Charged Higgs Boson searches with ATLAS - results from the CSC note, March 08 -

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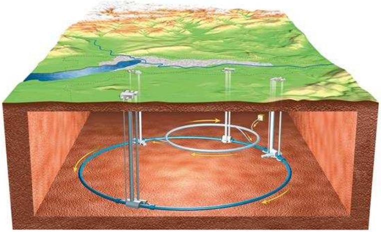
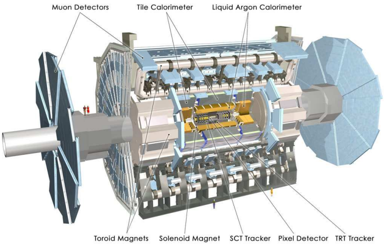
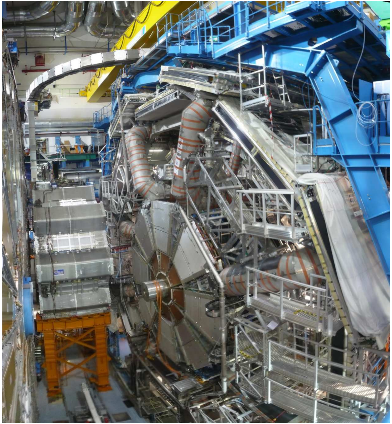
Overview

1. The ATLAS detector
2. Basics of charged Higgs Bosons
3. Main charged Higgs search channels
4. Estimation of the $t\bar{t}$ background from data
5. Results

The ATLAS detector







- LHC: proton-proton collider, 14 TeV
- expect first collisions in Summer 08 (starting with 10 TeV)

Higgs mass corrections and the hierarchy probem

- From LEP we know:
  Higgs must be light, m$_H \geq 114.4$ GeV

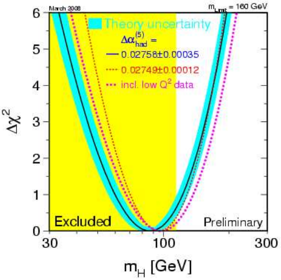
- Higgs mass receives corrections from loops containing particles that couple to the Higgs field.

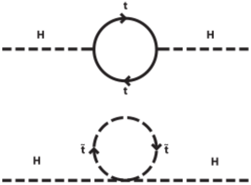
- if $\mathcal{L} = ... - \lambda_f H \bar{f} f$, the correction is:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + ...$$

  Λ_{UV}: ultraviolet momentum cutoff should be interpreted as the scale where new physics enters (m$_P \sim 10^{19}$ GeV)

- need new physics at TeV scale





Solutions of the hierarchy problem

four options:

- Higgs is not fundamental (technicolour)
- the cut-off scale is *much* lower then m_P (extra dimensions)
- some other theories (little Higgs)
- there is a striking cancellation between the various Δm_H^2 terms

$\rightarrow$ this cancellation of corrections to scalar masses appears actually *automatically* if there is a symmetry that relate fermions to bosons, a.k.a. Supersymmetry (SUSY)

$$\boxed{Q|\text{Boson}\rangle = |\text{Fermion}\rangle,\ Q|\text{Fermion}\rangle = |\text{Boson}\rangle}$$

- we consider MSSM (Minimal supersymmetric extension of the Standard Model) with two Higgs Doublets

Charged Higgs Bosons in MSSM (1)

Chiral Higgs supermultiplets in the minimal extension of SM

Name	spin 0	spin 1/2	SU(3)$_C$, SU(2)$_L$, U(1)$_Y$
H_u	$(H_u^+ \; H_u^0)$	$(\tilde{H}_u^+ \; \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +1/2)$
H_d	$(H_d^0 \; H_d^-)$	$(\tilde{H}_d^0 \; \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -1/2)$

- in SUSY only Y=1/2 Higgs multiplets can have the necessary Yukawa couplings to give masses to up-type quarks
- Y=-1/2 Higgs multiplets needed to give masses to down-type quarks and charged leptons

Charged Higgs Bosons in MSSM (2)

