charged and other BSM Higgs

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on behalf of the CMS collaboration

- ✓ Charged Higgs in top quark decays
- ✓ Doubly charged Higgs
- ✓ BSM Higgs: light pseudo-scalar, non-SM Higgs decay

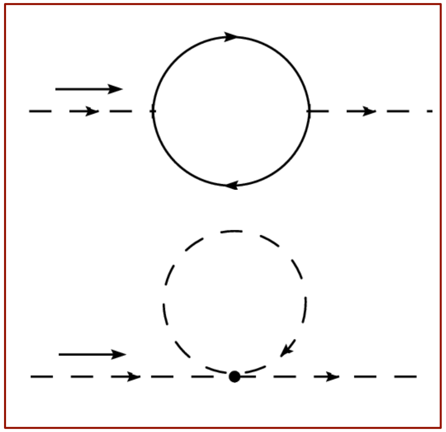
Higgs and the SM

Contributions grow with Λ:

$m^2 = m_0^2 + g^2\Lambda^2$

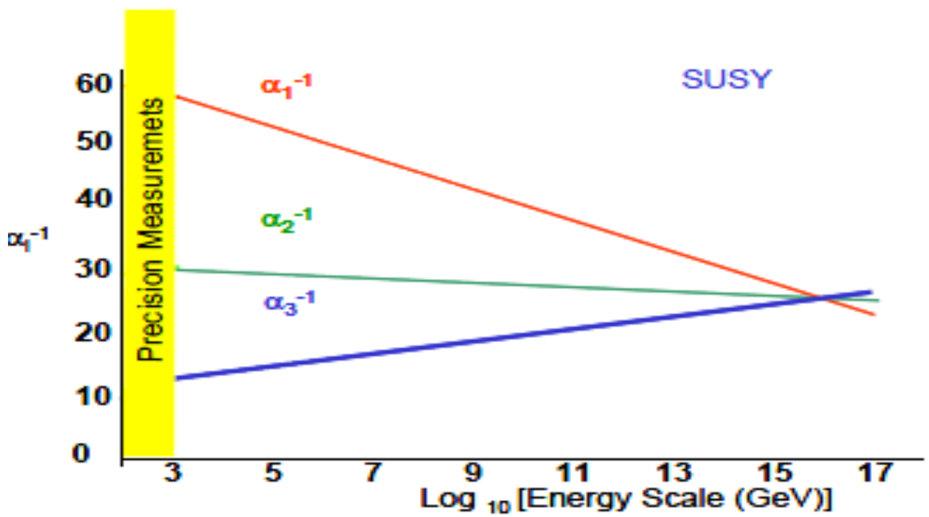
- SM is a successful theory
- Nothing prevents the SM to survive up to the Planck scale if the Higgs mass is 125 GeV. However, it is unnatural.
- If the cutoff scale Λ is very large, fine tuning of m_H is a problem.
  - Contributions grow with Λ (upper scale validity of the SM)
  - The Higgs mass depends quadratically on Λ: $m^2 = m_0^2 + g^2\Lambda^2$
- Need to to find an explanation for light Higgs mass. It should be in the EW scale.
- Is there a symmetry that protects the Higgs mass from receiving large corrections?

cancelation?



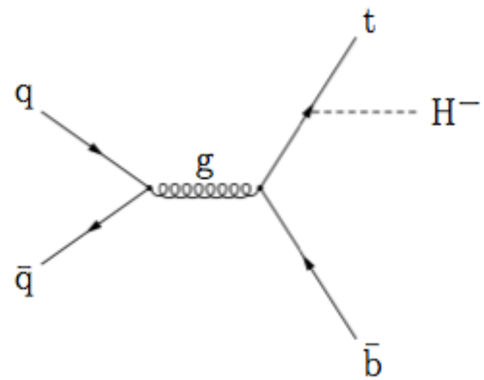
Higgs and the SM (cont.)

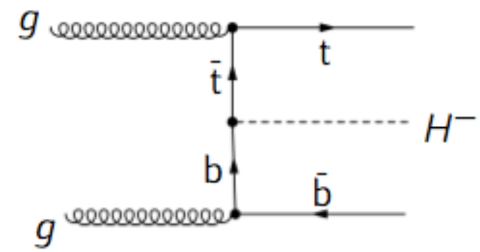
- SUSY postulates a new symmetry between fermions and bosons
  - Loops of particles and their SUSY partners have the ability to cancel the quadratic divergences in the Higgs field self-couplings, solving the naturalness problem
  - SUSY foresees unification of couplings at large energy scales ~10^{15} GeV
  - Provides DM candidates (LSP)
- It tells many nice things, but the LHC may not be able to find it
- # of experimental scenarios is large
- Here, focus on what has been done

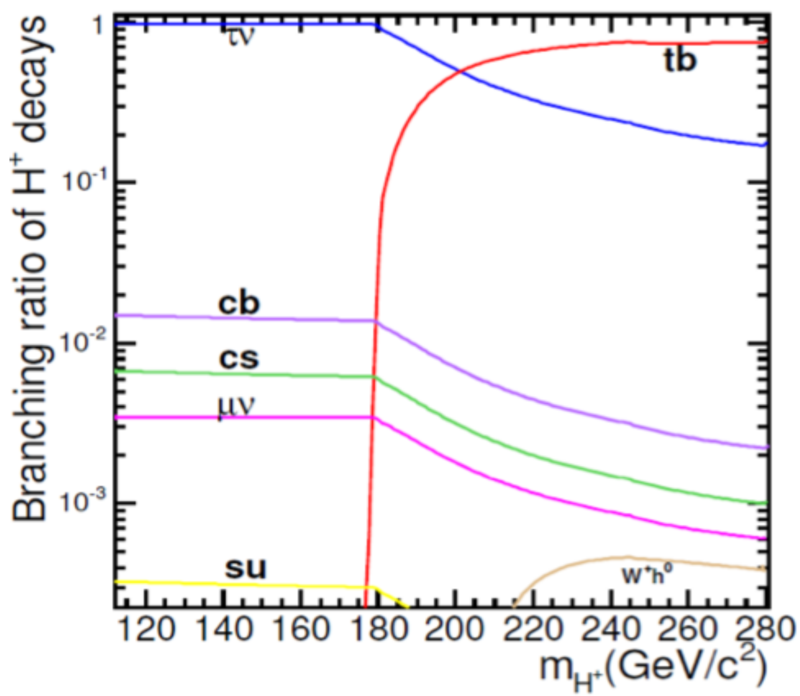


Charged Higgs

- Study non-SM Higgs in two mass regimes:
- $m_H < m_{top}$
  - Mostly produced in top quark decays
  - Large tanβ: $H^{\pm} \rightarrow \tau^{+}\nu$
  - Small tanβ (<1): $H^{+} \rightarrow cs$
- $m_H > m_{top}$
  - Produced in gluon-gluon fusion
  - Main decays: $H^{+} \rightarrow tb$, $H^{+} \rightarrow \tau^{+}\nu$
- Main backgrounds: ttbar, W+jets



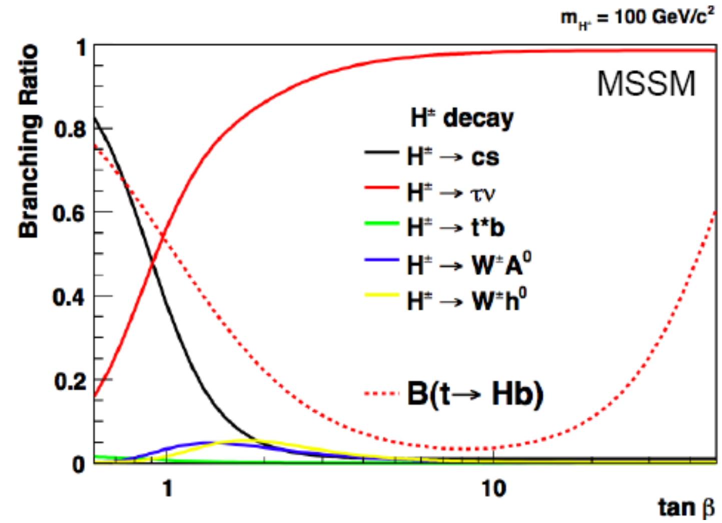




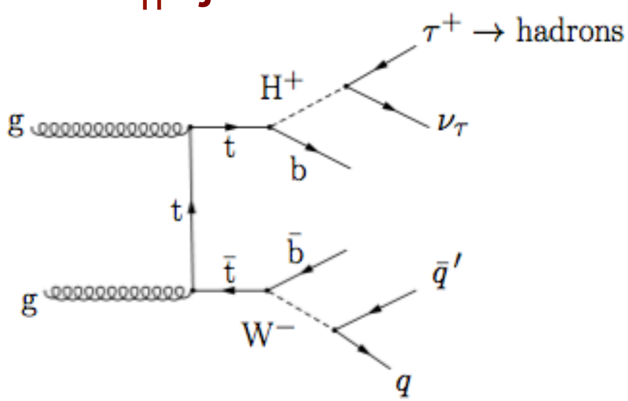
Charged Higgs in top quark decays

JHEP 07(2012)143, HIG-12-052

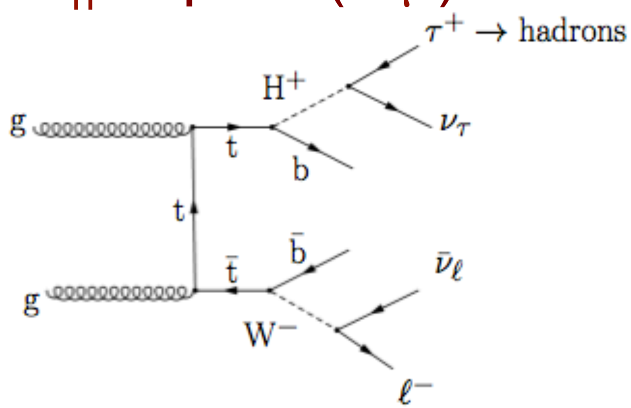
- Look for charged Higgs in three final states:
  - Tau+lepton (electron or muon)
  - Dilepton (tau decays leptonically)
  - Fully hadronic: tau+jets



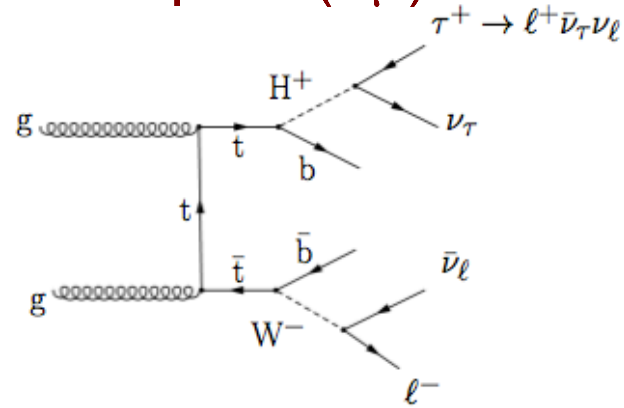
τ_h+jets



τ_h+lepton (e/μ)

