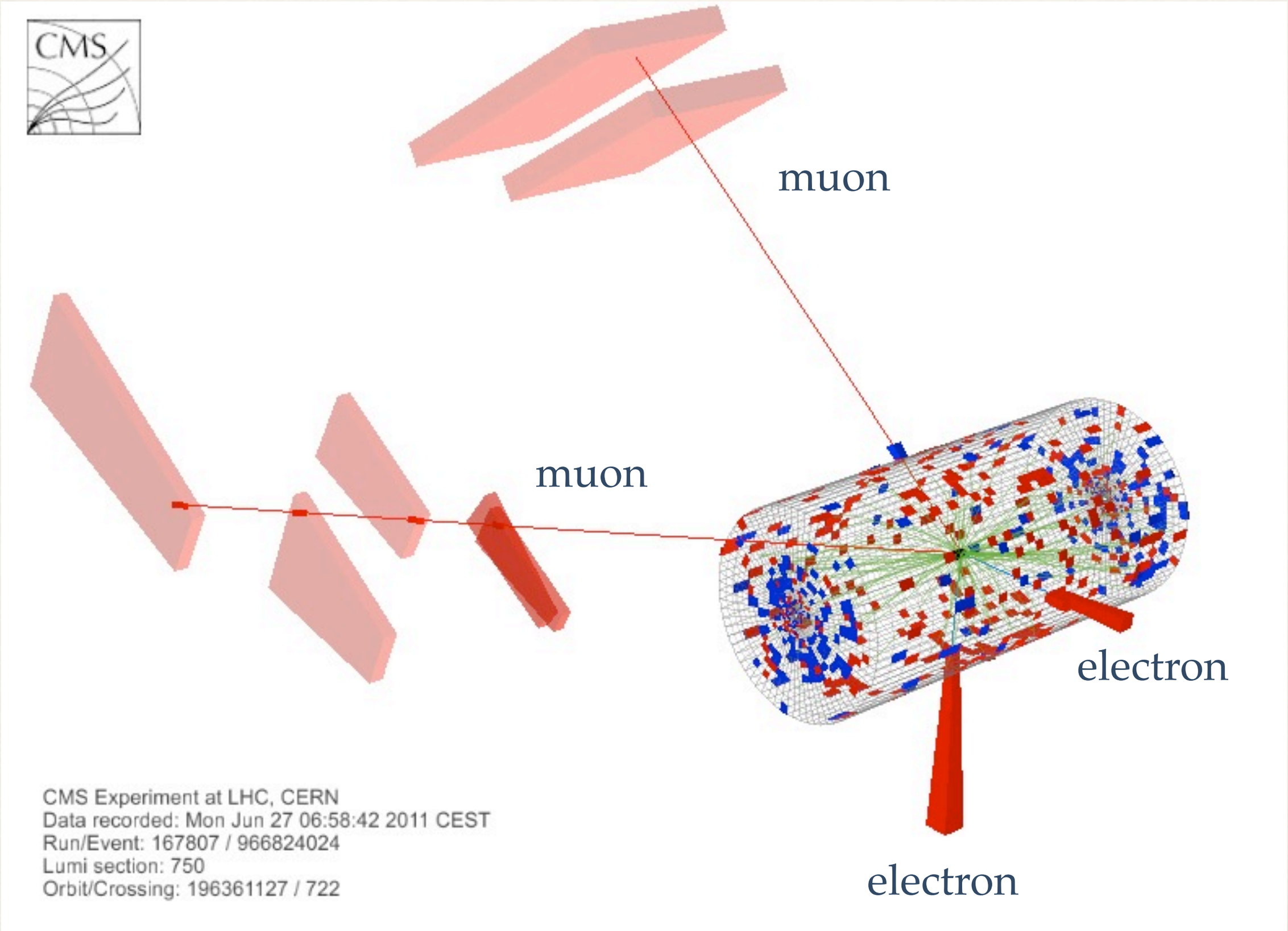
negligible non-ZZ backgrounds
(1.9 ± 0.1 bkg with m_{ZZ}<180 GeV)

- 6 events with m_{ZZ}<180 GeV, but not compatible with one SM H of defined mass. With events having 2 Z's with m_{ll}>60 GeV:

- $\sigma(pp \to ZZ + X) \times \mathcal{B}(ZZ \to 4\ell) = 17.5^{+6.3}_{-4.4}(\mathrm{stat.}) \pm 0.7(\mathrm{syst.}) \pm 1.1(\mathrm{lumi.})\,fb$

$\sigma^{th.}$ (NLO) = 28.32 ± 1.95 fb

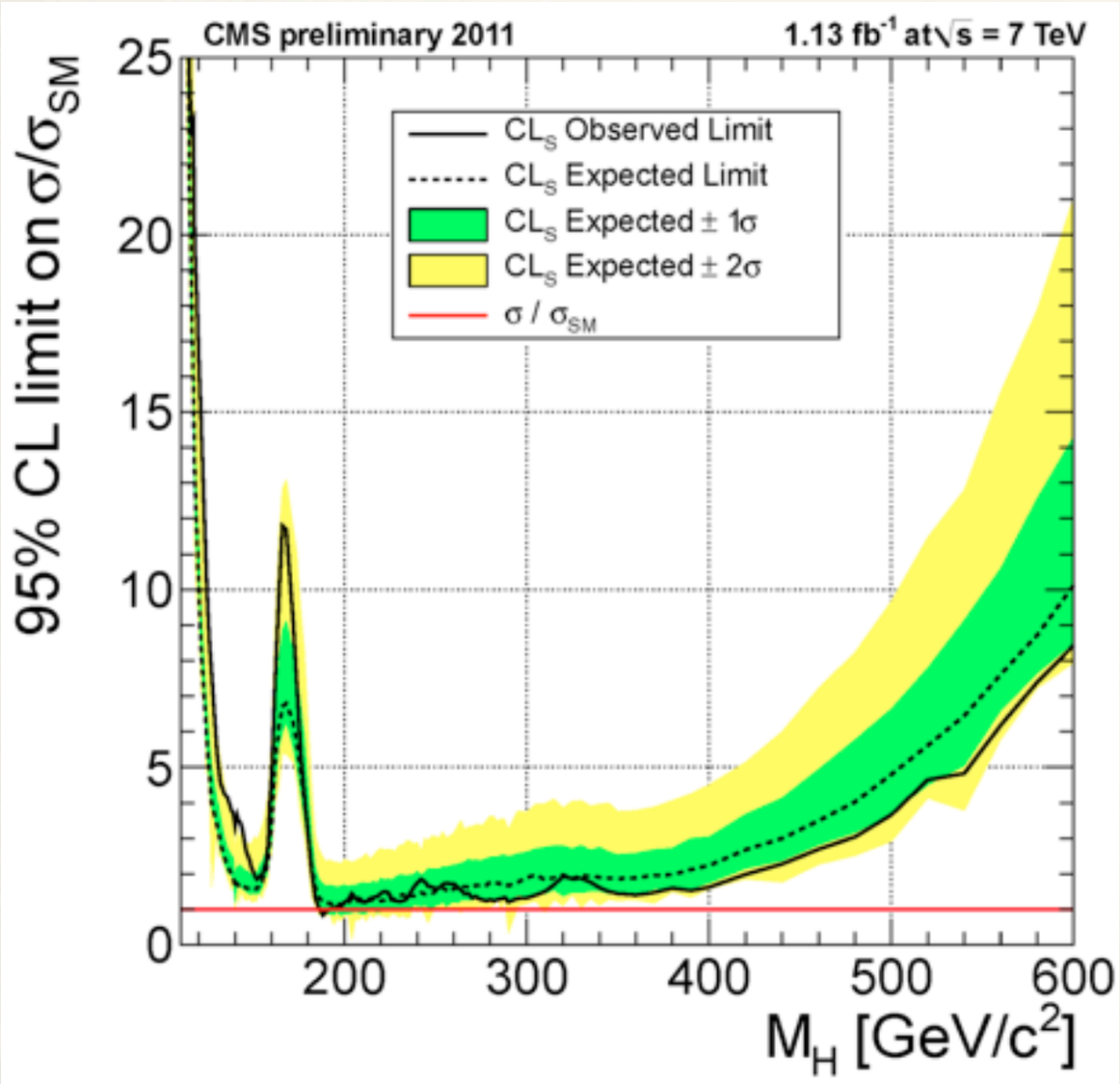
The highest mass ZZ event



Exclusion limits

H→ZZ*→4l
1.1 fb^{-1}

- Signal extraction: full mZZ used:
  - signal: Breit Wigner (decay) ⊗ Crystal-Ball function (resolution)
  - background: empirical parametric model

