Higgs Physics at FCC-hh

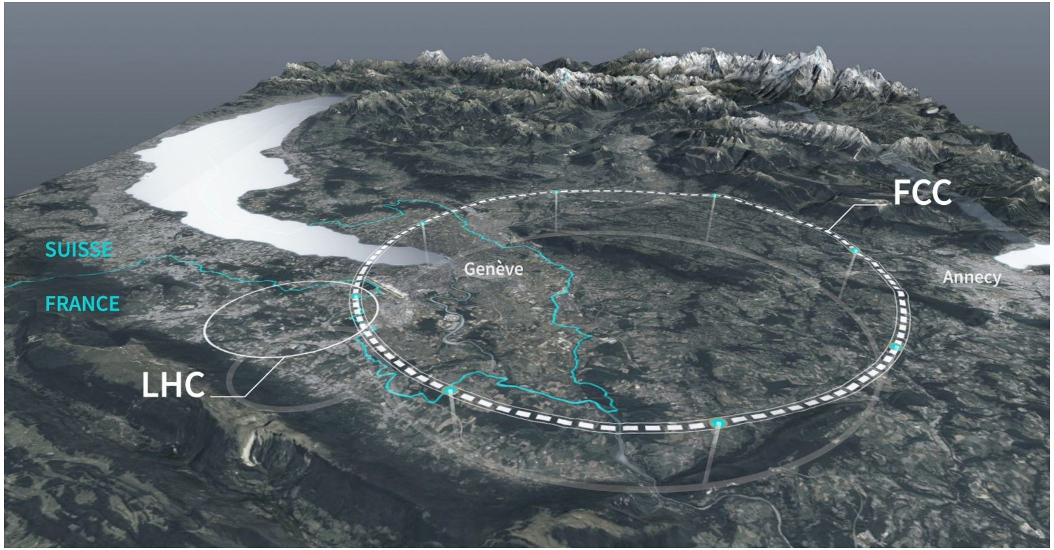
Birgit Stapf

05.11.2024 | Higgs 2024 | Uppsala

Introduction

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

- FCC feasibility study is ongoing, midterm review recently concluded
- Baseline tunnel ~ 91 km



Introduction

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

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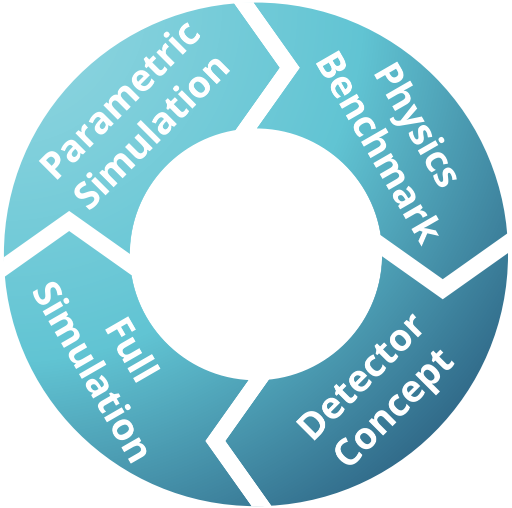
Main limitations for FCC-hh from dipole magnets, synchrotron radiation and extreme levels of pile-up → alternative FCC-hh running scenarios under study to the CDR baseline plan of 30 ab^{-1} @ 100 TeV

