Di-Higgs with missing transverse momentum at FCC-hh

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

FCC hh ee he

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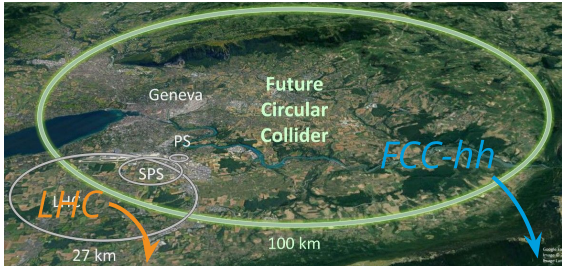
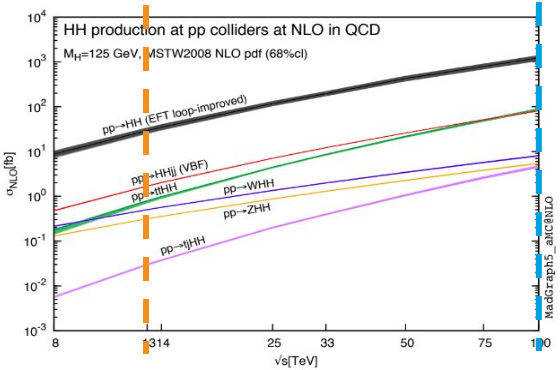
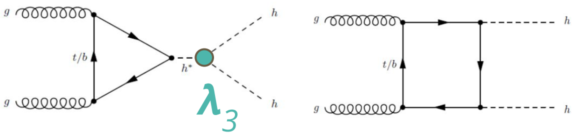
Di-Higgs with E_T^{Miss} @ FCC-hh: What & why?

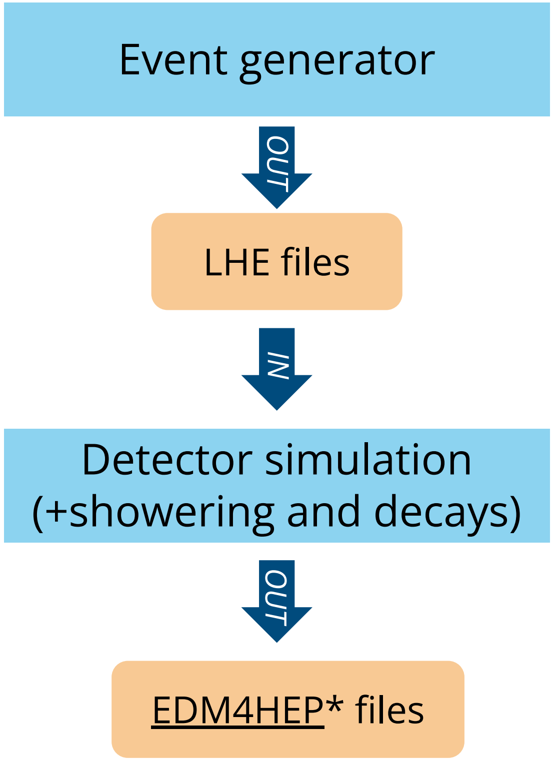






- **FCC-hh**: *pp*-collisions at 100 TeV, collect 30 ab^{-1} of data in runtime of ~25 years
  - Operate at both the energy and precision frontier
  - Previously presented general overview
- Measuring the **Higgs self-coupling via di-Higgs production** is key benchmark for FCC-hh
  - SM: $\sigma(ggHH) \sim O(1000)$ smaller than $\sigma(ggH)$
  - Achieve precision through large cross-section and data-set, both given at FCC-hh: 20 x precision of LHC
  - Allows to access also rarer, more difficult channels
    - Update to $bbll{+}E_T^{Miss}$ analysis previously presented

Analysis overview & technical details



Samples in the FCC-hh event database

- $ggF\ HH$ signals generated with Powheg
- Backgrounds with Madgraph

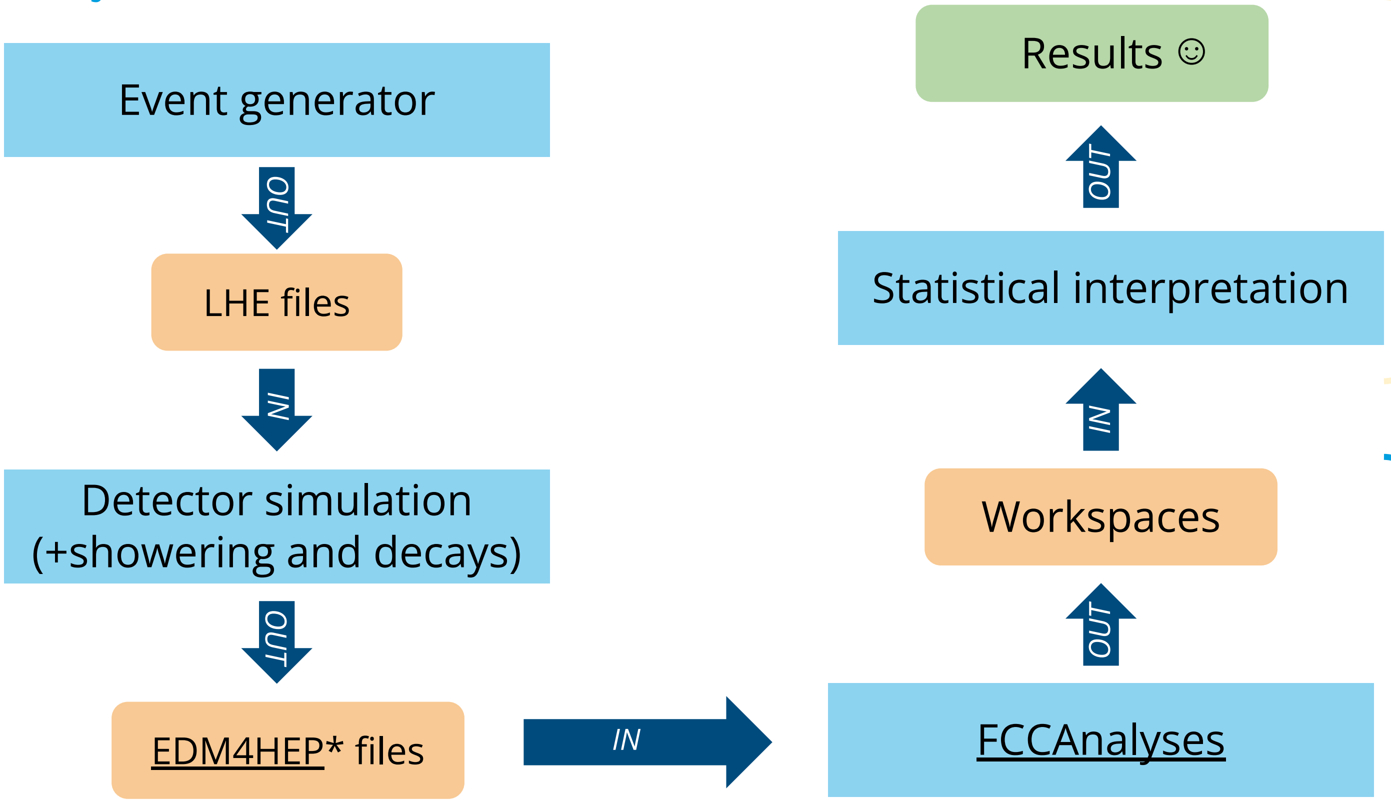
Decays and showering with Pythia

Fast, parametrized detector simulation with Delphes with the FCC-hh card

- Performance similar to LHC experiments assumed
- Effect of pile-up indirectly considered in resolution & efficiency parametrizations

