TECHNISCHE UNIVERSITÄT DRESDEN

TOHOKU UNIVERSITY

High Energy Accelerator Experiments Group Tohoku University

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

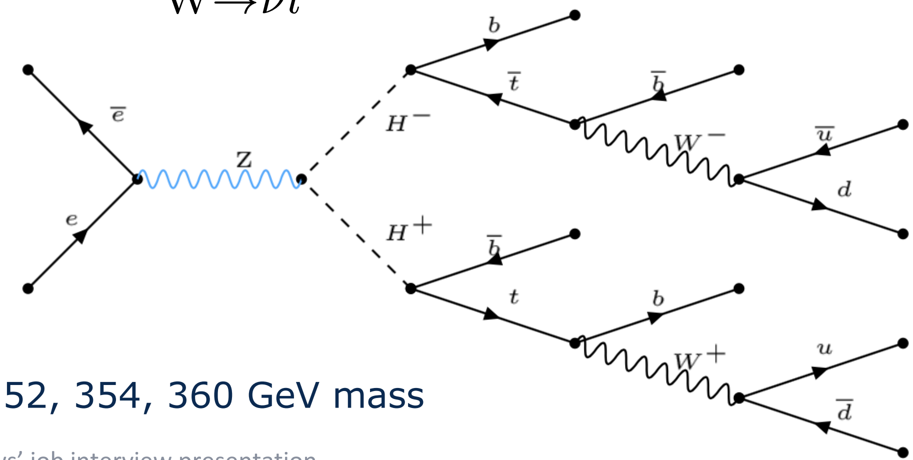
Presentation by Christian Drews

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

Overview

- Full simulation study of ILC/ILD
- $m_{H\pm}$ = 350 GeV   cross section = 9 fb   BR(H±→bt) = 90%
- E^+e^- -> H^+H^- -> tb tb -> Wbb Wbb $\xrightarrow{W\rightarrow 2\ \mathrm{jets}}$ 8 jets (hadronic)

  Wbb Wbb $\xrightarrow[W\rightarrow \nu l]{W\rightarrow 2\ \mathrm{jets}}$ 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
  - Samples with 340, 346, 348, 350, 352, 354, 360 GeV mass



Neutrino four momentum

- 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?
- 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 momentum

- Missing Momentum Method (MMM)
  - Using momentum form MEM for energy estimation

$$p_{\nu,\mathrm{MMM}} = (|\vec{p}_{\nu,\mathrm{MEM}}|, \vec{p}_{\nu,\mathrm{MEM}})$$

- Missing Tranversal Momentum Method (MTMM)
  - Using only the momentum in transversal momentum

$$\frac{m_{\mathrm{W}}^2}{2} = E_\nu E_\ell - \vec{p_\nu}\vec{p_\ell} = E_l\sqrt{p_{\nu x}^2 + p_{\nu y}^2 + p_{\nu z}^2} - p_{\nu x}p_{\ell x} - p_{\nu y}p_{\ell y} - p_{\nu z}p_{\ell z}$$

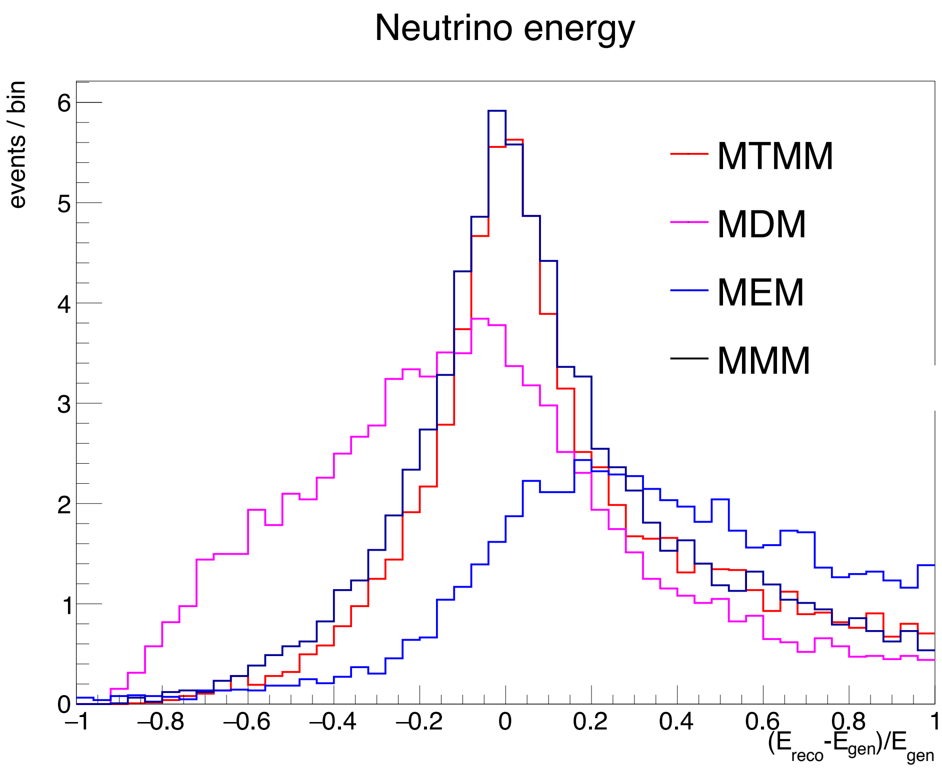
has two solutions

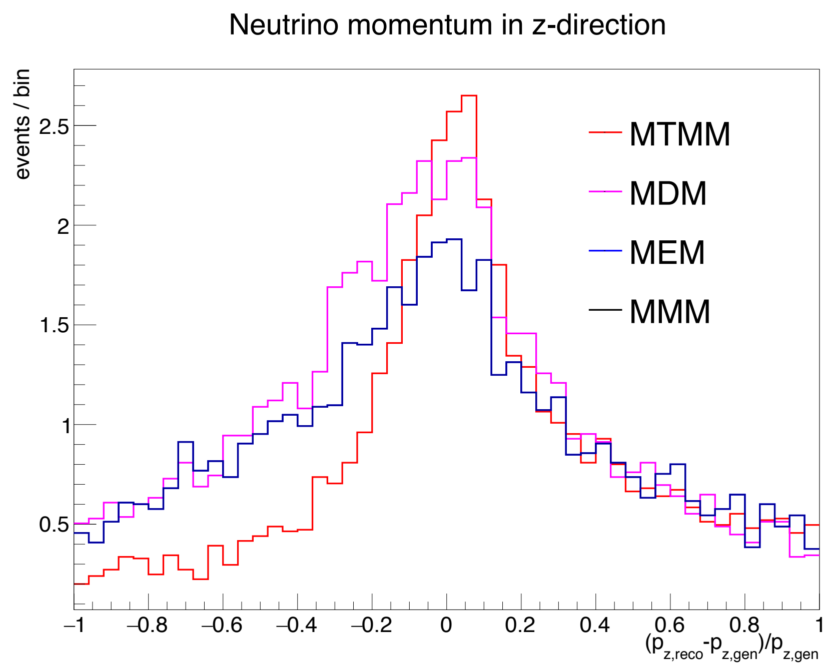
$$p_{\nu z} = \frac{\pm K + p_{\ell z}[2(p_{\ell y}p_{\nu y} + p_{\ell x}p_{\nu x}) + m_{\mathrm{W}}^2]}{2(p_{\ell x}^2 + p_{\ell y}^2)}$$

$$K = E_l\sqrt{4[(2p_{\ell x}p_{\nu x} + m_{\mathrm{W}}^2)p_{\ell y}p_{\nu y} - p_{\ell x}^2 p_{\nu y}^2 - p_{\ell y}^2 p_{\nu x}^2 + m_{\mathrm{W}}^2 p_{\ell x}p_{\nu x}] + m_{\mathrm{W}}^4}$$

Neutrino reconstruction

MTMM	Transversal momentum
MDM	Direction
MEM	Standard with missing energy
MMM	Only using momentum





Event selection

- Different event selections were used
  - Static cuts
  - BDT
- Optimizations
  - Signal significance
  - Significance for correctly paired signal (BDT + separate BDTG)

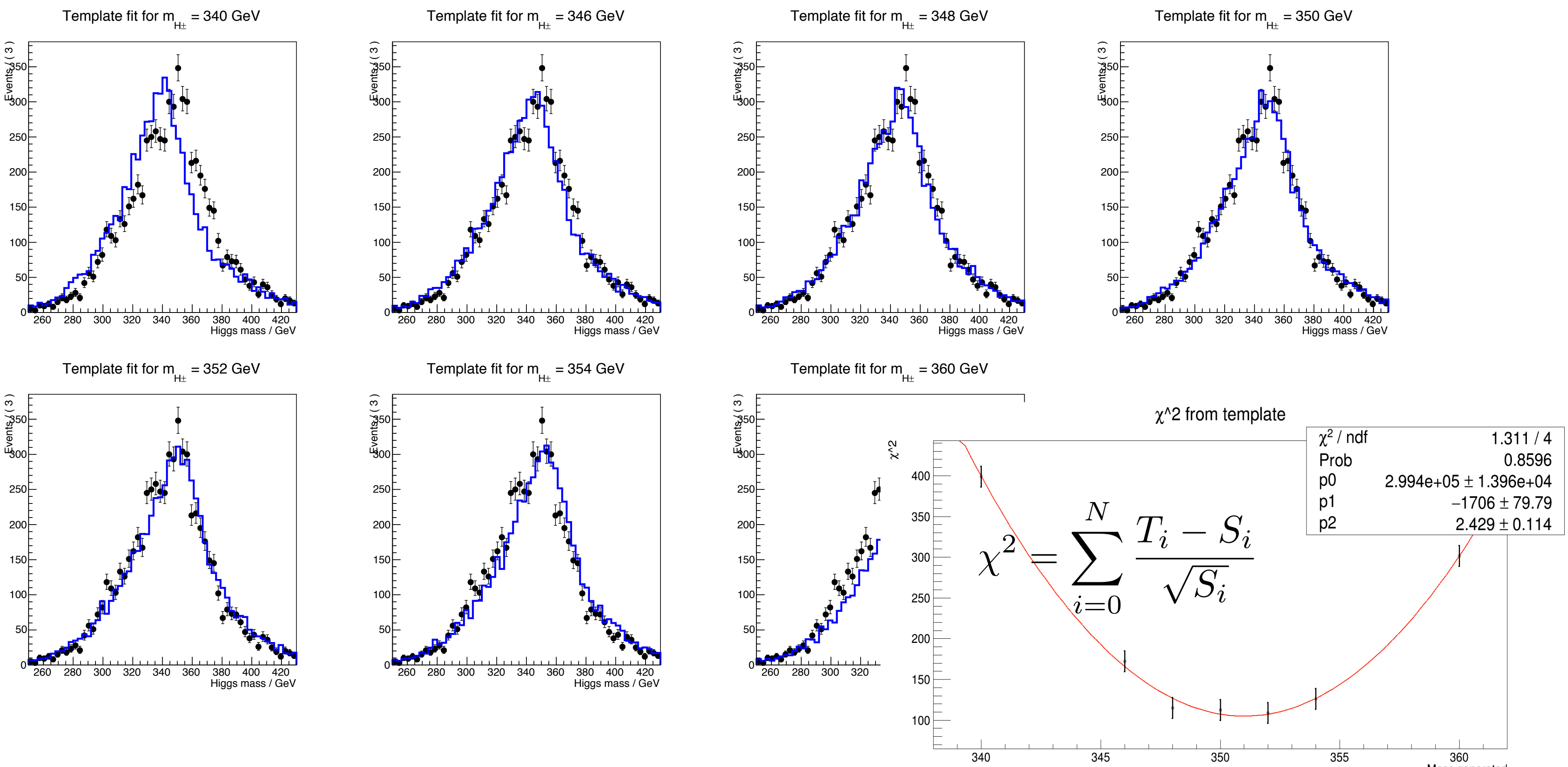
Cut type	Optim. type	Mode	Sig	o. Sig	Z(h)	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$(sl)	$t\bar{t}$(h)	$t\bar{t}h$(sl)	$t\bar{t}h$(h)	other
Static cuts		(h)	1982	46	0	138	106	454	16	200	12	0
Static cuts		(sl)	3090	586	139	208	181	95	678	53	327	26
Static cuts	corr. paired	(h)	579	699	0	50	61	112	2	103	4	0
Static cuts	corr. paired	(sl)	721	1154	0	46	54	12	122	12	121	0
BDT		(h)	2156	59	0	136	104	363	12	206	18	5
BDT		(sl)	3495	519	139	215	161	59	640	39	373	23
BDT	corr. paired	(h)	671	483	0	24	27	65	2	54	2	0
BDT	corr. paired	(sl)	865	936	0	18	30	5	63	4	69	0

