Results and plans from the FCC-hh physics performance WG

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Introduction

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

Main limitations for FCC-hh from dipole magnets, synchrotron radiation and extreme levels of pile-up → alternative FCC-hh running scenarios under study to the CDR baseline plan of 30 ab^{-1} @ 100 TeV

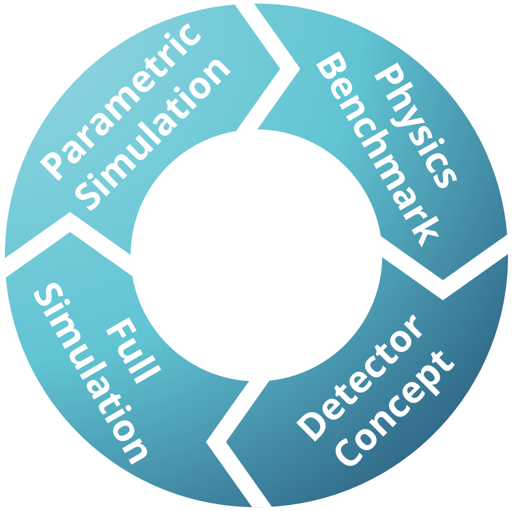
FCC-hh ESPP2025 Physics & performance group started last autumn as a common platform for all ongoing FCC-hh projection studies for the strategy update

	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*

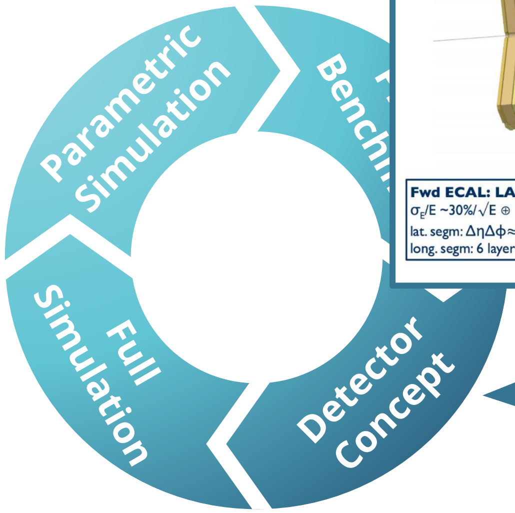
F. Zimmermann

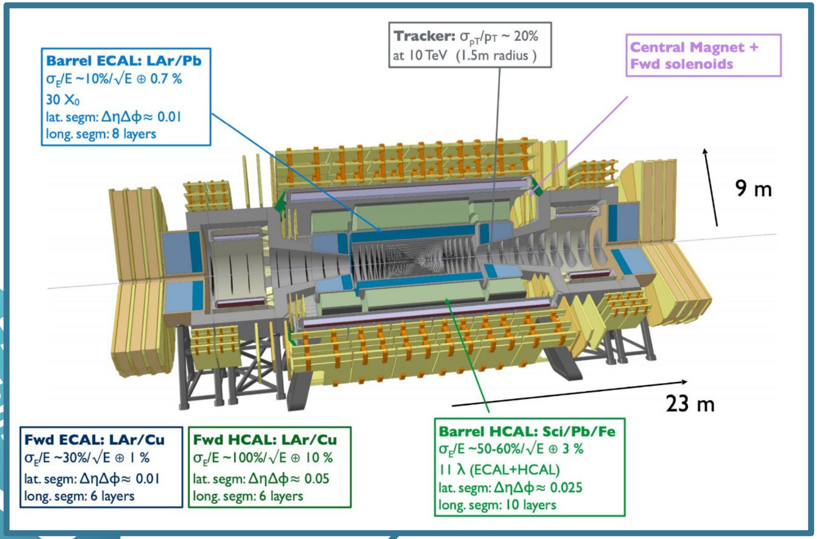
**F12 includes 3 different scenarios for high, low lumi & low PU*

FCC-hh projection study workflow



FCC-hh projection study workflow



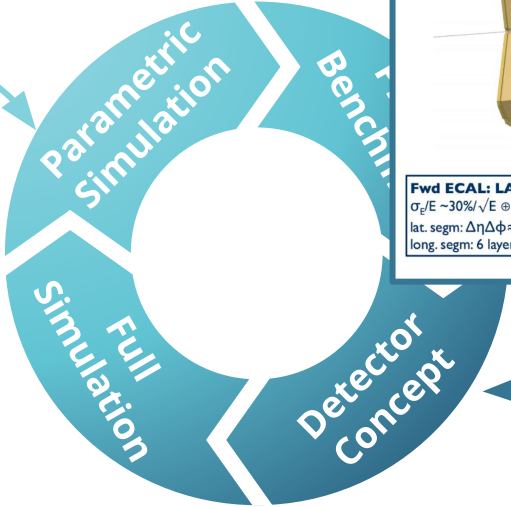


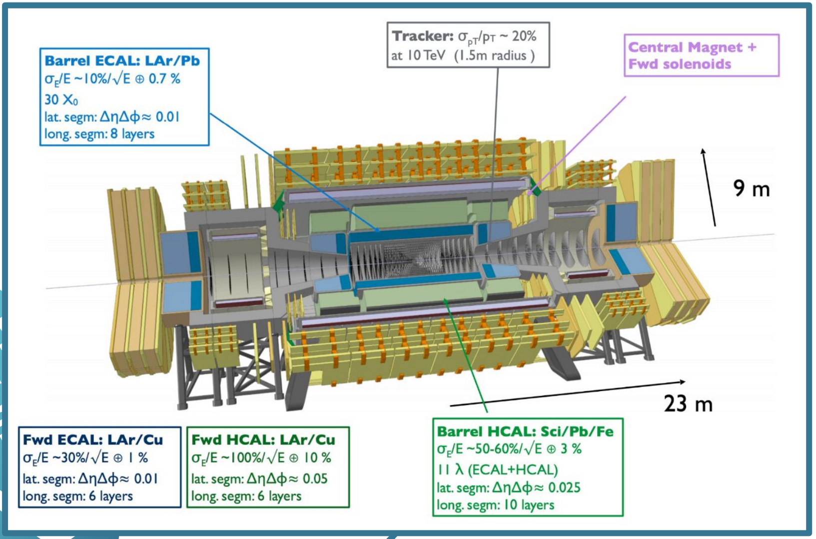
Reference detector design from the CDR

CERN-ACC-2018-0058

FCC-hh projection study workflow

DELPHES
fast simulation





Efficiencies & resolutions as functions of p_T and η

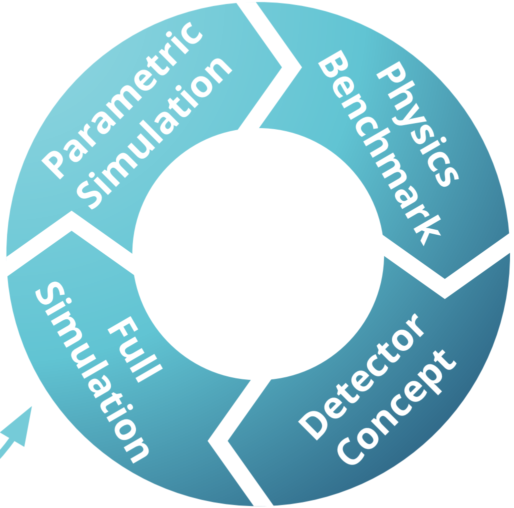
- Official FCC-hh scenarios
- Rely on common software stack: key4hep
- Note: No direct pile-up overlay, assume LHC levels in the parametrizations

Reference detector design from the CDR

CERN-ACC-2018-0058

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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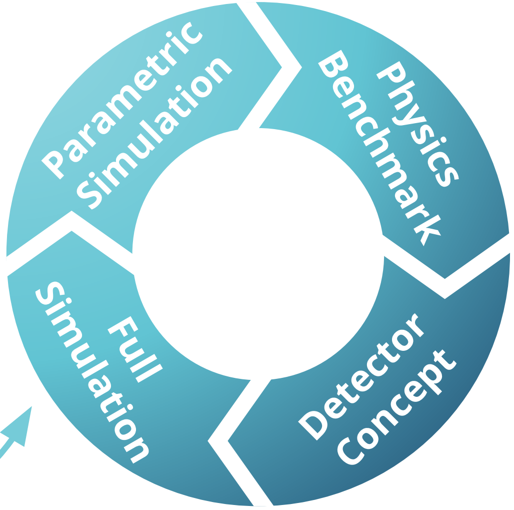


Performance studies

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

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
- 💡 Higgs width measurement through VBF HWW off-shell
- 💡 ***Differential cross-sections as input to global fits***
  - High pT ttbar production
- ....

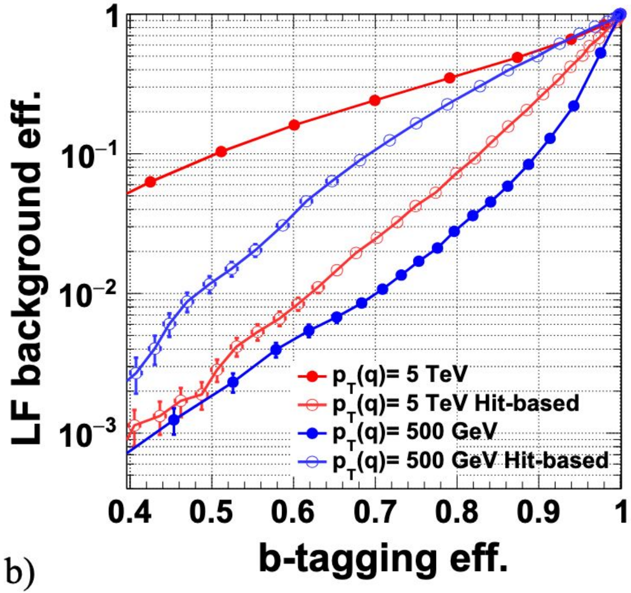
Jet Flavour Tagging with transformer architecture

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

Motivation for the study:

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

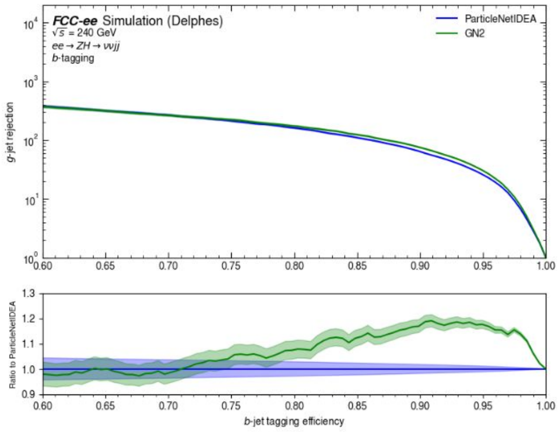
- CDR included initial studies into flavour tagging efficiencies with the FCC-hh tracker layout relying on calculation of the track covariance matrix



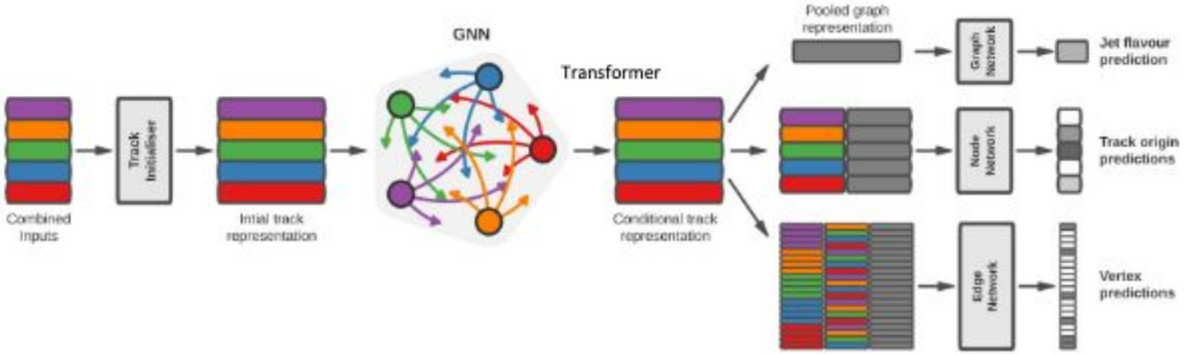
b)