** Developed with DESY involvement ☺*

Analysis overview & technical details



Combine and HHInference tools to extract precision on μ_{HH} and κ_λ $(= \lambda_3/\lambda_3^{SM})$

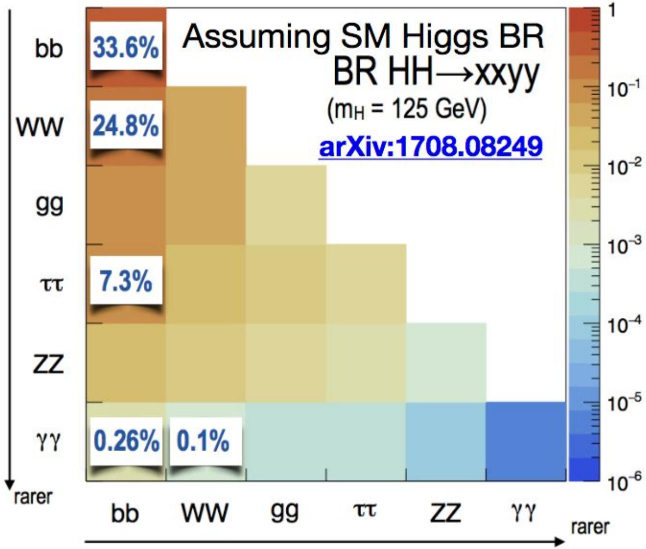
Simple cut-based event selection based on signal kinematics

Stransverse mass as discriminant

* Developed with DESY involvement ☺

$bbll+E_T^{Miss}$ signals

New: Unified analysis

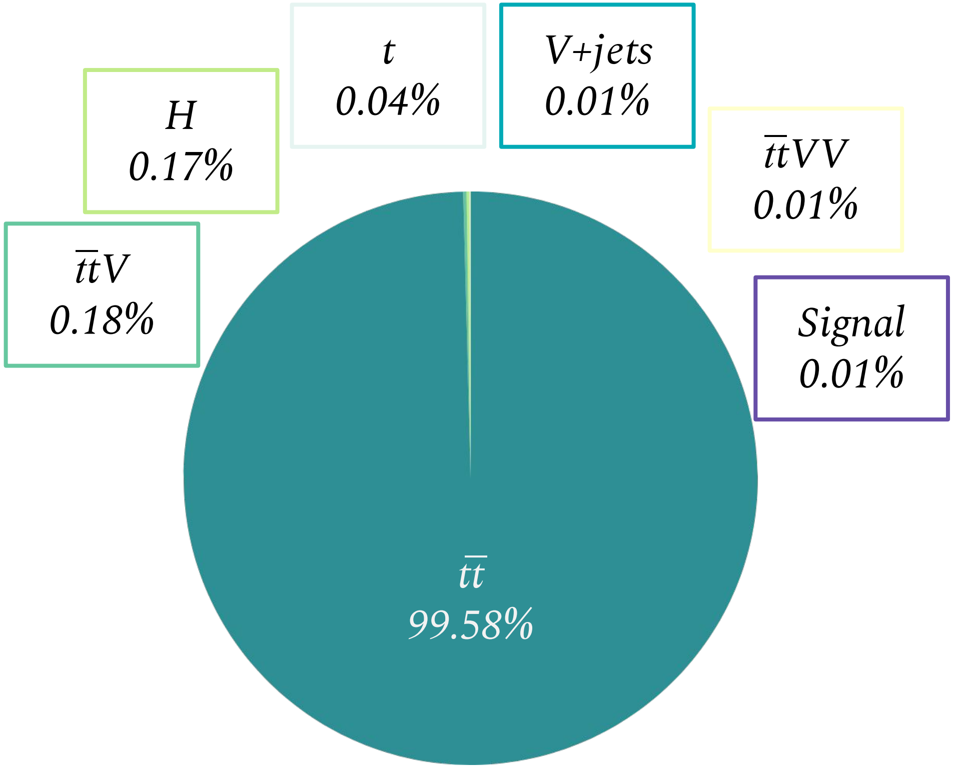


Signal	$BR(HH\rightarrow X)$	Advantage
$bbWW(l\nu l\nu)$	2.24%	Largest BR in $bb+2l+E_T^{Miss}$ final state Established for HH-studies @ LHC
$bb\tau\tau(l\nu\nu l\nu\nu)$	0.88%	$e\mu$ channel established for single Higgs studies @ LHC
$bbZZ(ll\nu\nu)$	0.12%	Reconstruct $Z(ll)$ decay

- Signal signature: Lepton pair + E_T^{Miss} + 2 b-jets, three main categories
  - DFOS lepton pair ($e\mu$) - $bbWW$ and $bb\tau\tau$ signals
  - SFOS lepton pair (ee or $\mu\mu$), m_{ll} not on Z peak - $bbWW$ and $bb\tau\tau$ signals
  - SFOS lepton pair (ee or $\mu\mu$), m_{ll} on Z peak - $bbZZ$ (and $bb\tau\tau$) signals

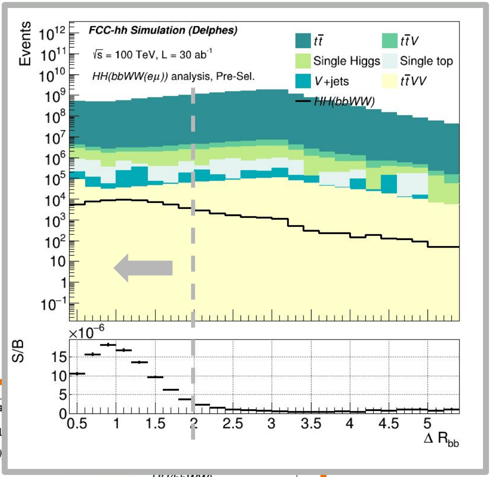
$bbll+E_T^{Miss}$ backgrounds

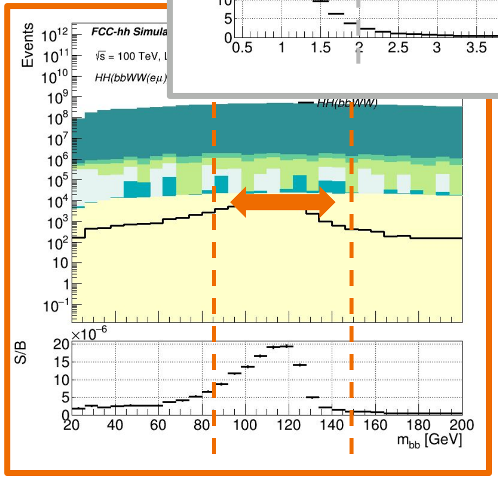
New:
More backgrounds

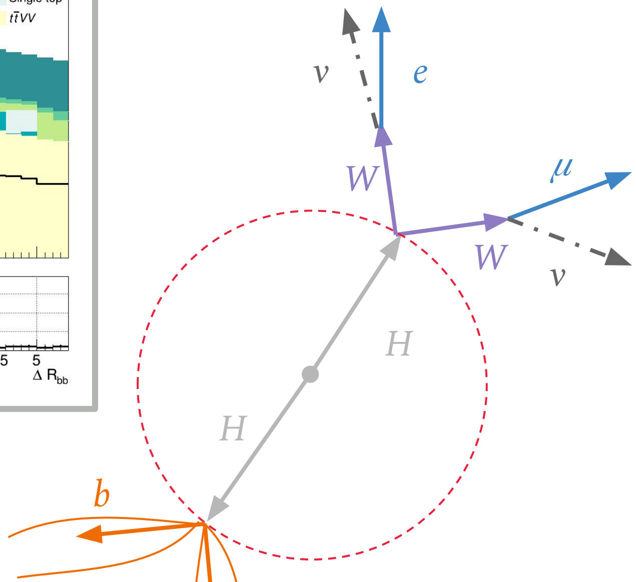


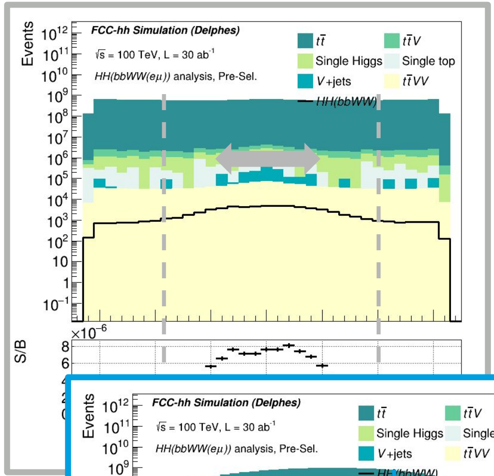
- Events at pre-selection level:
  - Require 2 b-jets, 2 leptons
- Extremely large background from $t\bar{t}$
  - Dileptonic final state irreducible
- Subleading contributions from $t\bar{t}V$, and single Higgs production (all modes)
- How to suppress?