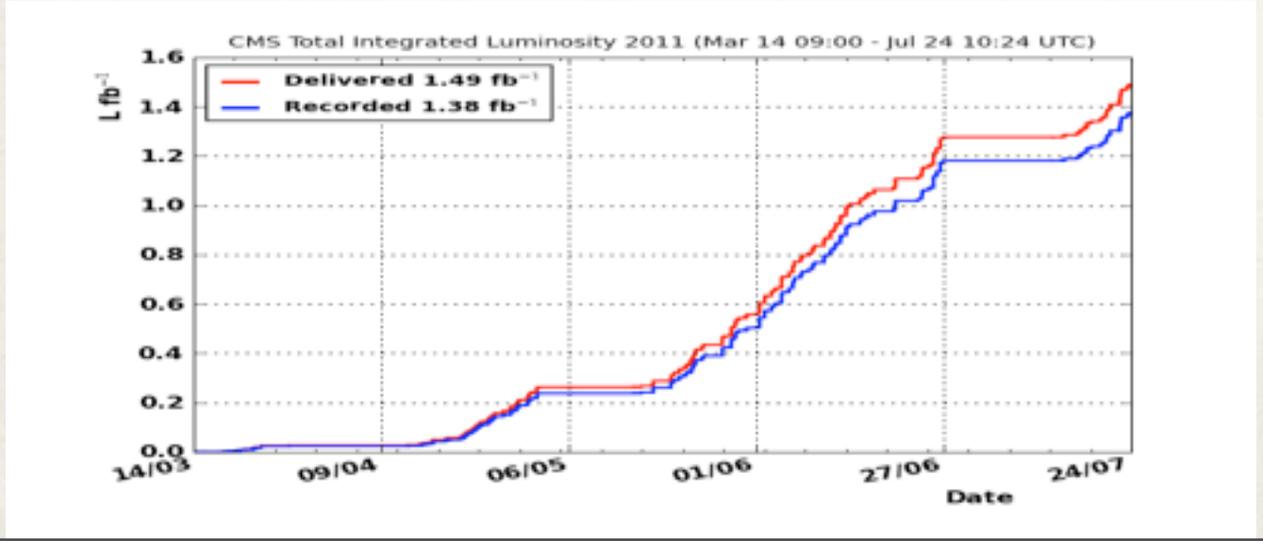


- Sensitivity to [1-2] x SM cross section in m_H = 180 - 420 GeV

- In the 4th fermion generation scenario excludes 2 ranges:
  - m_H = [138 - 162] GeV
  - m_H = [178 - 502] GeV

Conclusions

- CMS searched for Standard Model Higgs in WW and ZZ with 1.1 fb^{-1} at 7 TeV
- No convincing evidence for Higgs boson has been observed (yet)
- $H \to WW^* \to 2l2\nu$ excludes a Higgs boson in the **mass range $150 < m_H < 193$ GeV**
  - broad excess within 2σ in the range $120 < m_H < 170$ GeV
- $H \to ZZ^* \to 2l2\nu$ and $2l2q$ contribute to $H \to WW^*$ for Higgs exclusion at high masses (see J.Olsen's talk on combination)
- $H \to ZZ^* \to 4l$ consistent with SM backgrounds, slightly more events than expected for $m_H < 180$ GeV

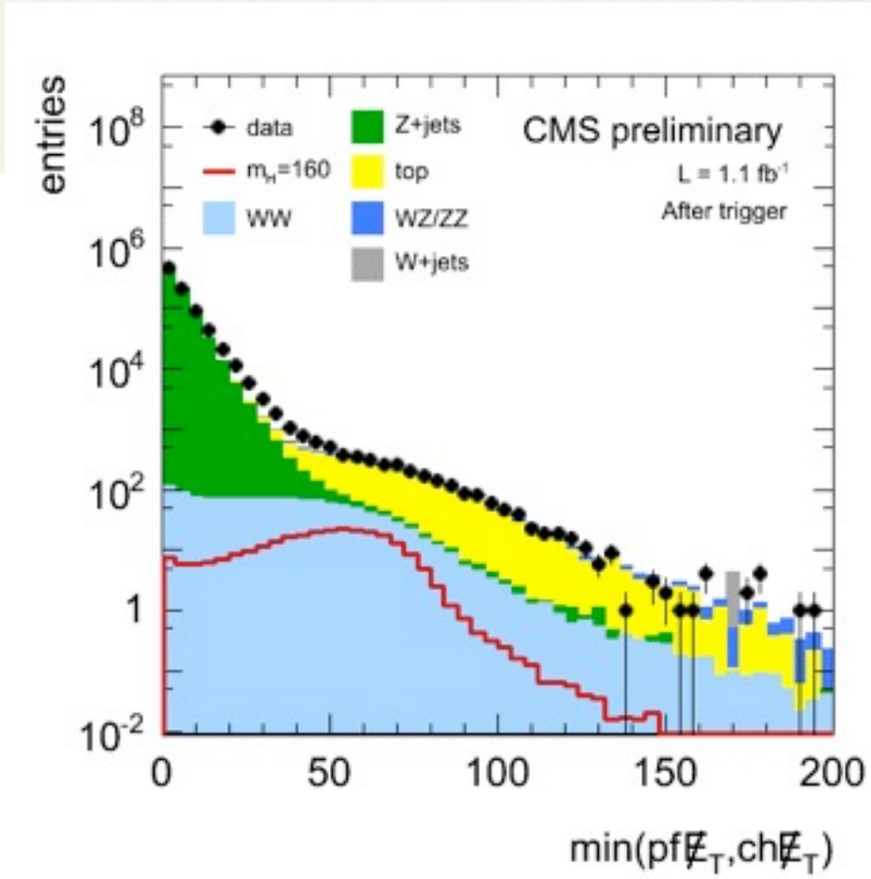


LHC restarted after technical stop: eagerly looking at new data!

Backup

Drell-Yan estimation in H→WW*

- Primary DY estimate in each mass bin using "$R_{out/in}$" method
  - Land in signal reason due to fake MET:
    - mis-measurement of leptons, recoiling jets, instrumental noise
    - fake MET increases with increasing pile-up
  - Events counted in Z-peak and propagated back to signal region
    - $R_{out/in}$ taken from MC and cross checked in data
  - Other background subtracted out using opposite flavor counts
  - WZ and ZZ contribution subtracted out from data
    - 10% conservative error given to this contribution



min(pf$\not{E}_T$,ch$\not{E}_T$)

