The measurement of $h \rightarrow \tau^+\tau^-$ with tau reconstruction using impact parameters

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Introduction

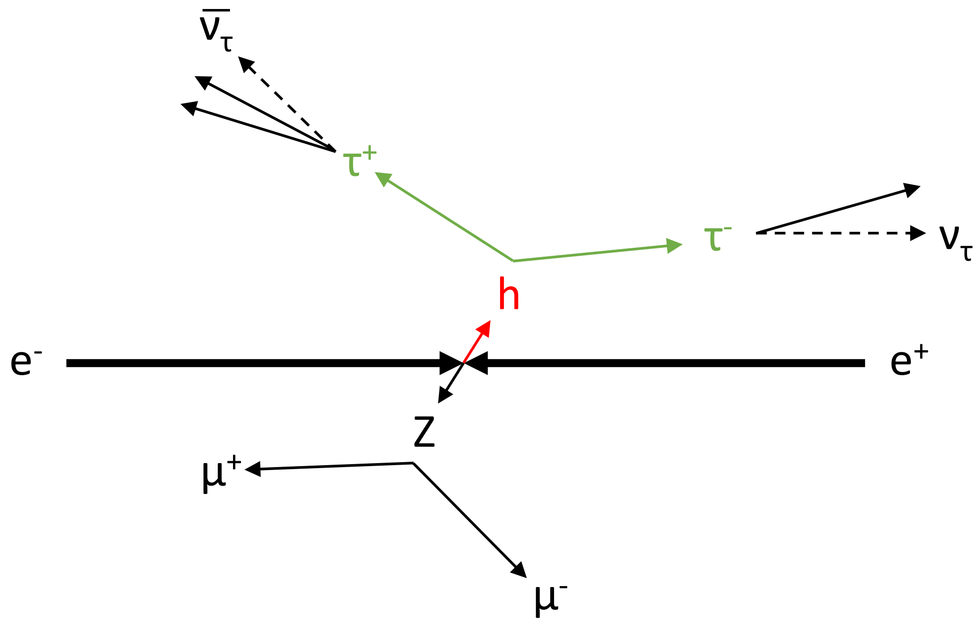
- New physics at the TeV scale can imply deviations in the Higgs couplings of the order of a few percent
- In the 250 GeV stage of the ILC, ILD will make a measurement of the branching fraction of Higgs to taus
- Existing projections[1] use traditional tau reconstructions methods, but the measurement precision might be improved using reconstruction with impact parameters[2]
- A comparison is made for the $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ channel, because its reconstruction is effective

[1] S. Kawada et al., A study of the measurement precision of the Higgs boson decaying into tau pairs at the ILC, arXiv:1509.01885

[2] D. Jeans, Tau lepton reconstruction at collider experiments using impact parameters, arXiv:1507.01700v3