Table 2.10: Remaining background after the event selections; (h) stands for hadronic and (sl) stands for semi-leptonic

Mass measurement

- Template method
  - Compare mass distribution shape -> calculation Chi^2
  - Get uncertainty from Chi^2 parabola
- Shape method
  - Get shape of BG, correctly paired signal and false paired signal
  - Calibrate fitted mean to Higgs mass
- Combined method
  - Reduce fitting variables to Higgs mass from cor. and false paired signal

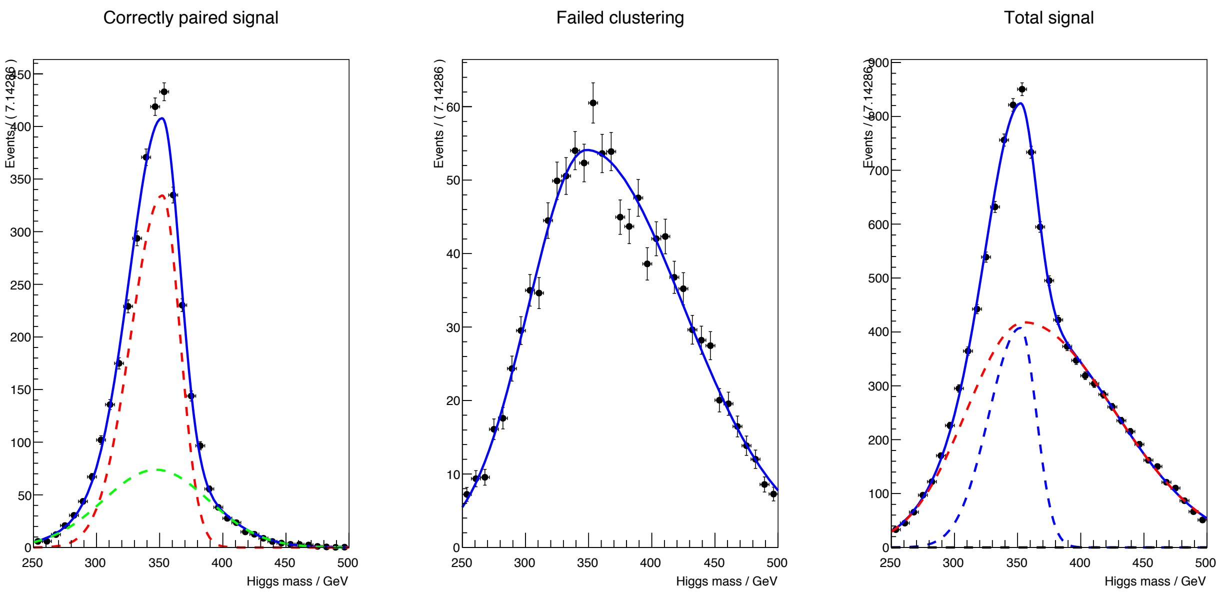
Template method



$$\chi^2 = \sum_{i=0}^{N} \frac{T_i - S_i}{\sqrt{S_i}}$$

Shape method

- Get signal shape (Static Cuts)



Static cuts

N_S (exp.) = 5491

Correctly paired: (24.5%):

μ: 352.1 GeV

σ_L: 24.8 GeV

σ_R: 12.8 GeV

Wrong paired (75.5%):

μ: 355.1 GeV

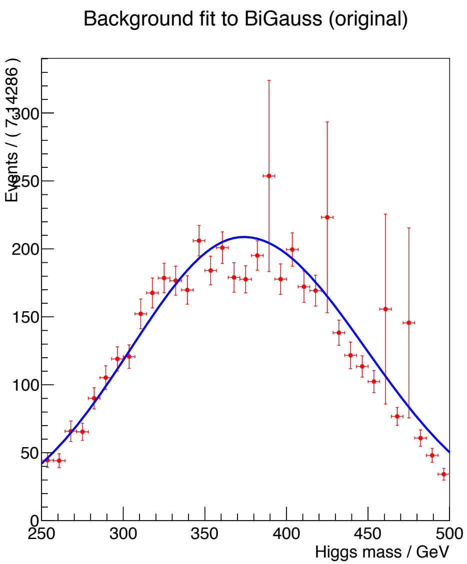
σ_L: 45.6 GeV

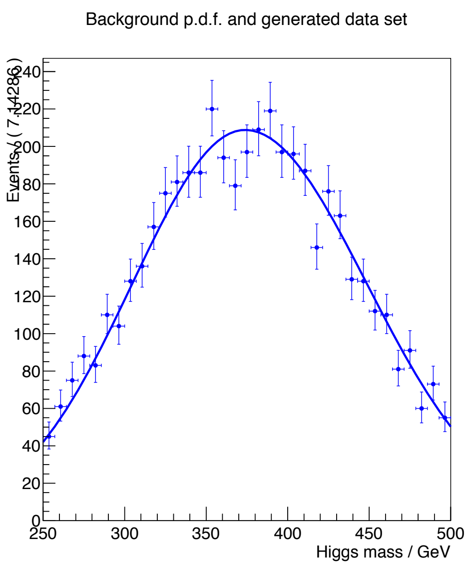
σ_R: 71.5 GeV

red. χ^2 = 2.05

Shape method

- Get background shape (Static Cuts)





Static cuts

N_B (exp.) = 2418

μ = 373.8 GeV

σ_L: 69.2 GeV

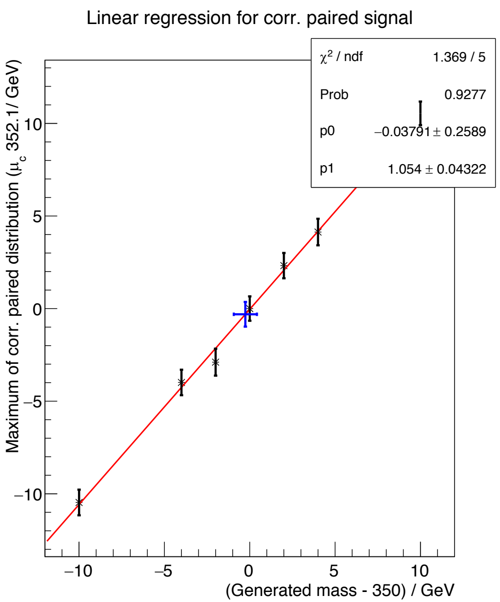
σ_R: 74.8 GeV

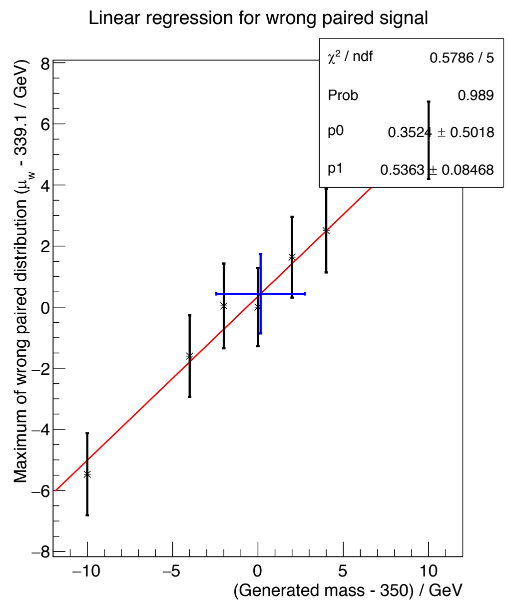
red. χ^2 (original BG) = 3.06

red. χ^2 (gen BG) = 0.96

Shape method – mass estimation (BDT – correctly paired)

- Linear regression for signal distribution maximum and generated mass
- Test data set (blue)





BDT correctly paired

$m_{c,H}$/GeV = 349.74 ± 0.68 (Corr. pairing)

$m_{w,H}$/GeV = 350.16 ± 2.59 (Wrong pairing)

$m_{a,H}$/GeV = 349.77 ± 0.66 (combined)

$m_{r,H}$/GeV = 349.83 ± 0.46 (reduced)