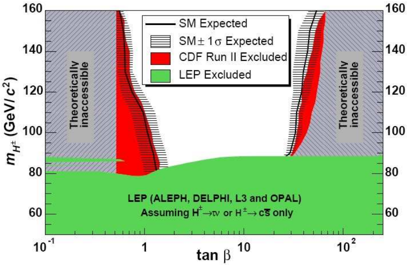
- after EW symmetry breaking 5 Higgs Bosons remain:
  - h^0,H^0: CP even
  - A^0: CP odd
  - $H^{\pm}$: charged
- at tree-level the Higgs sector is fixed by:
  - m_A (or $m_H^{\pm}$, $m_A^2 = m_H^{\pm 2} + m_W^2$)
  - $\tan\beta = v_2/v_1$ (v_i: vev of Higgs fields)
- we check two benchmark scenarios
  - scenario A ($H^+ \to$ Susy particles supressed)
  - scenario B (shifts m_h to high values acc. to LEP)

all values in GeV

$m_{top}=175$	$m_{SUSY}=1000$	$A_t=1000$	$\mu=200$	$M_2=1000$	$M_3=1000$
$m_{top}=175$	$m_{SUSY}=500$	$X_t=1000$	$\mu=200$	$M_2=200$	$M_3=800$

where $A_t = X_t + \mu\tan\beta$

CDF exclusion limits



Phys. Rev. Lett. 96, 042003 (2006)

- H^+ upper mass limit 79.3 GeV (95% CL)
- tanβ region around 1-30 not covered

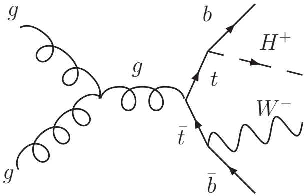
Charged Higgs Boson production

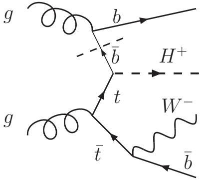
low mass: $m_{H^+} < m_{top} - m_b$

- charged Higgs produced by on shell top quark decay: $t \rightarrow H^+ b$
- at the LHC top quarks are mainly produced in pairs
- H^+ production through single top quarks not considered

high mass: $m_{H^+} \gtrsim m_{top} - m_b$

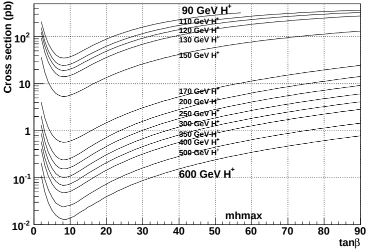
- two different modes: $gb \rightarrow H^+ t$, $gg \rightarrow tbH^+$
- additionally for intermediate mass region $m_H \sim 170$ GeV: 20-30% contribution from $t \rightarrow H^+ b$ (see above)



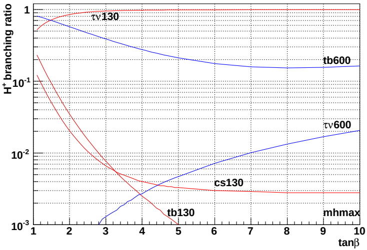


Charged Higgs Boson production and decay

$\sigma[t\bar{t} \rightarrow (H^+b)(Wb)]$



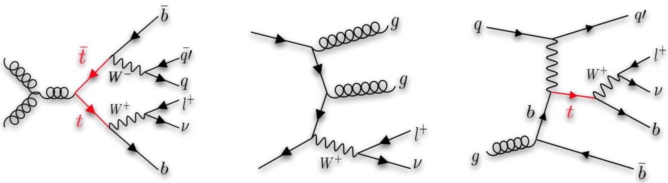
$Br(H^+)$



A. Sopczak (ATL-COM-PHYS-2008-013)

- xsec$[t\bar{t} \rightarrow (Wb)(W\bar{b})]$: NLO
- BR($t \rightarrow H^+ b$): FeynHiggs 2.6.2
- not considered: $H^+ \rightarrow W^+ h^0$
- low mass (red) almost exclusive decay: $H^+ \rightarrow \tau\nu$
- high mass (blue) most important contribution $H^+ \rightarrow tb$
- $\sigma(\text{Signal}) = 2\sigma_{tt}[Br(t \rightarrow H^+ b)][1 - Br(t \rightarrow H^+ b)]$

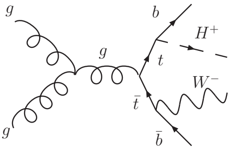
Backgrounds

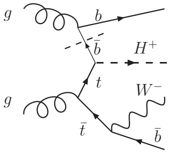


mode	xsec[pb]
$t\bar{t}$ (1l)	452
W+jets	912
Wt	29
s-chan	3.5
t-chan	80

- $t\bar{t}$ is the dominant background (same topology, high xsec)
- single top production also possible through EW Wtb vertex
- these modes should be less important due to small cross sections wrt. $t\bar{t}$ (diff. topo.)
- inclusive W+jets production important due to its high cross section (different topo., but high xsec)
- not shown: QCD background (very high xsec, no MC available)