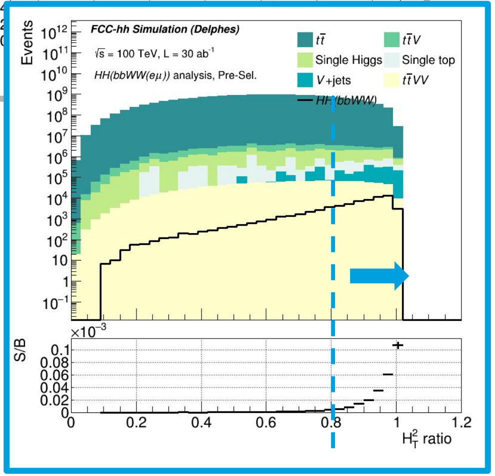
Event kinematics & selection











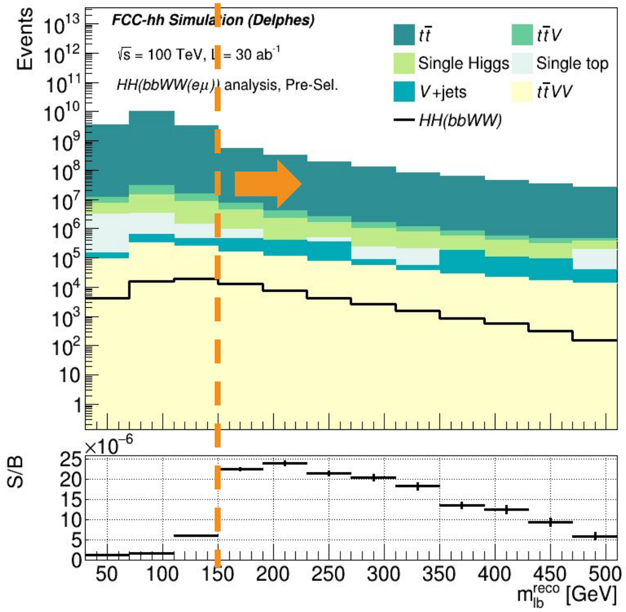
Selection based on invariant masses, angles, p_T balance of the event ..

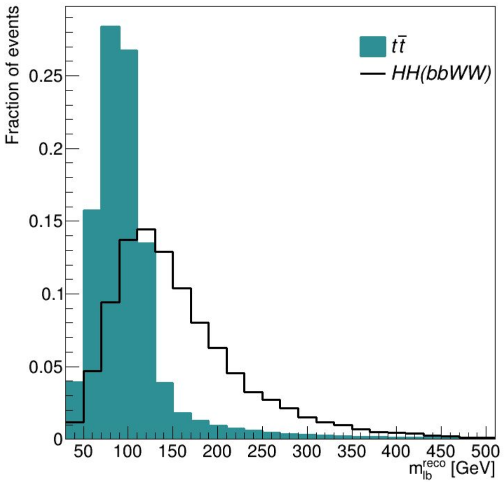
New!

Event kinematics & selection

.. and variables more specifically targeted at a certain background, e.g. m_{lb}^{reco} to reduce $t\bar{t}$

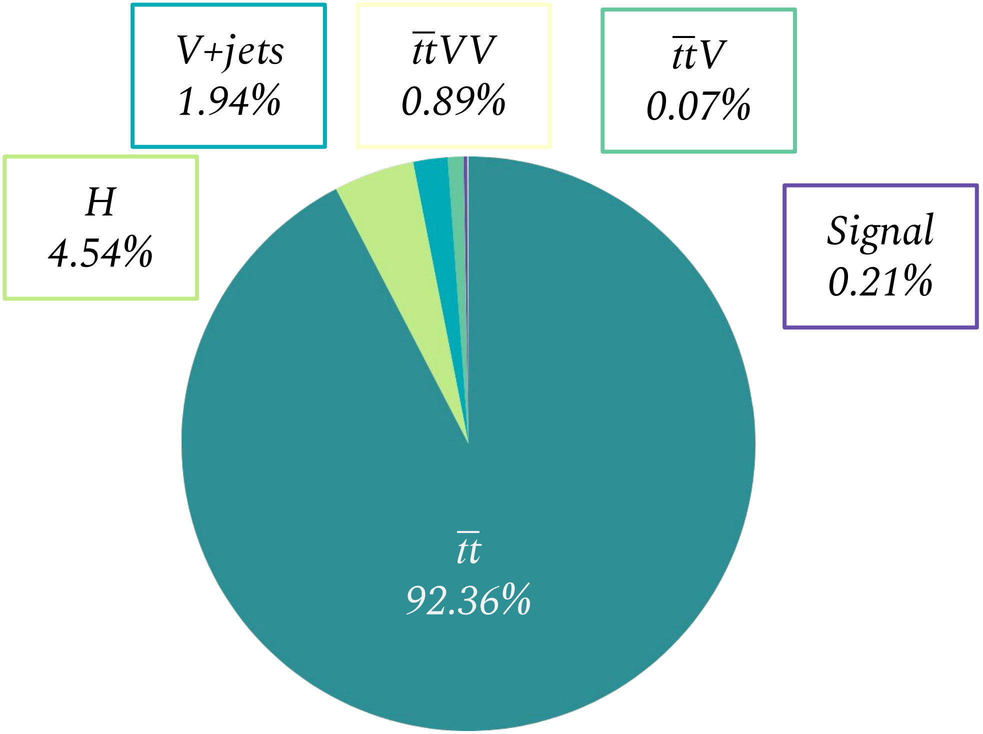
- Defined for top-quark mass measurements in dileptonic channel





$$m_{lb}^{\mathrm{reco}} = \min\left(\frac{m_{l_1b_1} + m_{l_2b_2}}{2}, \frac{m_{l_2b_1} + m_{l_1b_2}}{2}\right)$$

Event kinematics & selection

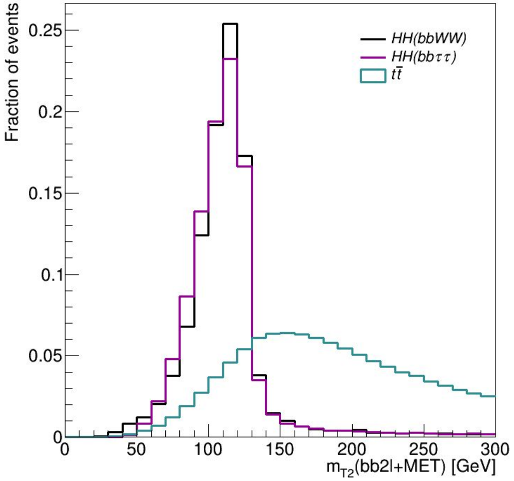


- Revisit events after full selection
  - Single top fully suppressed, most other backgrounds greatly reduced, e.g. $t\bar{t}$ acceptance 0.06%
- $S/\sqrt{B}$ ~ 7 in the DFOS and SFOS, no Z categories (only 0.7 in SFOS, Z peak)
- Further exploit:
  - Categorize in bins of $|\Delta\phi(ll, E_T^{Miss})|$
  - Signal shape w.r.t . backgrounds