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

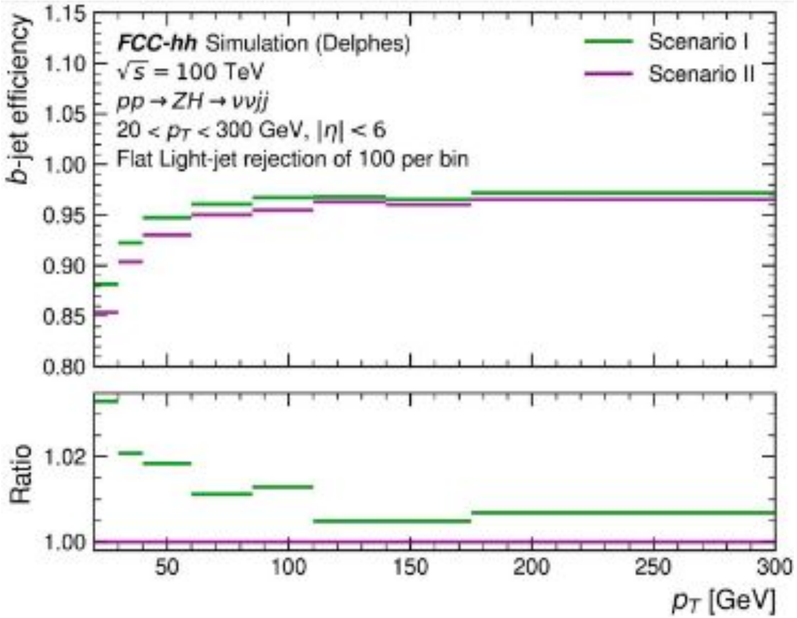


Jet Flavour Tagging with transformer architecture

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

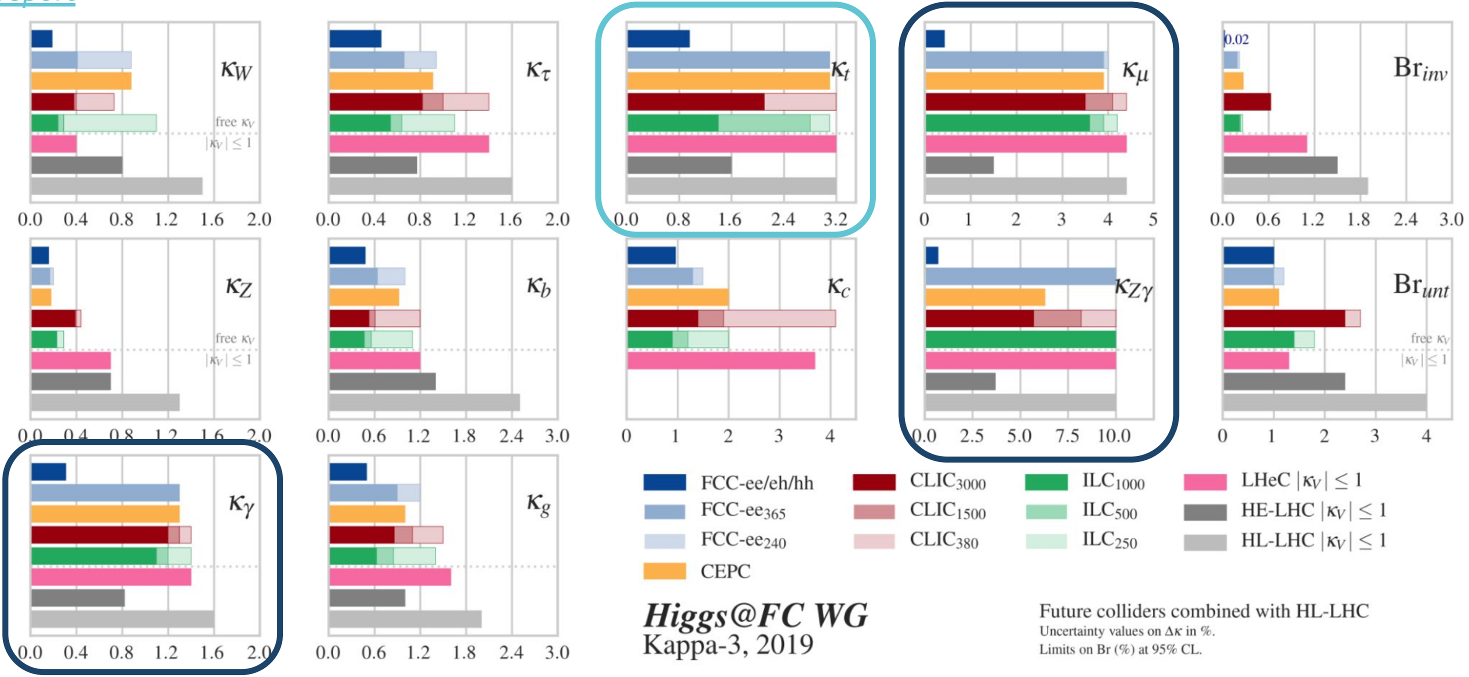
- Performance study of transformer model (GN2), with Delphes TrackCovariance module implementing tracker layout
  - Validated against FCC-ee & CDR
- Find b-tagging efficiencies > 95% (70%) with 1% mis-tagging at rates in moderate (high) pT range, maintained up to $|\eta| < 5$

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



Higgs couplings precision measurements

Granada report

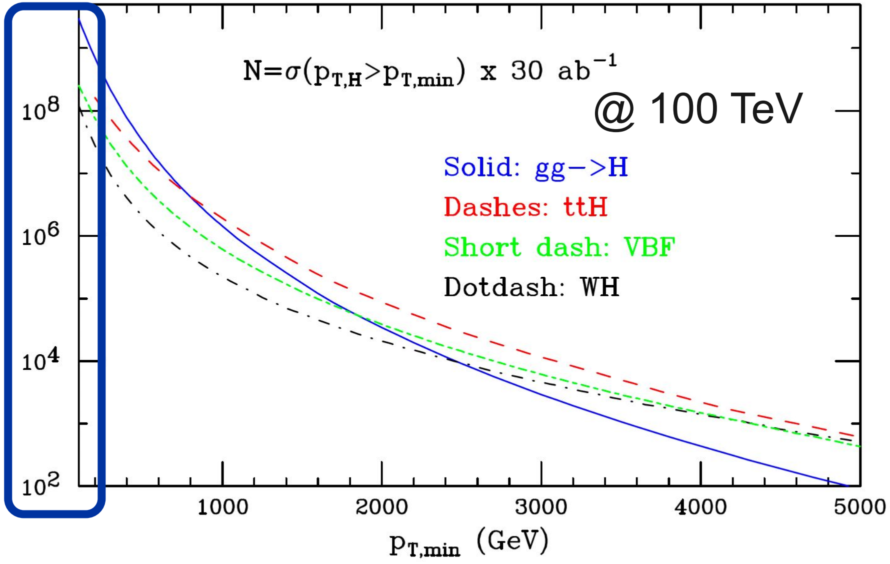


Significant precision improvements in couplings measurements in rare decay modes that remain (statistically) limited at **FCC-ee**/**HL-LHC**, or are not directly accessible at **FCC-ee**

Higgs couplings: Analysis strategy

CERN-ACC-2018-0045

Expected number of Higgses



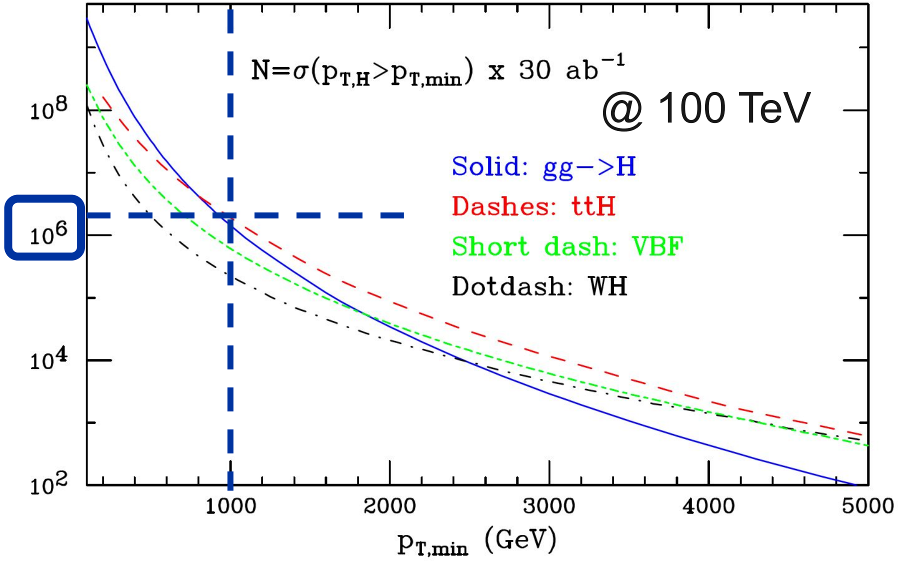
In total ~ 10^{10} single Higgs (and ~ 10^7 Higgs pair) events expected

Cross-section and integrated luminosity both increase by x 10 compared to HL-LHC

→ Factor 10 reduction of statistical uncertainties, systematic uncertainties will dominate even in rare channels

Higgs couplings: Analysis strategy

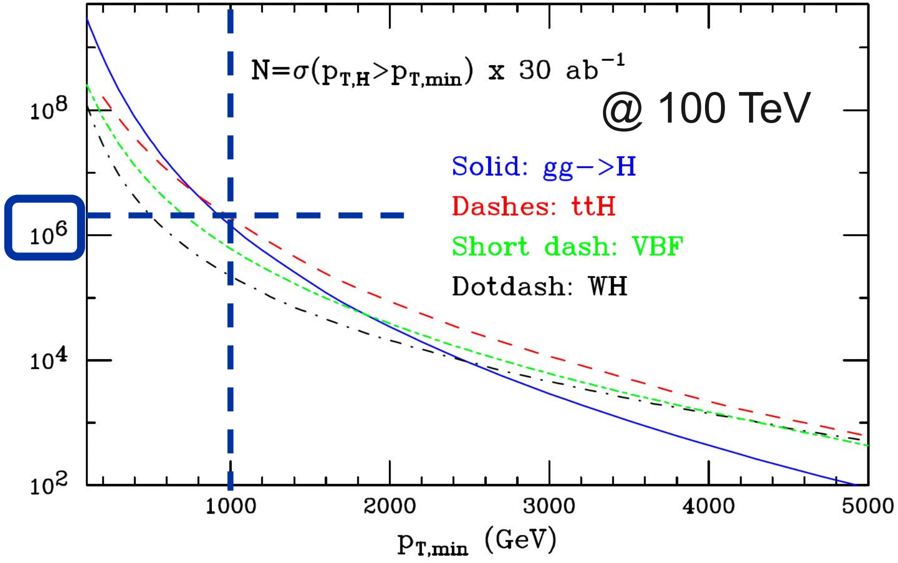
[CERN-ACC-2018-0045]

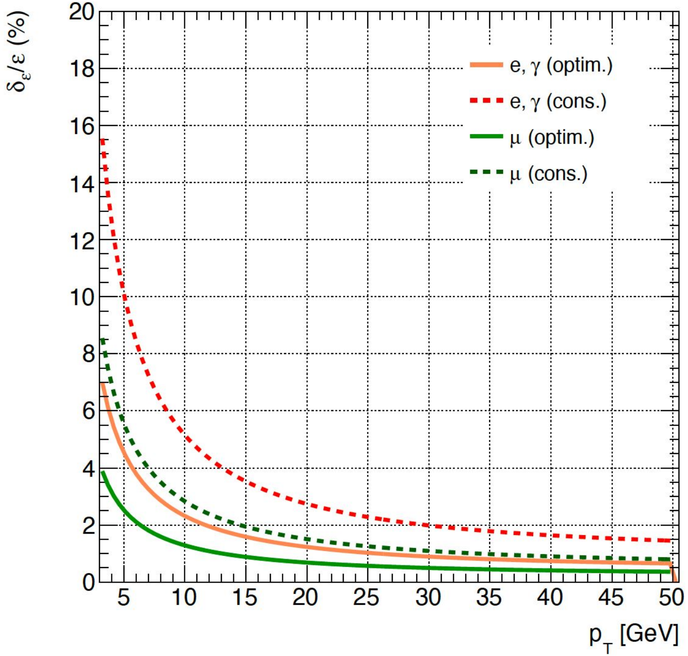


Systematic uncertainties will dominate
But: Large statistics even at high p_T …

Higgs couplings: Analysis strategy

CERN-ACC-2018-0045





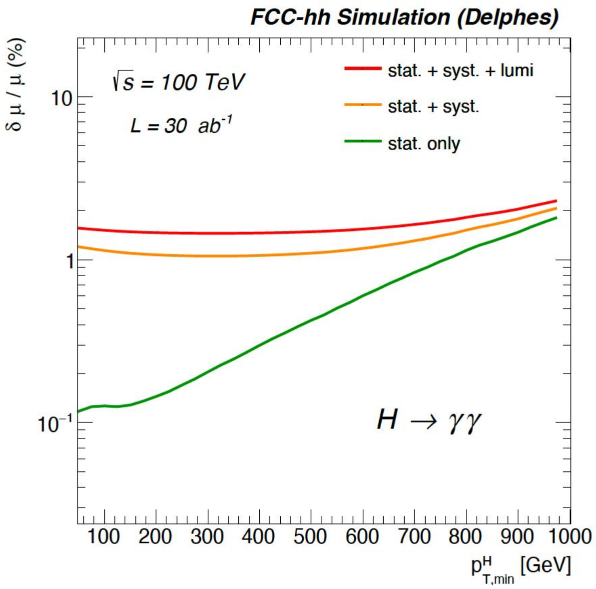
Systematic uncertainties will dominate
But: Large statistics even at high p_T …

