Projections for Higgs self-coupling measurements via Di-Higgs production with ILD at multiple COM energies

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Introduction

Physical fundamentals and methods for direct measurements of the Higgs self-coupling at future Higgs factories

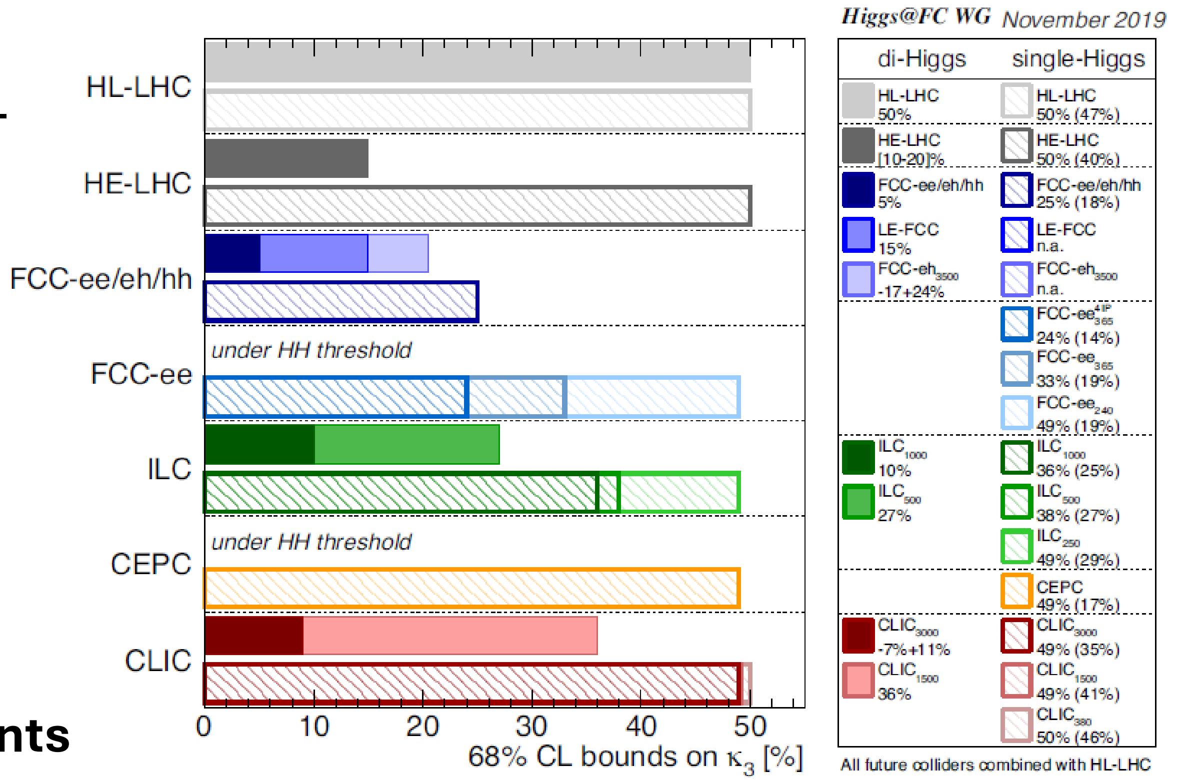
The Higgs self-coupling λ in the SM

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

v vacuum expectation value (vev) of Higgs field h

m_H mass of Higgs boson

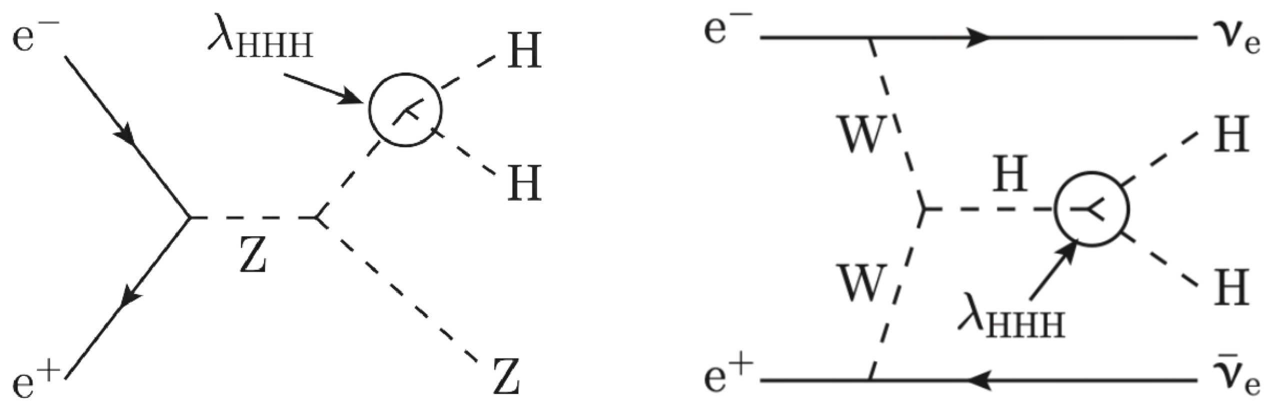
- SM: λ_{SM} fixed since m_H is known [At/Cm12]
  - deviation from $\lambda = \lambda_{SM}$ hints at BSM physics
  - beyond the SM, many values are possible
    strong-case for **model-independent measurements**
  - most projections assume $\lambda = \lambda_{SM}$

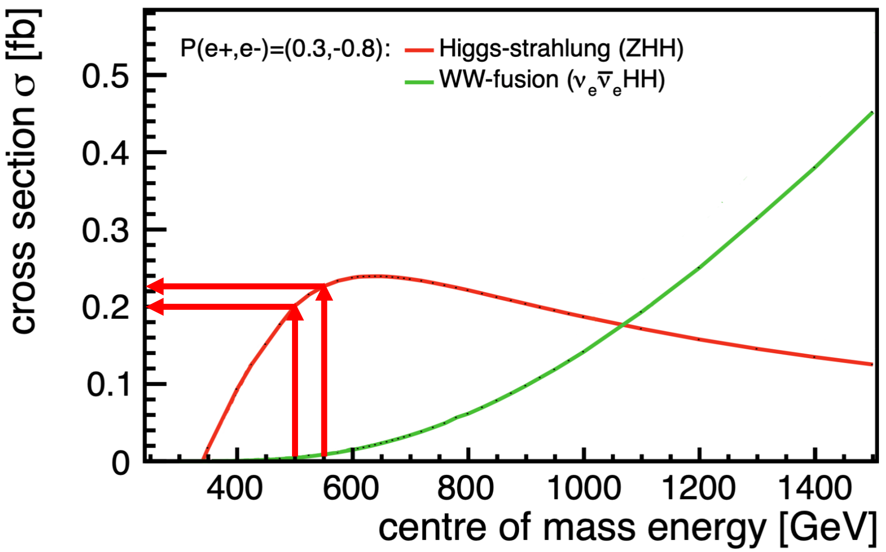


Projected sensitivity at 68% probability for k_3.
From [Db20]

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

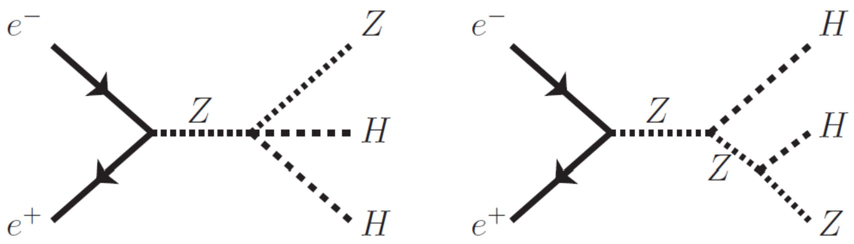
- *Direct access* to λ through double-Higgs production
  - Di-Higgs strahlung (**ZHH**; dominant < 1 TeV)
  - vector boson fusion (**$\nu\bar{\nu}$HH**; dominant > 1 TeV)





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

- Degradation of sensitivity in ZHH by diagrams without λ



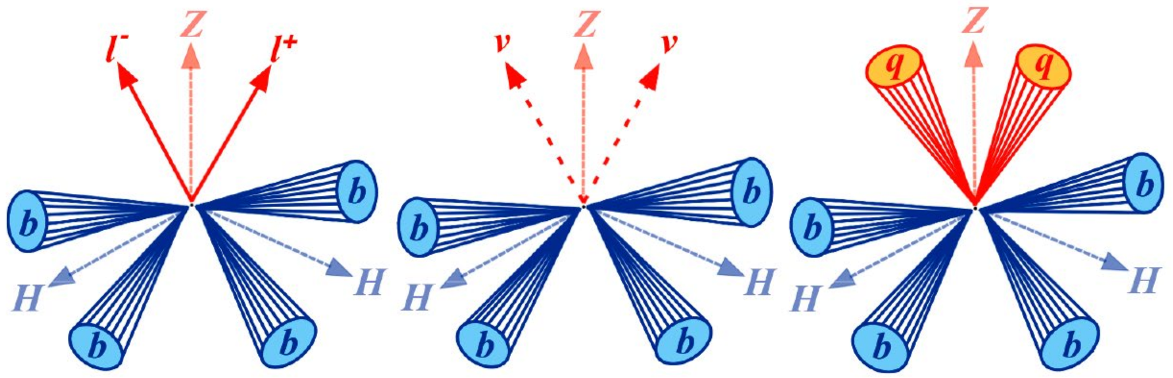
The ZHH Analysis

- Extensive projections at **ILD @ ILC500**
  - Based on ILD detector concept (DBD2013, IDR2020) and *fully simulated* event samples
  - Last projections from 2016 (DESY-Thesis-16-027)
  - 17 background and **3 signal channels**
  - Multivariate (MVA) tools for multiple steps
    e.g. lepton and flavor tagging, background rejection etc.

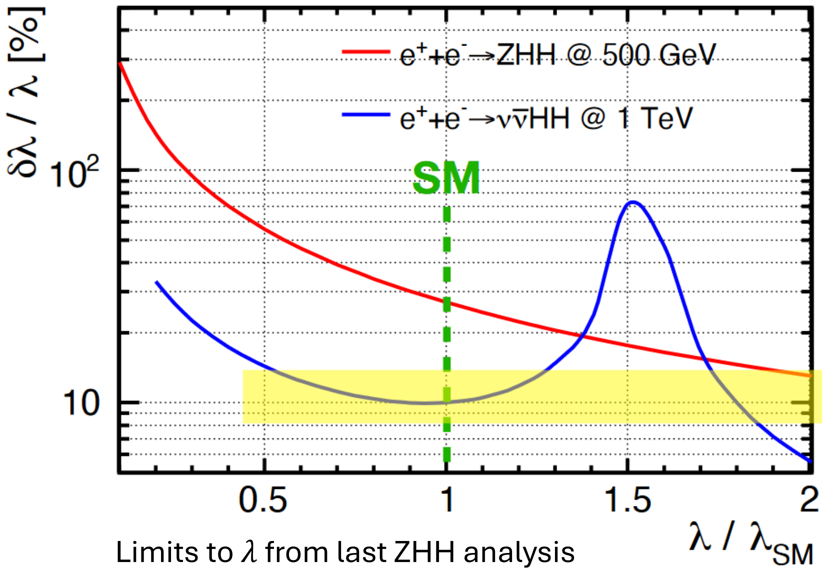
- Precision reach after running 4ab^{-1} at $500\ \text{GeV}\ \left(\text{HH} \rightarrow b\bar{b}b\bar{b} + \text{HH} \rightarrow b\bar{b}W^{\pm}W^{\mp}\right)$

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

$$\Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 26.6\% \quad (10\% \text{ with additional upgrade to 1 TeV})$$



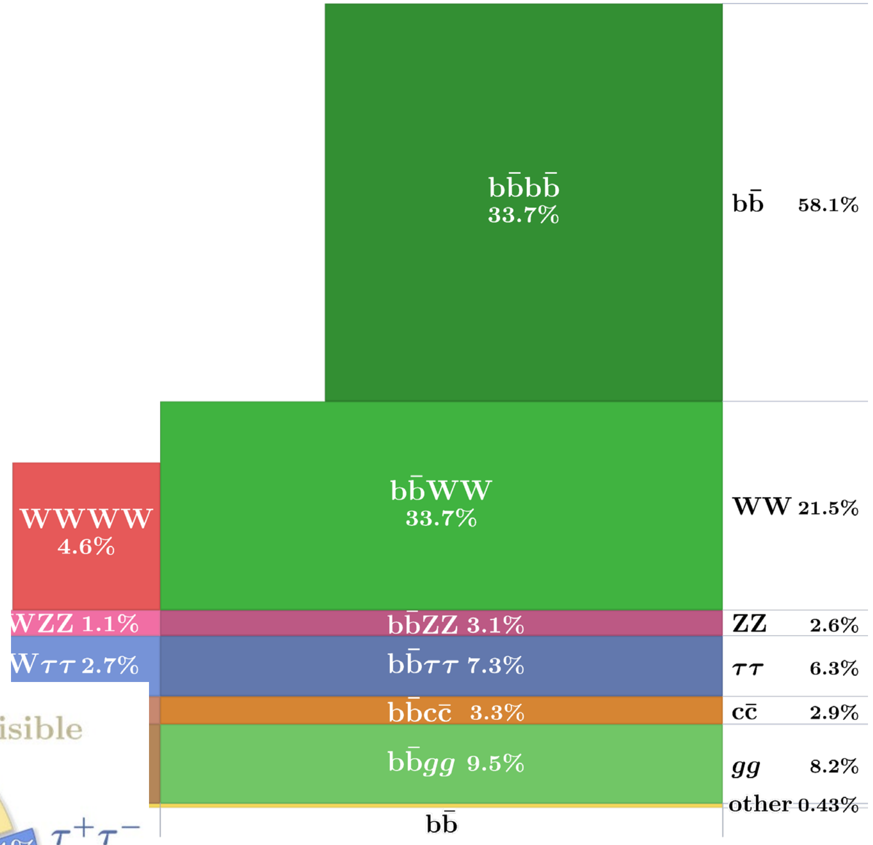
Lepton, neutrino and hadron channel of the signal process ZHH.
From [Du16]



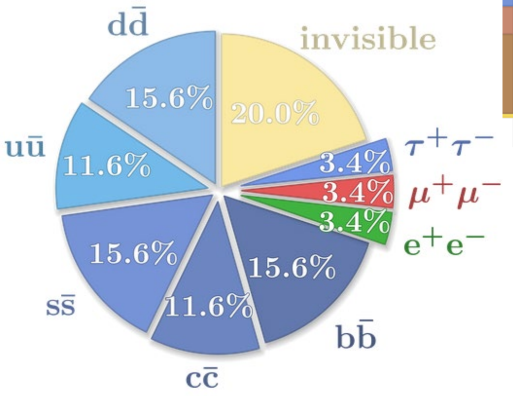
Limits to λ from last ZHH analysis

Improving on the last Analysis

- All signal channels evolve around $HH \rightarrow b\bar{b}b\bar{b}$
  - Large[1] gains possible from new tagging algorithms analysis depends on ϵ_b by $o(x^4)$
  - Even more important for background suppression in hadronic channel
- Lepton channel
  - Profits[2] from lepton ID improvements by $o(x^2)$
  - Tagging of tau events possible in the future



Branching Ratios of Di-Higgs Decays



Branching Ratios of Z decays

[1] Talks by Taikan Suehara and Sarah Aumiller

[2] Talk by Ulrich Einhaus

Bottlenecks in the ZHH analysis

- 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 $H \rightarrow b\bar{b}$ is the dominant Higgs decay channel
- adding $Z \rightarrow \tau\tau$ 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

