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High Energy Accelerator Experiments Group Tohoku University

STUDY OF CHARGED HIGGS BOSONS SEARCH AT THE ILC FOR A COLLISION ENERGY OF 1 TEV

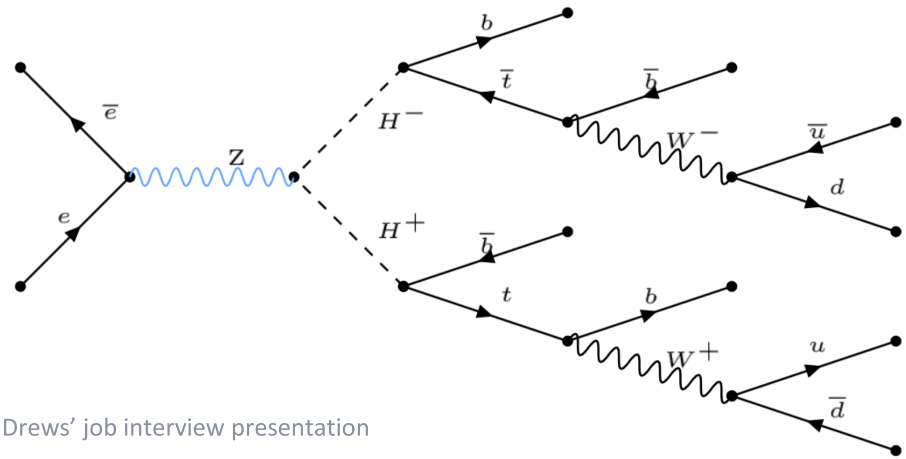
Presentation by Christian Drews

Academic advisors: Professor Hitoshi Yamamoto (Tohoku Uni.)
Professor Arno Straessner (TU Dresden)

Overview

- Full simulation study of ILC/ILD
- $m_{H\pm}$ = 350 GeV
- e^+e^- -> H^+H^- -> tb tb -> Wbb Wbb $\xrightarrow{W\rightarrow 2\text{ jets}}$ 8 jets (hadronic)

  Wbb Wbb $\xrightarrow[W\rightarrow \nu l]{W\rightarrow 2\text{ jets}}$ 6 jets + lepton
- Major background:
  - ttH/ttZ/ttg -> ttbb
  - tt -> bWbW
  - HA -> bbbb (SUSY)
  - H/A -> tt at resonance
  - Ignoring SUSY background
- Goal: $m_{H\pm}$ meassurment



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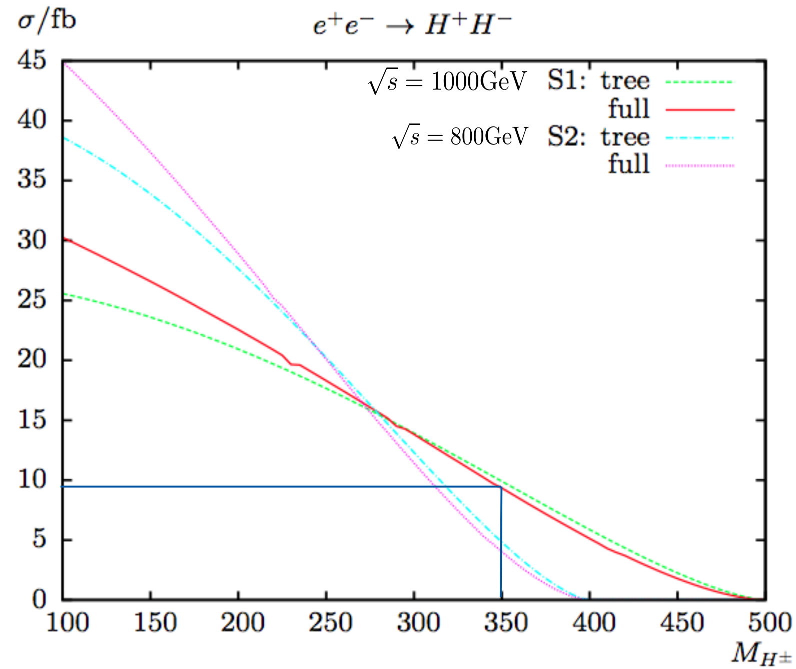
Cross section

- $\sigma \approx 9$ fb with P = (-80%,20%) 10.4 fb
- $\mathcal{L}$ = 1000 1/fb
- N = 9000 $H^{\pm}$ events
- Assuming BR($H^{\pm}$->tb) = 90%
- BR(t -> bW) = 100%
- BR(W -> 2jets) = 67.6%
- BR(W –> ev) = 10.75
- BR(W –> ev) = 10.57
- Hadronic: 5100 events
- Semileptonic: 3200 events



Source: ***Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis***
Heinemeyer, S. and Schappacher, C. Eur. Phys. J. (2016)

Analysis Overview

- Isolated Lepton selection
- Reduce beam background by kt-Algorithm
- Jet-clustering and flavor tagging (LCFIplus)
- Calculating neutrino four-momentum (only semi-leptonic)
- Jet-pairing
- Extracting signal and background mass shape
- Added fit to find Higgs-mass

kt Algorithm (beam background removal)

- Calculate the distance between to all tracks

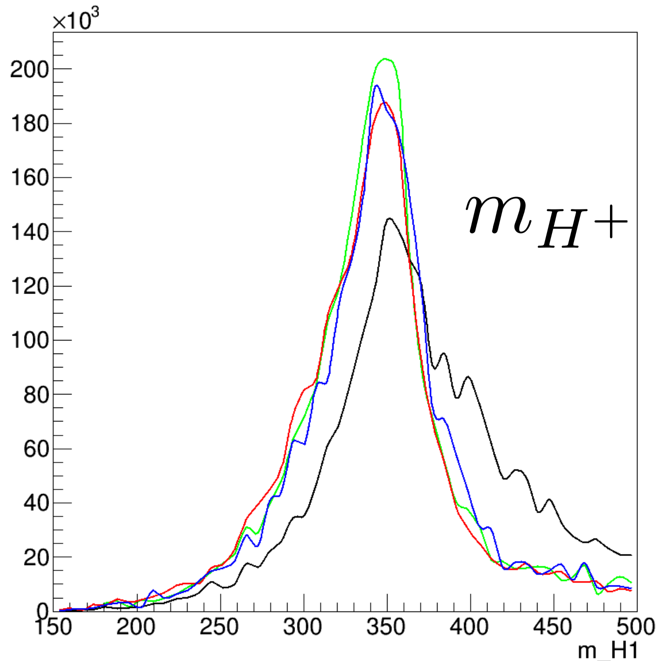
$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}}{R}$$

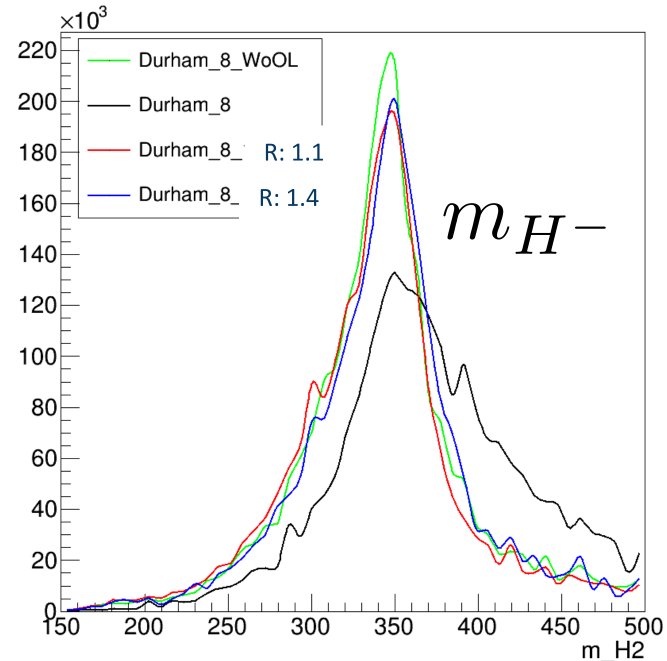
with $\Delta R_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$

η pseudo rapidity, ϕ azimuth

- Find smallest d_{ij}
- If $d_{ij} < d_{iB} = p_{Ti}^2$ merge tracks, if not remove Track (B: Beam)
  - Remove particles that are closer to the beam than to the closest track i
- Continue to step one until there are only the requested number of jets

