Implications of 98 GeV and 125 GeV Higgs scenario in non-decoupling SUSY

Dilip Kumar Ghosh

Department of Theoretical Physics

Indian Association for the Cultivation of Science
Kolkata, India

2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck, Hsinchu (Taiwan)

Collaborators:B. Bhattacherjee, M. Chakraborti, A. Chakraborty, U. Chattopadhyay, D. Das

Ref: [Phys. Rev. D 88 (2013) 035011]

Plan of the talk

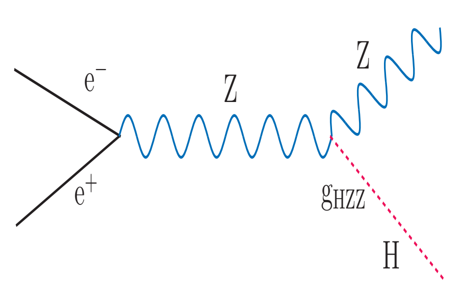
- Higgs@LEP ?
- Inclusive LEP-LHC Higgs (ILLH) scenario
- ILLH @MSSM and NMSSM
- Collider analysis and results
- Updated analysis (in progress)
- Summary

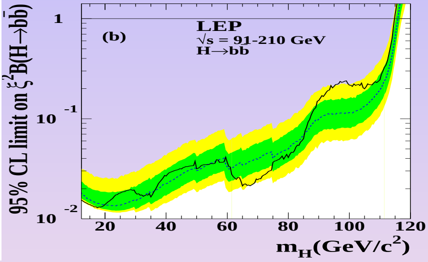
- A SM like Higgs particle has been found by the ATLAS & CMS collaboration of the LHC experiment with $m_h \simeq 125$ GeV.

- **Did LEP give us any hint about Higgs ?**

Higgs@LEP ?

- At LEP, Higgs boson is searched in $e^+e^- \to ZH$ channel.
- Combined analysis of four LEP experiments: $M_h > 114.4$ GeV @ 95% C.L.





- Parameter: $\zeta \equiv \left(\frac{g_{HZZ}^{BSM}}{g_{HZZ}^{SM}}\right) = \sin(\beta - \alpha)$

  (α: Higgs mixing angle, tanβ: ratio of VEVs)
- A mild excess ($\sim 2.3\sigma$) of Higgs-like events $e^+e^- \to Zh$ with a mass near 98 GeV.

- Both LEP and LHC events can be explained simultaneously in MSSM, and NMSSM.
- MSSM: Five Higgses : $h^0, H^0, A^0, H^\pm$.
- At tree level, M_A and $\tan\beta$ controls the MSSM Higgs sector.
- Higgs couplings to gauge bosons and fermions are functions of β and α.
- W^+W^-H, HZZ, ZAh, $W^\pm H^\mp h$, $ZW^\pm H^\mp h$ and $\gamma W^\pm H^\mp h \propto \cos(\beta-\alpha)$.
- W^+W^-h, hZZ, ZAH, $W^\pm H^\mp H$, $ZW^\pm H^\mp H$ and $\gamma W^\pm H^\mp H \propto \sin(\beta-\alpha)$.

- decoupling : $M_A \geq 300$ GeV and $\cos^2(\beta-\alpha) \to 0 \implies \sin^2(\beta-\alpha) \to 1$.
- In decoupling limit : One can interpret the newly observed state at 125 GeV as the light CP even Higgs boson with SM like couplings.
- non-decoupling : $M_h \sim M_A \sim M_H \sim M_Z$ or $\sin^2(\beta-\alpha) \to 0 \implies \cos^2(\beta-\alpha) \to 1$.
- This would mean larger coupling strength of H with the SM gauge bosons.
- We may explore the possibility of $M_H \sim 125$ GeV, instead of h as the discovered new resonance.
- H behaves like $h_{\rm SM}$ and h has weaker couplings to W/Z.