Status of the Analysis

Progress on ZHH

- **Framework for analysis with fully-simulated samples now running** using law [*]
  - covering SM backgrounds for 2f, 4f, 6f, 8f and incorporating weighting for $P(e^+, e^-) = (+0.3, -0.8)$
- **Optimization of cuts in progress** (next slides)
- **550 GeV sample production ongoing** with colleagues from SLAC and U Tokyo
  - Motivated by 550 GeV COM studies; have shown over proportional improvement over 500 GeV meas.
  - Investigation of early 2f/4f samples with fast simulation (SGV) in progress
  - Production of 6f/8f background samples ongoing

```
Using     : 44.04M events
Available: 58.74M events
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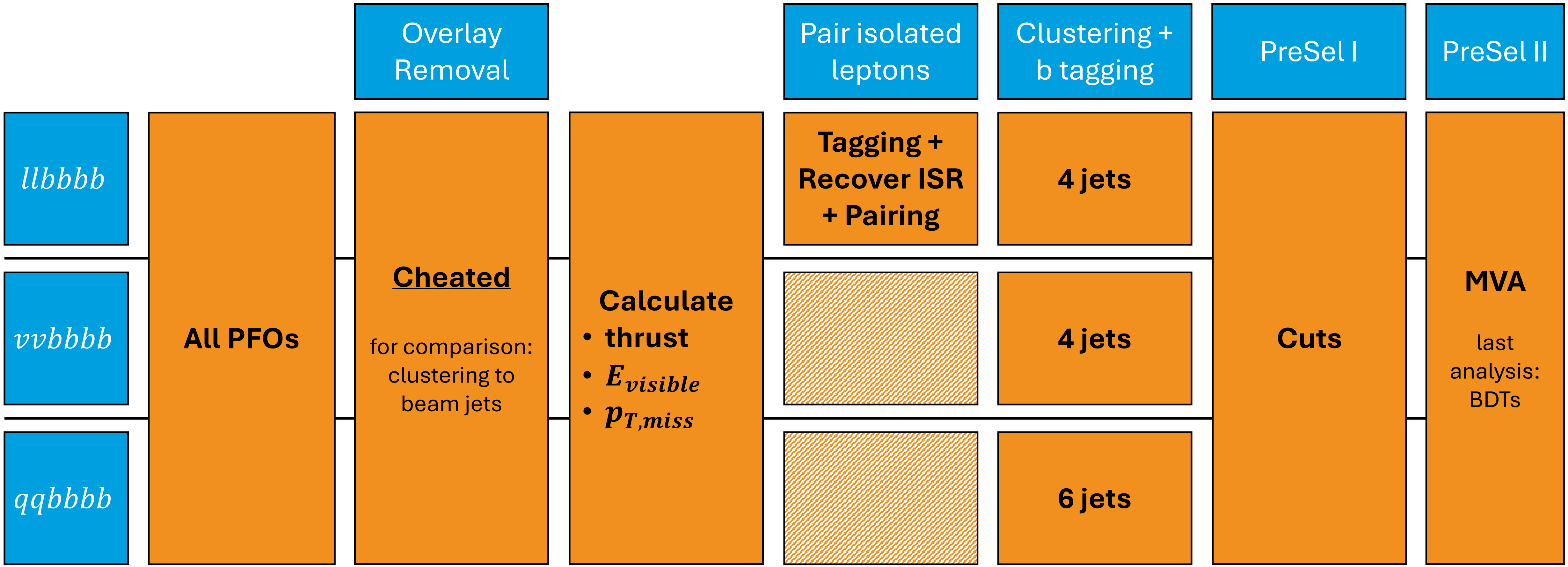
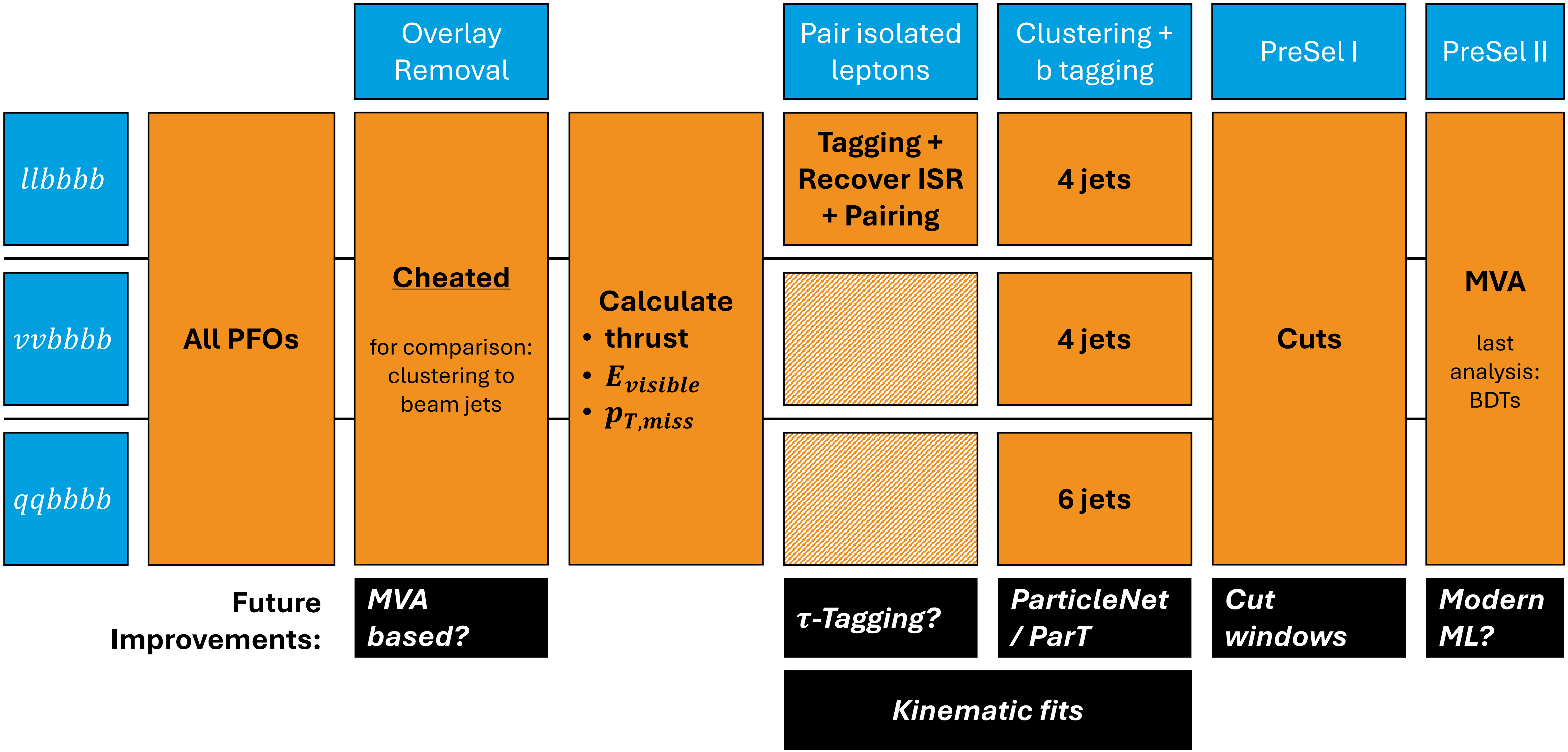
Number of events considered.

[*] luigi analysis workflows

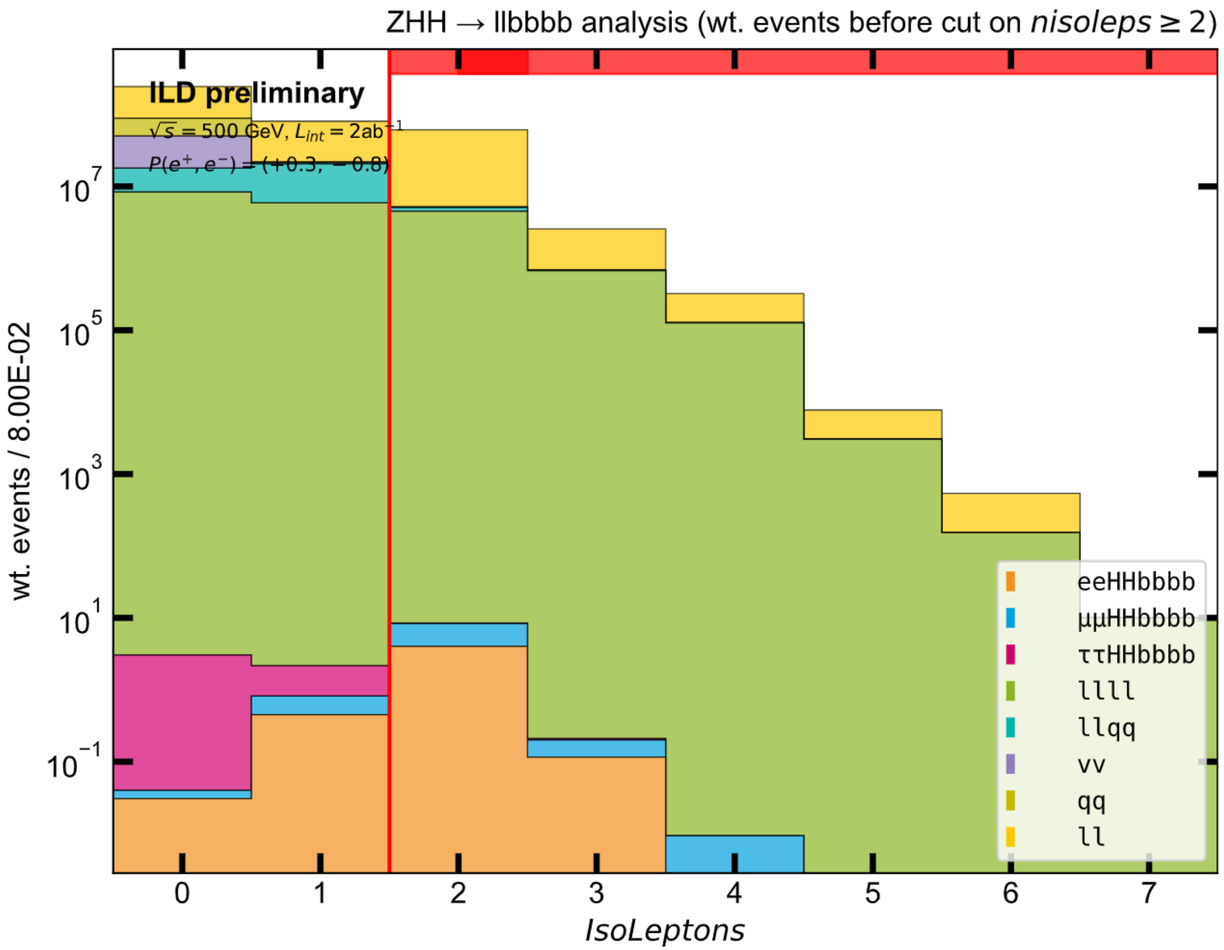
Analysis Flow

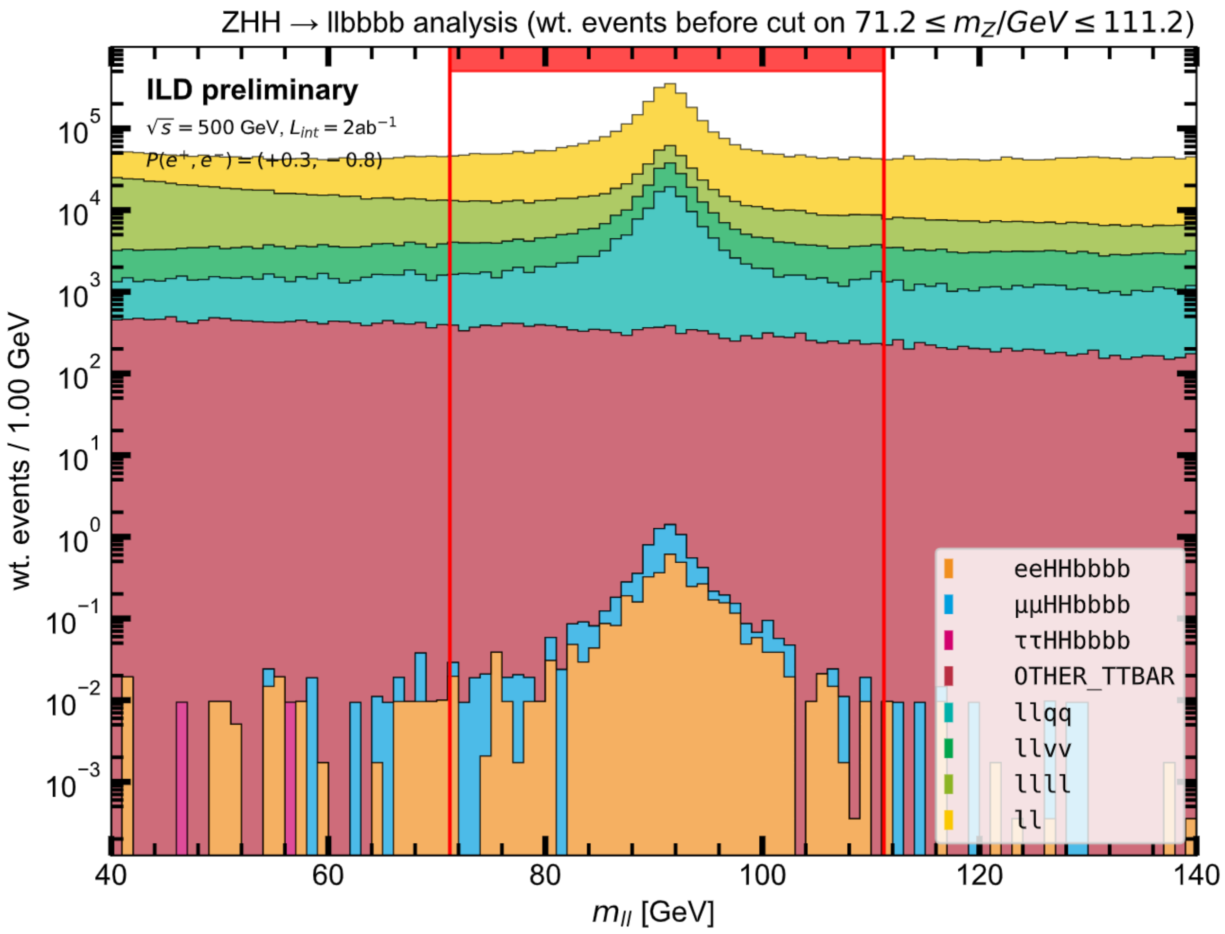


Analysis Flow



Preselection: Leptonic Channel – ZHH → $l\bar{l}b\bar{b}b\bar{b}$





Preselection: Leptonic Channel – ZHH → $l\bar{l}b\bar{b}b\bar{b}$

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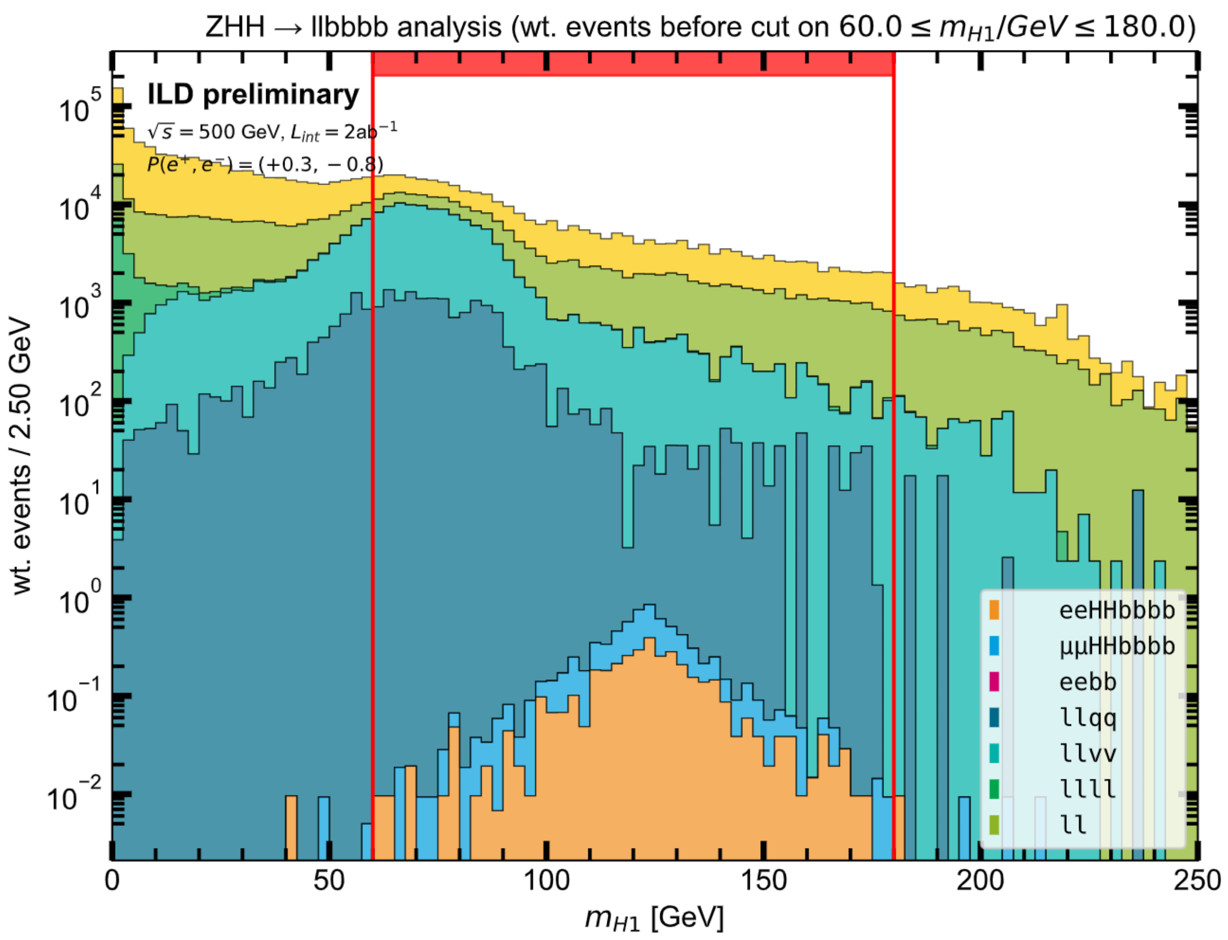

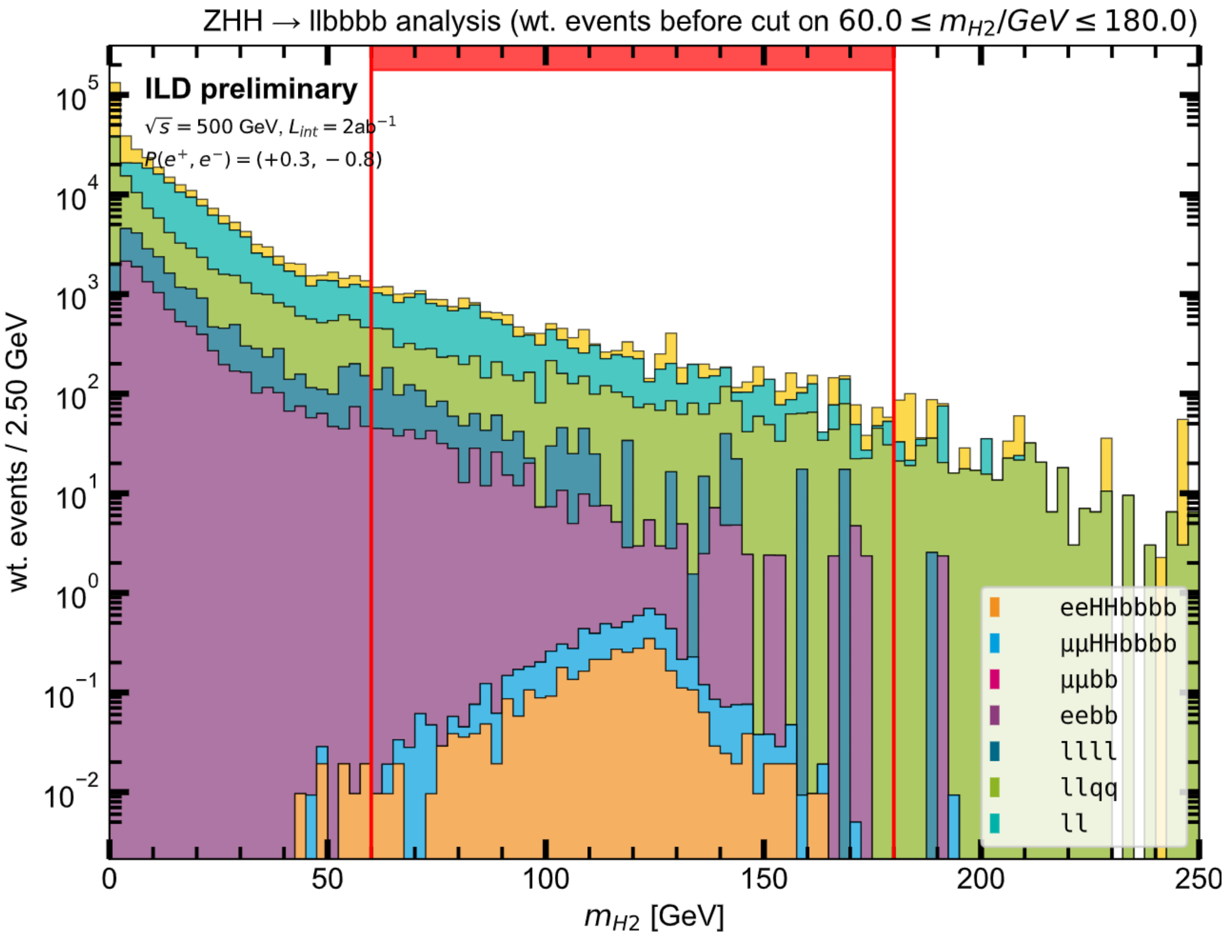

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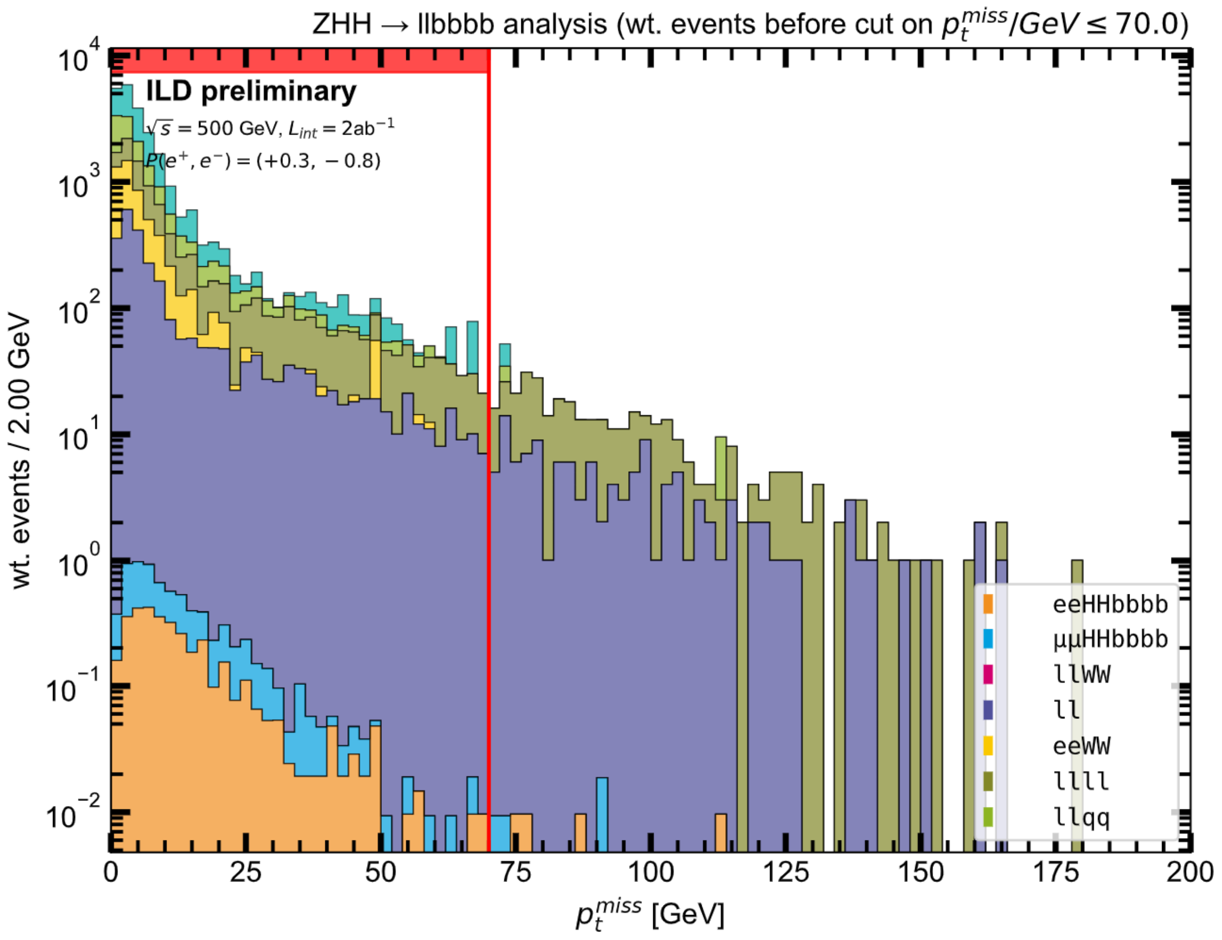

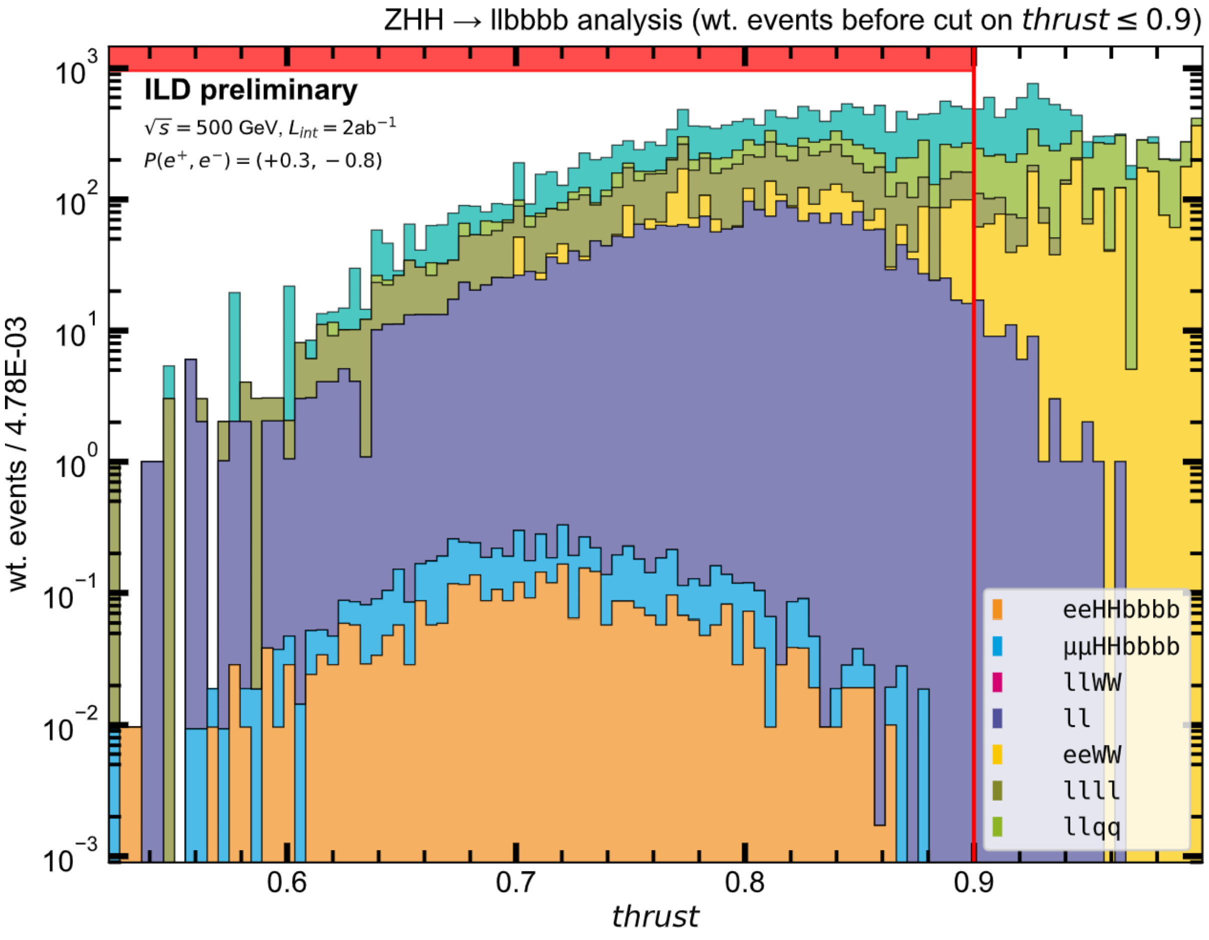

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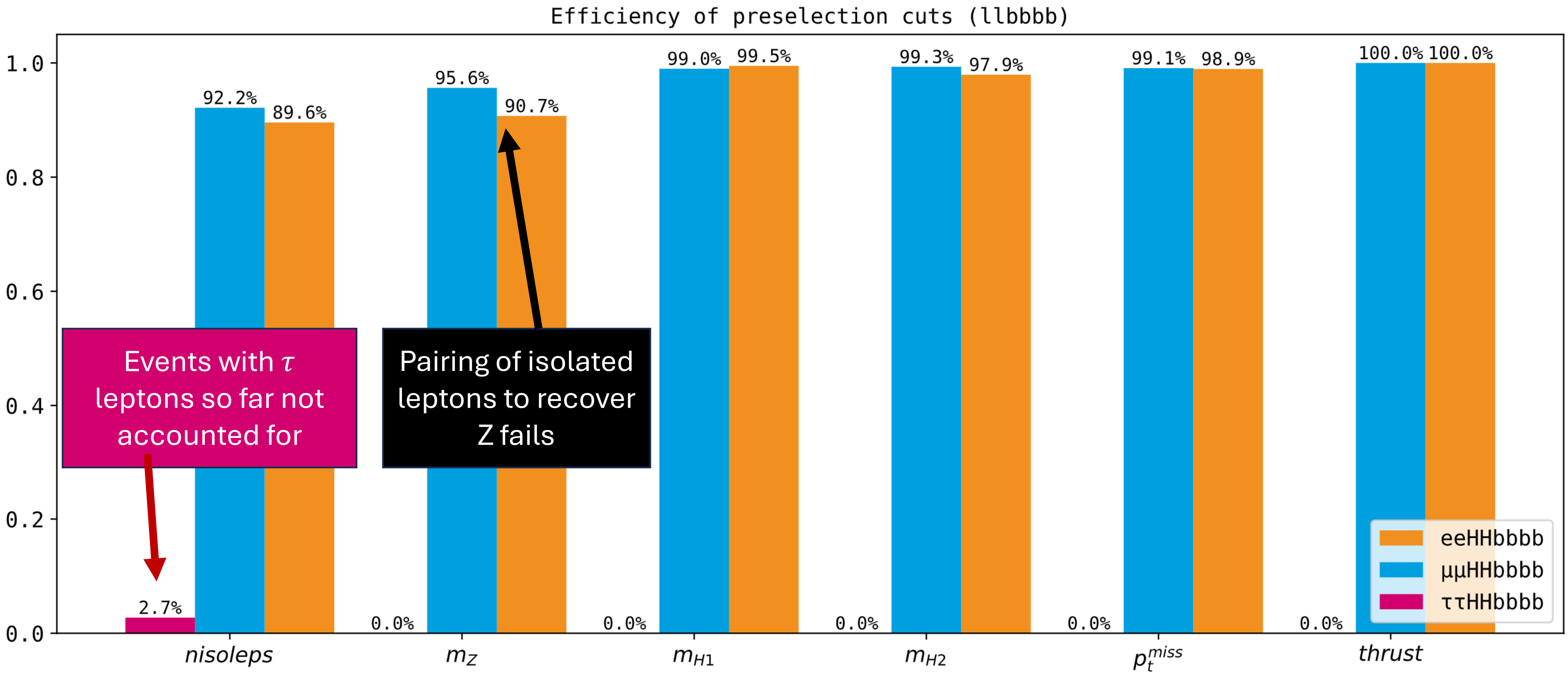
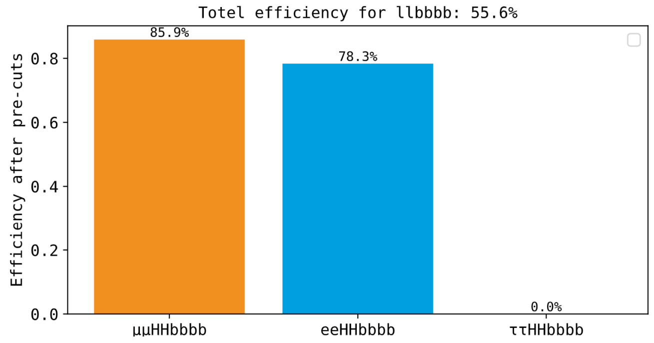
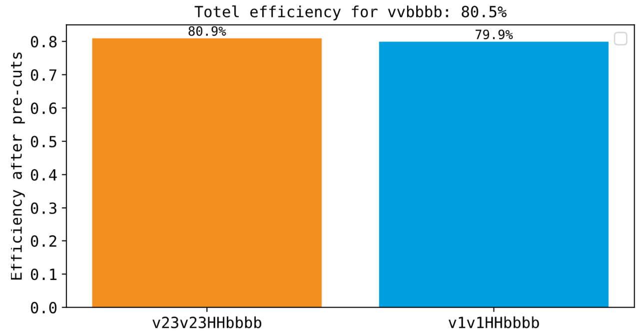


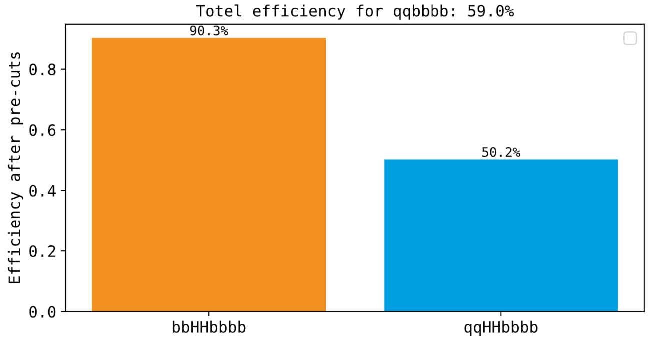
Preselection: Comparison of Efficiencies

- already now, **preselection efficiencies match last analysis** at similar background rejection
- 5-10% further increase in efficiency expected by optimizing cuts
