Prospects for light Higgs measurements at the 250 GeV ILC

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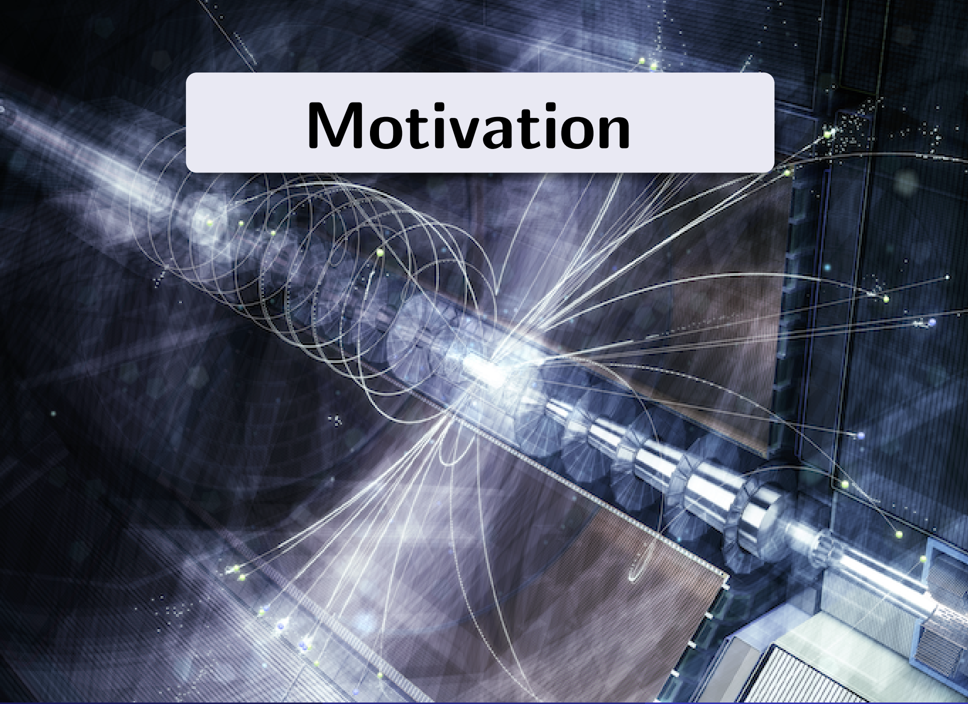
Outline

1. Motivation
2. Analysis setup
3. Tau reconstruction
4. First results
5. Tau tagging
6. Conclusions

Results being prepared for LCWS'2023

All results are very preliminary

Motivation



Experimental hints... arXiv:2203.13180

DESY 22-057
IFT-UAM/CSIC–22–033

Mounting evidence for a 95 GeV Higgs boson

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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.

N2HDM model arXiv:2203.13180

Parameters of the best-fit point for which the minimal value of χ^2 is found (BP1)

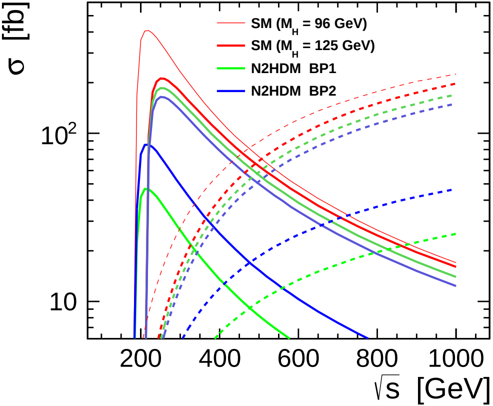
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$		
95.68	125.09	713.24	811.20	677.38		
$\tan\beta$	α_1	α_2	α_3	m_{12}	v_S	
10.26	1.57	1.22	1.49	221.12	1333.47	
$\mathrm{BR}_{h_1}^{bb}$	$\mathrm{BR}_{h_1}^{gg}$	$\mathrm{BR}_{h_1}^{cc}$	$\mathrm{BR}_{h_1}^{\tau\tau}$	$\mathrm{BR}_{h_1}^{\gamma\gamma}$	$\mathrm{BR}_{h_1}^{WW}$	$\mathrm{BR}_{h_1}^{ZZ}$
0.005	0.348	0.198	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.

