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

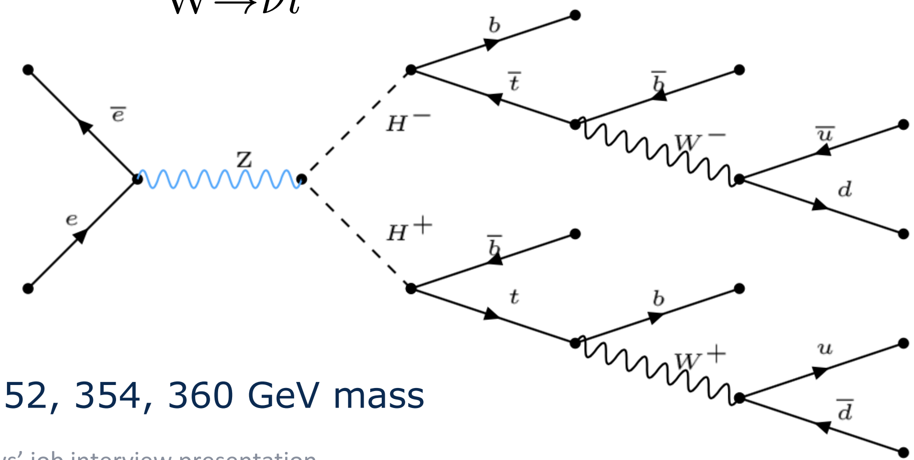
Presentation by Christian Drews

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 $\xrightarrow{W\to 2\text{ jets}}$ 8 jets (hadronic)

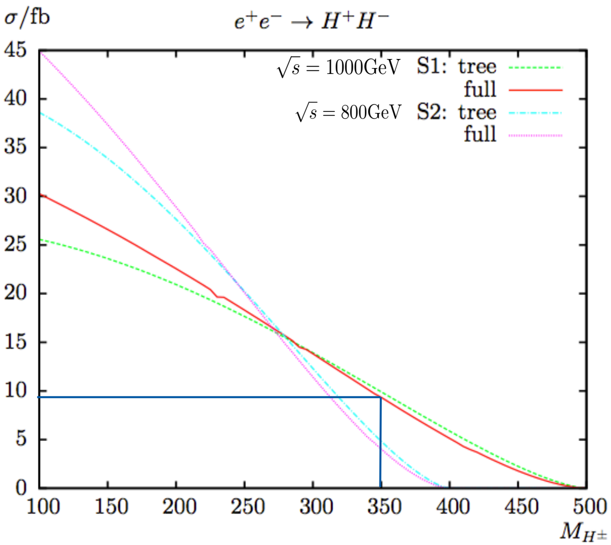
  Wbb Wbb $\xrightarrow[W\to\nu l]{W\to 2\text{ jets}}$ 6 jets + lepton (semi-lep.)
- Major background:
  - ttH/ttZ/ttg -> ttbb
  - tt -> bWbW
  - HA -> bbbb (SUSY)
  - H/A -> tt at resonance
  - Ignoring SUSY background



- Goal: $m_{H\pm}$ meassurment
  - Samples with 340, 346, 348, 350, 352, 354, 360 GeV mass

Cross section

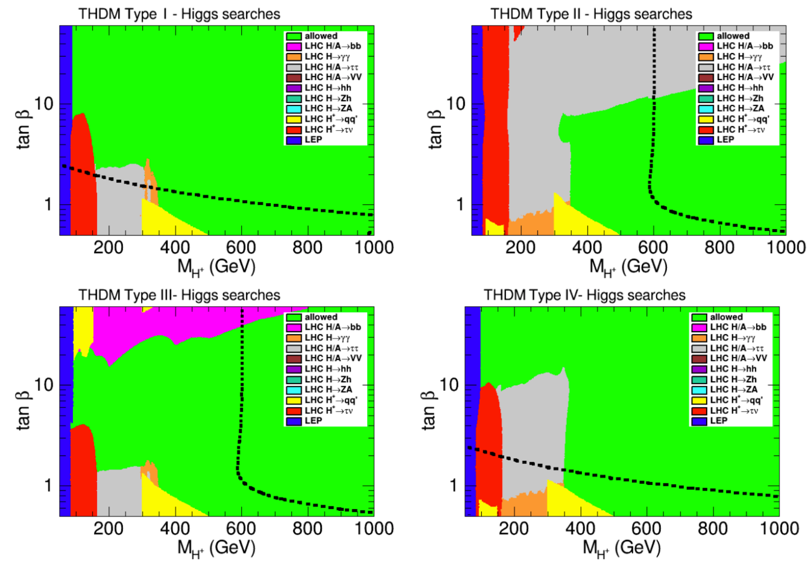
- $\sigma \approx$ 9 fb with P = (-80%,20%) 10.4 fb
- $\mathcal{L}$ = 1000 1/fb
- Hadronic: 5100 events
- Semileptonic: 3200 events



