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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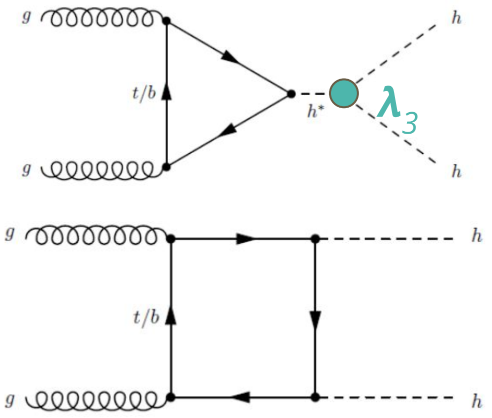
DESY.

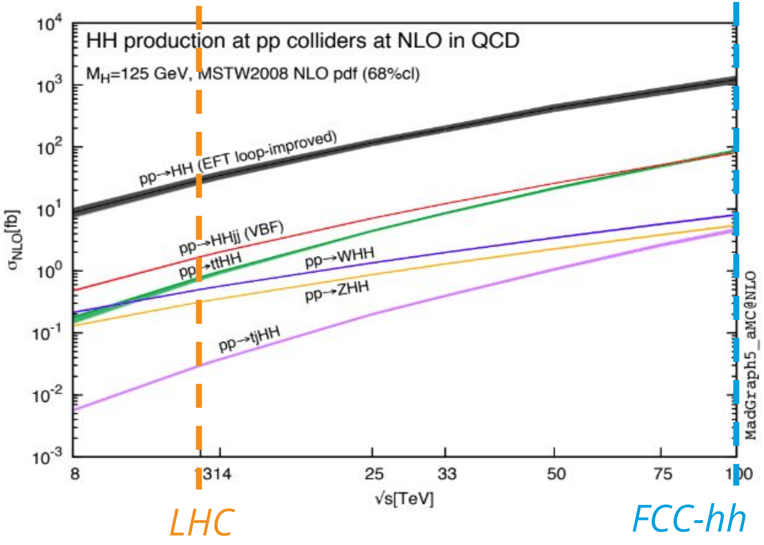
Di-Higgs with E_T^{Miss} @ FCC-hh: What & why?

- A key benchmark for FCC-hh is measuring the Higgs self-coupling via di-Higgs production



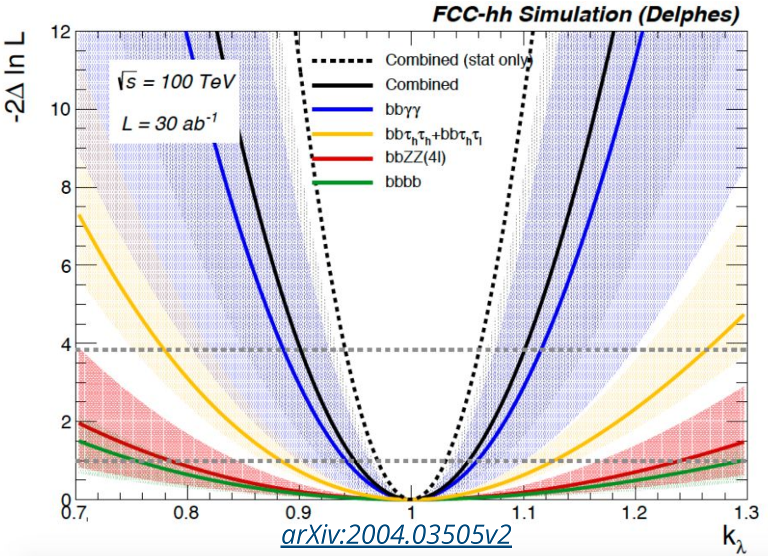
  - SM: $\sigma(ggHH)$ ~ $O(1000)$ smaller than $\sigma(ggH)$
- Precision measurement down to few % - how?

Precision through large cross-section + data set



- FCC-hh w. 30 ab^{-1} compared to HL-LHC:
  - 400 x signal yields, 20 x precision

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



arXiv:2004.03505v2

Avg. interactions/bunch cross.

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

- Several channels already well established
  - $bb\gamma\gamma$: Most sensitive, established at LHC
  - $bbZZ(4l)$: Very rare new channel at FCC-hh
- Other new channels at FCC-hh? What can we learn from them?
- Consider final states with neutrinos:
  - E_T^{Miss} very challenging in the future, due to increasing pile-up
  - Goal: Identify which channels are worth studying and use them for investigations into E_T^{Miss} reconstruction

Possible final states with E_T^{Miss}

Channel	BR($HH \rightarrow X$)	Advantages	Disadvantages
$bbZZ(ll\nu\nu)$	0.12%	4x higher BR than $bbZZ(4l)$ SFOS lepton pair from Z	Large backgrounds One Z-decay is off-shell
$bb\tau\tau(dilep.)$	0.88%	Higher BR, due to higher $H(\tau\tau)$ DFOS (emu) established for single Higgs studies @ LHC	Large backgrounds Neutrinos in both τ decays
$bbWW(l\nu l\nu)$	2.24%	Higher BR, due to higher $H(WW)$ Established for single and di-Higgs studies @ LHC	Large backgrounds Neutrinos in both W decays

Technicalities

Event generator

↓

Detector simulation

↓

Samples

↓

Physics analysis & statistical interpretation

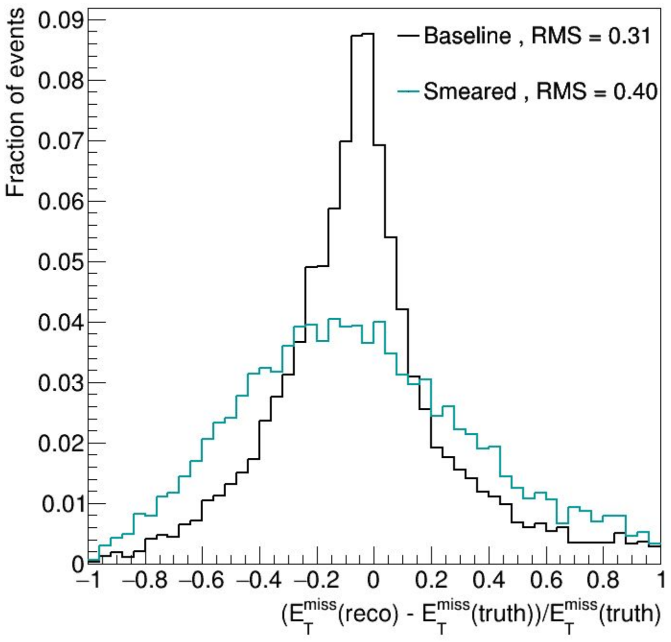
Samples in the FCC-hh event database
- ggF signals generated with Powheg, backgrounds with MG
- Parametrized detector simulation with Delphes with the FCC-hh card
- In EDM4HEP format

- Event selection with FCCAnalyses FW
- Interpretation with CMS combine & HHInference tools

Thanks a lot to Clement Helsens for software help!