$\Delta_{c,const}$: 0.2456

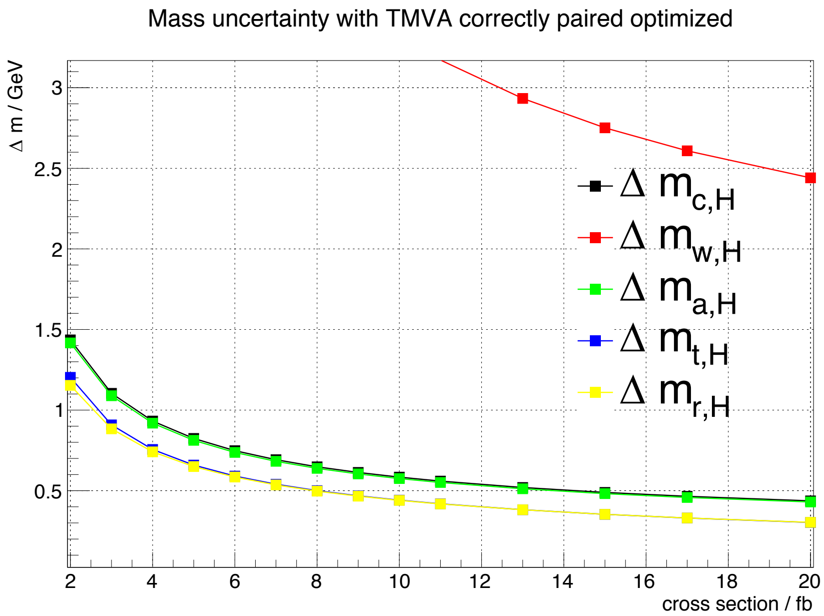
$\Delta_{c,linear}$: -0.012

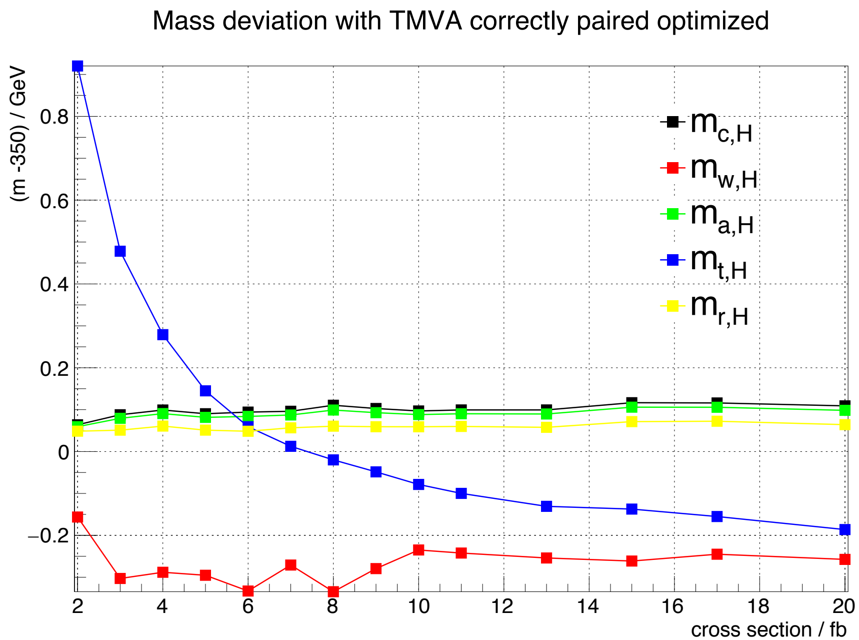
$\Delta_{c,fit}$: 0.6319

$m_{c,H}$/GeV = (1.05 ± 0.04) μ_c + (352.1 ± 0.26)

$m_{w,H}$/GeV = (0.54 ± 0.08) μ_w + (339.09 ± 0.5)

MC toy with varied cross section (BDT – correctly paired)

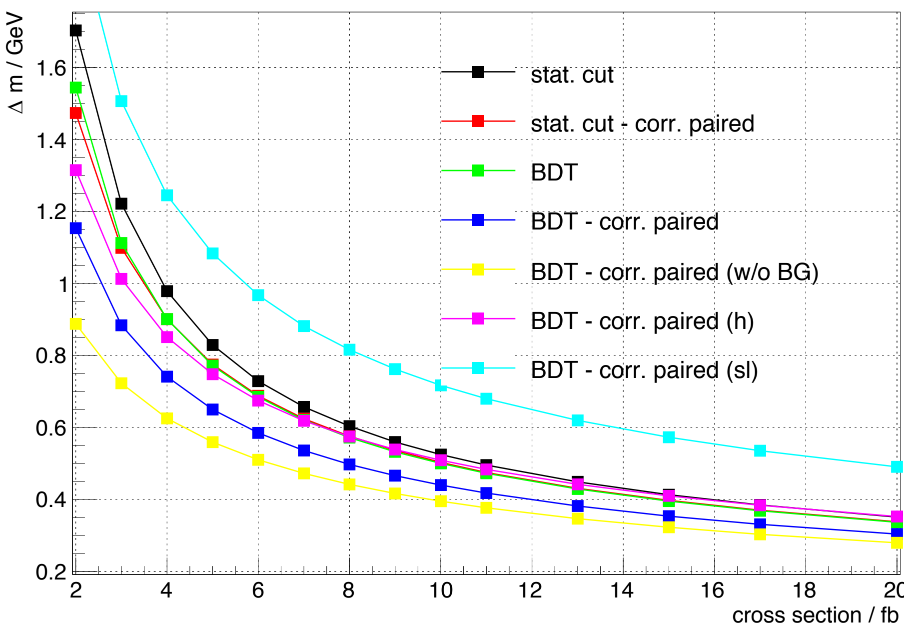




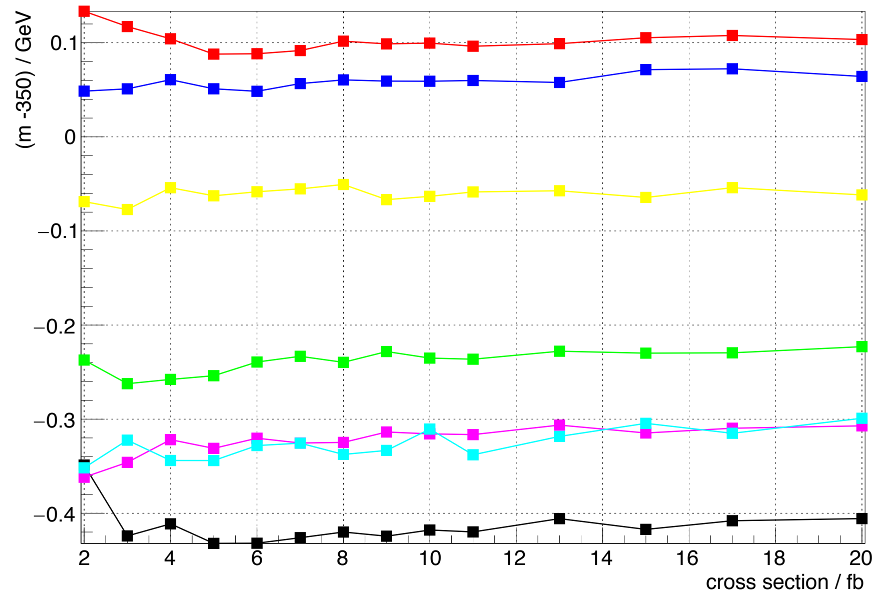
- Result from 10 000 toy MC

MC toy with varied cross section (BDT – correctly paired)

Mass uncertainty with reduced shape method



Mass deviation with reduced shape method



- Result from 10 000 toy MC

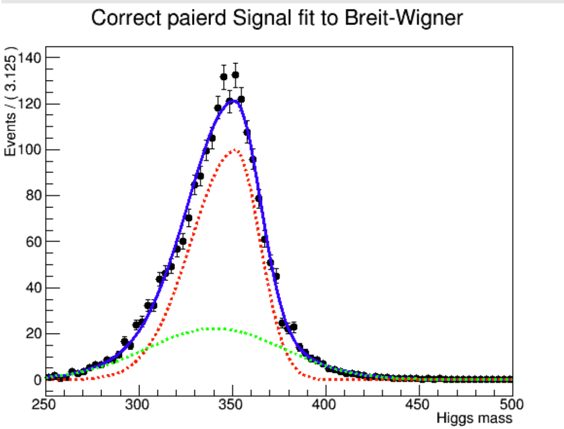
Result

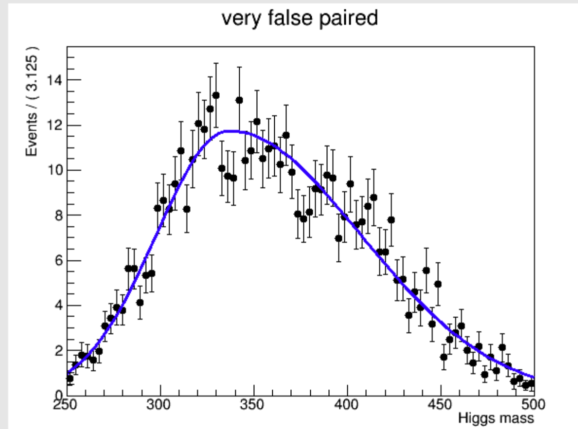
- 0.5 GeV mass precision
- Neutrino four momentum reconstruction with Missing Momentum Method was used
- Missing Transversal Momentum Method has great potential

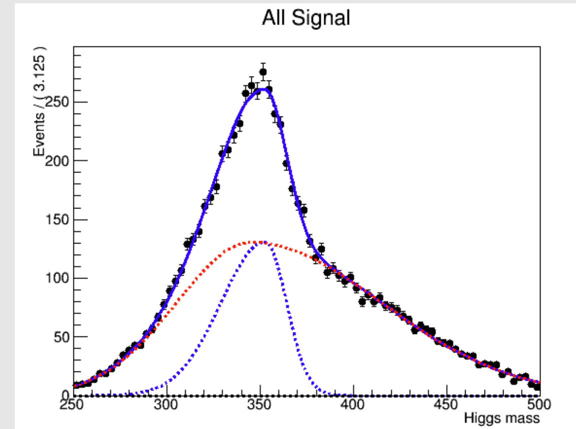
Cut type	Optim. type	Mode	Signif.	Corr. pair Signif.	Effi.	Purity	mass precision with $\sigma = 9$ fb
Static cuts		hadronic	44.6	17.9	65 %	64 %	0.56 GeV
Static cuts		semi-lep.	36.5	17.3	43 %	67 %	
Static cuts	corr. paired	hadronic	37.2	21.9	62 %	66 %	0.54 GeV
Static cuts	corr. paired	semi-lep.	31.5	19.0	55 %	63 %	
BDT		hadronic	49.1	20.9	73 %	67 %	0.53 GeV
BDT		semi-lep.	38.6	19.4	46 %	71 %	
BDT	corr. paired	hadronic	38.5	26.6	74 %	82 %	0.47 GeV
BDT	corr. paired	semi-lep.	31.5	23.0	64 %	79 %	

