Higgs self-coupling measurement at the ILC

DPG-Frühjahrstagung der Sektion Materie und Kosmos (SMuK) | 2025/04/03 | Göttingen

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The Higgs self-coupling λ in the SM

$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + o(h^4); \lambda_{SM} = \frac{m_H^2}{2v^2}$$

v vacuum expectation value (vev) of Higgs field h

m_H mass of Higgs boson

- in SM: λ_{SM} fixed since m_H is known [At/Cm12]
  - deviation from $\lambda = \lambda_{SM}$ hints at BSM physics
  - beyond the SM, many values are possible
    strong-case for **model-independent measurements**
  - most projections assume $\lambda = \lambda_{SM}$

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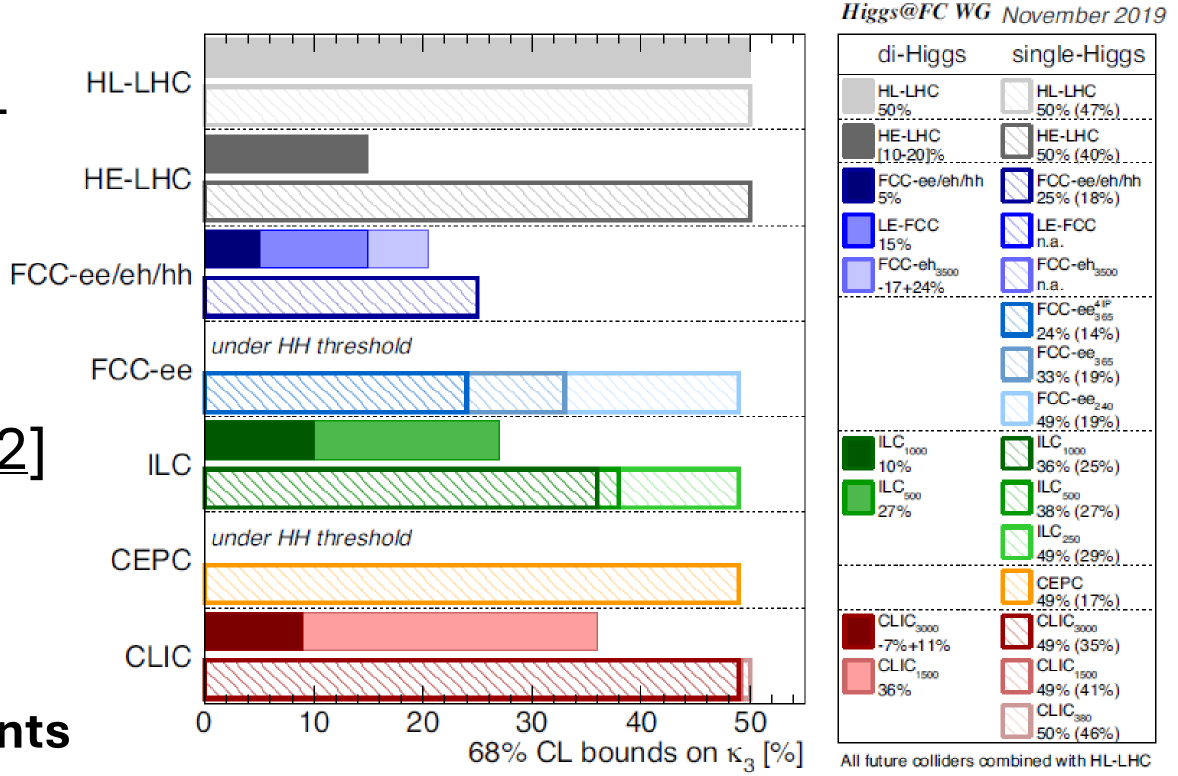

Projected sensitivity at 68% probability for k_3.
From [Db20]

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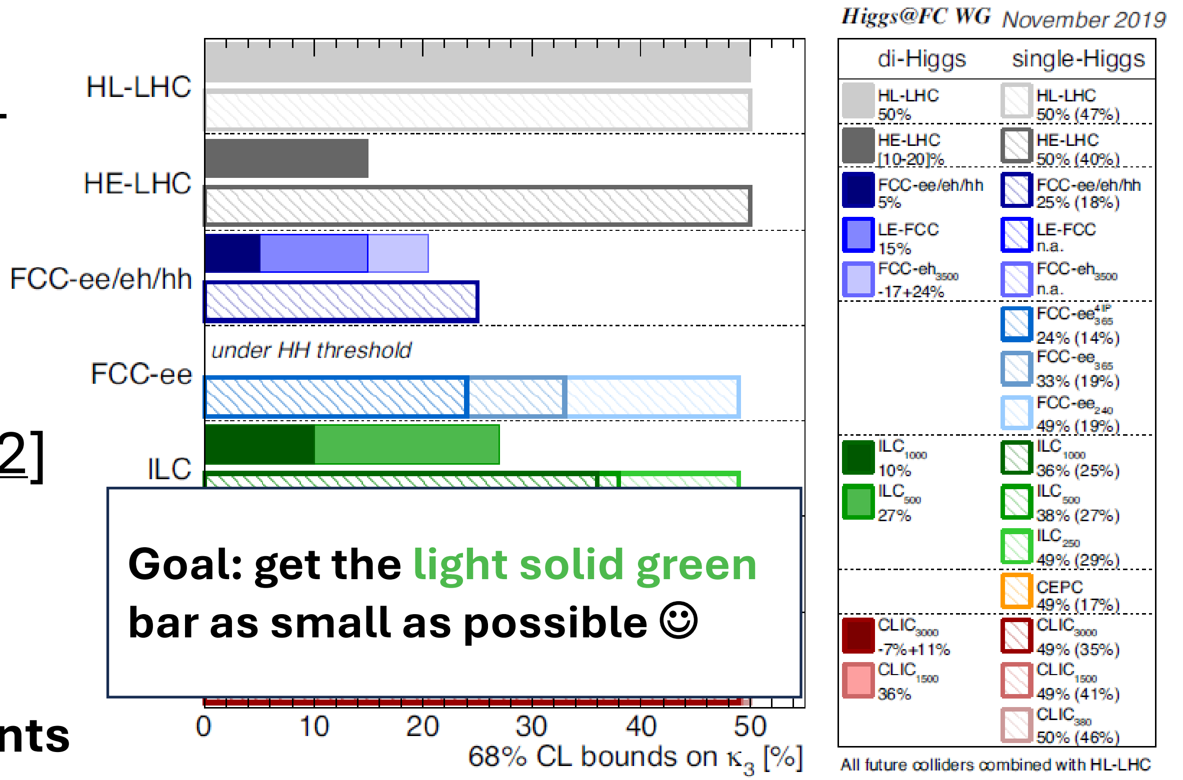

Goal: get the light solid green bar as small as possible ☺

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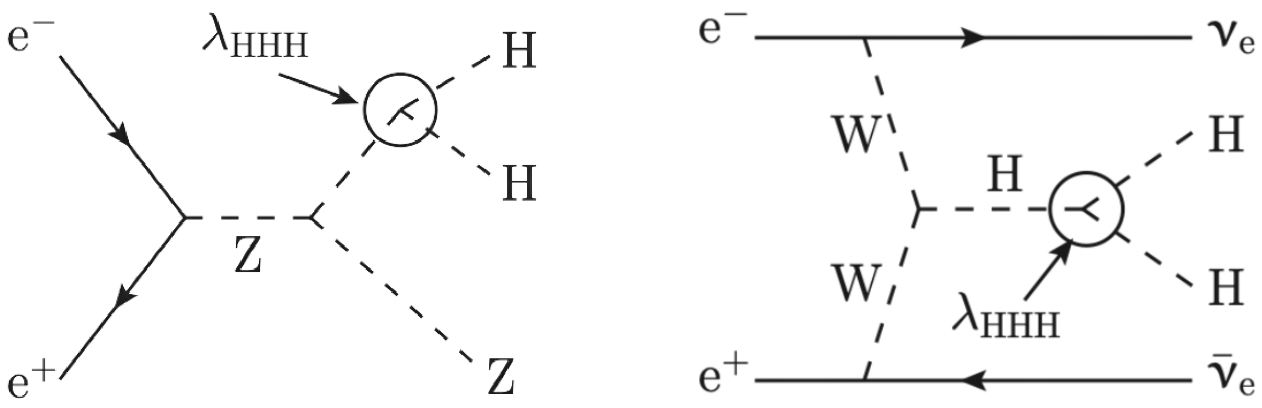
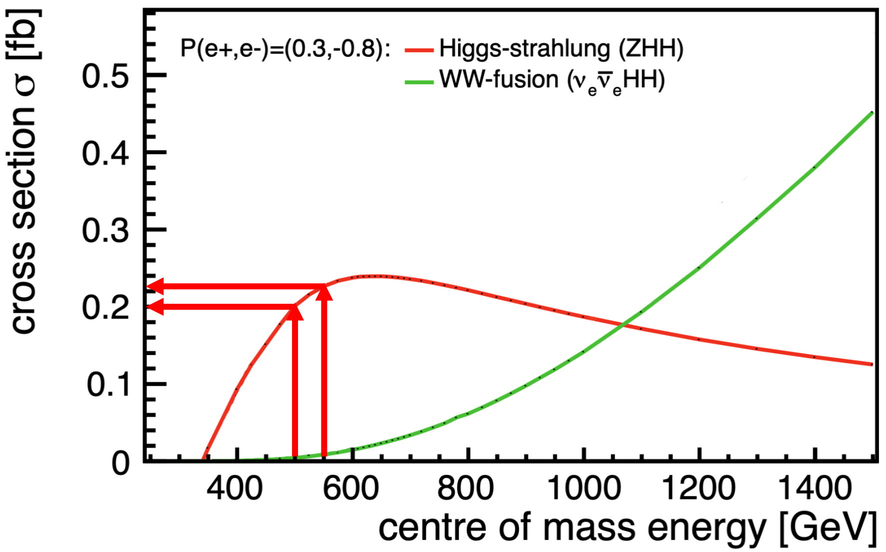
Measuring the Higgs self-coupling at e+e- colliders

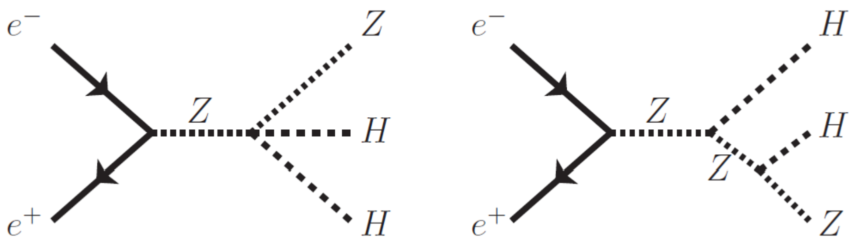
- *Direct access* to λ through double-Higgs production
  - Di-Higgs strahlung (**ZHH**; dominant < 1 TeV)
  - vector boson fusion (**VBF**; dominant > 1 TeV)





Cross-section of Di-Higgs production processes.
From [Du16]