- Improvements through modern jet-tagging, PID etc. stil to be included

	Last	Now
llbbbb	53.8%	55.6%
vvbbbb	75.4%	80.5%
qqbbbb	58.8%	59.0%







Outlook and Summary

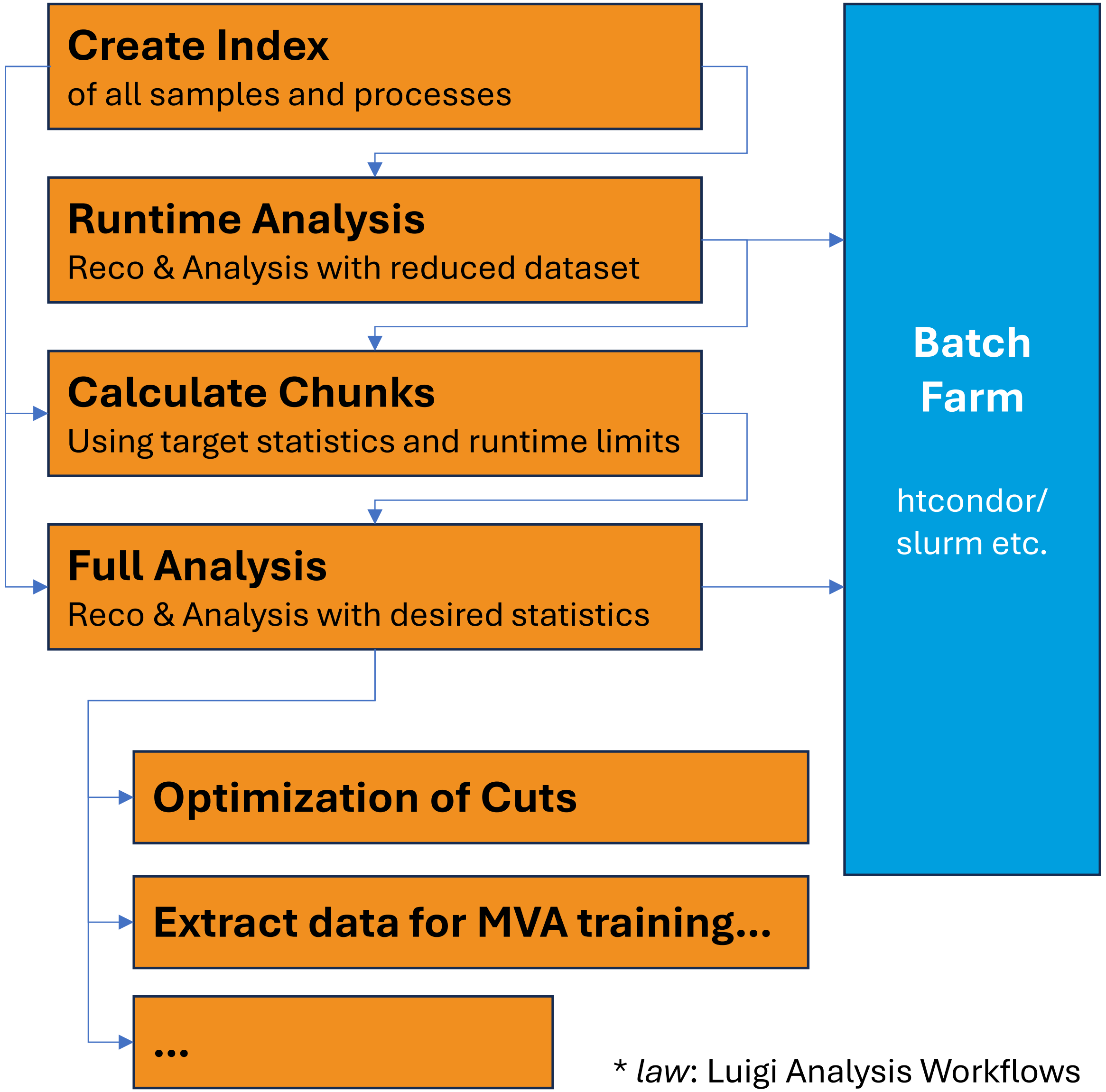
- Automated framework for a new ZHH analysis is set up
- Preselection efficiencies for all channels line up with last study at similar rejection
  - ~10% improvement expected by optimizing cuts
- **Effort on 550 GeV sample production** ongoing
- Next steps:
  - Large improvements expected from upgrading to state-of-the-art analysis tools
  - **Integrate modern jet tagging** and particle ID
  - Implement final event selection using current ML techniques and **extract limits on** λ_{ZHH}
- **Better than 20% sensitivity on λ in reach**
  through demonstrated reconstruction improvements

Thank you for listening!

Backup

Faster Progress through Data Pipelines

- Problem: highly heterogenous data requires reliable bookkeeping and job submission
- Solution: based analysis on luigi+law* to
  - organizes flow of data more transparent,
  - manages job submissions, resubmission etc.
  - makes the central book-keeping easier
- Status: Working/Done.



* *law*: Luigi Analysis Workflows

Preselection: Neutrino Channel – ZHH → $\nu\bar{\nu}b\bar{b}b\bar{b}$

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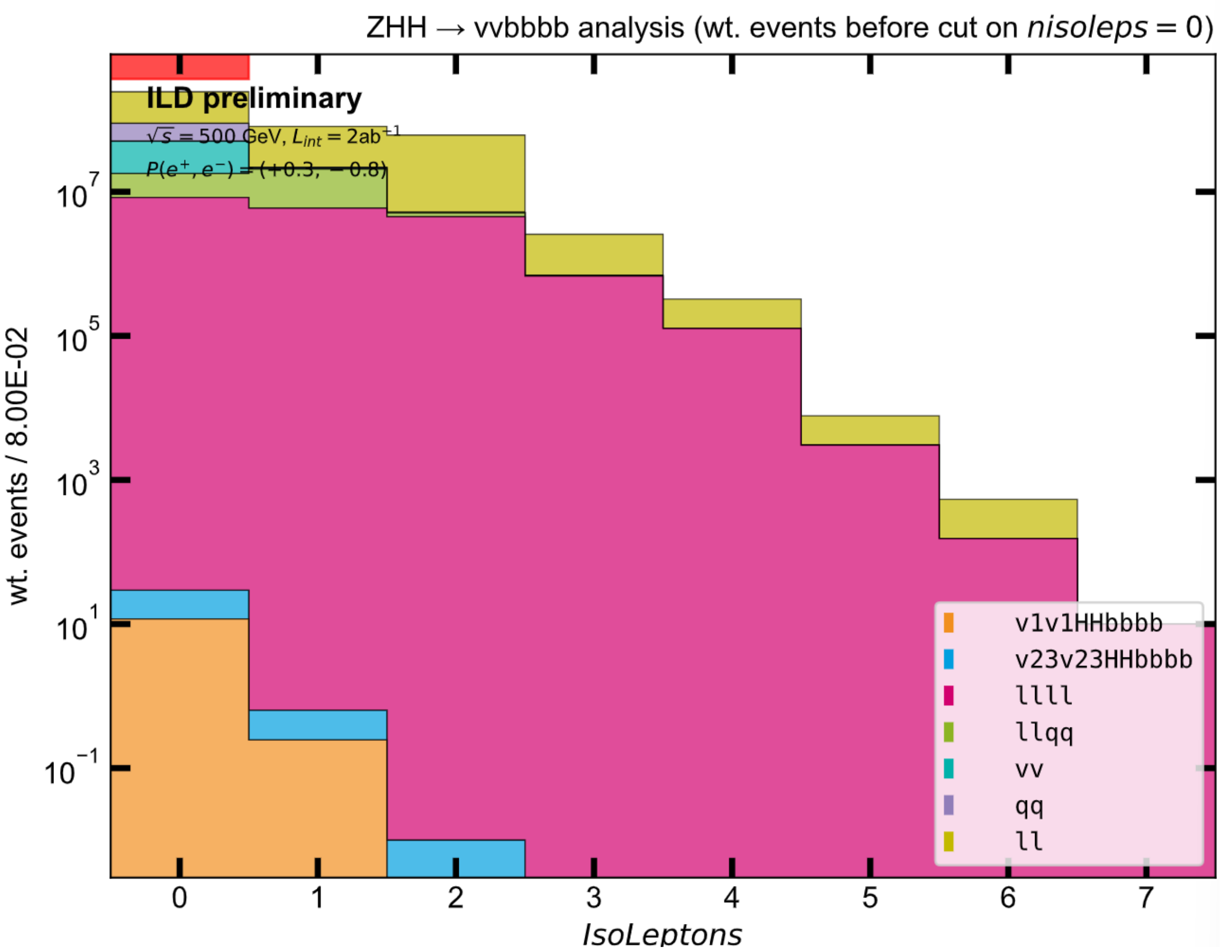

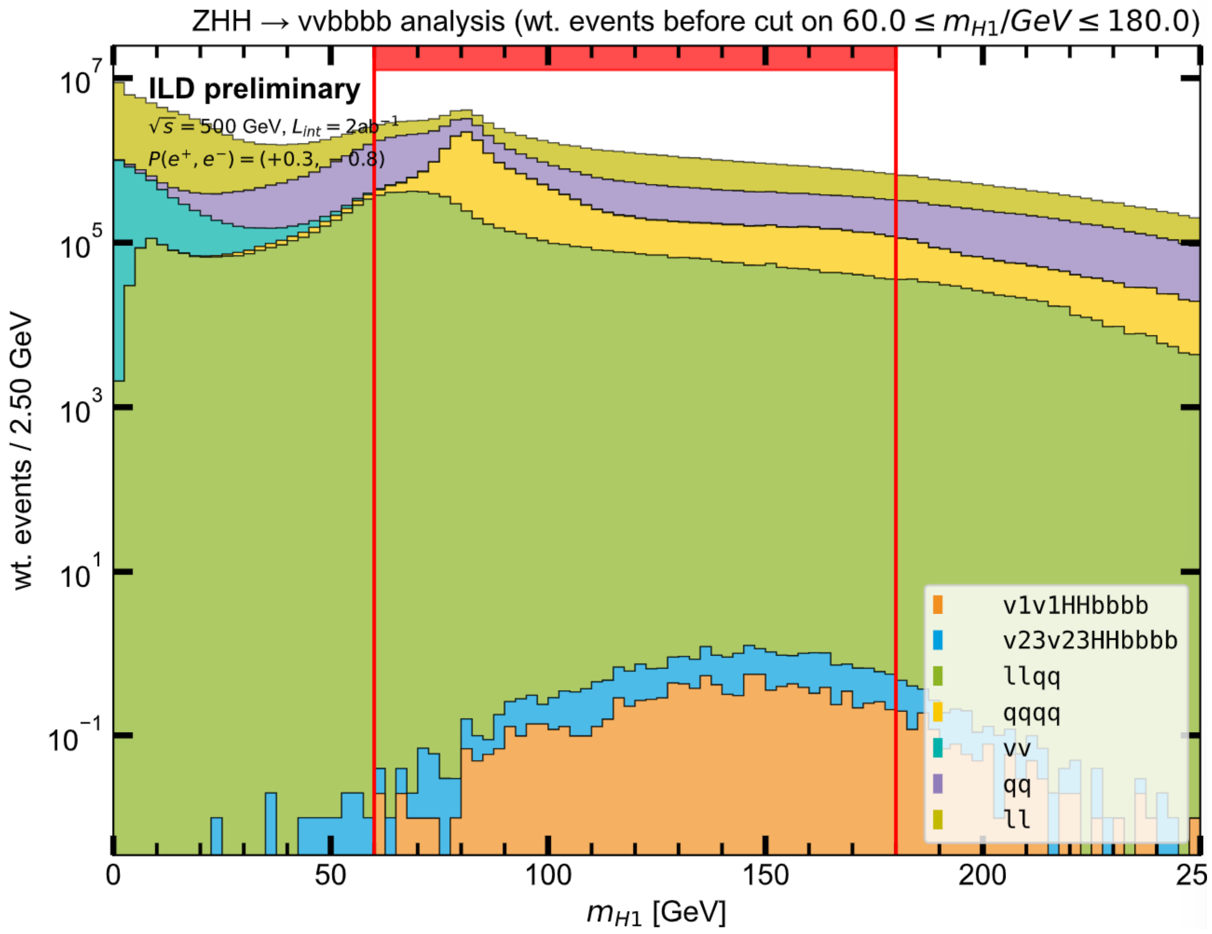

Preselection: Neutrino Channel – ZHH → $\nu\bar{\nu}b\bar{b}b\bar{b}$

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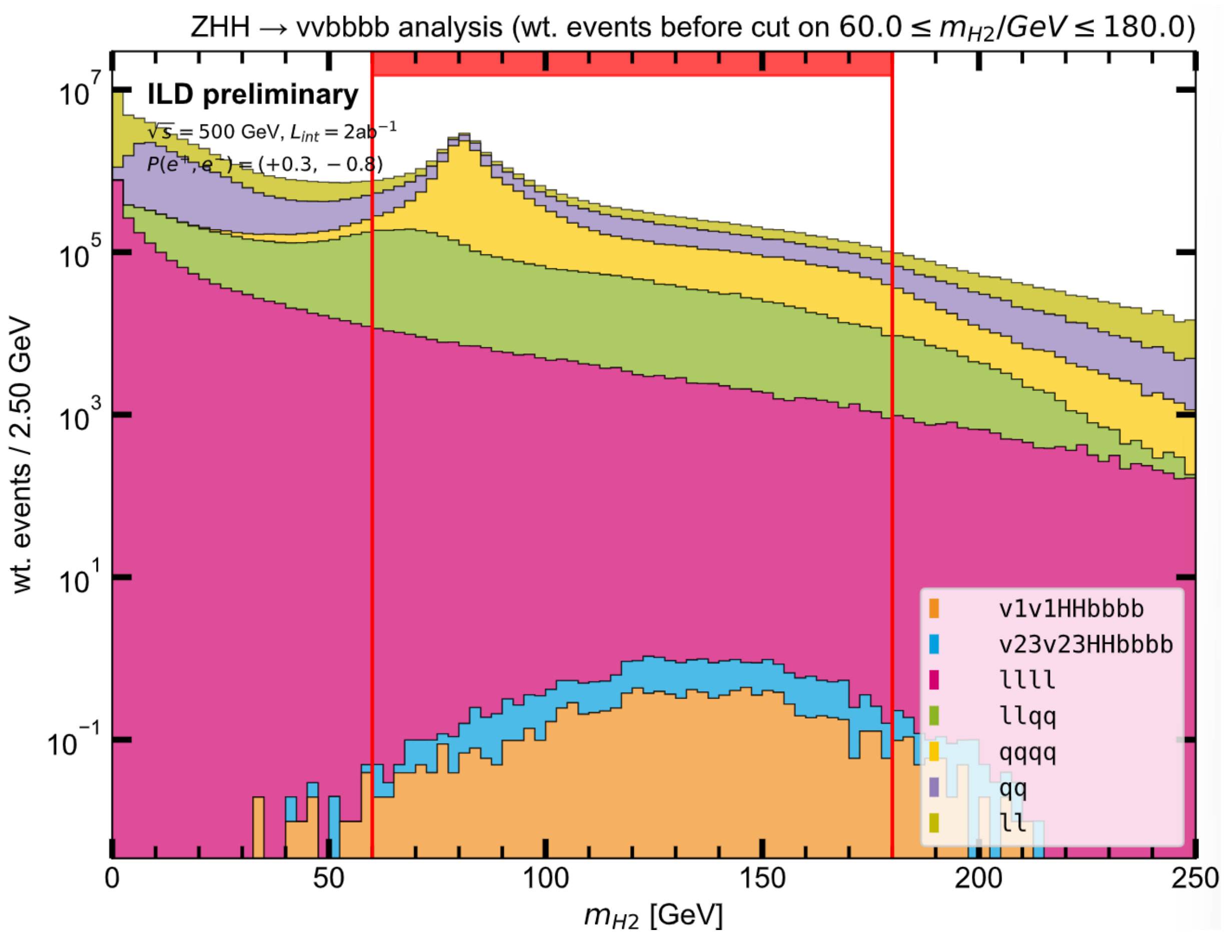

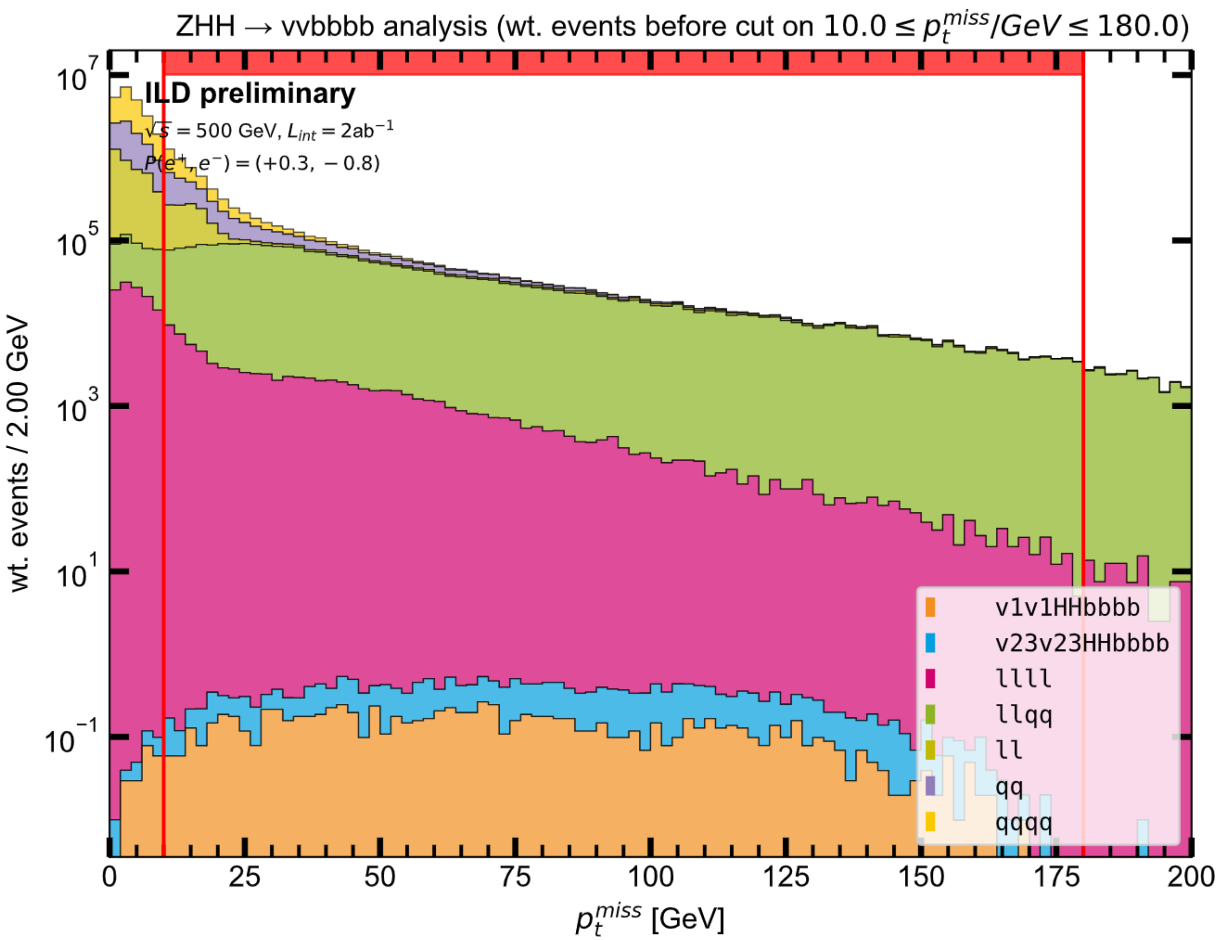

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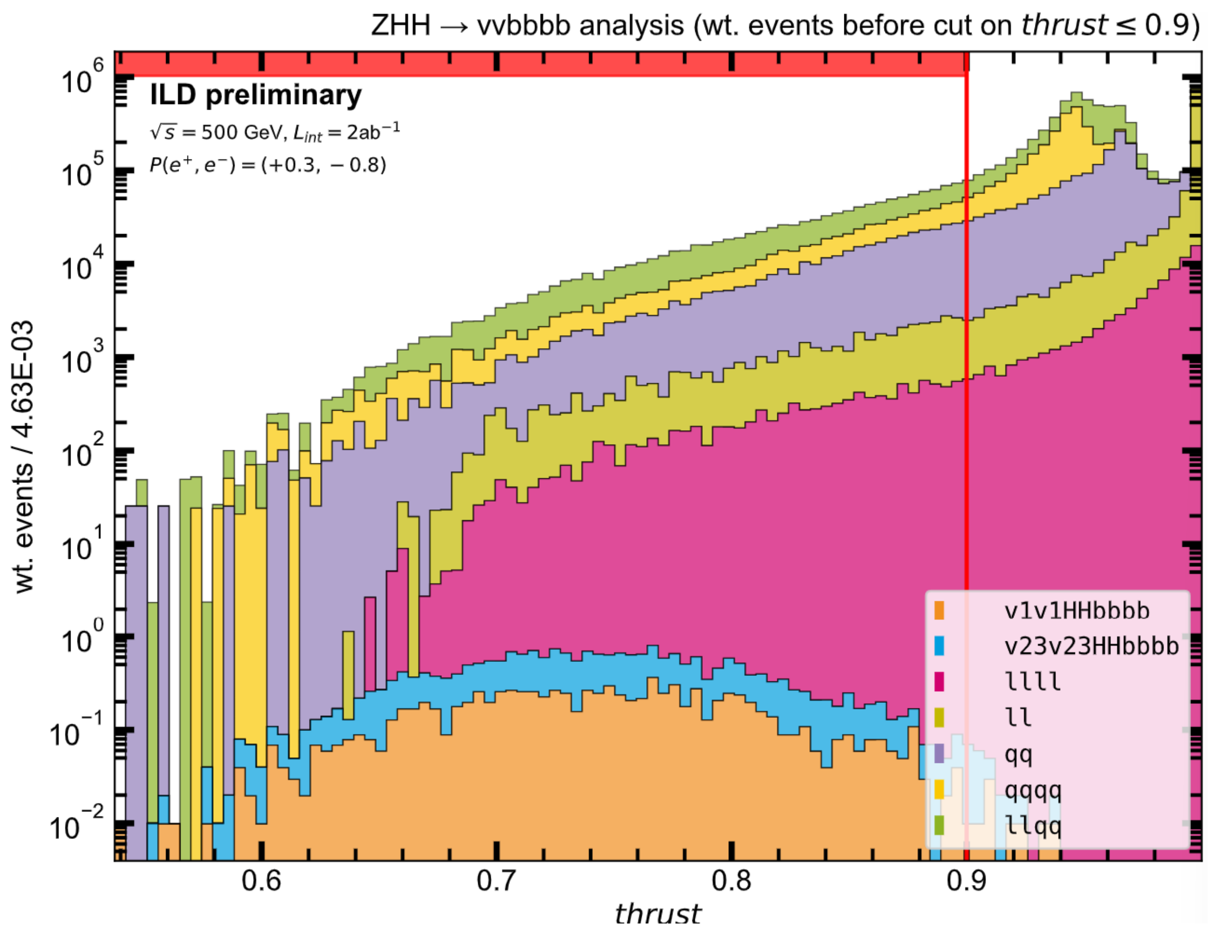

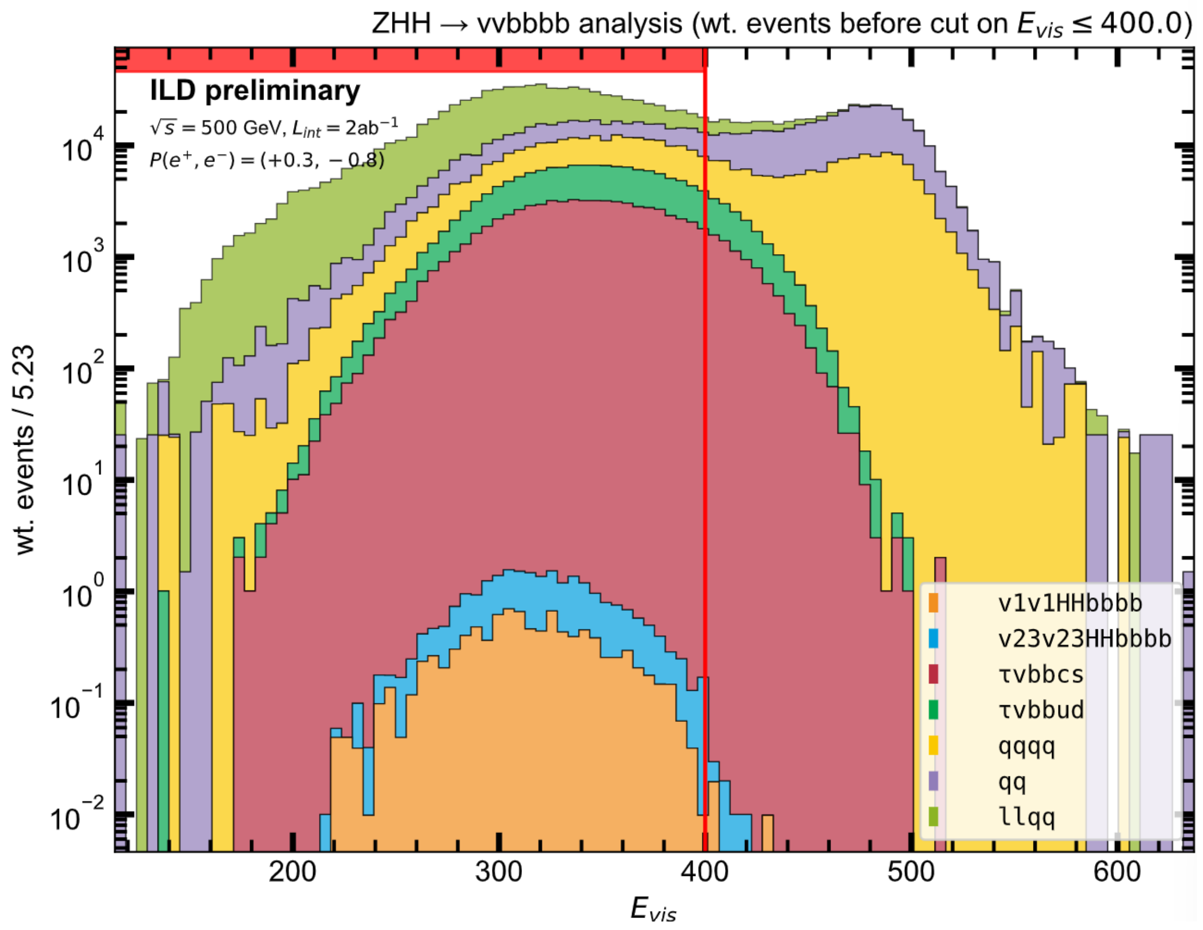

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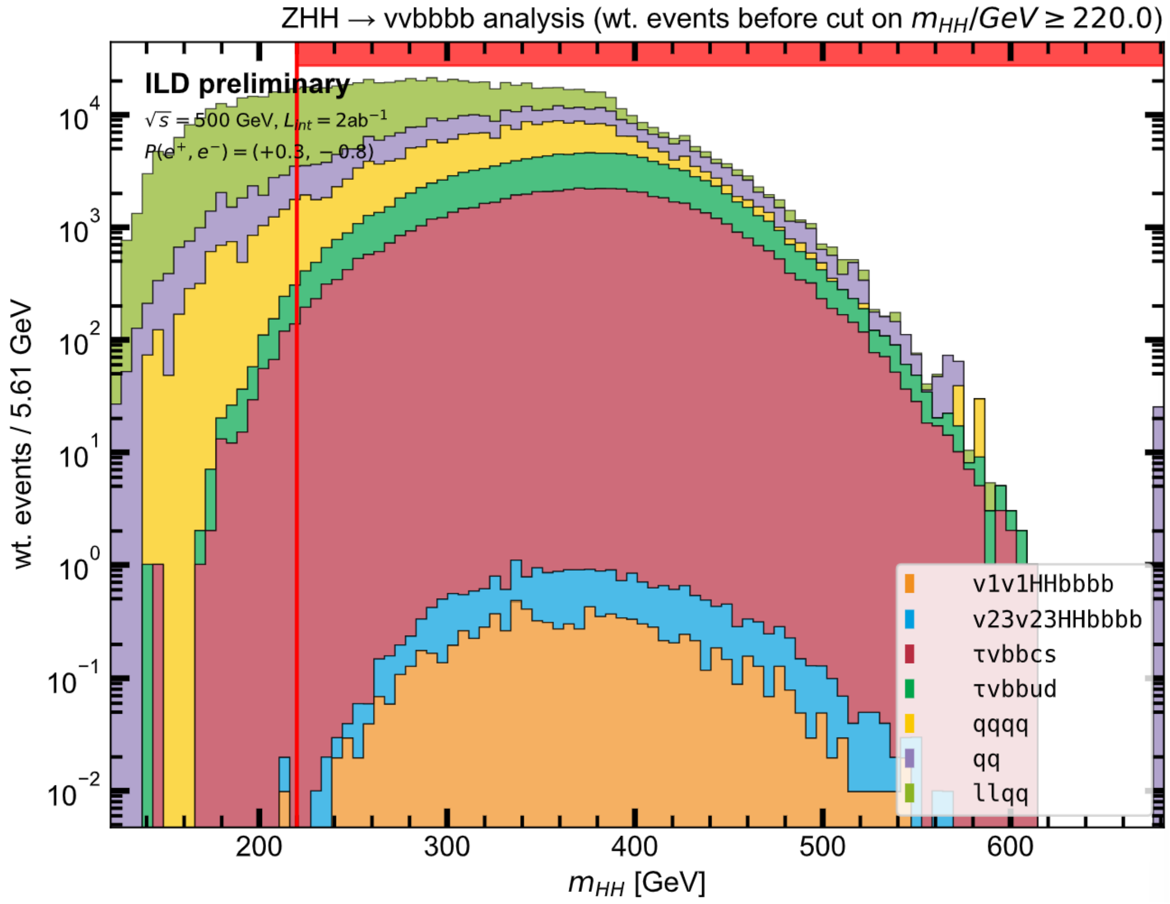
