Prospects for light Higgs measurements at the 250 GeV ILC

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Track 1: Physics at e^+e^- colliders
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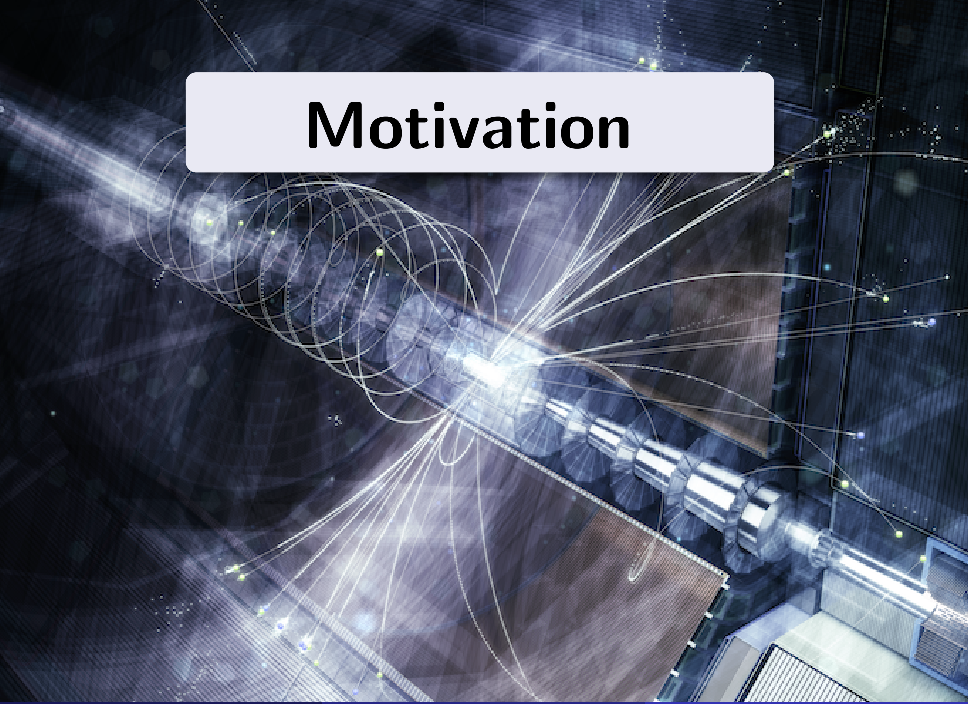
Outline

All presented results are preliminary

Motivation



Motivation

Experimental hints... arXiv:2203.13180

DESY 22-057
IFT-UAM/CSIC–22–033

Mounting evidence for a 95 GeV Higgs boson

T. Biekötter*[1], S. Heinemeyer†[2] and G. Weiglein‡[1,3]

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[2]*Instituto de Física Teórica UAM-CSIC, Cantoblanco, 28049, Madrid, Spain*
[3]*II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

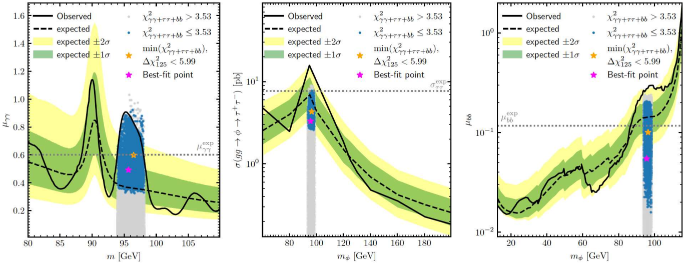
Abstract

In 2018 CMS reported an excess in the light Higgs-boson search in the diphoton decay mode at about 95 GeV based on Run 1 and first year Run 2 data. The combined local significance of the excess was $2.8\,\sigma$. The excess is compatible with the limits obtained in the ATLAS searches from the diphoton search channel. Recently, CMS reported another local excess with a significance of $3.1\,\sigma$ in the light Higgs-boson search in the di-tau final state, which is compatible with the interpretation of a Higgs boson with a mass of about 95 GeV. We show that the observed results can be interpreted as manifestations of a Higgs boson in the Two-Higgs Doublet Model with an additional real singlet (N2HDM). We find that the lightest Higgs boson of the N2HDM can fit both excesses simultaneously, while the second-lightest state is such that it satisfies the Higgs-boson measurements at 125 GeV, and the full Higgs-boson sector is compatible with all Higgs exclusion bounds from the searches at LEP, the Tevatron and the LHC as well as with other theoretical and experimental constraints.

Experimental hints... arXiv:2203.13180

N2HDM type IV: fitting all three excesses: [*T. Biekötter, S.H., G. Weiglein '22*]

$pp \to h_{95} \to \gamma\gamma$ $gg \to h_{95} \to \tau^+\tau^-$ $e^+e^- \to Zh_{95} \to Zb\bar{b}$



gray lines: central values of excesses

$\Rightarrow$ type IV can fit the $\gamma\gamma$, $\tau\tau$ and bb excesses very well

Sven Heinemeyer, First ECFA WS on e^+e^- Higgs/EW/top factories (DESY), 05.10.2022 30