opposite flavor events measured in Z-peak

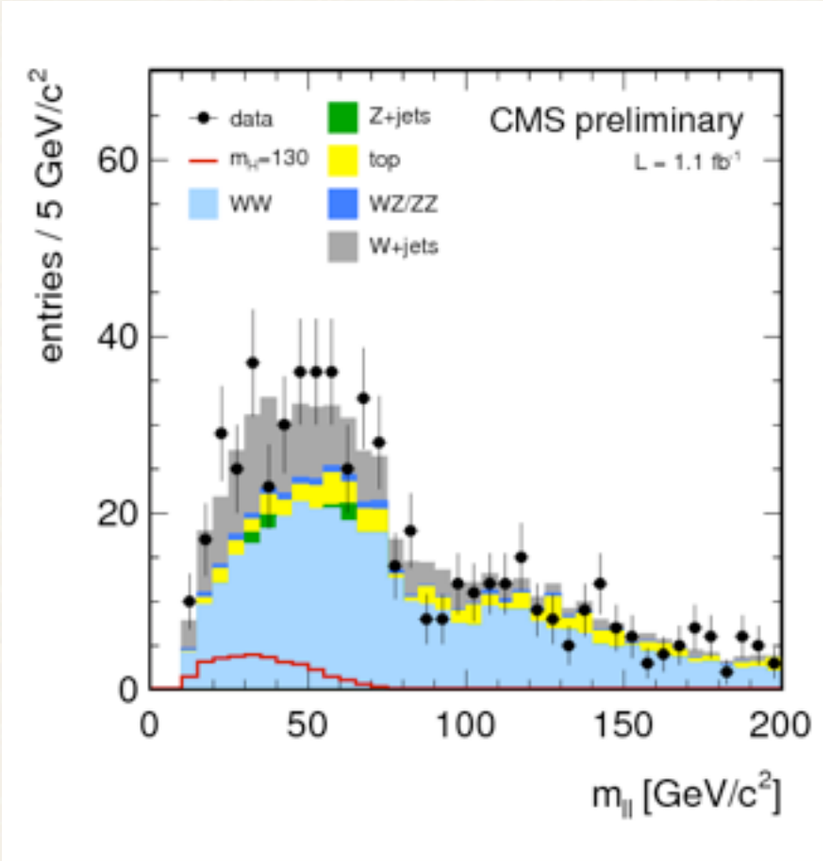
expected VZ contribution from MC

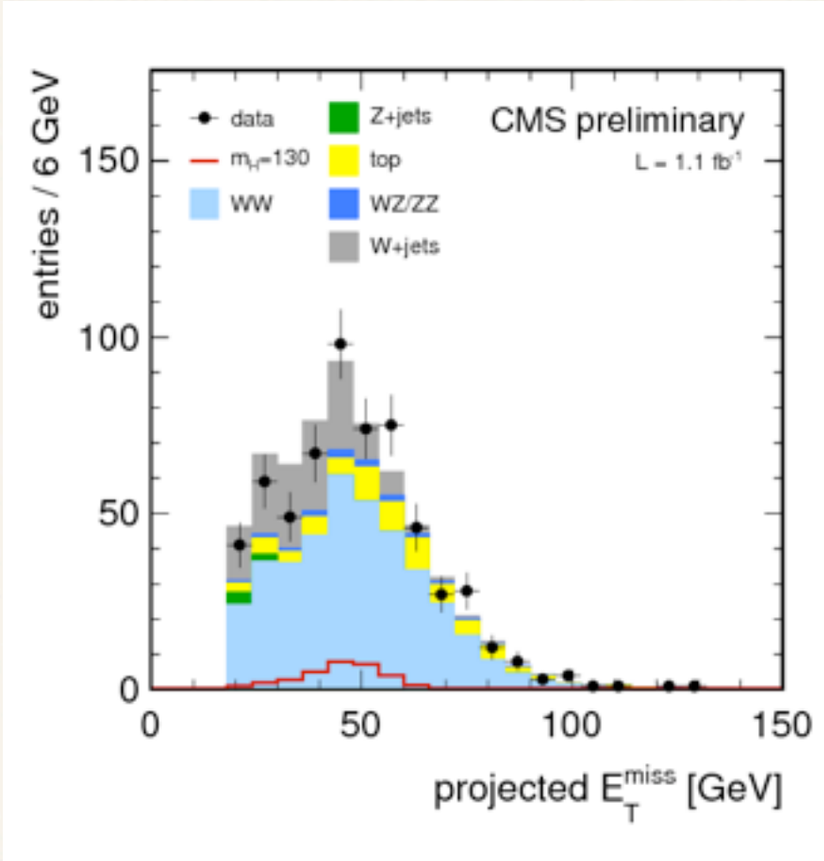
$$N_{out}^{ll,exp} = R_{out/in}^{ll,loose}(N_{in}^{ll} - 0.5N_{in}^{e\mu}k_{ll} - N_{\text{control}}^{ZV,\,\text{sim.}})$$

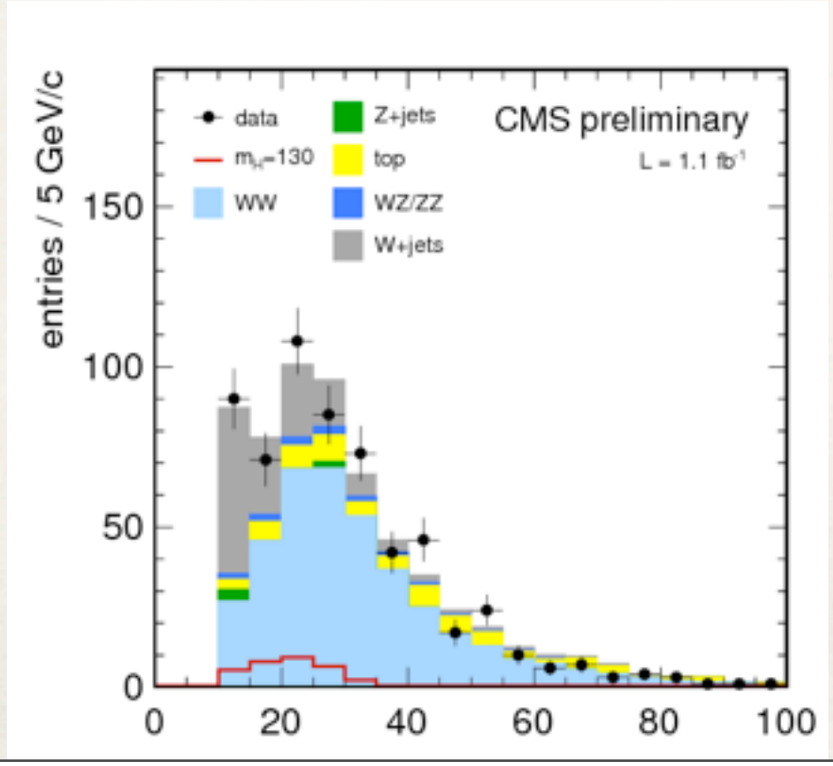
same flavor events measured in Z-peak

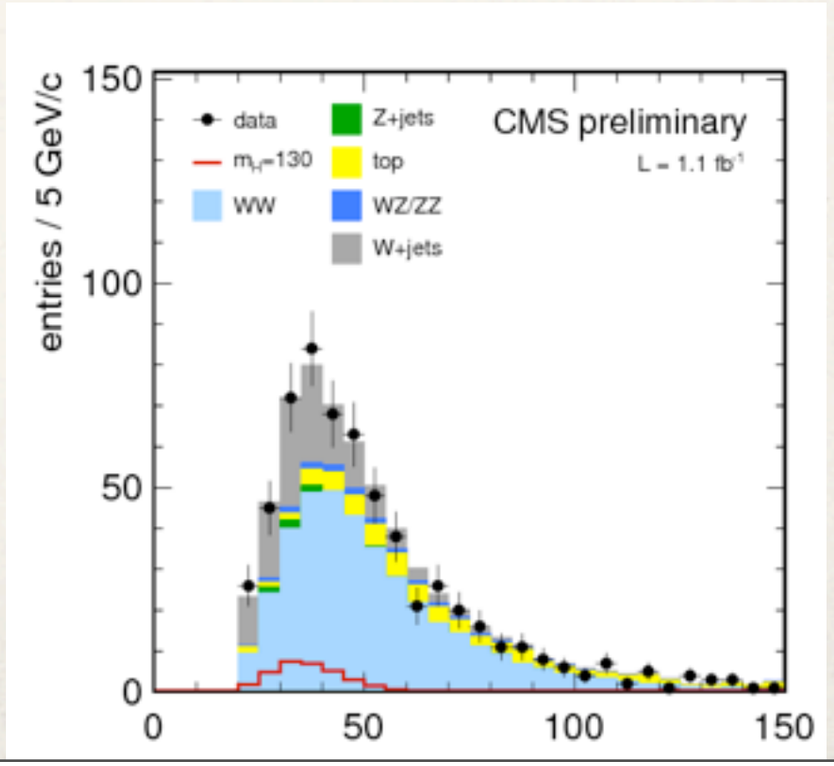
correction for differences in lepton efficiency