… where experimental systematic uncertainties on efficiencies are smaller

Higgs couplings: Analysis strategy

CERN-ACC-2018-0045

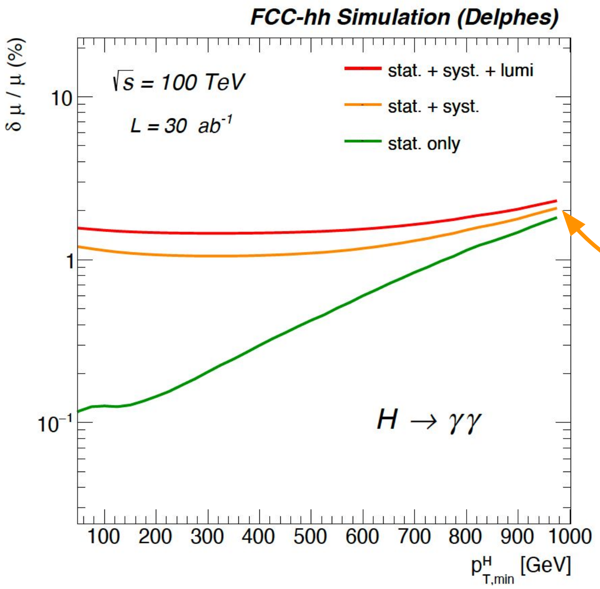
Signal strength precision



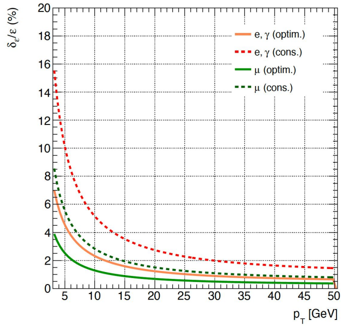
Higgs couplings: Analysis strategy

CERN-ACC-2018-0045

Signal strength precision



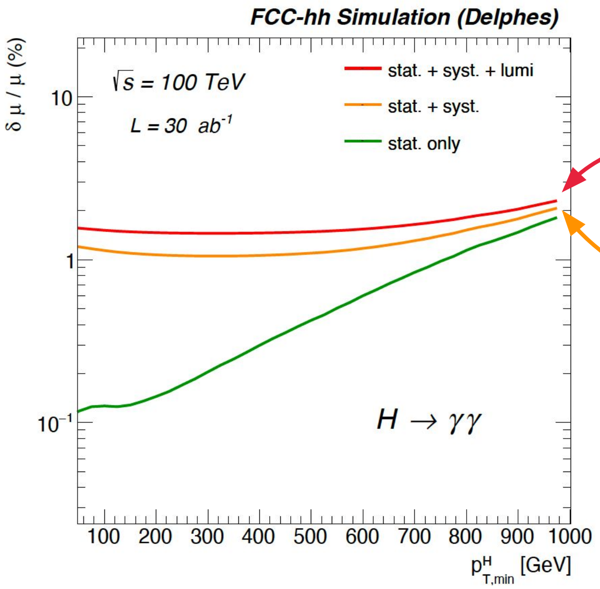
With efficiency uncertainties



Higgs couplings: Analysis strategy

[CERN-ACC-2018-0045]

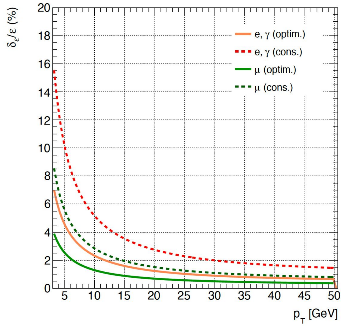
Signal strength precision



With additional flat uncertainties

- 1% on luminosity
- 1% on $\boldsymbol{\sigma}_{prod}$

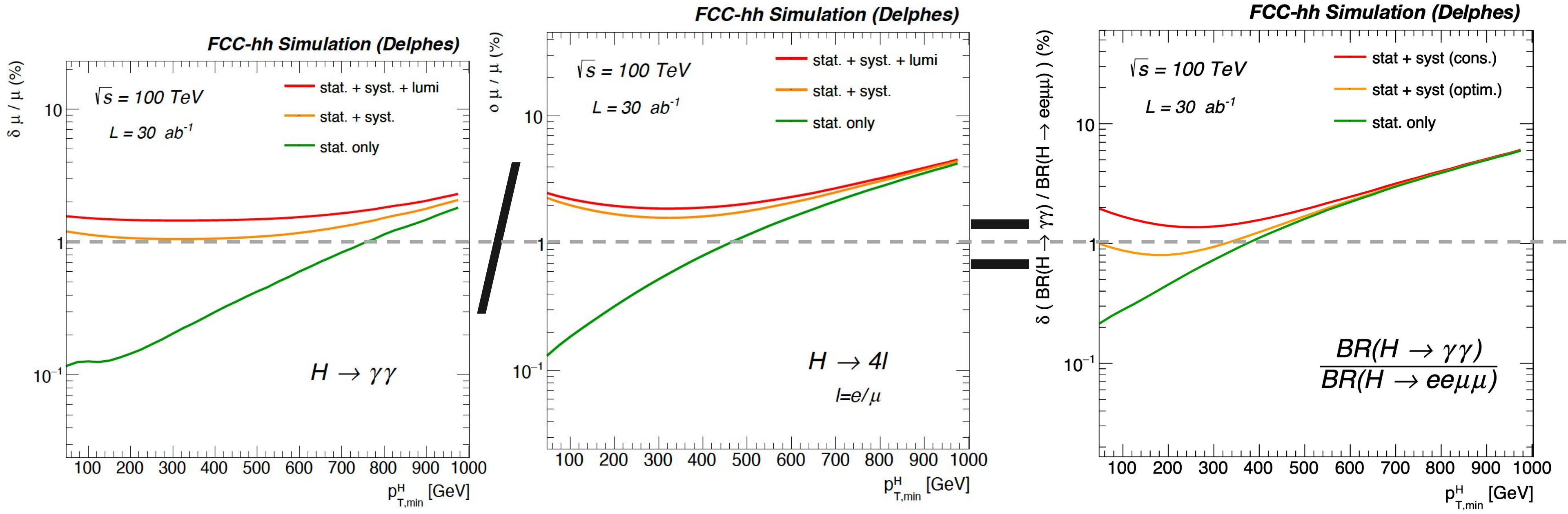
With efficiency uncertainties



Higgs couplings: Analysis strategy

CERN-ACC-2018-0045

Signal strength precision *BR ratio precision*

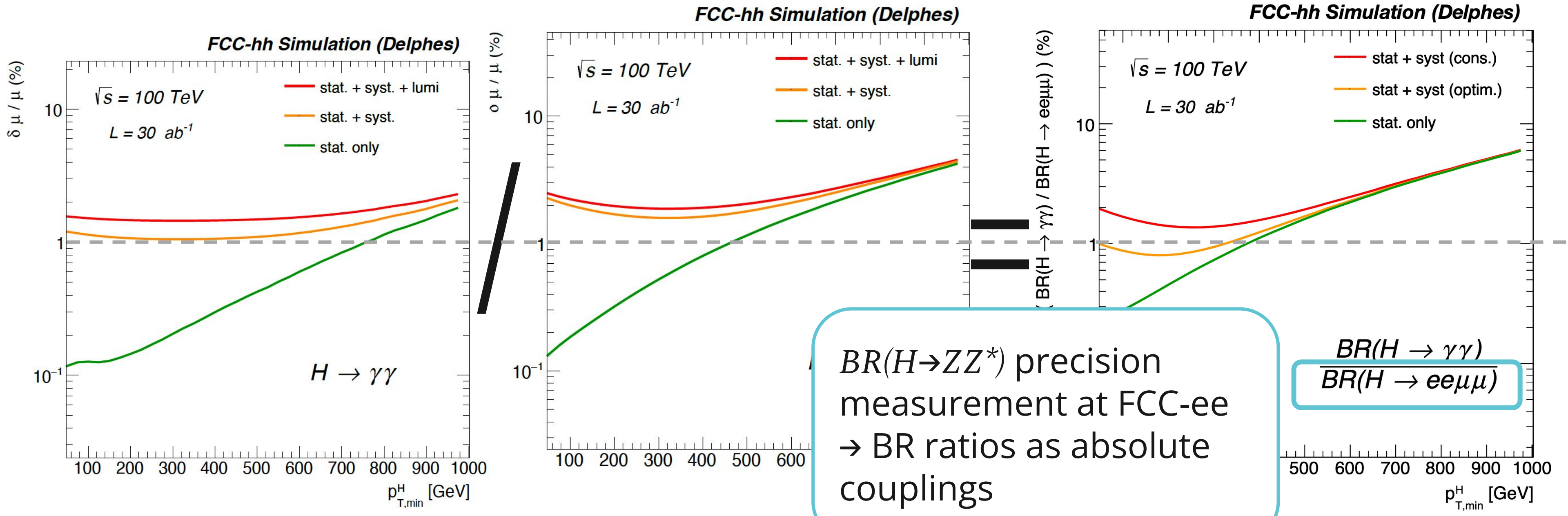


Systematic uncertainties (partially) cancel in ratio

Higgs couplings: Analysis strategy

CERN-ACC-2018-0045

Signal strength precision *BR ratio precision*



BR(H→ZZ)* precision measurement at FCC-ee → BR ratios as absolute couplings

Systematic uncertainties (partially) cancel in ratio

Higgs couplings: Previous results

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

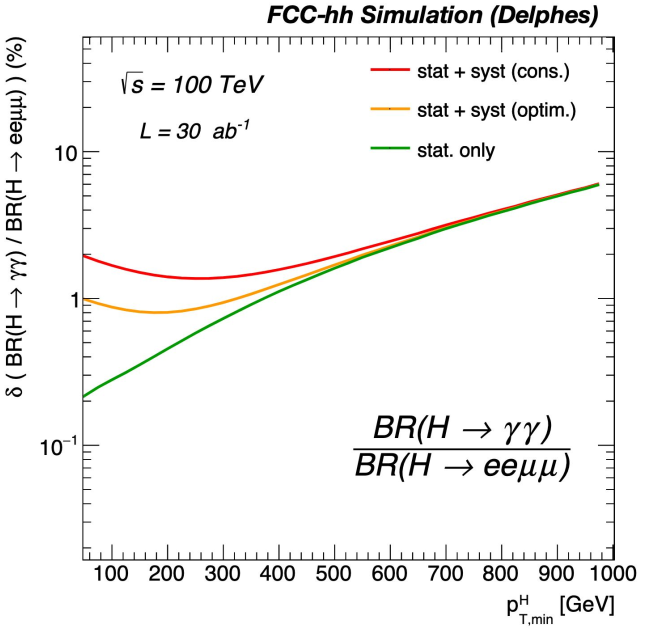
First estimate of precision at alternative energies by rescaling statistical uncertainties:

- With ± 20 TeV : σ_{prod} ± 30%

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

Rerunning the analyses is a work in progress

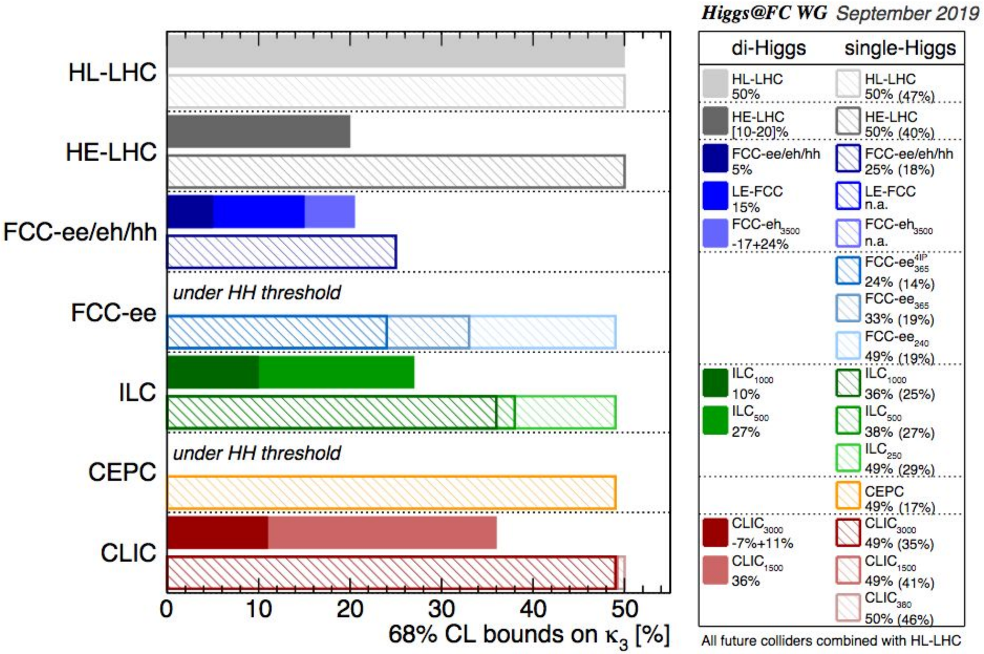
BR ratio precision



Higgs couplings: First results from $H(\mu\mu)/H(4\mu)$

Higgs self-coupling precision measurements

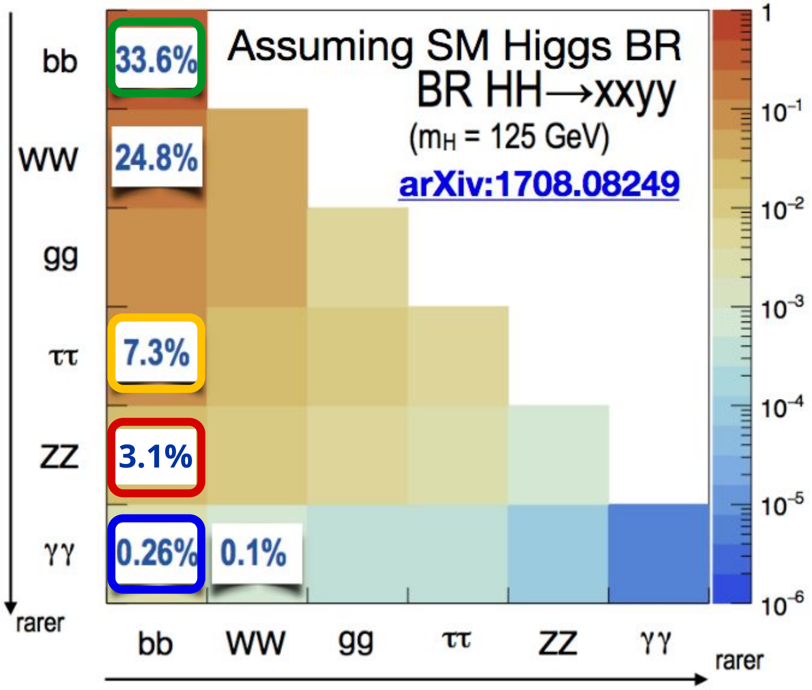
[Granada report]

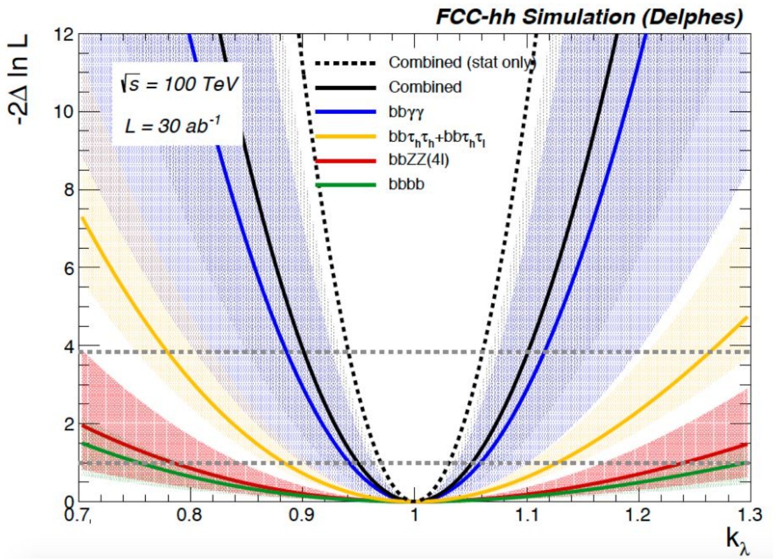


Large dataset & increased cross-section at baseline CDR FCC-hh offers %-level κ_λ precision

Higgs self-coupling precision measurements

CERN-TH-2020-052

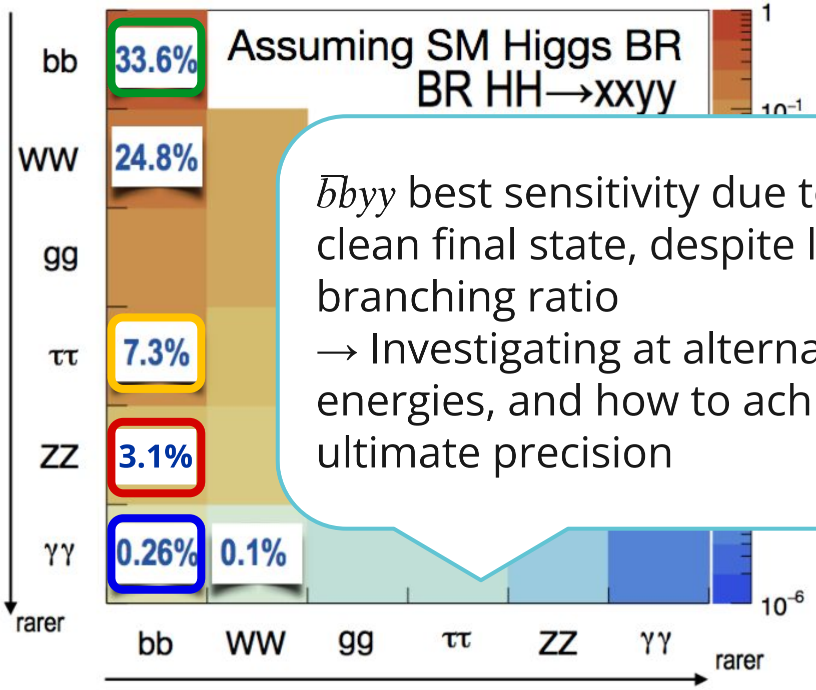




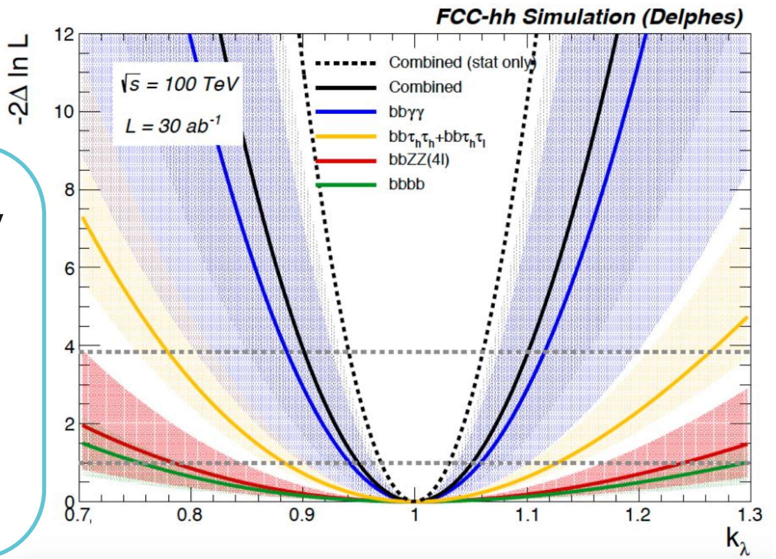
	Combined precision
$\delta\kappa_\lambda$ (68% CL)	3.0% - 7.8%

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



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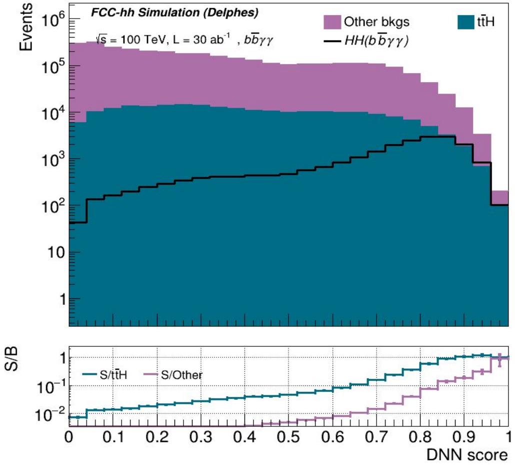
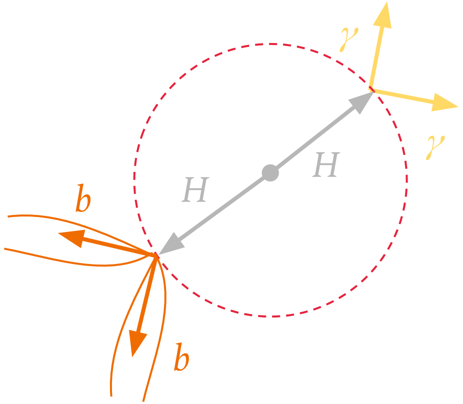
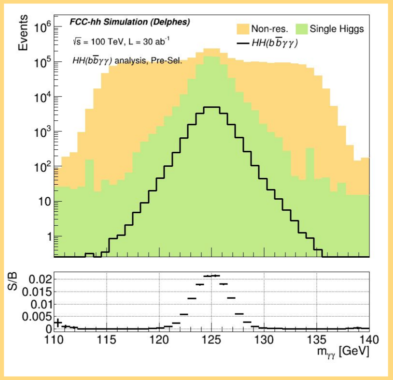
Re-optimized $b\bar{b}\gamma\gamma$ analysis strategy

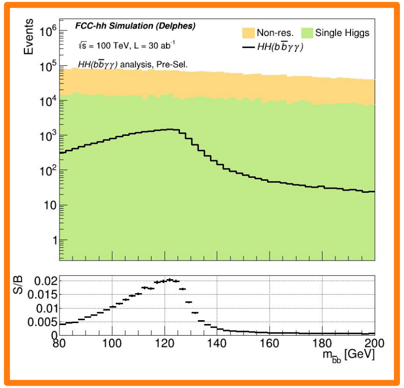
Angela Taliercio, Paola Mastrapasqua, Birgit Stapf at FCC-hh ESPP meeting

