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Summary of non-SM Higgs boson searches at the LHC

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(on behalf of the ATLAS and CMS collaborations)

Outline

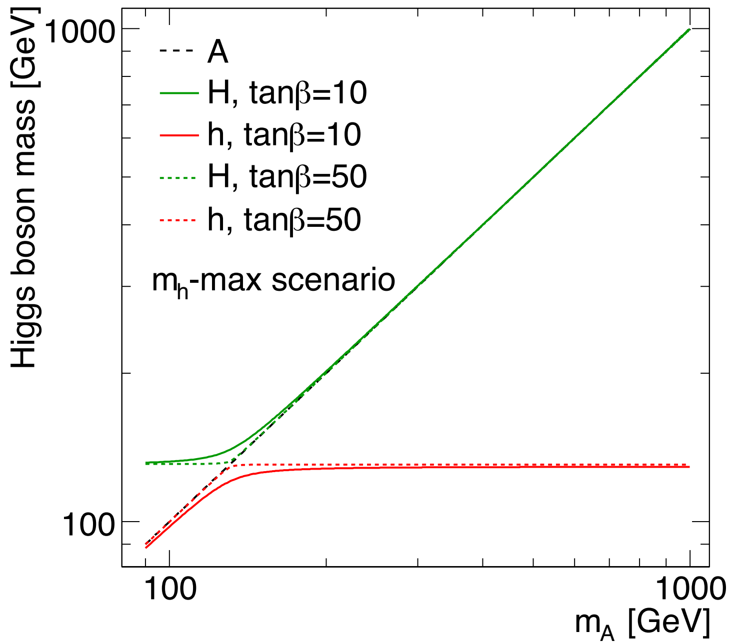
Model	Channel	ATLAS	fb^{-1}	CMS	fb^{-1}
2HDM (MSSM)	$h/H/A \to \tau\tau$	ATLAS-CONF-2011-132	1.06	arXiv:1202.4083	4.6
	$H^{\pm} \to \tau\nu$	arXiv:1204.2760	4.6	CMS-HIG-11-019	2
	$H^{\pm} \to cs$	ATLAS-CONF-2011-094	0.04		
NMSSM	$a_1 \to \mu\mu$	ATLAS-CONF-2011-020	0.04	CMS-HIG-12-004	1.3
Fermiophobic	$h \to \gamma\gamma$	arXiv:1205.0701	4.9	CMS-HIG-12-002	4.8
Doubly Charged	$\Phi^{\pm\pm} \to l^{\pm}l^{\pm}$	arxiv:1201.1091	1.6	CMS-HIG-12-005	4.6

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11029TWiki

2 Higgs Doublet Models (MSSM)

- 5 Higgs bosons: **h, H, A, H$^\pm$**
- Higgs sector completely defined at tree level by 2 parameters: **m_A, tanβ**
- In MSSM couplings to down-type fermions can be enhanced (**b-quark and tau-lepton modes dominant**) while vector couplings suppressed
- Depending on tanβ, h or H are nearly mass degenerate with A: **one light** and **one heavy** neutral Higgs signal



Neutral MSSM Higgs boson coupling strengths

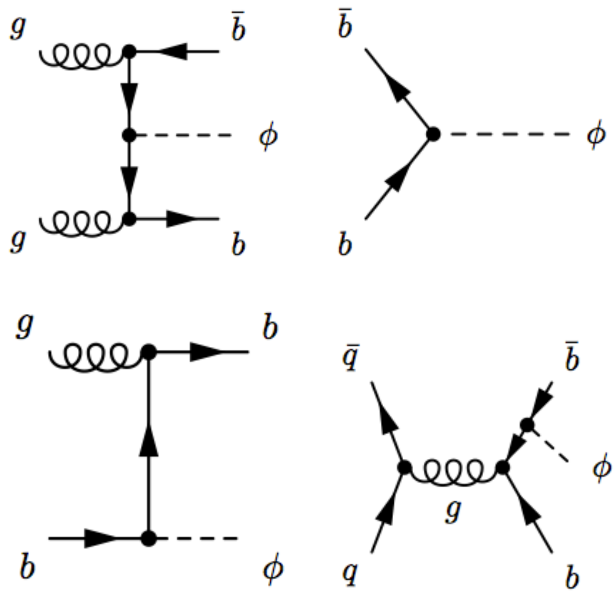
Higgs Boson	f_u	f_d	W/Z
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\alpha-\beta)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\alpha-\beta)$
A	$1/\tan\beta$	$\tan\beta$	-

w.r.t SM couplings...

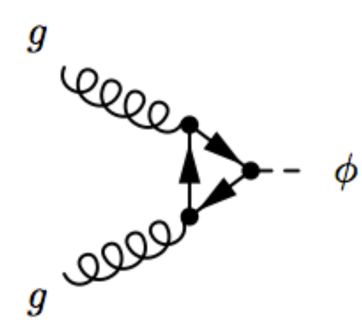
Neutral MSSM Higgs bosons

- Production modes:
  - gluon-fusion
  - b-quark associated
- Decay modes:
  - bb (~90%) (huge bkg)
  - **ττ (~10%)**
- h/H/A → ττ:
  - had-had (44%) (ATLAS 1fb^{-1})
  - lep-had (46%) (ATLAS 1fb^{-1}+CMS 4.7fb^{-1})
  - lep-lep (10%) (ATLAS 1fb^{-1}+CMS 4.7fb^{-1})

b-quark associated
(enhanced at high tanβ)



Gluon Fusion



Selection

$\tau_h + \tau_h$

- At least 2 τ_h
- No electrons or muons
- $q(\tau_1).q(\tau_2)<0$
- EtMiss>25 GeV

$e/\mu + \tau_h$

- 1 electron or muon
- 1 τ_h
- $q(e/\mu).q(\tau_h)<0$
- Suppression of W+jets and ttbar using kinematics

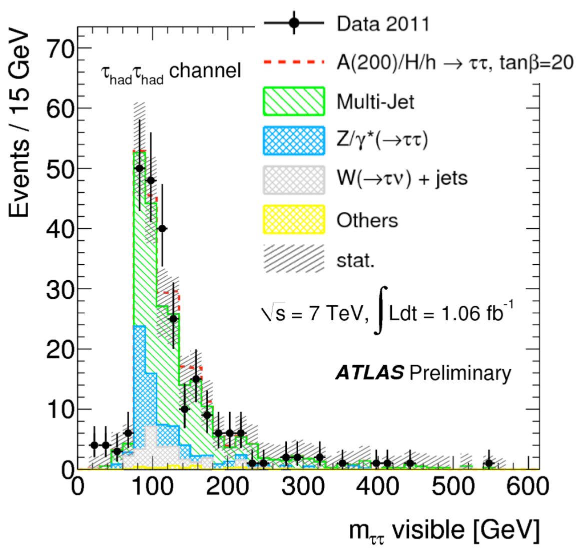
$e + \mu$

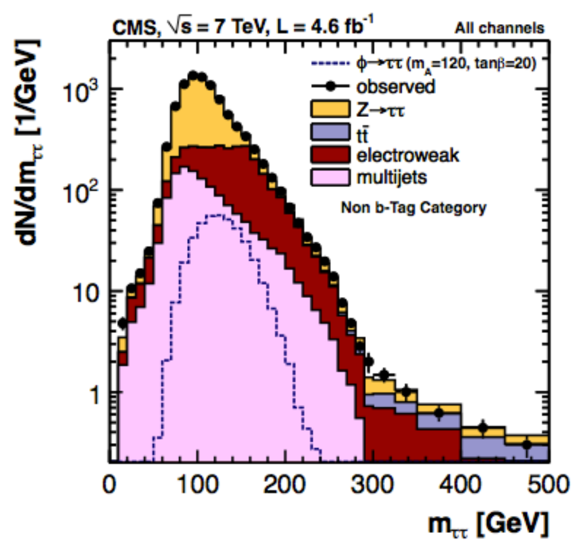
- 1 electron and 1 muon
- $q(e).q(\mu)<0$
- Suppression of top-quark and di-boson using kinematics

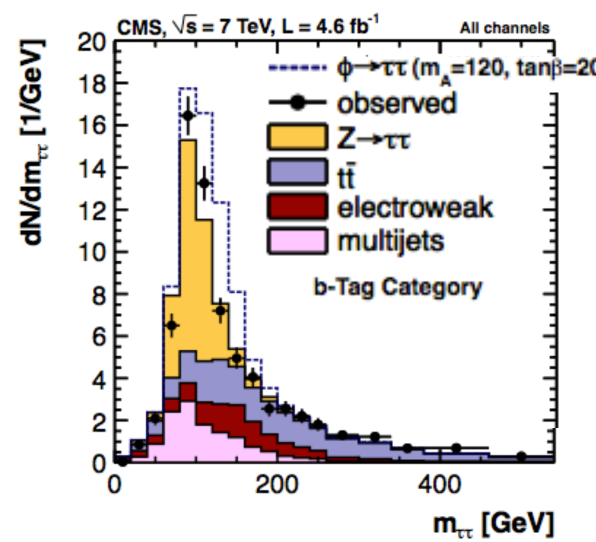
Event Categorisation (based on presence of b-jets) (CMS only)

•**b-tagged:** at least one b-tagged jet found

•**b-vetoed:** no b-tagged jets found



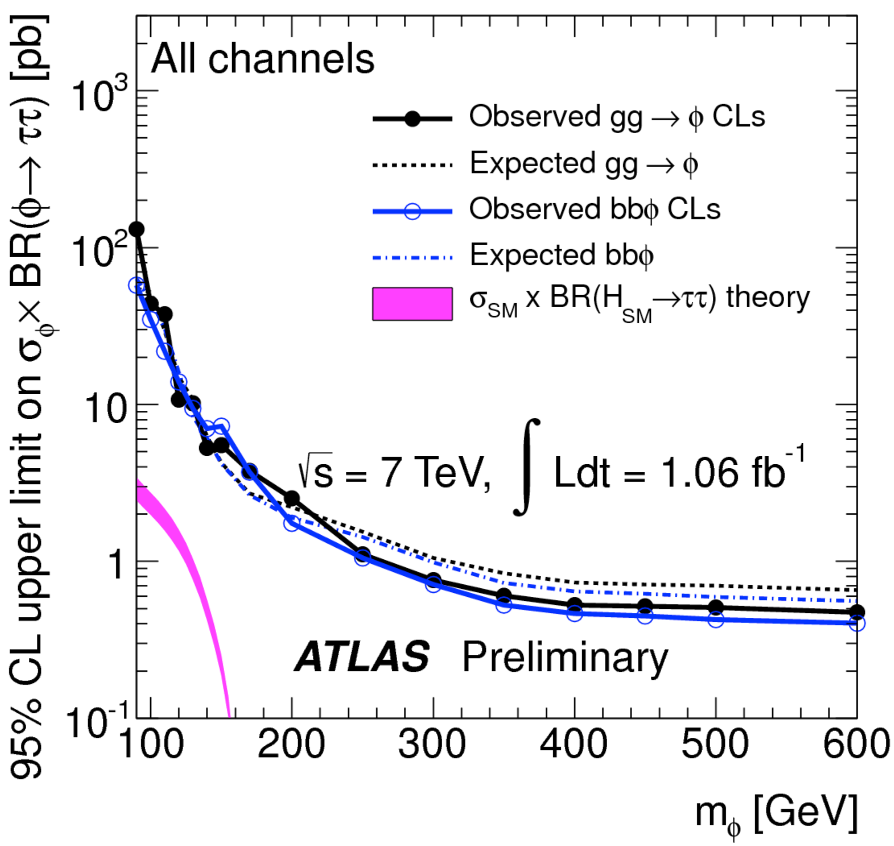




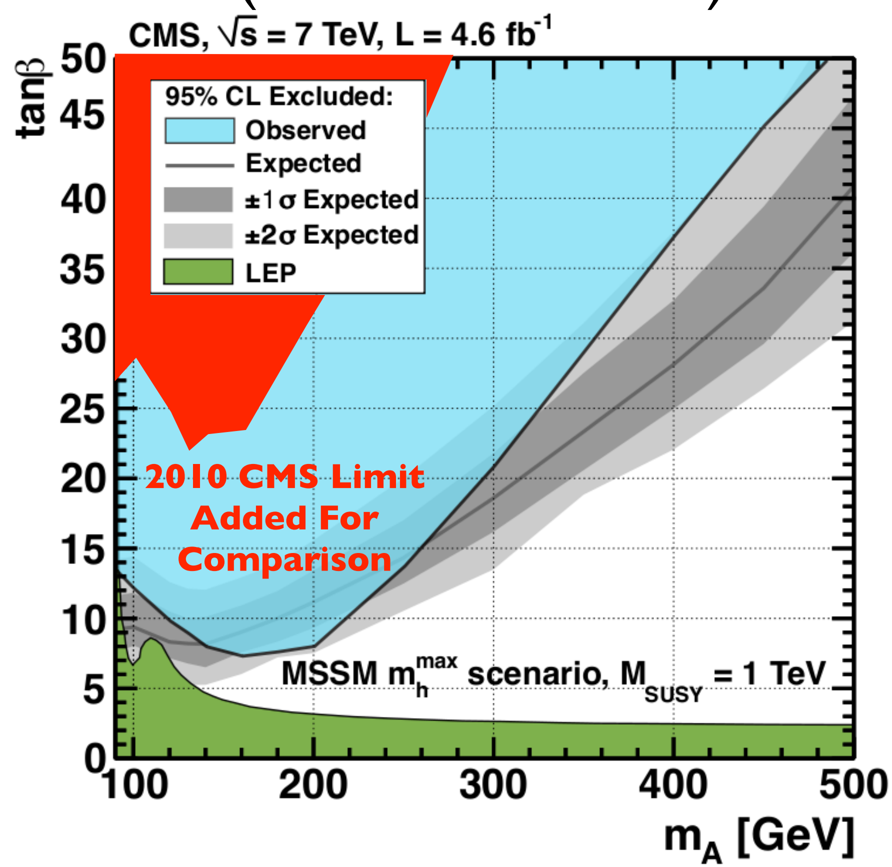
Limits

- Limits extracted from mass distributions
- 2011 results extend much further than 2010!

Model Indep. Limit (ATLAS)

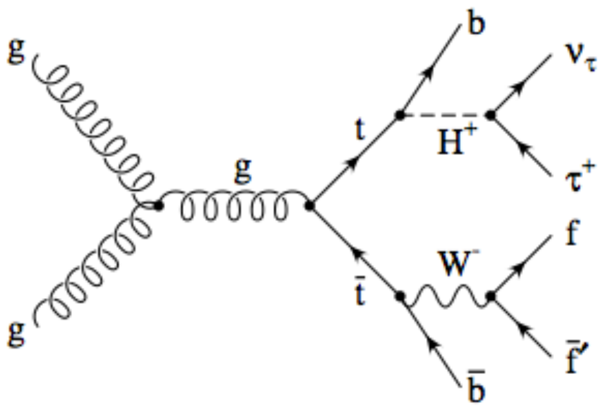


MSSM Limit (CMS)
(m_h-max scenario)



Charged Higgs Bosons

- Production:
  - $m_{H\pm}<m_t$: top-quark decay
  - $m_{H\pm}>m_t$: $gb \rightarrow tH^\pm$ (important, but requires more data!)
- Decay modes:
  - $\tan\beta>3$: $H^\pm \rightarrow \tau\nu$ dominates
  - $\tan\beta<1$: $H^\pm \rightarrow cs$ significant BR



- Channels:

$t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\boldsymbol{\tau_\ell 3\nu})(\boldsymbol{q\bar{q}'})$	(lepton+jets)	(ATLAS)
$t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\boldsymbol{\tau_h 2\nu})(\boldsymbol{\ell\nu})$	(tau+lepton)	(ATLAS+CMS)
$t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\boldsymbol{\tau_h 2\nu})(\boldsymbol{q\bar{q}'})$	(tau+jets)	(ATLAS+CMS)
$t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_\ell 3\nu)(\ell\nu)$	(lep+lep)	(CMS+ATLAS)
$t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(c\bar{s})(\ell\nu)$	(see backup...)	(ATLAS)

Selection

lepton+jets

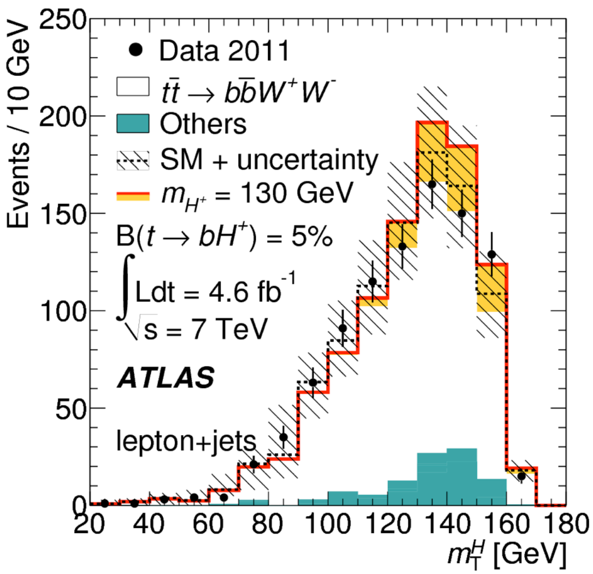
- 1 electron or muon
- no taus
- at least 4 jets (2 b-tagged)
- large EtMiss
- correctly reconstructed hadronic top decay
- kinematic selection to reduce SM top background

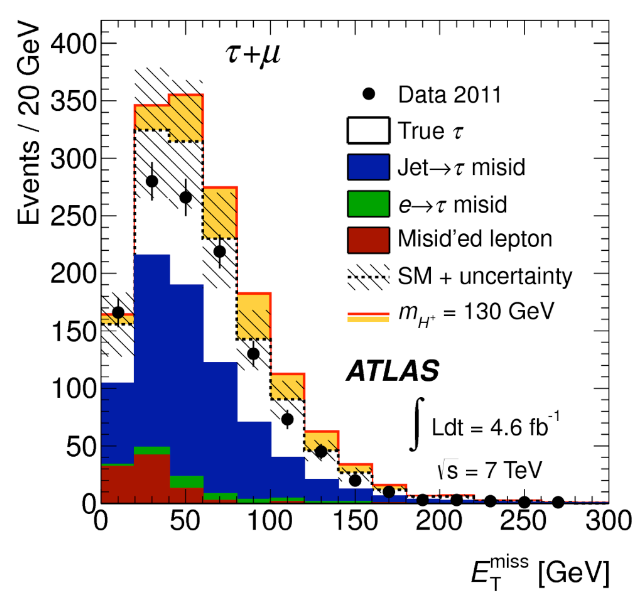
tau+lepton

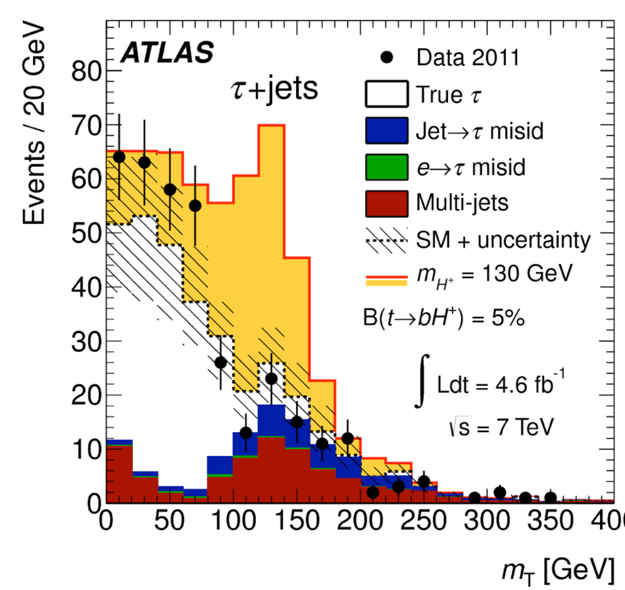
- 1 electron or muon
- 1 τ_h
- $q(e/\mu).q(\tau_h)<0$
- at least 2 jets (≥1 b-tagged)
- Σp_T > 100 GeV

tau+jets

- at least 4 jets (≥1 b-tagged)
- 1 τ_h
- no electrons or muons
- large EtMiss
- correctly reconstructed hadronic top decay

