Latest news on the Higgs self-coupling prospects at 550 GeV with ILD

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[4] University of Tokio

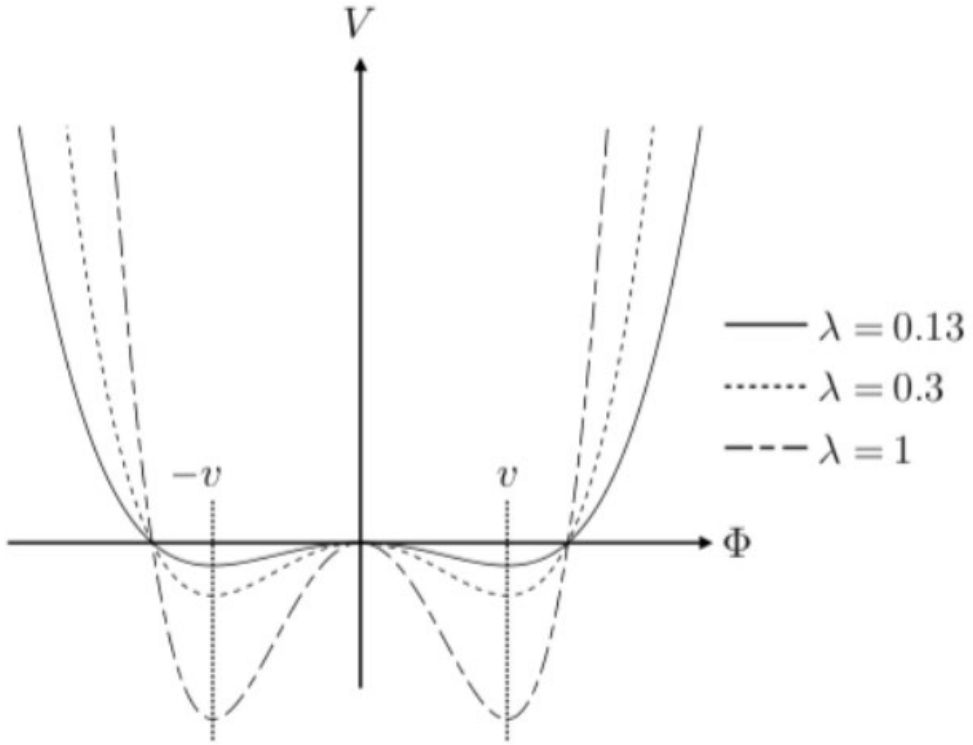
Universität Hamburg
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The Higgs Self-Coupling λ

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

v	vacuum expectation value (vev) of Higgs field h
m_H	mass of Higgs boson

- defines shape of Higgs potential
- in SM: λ_{SM} fixed since m_H is known
  - deviation from $\lambda = \lambda_{SM}$ hints at BSM physics
  - beyond the SM, many values of λ are possible
    → motivates **measurements with minimal model dependencies**



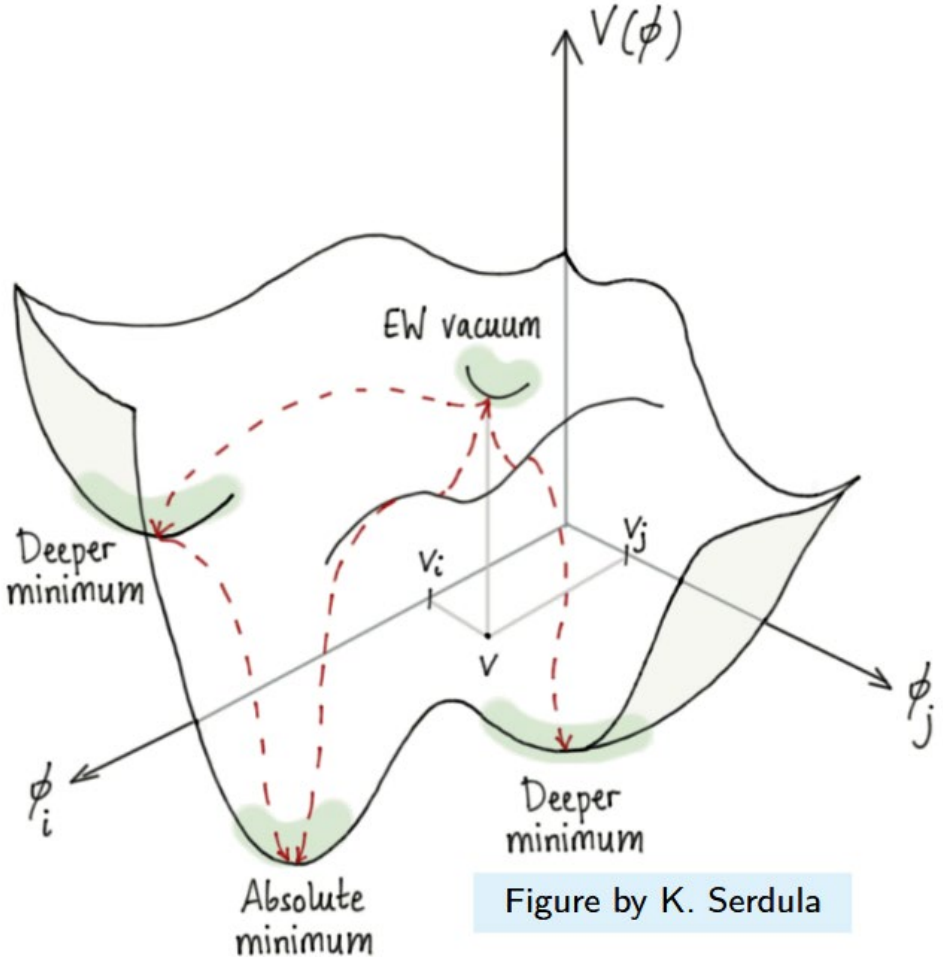
Does the Higgs mechanism work as we think it does…