N2HDM model arXiv:2203.13180

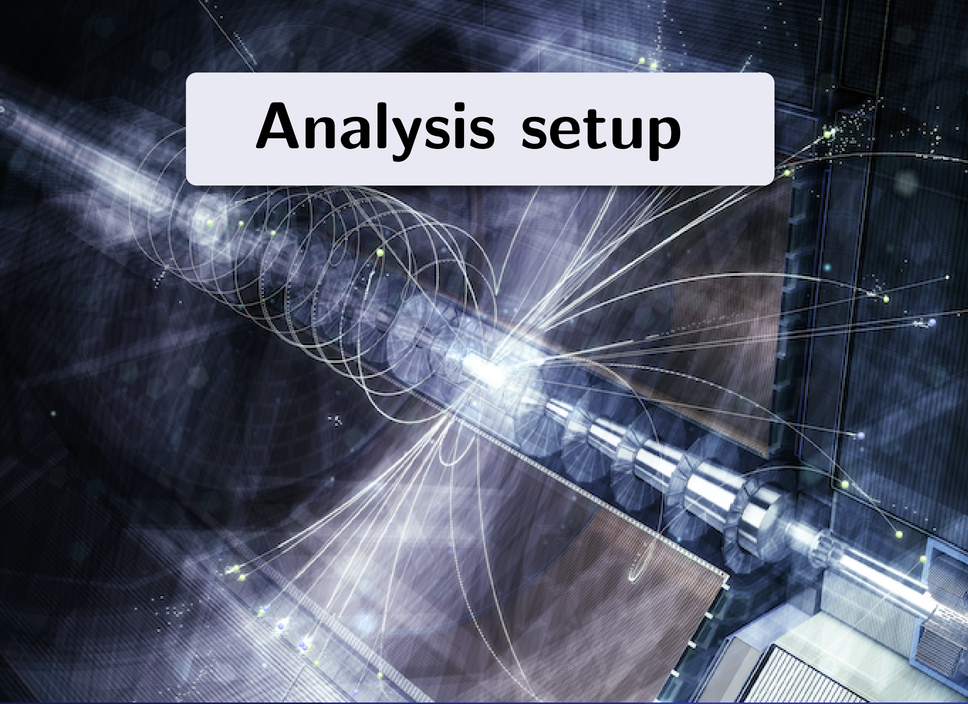
Parameters of the best-fit point (minimal value of χ^2) $\Rightarrow$ **BP1**

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$		
95.68	125.09	713.24	811.20	677.38		
$\tan\beta$	α_1	α_2	α_3	m_{12}	v_S	
10.26	1.57	1.22	1.49	221.12	1333.47	
$\mathrm{BR}_{h_1}^{bb}$	$\mathrm{BR}_{h_1}^{gg}$	$\mathrm{BR}_{h_1}^{cc}$	$\mathrm{BR}_{h_1}^{\tau\tau}$	$\mathrm{BR}_{h_1}^{\gamma\gamma}$	$\mathrm{BR}_{h_1}^{WW}$	$\mathrm{BR}_{h_1}^{ZZ}$
$\Rightarrow$ 0.005	0.348	0.198	$\Rightarrow$ 0.412	$6.630 \cdot 10^{-3}$	0.025	$3.382 \cdot 10^{-3}$
$\mathrm{BR}_{h_2}^{bb}$	$\mathrm{BR}_{h_2}^{gg}$	$\mathrm{BR}_{h_2}^{cc}$	$\mathrm{BR}_{h_2}^{\tau\tau}$	$\mathrm{BR}_{h_2}^{\gamma\gamma}$	$\mathrm{BR}_{h_2}^{WW}$	$\mathrm{BR}_{h_2}^{ZZ}$
0.553	0.085	0.032	0.069	$2.537 \cdot 10^{-3}$	0.228	0.028
$\mathrm{BR}_{h_3}^{tt}$	$\mathrm{BR}_{h_3}^{bb}$	$\mathrm{BR}_{h_3}^{\tau\tau}$	$\mathrm{BR}_{h_3}^{h_1h_1}$	$\mathrm{BR}_{h_3}^{h_1h_2}$	$\mathrm{BR}_{h_3}^{h_2h_2}$	$\mathrm{BR}_{h_3}^{WW}$
0.123	0.739	0.000	0.002	0.072	0.030	0.022
BR_{A}^{tt}	BR_{A}^{bb}	$\mathrm{BR}_{A}^{\tau\tau}$	$\mathrm{BR}_{A}^{Zh_1}$	$\mathrm{BR}_{A}^{Zh_2}$	$\mathrm{BR}_{A}^{Zh_3}$	$\mathrm{BR}_{A}^{WH^\pm}$
0.053	0.173	0.000	0.024	0.001	0.015	0.734
$\mathrm{BR}_{H^\pm}^{tb}$	$\mathrm{BR}_{H^\pm}^{\tau\nu}$	$\mathrm{BR}_{H^\pm}^{Wh_1}$	$\mathrm{BR}_{H^\pm}^{Wh_2}$			
0.922	0.000	0.073	0.003			

Table 1: Parameters of the best-fit point for which the minimal value of χ^2 is found ($\chi^2 = 88.07$, $\chi^2_{125} = 86.24$) and branching ratios of the scalar particles in the type IV scenario. Dimensionful parameters are given in GeV, and the angles are given in radian.

Interesting pattern for light Higgs: no $b\bar{b}$ decays, $\tau^+\tau^-$ decays dominate...

Analysis setup



Signal model many thanks to Thomas Biekötter

UFO file for Singlet-extended Two Higgs doublet model (S2HDM)
See arXiv:2108.10864 for more details.

Difference with N2HDM: complex instead of a real singlet field.
Equivalent to N2HDM, when the additional dark-matter candidate heavy.

Modified by Thomas Biekötter for type IV couplings.

BP1

h_1 production cross section at 250 GeV: $\sim$11% of the SM cross section
for $m_{h_{SM}} = 95.68$ GeV

Scalar branching ratios from arXiv:2203.13180 used.

Problem with UFO interface in Whizard ⇒ fixed in 3.1.1 release !