	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*

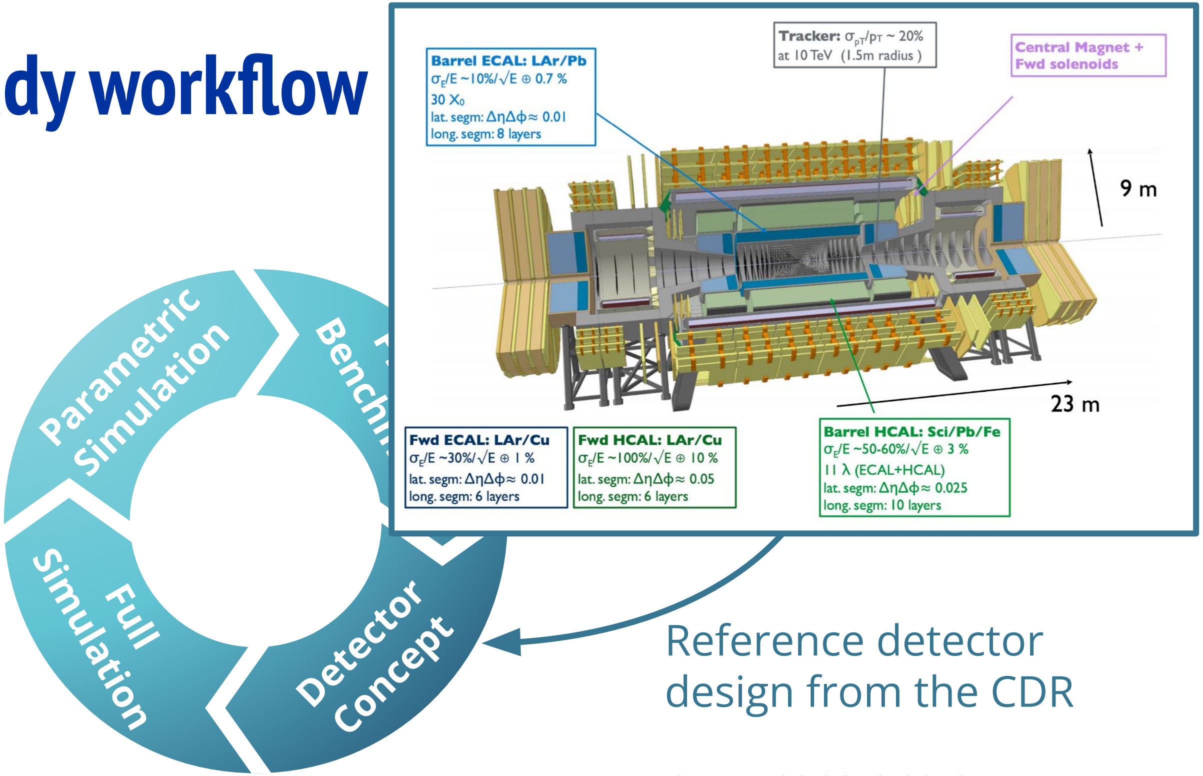
F. Zimmermann

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

FCC-hh projection study workflow



FCC-hh projection study workflow

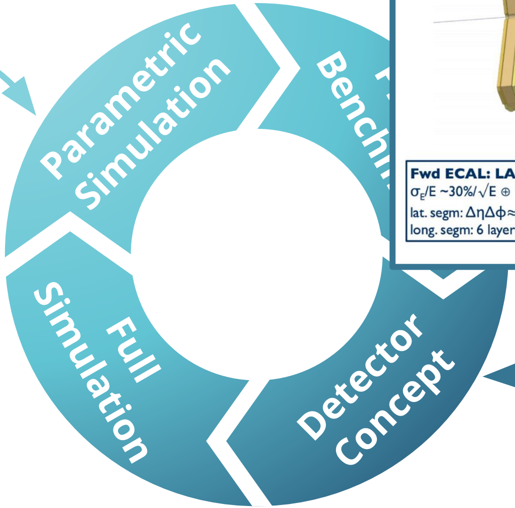


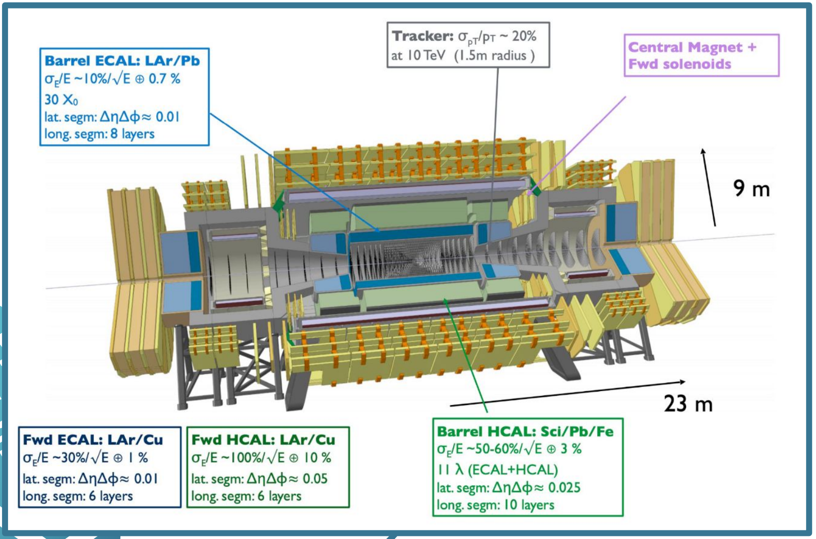
Reference detector design from the CDR

CERN-ACC-2018-0058

FCC-hh projection study workflow

DELPHES
fast simulation





Efficiencies & resolutions as functions of p_T and η

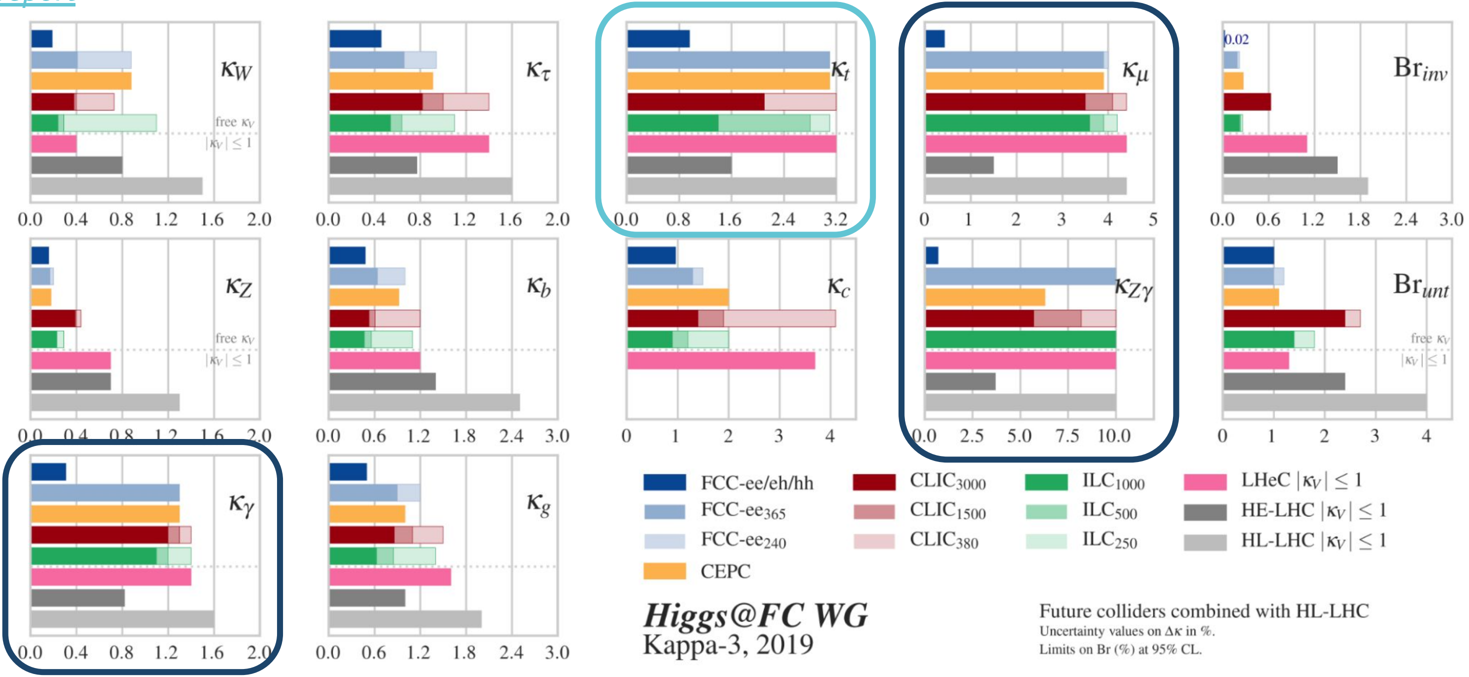
- Official FCC-hh scenarios
- Rely on common software stack: key4hep
- Note: No direct pile-up overlay, assume LHC levels in the parametrizations

Reference detector design from the CDR

CERN-ACC-2018-0058

FCC-hh complementary to Higgs @ FCC-ee: Single Higgs

Granada report

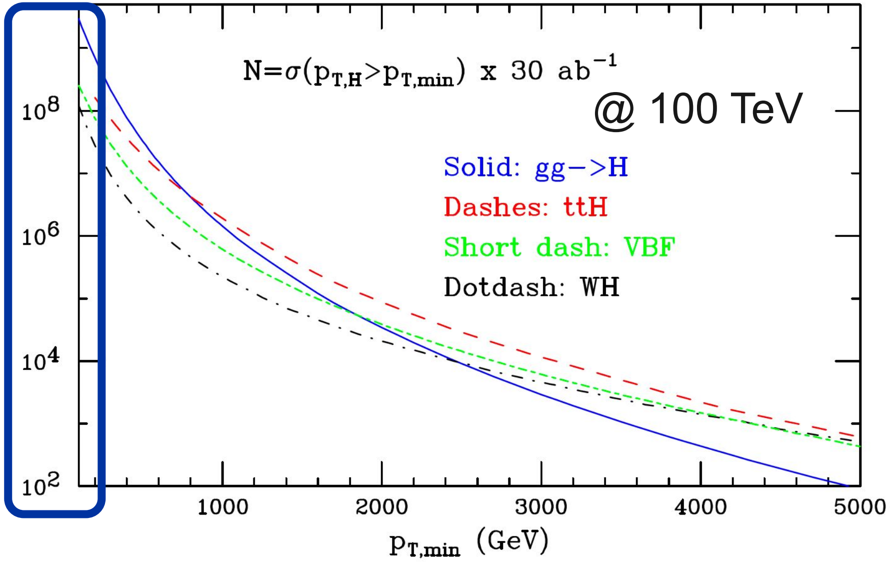


Significant precision improvements in couplings measurements in rare decay modes that remain (statistically) limited at **FCC-ee**/**HL-LHC**, or are not directly accessible at **FCC-ee**

Higgs couplings: Precision for rare decay modes

CERN-ACC-2018-0045

Expected number of Higgses



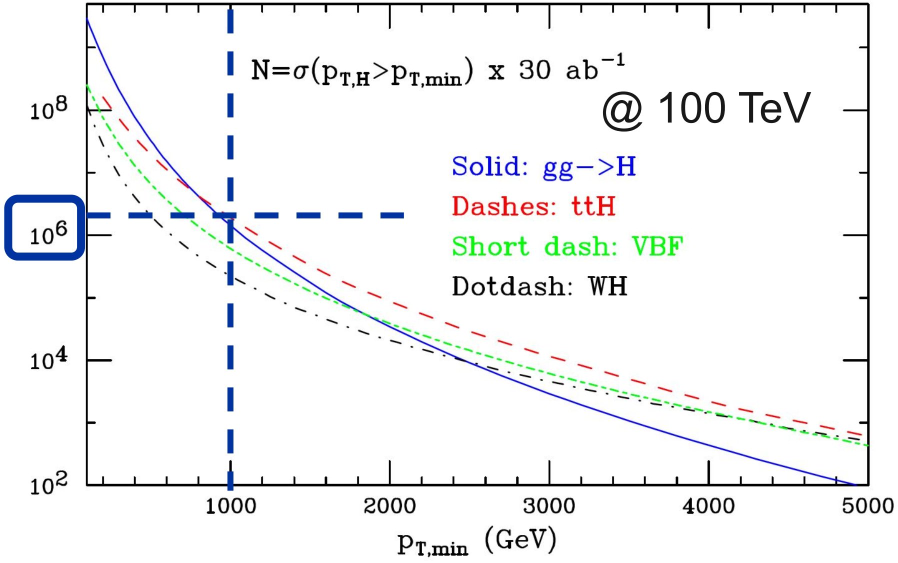
In total ~ 10^{10} single Higgs (and ~ 10^{7} Higgs pair) events expected

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: Precision for rare decay modes