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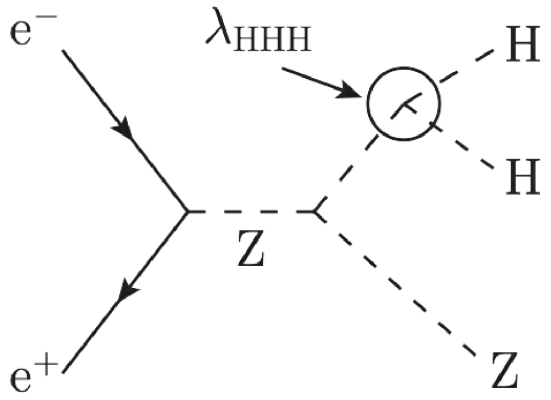
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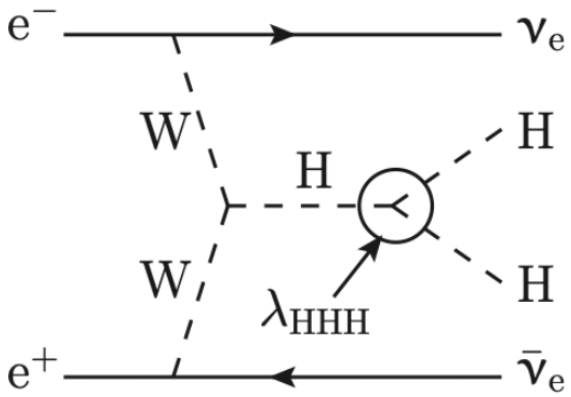
...or completely different?

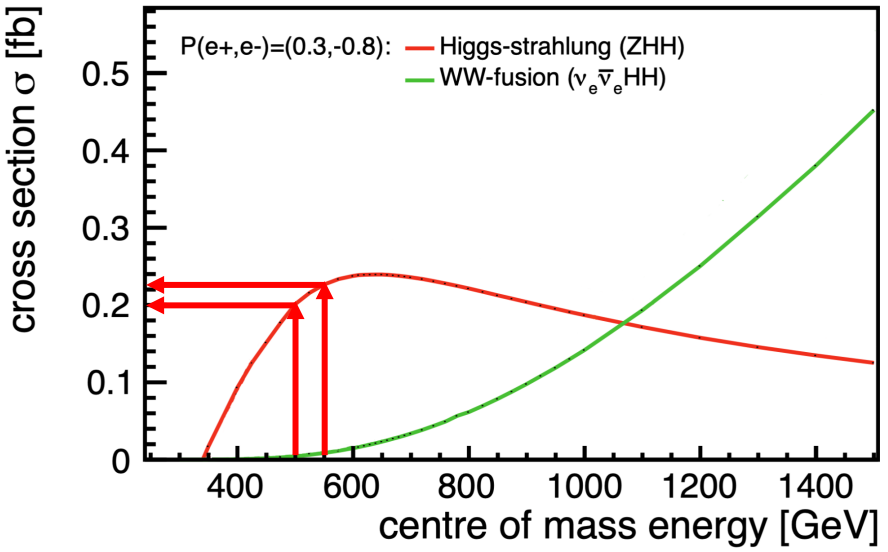
Higgs Self-Coupling Measurement at e+e- Colliders

- Access to λ through **double-Higgs production**
  - Di-Higgs strahlung (**ZHH**; dominant < 1 TeV)



  - vector boson fusion (**$\nu\bar{\nu}$HH**; dominant > 1 TeV)