Analysis setup

Event samples

Generated using Whizard 3.1.1

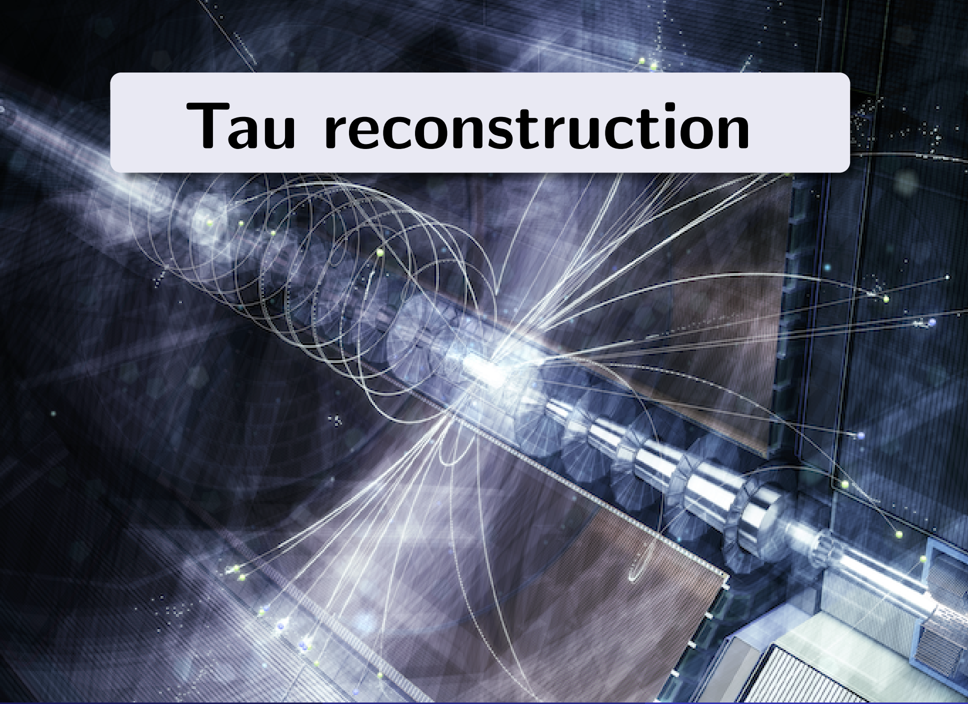
Signal sample: with S2HDM UFO model

Four-fermion background samples: built-in SM_CKM model
- with restriction set to remove SM Higgs boson contribution
- SM-like h_2 contribution included using S2HDM UFO model

Consider ILC running at 250 GeV with $-80\%/+30\%$ beam polarisation
Integrated lumionsity of $900\,\mathrm{fb}^{-1}$

Fast detector simulation with Delphes ILCgen model

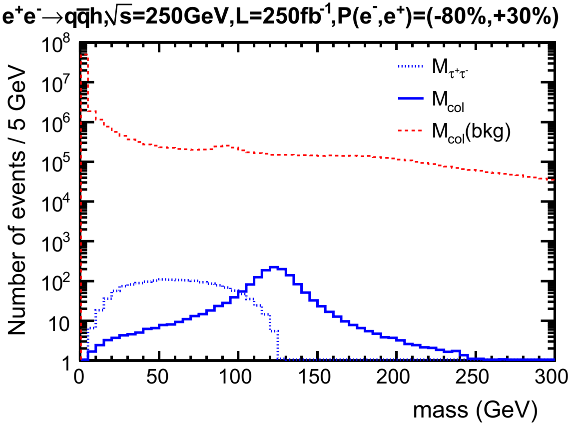
Tau reconstruction



Collinear approximation

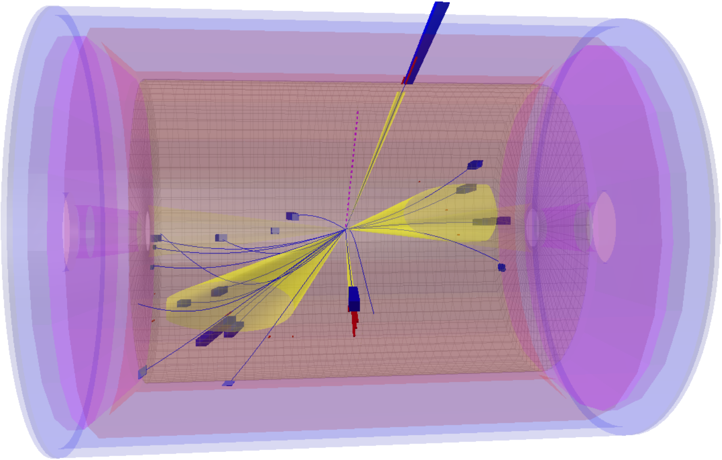
arXiv:1509.01885

Used in the study of Higgs boson decaying into tau pairs at the ILC:



Collinear approximation

Example signal events, with hadronic tau decays (four jets).



Collinear approximation

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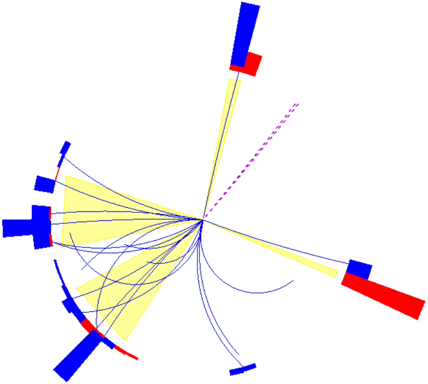
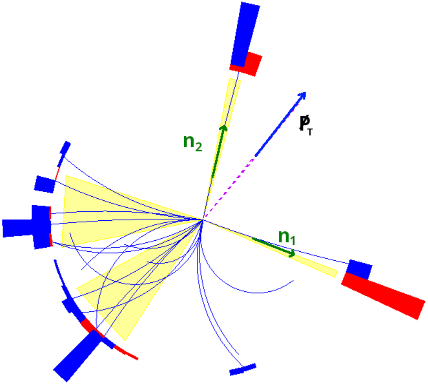


Collinear approximation

Example signal events, with hadronic tau decays (four jets).