Analysis strategy

$bbWW(e\mu)$ *signal*



- Signal signature: Lepton pair + E_T^{Miss} + 2 b-jets
  - $bbZZ$: ee or $\mu\mu$ pair, offshell Z in $Z(\nu\nu)$ decay
  - $bbWW$, $bb\tau\tau$: Only $e\mu$ channel studied
- Select leptons isolated from b-jets ($\Delta R > 0.4$)
- E_T^{Miss} reconstruction baseline as per Delphes
  - Resolution comparable to LHC conditions
  - $bbWW(e\mu)$ also studied with smeared E_T^{Miss}
- Main backgrounds: $t\bar{t}$, V+jets, $t\bar{t}V(V)$, $t\bar{t}H$
- Simple cut-based kinematic event selection
- Pseudo-invariant mass as discriminant

Illustration of $bbWW(e\mu)$ event kinematics & selection

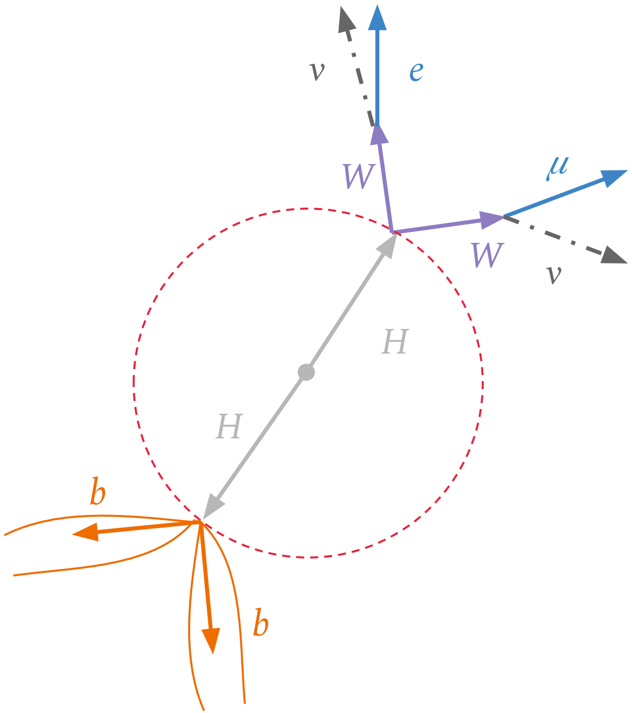
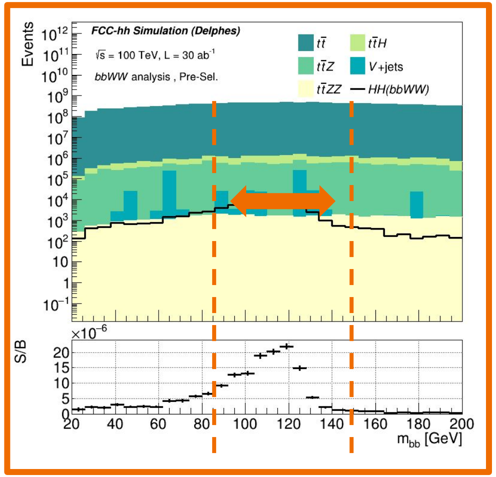


Illustration of $bbWW(e\mu)$ event kinematics & selection



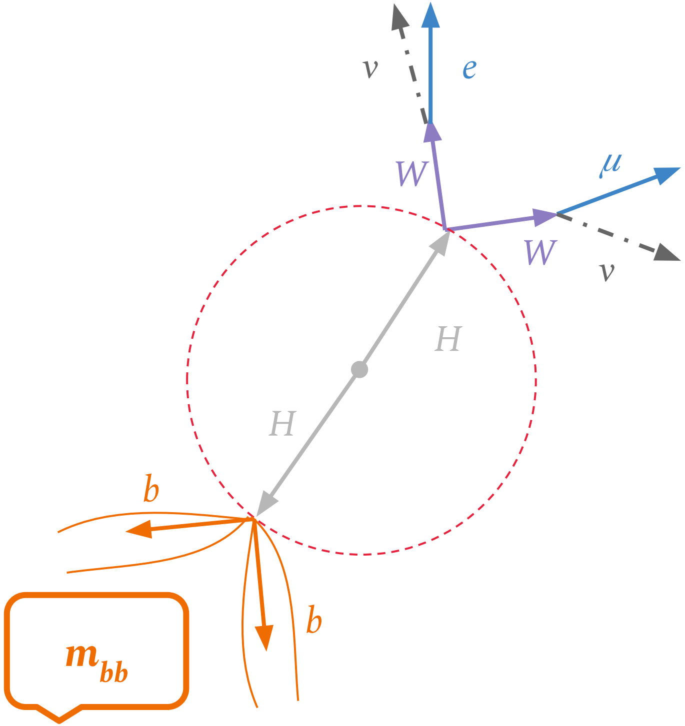
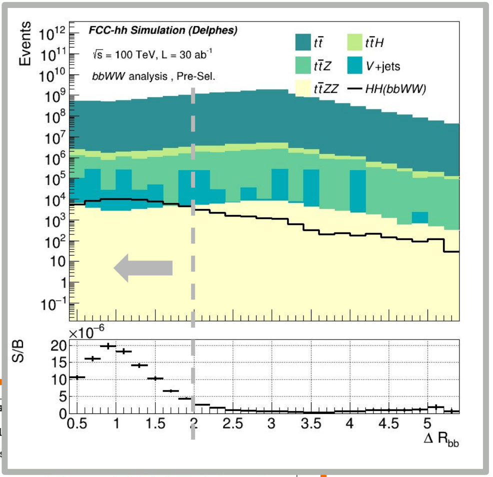
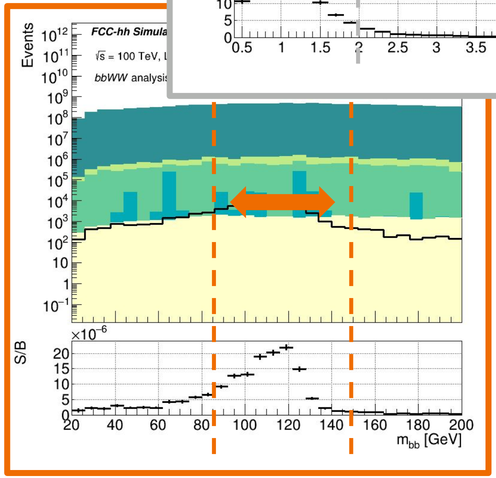
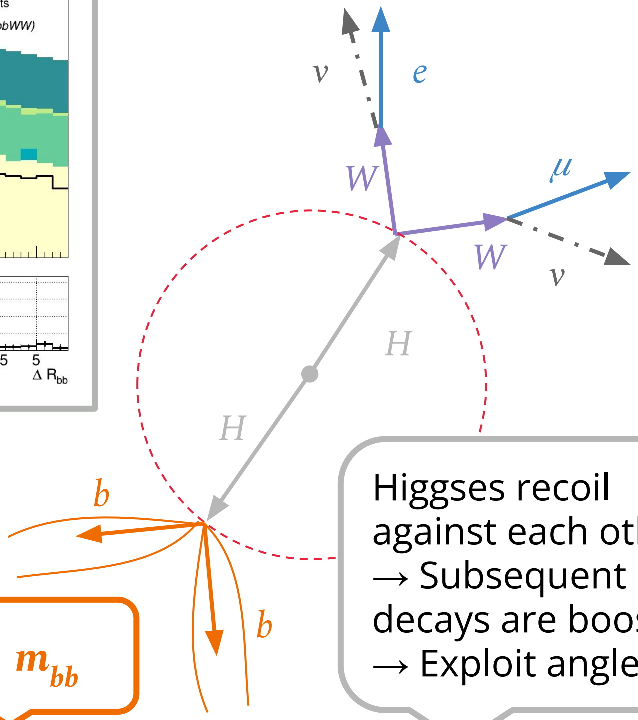
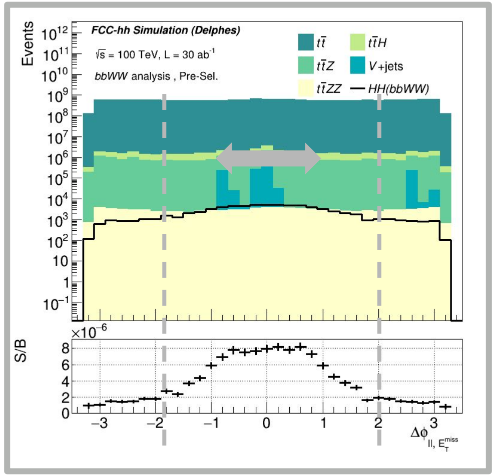