Pre-selected events → DNNs categorization to suppress the bkg





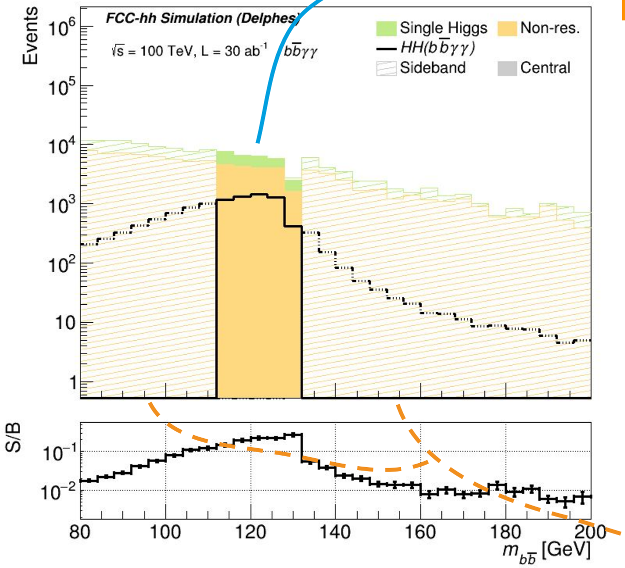


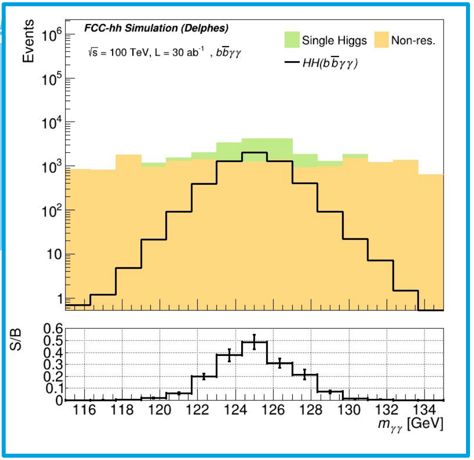


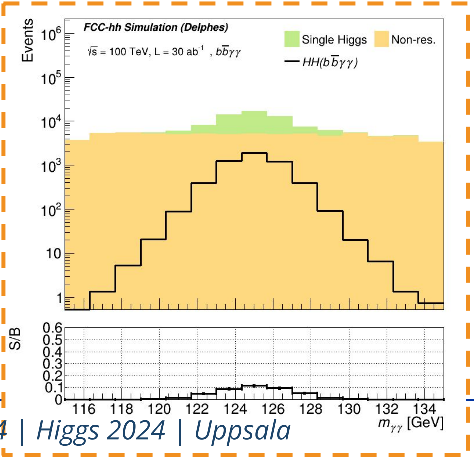
- Backgrounds:
  - Non-resonant QCD: $\gamma\gamma$+jets and γ+jets
  - Single Higgs production

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

Angela Taliercio, Paola Mastrapasqua, Birgit Stapf at FCC-h







Categorize based on $m_{\bar{b}b}$

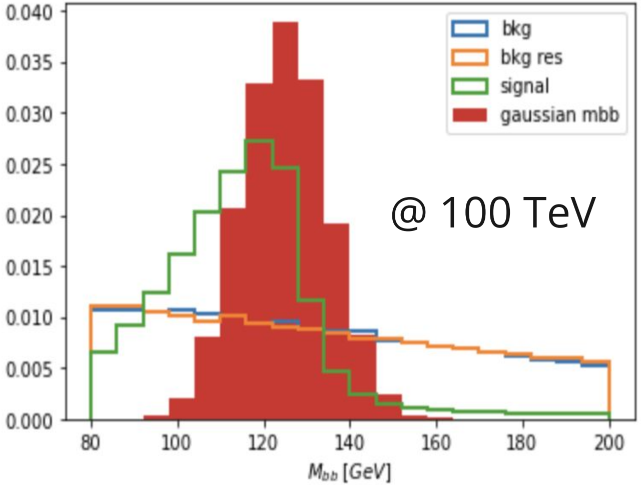
Sideband

Central region

Fit $m_{\gamma\gamma}$

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

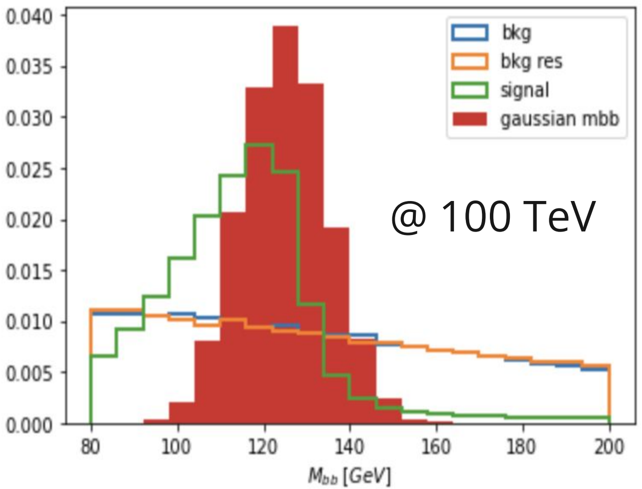
[Angela Taliercio, Paola Mastrapasqua, Birgit Stapf at FCC-hh ESPP meeting]

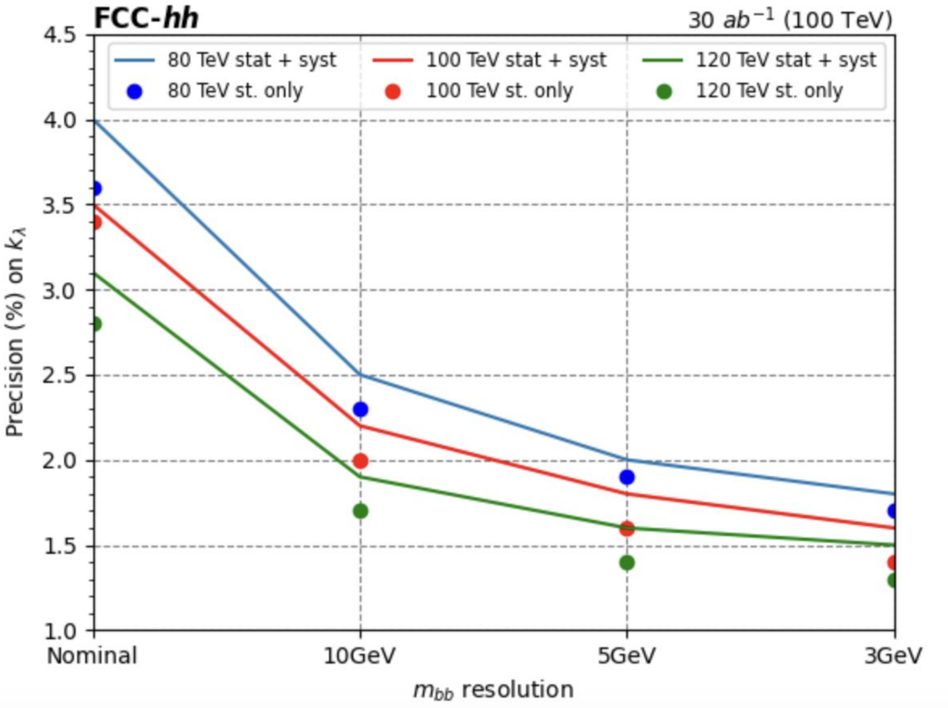


	m_{bb} resolution			
	Nominal	10 GeV	5 GeV	3 GeV
$\boldsymbol{\delta\kappa_\lambda}$ (68% CL - stat. only)	3.2%	2.5%	2.0%	1.8%

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

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





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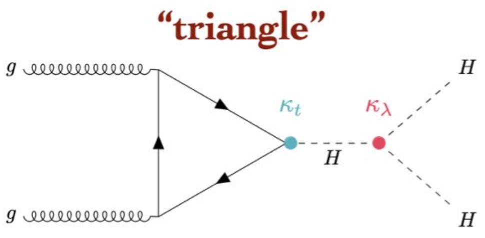
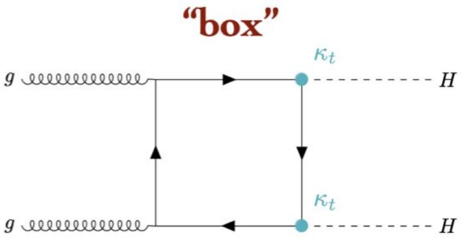
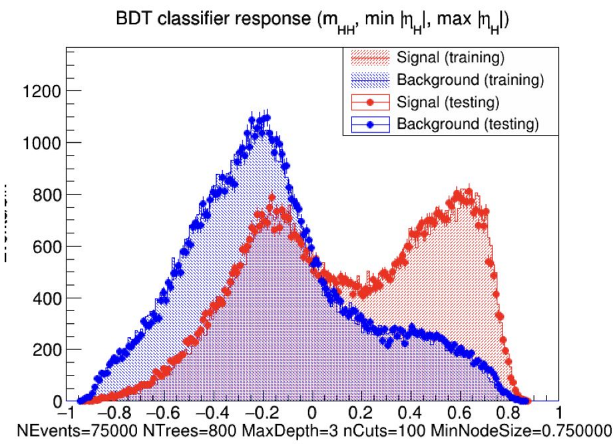
Impact of m_{bb} resolution is critical

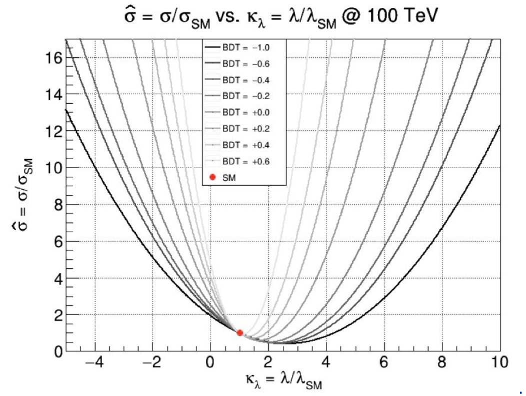
Next step for $\bar{b}b\gamma\gamma$ analysis: Separating triangle vs box diagrams

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





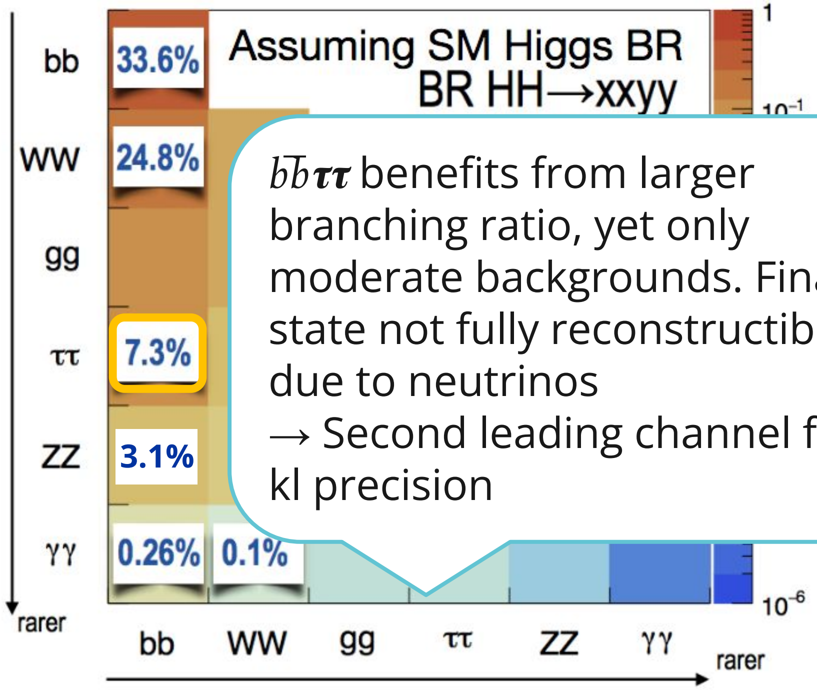




- Dominant mode of gluon-gluon Higgs pair production has two (interfering) diagrams
- Only the triangle diagram contribution contains a Higgs-self coupling vertex
- Ongoing work to apply Bastien Voirin's BDT classifier which separates the triangle from the box contribution based on the Higgs' kinematics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

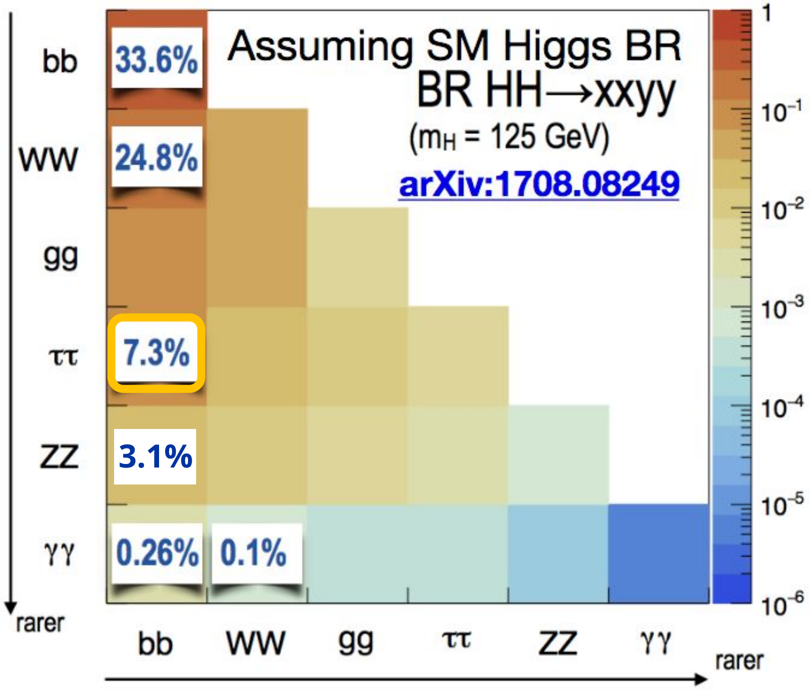
Improved $b\bar{b}\tau\tau$ analysis with advanced ML techniques