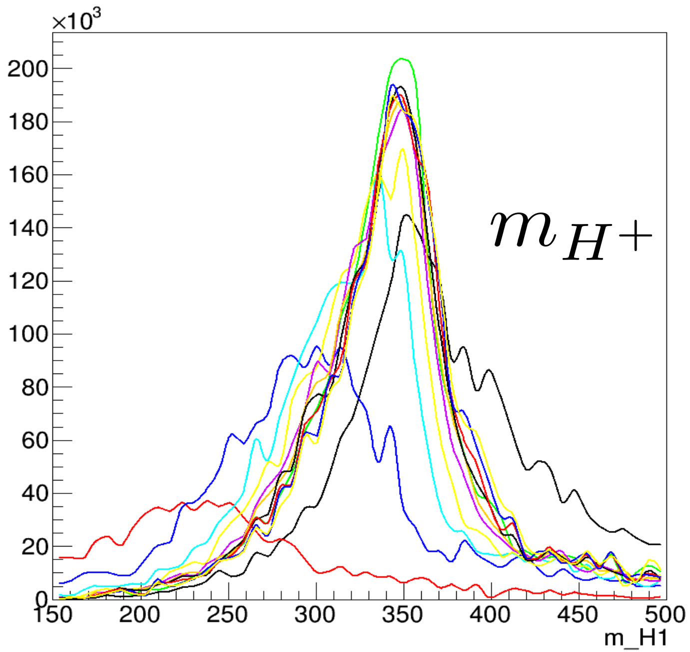
Find R for kt-Algorithm

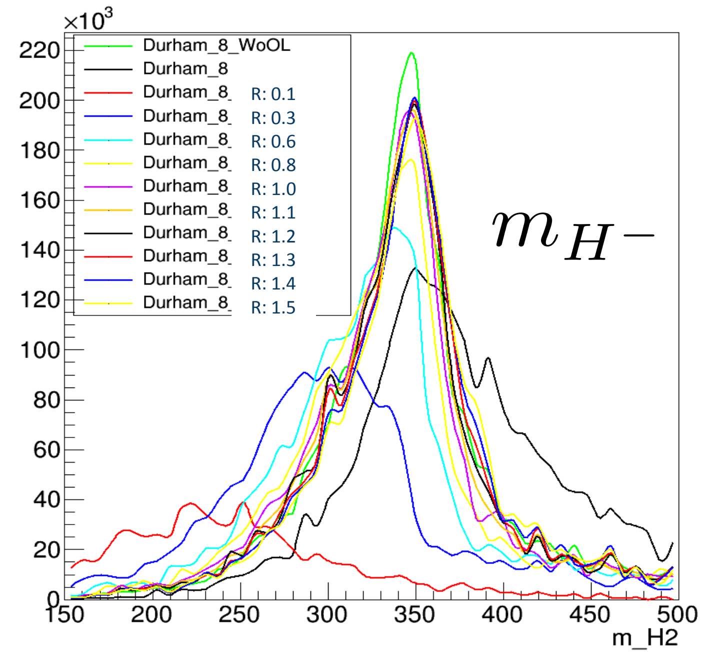




Reconstructed H^+ and H^- mass with realistic clustering and pairing with generator information

Find R for kt-Algorithm





Reconstructed H^+ and H^- mass with realistic clustering and pairing with generator information

Chi² - Jet Pairing (hadronic)

	w/o overlay	R: 1.3	with overlay	
B-tag efficiency	44.6	42.5	38.0	the 4 b-jets have highest b-tag in the event
Clustering works well	50.7	49.4	40.2	For every color singlet there are 2 jets with a major fraction from this singlet
Pairing works	27.8	***25.0***	17.2	Jet pairing agrees with major color singlet fraction in jet

$$\chi^2 = \left| \frac{(m_{j_1 j_2 j_3 j_4})^2 - (m_{j_5 j_6 j_7 j_8})^2}{2\sigma_{H^+}^2} \right| + \left(\frac{m_{j_2 j_3 j_4} - M_t}{\sigma_t} \right)^2$$

$$+ \left(\frac{m_{j_6 j_7 j_8} - M_t}{\sigma_t} \right)^2 + \left(\frac{m_{j_3 j_4} - M_W}{\sigma_W} \right)^2 + \left(\frac{m_{j_7 j_8} - M_W}{\sigma_W} \right)^2$$

Lepton Selection

- Using the IsolatedLeptonTaggingProcessor
  - From MarlInReco
  - Based on MVA
- Open task: reduce false Lepton Tag in hadronic Channel
  - With event shape or b-tag
  - But actually the pairing efficiency is not effected

	Total (%)	w/o tau (%)
Lepton Tag	60.3	90.4
Correct Tag	60.0	90.0
False Lepton Tagged	0.3	0.4
Electron	29.5	89.4 (w/o tau and myon)
Myon	30.3	90.5 (w/o tau and electron)
False Lepton Tag in hadronic	2.1	

Neutrino Four-vector

- Method 1: Missing-Energy-Method (MEM)

$$p_{\text{vis}} = \sum_{i=1}^{N_{\text{PFO}}} p_i \qquad p_{\text{CMS}} = (1000, 0, 0, 1000 \cdot \sin(0.014/2))$$

$$p_{\nu,\text{MEM}} = (p_{\text{CMS}} - p_{\text{vis}})$$

  - Should I Sum pfos or jets? LCFIplus doesn't cluster all particles to jets?
- Method 2: Neutrino-Direction-Method (NDM)
  - Using the Direction of Missing-Energy-Method and calculation the Enerty by fixing W-Mass

$$E_{\nu,\text{NDM}} = \frac{m_W^2}{E_l(1-\alpha)} \qquad \alpha = \frac{\vec{p}_{\nu,\text{MEM}} \cdot \vec{p_l}}{|\vec{p}_{\nu,\text{MEM}}||\vec{p_l}|}$$

$$p_{\nu,\text{NDM}} = (E_{\nu,\text{NDM}}, E_{\nu,\text{NDM}} \frac{\vec{p}_{\nu,\text{MEM}}}{|\vec{p}_{\nu,\text{MEM}}|})$$

Neutrino Four-vector

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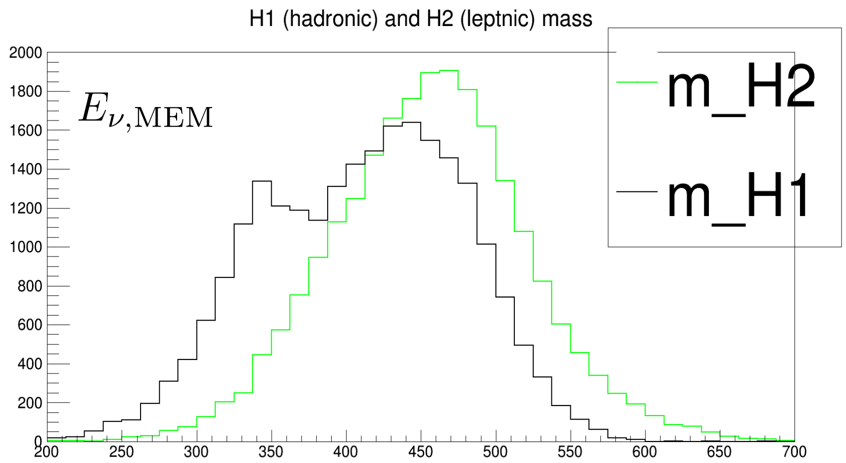
$$p_{\nu,\text{NDM}} = (E_{\nu,\text{NDM}}, E_{\nu,\text{NDM}} \frac{\vec{p}_{\nu,\text{MEM}}}{|\vec{p}_{\nu,\text{MEM}}|})$$

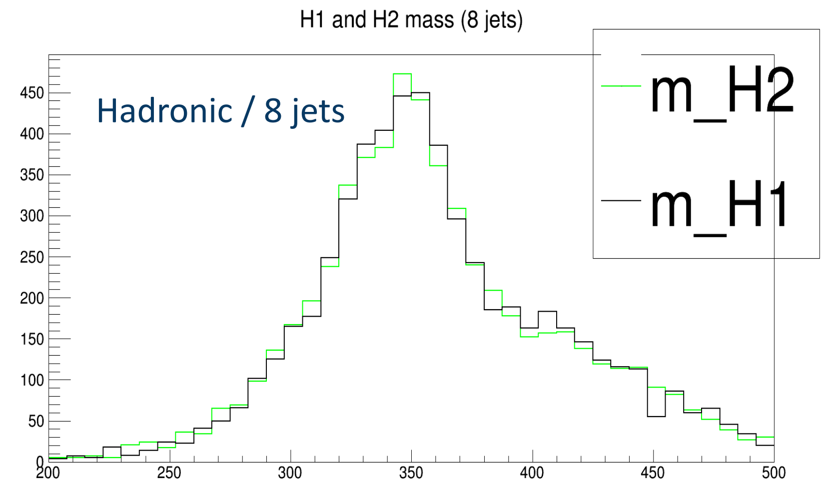
Better Idea: only use missing transversal Energy and direction

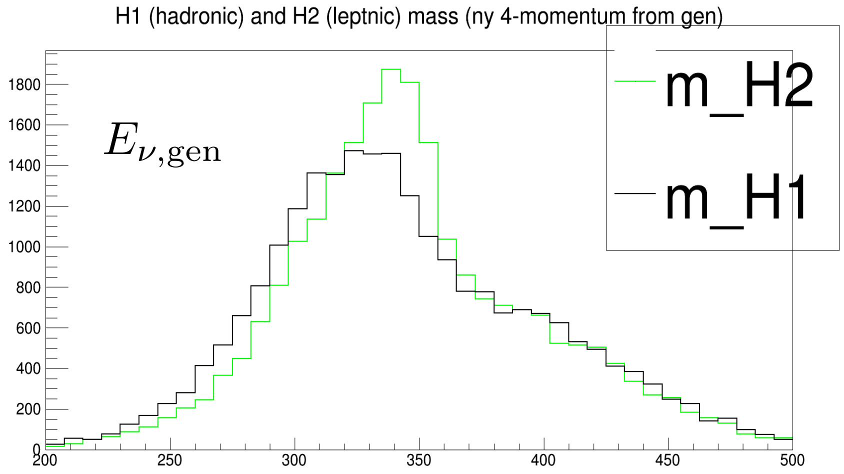
Higgs mass reconstructed with Jet pairing