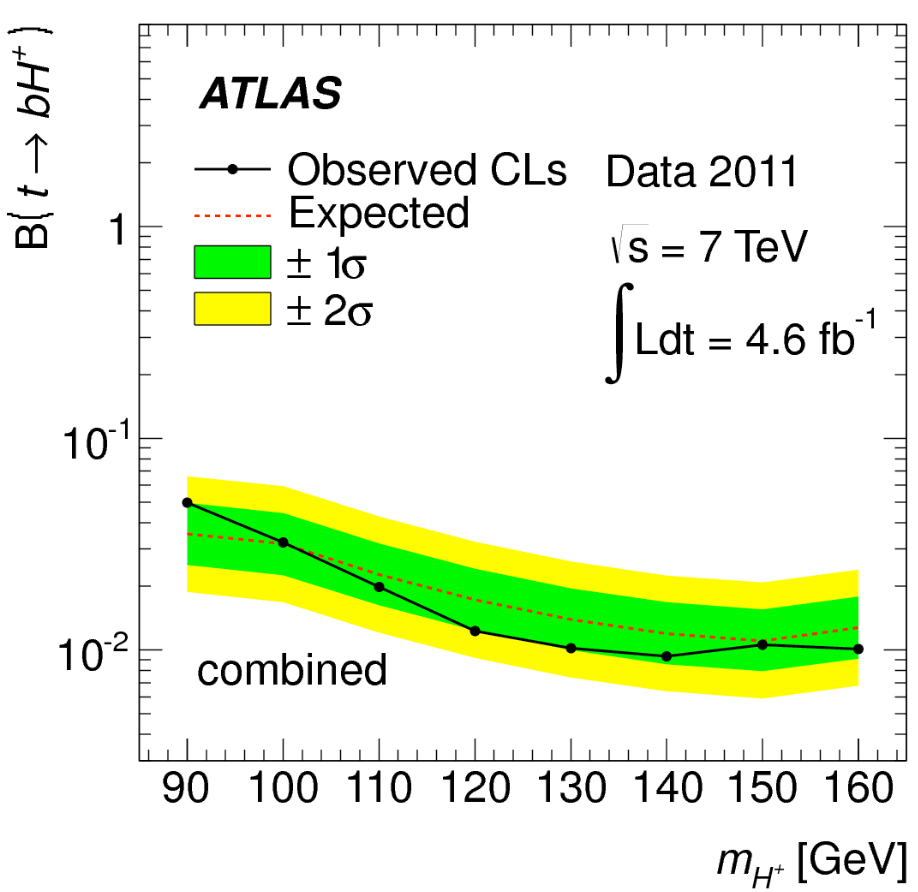


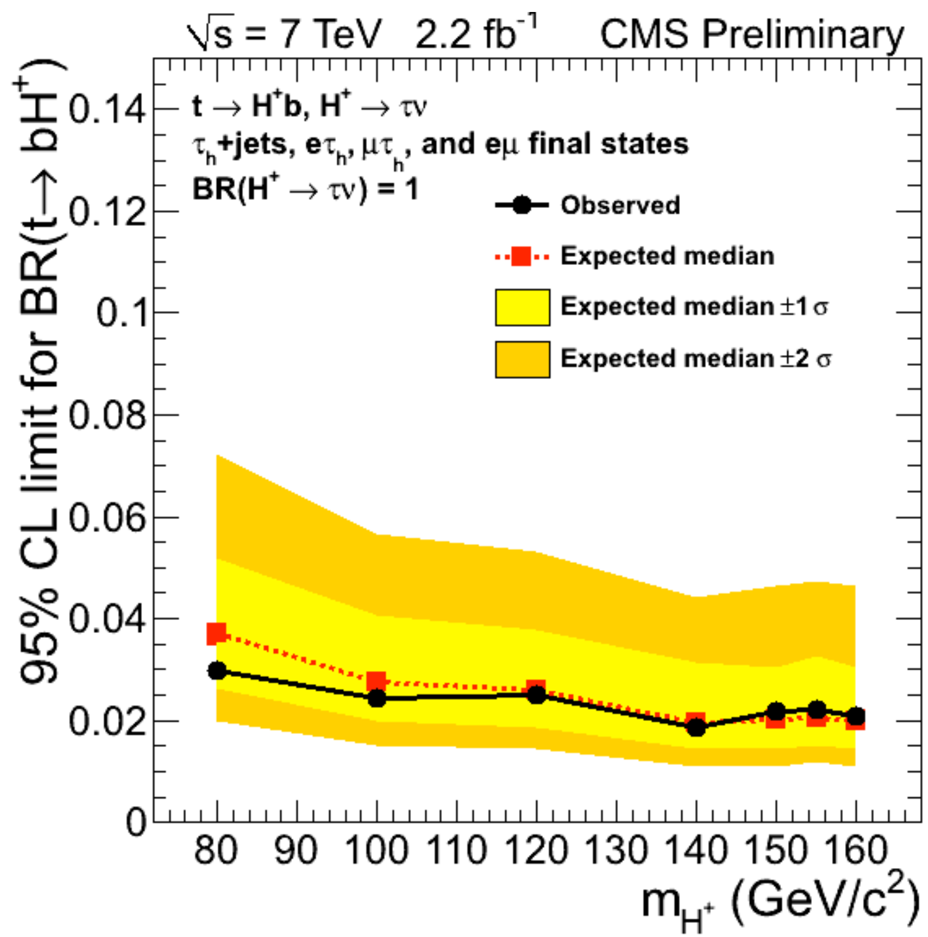




Charged Higgs Limits

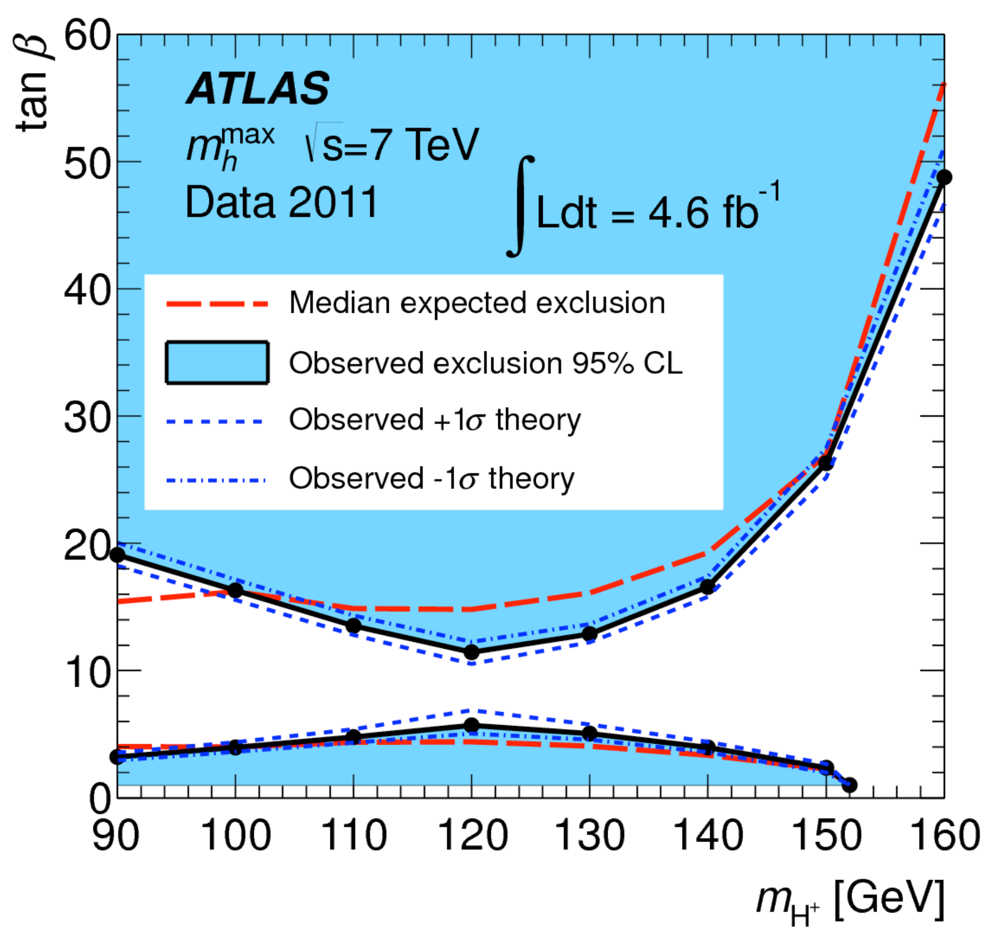
- Limits on BR($t \to bH^\pm$) extracted from the primary discriminating variable in each channel (eg. m_T, EtMiss...) assuming Br($H^\pm \to \tau\nu$)=1
- Limit 1-5% for $m_{H\pm}$<160 GeV (Tevatron limit 15-20%)

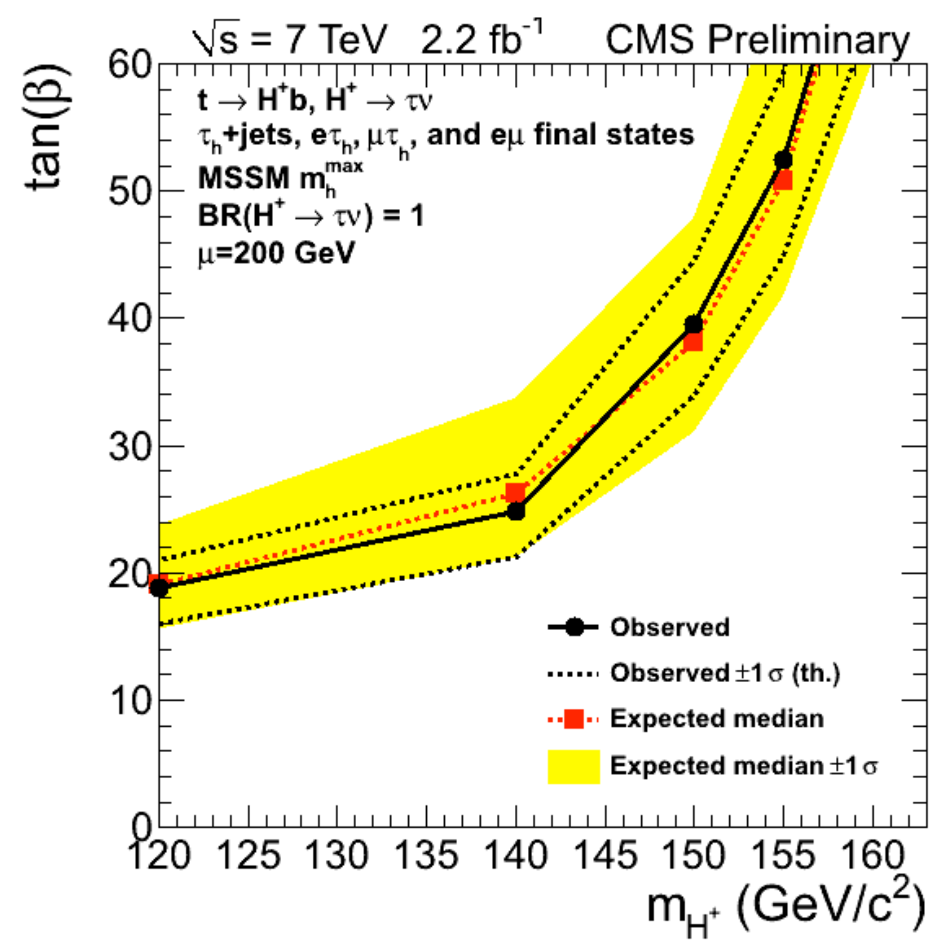




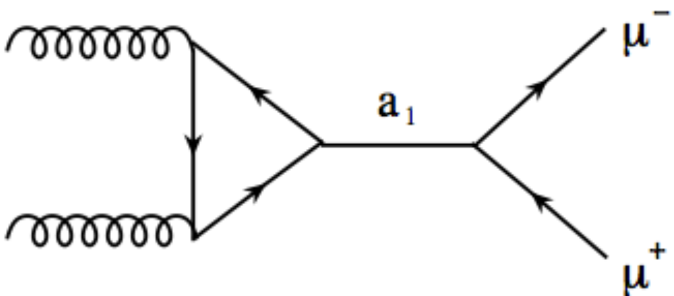
Charged MSSM Higgs Limits

- Limits on a charged MSSM Higgs bosons (m_h-max scenario)





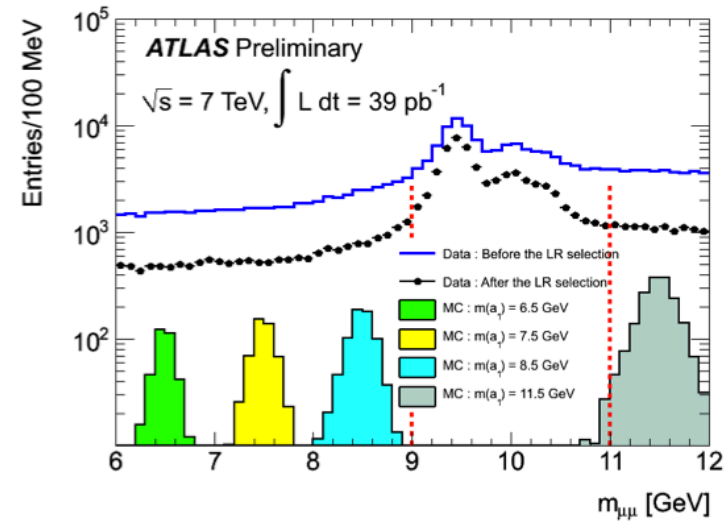
NMSSM

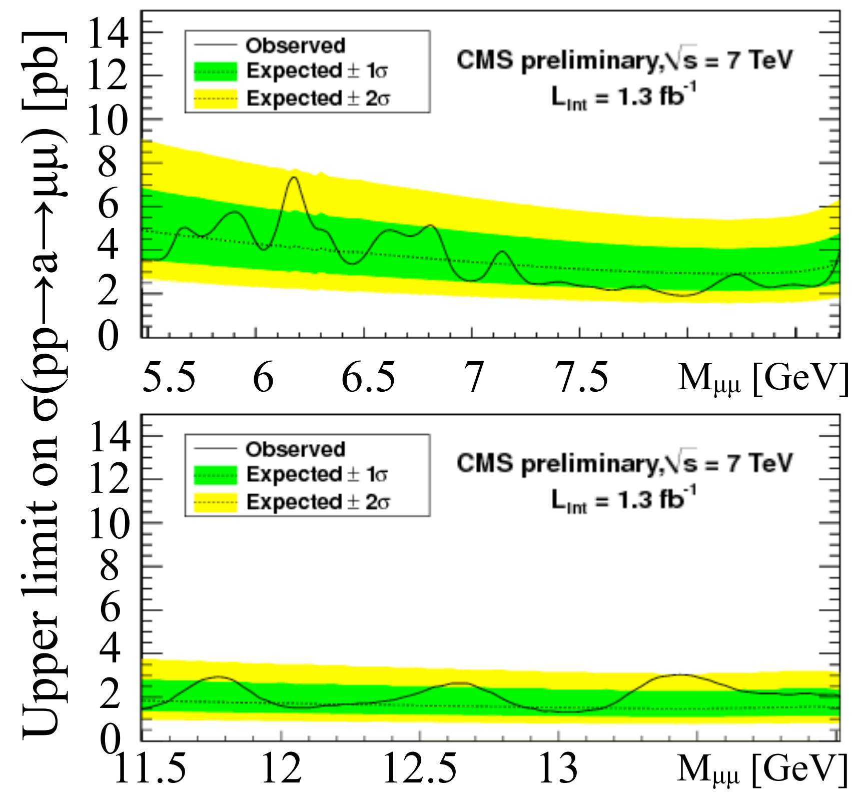


- **NMSSM**: introduces a **singlet scalar field** to solve μ problem
  - 3 CP-even scalars (h_1,h_2,h_3)
  - 2 CP-odd scalars (**a_1**,a_2)
  - 2 Charged (H^+,H^-)
- a_1 can be **very light**: $m_{a1}<2m_B$

Analysis

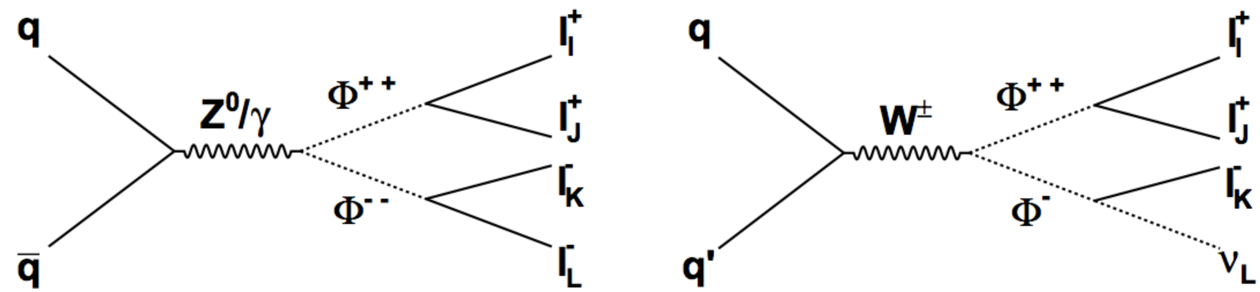
- Search for narrow resonance in di-muon invariant mass distribution between 5.5 and 14 GeV (not including ϒ region)
- Require opposite-sign isolated di-muons
- Pick best di-muon comb. using vertex info
- Set limits by **fitting to mass spectrum**





Doubly Charged Higgs

- Minimal type II neutrino see-saw model has one Higgs triplet, Φ
- Contains $\Phi^{\pm\pm}$
- Observation of $\Phi^{\pm\pm}$ would make type II see-saw most promising framework for neutrino mass generation.



Assumptions:

- $\Phi^{\pm\pm}$ and $\Phi^{\pm}$ degenerate in mass
- $\Phi^{\pm\pm} \rightarrow WW$ suppressed

No other assumptions on $\Phi^{\pm\pm}$ branching fractions.