Signal process topology

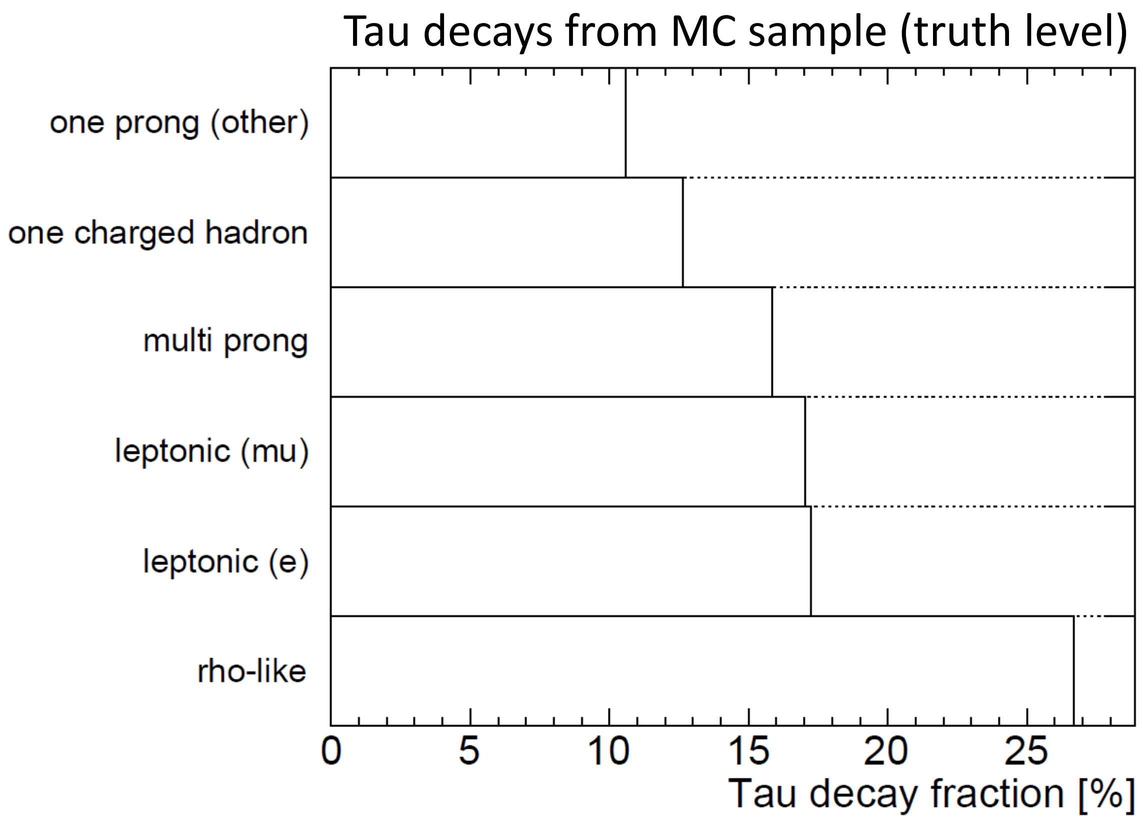
- At 250 GeV Zh production is dominant
- The Z and Higgs boson will be produced with low momentum
- The two tau jets will be highly boosted
- The taus will travel up to a few mm before decaying into a neutrino, one or more charged particles, and possibly neutral particles
- There will be small opening angle between the decay products
- The recoiling Z will decay to a pair of muons



Tau decay modes

Distinguish the tau decays by their visible decay products:

- Leptonic (e and mu)
- One charged hadron (mostly pions)
- ρ-like is one charged pion and one neutral pion
- One prong (other) is one charged hadron and neutrals
- All others are considered multi-prong

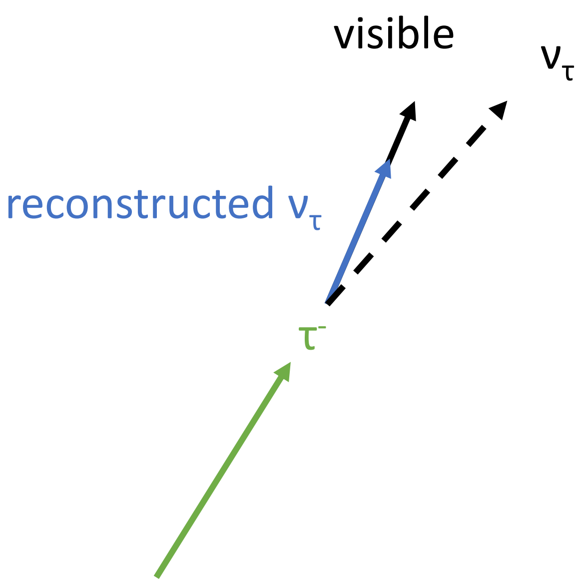


Reconstruction of tau momentum

Taus decay to at least one neutrino which is not measured. How can the momentum be reconstructed? (3 unknowns per tau)

The collinear approximation

- The tau is highly boosted so the neutrino momentum is assumed to be in the same direction as the visible decay products (2 constraints per tau)
- The magnitude can be found by requiring e.g. the missing momentum of the event to be balanced (2 constraints in total)
  - Or using the tau mass (1 constraint per tau)