- Degradation of sensitivity in ZHH by diagrams without λ



Measuring the Higgs self-coupling at e+e- colliders

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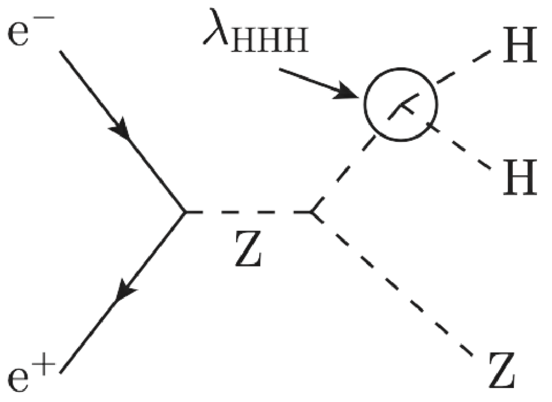
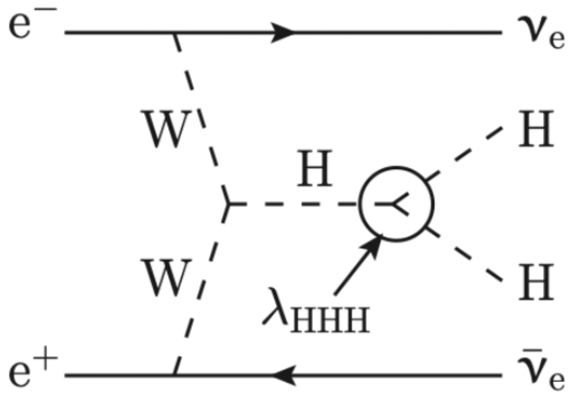
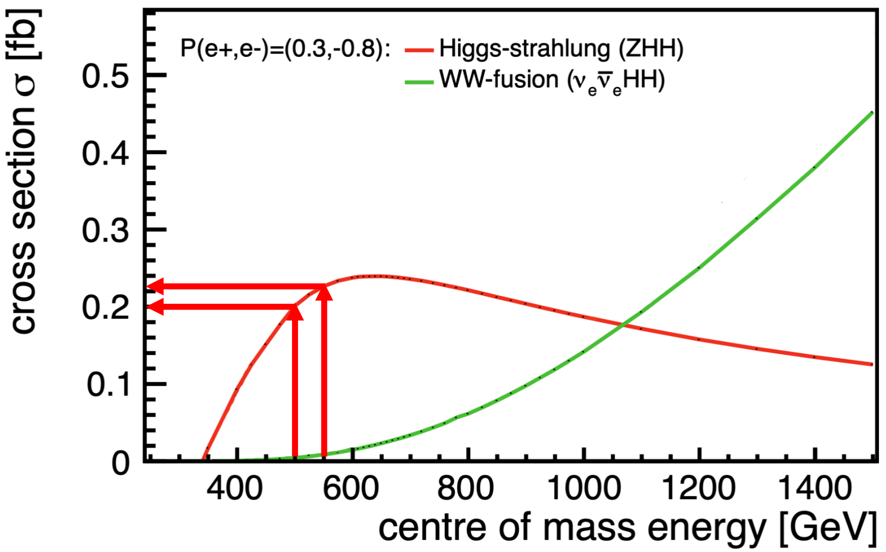
- *Direct access* to λ through double-Higgs production
  - Di-Higgs strahlung ($\mathbf{ZHH}$; dominant < 1 TeV)

Focus of this talk







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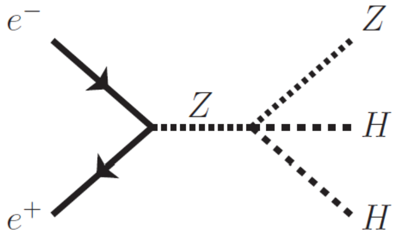
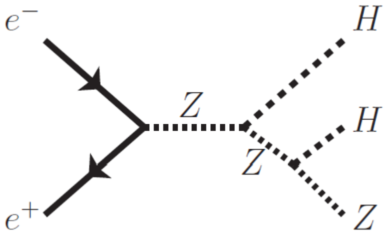




Starting point: Last ZHH Analysis (2016)

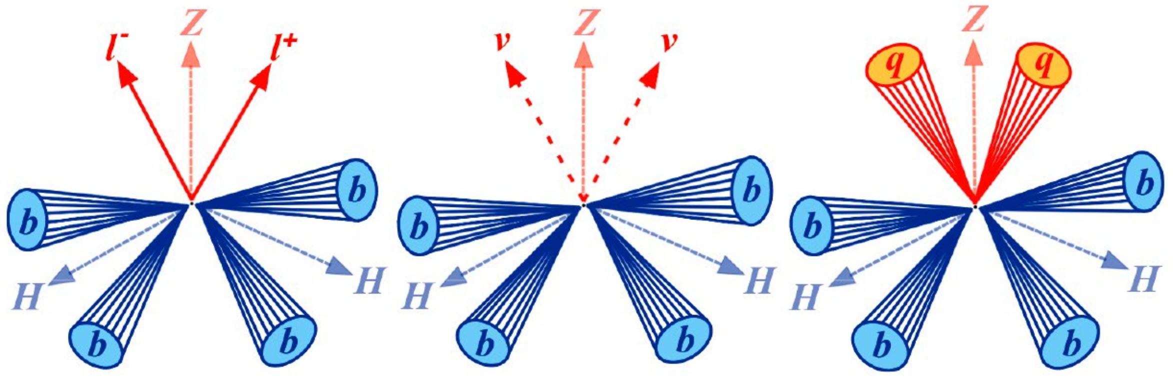
- Extensive projections at **ILD @ ILC500**
  - Based on ILD detector concept (DBD2013, IDR2020) and *fully simulated* event samples
  - 17 background and **3 signal channels**
  - Multivariate (MVA) tools for multiple steps
    e.g. lepton and flavor tagging, background rejection etc.
- Precision after running 4ab^{-1} at 500 GeV:

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

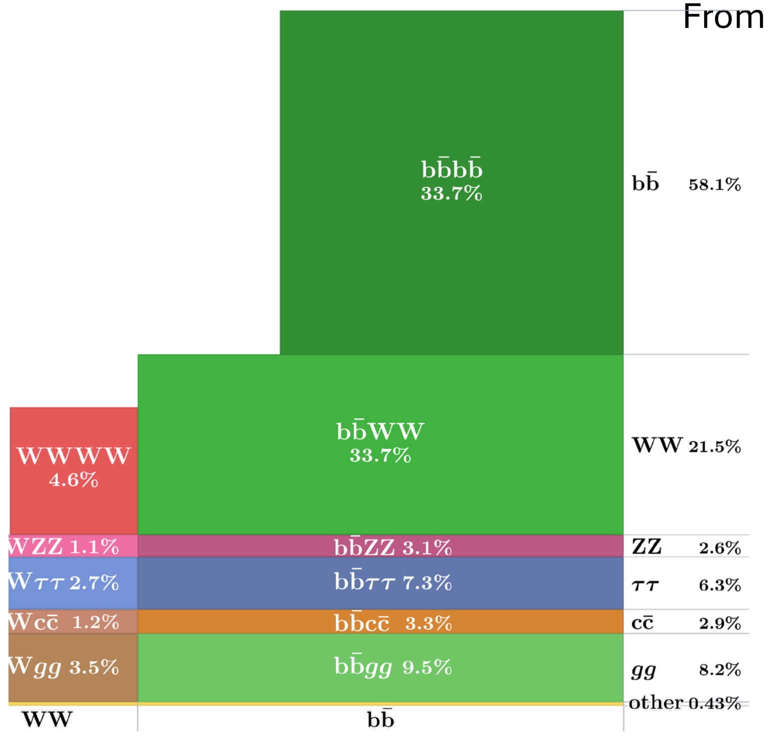
8σ observation for ee → ZHH

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

only 3σ observation for ee → ZHH



Lepton, neutrino and hadron channel of the signal process ZHH.
From [Du16]



Branching Ratios of Di-Higgs Decays

Structure of the Analysis

Channel		Overlay Removal	Event variables	Pair isolated leptons	Clustering + b tagging	Preselection	Final Selection
$llbbbb$	**All PFOs**	Different approaches: **A.** Cheated **B.** Clustering to beam jets	**Calculate** • $E_{visible}$ • $p_{T,miss}$ • thrust	**Tag + Recover ISR + Pairing**	**4 jets**	**Cuts**	**MVA**
$\nu\nu bbbb$					**4 jets**		
$qqbbbb$					**6 jets** 5jets to recon-struct top decays		
Future Improvements:		***ML-based?***		***τ-Tagging?*** ***Kinematic fits*** (✓)	***ParticleNet / ParT*** (✓) ***Kinematic fits*** (✓)		***Modern ML, direct clas-sification***

Towards new projections / Analysis improvements

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- Goal: extract projections with state-of-the-art methods; now at $E_{CM} = 550\ \mathrm{GeV}$

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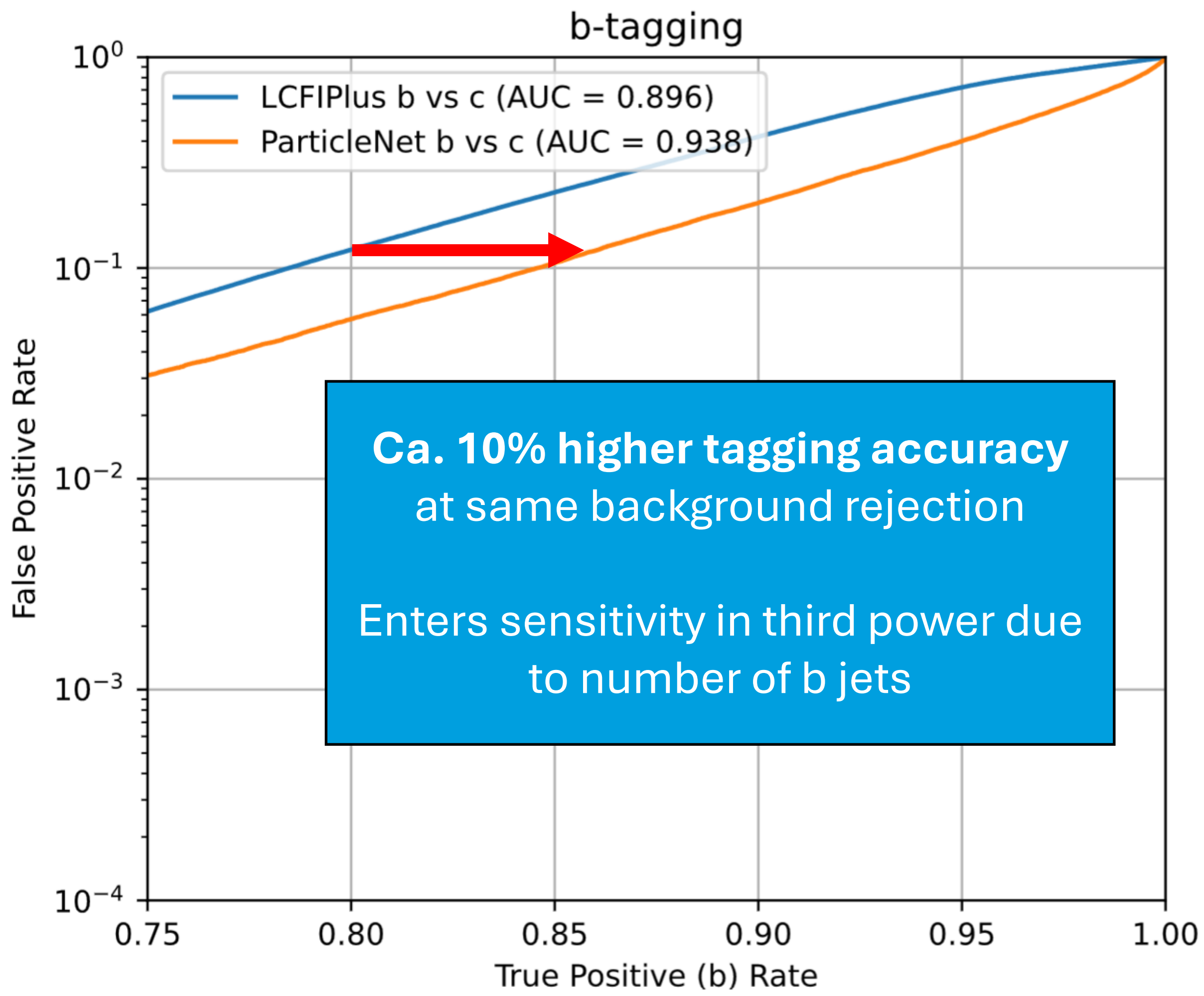
- Goal: extract projections with state-of-the-art methods; now at $E_{CM} = 550\ \mathrm{GeV}$
- Major improvements expected due to
  - **B-jet-tagging with machine learning**
    ParticleNet, ParticleTransformer