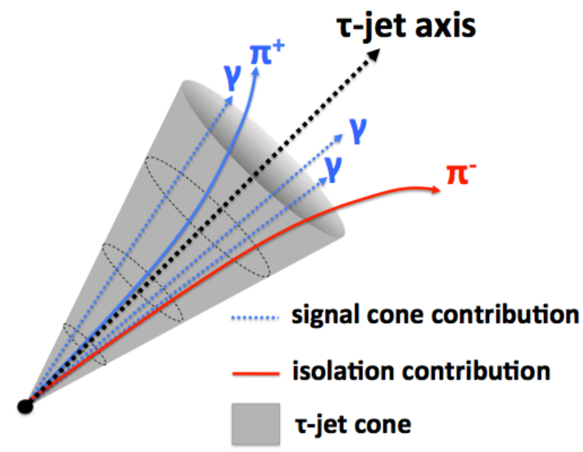


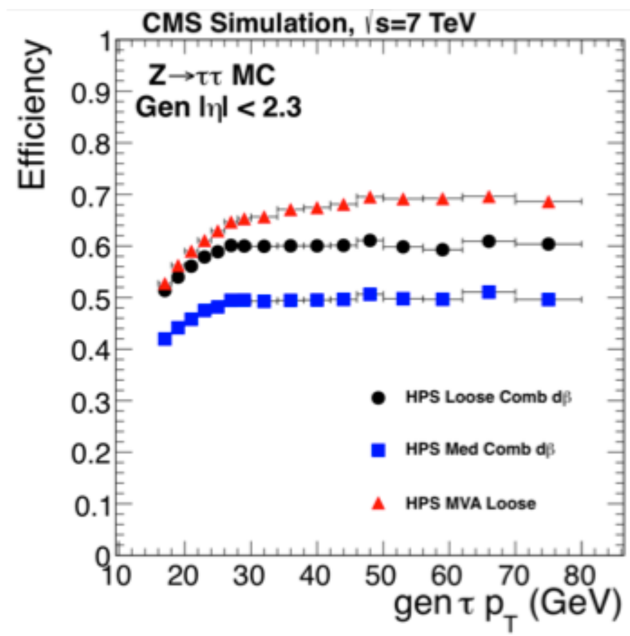
di-lepton (eμ)



Tau jet identification

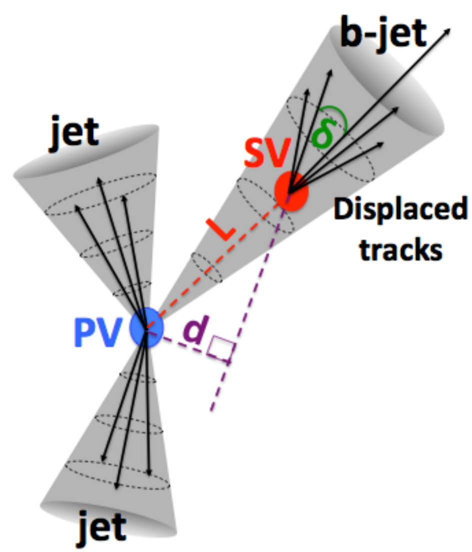
- Taus decay 65% to hadrons (i.e. jets) and 35% to leptons
  - Hadronic tau decays are reconstructed with Particle-Flow (PF)
  - narrow jet with few tracks
  - Leptonic tau decays are similar to prompt leptons (lepton p_T is softer, 3-body decay)
- Hadronic tau decays
  - Main background from jets/electrons
  - Identified based on decay modes, charged hadrons, and ECAL deposits
- ``Hadron Plus Strips'' (HPS) algorithm
  - Uses photon conversion in tracker ($\gamma \to e^+e^-$)
  - Combines PF EM particles ($\gamma, e^\pm$) in "strips"
  - "strips" are combined with PF charged hadrons
  - Individual decay modes are reconstructed
- Fake Rate ~3% for 70% efficiency





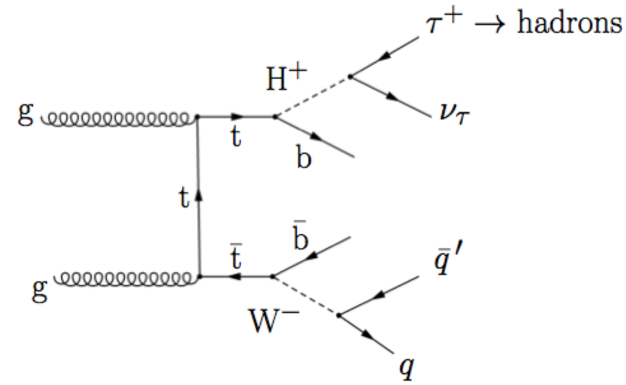
b-tagging

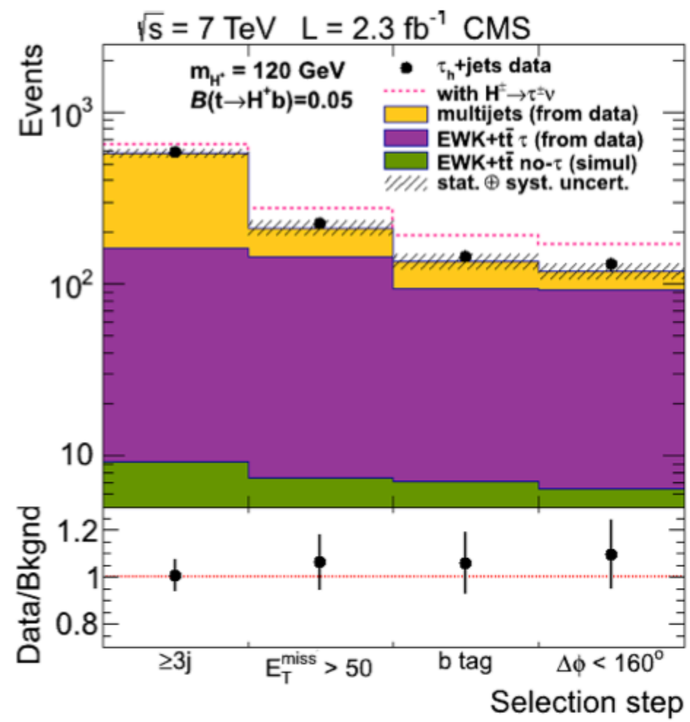
- b-tagging with Track Counting High efficiency (TCHE) algorithm
- Maximizes efficiency of finding b-jets
- Relies on tracks with large impact parameter (d_{track})
- Tracks ordered in decreasing d_{track} significance (S_{IP})
- Jet b-tagged if S_{IP}>1.7
- For p_T=50-80 GeV, tagging rate ~76% (mistag rate ~13%)



1) Fully hadronic: tau+jets

- Main backgrounds: QCD multi-jet, ttbar, W+jets
- Event selection:
  - Trigger: single tau+MET trigger
  - Require one tau jet p_T>40 GeV
  - MET>50 GeV
  - At least 3 jets, p_T>30 GeV
  - At least one b-tagged jet
  - $\Delta\phi(\tau,MET)<160^o$
  - Reconstruct $M_T(\tau,MET)$





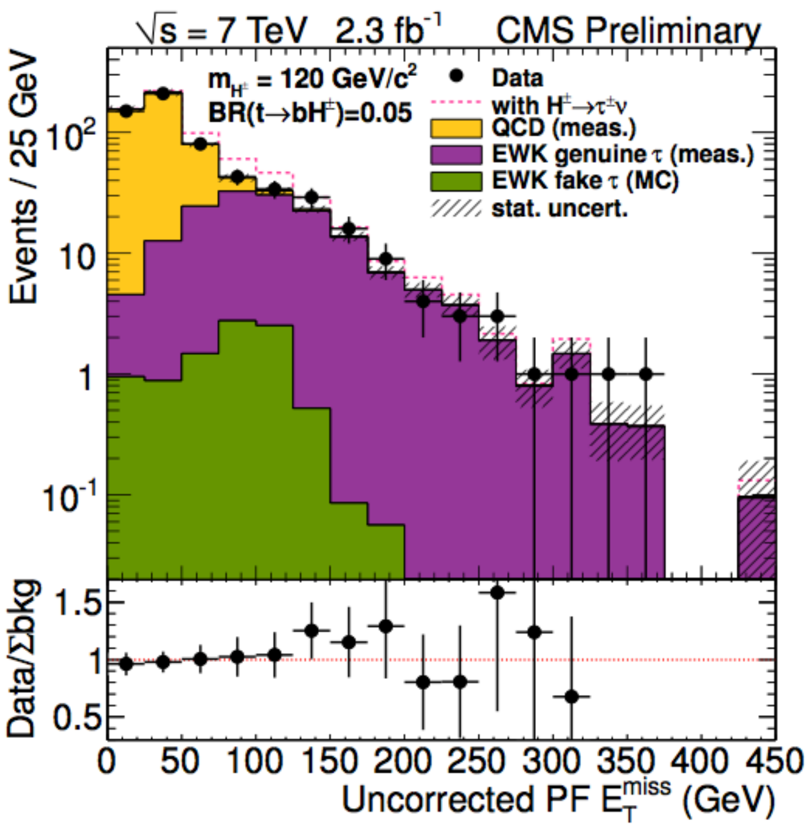
Intermediate step: data-driven

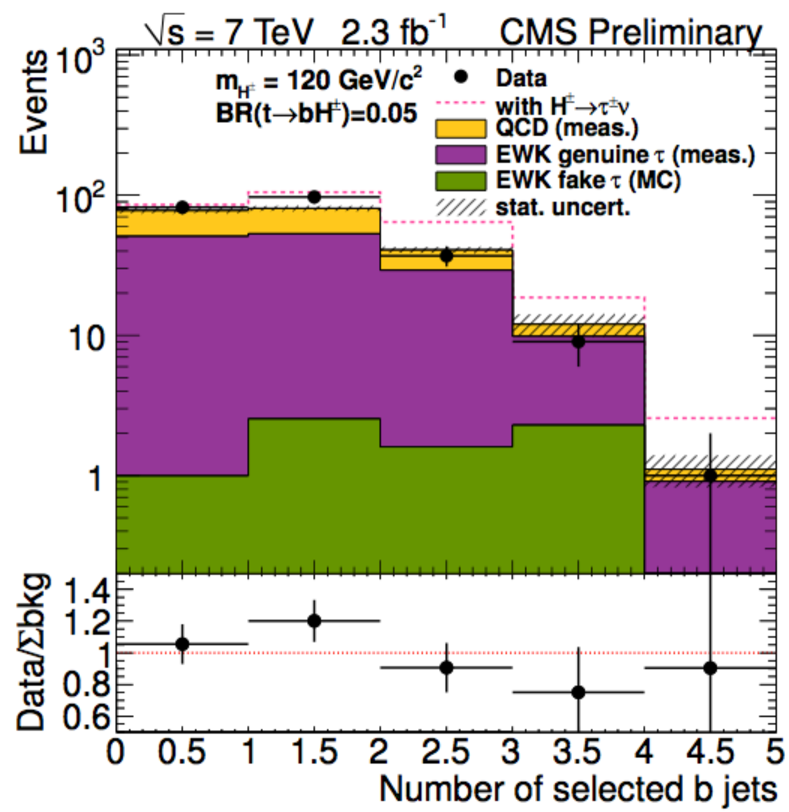
After τ-jet, lepton veto, ≥3 jets

- Main backgrounds well described
- MET>50 GeV suppresses QCD

+ MET cut

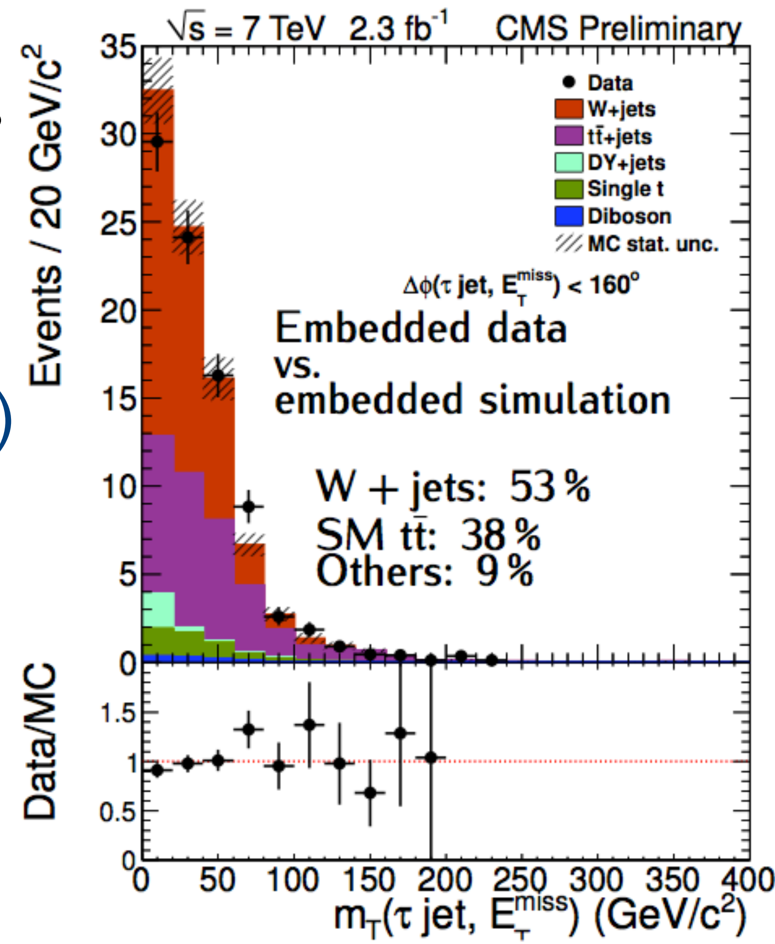
- Small excess for 1 b-tagged jet
- Good agreement overall