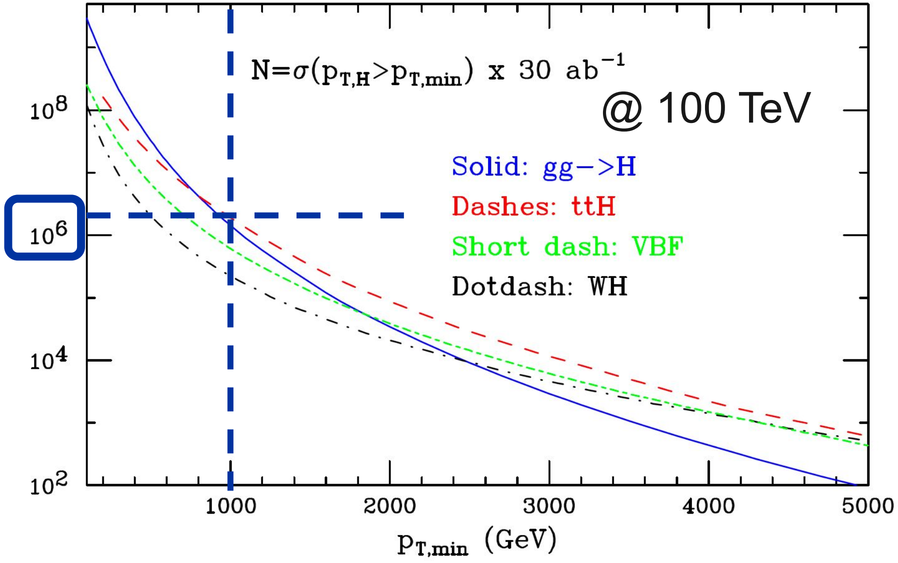
CERN-ACC-2018-0045

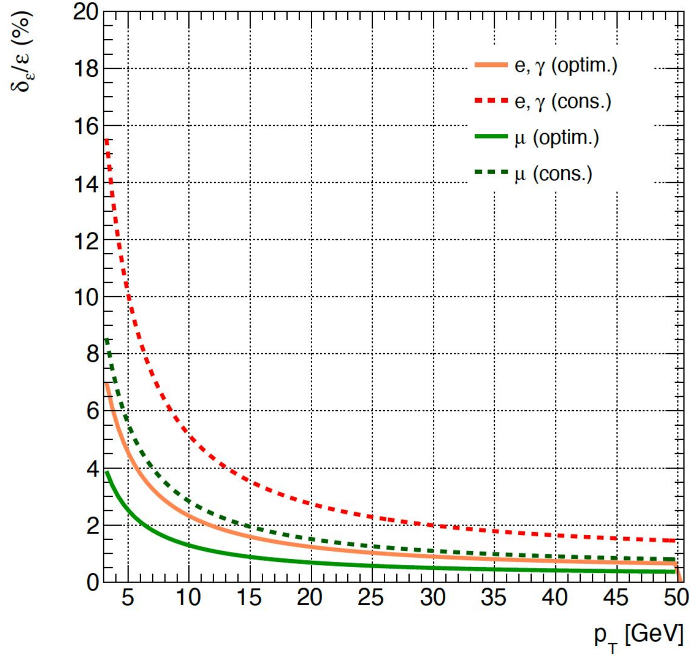


Systematic uncertainties will dominate
But: Large statistics even at high p_T ...

Higgs couplings: Precision for rare decay modes

CERN-ACC-2018-0045





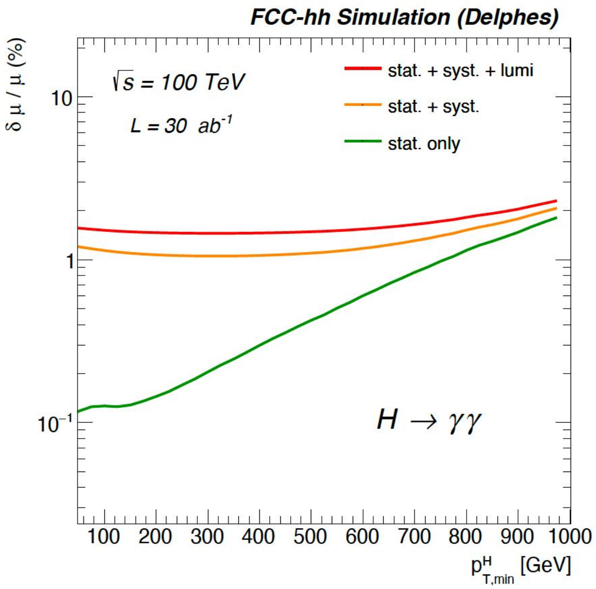
Systematic uncertainties will dominate
But: Large statistics even at high p_T …

… where experimental systematic uncertainties on efficiencies are smaller

Higgs couplings: Precision for rare decay modes

CERN-ACC-2018-0045

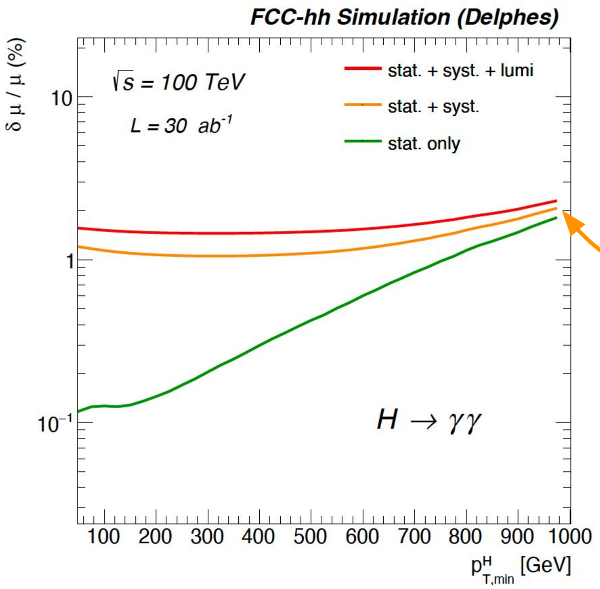
Signal strength precision



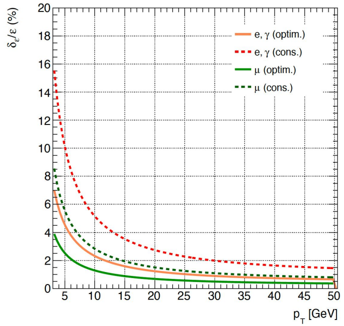
Higgs couplings: Precision for rare decay modes