Reconstruction of tau momentum

Reconstruction using impact parameters

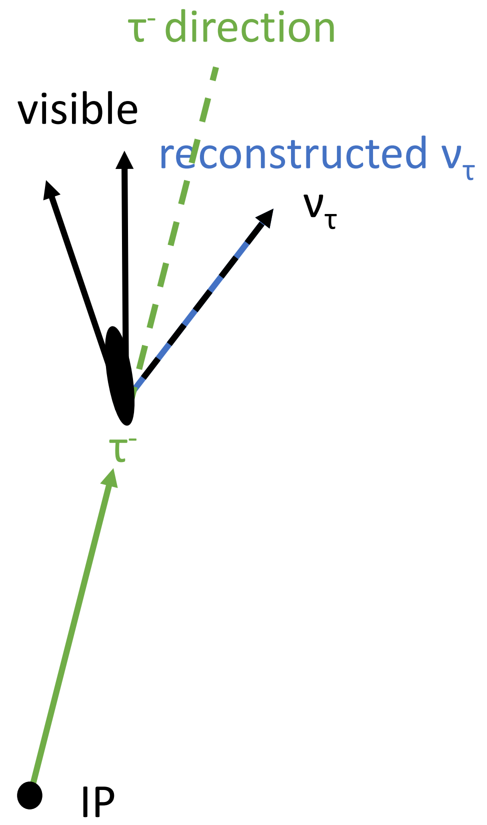
In multiprong decays:

- The direction of tau momentum is along the line from the interaction point to the tau vertex (2 constraints per tau)
- The magnitude is found by imposing the tau mass constraint (1 constraint per tau)

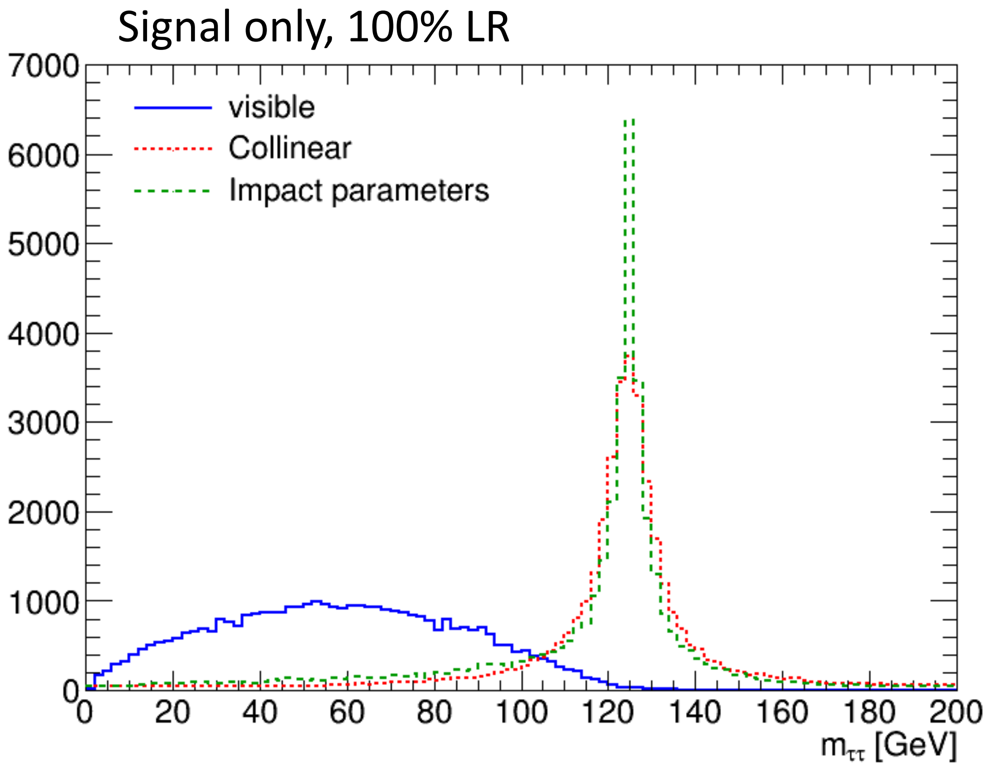
In one prong decays the tau vertex cannot be fully reconstructed (-1 constraint per tau), so the missing transverse momentum is minimized (+2 constraint in total)

For multiprong decays: error of tau vertex in the longitudinal direction is large so also use one prong method

Fall back on collinear method if no solution is found (~15%)