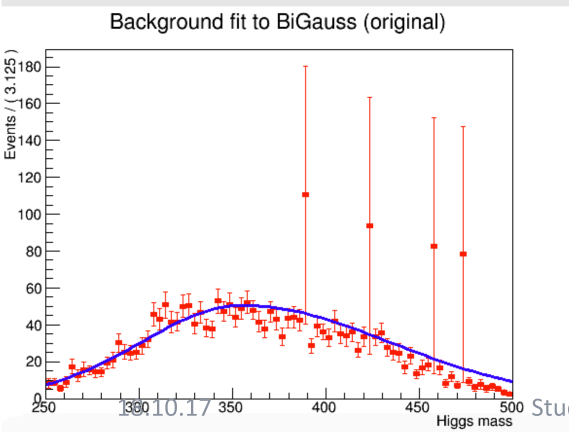
Backup

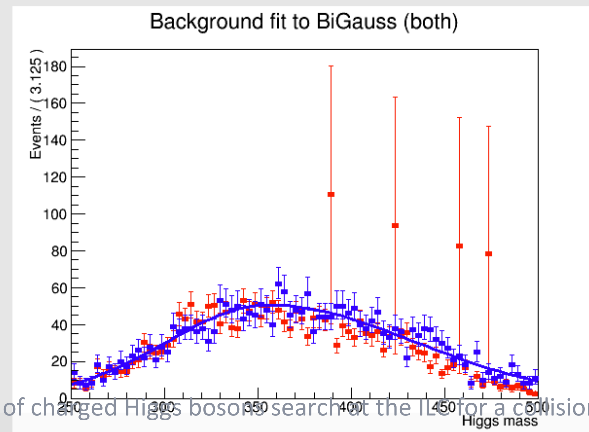
Static cuts











no cut m_H1/m_H2

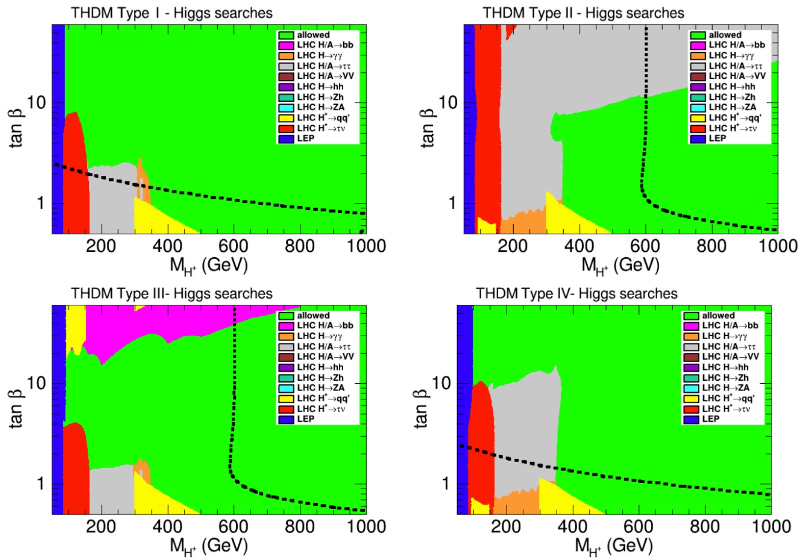
χ^2 (cor. pair) = 0.0

χ^2 (false pair) = 1.17941674959

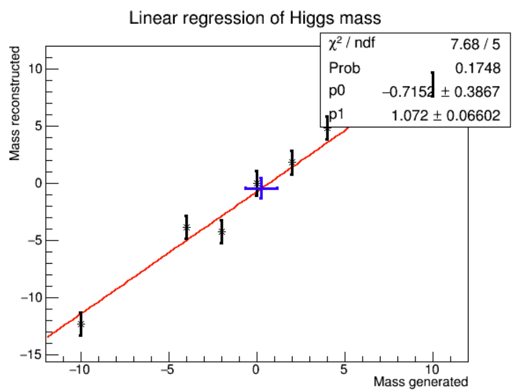
χ^2 (all signal) = 1.32537570011

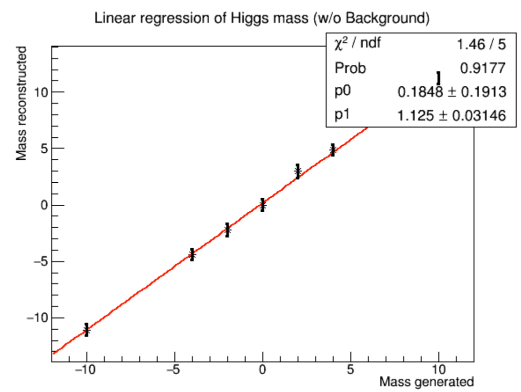
χ^2 (original BG) = 4.59289973065

χ^2 (gen BG) = 1.1154077007


THDM Type I - Higgs searches
THDM Type II - Higgs searches
THDM Type III- Higgs searches
THDM Type IV- Higgs searches
allowed
LHC H/A→bb
LHC H→γγ
LHC H/A→ττ
LHC H/A→VV
LHC H→hh
LHC H→Zh
LHC H→ZA
LHC H±→qq'
LHC H±→τν
LEP
tan β
M_{H±} (GeV)

Static cuts





mean_test: (340.50544556077364, 0.8972169561338035)

m_H_test: 350.256557321 ± 0.911446596581

m_H_test: 351.780104696 ± 4.91384948219 (False pairing)

m_H_test: 351.018331008 ± 0.644490069132 (combined)

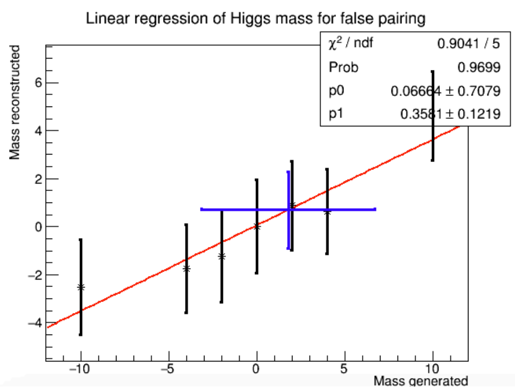
Δ_{const}: 0.360645772729

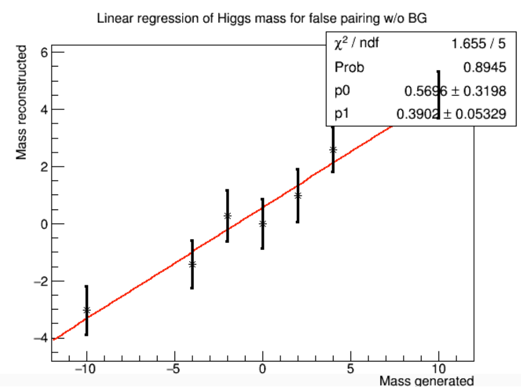
Δ_{linear}: -0.0252633508819

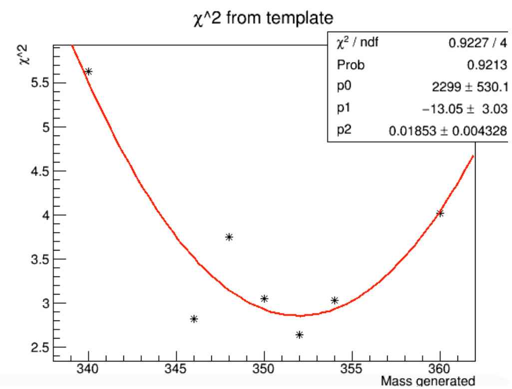
Δ_{fit}: 0.836678724561

b: 1.0723554093 ± 0.0660187568936

a: -0.71516969819 ± 0.386740445229



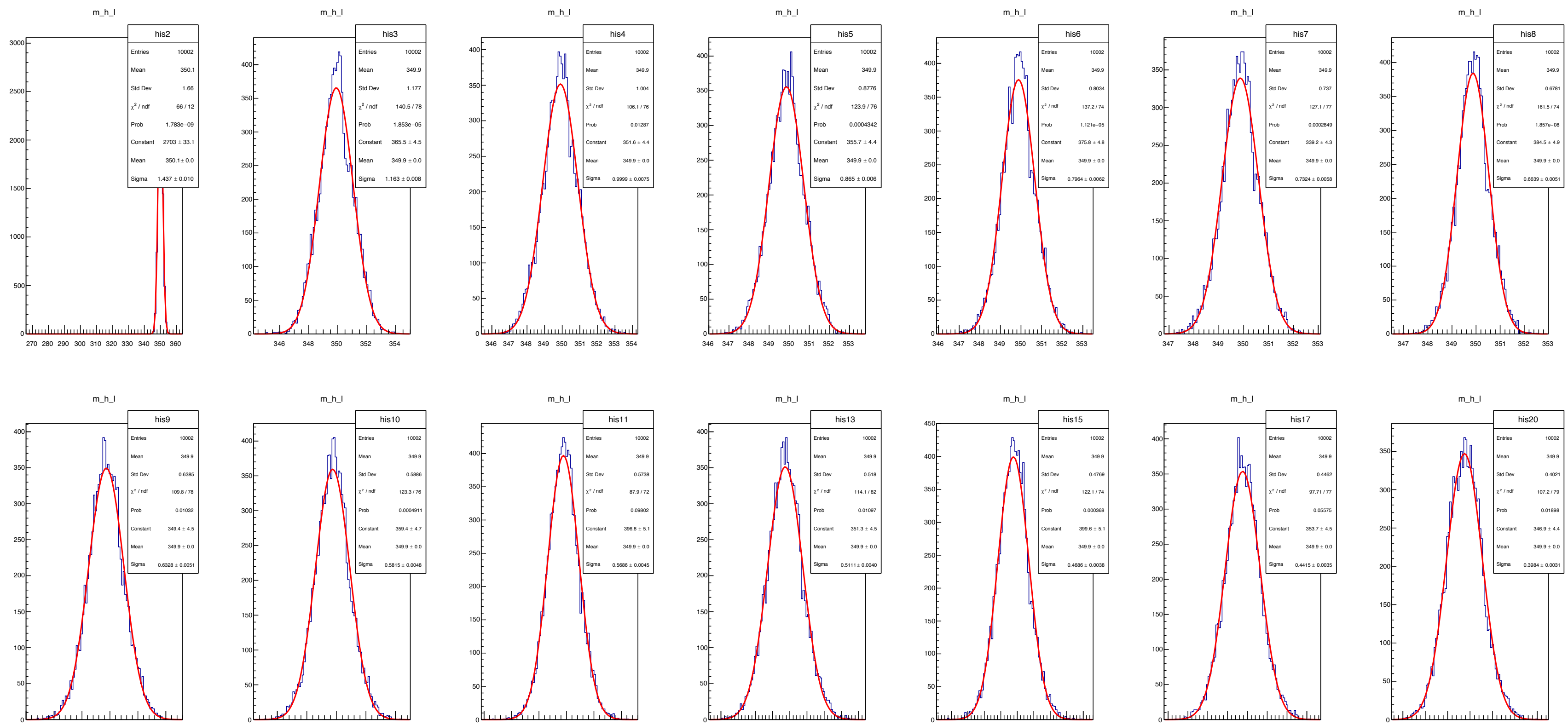




TECHNISCHE UNIVERSITÄT DRESDEN

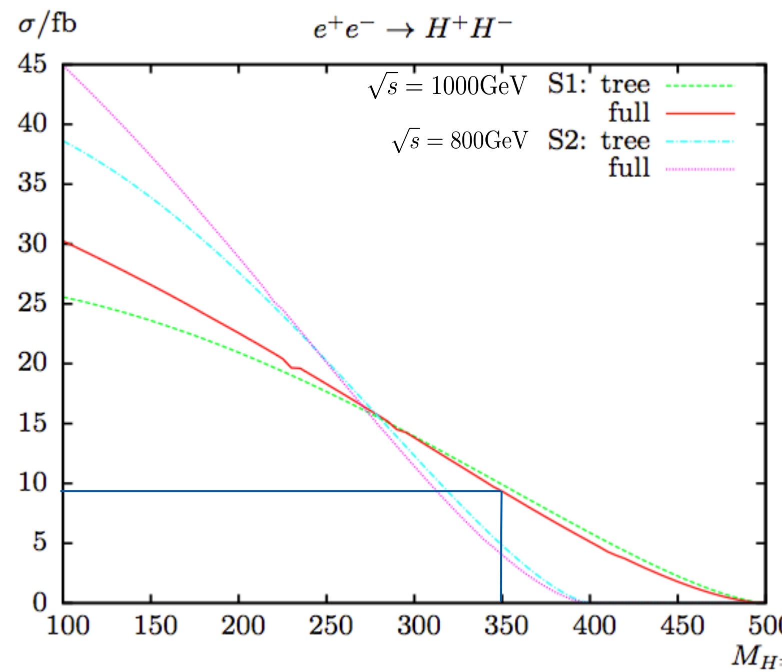
TOHOKU UNIVERSITY

MC toy with varied cross section



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 –> eν) = 10.75
- BR(W –> eν) = 10.57
- Hadronic: 5100 events
- Semileptonic: 3200 events

