

CP-violating Higgs at Tevatron

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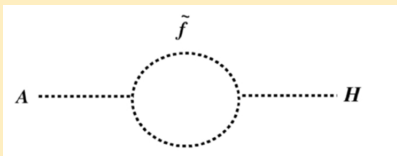
Focus Week on LHC Physics, IPMU, University of Tokyo

in collaboration with A. Datta and M. Drees

- 1 Introduction
- 2 Results (Tevatron and LHC (preliminary))
- 3 Summary

Explicit CP-violation and Higgs sector

The soft breaking parameters in MSSM can be **complex**.


$$\propto \frac{m_{\tilde{f}}^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \Im m(A_f \mu)$$

⇒ Non vanishing CP-phases lead to **mixing among CP-even and CP-odd Higgses**.

References:

A. Pilaftsis, Phys.Rev.D58:096010,1998;

D. A. Demir, Phys.Rev.D60:055006,1999;

Choi et al. Phys.Lett.B481:57-66,2000;

Carena et al., Nucl.Phys.B659:145-178,2003 and etc.

Explicit CP-violation and Higgs sector contd.

$$(\phi_1, \phi_2, \mathbf{a})^T = O_{\alpha i} (H_1, H_2, H_3)_i^T, \quad (1)$$

$$\mathcal{L}_{HVV} = g M_W \left(W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu \right) \sum_i g_{H_i VV} H_i, \quad (2)$$

$$\begin{aligned} g_{H_i VV} &= c_\beta O_{\phi_1 i} + s_\beta O_{\phi_2 i}, \\ g_{H_i H_j Z} &= \text{sign}[\det(O)] \varepsilon_{ijk} g_{H_k VV}, \\ g_{H_i H^+ W^-} &= c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i} - i O_{a i}, \end{aligned} \quad (3)$$

$$\sum_{i=1}^3 g_{H_i VV}^2 = 1 \quad \text{and} \quad g_{H_i VV}^2 + |g_{H_i H^+ W^-}|^2 = 1 \quad \text{for each } i. \quad (4)$$

CPX-scenario

$$M_{SP}^2 \sim \frac{m_t^4}{v^2} \frac{\text{Im}(\mu A_t)}{32\pi^2 M_{SUSY}^2} \left(1, \frac{|A_t|^2}{M_{SUSY}^2}, \frac{|\mu|^2}{\tan\beta M_{SUSY}^2}, \frac{2\text{Re}(\mu A_t)}{M_{SUSY}^2} \right), \quad (5)$$

$$\begin{aligned} \tilde{M}_Q &= \tilde{M}_t = \tilde{M}_b = M_{SUSY} = 500\text{GeV}, & \mu &= 4M_{SUSY}, \\ |A_t| &= |A_b| = 2M_{SUSY}, & \arg(A_t) &= \arg(A_b) = 90^\circ, \\ |m_{\tilde{g}}| &= 1\text{TeV}, & \arg(m_{\tilde{g}}) &= 90^\circ, \end{aligned} \quad (6)$$

$\Rightarrow M_{H^\pm}$ and $\tan\beta \rightarrow$ Higgs sectors.

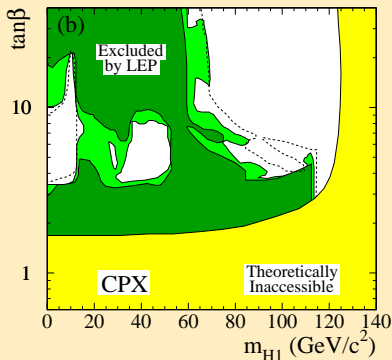
\Rightarrow 1st and 2nd generations are heavy and Gaugino sectors in two loop.

Recent work similar to our study:

Carena et al., arXiv:0712.2466 [hep-ph];

Bandyopadhyay et al., arXiv:0710.3016 [hep-ph]

LEP allowed region for $m_t=174.3$ GeV



Ref: hep-ex/0602042

$\Rightarrow e^+e^- \rightarrow H_1 Z / H_1 H_2$, $g_{H_1 ZZ}$ is **suppressed** for maximal CP-violation.

$\Rightarrow H_1 (H_2)$ decay dominantly into $b\bar{b}$ ($H_1 H_1$) mode.

\Rightarrow Allowed regions shrink if m_t decreases.