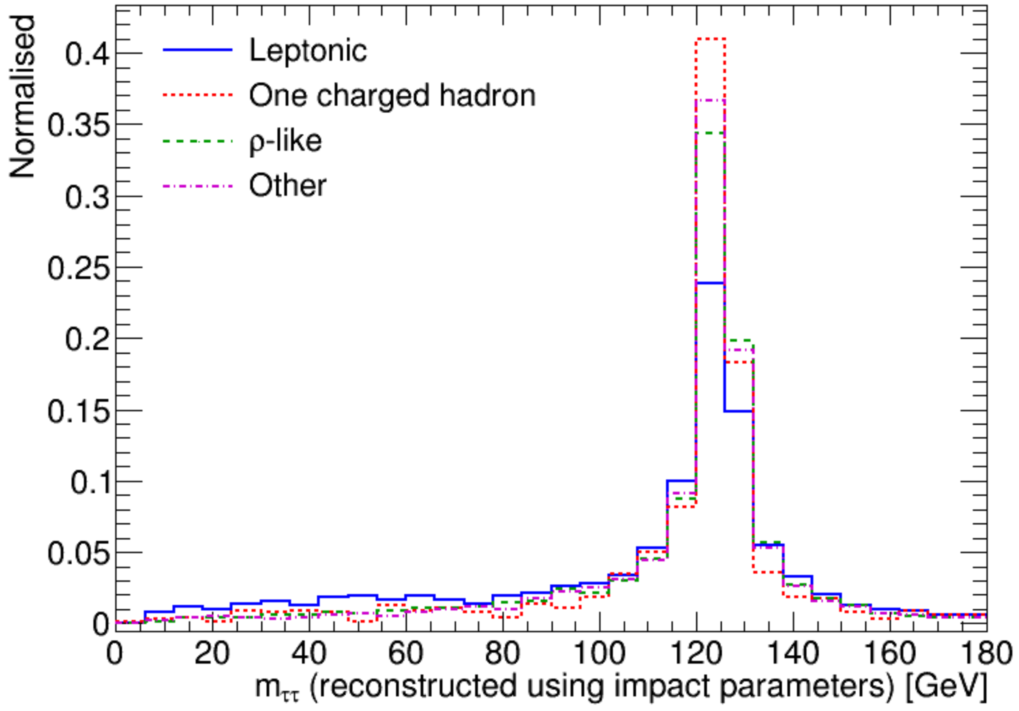
Collinear mass and impact parameter mass



- The visible mass is unprecise has its maximum below the actual value
- In the collinear approximation the mass peaks at the correct value
- Using impact parameters the mass is more precise (more peaked)
  - But the tail is slightly longer

Reconstructed tau pair mass per decay mode

Signal only, 100% LR



Requiring both taus to have the same decay mode:

- The most narrow peak is the $\tau \to \pi\nu_\tau$ process
- The ρ-like decay and other one prongs and multiprong decay can also be reconstructed well
- Although the impact parameter method is not applicable to the leptonic decay mode because of extra neutrinos, it still work OK

Events samples and reconstruction

- Look at Daniels ILD samples (ILCSoft v01-19-04) in the $e^+e^- \rightarrow \mu^+\mu^-\tau^+t^-$ channel
- Use $P(e^-,e^+)$=(-80%,30%) data from the updated H20 run scenario at 250 GeV
  - Effectively use weights LL:LR:RL:RR 0.315:0.585:0.035:0.065
- To start, only the irreducible (Higgsless) background is taken into account, because the other backgrounds are almost completely be eliminated using cuts
- The reconstruction and cuts from a previous analysis by Kawada will be followed

Event reconstruction

1. Muons are selected (using `IsolatedLeptonFinder`)
    1. Leptons have $|d_0/\ \sigma_{do}| < 3$ and $|z_0/\ \sigma_{zo}| < 3$
    2. Identify muons by $E_{ECal} < E_{HCal}$ and $(E_{ECal} + E_{HCal})/P_{Track} < 0.6$
        - Photons within $\cos(\theta) > 0.999$ are added to the lepton mass
    3. The muon pair with its mass closest to the Z mass is selected
2. Select taus
    1. Repeat until there are no more charged particles:
        1. Select the highest momentum charged particle
        2. particles are added in a cone with 1 rad. half angle, while the candidate mass is smaller than the expected tau mass
            - If there are exactly 2 photons, the momentum is scaled such that it equals the pion mass
    2. The highest energy tau candidate of each charge is selected

