Reconstructing Higgs pair production events.

ECFA Higgs Factories: 2nd Topical Meeting on Reconstruction

Julie Munch Torndal

July 12, 2023

Higgs self-coupling

Higgs potential in SM after SSB

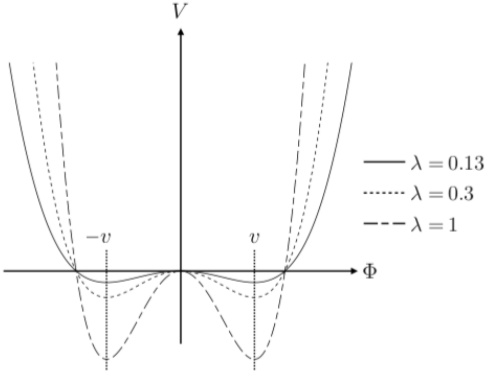
$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4} \lambda_4 h^4$$

with $\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2\nu^2}$

Measure $\boldsymbol{\lambda}$

- $\rightarrow$ determine shape of **Higgs potential**
- $\rightarrow$ establish **Higgs mechanism** experimentally
- $\rightarrow$ determine how the Universe froze in the EW sector, giving mass to gauge bosons, fermions, and the Higgs itself

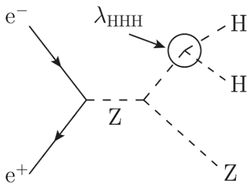
BSM: deviations in $\lambda \rightarrow$ new physics in Higgs sector

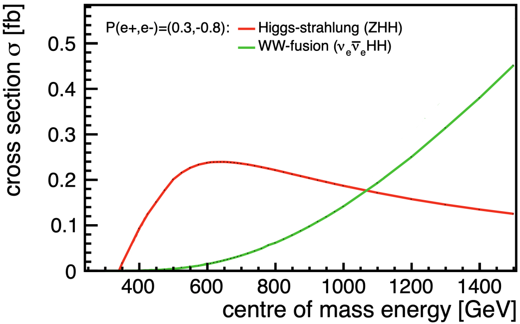


Higgs pair production in e^+e^- collisions

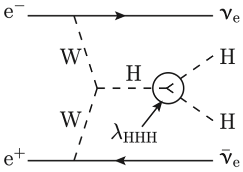
- direct access to Higgs self-coupling through Higgs pair production

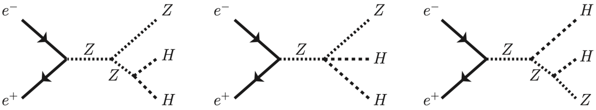
Di-Higgs strahlung:
dominant below 1 TeV

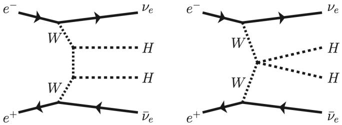




WW fusion:
dominant above 1 TeV







→ constructive interference

→ destructive interference

Higgs pair production in e^+e^- collisions

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Di-Higgs strahlung:
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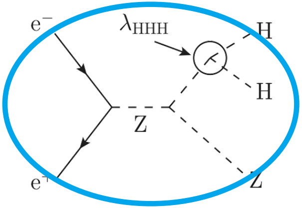
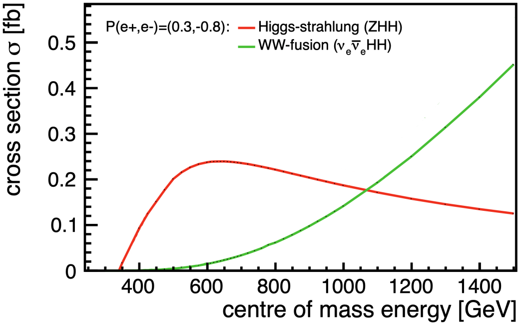


→ **only ∼400 events**



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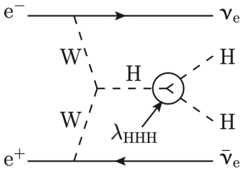
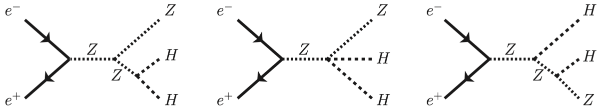
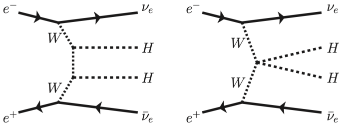






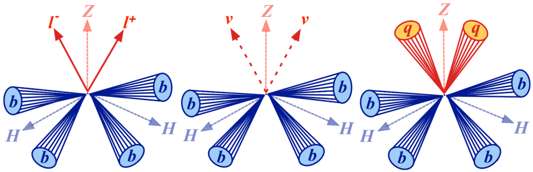
→ constructive interference

→ destructive interference

The analysis from nearly a decade ago

DESY-THESIS-2016-027

State-of-the-art projections at ILC performed 7-10 years ago



Precision reach

After full ILC running scenario ($HH \to bbbb$ + $HH \to bbWW$)

$\to \Delta\sigma_{\text{ZHH}}/\sigma_{\text{ZHH}} = 16.8\%$

$\to \Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 26.6\%$

$\to \Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 10\%$ when combined with additional running scenario at 1 TeV

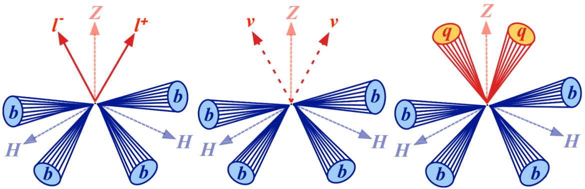
Discovery potential clearly demonstrated

Strategy for further improvements

Better reconstruction tools now $\to$ improve precision on σ_{ZHH} and λ_{SM} !