Ca. 10% higher tagging accuracy
at same background rejection

Enters sensitivity in third power due to number of b jets

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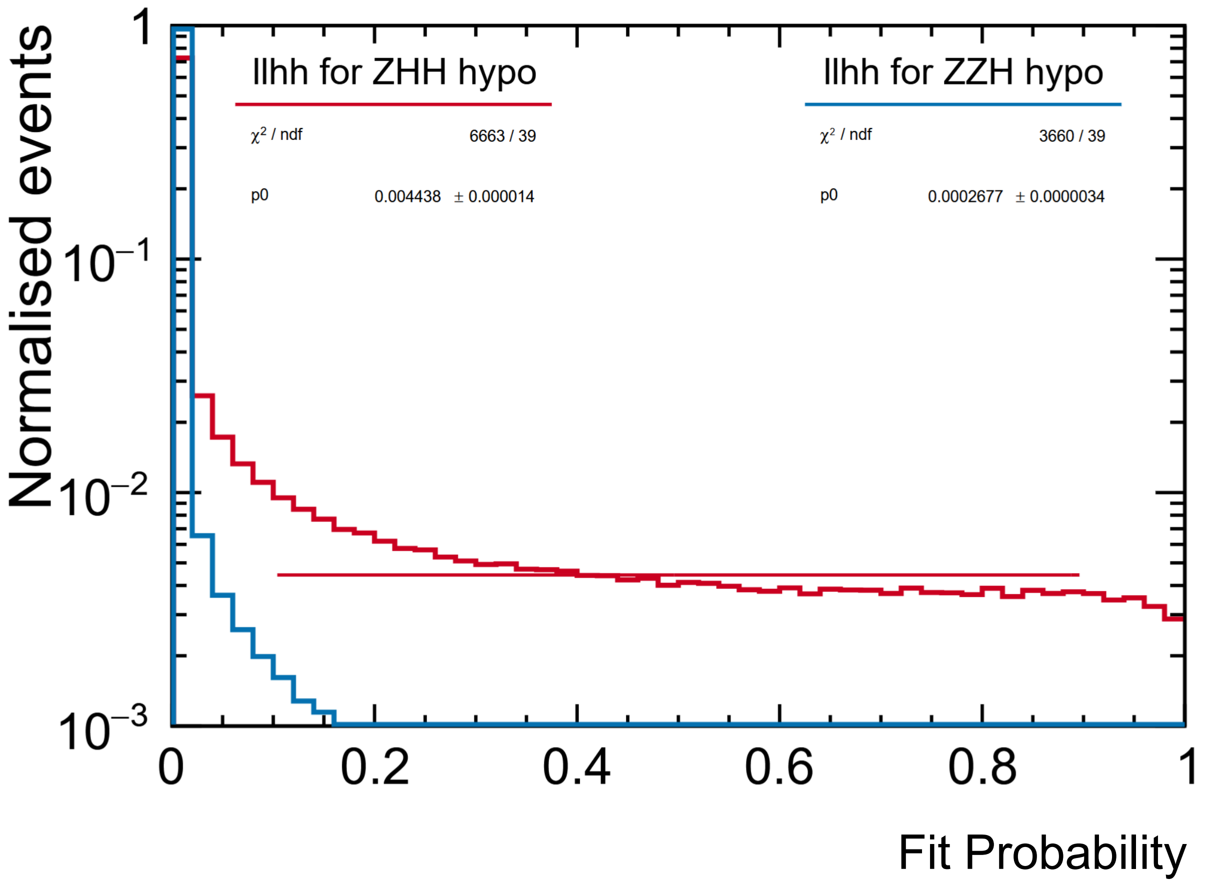
  - Better use of kinematic information
    check consistency of event kinematics with hypotheses
    - **Kinematic fits**



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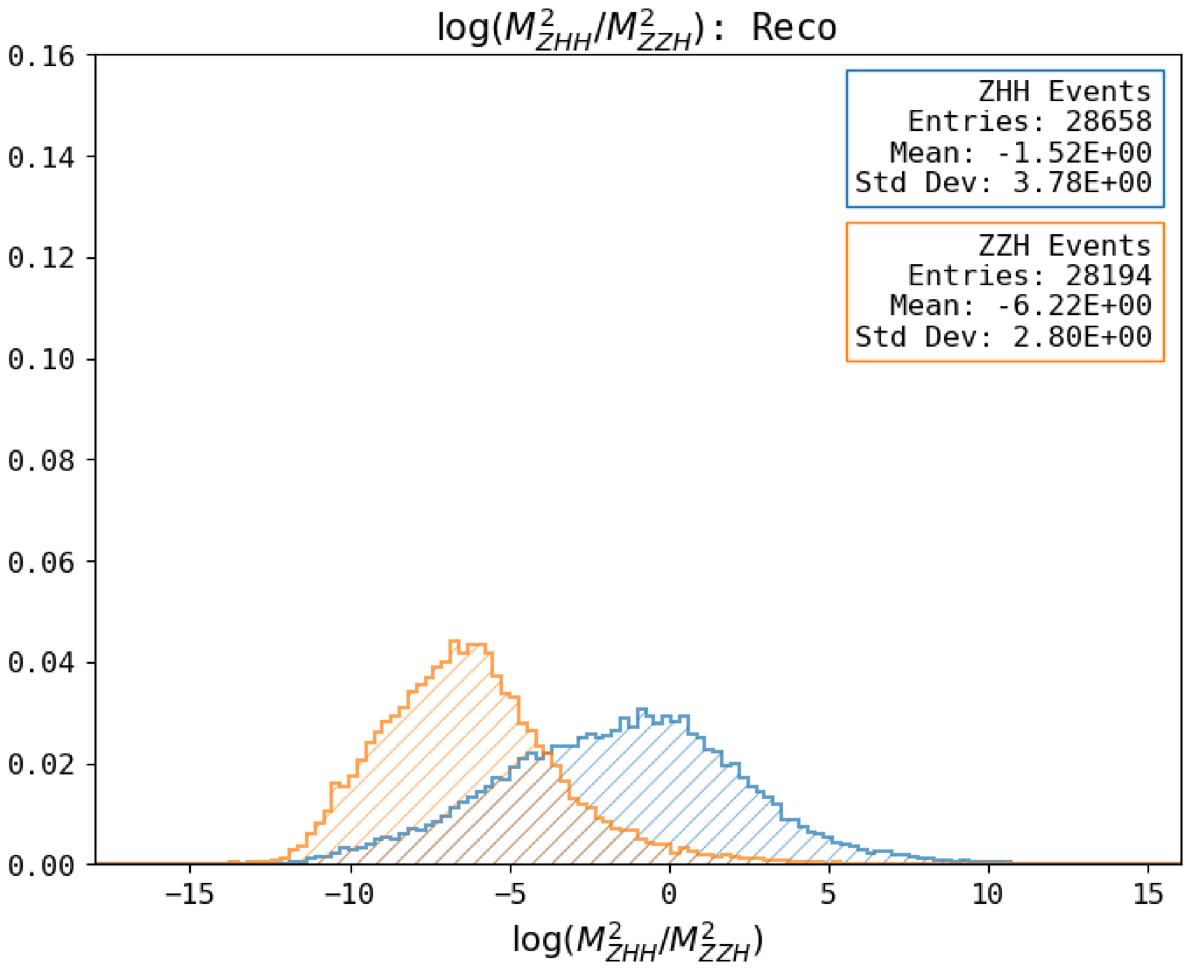
    - Kinematic fits
    - **Matrix element inferred variables**
  - Inclusion of VBF contribution to signal
    higher at increased energies



A classifier motivated by the "matrix element method"