Basic event selection

- Use some basic pre-selection cuts:
  - Number of charged PFOs < 7
  - Selected pair of leptons of opposite charge
  - Pair of tau candidates of opposite charge

Number of signal events

	LR sample	RL sample
Total number of generated events	47570	45594
Pair of isolated leptons	44653	42785
number of charged PFOs < 7	40392	38665
Pair of tau candidates	37950	36228

Comparison with cut flow from Kawada

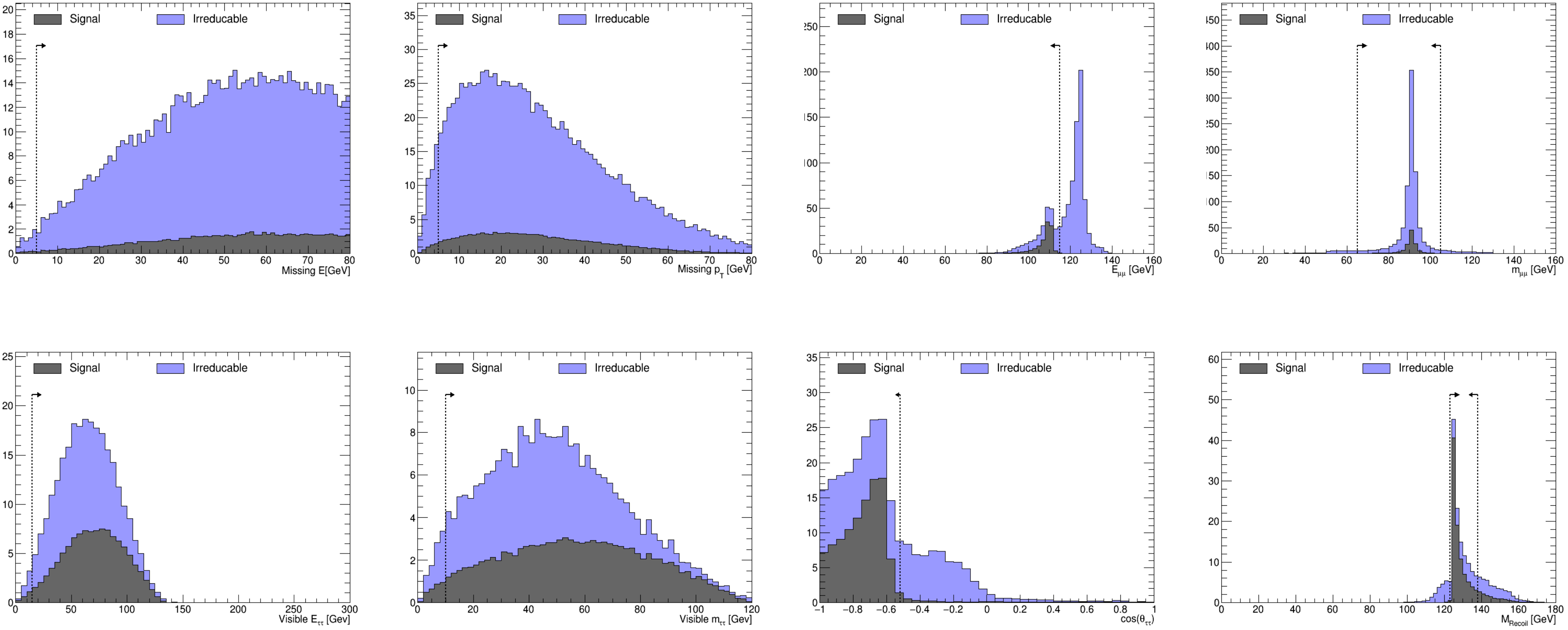
Number of events for 250 fb^{-1}

Cut	My cut flow: Signal	My cut flow: Irreducible 4f	Selected form Kawada's thesis: Signal	Selected form Kawada's thesis: Other higgs	Selected form Kawada's thesis: 4f
Preselected events	129	1024	133	56	6382
Missing E > 5 GeV | E_{vis} > 245 GeV	125	981	132	55	3960
Missing p_T > 5 GeV	120	938	126	54	2673
|Missing $\cos(\theta)$| <0.97	119	895	124	53	2480
65 GeV < $m_{\mu\mu}$ < 105 GeV	113	799	122	52	756
$E_{\mu\mu}$ < 115 GeV	112	154	121	50	559
Visible $E_{\tau\tau}$> 15 GeV	110	150	119	50	270
Visible $M_{\tau\tau}$ > 10 GeV	108	146	117	44	192
$\cos(\theta_{\tau\tau})$ < -0.52	104	82	116	6	117
123 < M_{recoil}< 138 GeV	90	32	99	5	41