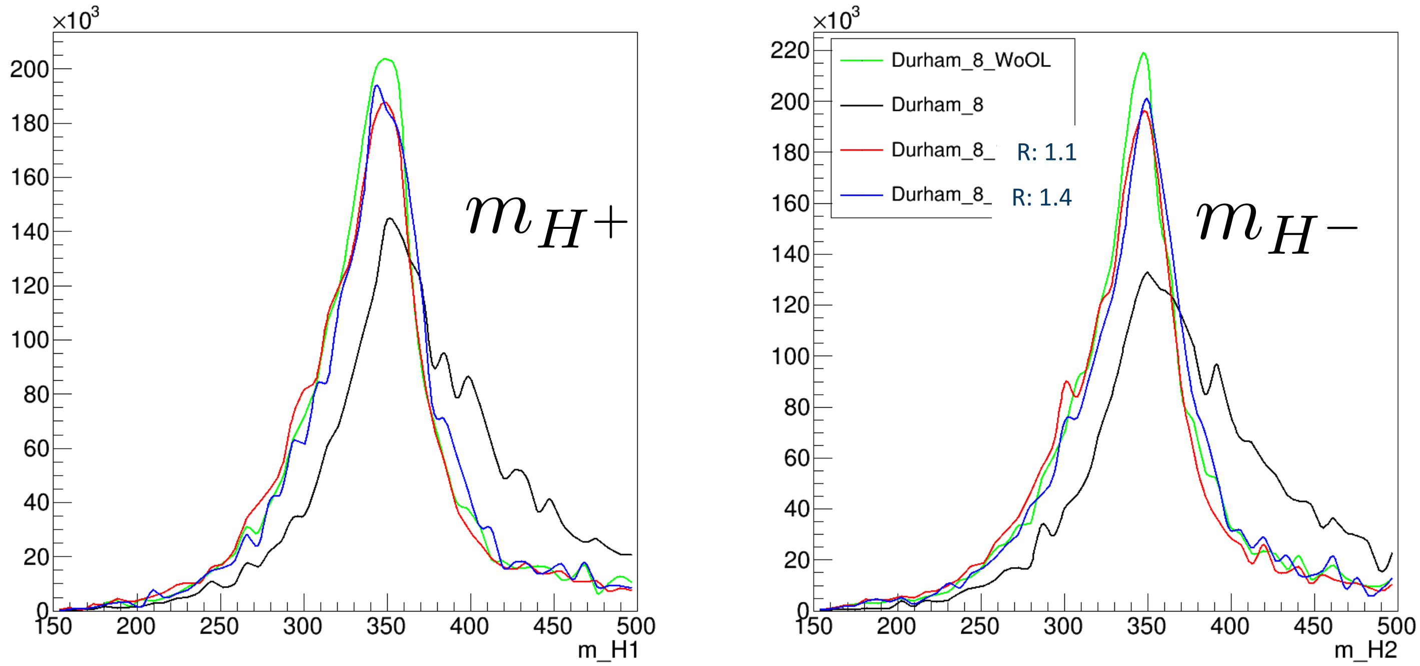


Source: ***Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis***
Heinemeyer, S. and Schappacher, C. Eur. Phys. J. (2016)

Analysis Overview

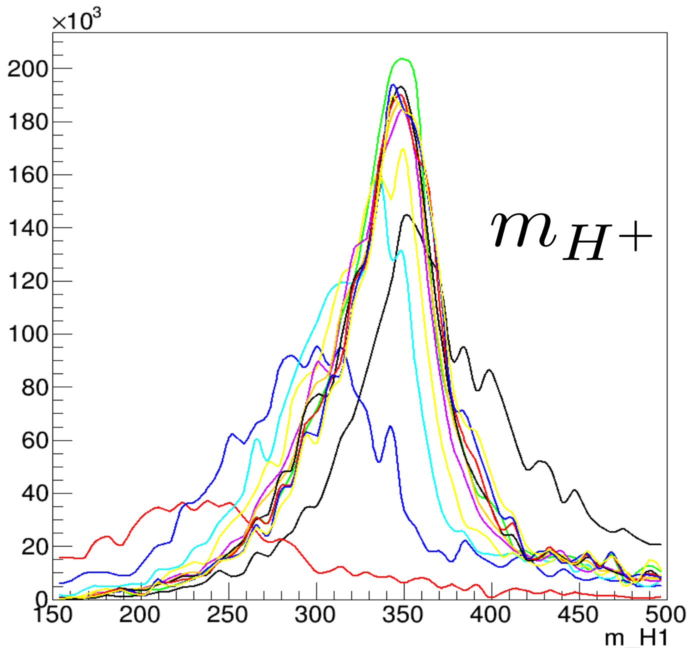
- Isolated Lepton selection
- Reduce beam background by kt-Algorithm
- Jet-clustering and flavor tagging (LCFIplus)
- Calculating neutrino four-momentum (only semi-leptonic)
- Jet-pairing
- Extracting signal and background mass shape
- Added fit to find Higgs-mass

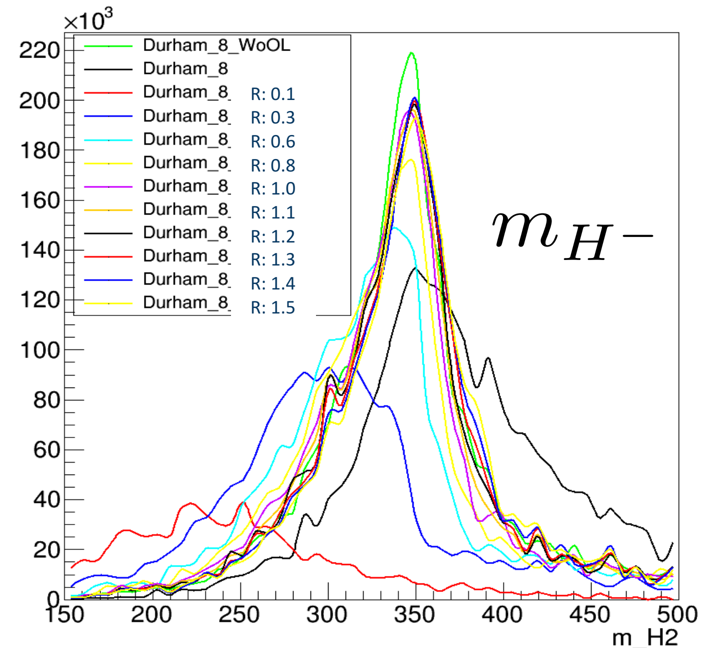
Find R for kt-Algorithm



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 MarilnReco
  - 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

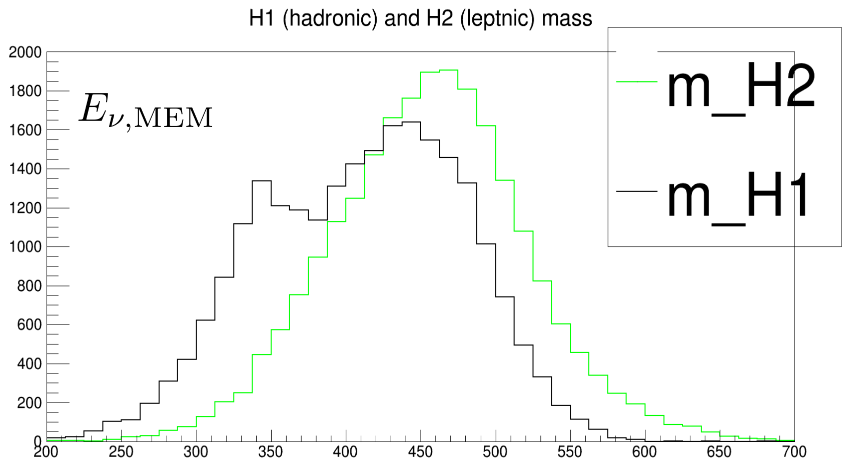
$$E_{\nu,\text{NDM}} = \frac{m_W^2}{E_l(1-\alpha)} \qquad \alpha = \frac{\vec{p}_{\nu,\text{MEM}} \cdot \vec{p_l}}{|\vec{p}_{\nu,\text{MEM}}||\vec{p_l}|}$$

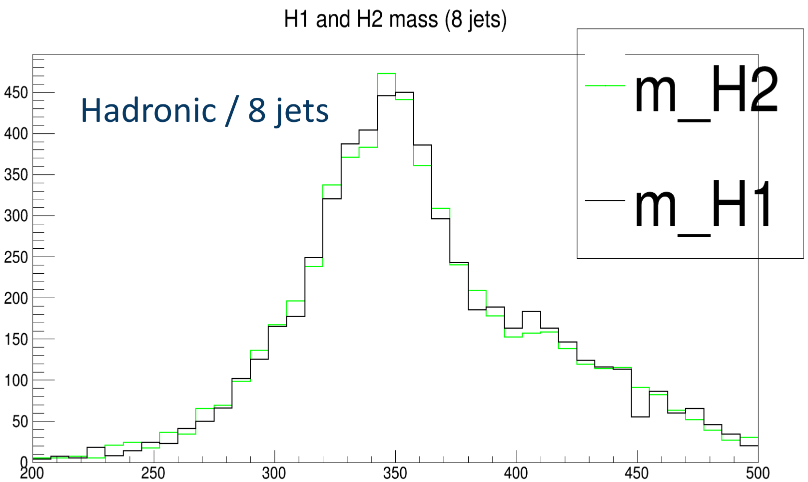
$$p_{\nu,\text{NDM}} = (E_{\nu,\text{NDM}}, E_{\nu,\text{NDM}} \frac{\vec{p}_{\nu,\text{MEM}}}{|\vec{p}_{\nu,\text{MEM}}|})$$

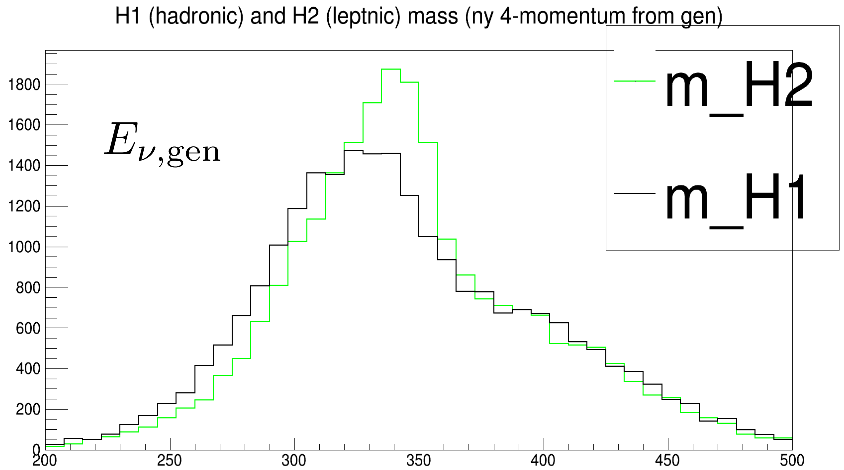
Higgs mass reconstructed with Jet pairing

