Results and plans from the FCC-hh physics performance WG

Birgit Stapf, with co-coordinators Angela Taliercio and Sarah Williams

16.01.2025 | FCC Physics Workshop | CERN

Introduction: FCC-hh running scenarios

FCC-hh: Hadron collider phase of the FCC integrated programme

CDR baseline plan was 30 ab^{-1} of pp-collision data @ 100 TeV

Main limitations: dipole magnets, synchrotron radiation and extreme levels of pile-up
→ alternative FCC-hh running scenarios

	F12 scenarios*	F14	F17	F20	*HL-LHC*
CM energy / TeV	72	84	102	120	*14*
Dipole field / T	12	14	17	20	*8.3*
Init. pile-up	580 - 2820	590	732	141	*135*
Lumi/year / fb^{-1}	950 - 2000	920	920	370	*240*

F. Zimmermann

**F12 includes 3 different scenarios for high, low lumi & low PU*

Introduction: The physics & performance working group

FCC-hh ESPP2025 Physics & Performance group started: Common platform for all ongoing FCC-hh projection studies

September 2024

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Main goals for FCC-hh ESPP summary report:

- Key Higgs benchmarks for other energies
- Ultimate precision on Higgs self-coupling
- Solidify assumptions on detector performance
- Unexplored channels/new physics cases

Introduction: The physics & performance working group

[FCC-hh ESPP2025 Physics & Performance group](#) started:
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- Key Higgs benchmarks for other energies
- Ultimate precision on Higgs self-coupling
- Solidify assumptions on detector performance
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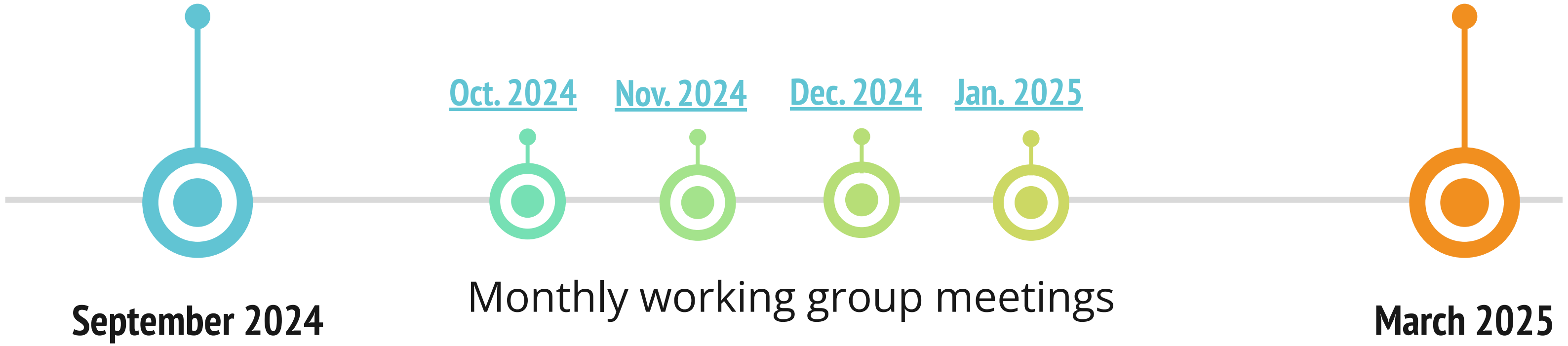
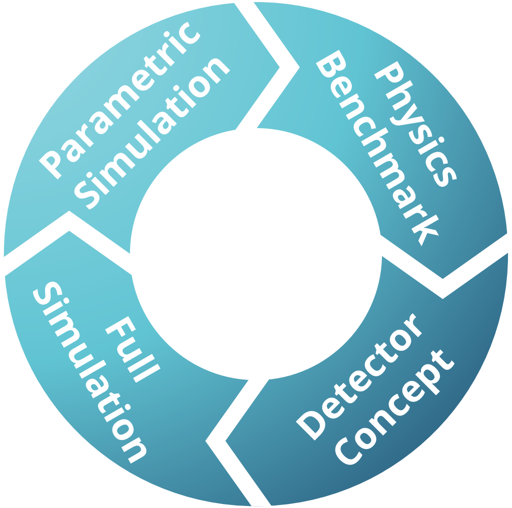


FCC-hh projection study workflow



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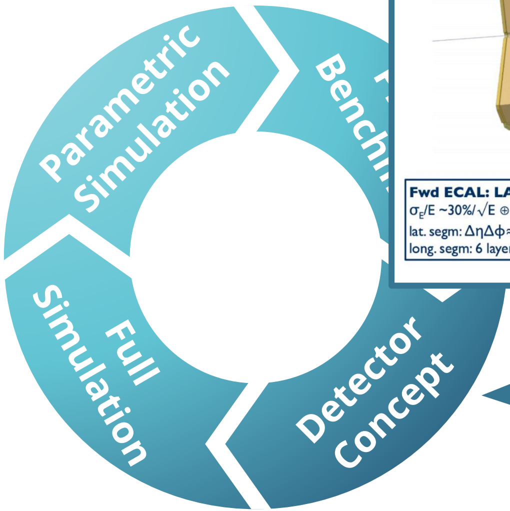
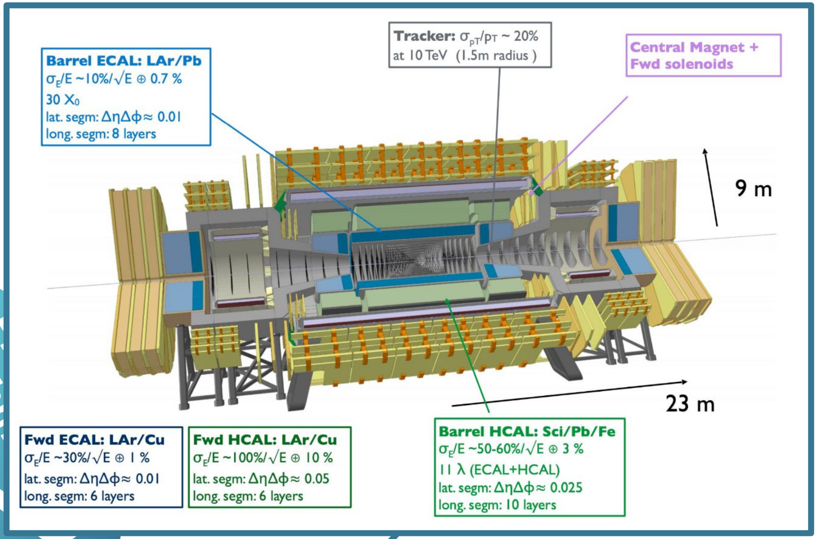


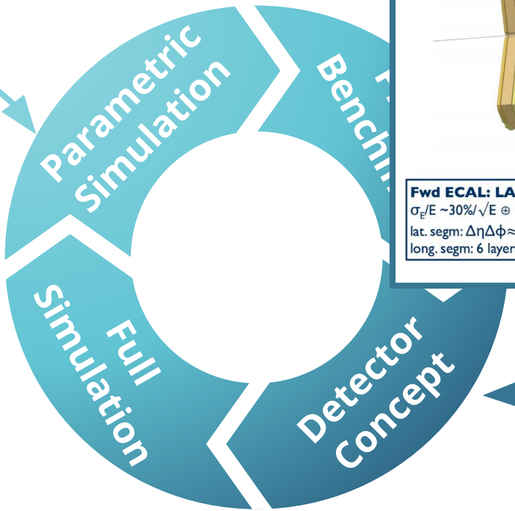


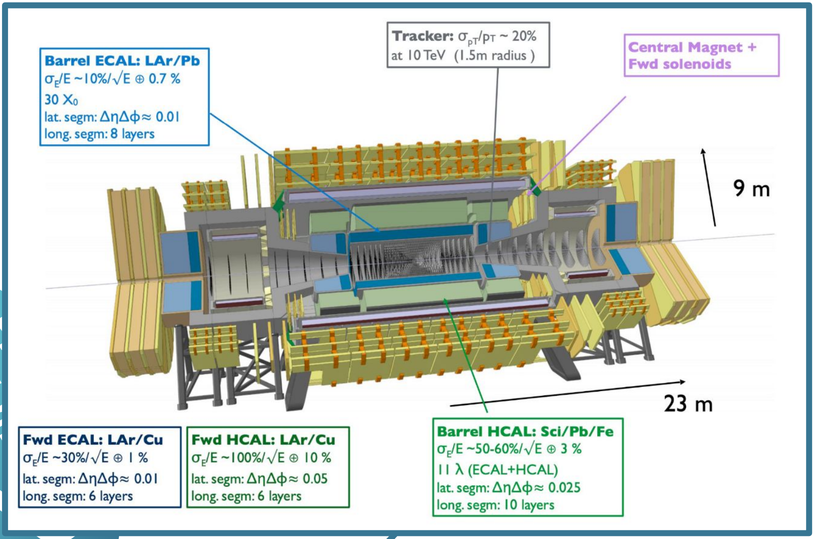
Reference detector design from the CDR

CERN-ACC-2018-0058

FCC-hh projection study workflow

DELPHES
fast simulation





Reference detector design from the CDR

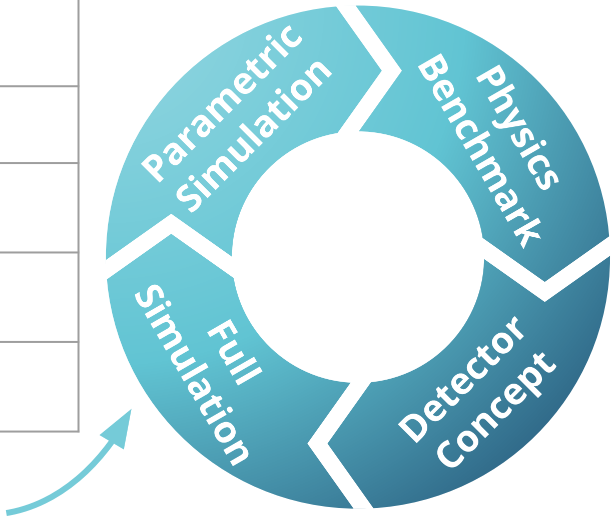
CERN-ACC-2018-0058

Efficiencies & resolutions as functions of p_T and η

- Official FCC-hh scenarios
- Rely on common software stack: key4hep
- Note: No direct pile-up overlay, assume LHC levels in the parametrizations

Overview of topics

Covered in this presentation
Update of 2019 study: Reoptimized and/or at alternate energies
Completely new study
💡 - Idea or initial exploration
⚙️ - Ongoing work
⭐ - Advanced ongoing work



Performance studies

- ⭐ ***Flavour tagging with transformer architecture***
- 💡 Full simulation tracking with timing e.g. ACTS
- 💡 Pile-up impact studies
- ....

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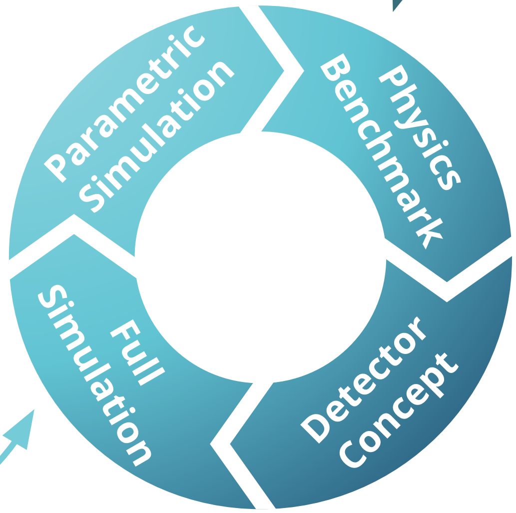

Performance studies

- ⭐ ***Flavour tagging with transformer architecture***
- 💡 Full simulation tracking with timing e.g. ACTS
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- ....

Physics studies

- Higgs couplings in rare decays
  - ⚙️ ***Ratio $H(\mu\mu)/H(4\mu)$***
- Top-Yukawa coupling
  - 💡 Ratio $\bar{t}tH(\bar{b}b)/\bar{t}tZ(\bar{b}b)$
  - 💡 $\bar{t}tH(\gamma\gamma)$ channel
- Higgs self-coupling
  - ⭐ ***$\bar{b}b\gamma\gamma$ channel***
  - ⚙️ ***$\bar{b}b\tau\tau$ channel***
  - ⭐ $\bar{b}bll{+}E_T^{miss}$ channel
- ⚙️ HVV CPV couplings
- 💡 Higgs width measurement
- 💡 ***Differential cross-sections as input to global fits***
- ....

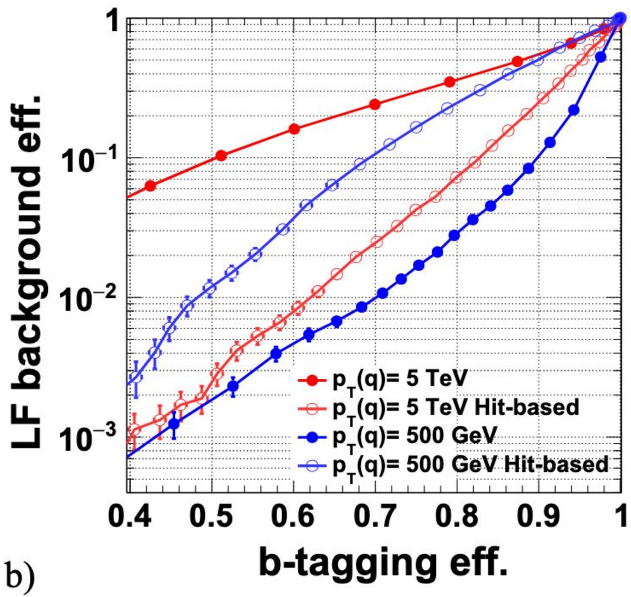
Jet Flavour Tagging with transformer architecture

Wei Sheng Lai, Nikita Pond, Tim Scanlon, Sebastien Rettie, Sam Van Stroud

Motivation for the study:

- Current FCC-hh Delphes scenarios assume flavour tagging efficiencies (at least as) good as latest CMS performance with ParticleNET
  - Can we actually reach this?