Illustration of $bbWW(e\mu)$ event kinematics & selection





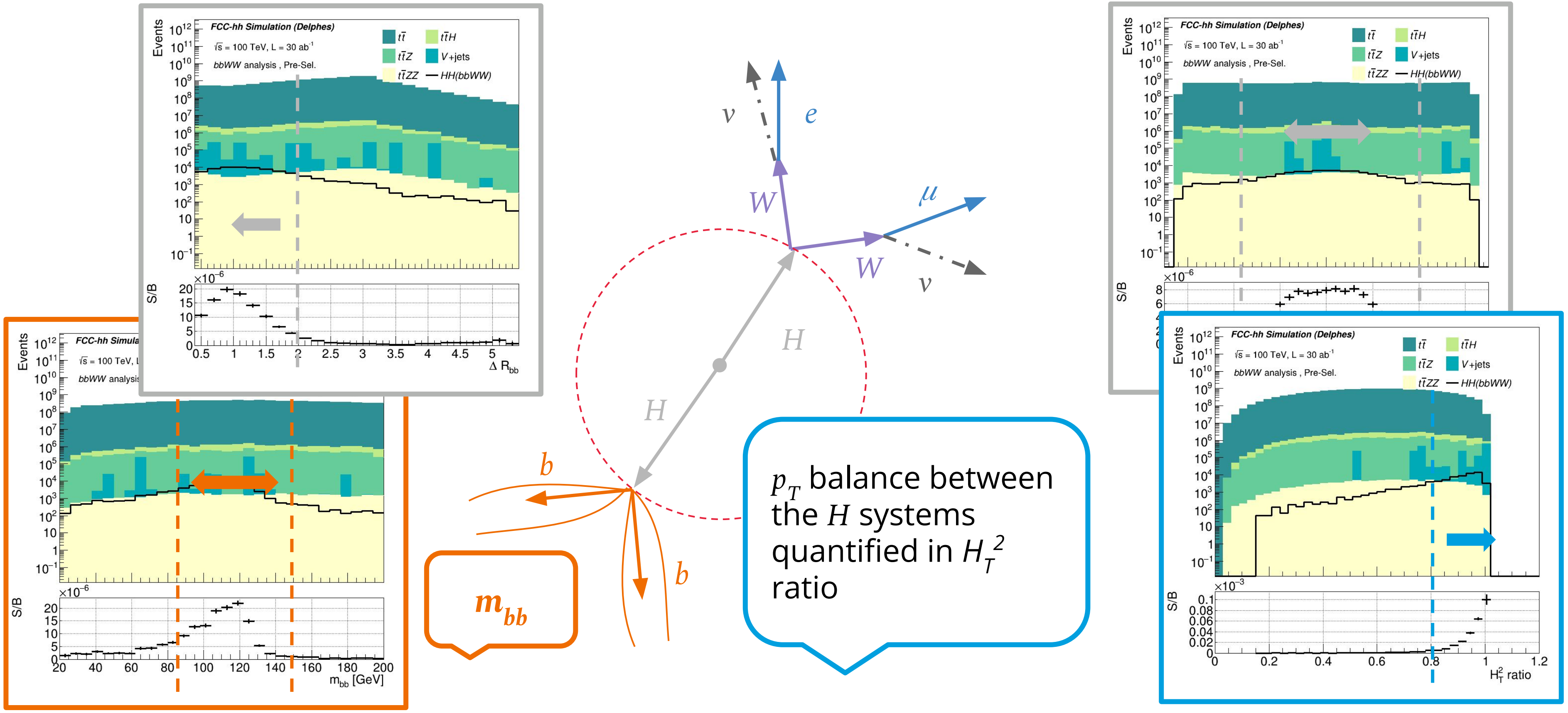




m_{bb}

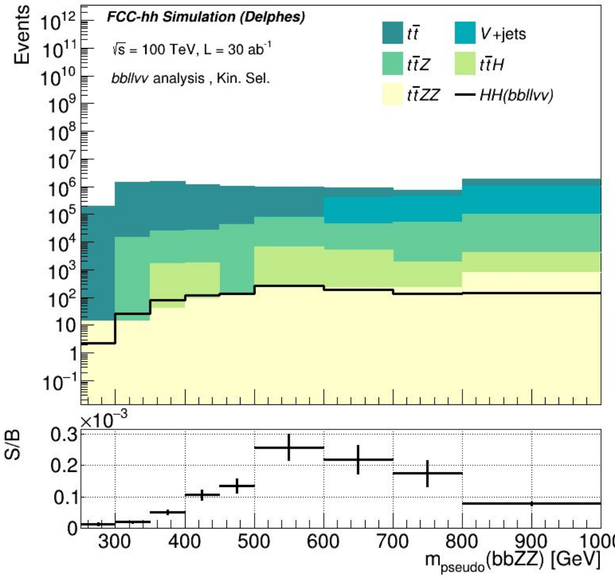
Higgses recoil against each other
→ Subsequent decays are boosted
→ Exploit angles!