Background measurement

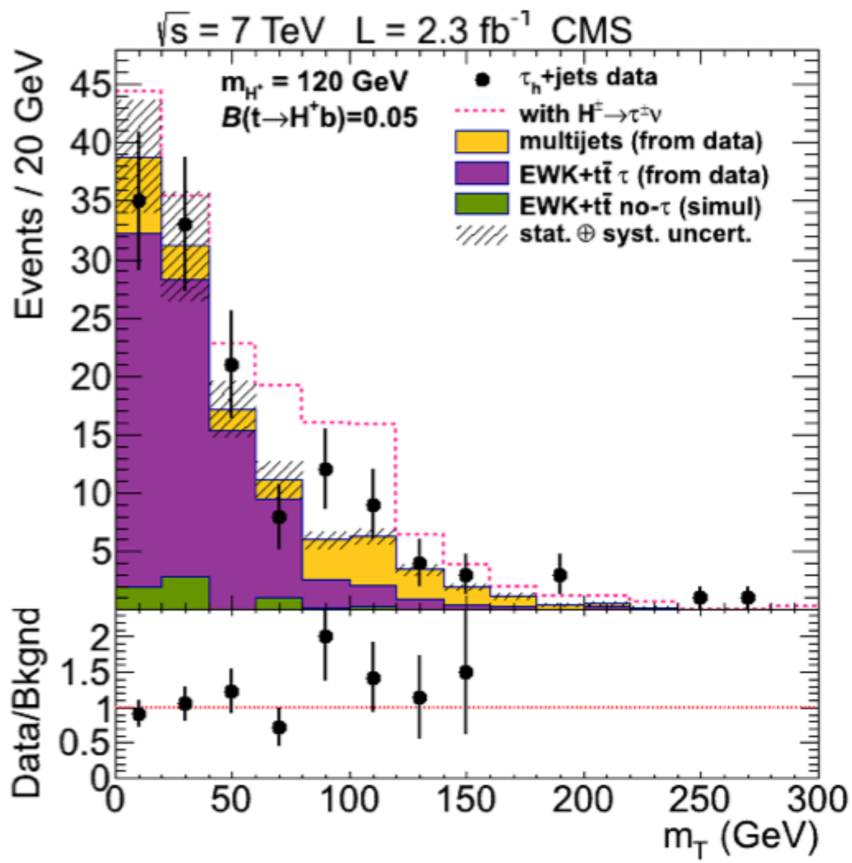
- Multi-jet background (from data)
  - Background from QCD with a jet is misidentified as τ_h, no genuine source of MET
  - Shape and normalization measured separately
  - Factorized in bins of tau p_T
- EWK and ttbar with genuine taus (from data)
  - Based on tau embedding method
  - Select events with one isolated muon
  - Replace muon with tau
- EWK and tau fake (e/mu/jets mis-id as tau)
  - Small, estimated from simulation



Event yield summary

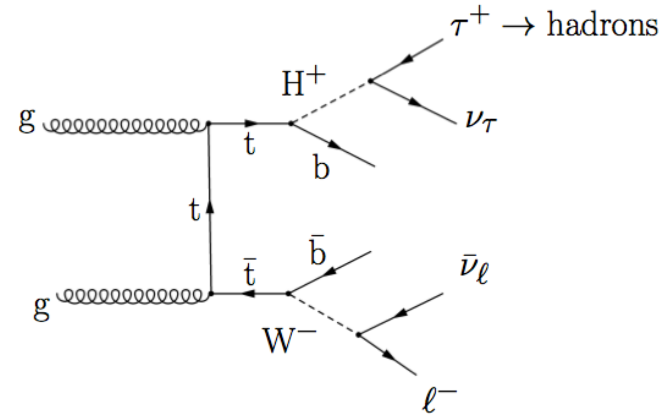
- After all cuts:
  - QCD multi-jet largely suppressed
  - EWK+ttbar (tau): irreducible
  - EWK+ttbar (no tau): negligible
  - Small excess around 80-100 GeV
- M_T used in a CLs binned maximum likelihood ratio fit to extract limits

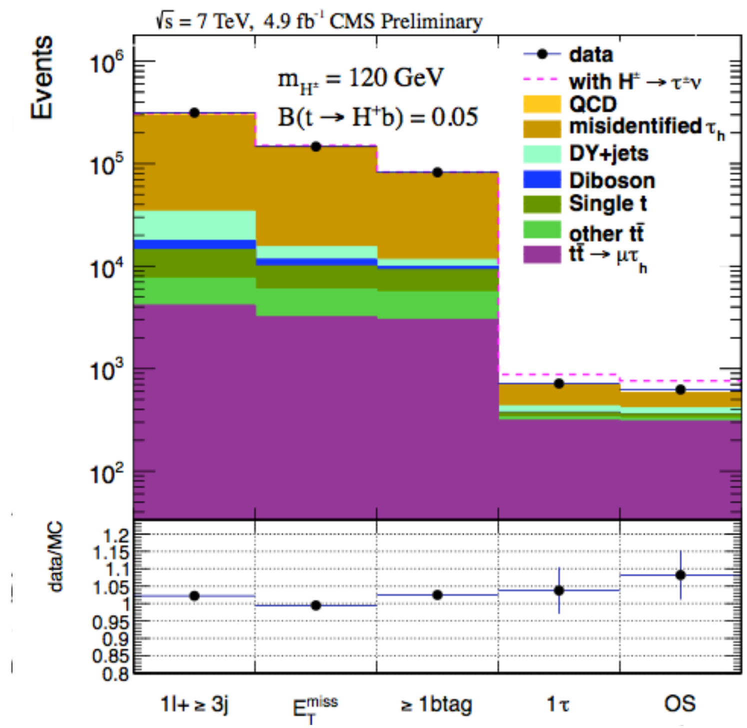
Source	$N_{\mathrm{ev}}^{\tau_h+\mathrm{jets}} \pm$ stat. $\pm$ syst.
HH + WH, $m_{\mathrm{H}^+} = 120\,\mathrm{GeV}$, $\mathcal{B}(\mathrm{t} \rightarrow \mathrm{H}^+\mathrm{b}) = 0.05$	$51 \pm 4 \pm 8$
multijets (from data)	$26 \pm 2 \pm 1$
EWK+t$\bar{\mathrm{t}}$ τ (from data)	$78 \pm 3 \pm 11$
EWK+t$\bar{\mathrm{t}}$ no-τ	$6.0 \pm 3.0 \pm 1.2$
residual $\mathrm{Z}/\gamma^* \rightarrow \tau\tau$	$7.0 \pm 2.0 \pm 2.1$
residual WW $\rightarrow \tau\nu_\tau\tau\nu_\tau$	$0.35 \pm 0.23 \pm 0.09$
Total expected background	$119 \pm 5 \pm 12$
Data	130



2) Tau+lepton (e/μ)

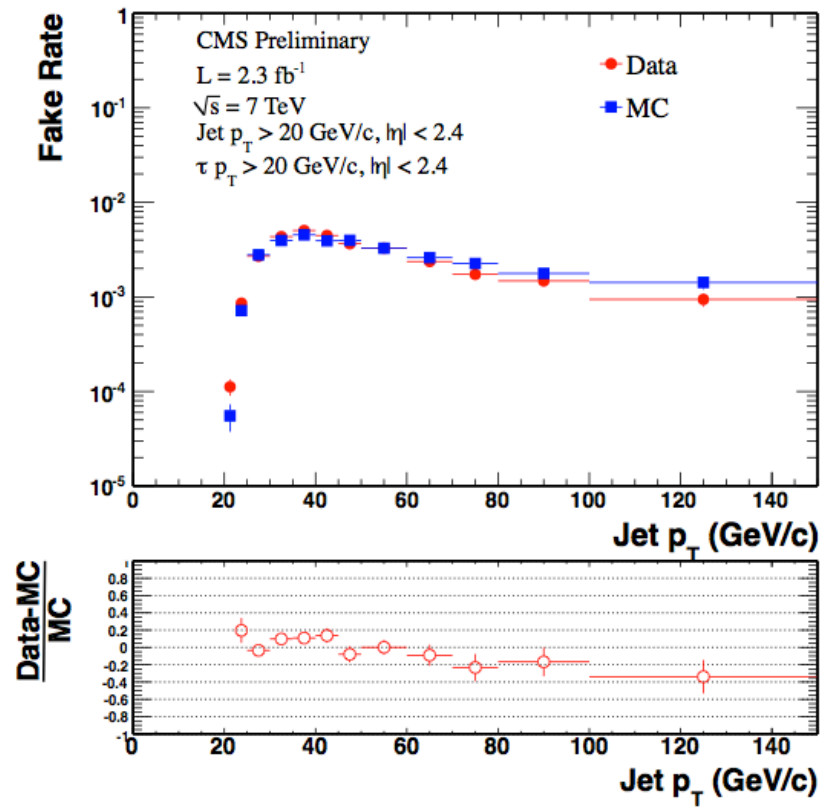
- Main backgrounds: ttbar, W+jets
- Event selection:
  - Trigger: single muon (electron+jets) trigger
  - One isolated electron/muon p_T>35(30) GeV
  - At least 2 jets p_T>35(30) GeV
  - MET>45(40) GeV
  - One tau p_T>20 GeV
  - Opposite-sign (tau,lepton)
  - At least one b-tagged jet