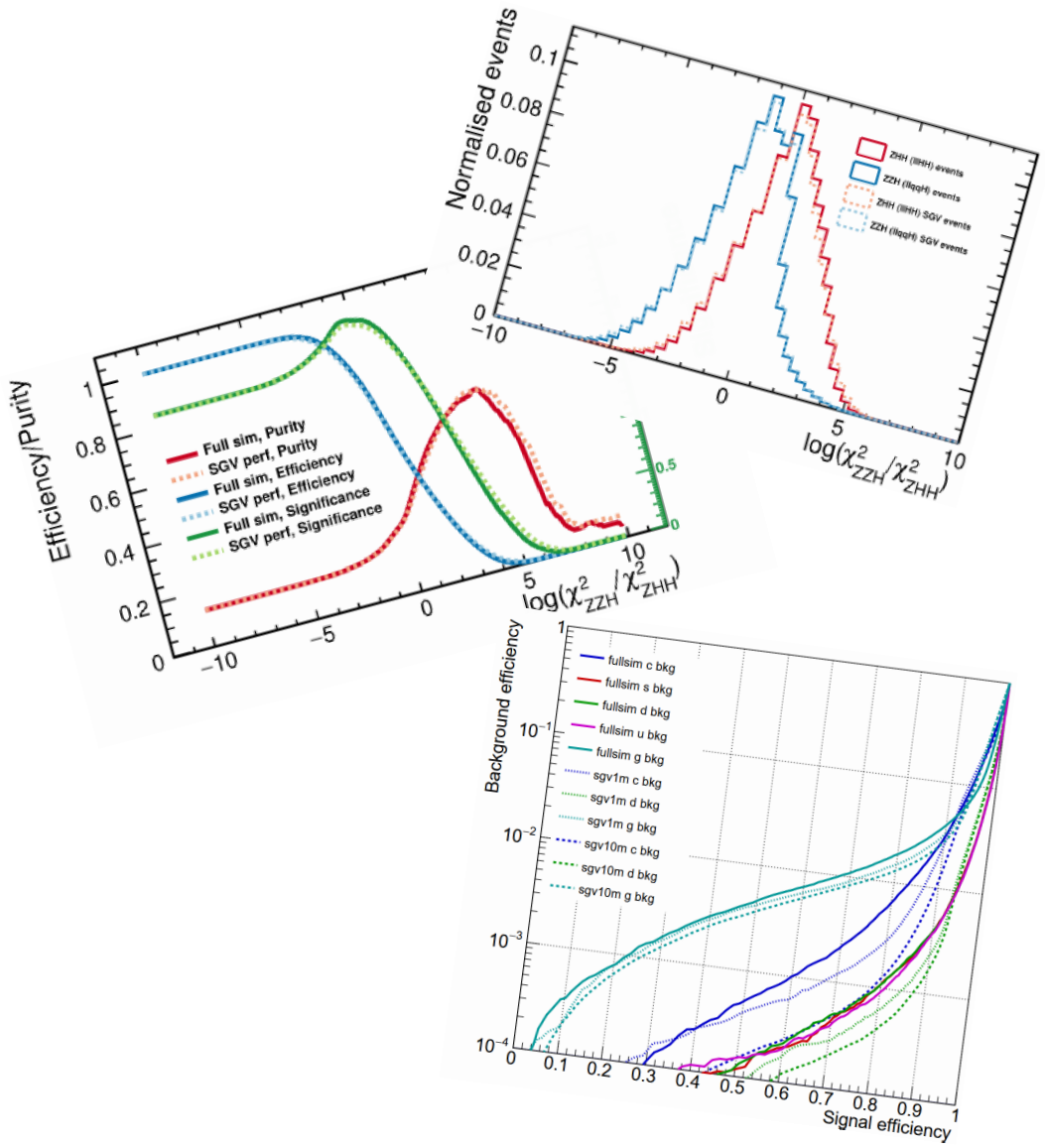
Cross-section of Di-Higgs production processes.
From [C.Duerig, 2016]

Collider	$\mathcal{L}$ [ab^{-1}]	$\lvert P(e^-, e^+)\rvert$ [%]	$\sqrt{s}$ [GeV]
ILC	4	$(80, 30)$	500/550
C^3	4	$(80, 30)$	550
LCF	8	$(80, 60)$	550

Running scenarios for the di-Higgs program of linear colliders

Higgs Self-Coupling Measurement at e+e- Colliders

- 2014 ZHH analysis with ILD@ILC500
  [DESY-THESIS-2016-246, C. Duerig]
  - Combined result: **2014 analysis** ILC500, 4ab^{-1}, $(80\%, 30\%)$ $\Delta\lambda_{SM}/\lambda_{SM} = 26.6\%$
  - 8σ observation of ZHH production, only 3σ for λ_{SM}
- Since 2022: Re-analysis of ZHH ongoing
  - With SGV fast-simulation of ILD@ILC550
    Includes full 4+6 fermion backgrounds as well as ttH and ttZ
  - Use significantly improved reconstruction
    - Kinematic reconstruction
      Kinematic fits, ErrorFlow, neutrino correction of semileptonic B- and C-decays
    - ParticleTransformer flavortag [2603.18814]
  - Revision of running scenarios
    More ambitious luminosity and polarization parameters

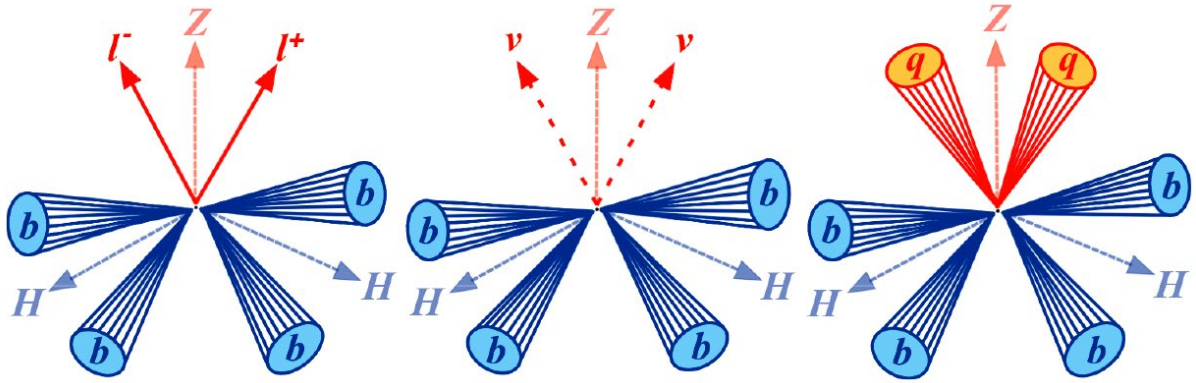


Summary of recent key reconstruction improvements

Event Selection Overview

- ZHH as main signal
  - Focus on $\mathrm{HH} \rightarrow \mathrm{b\bar{b}b\bar{b}}$ final state
    Non-$\mathrm{b\bar{b}b\bar{b}}$ signal treated separately by MVA
- Subdivision into channels by Z-decay:
  - Charged lepton* channel: llHH
  - Neutrino channel: $\nu\nu\mathrm{HH}$
    - Sensitivity also to VBF contribution