CSC analyses





Light Higgs

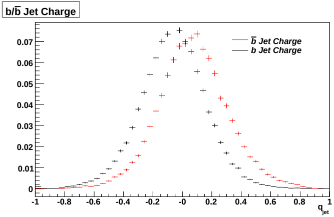
- $\tau_{\mathrm{had}}+\mathrm{W}_{\mathrm{had}}$ channel $\mathrm{t\bar{t}} \to (\mathrm{H}^+\mathrm{b})(\mathrm{W\bar{b}}) \to (\tau_{\mathrm{jet}}\bar{\nu}_\tau\nu_\tau \mathrm{b})(\mathrm{qq\bar{b}})$
  high branching ratio, m_T reconstruction, difficult to trigger
- $\tau_{\mathrm{lep}}+\mathrm{W}_{\mathrm{had}}$ channel $\mathrm{t\bar{t}} \to (\mathrm{H}^+\mathrm{b})(\mathrm{W\bar{b}}) \to (l\bar{\nu}_\tau\nu_\tau\bar{\nu}_l \mathrm{b})(\mathrm{qq\bar{b}})$
  easy trigger, m_T reconstruction, high $\mathrm{t\bar{t}}$ background
- $\tau_{\mathrm{had}}+\mathrm{W}_{\mathrm{lep}}$: $\mathrm{t\bar{t}} \to (\mathrm{H}^+\mathrm{b})(\mathrm{W\bar{b}}) \to (\tau_{\mathrm{jet}}\bar{\nu}_\tau\nu_\tau \mathrm{b})(\mathrm{qq\bar{b}})$
  easy trigger, low background, neutrinos on both sides

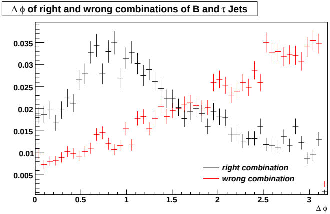
Heavy Higgs

- $\mathrm{H}^+ \to \mathrm{tb}$ channel: $\mathrm{gg/g\bar{b}} \to \mathrm{t}[\mathrm{\bar{b}}]\mathrm{H}^+ \to \mathrm{W_{qq}b}\ [\bar{b}]l\nu_l\ \mathrm{bb}$
  full Higgs mass reconstruction, complex signature
- $\mathrm{H}^+ \to \tau\nu$ channel: $\mathrm{gg/g\bar{b}} \to \mathrm{t}[\mathrm{\bar{b}}]\mathrm{H}^+ \to \mathrm{W_{qq}b}\ [\bar{b}]\tau_{\mathrm{jet}}\nu_{\bar{\tau}}$
  low background, m_T reconstruction, low branching ratio

$t\bar{t} \rightarrow (H^+b)(W\bar{b}) \rightarrow (l\nu_l\nu_\tau\nu_{\bar{\tau}}b)(qq\bar{b})$

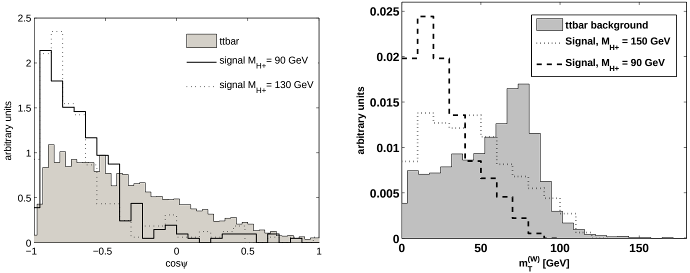
- W boson resonance and top quark fully reconstructed
- b-$\bar{b}$ flavour tagging performed using b jet-lepton angular correlation and b jet charge distribution





- likelihood combination gives 68% purity

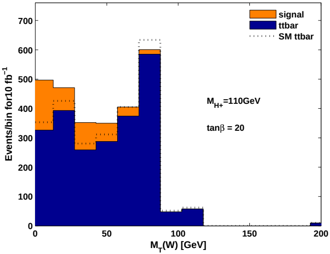
$t\bar{t} \rightarrow (H^+b)(W\bar{b}) \rightarrow (l\nu_l\nu_\tau\nu_{\bar{\tau}}b)(qq\bar{b})$