Analysis strategy

DESY-THESIS-2016-027



Event reconstruction

Overlay removal

- $\gamma\gamma \rightarrow$ low-p_T hadrons
- Expect $\langle N_{overlay} \rangle = 1.05$ particles/event

Isolated lepton tagging

- identify leptons for selection or rejection

Jet reconstruction

- cluster together remaining event

Flavor tagging

- look for b-jets

Event selection

Cut-based preselection

- $ZHH \rightarrow \ell\ell bbbb$
- $ZHH \rightarrow \nu\nu bbbb$
- $ZHH \rightarrow qqbbbb$

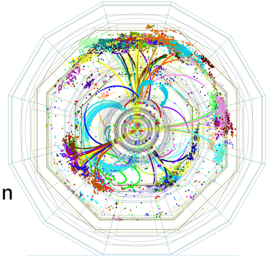
Kinematic fitting

- hypotheses testing to separate ZHH from ZZH background

Event selection

- based on MVAs

Strategy for improving the Higgs self-coupling measurement at ILC



DESY-THESIS-2016-027

Overlay removal

$\gamma\gamma \to$ low-p_T hadrons

Expect $\langle N_{overlay} \rangle = 1.05$ event @ 500 GeV

- ☑ Better modelling of the $\gamma\gamma$ overlay
- ⋯ Advanced overlay removal strategy

Isolated lepton tagging

Optimised for $\ell = \{e, \mu\}$

- ⋯ Dedicated search for τs

  For $\varepsilon_\tau \sim \varepsilon_{e,\mu}$
  $\to 8\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Jet clustering

- ☐ Perfect jet clustering

  $\to \sim 40\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Flavor tagging

- ☑ Improve b-tagging efficiency

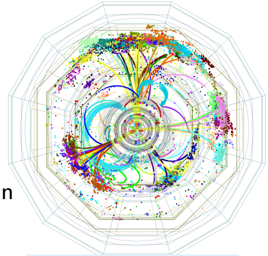
  For 5% relative improvement in $\varepsilon_{b\text{-tag}}$
  $\to 11\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Error parametrisation in kinematic fitting

Mass resolution $\propto$ jet energy resolution

- ☑ Errorflow: Energy resolution parametrisation for individual jets

Strategy for improving the Higgs self-coupling measurement at ILC



DESY-THESIS-2016-027

Overlay removal
$\gamma\gamma \rightarrow$ low-p_T hadrons
Expect $\langle N_{overlay} \rangle = 1.05$ event @ 500 GeV

- ☑ Better modelling of
- ☐ Advanced overlay r

Isolated lepton taggi
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For $\varepsilon_\tau \sim \varepsilon_{e,\mu}$
$\rightarrow 8\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Jet clustering

- ☐ Perfect jet clustering

$\rightarrow \sim 40\%$ relative improvement in

iency

ement in $\varepsilon_{b\text{-tag}}$
ement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Improvements in reconstruction tools has the potential to bring the sensitivity to **better than 20%**

Error parametrisation in kinematic fitting
Mass resolution $\propto$ jet energy resolution

- ☑ Errorflow: Energy resolution parametrisation for individual jets

Overlay removal

✔ Better modelling of the $\gamma\gamma$ overlay

- Previous: $\langle N_{overlay} \rangle = 1.7$ particles/event $\rightarrow$ pessimistic results
- Now: $\langle N_{overlay} \rangle = 1.05$ particles/event $\rightarrow$ more realistic results

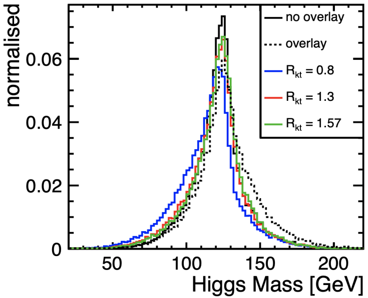
Standard overlay removal strategy

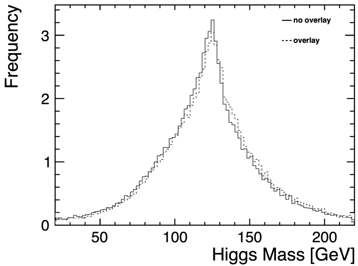
- cluster $\gamma\gamma \rightarrow$ low-p_T hadrons into very forward beam jets and remove $\rightarrow$ uncover original event

Problem: Overlapping jets $\rightarrow$ mis-clustering of jets complicating overlay removal