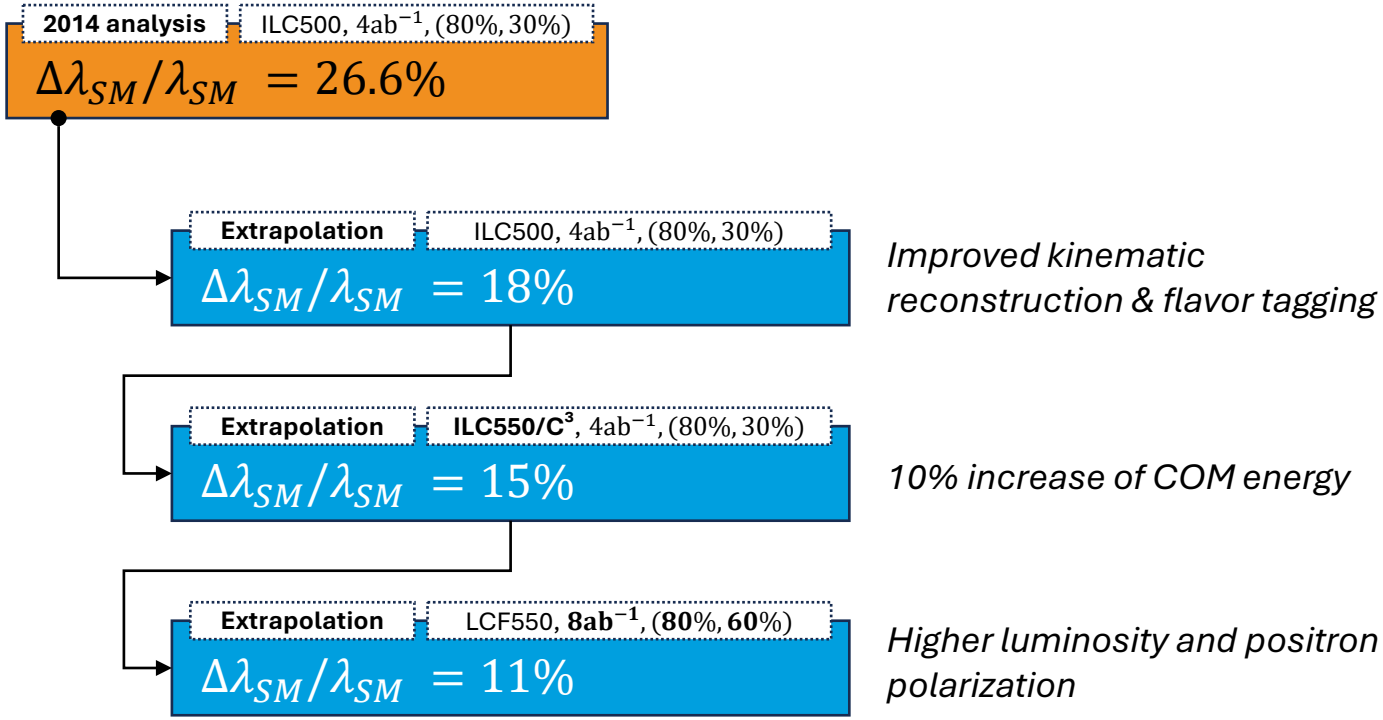
    More on the neutrino channel in the next talk by Julie
  - Hadronic channel: qqHH
- Strategy: Cut-based preselection + multiclassifier-based final selection



*: $\mathrm{l} = e, \mu, \tau$

ILD Note (2025)

- Submission of projections as input to ESPPU Briefing Book [2509.14148]
  - Includes extrapolation based on proven reconstruction gains
  - Confirmed extrapolation in lepton channel



Improved kinematic reconstruction & flavor tagging

10% increase of COM energy

Higher luminosity and positron polarization

ILD-PHYS–2025-001
18 September 2025

Update of the Higgs Self-coupling Projections from Di-Higgs Production in Detailed Simulation of the ILD Concept

P(e^-), P(e^+)	channel	decay mode	S	B	$S/\sqrt{S+B}$	$\delta\sigma/\sigma$[%]
−80%, +30%	eeHH	inclusive	5.4	7.0	1.5	65
		HH → 4b	3.8		1.2	86
	μμHH	inclusive	6.9	8.9	1.7	58
		HH → 4b	4.1		1.1	88
	ννHH (ZHH only)	inclusive	6.1	6.5	1.8	55
		HH → 4b	6.0		1.7	60
	bbHH	inclusive	12.3	21.9	2.1	47
		HH → 4b	11.7		2.0	49
	qqHH	inclusive	18.0	55.0	2.1	47
		HH → 4b	16.0		1.9	53
−80%, +30%	combined	inclusive			4.2	24
		HH → 4b			3.6	28
+80%, −30%	eeHH	inclusive	4.0	4.2	1.4	72
		HH → 4b	2.8		1.1	95
	μμHH	inclusive	5.1	5.3	1.6	63
		HH → 4b	2.9		1.0	98
	ννHH	inclusive	5.2		2.1	48
		HH → 4b	5.1		2.1	49
	bbHH	inclusive	8.6	7.0	2.2	46
		HH → 4b	8.2		2.1	48
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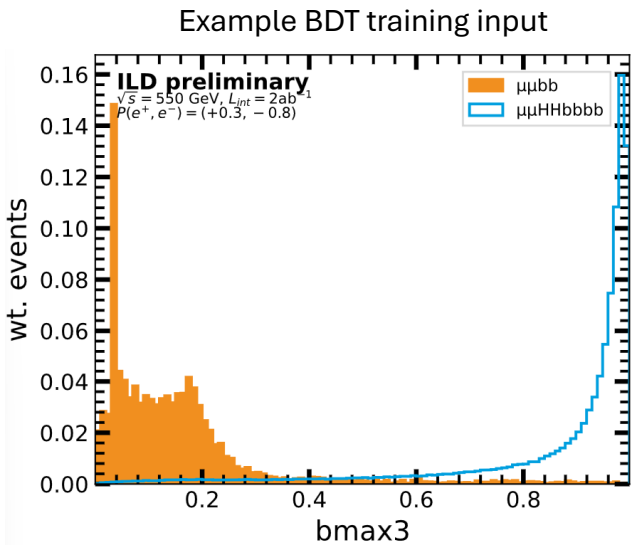
Physics Results in the Charged Lepton and Neutrino Channels