Columns with main differences (← Missing E > 5 GeV \| E_{vis} > 245 GeV; ← $\cos(\theta_{\tau\tau})$ < -0.52)

- Backgrounds with < 1 events are not shown from Kawada's thesis
- It seems some reducible 4f and Higgs events are still missing in this analysis
- Kawada's main BDT analysis has 102 signal and 31 background events

Cut flow in diagrams

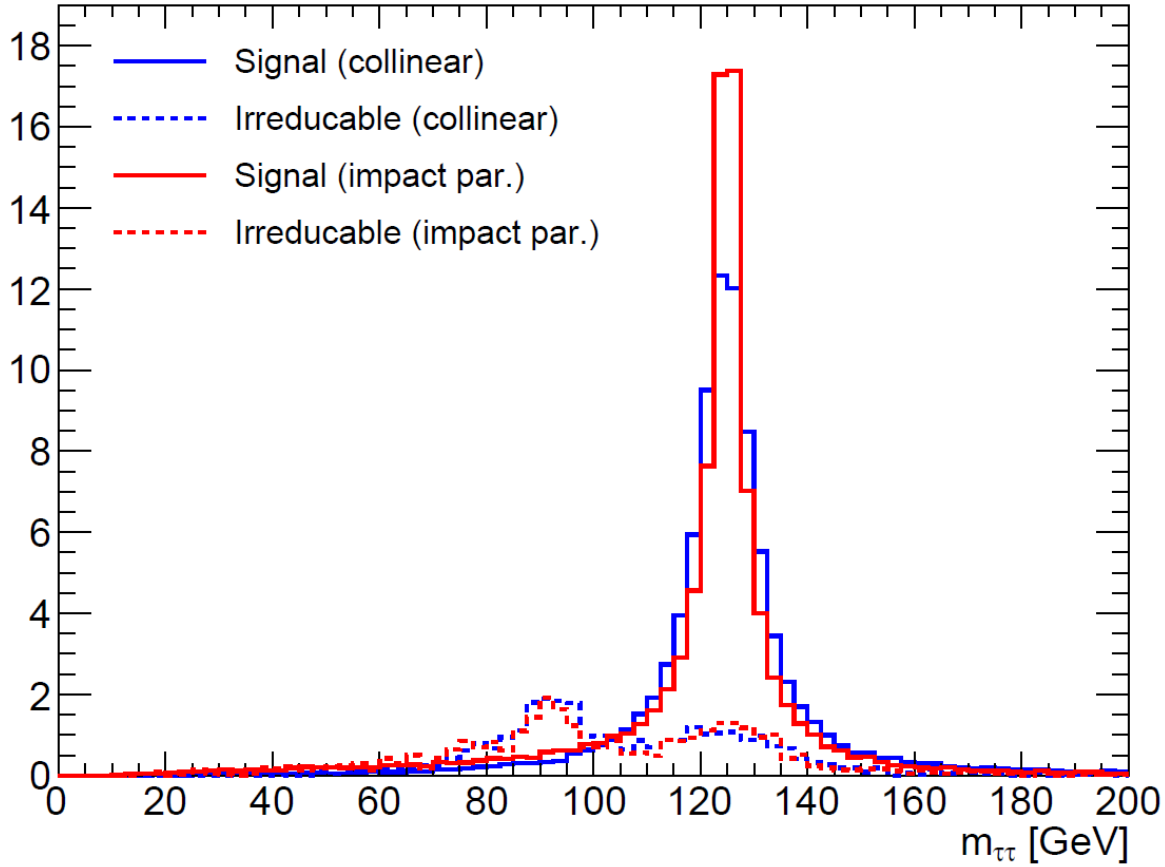


Comparison after example cut flow

- Kawada does not cut on $m_{\tau\tau}$ (collinear)
- Reconstruction method does not affect background by a lot
- Here a cut on the collinear mass is more effective