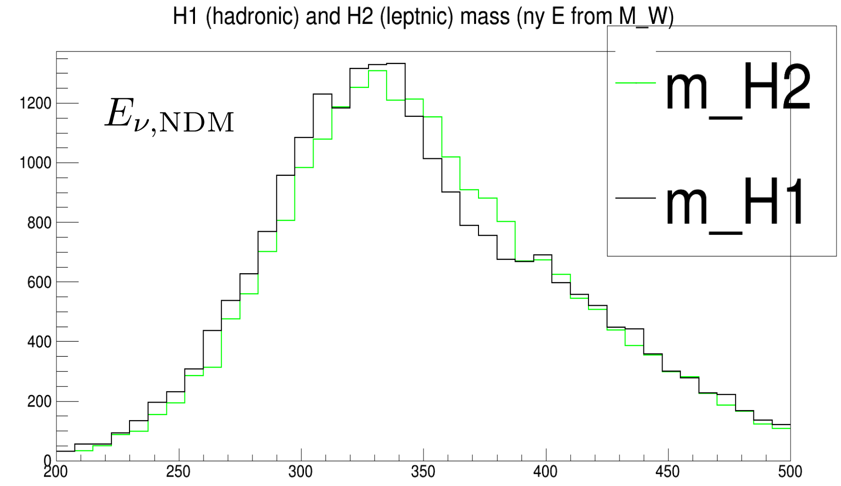
- Chi^2 minimization method

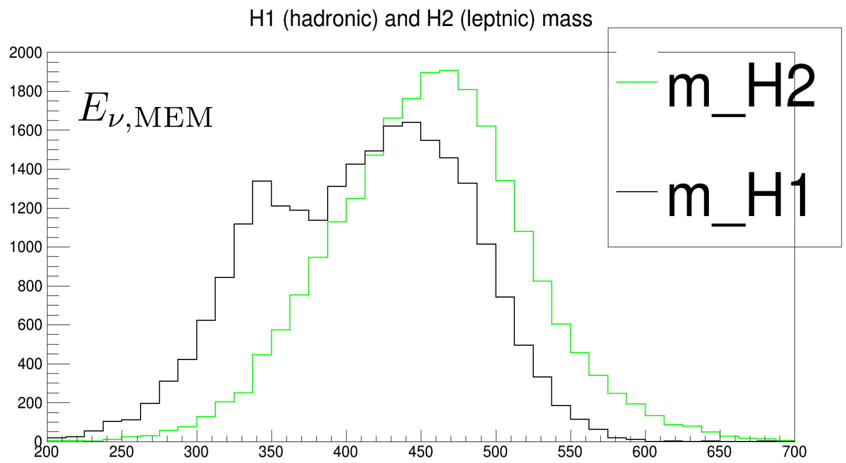
$$\chi^2 = \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma_{H^+}^2} \right| + \left(\frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2 + \left(\frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2 + \left(\frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2 + \left(\frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2$$

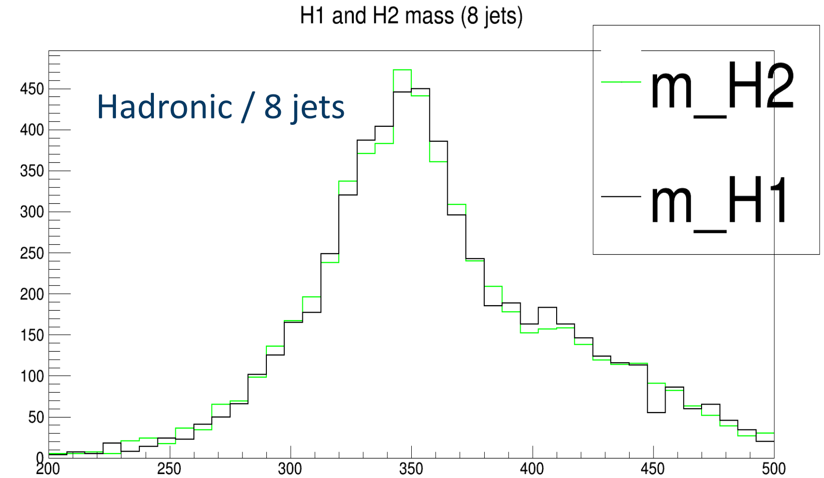





H1 (hadronic) and H2 (leptnic) mass (ny 4-momentum from gen)
m_H2
m_H1
$E_{\nu,\mathrm{gen}}$

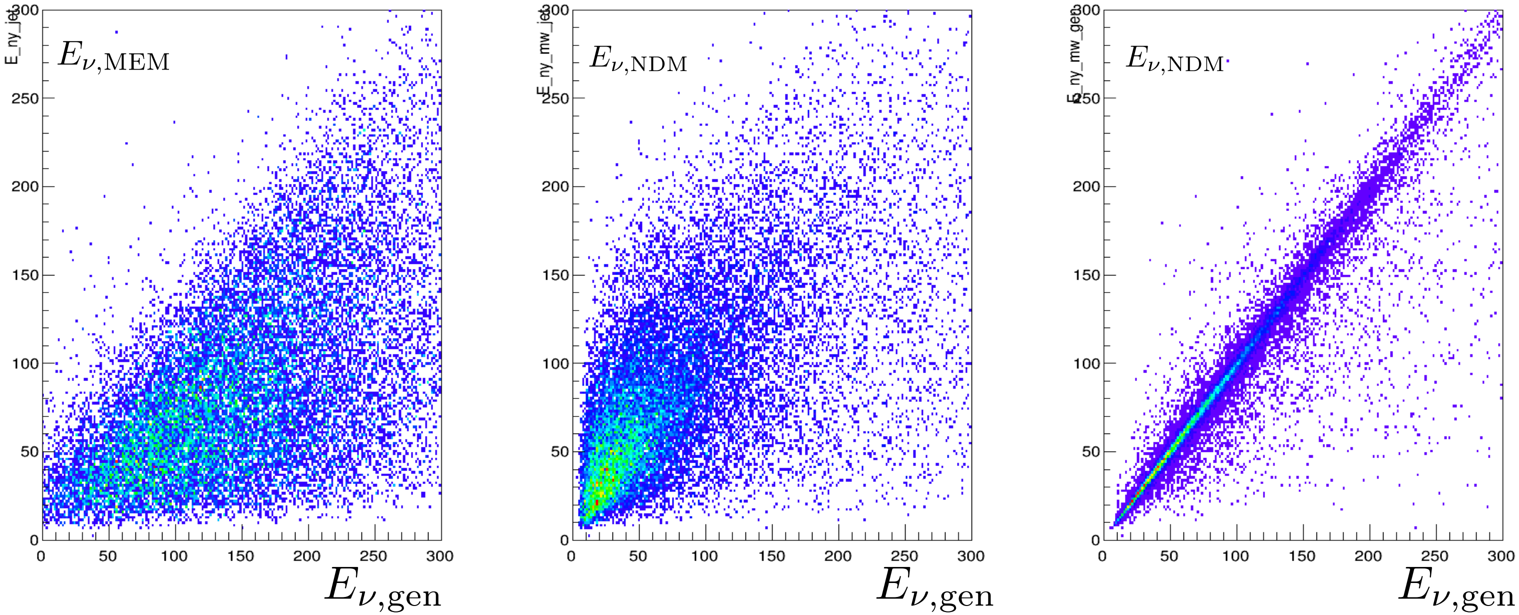

H1 (hadronic) and H2 (leptnic) mass (ny E from M_W)
m_H2
m_H1
$E_{\nu,\mathrm{NDM}}$


H1 (hadronic) and H2 (leptnic) mass
m_H2
m_H1
$E_{\nu,\mathrm{MEM}}$


H1 and H2 mass (8 jets)
m_H2
m_H1
Hadronic / 8 jets

Neutrino Four-vector

Neutrino direction from Generator



Cuts (leptonic)