- MSSM excluded
- Brought parameter space allowed

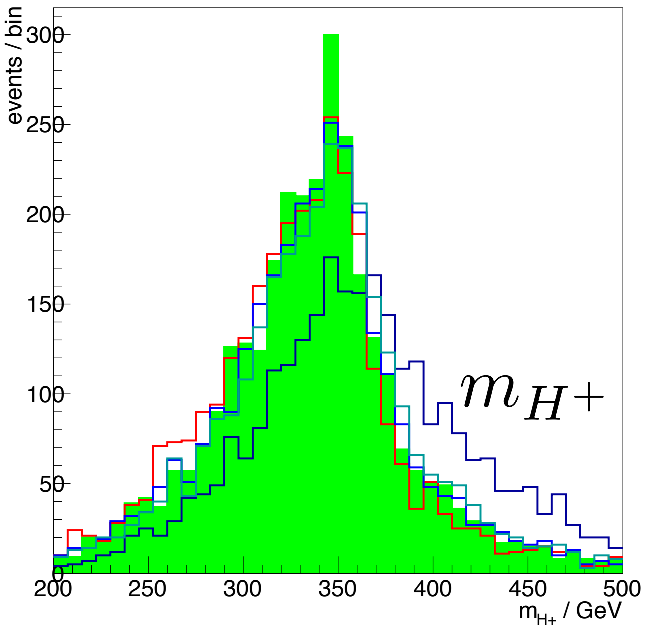
Allowed parameter space

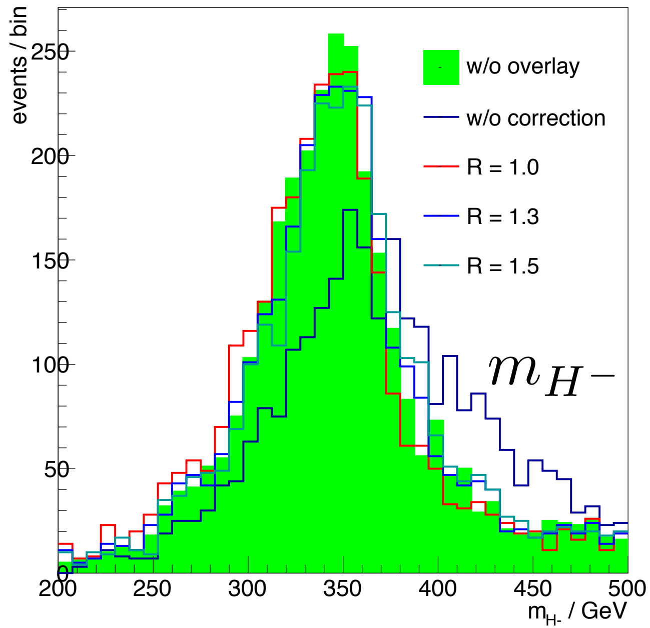
Source: A. Arbey et al. “**Status of the Charged Higgs Boson in Two Higgs Doublet Models**.” In: (2017). arXiv: 1706.07414 [hep-ph].



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)

Beam background reduction with kt-Algorithm





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

R chosen to be 1.3

Jet pairing

- Jet pairing with chi squared minimization
  - j_1, j_2, j_3 and j_4 – jets with highest b-tag
  - For semi-leptonic: j_7 and j_8 are neutrino and lepton

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

	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

Neutrino four momentum

- Missing-Energy-Method (MEM)

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

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

  - Standard for most studies
- Missing-Direction-Method (MDM)
  - Using the Direction of Missing-Energy-Method and calculation the Enerty by fixing W-Mass