	Signal	Irreducible	$S/\sqrt{S+B}$
After cutflow	90	32	8.14
$M_{\tau\tau}$ > 100 GeV (collinear)	85	17	8.40
$M_{\tau\tau}$ > 100 GeV (impact parameters)	79	15	8.15

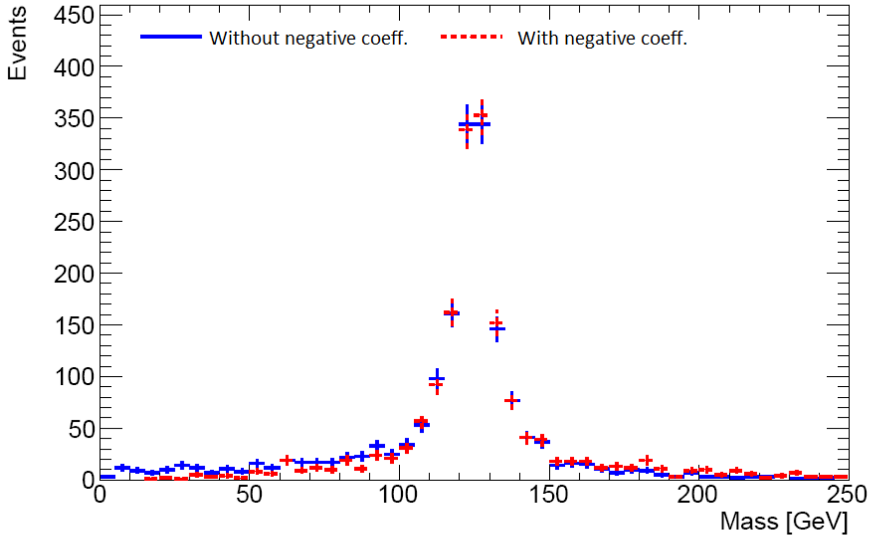
- Difference should be investigated



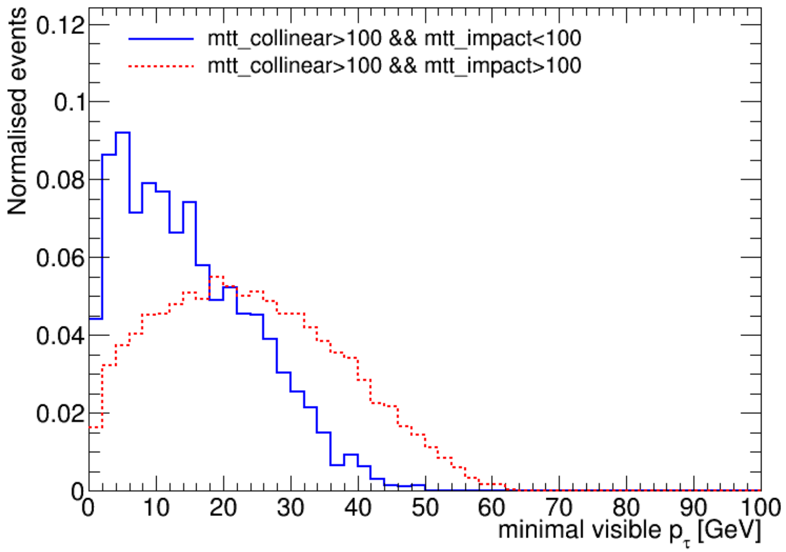
Signal peak is slightly narrower, but also longer tail

Possible cause of difference?

In some cases the impact parameter method might be to restrictive



For the collinear method, the effect requiring the coefficients of the neutrino momentum to be >=0, i.e. neutrino must travel in the same direction as the visible decay products



Events in which the collinear method did better generally had one low momentum tau. For these events the impact parameter is expected to be less effective