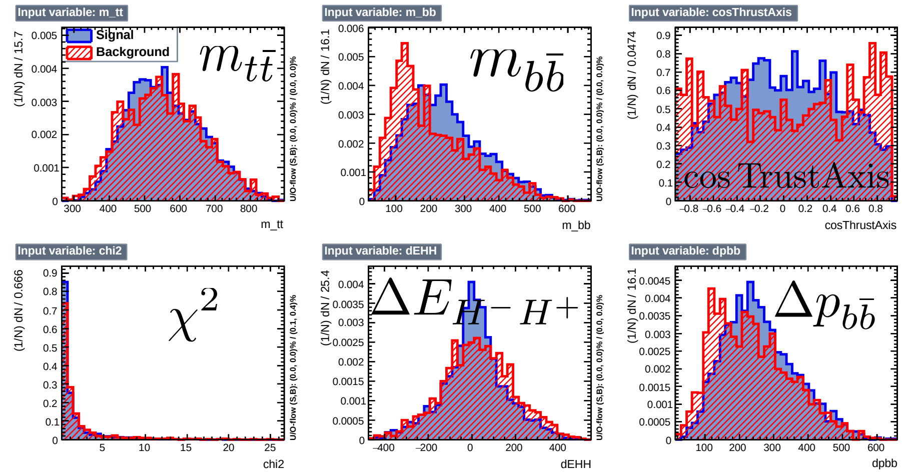
	h2dm_sl wp	h2dm_ slwm	2f_h	ttz	ttbb	6f_ttbar_ sl	6f_ttbar_ h	tth_sl	tth_slno bb	tth_h	tth_hno bb	h2dm_h	Signif	Effi	Purity
Highest 4 b-tags>2.45	1974	1968	36975	1643	1403	16692	16693	687	81	763	99	4294	13.66	0.80	0.05
evis6<1000.0	1967	1961	29640	1553	1323	16574	13614	686	81	688	90	3740	14.65	0.80	0.05
evis6>560.0	1944	1936	23165	1379	1197	14005	13401	652	69	687	88	3740	15.55	0.79	0.06
chi2H<31.0	1922	1919	22485	1375	1190	13898	13362	647	69	687	88	3738	15.50	0.78	0.06
y45>0.001	1891	1889	2930	1317	1111	9488	12596	632	67	685	88	3734	19.80	0.77	0.10
chi2t1+chi2t2<11.0	1884	1885	2930	1315	1109	9469	12592	630	67	685	88	3732	19.76	0.77	0.10
principleThrust<0.825	1752	1752	827	870	551	2529	3258	452	48	513	69	3576	27.53	0.71	0.22
minorThrust>0.12	1739	1741	535	859	546	2406	3176	448	47	511	68	3564	27.83	0.71	0.22
|cosThrustAxis|<0.915	1691	1690	486	677	501	2016	2488	402	43	466	60	3480	28.58	0.69	0.24
missMass>-160.0	1678	1675	438	663	493	1863	2352	393	42	460	59	3464	28.77	0.68	0.25
missPt<240.0	1651	1647	438	654	480	1691	2352	381	40	460	58	3464	28.58	0.67	0.25
missPz<200.0	1634	1629	389	630	457	1532	2050	365	39	445	57	3449	28.98	0.66	0.26
One Isolated Lepton	970	998	0	153	139	547	17	202	18	8	7	48	35.30	0.40	0.63

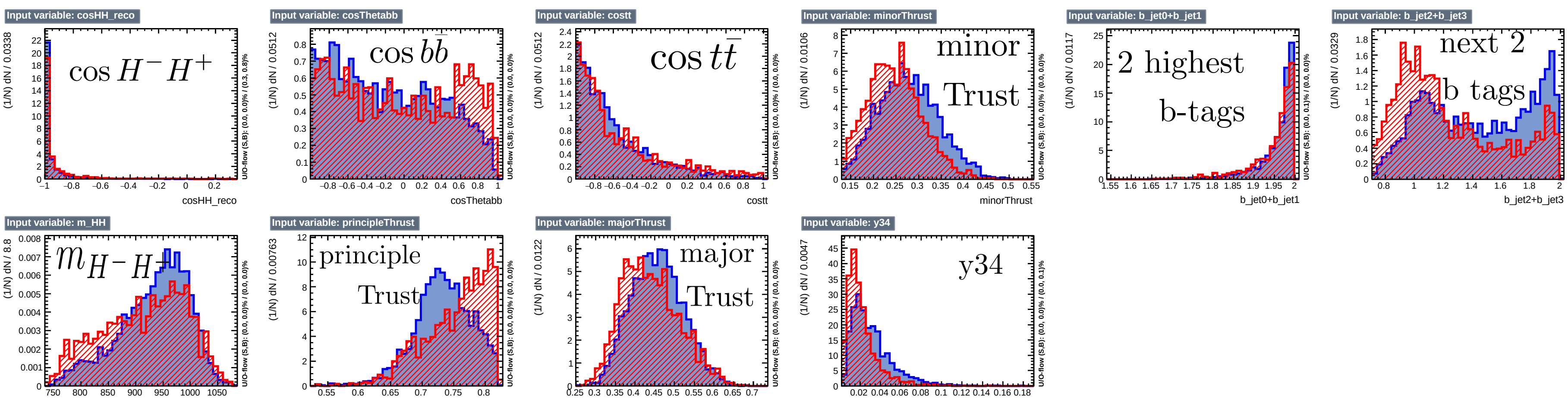
Cuts (hadronic)

	h2dm_h	2f_h	ttz	ttbb	6f_ttbar_sl	6f_ttbar_h	4f_h	tth_sl	tth_h	tth_ hnobb	h2dm_ slwp	h2dm_ slwm	Signif	Effi	Purity
all	5100	5666668	8355	2059	219456	201922	3489997	898	933	681	2457	2457	2.06	1.00	0.00
Highest 4 b-tags>2.7	3906	18533	1097	1182	7406	8156	5921	607	677	53	1778	1767	18.37	0.77	0.09
evis8<1080.0	3895	17862	1094	1177	7384	7974	4450	606	676	52	1776	1765	18.50	0.76	0.09
evis8>770.0	3809	11477	695	791	3335	6870	4450	357	609	42	1354	1335	21.74	0.75	0.12
chi2H<23.0	3806	9996	693	781	3241	6707	885	354	608	42	1338	1322	22.39	0.75	0.13
chi2t<8.0	3804	9941	691	781	3220	6701	885	352	607	42	1330	1316	22.41	0.75	0.13
y67>0.00025	3746	538	570	618	969	4239	233	245	595	41	1013	1004	32.13	0.73	0.28
principleThrust <0.82	3551	243	372	284	325	1018	47	160	417	29	931	924	39.06	0.70	0.43
minorThrust >0.13	3531	146	366	281	314	971	47	158	414	28	921	915	39.35	0.69	0.44
|cosThrustAxis| <0.925	3465	146	297	263	276	831	47	146	383	27	904	898	39.64	0.68	0.45
missMass>-130.0	3433	97	290	254	239	770	47	138	375	27	880	875	39.95	0.67	0.46
missPt<120.0	3418	97	274	236	181	767	47	116	374	25	742	747	40.90	0.67	0.49
missPz<210.0	3417	97	272	234	181	760	47	115	372	25	741	746	40.94	0.67	0.49
Isolated Lepton Veto	3380	97	231	204	96	753	47	54	366	22	306	291	44.37	0.66	0.58

Boosted Decision Tree (Input)

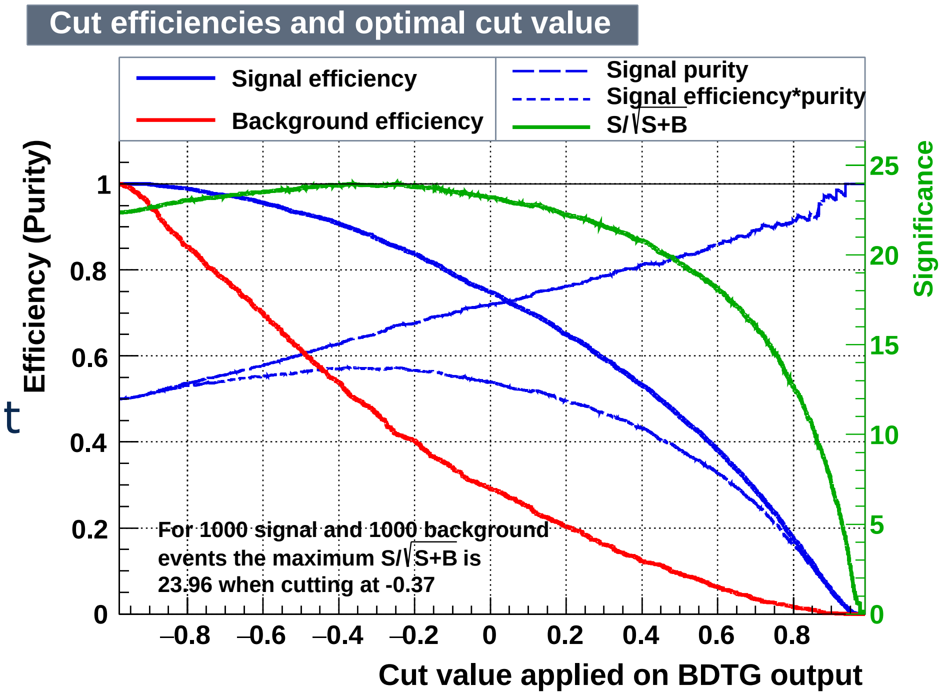
- For further Background reduction
- Here for hadronic
- Trained only on main background after static cuts





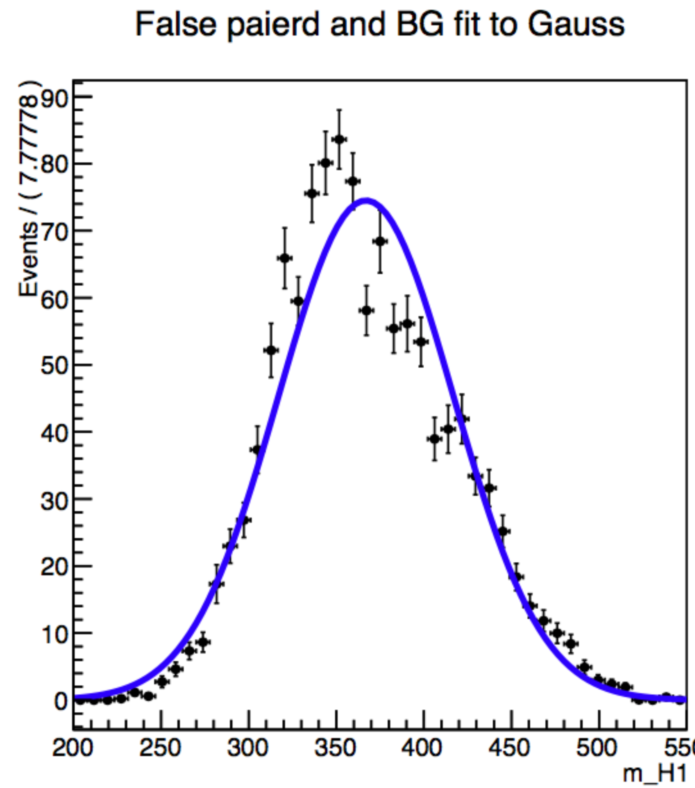
Boosted Decision Tree

- For further Background reduction
- Here for hadronic
- Trained only on main background after static cuts
- About 1.5σ gain
- Its quite difficult to apply result of TMVA to cuts