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

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

Neutrino four momentum

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

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

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

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

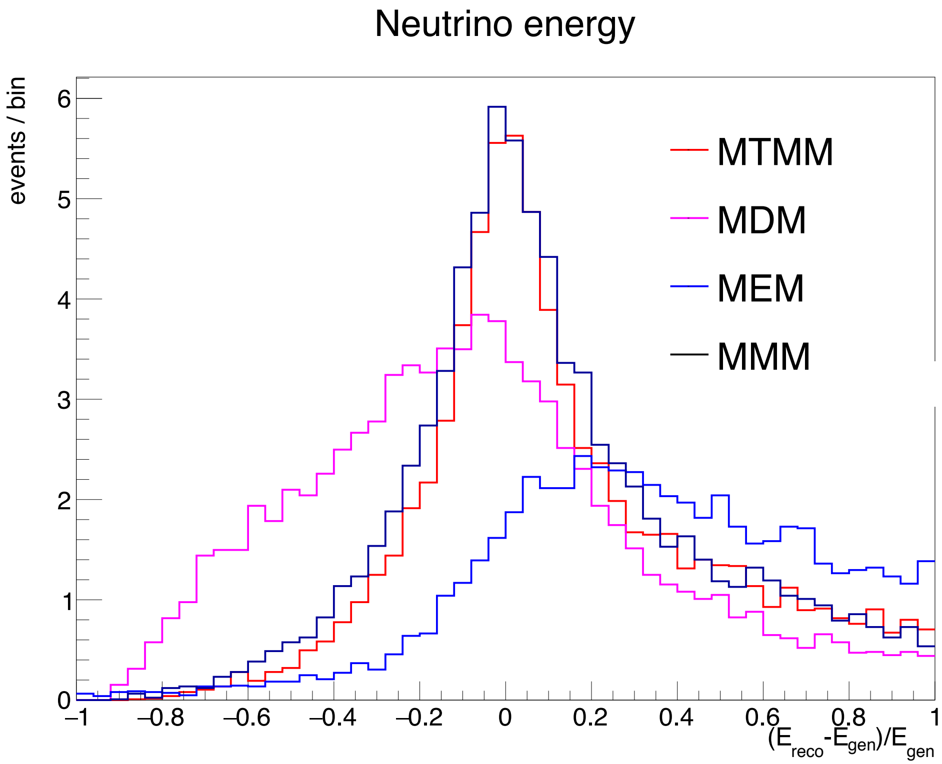
has two solutions

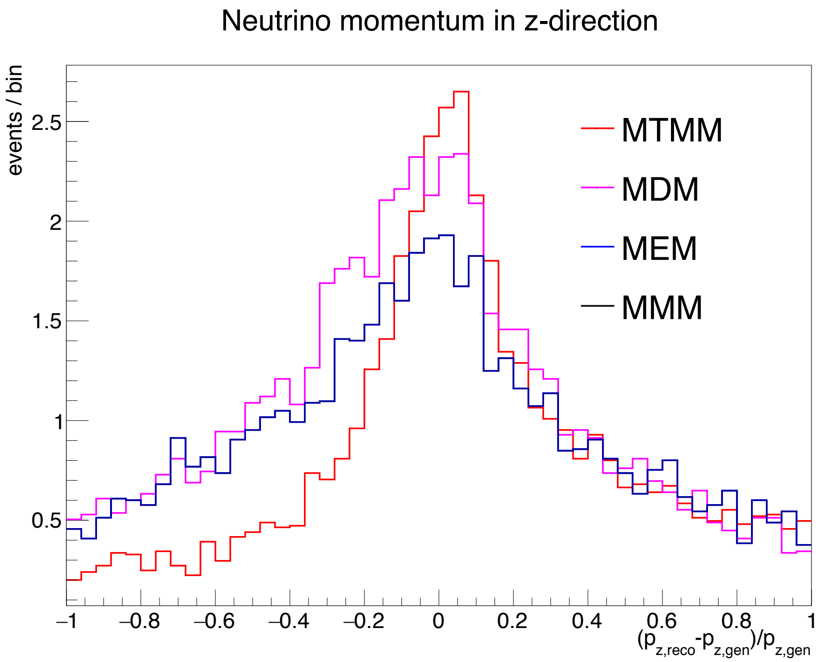
$$p_{\nu z} = \frac{\pm K + p_{\ell z}[2(p_{\ell y}p_{\nu y} + p_{\ell x}p_{\nu x}) + m_{\mathrm{W}}^2]}{2(p_{\ell x}^2 + p_{\ell y}^2)}$$

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

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)