- CDR included initial studies into flavour tagging efficiencies with the FCC-hh tracker layout relying on calculation of the track covariance matrix

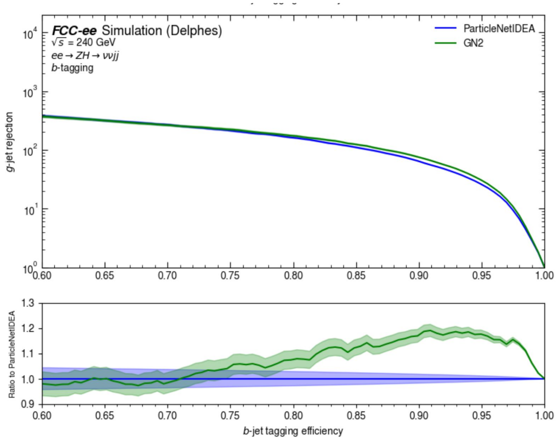


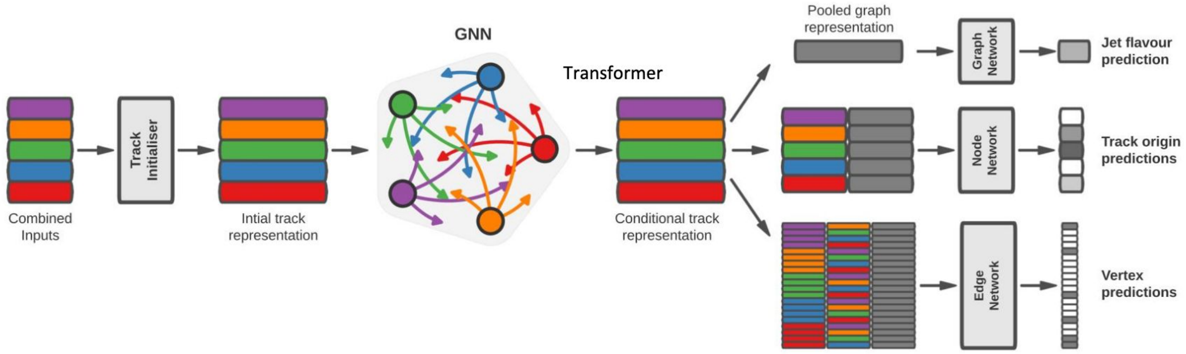
b)

Jet Flavour Tagging with transformer architecture

Wei Sheng Lai, Nikita Pond, Tim Scanlon, Sebastien Rettie, Sam Van Stroud

- Performance study of transformer model (GN2), with Delphes TrackCovariance module implementing tracker layout
  - Validated against FCC-ee & CDR



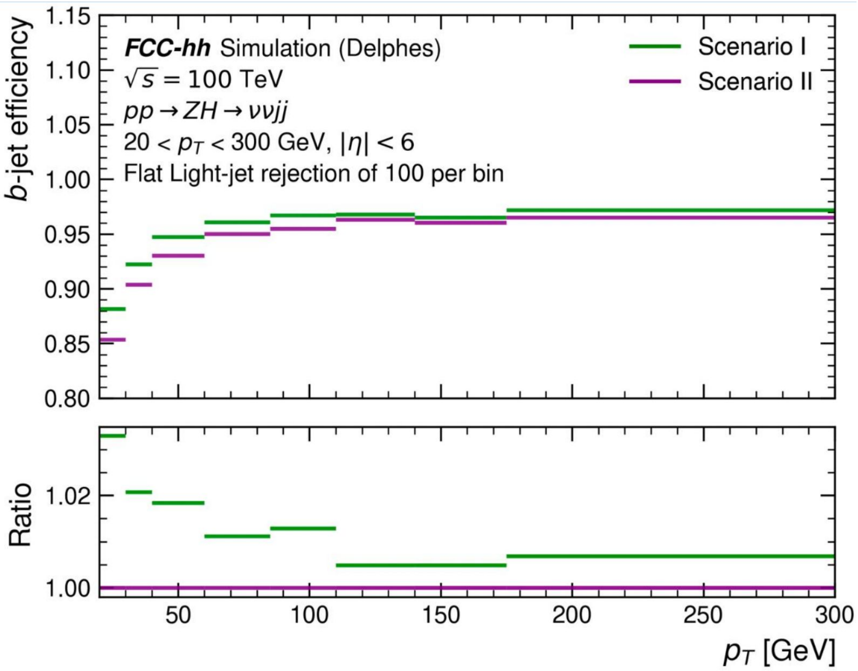


Jet Flavour Tagging with transformer architecture

Wei Sheng Lai, Nikita Pond, Tim Scanlon, Sebastien Rettie, Sam Van Stroud

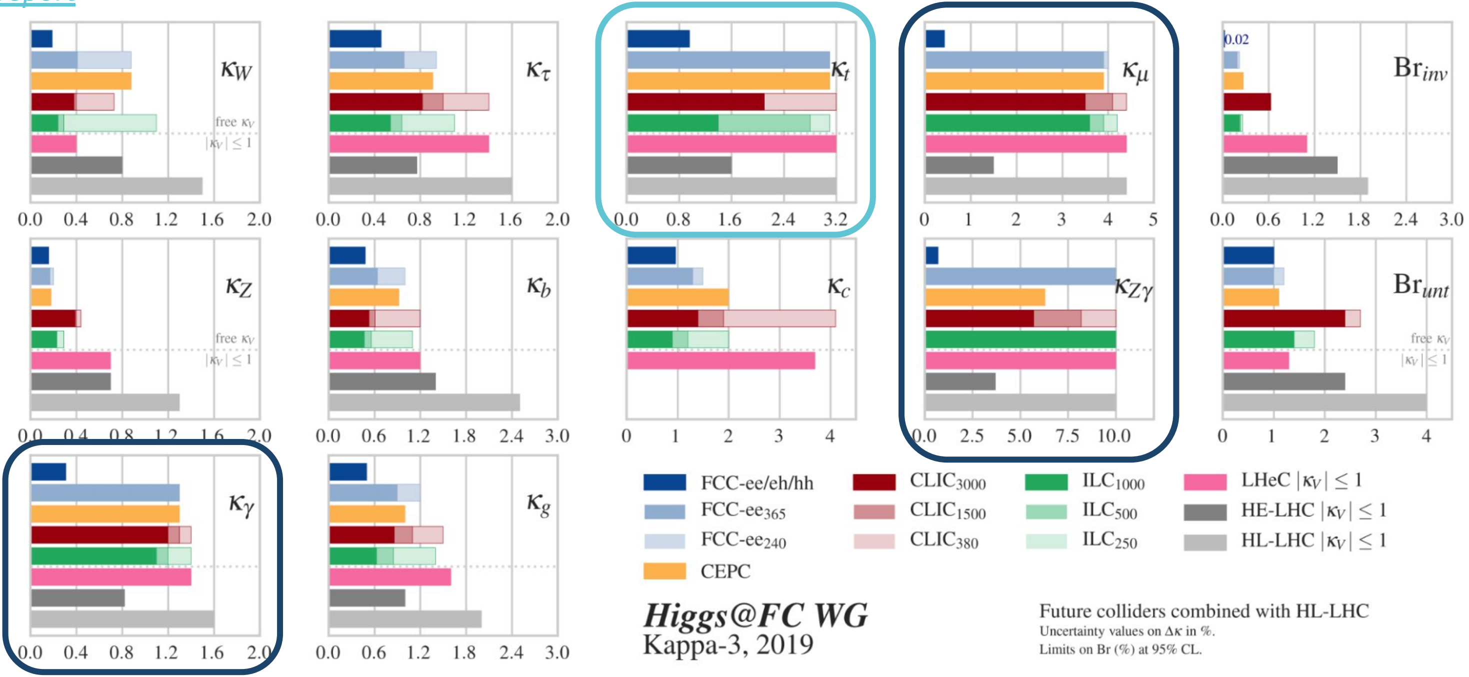
- Performance study of transformer model (GN2), with Delphes TrackCovariance module implementing tracker layout
  - Validated against FCC-ee & CDR
- Find b-tagging efficiencies > 95% (70%) with 1% mis-tagging at rates in moderate (high) pT range, maintained up to $|\eta| < 5$

- Next steps: Further study impact of pile-up? Connect with tracking with timing studies?



Higgs couplings precision measurements

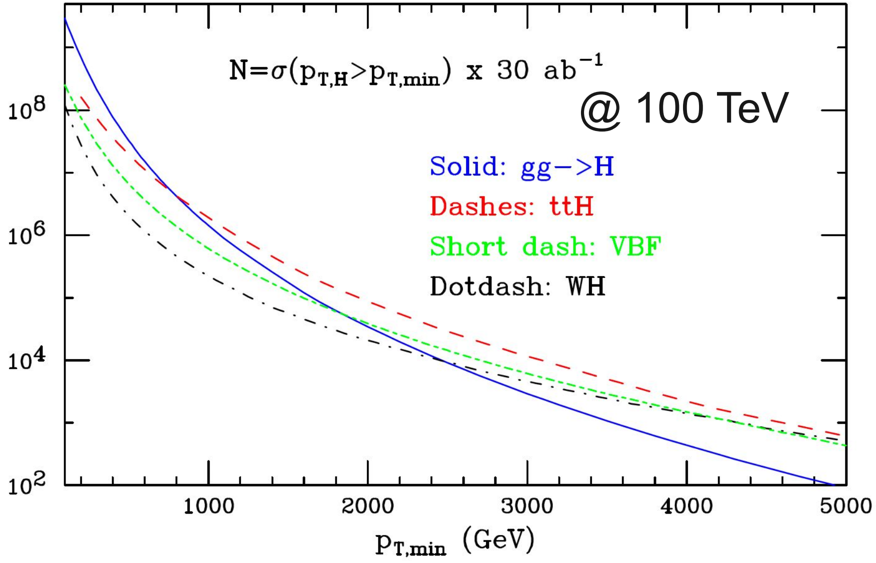
Granada report



Significant precision improvements in couplings measurements in rare decay modes that remain (statistically) limited at **FCC-ee**/**HL-LHC**, or are not directly accessible at **FCC-ee**

Higgs couplings: Analysis strategy

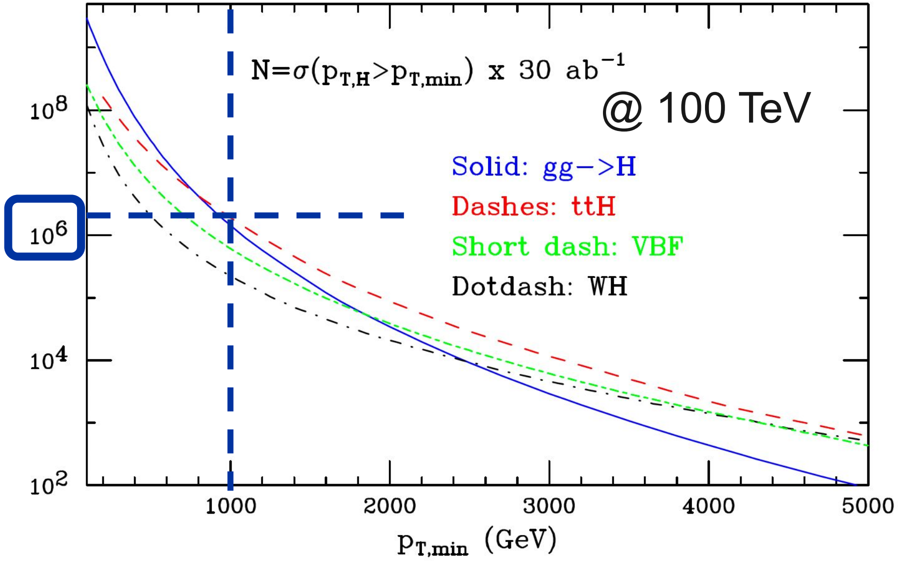
[CERN-ACC-2018-0045]



Systematic uncertainties will dominate

Higgs couplings: Analysis strategy

CERN-ACC-2018-0045



Systematic uncertainties will dominate

But: Large statistics even at high p_T ...