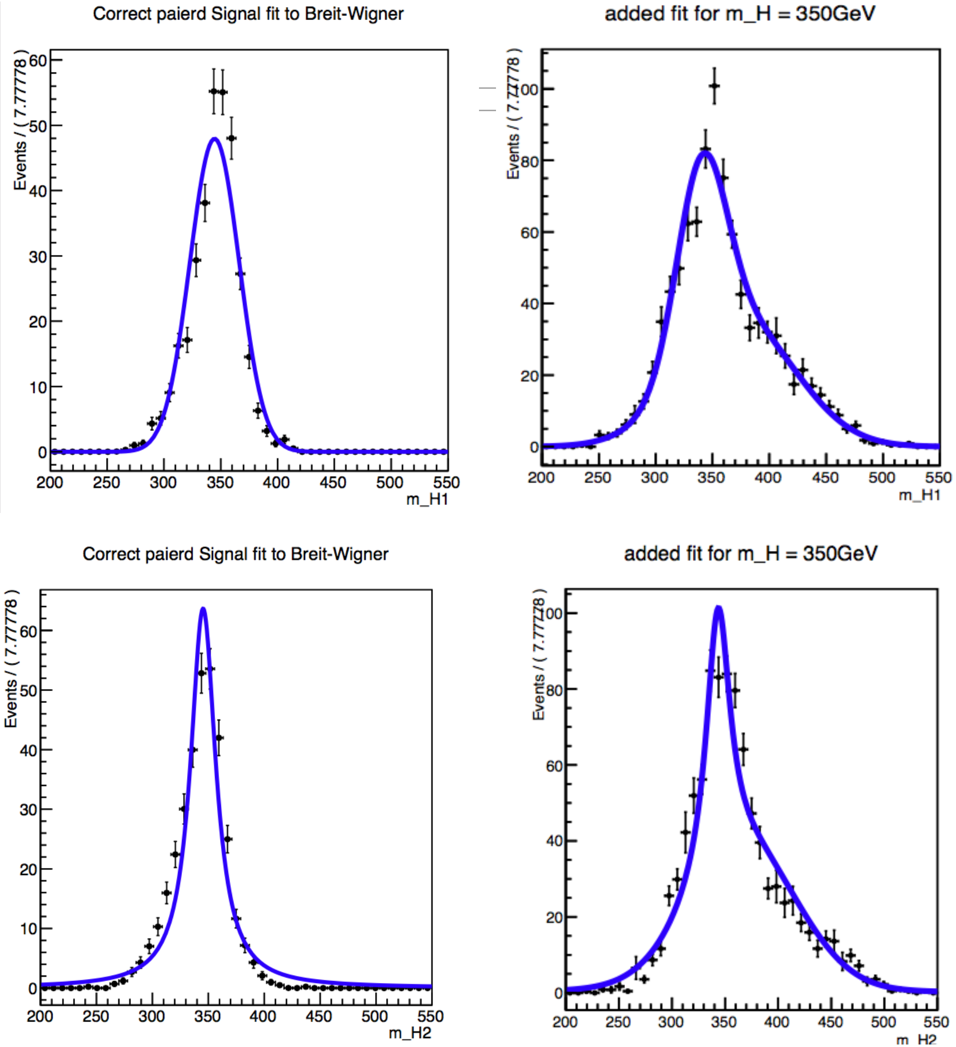
Mass distribution of Background

- BG and Signal with failed pairing has similar shape
- Fitting with Gauß-distribution

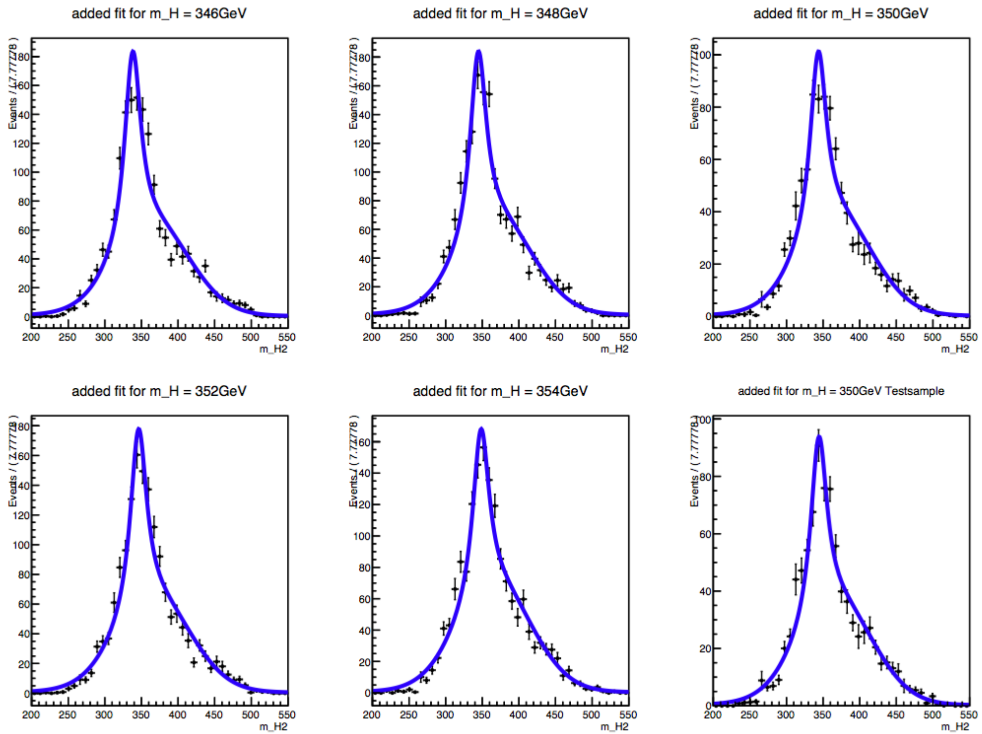


Mass fit

- Fit correctly paired Signal with Breigt-Wigner or Gauß-distribution
- Gauß – good tail agreement
- Breit-Wigner – good agreement at the tip
- For mass extraction tip is esential -> Breit-Wigner in favor

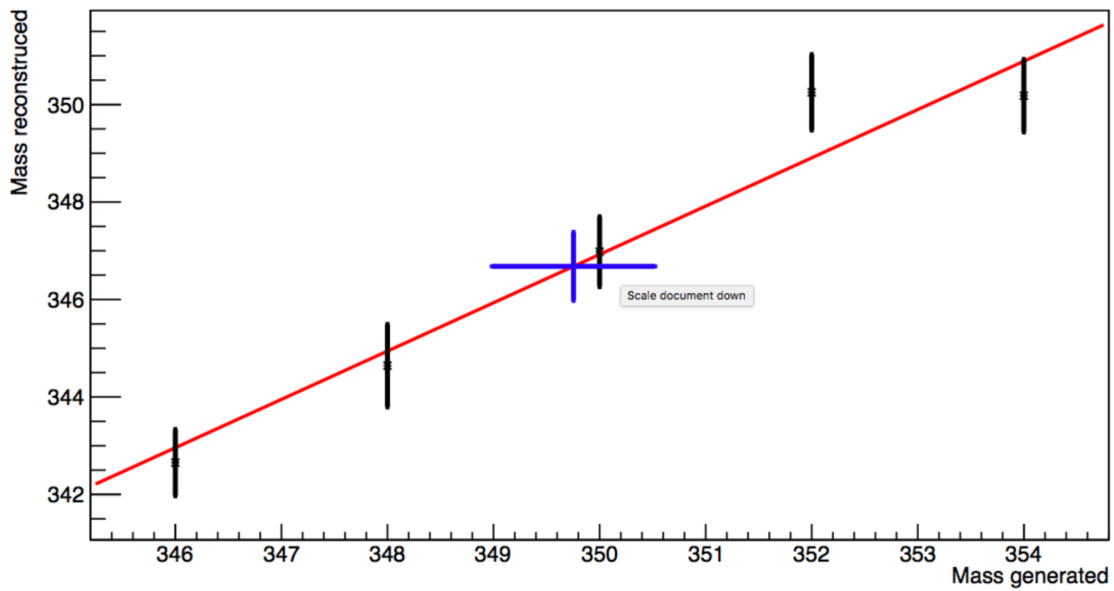


Mass fit for different Higgs-mass



Mass fit for different Higgs-mass

- Linear regression for 5 different Higgs-masses
- Calculation the generated mass for a testing sample
- Problem: Is it linear or dominated by fitting effects?
- Expected Resulution < 1 GeV