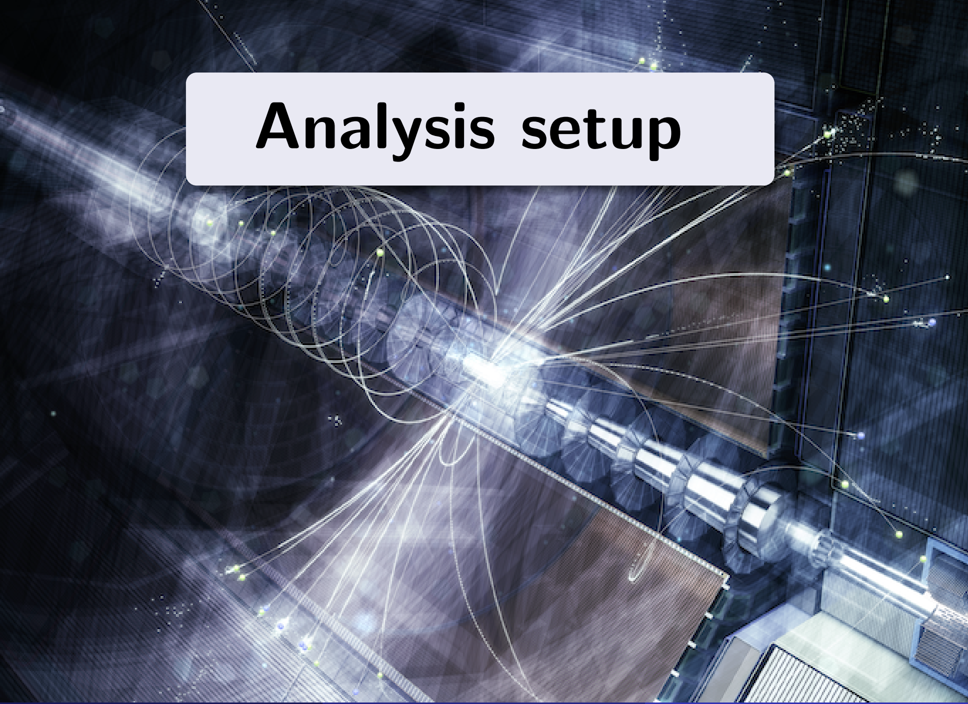
Interesting pattern for light Higgs: no $b\bar{b}$ decays, $\tau^+\tau^-$ decays dominate...

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)



Analysis setup



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.