H→WW* + 0 jet kinematics

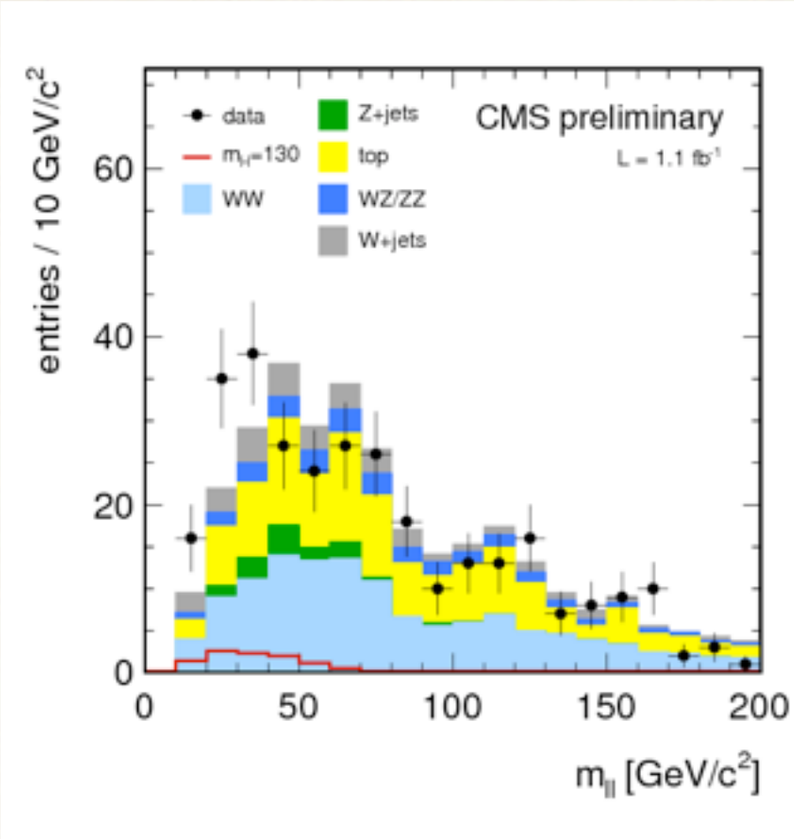


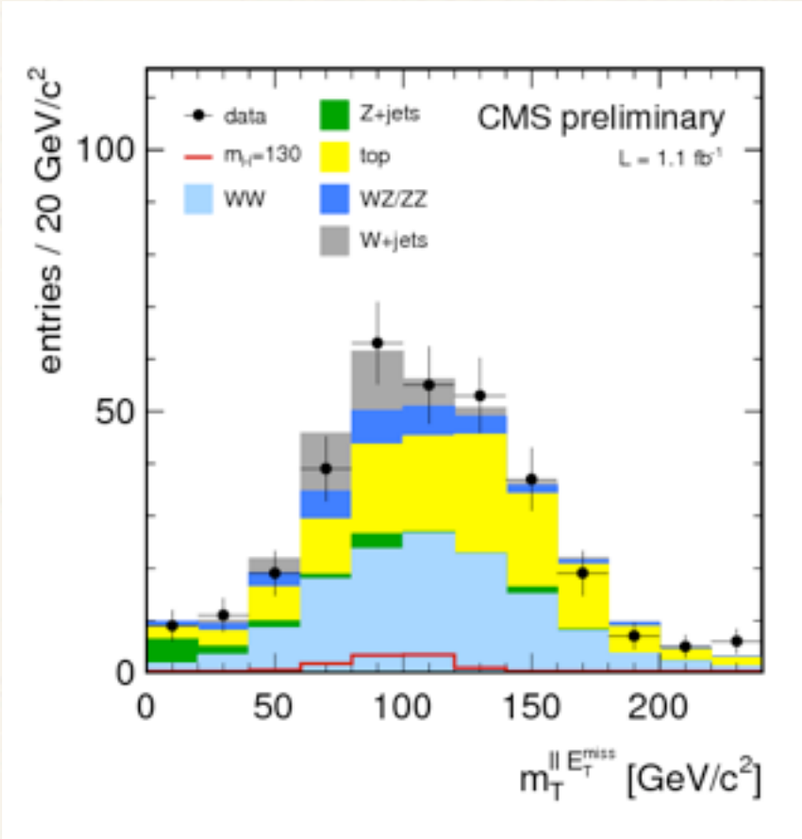


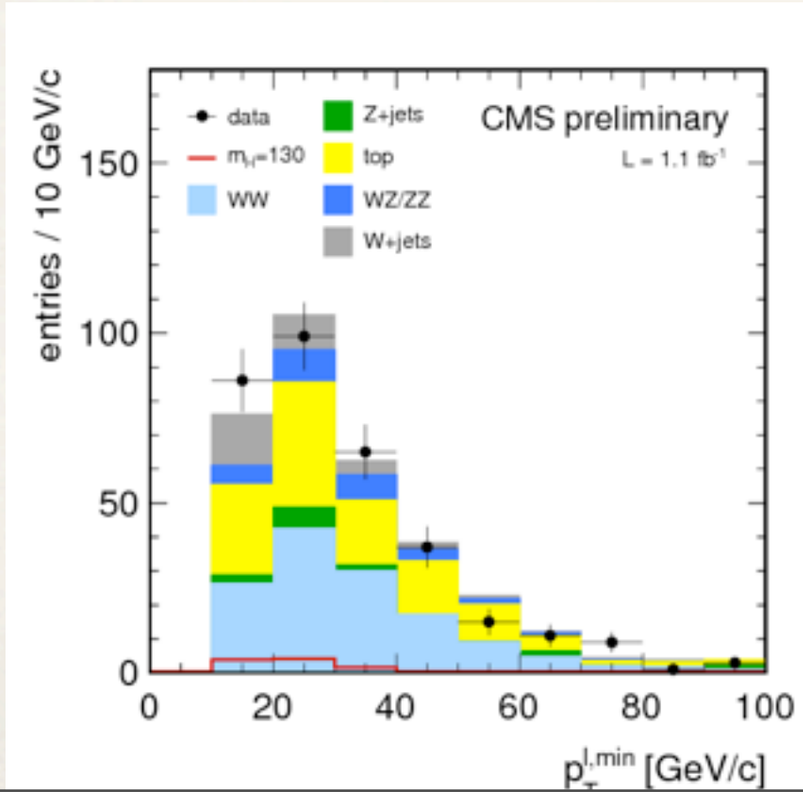


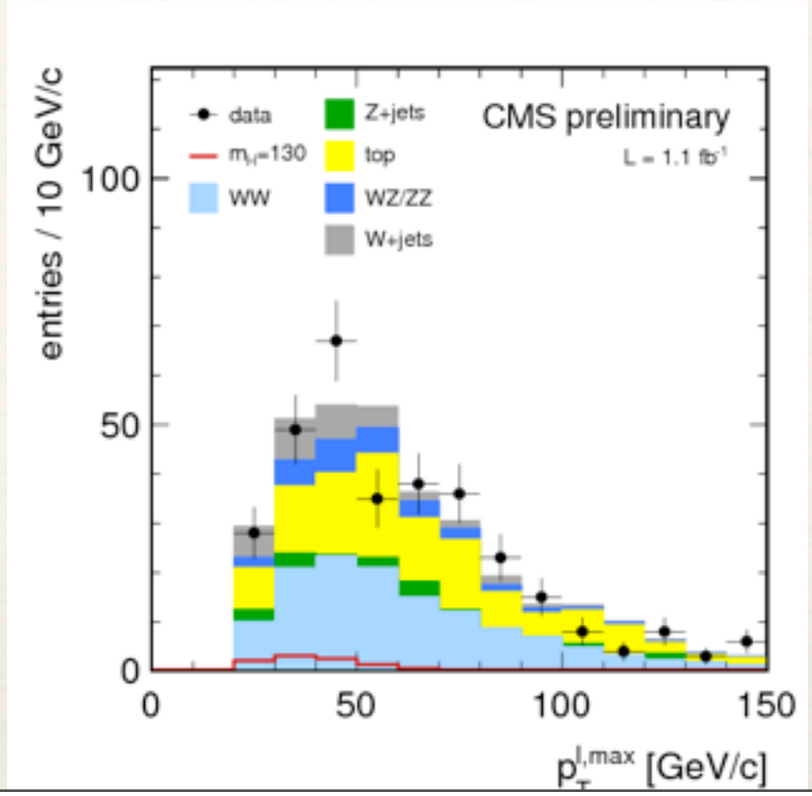


H→WW* + 1 jet kinematics