CERN-ACC-2018-0045

Signal strength precision



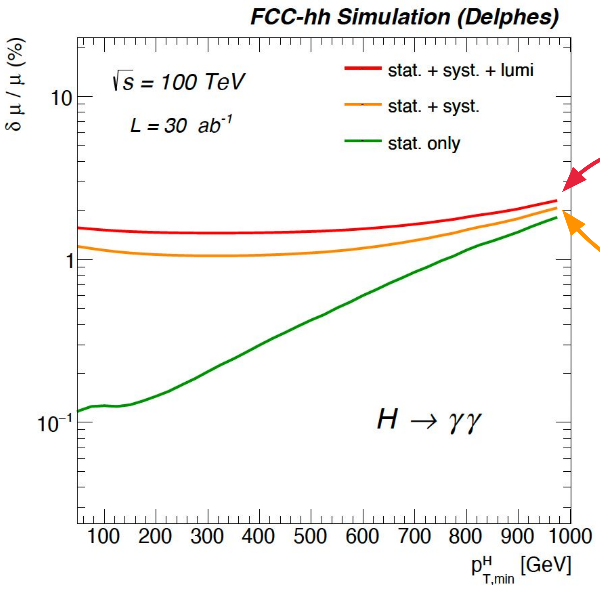
With efficiency uncertainties



Higgs couplings: Precision for rare decay modes

CERN-ACC-2018-0045

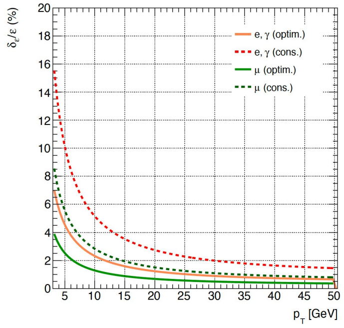
Signal strength precision



With additional flat uncertainties

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

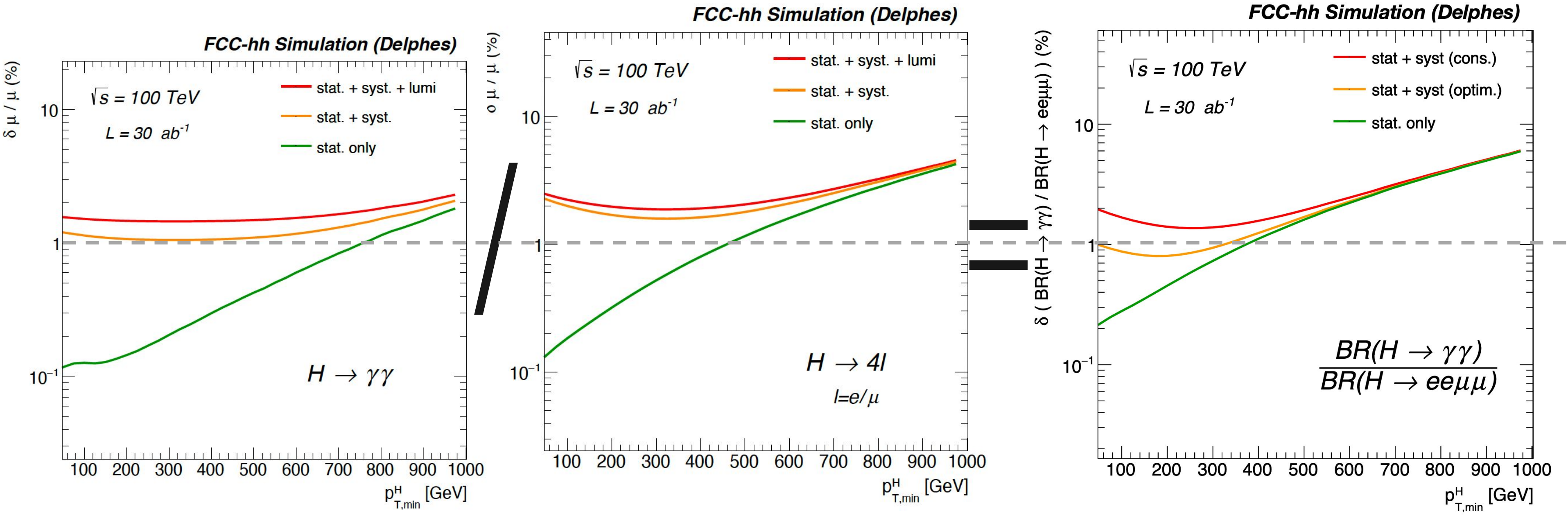
With efficiency uncertainties



Higgs couplings: Precision for rare decay modes

CERN-ACC-2018-0045

Signal strength precision *BR ratio precision*

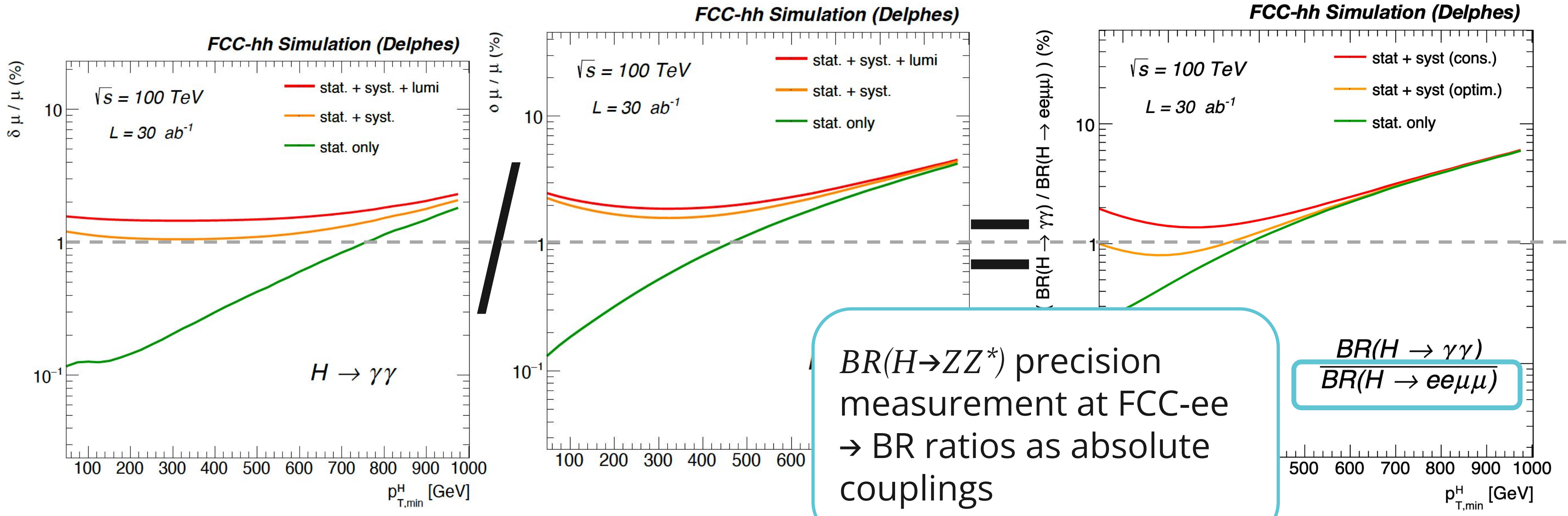


Systematic uncertainties (partially) cancel in ratio

Higgs couplings: Precision for rare decay modes

[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: Precision for rare decay modes

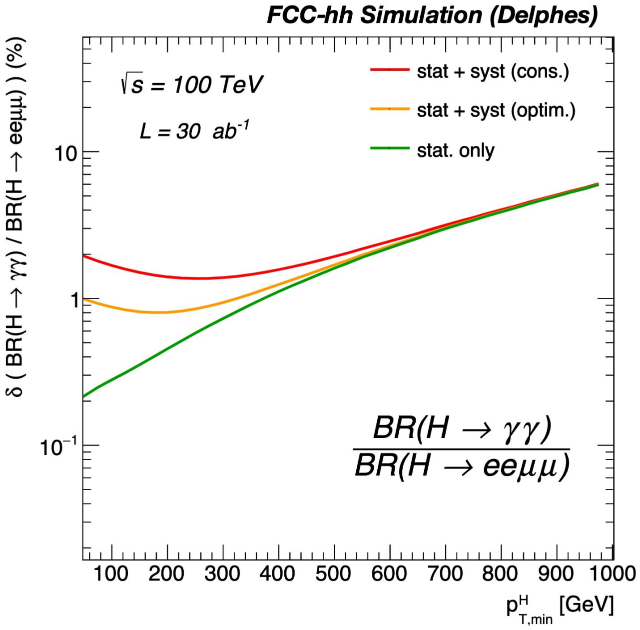
M. Mangano at FCC physics workshop

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

- 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



Rerunning the analyses is a work in progress

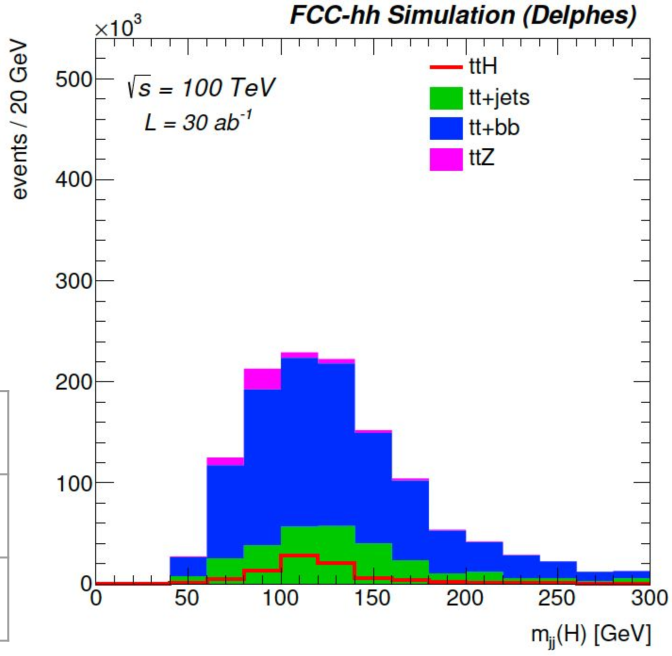
Higgs couplings: Top Yukawa coupling

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

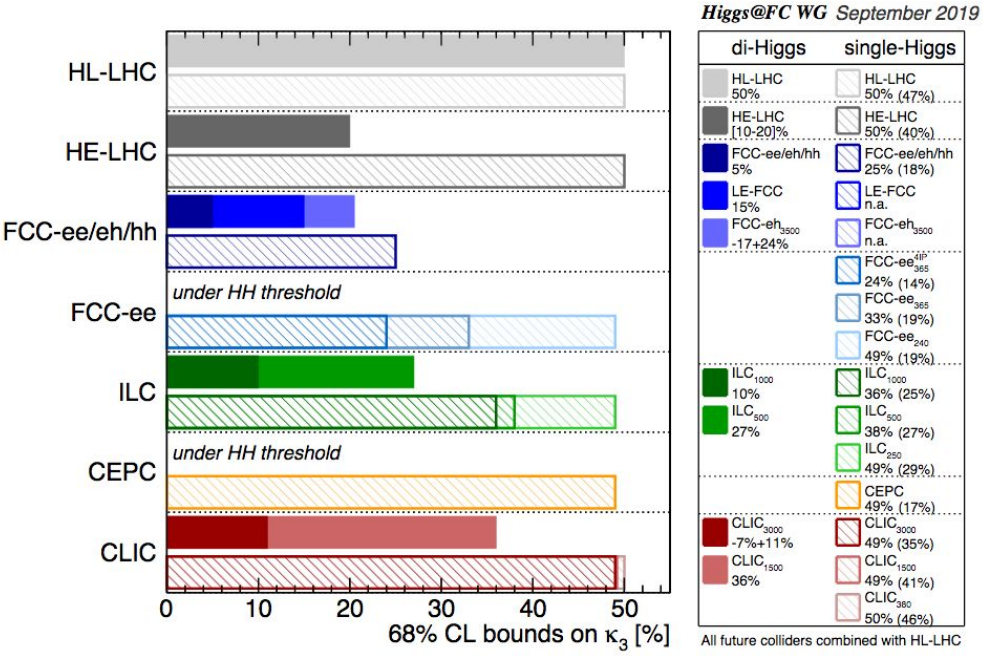
	Precision in %		
Coupling	80 TeV	100 TeV	120 TeV
$\delta g_t / g_t$	1.2	1	0.85