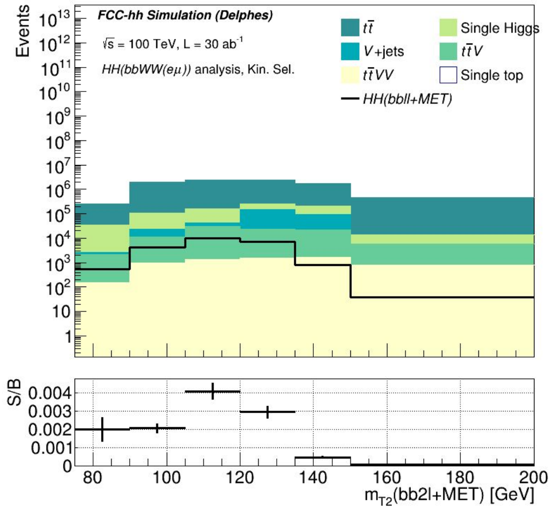
Stransverse mass

New!

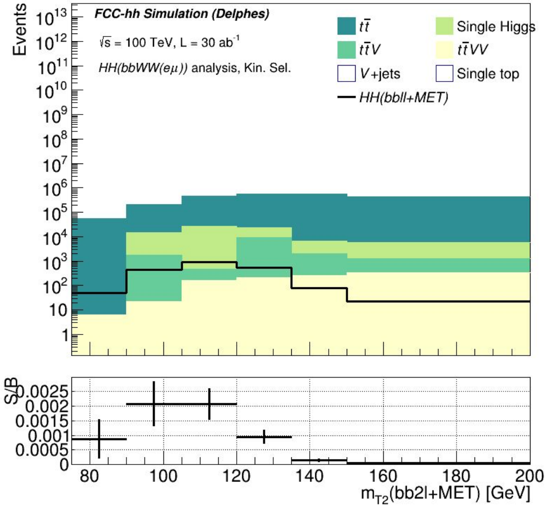
DFOS, pre-selection



DFOS, low dPhi



DFOS, high dPhi



- Stransverse mass m_{T2} specific algorithm designed to predict invisible contribution to the mass of a parent particle that decays semi-invisibly
  - Here: Capture the full HH decay

New!

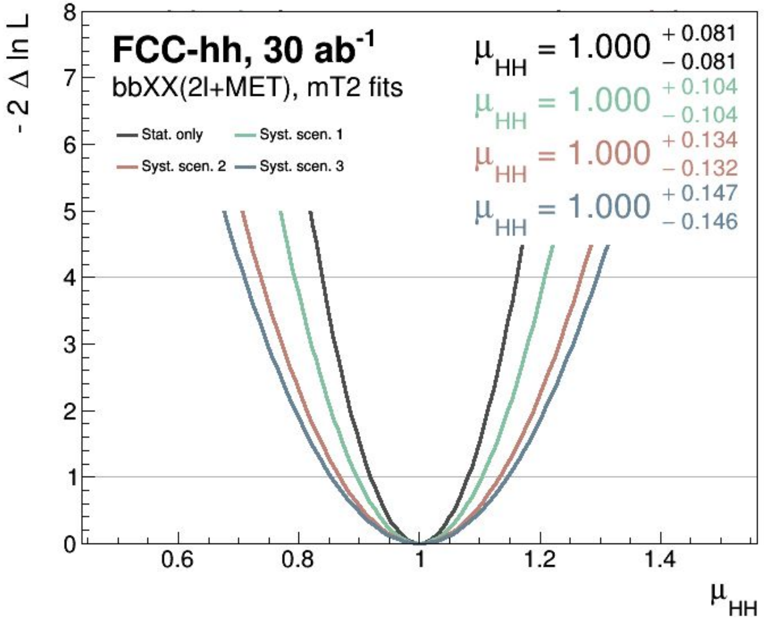
Results: Systematics

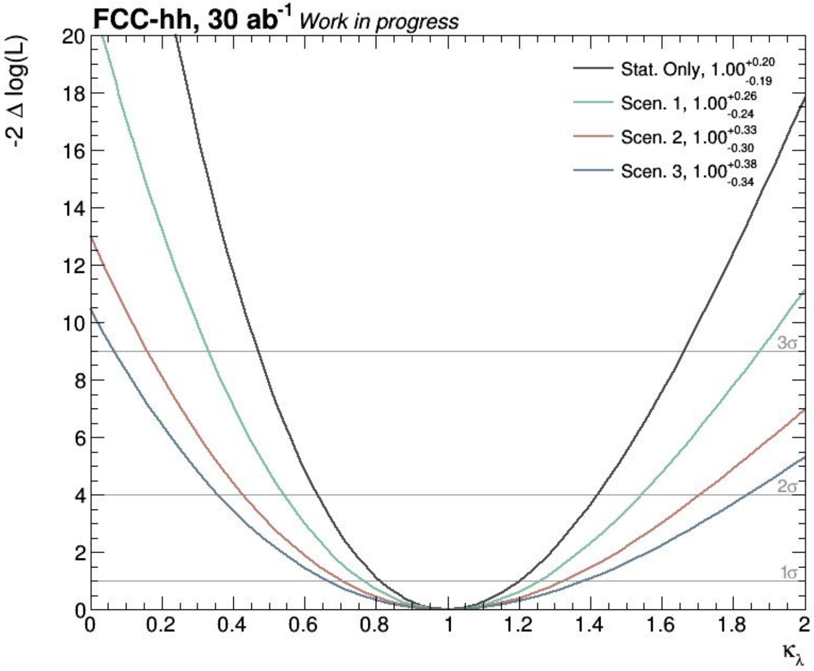
Source of uncertainty	Scenario 1	Scenario 2	Scenario 3	Applies to
Lepton ID / lepton	0.5%	1%	2%	HH, $t\bar{t}V(V)$, H
b-jet ID / b-jet	0.5%	1%	2%	HH, $t\bar{t}V(V)$, H
Luminosity	0.5%	1%	2%	HH, $t\bar{t}V(V)$, H
Data-driven V + jets est.	-	1%	1%	V + jets
Data-driven $t\bar{t}$ est.	-	-	1%	$t\bar{t}$
Signal cross-section	0.5%	1%	1.5%	HH

- In addition to stat. only precision consider three scenarios for systematics
  - Following previous di-Higgs studies@FCC-hh
- Applied as rate systematics only, no shape effect (currently)

New!