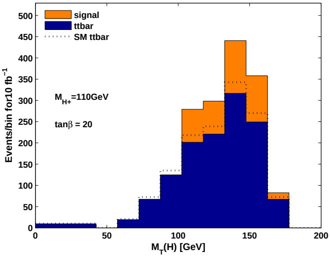


- cut on 'decay angle' $\cos\theta^* = \frac{2m_{\ell b}^2}{m_{top}^2 - m_W^2} - 1$
  (b jet and lepton have to be on the same side)
- but we loose a lot of events by requiring 2 b jets wrt $t\bar{t}$

- generalized transverse mass calculated for the Higgs:

$$(m_T^{H^+})^2 = (\sqrt{m_{top}^2 + (\vec{p}_T^{lep} + \vec{p}_T^{b} + \vec{p}_T^{miss})^2} - p_T^b)^2 - (\vec{p}_T^{miss} + \vec{p}_T^{lep})^2$$

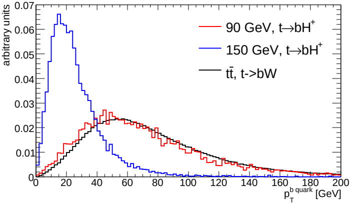


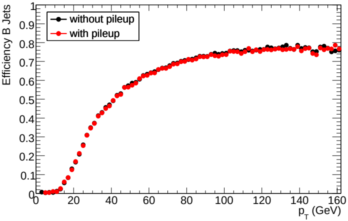


- finally both transverse masses are used for the significance calculation

$t\bar{t} \rightarrow (H^+b)(Wb) \rightarrow (\tau_{jet}\bar{\nu}_\tau\nu_\tau b)(l\bar{\nu}_l b)$

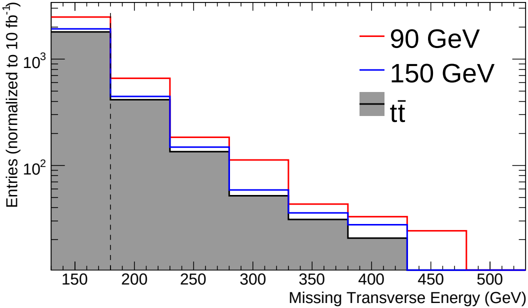
- most difficult channel because of the neutrinos on both sides
- avoid $t\bar{t}$ enrichment by requiring only one b jet





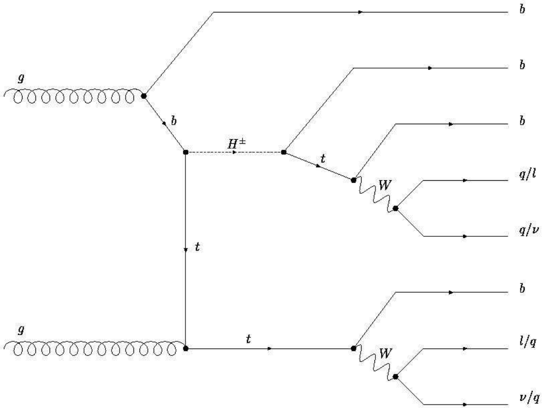
$t\bar{t} \rightarrow (H^+b)(Wb) \rightarrow (\tau_{jet}\bar{\nu}_\tau \nu_\tau b)(l\bar{\nu}_l b)$

- signal can still be extracted as the excess of τ jets wrt SM
- but no possibility to extract any shaped variables



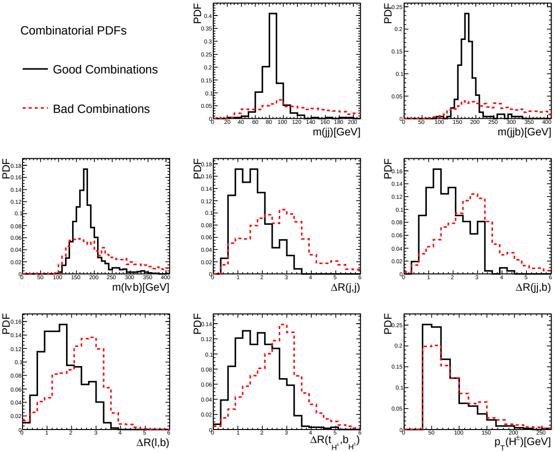
$gg/g\bar{b} \rightarrow t[\bar{b}]H^{+} \rightarrow W_{qq}b\ [\bar{b}]l\nu_l\ bb$