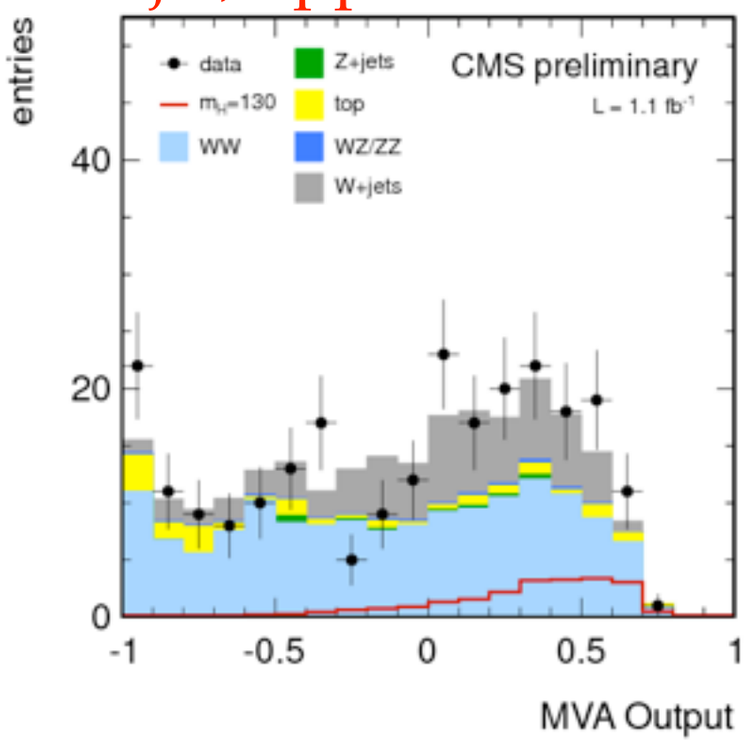




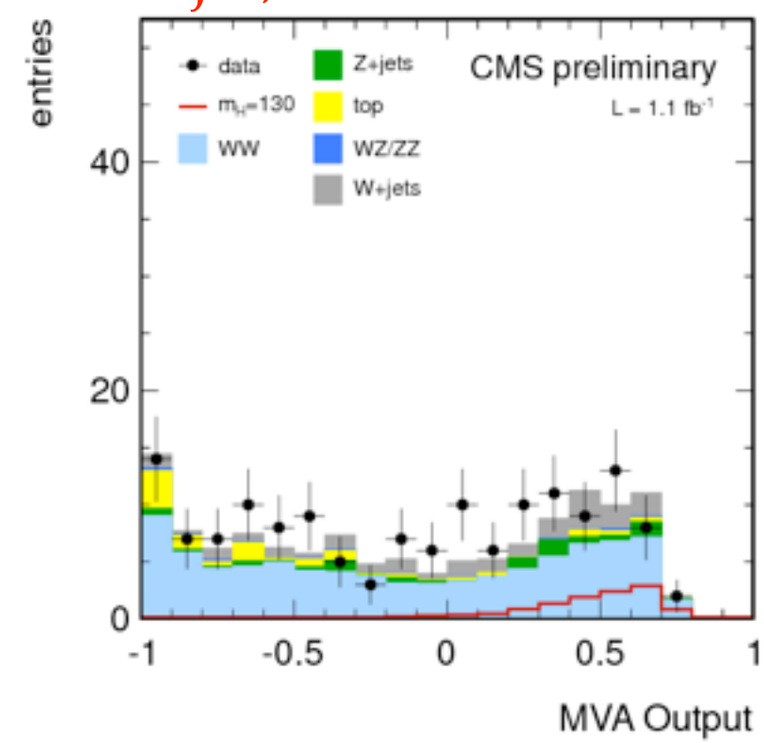


H→WW* BDT output

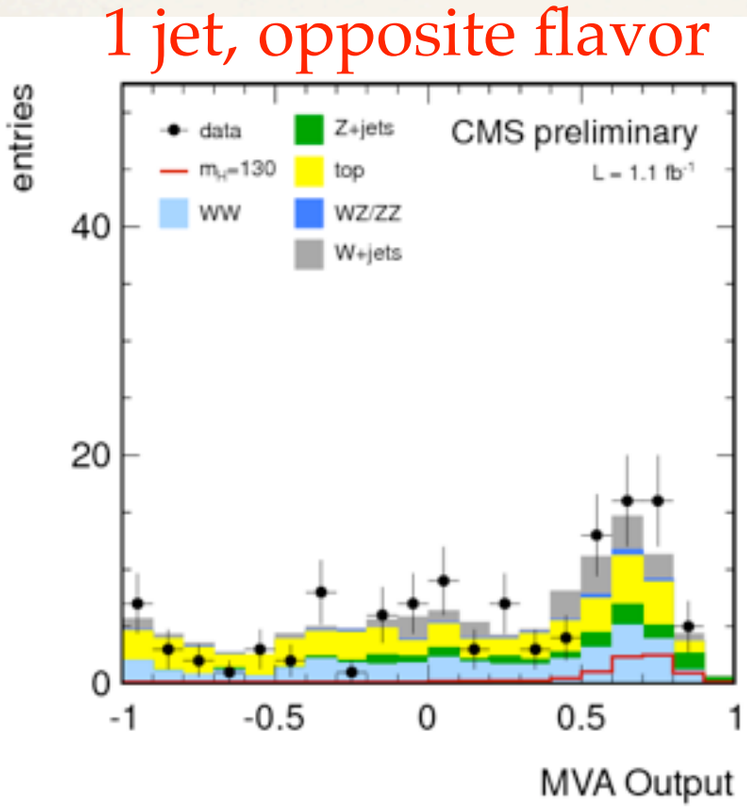
0 jet, opposite flavor



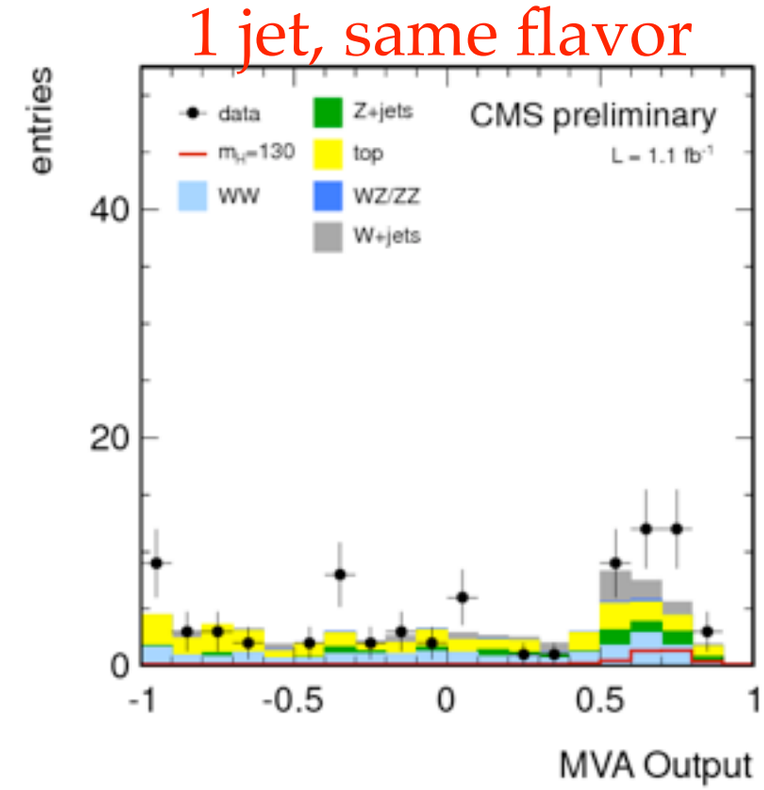
0 jet, same flavor