Results: Combined, expected sensitivity



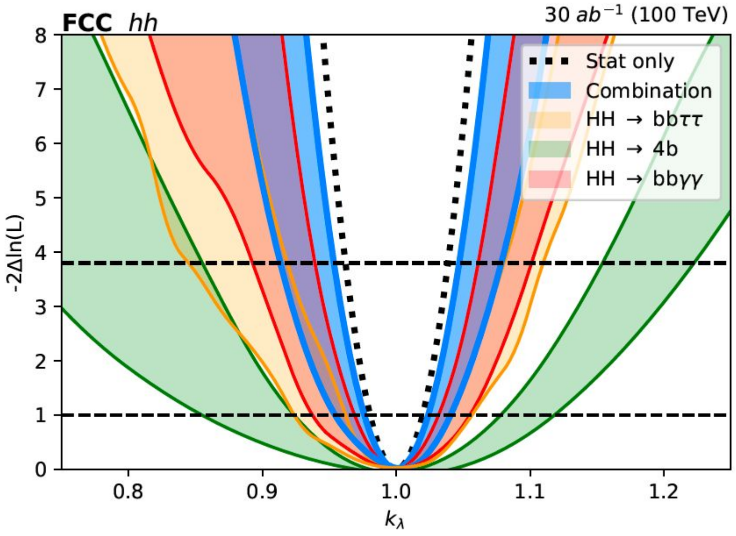


- Signal strength μ_{HH}

- Higgs self-coupling modifier κ_λ (= λ_3/λ_3^{SM}) interpretation with HHInference tools
  - Inputs: κ_λ = 0.4, 1., 2.4, 3.0

New!

Results: bbll+MET in context



arXiv:2203.08042

- Most sensitive channels well explored already for FCC-hh potential
- Latest combined projection from *bbyy*, *4b* and $bb\tau\tau$ (full + semi hadronic) achieves 2% (stat.only) precision on $\boldsymbol{\kappa_\lambda}$
  - $bbll+E_T^{Miss}$ performance about factor 2 worse than *4b* stand-alone, or earlier studies of $bb\tau\tau$
- Compared to earlier studies, $bbll+E_T^{Miss}$ performance similar to much cleaner (but rarer) *bb4l* and factor 2 better than (more abundant) semileptonic *bbWW(2jlv)*

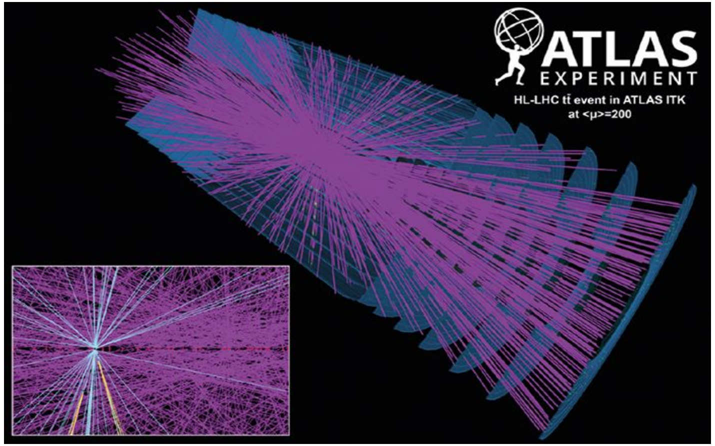
Work in progress: Impact of E_T^{Miss} performance degradation

New!

Avg. interactions/bunch cross.

Now	$O(10)$	$O(100)$	$O(1000)$	*Future*
	LHC	*HL-LHC*	*FCC-hh*	

$\langle\mu\rangle = 200$

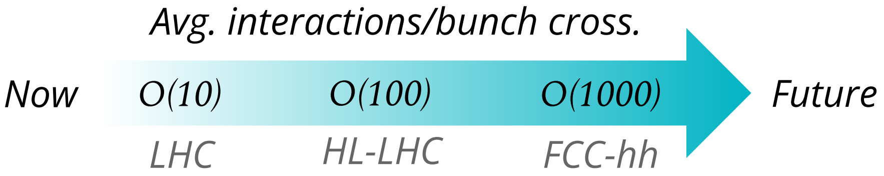


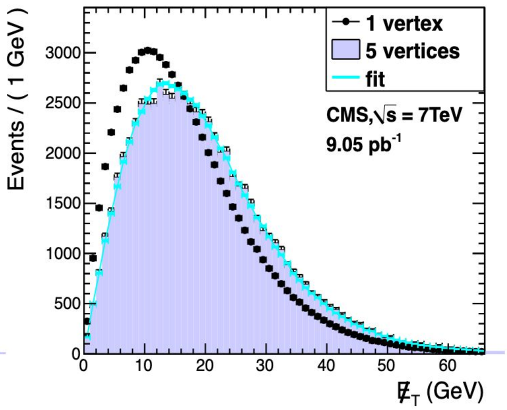
[Source]

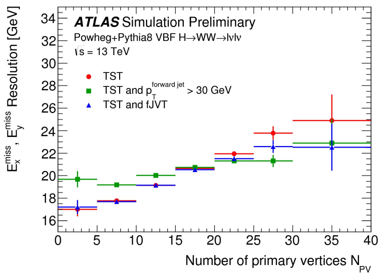
- Reconstruction of E_T^{Miss} will get increasingly challenging in the future, due to the increasing pile-up
  - Not studied for the FCC-hh yet
  - Usually assume precise timing detectors will be available & suppress to ~ LHC levels

Work in progress: Impact of E_T^{Miss} performance degradation

New!



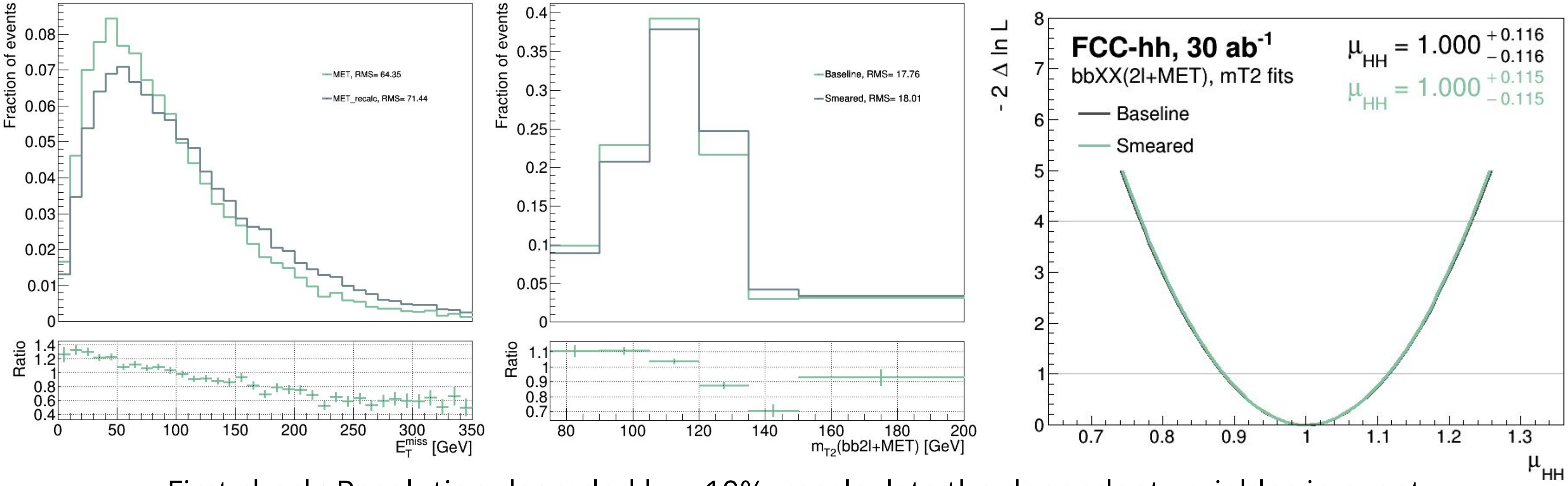




- Reconstruction of ETMiss will get increasingly challenging in the future, due to the increasing pile-up
  - Not studied for the FCC-hh yet
  - Usually assume precise timing detectors will be available & suppress to max LHC levels
- From LHC experience, have an idea of what happens with increasing <μ>
  - Resolution broades, and mean may shift as well
  - Try to apply this with Gaussian+uniform smearing and check impact

Work in progress: Impact of E_T^{Miss} performance degradation

New!