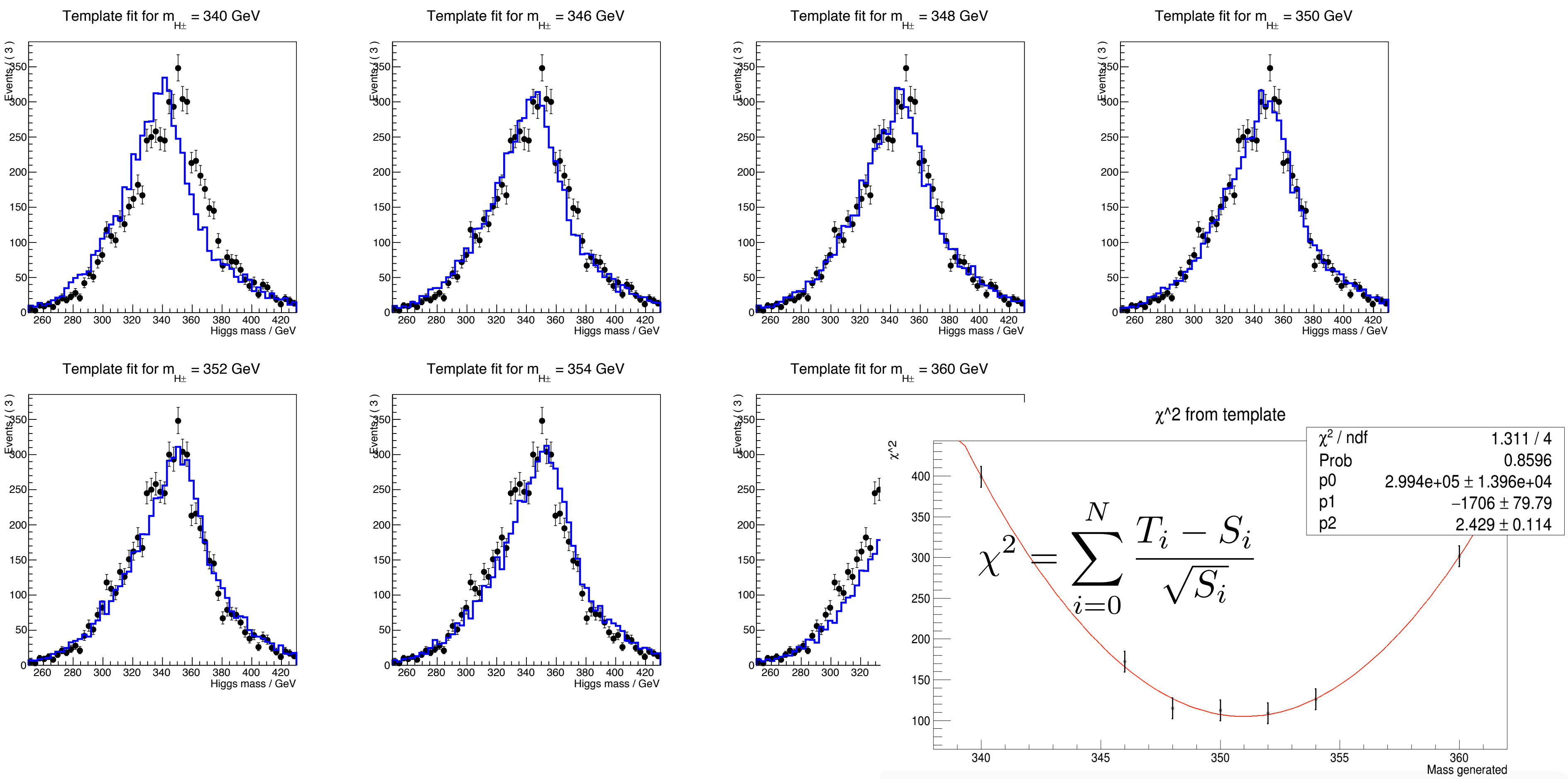
Cut type	Optim. type	Mode	Sig	o. Sig	Z(h)	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$(sl)	$t\bar{t}$(h)	$t\bar{t}h$(sl)	$t\bar{t}h$(h)	other
Static cuts		(h)	1982	46	0	138	106	454	16	200	12	0
Static cuts		(sl)	3090	586	139	208	181	95	678	53	327	26
Static cuts	corr. paired	(h)	579	699	0	50	61	112	2	103	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

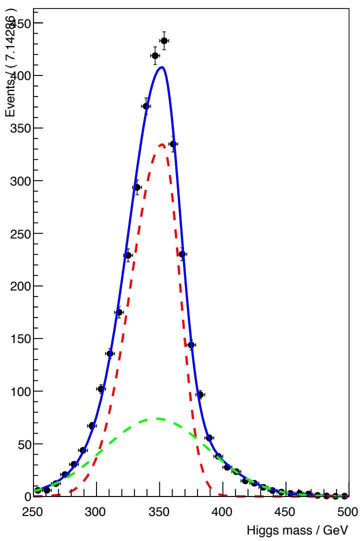


$$\chi^2 = \sum_{i=0}^{N} \frac{T_i - S_i}{\sqrt{S_i}}$$

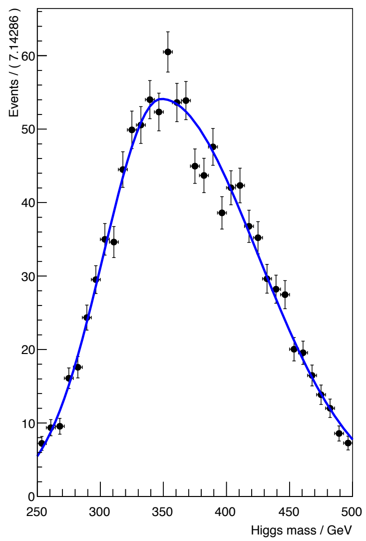
Shape method

- Get signal shape (Static Cuts)