1 jet, opposite flavor

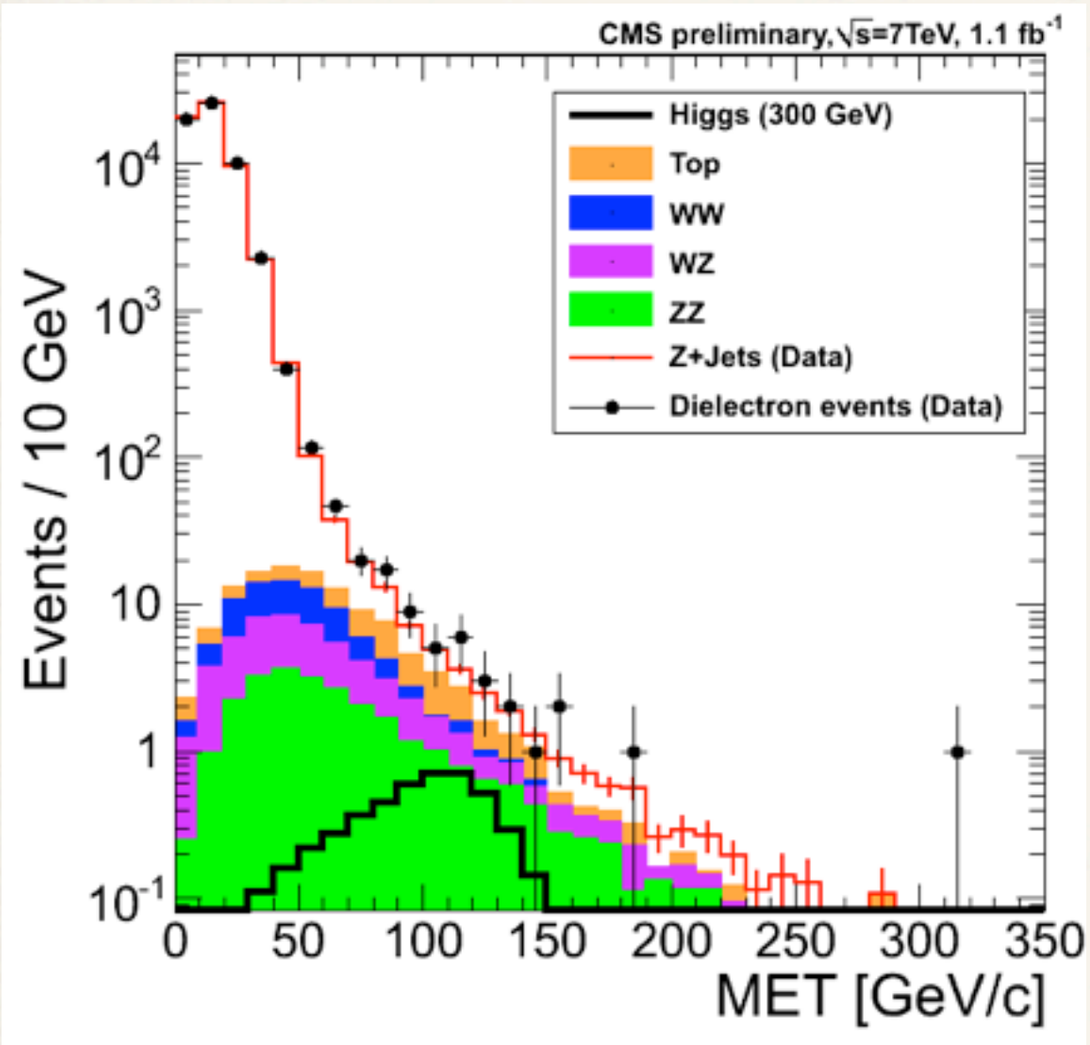


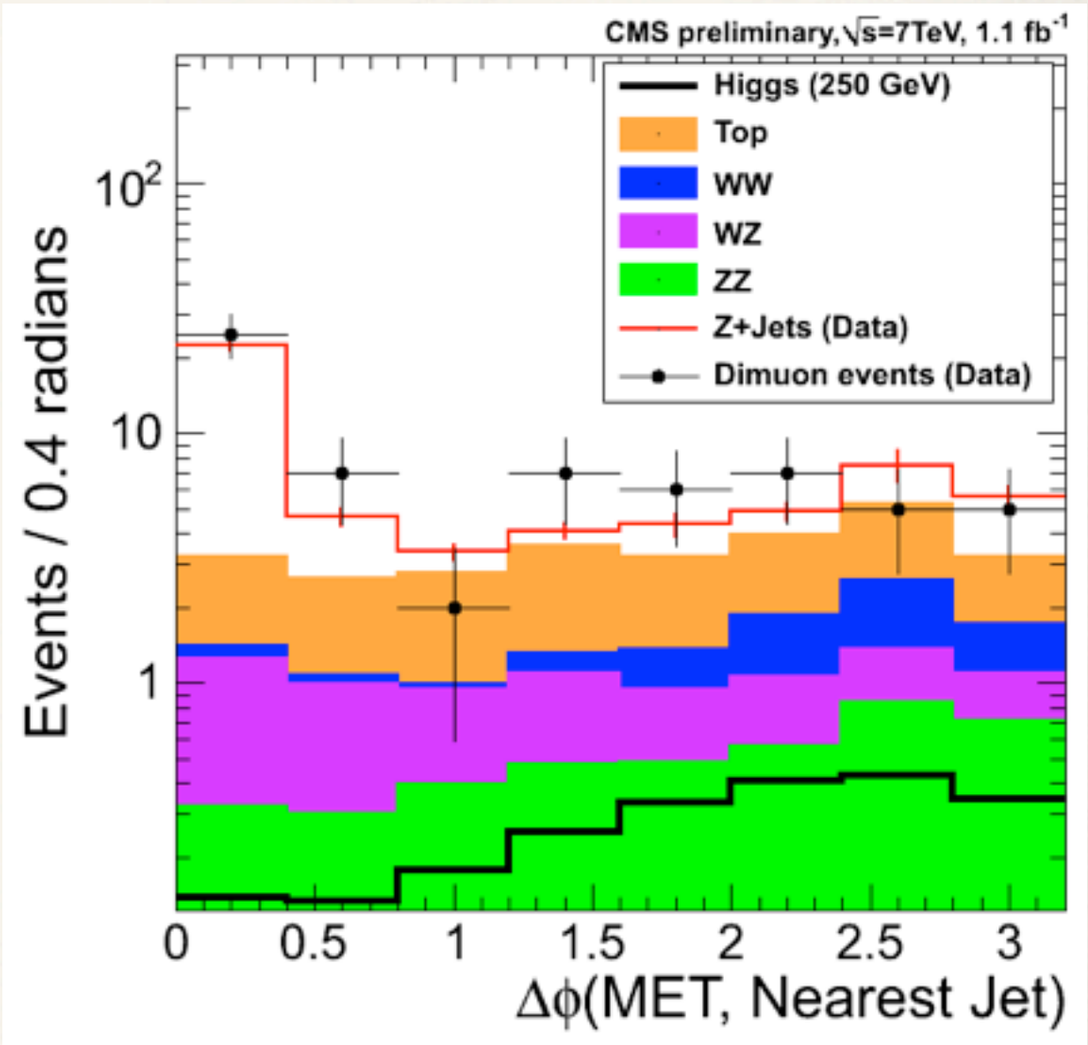
1 jet, same flavor



H→ZZ*→2l2ν: kinematics

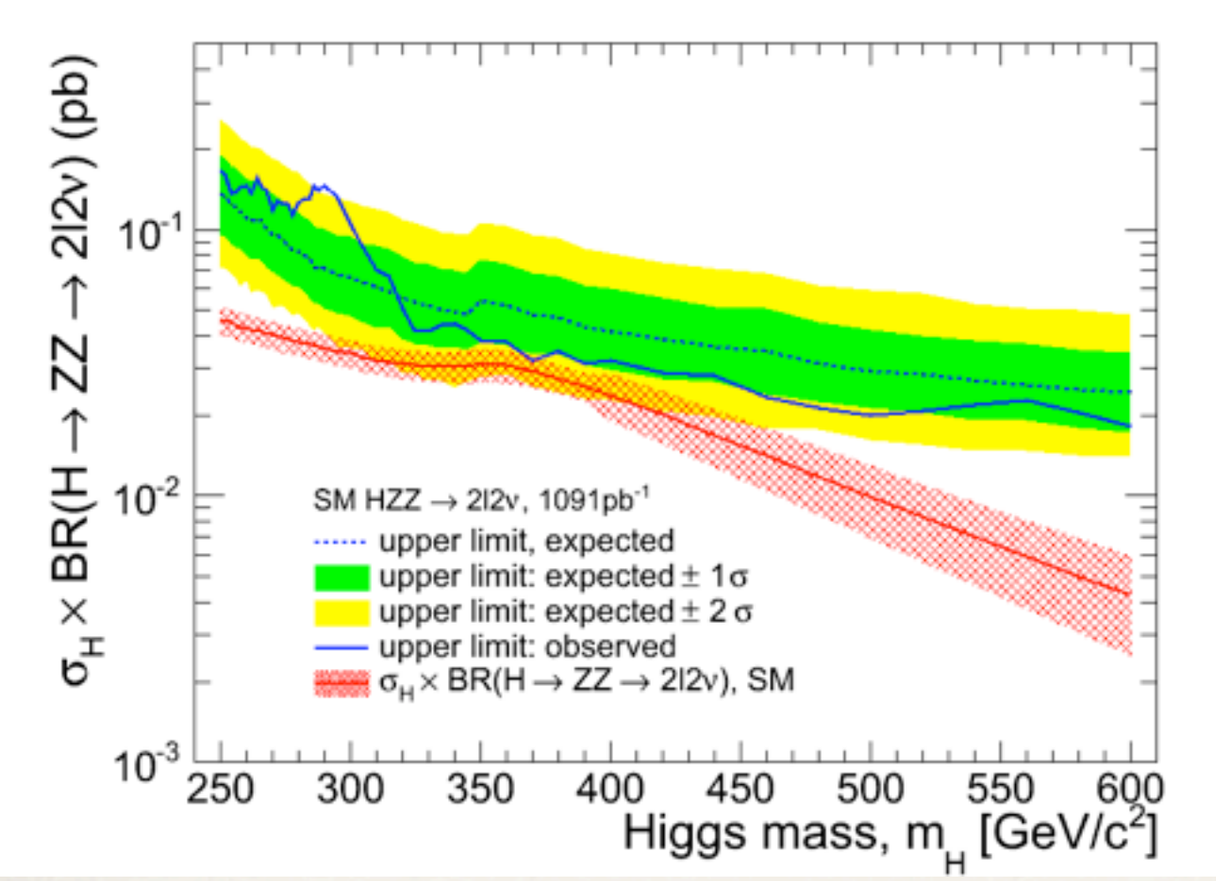
- E_T^{miss} modeled with γ+jets control sample