- First check: Resolution degraded by ~10%, recalculate the dependent variables in event selection and stransverse mass, check μ_{HH} precision (stat. only in DFOS category)
    - Impact very small

Conclusions & Outlook

- FCC-hh will bring precision measurement of Higgs self-coupling via di-Higgs
- Explored previously uncovered $bbll{+}E_T^{Miss}$ final state
    - $bZZ(llvv)$, $bbWW(lvlv)$ and $bb\tau\tau(lvvlvv)$ signals
- Simple cut-based analysis using kinematic variables, large background from ttbar
- Extracted $\boldsymbol{\mu}_{HH}$ and $\boldsymbol{\kappa}_{\lambda}$ precision using DFOS+SFOS events and w. diff. systematics
    - $\boldsymbol{\mu}_{HH}$ stat only precision reaches 8% stat only, 15% w. largest systematics
    - $\boldsymbol{\kappa}_{\lambda}$ 20% stat only, 35% w. largest systematics
- Work in progress:
    - Studying impact of E_T^{Miss} performance further
    - MVA analysis instead of cut-based
    - Combination with other channels, also updating Delphes scenarios

Bonus

Event selection & categorization

	Analysis category		
	DFOS	SFOS, no Z-peak	SFOS, on Z-peak
Main signals	$b\bar{b}WW^*$, $b\bar{b}\tau\tau$	$b\bar{b}WW^*$, $b\bar{b}\tau\tau$	$b\bar{b}ZZ^*$, $b\bar{b}\tau\tau$
Selection variable		Criterion	
Lepton pair	$e\mu$	ee or $\mu\mu$	ee or $\mu\mu$
Number of b-jets		≥ 2	
m_{bb}		85 - 105 GeV	
ΔR_{bb}		< 2	
$\Delta R_{\ell\ell}$		< 1.8	
$H_{\mathrm{T2}}^{\mathrm{ratio}}$		> 0.8	
m_{lb}^{reco}		> 150 GeV	
$\Delta\phi(\ell\ell, E_T^{\mathrm{miss}})$	< 2		< 1.2
$m_{\ell\ell}$	10 - 80 GeV		81 - 101 GeV
$\Delta\phi(\ell\ell, E_T^{\mathrm{miss}})$-categories	< 1.2 ("low") and $1.2 - 2.0$ ("high")		-

Table 3.25.: Overview of the harmonized event selection and categorization.

Example cutflows

Criterion	Signal	$t\bar{t}$	Total acceptance in % Single top	V + jets	$t\bar{t}V$	$t\bar{t}VV$	Single Higgs
≥ 1 OS $e\mu$-pair	100.00	100.00	100.00	100.00	100.00	100.00	100.00
≥ 2 b-jets	100.00	100.00	100.00	100.00	100.00	100.00	100.00
$85 < m_{bb} < 150$ GeV	75.33	26.79	19.61	20.88	23.59	19.22	25.43
$\Delta R_{bb} < 2$	65.10	10.38	5.88	17.55	11.14	11.00	14.86
$10 < m_{\ell\ell} < 80$ GeV	60.44	4.07	3.92	11.18	3.72	2.82	6.90
$\Delta R_{\ell\ell} < 1.8$	56.30	2.38	1.96	11.18	2.23	2.00	4.82
$\lvert\Delta\phi(\ell\ell, E_T^{\text{miss}})\rvert < 2$	50.82	1.61	0.00	11.18	1.53	1.57	3.96
$H_{\text{T2}}^{\text{ratio}} > 0.8$	47.61	1.08	0.00	11.18	1.18	1.37	3.45
$m_{lb}^{\text{reco}} > 150$ GeV	26.58	0.06	0.00	11.18	0.30	0.59	1.64

Table 3.17.: Absolute acceptances of the event selection criteria for $b\bar{b}WW^*(e\mu + E_{\text{T}}^{\text{miss}})$ signal and backgrounds. The pre-selected number of events as given in Table 3.15 is used as a reference to determine the absolute acceptance for each process.

Example cutflows

Criterion	Signal	$t\bar{t}$	Single top	$V+\text{jets}$	$t\bar{t}V$	$t\bar{t}VV$	Single Higgs
	Expected events with 30 ab^{-1}						
≥ 1 OS $e\mu$-pair	7.06E+04	1.86E+10	8.07E+06	2.02E+06	3.43E+07	1.28E+06	3.23E+07
≥ 2 b-jets	7.06E+04	1.86E+10	8.07E+06	2.02E+06	3.43E+07	1.28E+06	3.23E+07
$85 < m_{bb} < 150$ GeV	5.32E+04	4.97E+09	1.58E+06	4.22E+05	8.09E+06	2.46E+05	8.23E+06
$\Delta R_{bb} < 2$	4.60E+04	1.93E+09	4.75E+05	3.55E+05	3.82E+06	1.41E+05	4.81E+06
$10 < m_{\ell\ell} < 80$ GeV	4.27E+04	7.56E+08	3.16E+05	2.26E+05	1.28E+06	3.61E+04	2.23E+06
$\Delta R_{\ell\ell} < 1.8$	3.98E+04	4.41E+08	1.58E+05	2.26E+05	7.66E+05	2.56E+04	1.56E+06
$\lvert\Delta\phi(\ell\ell, E_T^{\text{miss}})\rvert < 2$	3.59E+04	2.99E+08	0.00E+00	2.26E+05	5.25E+05	2.00E+04	1.28E+06
$H_{\text{T2}}^{\text{ratio}} > 0.8$	3.36E+04	2.01E+08	0.00E+00	2.26E+05	4.04E+05	1.75E+04	1.12E+06
$m_{lb}^{\text{reco}} > 150$ GeV	1.88E+04	1.08E+07	0.00E+00	2.26E+05	1.03E+05	7.61E+03	5.30E+05

Table 3.15.: Cutflow of the kinematic event selection for the $b\bar{b}WW^*$ $(e\mu)$ signal and backgrounds. Expected numbers of events with a dataset of 30 ab^{-1} are shown, using the cross-sections from Table 3.1 to normalize. Here all samples were pre-filtered with the pre-selection.

Example cutflows

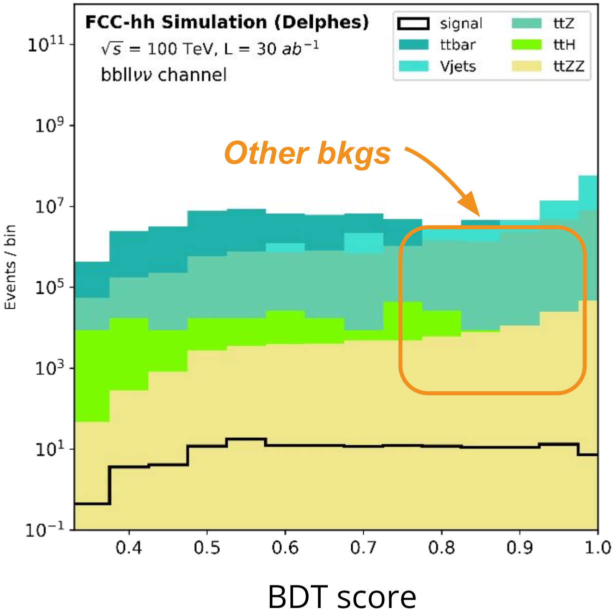
Criterion	Signal	$t\bar{t}$	Single top	$V+$jets	$t\bar{t}V$	$t\bar{t}VV$	Single Higgs
	Relative acceptance in %						
≥ 1 OS $e\mu$-pair	100.00	100.00	100.00	100.00	100.00	100.00	100.00
≥ 2 b-jets	100.00	100.00	100.00	100.00	100.00	100.00	100.00
$85 < m_{bb} < 150$ GeV	75.33	26.79	19.61	20.88	23.59	19.22	25.43
$\Delta R_{bb} < 2$	86.43	38.74	30.00	84.06	47.24	57.25	58.44
$10 < m_{\ell\ell} < 80$ GeV	92.83	39.26	66.67	63.70	33.39	25.61	46.42
$\Delta R_{\ell\ell} < 1.8$	93.14	58.30	50.00	100.00	60.02	70.94	69.83
$\lvert\Delta\phi(\ell\ell, E_T^{\text{miss}})\rvert < 2$	90.27	67.94	0.00	100.00	68.48	78.35	82.27
$H_{\text{T2}}^{\text{ratio}} > 0.8$	93.70	67.03	0.00	100.00	76.96	87.16	87.10
$m_{lb}^{\text{reco}} > 150$ GeV	55.81	5.37	0.00	100.00	25.57	43.55	47.44