Conclusions

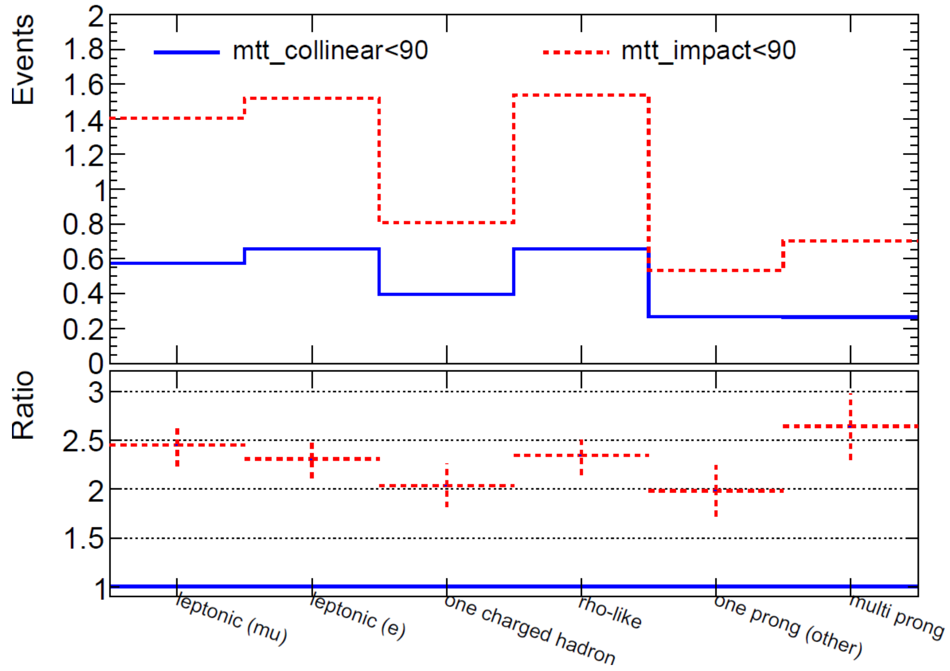
- A small part of the Higgs branching ratio to taus was repeated for the $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ channel
- The impact parameter method was applied, and does in some cases gives a better reconstruction performance (narrower peak)
- However an additional cut on the tau pair mass reconstructed using impact parameters does not outperform the tau pair mass using the collinear approximation

- The cause of differences should be investigated
- All backgrounds should be included, to re-optimize cut flows

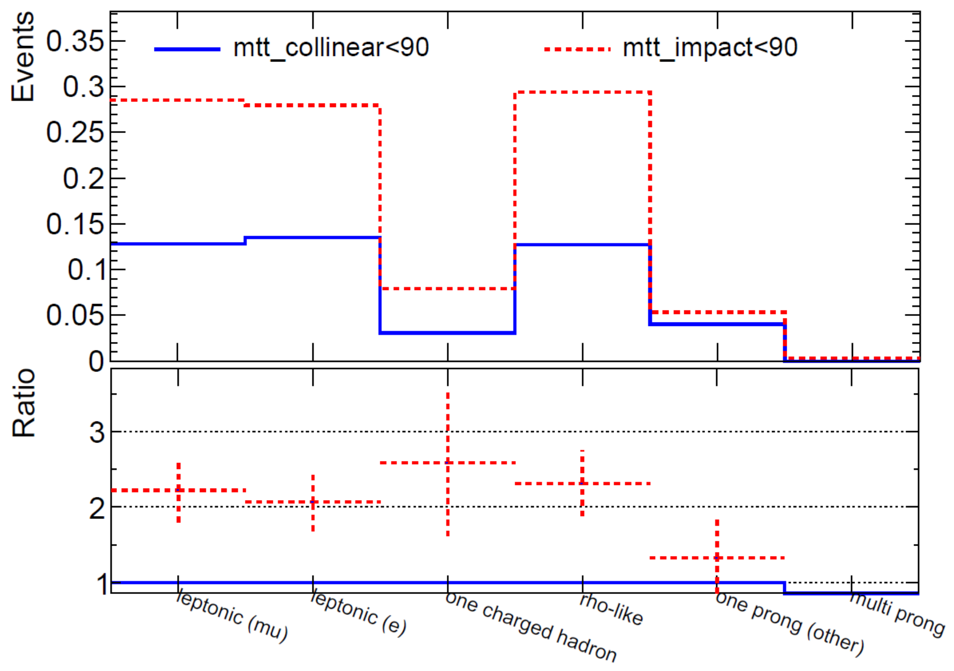
Decay modes in tail

- No specific differences between decay modes

Negative tau decay (all positive tau decays)



Negative and positive tau decay are the same



Collinear approximation using tau mass

- Visible mass
- Collinear approximation using missing transverse momentum
- Collinear approximation using tua mass