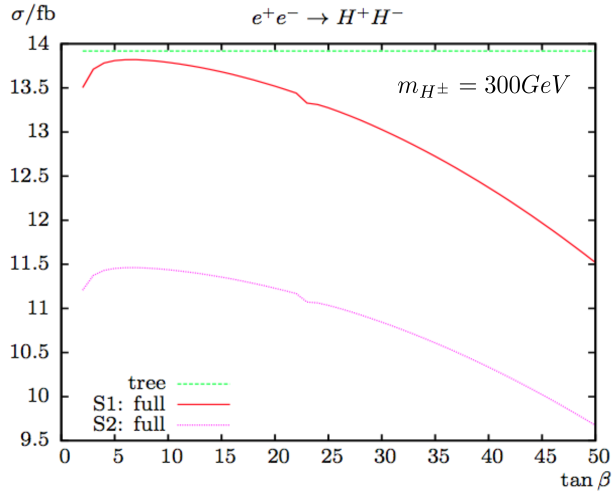
Plan

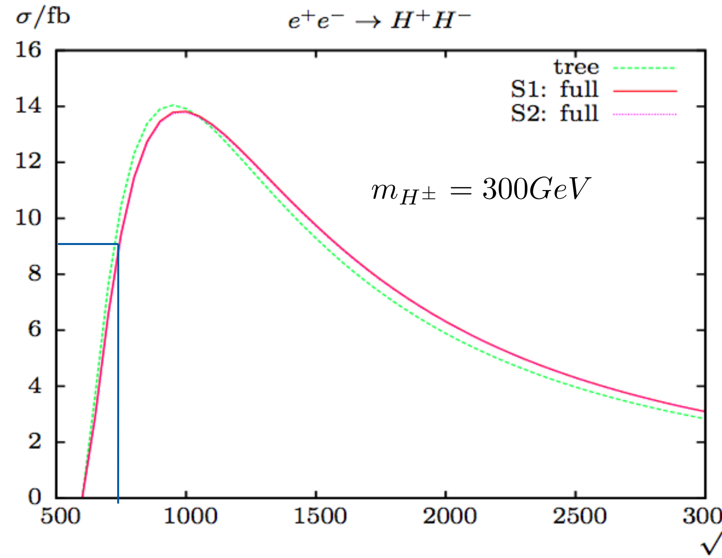
- Toy Monte Calrlo Study
- Add pt Method for neutrino four momentum
- Do fitting for semi-leptonic mode
- Goal:
    - mass fit -> mass resolution measurement
    - Detection efficiency
      -> cross section times branching ratio
- Bonus: (most probable imposibale)
    - Research how to distinguish H+ and H-
    - Study of CP-violation measurement

Backup

Cross section

- σ(tanβ) const. on tree-level
- 1 TeV below maximum of σ

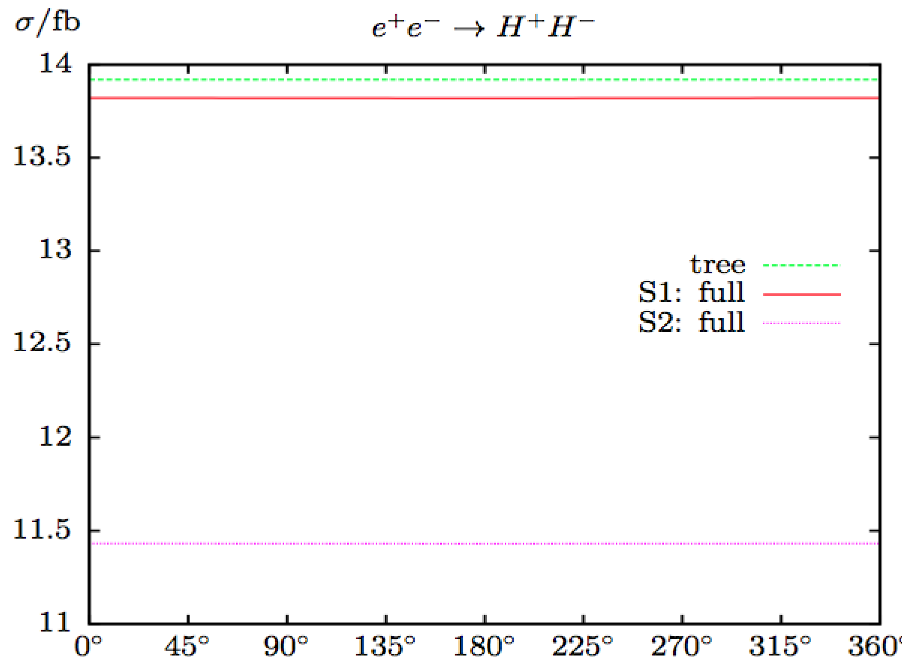




Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
S1	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500
S2	800	4	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

Source: ***Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis***
Heinemeyer, S. and Schappacher, C. Eur. Phys. J. (2016)

Cross section



Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
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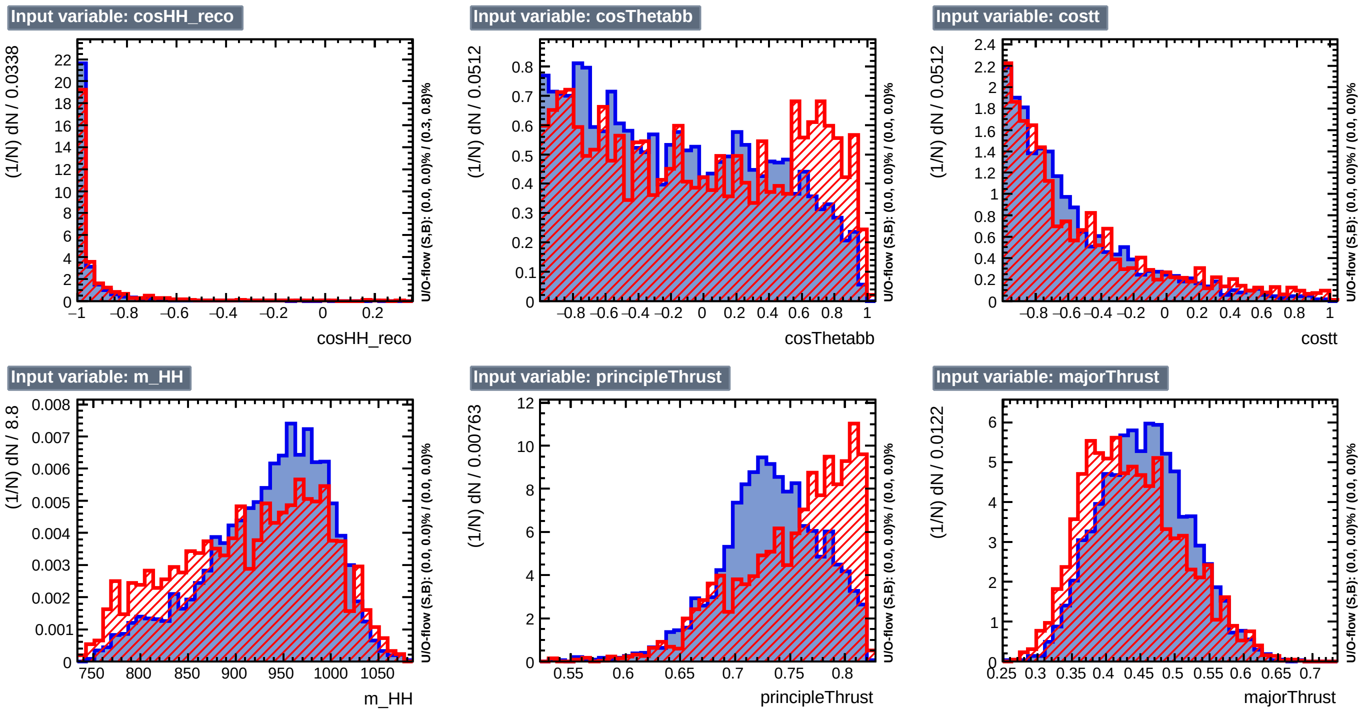
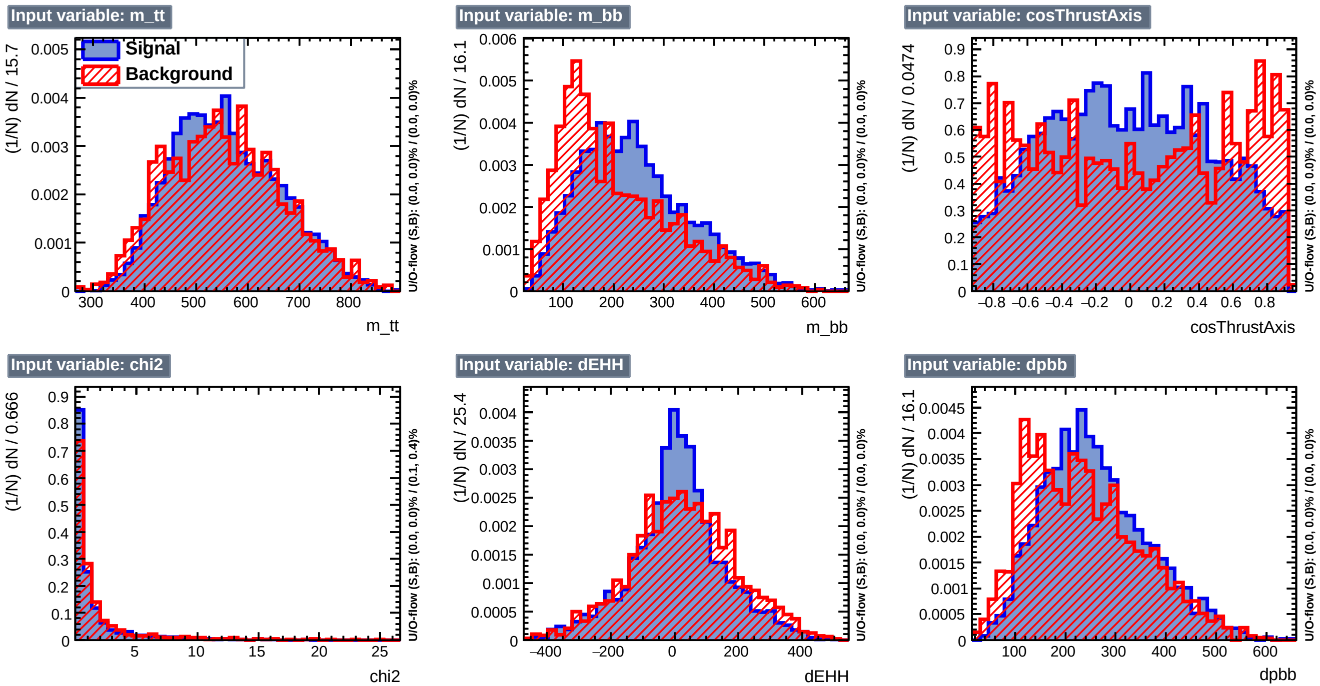
Boosted Decision Tree (Input)