MSSM parameter space scan

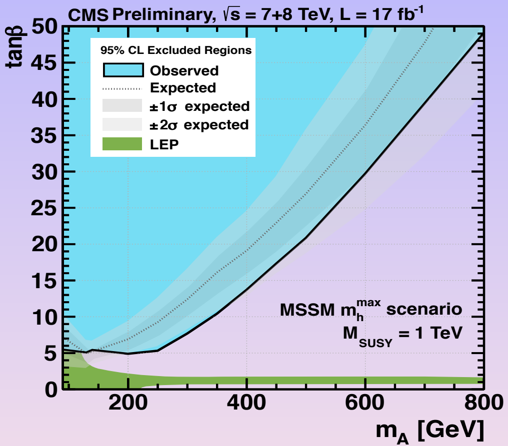
- We generate approximately 70 million random points in the following combined range of parameters:
- We consider $m_t^{\rm pole} = 173.3 \pm 2.8$ GeV.

$$3 < \tan\beta < 5.5,\ 0.085 < M_A < 0.2\ \text{TeV},\ 0.3\ \text{TeV} < \mu < 12\ \text{TeV},$$
$$0.05\ \text{TeV} < M_1, M_2 < 1.5\ \text{TeV},\ 0.9\ \text{TeV} < M_3 < 3\ \text{TeV},$$
$$-8\ \text{TeV} < A_t < 8\ \text{TeV},\ -3\ \text{TeV} < A_b,\ A_\tau < 3\ \text{TeV},\ A_u = A_d = A_e = 0,$$
$$0.3\ \text{TeV} < M_{\tilde{q}_3} < 5\ \text{TeV},\ \text{where},\ \tilde{q}_3 \equiv \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$$
$$M_{\tilde{q}_i} = 3\ \text{TeV}, \text{for}\ i = 1,2\ \text{ and }\ M_{\tilde{\ell}_i} = 3\ \text{TeV}, \text{for}\ i = 1,2,3.$$

- CMS has constrained $\tan\beta - M_A$ plane from $H/A \to \tau^+\tau^-$ decay.
- ATLAS has constrained $\tan\beta - M_{H^\pm}$ plane from $H^+ \to \tau^+\nu_\tau$ in $t\bar{t}$ events, where one $t \to bH^+$.

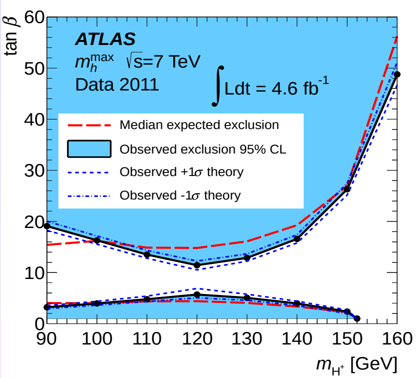
[CMS-PAS-HIG-2012-050],[ATLAS Collaboration, JHEP 06 (2012),039]

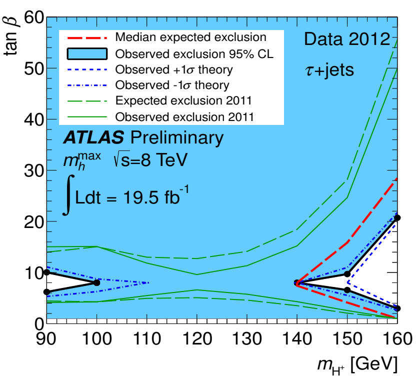
CMS exclusion in $\tan\beta - M_A$ plane



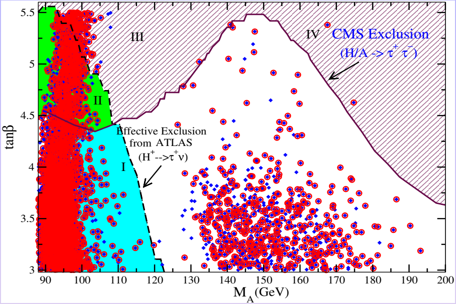
- $90 < M_A < 250$ GeV for $\tan\beta > 5.5$ is excluded.

ATLAS exclusion in $\tan\beta - M_{H^\pm}$ plane



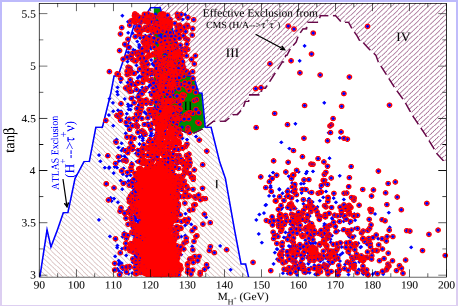


- $90 < M_{H^\pm} < 150$ GeV for $2 < \tan\beta < 6$ is excluded.