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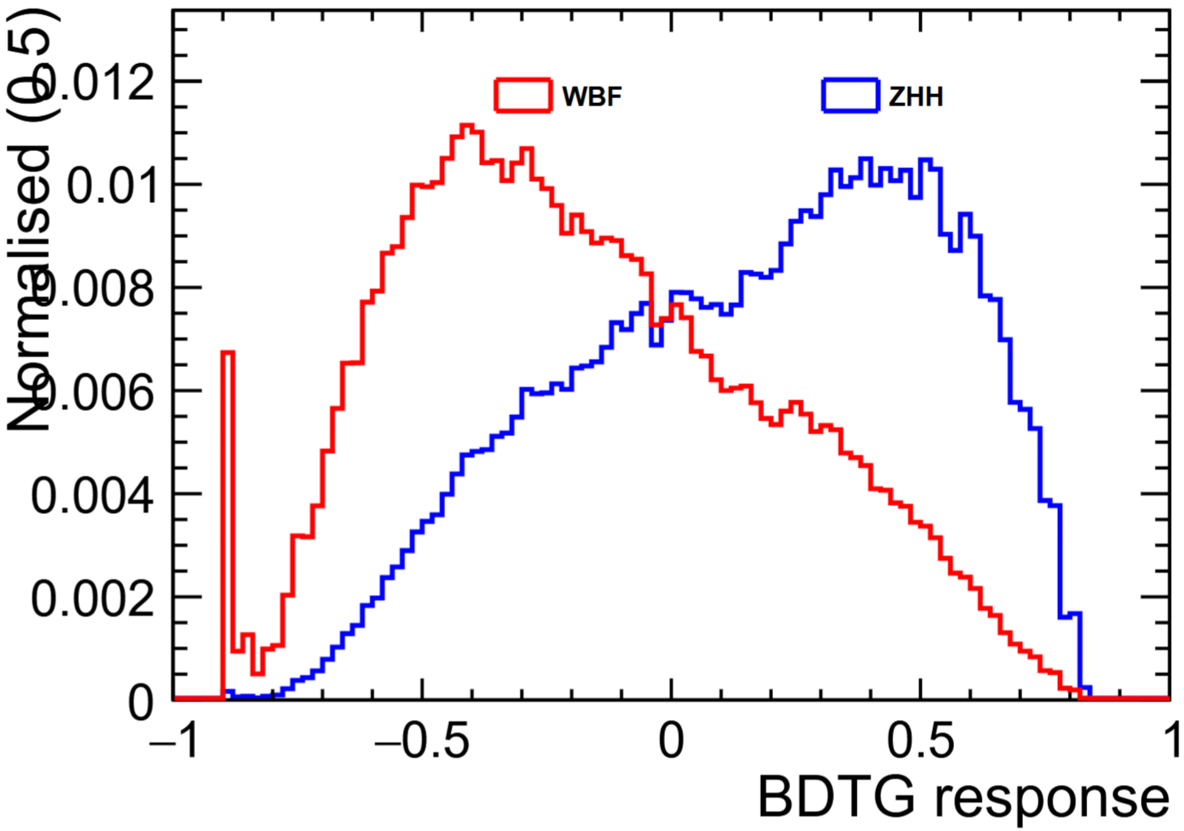
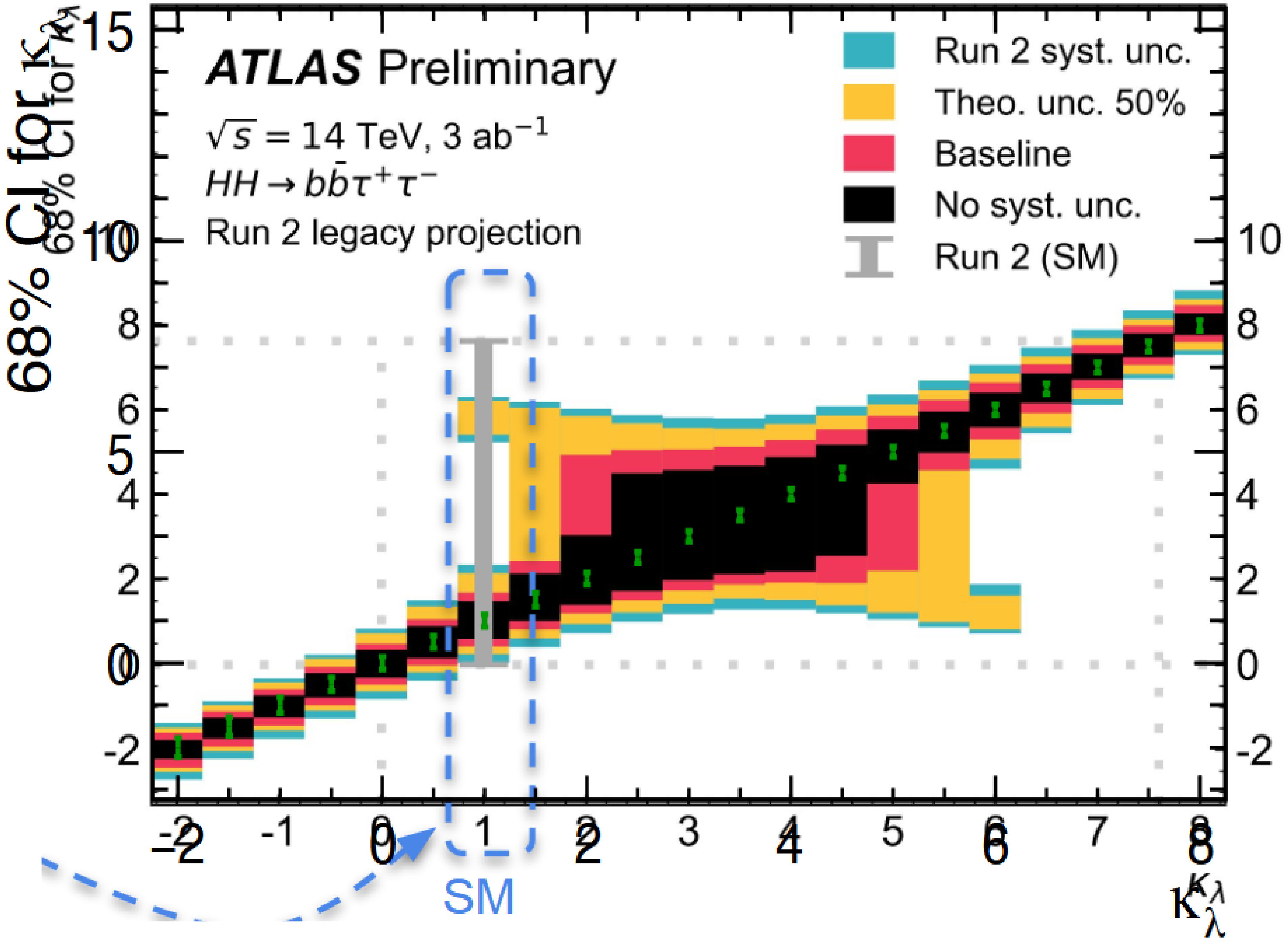
Extrapolation: improve total sensitivity $\Delta\lambda_{SM}/\lambda_{SM}$ from 27% → **15%**



Extrapolation Comparison with HL-LHC ($bb\tau\tau$ only)



ILC 550 GeV

Good sensitivity across a range of non-SM values of λ

Summary and Outlook

- Set up an automated framework for the new ZHH analysis
  - Added kinematic fits, MEM and modern jet tagging to the existing baseline
  - Preselection efficiencies for all channels line up with last study at similar rejection
- **Effort on 550 GeV sample production** ongoing
- Next steps:
  - Finalize production of physics background samples
  - Validate ML overlay removal
  - Tune preselection
  - Train channel-specific MVAs to carry out final event selection
  - **Extract limits on λ_{ZHH}**

From extrapolations: sensitivity on λ …

18% at $500\ \mathrm{GeV}$ @ $4ab^{-1}$
15% at $550\ \mathrm{GeV}$ @ $4ab^{-1}$
11% at $550\ \mathrm{GeV}$ @ $8ab^{-1}$

Backup

Event Selection - Overview

- Based on same strategy as 2016 study
  - stared variables* explained below; ***italic-bold*** variables new

New: LO matrix elements (ll, qq), kinematic fits (masses, chi2, fit probabilities)

	llHH (llbbbb)	**ννHH** (ννbbbb)	**qqHH** (qqbbbb) split into bbHH and light qqHH
1st Background / Variables	$llbb$ / 9 variables: mZ, thrust, costhrust, pjmax(2jets)*, cos(Z,jet)max*, npfos, npfosmin(4j)*, yminus*, yplus*	$bbbb$ / 6 variables: Evis, ptmiss, thrust, pjmax(6jets)*; **ZZ**: mZ1, mZ2	$bbbb$ / 9 variables: costhrust, pjmax(6jets)*, yminus*, npfos, npfosmin(6j)*; **ZZ**: mZ1, mZ2, pjmax(4jets)*, cosjmax(4jets)
2nd Background / Variables	$lvbbqq$ / 7 variables: Evis, mZ, plmin*, m(b34)*, ptmiss, npfos, mva(lepsmall)*	$lvbbqq$ / 11 variables: npfos, npfosmin(5j)*, mMiss; **ZHH**: mH1, mH2; **tt**: mW1, mW2, mt1, mt2; pcmax*, yminus*	$bbqqq$ / 12 variables: npfos*, pjmax(6jets)*, cosbmax*; **tt**: mW1, mW2, mt1, mt2, χ^2_{tt}; **ZHH**: mH1, χ^2_{ZHH}, mH2, **mZ**
3rd Background / Variables	$ZZH, ZZZ \rightarrow llbbbb$ / 12**+2** variables: χ^2_{ZHH}*, χ^2_{ZZH}*, ***LCME ZHH****, ***LCME ZZH****; ZHH: mH1, mH2; ZZH: mH, mZ, p1st*, cos1st* ; ZZZ: mZ1, mZ2, p1st*, cos1st*	$ZZH, ZZZ \rightarrow \nu\nu bbbb$ / 12 variables; see $llHH$	$ZZH, ZZZ \rightarrow qqbbbb$ / 12 variables; see $llHH$

Explanation of variables: **pjmax(n jets)** - leading jet momentum when clustering into n jets / **cos(Z,jet)max** – largest angle between reconstructed Z and two of the four jets / **npfosmin, npfosmax** – smallest, largest number of PFOs in a jet / **yminus, yplus** – likeliness to be a four instead of three jet event, three instead of two jet event (similar for other selection) / **plmin** – smallest isolated lepton momentum / **m(b34)** – invariant mass of jet system related to bmax3 and bmax4 / **mva(lepsmall)** – MVA output in the isolated lepton tagging, lepsmall denotes the smaller value of the two / χ^2_{ZHH} and χ^2_{ZZH} - chi squared values from kinematic fits under ZHH and ZZH hypothesis, respectively / **LCME ZHH, ZZH** – log of leading order ZHH and ZZH matrix elements / **p1st, cos1st** – largest momentum (for ZZH, ZZZ: of boson candidate) and cos of associated polar angle / **pcmax** – largest momentum of a charged PFO / **cosjmax(n jets)** – polar angle of jet with largest momentum