Construct benchmark models with different leptonic branching fractions

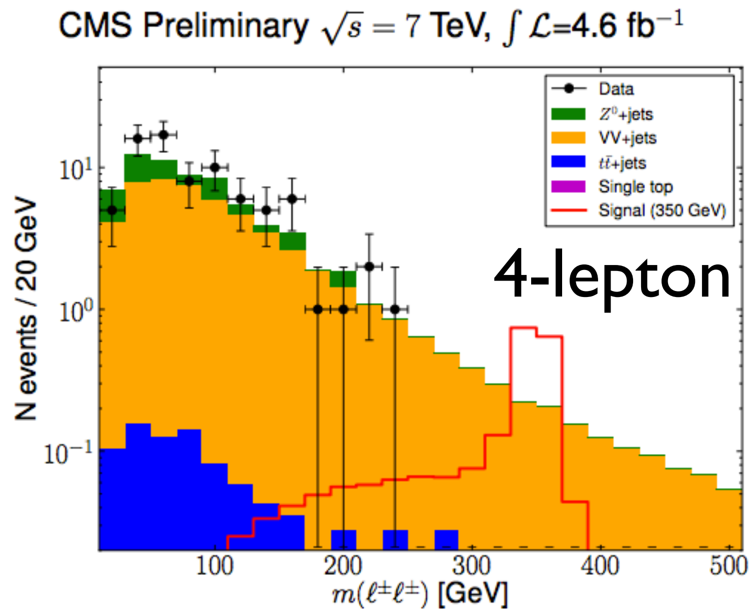
Branching fractions

Benchmark point	ee	eμ	eτ	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	0.50	0	0	0.125	0.25	0.125
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

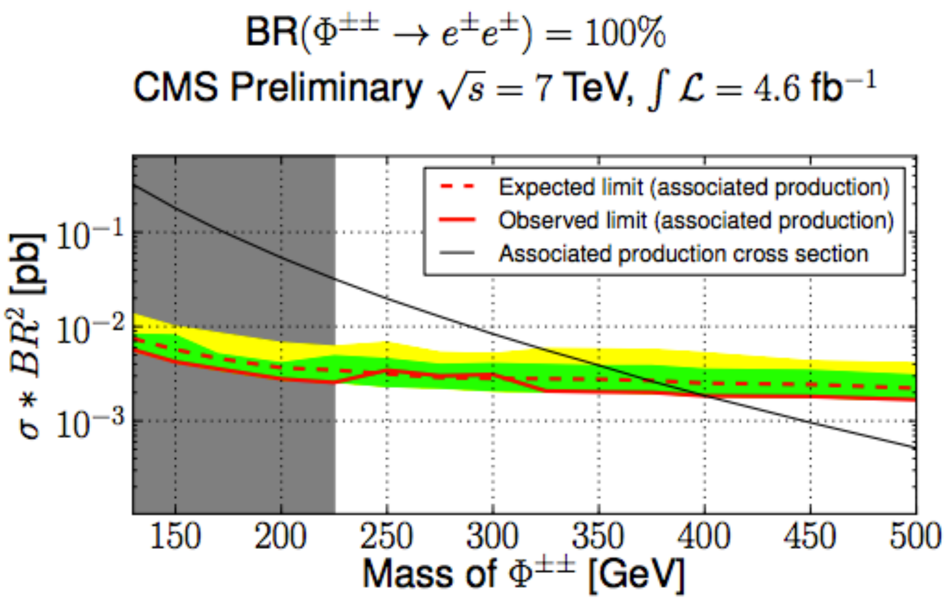
Analysis (CMS)

Selection

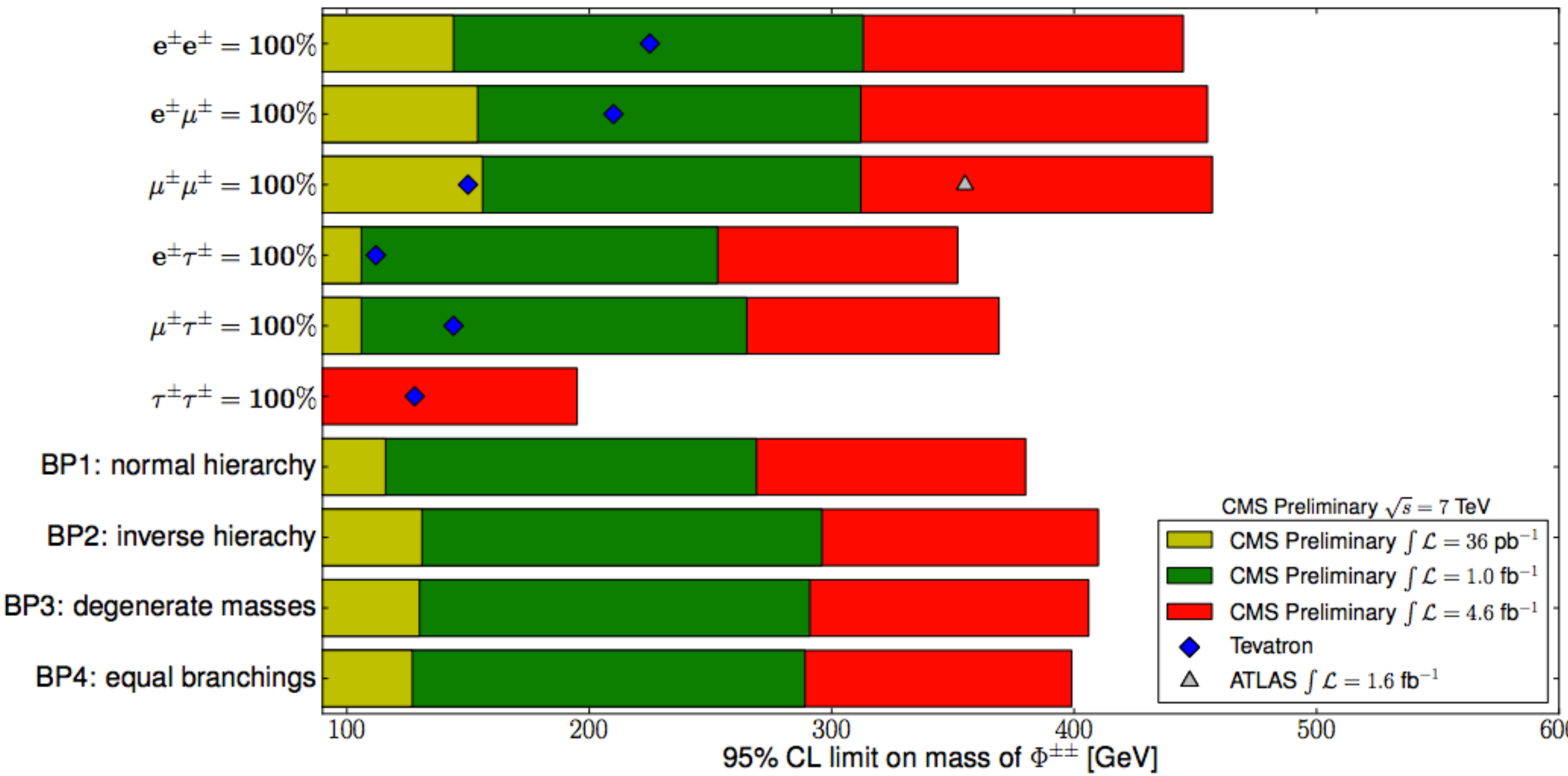
- At least 2 leptons
- Discard pairs at low mass or near Z peak
- Large Σp_T
- Same-sign leptons not back-to-back
- Moderate EtMiss (tau channels)



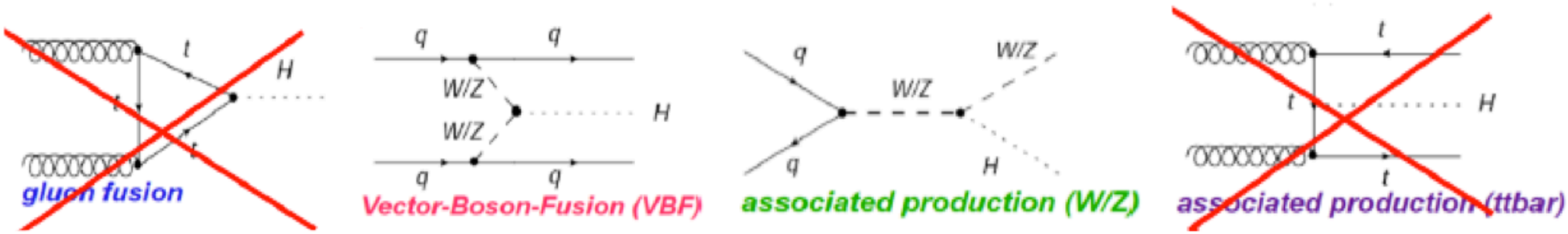
- Analyse both 3 and 4-lepton final states with:
  - $\Phi^{\pm\pm} \rightarrow ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$
- Limits extracted by counting events in mass window
- Background in light-lepton channels estimated from mass side-band fit
- Background in tau channels estimated using 2D-sideband, defined with tauID and mass (3τ) or Σp_T (4τ)



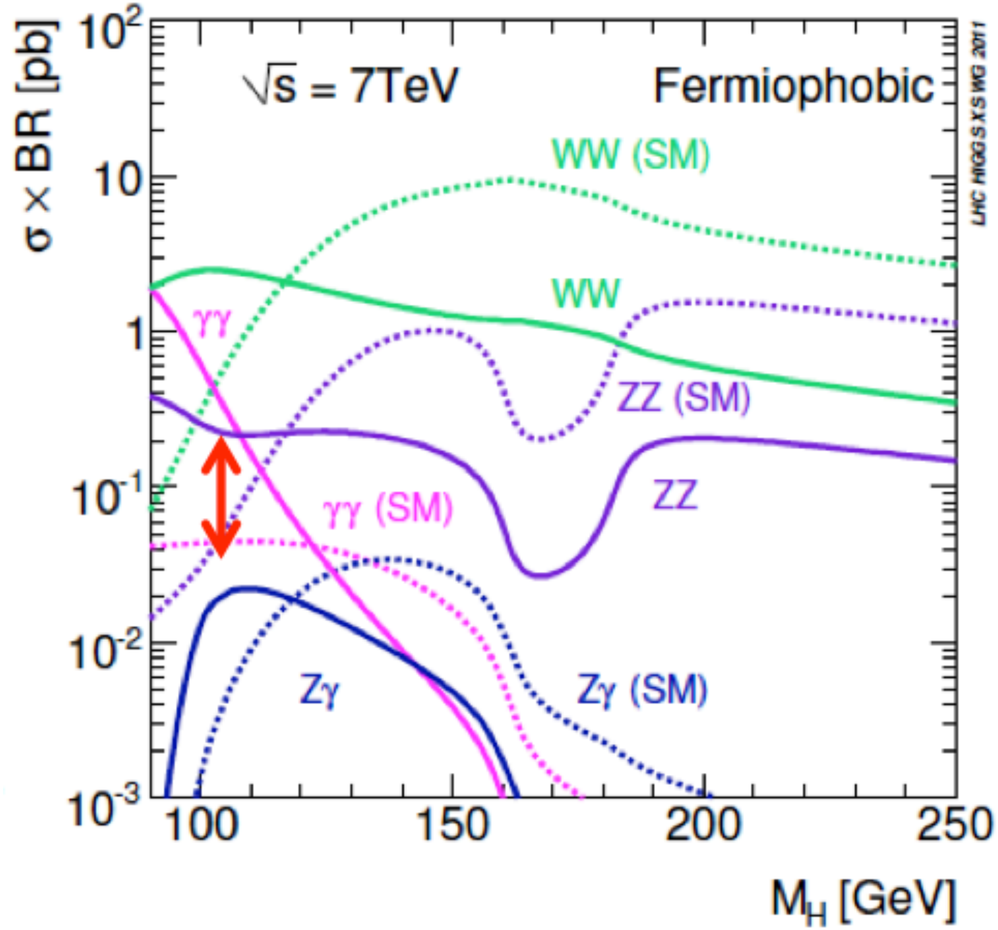
Doubly Charged Higgs Limits



Fermiophobic Higgs



- **Suppressed Higgs couplings to fermions** in 2HDM and Higgs triplet models
- Here: simple benchmark model (LEP)
  - no fermion-Higgs couplings
  - SM boson-Higgs couplings
- Decays to **γγ**, WW, ZZ, Zγ
- Larger σxBR than SM for light Higgs
- higher Higgs p_T



Fermiophobic Higgs Limits

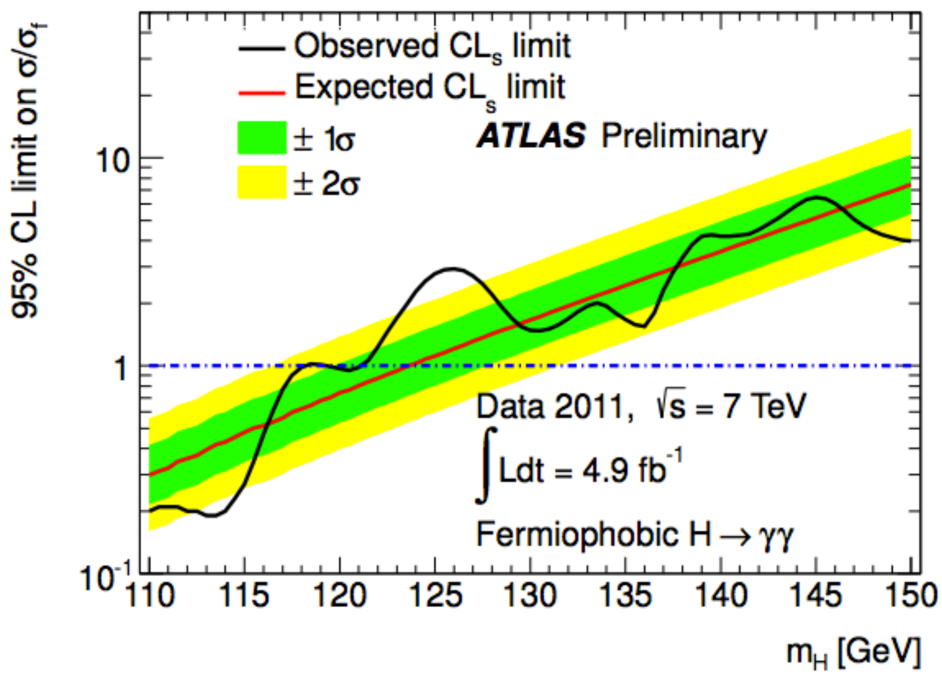
Selection

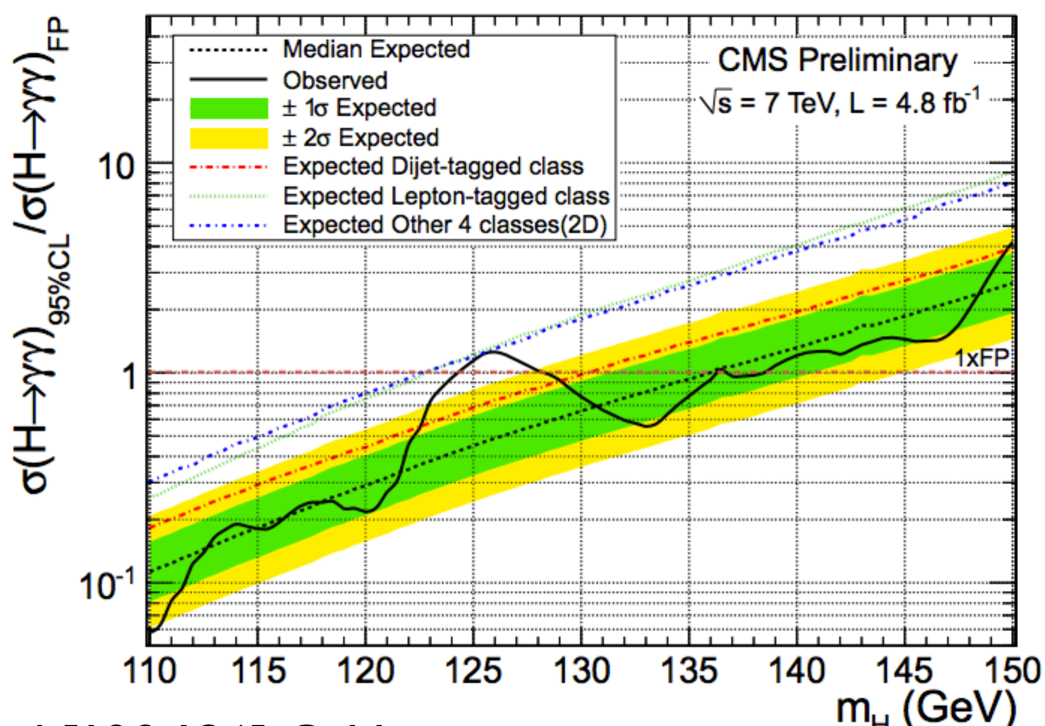
- 2 isolated photons
- Categorise events for best sensitivity

Event Categorisation

- CMS:
  - dijet-tagged (VBF production)
  - lepton-tagged (VH production)
  - inclusive (not tagged)
- ATLAS:
  - 9 categ. using p_{Tt}, η, (un)converted γs

- Limits extracted from fit to di-photon mass sepctrum





excluded at 95% CL in ranges [110,124] and [128,136] GeV...

Summary

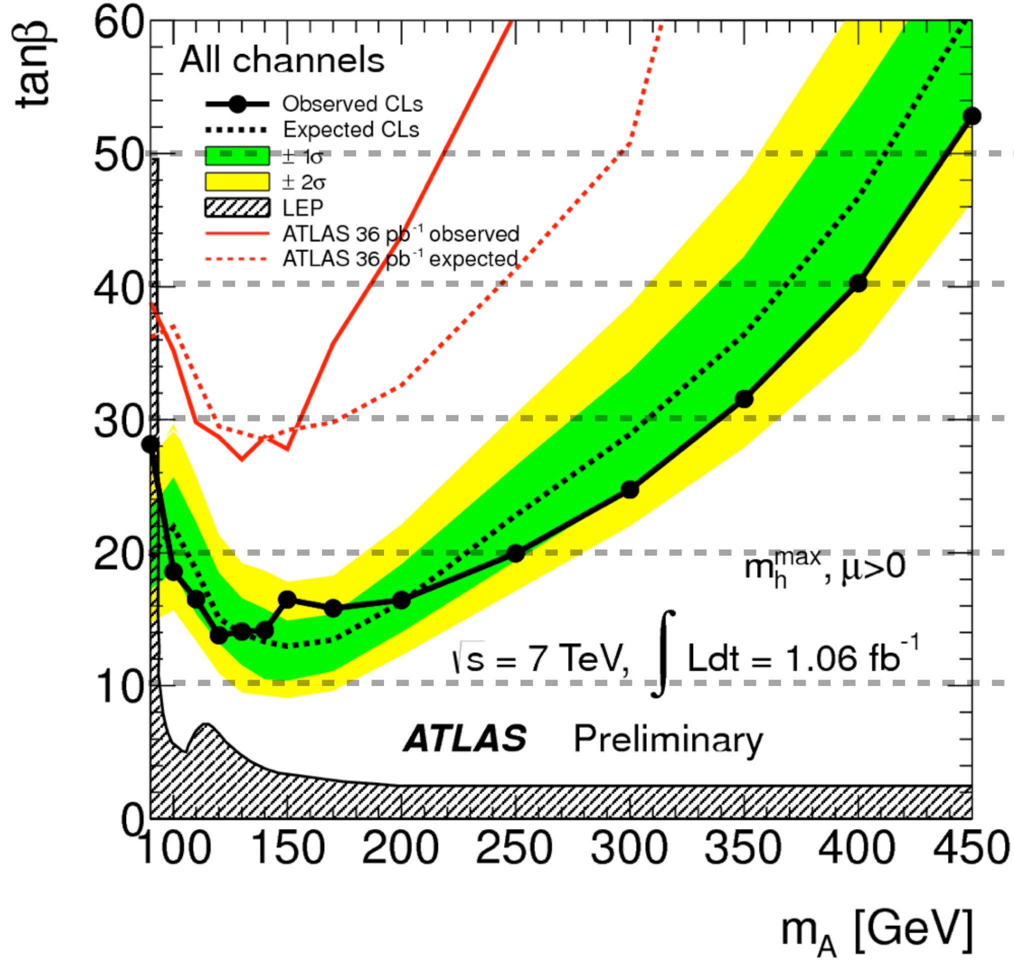
- Charged and neutral MSSM Higgs bosons ruled out over large regions of parameter space
- Doubly charged Higgs boson ruled out below ~400 GeV
- Still lots of parameter-space left at high-mass
- Fingers crossed we'll find something, so stay tuned!