- The blue points satisfy following constraints:
  - Lower limits on SUSY particles
  - $95\ \mathrm{GeV} < m_h < 101\ \mathrm{GeV}$; $122\ \mathrm{GeV} < m_H < 128\ \mathrm{GeV}$.
  - $0.1 < \sin^2(\beta - \alpha) < 0.25$.
  - $R^{H_2}_{gg}(\gamma\gamma)_{\mathrm{min}} > 0.5$, [CMS : $\hat{\mu} = 0.78^{+0.28}_{-0.26}$].
  - $2.77 \times 10^{-4} < \mathrm{Br}(b \to s\gamma) < 4.09 \times 10^{-4}$ at 3σ level.
    $[\mathrm{Br}(b \to s\gamma)(\mathrm{exp}) = (3.43 \pm 0.22) \times 10^{-4}]$. [arXiv:1207.1158].
  - $0.67 \times 10^{-9} < \mathrm{Br}(B_s \to \mu^+\mu^-) < 6.22 \times 10^{-9}$ at 2σ level.
- The red circles (enclosing blue points) shows points satisfy the DM relic density constraint (only upper limit): $0.112 < \Omega_{\tilde{\chi}^0_1} h^2 < 0.128$.

ILLH in MSSM



- From our previous figure : 130 GeV$< M_A <$200 GeV for $3 < \tan\beta < 5.5$.
- Direct constraint from $H^{\pm} \to \tau^{+}\nu_{\tau}$ (ATLAS) : blue solid line.
- Exclusion from $H/A \to \tau^{+}\tau^{-}$: maroon line
- The region of $M_{H^{\pm}} < 145$ GeV becomes entirely disallowed via $H^{+} \to \tau^{+}\nu_{\tau}$ from ATLAS.
- $150 < M_{H^{\pm}} < 200$ GeV.

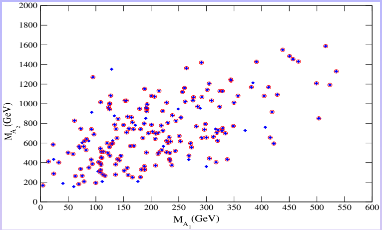
Sample benchmark point in MSSM parameter space

M_t	M_A	$\tan\beta$	μ	M_1	M_2	M_3	A_t	A_b
173.6	167.5	5.0	5429.8	527.9	119.2	1416.6	5729.2	-217.1
A_τ	$M_{\tilde{q}_{3L}}$	$M_{\tilde{t}_R}$	$M_{\tilde{b}_R}$	M_h	M_H	$M(H^\pm)$	$M_{\tilde{t}_1}$	$M_{\tilde{b}_1}$
-115.2	1712.6	1602.2	426.7	97.7	125.1	182.1	999.2	539.1
$M_{\tilde{g}}$	$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$\mathrm{BR}(b \to s\gamma)$	Ωh^2	$\zeta\sigma^{SI}_{(p-\chi)}$				
1608.9	2.8×10^{-9}	3.8×10^{-4}	4.5×10^{-4}	5.5×10^{-11}				

- All masses are in GeV unit
- cross-section is pb unit.

- Main issues of our analysis in MSSM :

- In MSSM one can have 98 GeV and 125 GeV Higgs bosons.
- This restrict : $3 < \tan\beta < 5.5$, $130~\mathrm{GeV} < M_A < 200~\mathrm{GeV}$ and $150~\mathrm{GeV} < M_{H\pm} < 200~\mathrm{GeV}$



- $\lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$.
- 3 (2) CP even (odd) neutral Higgses, $H_i, i = 1, 2, 3$ and $A_i, i = 1, 2$, and $H^\pm$.
- We vary λ, κ, A_λ, A_κ, A_0, m_0, $m_{1/2}$, $\tan\beta$, $\mu_{\rm eff}$ using NMSSMTools3.2.4.
- In this parameter (figure) space of interest, $M_{A_2} \sim M_{H_3} \sim M_{H^\pm}$.
- Heavy mass scale ($M_A > 200$ GeV) $\Longrightarrow$ can accommodate $m_h \sim 98$ GeV (not possible in MSSM with $M_A > 200$ GeV.)
- Indirect exclusion: A bit tough, particle masses relatively heavy, so less sensitive at the LHC.
- Exclusion is Model dependent.
- Can we discover/exclude this at LHC in a model independent way ?