Same uncertainty scaling as on previous slide

Higgs self-coupling precision measurements

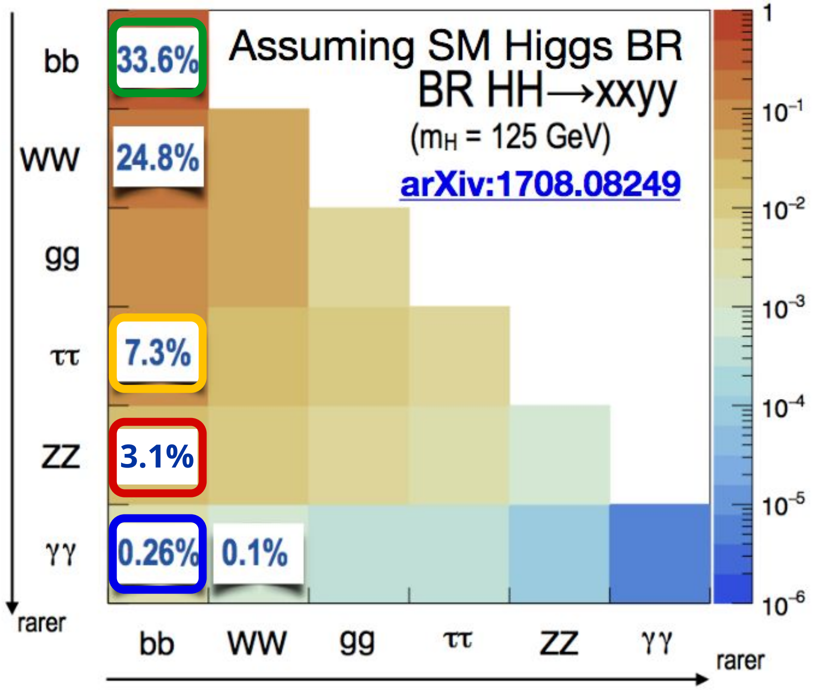
[Granada report]

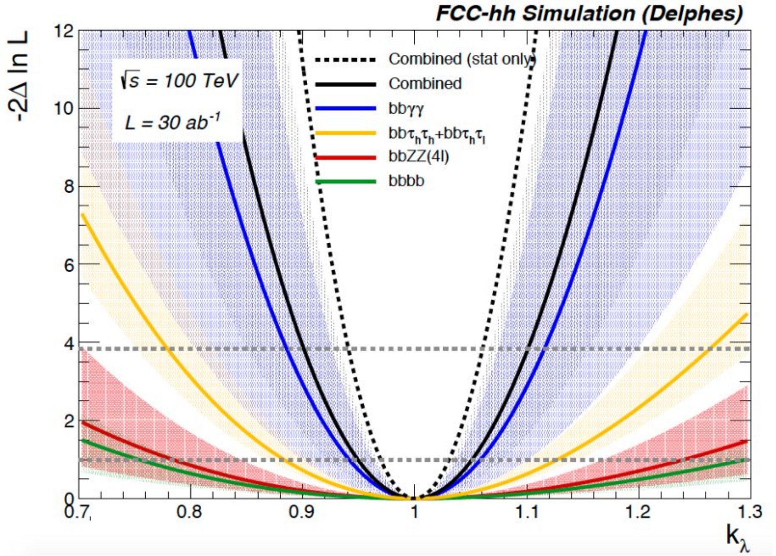


Large dataset & increased cross-section at baseline CDR FCC-hh offers %-level κ_λ precision

Higgs self-coupling precision measurements

CERN-TH-2020-052

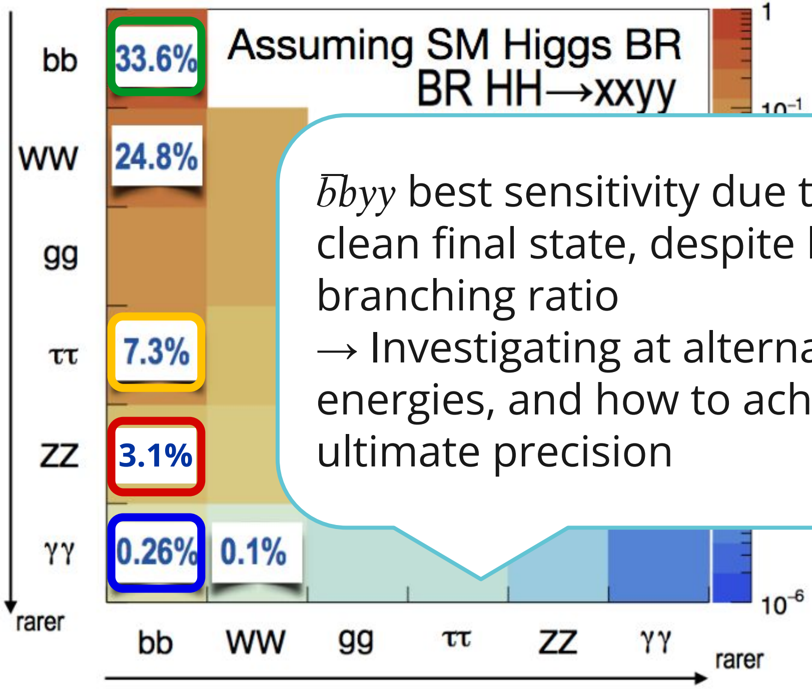




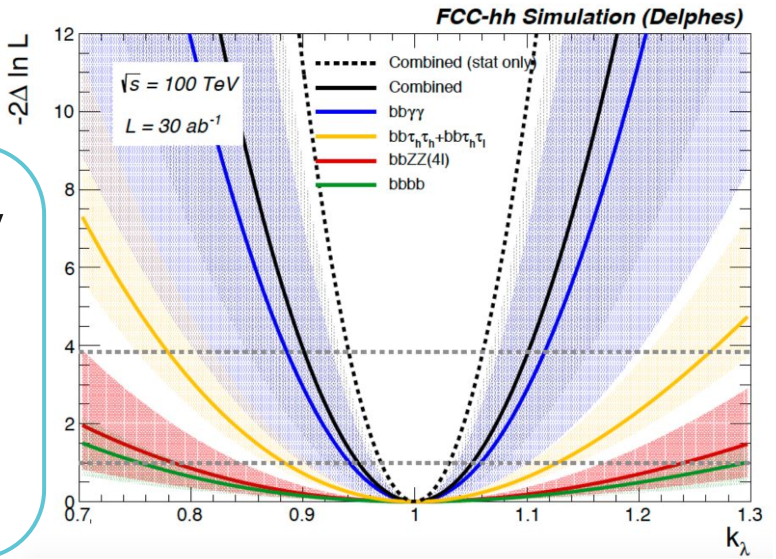
	Combined precision
$\delta\kappa_\lambda$ (68% CL)	3.0% - 7.8%