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

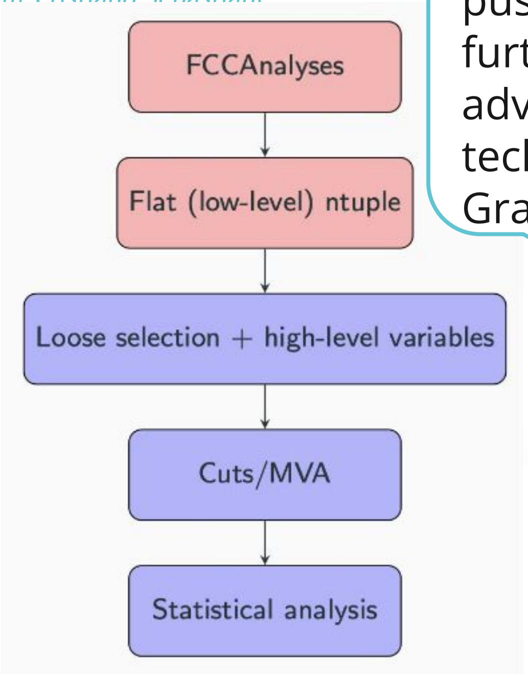


$b\bar{b}\tau\tau$ benefits from larger branching ratio, yet only moderate backgrounds. Final state not fully reconstructible due to neutrinos
→ Second leading channel for kl precision

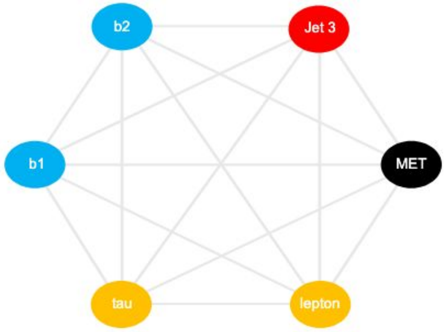
Improved $\bar{b}b\tau\tau$ analysis with advanced ML techniques @ 100 TeV



m Cristiano Sebastiani



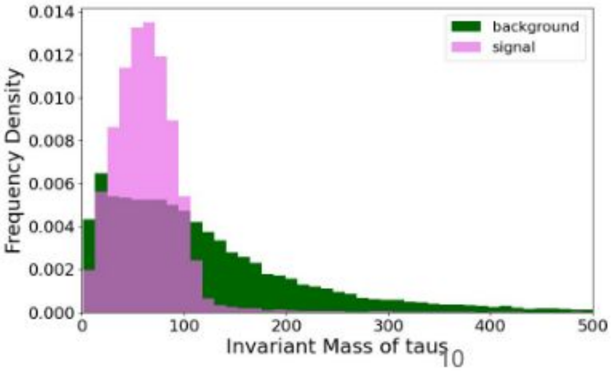
⚙️ Ongoing work to push sensitivity even further by employing advanced ML techniques, such as Graph Neural Net (GNN)



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

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

Input distributions (example)

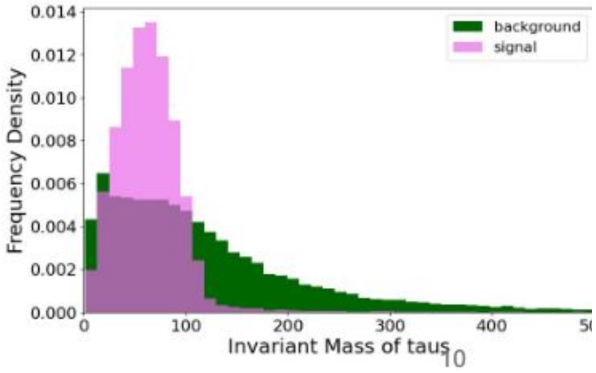


- Analysis of $\bar{b}b\tau_{lep}\tau_{had}$ and $\bar{b}b\tau_{had}\tau_{had}$ signal events
- **Backgrounds** from top and single Higgs production, as well QCD+EW continuum (Drell-Yan Z+jets)

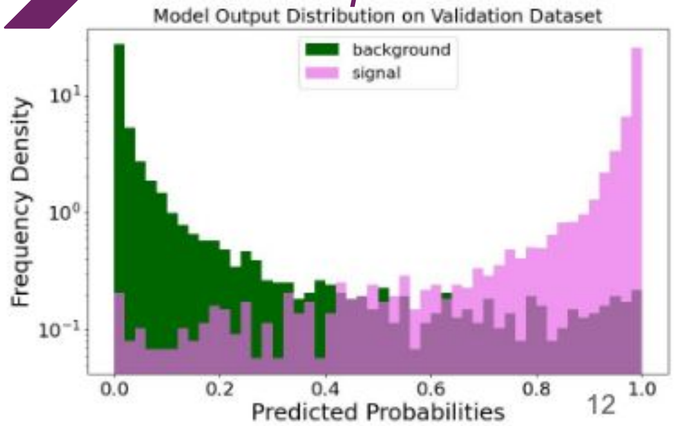
Improved $\bar{b}b\tau\tau$ analysis with advanced ML techniques @ 100 TeV

Sam Val… ine, Lennox Wood, Monica D'Onofrio, Jor… …gens, Carl Gwilli… …ani

Input distributions (example)



GNN performance



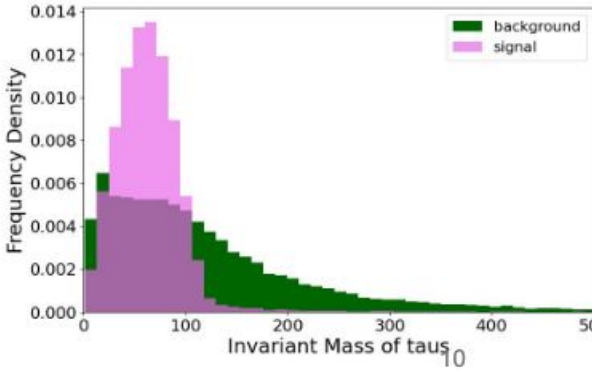
- Analysis of $\bar{b}b\tau_{lep}\tau_{had}$ and $\bar{b}b\tau_{had}\tau_{had}$ signal events
- **Backgrounds** from top and single Higgs production, as well QCD+EW continuum (Drell-Yan Z+jets)

- 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

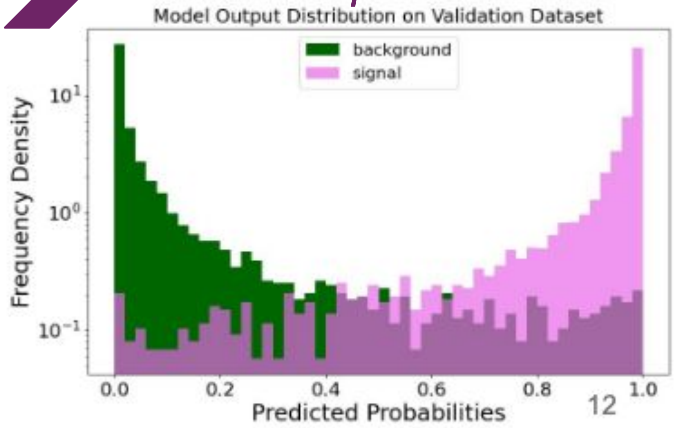
Improved $\bar{b}b\tau\tau$ analysis with advanced ML techniques @ 100 TeV

Sam Valentine, Lennox Wood, Monica D'Onofrio, Jor... ...gens, Carl Gwilli... ...ani

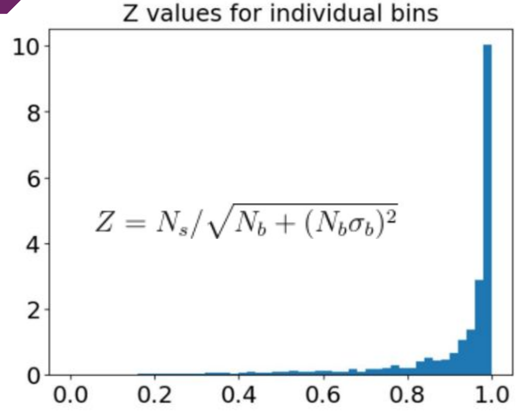
Input distributions (example)



GNN performance



Sensitivity



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- 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

LO

NLO

NNLO

Repeat the kappa framework fits (see Simone's talk) for alternative FCC-hh running scenarios & combinations of Future Colliders

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

- 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,

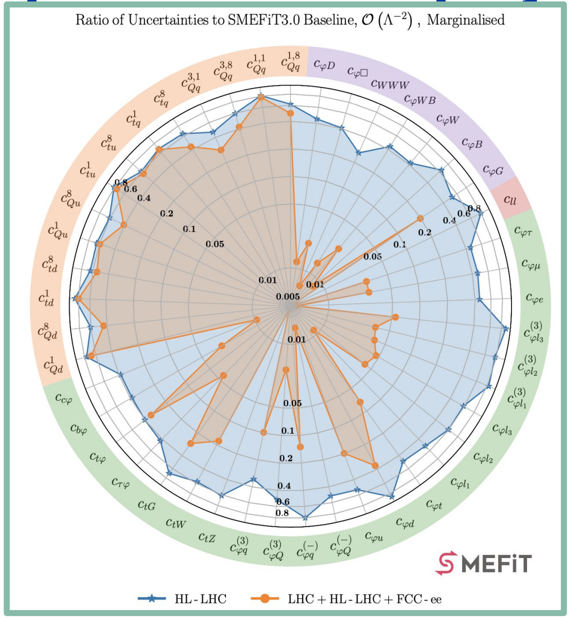
LO

Repeat the kappa framework fits (see Simone’s talk) for alternative FCC-hh running scenarios & combinations of Future Colliders

NLO

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

NNLO



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- Required theory input: Repetition of HL-LHC EFT calculations for the FCC-hh energy scenarios

Outlook: Towards global fits with updated FCC-hh projections

Juan Rojo,

LO

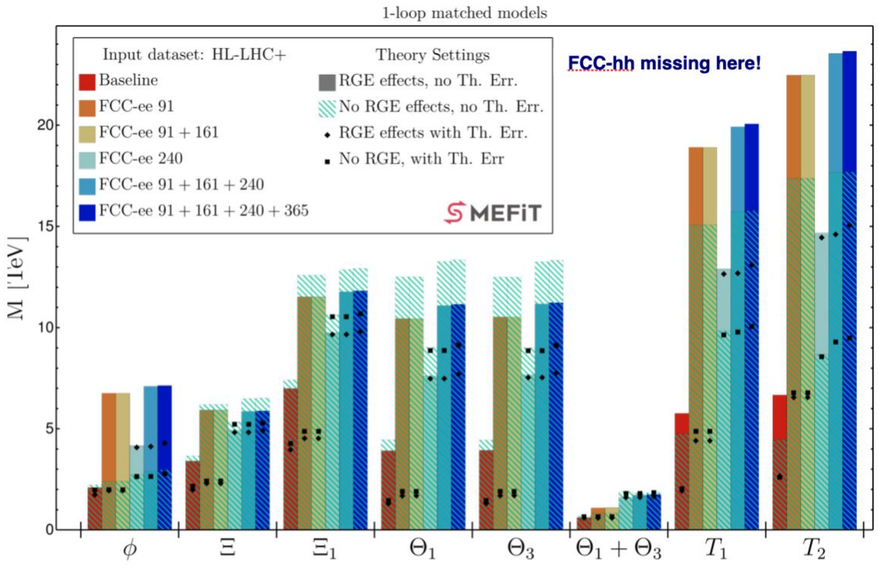
Repeat the kappa framework fits (see Simone’s talk) for alternative FCC-hh running scenarios & combinations of Future Colliders

NLO

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

NNLO

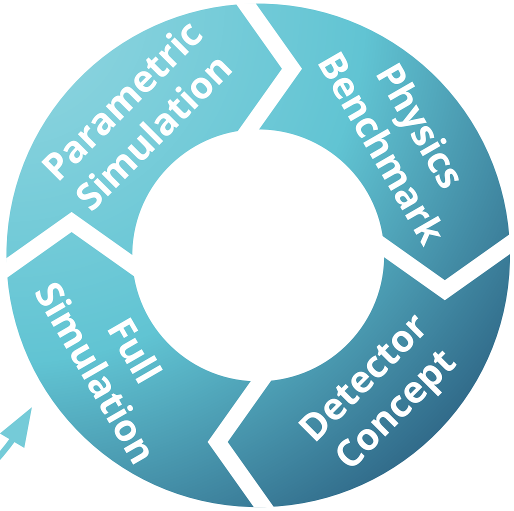
Ultimate goal: Global SMEFT fit with differential distributions from FCC-hh