Advanced overlay removal strategy

- More detailed study needed to determine whether more advanced removal strategy is needed





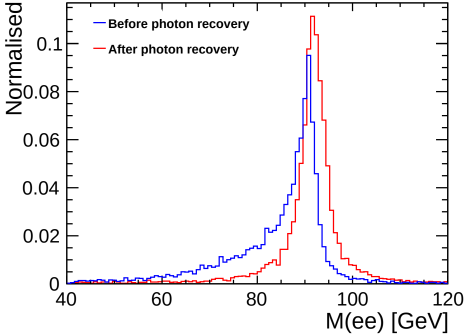
Isolated lepton tagging

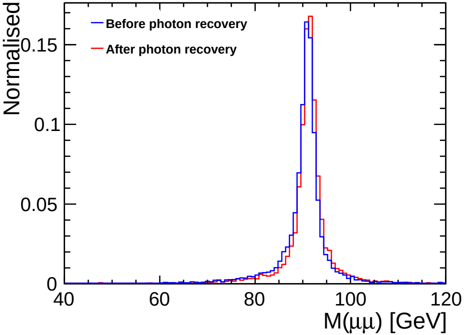
Step 1: identify all isolated leptons

- based on a MVA approach
- optimised for $\ell = e, \mu$

Step 2: pair selection

- closest to Z-mass + opposite charge requirement
- followed by BS/FSR recovery



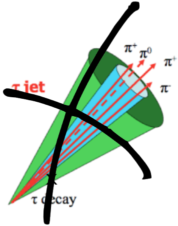


Dedicated search for τs

- Separate method for tau lepton reconstruction

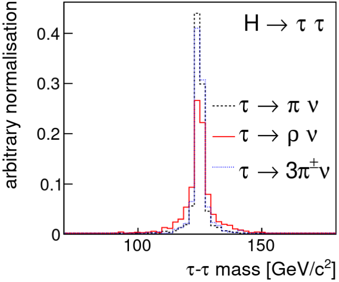
Tau lepton reconstruction
Event reconstruction

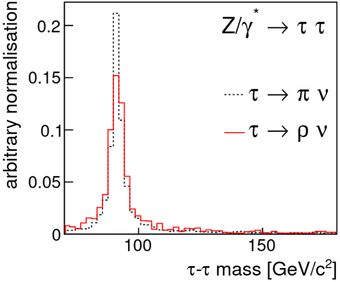
arXiv:1507.01700



Reconstruction using impact parameters

- requires accurate τ vertex + precise measurement of decay products
- parametrisation only for single neutrino production
- $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ simulated in ILD

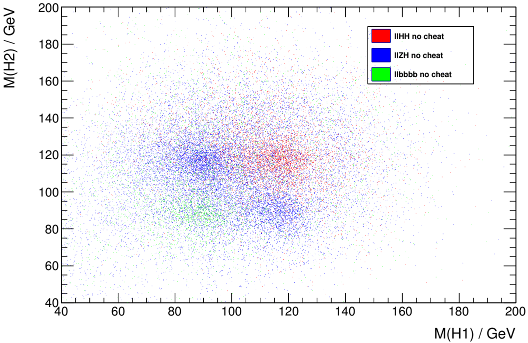




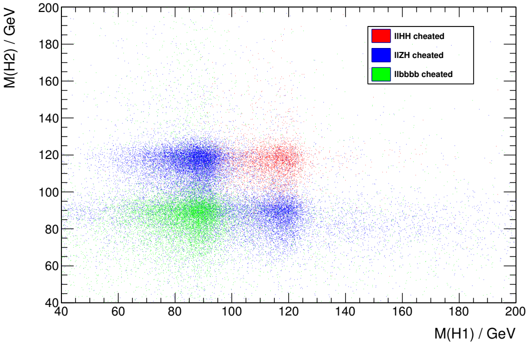
Jet clustering

Junping Tian, Claude Dürig, 2012

☑ Durham algorithm:



☐ Perfect jet clustering:

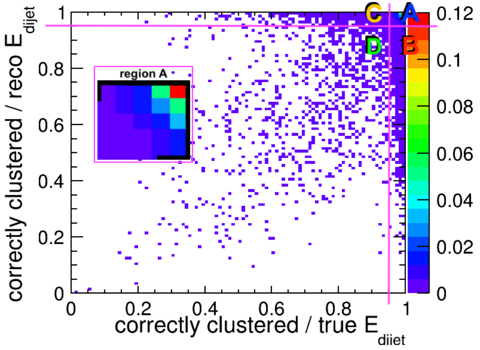


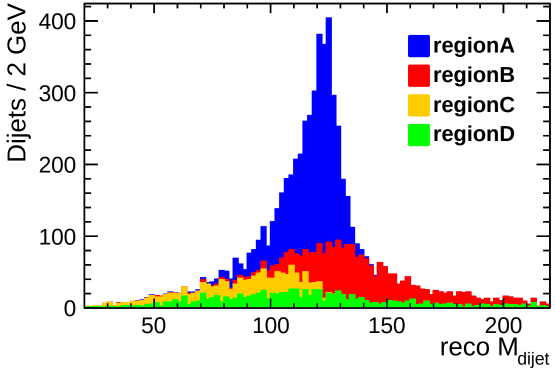
- jet-finding ambiguities from high multiplicities in ZHH, ZZH and ZZZ events