Results in μμHH and eeHH

- Preselection cuts
  - $n_{IsoLeptons} \geq 2$
  - $ll = \mu^+\mu^- \, (e^+e^-)$
  - $20 \leq M_{ll}^{4C}/GeV \leq 150$
  - $50 \leq M_{j_1 j_2}^{4C}/GeV \leq 200$
  - $50 \leq M_{j_3 j_4}^{4C}/GeV \leq 200$
  - $p_{t,mis} \leq 70\ GeV$
  - thrust ≤ 0.9

Event selection / 2025 / 2026

- Four consecutive binary BDTs ✓ One multiclass BDT
- BDTs with fixed hyperparams. ✓ BDT hyperparameter search
- Using almost full 4f+6f SM bkgs. ✓ Using full 4f+6f+tth+ttZ SM bkgs.

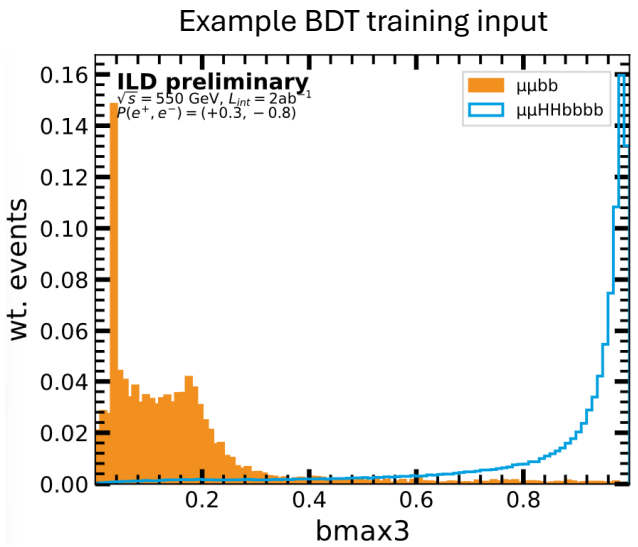


$S/\sqrt{S+B}$	2014	Extrapolation	2025	2026
eeHH $(\mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$	0.84	1.2	1.28	1.32
eeHH (incl.)	1.14	1.5		1.60
μμHH $(\mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$	0.82	1.1	1.39	1.47
μμHH (incl.)	1.36	1.7		1.92
ττHH	-			WIP*