Table 3.16.: Relative acceptances of the event selection criteria for $b\bar{b}WW^*(e\mu + E_{\text{T}}^{\text{miss}})$ signal and backgrounds. The relative acceptance is calculated at the number of events at a given criterion, divided by that at the previous criterion.

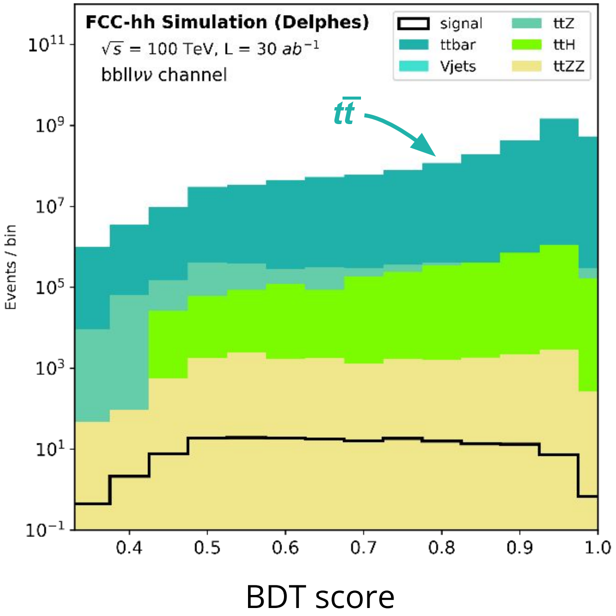
BDT for bbZZ

- Masters thesis by Kevin Laudamus
- BDT able to improve bbZZ upper limits from ~ 4 to ~2-2.5, depending on setup, also has higher signal efficiency