- only channel which allows full Higgs mass reconstruction
- high combinatorial background from jets



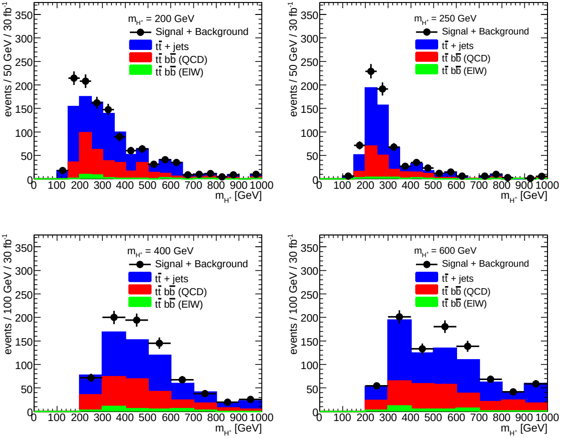
$gg/g\bar{b} \rightarrow t[\bar{b}]H^{+} \rightarrow W_{qq}b\ [\bar{b}]l\nu_{l}\ bb$

- try to find right combination of jets by combinatorial likelihood



$gg/g\bar{b} \rightarrow t[\bar{b}]H^+ \rightarrow W_{qq}b\ [\bar{b}]l\nu_l\ bb$

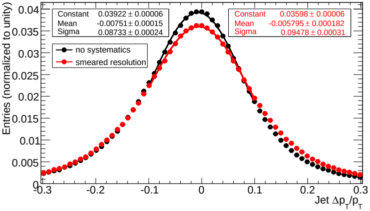
- physical background $t\bar{t}$ +jets is reduced by another likelihood (require 4 b jets, pdf's not shown)
- reconstruct charged Higgs mass



Systematic Uncertainties

To evaluate systematic uncertainties, several effects where taken into account.

Most important: smearing of the jet energy scale



Uncertainty	Value	x-sec[fb] S	x-sec[fb] B
None		30	78
τ E Resolution	$0.45 \times \sqrt{E}$	32	76
τ E Scale	-5%	30	71
	$+5\%$	32	79
τ-tag Efficiency	$\pm 5\%$	27	77
Jet E Resolution	$0.45\sqrt{E}, \|\eta\| < 3.2$ $0.63\sqrt{E}, \|\eta\| > 3.2$	32	80
Jet E Scale	$+7(15)\%, \|\eta\| < (>) 3.2$	40	93
	$-7(15)\%, \|\eta\| < (>) 3.2$	24	64
b-tag Efficiency	$\pm 5\% \epsilon_{btag}$	30	76
b-tag Rejection	-10%	30	78
	+10%	30	77
μ E Resolution	$0.011/P_T \oplus 0.00017$	30	79
μ E Scale	-1%	31	77
	+1%	30	78
μ Efficiency	$\pm 1\%$	30	78
e E Resolution	$0.0073 \times E_T$	30	77
e E Scale	-0.5%	30	77
	+0.5%	31	77
e Efficiency	$\pm 0.2\%$	30	78
Luminosity	-3%	29	76
	+3%	31	80

Background estimation from data (1)

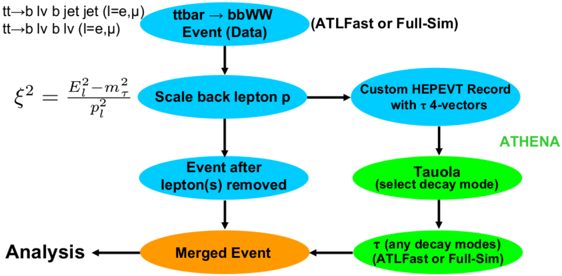
- get clean $t\bar{t} \rightarrow ll$ sample from data
  - two isolated muons (E_T in cone (0.3)<20 GeV)
  - Z veto (90 GeV $< m_{\mu\mu} <$ 110 GeV)
  - $E_T^{miss} >$ 40 GeV