* Study with recently developed, ML-based hadronic τ ID in progress

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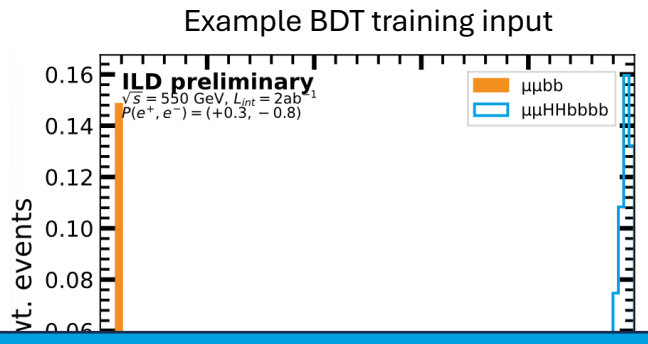
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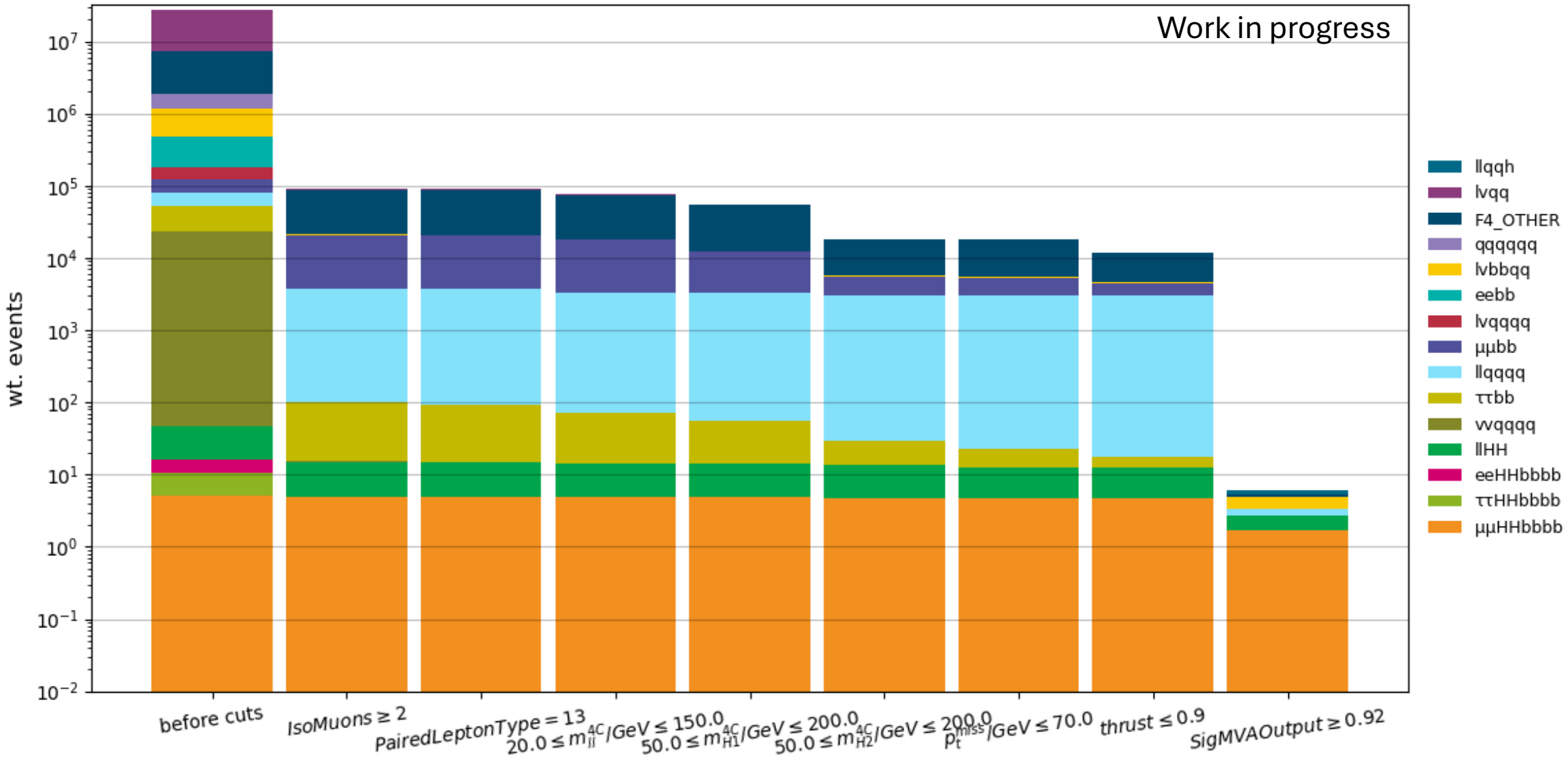
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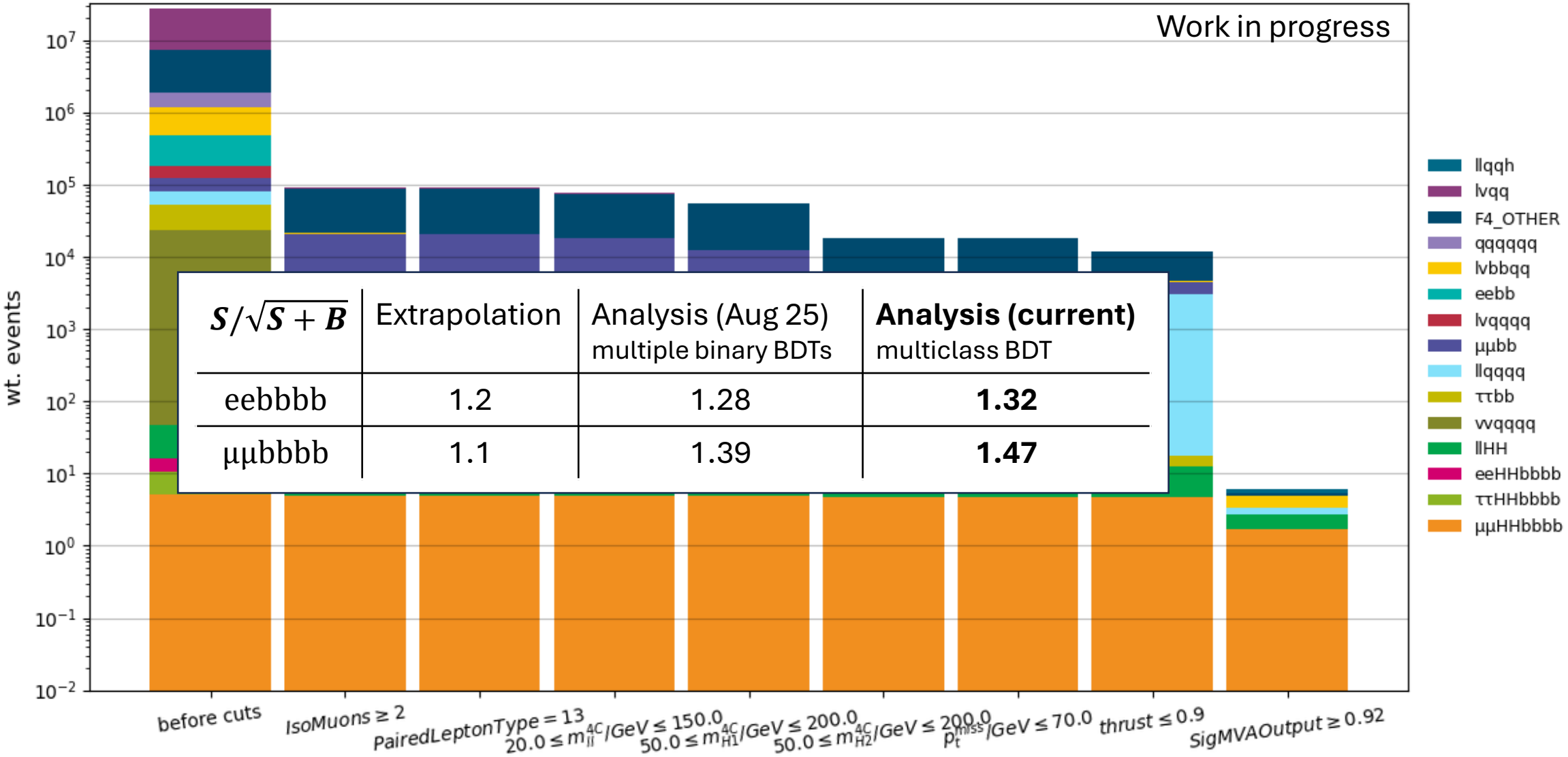
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Analysis of eeHH and μμHH confirms and exceeds extrapolation