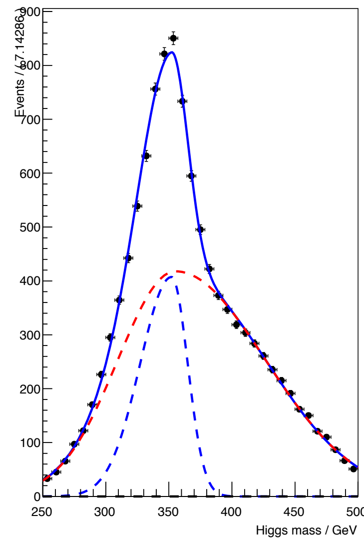
Correctly paired signal



Failed clustering



Total signal



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

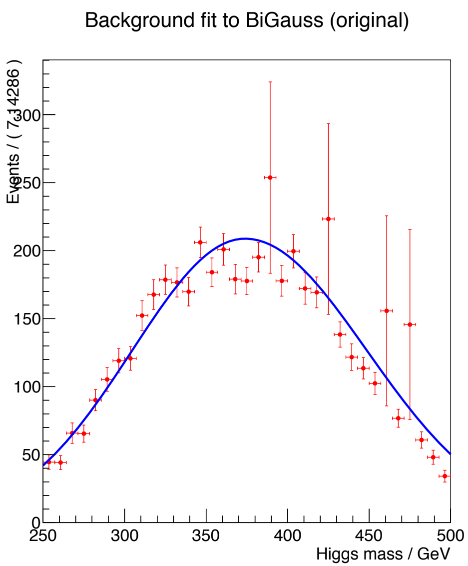
σ_L: 45.6 GeV

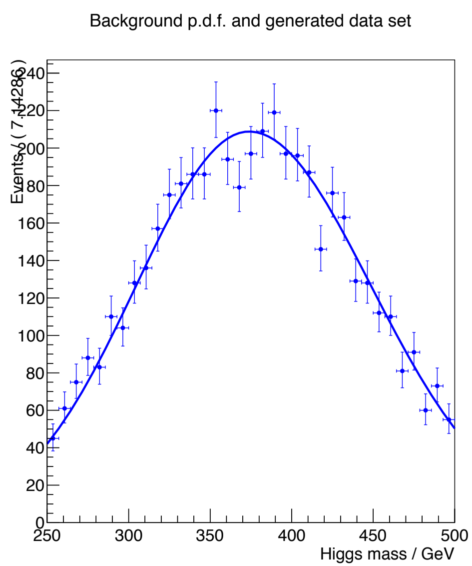
σ_R: 71.5 GeV

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

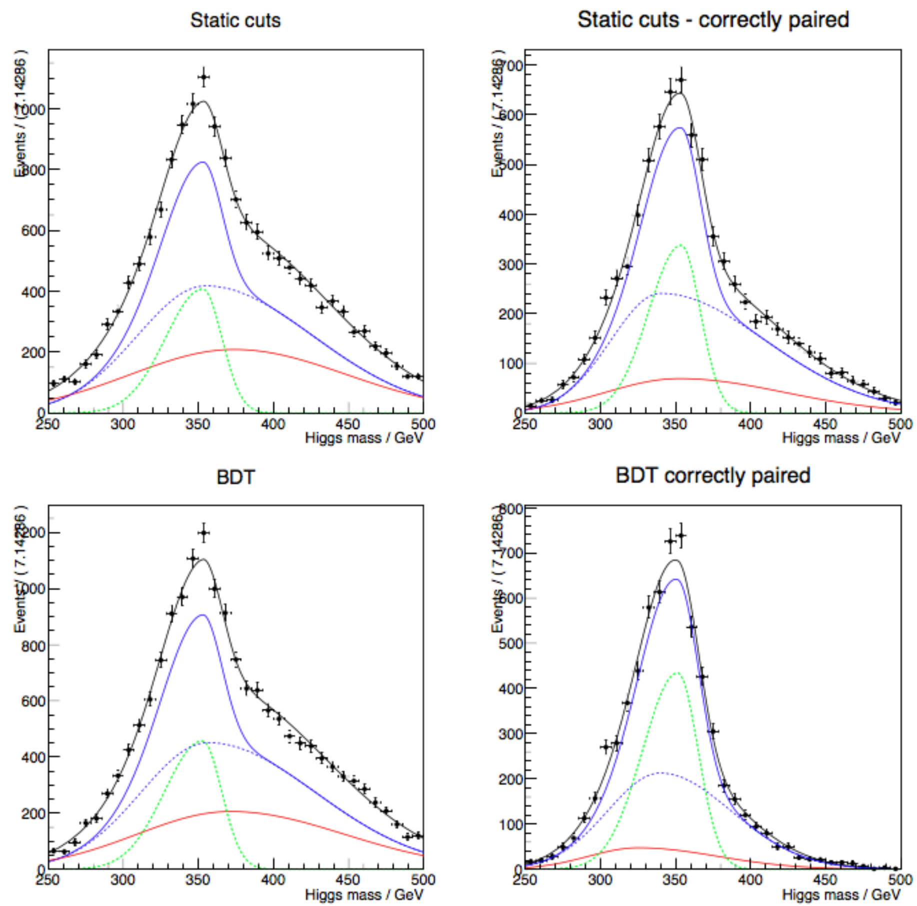
σ_R: 74.8 GeV

red. χ^2 (original BG) = 3.06

red. χ^2 (gen BG) = 0.96

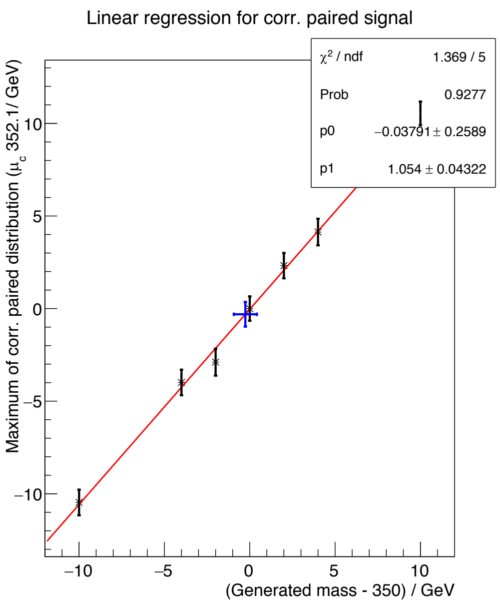
Added fit