Higgs couplings: Analysis strategy

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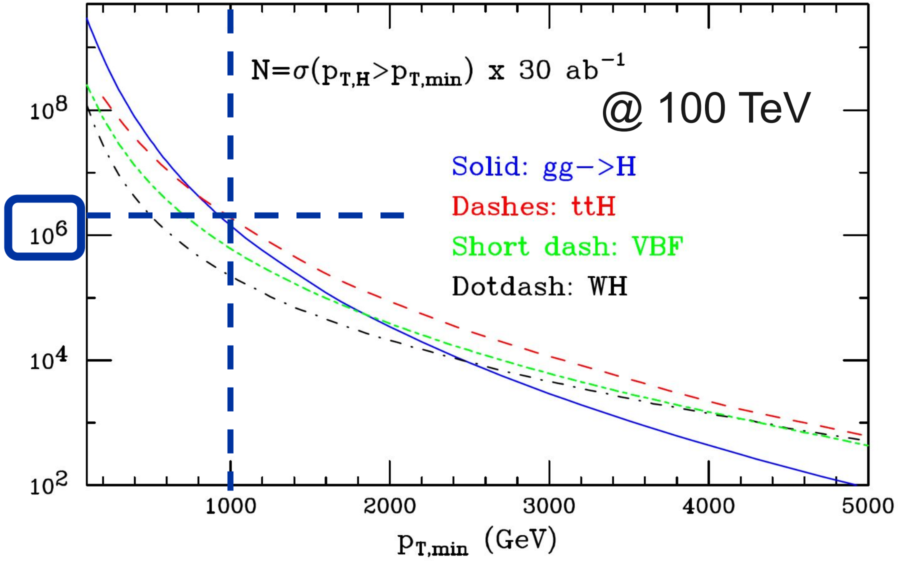
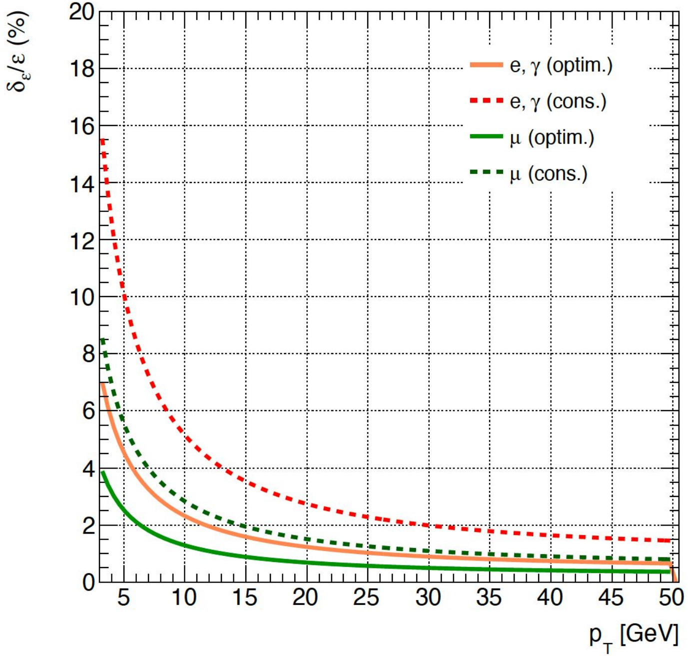




Systematic uncertainties will dominate
But: Large statistics even at high p_T …

… where experimental systematic uncertainties on efficiencies are smaller

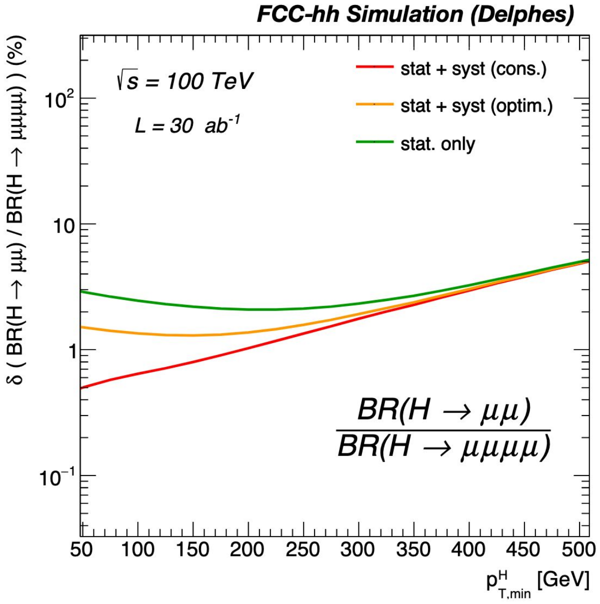
Higgs couplings: Previous results

[Michelangelo Mangano at last year's FCC physics workshop]

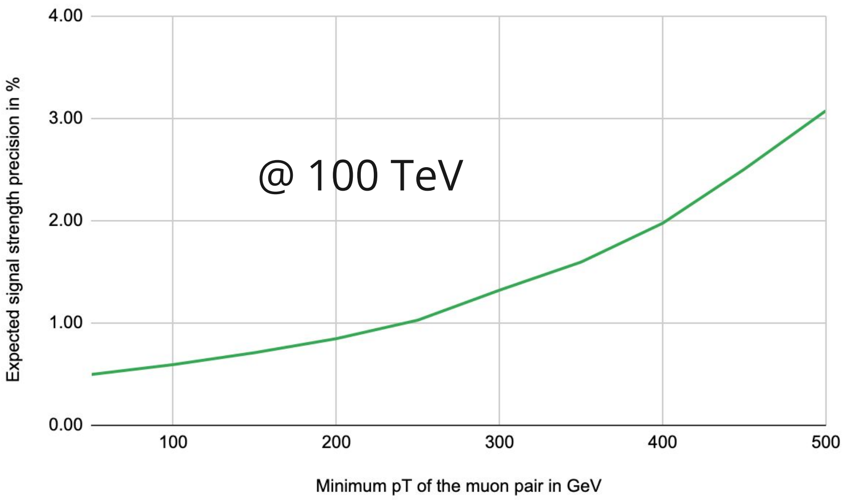
- Additionally exploit ratio with $BR(H\rightarrow ZZ^{*}\rightarrow 4l)$
  - Further cancel systematics
  - Absolute coupling with FCC-ee $BR(H\rightarrow ZZ^{*})$ result
- Rescaling statistical uncertainties to other energies:
  - With ± 20 TeV : $\boldsymbol{\sigma}_{prod}$ ± 30%

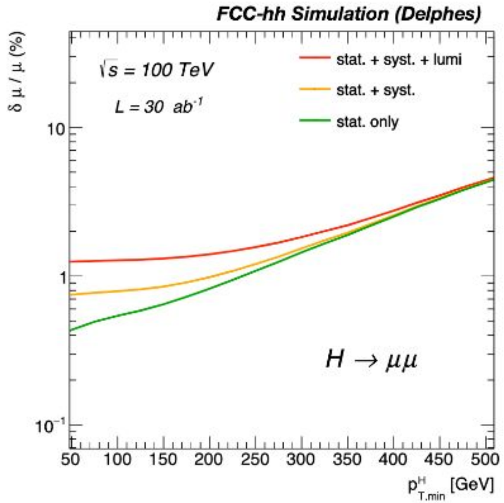
	Precision in %		
Coupling	80 TeV	100 TeV	120 TeV
$\boldsymbol{\delta}\, g_{H\gamma\gamma}/\, g_{H\gamma\gamma}$	0.4	0.4	0.4
$\boldsymbol{\delta}\, g_{H\mu\mu}/\, g_{H\mu\mu}$	0.7	0.65	0.6
$\boldsymbol{\delta}\, g_{HZ\gamma}/\, g_{HZ\gamma}$	1.0	0.9	0.8

BR ratio precision



Higgs couplings: Status of $H(\mu\mu)$





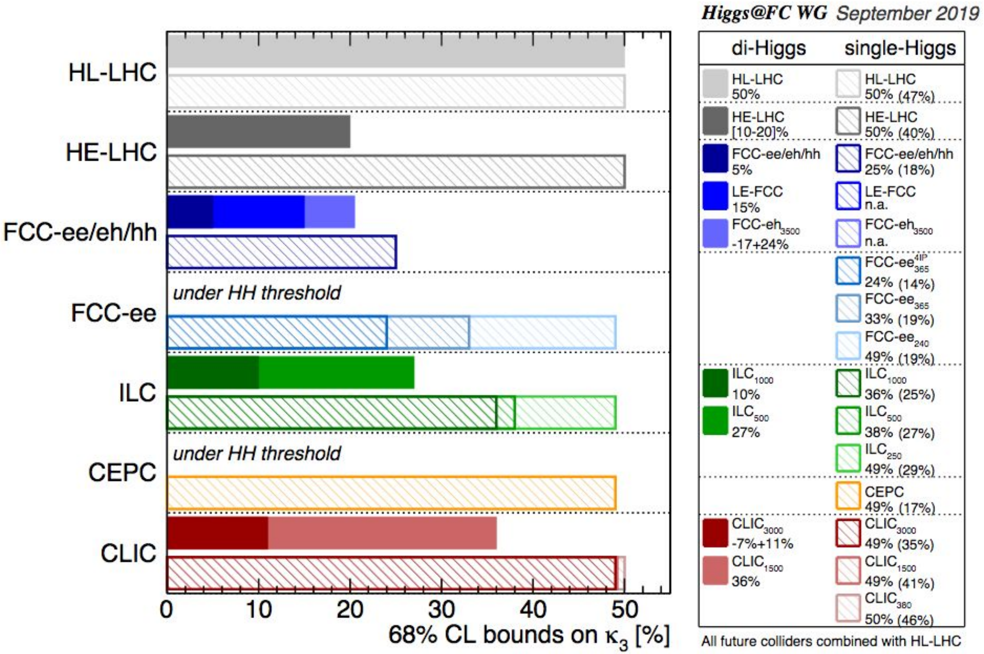
- Reproduced signal strength precision scan @ 100 TeV, with statistical uncertainties only
    - Cut & count in 1 GeV bin around m_H
    - Backgrounds only $\mu\mu$ continuum

Next steps

- Validation of new samples & first results at other energies (72, 80, 120 TeV) ongoing
- Integrate systematic uncertainties
- Determine ratio with $H(4\mu)$
- Move to template fit of $m_{\mu\mu}$
- Missing backgrounds?

Higgs self-coupling precision measurements

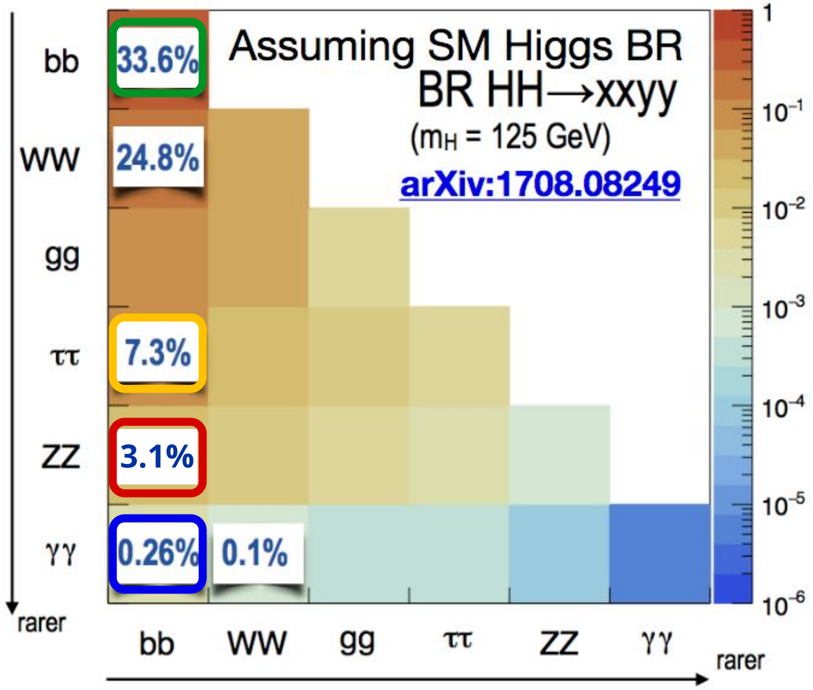
Granada report

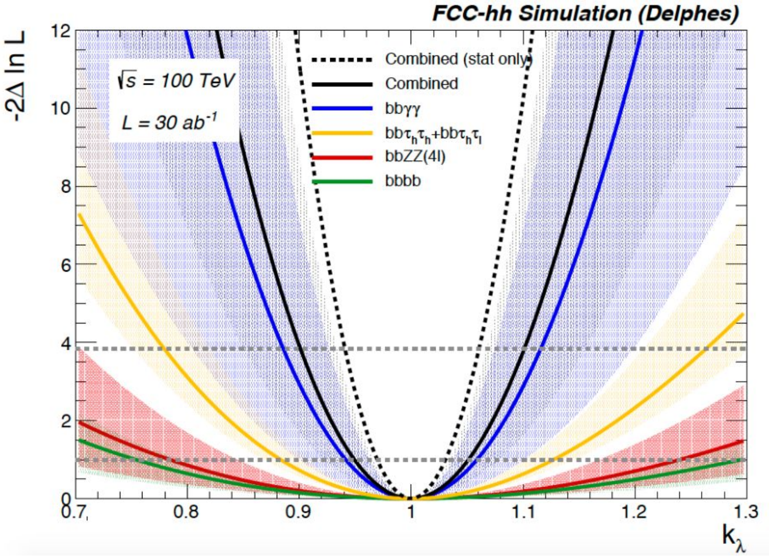


Large dataset & increased cross-section at baseline CDR FCC-hh offers %-level κ_λ precision