Numerical Analysis

- Tevatron Run-II: $\sqrt{s}=1.96\text{TeV}$, $Q= \sqrt{\hat{s}}$ and CTEQ5L PDF
- CPsuperH: Spectrum and Couplings;
Refs: hep-ph/0307377 and arXiv:0712.2360 [hep-ph],(also FeynHiggs);
- Pythia 6.408: Signal with SLHA input file;
- MadGraph/MadEvent v4.2.8 :SM backgrounds (Thanks to Rikkert);
- ISR/FSR, Hadronization and Fragmentation ;
- Gaussian smearing of jet and lepton;
- PYCELL Granularity: $|\eta| \leq 3.6$, $\delta\eta=.16$, $\delta\phi=0.098$;
- $\Delta R=0.4$;
- $m_t=172.6$ GeV;

Signature

$p\bar{p} \rightarrow WH_2 \rightarrow \ell\nu_\ell H_1 H_1 \rightarrow \ell\nu_\ell b\bar{b}b\bar{b}$:

$\ell + 4 - jets + \cancel{E}_T$, where $\ell = e$ or μ and n-btag (n=2 or 3)

$$C_{211_{4b}} = \sigma_{SM}(p\bar{p} \rightarrow WH_2) g_{h_2 VV}^2 Br(H_2 \rightarrow H_1 H_1) \\ \times Br(H_1 \rightarrow b\bar{b})^2 2Br(W \rightarrow e\nu_e);$$

$W \rightarrow W^\pm$ and 2 is for $\ell = e$ and μ .

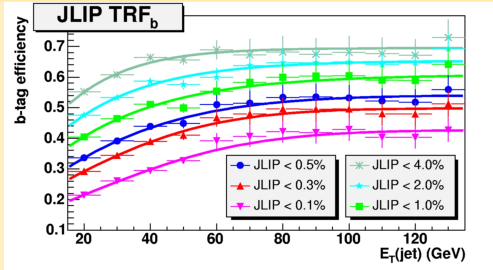
CPX-Benchmark points

CPX	m_{H^\pm}	$\tan\beta$	m_{H_1}	m_{H_2}	$\sigma_{SM}(pb)$	$C_{211_{4b}}(pb)$
1	132.0	4.0	36.0	101.6	108.5	21.6
2	141.0	3.4	40.5	104.4	97.9	12.3
3	135.5	4.2	51.1	103.8	102.2	14.6
4	131.5	4.4	44.2	102.4	106.6	19.9
5	128.5	5.8	51.5	104.0	99.3	9.0

Selection

- S1: $N_{jet} \geq 4$.
- S2: $E_T^{j1,j2,j3,j4} > 10.0 \text{ GeV}$ and $|\eta^{j1,j2,j3,j4}| < 3.0$.
- S3: $N_{lepton} \geq 1$, $E_T^l > 15.0 \text{ GeV}$ and $|\eta^l| < 2.0$.
- S4: $\cancel{E}_T > 15 \text{ GeV}$ where \cancel{E}_T from visible object.
- S5a(b): $N_{btag} \geq 2(3)$; $|\eta^{b-jet}| < 1.2, \Delta R(j, B - hadron) \leq 0.2$.
- S6: $H_T = \cancel{E}_T + \sum_{obj} E_T \leq 300 \text{ GeV}$.
- S7a(b): $\Delta\phi(b1, b2) \leq 2.61(2.09)$.
- S8: $N_{obj} = N_{lepton} + N_{jet} \leq 6$.

b-tagging



Refs:

K. Hanagaki, FERMILAB-CONF-05-647-E;

C. Neu, FERMILAB-CONF-06-162-E;

T. Wright, arxiv: 0707.0712[hep-ex];

⇒ E_T^{jet} dependent b-tagging efficiencies in event by event.

⇒ **Scale** ≈ 1 with CDF $t\bar{t}$ analysis, Phys.Rev.D71:052003,2005.

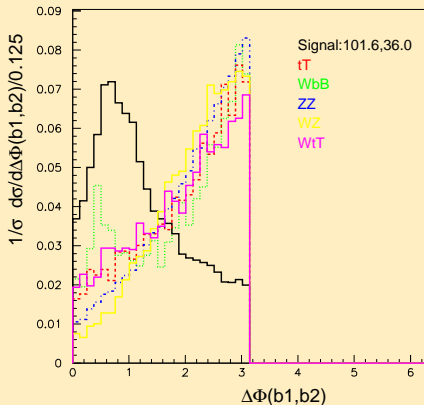
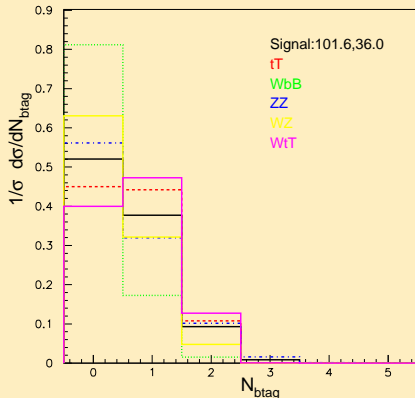
Efficiencies						
m_{H_2}, m_{H_1}	C1-4	I5a	I5b	I7a	I7b	I6
101.6,36.0	.155	.102	.009	.914	.810	.937
104.4,40.5	.172	.105	.009	.923	.832	.950
103.8,51.1	.201	.102	.010	.929	.851	.937
102.4,44.2	.174	.097	.008	.935	.855	.938
104.0,51.5	.202	.103	.010	.930	.849	.937
$t\bar{t}$	.511	.108	.00021	.705	.481	.462
$Wb\bar{b}$	.014	.015	.00002	.694	.502	.986
ZZ	.026	.118	.01735	.679	.434	.945
WZ	.054	.048	.00008	.696	.432	.968
$Wt\bar{t}$	.619	.127	.00062	.738	.530	.102