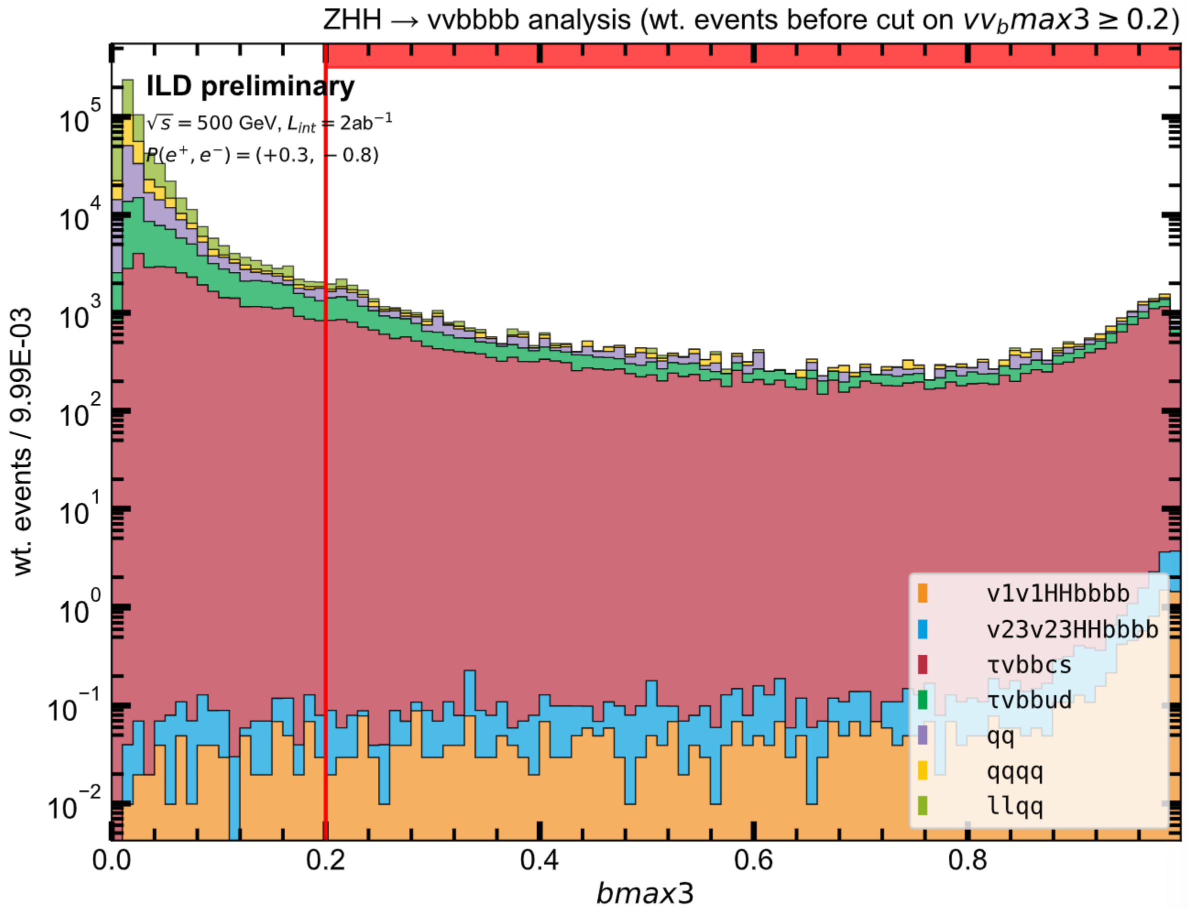
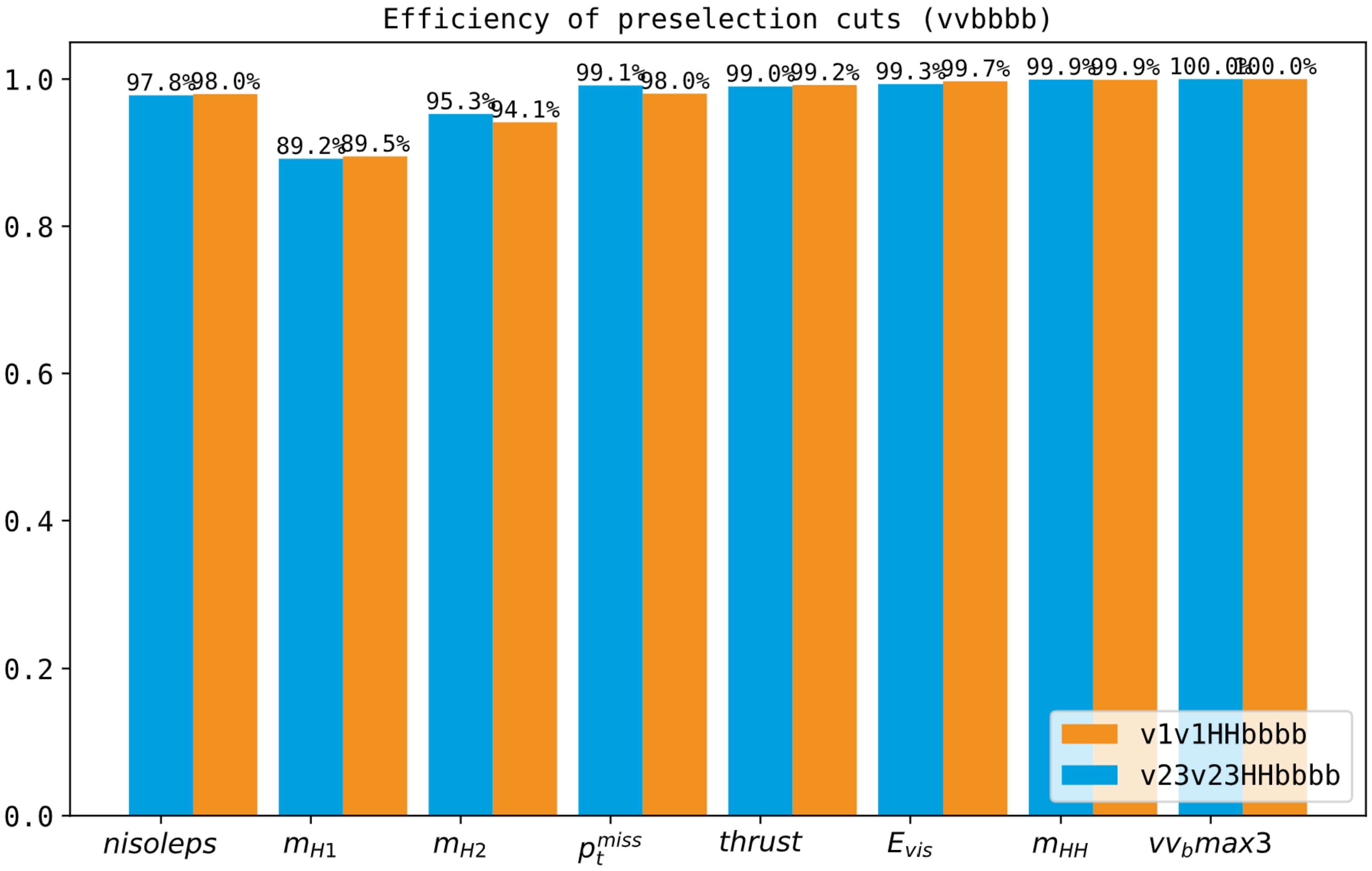




Preselection: Hadron Channel – ZHH → $\nu\bar{\nu}b\bar{b}b\bar{b}$



Preselection: Hadron Channel – ZHH → $q\bar{q}b\bar{b}b\bar{b}$

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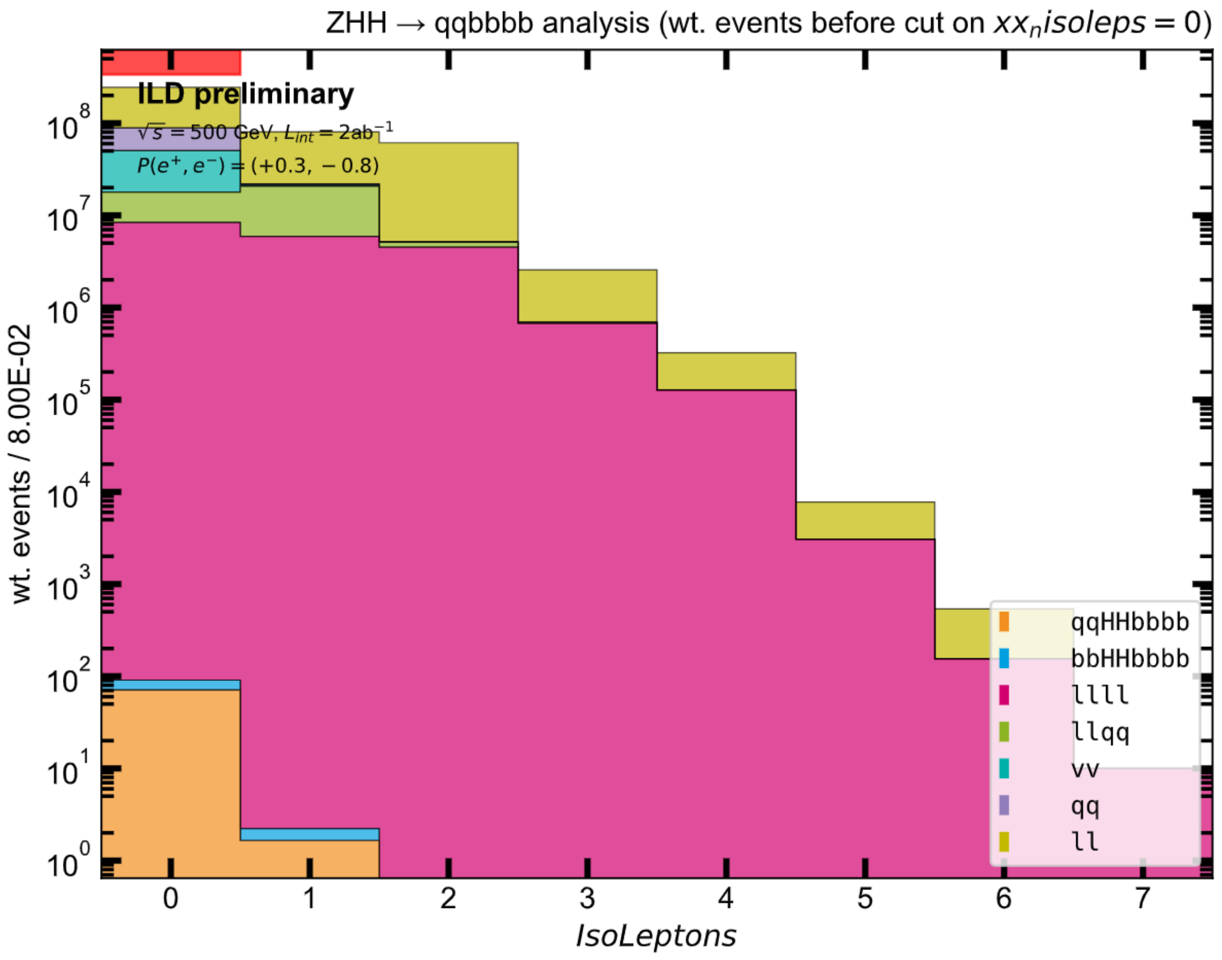

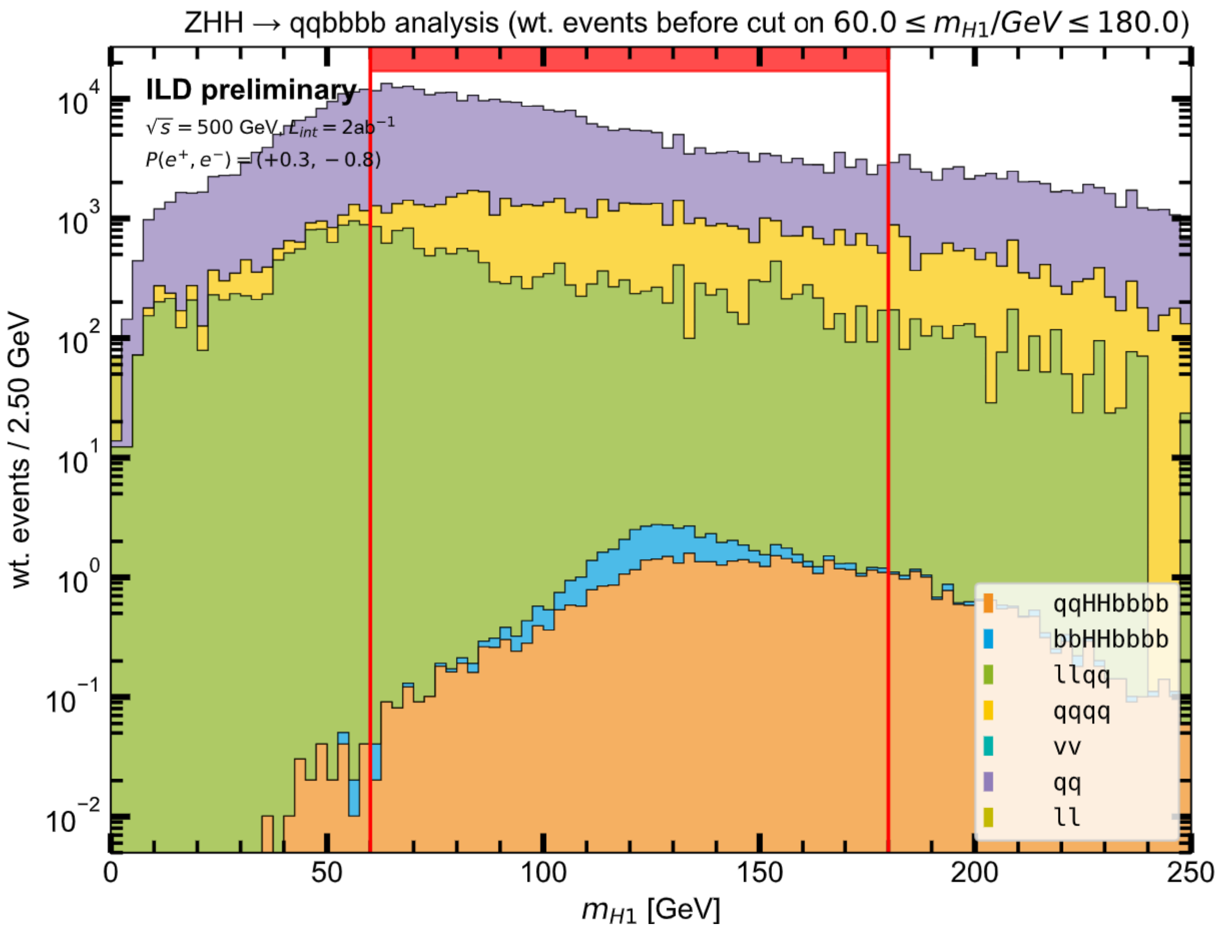

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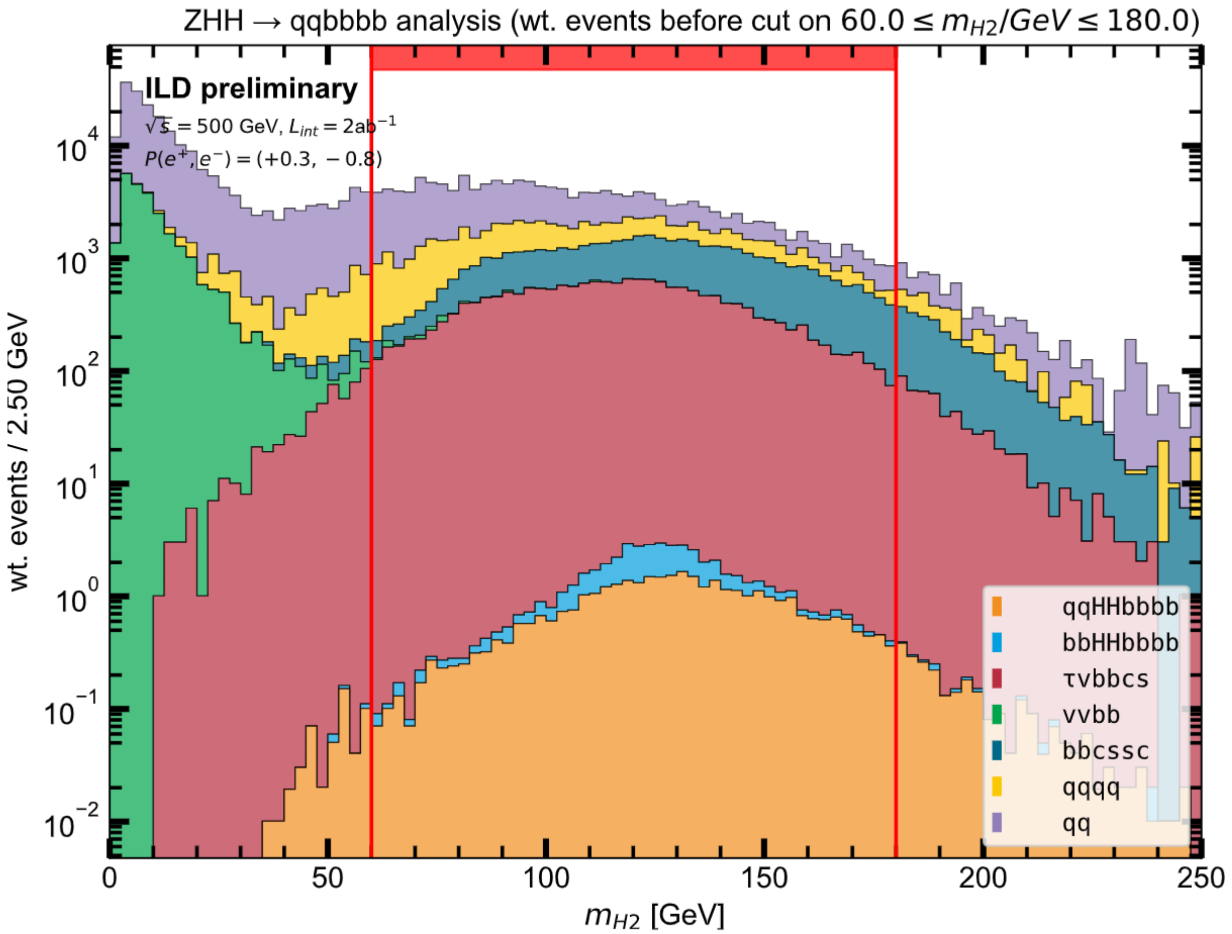

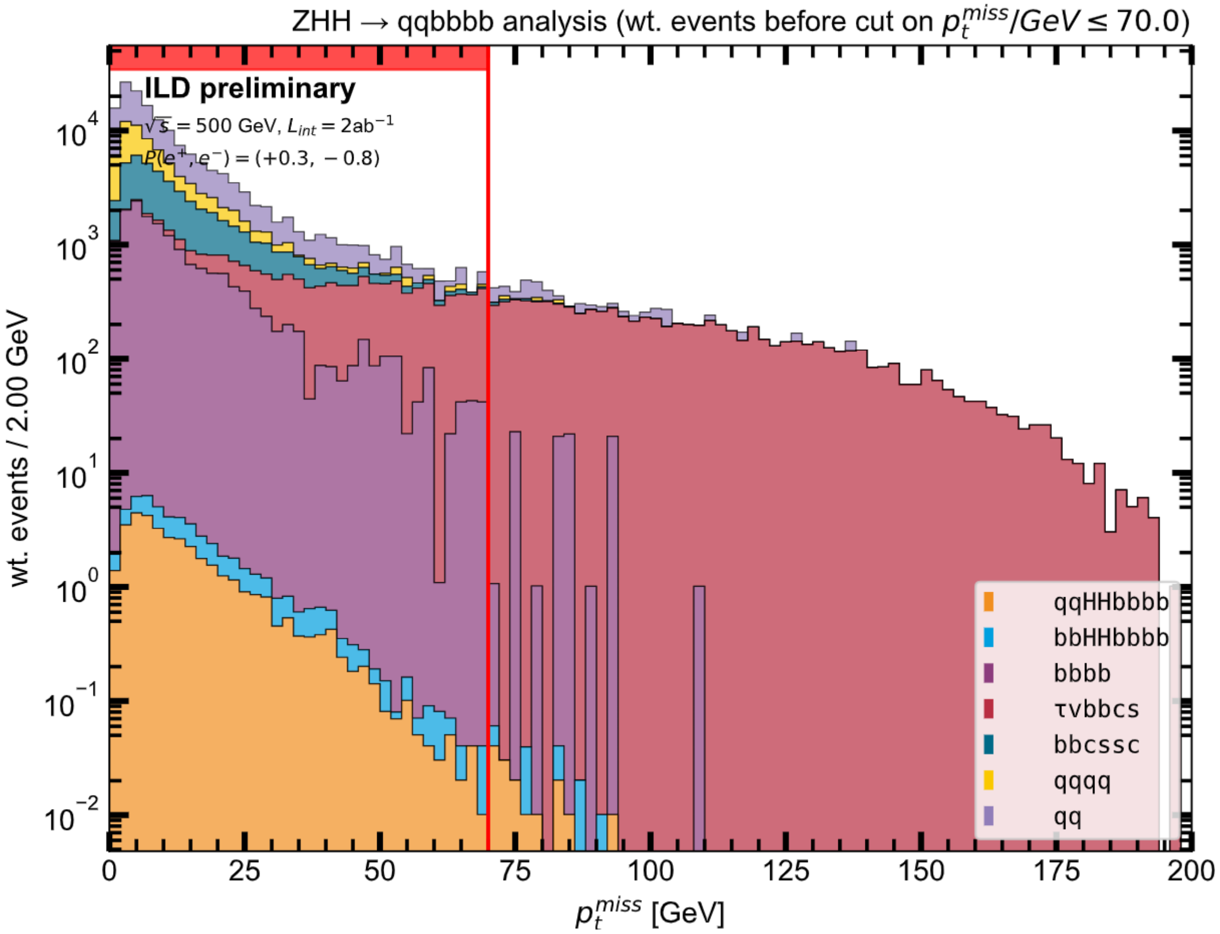

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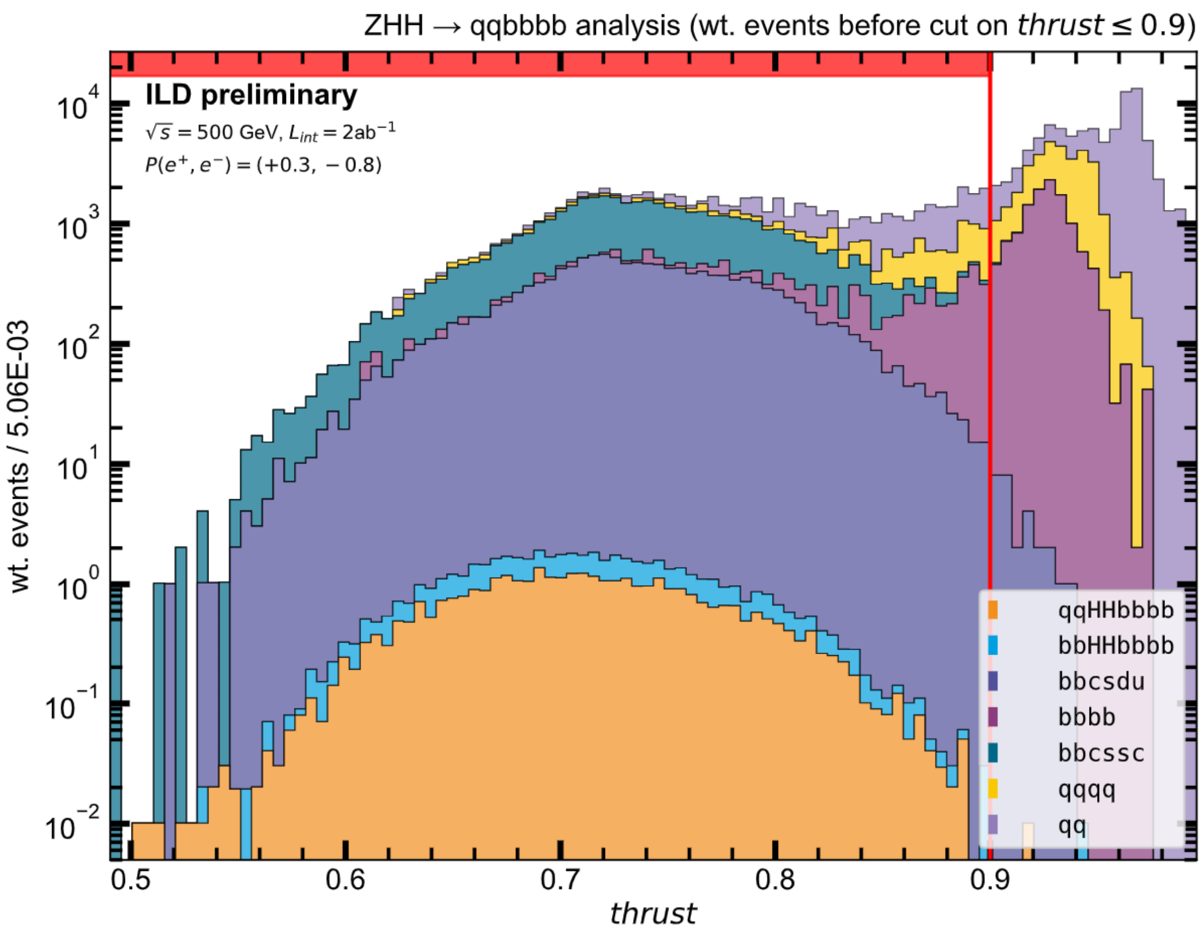

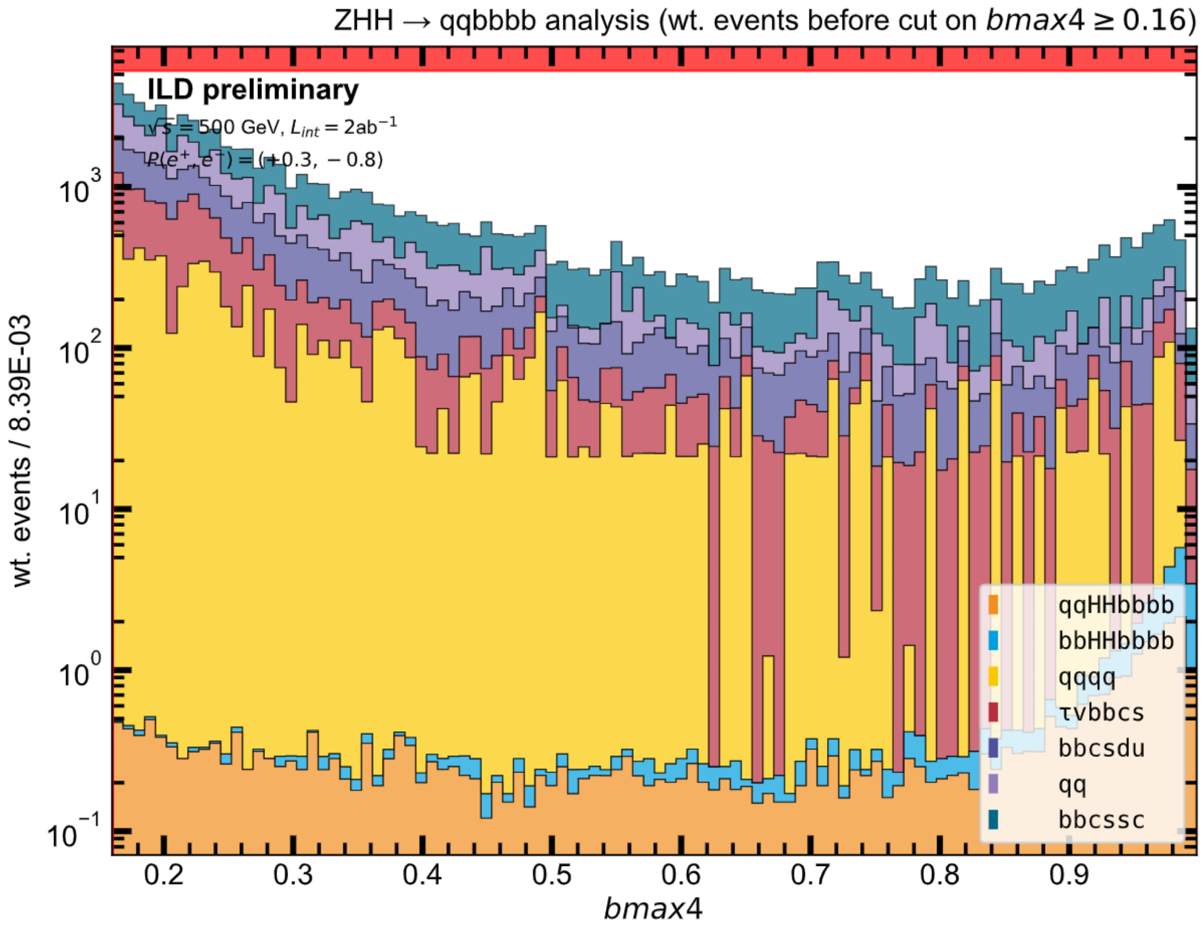

Preselection: Hadron Channel – $ZHH \rightarrow q\bar{q}b\bar{b}b\bar{b}$

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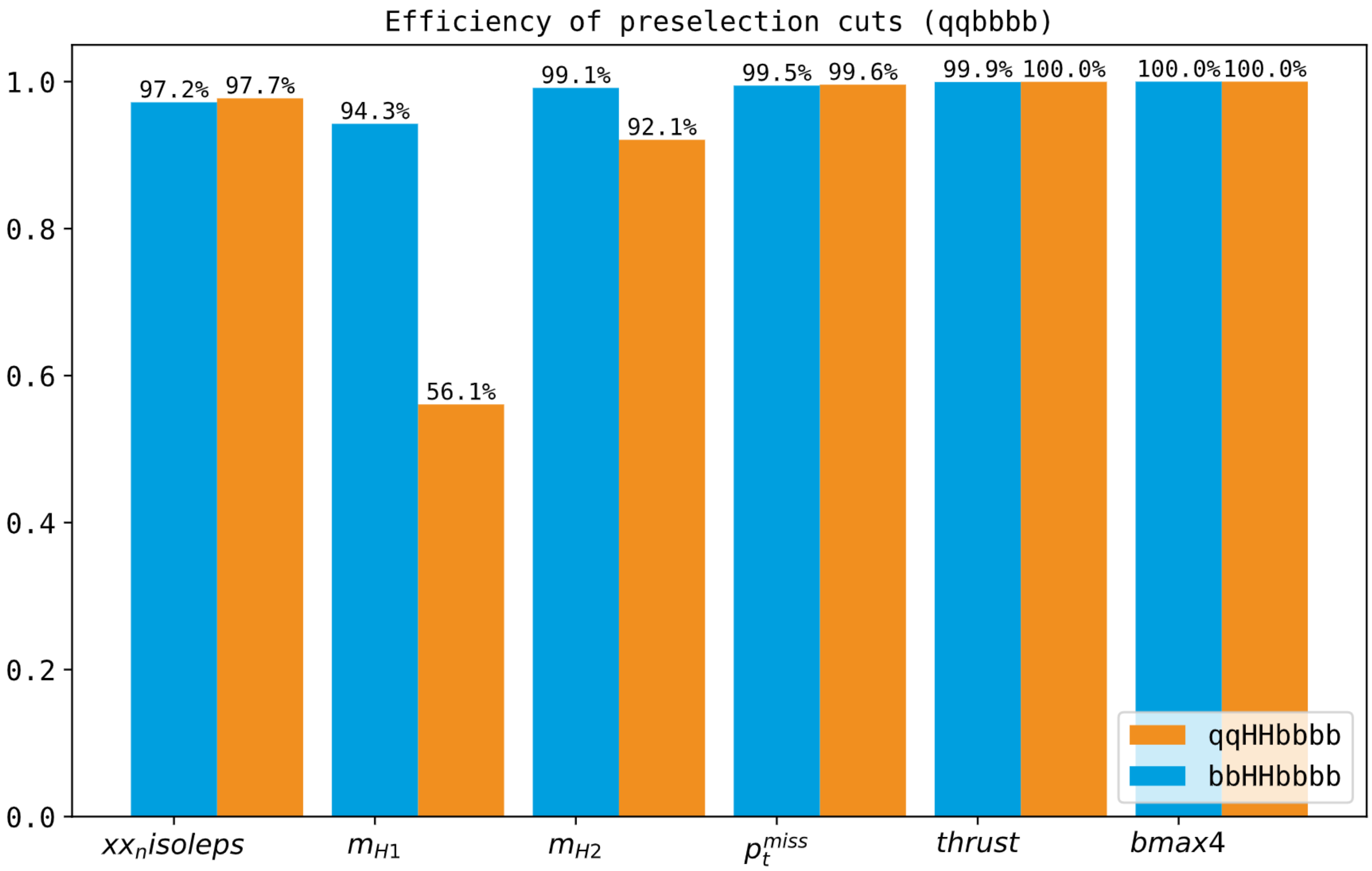
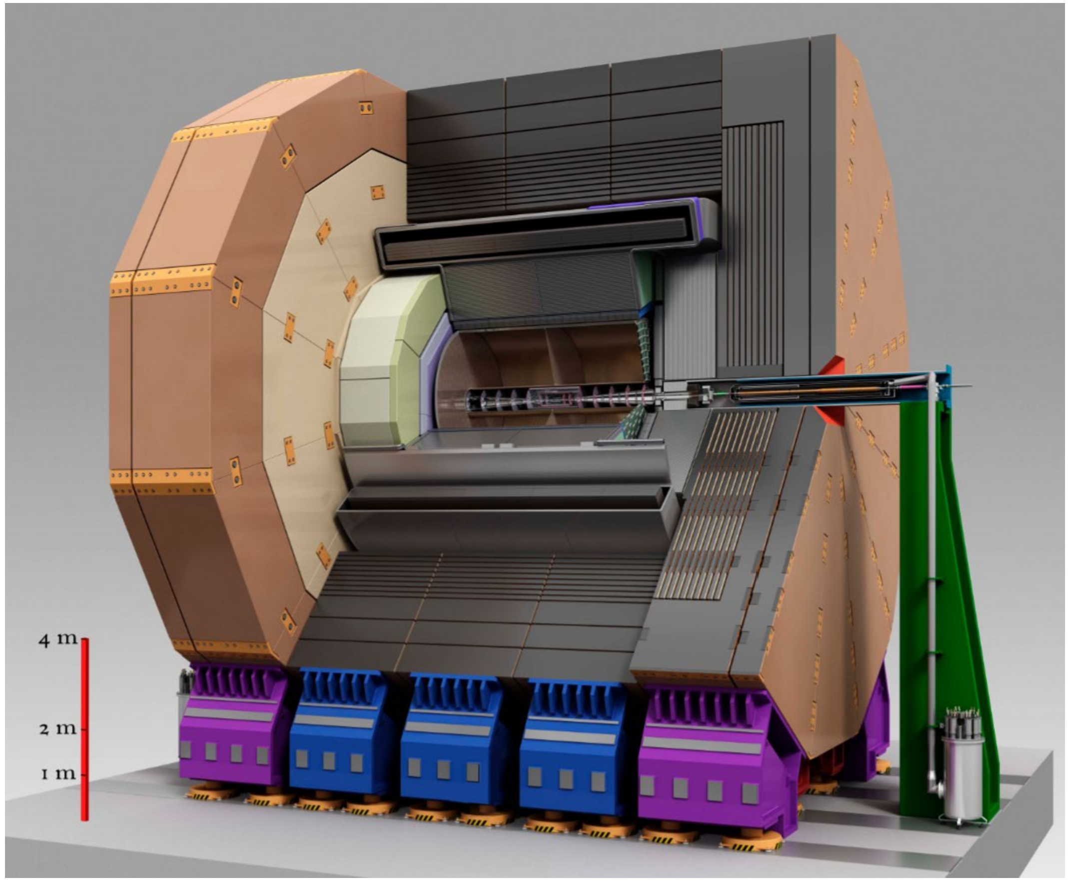


The International Large Detector (ILD)

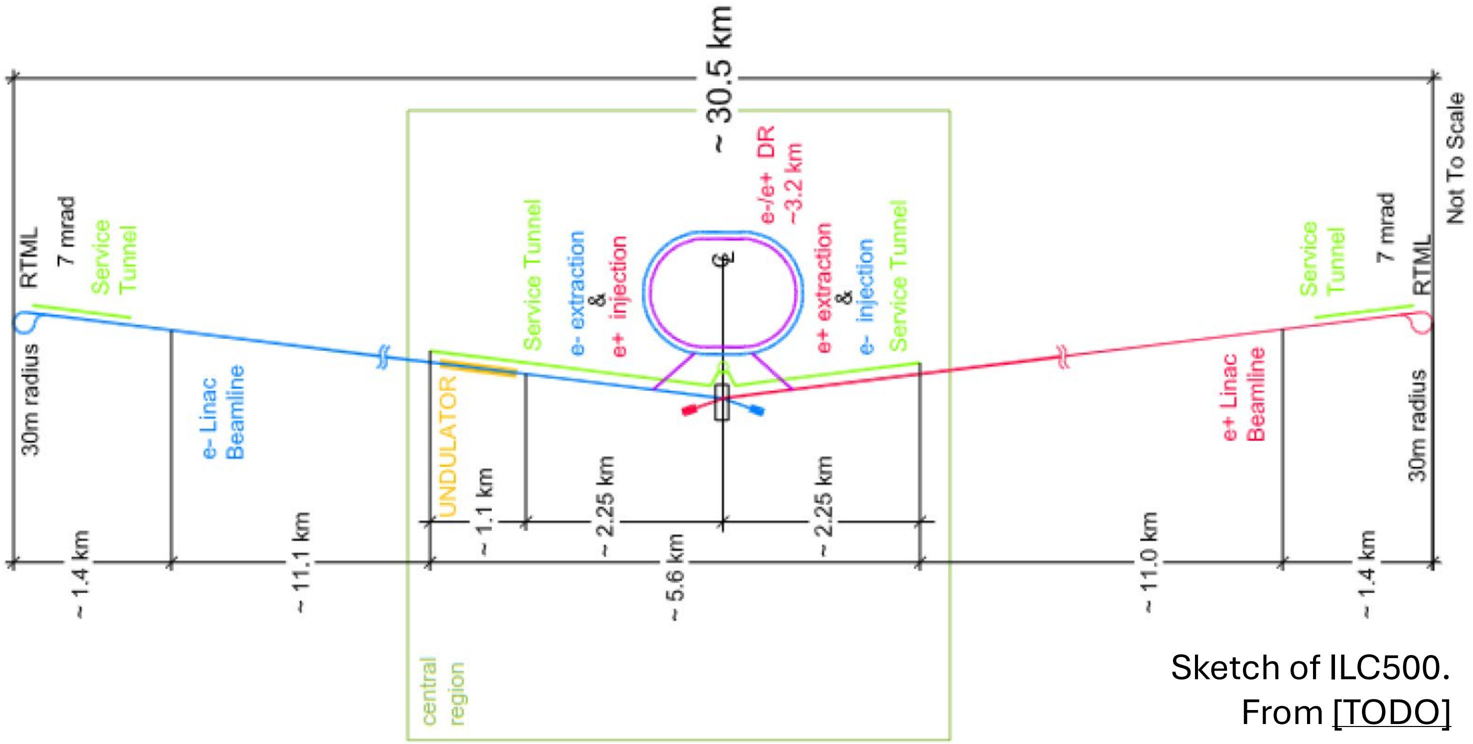
- well charatecterized, highly granular detector concept [IDR]
- designed around particle flow concept
  - allows reconstruction of individual physics objects (Particle Flow Objects, PFOs)
- full Geant4-based simulation available
  - including links between truth/reconstructed particles
- in the following: assuming ILD @ ILC500



Rendering of the ILD detector. From [Ba19]

The International Linear Collider (ILC)

- linear collider concept with multiple energy stages $\left(\frac{\sqrt{s}}{\text{GeV}} = 250, \mathbf{500}, 1000\right)$
  - $500\ \text{GeV}$ stage allows direct measurements of λ through di-Higgs production
- mature concept (TDR), technologies available (superconducting RF-cavities etc.)



Sketch of ILC500.
From [TODO]

Future Higgs Factories

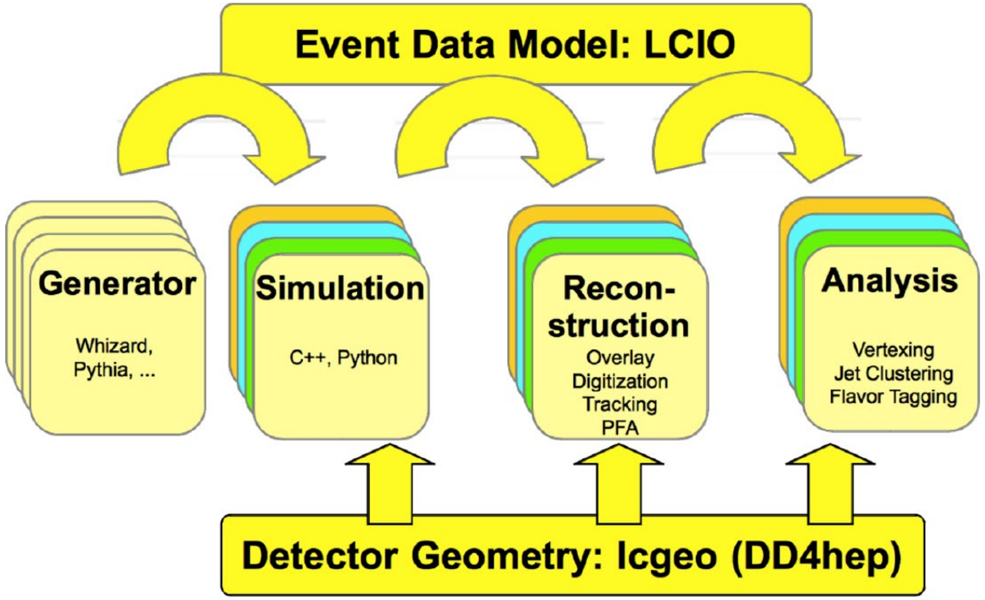
- goal: high production of Higgs bosons
- e^+e^- colliders for precision measurements
- different concepts proposed:
  - linear (ILC, CLIC, C^3):
    - maximum energy constrained by length
    - *direct* measurements of λ possible
    - measurements with polarized beams possible
  - circular (FCC-ee, CEPC):
    - maximum energy limited by synchrotron radiation
    - higher luminosities through beam reuse

Collider	$\sqrt{s}$	$\mathcal{P}(e^-/e^+)[\%]$	N_{det}	$\mathcal{L}[\text{abarn}^{-1}\text{s}^{-1}]$
ILC	250 GeV	$\pm 80/\pm 30$	1	2.0
	500 GeV	$\pm 80/\pm 30$	1	4.0
	1000 GeV	$\pm 80/\pm 30$	1	8.0
CLIC	380 GeV	$\pm 80/0$	1	1.0
	1.5 TeV	$\pm 80/0$	1	2.5
	3.0 TeV	$\pm 80/0$	1	5.0
C^3	250 GeV	$\pm x/0$	?	1.3
	550 GeV	$\pm x/0$	?	2.4
FCC-ee	M_Z	0/0	2	150
	$2M_W$	0/0	2	10
	240 GeV	0/0	2	5
	$2m_{top}$	0/0	2	1.5
CEPC	M_Z	0/0	2	16
	$2M_W$	0/0	2	2.6
	240 GeV	0/0	2	5.6
HALHF	250 GeV	0/0	1	≈ 2

Comparison of selected physics programs at the proposed accelerators ILC, CLIC, FCCee, CEPC, C^3 and HALHF. From [Db20]

Software

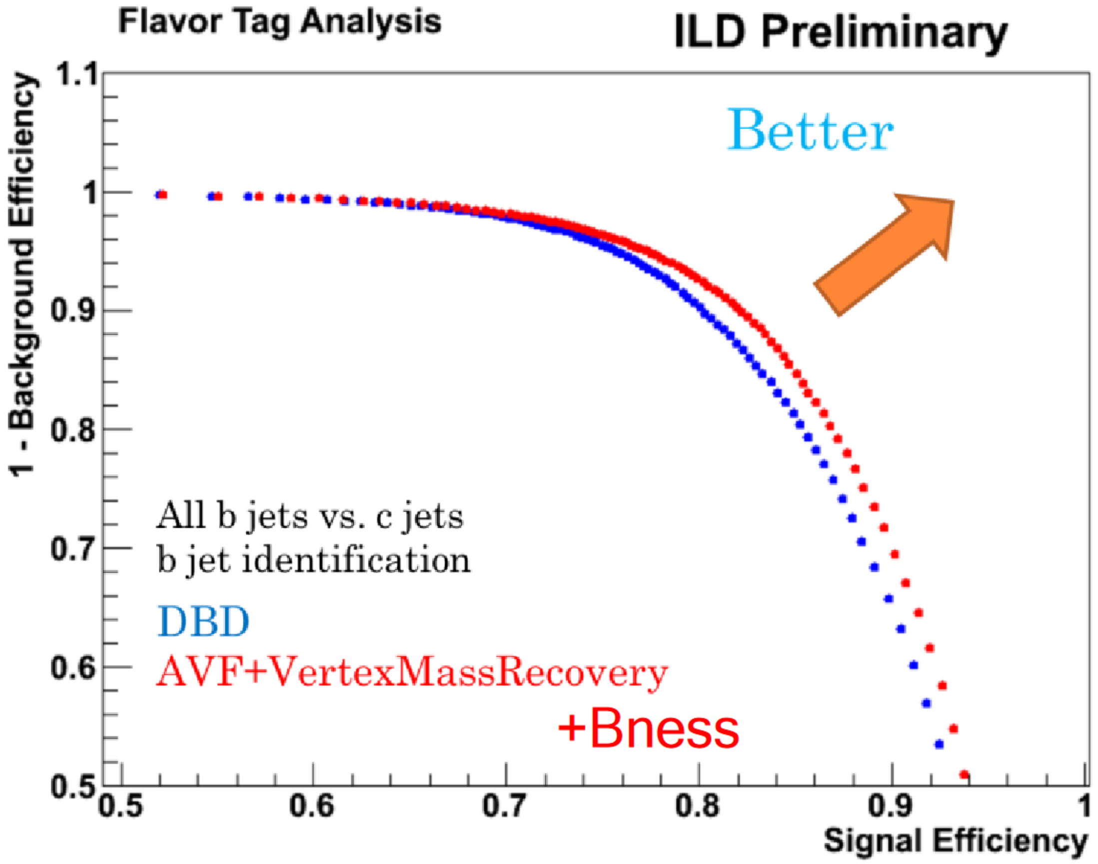
- iLCSoft software stack
- Marlin for reconstruction; important in existing ZHH-analysis:
  - TrueJet: jet-clustering of PFOs using truth information
  - isolated lepton tagging: decision trees for tagging leptons



Event flow in the iLCSoft stack. From [TODO]

Flavor tagging with LCFIPlus

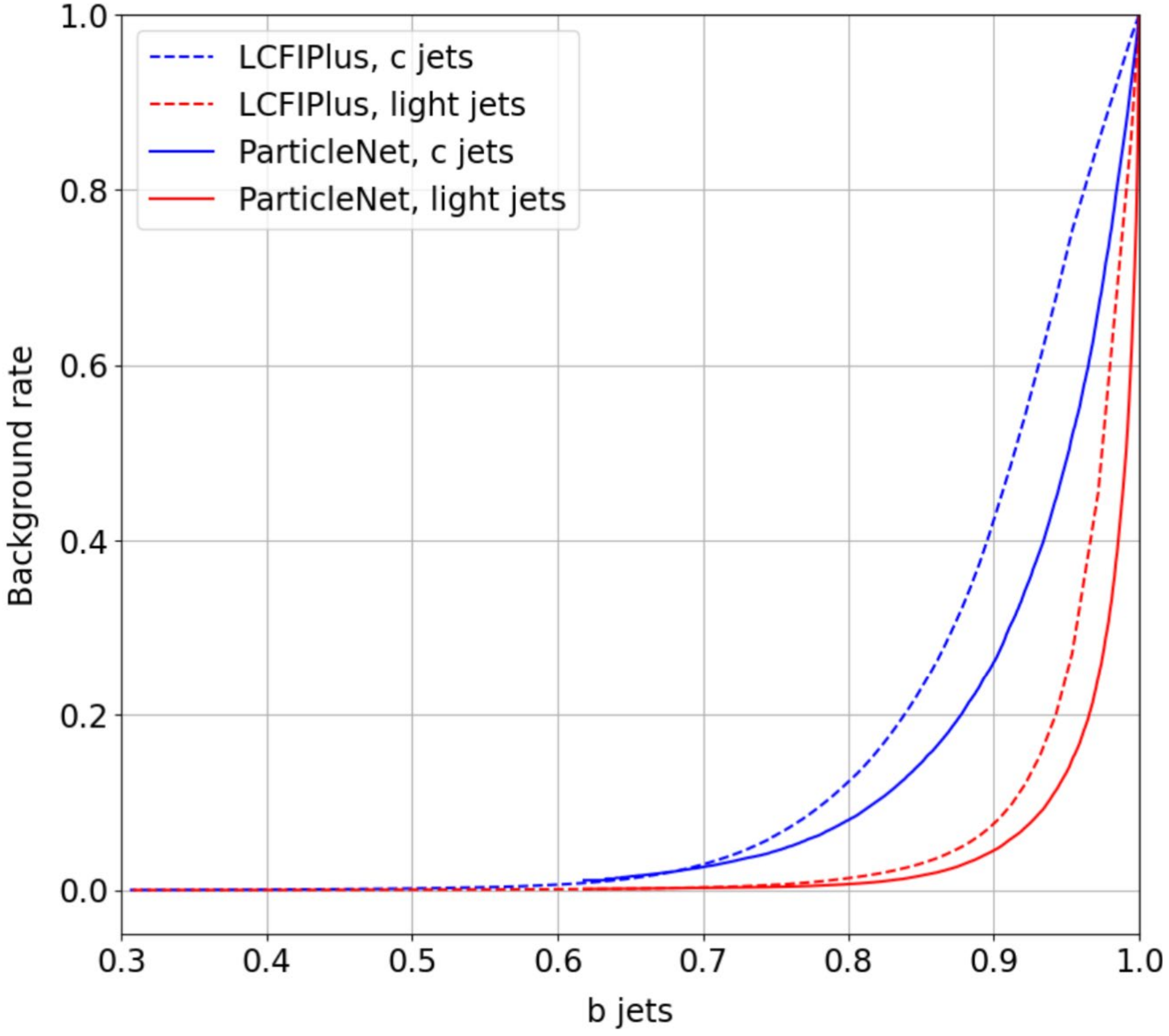
- improved b-tagging efficiency in current ILD standard LCFIPlus since SOTA projections from 2016
  - 5% relative improvement in ϵ_{b-tag} at same purity
  - 11% expected improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$



T. Suehara [2017]

Flavor tagging with ML (ParticleNet)

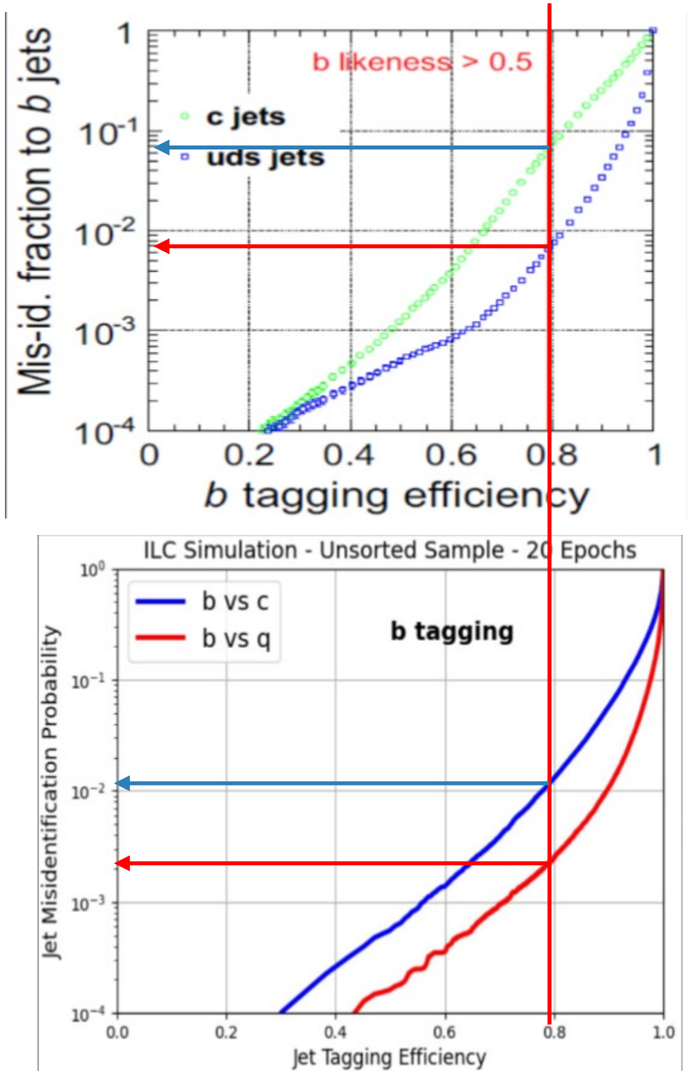
- improved b-tagging efficiency since state-of-the-art projections from 2016
- ML models (DeepJet, ParticleNet, ParT) show highly improved rejection compared to LCFIPlus
- status: ready for use (in MarlinML)