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

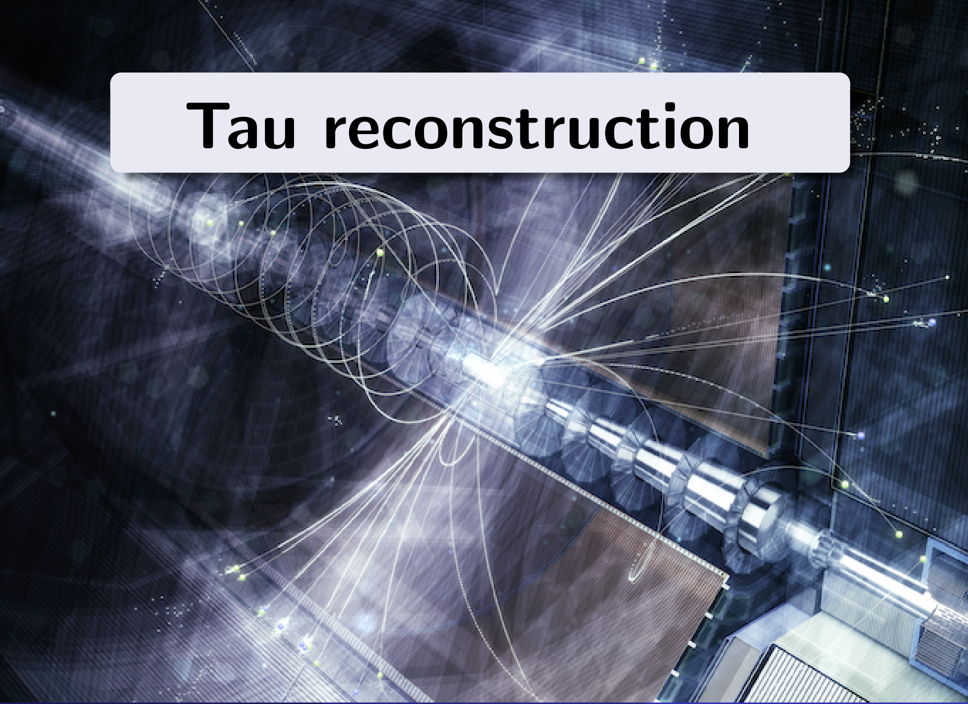
Signal sample: with S2HDM UFO model

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

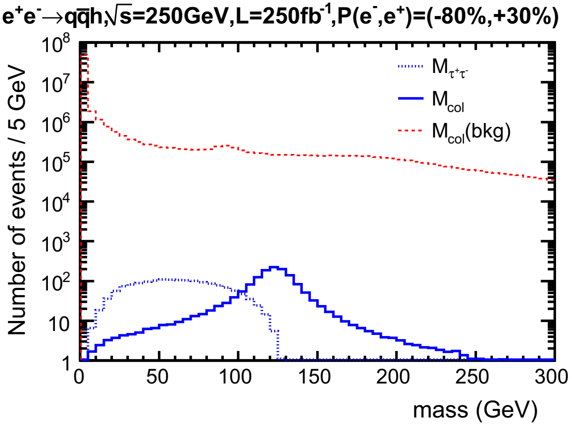
Tau reconstruction



Collinear approximation

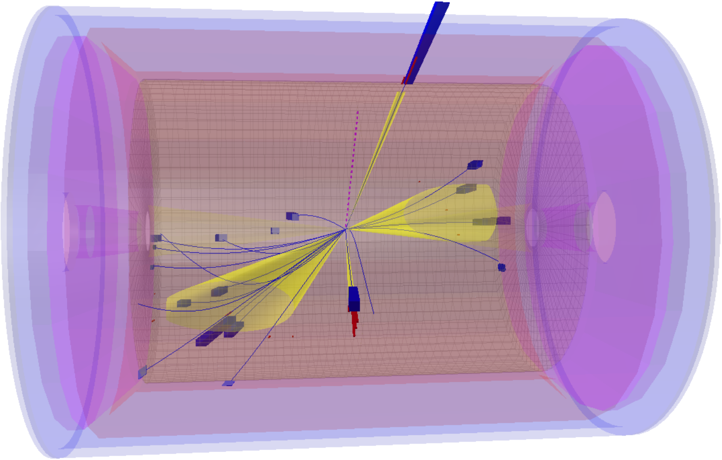
arXiv:1509.01885

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).



Tau reconstruction

Collinear approximation

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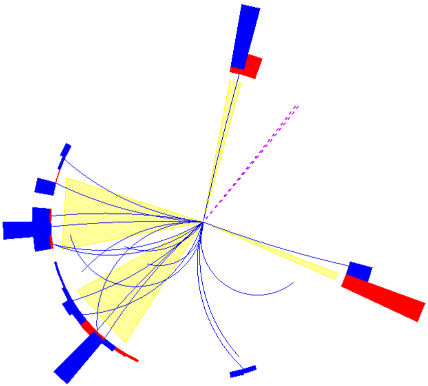
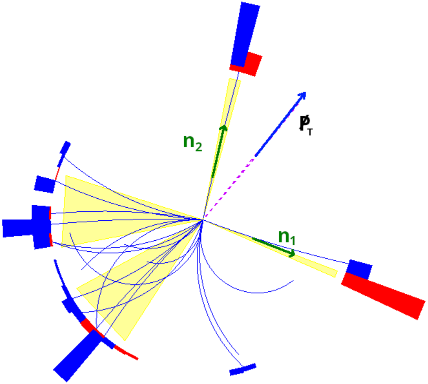


Collinear approximation

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:

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

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

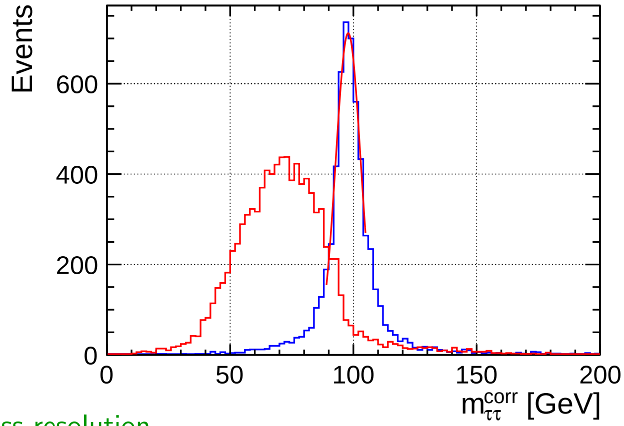
Unique solution

Tau reconstruction

Collinear approximation

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

Hadronic tau decays (two jets with tau-tag)

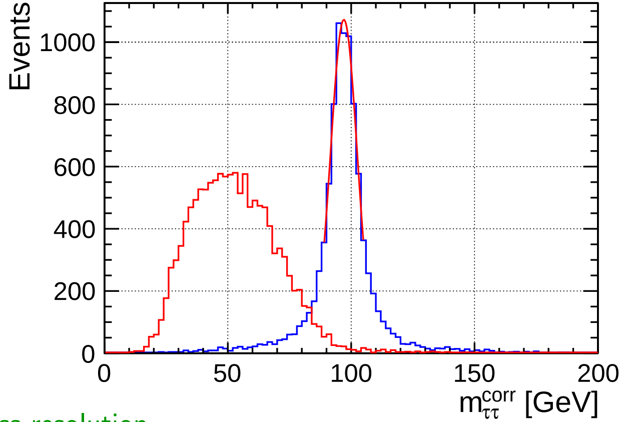


5.0 GeV mass resolution

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)

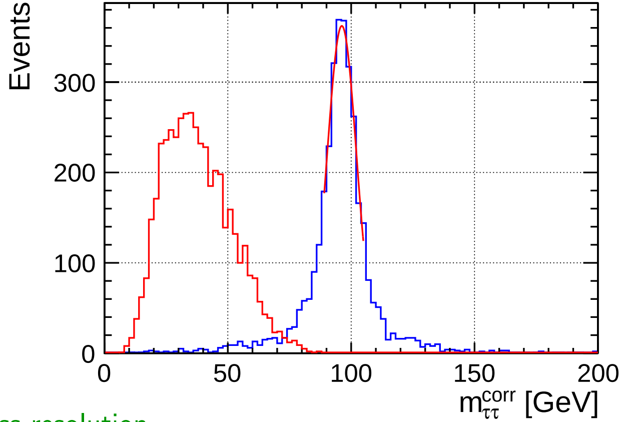


5.4 GeV mass resolution

Collinear approximation

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

Leptonic tau decays (two isolated leptons)