Higgs self-coupling precision measurements

CERN-TH-2020-052



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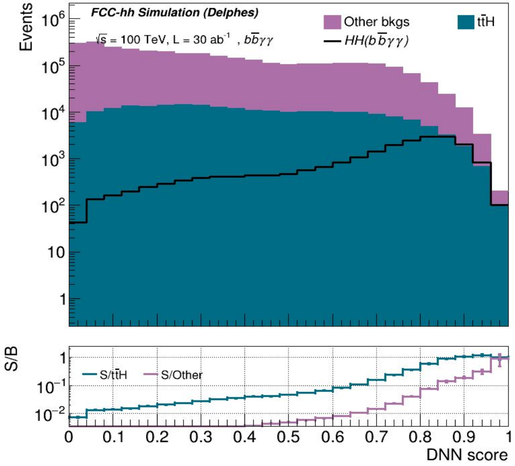
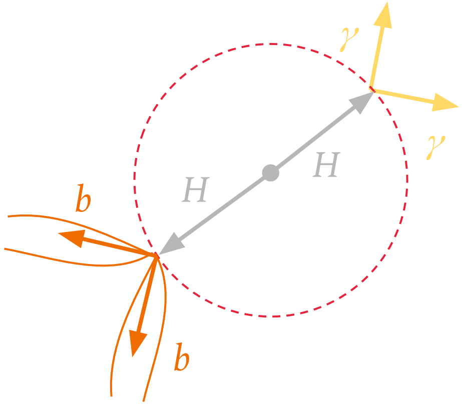
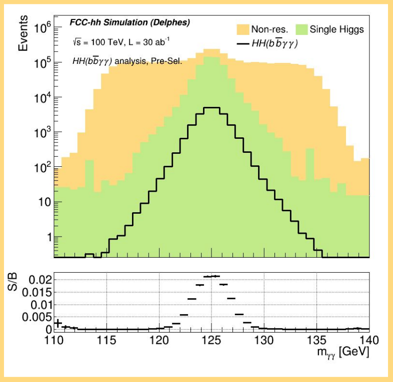
Re-optimized $\bar{b}b\gamma\gamma$ analysis strategy

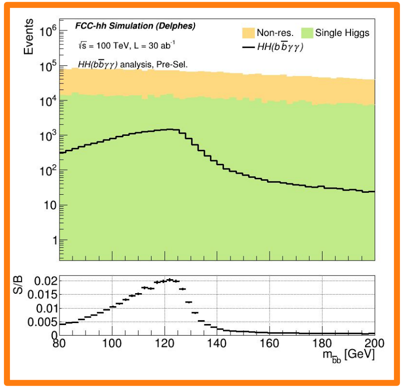
[A. Taliercio, P. Mastrapasqua, B.Stapf at FCC-hh ESPP meeting]

Pre-selected events → DNNs categorization to suppress the bkg





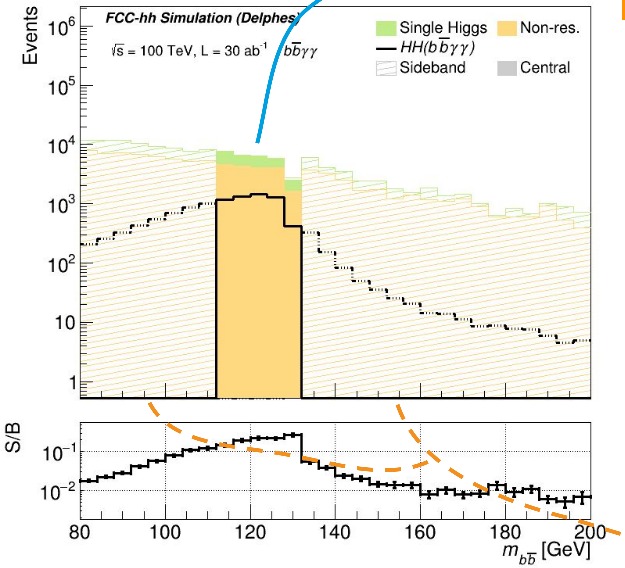


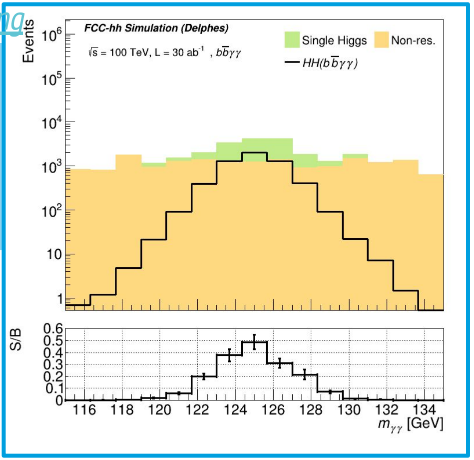


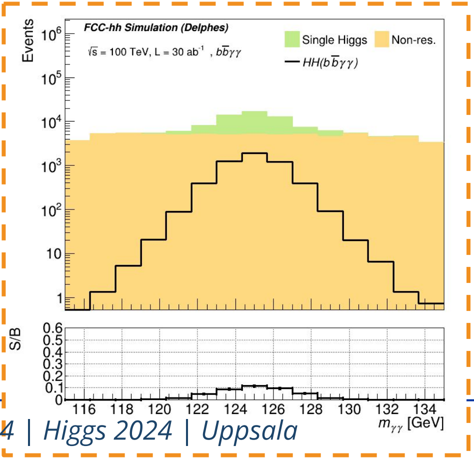
- Backgrounds:
  - Non-resonant QCD: ***γγ***+jets and ***γ***+jets
  - Single Higgs production

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

[A. Taliercio, P. Mastrapasqua, B.Stapf at FCC-hh ESPP meeting](#)







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

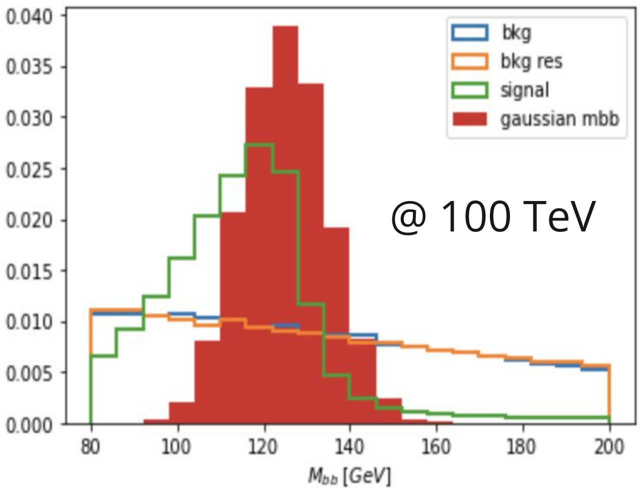
Sideband

Central region

Fit $m_{\gamma\gamma}$

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

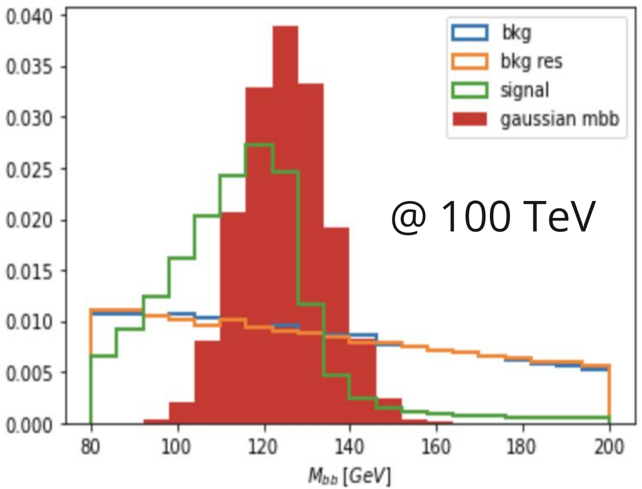
A. Taliercio, P. Mastrapasqua, B.Stapf at FCC-hh ESPP meeting