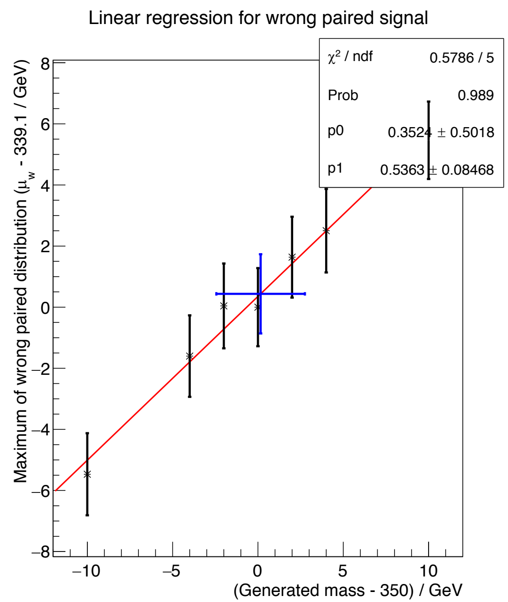
- Added fit for different event selections for shape method
- All fit parameter fixed except mean of signal distributions
- Background
- Signal (solid)
  - Wrong paired signal (dashed)
  - Correctly paired signal



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

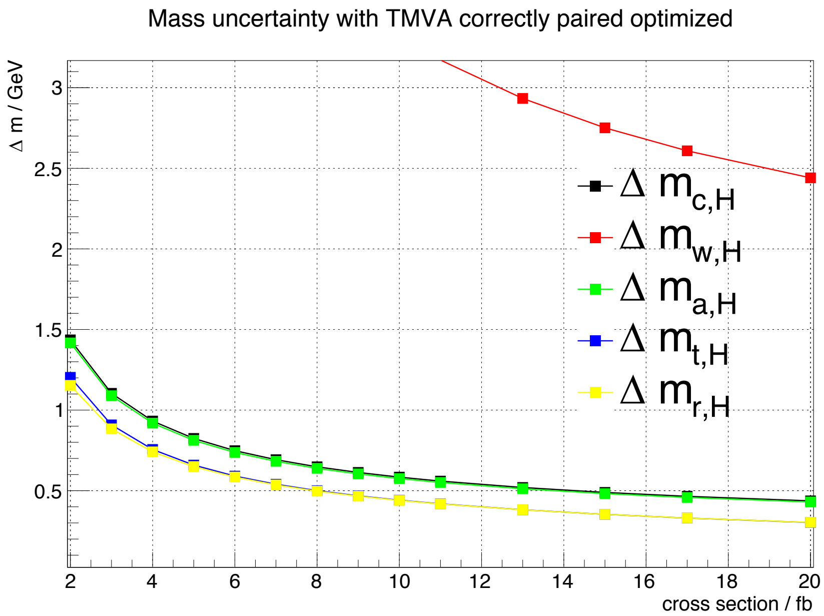
$\Delta_{c,linear}$: -0.012

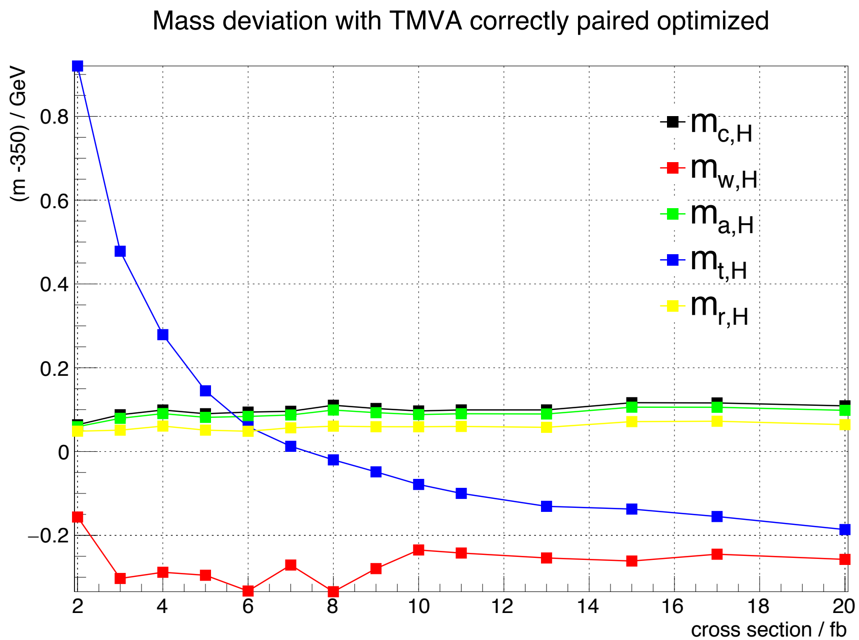
$\Delta_{c,fit}$: 0.6319

$m_{c,H}$/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)