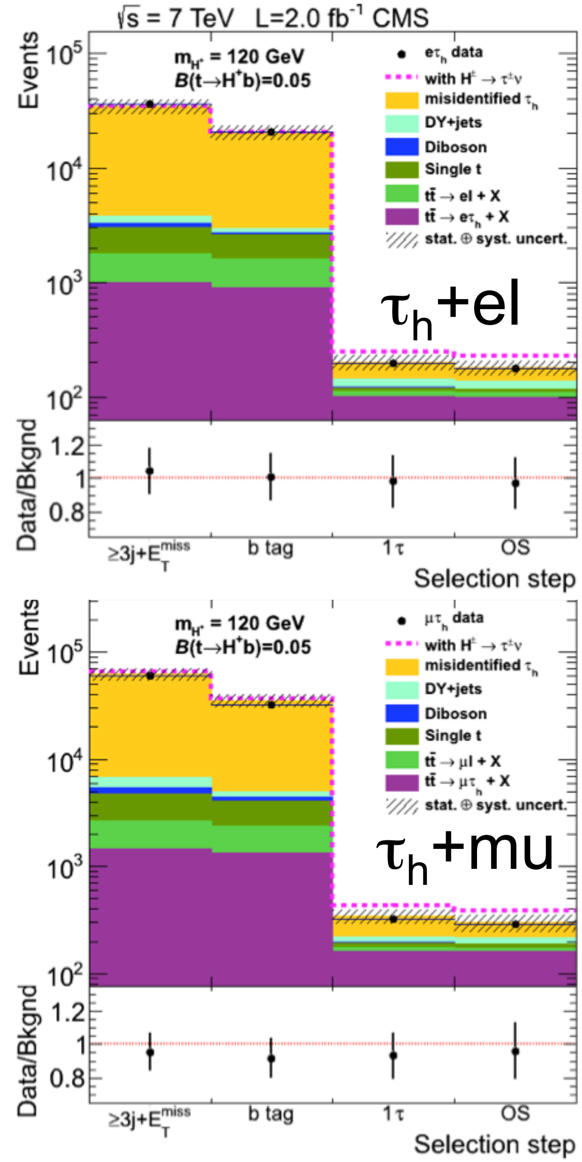
Background estimate

- Main background: ttbar and ``fake" τ-jets
- Fake background estimated from data
  - Select "W+≥3jet" events (1 lepton+MET+≥3jets)
  - Apply to every jet, the ``jet→tau probability"
  - Tau fake probability evaluated from data from jets (multijet, W+jets)
  - Parametrized as function of p_T, η, jet width (R)
  - quark vs gluon jet composition
- Good agreement with expectations



Event yields

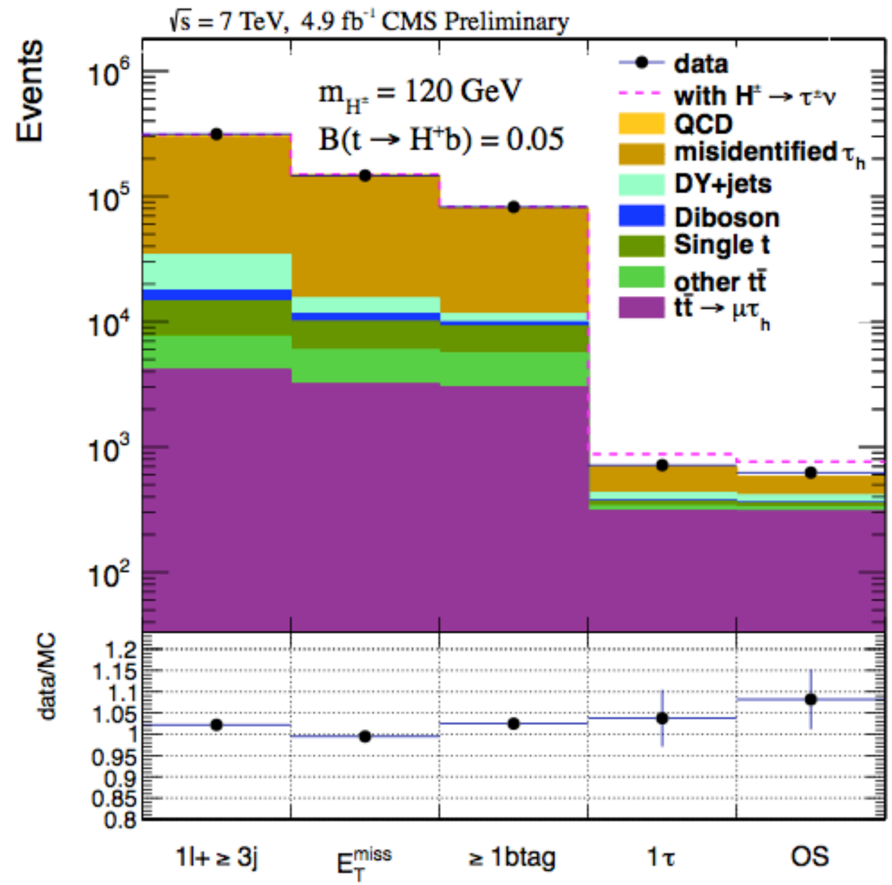
Source	$e\tau_h$: $N_{ev}^{e\tau_h} \pm$ stat. $\pm$ syst.	$\mu\tau_h$: $N_{ev}^{\mu\tau_h} \pm$ stat. $\pm$ syst.
HH+HW, $m_{H^+} = 120\,GeV$, $\mathcal{B}(t \to H^+b) = 0.05$	$51 \pm 3 \pm 8$	$89 \pm 4 \pm 13$
misidentified τ (from data)	$54 \pm 6 \pm 8$	$89 \pm 9 \pm 11$
$t\bar{t} \to WbW\bar{b} \to \ell\nu b\ \tau\nu\bar{b}$	$100 \pm 3 \pm 14$	$162 \pm 4 \pm 23$
$t\bar{t} \to WbW\bar{b} \to \ell\nu b\ \ell\nu\bar{b}$	$9.0 \pm 0.9 \pm 1.8$	$13.0 \pm 1.2 \pm 2.5$
$Z/\gamma^* \to ee, \mu\mu$	$4.8 \pm 1.8 \pm 1.3$	$0.7 \pm 0.7 \pm 0.7$
$Z/\gamma^* \to \tau\tau$	$17.0 \pm 3.3 \pm 3.0$	$26.0 \pm 4.3 \pm 6.1$
single top quark	$7.9 \pm 0.4 \pm 1.1$	$13.5 \pm 0.5 \pm 1.9$
diboson	$1.3 \pm 0.1 \pm 0.2$	$2.0 \pm 0.2 \pm 0.3$
Total expected background	$194 \pm 8 \pm 20$	$306 \pm 11 \pm 32$
Data	176	288



Event yields: tau+muon update

- Dominant background is from fakes
- Tau dilepton ttbar events: irreducible
- Other backgrounds are small

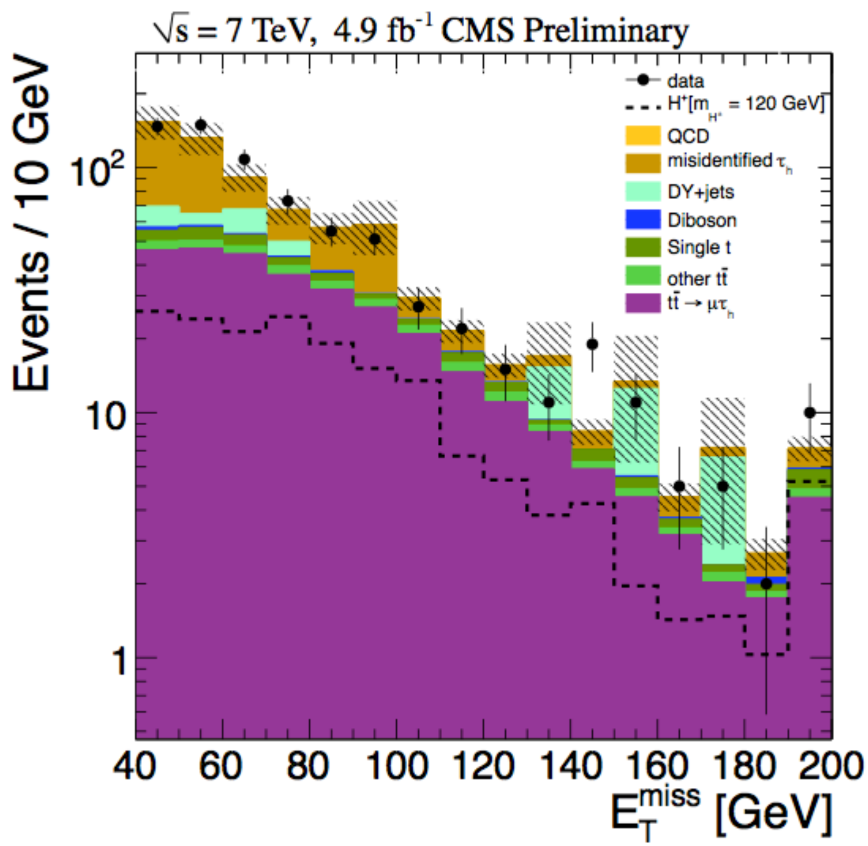
Source	N_{events} ($\pm$ stat. $\pm$ syst.)
HH+HW, m_{H^+}=120 GeV, $\mathcal{B}(t \to H^+ b)$=0.05	$179.3 \pm 8.7 \pm 22.1$
τ fakes (from data)	222.0 ± 11.4
$t\bar{t} \to WbWb \to (\mu\nu b)\ (\tau_h \nu b)$	$304.7 \pm 2.8 \pm 25.9$
$t\bar{t} \to WbWb \to (\ell\nu b)\ (\ell\nu b)$	$21.4 \pm 0.7 \pm 6.9$
$Z/\gamma^* \to ee, \mu\mu$	$0.4 \pm 0.4 \pm 0.1$
$Z/\gamma^* \to \tau\tau$	$50.6 \pm 17.6 \pm 20.7$
Single top	$26.6 \pm 1.2 \pm 3.3$
VV	$4.4 \pm 0.5 \pm 0.7$
Total expected from SM	$630.1 \pm 17.9 \pm 46.9$
Data	620

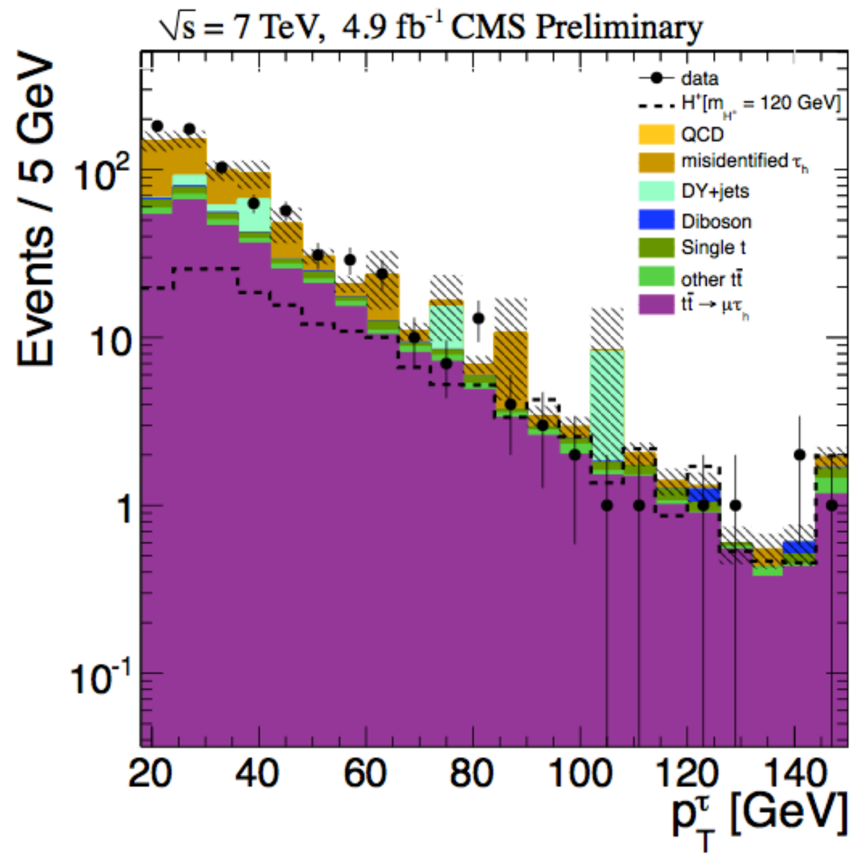


Tau+muon final state

After full event selection:

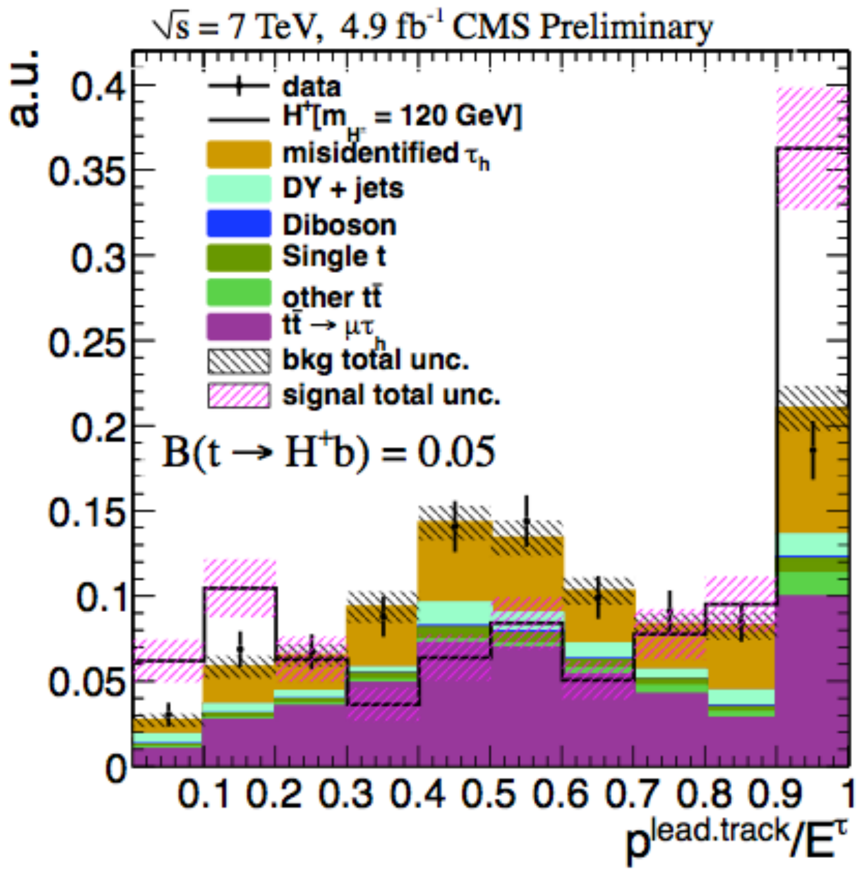
- MET and tau p_T distributions
- Good agreement data vs backgrounds

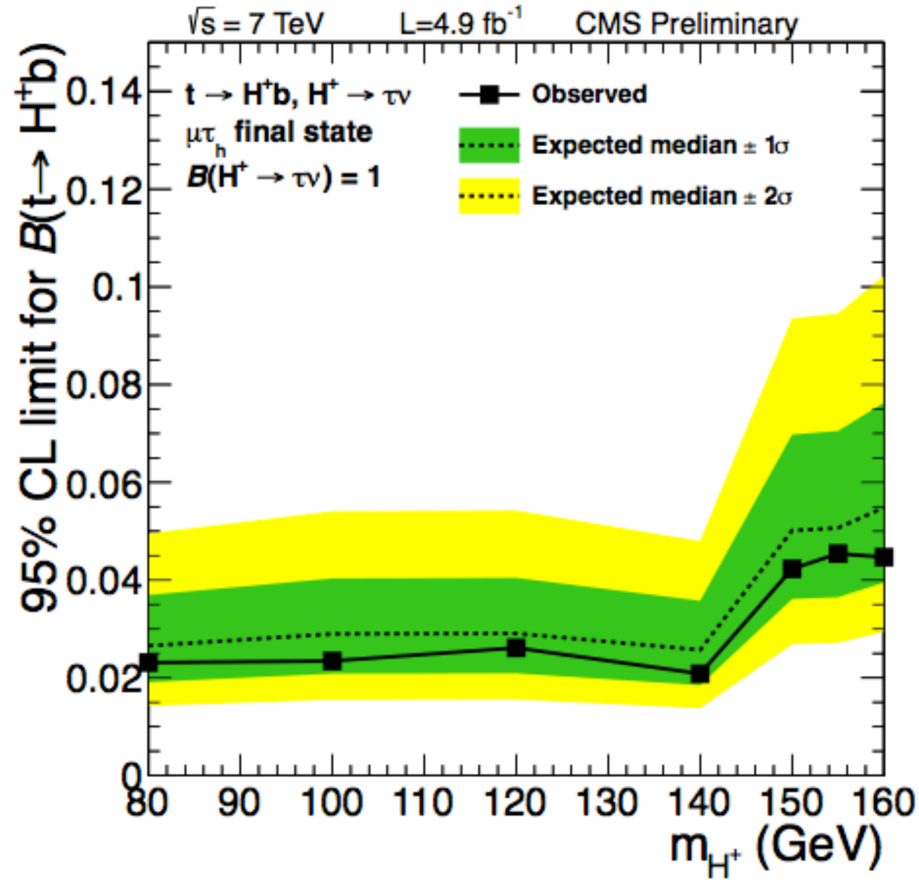




Tau+lepton: limits (cont.)

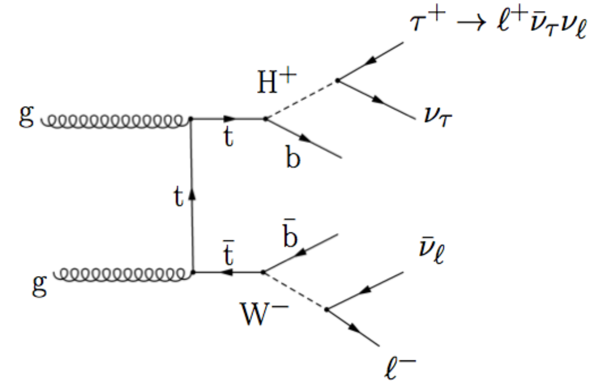
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties



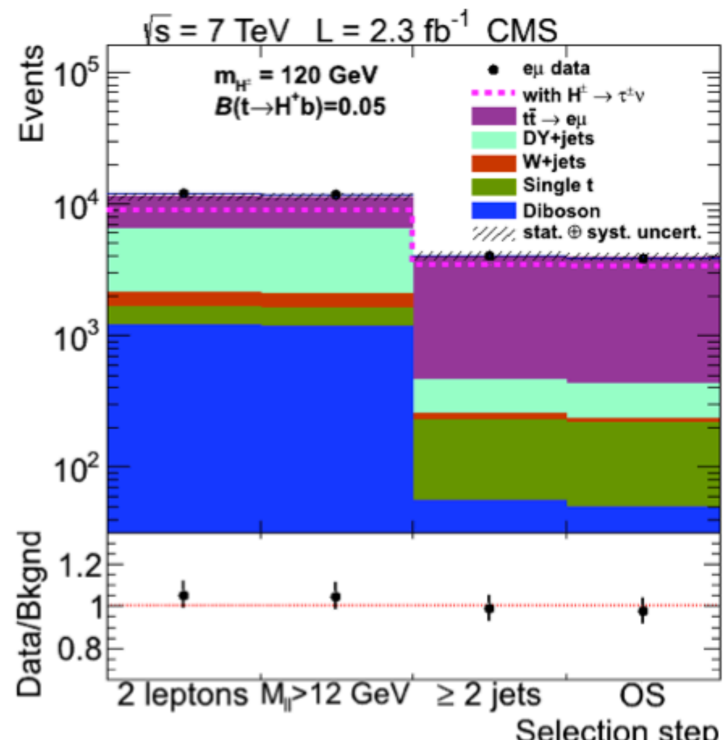


3) Dilepton (eμ) final state

- Tau decays leptonically
- Main background: ttbar
- Event selection:
  - eμ trigger: ele+mu (p_T>20 GeV)
  - At least 2 jets (p_T>30 GeV)
- Expect deficit of events (softer τ p_T)



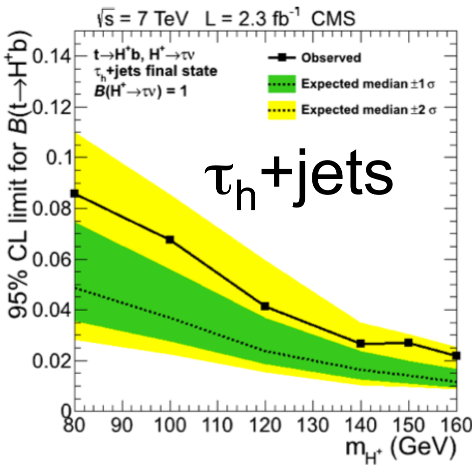
Source	$N_{ev}^{e\mu} \pm$ stat. $\pm$ syst.
HH+WH, $m_{H^+} = 120\,GeV$, $\mathcal{B}(t \to H^+ b) = 0.05$	$125 \pm 9 \pm 13$
$t\bar{t}$ dileptons	$3423 \pm 35 \pm 405$
other $t\bar{t}$	$23 \pm 3 \pm 3$
$Z/\gamma^* \to \ell\ell$	$192 \pm 12 \pm 19$
W+jets	$14 \pm 6 \pm 2$
single top quark	$166 \pm 3 \pm 18$
diboson	$48 \pm 2 \pm 5$
Total expected background	$3866 \pm 38 \pm 406$
Data	3875

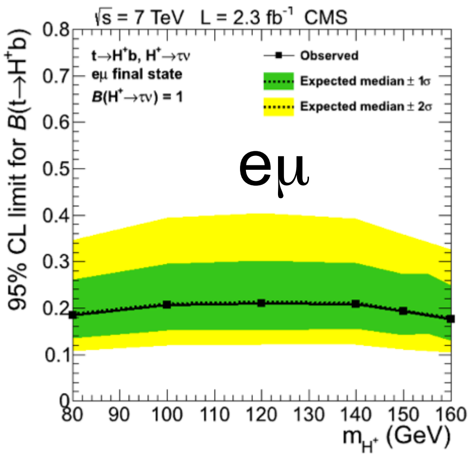


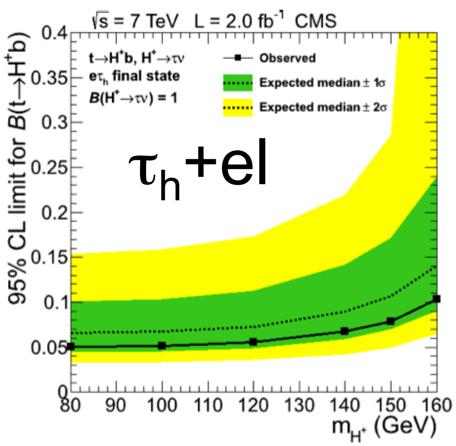
Combined limits

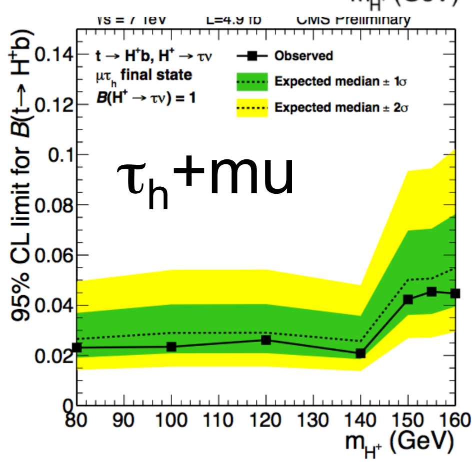
signal modeled as excess/deficit of event yields