Tau leptons are very boosted.

Assume neutrinos from tau decays emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

$$\vec{\not p}_T \quad = \quad E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2}$$

where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau-tagged jets (!).

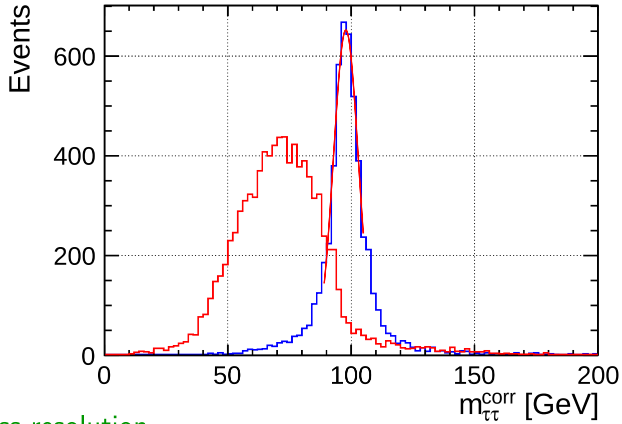
Unique solution

Tau reconstruction

Collinear approximation

Distribution of the raw and corrected mass of the tau candidate pair.

Hadronic tau decays (two jets with tau-tag)

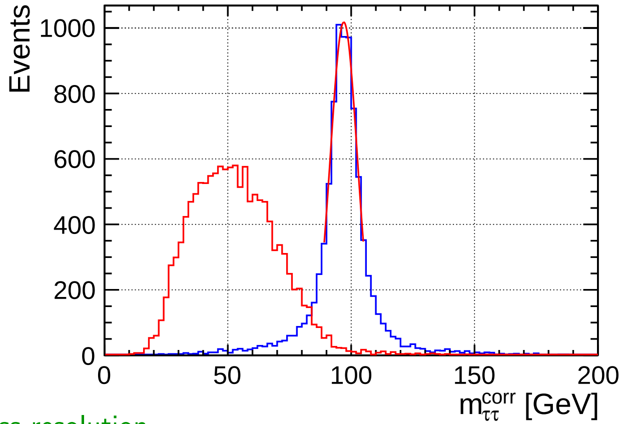


5.0 GeV mass resolution

Collinear approximation

Distribution of the raw and corrected mass of the tau candidate pair.

Semi-leptonic tau decays (one lepton + one jet with tau-tag)

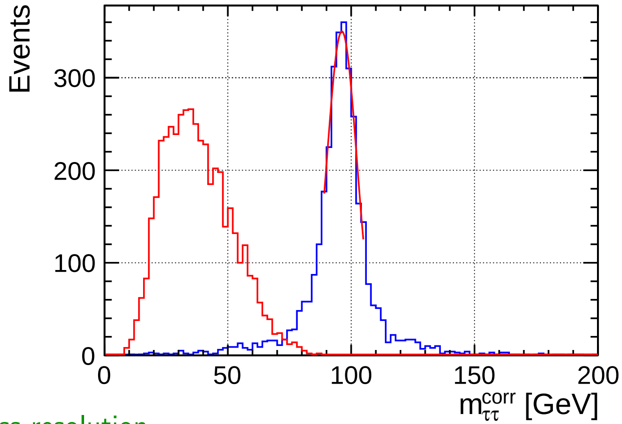


5.4 GeV mass resolution

Collinear approximation

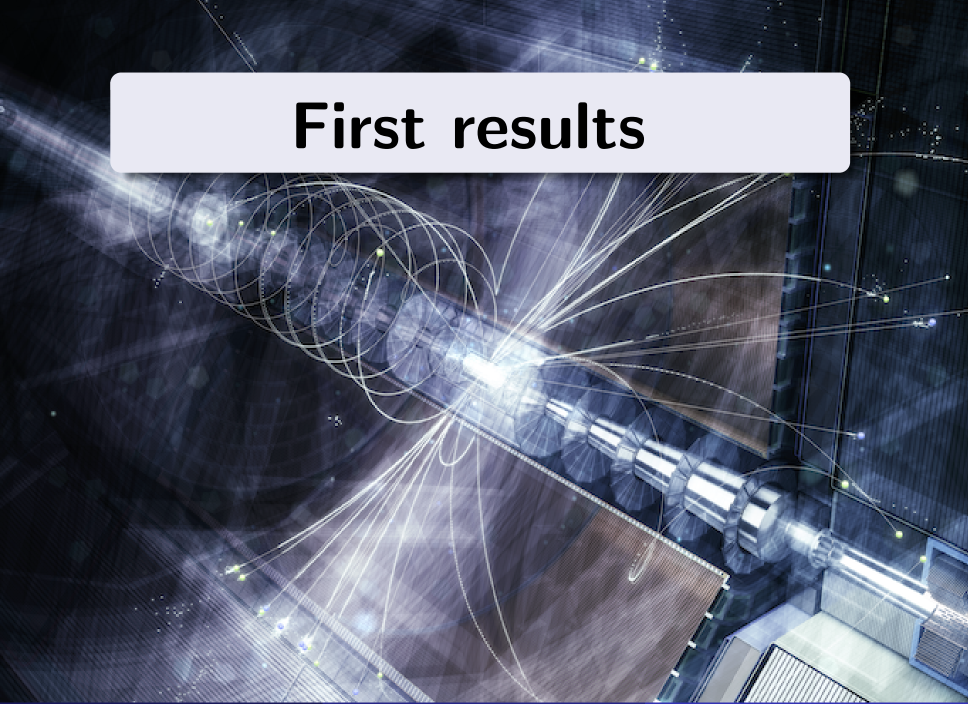
Distribution of the raw and corrected mass of the tau candidate pair.