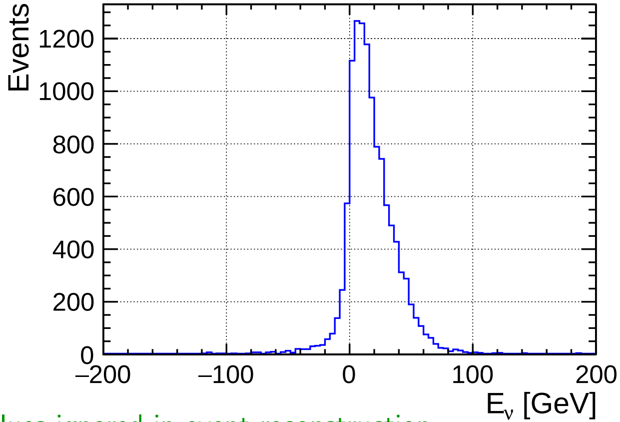


6.0 GeV mass resolution

Collinear approximation

Distribution of the neutrino energies from transverse momentum balance.

Hadronic tau decays (two jets with tau-tag)

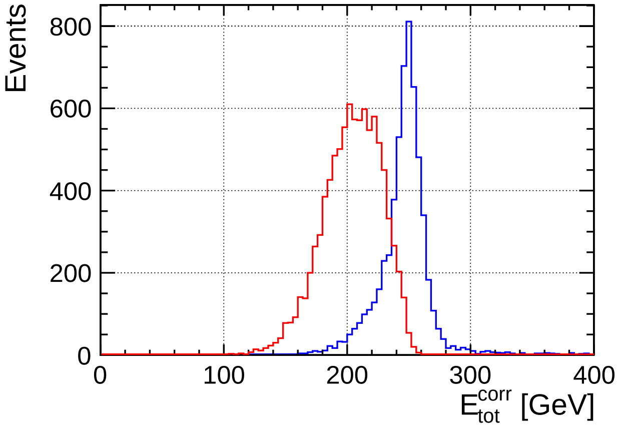


Negative values ignored in event reconstruction

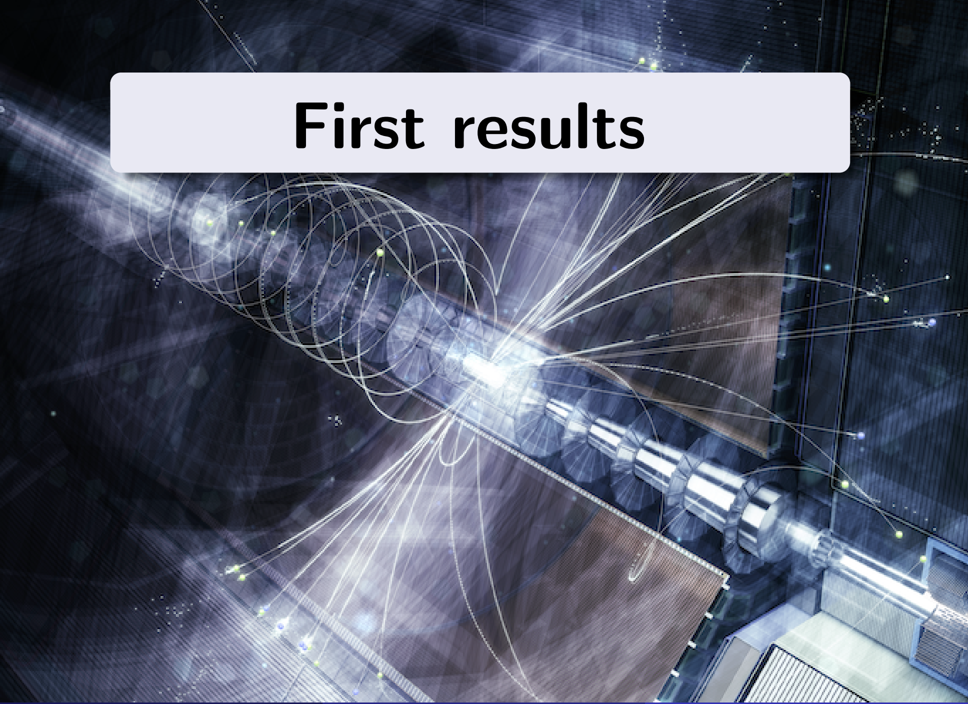
Collinear approximation

Distribution of the raw and corrected energy of the event.