Illustration of $bbWW(e\mu)$ event kinematics & selection

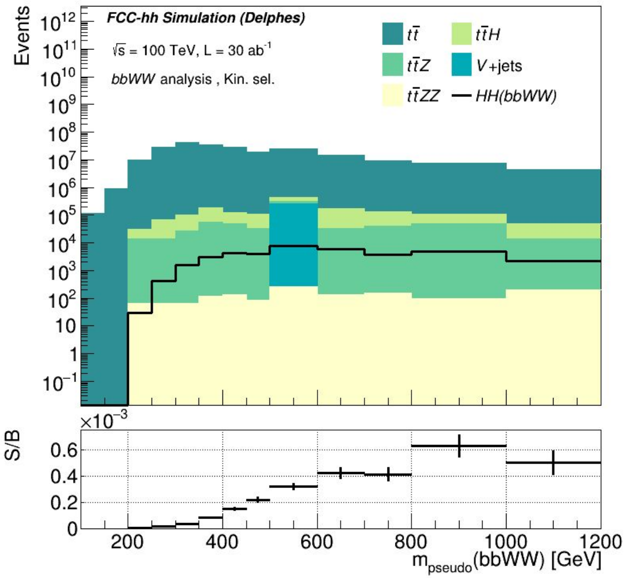


Pseudo-invariant mass

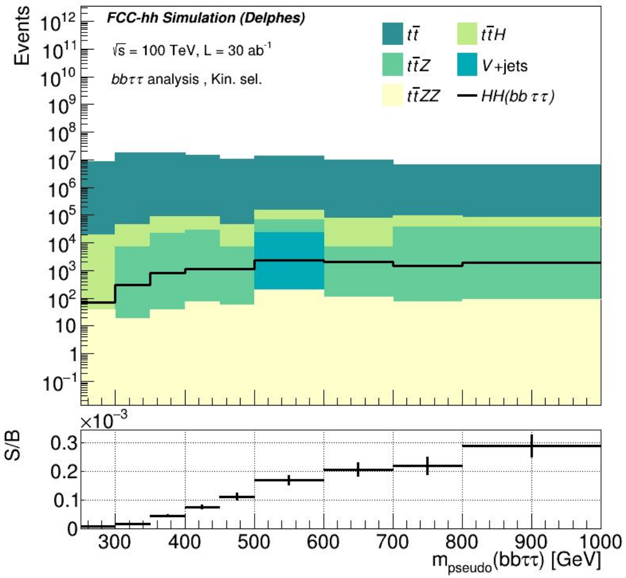
bbZZ(llvv)



bbWW(eμ)



bbττ(eμ)



- Defined as: Invariant mass of the 4-vector built from bb, ll and $(E_T^{Miss}, E_X^{Miss}, E_Y^{Miss}, 0)$

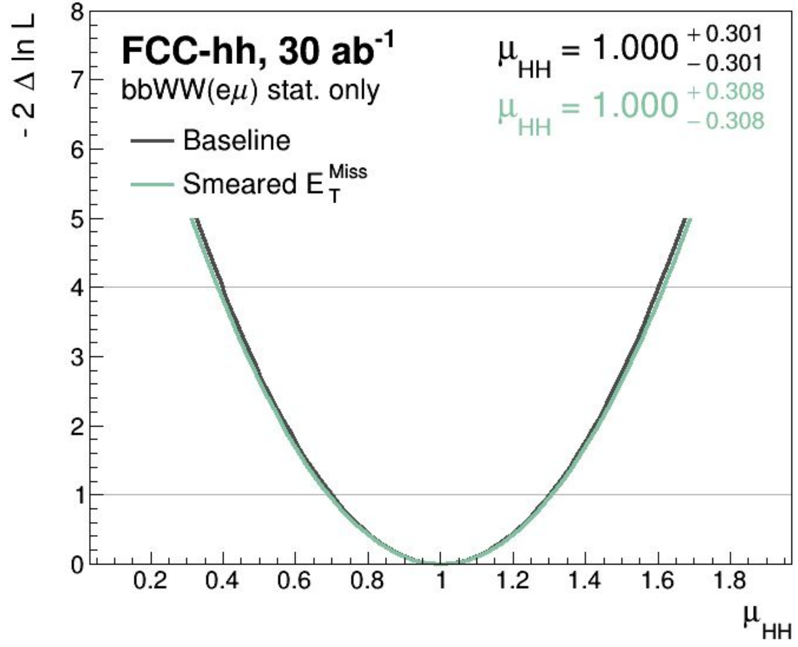
Results & comparison

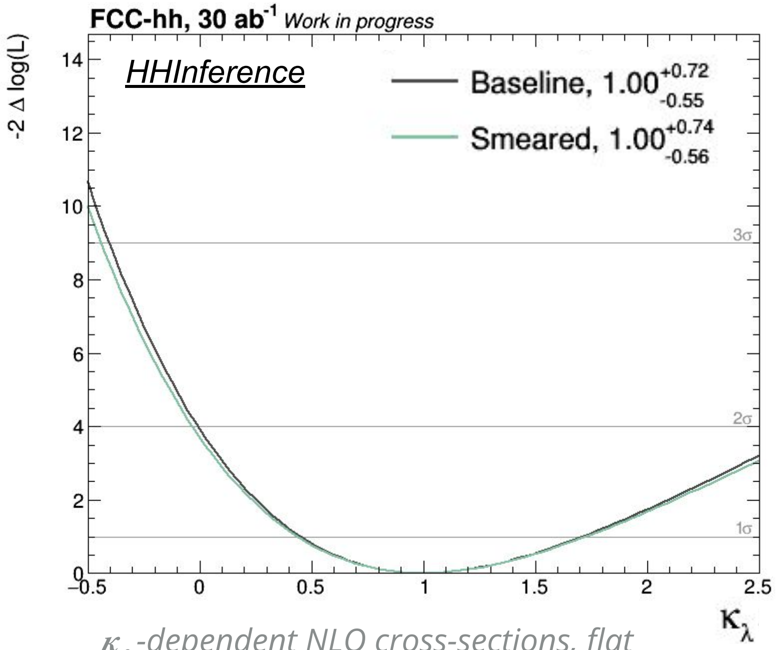
	$bbZZ(ll\nu\nu)$	$bb\tau\tau(e\mu)$	$bbWW(e\mu)$
S/√B **at pre-selection**	0.03	0.21	0.52
S/√B **with kin. sel.**	0.38	1.18	2.64
Median exp. limit on μ_{HH}	4.62	1.41	0.55

- Individual fit per channel, without systematics
- $bbZZ(ll\nu\nu)$ more challenging than $bbZZ(4l)$, despite higher BR
- Dileptonic $bb\tau\tau(e\mu)$ channel less sensitive than hadronic channels, which reach 8-10% (stat. only) precision in previous studies
- $bbWW(e\mu)$ best sensitivity, due to highest BR

Expected sensitivity in $bbWW(e\mu)$ channel

- $bbWW(e\mu)$ most promising channel, allowing to measure μ_{HH} and $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$
  - Semi-leptonic $bbWW(2jl\nu)$ shown to reach 40% κ_λ -sensitivity, here using only $e\mu$