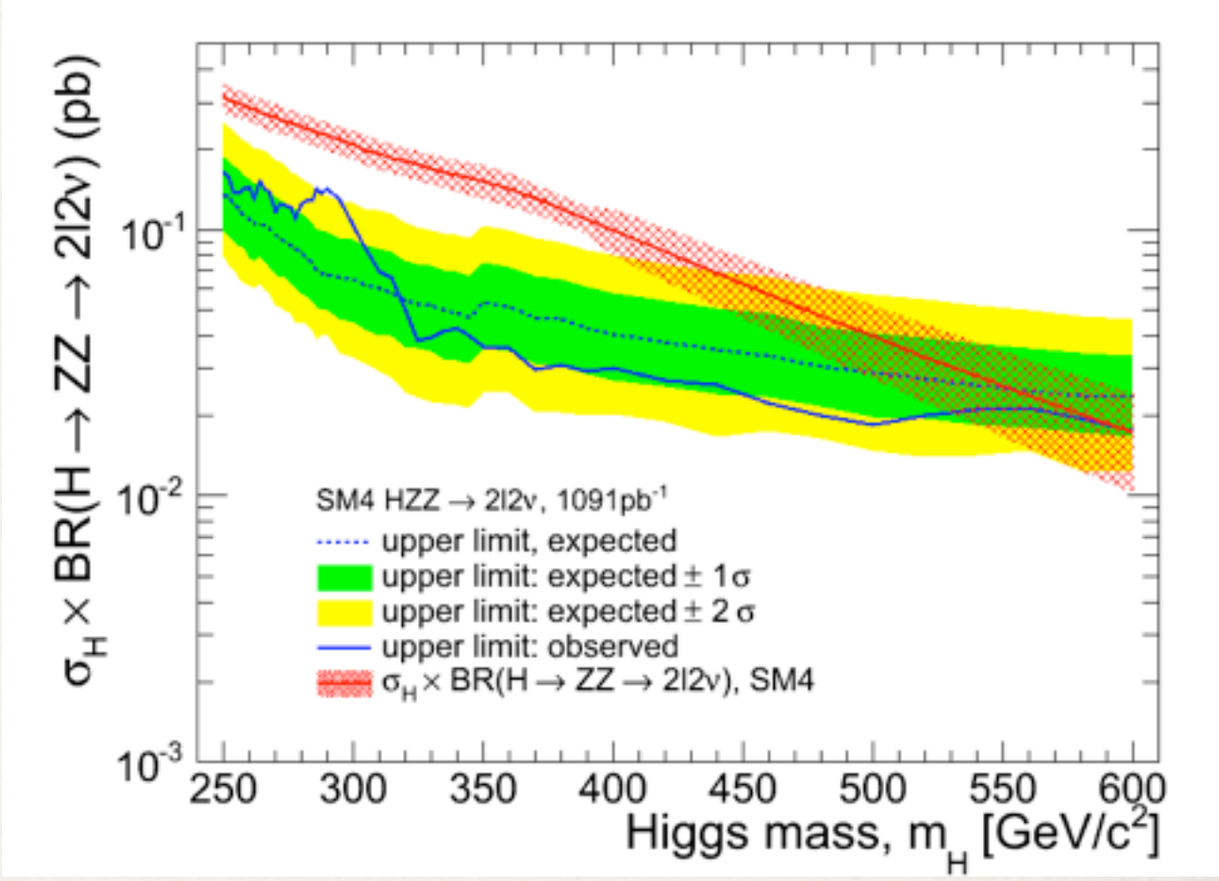


H→ZZ*→2l2ν: SM and 4th generation

- Limits evaluated on σ_H x BR(H→ZZ→2l2ν)
- BR(H→ZZ) enhanced in presence of a 4th generation of heavy fermions