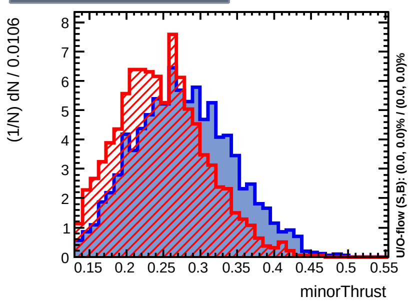


Boosted Decision Tree

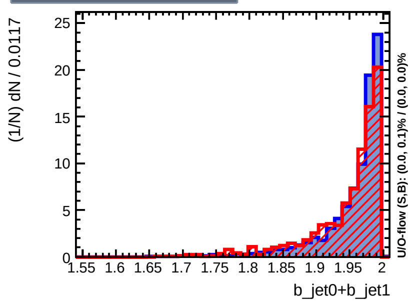


Boosted Decision Tree

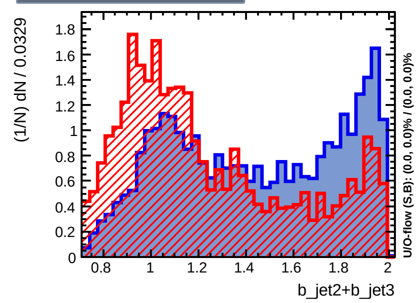
Input variable: minorThrust



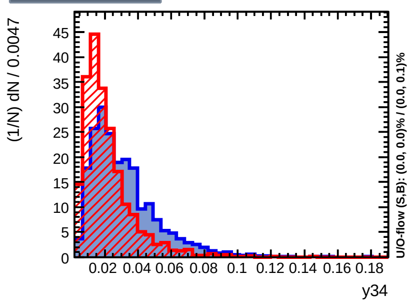
Input variable: b_jet0+b_jet1



Input variable: b_jet2+b_jet3

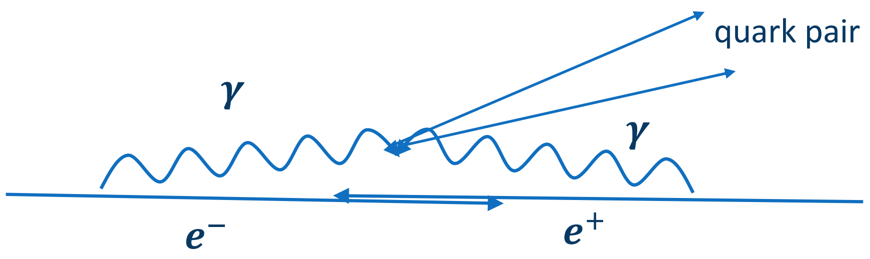


Input variable: y34



Analysis Strategy – Beam Background

- In average 2.7 beam background events per bunch crossing
- In these samples old number of 4.1 events per bunch crossing
- Has major influence on jet clustering
- Use kt-algorithm from fastjet package to reduce backgrond
  - R: Generalized radius of jets
  - Vary R to optimal mass resolution
- Use Satoru Jetfinder for clustering



Fastjet Finder – kt Algorithm (beam background removal)

- Calculate the distance between to all tracks

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}}{R}$$

  with $\Delta R_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$

  η pseudo rapidity, ϕ azimuth

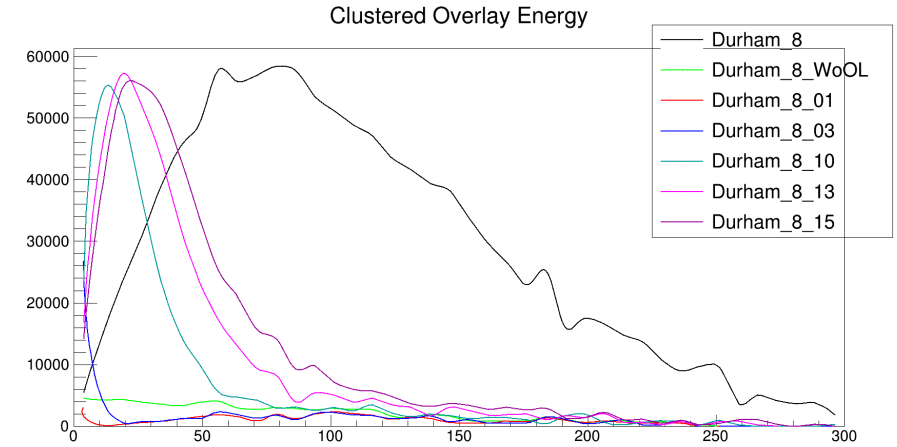
- Find smallest d_{ij}
- If $d_{ij} < d_{iB} = p_{Ti}^2$ merge tracks, if not remove Track (B: Beam)
  - i Remove particles that are closer to the beam than to the closest track
- Continue to step one until there are only the requested number of jets