Higgs self-coupling precision measurements

CERN-TH-2020-052

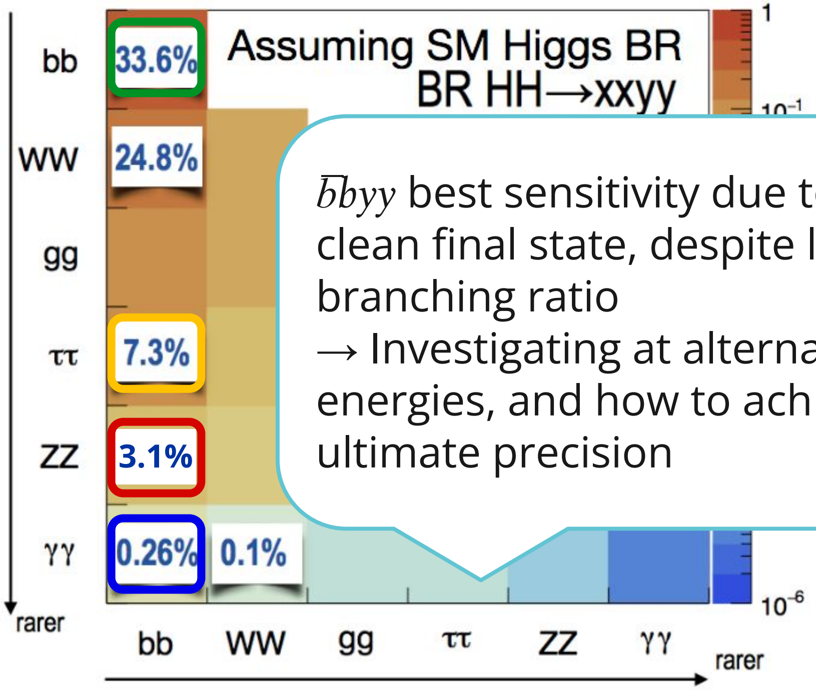




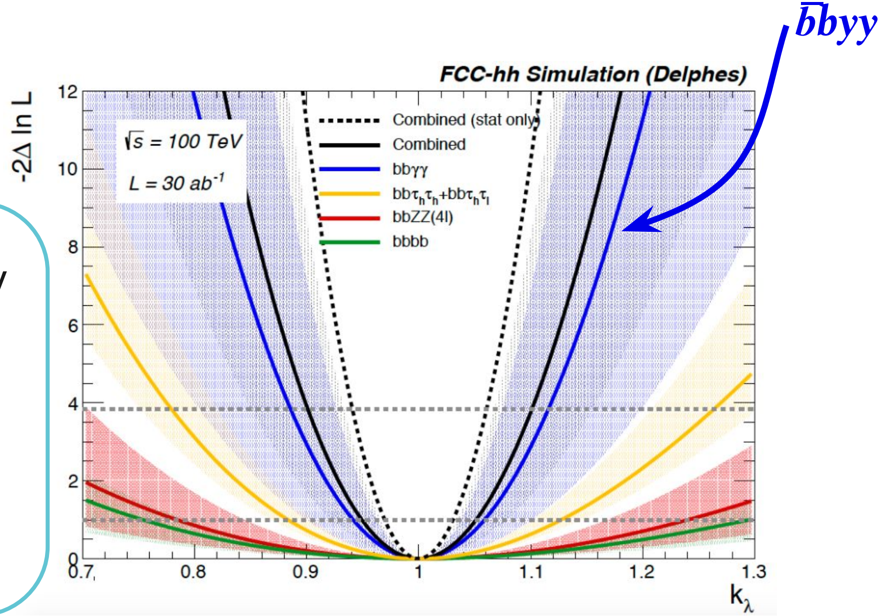
	Combined precision
$\delta\kappa_\lambda$ (68% CL)	3.0% - 7.8%

Higgs self-coupling precision measurements

CERN-TH-2020-052



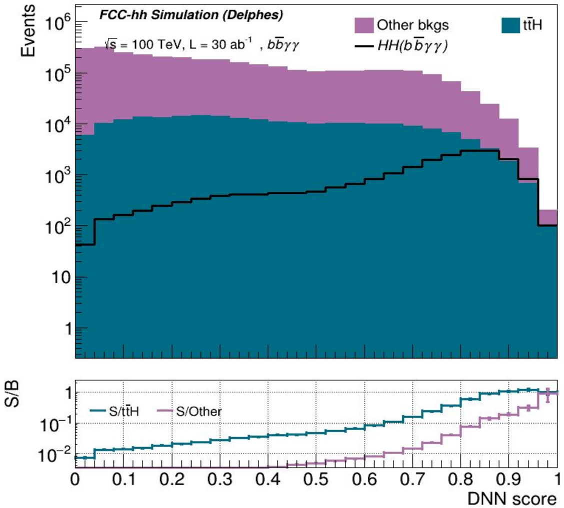
$\bar{b}byy$ best sensitivity due to very clean final state, despite low branching ratio
→ Investigating at alternative energies, and how to achieve ultimate precision



Re-optimized $\bar{b}b\gamma\gamma$ analysis strategy

Angela Taliercio, Paola Mastrapasqua, Birgit Stapf at FCC-hh ESPP meeting

DNN categorization (example)



- DNNs suppress backgrounds from single Higgs (esp. ttH) and non-resonant QCD (**γγ**+jets and **γ**+jets)

Re-optimized $b\bar{b}\gamma\gamma$ analysis strategy

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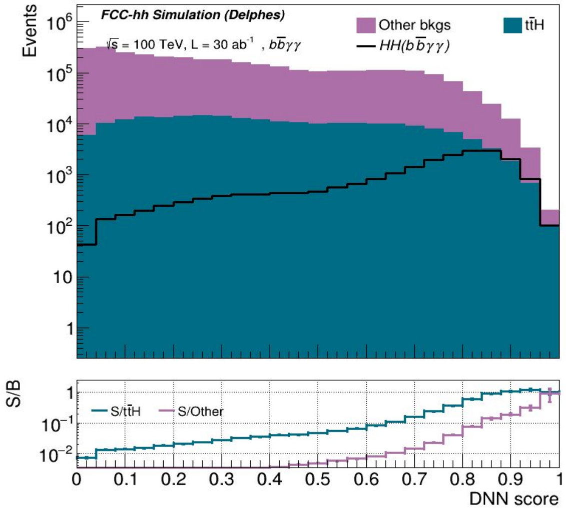
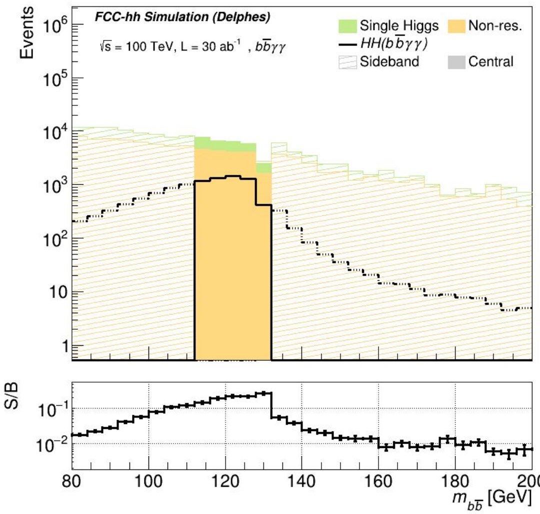
DNN categorization (example)

Bin in $m_{b\bar{b}}$





- DNNs suppress backgrounds from single Higgs (esp. ttH) and non-resonant QCD (**γγ**+jets and **γ**+jets)
- Most sensitive region (=highest signal/background ratio) near the Higgs mass

Re-optimized $b\bar{b}\gamma\gamma$ analysis strategy

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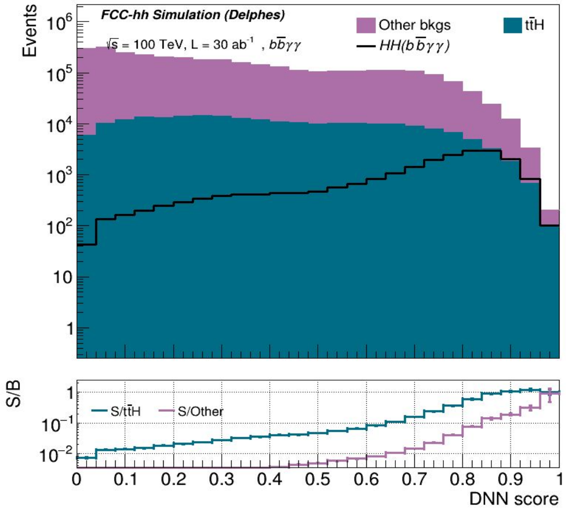

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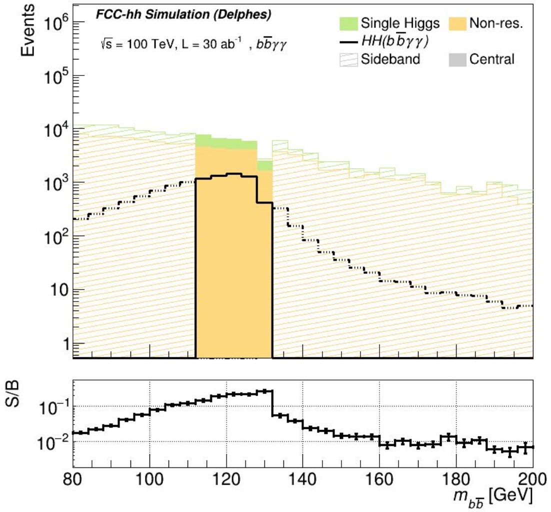
Bin in $m_{b\bar{b}}$

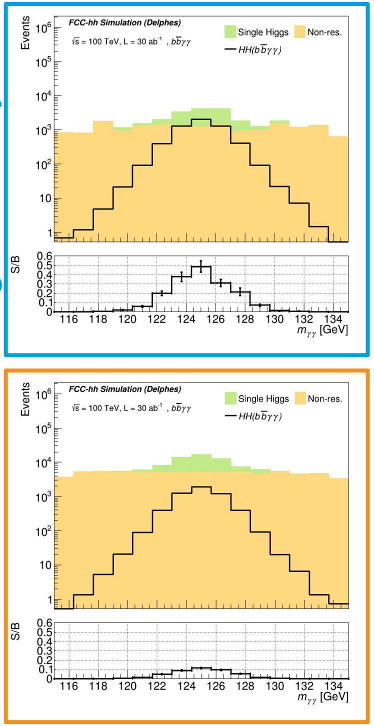


- Most sensitive region (=highest signal/background ratio) near the Higgs mass

Fit $m_{\gamma\gamma}$

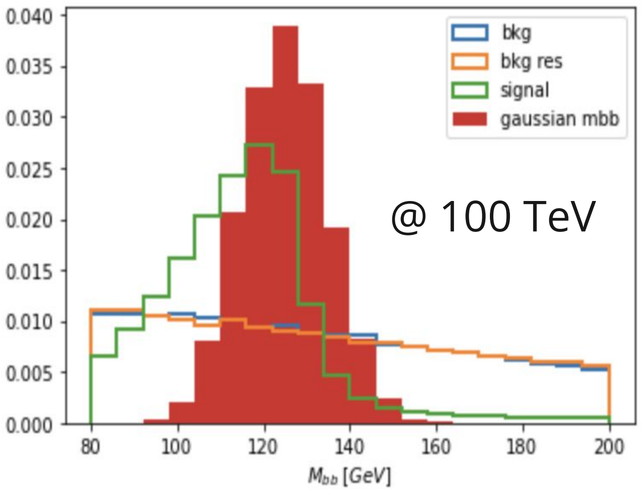
High sensitivity bin

Less sensitive bin



Updated $\bar{b}b\gamma\gamma$ analysis results

Angela Taliercio, Paola Mastrapasqua, Birgit Stapf at FCC-hh ESPP meeting



	m_{bb} resolution			
	Nominal	10 GeV	5 GeV	3 GeV
$\delta\kappa_\lambda$ (68% CL - stat. only)	3.2%	2.5%	2.0%	1.8%

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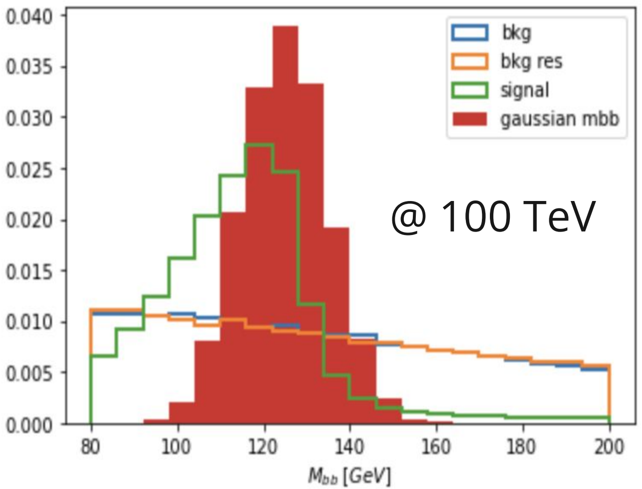

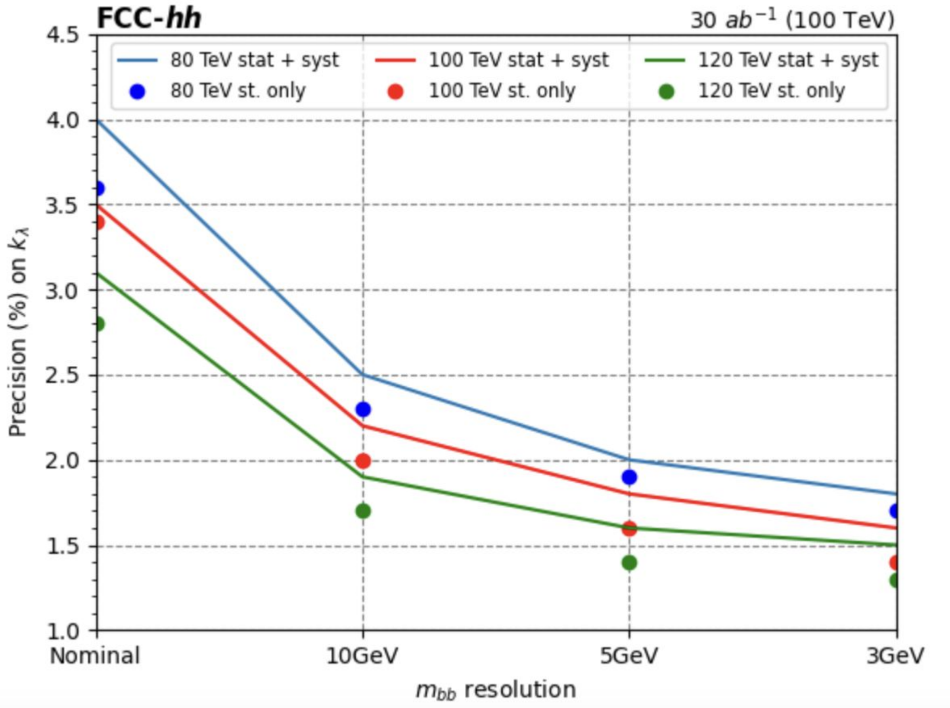

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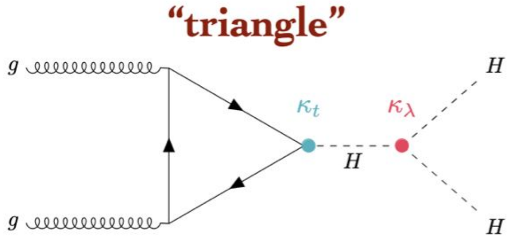
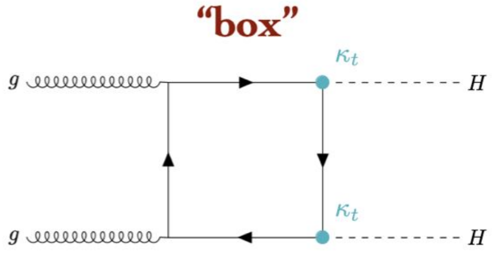
Impact of m_{bb} resolution is critical