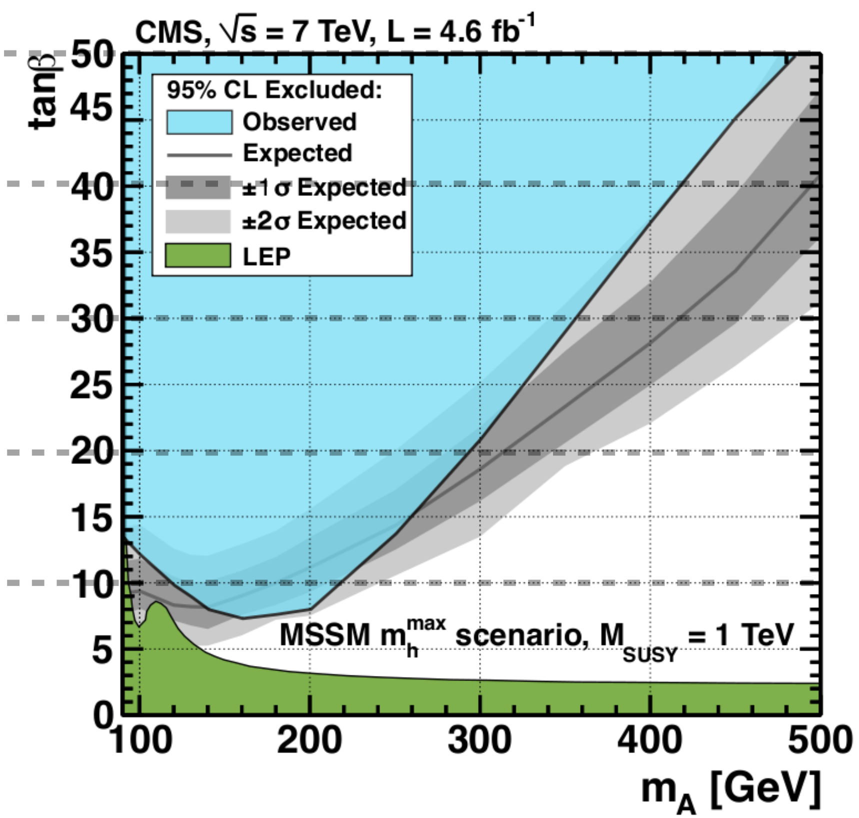
Backup

Neutral MSSM Higgs Boson Searches

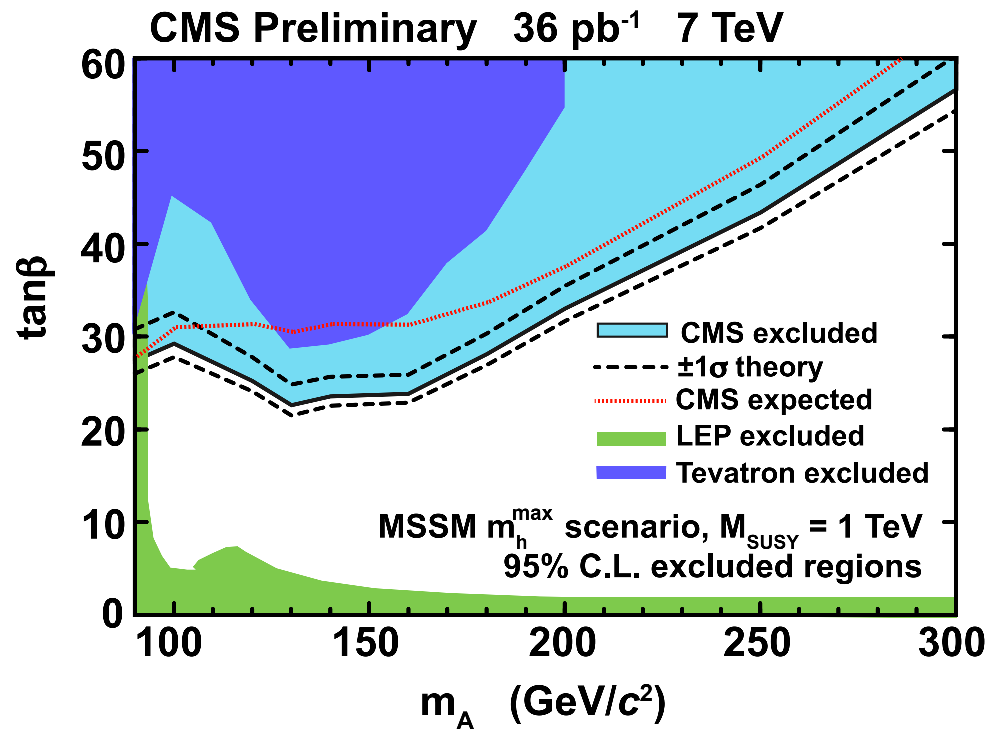
Limits

- Limits extracted from mass distribution
- 2011 results extend much further than 2010!





2010 Limit



CMS Preliminary 36 pb^{-1} 7 TeV
tanβ
m_A (GeV/c^2)
CMS excluded
±1σ theory
CMS expected
LEP excluded
Tevatron excluded
MSSM m_h^{max} scenario, M_{SUSY} = 1 TeV
95% C.L. excluded regions

ATLAS Summary Tables

MC Contributions (m_A=120 GeV, tanβ=20)

	Data	Total MC bkg (w/o QCD)	W+jets	Di-boson	$t\bar{t}$+ single-top	$Z/\gamma^* \to ee,\mu\mu$	$Z/\gamma^* \to \tau^+\tau^-$	A/H/h signal
$e\mu$	2472	2496±27	30±15	109±5	100±2	40±4	2217±22	155±6
$e\tau_{had}$	626	775±40	188±31	4.1±0.5	33± 3	64±5	486±24	41±4
$\mu\tau_{had}$	1287	1378±43	239±33	5.4±0.6	51±4	105±7	978±26	75±5
$\tau_{had}\tau_{had}$	245	76± 7	25±5	1.4±0.3	2.0±0.9	-	48±5	19±1

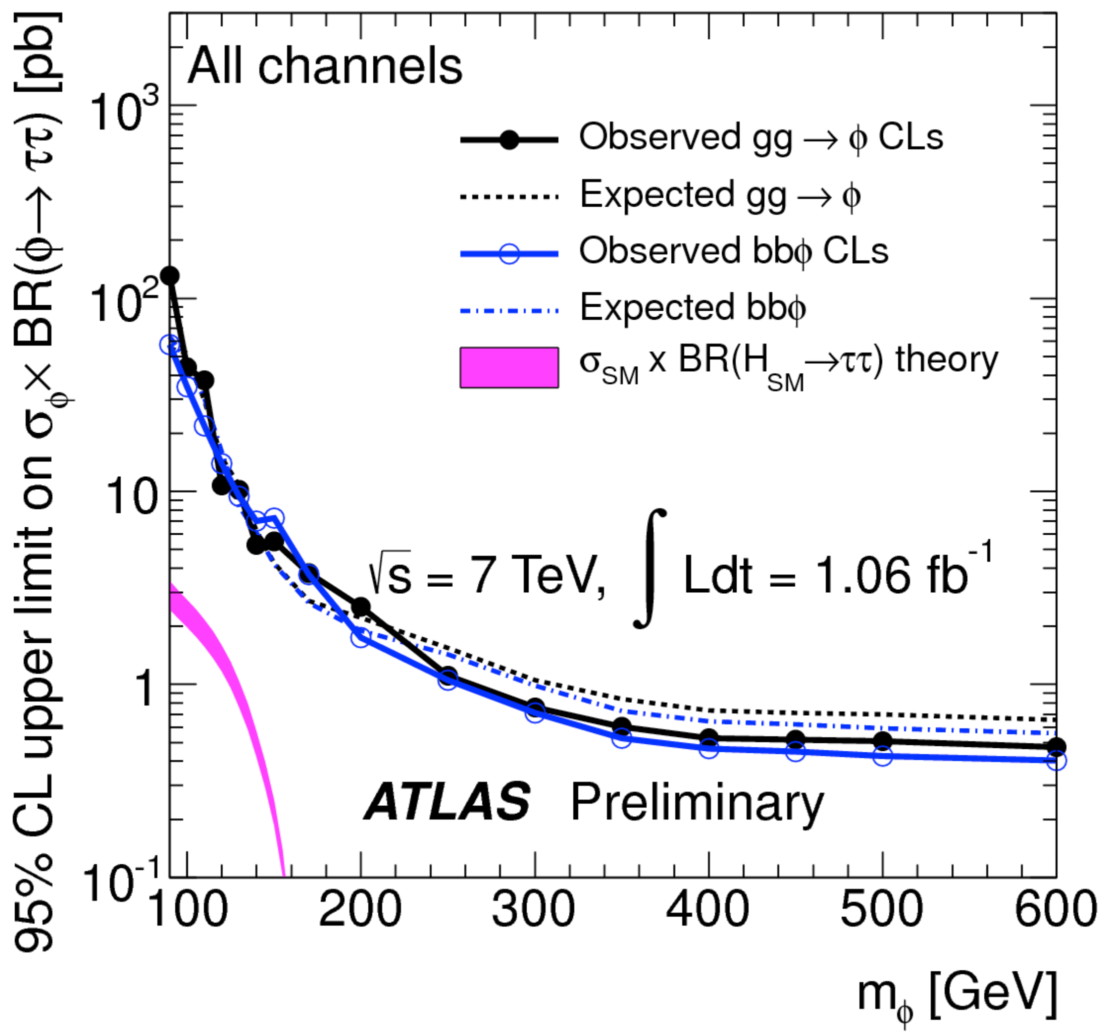
Event Totals

Final state	Exp. Background	Data
$e\mu$	$(2.6 \pm 0.2) \times 10^3$	2472
$\ell\tau_{had}$	$(2.1 \pm 0.4) \times 10^3$	1913
$\tau_{had}\tau_{had}$	$233\,^{+44}_{-28}$	245
Sum	$(4.9 \pm 0.6) \times 10^3$	4630

Systematic Uncertainties (%)

	W+jets	Di-boson	$t\bar{t}$+ single-top	$Z/\gamma^* \to ee,\mu\mu$	$Z/\gamma^* \to \tau^+\tau^-$	Signal
$\sigma_{inclusive}$	-/-/5	7	10	5/5/-	5	14/14/16
Acceptance	-/-/20	4/2/7	3/2/9	2/14/-	5/14/14	5/7/9
e efficiency	-/-/0.8	4/3.1/0.5	4/3.6/0.3	4/3.1/-	4/3.0/0.5	4/3.6/0.1
μ efficiency	-/-/0.3	2/1.2/0.4	2/1.1/0.0	2/1.3/-	2/1.8/0.4	2/1.0/0.1
τ efficiency and fake rate	-/-/21	-/9.1/15	-/9.1/13	-/48/-	-/9.1/15	-/9.1/15
Energy scales and resolution	$-/-/^{+34}_{-21}$	$2/^{+19}_{-9}/^{+26}_{-12}$	$6/^{+5}_{-4}/12$	$1/^{+39}_{-25}/-$	$1/11/^{+63}_{-23}$	$1/^{+30}_{-23}/^{+9}_{-8}$
Luminosity	-/-/3.7	3.7	3.7	3.7/3.7/-	3.7	3.7
Total uncertainty	$-/-/^{+45}_{-36}$	$10/^{+23}_{-16}/^{+32}_{-22}$	13/15/23	$8/^{+64}_{-56}/-$	$9/21/^{+67}_{-31}$	$16/^{+35}_{-30}/^{+26}_{-25}$

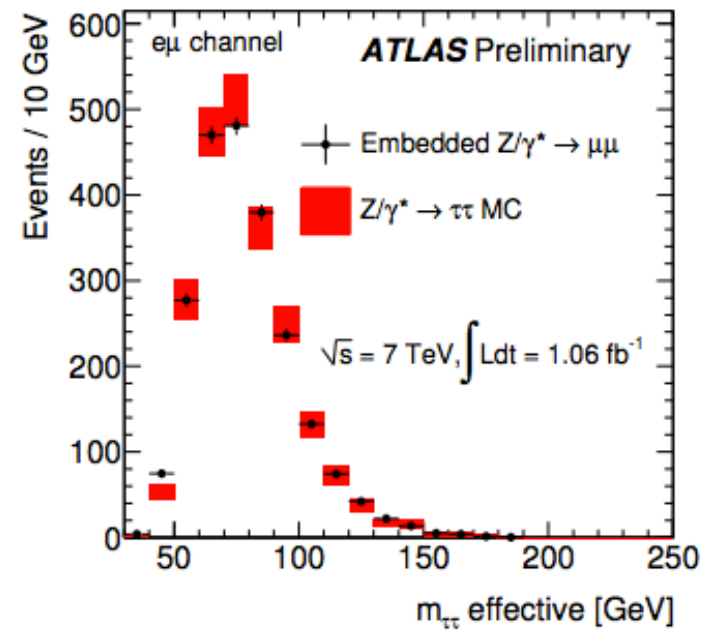
ATLAS Model Indep. Limits



MSSM A/H/h→ττ→eμ (ATLAS)

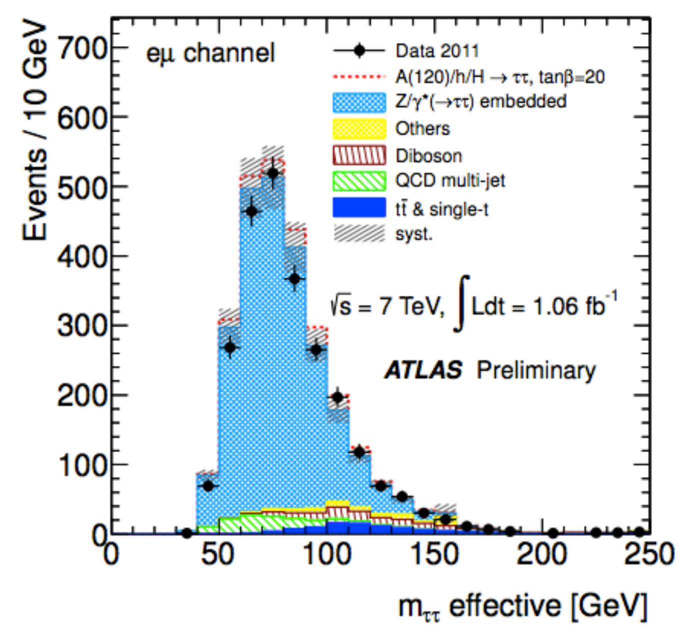
Selection

- Trigger: e(20) or mu(18)
- Offline: 1 e(22) and 1 mu(10) or 1 e(15) and 1mu(20) (isolated)
- q(e).q(mu) < 0
- ΣpT(e,mu,EtMiss) < 120 GeV
- Δφ(e,mu)>2.0



- Use effective mass as final discriminator:

$$m_{\tau\tau}^{\text{effective}} = \sqrt{(p_{\tau^+} + p_{\tau^-} + p_{\text{miss}})^2},$$



- Major Backgrounds:
  - Z/γ→ττ (embedding)
  - Multijet (2D-sideband: lepton isolation, charge product)

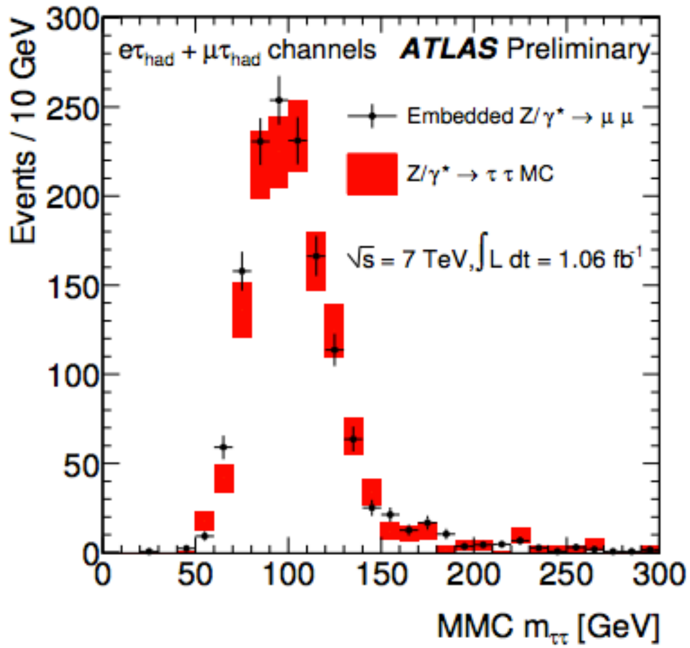
MSSM A/H/h→ττ→lh (ATLAS)

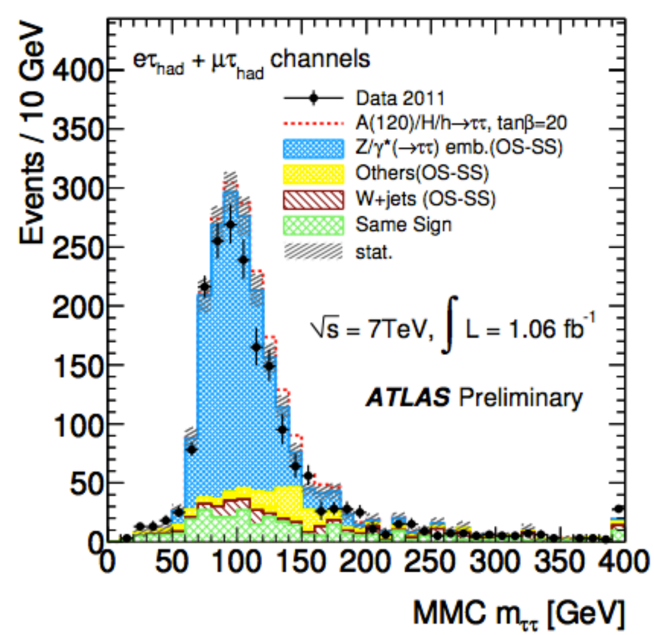
Selection

- Trigger: e(20) or mu(18)
- Offline: 1 e(25) or 1 mu(20) (isolated)
- 1 tau(20)
- No additional leptons
- q(l).q(tau) < 0
- EtMiss > 20 GeV
- m_T(l,EtMiss) < 30 GeV

- Use MMC mass (likelihood estimated mass) as final discriminator (see backup slide)
- Major Backgrounds:
  - Z/γ→ττ (embedding)
  - Multijet + W+jets (OS-SS method):

$$n_{OS}^{Bkg} = n_{SS}^{Bkg} + n_{OS-SS}^{W} + n_{OS-SS}^{Z} + n_{OS-SS}^{other},$$

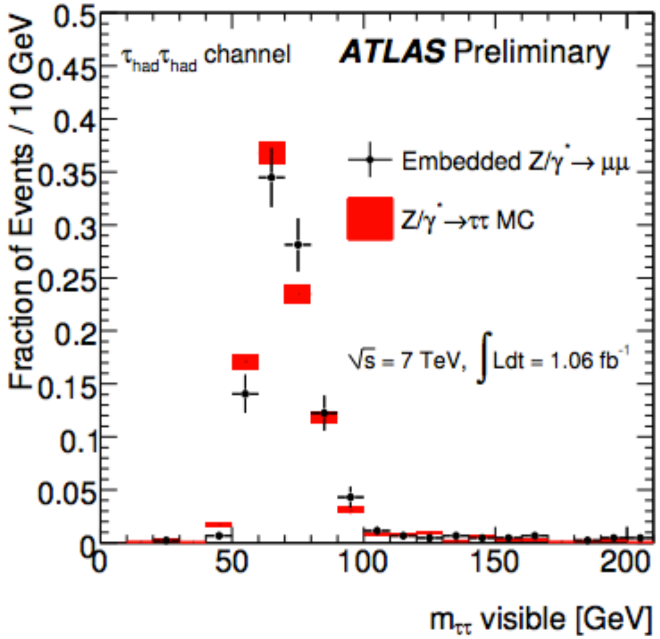




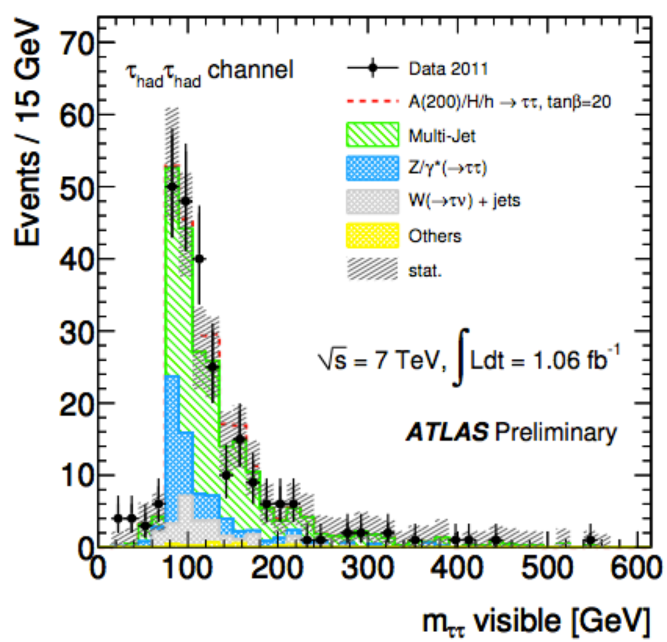
MSSM A/H/h→ττ→hh (ATLAS)

Selection

- Trigger: di-tau (29/20)
- Offline: 2 taus (45/30)
- q(tau1).q(tau2) < 0
- No leptons
- EtMiss > 25 GeV



- Use 'visible mass' as final discriminator
- Major Backgrounds:
  - Z/γ→ττ (MC, with embedding check)
  - Multijet (2D-sideband: tau ID, charge product)