Flavor tagging performance of LCFIPlus vs. ParticleNet using ILD full simulation. M. Meyer [2023]

Flavor tagging with ML (ParT)

- improved b-tagging efficiency since state-of-the-art projections from 2016
- ML models (DeepJet, ParticleNet, ParT) show highly improved rejection compared to LCFIPlus
- status: ready for use (in MarlinML)



Flavor tagging performance of LCFIPlus (top) vs. ParT (bottom) at ILD full simulation. T. Suehara [2023]

Neutrino correction with kinematic fitting

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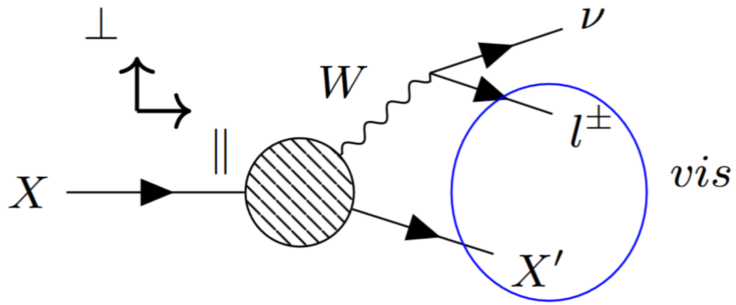
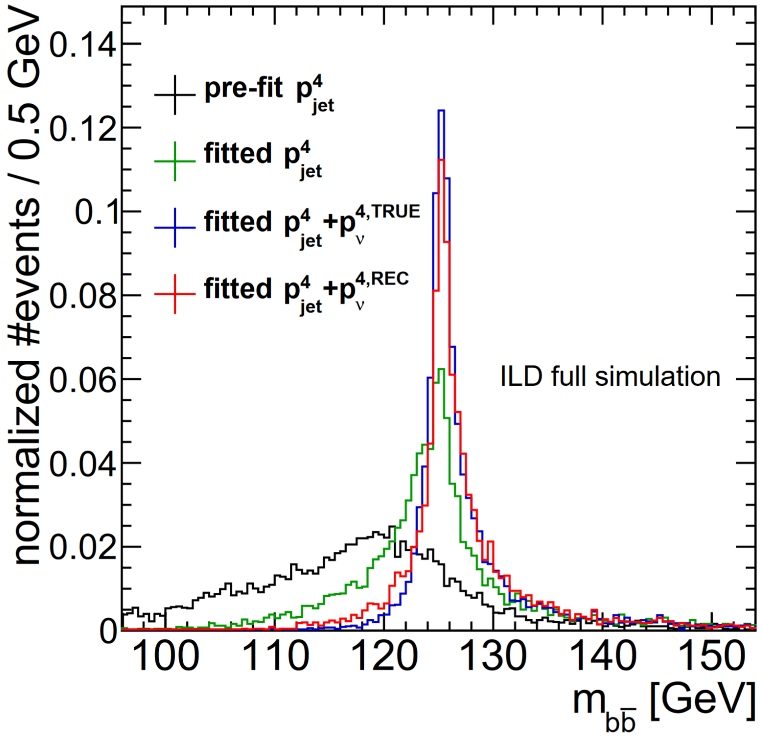
- for semileptonic decay (SLD) processes
  - already in $\mathrm{ZH} \rightarrow b\bar{b}/c\bar{c}$, 66% of events include at least one SLD
- procedure:
  - identify/tag heavy quark jet
  - identify lepton in jet
  - calculate neutrino four momentum from kinematics with kinematic fitting, the best solution is selected
- status: in production (in MarlinReco)



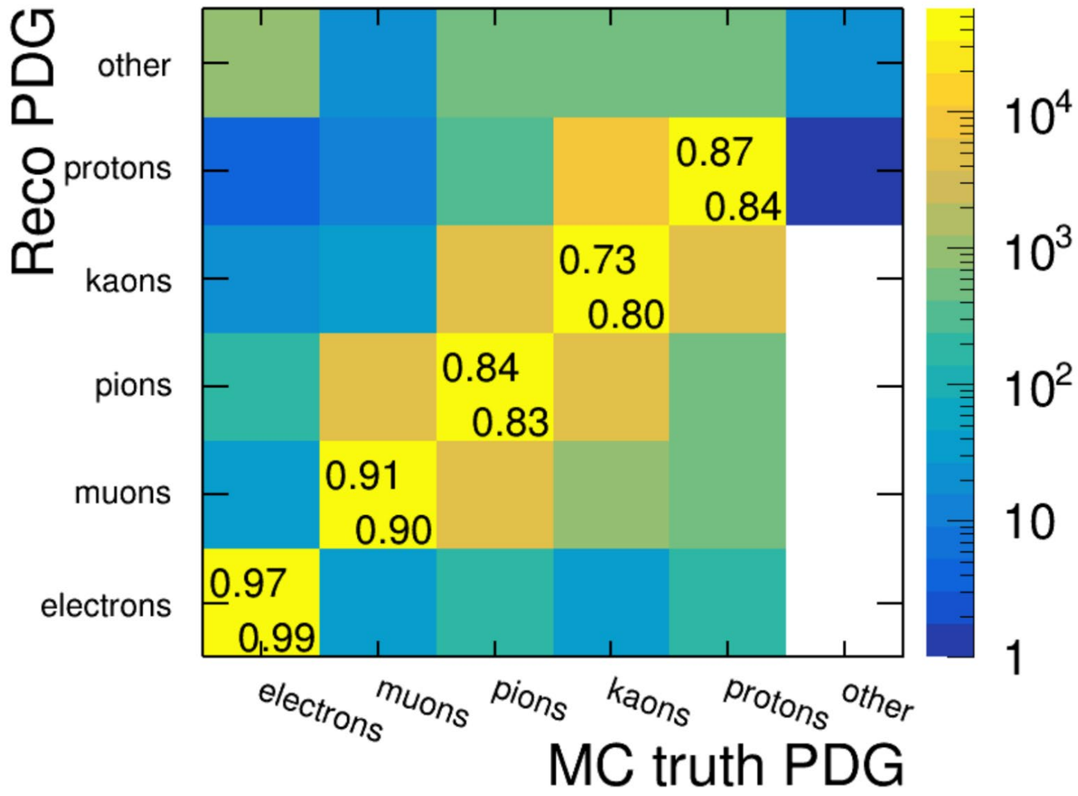
Recovering the neutrino kinematics. Y. Radkhorrami [2022]



Improved di-jet mass reconstruction. Y. Radkhorrami [2022]

Comprehensive Particle Identification (CPID)

- modular and highly configurable PID toolkit
  - "plug-and-play" of multiple data sources e.g. at ILD: dE/dx, TOF, cluster shape
  - extension through custom inference modules e.g. MVA/ML models etc.
- includes default weights for BDT model
- status: in production (in MarlinReco)



Confusion matrix for single charged partilces at ILD.
U. Einhaus (2023)

Motivation: Misclustering in the ZHH analysis

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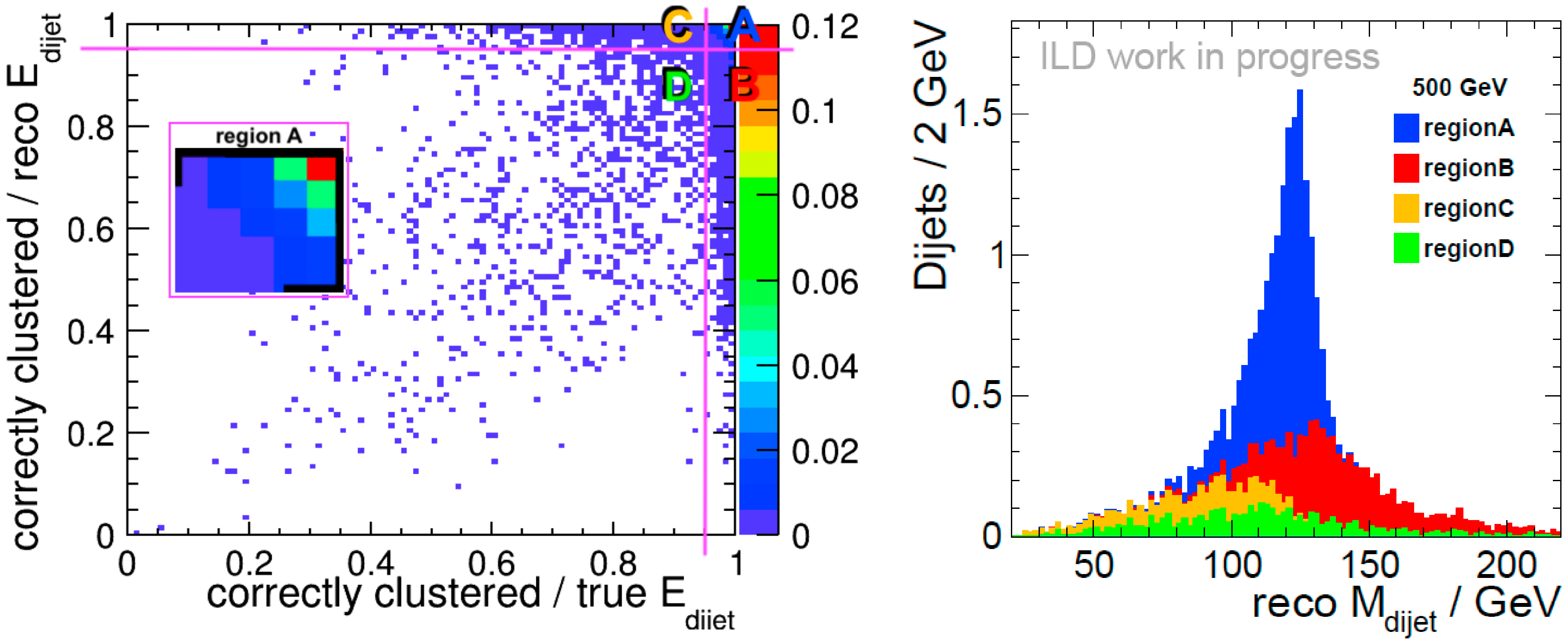
- misclustering of PFOs to jets deteriorates the sensitivity to λ by ≈ 2 [Du16]