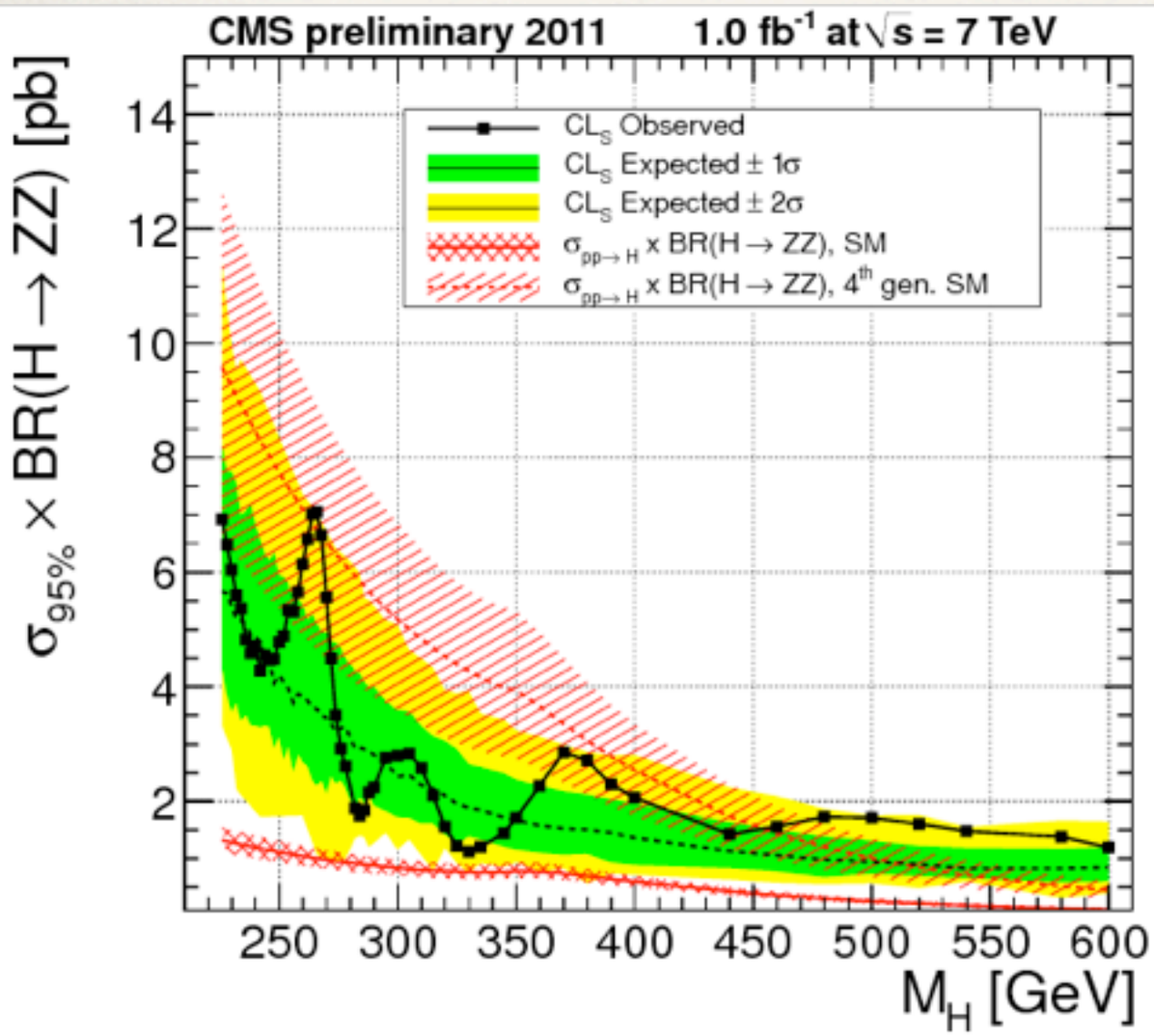


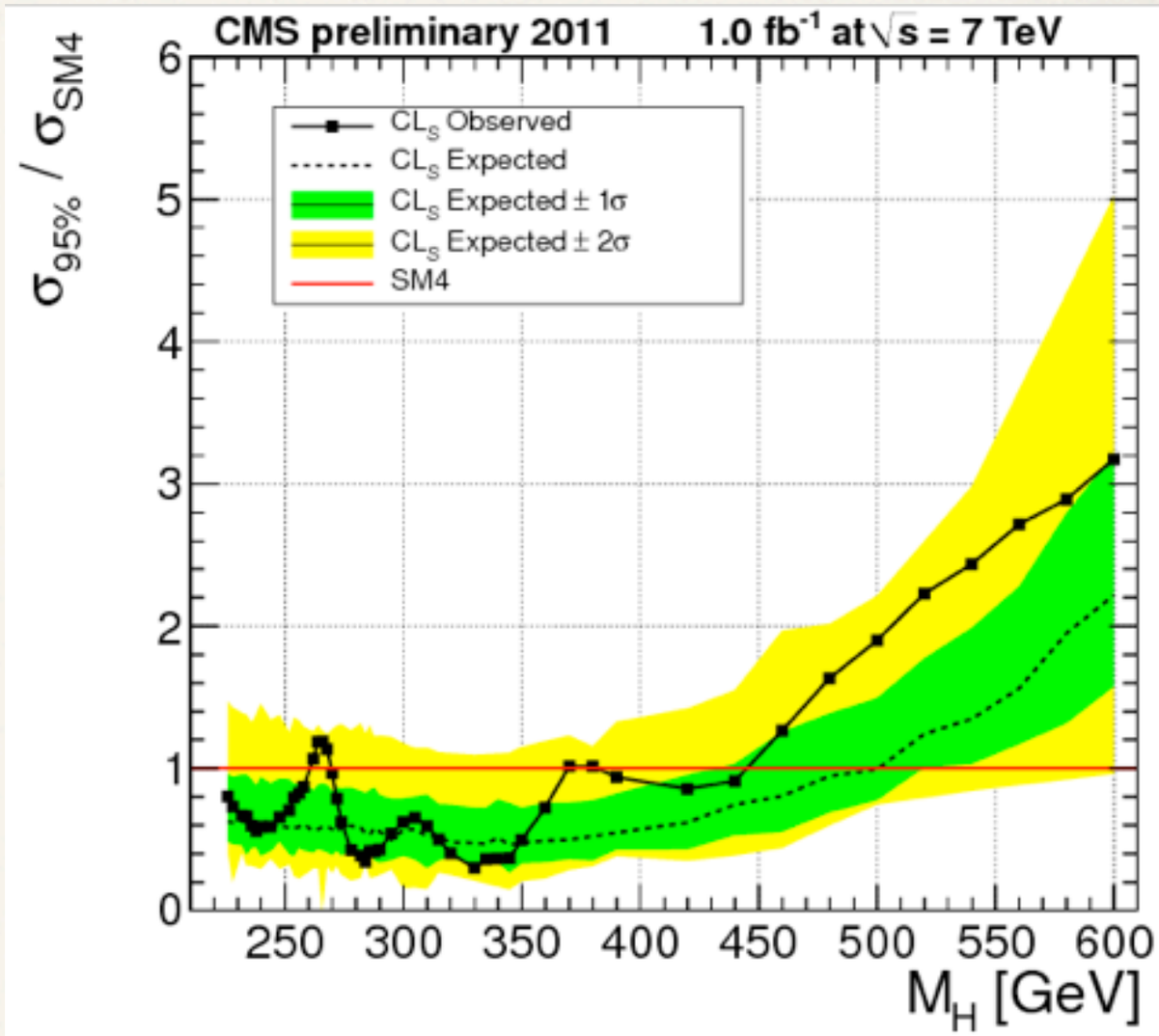
Standard Model cross section



4th generation cross section

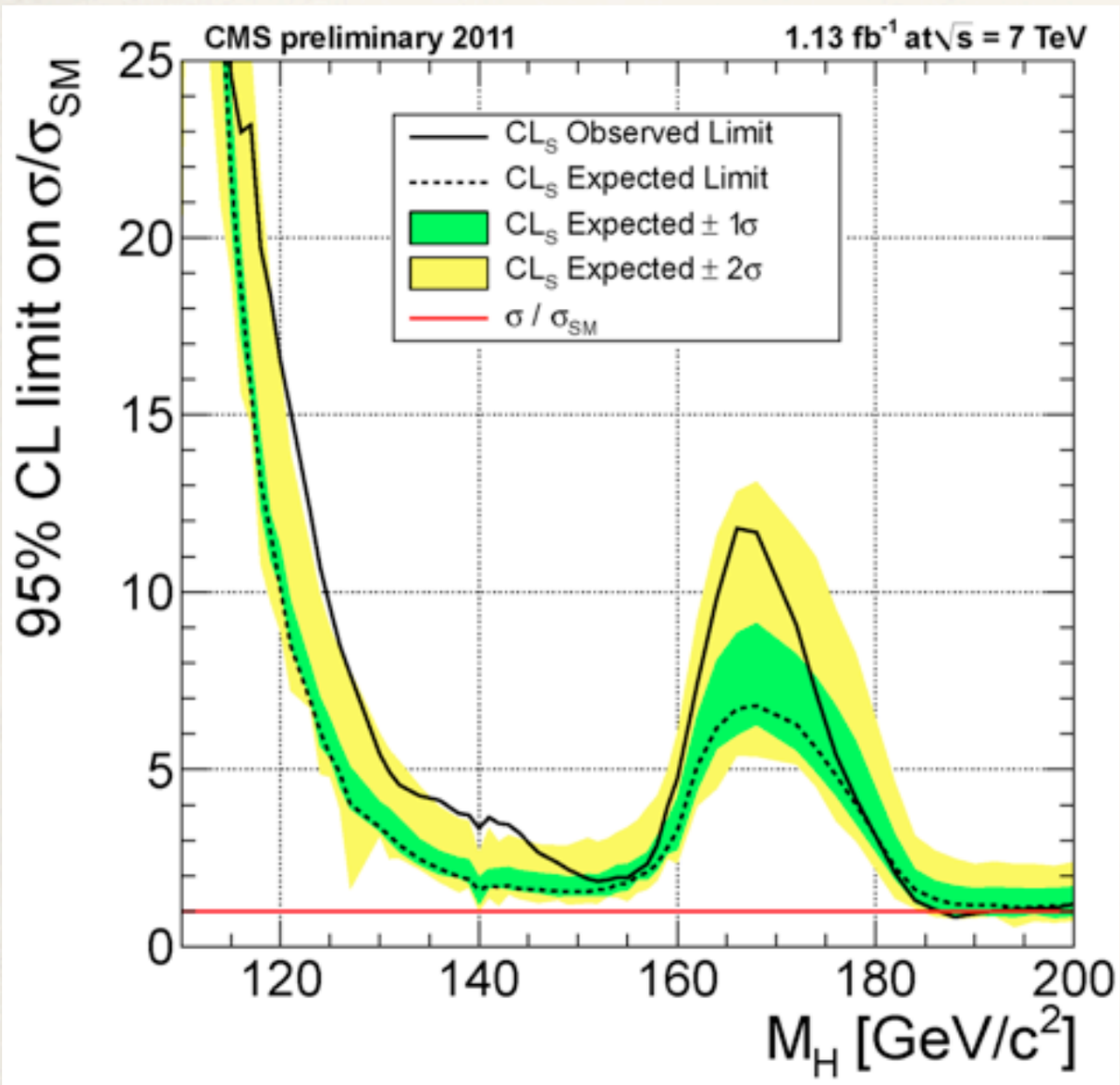
H→ZZ*→2l2q: 4th generation limits





HZZ(4l): SM zoom and SM4

SM, zoom



4th generation