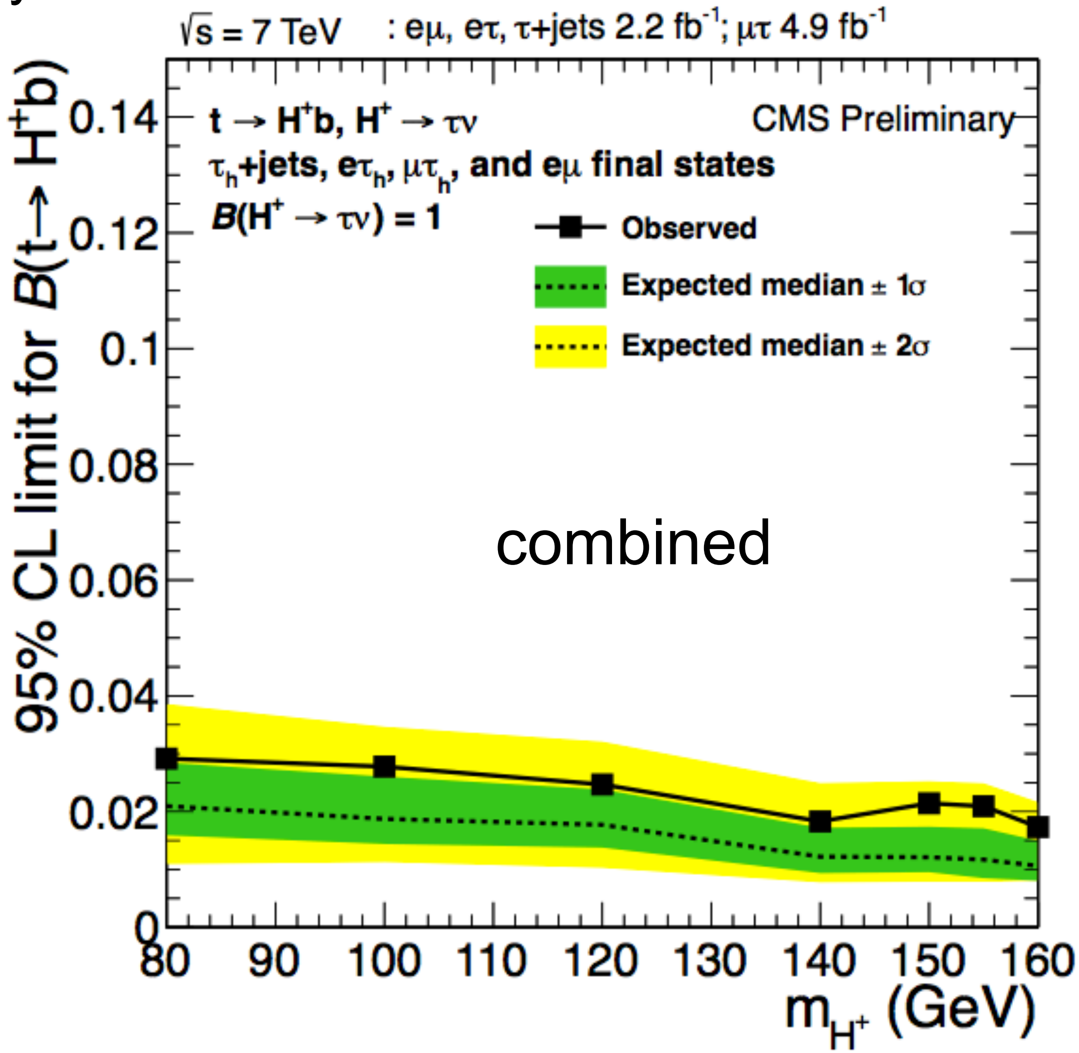
$$\Delta N = N_{t\bar{t}}^{\mathrm{MSSM}} - N_{t\bar{t}}^{\mathrm{SM}} = 2x(1-x)N_{\mathrm{WH}} + x^2 N_{\mathrm{HH}} + [(1-x)^2 - 1]N_{t\bar{t}}^{\mathrm{SM}}$$







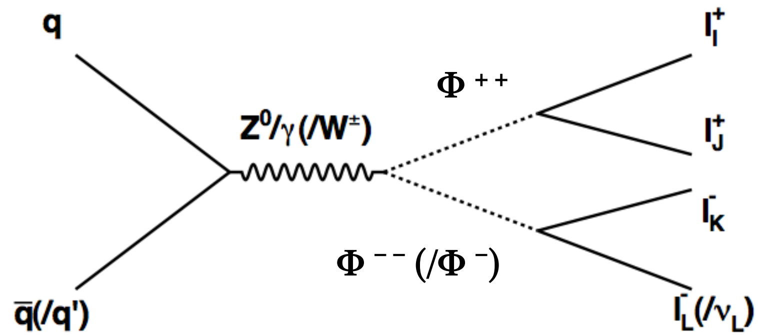


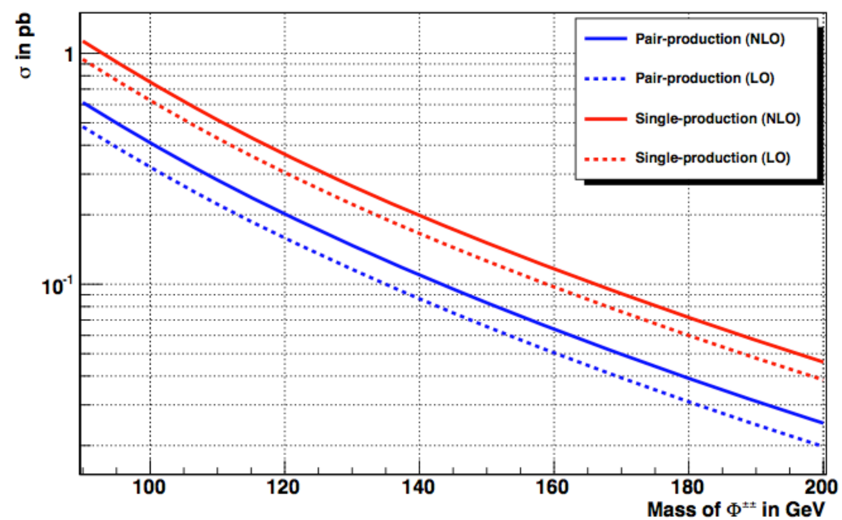


Doubly charged Higgs

EPJC 72 (2012) 2189

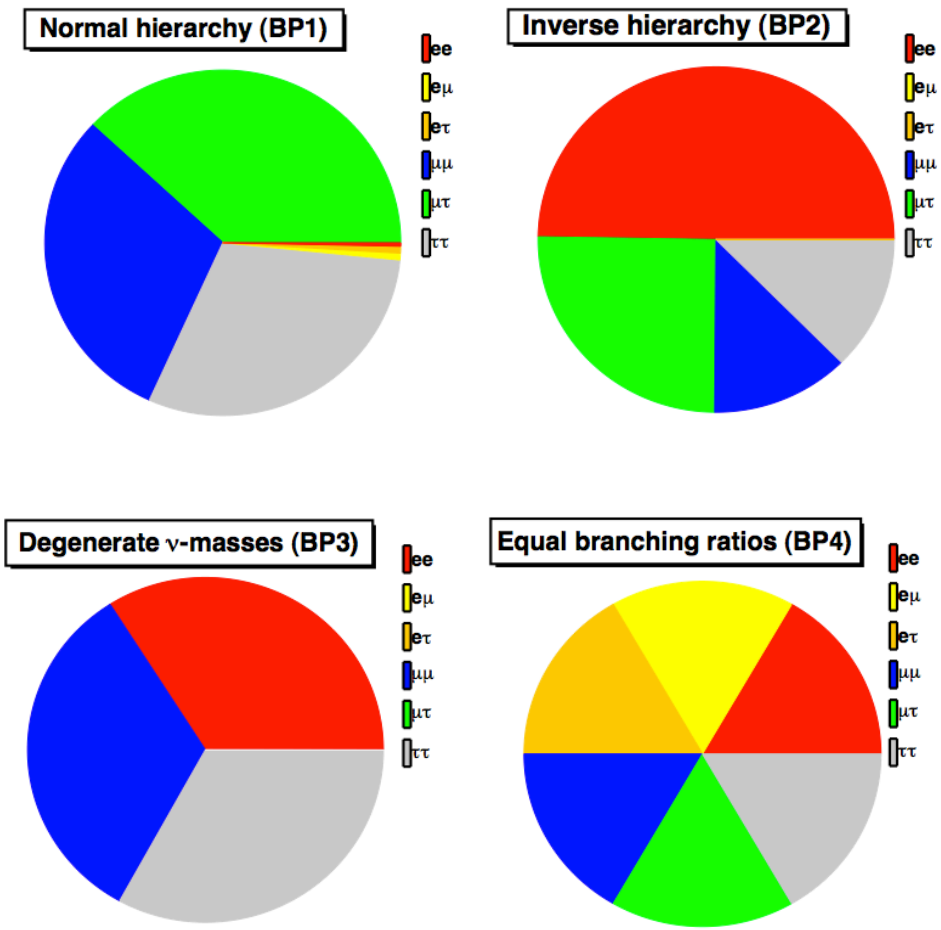
- Model
  - SM is extended with scalar triplet (Φ^{++}, Φ^{+}, Φ^{o})
  - Triplet responsible for neutrino masses
  - Search for doubly- and singly-charged
  - DY pair production is most common
  - Φ^{++} decays to SS lepton pair of any flavor combination
- Associated production
  - $pp \to W^* \to \Phi^{++}\Phi^{-}$
  - xsection at LHC is ~2x higher than pair production
  - VBF channel: $pp \to W^+W^- \to \Phi^{++}$+jets (difficult)
- Search with ≥3 leptons of any flavor
  - Search for excess of events in one or more flavor combinations of SS lepton pairs





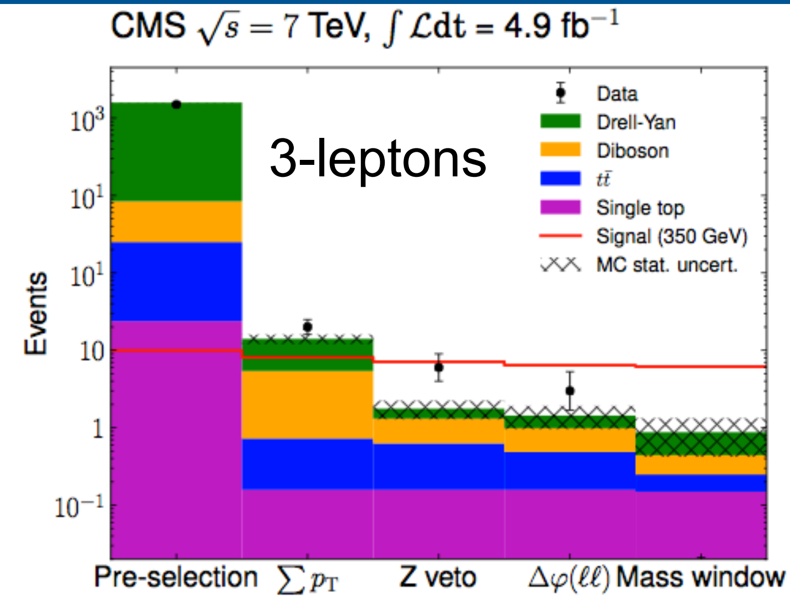
Experimental signature

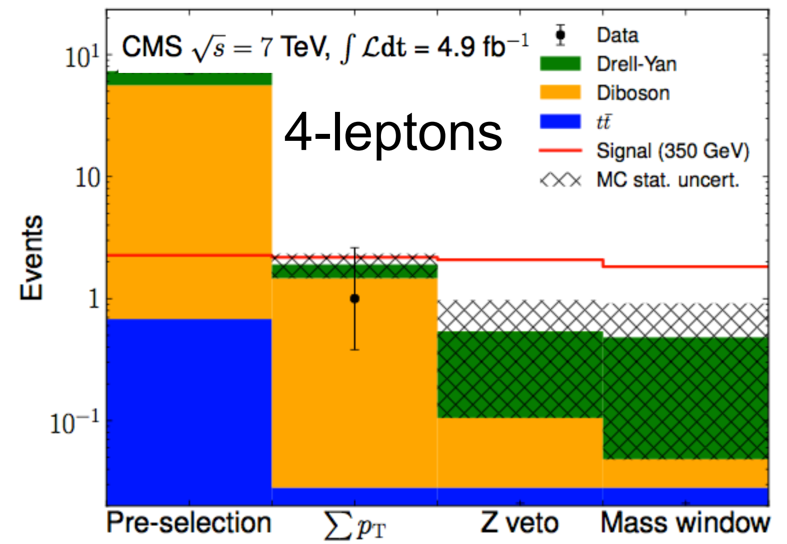
- Couplings directly linked to neutrino mass matrix
  - As we don't know ν mass matrix, we don't know BRs
  - Search for BR($\Phi^{++} \to l^+l^+$)=100% (l=e,μ,τ)
  - Four additional model-dependent points
- Look for 3 or 4 prompt isolated leptons in final state
- Unlike SM, combination of interest is SS
- Due to flavor non-conservation, final states can be combination of any flavor
- Fully inclusive search