Prospect of observing 98 GeV Higgs @ Colliders

Can we find this 98 GeV Higgs @LHC ?

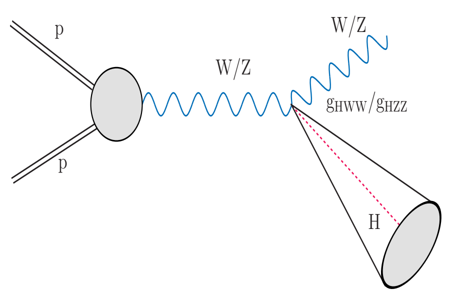
- A combination of a 98 GeV & a 125 GeV Higgs boson in the nondecoupling limit of MSSM and in NMSSM.
- Nondecoupling limit of MSSM: $\Longrightarrow$ relatively light Higgs bosons $\Longrightarrow$ can be probed at the early run of the LHC.
- Non observation of such light Higgs bosons will indirectly exclude the possibility of scenario with a 98 GeV Higgs boson.

- Previous attempts :
- At 8 TeV LHC, 5σ signal for $pp \to H^\pm A^0, H^\pm h^0 \to \tau^\pm \nu b\bar{b}$ and $pp \to H^+ H^- \to \tau^+ \nu \tau^- \bar{\nu}$ can be observed with an integrated luminosity of $7(11)\ \mathrm{fb}^{-1}$ and $24(48)\ \mathrm{fb}^{-1}$, respectively for $M_A = 95(130)$ GeV.
- At the 14 TeV energy : 5σ signal can be observed with an integrated luminosity of $4(7)\ \mathrm{fb}^{-1}$ and $10(19)\ \mathrm{fb}^{-1}$ respectively. [N.D.Christensen etal. 2012]
- ATLAS search : $130 < M_A < 200$ GeV for $\tan\beta \sim 3 - 5.5$ ruled out the above analysis and some others.

[M. Drees, PRD (2005) & (2012), N.D.Christensen etal. 2012, M. Asano etal. PRD (2012), S. Scopel etal. PRD (2013)].

Can we find this 98 GeV Higgs @LHC ?

- Gluon fusion: g g $\to$ H $\to$ $b\bar{b}$ for 98 GeV Higgs boson, large QCD jet background, difficult to prove.
- Di-photon via Gluon fusion: Heavily suppressed BR(H $\to \gamma\gamma$) for a 98 GeV Higgs, hard to distinguish from the continuous backgrounds.
- VBF production: not so sensitive for a 98 GeV Higgs boson.
- Higgs-strahlung process (VH): H is produced along with a gauge boson W/Z, may have sufficient boost (large p_T of Higgs)



- 2.3σ excess in the LEP constrains the effective coupling :

  $$g^{BSM}_{ZZh}/g^{SM}_{ZZh} \simeq 0.3 - 0.5$$

  $\Rightarrow$ controls the 98 GeV Higgs production cross-section in Vh at LHC

  $\Rightarrow$ A Model independent input parameter.

- We follow ATLAS simulation considering 20% LEP excess and apply the Jet Substructure technique.

- $\not{E}_T > 30$ GeV and $p_T^{e/\mu} > 30$ GeV [$hW, W \to \mu\nu, e\nu$]
- $80 < m_{\ell\ell} < 100$ GeV, [$hZ, Z \to e^+e^-/\mu^+\mu^-$]
- $\not{E}_T > p_T^{\rm min}$, with $p_T^{\rm min} = 200$ GeV [$hZ, Z \to \nu\bar{\nu}$ and hW, $W \to \ell\nu$, ℓ is missing.]

Process	Significance ($\frac{S}{\sqrt{B}}$)	Combined
$\ell\nu b\bar{b}$	1.7	
$\ell^+\ell^- b\bar{b}$	0.9	2.5
$\not{E}_T b\bar{b}$	1.6	

1. 98 GeV Higgs at the 14 TeV LHC with 300 $\rm fb^{-1}$ luminosity is $\sim 2.5\sigma$.
2. This signal significance may be reduced further if systematic uncertainties in the SM background estimations are considered.