Bottlenecks in the ZHH analysis

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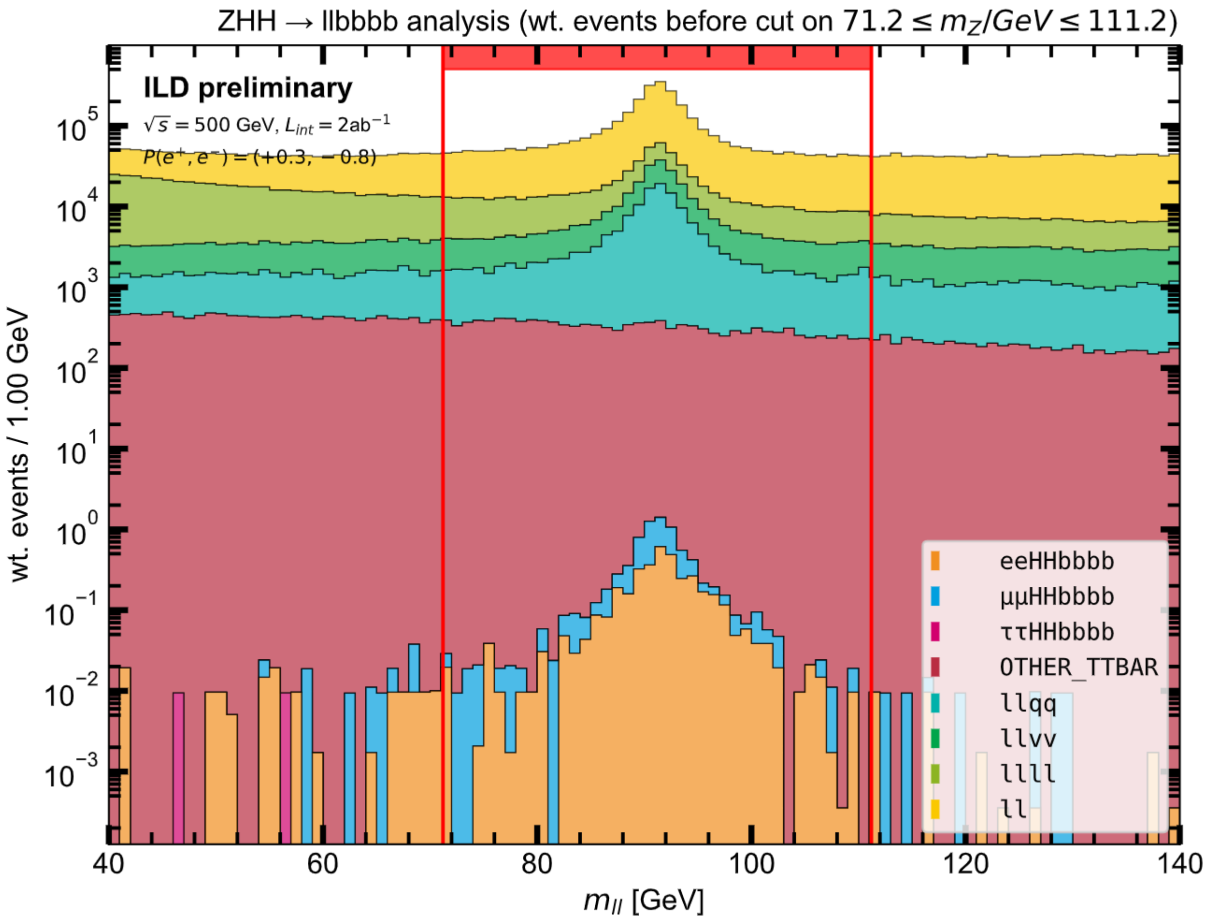
- jet pairing and jet misclustering: “perfect“ jet clustering → 40% improvement
  improve di-jet mass resolution
- removal of $\gamma\gamma$ overlay: 15% improvement expected
  important to tackle initial state radiation (ISR)
- flavor tagging: 11% improvement expected from 5% eff. increase with newer LCFIPlus
  important as $H \to b\bar{b}$ is the dominant Higgs decay channel
- adding $Z \to \tau\tau$ channel: 8% improvement expected
  include a yet unaccounted decay channel
- more modern ML architectures for signal/background selection
  improvement expected when transitioning from BDTs to (e.g.) transformer-based models etc.
- separation of ZHH diagrams with/without the self-coupling
  would directly improve the sensitivity on λ (lower sensitivity factor)

All improvements are relative

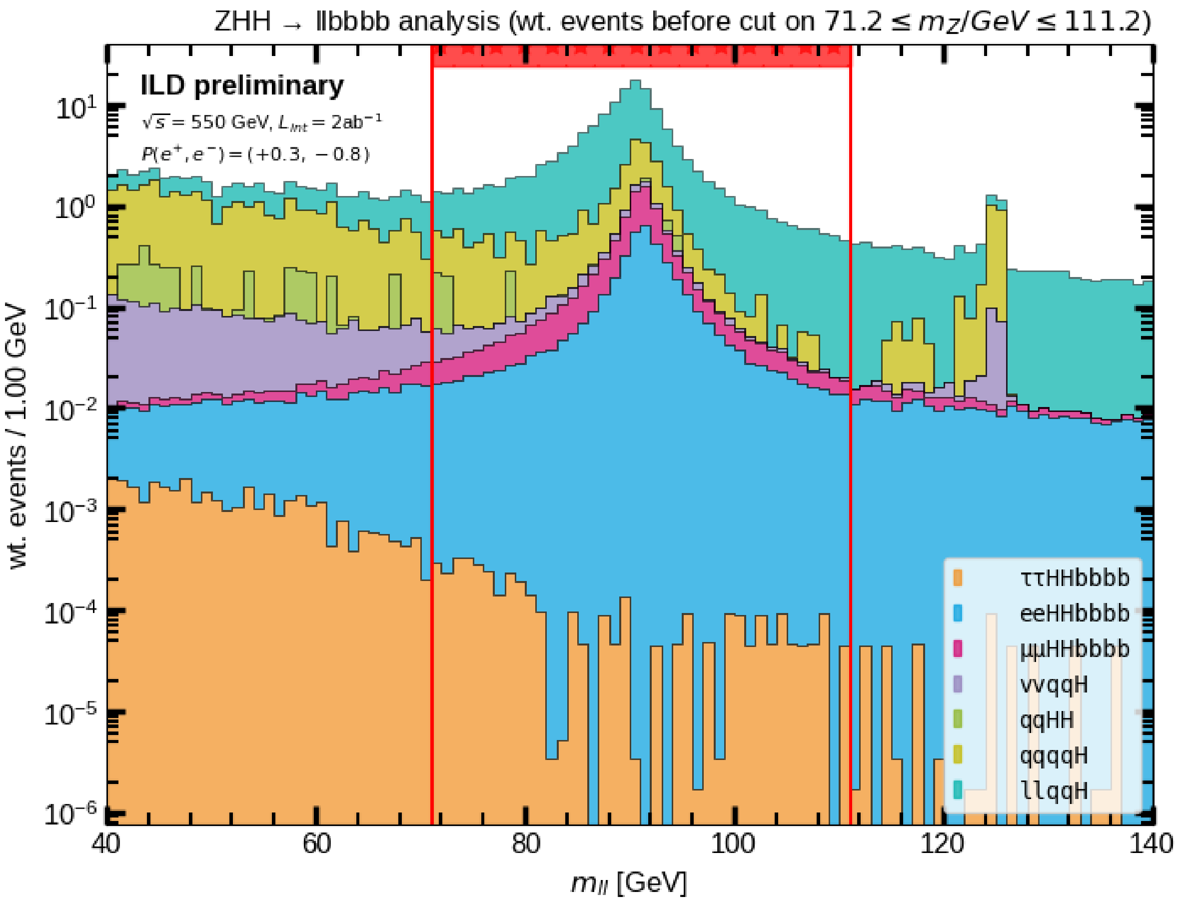
Expected improvements from DESY-Thesis-16-027