Hadronic tau decays (two jets with tau-tag)

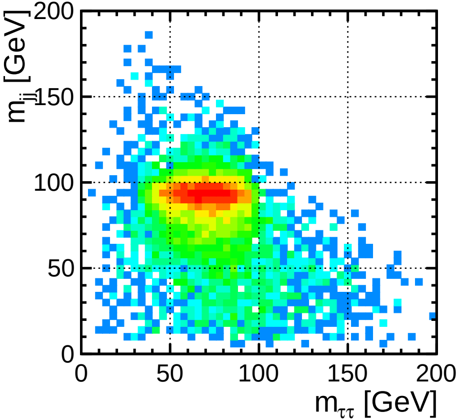


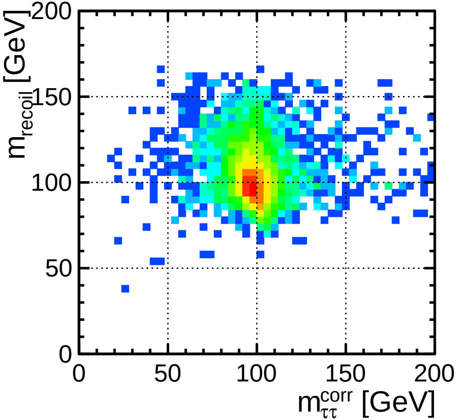
First results



Event kinematics

Signal in hadronic tau decay channel (two jets with tau-tag)

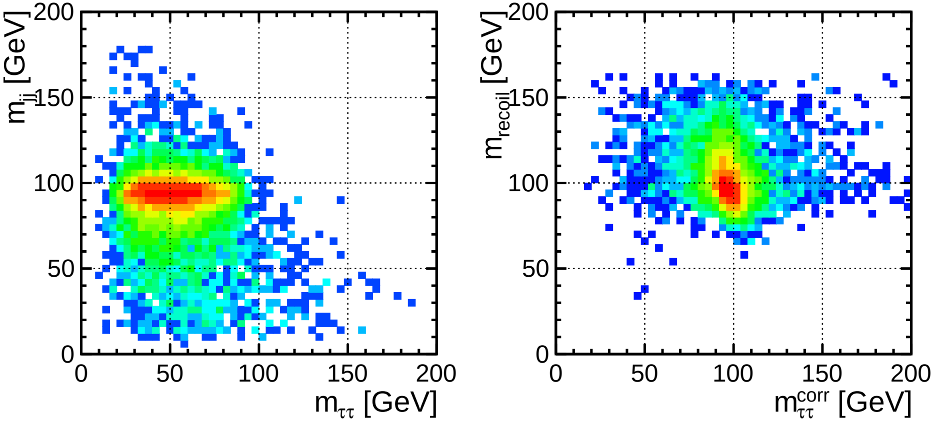




⇒ apply simple window cuts on reconstructed Z, h_2 and recoil mass

Event kinematics

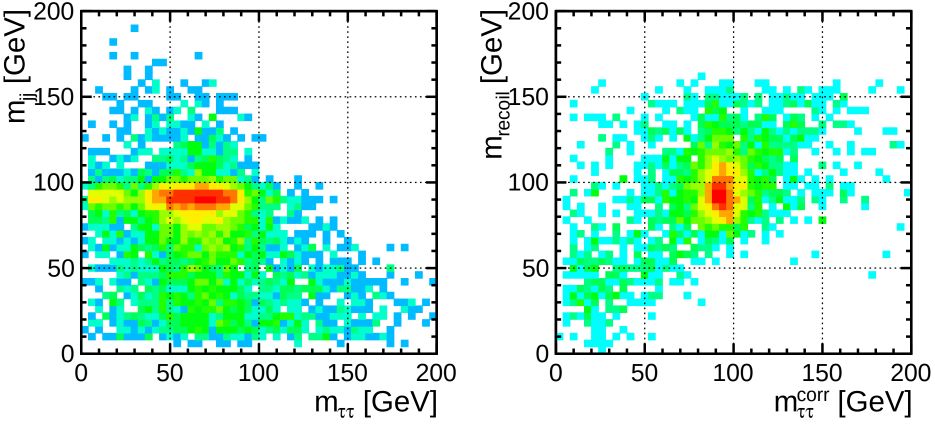
Signal in semi-leptonic tau decay channel (one lepton + one jets with tau-tag)