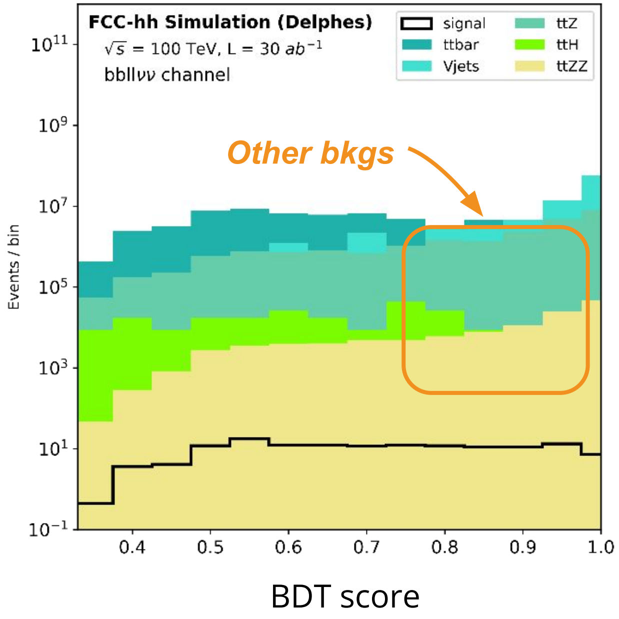


κ_λ-dependent NLO cross-sections, flat k-factor, acceptance + shape effects

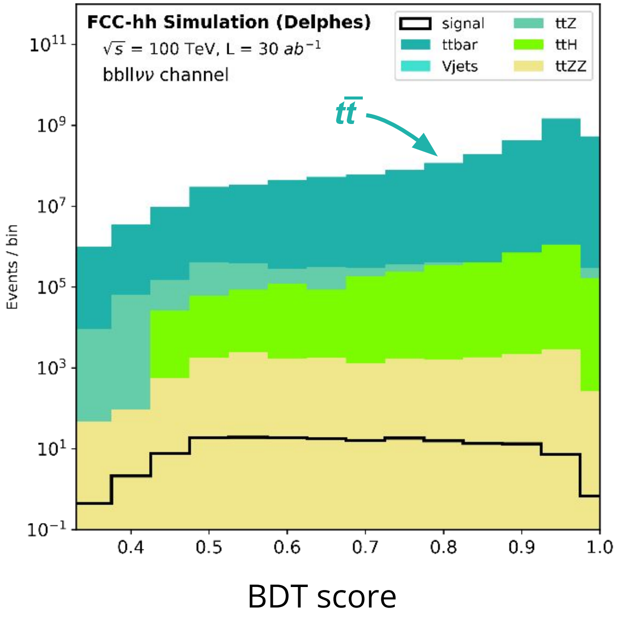
Further optimization and studies

- Include systematics, especially related to E_T^{Miss} reconstruction
- Explore machine learning for the three channels
- Combine the channels

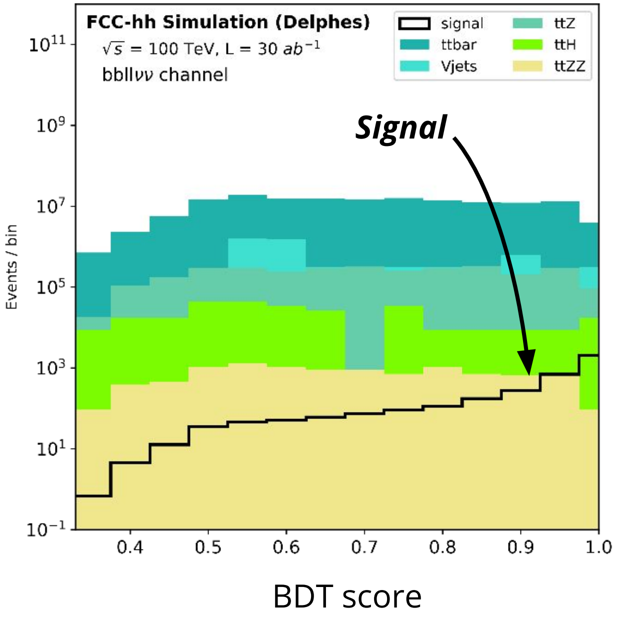
Others classification



$t\bar{t}$ classification



Signal classification

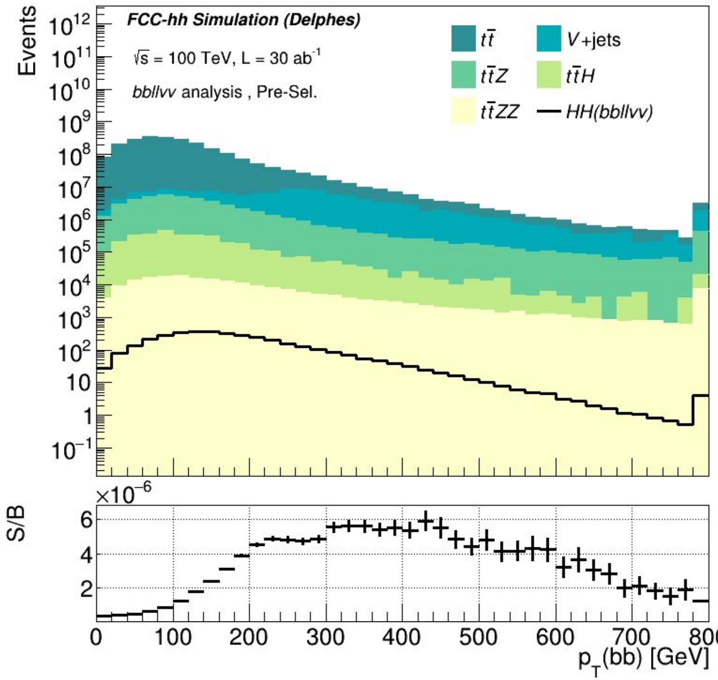


Conclusions & Outlook

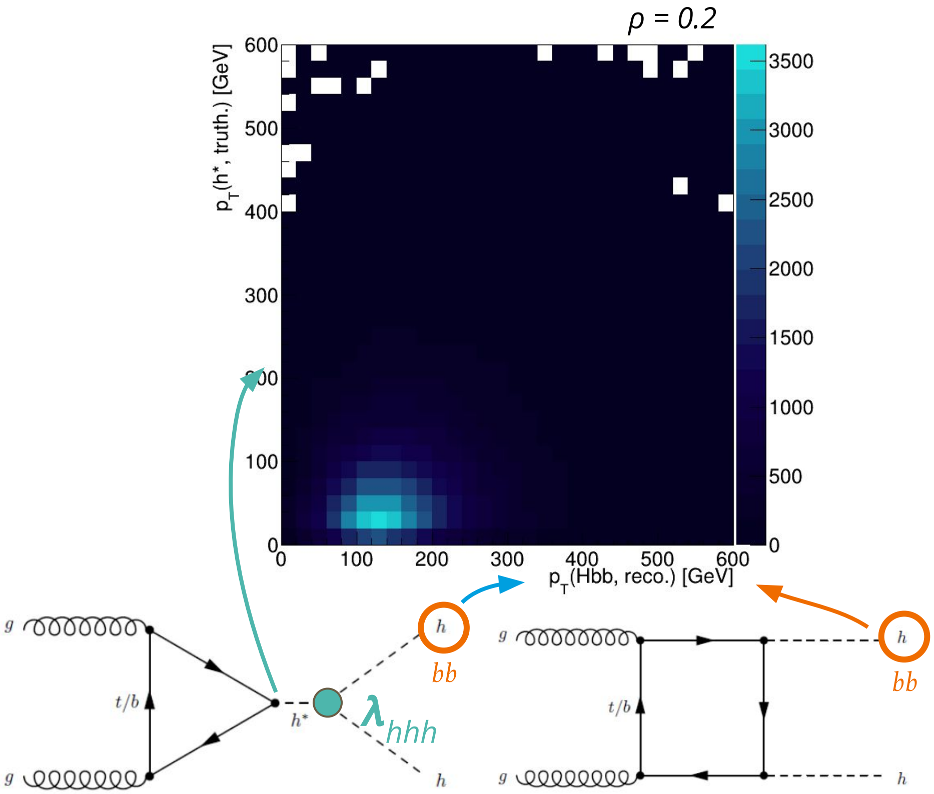
- FCC-hh will bring precision measurement of Higgs self-coupling via di-Higgs
- Explicitly consider channels with neutrinos - even though they are challenging due to large backgrounds - with goal to study E_T^{Miss}
- Cut-based analyses of $bbZZ(ll\nu\nu)$ and $bbWW(e\mu)$, $bb\tau\tau(e\mu)$
  - $bbWW(e\mu)$ most promising, reaching 30% (stat.only) sensitivity on μ_{HH} on its own, stable w.r.t. worsening of E_T^{Miss} resolution
  - Combination of channels will be more powerful
- Working on including systematic uncertainties, improving the analyses with BDTs and more in-depth studies of E_T^{Miss} performance