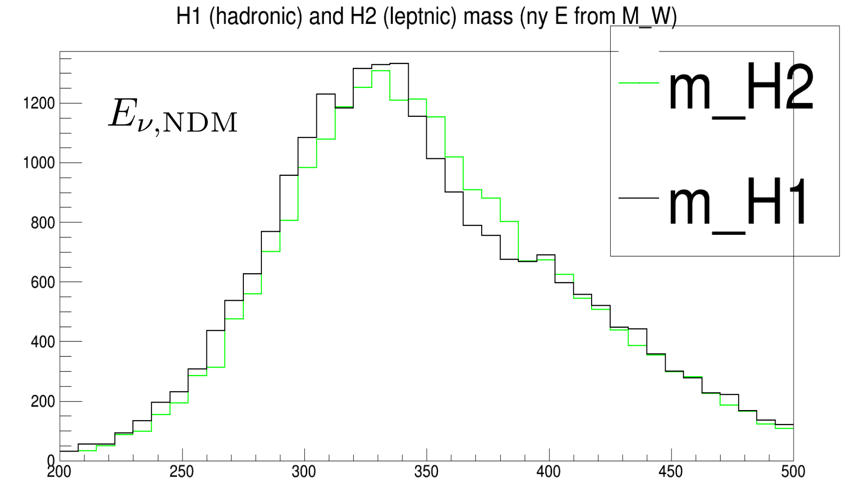
- Chi^2 minimization method

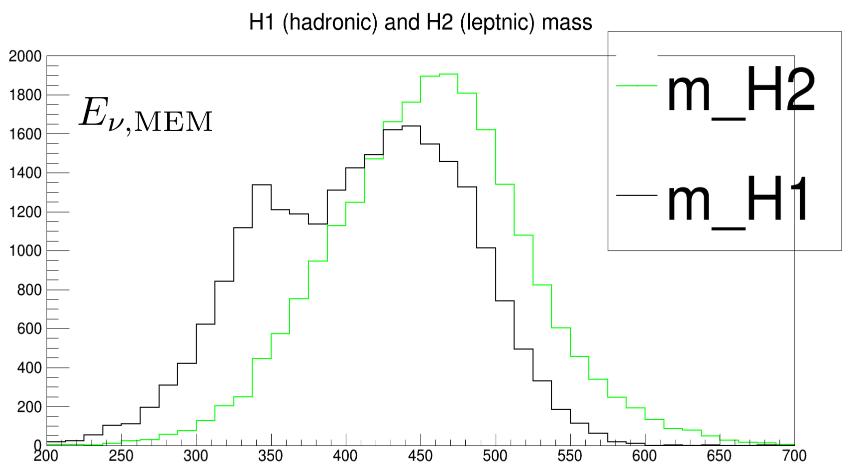
$$\chi^2 = \left|\frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma_{H^+}^2}\right| + \left(\frac{m_{j_2j_3j_4} - M_t}{\sigma_t}\right)^2 + \left(\frac{m_{j_6j_7j_8} - M_t}{\sigma_t}\right)^2 + \left(\frac{m_{j_3j_4} - M_W}{\sigma_W}\right)^2 + \left(\frac{m_{j_7j_8} - M_W}{\sigma_W}\right)^2$$

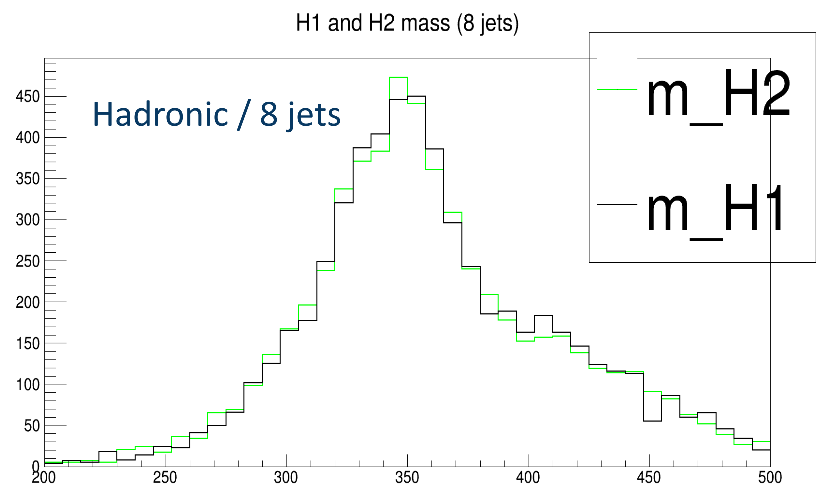




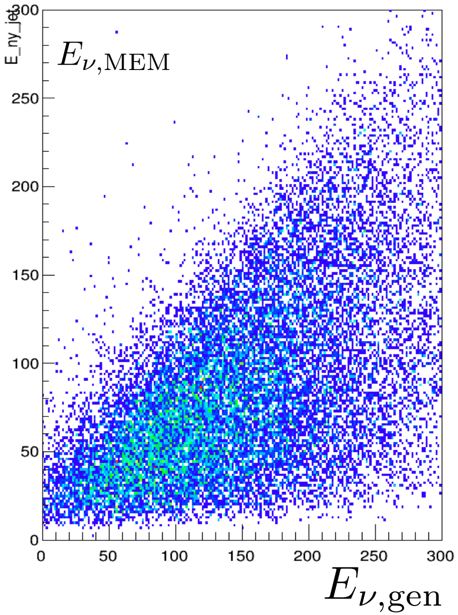

H1 (hadronic) and H2 (leptnic) mass (ny 4-momentum from gen)
m_H2
m_H1
$E_{\nu,\mathrm{gen}}$

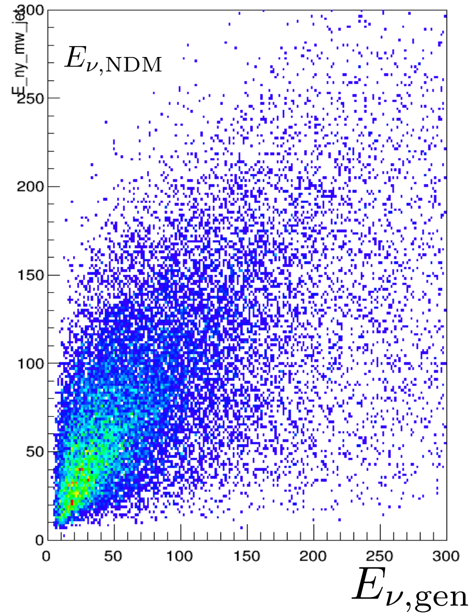

H1 (hadronic) and H2 (leptnic) mass (ny E from M_W)
m_H2
m_H1
$E_{\nu,\mathrm{NDM}}$