$\rightarrow$ degrades mass resolutions $\rightarrow$ reduces separation $\rightarrow$ reduces $\delta\lambda$ by factor ~ 2

Misclustering

Jet clustering





Misclustering

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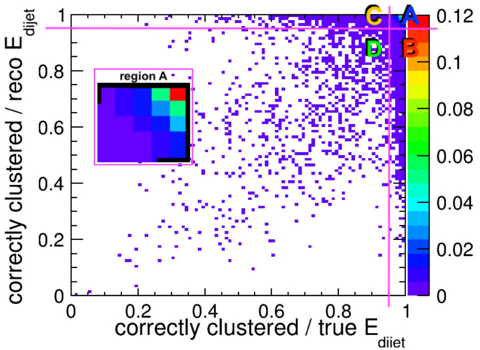
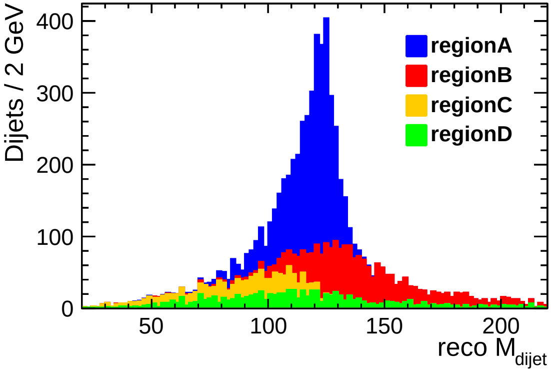
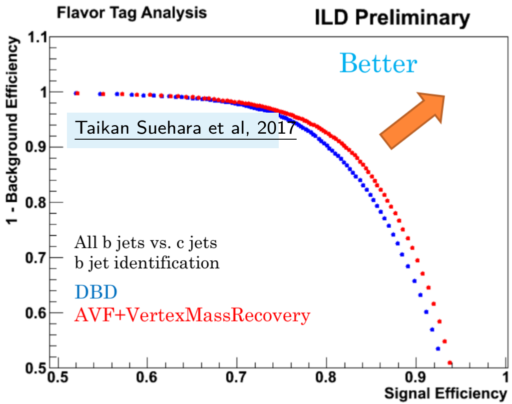




Advanced jet clustering methods needed to address regions B, C, and D!

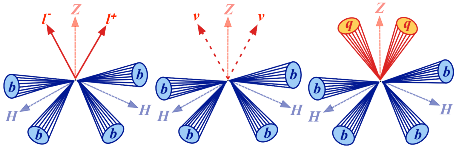
Flavor tagging

☑ Improve *b*-tagging efficiency



Example @ 80% signal efficiency:

	DBD	new	ATLAS
1-eff(c)	90%	95%	75%
Rejection factor	10	20	4



Better signal efficiencies observed in preselections

DESY.

Preselection in neutrino channel

Flavor tagging

PRELIMINARY

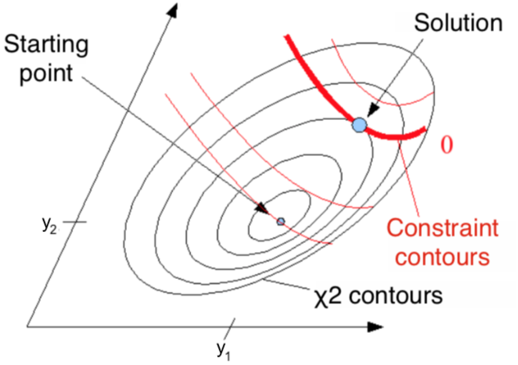
Selection	$\nu\nu HH$ (new)	$\nu\nu HH$ (old)	ϵ_{sig} (new)	ϵ_{bkg} (old)
Initial	89.8 ± 0.6	80.14	1.0	1.0
$\#\ell_{ISO} = 0$	70.9 ± 0.6	62.4 ± 0.1	0.79	0.78
$\|M_{jj} - M_H\| > 80$ GeV	69.0 ± 0.5	61.0 ± 0.1	0.77	0.76
bmax3 > 0.2	55.1 ± 0.5	28.2 ± 0.1	0.61	0.35
60 GeV< M_{jj} <180 GeV	53.2 ± 0.5	27.3 ± 0.1	0.59	0.34
10 GeV < p_T < 180 GeV	52.5 ± 0.5	27.0 ± 0.1	0.59	0.34
thrust < 0.9	52.2 ± 0.5	26.8 ± 0.1	0.58	0.33
E_{vis} < 400 GeV	51.8 ± 0.5	26.6 ± 0.1	0.58	0.33
$M(HH) > 220$ GeV	49.0 ± 0.5	25.7 ± 0.1	0.55	0.32

- $\nu\nu HH$: 74 % relative improvement after b-tag cut

Kinematic fitting

Exploit well-known initial state in e^+e^- colliders for:

- Improve kinematics, e.g. mass resolution
- Hypothesis testing
- Jet-pairing



χ^2-function to minimise:

$$L(y) = \Delta y^T \mathbf{V}(y)^{-1} \Delta y + 2 \sum_{k=1}^{m} \lambda_k f_k(a, y)$$

- y: set of measured parameters
- a: set of unmeasured parameters
- Δy: corrections to y
- $\mathbf{V}(y)$: covariance matrix for y
- f_k: set of constraints expressing the fit model
- λ_k: lagrange multipliers

ErrorFlow

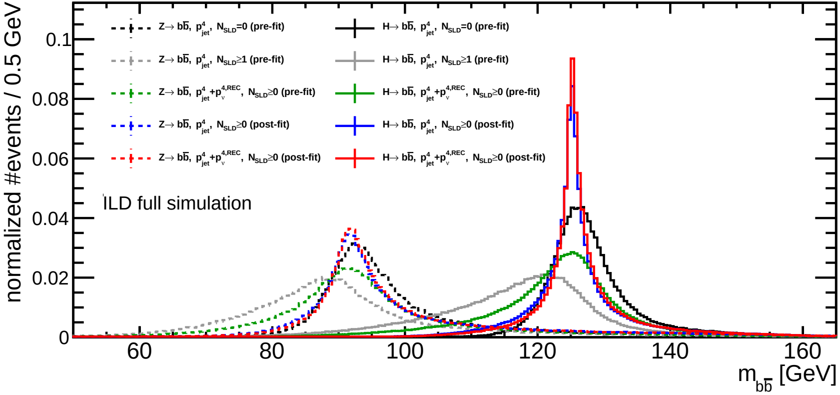
Kinematic fitting

Yasser Radkhorrami, 2023

☑ Parametrize sources of uncertainties for *individual* jets:

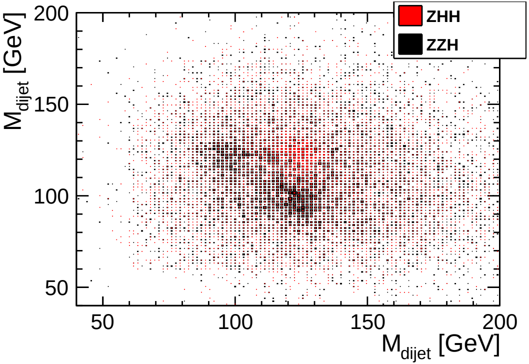
$$\sigma_{E_{jet}} = \sigma_{Det} \oplus \sigma_{Conf} \oplus \sigma_{\nu} \oplus \sigma_{Clus} \oplus \sigma_{Had} \oplus \sigma_{\gamma\gamma}$$

- σ_{Det}: Detector resolution
- σ_{Conf}: Particle confusion in Particle Flow Algorithm
- σ_{ν}: Neutrino correction



Hypothesis testing
Kinematic fitting

PRELIMINARY



- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)

→

Calculate χ^2 for ZHH and ZZH hypotheses for both ZHH and ZZH events

ZHH hypothesis:

- 4-momentum conservation
- 2 $\times$ Higgs mass constraints

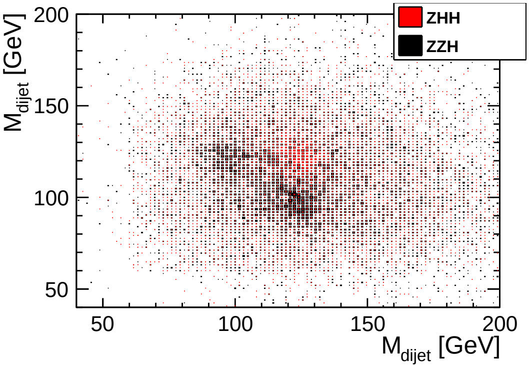
ZZH hypothesis:

- 4-momentum conservation
- Higgs mass constraint + Z mass constraint

Hypothesis testing

Kinematic fitting

PRELIMINARY



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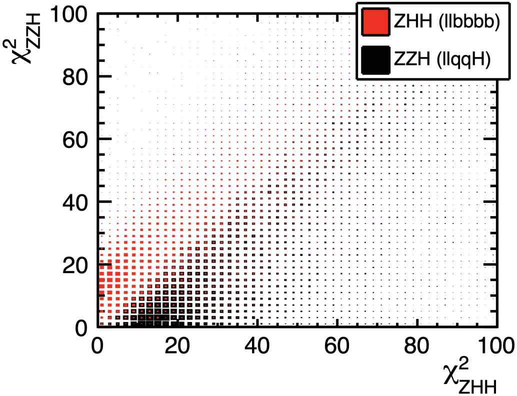
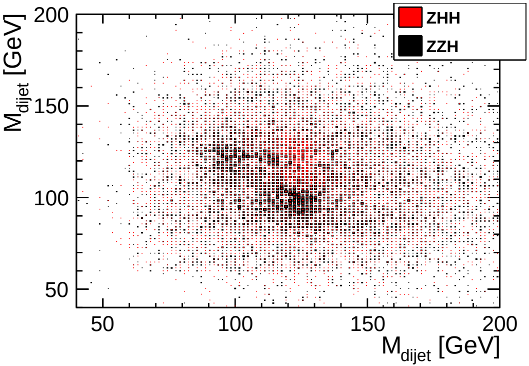


- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)
- Hypothesis testing showed good separation for low χ^2-values of signal (*ZHH*) and background (*ZZH*) in previous analysis DESY-THESIS-2016-027

Hypothesis testing
Kinematic fitting

PRELIMINARY



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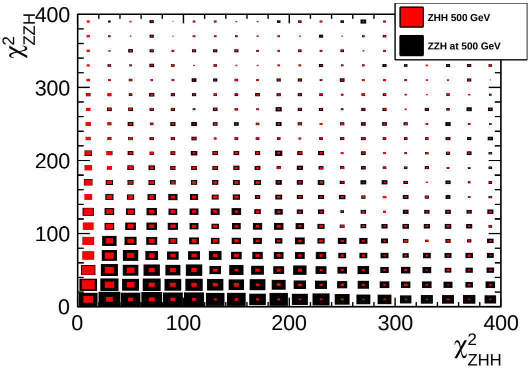
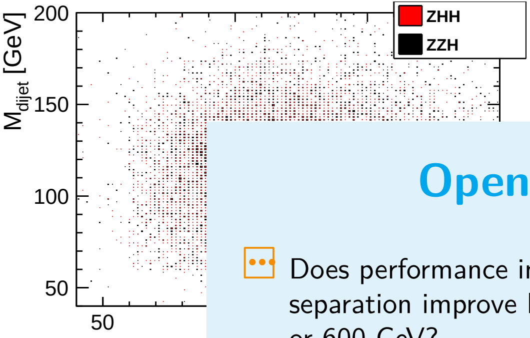


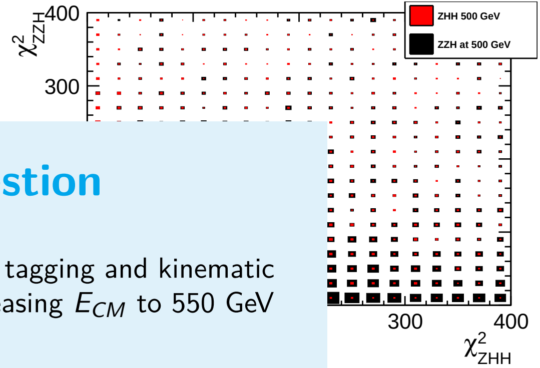
- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)
- With ErrorFlow → larger separation of signal (*ZHH*) and background (*ZZH*)

Hypothesis testing

Kinematic fitting

PRELIMINARY





Open question

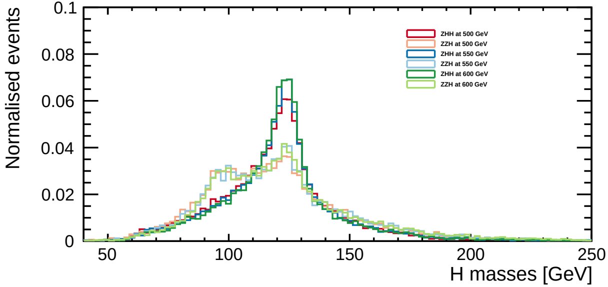
- Does performance in flavor tagging and kinematic separation improve by increasing E_{CM} to 550 GeV or 600 GeV?

- Pre-fitted dijet-m… between signal (ZHH) and background (ZZH)

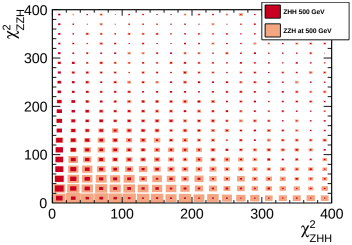
…paration of signal (ZHH) and background (ZZH)

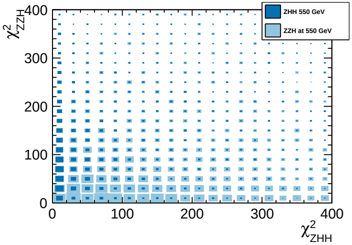
Kinematic fitting at higher E_{CM}

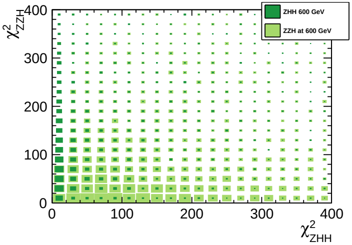
PRELIMINARY



- Sharper dijet mass distributions for ZHH at 550 GeV and 600 GeV compared to at 500 GeV – but also for ZZH
- Comparable kinematic fit performance thus far







Conclusion and outlook

- Discovery potential of Higgs self-coupling at ILC clearly demonstrated in the past
- Improvements concerning overlay modelling, tau searches, flavor tagging, error parametrisation and neutrino correction since then
- Improvements in reconstruction tools are expected to improve the sensitivity to **better than 20%** at ILC500

Open issues:

- Question of which center-of-mass energy
  - most pressing short term goal to address for ZHH analysis
- Advanced jet clustering methods urgently needed to address misclustering!