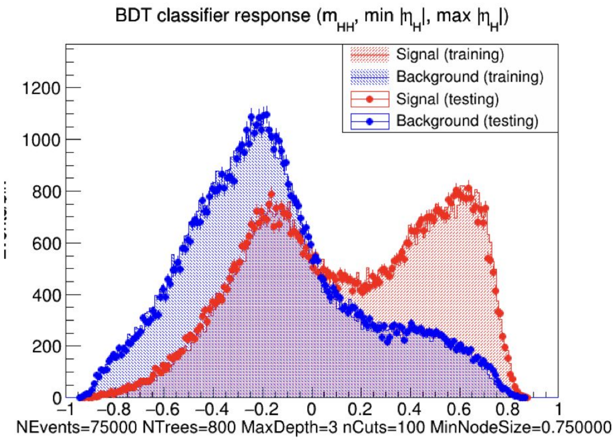
Next step for $\bar{b}b\gamma\gamma$ analysis: Separating triangle vs box diagrams

Bastien Voirin, Claude Charlot, [Angela Taliercio, Paola Mastrapasqua, Birgit Stapf]



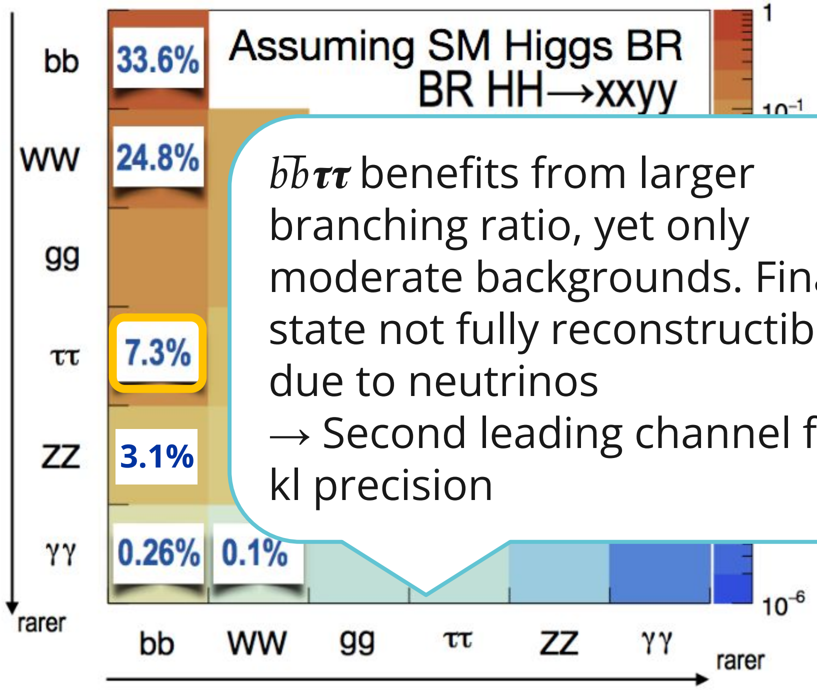


- Dominant mode of gluon-gluon fusion Higgs pair production has two (interfering) diagrams
- Only the triangle diagram contribution contains a Higgs-self coupling vertex
- Ongoing work to apply Bastien Voirin's BDT classifier which separates the triangle from the box contribution based on the Higgs' kinematics to the bbyy analysis to further boost sensitivity

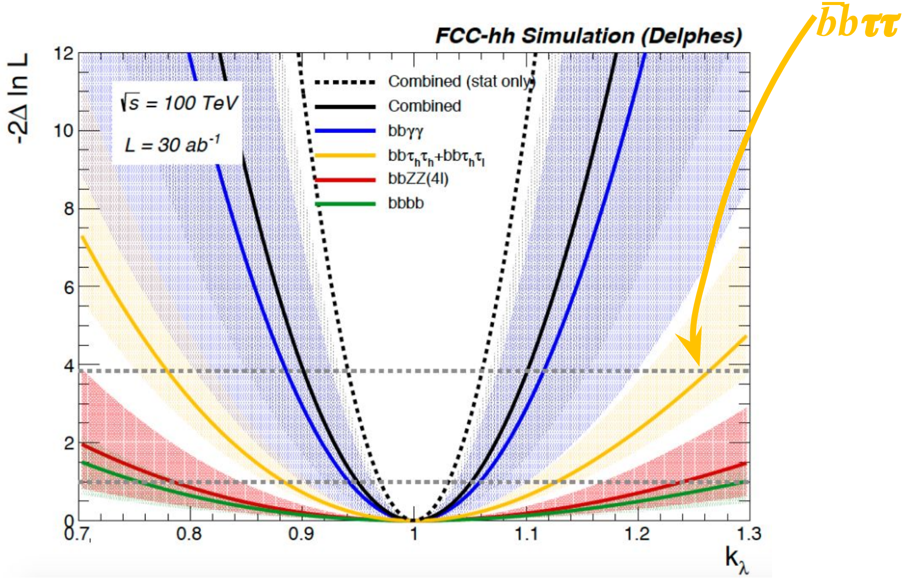


$b\bar{b}\tau\tau$ analysis with advanced ML techniques @ 100 TeV

Sam Valentine, Lennox Wood, Monica D'Onofrio, Jordy Degens, Carl Gwilliam, Cristiano Sebastiani



$b\bar{b}\tau\tau$ benefits from larger branching ratio, yet only moderate backgrounds. Final state not fully reconstructible due to neutrinos
→ Second leading channel for kl precision



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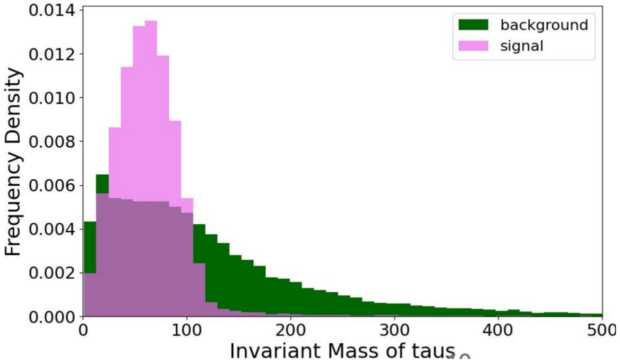
Input distributions (example)



- Analysis of $b\bar{b}\tau_{lep}\tau_{had}$ and $b\bar{b}\tau_{had}\tau_{had}$ signal events
- **Backgrounds** from top and single Higgs production, as well QCD+EW continuum (Drell-Yan Z+jets)

$b\bar{b}\tau\tau$ analysis with advanced ML techniques @ 100 TeV

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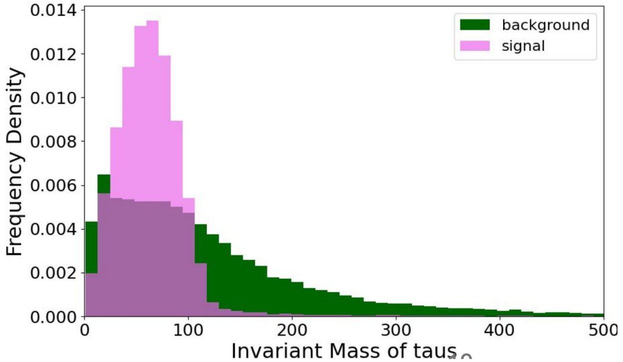
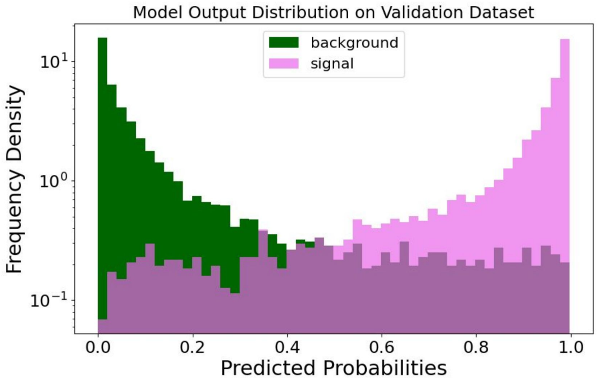
Input distributions (example)

GNN performance





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- **Backgrounds** from top and single Higgs production, as well QCD+EW continuum (Drell-Yan Z+jets)

- Best GNN performance with high-level variables of $b\bar{b}$ and $\tau\tau$ systems (inv. masses, radial distances, E_T^{miss} centrality)
- Small benefit with constraints from di-Higgs system

$\bar{b}b\tau\tau$ analysis with advanced ML techniques @ 100 TeV

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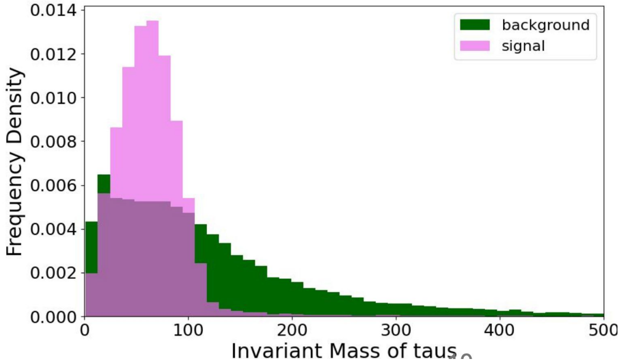
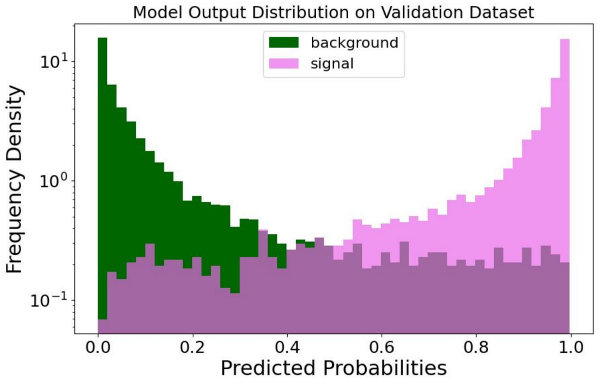
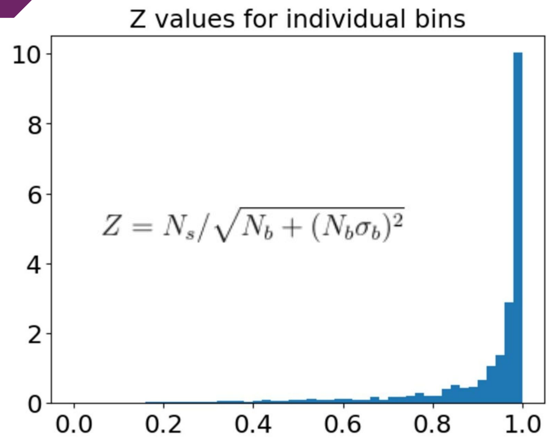


GNN performance



Sensitivity



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- **Backgrounds** from top and single Higgs production, as well QCD+EW continuum (Drell-Yan Z+jets)

- Best GNN performance with high-level variables of $\bar{b}b$ and $\tau\tau$ systems (inv. masses, radial distances, E_T^{miss} centrality)
- Small benefit with constraints from di-Higgs system

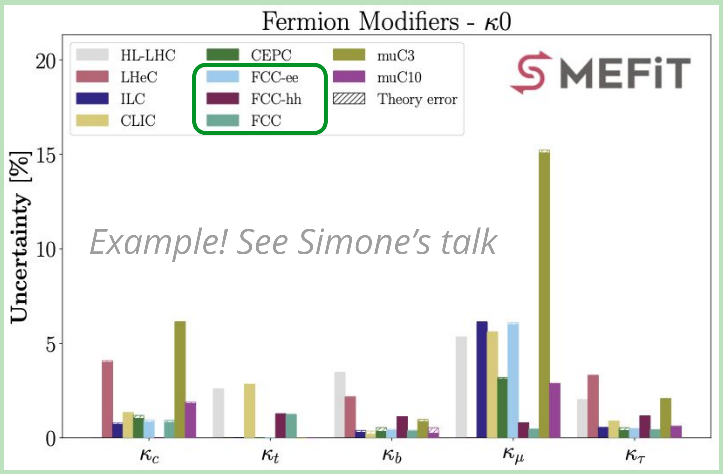
- First estimate of significance binned in GNN output shows improvement of ~ factor 2 over previous BDT analysis

Outlook: Towards global fits with updated FCC-hh projections

Juan Rojo, Simone Tentori, Jorge de Blas

"LO"