Cutflow in the Muon Channel

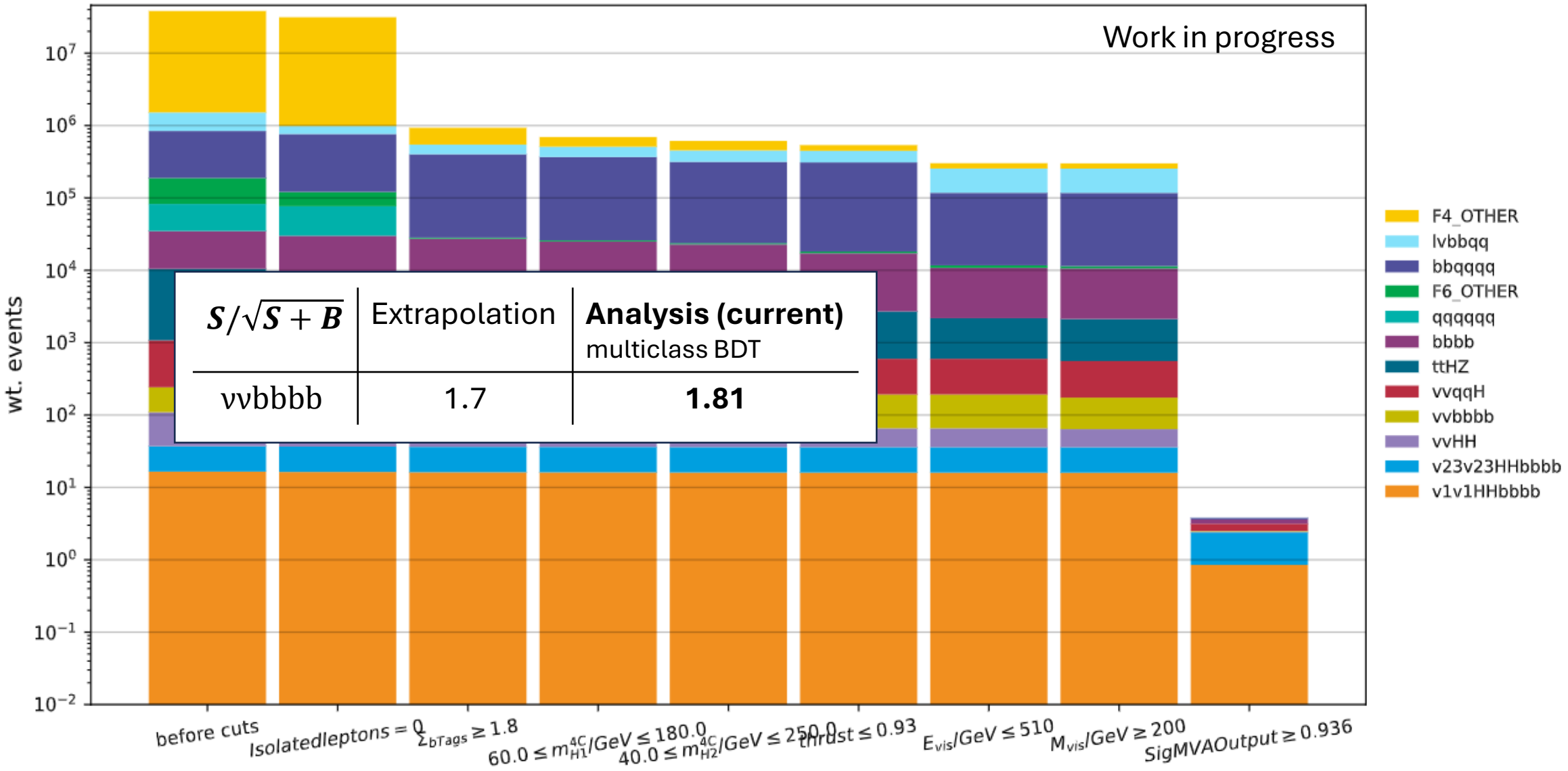


Cutflow and Results in the Charged Lepton Channel



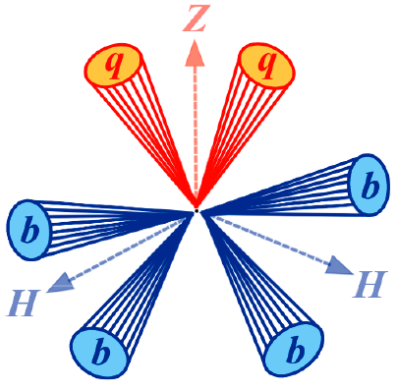
$S/\sqrt{S+B}$	Extrapolation	Analysis (Aug 25) multiple binary BDTs	**Analysis (current)** multiclass BDT
eebbbb	1.2	1.28	**1.32**
μμbbbb	1.1	1.39	**1.47**