⇒ apply simple window cuts on reconstructed Z, h_2 and recoil mass

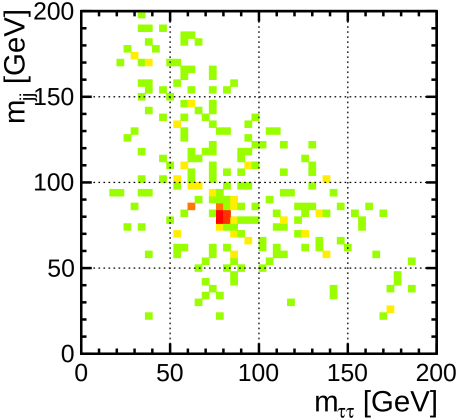
Event kinematics

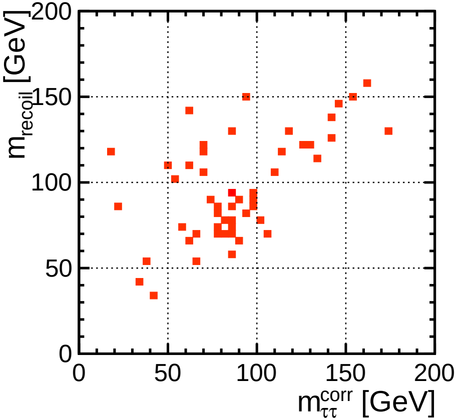
Background from $qq\tau\tau$ in hadronic tau decay channel (two jets with tau-tag)



Event kinematics

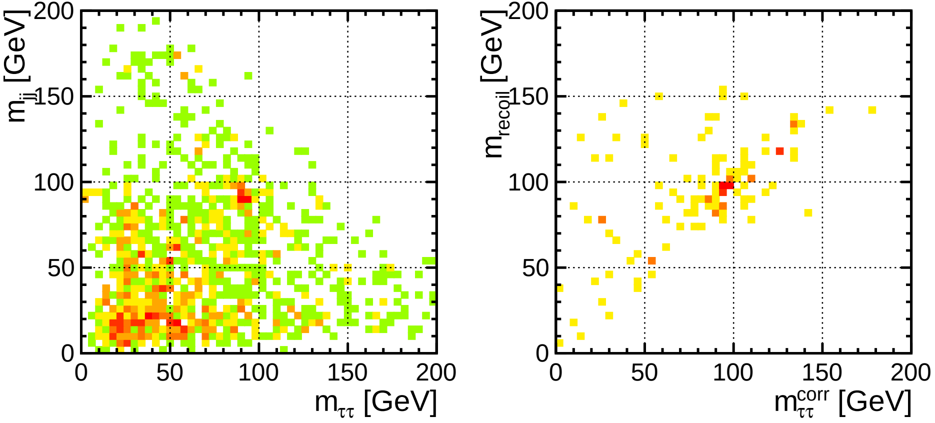
Background from *qqqq* in hadronic tau decay channel (two jets with tau-tag)





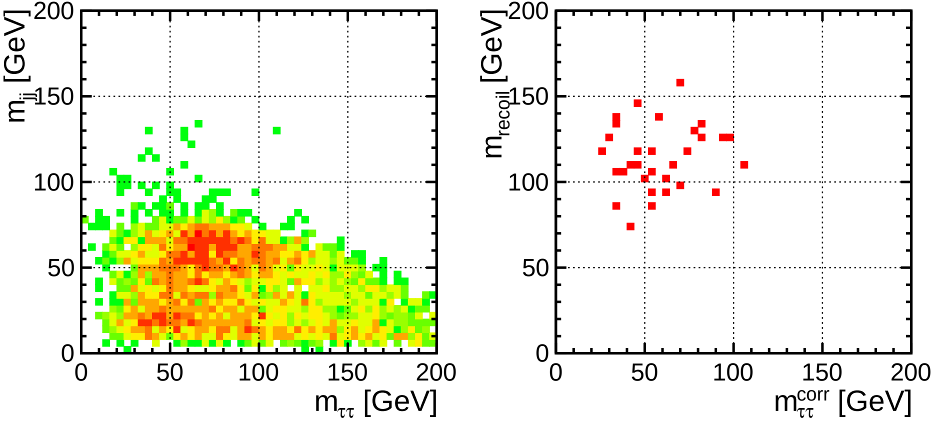
Event kinematics

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



Event kinematics

Background from $qql\nu$ in semi-leptonic tau decay channel



Results from cut-based selection

Hadronic events

Sample	Events expected after			Final
	Presel.	Z mass	h_1 + rec	eff.
Signal	1234.69	780.233	457.125	3.428
$qqqq$	38636	7998.86	754.61	0.005
$ql\nu$	4793.66	104.21	0	0
$qq\tau\nu$	98069.7	641.623	0	0
$qqll$	929.392	44.2568	0	0
$qq\tau\tau$	10283.6	5436.26	2231.6	1.493
$qqvv$	1426.37	5.72841	0	0
h_2 bg	1889.55	861.902	22.1	0.02
Total	156028	15092.8	3008.31	
Significance			7.765	

Results from cut-based selection

Semi-leptonic events

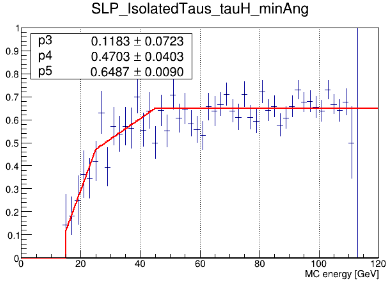
Sample	Events expected after			Final
	Presel.	Z mass	h_1 + rec	eff.
Signal	1738.75	1226.29	734.493	5.508
$qqqq$	150.922	0	0	0
$qql\nu$	491142	3334.72	208.42	0.002
$qq\tau\nu$	70134.4	493.556	0	0
$qqll$	17053.6	1932.55	501.577	0.034
$qq\tau\tau$	13011.5	8337.5	3306.3	2.212
$qq\nu\nu$	34.3705	0	0	0
h_2 bg	2552.55	1204.45	22.1	0.02
Total	594079	15302.8	4038.4	
Significance	10.632			