κ-framework fits for alternative FCC-hh running scenarios & combinations of Future Colliders



- Required experimental inputs: updated incl. Higgs signal strength measurements @ 72, 80 (84)*, 100, 120 TeV

Outlook: Towards global fits with updated FCC-hh projections

Juan Rojo, Simone Tentori, Jorge de Blas

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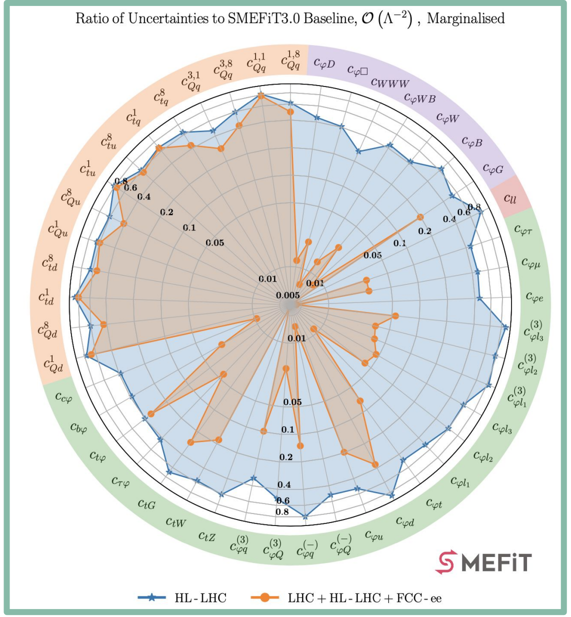
"NLO"

FCC-hh interpretations in global SMEFT fits with inclusive signal strengths



- Required experimental inputs: updated incl. Higgs signal strength measurements @ 72, 80 (84)*, 100, 120 TeV
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κ-framework fits for alternative FCC-hh running scenarios & combinations of Future Colliders

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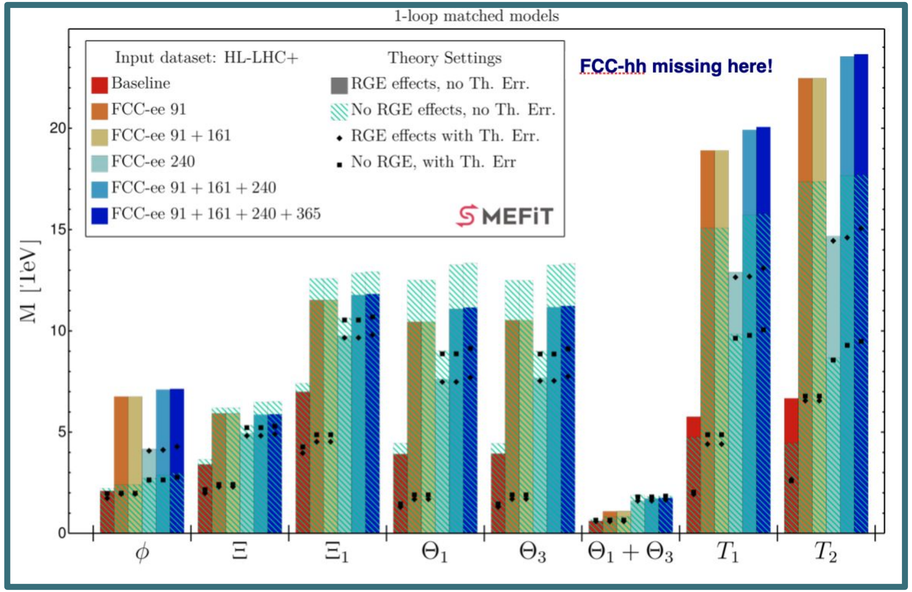
FCC-hh interpretations in global SMEFT fits with inclusive signal strengths

"NNLO"

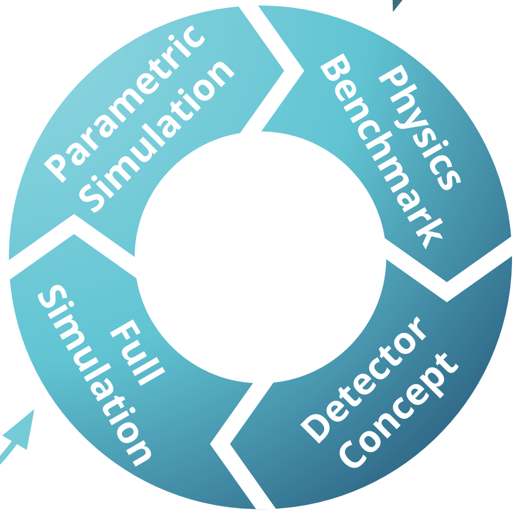
Ultimate goal: Global SMEFT fit with differential distributions from FCC-hh



- Required experimental inputs: differential distributions for Higgs, top, diboson, Drell-Yan etc. observables, and matching to UV models, with systematic uncertainties
- Required theory input: Repetition of HL-LHC EFT calculations for the FCC-hh energy scenarios

Summary

Covered in this presentation
Update of 2019 study: Reoptimized and/or at alternate energies
Completely new study
💡 - Idea or initial exploration
⚙️ - Ongoing work
⭐ - Advanced ongoing work



Performance studies

- ⭐ ***Flavour tagging with transformer architecture***
- 💡 Full simulation tracking with timing e.g. ACTS
- 💡 Pile-up impact studies
- ....

Physics studies

- Higgs couplings in rare decays
  - ⚙️ ***Ratio*** $\boldsymbol{H(\mu\mu)/H(4\mu)}$
- Top-Yukawa coupling
  - 💡 Ratio $\bar{t}tH(\bar{b}b)/\bar{t}tZ(\bar{b}b)$
  - 💡 $\bar{t}tH(\gamma\gamma)$ channel
- Higgs self-coupling
  - ⭐ $\boldsymbol{\bar{b}b\gamma\gamma}$ ***channel***
  - ⚙️ $\boldsymbol{\bar{b}b\tau\tau}$ ***channel***
  - ⭐ $\bar{b}bll+E_T^{miss}$ channel
- ⚙️ HVV CPV couplings
- 💡 Higgs width measurement
- 💡 ***Differential cross-sections as input to global fits***
- ....

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Physics studies

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  - 💡 $t\bar{t}H(\gamma\gamma)$ channel
- ggs self-coupling
  - ⭐ ***$b\bar{b}\gamma\gamma$ channel***
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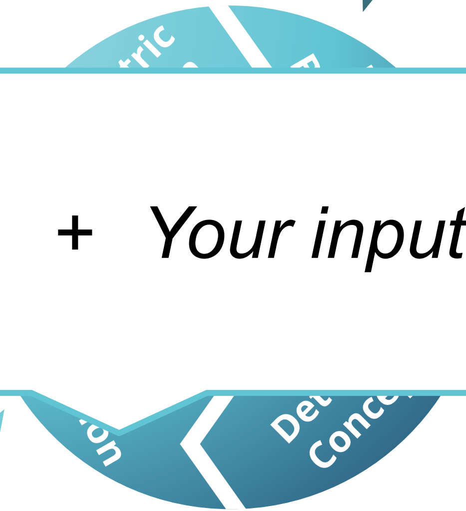


+ *Your input!*

Performance studies

- ⭐ ***Flavour tagging with transformer architecture***
- 💡 Full simulation tracking with timing e.g. ACTS
- 💡 Pile-up impact studies
- ....

Organisation, resources & links

If you are interested, join our FCC-hh physics & performance group!

- Monthly (zoom) meetings Thursday's at 4PM (CERN time)
    - Might increase frequency, call for presentations next week
    - Mailing lists: *fcc-ped-hh-physicsperformance-espp25*
    - Mattermost: FCC-hh ESPP 2025 P&P discussion
- Also monthly general meetings for FCC-hh ESPP2025 input
    - Mailing list: *fcc-ped-hh-espp25*

Resources available on common software frameworks and tools

- FCC-hh P&P working group documentation page
- Hands-on tutorial during first WG meeting *(recording available!)*
- Database of FCC-hh samples

Organisation, resources & links

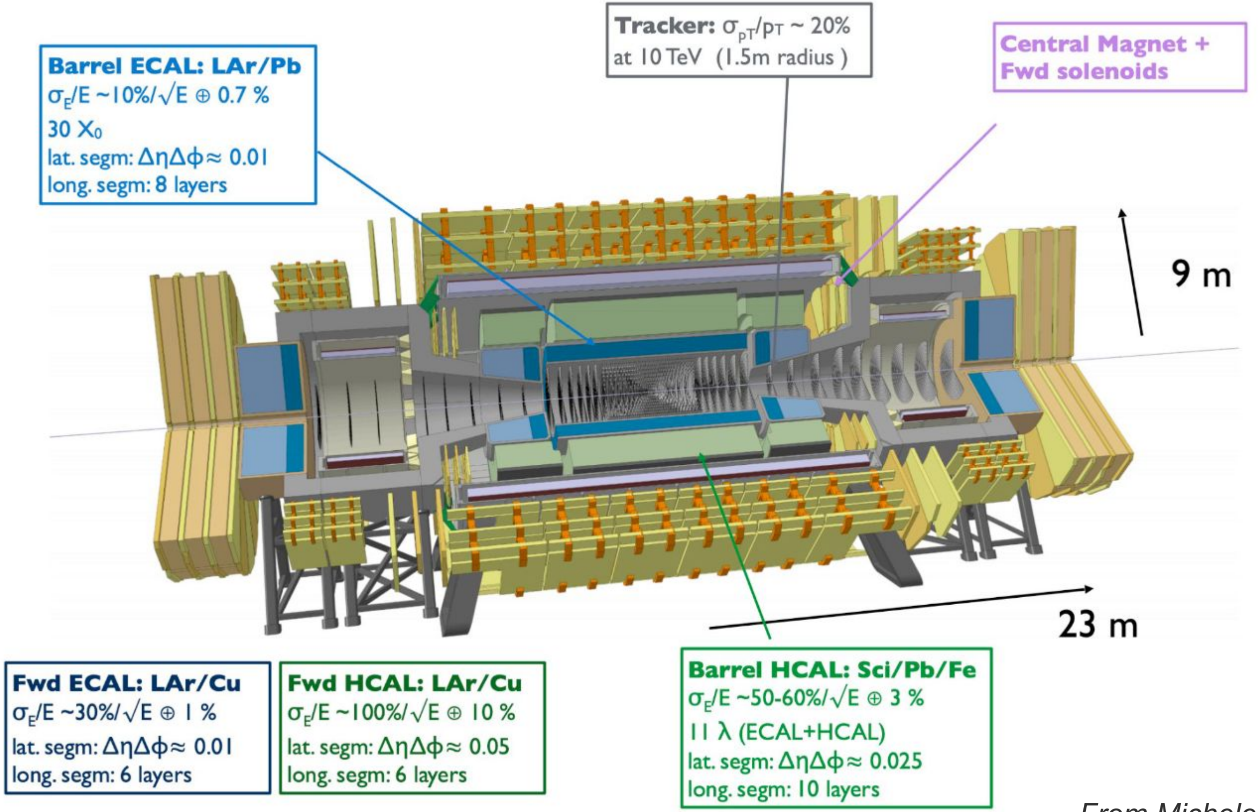
Further references on physics studies:

- Studies on sensitivity to HVV CPV couplings using CP-odd observables and ML techniques at FCC-hh (and FCC-ee)
- Higgs Self Couplings Measurements at Future proton-proton Colliders: a Snowmass White Paper

References from 2019 studies *(results are still relevant!)*

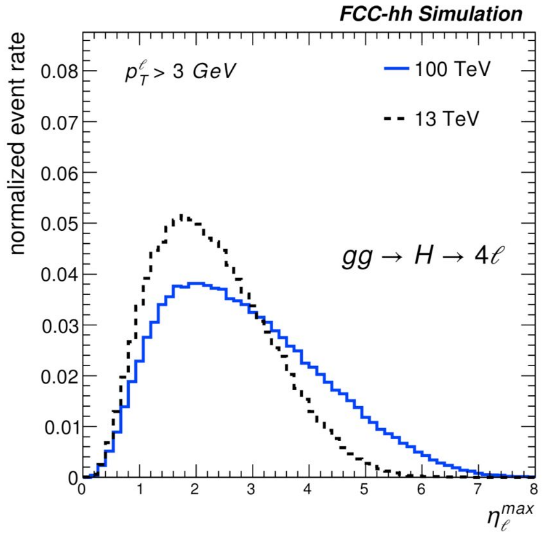
- Heavy resonances at energy-frontier hadron colliders
- Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV p–p collider
- hh + Jet production at 100 TeV
- Higgs Boson studies at future particle colliders
- Higgs measurements at FCC-hh

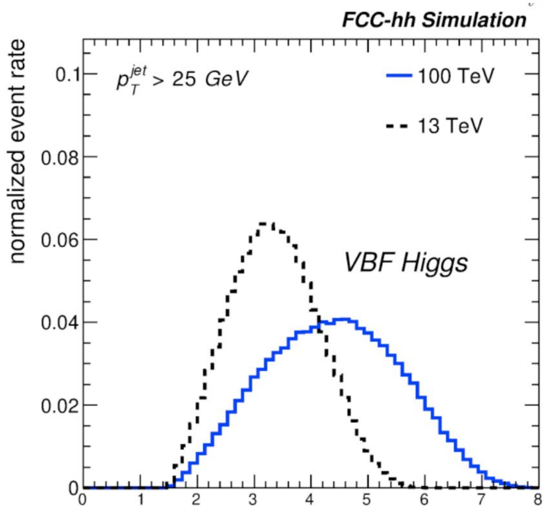
FCC-hh baseline detector concept



From Michele Selvaggi

FCC-hh baseline detector concept





SM physics more forward at 100 TeV
→ Precision spectroscopy and calorimetry up to $|\eta| < 4$
→ Tracking and calorimetry up to $|\eta| < 6$