Bonus

Corners of phase-space: High pT

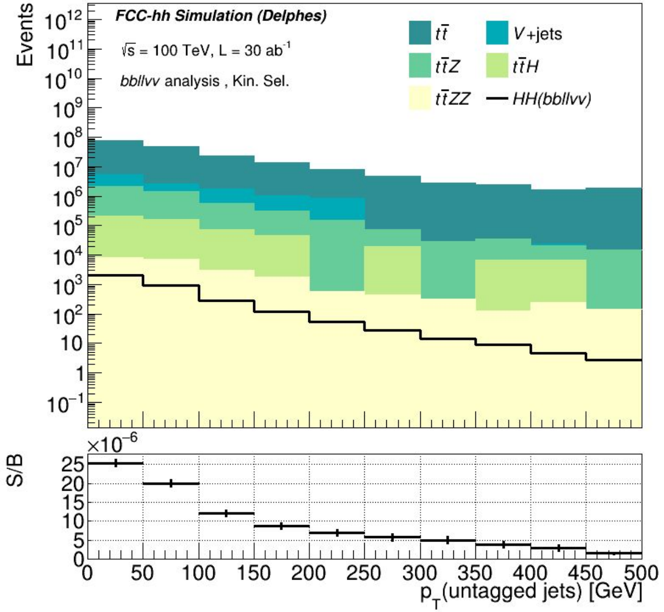


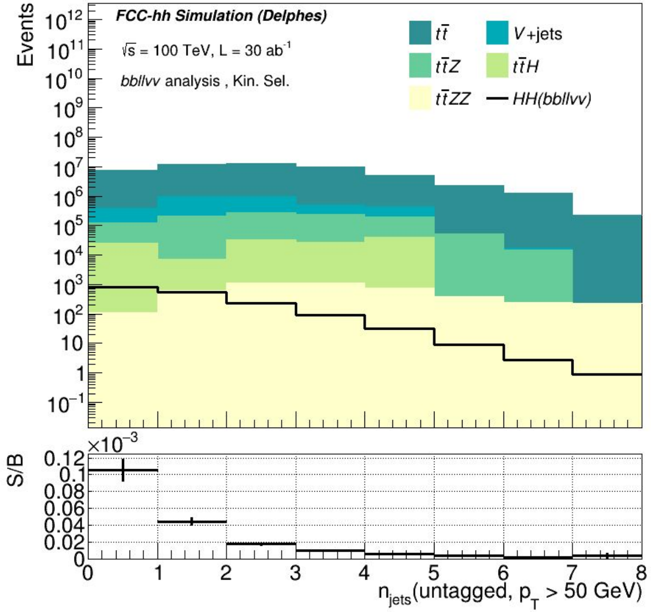
S/B improves in high Higgs p_T region, may be possible with a dataset as large as 30 ab^{-1}
→ Analysis would require reoptimization



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

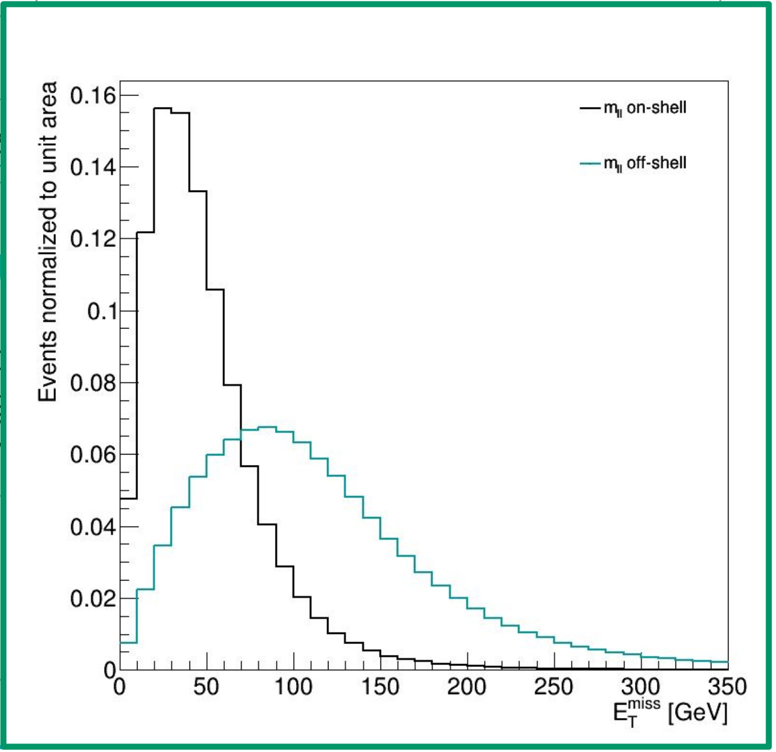
Analysis overview

	$bbZZ(ll\nu\nu)$	$bbWW(e\mu)$ & $bb\tau\tau(e\mu)$
Signature	SFOS lep. pair + E_T^{Miss} + 2 b-jets	DFOS lep. pair + E_T^{Miss} + 2 b-jets
Object reconstruction	Leptons isolated from b-jets (dR > 0.4) MET reconstruction as per Delphes: Resolution is comparable to LHC	
Backgrounds considered	*ttbar* *V*+jets *ttV, ttVV, ttH*	
Specifics	Off-shell *Z* assumed in $Z(\nu\nu)$	$e\mu$ channel only
Strategy	Cut-based kinematic event selection Expected sensitivity from shape fits to pseudo-invariant mass	