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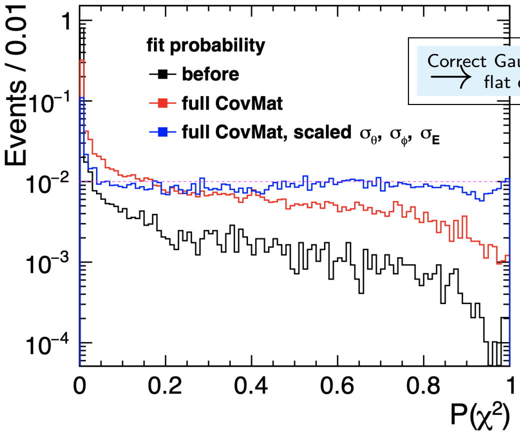
Thank you.

Backup

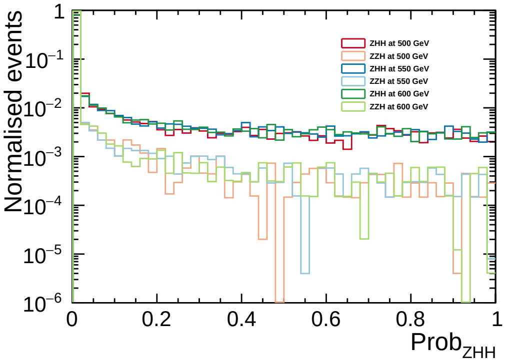
Fit probabilities



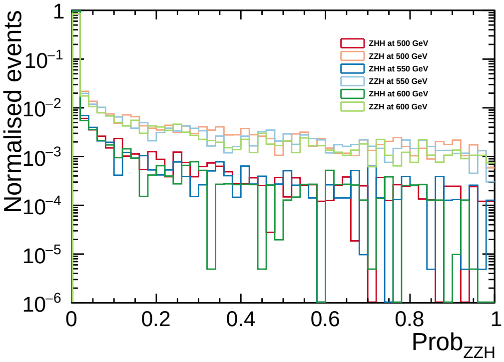
Correct Gaussian errors
→ flat distribution!

Fit probabilities for converged fits

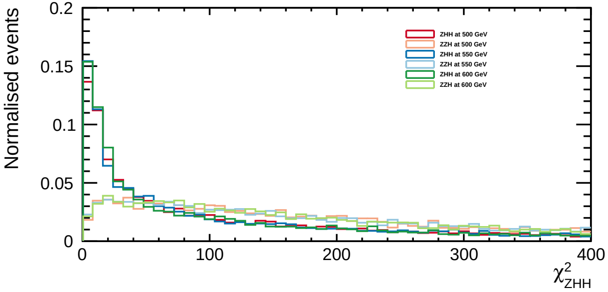
Fit prob for ZHH hypo:

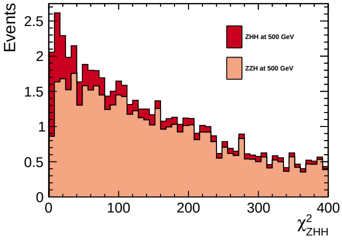


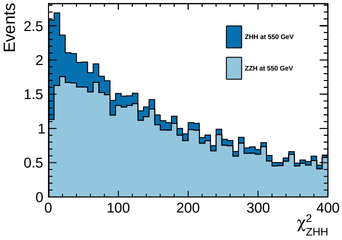
Fit prob for ZZH hypo:

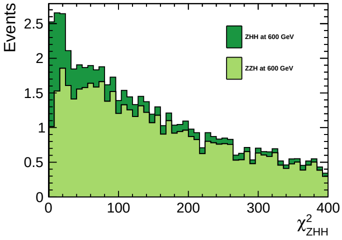


χ^2_{ZHH}

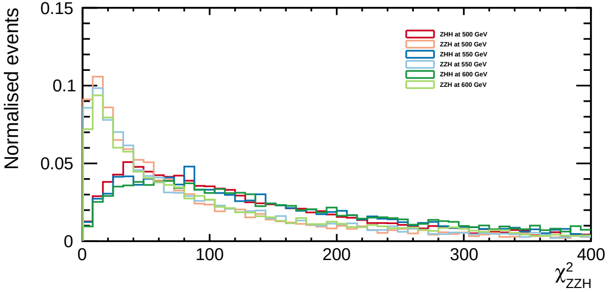

ZHH at 500 GeV
ZZH at 500 GeV
ZHH at 550 GeV
ZZH at 550 GeV
ZHH at 600 GeV
ZZH at 600 GeV
Normalised events
χ^2_{ZHH}