- 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 $H(\mu\mu)/H(4\mu)$**
- Top-Yukawa coupling
  - 💡 Ratio $t\bar{t}H(b\bar{b})/t\bar{t}Z(b\bar{b})$
  - 💡 $t\bar{t}H(\gamma\gamma)$ channel
- Higgs self-coupling
  - ⭐ **$b\bar{b}\gamma\gamma$ channel**
  - ⚙️ **$b\bar{b}\tau\tau$ channel**
  - ⭐ $b\bar{b}ll+E_T^{miss}$ channel
- 💡 Higgs width measurement through VBF HWW off-shell
- 💡 Differential cross-sections as input to global fits
  - High pT ttbar production
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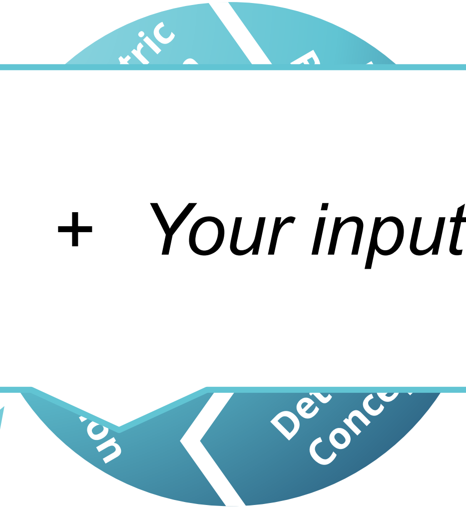

+ *Your input!*

Performance studies

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Organisation, resources & links

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

- Monthly (zoom) meetings Thursday's at 4PM (CERN time)
  - Next meeting? Increase frequency?
- Mailing lists: *fcc-ped-hh-espp25* , *fcc-ped-hh-physicsperformance-espp25*
- Mattermost:

Resources available on common software frameworks and tools

- FCC-hh P&P working group documentation page
- LINK TO RECORDING OF HANDS ON TUTORIAL
- LINK TO DATABASE OF EVENTS

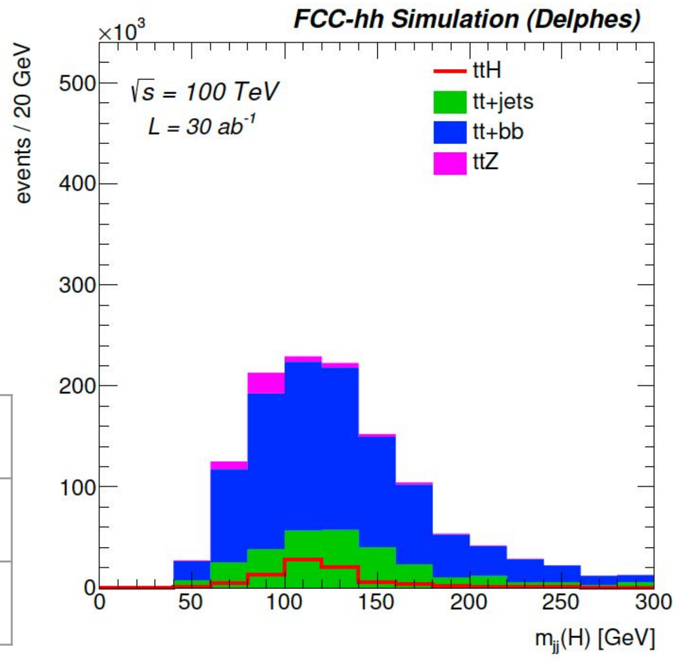
Higgs couplings: Top Yukawa coupling

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

Exploit the ratio of $\bar{t}tH$ over $\bar{t}tZ$ for syst. cancellation

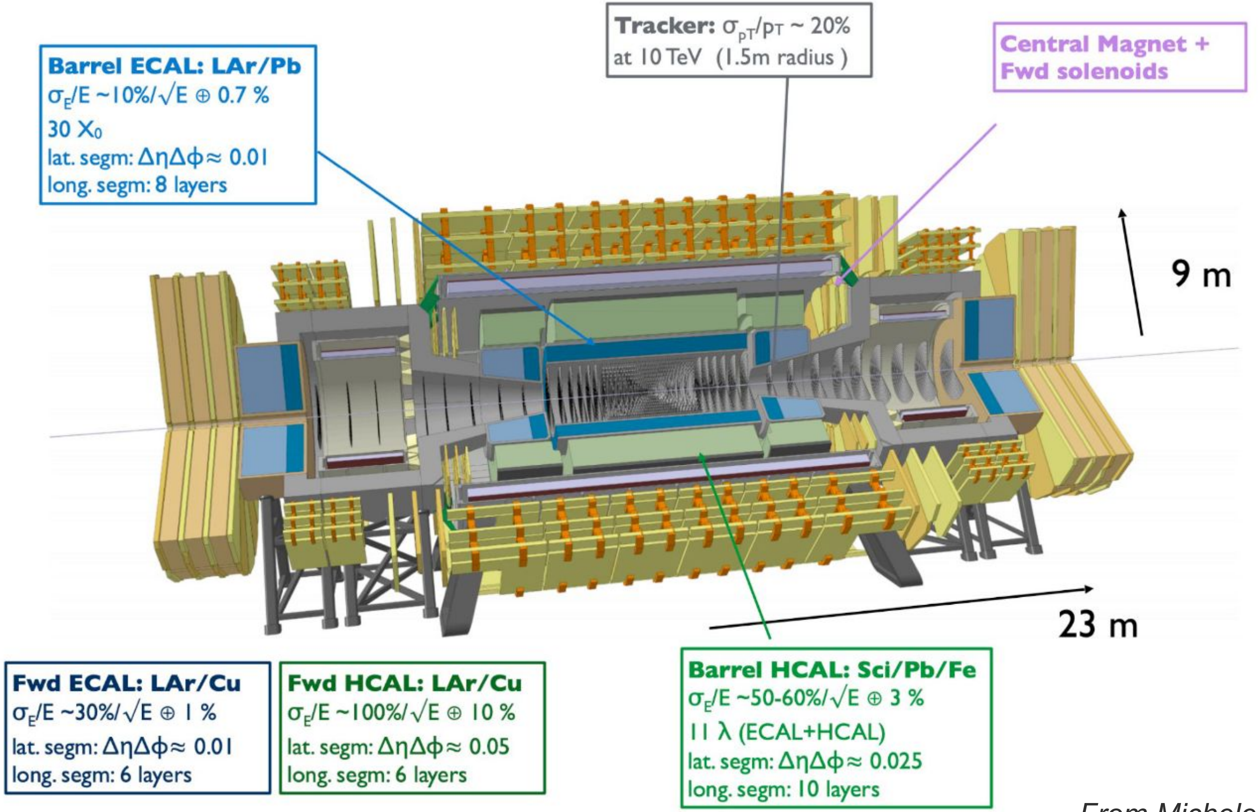
- Boosted top, $H \to \bar{b}b$ decays, $p_T(H,t)$ > 250 GeV
- Fit $\bar{t}tH$ and $\bar{t}tZ$ simultaneously with m_{jj} templates
- Assume precise measurement of $\bar{t}tZ$ from FCC-ee, and of backgrounds from control regions

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



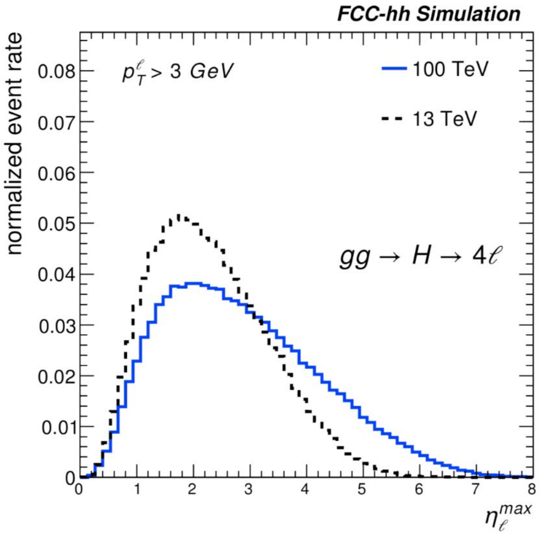
Same uncertainty scaling as on previous slide

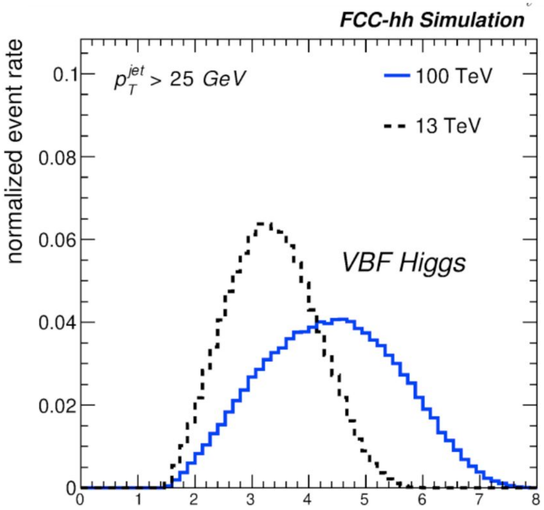
FCC-hh baseline detector concept



From Michele Selvaggi

FCC-hh baseline detector concept





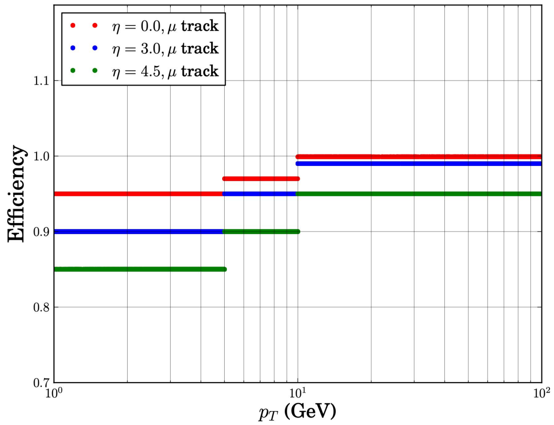
SM physics more forward at 100 TeV
→ Precision spectroscopy and calorimetry up to |η| < 4
→ Tracking and calorimetry up to |η| < 6