Cutflow and Results in the Neutrino Channel



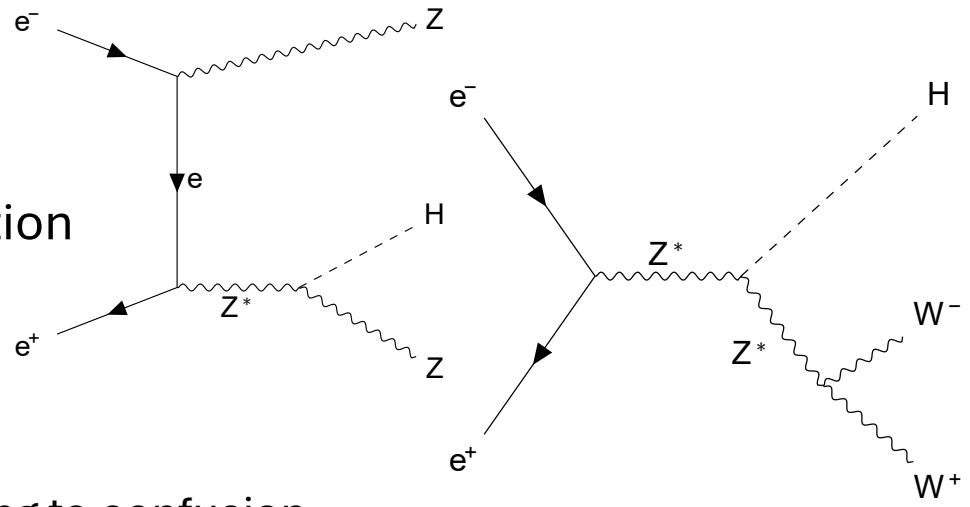
$S/\sqrt{S+B}$	Extrapolation	**Analysis (current)** multiclass BDT
νν**bbbb**	1.7	**1.81**

Challenges in the Hadron Channel



- High jet multiplicity → hard to find correct jet-pairing
  - Idea/WIP: Use quark/anti-quark tagging to find permutation matching best to ZHH
    High gains demonstrated in ttH analysis See talk by Yuyang tomorrow
- Strong irreducible backgrounds: $q\bar{q}b\bar{b}b\bar{b}$ from $t\bar{t}$, ZZH, WWH, ZZZ etc.
  - At $\sqrt{s} = 550$ GeV: $\sigma(\mathrm{WWH}) \approx 10 \cdot \sigma(\mathrm{ZZH})$
    - Adds additional complexity for kinematic reconstruction
  - Idea/WIP: Use (weighted) matrix elements for event separation
  - Idea #2: Separate kinematic fit hypothesis for WWH
- Jet misclustering

  The more quarks in an event, the more likely jets are to overlap, leading to confusion



Example set of Feynman diagrams for ZZH and WWH giving rise to qqqqH

Scalable Physics Analyses with hep_workflows

- Published hep_workflows for scalable, end-to-end physics analysis
- It covers:
  1. Event generation in Whizard
  2. Detector sim. and reco. with SGV or ddsim+Gaudi/k4run
  3. Reco. and analysis with Gaudi/k4run or Marlin
- The framework…
  - streamlines tool interplay and manages HTCondor submissions
  - is completely key4hep-based
  - has a Docker image and runs examples locally as part of CI:
    - Whizard + SGV + Marlin
    - Whizard + SGV + Gaudi
    - Whizard + ddsim + 2x Gaudi

Example config to produce 100k ZH events at ILC250, run SGV simulation of ILD and Marlin analysis

```python
class TestE250ZHFastMarlinConfig(AnalysisConfiguration):
    tag = '250-e2e2h-ild-fast-marlin'
    sqrt_s = 250.

    task_kwargs = {
        'RecoAbstract': {
            'steering_file': '$ANALYSIS_PATH/high_level_reco.xml',
            'output_file': 'reco.slcio',
            'check_output_lcio_files': ['reco.slcio'],
        }
    }

    whizard_options:list[WhizardOption] = [{
        'process_name': 'e2e2h',
        'process_definition': '',
        'template_dir': '$ANALYSIS_PATH/resources/whizard_template',
        'sindarin_file': 'whizard.base250.sin',
        'iters_per_polarization': {
            'eL.pR': 1,
            'eR.pL': 1
        },
        'nevents': 100_000
    }]

    def sgv_inputs(self, task):
        return whizard_to_sgv_inputs(self.sqrt_s, task)

    def setup(self):
        from .provisioning import provision_sgv

        provision_sgv()
```

```
> law run WhizardEventGeneration --tag=250-e2e2h-ild-fast-marlin
> law run FastSimSGV --tag=250-e2e2h-ild-fast-marlin
> law run RecoFinal --tag=250-e2e2h-ild-fast-marlin
```

Conclusion

- Work on the hadron channel and the $ZHH \rightarrow \tau^+\tau^-HH$ channel ongoing
  - Combination of flavor and kinematic information crucial
- Modern reconstruction improves sensitivity in ILD ZHH re-analysis
  - Significant improvements through ParT-based flavor tag, ErrorFlow and kinematic fits
  - Further improvement by using multiclass BDTs for event scores
    - Still, room for more: matrix elements, jet clustering
  - From $[\Delta\lambda/\lambda]_{SM} = 27\%$ **at ILC500 in the 2014 projection to…**

    ILC550 @ $\mathcal{L} = 4ab^{-1}$: $[\Delta\lambda/\lambda]_{SM} \rightarrow 15\%$
    LCF550 @ $\mathcal{L} = 8ab^{-1}$: $[\Delta\lambda/\lambda]_{SM} \rightarrow 11\%$
  - **Extrapolation for LCF in ECFA report well-justified, if not conservative**
    - **Proven so far for the lepton and neutrino channel**