CMS Summary Tables

e-had m_A=120 GeV, tanβ=10

	MSSM	
Process	*Non b-Tag*	*b-Tag*
$Z \to \tau\tau$	14259 ± 1037	135 ± 9
Multijets	6404 ± 301	100 ± 7
W+jets	5432 ± 377	39 ± 3
$Z \to ll$	6146 ± 502	28 ± 4
$t\bar{t}$	47 ± 7	75 ± 11
Dibosons	105 ± 22	1 ± 1
Total Background	32392 ± 1249	378 ± 17
$H \to \tau\tau$	279 ± 29	26 ± 4
Data	32051	391

mu-had m_A=120 GeV, tanβ=10

	MSSM	
Process	*Non b-Tag*	*b-Tag*
$Z \to \tau\tau$	29795 ± 2114	259 ± 18
Multijets	6387 ± 115	160 ± 9
W+jets	9563 ± 628	110 ± 9
$Z \to ll$	924 ± 115	3 ± 1
$t\bar{t}$	101 ± 15	145 ± 20
Dibosons	217 ± 46	5 ± 2
Total Background	46987 ± 2211	681 ± 30
$H \to \tau\tau$	502 ± 52	45 ± 6
Data	47178	680

e-mu m_A=120 GeV, tanβ=10

	MSSM	
Process	*Non b-Tag*	*b-Tag*
$Z \to \tau\tau$	11718 ± 797	112 ± 11
Multijet and W+jets	474 ± 147	15 ± 5
$t\bar{t}$	161 ± 15	289 ± 35
Dibosons	527 ± 84	55 ± 10
Total Background	12881 ± 815	471 ± 38
$H \to \tau\tau$	161 ± 10	17 ± 1.6
Data	12761	468

MSSM Higgs	Expected $\tan\beta$ limit					
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. $\tan\beta$ limit
90	5.19	7.01	8.37	10.6	12.8	12.2
100	6.49	7.45	8.78	10.8	13.4	11.8
120	4.50	6.47	8.09	9.89	12.0	9.84
130	5.37	6.71	7.85	9.69	11.5	9.03
140	5.62	6.63	7.90	9.69	11.6	8.03
160	5.57	6.99	8.51	10.4	12.5	7.11
180	6.75	8.14	9.53	11.3	13.8	7.50
200	7.84	9.12	10.5	12.8	15.0	8.46
250	10.3	12.3	13.9	16.8	19.4	13.8
300	13.5	15.7	18.4	21.4	24.5	20.9
350	17.7	20.1	23.0	26.9	31.1	29.1
400	21.9	24.3	27.9	32.4	37.3	37.3
450	25.0	29.2	33.3	38.8	44.7	45.2
500	30.3	35.7	40.5	47.1	55.0	51.9

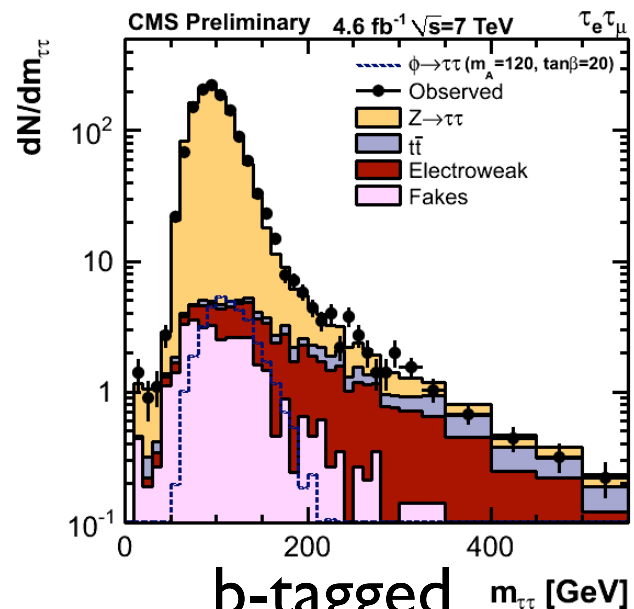
MSSM A/H/h→ττ→eμ (CMS)

Selection

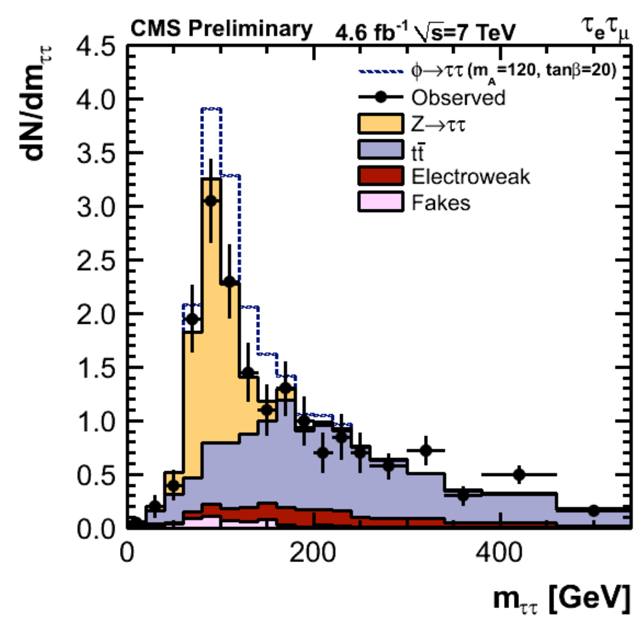
- Trigger: e-mu
- Offline: 1 electron and 1 muon (20/10) (isolated)
- q(e).q(mu) < 0
- $p_\zeta - 0.85 p_\zeta^{vis} > -25$ GeV (see backup)
- At most 1 jet(30)
- b-tagging categories:
  - b-tagged: ≥ 1 b-tag(20)
  - b-vetoed: 0 b-tag(20)

- Use maximum likelihood mass as final discriminator
- Major Backgrounds:
  - Z/γ→ττ (embedding)
  - Multijet+Wjets (lepton isolation fake-factors)

b-vetoed



b-tagged



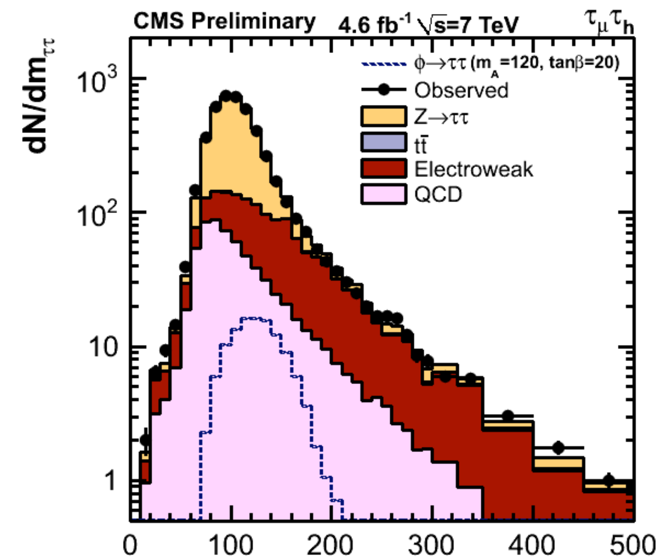
MSSM A/H/h→ττ→lh (CMS)

Selection

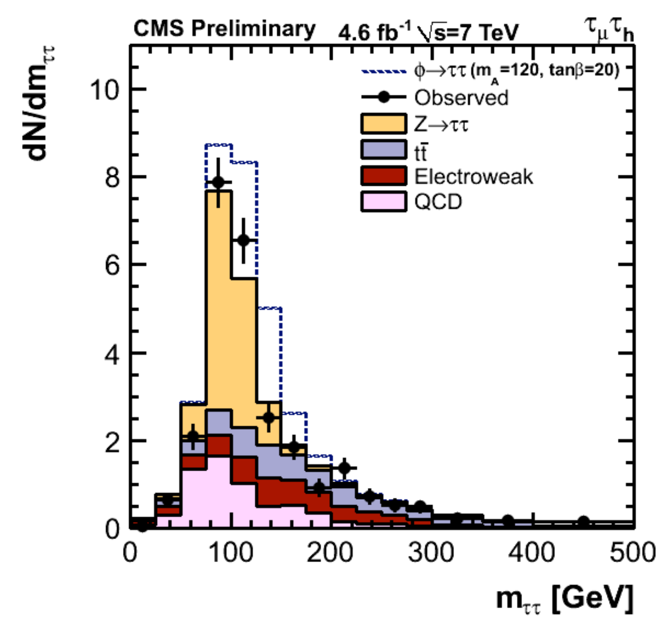
- Trigger: e-tau or mu-tau
- Offline: 1 e(20) or 1 mu(17) (isolated)
- 1 tau(20)
- No additional leptons
- q(l).q(tau) < 0
- $p_\zeta - 0.5p_\zeta^{vis} > -20$ GeV (see backup)

- Use MMC mass (likelihood estimated mass) as final discriminator (see backup slide)
- Major Backgrounds:
  - Z/γ→ττ (embedding)
  - Multijet (SS control region)
  - W+jet (high m_T control region)

b-vetoed



b-tagged



Charged Higgs Boson Searches

ATLAS Summary Tables

Sample	Event yield (lepton+jets)
$t\bar{t}$	$840 \pm 20 \pm 150$
Single top quark	$28 \pm 2\ {}^{+8}_{-6}$
W+jets	$14 \pm 3\ {}^{+6}_{-3}$
Z+jets	$2.1 \pm 0.7\ {}^{+1.2}_{-0.4}$
Diboson	$0.5 \pm 0.1 \pm 0.2$
Misidentified leptons	$55 \pm 10 \pm 20$
$\sum$ SM	$940 \pm 22 \pm 150$
Data	933
$t \to bH^+$ (130 GeV)	$120 \pm 4 \pm 25$
Signal+background	$990 \pm 21 \pm 140$

Sample	Event yield (τ+lepton)	
	$\tau + e$	$\tau + \mu$
True τ	$430 \pm 14 \pm 59$	$570 \pm 15 \pm 75$
Misidentified jet$\to \tau$	$510 \pm 23 \pm 86$	$660 \pm 26 \pm 110$
Misidentified $e \to \tau$	$33 \pm 4 \pm 5$	$34 \pm 4 \pm 6$
Misidentified leptons	$39 \pm 10 \pm 20$	$90 \pm 10 \pm 34$
$\sum$ SM	$1010 \pm 30 \pm 110$	$1360 \pm 30 \pm 140$
Data	880	1219
$t \to bH^+$ (130 GeV)	$220 \pm 6 \pm 29$	$310 \pm 7 \pm 39$
Signal+background	$1160 \pm 30 \pm 100$	$1570 \pm 30 \pm 130$

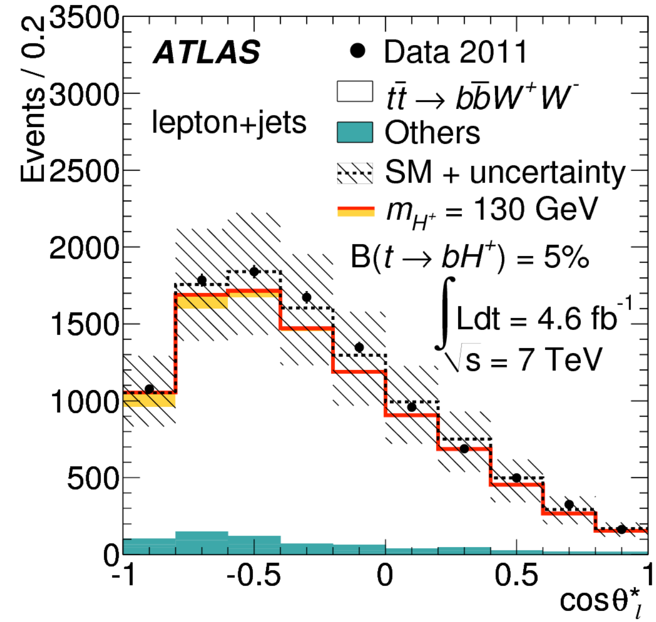
Sample	Event yield (τ+jets)
True τ (embedding method)	$210 \pm 10 \pm 44$
Misidentified jet$\to \tau$	$36 \pm 6 \pm 10$
Misidentified $e \to \tau$	$3 \pm 1 \pm 1$
Multi-jet processes	$74 \pm 3 \pm 47$
$\sum$ SM	$330 \pm 12 \pm 65$
Data	355
$t \to bH^+$ (130 GeV)	$220 \pm 6 \pm 56$
Signal+background	$540 \pm 13 \pm 85$

Source of uncertainty	Normalisation uncertainty	Shape uncertainty
lepton+jets: lepton misidentification		
Choice of control region	6%	-
Z mass window	4%	-
Jet energy scale	16%	-
Jet energy resolution	7%	-
Sample composition	31%	-
τ+lepton: jet$\to \tau$ misidentification		
Statistics in control region	2%	-
Jet composition	11%	-
Object-related systematics	23%	3%
τ+lepton: e$\to \tau$ misidentification		
Misidentification probability	20%	-
τ+lepton: lepton misidentification		
Choice of control region	4%	-
Z mass window	5%	-
Jet energy scale	14%	-
Jet energy resolution	4%	-
Sample composition	39%	-
τ+jets: true τ		
Embedding parameters	6%	3%
Muon isolation	7%	2%
Parameters in normalisation	16%	-
τ identification	5%	-
τ energy scale	6%	1%
τ+jets: jet$\to \tau$ misidentification		
Statistics in control region	2%	-
Jet composition	12%	-
Purity in control region	6%	1%
Object-related systematics	21%	2%
τ+jets: e$\to \tau$ misidentification		
Misidentification probability	22%	-
τ+jets: multi-jet estimate		
Fit-related uncertainties	32%	-
$E_{\mathrm{T}}^{\mathrm{miss}}$-shape in control region	16%	-

$H^{\pm}$, lepton+jets (ATLAS)

Selection

- Trigger: e(20-22) <u>or</u> mu(18)
- Offline: 1 e(25) OR 1 mu(20) (isolated)
- No additional leptons or taus
- ≥4 jets(20), 2 b-tagged
- if $|\Delta\varphi(l,\text{EtMiss})| \geq \pi/6$: EtMiss > 40 GeV
- else: EtMiss$|\sin\Delta\varphi|$ > 20 GeV
- Reconstruct hadronic top-decay (χ^2>5)
- $\cos\theta_l < -0.6$, m_T<60 GeV (defs. on next slide)



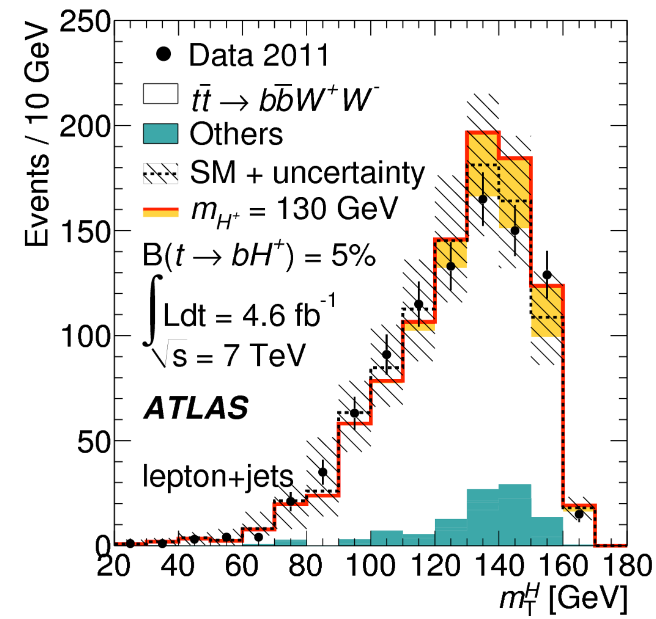
- Reconstruct Hadronic top decay by picking combination of jets which minimise:

$$\chi^2 = \frac{(m_{jjb} - m_{\text{top}})^2}{\sigma^2_{\text{top}}} + \frac{(m_{jj} - m_W)^2}{\sigma^2_W},$$

- Extract limit from transverse Higgs mass dist.
- Major Backgrounds:
  - **Misidentified leptons** (loose lepton control region)
    - p_r - Zll tag and probe
    - p_m - low EtMiss CR

$$N^T_m = \frac{p_m}{p_r - p_m}(p_r N^L - N^T).$$

  - **ttbar** (normalise in $-0.2<\cos\theta_l<1$)



H±, lepton+jets (ATLAS)

- Discriminating variables:
  - Invariant mass of b-jet and lepton

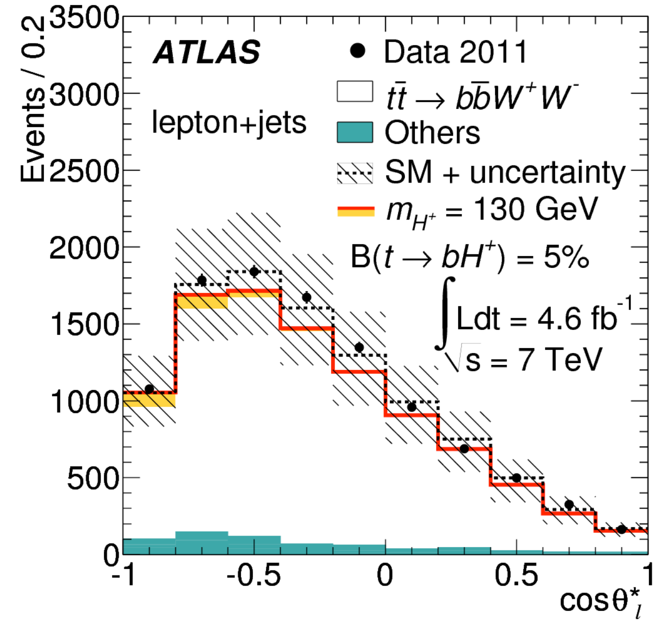
$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\rm top}^2 - m_W^2} - 1 \simeq \frac{4\, p^b \cdot p^l}{m_{\rm top}^2 - m_W^2} - 1.$$

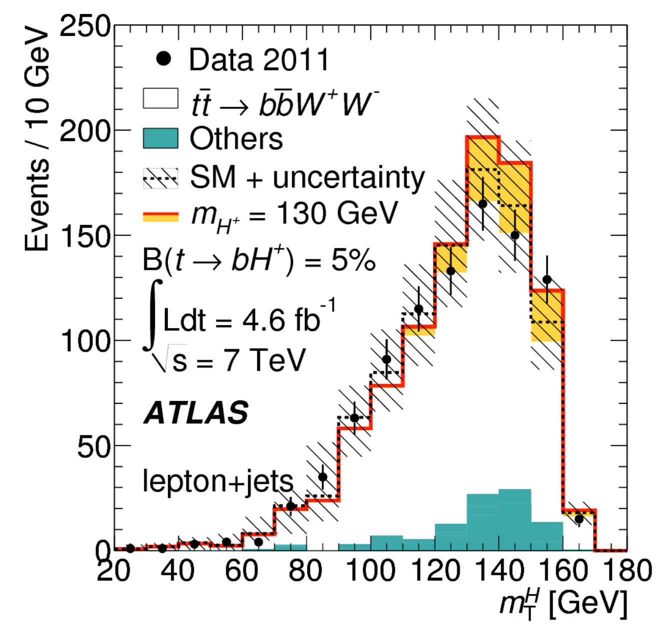
  - Transverse Higgs mass

$$(m_{\rm T}^H)^2 = \left(\sqrt{m_{\rm top}^2 + (\vec{p_{\rm T}}^{\,l} + \vec{p_{\rm T}}^{\,b} + \vec{p_{\rm T}}^{\,\rm miss})^2} - p_{\rm T}^b\right)^2 - \left(\vec{p_{\rm T}}^{\,l} + \vec{p_{\rm T}}^{\,\rm miss}\right)^2.$$

  - Transverse W mass

$$m_{\rm T}^W = \sqrt{2p_{\rm T}^l E_{\rm T}^{\rm miss}(1 - \cos\phi_{l,\rm miss})}.$$