[ATLAS Collaboration, Report No. ATL-PHYS-PUB-2009-008]

- Associated production of 98 GeV Higgs boson with top quarks:

$$pp \to t\bar{t}h(h \to b\bar{b})$$

- $\sigma(pp \to t\bar{t}h) \sim 1$ pb for $m_h \sim 100$ GeV. at 14 TeV run of LHC. [CERN Yellow Report Page At 14TeV]
- Translated the results already performed by Tilman Plehn et. al. for ~ 115 GeV Standard Model Higgs boson at 14 TeV LHC. [T. Plehn et.al. PRL 104, 111801 (2010)]
- While translating the results of Tilman Plehn for our choice of Higgs mass, we expect enhancements of 60% and 20% in Higgs production rate and background estimation.
- In our analysis, we scale the signal and background by 1.6 and 1.2, respectively for $h(m_h = 98\ \mathrm{GeV}) \to b\bar{b})$.
- For an integrated luminosity of 300 fb^{-1} with two tagged b-jets the significance $\sim 3.1\sigma$, while for three b-tag sample $\sim 2.6\sigma$.
- Jet Substructure may marginally exclude the 98 GeV Higgs: experimental collaborations need to perform further detailed analysis.
- In NMSSM A 98 GeV Higgs production from the decay of heavy Higgs bosons as well as from the cascade decays of other sparticles may play an important role at the LHC. [S.F. King et.al. NPB 870,323 (2013); Z.Kang et.al. PRD 88,015006 (2013)]

ILC

- There has been a plan to build e^+e^- linear collider (ILC) with $\sqrt{s} \sim 250$ GeV - 1000 GeV.
- Like LEP, the Higgs boson will be produced in $e^+e^- \to Zh$ channel.
- ILC will be an ideal machine for the Higgs precision study.
- In our analysis, we assume $h \to b\bar{b}$ decay mode, while Z can decay leptonically or hadronically.
- We use MadGraph5 to estimate the signal as well as SM background cross-section for the 98 GeV Higgs boson.
- For $\sqrt{s} = 250$ GeV, $\sigma(e^+e^- \to Zh) = 350$ fb, whereas $\sigma(e^+e^- \to ZZ) \sim 1.1$ pb.
- We find that a 98 GeV Higgs boson can be easily discovered / excluded at the 250 GeV ILC with a $100\ \mathrm{fb}^{-1}$ luminosity.
- Discovery potential at the LHC is marginal.
- ILC is an ideal machine to study this scenario.

Updated analysis (work in progress)

- We relook the MSSM parameter space in the light of updated Higgs data:

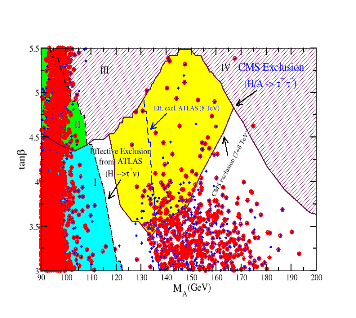
- ATLAS limits :

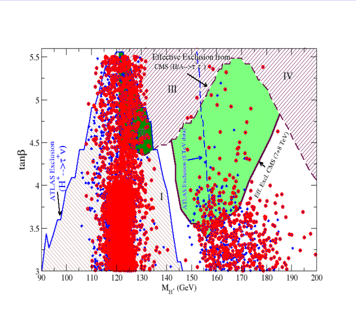
$$R_{\gamma\gamma} \;:\; 1.55^{+0.33}_{-0.28}@[7\ \text{TeV}(4.8) + 8\ \text{TeV}(20.7)]$$
$$R_{ZZ^*} \;:\; 1.43^{+0.40}_{-0.35}@[7\ \text{TeV}(4.6) + 8\ \text{TeV}(20.7)]$$
$$R_{b\bar{b}} \;:\; 0.2^{+0.7}_{-0.6}@[7\ \text{TeV}(4.7) + 8\ \text{TeV}(20.3)]$$
$$R_{\tau^+\tau^-} \;:\; 1.4^{+0.5}_{-0.4}@[8\ \text{TeV}(20.3)]$$