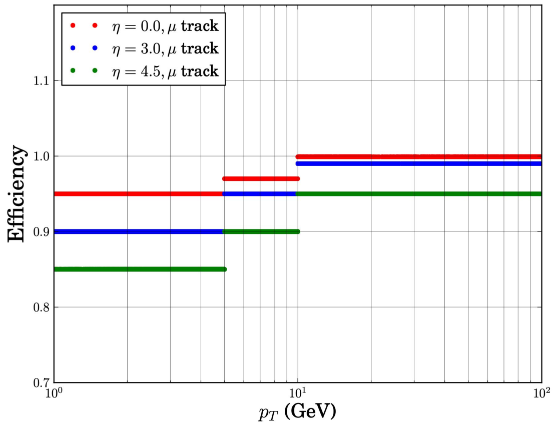
Delphes scenarios for FCC-hh

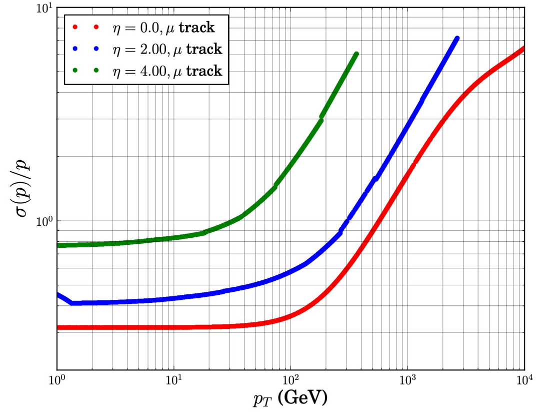
Example parametrization for muons

- Two current Delphes scenarios for FCC-hh:
  - Scenario I: Idealistic scenario for ultimate precision
  - Scenario II: Baseline scenario based on FCC-hh detector concept from CDR

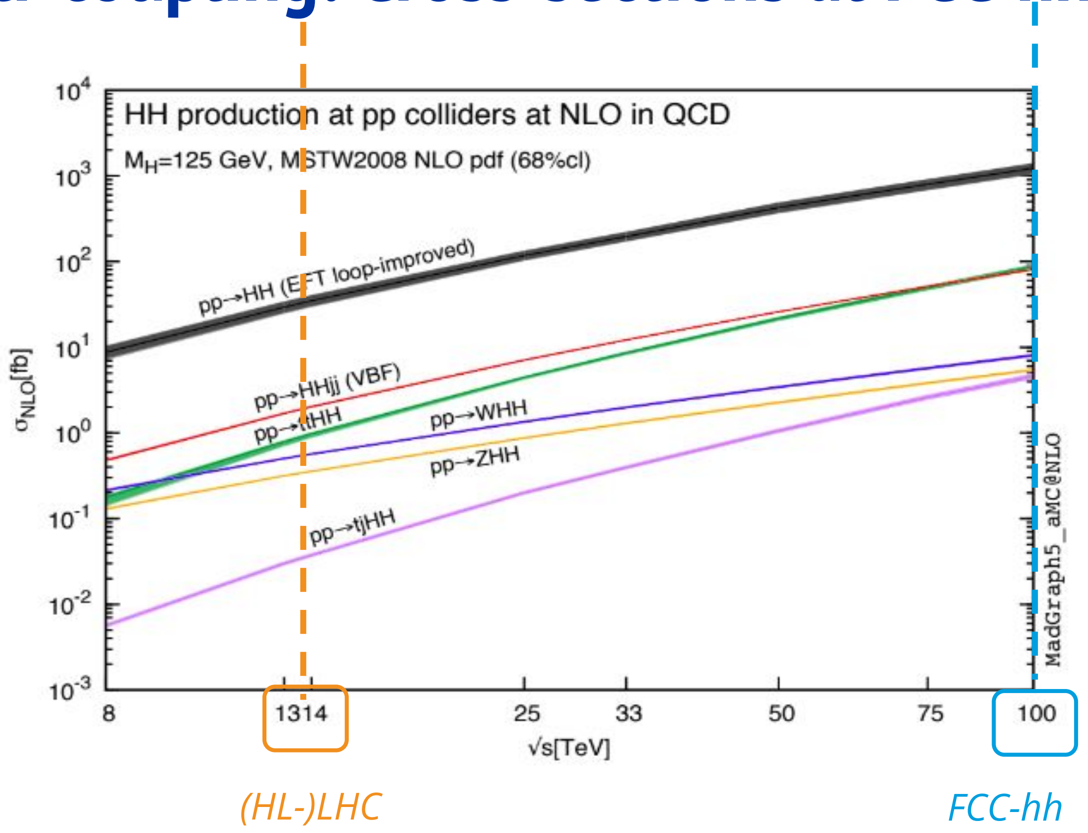
	Relative p resolution		Efficiency	
	Scenario I	Scenario II	Scenario I	Scenario II
Electrons	0.4-1%	0.8-3%	76-95%	72-90%
Muons	0.5-3%	1-6%	90-99%	88-97%
Medium b-tagging			80-90%	76-86%

Note: Both scenarios implement fixes w.r.t the original, e.g. bremsstrahlung for electrons, multiple scattering, resolutions in forward region





Higgs self-coupling: Cross-sections at FCC-hh



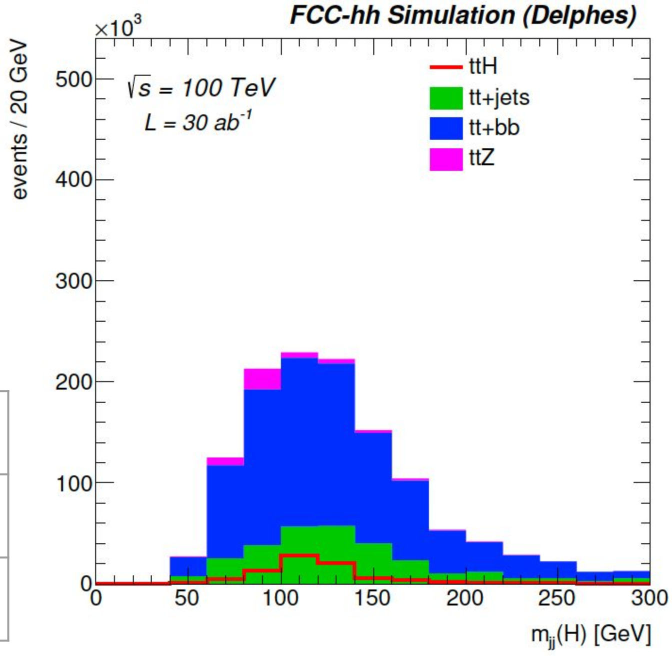
Higgs couplings: Top Yukawa coupling

CERN-ACC-2018-0045 & M. Mangano at FCC physics workshop

Exploit the ratio of $t\bar{t}H$ over $t\bar{t}Z$ for syst. cancellation

- Boosted top, $H \to b\bar{b}$ decays, $p_T(H,t)$ > 250 GeV
- Fit $t\bar{t}H$ and $t\bar{t}Z$ simultaneously with m_{jj} templates
- Assume precise measurement of $t\bar{t}Z$ from FCC-ee, and of backgrounds from control regions

	Precision in %		
Coupling	80 TeV	100 TeV	120 TeV
$\delta g_t / g_t$	1.2	1	0.85



Scaling of statistical uncertainty as extrapolation

Higgs self-coupling projections: Systematic uncertainties

Source of uncertainty	Syst. 1	Syst. 2	Syst. 3	Applies to	Correlated
Common systematics					
b-jet ID / b-jet	0.5%	1%	2%	Signals, MC bkgs.	✓
Luminosity	0.5%	1%	2%	Signals, MC bkgs.	✓
Signal cross-section	0.5%	1%	1.5%	Signals, MC bkgs.	✓
$b\bar{b}\gamma\gamma$ systematics					
γ ID / γ	0.5%	1%	2%	Signals, MC bkgs.	✗
$b\bar{b}\ell\ell + E_T^{miss}$ systematics					
Lepton ID / lepton	0.5%	1%	2%	Signals, MC bkgs.	✗
Data-driven bkg. est.	-	1%	1%	$V +$ jets	✗
Data-driven bkg. est.	-	-	1%	$t\bar{t}$	✗

- Following previous di-Higgs studies@FCC-hh
- Applied as rate systematics only, no shape effect

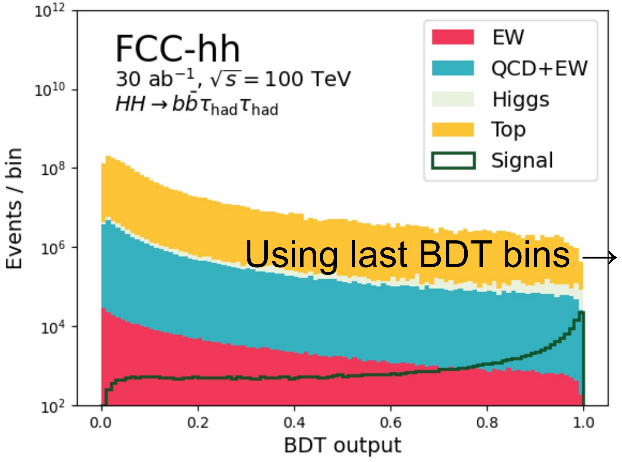
$b\bar{b}\gamma\gamma$ analysis: Center of mass energy scan

	80 TeV	100 TeV	120 TeV
No assumption on mbb	4.0% - st. only 3.6%	3.5% - st. only 3.4%	3.1% - st. only 2.8%
mbb res 10 GeV	2.5% - st. only 2.3%	2.2% - st. only 2.0%	1.9% - st. only 1.7%
mbb res 5 GeV	2.0% - st. only 1.9%	1.8% - st. only 1.6%	1.6% - st. only 1.4%
mbb res 3 GeV	1.8% - st. only 1.7%	1.6% - st. only 1.4%	1.5% - st. only 1.3%

Feasibility study for di-Higgs in $\bar{b}b\tau\tau$ events @ 100 TeV

Sam Valentine, Lennox Wood, Monica D'Onofrio, Jordy Degens, Carl Gwilliam, Cristiano Sebastiani

Previous studies using a BDT were developed in 2022 (see presentation at Higgs pair by Matt Sullivan)
Results taking into account both τL – τH and τH τH
Very good sensitivity, comparable with published studies (https://arxiv.org/pdf/2004.03505)



	HH+jet study	WIP study
	Yield [fb^{-1}]	
Signal	0.14	1.22
Background	0.96	38.94
	$S/\sqrt{B}$	
$\tau_\ell\tau_h$	24.97	32.32

$b\bar{b}\tau_\ell\tau_h$ comparison

Feasibility study for di-Higgs in $\bar{b}b\tau\tau$ events @ 100 TeV

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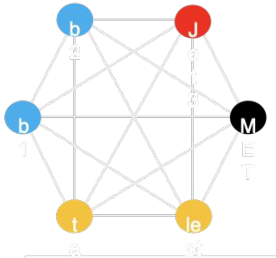
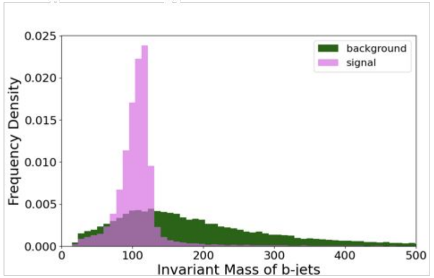
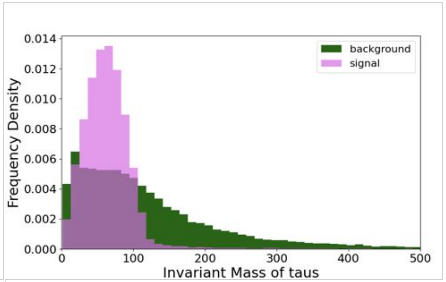
Graph for each event, each object is a node
Fully connected, each node has several features
Different models tested (GCN, GAT)
Systematic evaluation of performance based on relevant metrics (S vs B separation, AUC)

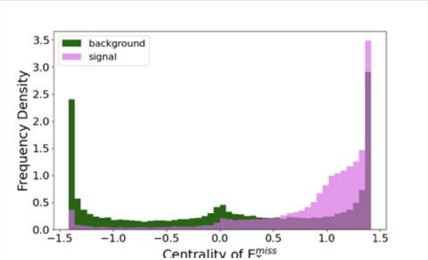


Event 1:	pT	eta	phi
tau	25.551097869873047	2.0833067893981934	1.6441311836242676
l1	233.71524047851562	1.5203982591629028	-2.497894525527954
b1	209.0316162109375	1.6601777076721191	0.5068551898002625
b2	33.84409713745117	1.8450242280960083	2.5926644802093506
energy	4.8641037940979	nan	-0.2831399738788605