ZHH at 500 GeV
ZZH at 500 GeV
Events
χ^2_{ZHH}

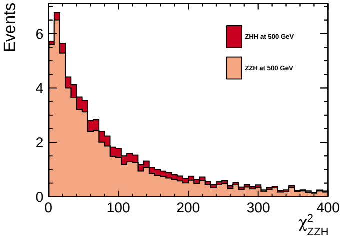

ZHH at 550 GeV
ZZH at 550 GeV
Events
χ^2_{ZHH}


ZHH at 600 GeV
ZZH at 600 GeV
Events
χ^2_{ZHH}

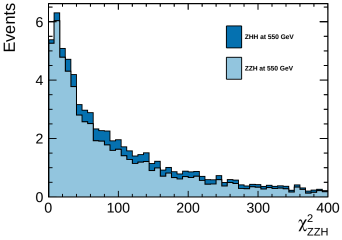
χ^2_{ZZH}



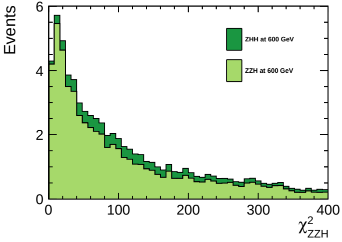
Normalised events
0.15
0.1
0.05
0
0
100
200
300
400
χ^2_{ZZH}
ZHH at 500 GeV
ZZH at 500 GeV
ZHH at 550 GeV
ZZH at 550 GeV
ZHH at 600 GeV
ZZH at 600 GeV



Events
ZHH at 500 GeV
ZZH at 500 GeV
χ^2_{ZZH}

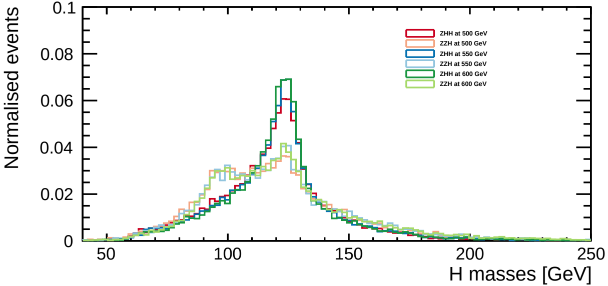


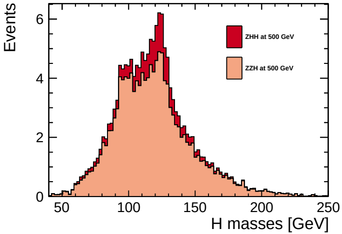
Events
ZHH at 550 GeV
ZZH at 550 GeV
χ^2_{ZZH}

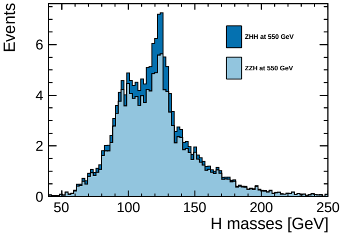


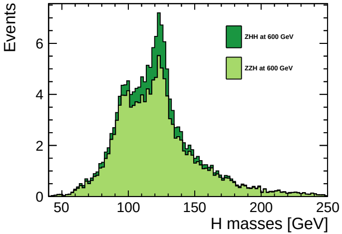
Events
ZHH at 600 GeV
ZZH at 600 GeV
χ^2_{ZZH}

Di-jet masses pre ZHH fit

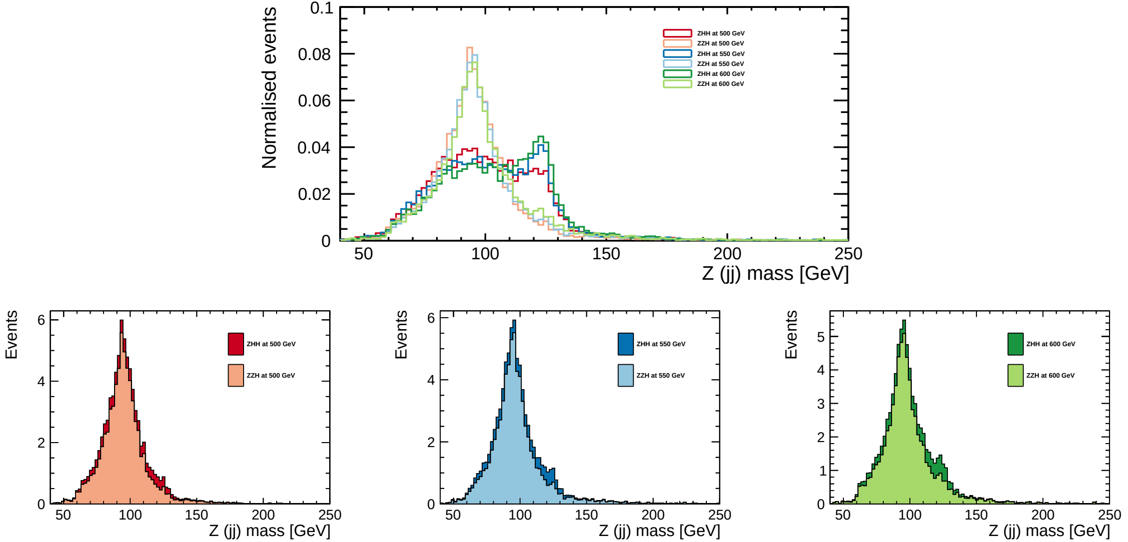








Di-jet Z mass pre ZZH fit



DESY.

Di-dijet H mass pre ZZH fit