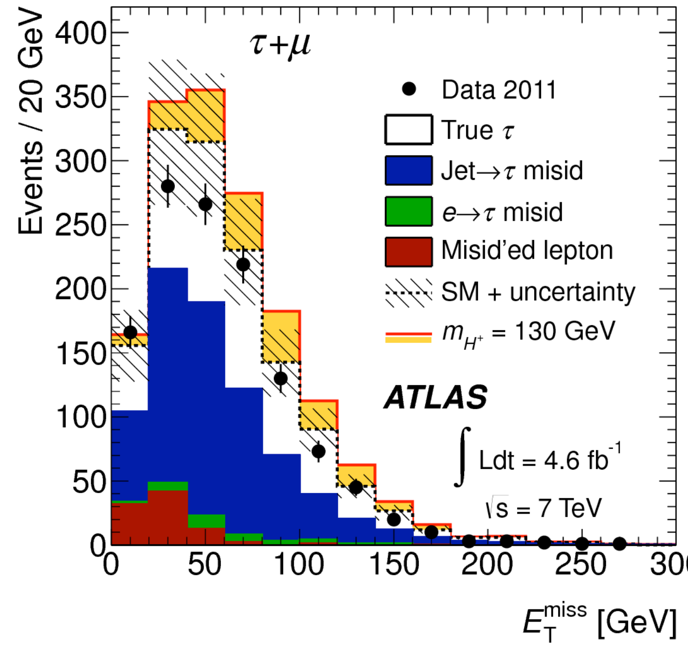




$H^{\pm}$, tau+lepton (ATLAS)

Selection

- Trigger: e(20-22) or mu(18)
- Offline: 1 e(25) OR 1 mu(20) (isolated)
- No additional leptons
- 1 tau(20)
- q(l).q(tau)<0
- ≥2 jets(20), ≥1 b-tagged
- Σp_T>100 GeV



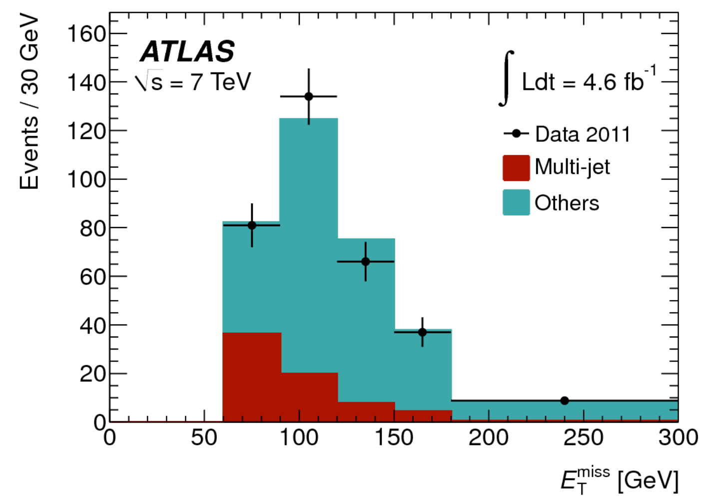
- Extract limit from EtMiss dist.
- Major Backgrounds:
  - **Misidentified leptons** (same as lepton+jets channel)
  - **Misidentified-taus:** (MC without Tau ID scaled by mis-ID measured in Zee or Wmunu control regions)

Sample	Event yield (τ+lepton) $\tau + e$	Event yield (τ+lepton) $\tau + \mu$
True τ	430 ± 14 ± 59	570 ± 15 ± 75
Misidentified jet→ τ	510 ± 23 ± 86	660 ± 26 ± 110
Misidentified $e \to \tau$	33 ± 4 ± 5	34 ± 4 ± 6
Misidentified leptons	39 ± 10 ± 20	90 ± 10 ± 34
$\sum$ SM	1010 ± 30 ± 110	1360 ± 30 ± 140
Data	880	1219
$t \to bH^+$ (130 GeV)	220 ± 6 ± 29	310 ± 7 ± 39
Signal+background	1160 ± 30 ± 100	1570 ± 30 ± 130

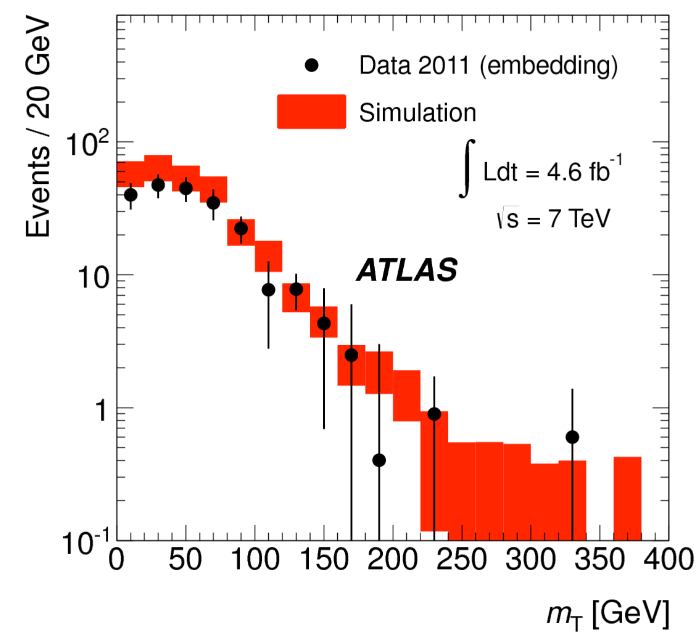
$H^{\pm}$, tau+jets (ATLAS)

Selection

- Trigger: tau(29)+EtMiss(35)
- Offline: 1 tau(40)
- No leptons
- $\geq$4 jets(20), $\geq$1 b-tagged
- EtMiss > 65 GeV
- EtMiss / $0.5\sqrt{\Sigma p_T}$ > 13 GeV$^{1/2}$
- m_{jjb} [120,240] (highest p_T jjb comb)



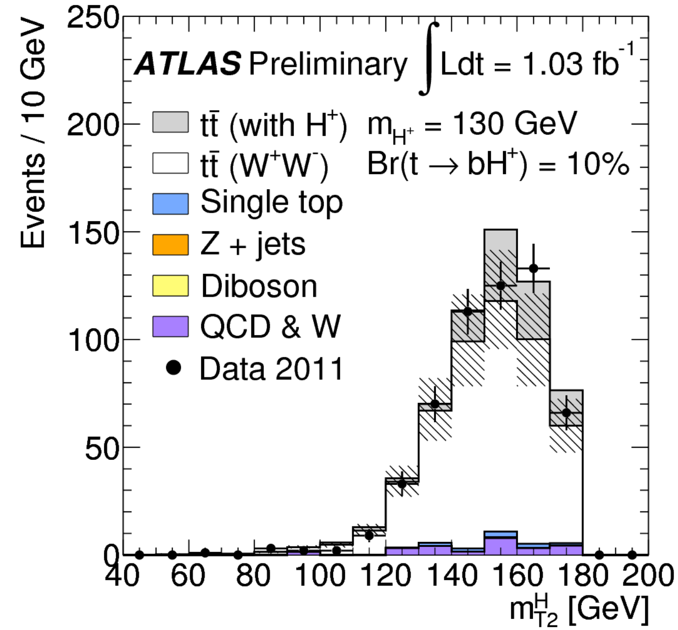
- Extract limit from transverse Higgs mass dist. $$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos\phi_{\tau,miss})},$$
- Major Backgrounds:
  - **Mulitjet:** (template fit of EtMiss)
    - Multijet CR: Fail Tau ID, no b-jet
  - **Misidentified-taus:** (as in tau+lep)
  - **Real-taus:** (ttbar embedding)



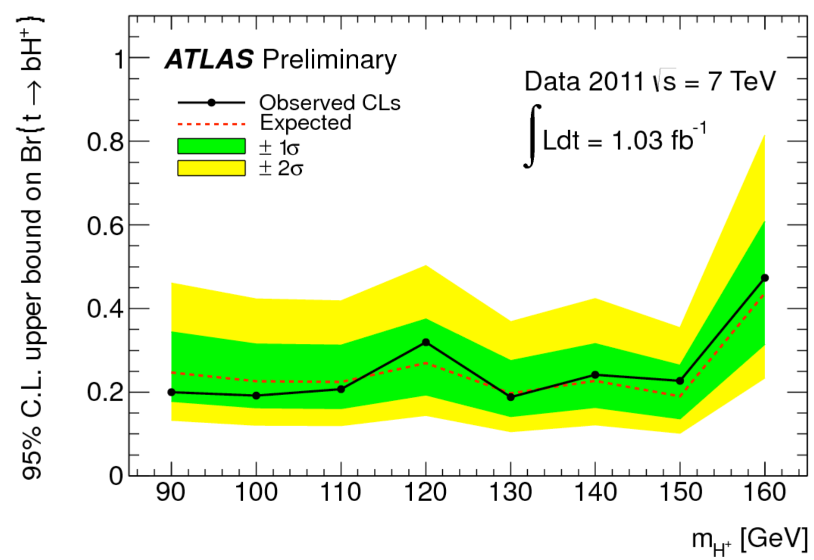
$H^{\pm}$, di-lepton (ATLAS, $1 fb^{-1}$)

Selection

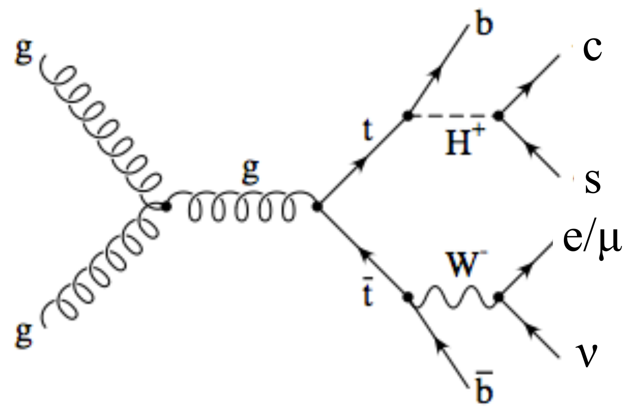
- Trigger: e(20) or mu(18)
- Offline: exactly 2 leptons (e(25), μ(20))
- ≥2 jets(20), 2 b-tagged
- ee or μμ:
  - m_{ll}>15 GeV and $|m_{ll}-m_Z|$>10 GeV
  - EtMiss > 40 GeV
- eμ: ΣE_T(leptons,jets)>130 GeV
- m_{T2} converged
- $\cos\theta_l$ < -0.6 (H^+ side)



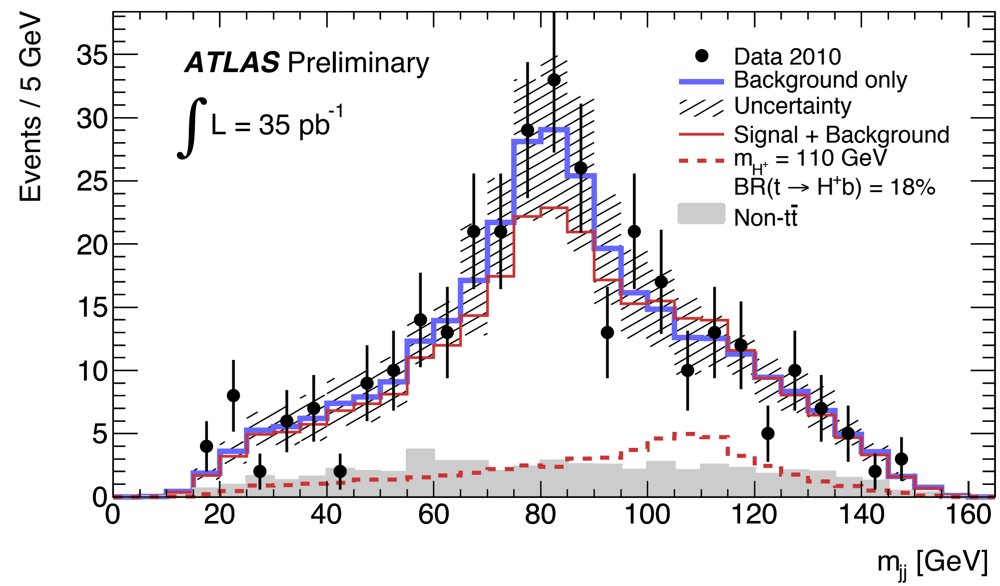
- Select correct l-b pairing:
  1. Eliminate bad pairs with $\cos\theta_l$>1
  2. Minimise $\Delta R(l,b)_1 + \Delta R(l,b)_2$
- Extract limit from transverse higgs mass dist.
- Major Backgrounds:
  - **Misidentified leptons** (same as lepton +jets)
  - **ttbar** (normalise in $-0.4<\cos\theta_l<1$)

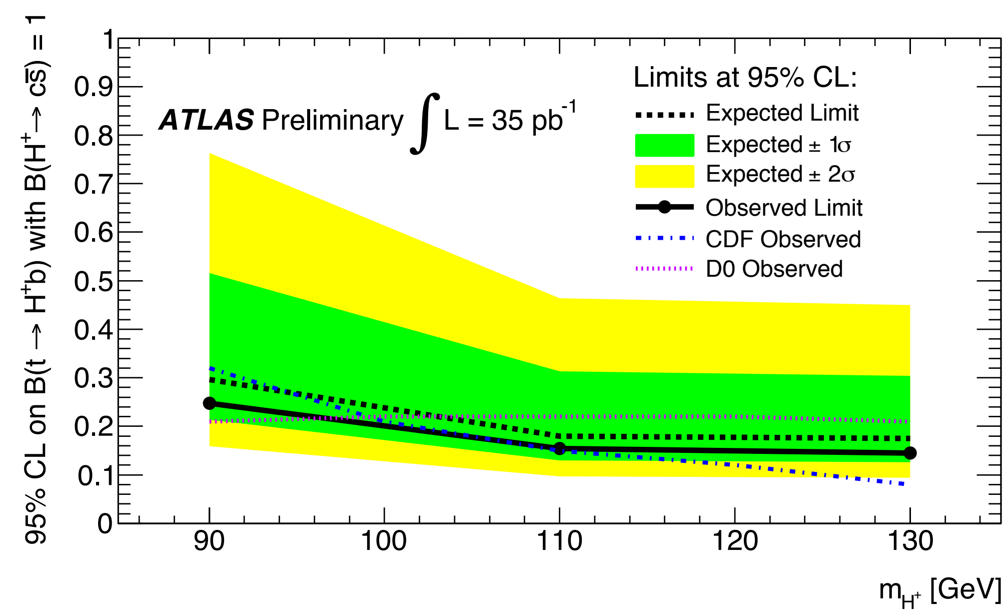


$H^{\pm} \to cs$ (ATLAS)



- $H \to cs$ dominates for $\tan\beta<1$
- Require large EtMiss and m_T to suppress multijet background
- Kinematic fit with W and top mass constraints to find best $H^{\pm}$ candidate
- Set limits on $BR(t \to H^{\pm}b)$ assuming $BR(H^{\pm} \to cs)=100\%$





CMS Event Summary Tables

tau+jets

Source	$N_{ev}^{\tau_h+jets}$ ±stat.±syst.
HH+HW, $m_{H^\pm} = 120$ GeV/c^2, BR($t \to H^+ b$)=0.05	$49 \pm 4 \pm 8$
multi-jets (data-driven)	$27 \pm 2 \pm 1$
EWK+$t\bar{t}$ τ (data-driven)	$78 \pm 3 \pm 12$
EWK+$t\bar{t}$ τ fakes (simulation)	$6 \pm 4 \pm 1.4$
$Z/\gamma^* \to \tau\tau$ (simulation)	$6.5 \pm 2.0 \pm 1.2$
$WW \to \tau\nu_\tau\tau\nu_\tau$(simulation)	$0.34 \pm 0.22 \pm 0.05$
Total expected background	$118 \pm 5 \pm 12$
Data	130

lep+tau

Source	$N_{ev}^{e\tau_h}$ ± stat. ± syst.	$N_{ev}^{\mu\tau_h}$ ± stat. ± syst.
HH+HW, m_{H^+}=120 GeV/c^2, BR($t \to H^+ b$)=0.05	$49 \pm 3 \pm 8$	$86 \pm 4 \pm 13$
τ fakes	$54 \pm 6 \pm 8$	$89 \pm 9 \pm 11$
$t\bar{t} \to WbWb \to \ell\nu b\ \tau\nu b$	$96 \pm 3 \pm 14$	$156 \pm 4 \pm 23$
$t\bar{t} \to WbWb \to \ell\nu b\ \ell\nu b$	$8.6 \pm 0.9 \pm 1.7$	$13 \pm 1.1 \pm 2.5$
$Z/\gamma^* \to ee, \mu\mu$	$4.5 \pm 1.7 \pm 1.3$	$0.7 \pm 0.7 \pm 0.7$
$Z/\gamma^* \to \tau\tau$	$16 \pm 3.2 \pm 2.9$	$25 \pm 4.2 \pm 6.3$
single top quark	$7.6 \pm 0.4 \pm 1.1$	$13.0 \pm 0.5 \pm 1.8$
di-boson	$1.2 \pm 0.1 \pm 0.2$	$2.0 \pm 0.2 \pm 0.3$
Total expected background	$188 \pm 7.9 \pm 20$	$298 \pm 11 \pm 32$
Data	176	288

e+mu

Source	$N_{ev}^{e\mu}$± stat. ± syst.
HH+HW, m_{H^+}=120 GeV/c^2, BR($t \to H^+ b$)=0.05	$121 \pm 9 \pm 13$
$t\bar{t}$ dileptons	$3323 \pm 34 \pm 397$
other $t\bar{t}$	$22 \pm 3 \pm 3$
$Z/\gamma^* \to ll$	$186 \pm 12 \pm 21$
W+jets	$14 \pm 6 \pm 2$
single top quark	$161 \pm 3 \pm 19$
di-boson	$47 \pm 2 \pm 5$
Total expected from SM	$3752 \pm 37 \pm 398$
Data	3875

CMS Syst. Summary Tables

lep+tau

	HH	WH	$t\bar{t}_{\ell\tau}$	$t\bar{t}_{\ell\ell}$	τ fakes	Single top	VV	DY($\mu\mu$)	DY($\tau\tau$)
JES+JER+MET	6.0	5.0	5.0	4.0		6.0	11.0	100.0	22.0
cross-section	$^{+7.0}_{-10}$					8.0	4.0	4.0	
pileup modeling	4.0	2.0	2.0	8.0		2.0	3.0	25.0	4.0
MC stat	5.0	4.0	2.0	9.0		4.0	9.0	100.0	16.0
luminosity	4.5					4.5			
τ-jet id	6.0	6.0	6.0			6.0	6.0		6.0
jet, $\ell \to \tau$ mis-id				15.0				15.0	
b-jet tagging	6.0	5.0	5.0	5.0		7.0			
jet$\to$b mis-id							8.0	8.0	9.0
τ fakes (stat)					10.0				
τ fakes (syst)					12.0				
lepton selections	2.0					2.0			

tau+jets

	HH	WH	multi jets	EWK+$t\bar{t}$ genuine τ			EWK+$t\bar{t}$ τ fakes		
				Emb.data	Res.DY	Res.WW	$t\bar{t}$	tW	W+jets
JES+JER+MET	4.7-14	9.0–18		7.1	26	23	8.1	1.0	$<$10
cross-section	$^{+7.0}_{-10.0}$	$^{+7.0}_{-10.0}$					$^{+7.0}_{-10.0}$	8.0	5.0
pileup modeling	0.3–4.2	0.6–5.2			7.8	3.9	7.1	15	10
MC stat	6.2–11	7.0–10			30	66	28	49	71
luminosity	4.5				4.5				
trigger	12–13	13		11	12	11	12	11	14
multi-jets stat.			6.5						
multi-jets syst.			3.8						
μ sample stat.				3.4					
multi-jet contamin.				0.3					
$f_{W\to\tau\to\mu}$				0.7	0.1	0.1			
muon selections				0.5	0.1	0.1			
lepton veto	0.3–0.5	0.5–0.7			0.9	1.2	0.9	0.6	0.3
τ-jet id	6.0	6.0		6.0	6.0	6.0			
jet, $\ell \to \tau$ mis-id							15		
b-jet tagging	1.1–2.1	1.0-1.7					1.4	1.6	
jet$\to$b mis-id					2.0	2.6			4.8