Tested S vs B separation using only object variables and using also complex reconstructed kinematic variables
Performance dramatically improved when kinematic variables such as b-jet pairs invariant mass, tau-lepton invariant mass etc are passed as individual nodes
Area-Under-Curve in ROC curve 0.82 0.99
Use also radial distances among b and tau objects and ETMiss centrality as in ATLAS di-Higgs studies



$$E_T^{miss} centrality = \frac{(x+y)^2}{\sqrt{x^2+y^2}}$$

$$x = \frac{\sin(\phi_{MET} - \phi_\tau)}{\sin(\phi_\ell - \phi_\tau)}$$

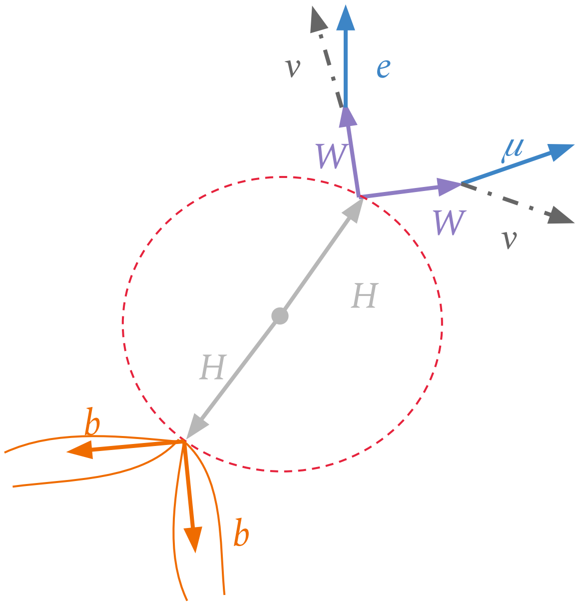
$$y = \frac{\sin(\phi_\ell - \phi_{MET})}{\sin(\phi_\ell - \phi_\tau)}$$

Excellent separation achieved

$\bar{b}bll+E_T^{miss}$ @ 100 TeV: Strategy overview

Birgit Stapf, Elisabetto Gallo, Kerstin Tackmann, Christophe Grojean

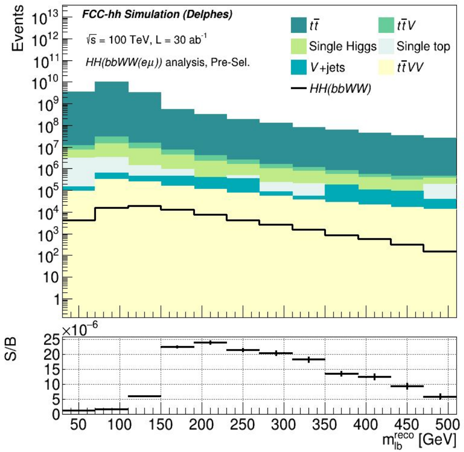
Signal signature

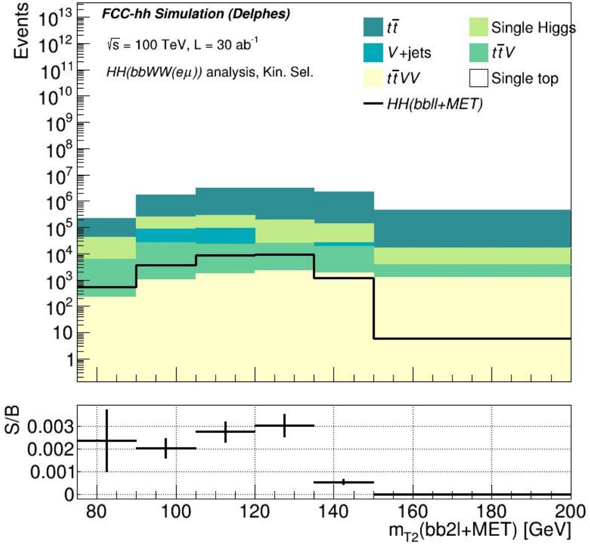


- Lepton pair + E_T^{Miss} + 2 b-jets
  - Leptons isolated from b-jets

- Cut-based event selection exploiting signal kinematics
  - Targeted suppression of $t\bar{t}$ background using

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

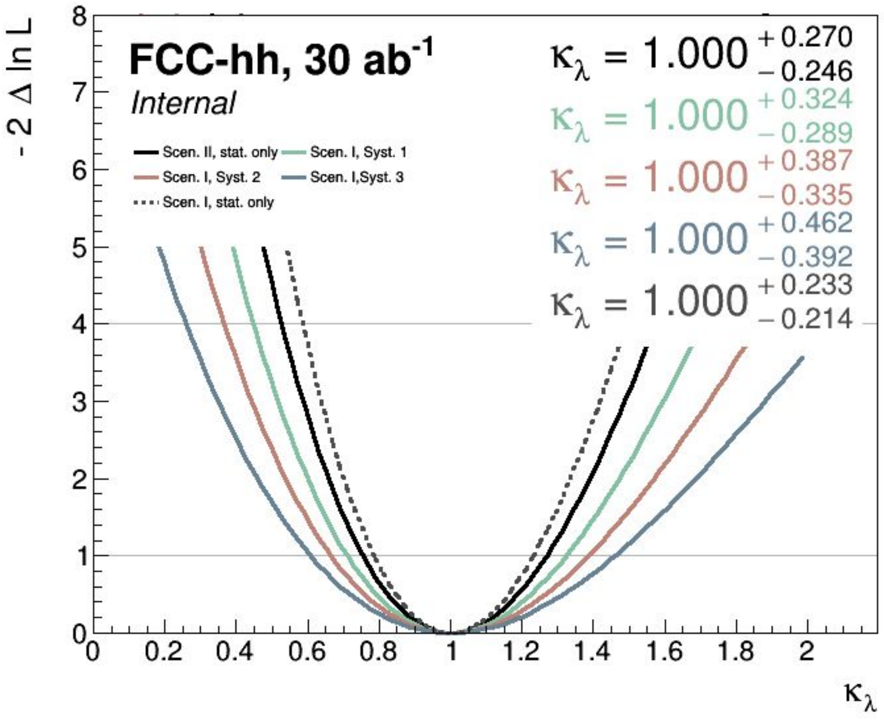




- Stransverse mass m_{T2} predicts invisible mass contribution
  - Capture the full HH decay
  - Fit to m_{T2} distribution in 5 categories depending on lepton flavours and if $Z(ll)$ decay

$\bar{b}bll+E_T^{miss}$ @ 100 TeV: Results

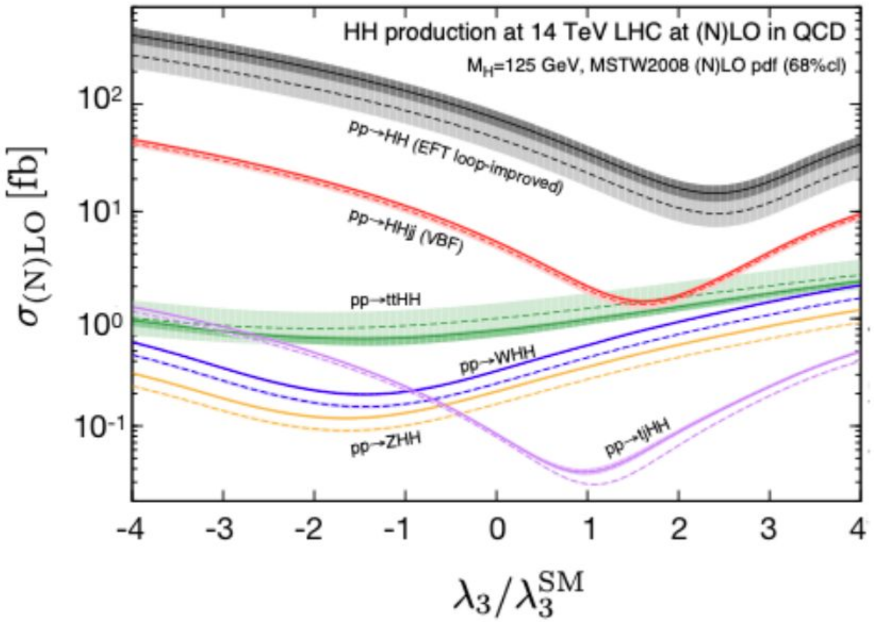
Birgit Stapf, Elisabetto Gallo, Kerstin Tackmann, Christophe Grojean

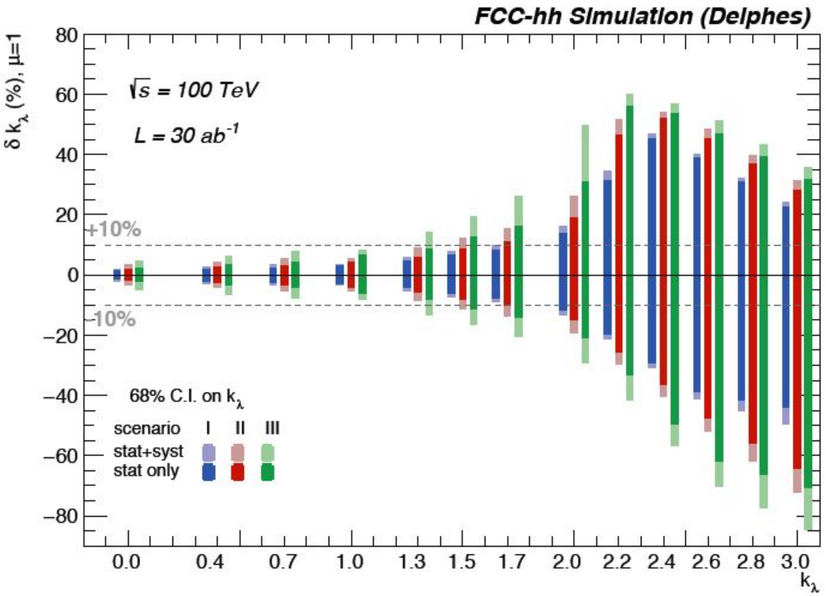


Higgs self-coupling modifier κ_λ interpretation

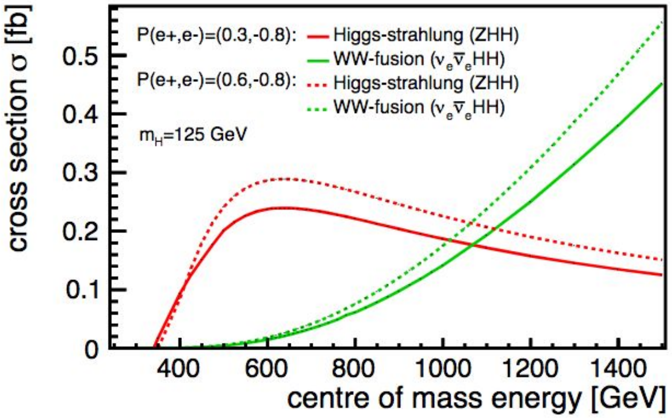
- Parametrized dependence of $\sigma(ggHH)$ on κ_λ
  - Inputs: κ_λ =1.0, 2.4, 3.0
- All other couplings fixed to SM
- NLO cross-sections at 100 TeV, with k-factor independent of κ_λ
- No Higgs BR dependance on κ_λ and uncertainties or other additional theory uncertainties

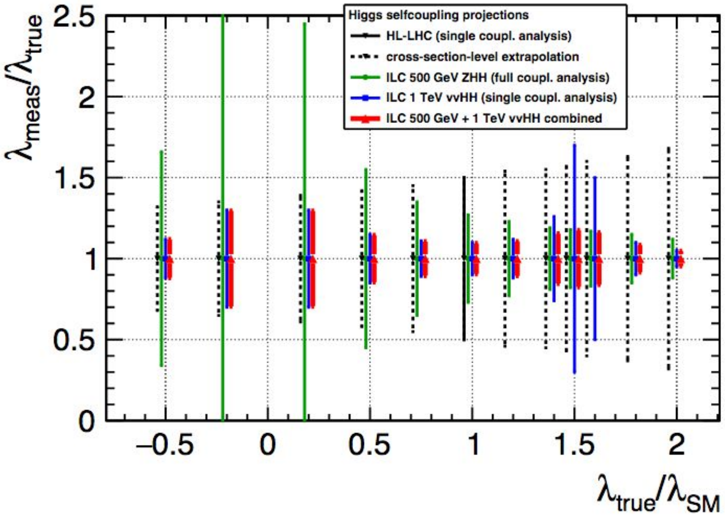
Di-Higgs cross-section dependance on κ_λ in pp-collisions





Higgs self-coupling @ ILC



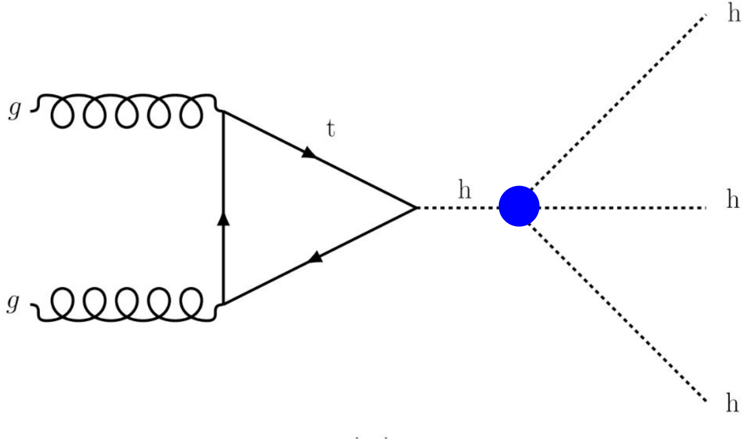


- Two production modes:
  - Higgsstrahlung, peaks ~500 GeV
  - WW-fusion, above ~1 TeV
  - → need runs at both energies for maximum κ_λ precision

- Studied dominant channels $4b$ and $bbWW$
- Advantage of e-collider: ZHH cross-section increases with , hence better constraints at values > 1 than pp-colliders

Quartic Higgs self-coupling

$$V(h) \approx m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4$$



Triple Higgs production measurements will remain challenging, even at FCC-hh due to very low cross-section

Again ~ O(100) smaller than the *HH* cross-section

Studies in final states with 4bs, tau pairs and photon pairs and more recently 6b

Number of selected signal events ~O(100)

Combining several channels 3σ may be reached