llHH / Z mass Cut

500 GeV Full Sim

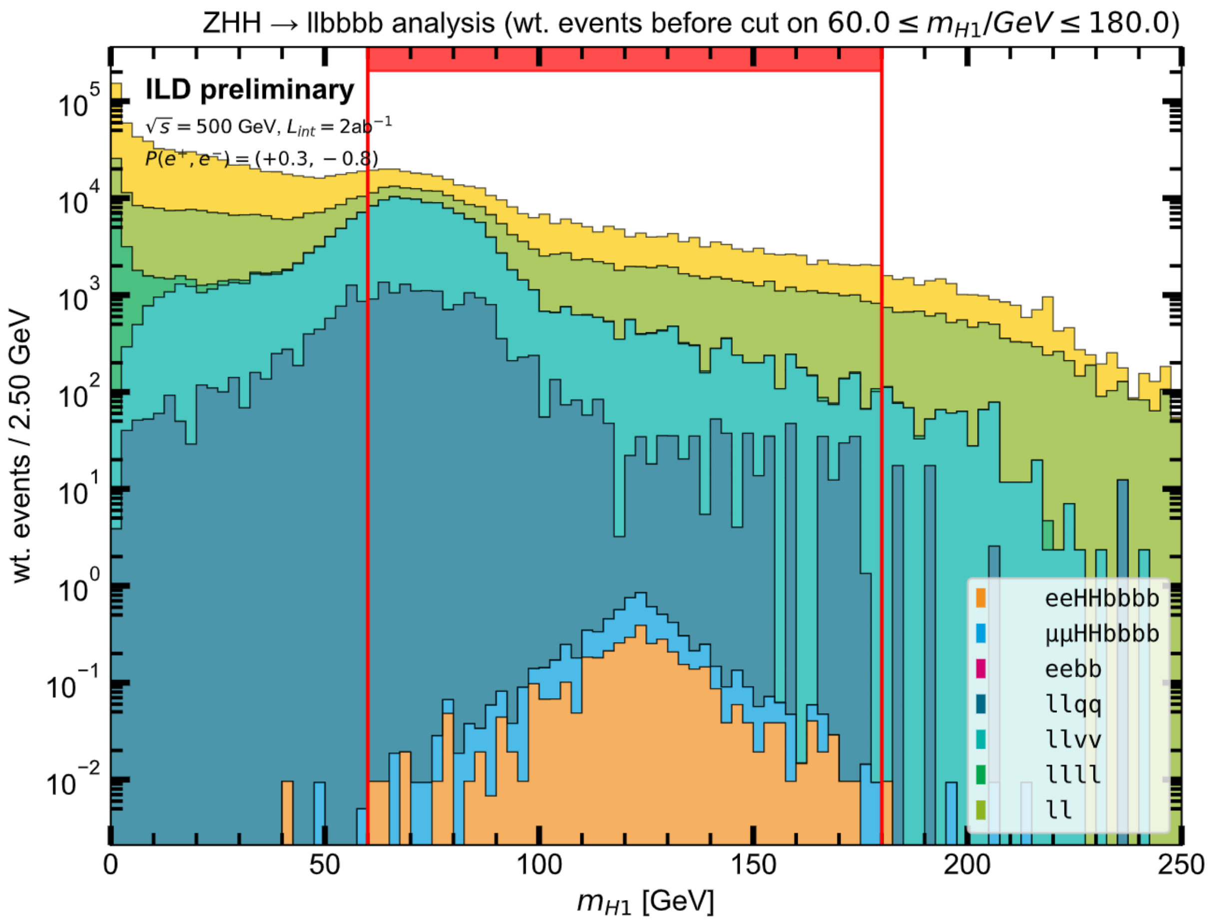


550 GeV Fast Sim

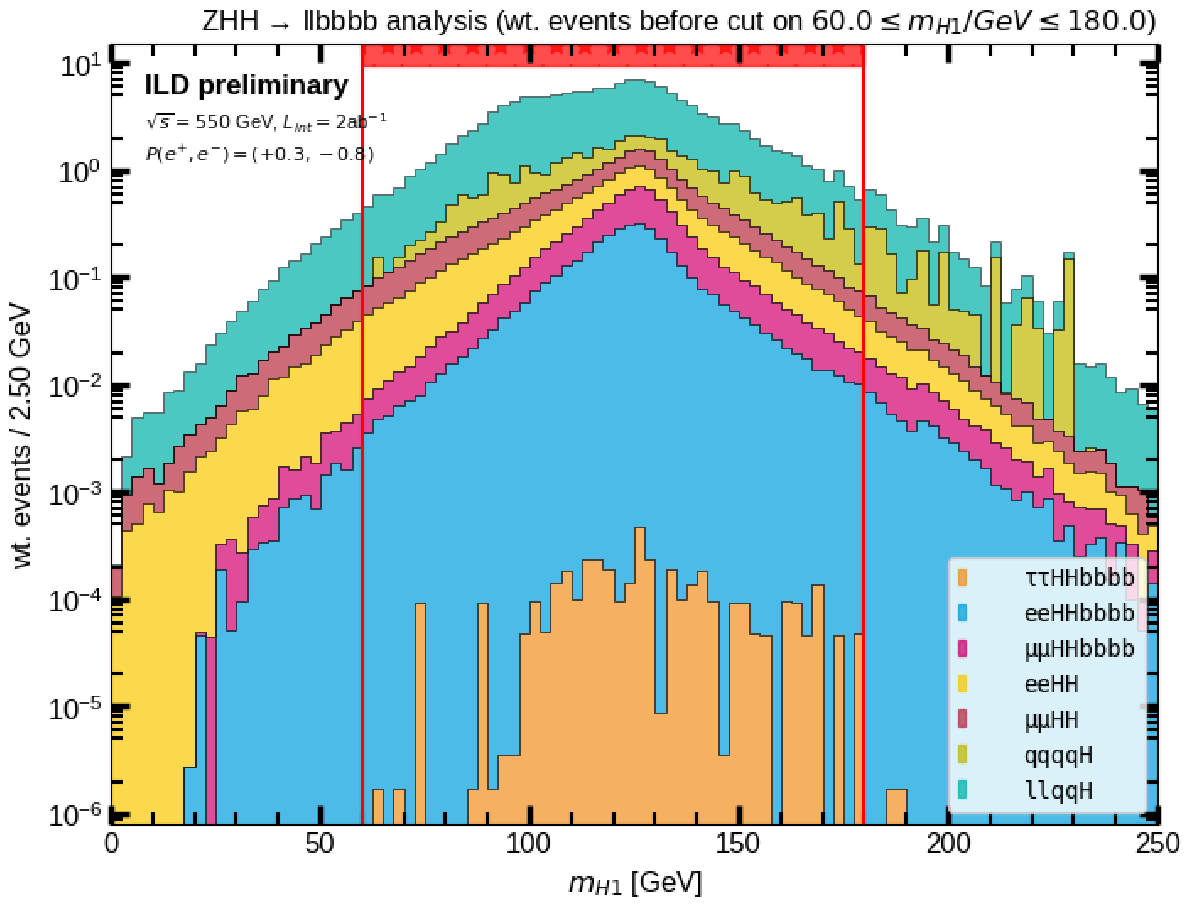


llHH / H1 mass Cut

500 GeV Full Sim

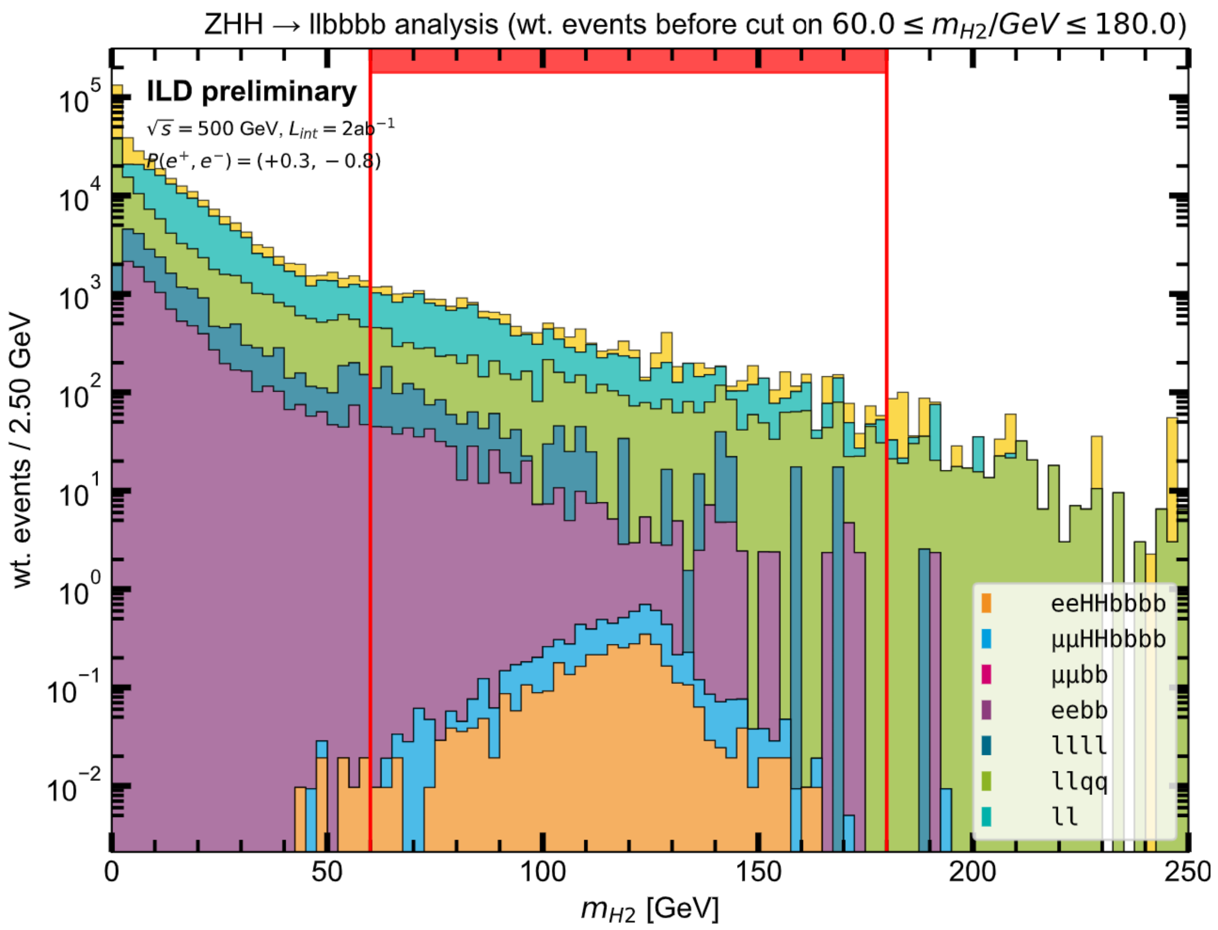


550 GeV Fast Sim

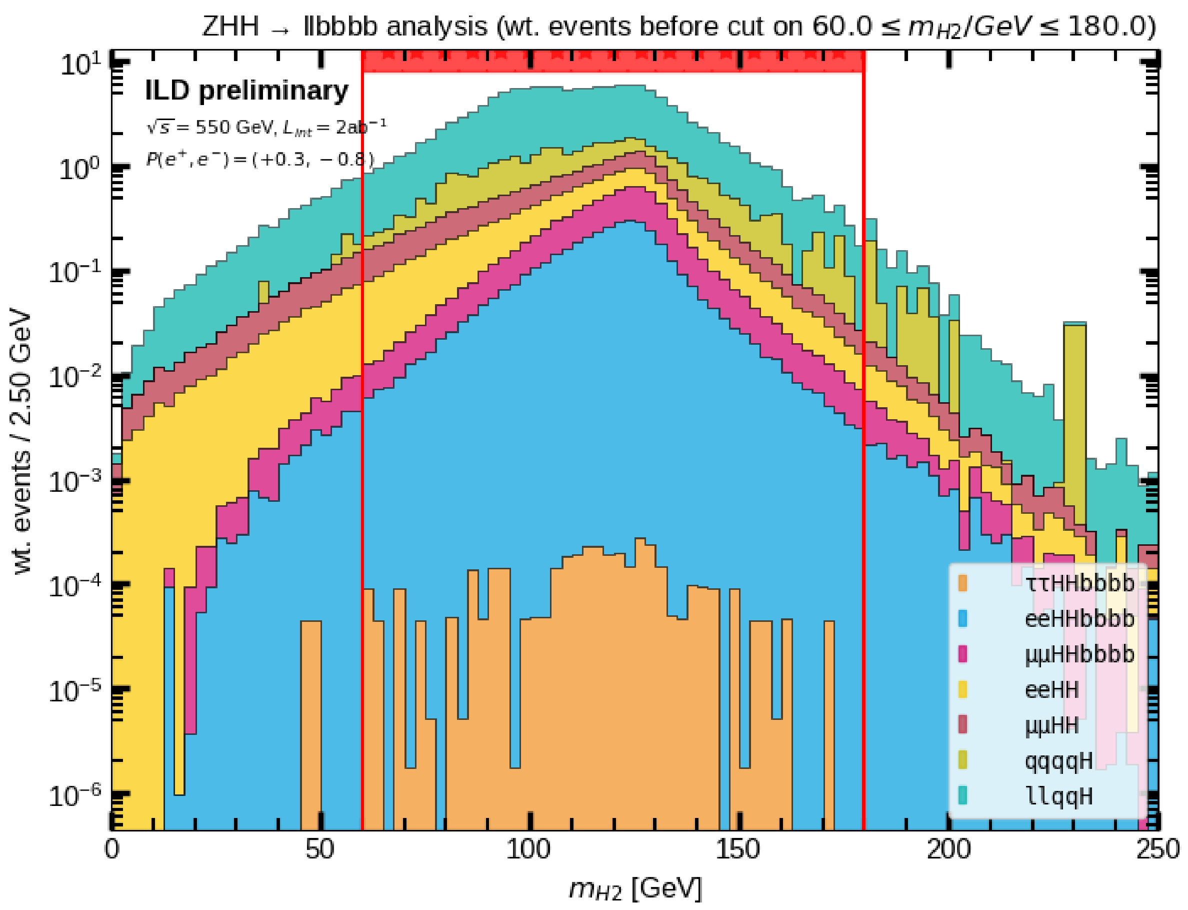


llHH / H2 mass Cut

500 GeV Full Sim

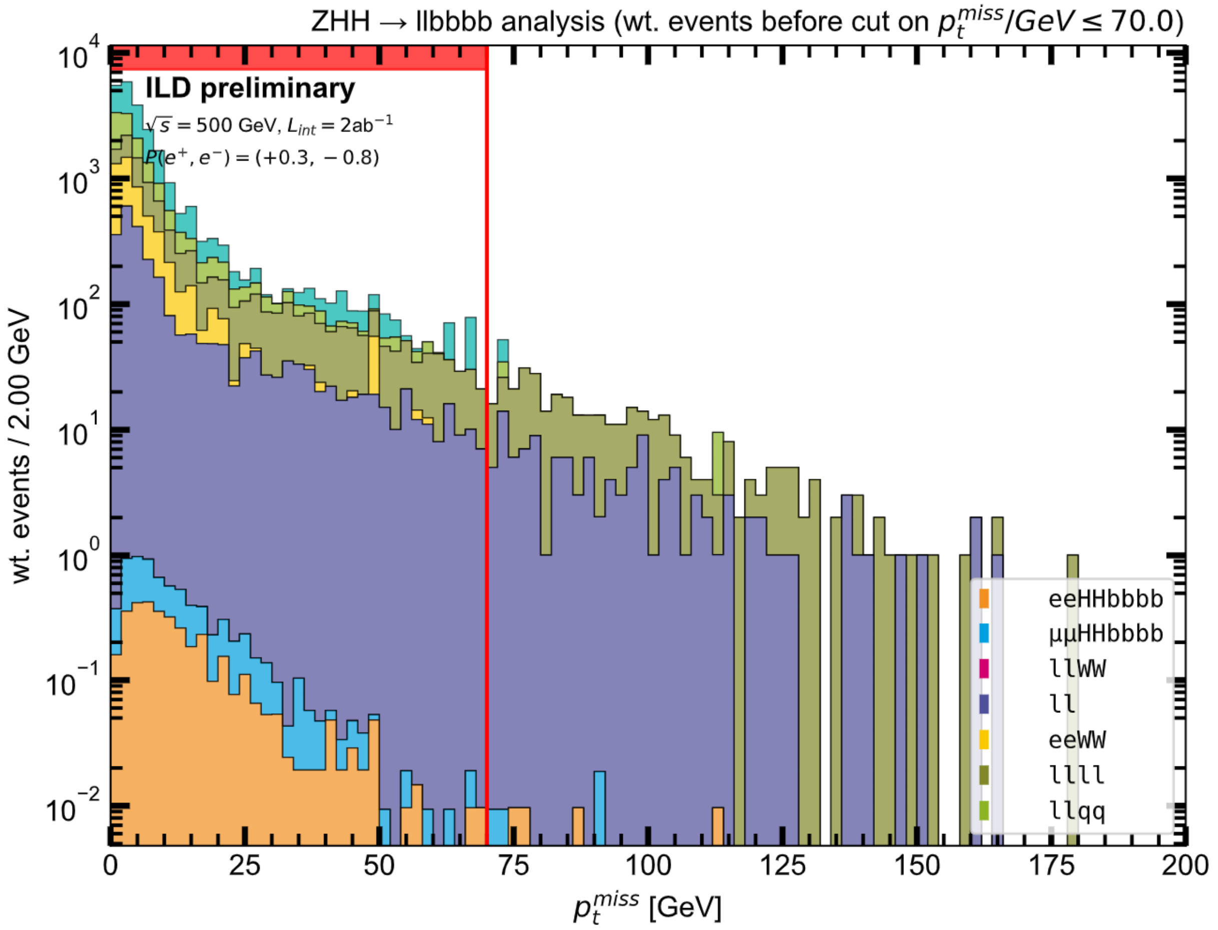


550 GeV Fast Sim