- quantification: purity vs efficiency of energy in reconstructed di-jets
- classify di-jets into 4 regions (A, B, C, D) based on threshold: $> 95\%$ on both axes
  - e.g. 45.5% of dijets in region A



Misclustering in ZHH events at ILC500. From [To23b]

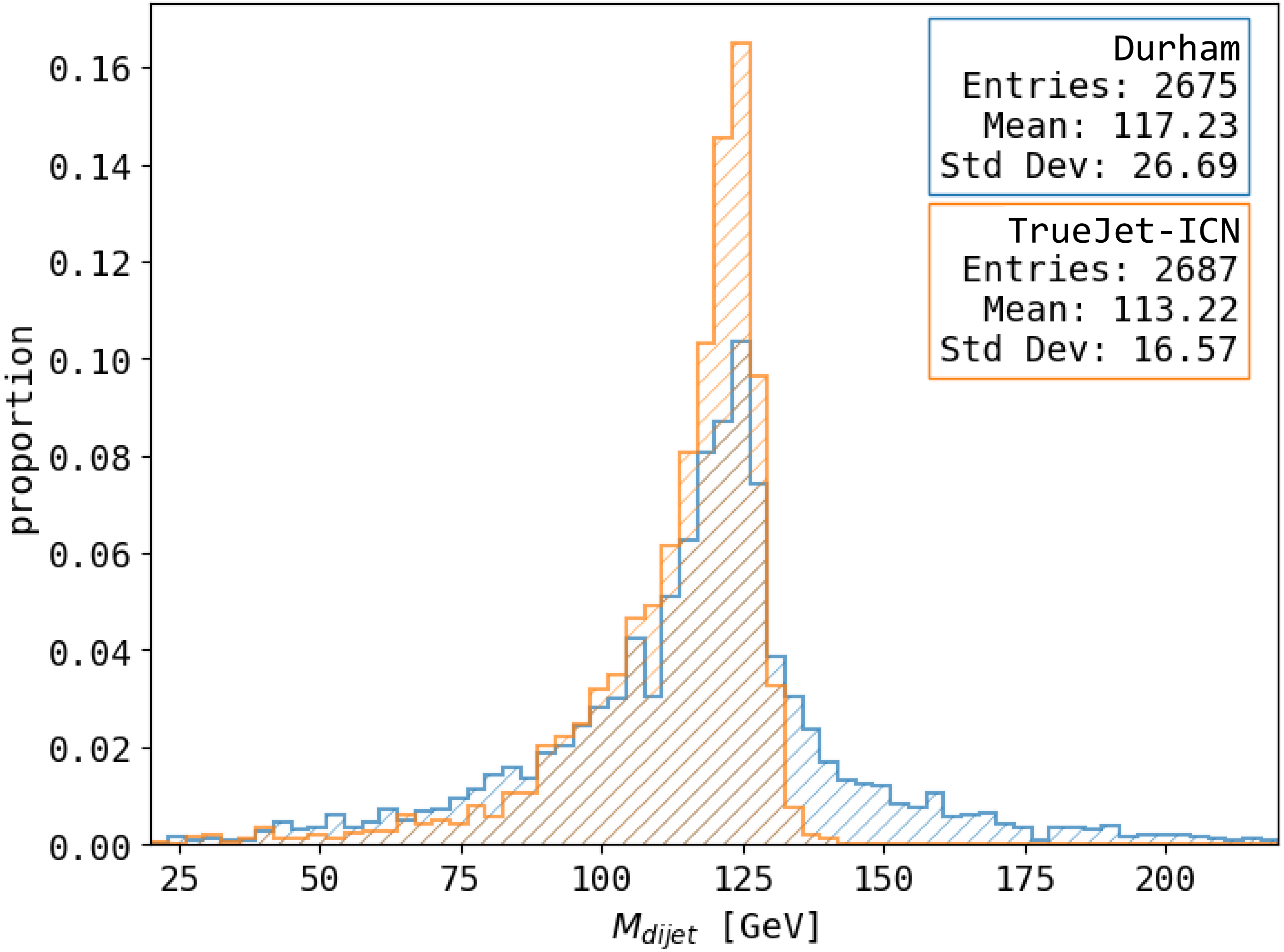
Misclustering in the ZHH analysis
J. Torndal, J. List (2023)

Supervised Jet Clustering

- idea: learn from truth-reco links to cluster PFOs into jets
  - upper performance bar given by TrueJet-ICN jet clustering
  - realistic target performance bounded by Durham and TrueJet

Inspired by: *Supervised jet clustering with graph neural networks for Lorentz boosted bosons*. Nachman et al. [Na20]

TrueJet: M. Berggren (2018)

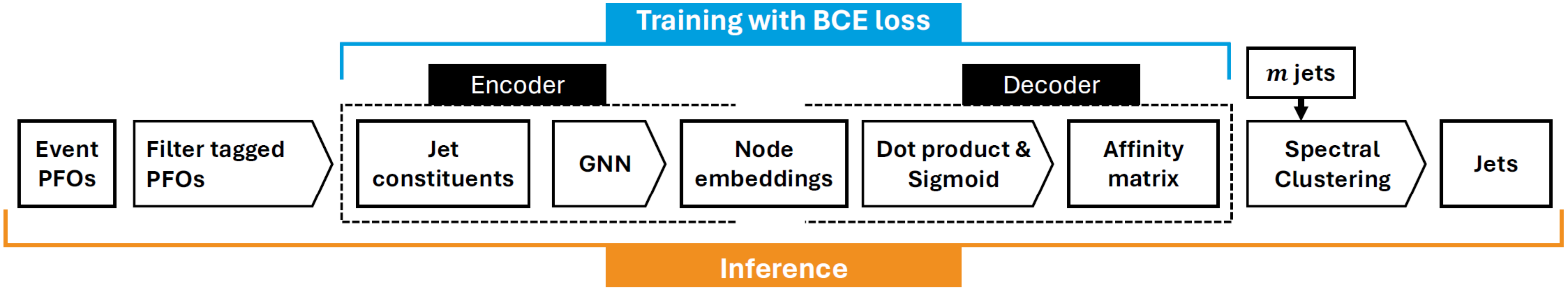


Di-jet mass reconstruction using Durham algorithm and TrueJet

Architecture: Supervised Jet Clustering with GNNs

TransformerConv operator from the paper *Masked Label Prediction: Unified Message Passing Model for Semi-Supervised Classification* [Sh20].

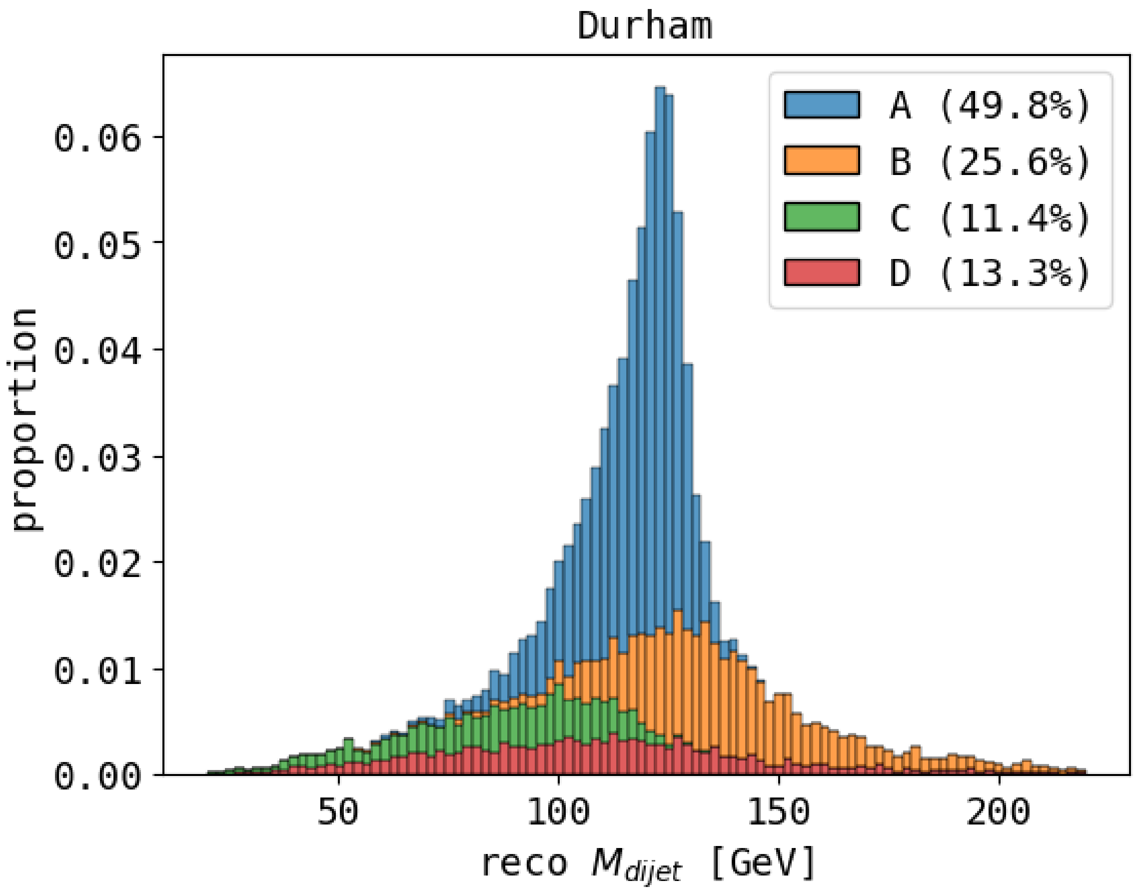
- here: implemented as hybrid model (**GNNSC**)
  - training a GNN in supervised manner to calculate edge scores
    here: using TransformerConv layer (implements message-passing and graph attention)
  - spectral clustering (SC) to build "jets"

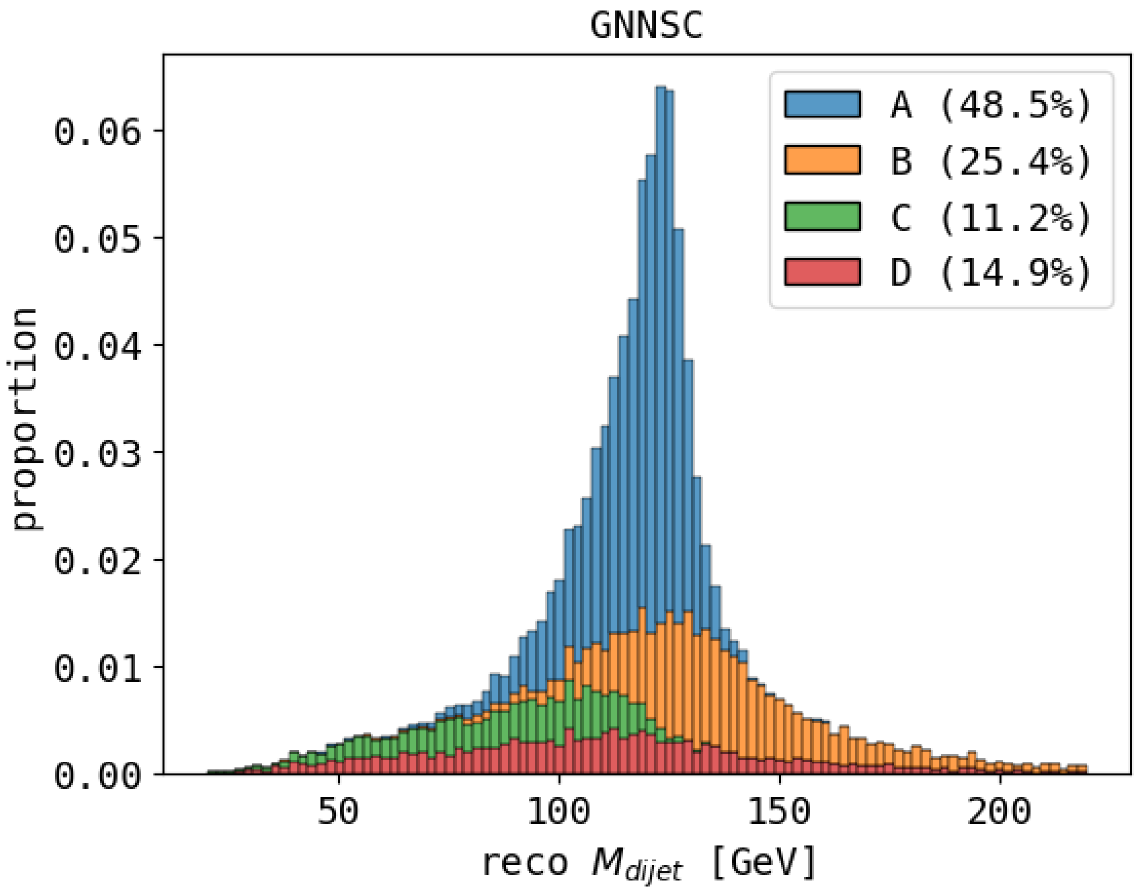


- advantages:
  - permutation invariant by construction
  - straightforward implementation
- disadvantages:
  - not fully differentiable
  - no inherent IRC-safety

Supervised Jet Clustering

- proof-of-concept ML model (GNNSC) shows performance on par with Durham
  - status: proof-of-concept (Marlin processor available)
  - in the future: investigate more powerful architectures





ErrorFlow

- assume full parameterization of errors 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

Y. Radkhorrami [2022]