Analysis strategy

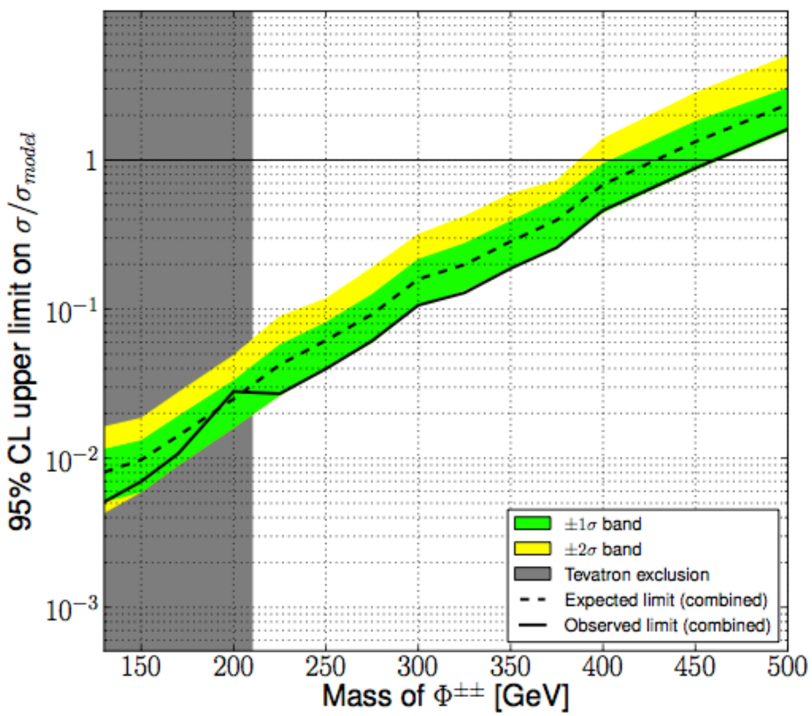
- Analysis separated in categories
  - Light leptons and τ_h
  - Σp_T, Z veto, $\Delta\phi$, MET
- Three leptons
  - Separate signal and bkg based on significance
  - *lll* and *ll*τ_h
- Four leptons
  - Substantially reduced backgrounds
  - llll, lllτ_h, ll$\tau_h\tau_h$ final states

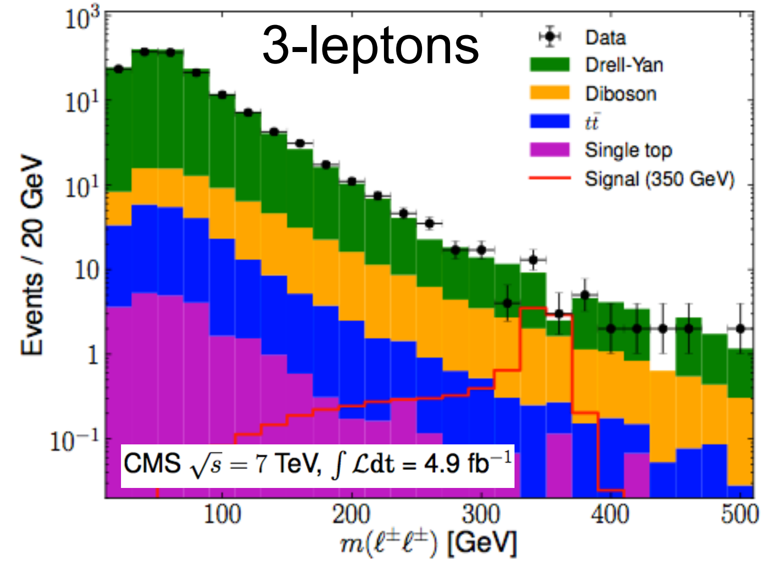


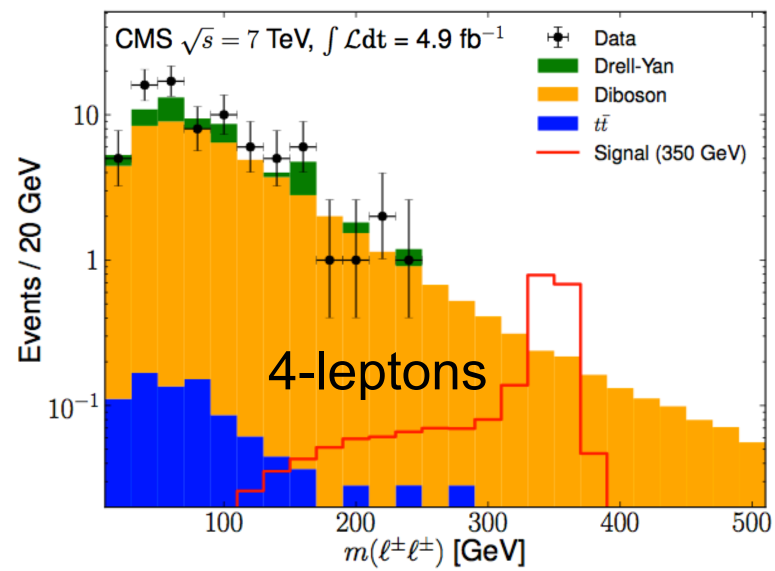


Inclusive search in leptonic final states

- Event selection:
  - double lepton trigger (p_T>17,8 GeV)
  - electron/muon/tau: p_T>15/5/15 GeV
- Backgrounds are small
  - determined from data (side-bands/"ABCD")



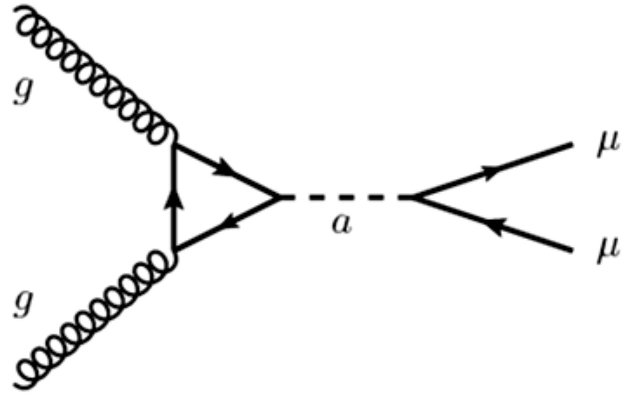


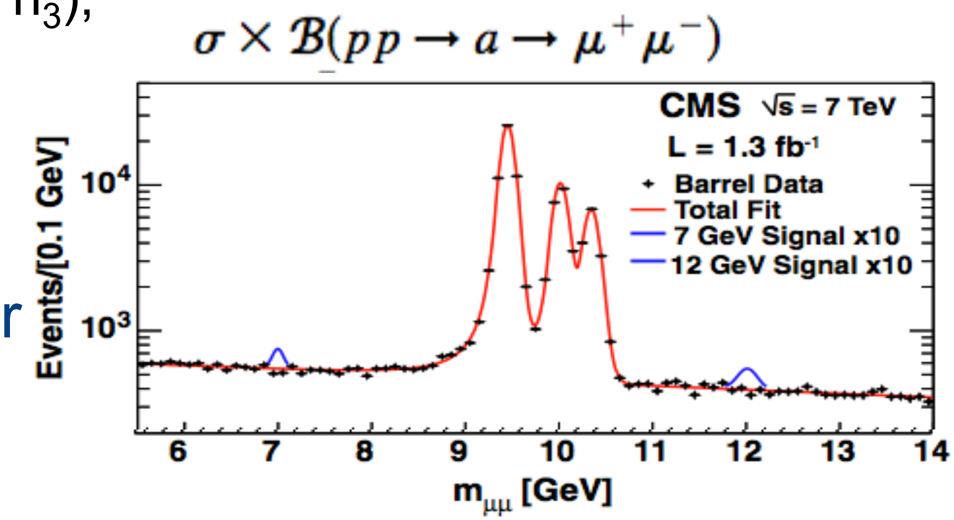


Light pseudo-scalar: $a \to \mu^+\mu^-$

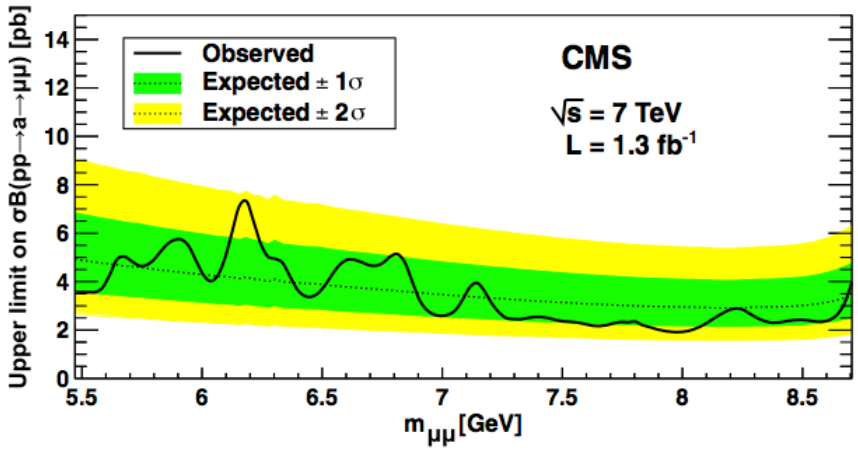
PRL 109,121801(2012)