- CMS limits :

$$R_{\gamma\gamma} \;:\; 0.78^{+0.28}_{-0.26}@[7\ \text{TeV}(5.1) + 8\ \text{TeV}(19.6)]$$
$$R_{ZZ^*} \;:\; 0.93^{+0.29}_{-0.25}@[7\ \text{TeV}(5.1) + 8\ \text{TeV}(19.7)]$$
$$R_{b\bar{b}} \;:\; 1.0^{+0.5}_{-0.5}@[7\ \text{TeV}(5.1) + 8\ \text{TeV}(18.9)]$$
$$R_{\tau^+\tau^-} \;:\; 0.87^{+0.29}_{-0.29}@[7\ \text{TeV}(4.9) + 8\ \text{TeV}(19.7)]$$

Updated ongoing analysis





- We studied the possibility that both the LEP excess in the $b\bar{b}$ final state with a 98 GeV Higgs boson and the LHC signal for a 125 GeV Higgs like object can be simultaneously explained in the most general MSSM framework.
- This can happen in nondecoupling zone of MSSM Higgs sector, where, $M_h \sim M_A \sim M_H \sim M_Z$ or $\sin^2(\beta - \alpha) \to 0 \Longrightarrow \cos^2(\beta - \alpha) \to 1$.
- We have found a region of parameter space in MSSM allowed by heavy flavour physics, CDM constraints, constraints from the XENON100 experiment on the DM direct detection cross-section.
- Both ATLAS & CMS searches on $H/A \to \tau^+\tau^-$ and $H^\pm \to \tau^+\nu_\tau$ from ATLAS collaboration severely constraint the parameter space : $130\ \mathrm{GeV} < M_A < 200\ \mathrm{GeV}$ and $150\ \mathrm{GeV} < M_{H^\pm} < 200\ \mathrm{GeV}$.
- For these ranges of M_A and $M_{H^\pm}$, $\tan\beta \sim 3 - 5.5$.
- We have shown that at the LHC it will be difficult to probe directly 98 GeV Higgs boson scenario, due low signal significance.

Work in progress..

- The most recent data (at 2σ) on Higgs search still allow MSSM parameter space where one can have simultaneously 98 GeV and 125 GeV Higgs boson.
- More precise measurement on Higgs may be able to rule out this scenario indirectly.
- ILC is an ideal machine to explore this possibility.

Thank You!

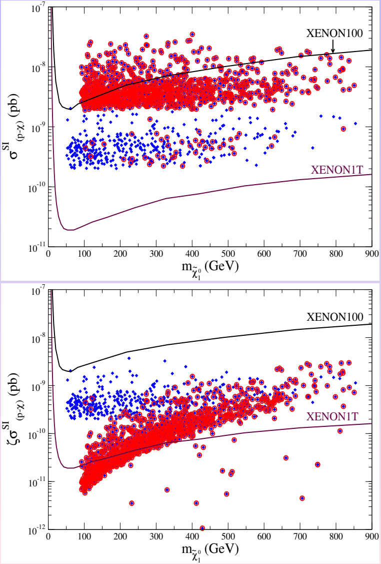
References

1. B. Bhattacherjee et. al., arXiv:1305.4020 [hep-ph].
2. R. Barate *et al.* [LEP Higgs WG], Phys. Lett. B **565**, 61 (2003).
3. T. Plehn et. al., Phys. Rev. Lett. **104**, 111801 (2010).
4. J. Butterworth et. al., Phys. Rev. Lett. **100**, 242001 (2008).
5. ATLAS Public NOTE: ATL-PHYS-PUB-2009-088