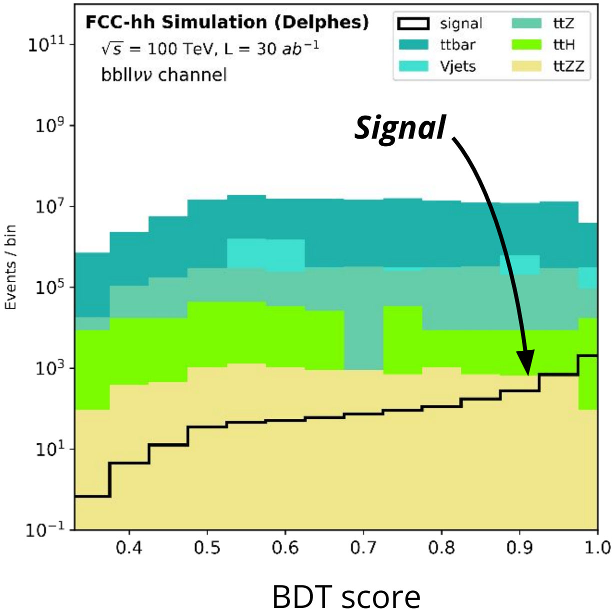
Others classification



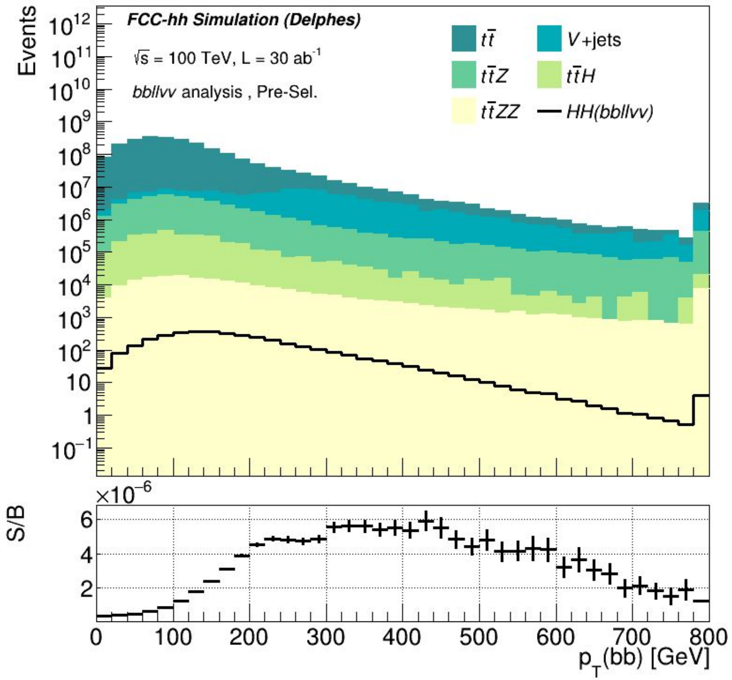
$t\bar{t}$ classification



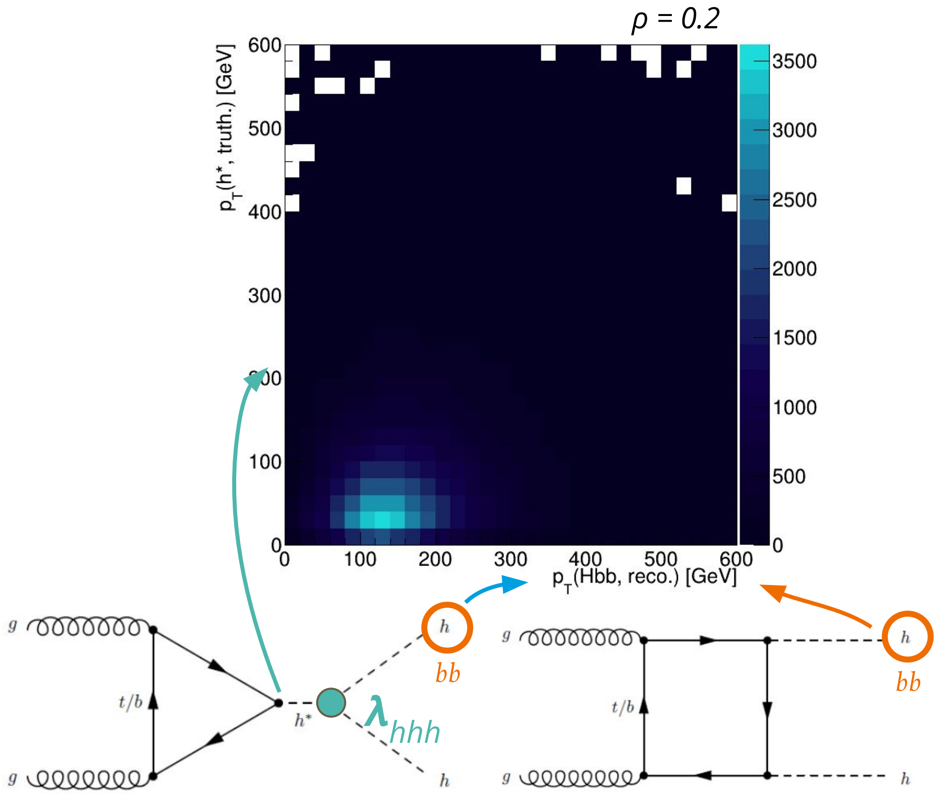
Signal classification



Corners of phase-space: High pT

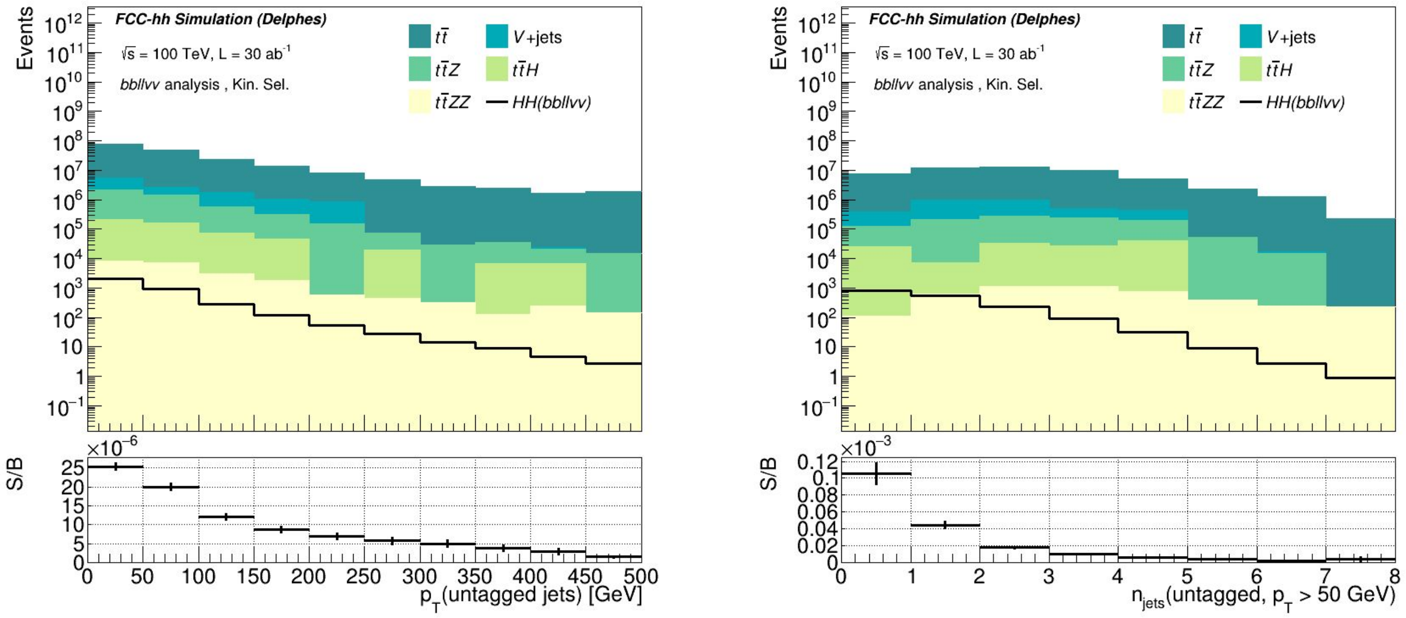


S/B improves in high Higgs p_T region, may be possible with a dataset as large as 30 ab^{-1}
→ Analysis would require reoptimization



What about kinematic correlations between individual H and the virtual H? Bias towards one of the diagrams?

Corners of phase-space: Jet multiplicity



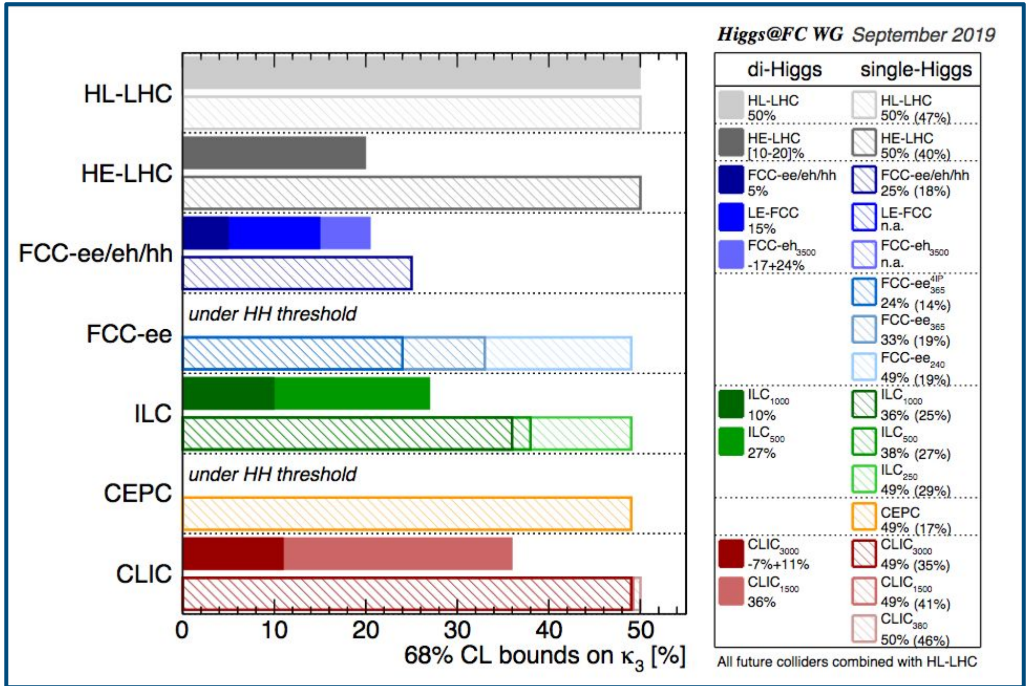
- Backgrounds seem to have more additional, untagged jets with higher pT
  - Veto on extra jets, or categories in jet-multiplicities might enhance potential
- However, this introduces extra uncertainties from theory side!
  - Set a pT threshold for the extra jets, here: 50 GeV

HT2 ratio

- Definition following ATLAS analysis of $bbl\nu l\nu$ channel: arXiv:1908.06765

H_{T2}	Scalar sum of the magnitudes of the momenta of the $H \to \ell\nu\ell\nu$ and $H \to bb$ systems, $$H_{\mathrm{T2}} = \lvert \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}^{\ell,0} + \mathbf{p}_{\mathrm{T}}^{\ell,1} \rvert + \lvert \mathbf{p}_{\mathrm{T}}^{b,0} + \mathbf{p}_{\mathrm{T}}^{b,1} \rvert$$
$H_{\mathrm{T2}}^{\mathrm{R}}$	Ratio of H_{T2} and scalar sum of the transverse momenta of the H decay products, $$H_{\mathrm{T2}}^{\mathrm{R}} = H_{\mathrm{T2}} / (E_{\mathrm{T}}^{\mathrm{miss}} + \lvert \mathbf{p}_{\mathrm{T}}^{\ell,0} \rvert + \lvert \mathbf{p}_{\mathrm{T}}^{\ell,1} \rvert + \lvert \mathbf{p}_{\mathrm{T}}^{b,0} \rvert + \lvert \mathbf{p}_{\mathrm{T}}^{b,1} \rvert),$$ where $\mathbf{p}_{\mathrm{T}}^{\ell(b),0\{1\}}$ are the transverse momenta of the leading {subleading} lepton (b-tagged jet)

Why di-Higgs at FCC-hh?



[arXiv:1905.03764v2]

FCC-hh is the only perspective for a Higgs self-coupling precision measurement

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Higgs self-coupling measurement is a clear benchmark channel for the FCC-hh