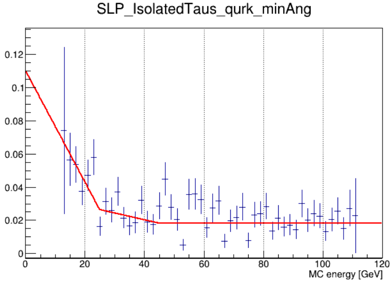
Tau tagging

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





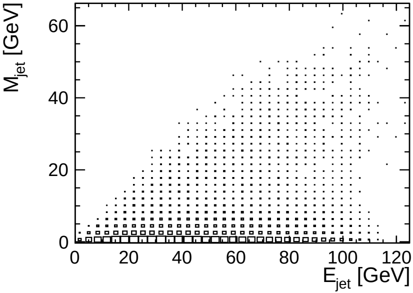
New approach

Weak point of the current Delphes model:

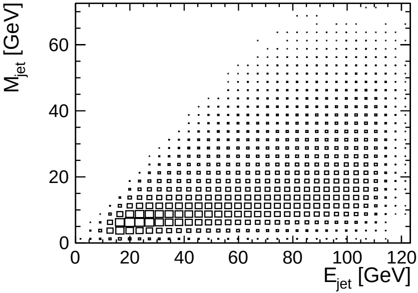
miss-tagging probability depends on the jet energy only.

However, tau jets and quark jets are very different!

Tau jets

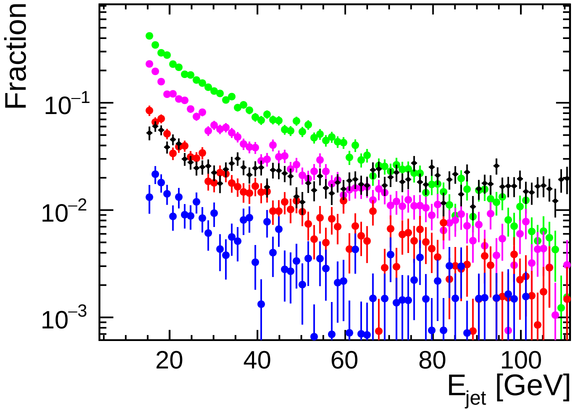


Quark jets



New approach

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



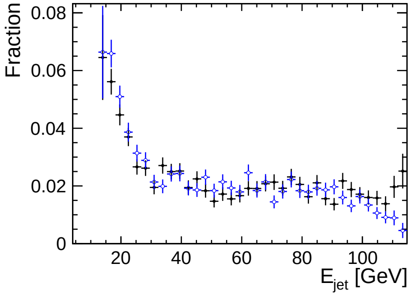
⇒ implement miss-tagging as energy dependent mass cut

Tau tagging

New approach

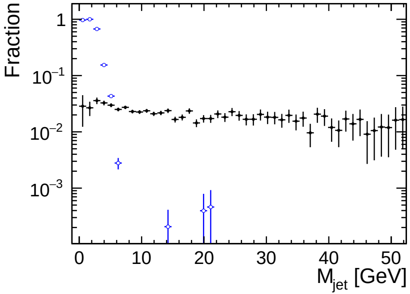
Alternative tau tagging implementation in ILCgen model.
Old vs new miss-tagging probability as a function of

jet energy



same dependence reproduced

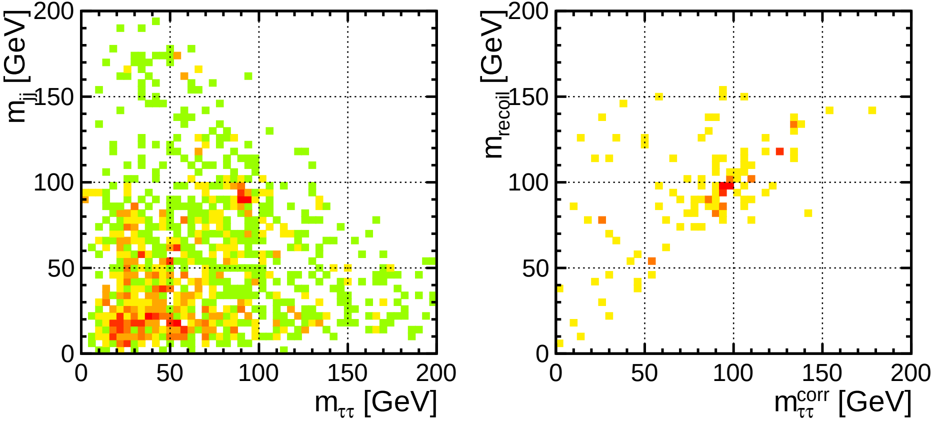
jet mass



qualitatively new dependence!