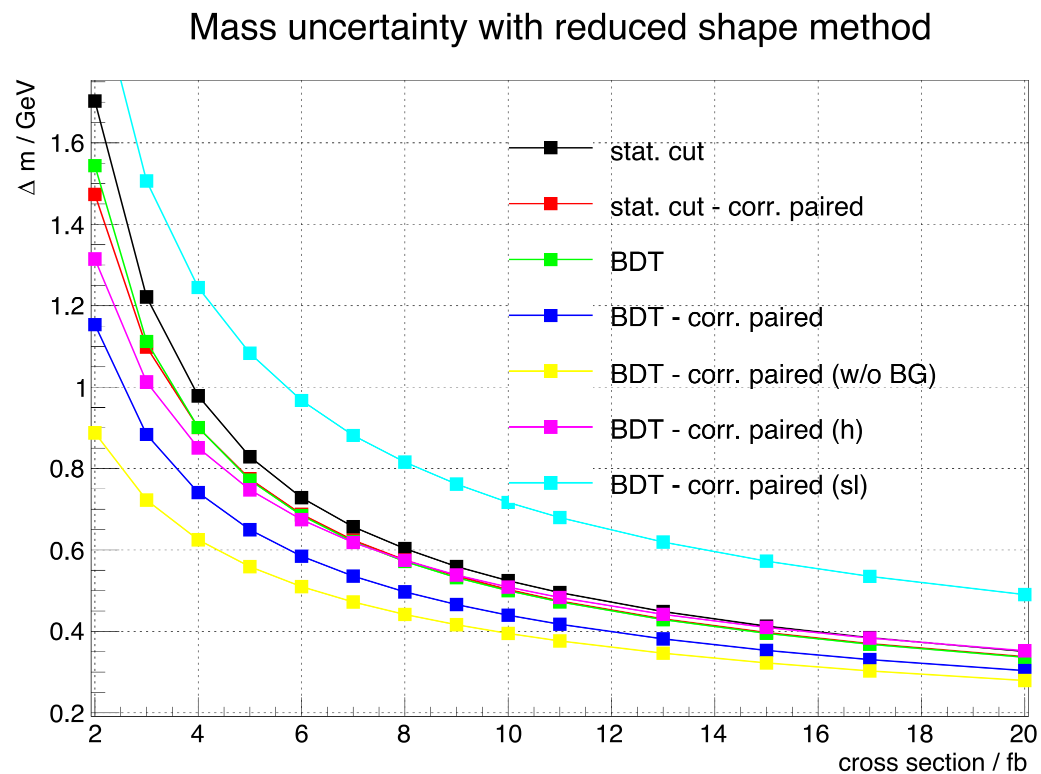




- Result from 10 000 toy MC

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

- Result from 10 000 toy MC samples
- 0.5 GeV mass precision
- Optimization for correctly paired signal beneficial



Result

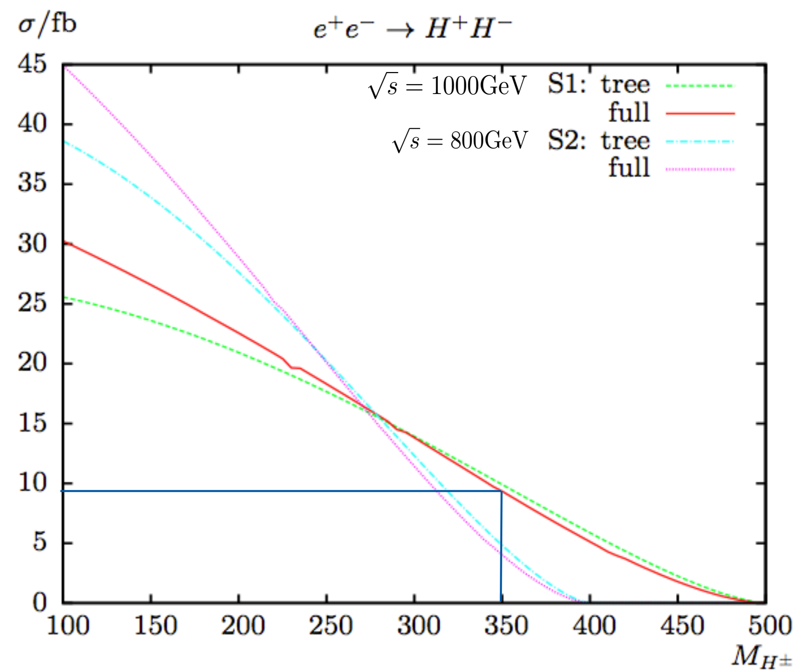
- 0.5 GeV mass precision
- Neutrino four momentum reconstruction with Missing Momentum Method was used
- Missing Transversal Momentum Method has great potential

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

Cross section

- $\sigma \approx$ 9 fb with P = (-80%,20%) 10.4 fb
- $\mathcal{L}$ = 1000 1/fb
- N = 10400 $H^{\pm}$ 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