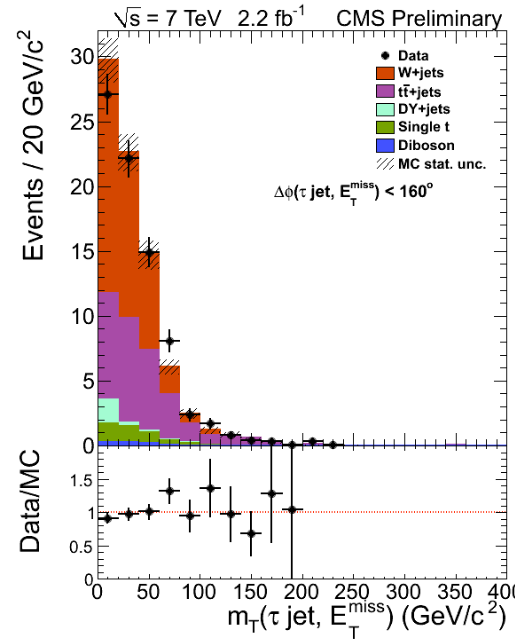
e+mu

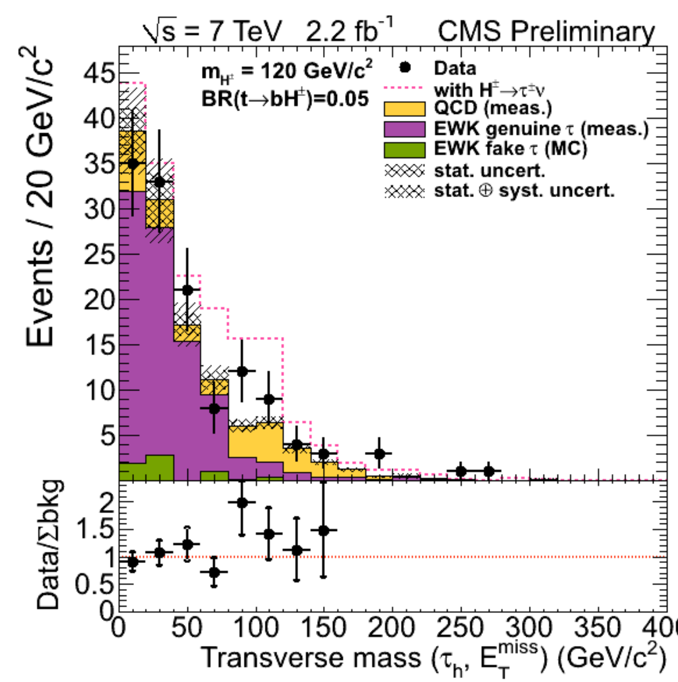
	HH	WH	$t\bar{t}$	DY(ll)	W+jets	Single top	VV
JES+JER+MET	2.1	2.0	2.0	6.0	10.8	4.0	6.5
cross section	$^{+7}_{-10}$			4.3	5.0	7.4	4.0
pileup modeling	4.5	4.5	5.0	5.5	4.0	5.5	5.5
MC stat	5.3	7.9	1.0	6.5	42.9	1.9	4.3
luminosity	4.5						
dilepton selection	2.5						

H±, tau+jets (CMS)

<u>**Selection**</u>

-

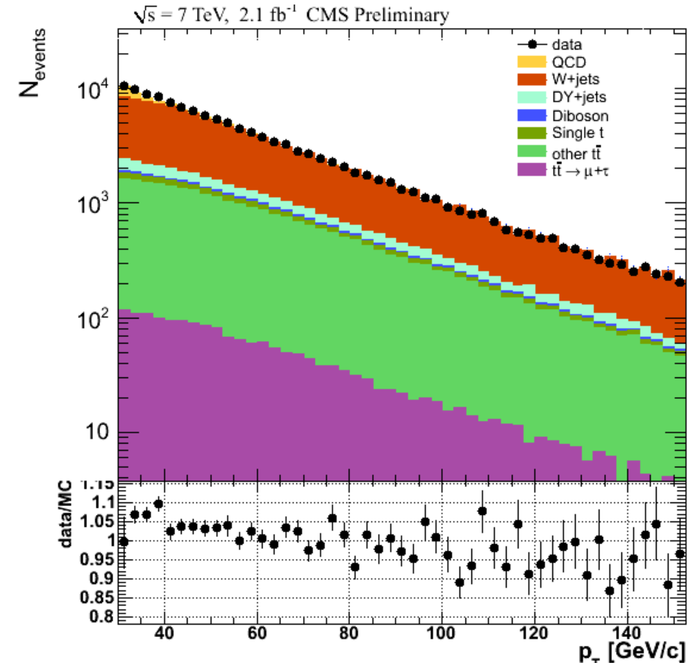


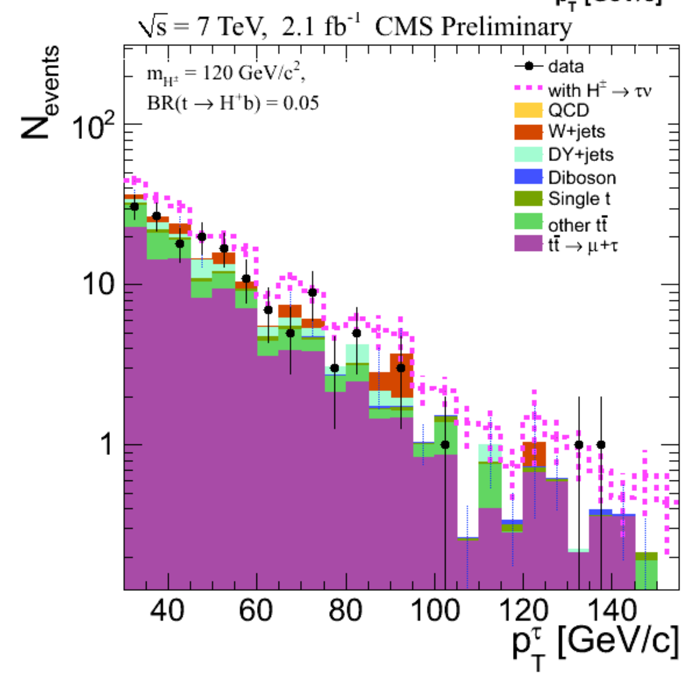


H±, tau+lepton (CMS)

Selection

-





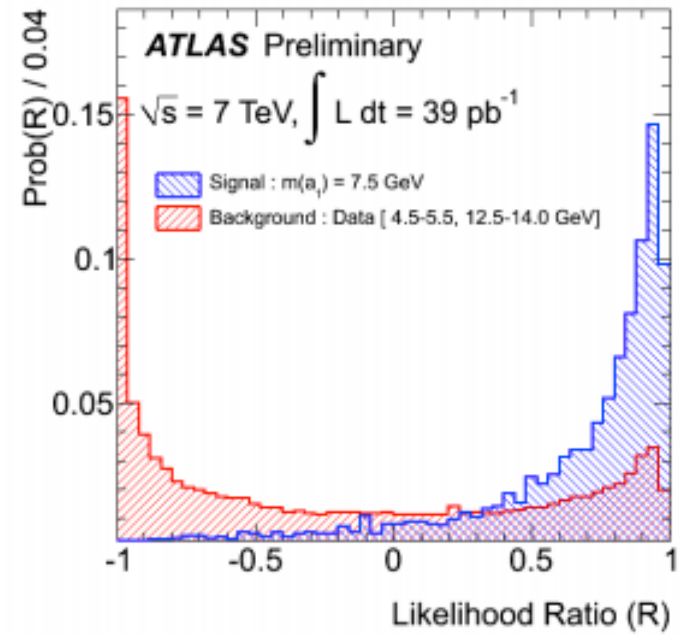
NMSSM: Light Neutral a1 Higgs

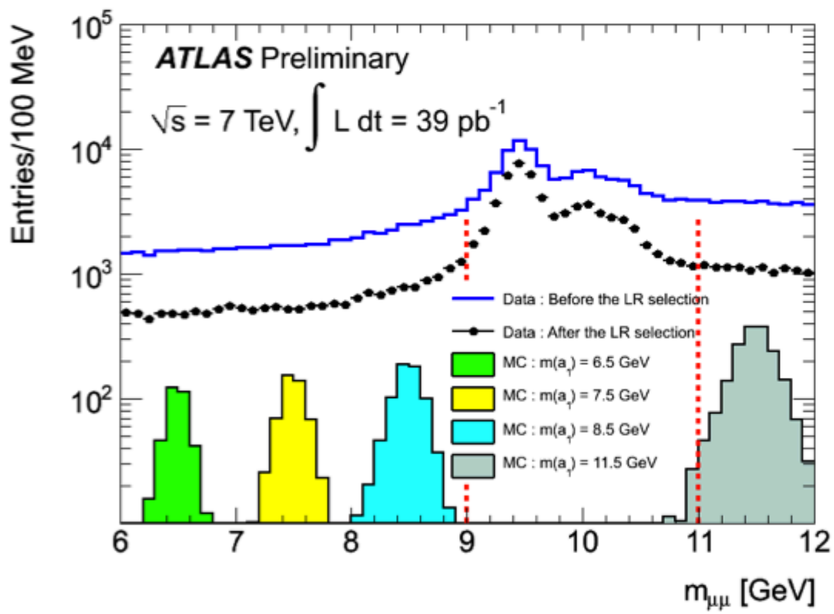
NMSSM a1→μμ (ATLAS)

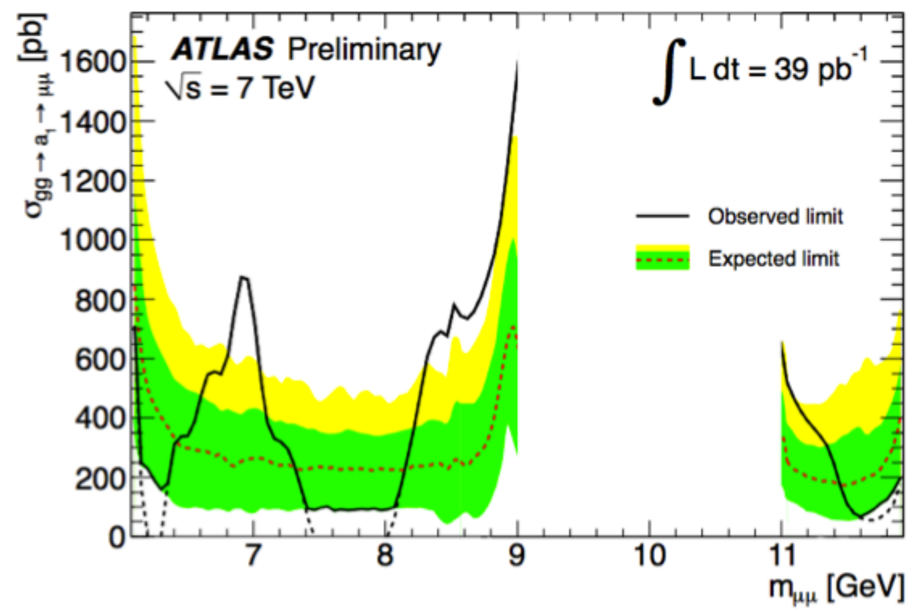
Selection

- Trigger: di-muon (4/4)
- Offline: at least 2 muons(4) (isolated)
- $q(mu_1).q(mu_2)<0$
- 4.5 < mass < 14.0 GeV
- Pick di-muon combination using **Likelihood Ratio** based on **vertex X^2/NDF** and **muon isolation**
  - LLH PDFs derived from data in sidebands

- Main Backgrounds: Multijet and Υ(1S)
- Set limits by fitting mass distribution





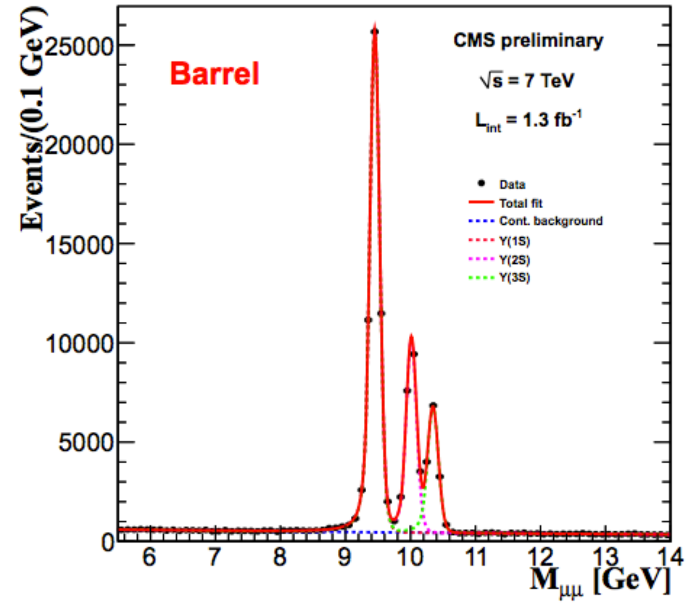


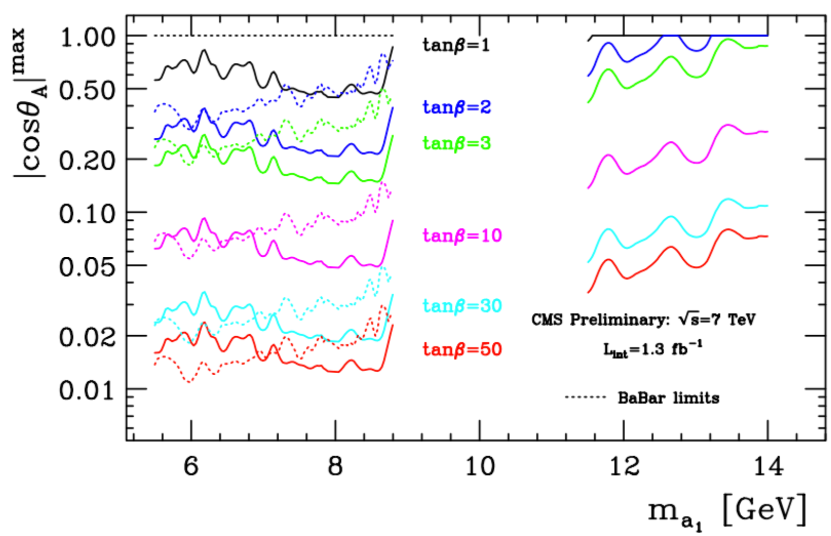
NMSSM a1→μμ (CMS)

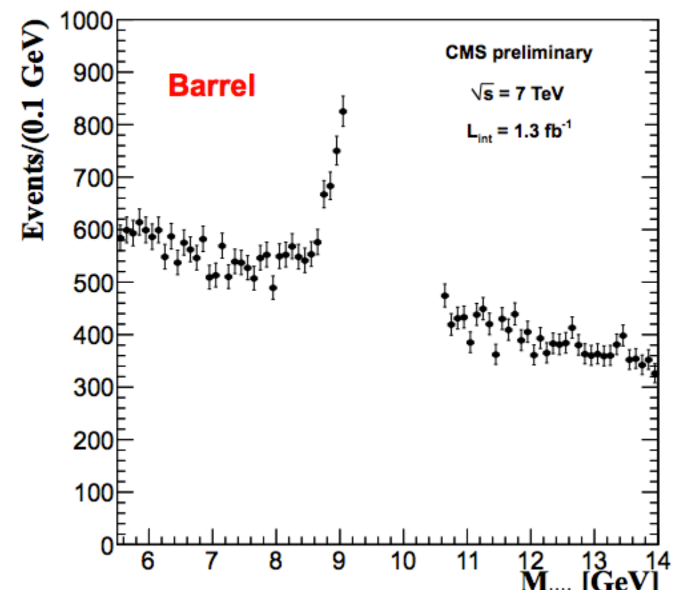
Selection

- Trigger:
  - opposite sign di-muon (3.5/3.5)
  - $p_T(\mu_1,\mu_2)>6$ GeV, $5.5<m(\mu_1,\mu_2)<14$ GeV
  - Primary Vertex, $d_0<0.5$
- Offline: at least 2 muons(5.5) (isolated)
- $q(mu_1).q(mu_2)<0$
- 5.5 < mass < 14.0 GeV
- Pick di-muon comb. with **highest vertex X^2 Prob**

- Main Backgrounds: Multijet and Υ(1S) (mass shapes from data)
- Set limits by fitting mass distribution







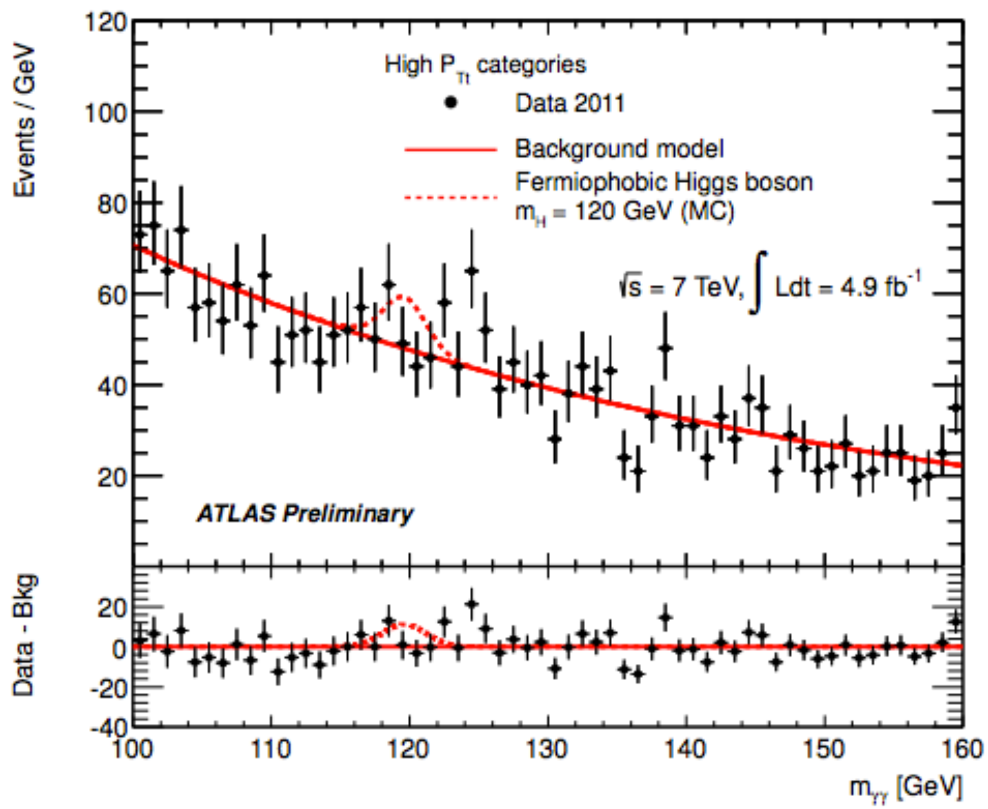
Fermiophobic Higgs

Fermiophobic H→γγ (ATLAS)

Selection

- Trigger: di-photon (20/20)
- Offline: 2 isolated photons (40/25)
- 9 categories based on:
  - (un)converted photons
  - p_T, η

- Main Backgrounds:
  - Prompt di-photon production
  - γ+jet, di-jet, Drell-Yann
- Limits extracted using unbinned maximum likelihood fit to di-photon mass spectrum in each category
- Excess at ~126 GeV is 1.6σ including look-elsewhere effect



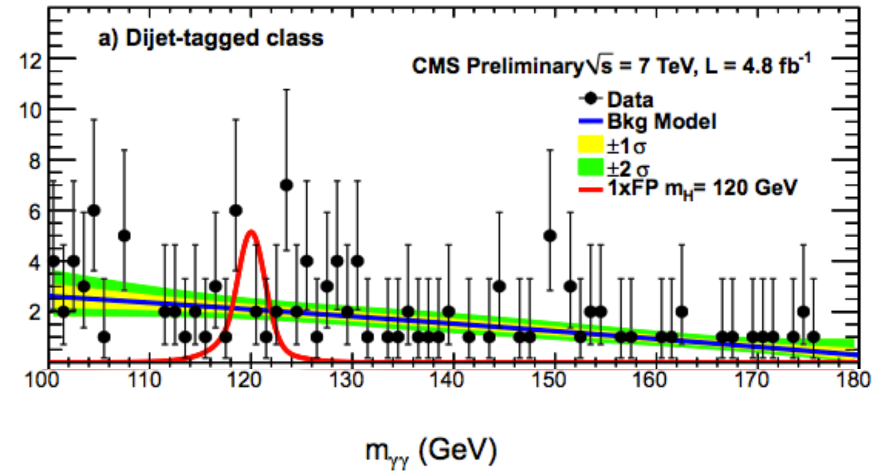
Fermiophobic H→γγ (CMS)