\Rightarrow I5a(b) \rightarrow 2(3)b-tag; I7a(b) $\rightarrow \Delta\phi(b1, b2) \leq 2.61(2.09)$.

\Rightarrow 3-btag might be helpful, however, **mis-tagging** is required.

$\Rightarrow \Delta\phi(b1, b2) \leq 2.09 \rightarrow \text{Signal(Backgd)} \approx 10(20-25)\%$.

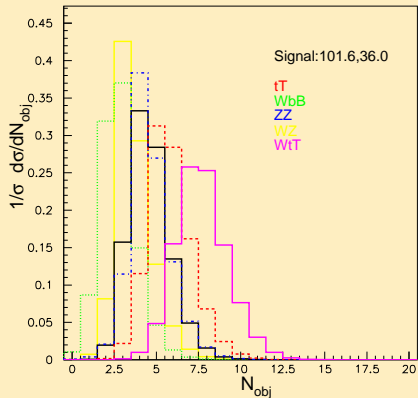
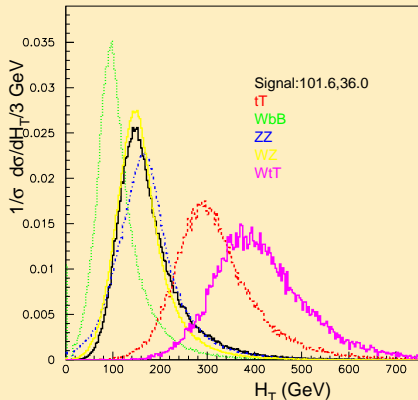
N_{btag} and $\Delta\phi(b1, b2)$



⇒ For 3-btag, more correct Higgs mass reconstruction.

⇒ $\Delta\phi(b1, b2)$ is the **crucial** discriminator.

H_T and N_{obj}



\Rightarrow More strict Veto on H_T and also on N_{obj} .

Events for $\int \mathcal{L} dt = 10 fb^{-1}$

Events								
m_{H_2}, m_{H_1}	C1	C2	C3	C4	C5a	C6	C7b	C8
101.6,36.0	126.0	68.0	36.5	33.5	5.6	3.7	3.3	2.7
104.4,40.5	76.1	42.2	23.1	21.2	3.4	2.3	2.1	1.7
103.8,51.1	99.7	57.1	32.0	29.5	4.7	3.3	3.0	2.4
102.4,44.2	126.5	68.6	37.9	34.7	5.4	3.6	3.3	2.7
104.0,51.5	61.9	35.6	19.9	18.3	2.9	2.0	1.8	1.4
$t\bar{t}/100$	154	141	94	88	9.7	2.2	1.6	1.3
$Wbb/100$	83.8	32.2	12.4	11.5	.75	.39	.29	.27
$ZZ/10$	216	162	27.4	10.5	.73	.35	.2	.16
WZ	202	106	42	39	2.2	1.3	.9	.7
$Wt\bar{t}$	8.1	8.0	5.4	5.0	.6	.03	.02	.01

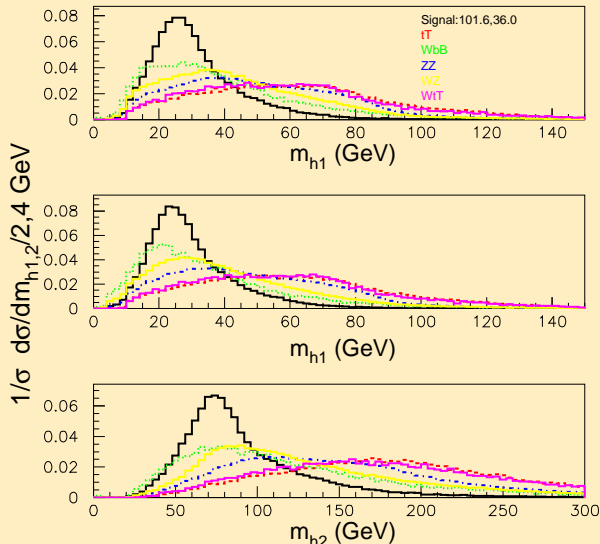
⇒ $t\bar{t}$ is the main background , **Very poor** Significance ≈ 0.22 .