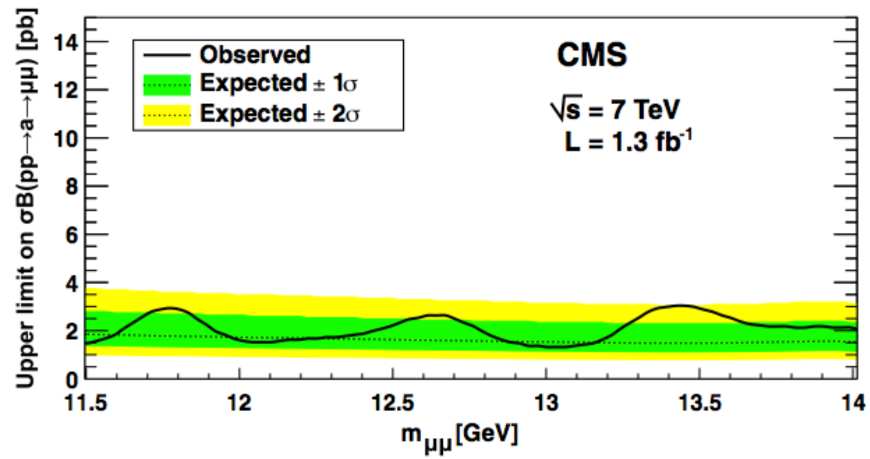
- Low-energy SUSY
  - solution to hierarchy problem
  - provides DM candidate
  - provides unification of gauge couplings
- Predicted in NMSSM
  - Expands MSSM: 3 CP-even scalars (h_1, h_2, h_3), 2 CP-odd (a_1, a_2), 2 charged ($H^\pm$)
  - Add scalar singlet to MSSM family
- Large cross section: $gg \to a \to \mu^+\mu^-$
- Search for general light pseudo-scalar Higgs (a) near Υ resonance

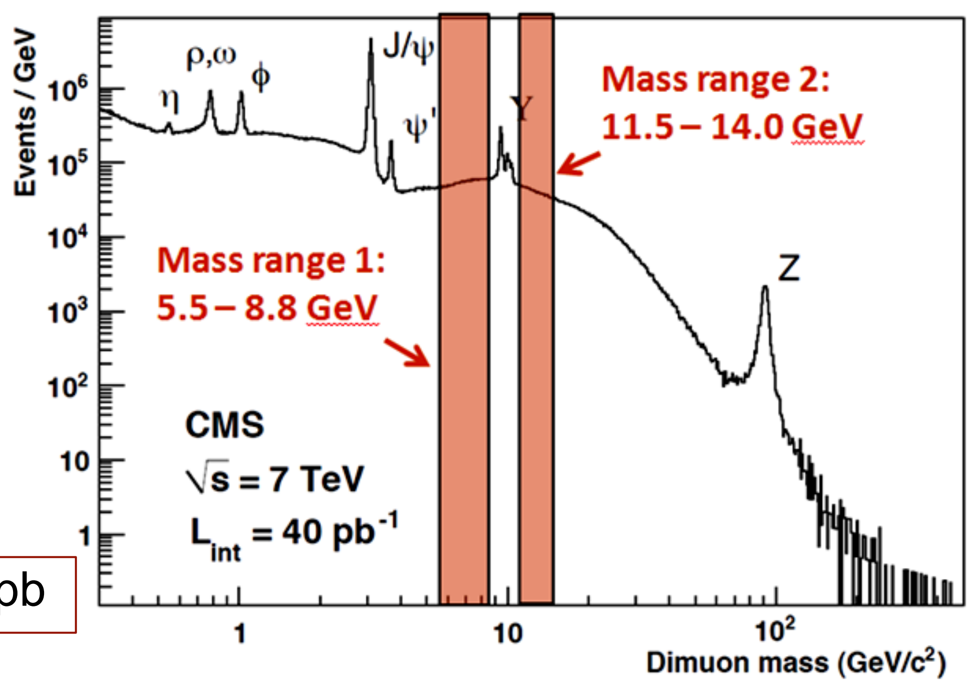




Constraints on a→μ⁺μ⁻ production







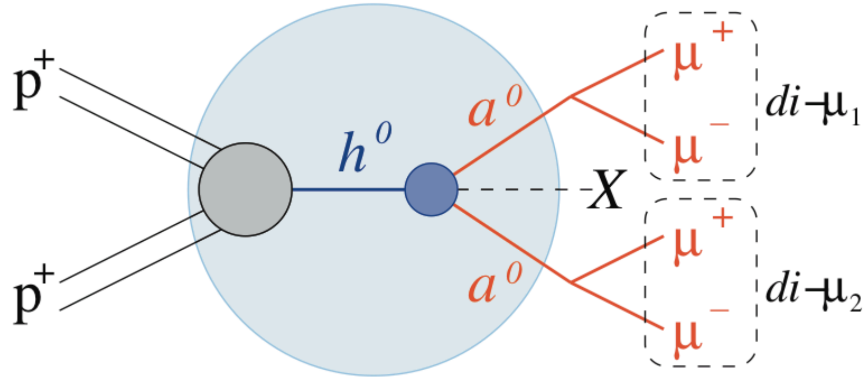
- Search below and above the Y family
- Set limits:
  - No excess found above background expectations

$\sigma \times \mathcal{B}(pp \to a \to \mu^+\mu^-)$ ~1.5-7.5 pb

non-SM Higgs decay: $h \to 2a \to 4\mu$

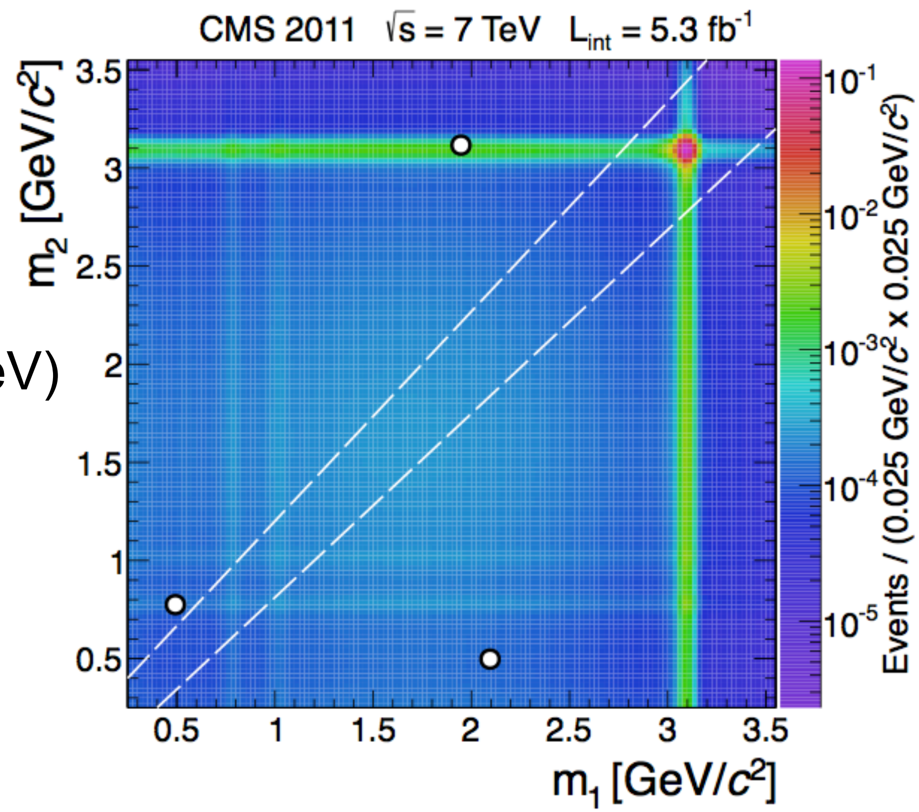
arXiv:1210.7619

- Explore non-SM decays of the Higgs boson (h)
  - include production of two new light boson (a^0)
- Search for generic Higgs decays: $h \to 2a + X \to 4\mu + X$
  - Predicted in several models (NMSSM, dark SUSY)
  - Complementary to direct SM Higgs searches
  - Sensitivity to new decays with small BRs that can't be excluded in standard Higgs measurements without much larger amounts of data
- Selection designed to have low sensitivity to model details
  - Find low mass muon pairs ("dimuons")
  - Require each event to have two dimuons
  - Require two dimuon masses to be consistent
- Results
  - Limits on production rates, benchmark models



Upper limit cross section

- Backgrounds from bbbar, prompt double J/Ψ production
- Event selection:
  - Trigger: double muon (17, 8 GeV)
  - At least 4 muons: p_T>8 GeV ($p_T^{lead\text{-}mu}$>17GeV)
  - Mass pairs should be consistent (<5 GeV)
  - Study detector resolution with low mass SM resonances
- Results
  - observe 3 events in off-diagonal region, consistent with bkg expectations
  - Signal region: zero events (1.0±0.5 bkg)



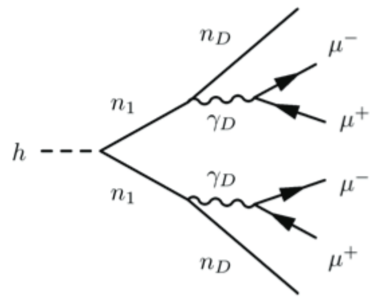
⇒ model-independent upper limit of 0.78±0.05 fb on the product of cross-section x BR x acceptance

NMSSM and Dark SUSY Limits

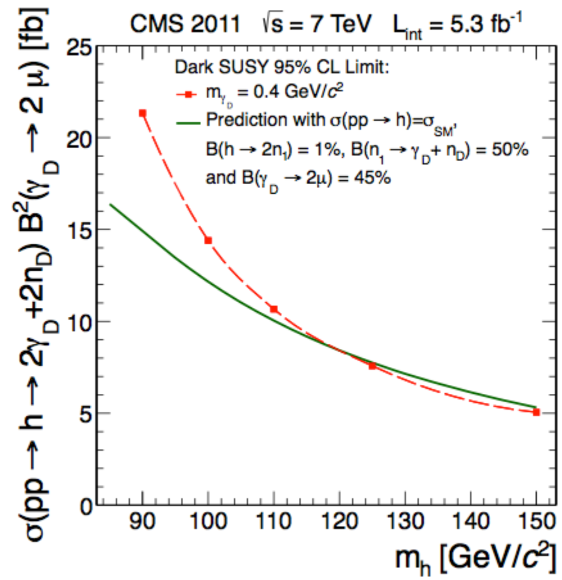
Results interpreted in NMSSM and dark SUSY

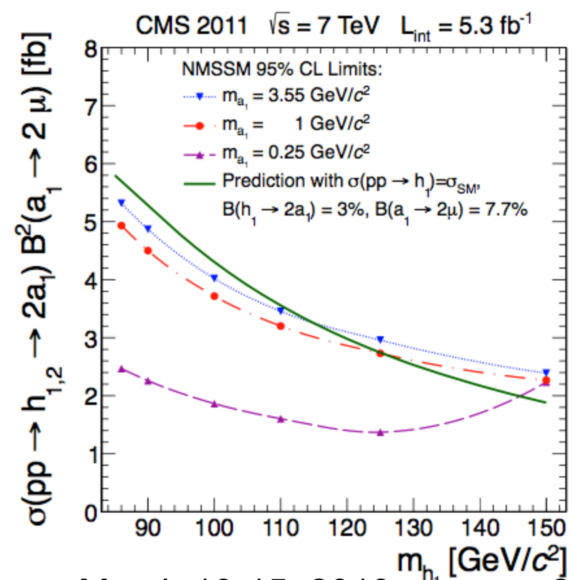
- Dark SUSY: h decay to pair of neutralinos (n_1): LSP

$n_1 \rightarrow n_D \gamma_D$ decays ($\gamma_D \rightarrow \mu\mu$; $n_D \rightarrow$ invisible)



- NMSSM: $h_{1,2} \rightarrow 2a_1$; $a_1 \rightarrow 2\mu$
- Compare to SM Higgs cross section





Summary

- Charged Higgs searches in top quark decays
  - Stringent limits
  - Light H^+ searches limited by systematics
- Other BSM searches show no indication of deviations
  - Doubly charged, light pseudo-scalar ($a \rightarrow \mu\mu$), non-SM Higgs decays
- Searches provide no hints for BSM yet

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