Process	cross section (pb)	events used	events passed	expected events in 1 fb^{-1}
$t\bar{t} \rightarrow \mu\mu$	9.3	1265	359	2641.2
$t\bar{t}$ background	823.7	46500	23	407.4
W+1J	65.3	5000	1	13.1
W+2J	71.0	9450	1	7.7
W+3J	53.3	6500	0	<8.2
W+4J	28.0	7000	3	12.0
W+5J	15.3	5000	0	<3.1
Z+1J	172.7	3750	3	138.2
Z+2J	65.7	14500	17	77.0
Z+3J	20.7	2000	6	62.1
Z+4J	5.9	5250	18	20.1
Z+5J	2.1	2950	11	8.0
$b\bar{b}(mu20mu20)$	261	2435	3	321.6
Total BG	-	-	-	1066.8

- efficiency=28% (signal events that survive selection)
- purity=71% (1-background/all events)

Background estimation from data (2)

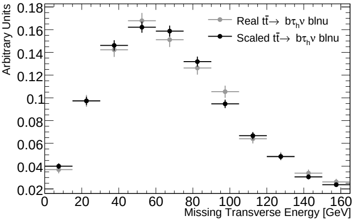
- replace μ by τ

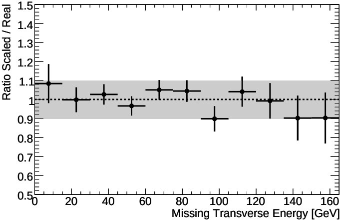


- scale 3-Vector of the lepton until it has τ mass

$$\xi^2 = \frac{E_\mu^2 - m_\tau^2}{|\vec{p}_\mu|^2}$$

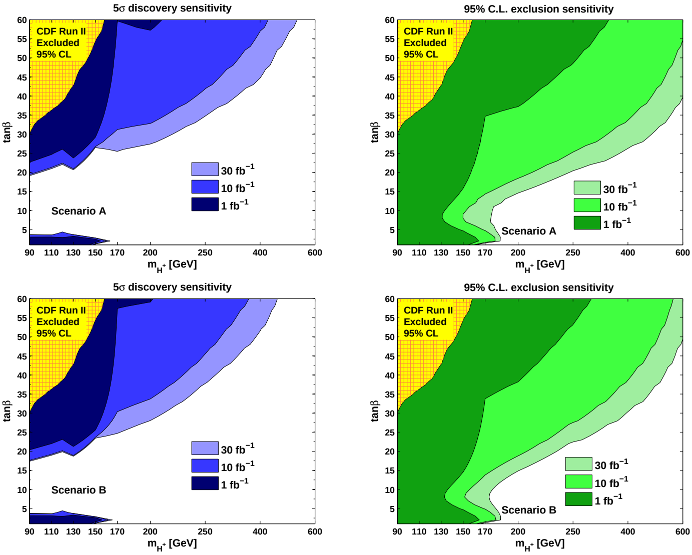
- τ decay products fed into the athena detector simulation
- '2^{nd} order' MC effect still included





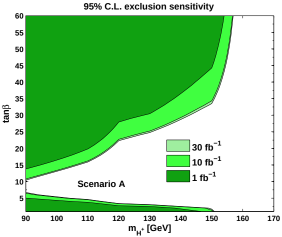
- error within 10%
- this is only due to worse jet resolution (wrt leptons)

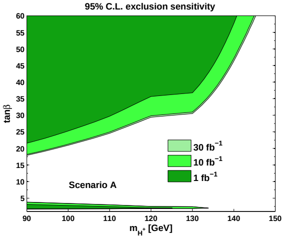
Final combined results (all five channels)

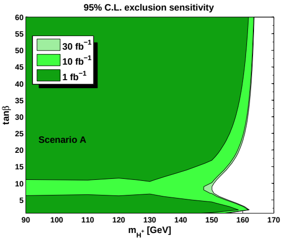


single results (only exclusion contours)

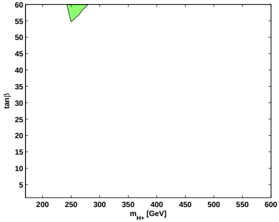
light Higgs

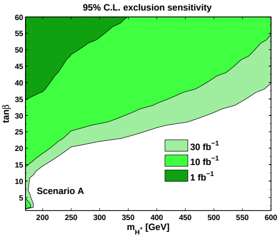






heavy Higgs





Backup

Significance calculation by profile Likelihood

- take some shaped histogram (i.e. higgs mass)
- model each bin as a Poisson variable with mean:

$$E[n_i] = \mu L \epsilon_i \sigma_i B_i + b_i \equiv \mu s_i + b_i$$
$$s_i = s_{tot} \int_{bins} f_s(x;\theta_s) dx$$
$$b_i = b_{tot} \int_{bins} f_b(x;\theta_b) dx$$