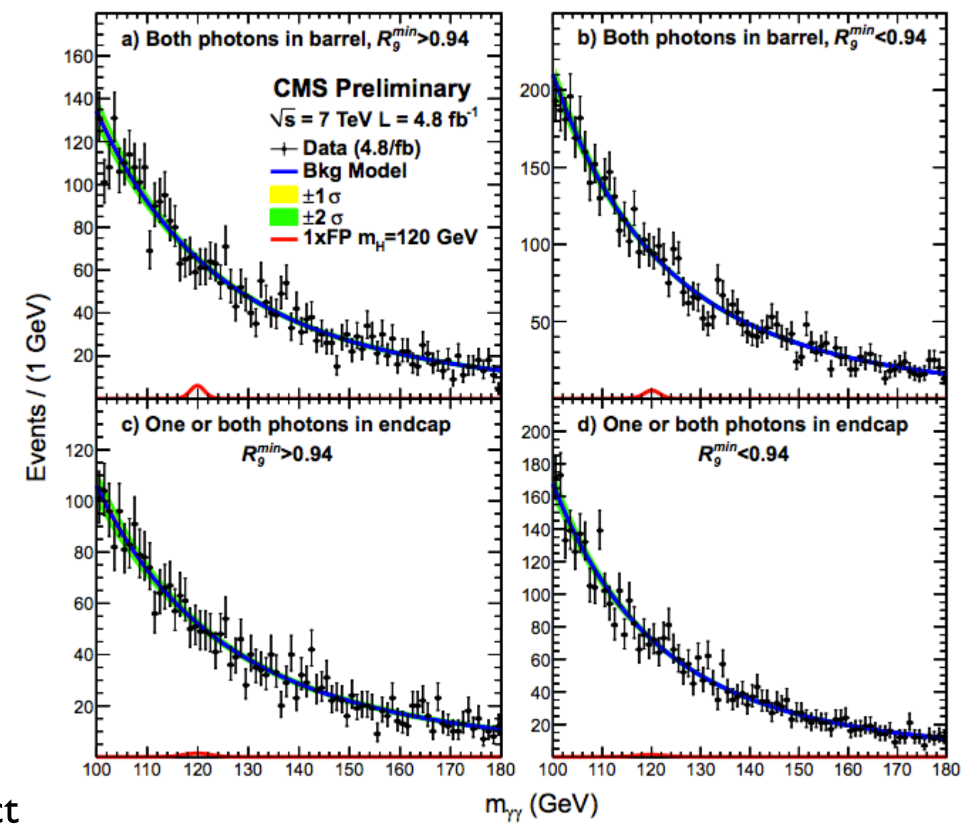
Selection

- Trigger: di-photon
- Offline: 2 isolated photons (not in 'crack')
- 3 categories:
  - **Di-jet tag:**
    - 2 jets (30/20), $\Delta\eta_{jj}>3.5$, $m_{jj}>350$ GeV
    - $|\eta_{\gamma\gamma}-\eta_{jj}|<2.5$, $|\varphi_{\gamma\gamma}-\varphi_{jj}|>2.6$
    - $p_T(\gamma_1)>55m_{\gamma\gamma}/120$, $p_T(\gamma_2)>25$ GeV
  - **Lepton tag:**
    - 1 e(20) or 1 mu, $\Delta R(l,\gamma)>1$
    - veto $m(e,\gamma)$ within 5 GeV of Z-mass
    - $p_T(\gamma_1)>45m_{\gamma\gamma}/120$, $p_T(\gamma_2)>25$ GeV
  - **Inclusive (not in tagged categories)**
    - $p_{T,\gamma\gamma}/m>0.1$
    - $p_T(\gamma_1)>m_{\gamma\gamma}/3$, $p_T(\gamma_2)>m_{\gamma\gamma}/4$
    - Split into 4 categories using η and photon ID.

- Main Backgrounds:
  - Prompt di-photon production
  - γ+jet and di-jet
- Likelihood using mass for tagged categories and 2D mass-$p_{T,\gamma\gamma}$ for inclusive

Excess at ~126 GeV, 1.2σ including look-elsewhere effect

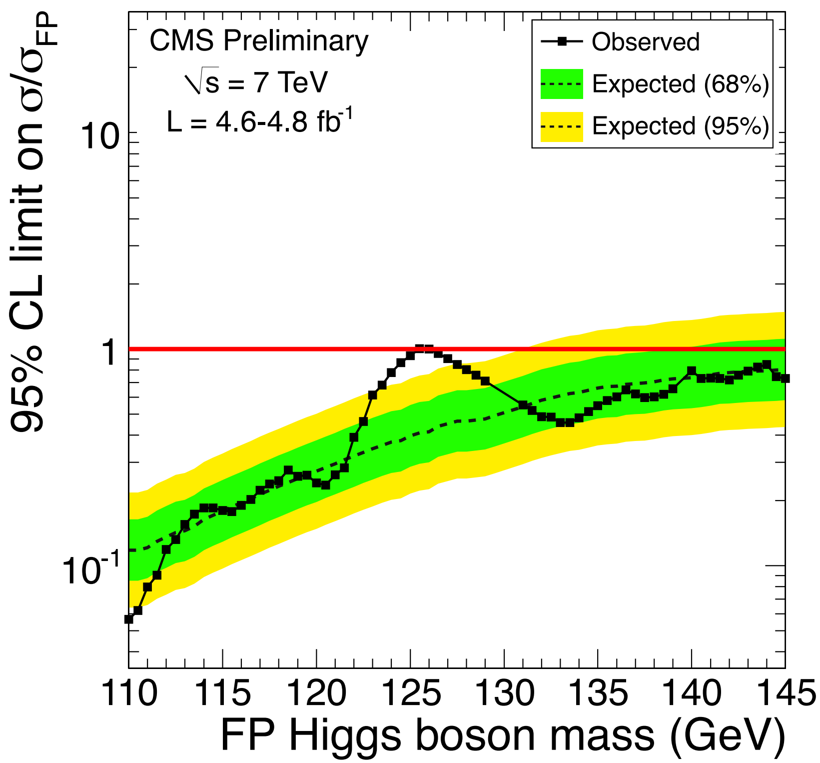


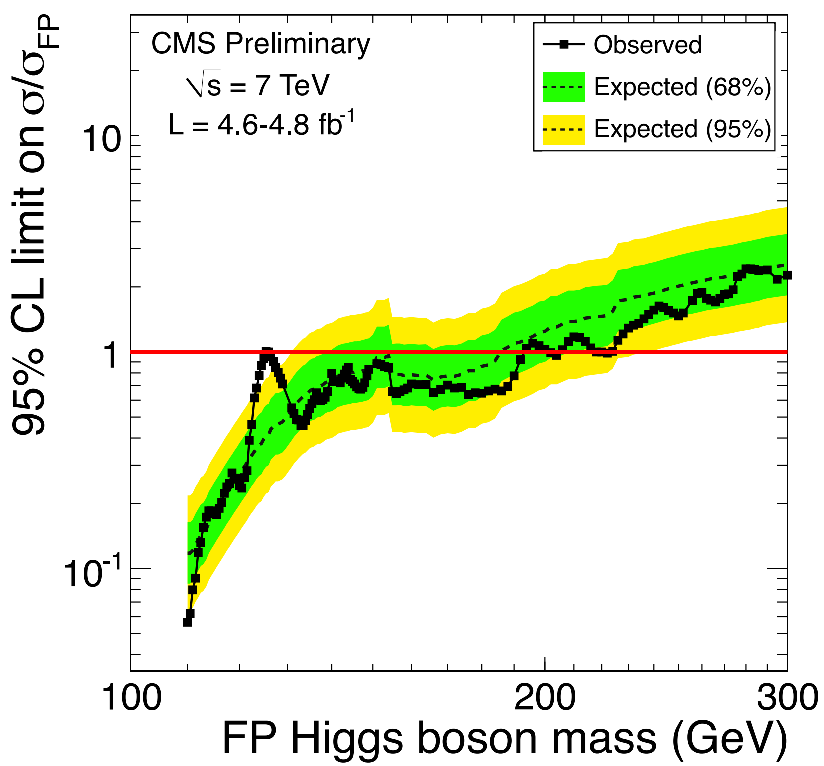


Other Fermiophobic-Higgs searches at CMS

- CMS has also released a fermiophobic-Higgs boson search including the WW and ZZ channels
- CMS-HIG-12-008

Combined Fermiophobic-Higgs limits





Doubly Charged Higgs

Doubly Charged Higgs (CMS)

Selection

- Trigger: di-lepton (17/8)
- Offline: At least 2 leptons (20/10)
- Discard pairs with m_{ll}<12 GeV

Table 2: Selections applied in various three-lepton final states

Variable	$ee, e\mu, \mu\mu$	$e\tau, \mu\tau$
$\sum p_T$	$> 1.1 \cdot m_{\Phi^{++}} + 60\,\mathrm{GeV}$	$> 0.85 \cdot m_{\Phi^{++}} + 125\,\mathrm{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	$> 80\,\mathrm{GeV}$	$> 80\,\mathrm{GeV}$
$\Delta\varphi$	$< m_{\Phi^{++}}/600\,\mathrm{GeV} + 1.95$	$< m_{\Phi^{++}}/200\,\mathrm{GeV} + 1.15$
E_T^{miss}	none	$> 20\,\mathrm{GeV}$
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$	$[m_{\Phi^{++}}/2; 1.1 \cdot m_{\Phi^{++}}]$

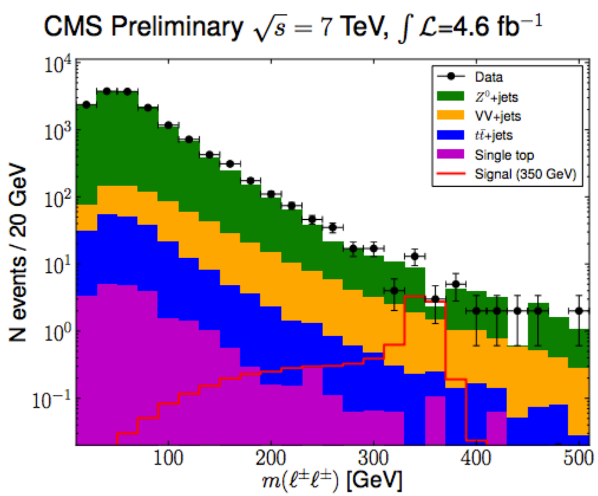
Table 3: Selections applied in various four-lepton final states

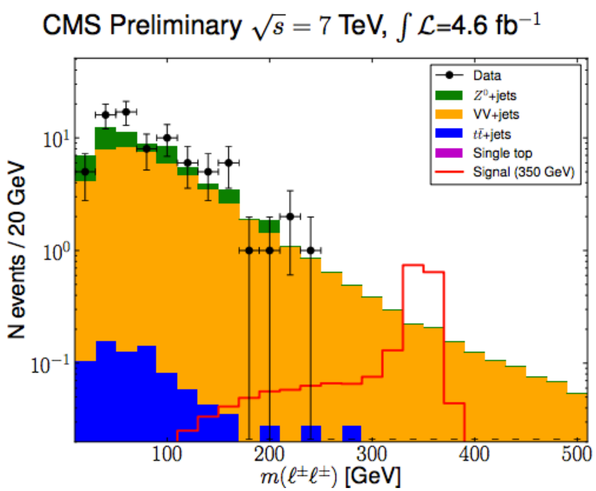
Variable	$ee, e\mu, \mu\mu$	$e\tau, \mu\tau$
$\sum p_T$	$> 0.6 \cdot m_{\Phi^{++}} + 130\,\mathrm{GeV}$	$> m_{\Phi^{++}} + 100\,\mathrm{GeV}$ or > 400 GeV
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	none	$> 10\,\mathrm{GeV}$
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$	$[m_{\Phi^{++}}/2; 1.1 \cdot m_{\Phi^{++}}]$

Table 4: Selections applied in 3τ and 4τ related final states

Variable	3τ	4τ
$\sum p_T$	$> m_{\Phi^{++}} - 10\,\mathrm{GeV}$ or $> 200\,\mathrm{GeV}$	$\sum p_T > 120\,\mathrm{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	$> 50\,\mathrm{GeV}$	$> 50\,\mathrm{GeV}$
$\Delta\varphi$	< 2.1	< 2.5
E_T^{miss}	$> 40\,\mathrm{GeV}$	none
Mass window	$[m_{\Phi^{++}}/2 - 20; 1.1 \cdot m_{\Phi^{++}}]$	none

- Main Backgrounds:
  - Prompt di-photon production
  - γ+jet, di-jet, Drell-Yann
- Limits extracted using unbinned maximum likelihood fit to di-photon mass spectrum in each category





Other Details

Maximum Likelihood Mass (CMS)

Mass Reconstruction (ATLAS)

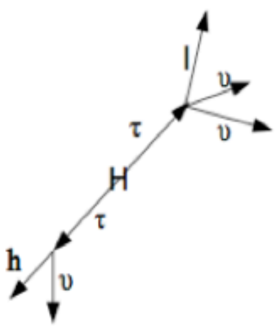
Neutral MSSM Higgs : Mass reconstruction

- **Visible mass :** $m_{\tau\tau}^{\mathrm{visible}}$ (invariant mass of visible tau decay products)

- **Effective mass:** $m_{\tau\tau}^{\mathrm{effective}} = \sqrt{(p_{\tau^+} + p_{\tau^-} + p_{\mathrm{miss}})^2}$

$$p_{\mathrm{miss}} = (E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{x}}^{\mathrm{miss}}, E_{\mathrm{y}}^{\mathrm{miss}}, 0)$$

- **Missing mass calculator (MMC):**

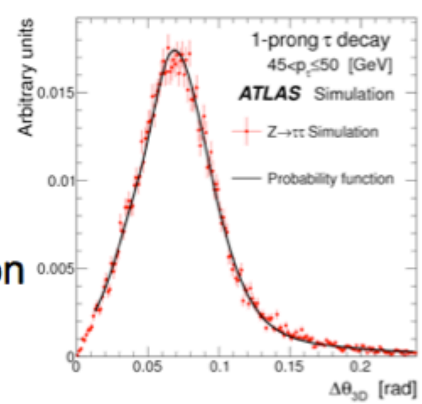


- 7 unknown parameters: two "missing" 3-momenta, $m_{\nu\nu}$
- 4 constraints from E_x^{miss}, E_y^{miss}, $m_{\tau 1}$, $m_{\tau 2}$

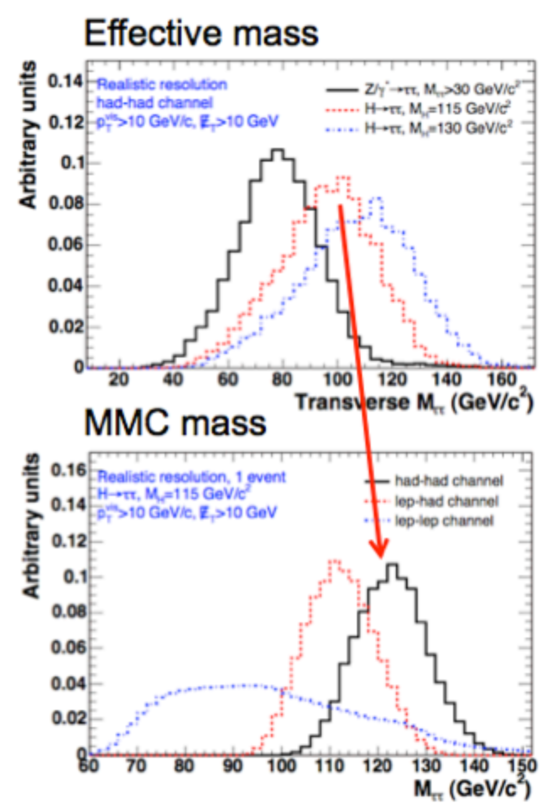
⇒ scan over $\Delta\Phi(\nu,l)$, $\Delta\Phi(\nu,h)$, $m_{\nu\nu}$

⇒ weight solution according to probability of 3D angle in solution

⇒ MMC mass = Max. of weighted $m_{\tau\tau}$ distribution



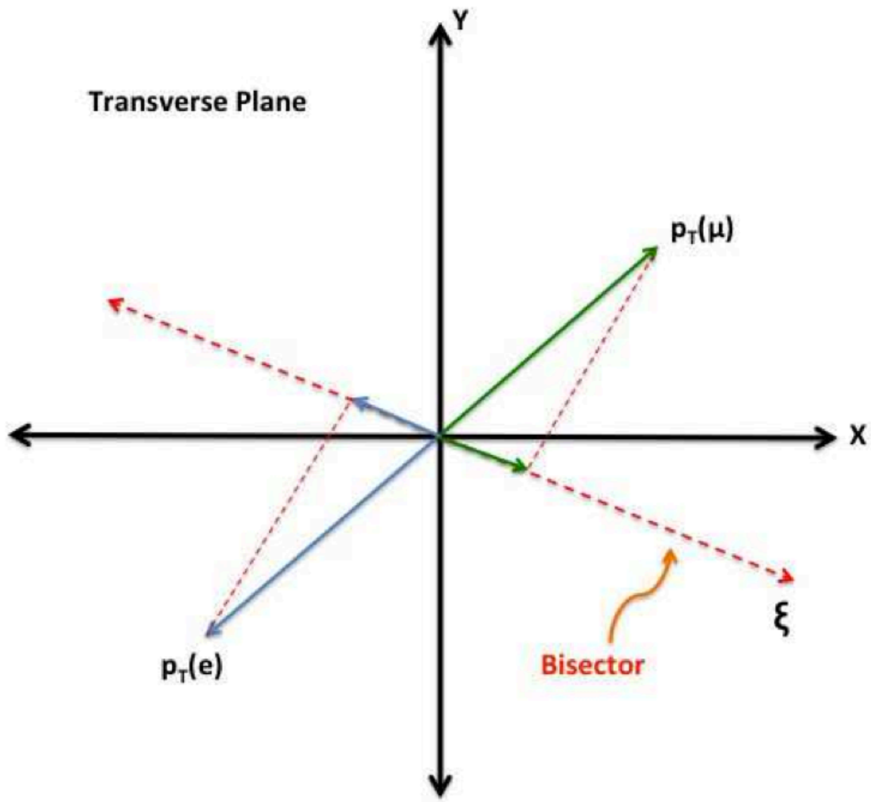
A.Elagin, P.Murat, A.Pranko, A.Safonov, Nucl. Inst. Meth. A654 (2011) 481

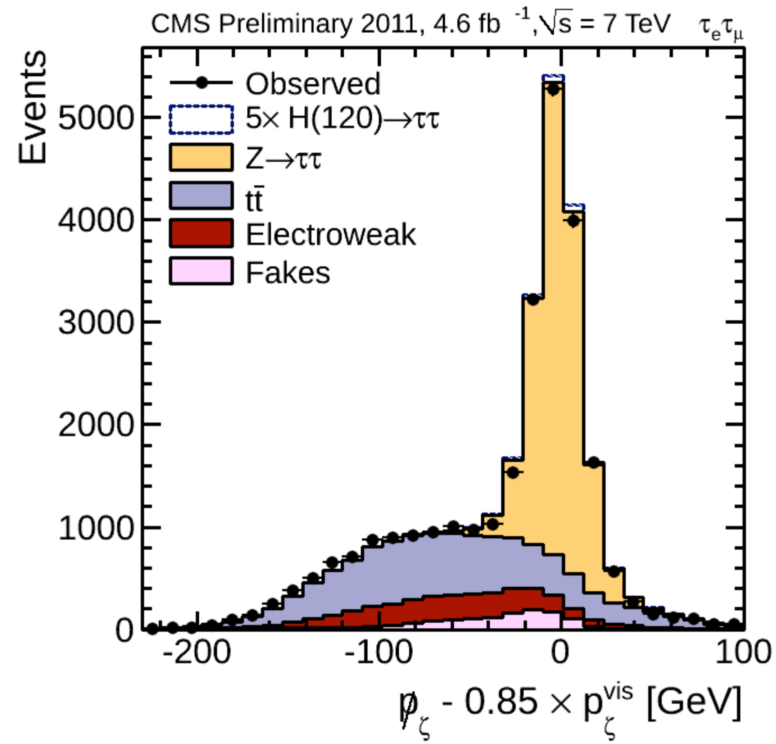


9

Slide from J. Dingfelder

P_ζ and P_ζ^{vis}





$$P_\zeta = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta + E_T^{miss} \cdot \zeta,$$

$$P_\zeta^{vis} = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta.$$