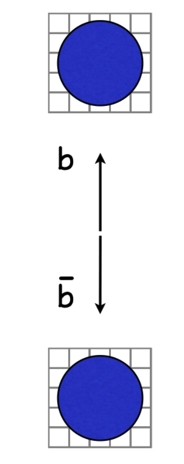
Backup slides

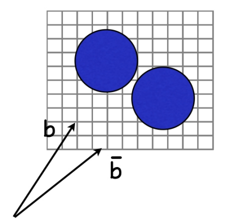
Dark matter direct detection

- Exclude points with over-abundant relic densities, include the possibility of multi-component dark matter.
- $\tilde{\chi}_1^0$-$\tilde{\chi}_1^\pm$ coannihilation: $\tilde{\chi}_1^0$ a pure bino & $\tilde{\chi}_1^\pm$ is pure wino.
- Heavy sleptons: no coannihilation with LSPs.
- spin-independent direct detection $\tilde{\chi}_1^0 - p$: Region above the solid (black) line discarded via XENON100 data
- Scaled cross-section ($\zeta\sigma^{SI}_{p\tilde{\chi}_1^0}$): under-abundant relic densities. $\zeta = \min\{1, \Omega_{\tilde{\chi}_1^0} h^2/(\Omega_{CDM}h^2)_{\min}\}$, where $(\Omega_{CDM}h^2)_{\min} = 0.112$
- Possibility at future direct-detection experiment XENON-1T



No Boost vs Boost



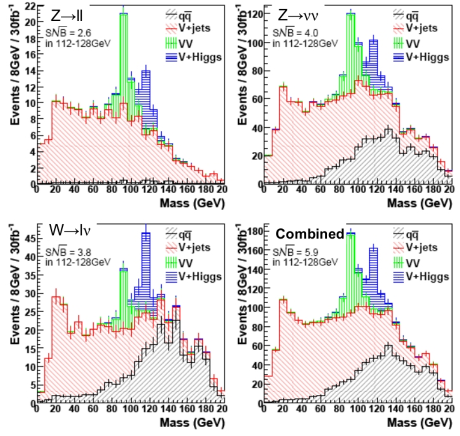


$m_H = 120$ GeV, $p_T \gtrsim 200 - 300$ GeV $\Longrightarrow$ large boost $\Longrightarrow$ $\Delta R \approx 2m_H/p_T \approx 1.2 - 0.8$
$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

$H \to b\bar{b}$ at rest $\Longrightarrow$ Two back to back jets

G. Kribs talk @ Fermilab (2011)

Application : $pp \to VH, (V = W^{\pm}, Z)$



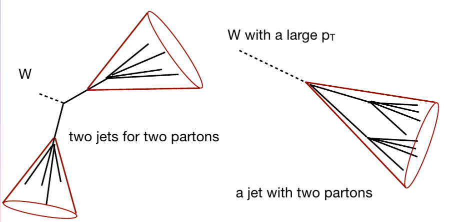
- $pp \to VH$, with $V = W^{\pm}, Z \Longrightarrow$
- $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$, $\nu\bar{\nu}b\bar{b}$ final state
- For Higgs to be boosted $p_T(H) > 200$ GeV
- Such a high $p_T(H) \Longrightarrow$ $\sigma_{\rm boosted}(WH/ZH) \sim 5\%$ of $\sigma_{\rm tot}(WH/ZH)$ @ 14 TeV

- ATLAS simulation @14 TeV with 30fb^{-1} luminosity : $N_S(m_H \sim 120\ \text{GeV}) \sim 13.5$ and $N_B \sim 20.3 \Longrightarrow \frac{S}{\sqrt{B}} = 3$

[J.Butterworth *etal.*, PRL (2008)], ATL-PHYS-PUB-2009-088, G. Kribs talk @ Fermilab (2011)

Fat jets

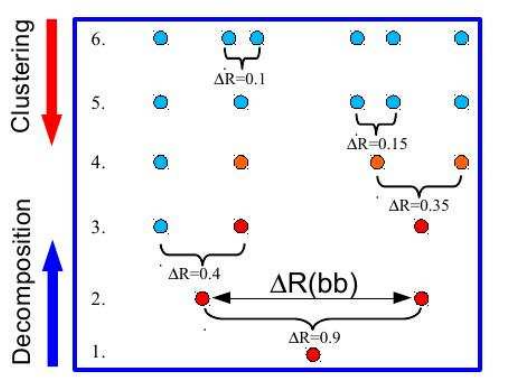
- Quantitatively, consider the following thumb rule for a two-body decay: To resolve the two partons of a $X \rightarrow q\ \bar{q}$ decay,choose a radius (or more generally a jet size) of $R < 2M_X\ /P_T$
- For $P_T \gg M_h$ $R \rightarrow$ very small (Overlap of Jet areas !)
- **These highly boosted jets are called "Fat Jets"**
- Example: Consider a hadronically decaying W Boson..