Analysis overview

	$bbZZ(ll\nu\nu)$	$bbWW(e\mu)$ & $bb\tau\tau(e\mu)$
Signature	SFOS lep. pair + E_T^{Miss} + 2 b-jets	
Object selection	Select leptons isolated from b-jets	
Backgrounds	*ttV,* *ggF and* *Sing* Non-reso	
Specifics	One Z is off-shell	

Here: Forcing ll-pair on-shell
$\leftrightarrow$
Smaller E_T^{Miss}



$bbWW(e\mu)$ cutflow - Baseline

	Expected events with 30 ab-1					
Criterion	**Signal**	***ttbar***	***V+jets***	***ttZ***	***ttH***	***ttZZ***
>= 1 OS emu-pair	7.12E+04	1.86E+10	4.76E+07	4.87E+07	3.97E+07	1.60E+05
>= 2 b-jets	7.12E+04	1.86E+10	2.03E+06	2.67E+07	2.74E+07	9.89E+04
85 < m_bb < 150 GeV	5.33E+04	4.97E+09	3.61E+05	5.99E+06	7.04E+06	1.90E+04
dR_bb < 2.0	4.60E+04	1.92E+09	3.60E+05	2.88E+06	4.13E+06	1.09E+04
m_ll < 80 GeV	4.58E+04	7.64E+08	3.60E+05	9.93E+05	1.82E+06	3.39E+03
dR_ll < 2.0	4.36E+04	5.01E+08	3.60E+05	6.92E+05	1.28E+06	2.42E+03
|dPhi_ll_MET| < 2.0	3.95E+04	3.43E+08	3.60E+05	5.07E+05	1.07E+06	1.78E+03
HT2 ratio > 0.8	3.72E+04	2.26E+08	3.60E+05	4.04E+05	9.18E+05	1.55E+03

$bbWW(e\mu)$ cutflow - Smeared E_T^{Miss}

	Expected events with 30 ab-1					
Criterion	**Signal**	***ttbar***	***Z+jets***	***ttZ***	***ttH***	***ttZZ***
>= 1 OS emu-pair	7.12E+04	1.86E+10	2.03E+06	2.67E+07	2.74E+07	9.89E+04
>= 2 b-jets	7.12E+04	1.86E+10	2.03E+06	2.67E+07	2.74E+07	9.89E+04
85 < m_bb < 150 GeV	5.33E+04	4.97E+09	3.61E+05	5.99E+06	7.04E+06	1.90E+04
dR_bb < 2.0	4.60E+04	1.92E+09	3.60E+05	2.88E+06	4.13E+06	1.09E+04
m_ll < 80 GeV	4.58E+04	7.64E+08	3.60E+05	9.93E+05	1.82E+06	3.39E+03
dR_ll < 2.0	4.36E+04	5.01E+08	3.60E+05	6.92E+05	1.28E+06	2.42E+03
|dPhi_ll_MET| < 2.0	3.94E+04	3.41E+08	3.60E+05	5.21E+05	1.07E+06	1.78E+03
HT2 ratio > 0.8	3.69E+04	2.29E+08	3.60E+05	4.04E+05	8.69E+05	1.46E+03

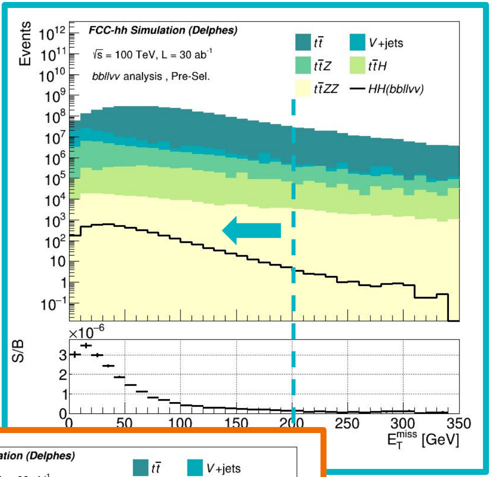
$bb\tau\tau(e\mu)$ cutflow

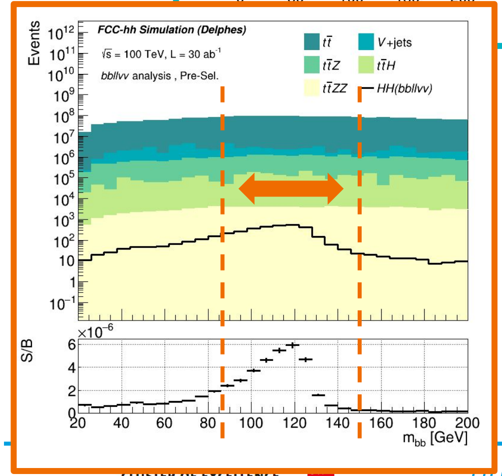
	Expected events with 30 ab-1					
Criterion	**Signal**	***ttbar***	***Z+jets***	***ttZ***	***ttH***	***ttZZ***
>= 1 OS emu-pair	2.89E+04	1.86E+10	2.03E+06	2.66E+07	2.74E+07	9.85E+04
>= 2 b-jets	2.89E+04	1.86E+10	2.03E+06	2.66E+07	2.74E+07	9.85E+04
85 < m_bb < 150 GeV	2.17E+04	4.97E+09	3.61E+05	6.05E+06	6.93E+06	1.88E+04
dR_bb < 2.0	1.89E+04	1.92E+09	3.60E+05	2.91E+06	4.05E+06	1.08E+04
15 < m_ll < 80 GeV	1.73E+04	7.29E+08	3.35E+05	9.96E+05	1.69E+06	3.18E+03
dR_ll < 2.0	1.56E+04	4.65E+08	3.35E+05	6.86E+05	1.17E+06	2.28E+03
MET > 70 GeV	1.31E+04	2.72E+08	9.55E+04	4.35E+05	8.07E+05	1.67E+03
|dPhi_ll_MET| < 1.2	1.30E+04	1.22E+08	9.55E+04	2.51E+05	5.71E+05	9.78E+02
|pT_ll + MET| > 100 GeV	1.30E+04	1.21E+08	9.55E+04	2.51E+05	5.71E+05	9.78E+02
HT2 ratio > 0.8	1.29E+04	1.13E+08	9.55E+04	2.29E+05	5.45E+05	9.59E+02