Leptonic tau decays (two isolated leptons)



6.1 GeV mass resolution

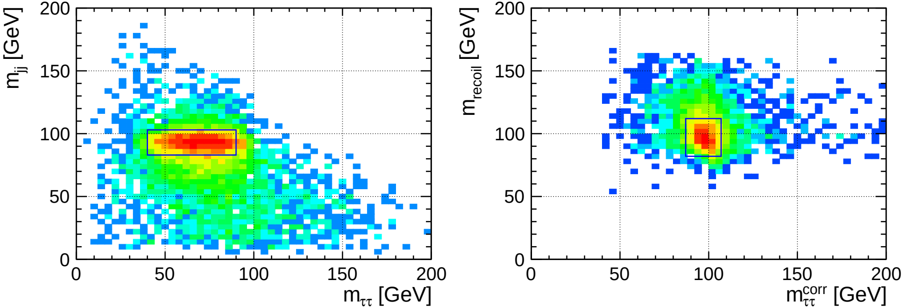
First results



Event kinematics

Signal in hadronic tau decay channel

no leptons, clustering into four jets, two jets with tau-tag



Right plot: after left plot box cut

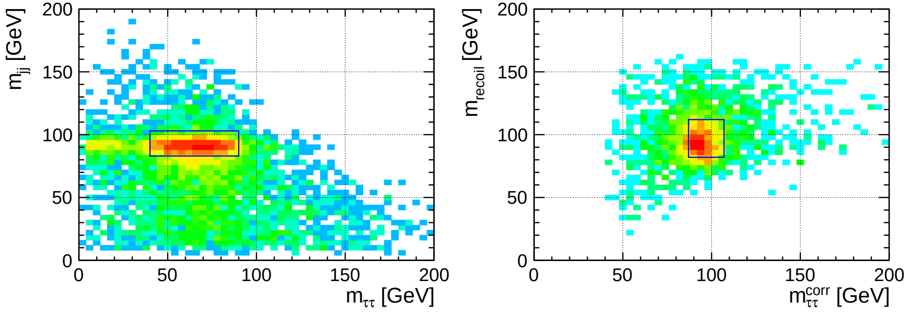
⇒ apply simple window cuts on:

- Z (jj) and h_1 ($\tau\tau$) invariant masses
- corrected h_1 mass and recoil mass

Event kinematics

Background from $qq\tau\tau$ in hadronic tau decay channel

no leptons, clustering into four jets, two jets with tau-tag



Right plot: after left plot box cut

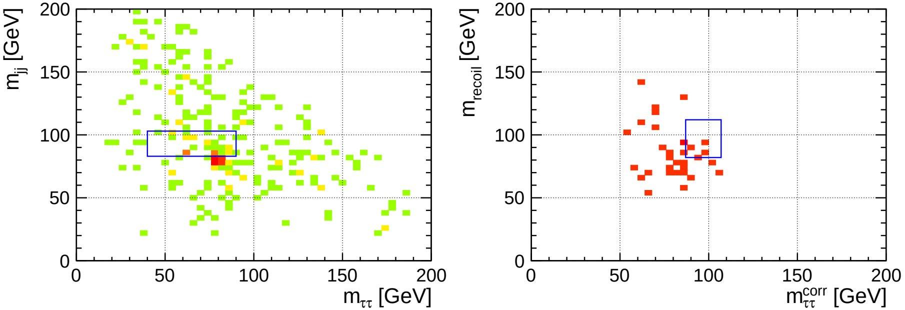
Dominated by $e^+e^- \rightarrow ZZ$ contribution

distribution very similar to signal events...

Event kinematics

Background from *qqqq* in hadronic tau decay channel

no leptons, clustering into four jets, two jets with tau-tag



Right plot: after left plot box cut

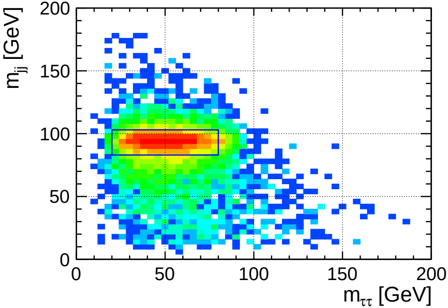
Dominated by $e^+e^- \to W^+W^-$ contribution

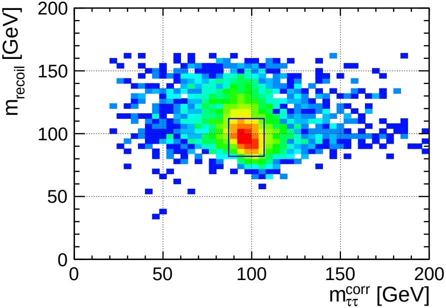
suppressed by tau-tag requirement...