⇒ NLO factor (≈ 1.3) Significance ≈ 0.24 .

⇒ Veto on **S8** improve the correct m_{H_1} and m_{H_2} reconstruction.

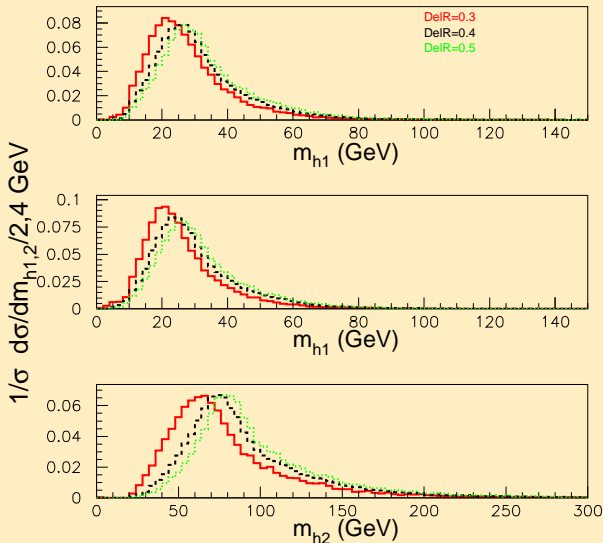
Mass reconstruction

⇒ Pair of jets → $|M_{ab} - M_{cd}|$ minimum and sum ≥ 20 GeV;



⇒ Veto $m_{H_1} \leq 50 \text{ GeV}$ and $m_{H_2} \leq 125 \text{ GeV}$ certainly help.

Mass reconstruction for different ΔR



⇒ Larger ΔR shift the Higgs peaks towards right.

LHC Selections and Efficiencies (preliminary)

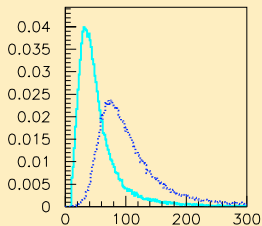
- S2: $E_T^j > 25.0$ GeV, $|\eta^j| < 4.5$ and $E_T^{js} \leq 100, 80, 70, 60$ GeV .
- S3: $N_{lepton} \geq 1$, $E_T^l > 20.0$ GeV and $|\eta^l| < 2.5$.
- S5: $N_{btag} \geq 2$; $|\eta^{b-jet}| < 2.5, \Delta R(j, B - hadron) \leq 0.2$.
- S6: $H_T = \cancel{E}_T + \sum_{obj} E_T \leq 250$ GeV .
- S7: $\Delta\phi(b1, b2) \leq 2.09$.
- S8: $N_{obj} \leq 6$; S1 and S4 are same as Tevatron

Efficiencies								
m_{H_2}, m_{H_1}	S1	S2	S3	S4	S5	S6	S7	C8
101.6, 36.0	.40	.03	.62	.91	.065	.80	.92	.0001
$t\bar{t}$	.89	.20	.68	.94	.133	.15	.51	.0005

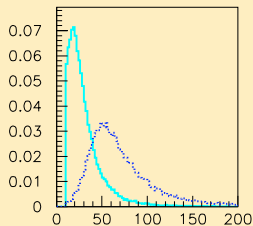
⇒ Signal: 5 and $t\bar{t}$: 8580 for $\int \mathcal{L} dt = 100 fb^{-1}$.

⇒ Veto on n-jets and Jets E_T (S1 and S2), 3b-tag, H_T and N_{obj} .
work in progress with M. Maity.