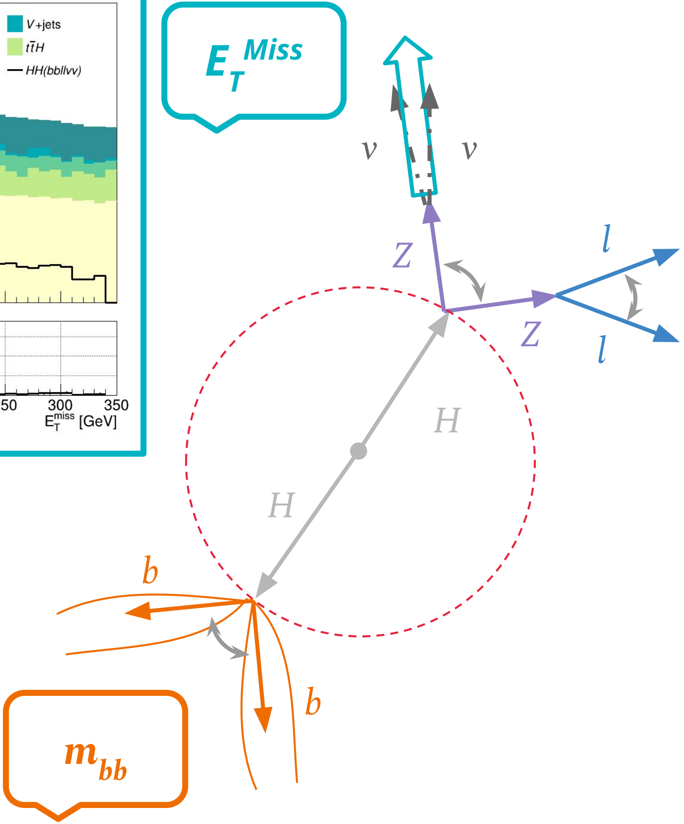
bbZZ(llvv) cutflow

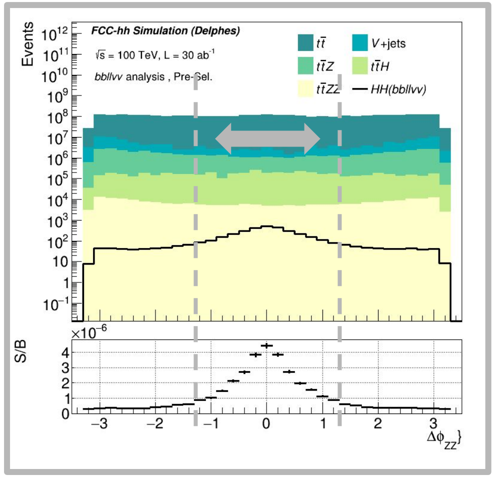
	Expected events with 30 ab-1					
Criterion	**Signal**	***ttbar***	***Z+jets***	***ttZ***	***ttH***	***ttZZ***
>= 1 DFOS lep-pair	8.10E+03	1.91E+10	2.14E+09	1.14E+08	4.24E+07	4.52E+05
>= 2 b-jets	4.05E+03	1.91E+10	9.72E+07	6.29E+07	2.89E+07	2.85E+05
81 < m_ll < 101 GeV	3.76E+03	2.22E+09	9.35E+07	4.43E+07	3.42E+06	2.28E+05
MET < 200 GeV	3.74E+03	2.09E+09	9.16E+07	4.14E+07	3.05E+06	1.86E+05
85 < m_bb < 150 GeV	2.84E+03	6.13E+08	1.60E+07	9.73E+06	7.97E+05	3.70E+04
|dPhi_ll_MET| < 1.2	2.21E+03	2.25E+08	3.33E+06	2.54E+06	3.28E+05	1.05E+04
dR_ll < 2.0	1.74E+03	6.86E+07	3.33E+06	1.63E+06	1.32E+05	7.11E+03
dR_bb < 2.0	1.60E+03	3.25E+07	2.31E+06	8.94E+05	7.44E+04	4.76E+03
dPhi_HH > 2.7	1.21E+03	7.81E+06	1.75E+06	3.76E+05	2.03E+04	1.87E+03

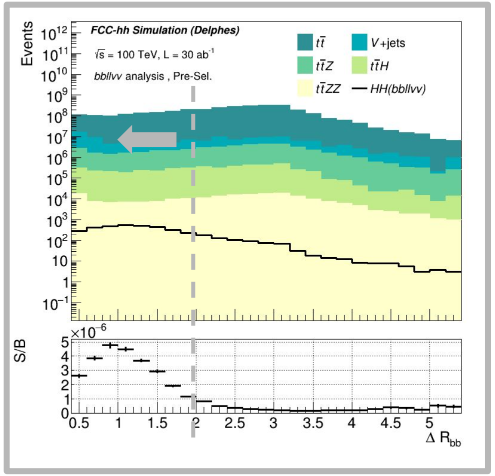
bbZZ(llvv) event kinematics & selection











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,

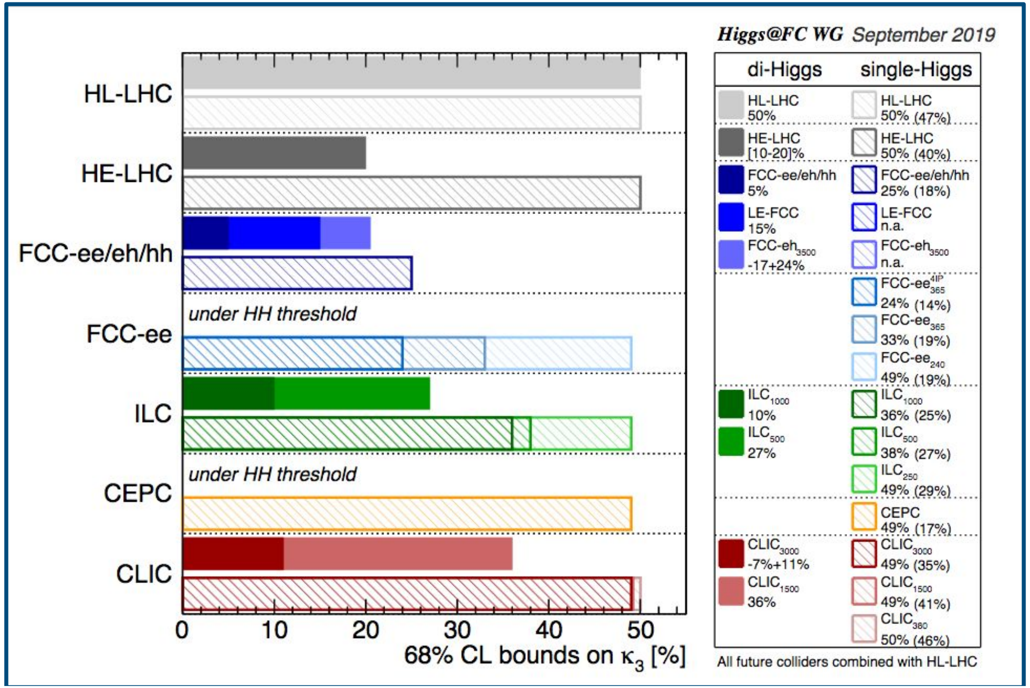
$$H_{T2} = |\mathbf{p}_T^{\text{miss}} + \mathbf{p}_T^{\ell,0} + \mathbf{p}_T^{\ell,1}| + |\mathbf{p}_T^{b,0} + \mathbf{p}_T^{b,1}|$$

H_{T2}^{R}	Ratio of H_{T2} and scalar sum of the transverse momenta of the H decay products,

$$H_{T2}^{R} = H_{T2}/(E_T^{\text{miss}} + |\mathbf{p}_T^{\ell,0}| + |\mathbf{p}_T^{\ell,1}| + |\mathbf{p}_T^{b,0}| + |\mathbf{p}_T^{b,1}|),$$

where $\mathbf{p}_T^{\ell(b),0\{1\}}$ 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