Event kinematics

Signal in semi-leptonic tau decay channel

one leptons, clustering into three jets, one jet with tau-tag





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- corrected h_1 mass and recoil mass

Results from cut-based analysis $900\,\mathrm{fb}^{-1}$ $(-80\%/+30\%)$

Hadronic tau decay selection

Sample	Events expected after			Final
	Presel.	Z mass	h_1 + rec	eff.
Signal	1234.69	711.957	423.921	3.179
$qqqq$	38636	4980.42	603.688	0.004
$ql\nu$	4793.66	104.21	0	0
$qq\tau\nu$	98069.7	296.134	0	0
$qqll$	929.392	29.5045	0	0
$qq\tau\tau$	10283.6	4360.07	2107.54	1.41
$qq\nu\nu$	1426.37	0	0	0
h_2	1889.55	486.201	22.1	0.02
Total	156028	10256.5	2733.33	
Significance	7.54			

Results from cut-based analysis $900\,\mathrm{fb}^{-1}$ $(-80\%/+30\%)$

Semi-leptonic final state selection

Sample	Events expected after			Final eff.
	Presel.	Z mass	h_1 + rec	
Signal	1738.75	1168.28	702.356	5.267
$qqqq$	150.922	0	0	0
$ql\nu$	491142	2917.88	208.42	0.002
$qq\tau\nu$	70134.4	444.201	0	0
$qqll$	17053.6	678.604	44.2568	0.003
$qq\tau\tau$	13011.5	7503.45	3219.61	2.154
$qq\nu\nu$	34.3705	0	0	0
h_2	2552.55	895.052	22.1	0.02
Total	594079	12439.2	3494.39	
Significance			10.84	

Tau tagging

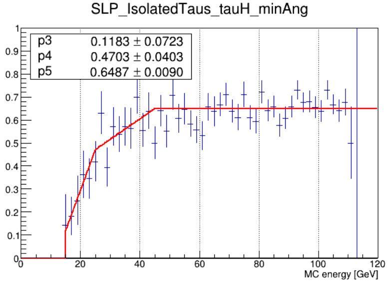
Tau tagging

Tau tagging in Delphes

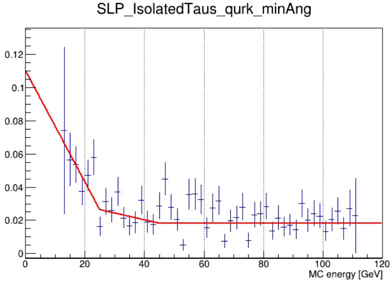
Tau tagging efficiency and miss-tagging probabilities in ILCgen Delphes model taken from ILD full simulation studies.

July 2020 results (Daniel Jeans) based on TaJet Finder by Taikan Suehara

Tagging efficiency



Miss-tagging probability



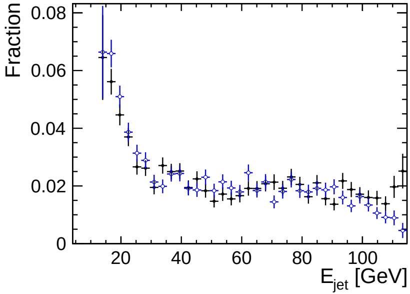
$e^+e^- \rightarrow W^+W^- \rightarrow qql\nu$ events

Tau tagging

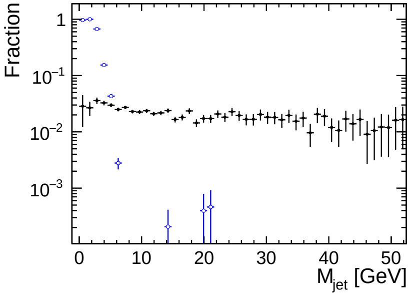
New tau-tagging approach in ILCgen detector model

Old tagging: miss-tagging probability depends on the jet energy only.
New: miss-tagging probability depends on the jet mass and energy

Miss-tagging vs jet energy



Miss-tagging vs jet mass



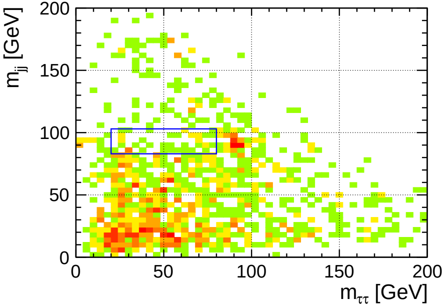
same dependence reproduced

qualitatively new dependence!

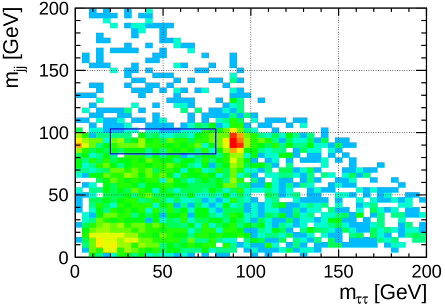
New tau-tagging approach

Background from *qqll* in semi-leptonic tau decay channel

Default tau tagging



New tau tagging



This channel turned out to be most sensitive to tau tagging change

Low mass jet from "lost" lepton has much higher probability to be tau-tagged...