- Question : How do I see the inside of this fat jet ?

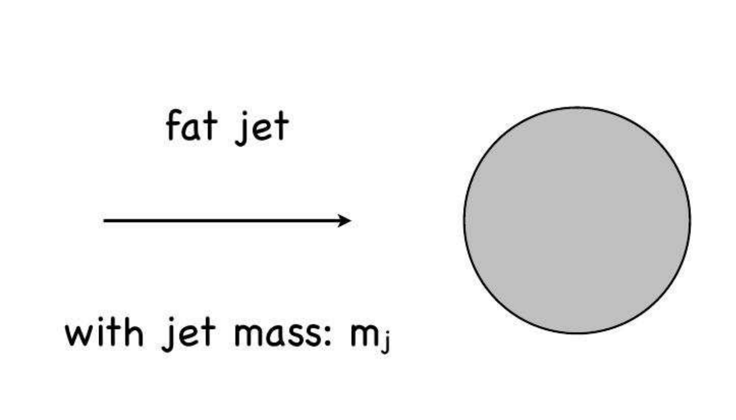
Jet Substructure

The basis of this technique involves an iterative jet clustering algorithm (e.g C/A), examining subjet kinematics step-by-step, and finally choosing the "best" subjets to form the fat-jet mass.



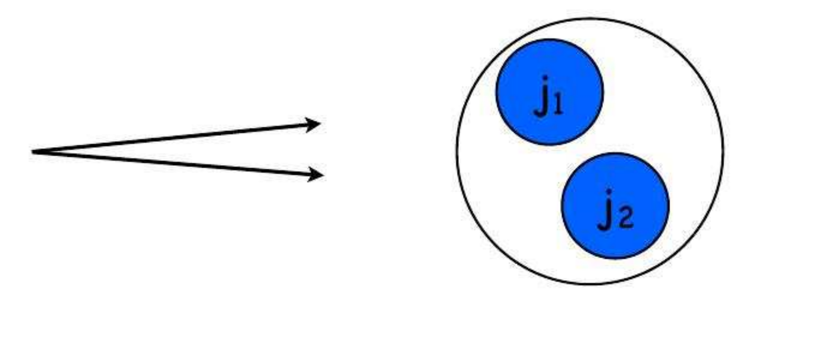
**Ref: Phys. Rev. Lett. 100.242001, Butterworth, Davison, Rubin & Salam

Jet Decomposition 1



Jet Decomposition 2

Step 1: Break the jet j into two subjets(j_1,j_2) by undoing its last stage of clustering s.t $m_{j_1} > m_{j_2}$.



Jet Decomposition 3

Step 2: a) Significant mass drop (MD),

$$m_{j_1} < \mu m_j$$

b) Splitting is nearly Symmetric

$$y = [min(P^2_{T_{j_1}}, P^2_{T_{j_2}})/m^2_j]\Delta R^2_{j_1,j_2} > y_{cut}$$

- Two parameters μ and y_{cut} are independent of Higgs mass and Higgs p_t.
- $$\mu = 0.667$$ $$y_{cut} = (0.3)^2$$

$\Rightarrow$ Helps to reject/minimize QCD contamination.

Jet Decomposition 4

Step 3: If y$>$ y_{cut}, consider j as heavy particle neighborhood and exit the loop.

Otherwise

Redefine j to be j_1 and go back to Step 1.

In practice, above procedure is not optimal for LHC, when the transverse momentum can be around 250-300 GeV.
Since,

$$m_x \sim 150 \text{ GeV} \quad \Rightarrow \quad R_{j_1,j_2} \sim 1.0 \rightarrow \text{Large}$$

$\Rightarrow$ Significant degradation due the Underlying Events (UE)

$\rightarrow$ UE $\propto R^4_{j_1,j_2}$

Filtering

- To minimize UE contamination $\Rightarrow$ Filter the subjets j_1, j_2 within a finer angular region, $R_{filt} < R_{j_1,j_2}$
- Consider 3 hardest p_T subjets 2b & gluon
- Most Effective result (In the context of Higgs search) $\Rightarrow$ $R_{filt} = min(R_{j_1,j_2}/2, 0.3)$
- (provided, both the subjets have tagged b's)