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

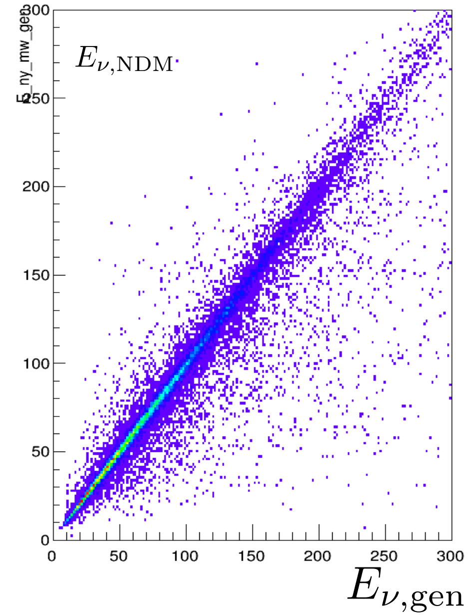

H1 and H2 mass (8 jets)
m_H2
m_H1
Hadronic / 8 jets

Neutrino Four-vector



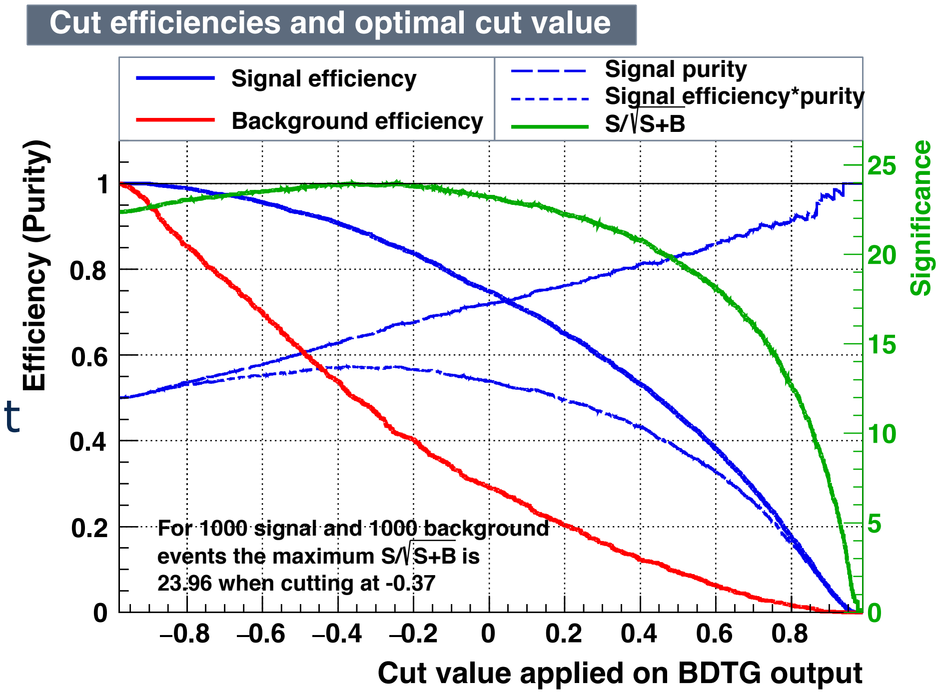


Neutrino direction from Generator



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

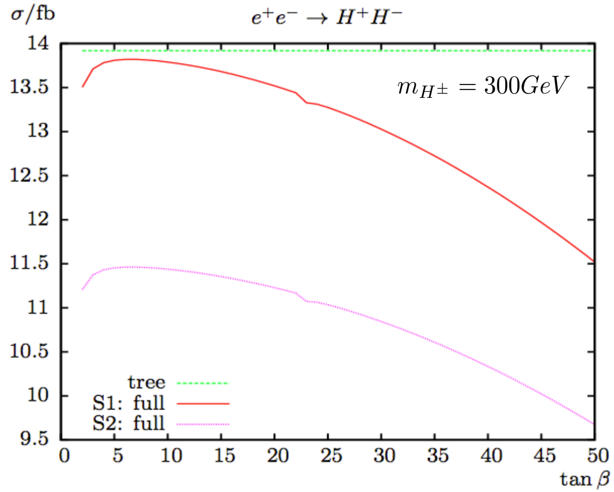


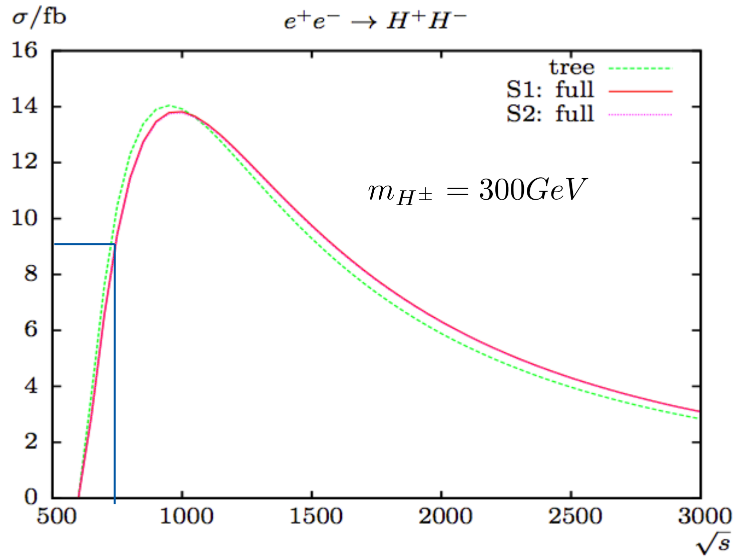
Plan

- 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

Cross section

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

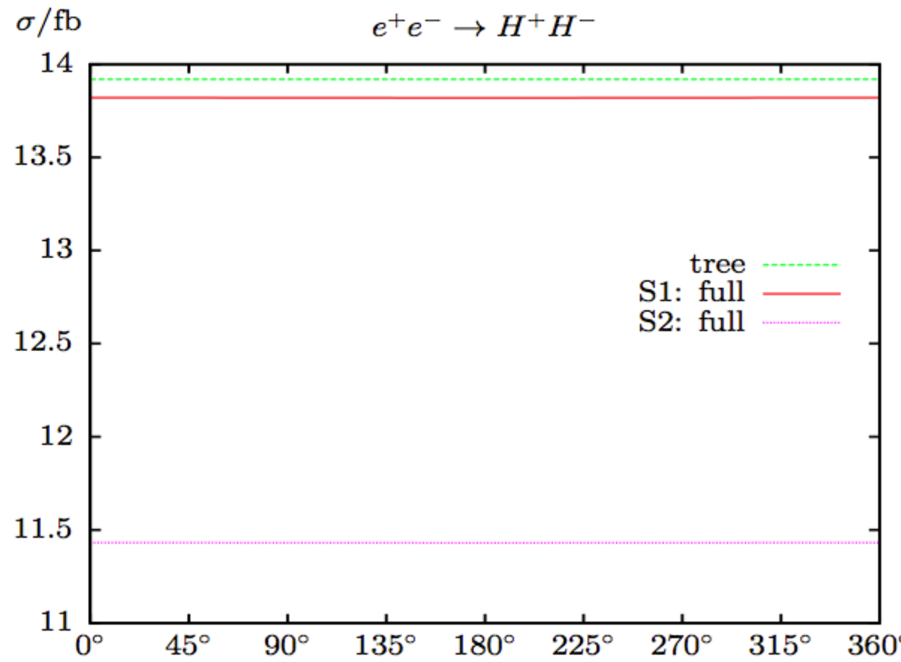




Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
S1	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500
S2	800	4	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

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)

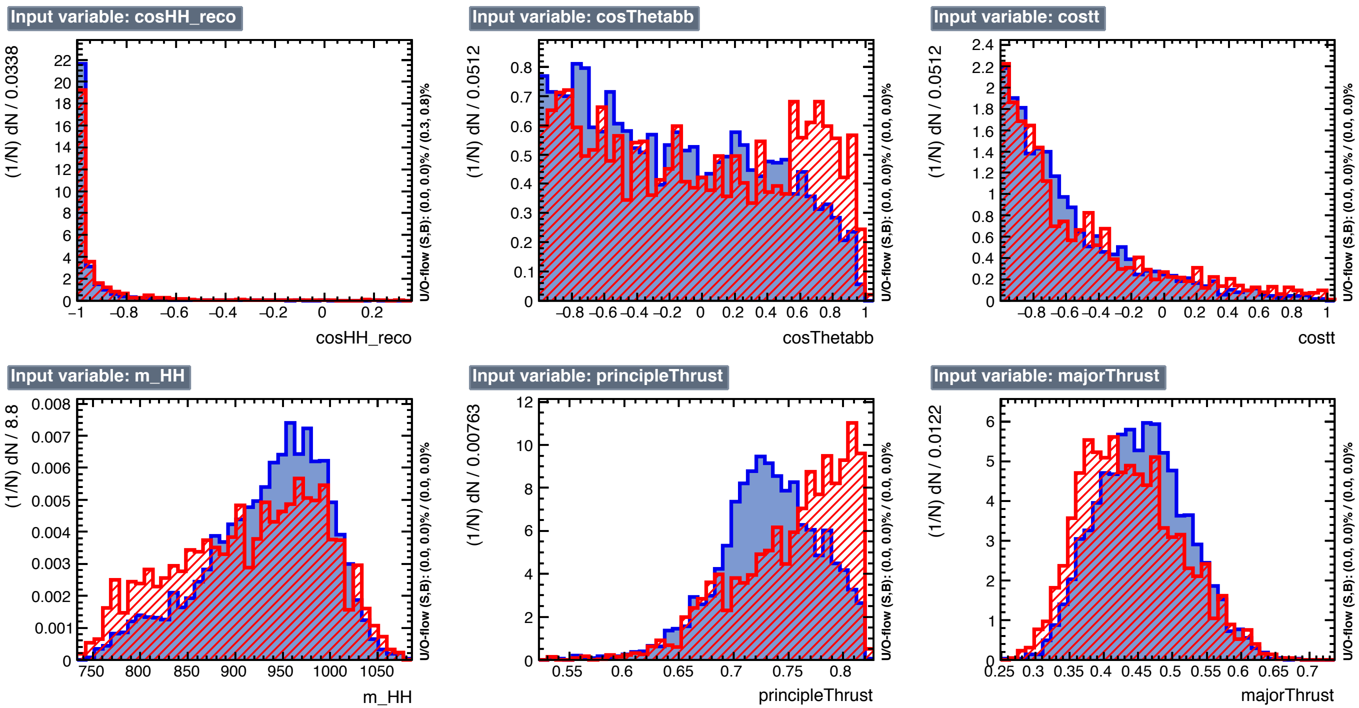
Cross section



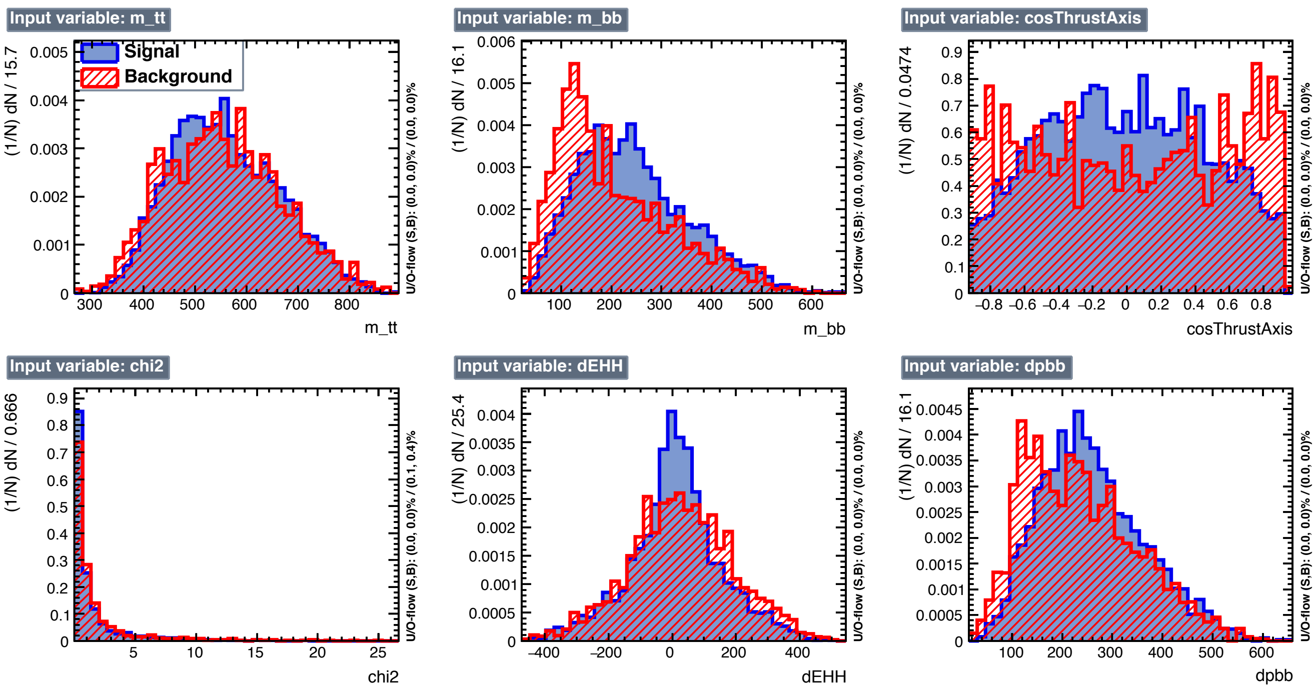
Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
S1	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500
S2	800	4	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

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)

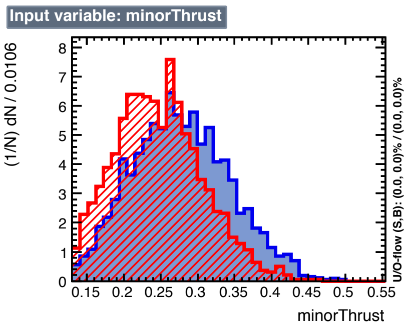
Boosted Decision Tree (Input)