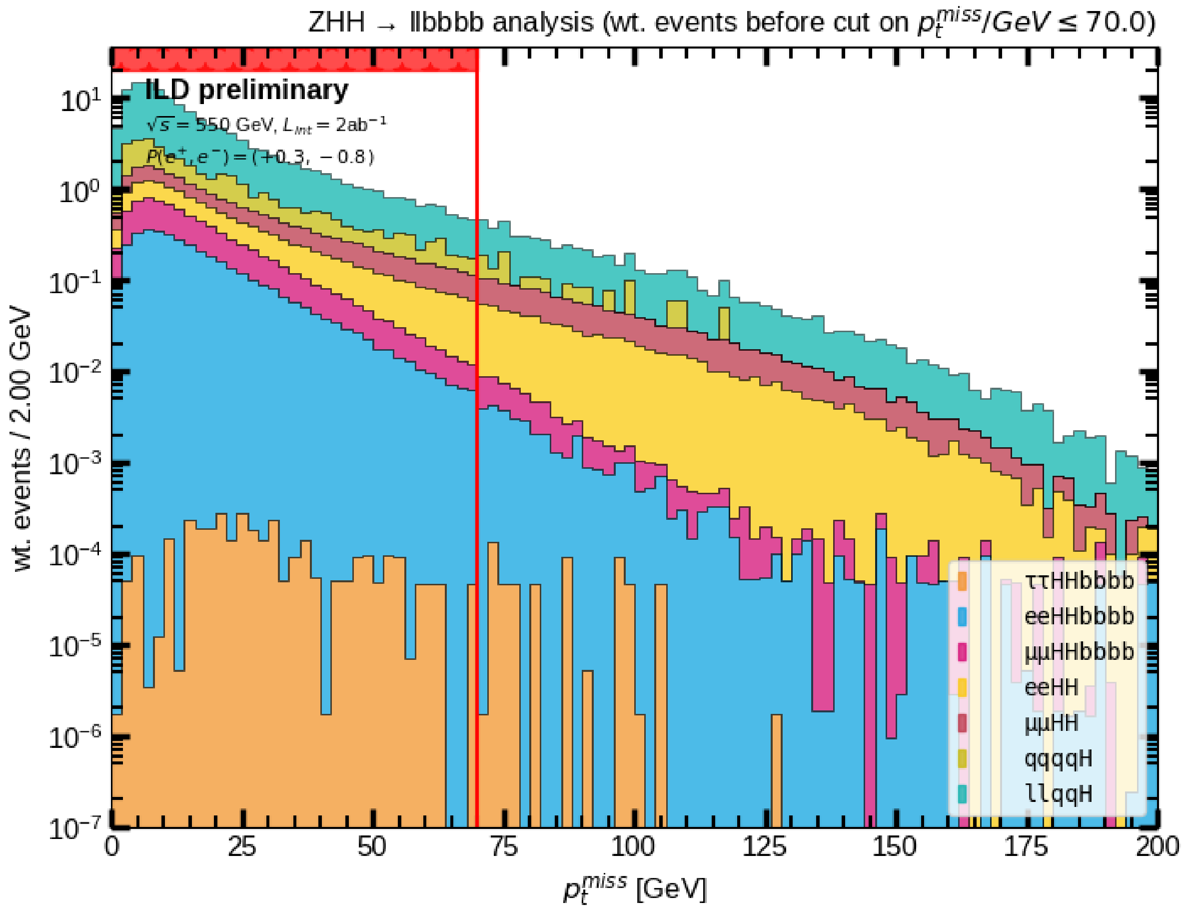


llHH / missing transverse momentum Cut

500 GeV Full Sim

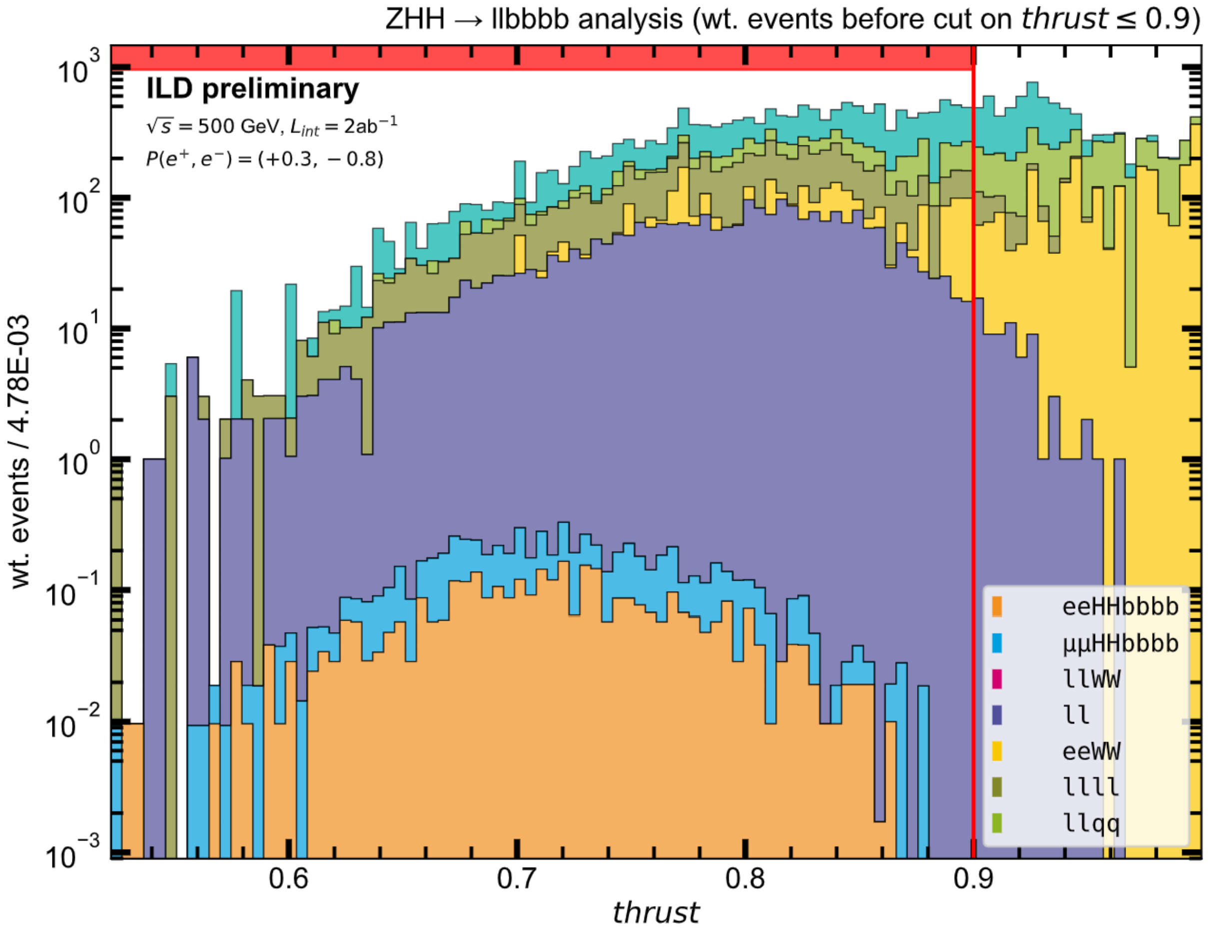


550 GeV Fast Sim

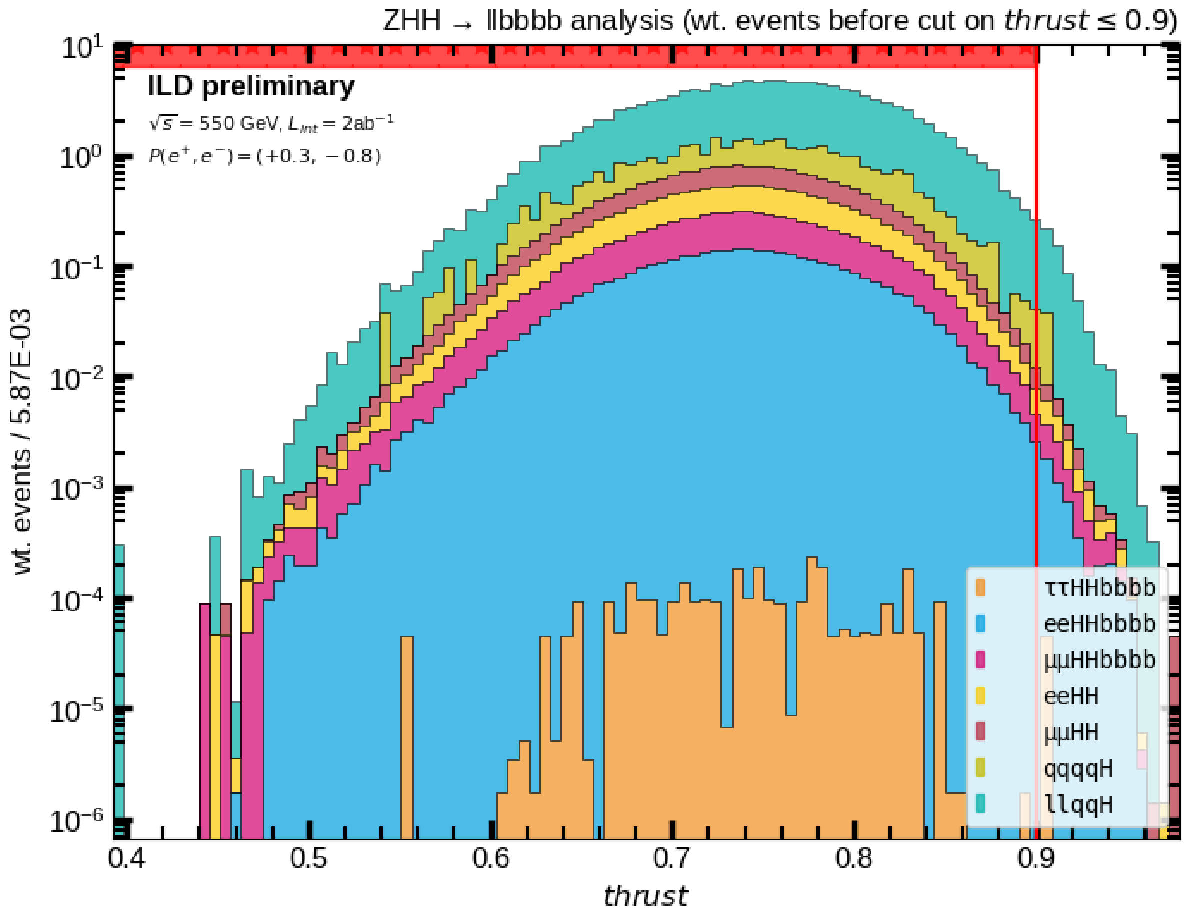


llHH / thrust Cut

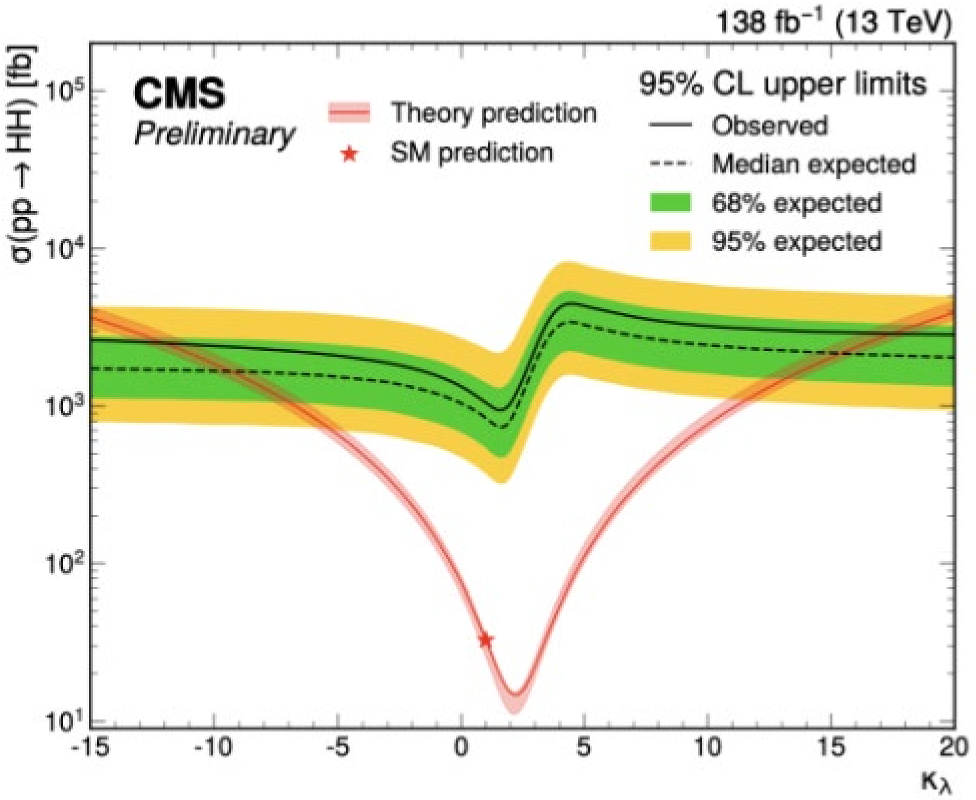
500 GeV Full Sim



550 GeV Fast Sim



Cross section for non-SM λ at the LHC

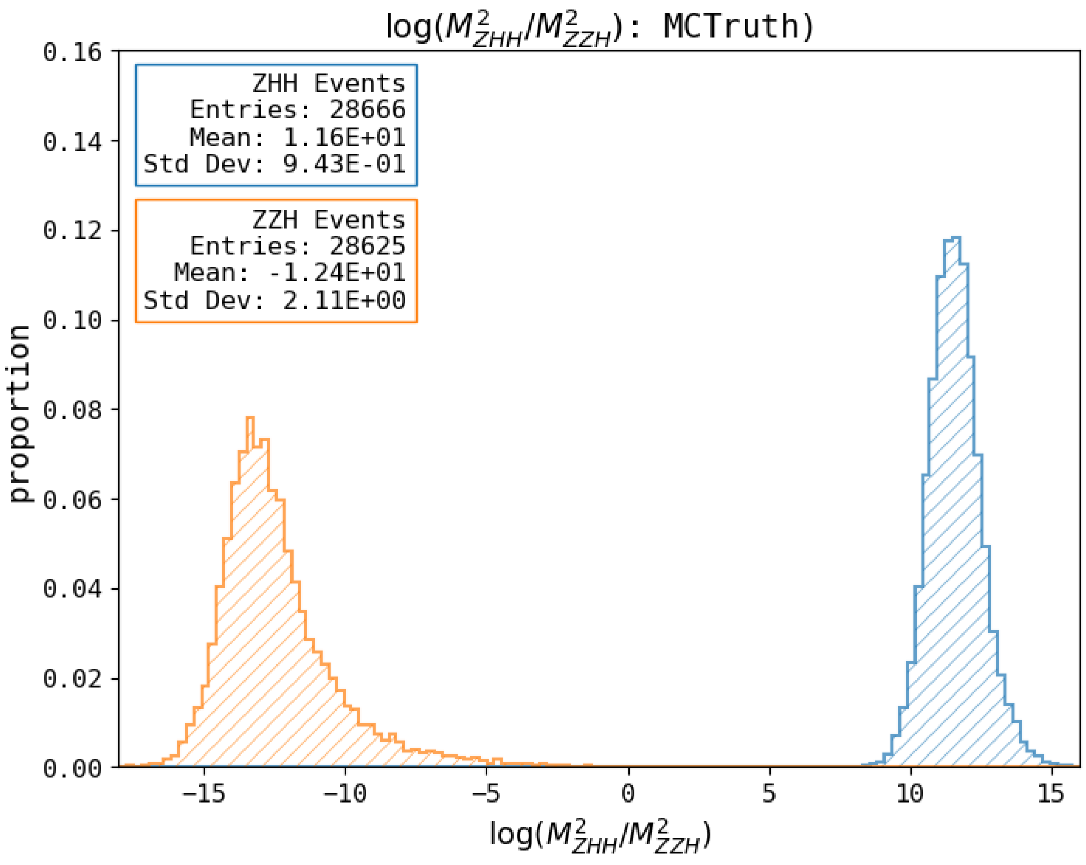