Old approach

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

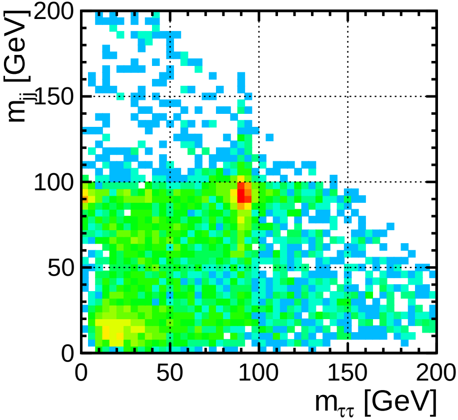


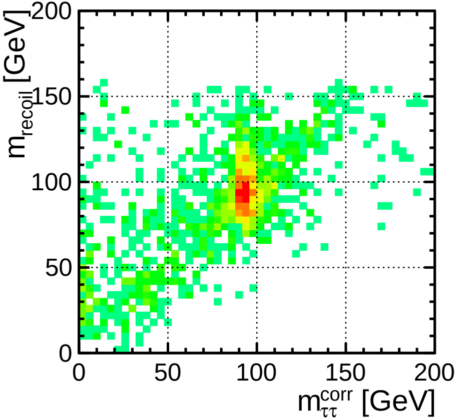
Turned out to be most sensitive to tau tagging change

Tau tagging

New approach

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





Increases by factor 16 (!) with new tau tagging...

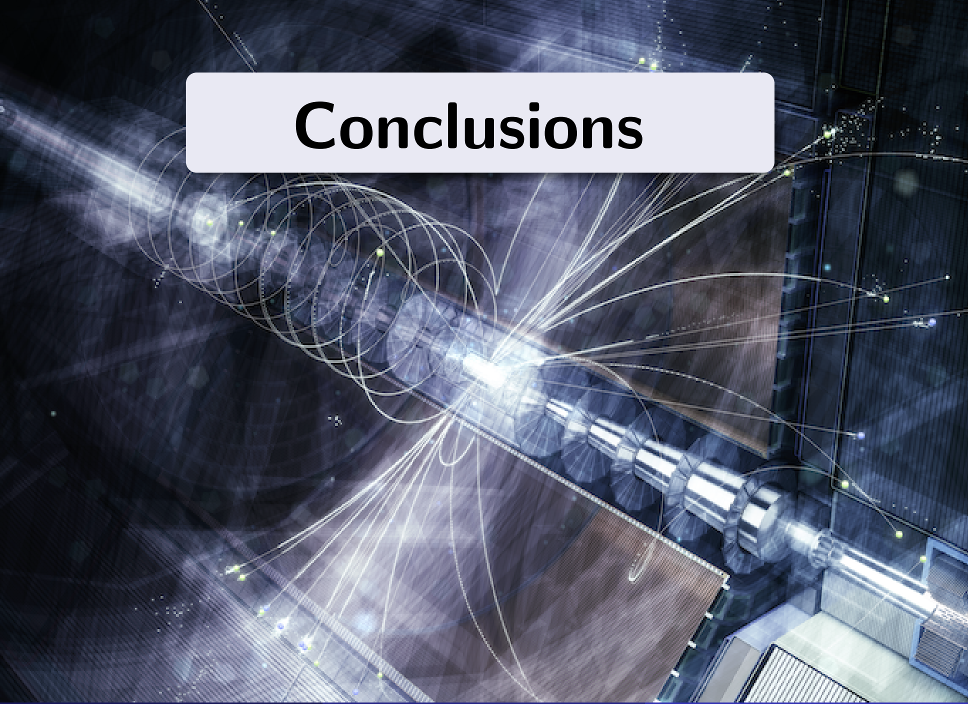
Results from cut-based selection with new tau tagging

Semi-leptonic events

hadronic channel much less affected

Sample	Events expected after			Final
	Presel.	Z mass	h_1 + rec	eff.
Signal	1781.03	1238.82	725.959	5.444
$qqqq$	0	0	0	0
$qql\nu$	1759070	16986.2	208.42	0.002
$qq\tau\nu$	250727	2072.94	0	0
$qqll$	85563.1	25152.6	8054.73	0.546
$qq\tau\tau$	13731.9	8530.32	3306.3	2.212
$qq\nu\nu$	22.9136	0	0	0
h_2 bg	3138.21	1292.85	0	0
Total	2112250	54034.8	11569.5	
Significance			6.547	

Conclusions



Conclusions

Scenarios with light scalars still not excluded

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

Conclusions

Scenarios with light scalars still not excluded

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

Fast simulation indicates that measurement with high significance possible.

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

Full simulation is a must to get reliable quantitative result.