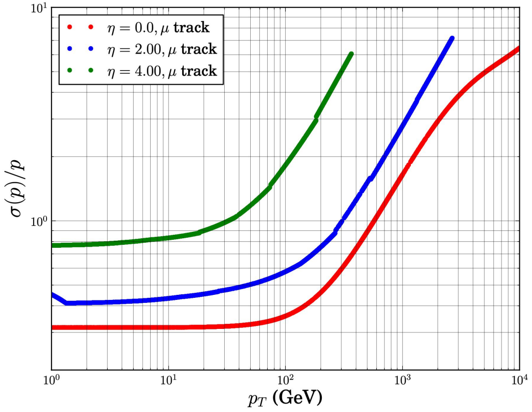
Delphes scenarios for FCC-hh

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

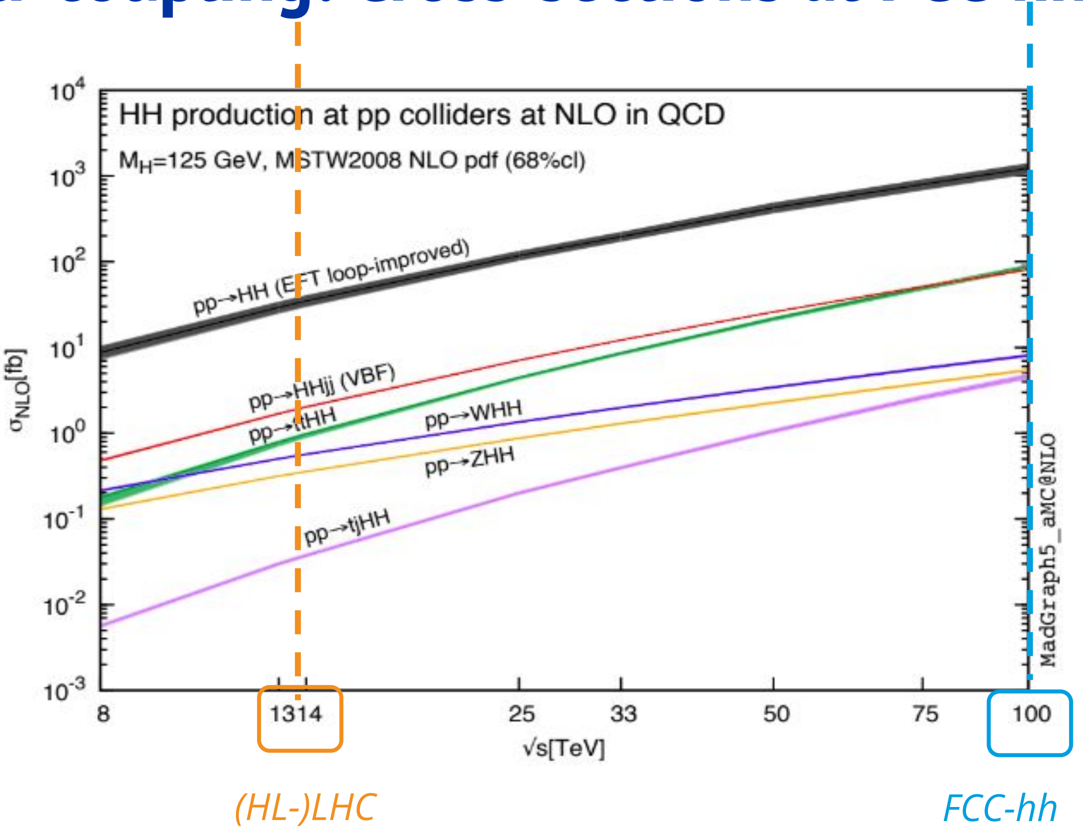
	Relative p resolution		Efficiency	
	Scenario I	Scenario II	Scenario I	Scenario II
Electrons	0.4-1%	0.8-3%	76-95%	72-90%
Muons	0.5-3%	1-6%	90-99%	88-97%
Medium b-tagging			80-90%	76-86%





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 self-coupling projections: Systematic uncertainties

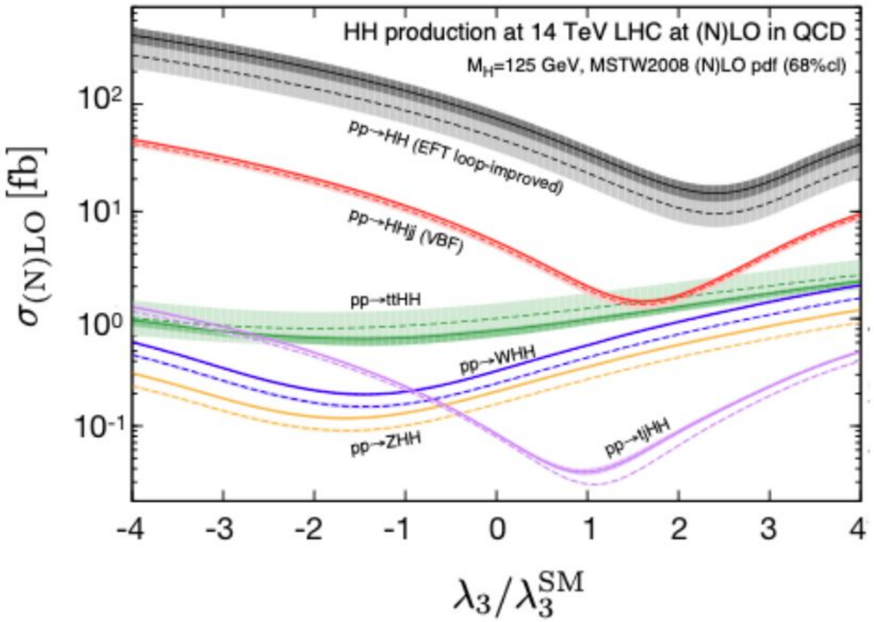
Source of uncertainty	Syst. 1	Syst. 2	Syst. 3	Applies to	Correlated
Common systematics					
b-jet ID / b-jet	0.5%	1%	2%	Signals, MC bkgs.	✓
Luminosity	0.5%	1%	2%	Signals, MC bkgs.	✓
Signal cross-section	0.5%	1%	1.5%	Signals, MC bkgs.	✓
$b\bar{b}\gamma\gamma$ systematics					
γ ID / γ	0.5%	1%	2%	Signals,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

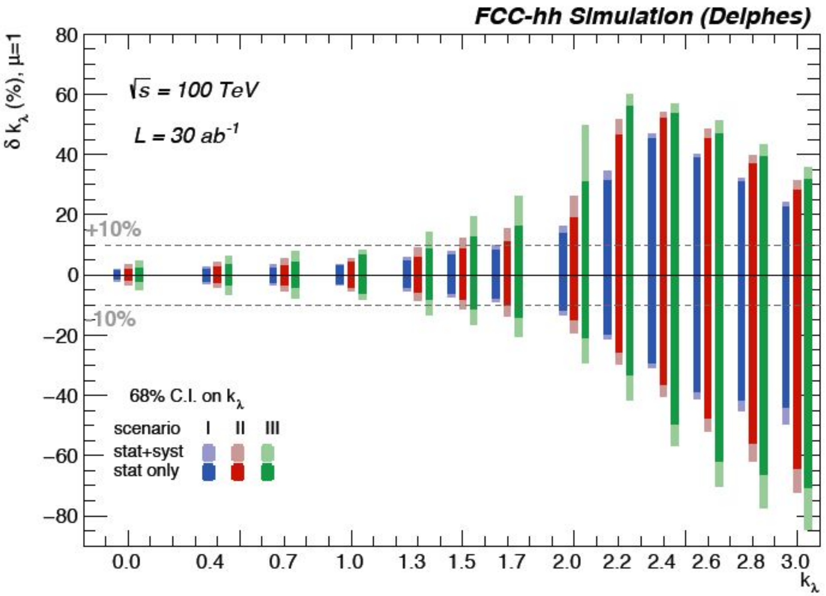
- Following previous di-Higgs studies@FCC-hh
- Applied as rate systematics only, no shape effect

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

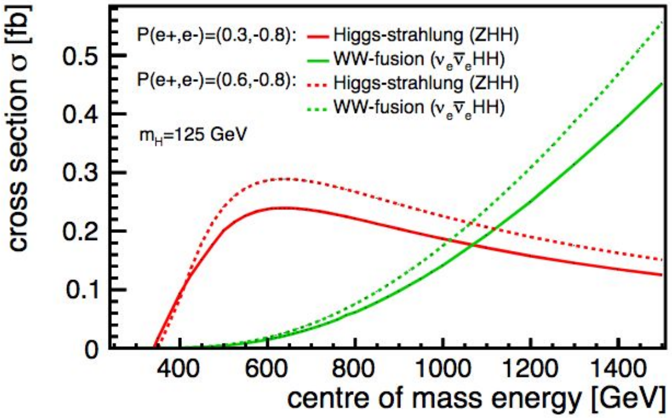
	80 TeV	100 TeV	120 TeV
No assumption on mbb	4.0% - st. only 3.6%	3.5% - st. only 3.4%	3.1% - st. only 2.8%
mbb res 10 GeV	2.5% - st. only 2.3%	2.2% - st. only 2.0%	1.9% - st. only 1.7%
mbb res 5 GeV	2.0% - st. only 1.9%	1.8% - st. only 1.6%	1.6% - st. only 1.4%
mbb res 3 GeV	1.8% - st. only 1.7%	1.6%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

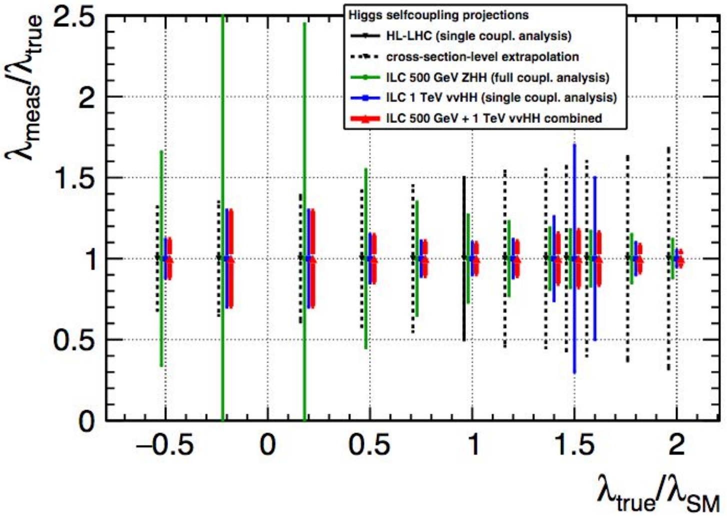
Di-Higgs cross-section dependance on κ_λ in pp-collisions





Higgs self-coupling @ ILC



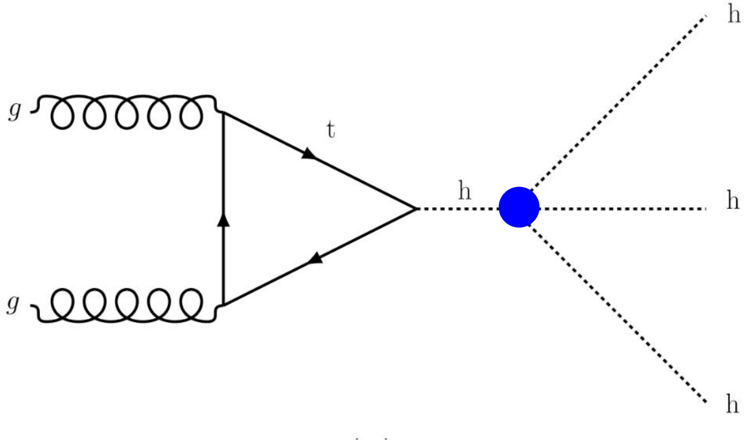


- Two production modes:
  - Higgsstrahlung, peaks ~500 GeV
  - WW-fusion, above ~1 TeV
  - → need runs at both energies for maximum κ_λ precision

- 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

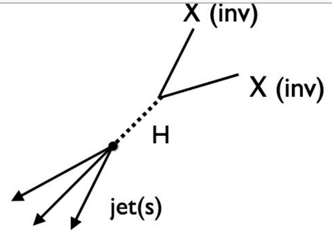
Again ~ O(100) smaller than the *HH* cross-section

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

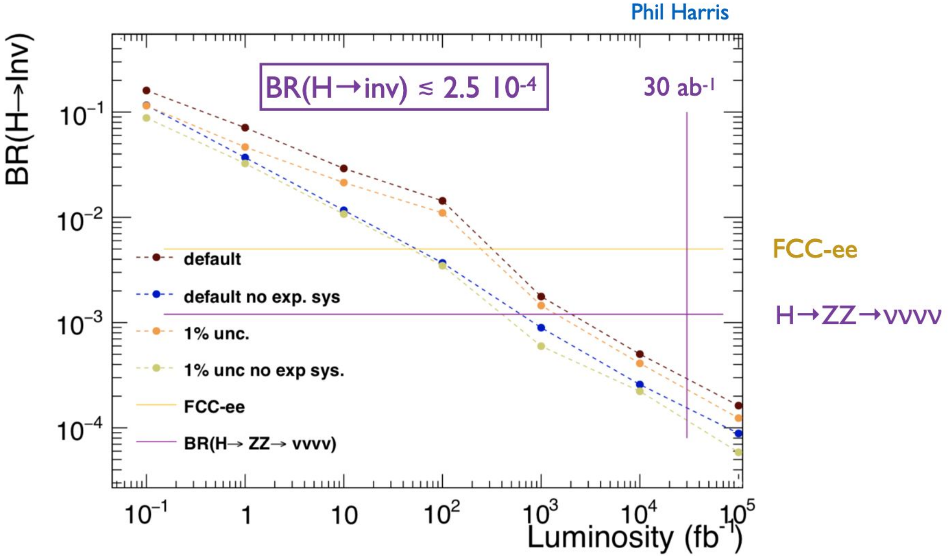
Number of selected signal events ~O(100)

Combining several channels 3σ may be reached

H→invisible



- Measure it from H + X at **large p_T(H)**
- Fit the E_T^{miss} spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z,W and γ spectra (low stat)
- Estimate Z→νν (W→lν) from Z→ee/μμ (W→lν) control regions (high stat).



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From M. Selvaggi