- status: in production (in MarlinReco)

The Matrix Element Method (MEM)

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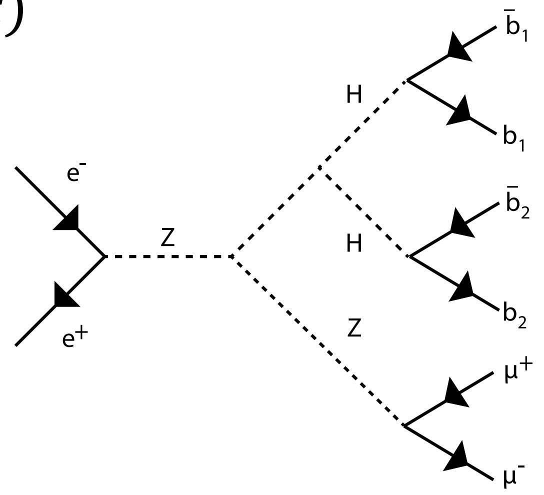
- method for calculating event-likelihoods, i.e. $p(\text{event } \boldsymbol{x} | \text{channel i}) = p_i(\boldsymbol{x})$
  - example use case: separate ZHH vs. ZZH $\rightarrow \mu^-\mu^+ b\bar{b}b\bar{b}$ using likelihood ratio lr

$$\text{lr} = \frac{p_{ZHH}}{p_{ZZH}}$$

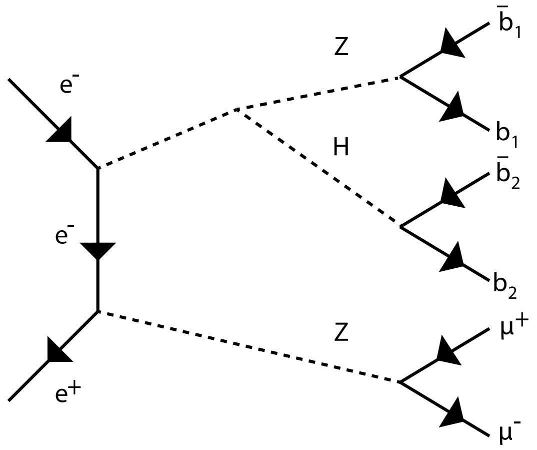
  - binary classification by cutting on lr



- for each event $\boldsymbol{y}$ and process i (ZHH, ZZH), solve integral

$$p_i\,(\boldsymbol{y}\,) = \frac{1}{\sigma_i \cdot A_i} \int |M_i(\boldsymbol{x})|^2 W_i(\boldsymbol{y}\,|\,\boldsymbol{x}) \epsilon_i(\boldsymbol{x}) d\boldsymbol{\Phi}_n(\boldsymbol{x})$$

  - $M_i(\boldsymbol{x})$ LO matrix element
  - $W_i(\boldsymbol{y}|\boldsymbol{x})$ transfer function (TF): PDF for measuring $\boldsymbol{y}$ given $\boldsymbol{x}$; fit from ILD full-simulation samples



A_i : acceptance of channel i
$\epsilon_i(\boldsymbol{x})$: detector efficiency

MEM Introduction with Examples

generator level check

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

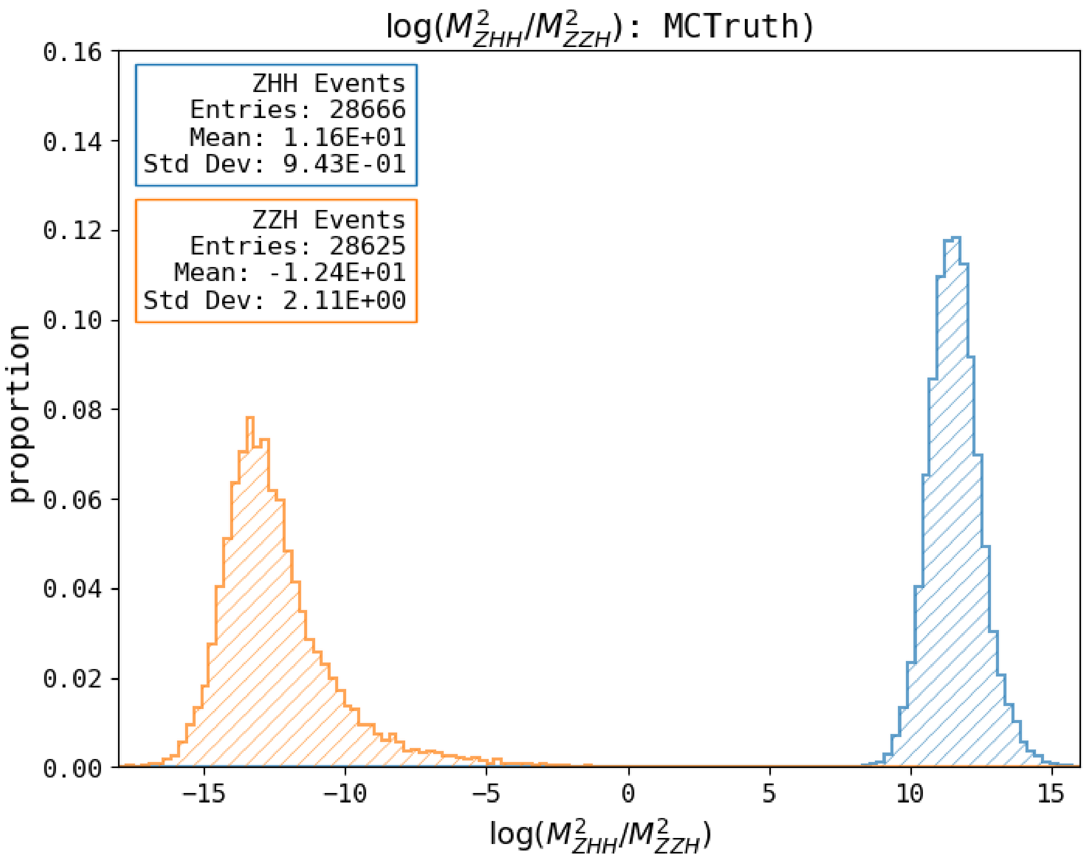
- excellent separation

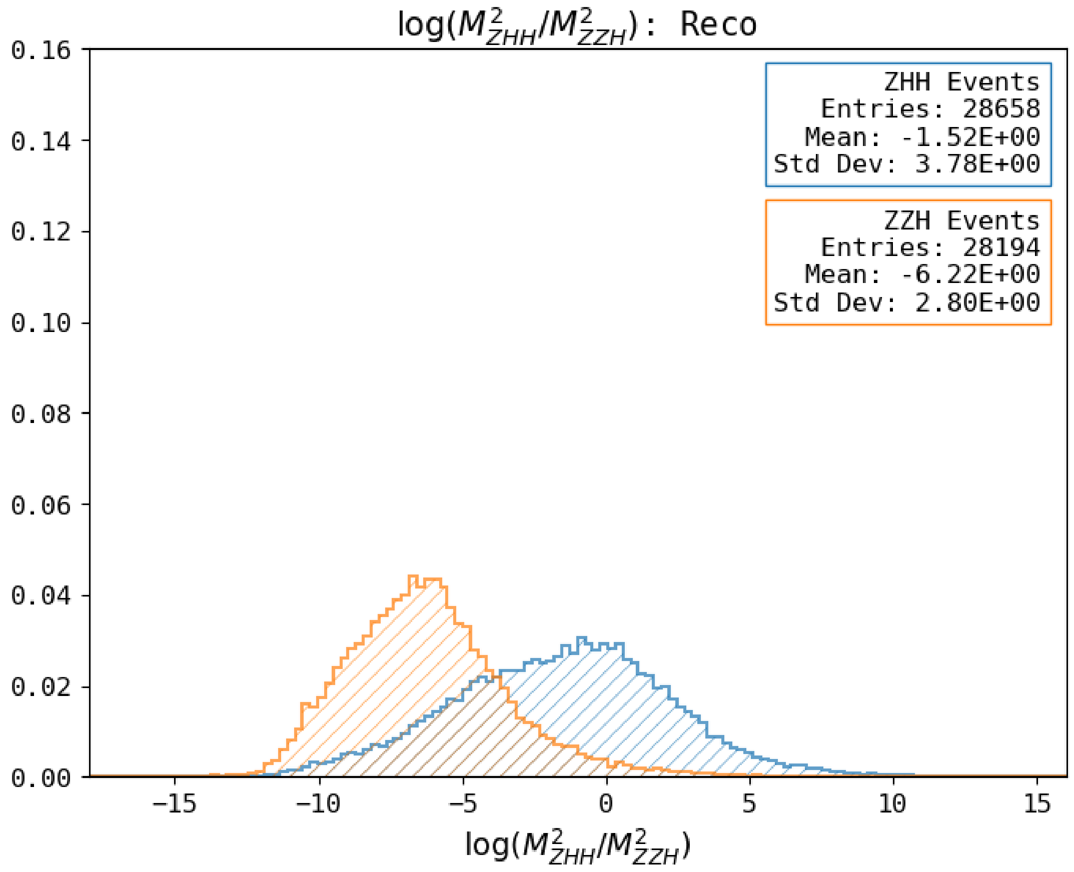
naive MEM

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

- separation power lost

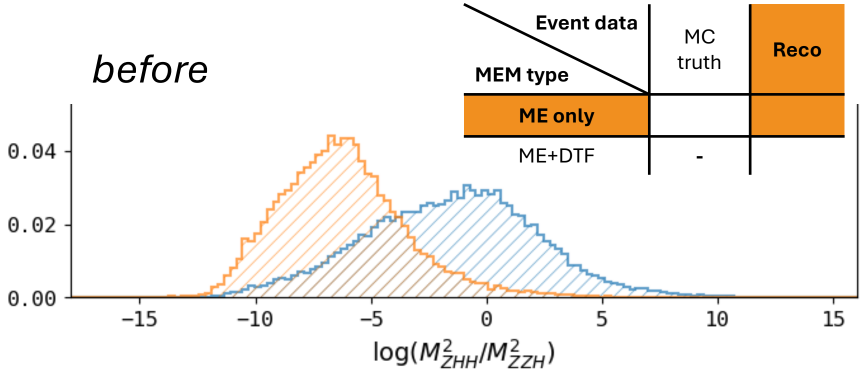
➔ need to describe smearing with TFs

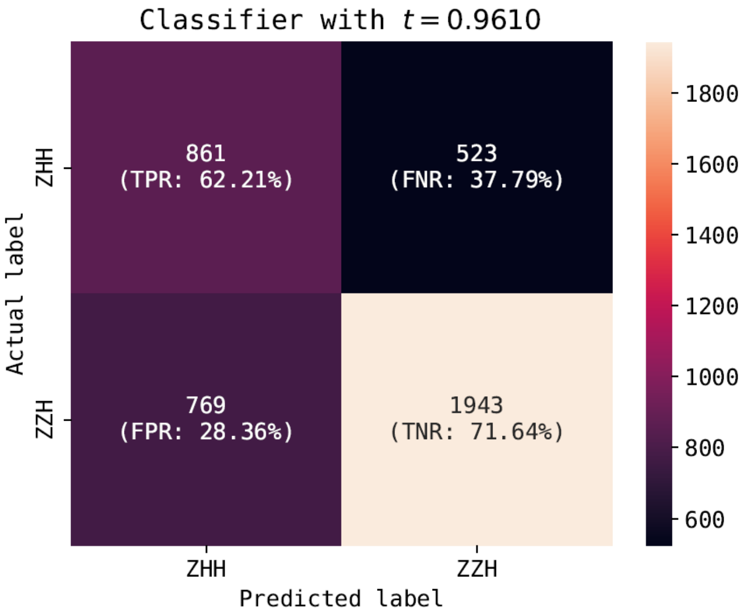


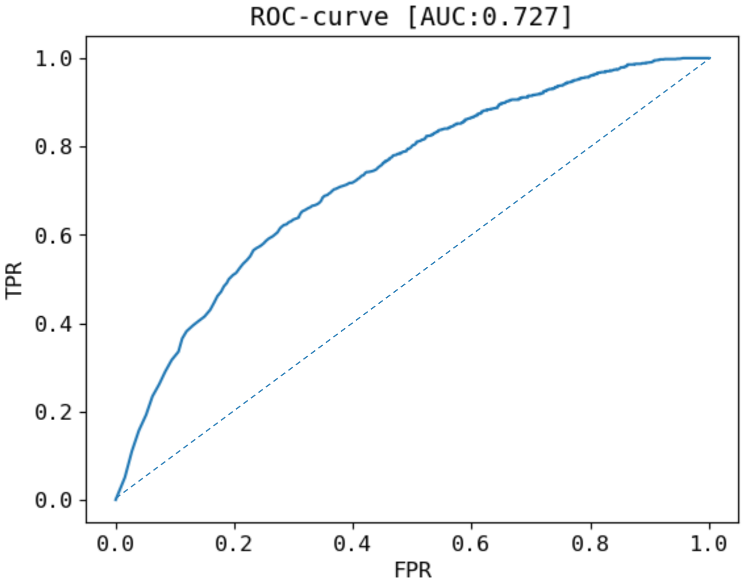


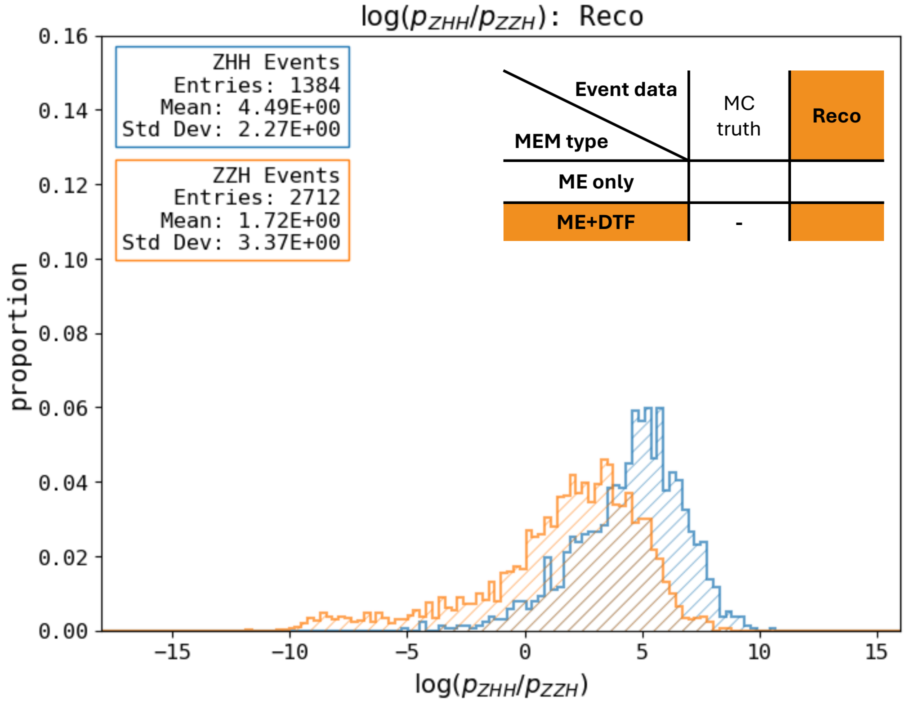
MEM Results

- obtained using VEGAS algorithm
- by including integration over transfer functions, some separation power is regained; $\mathrm{AUROC} = 0.73$









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