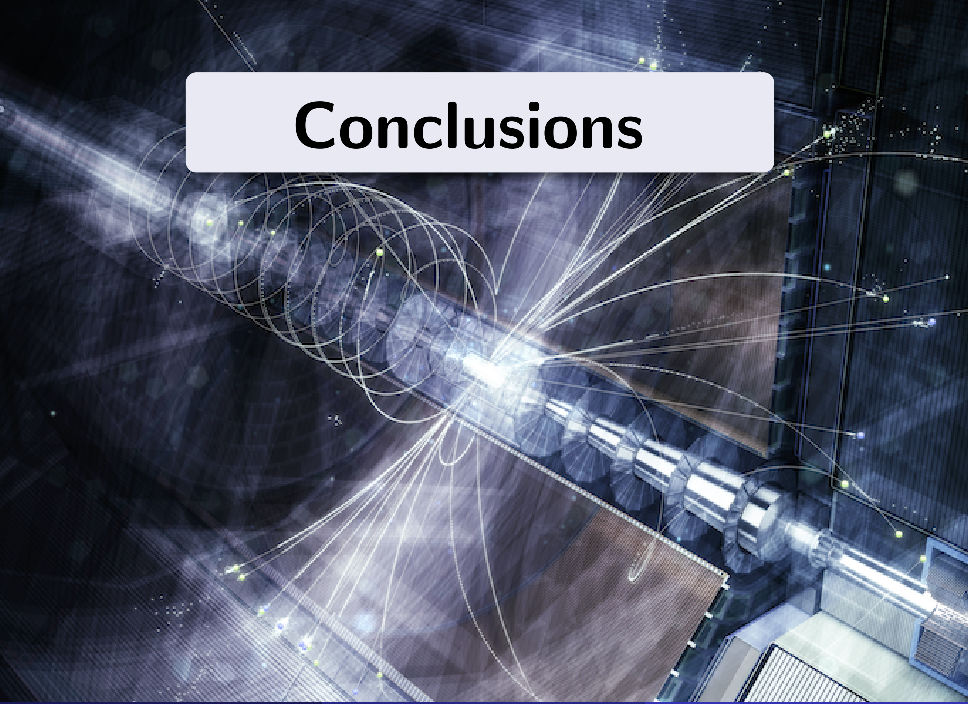
Results from cut-based selection $900\,\text{fb}^{-1}$ $(-80\%/+30\%)$

After all selection cuts, tau tagging description has surprisingly little impact on the final analysis result

Decay channel	Tau tagging	Events expected		Signal significance
		Signal	Total bg.	
Hadronic	old	423.9	2733.3	7.544
	new	435.0	3042.9	7.376
Semi-leptonic	old	702.4	3494.4	10.84
	new	692.9	3475.1	10.73
Leptonic	old	260.0	1353.0	6.474
	new	276.0	1376.4	6.791

Background dominated by $qq\tau\tau$,
which is affected by tagging changes in the same way as the signal

Conclusions



Conclusions

BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can be combined with non-standard decay patterns...

Decays to tau pairs for scalars with mass close to M_Z seem a challenging scenario and a good testing ground for our detector and analysis methods

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Fast simulation indicates that measurement with high significance possible.

The study will continue to get better understand of signal and background

Experimental sensitivity should significantly increase
when more advanced analysis methods (MVA) are used

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Fast simulation indicates that measurement with high significance possible.

The study will continue to get better understand of signal and background

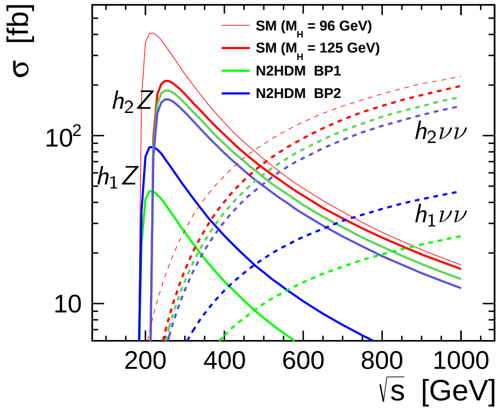
Experimental sensitivity should significantly increase
when more advanced analysis methods (MVA) are used

Full simulation is a must to get reliable quantitative result.

Thank you!

N2HDM model

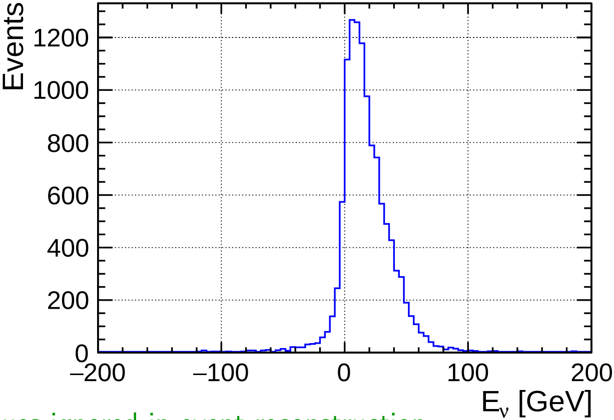
Production cross section for h_1 is about 11% of the SM cross section for this mass (for the considered best-fit point, BP1)



Collinear approximation

Distribution of the neutrino energies from transverse momentum balance.

Hadronic tau decays (two jets with tau-tag)