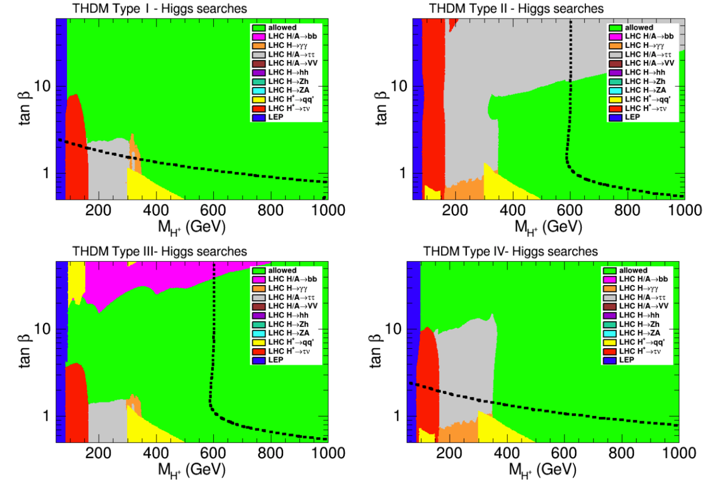
Source: ***Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis***
Heinemeyer, S. and Schappacher, C. Eur. Phys. J. (2016)

Allowed parameter space

Source: A. Arbey et al. “**Status of the Charged Higgs Boson in Two Higgs Doublet Models**.” In: (2017). arXiv: 1706.07414 [hep-ph].

Type	U_R	D_R	L_R	λ_{UU}	λ_{DD}	λ_{LL}
I	+	+	+	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	+	−	−	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
III	+	−	+	$\cot\beta$	$-\tan\beta$	$\cot\beta$
IV	+	+	−	$\cot\beta$	$\cot\beta$	$-\tan\beta$

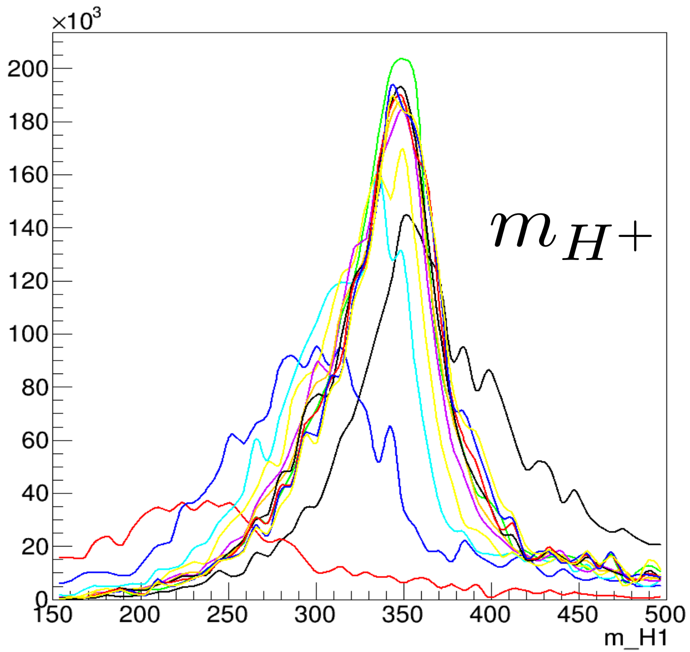
Table 1. Assignment of Z_2 charges for the right-handed fermions, and the resulting relations among Yukawa coupling matrices in the Z_2-symmetric types of 2HDM Yukawa sectors. The Higgs doublets Φ_1 and Φ_2 have Z_2 quantum numbers − and +, respectively.

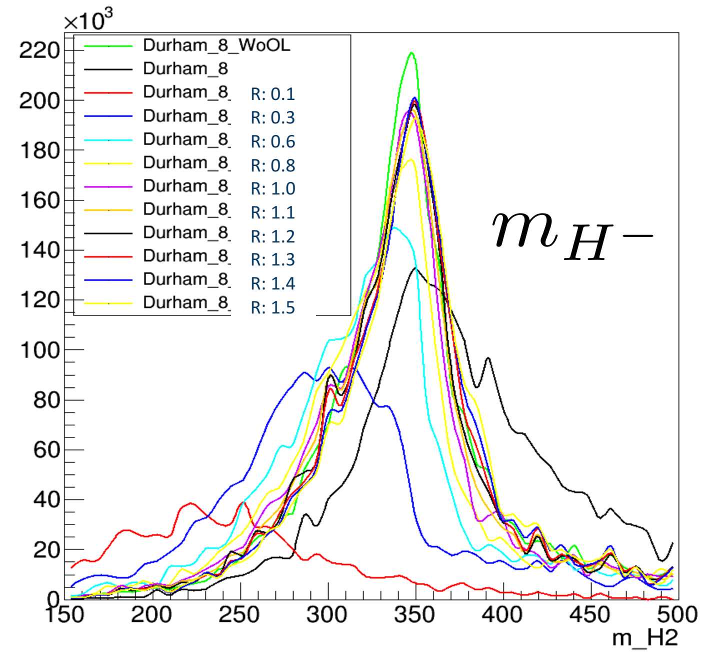


Analysis Overview

- 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

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	