The Matrix Element Method – An example

Generator level check

➢ excellent separation

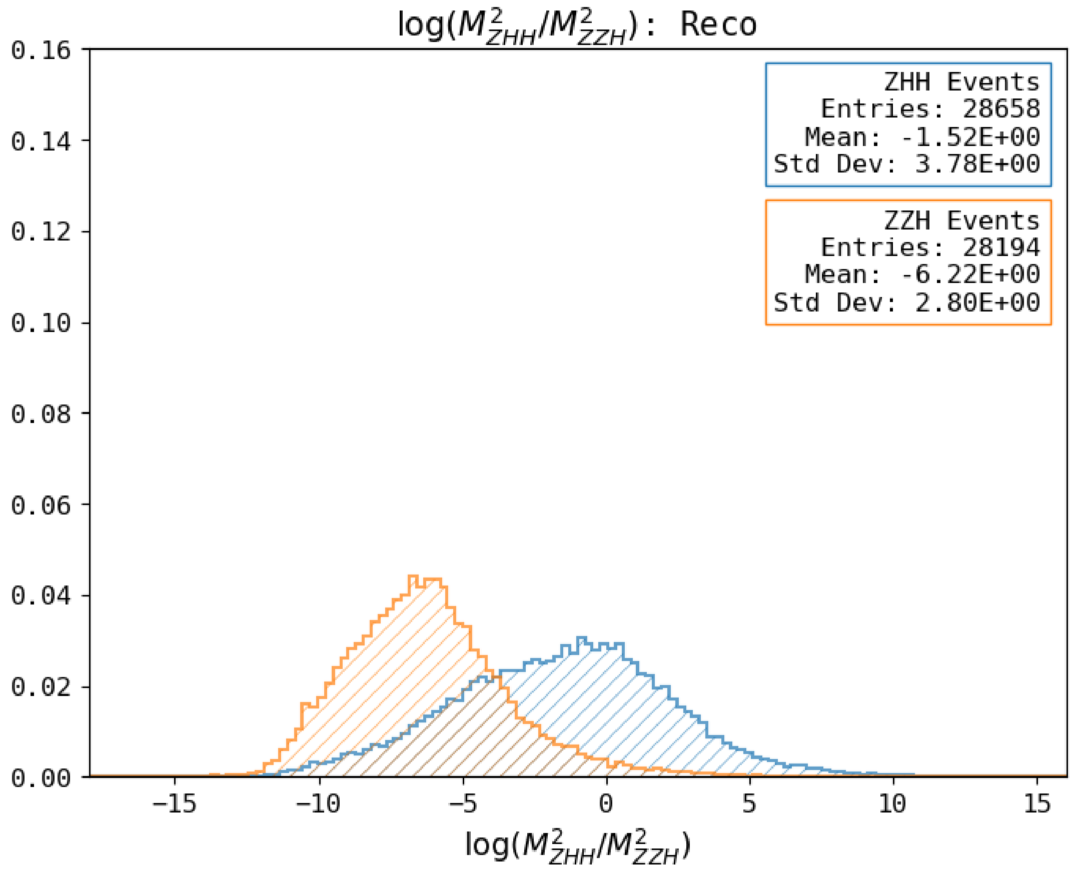
Event data / MEM type	MC truth	Reco
ME only		
ME+DTF	-	



Naive MEM

➢ even without any transfer functions, sep. power remains

Event data / MEM type	MC truth	Reco
ME only		
ME+DTF	-	



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