	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%

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

A. Taliercio, P. Mastrapasqua, B.Stapf at FCC-hh ESPP meeting



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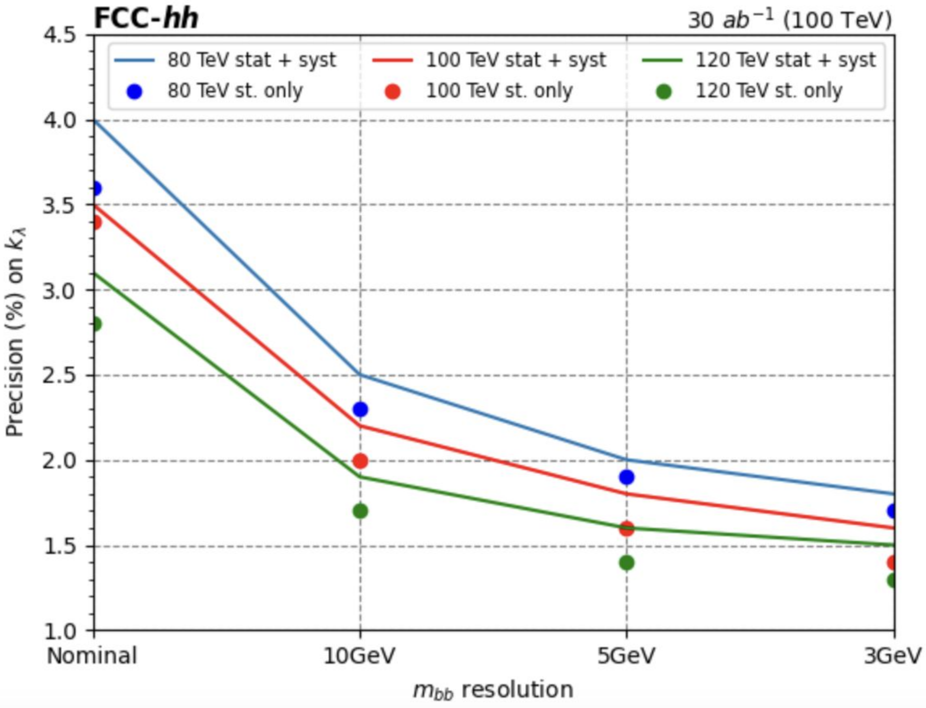
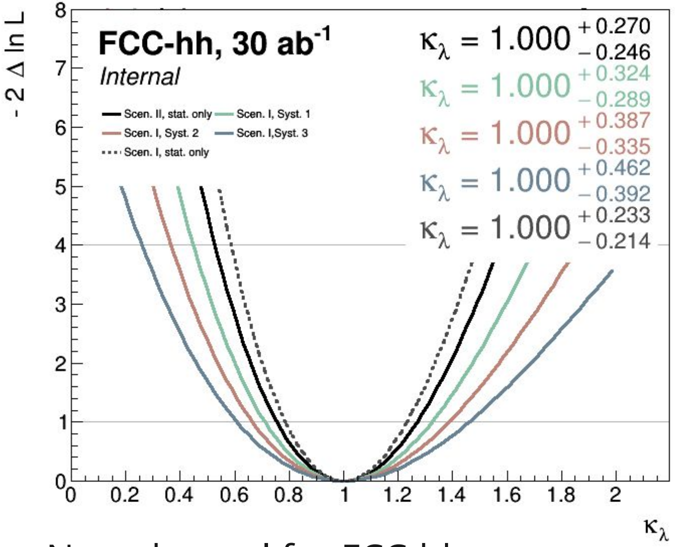


Impact of m_{bb} resolution is critical

Higgs self-coupling: Other final states

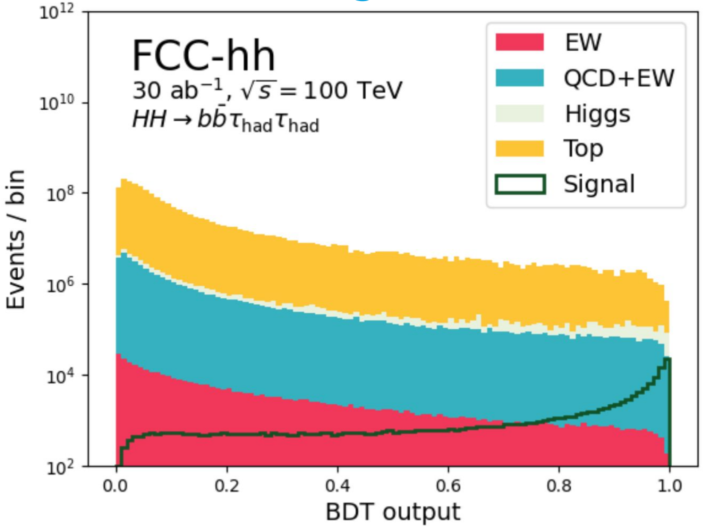
$\bar{b}bll{+}E_T^{miss}$ @ 100 TeV



New channel for FCC-hh, more complex final state involving E_T^{miss}

B.Stapf et al at FCC Physics workshop

$\bar{b}b\tau\tau$ @ 100 TeV



Re-optimising $\bar{b}b\tau\tau$ analysis with GNNs

M. D'Onofrio et al at FCC-hh ESPP meeting

Summary & outlook

FCC-hh offers great potential for high-precision Higgs physics, complementary to FCC-ee

- Higgs self-coupling, couplings in rare decay modes and the top Yukawa coupling

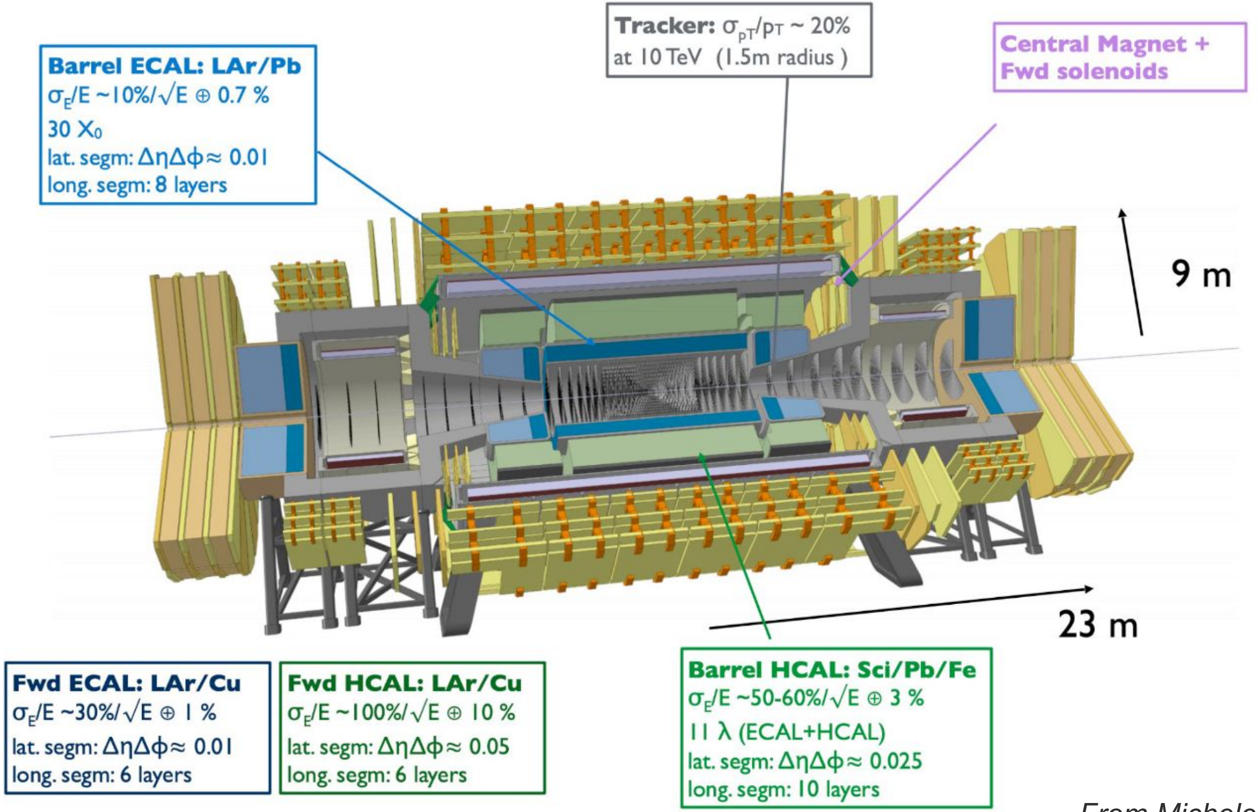
Ongoing effort to update the FCC-hh projections for European Strategy update next summer with many exciting opportunities to join (see M. Selvaggi at kick-off meeting)

- Alternative centre-of-mass energies under study
  - Focus on Higgs self-coupling & single Higgs branching ratios
- Optimizing analysis techniques & adding previously not-studied channels
  - New channels: $H \to WW$, $H \to \tau\tau$, $H \to c\bar{c}$ through ratios
- Moving towards more realistic detector simulation, impact of pile-up scenarios

If you are interested, join our team!