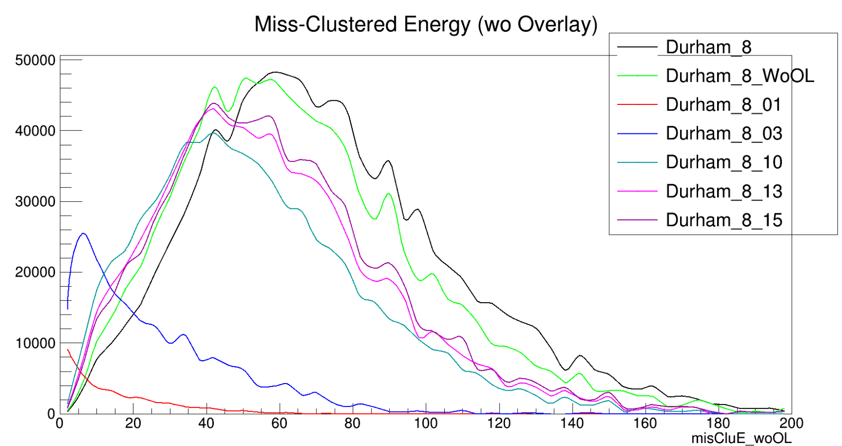
Choose R for kt algorithm

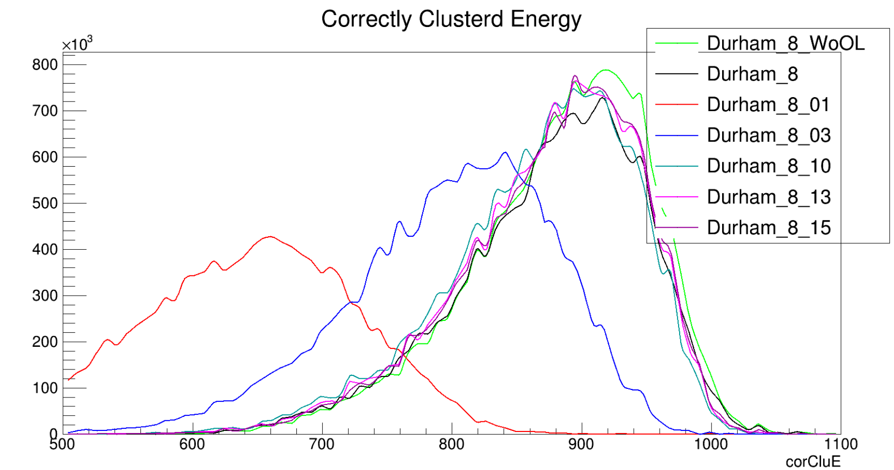
Durham_8: w/o correction

Durham_8_WoOL: overlay removed by generator information

Durham_8_13: R = 1.3

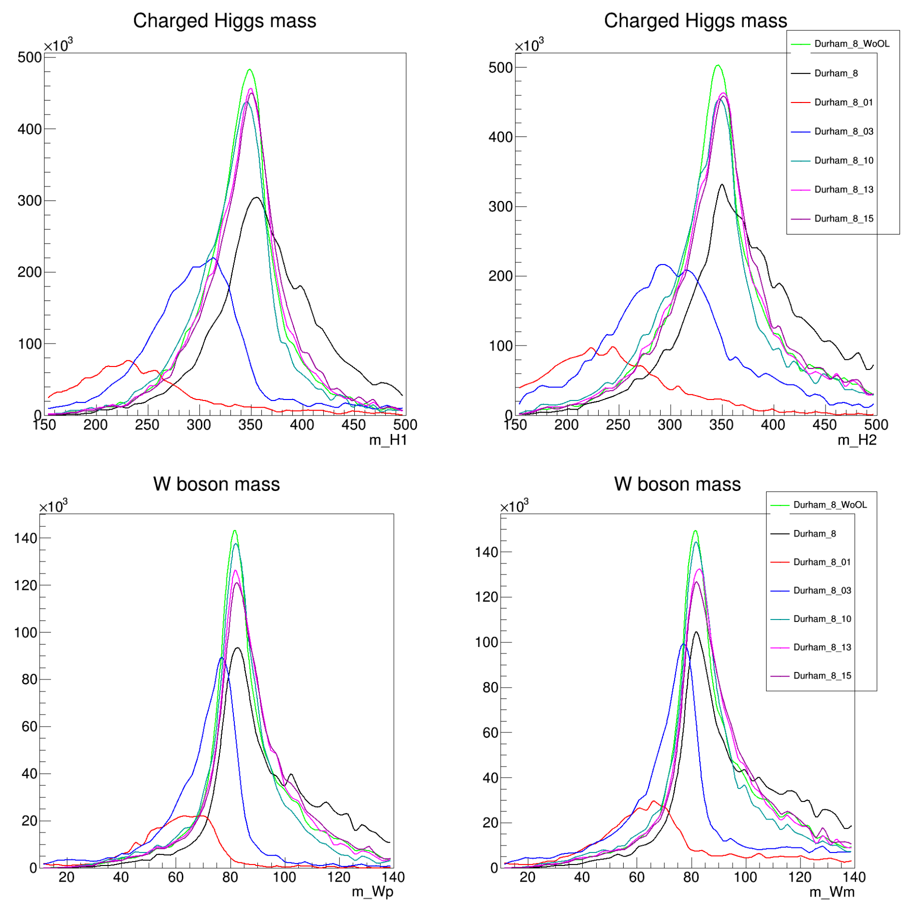


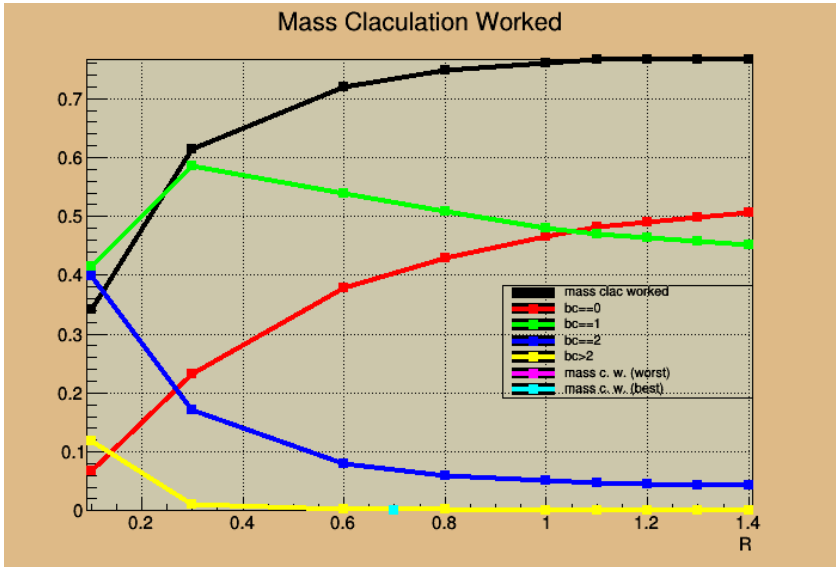


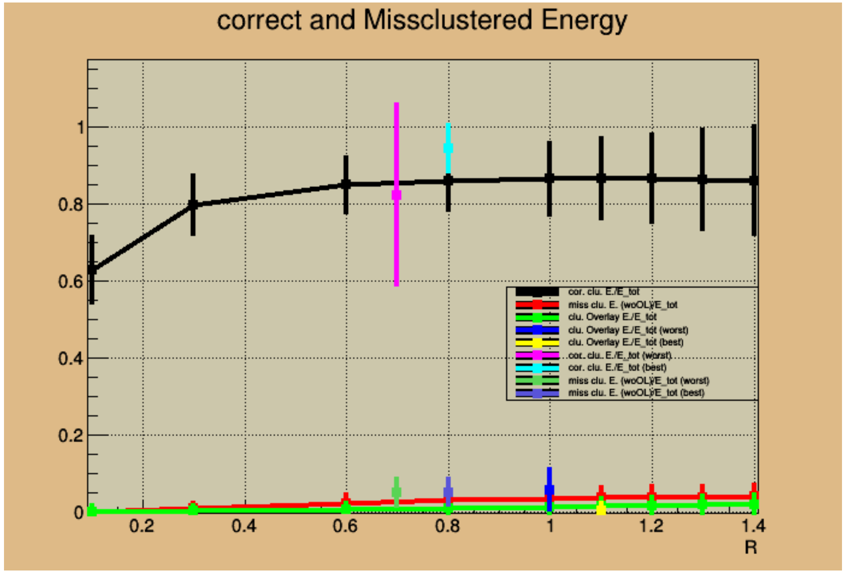


Choose R for kt algorithm

- For W mass R = 1.0 seems best
- For H mass R = 1.3 seems best
- Maybe b-jets have a wider spread
- I will continue with 1.3




Mass Claculation Worked
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
R
mass clac worked
bc==0
bc==1
bc==2
bc>2
mass c. w. (worst)
mass c. w. (best)


correct and Missclustered Energy
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
R
cor. clu. E./E_tot
miss clu. E. (woOL)/E_tot
clu. Overlay E./E_tot
clu. Overlay E./E_tot (worst)
clu. Overlay E./E_tot (best)
cor. clu. E./E_tot (worst)
cor. clu. E./E_tot (best)
miss clu. E. (woOL)/E_tot (worst)
miss clu. E. (woOL)/E_tot (best)

Analysis Strategy - Chi^2

- Choose σ from pairing with generator information
- Optimize for c for maximal pairing efficiency

$$\chi^2 = c_H \left| \frac{(m_{j_1 j_2 j_3 j_4})^2 - (m_{j_5 j_6 j_7 j_8})^2}{2\sigma_{H^+}^2} \right| + c_t \left(\frac{m_{j_2 j_3 j_4} - M_t}{\sigma_t} \right)^2$$

$$+c_t \left(\frac{m_{j_6 j_7 j_8} - M_t}{\sigma_t} \right)^2 + c_w \left(\frac{m_{j_3 j_4} - M_W}{\sigma_W} \right)^2 + c_w \left(\frac{m_{j_7 j_8} - M_W}{\sigma_W} \right)^2$$

$$\sigma_H = \sigma_t = 80\ GeV,\ \sigma_W = 48\ GeV$$

Analysis Strategy - Chi^2

- Choose σ from pairing with generator information
- Optimize for c for maximal pairing efficiency

$$\chi^2 = c_H \left| \frac{(m_{j_1 j_2 j_3 j_4})^2 - (m_{j_5 j_6 j_7 j_8})^2}{2\sigma^2_{H^+}} \right| + c_t \left(\frac{m_{j_2 j_3 j_4} - M_t}{\sigma_t} \right)^2$$

$$+ c_t \left(\frac{m_{j_6 j_7 j_8} - M_t}{\sigma_t} \right)^2 + c_w \left(\frac{m_{j_3 j_4} - M_W}{\sigma_W} \right)^2 + c_w \left(\frac{m_{j_7 j_8} - M_W}{\sigma_W} \right)^2$$

$$+ c_{\cos\theta_{HH}} \left(\frac{1 - \cos\theta_{HH}}{\sigma_{\cos\theta_{HH}}} \right)^2 + c_{\theta_{HH}} \left(\frac{\theta_{HH}}{\sigma_{\theta_{HH}}} \right)^2 + c_E \left(\frac{E_{H^-} - E_{H^+}}{\sigma_E} \right)^2 + c_p \left(\frac{\vec{p} - \vec{p}_{H^+}}{\sigma_p} \right)^2$$

Analysis Strategy - Chi^2

- First test optimization for c_H and c_cos
- c_H ~ 0.2 / c_cos ~ 30 (σ_cos = 1)
- Pairing efficiency 25 -> 27.5 %

$$\chi^2 = c_H \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma^2_{H^+}} \right| + c_t \left(\frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2$$

$$+c_t \left(\frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2 + c_w \left(\frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2 + c_w \left(\frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2$$

$$+c_{\cos\theta_{HH}} \left(\frac{1 - \cos\theta_{HH}}{\sigma_{\cos\theta_{HH}}} \right)^2$$

Analysis Strategy - Chi^2