- μ (signal strength) is the only parameter of interest
- the pdf's f_s and f_b can be obtained from MC or control samples
- systematic uncertainties can be inbluded through θ parameters

Significance calculation by profile Likelihood

- calculate Likelihood function for each channel i:
  $L_i = (\mu, \theta) = \prod_j \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_k \frac{u_k^{m_k}}{m_k!} e^{-u_k}$
- combine them straightforward for all channels:

$$L(\mu, \theta) = \prod L_i(\mu, \theta_i)$$

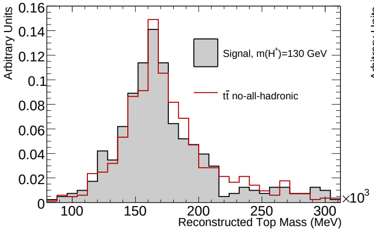
- construct profile likelihood ratio:

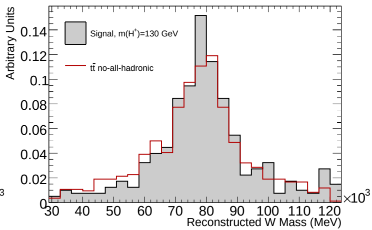
$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L_{max}(\hat{\mu}, \hat{\theta})}$$

  $\hat{\hat{\theta}}$: maximizes L for given μ, $\hat{\hat{\theta}} = \hat{\hat{\theta}}(\mu)$
  denominator: maximized Likelihood of full phase space
- of course $0 \leq \lambda \leq 1$,
  $\lambda = 1$ implies good agreement with hypothesis

$t\bar{t} \rightarrow (H^+b)(Wb) \rightarrow (\tau_{had}\nu b)(qqb)$

- a priori important channel: high branching ratio
- trigger: `tau35i+xe50` or `tau35i+xe40+3jet20`: 9-17% efficiency)



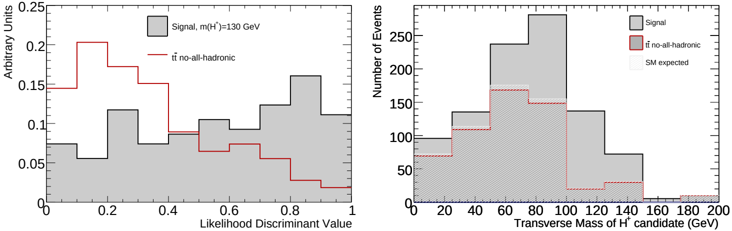


- full reconstruction of W side → apply mass window cuts
- E_T^{miss} is used to calculate the p_T^τ of second top
- use back-to-back characteristic of top quarks

$$p_T^{top2} = \vec{p}_T^{\,b} + \vec{p}_T^{\,\tau jet} + \vec{p}_T^{\,miss}$$

$t\bar{t} \rightarrow (H^+b)(Wb) \rightarrow (\tau_{had}\nu b)(qqb)$

- remaining events supposed to be mainly $t\bar{t}$
- many topologic variables (angles, inv. masses, ...) are combined in a likelihood discriminant
- finally the transverse Higgs mass is calculated



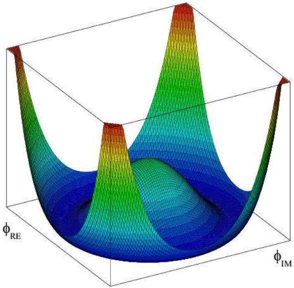
The Standard Model Higgs Sector

One fundamental question in particle physics is:

What's the origin of mass?

Answer: introduce scalar (Higgs-)field, and break electroweak symmetry.
Examples are already there:

- super conductivity (Meissner-Ochsenfeld effect)
- ferro magnetism



$$\mathcal{L}_{Higgs} = (\hat{D}_\mu \phi)^+ (\hat{D}^\mu \phi) + m_H^2 \phi^+ \phi - \lambda(\phi^+\phi)^2$$

$$|\langle\phi\rangle| = \sqrt{\frac{-m_H^2}{2\lambda}}$$