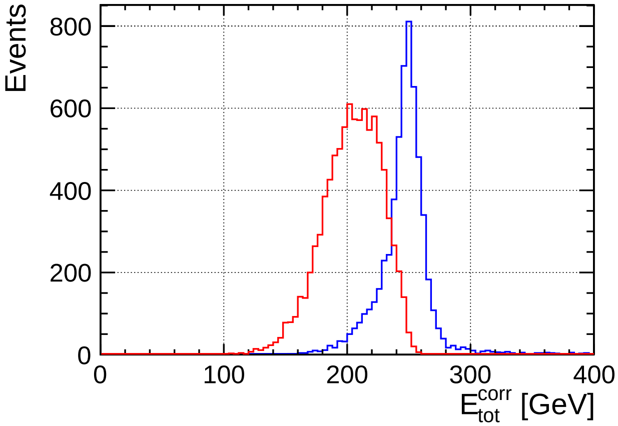


Negative values ignored in event reconstruction

Collinear approximation

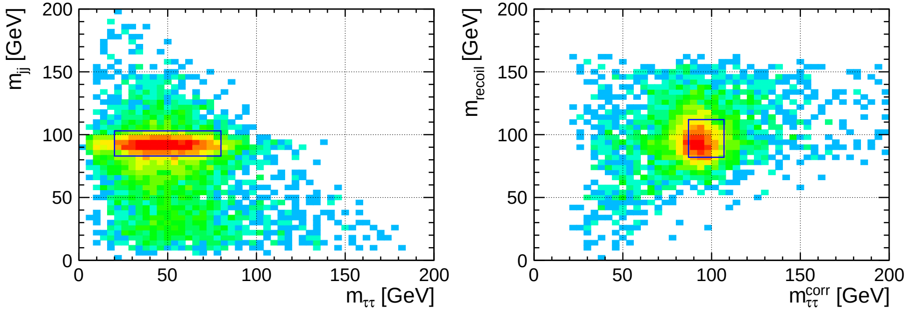
Distribution of the raw and corrected energy of the event.

Hadronic tau decays (two jets with tau-tag)



Event kinematics

Background from $qq\tau\tau$ in semi-leptonic tau decay channel
one leptons, clustering into three jets, one jet with tau-tag



Right plot: after left plot box cut

Dominated by $e^+e^- \rightarrow ZZ$ contribution
distribution very similar to signal events...

Event kinematics

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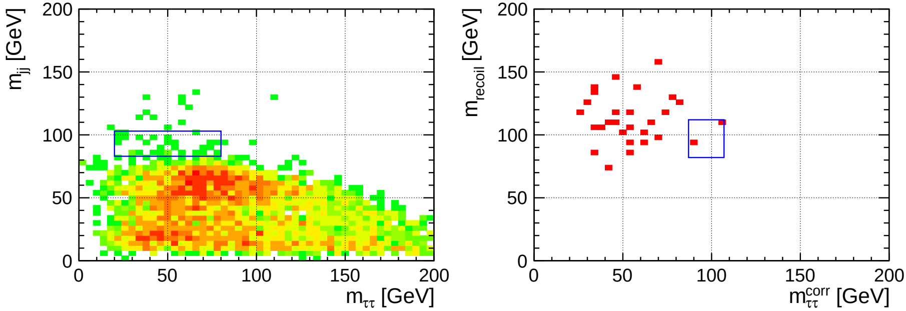


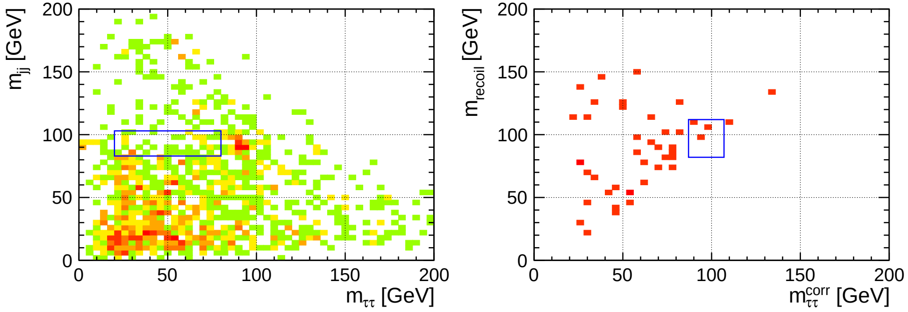
Right plot: after left plot box cut

Dominated by $e^+e^- \to W^+W^-$ contribution
Two-jet final state clustered into three jets...

Event kinematics

Background from *qqll* in semi-leptonic tau decay channel

one leptons, clustering into three jets, one jet with tau-tag



Right plot: after left plot box cut

Dominated by $e^+e^- \rightarrow ZZ$ contribution

one lepton has to be "lost"...

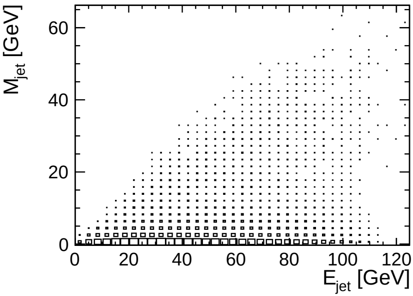
New tau-tagging approach

Weak point of the current Delphes model:

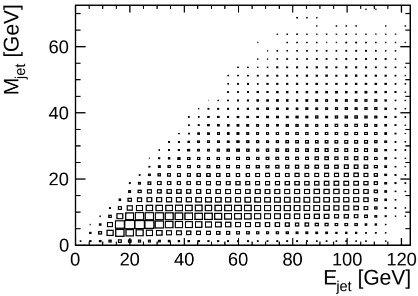
miss-tagging probability depends on the jet energy only.

However, tau jets and quark jets are very different!

Tau jets

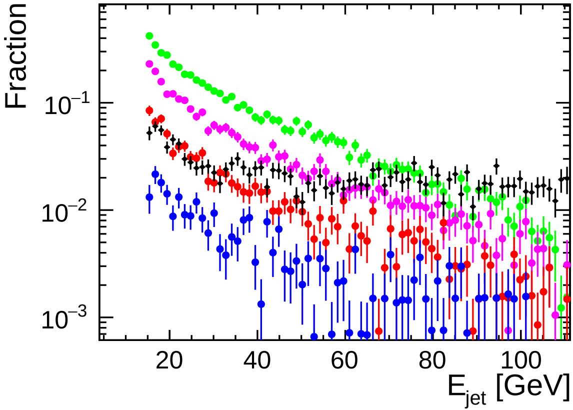


Quark jets



New tau-tagging approach

Fraction of quark jets with mass above 2 GeV, 3 GeV, 4 GeV and 5 GeV, compared with miss-tagging probability (black).



⇒ implement miss-tagging as energy dependent mass cut