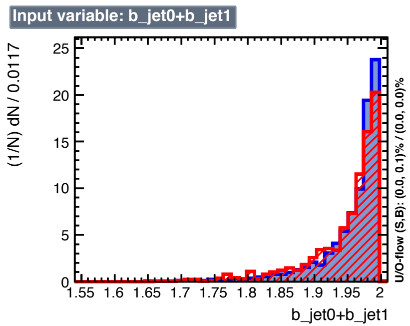


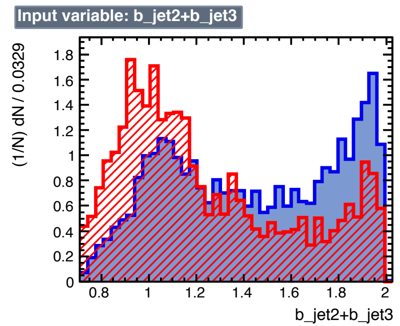
Boosted Decision Tree

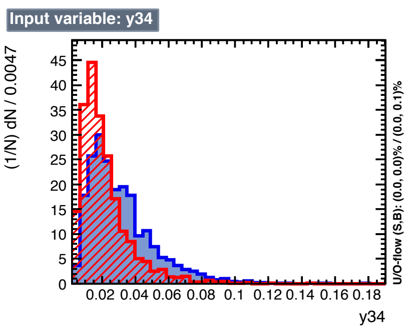


Boosted Decision Tree



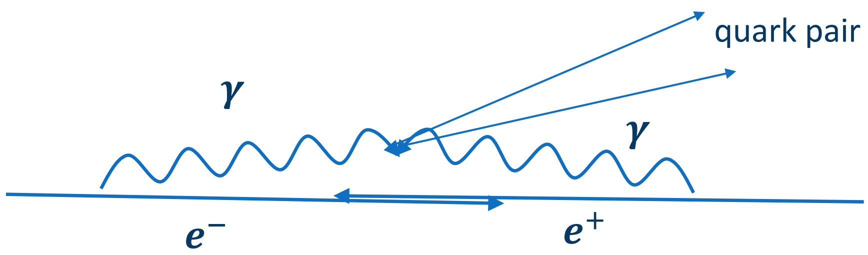






Analysis Strategy – Beam Background

- 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

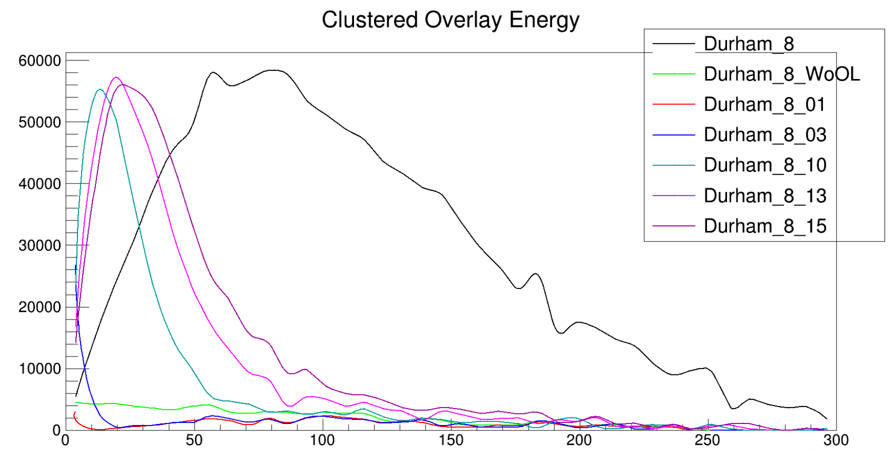
- Find smallest d_{ij}
- If $d_{ij} < d_{iB} = p_{Ti}^2$ merge tracks, if not remove Track (B: Beam)
  - Remo$i$ve particles that are closer to the beam than to the closest track
- Continue to step one until there are only the requested number of jets

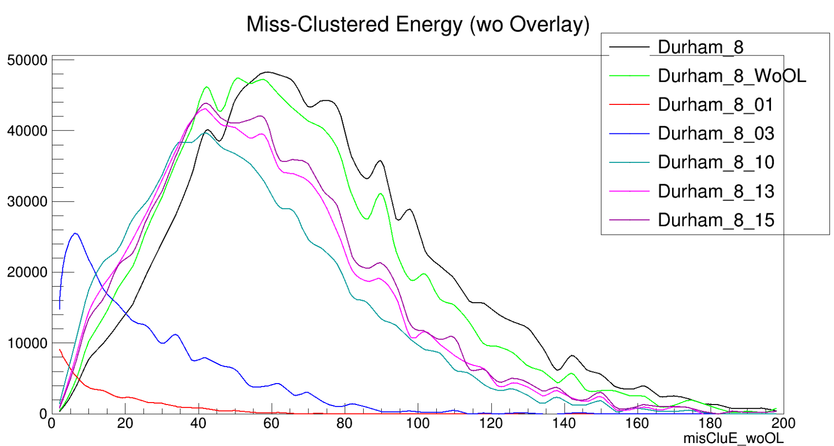
Choose R for kt algorithm

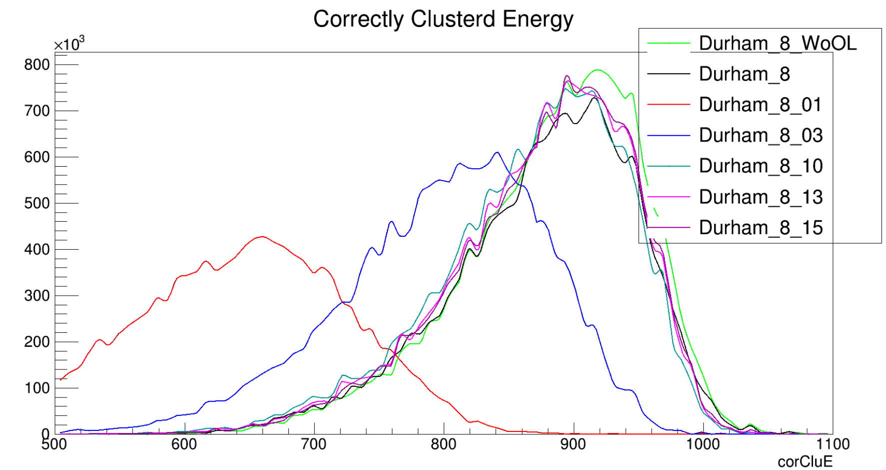
Durham_8: w/o correction

Durham_8_WoOL: overlay removed by generator information

Durham_8_13: R = 1.3

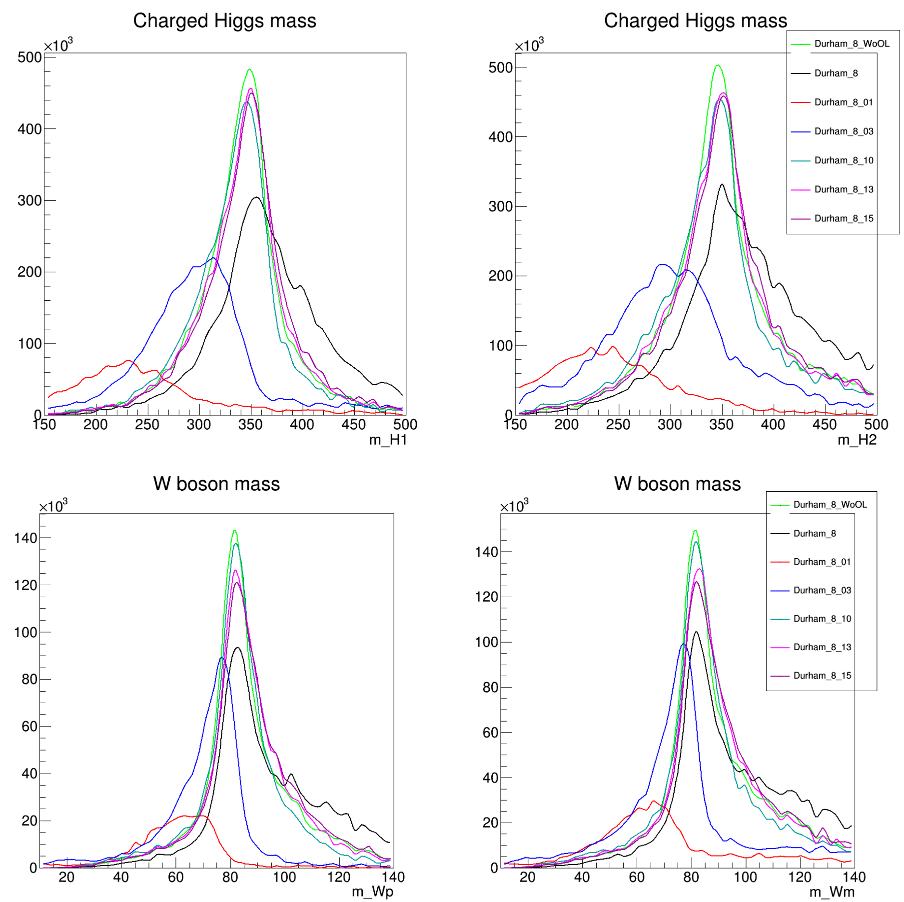


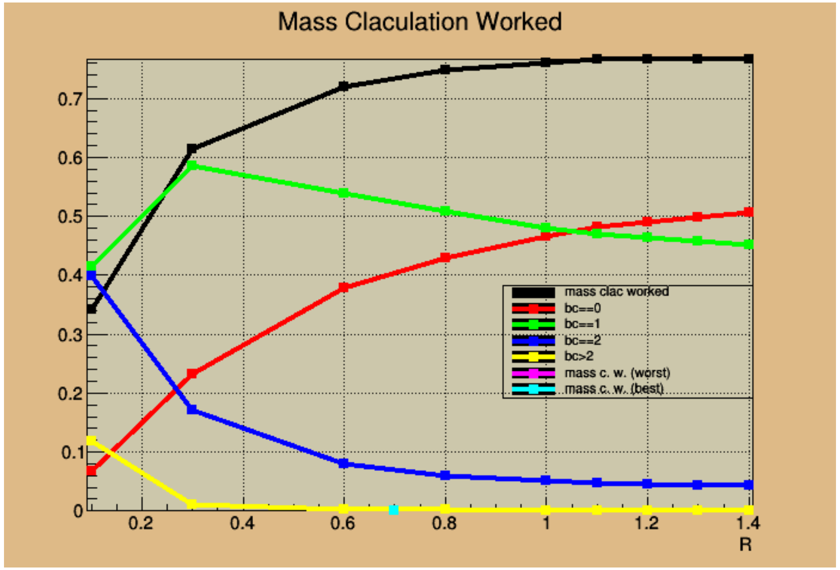


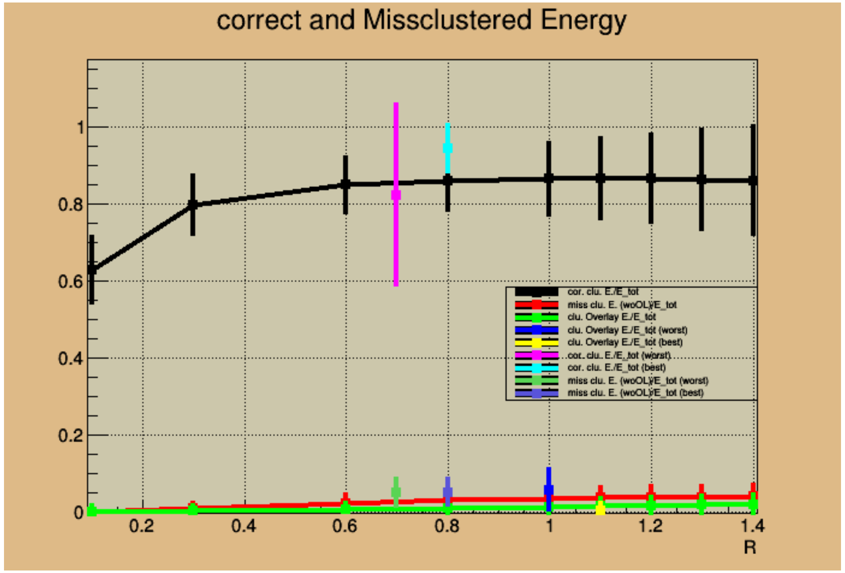


Choose R for kt algorithm

- 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
mass clac worked
bc==0
bc==1
bc==2
bc>2
mass c. w. (worst)
mass c. w. (best)
R


correct and Missclustered Energy
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)
R

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

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

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

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

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 %

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

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

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

Analysis Strategy - Chi^2