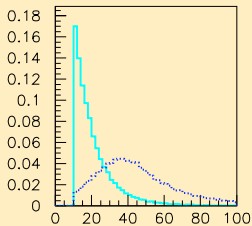
E_T^{jets} (S2) at LHC



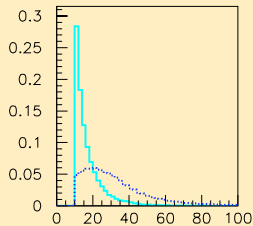
jet1 E_T



jet2 E_T



jet3 E_T

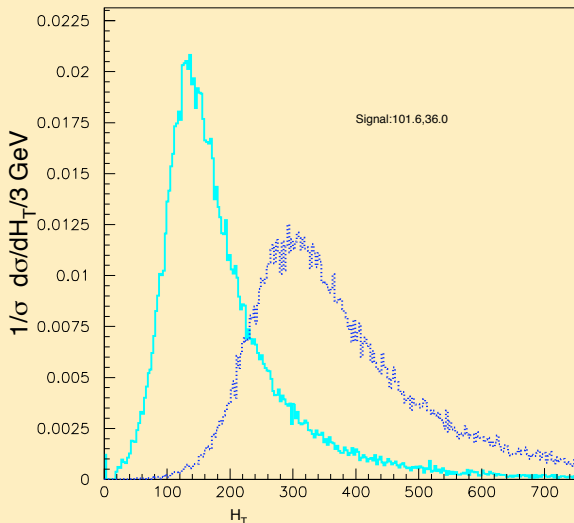


jet4 E_T

⇒ Signal and $t\bar{t}$ (deep blue).

⇒ Normalized to unity and bin-sizes are 2 GeV.

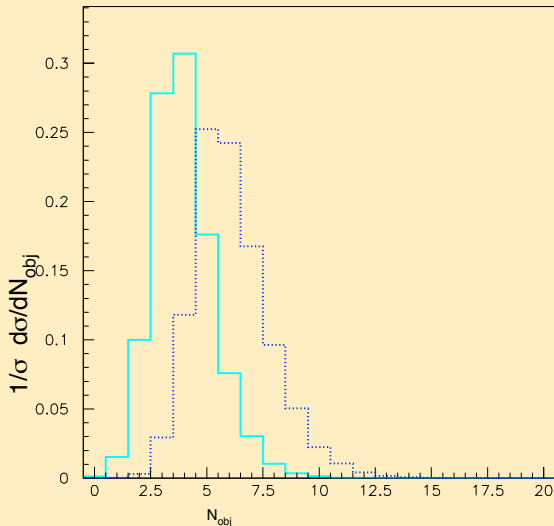
H_T (S6) at LHC



⇒ Signal and $t\bar{t}$ (deep blue).

⇒ $H_T < 250 \text{ GeV}$.

N_{obj} (S8) at LHC



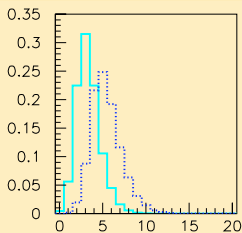
⇒ Signal and $t\bar{t}$ (deep blue).

⇒ Normalized to unity.

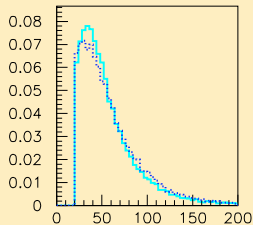
Summary and Outlook:

- LEP allowed lighter Higgs masses at Tevatron.
- $p\bar{p} \rightarrow WH_2 \rightarrow \ell + 4 - jets(2b - jets) + \cancel{E}_T$.
- E_T^{jet} dependent b-tagging efficiencies.
- Selection efficiencies are very poor, so the Significance.
- 3b-tagging will improve the Signal, however, mis-tagging is required.
- $\Delta\phi(b1, b2)$ is one of the crucial discriminator.
- More stringent veto on H_T and N_{obj} certainly improve the Significance.
- m_{H_1} and m_{H_2} peaks are very prominent over Backgrounds.
- LHC: preliminary, Jet Veto, 3b-tag, N_{obj} and overall optimization.
- Other decay modes (e.g., $H_1 \rightarrow \tau\tau$).

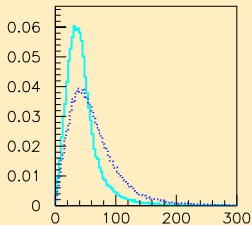
Important distributions at LHC



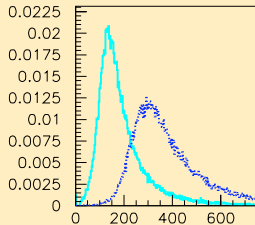
good jets



lep sel P_T in MET



missing E_T object



$E_{miss2zmet}$ w all sellepjet

⇒ Signal and $t\bar{t}$ (deep blue)

Cross-sections

cross-section in pb		
Process	σ	BR
Signal TeV	0.0216	1.0
$t\bar{t}$	5.0	0.34
$Wb\bar{b}$	36.0	0.21
ZZ	0.9	0.44
WZ	2.16	0.03
$Wt\bar{t}$	0.006	0.13
Signal LHC	0.39	1.0
$t\bar{t}$	500.0	0.34