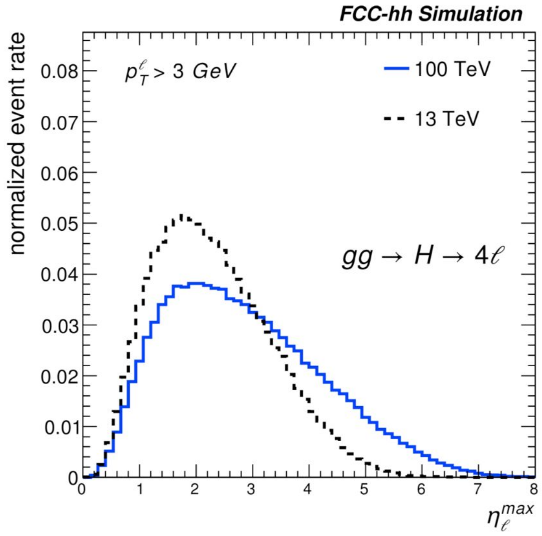
- FCC-hh P&P working group documentation page
- Mailing lists: *fcc-ped-hh-espp25* , *fcc-ped-hh-physicsperformance-espp25*

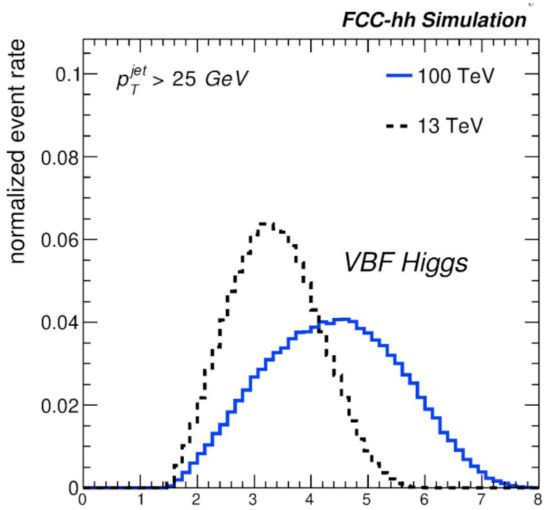
FCC-hh baseline detector concept



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 $|\eta| < 6$

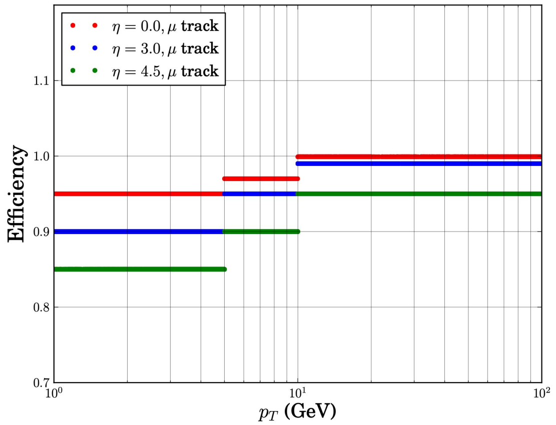
Delphes scenarios for FCC-hh

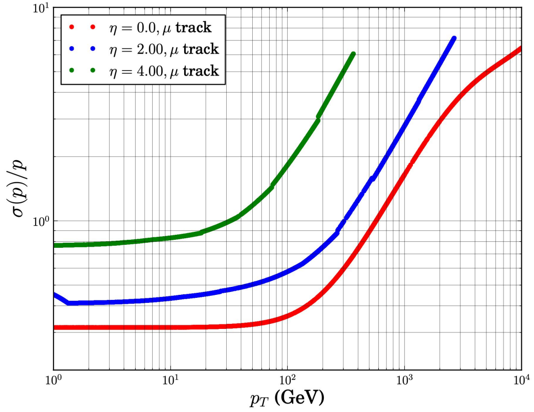
- Two current Delphes scenarios for FCC-hh:
  - Scenario I: Idealistic scenario for ultimate precision
  - Scenario II: Baseline scenario based on FCC-hh detector concept from CDR

	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%

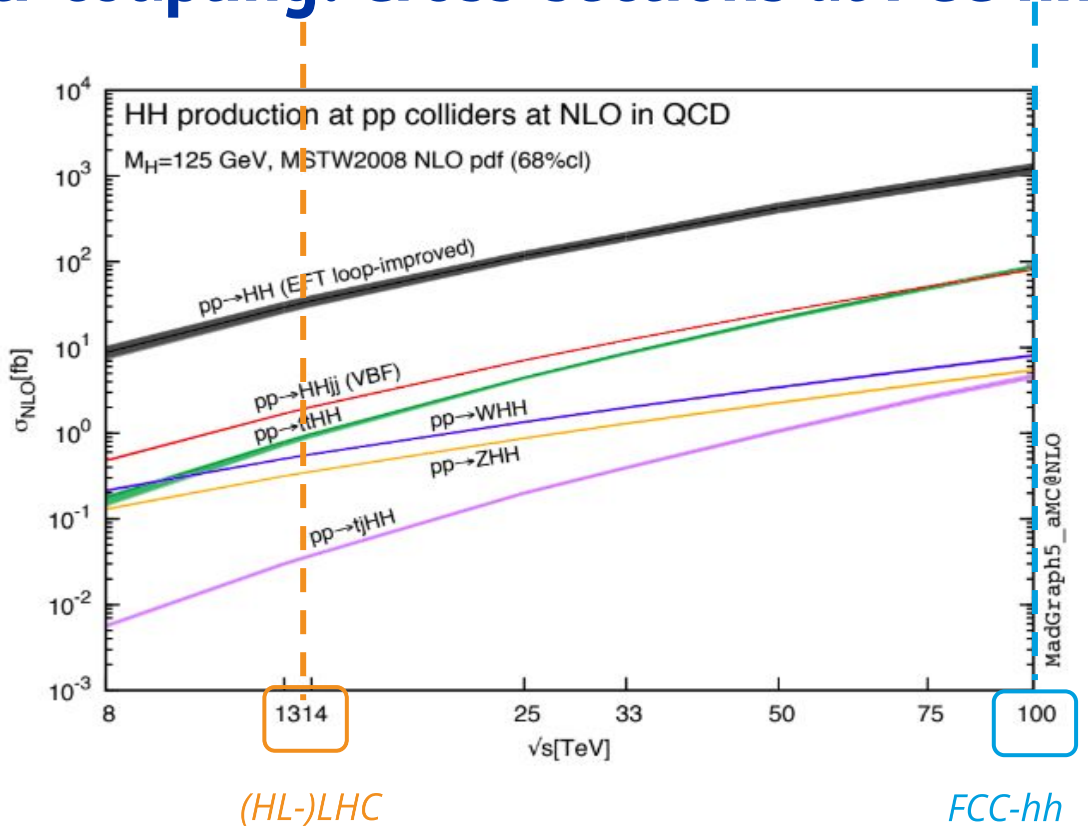
Note: Both scenarios implement fixes w.r.t the original, e.g. bremsstrahlung for electrons, multiple scattering, resolutions in forward region

Example parametrization for muons





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



Higgs self-coupling projections: Systematic uncertainties

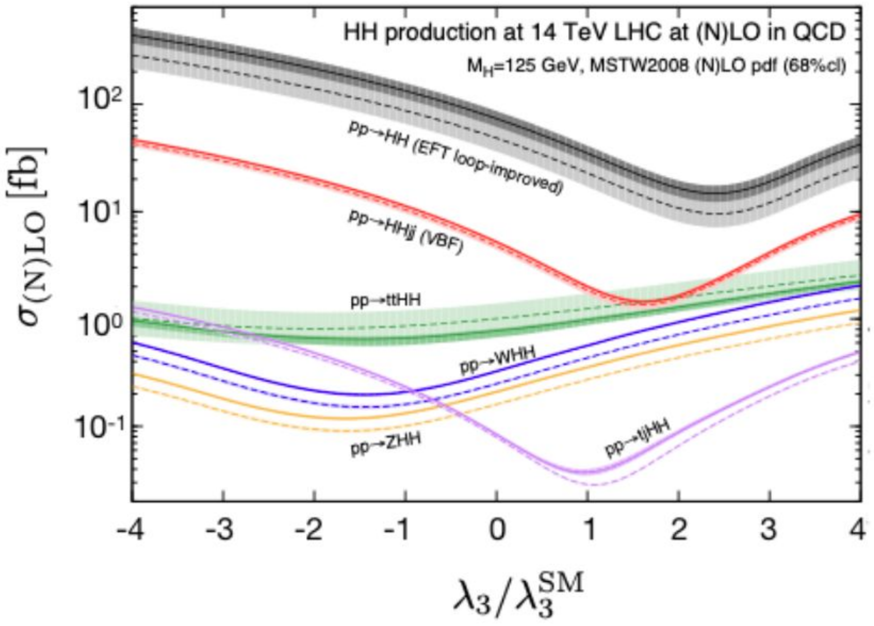
Source of uncertainty	Syst. 1	Syst. 2	Syst. 3	Applies to	Correlated
Common systematics					
b-jet ID / b-jet	0.5%	1%	2%	Signals, MC bkgs.	✓
Luminosity	0.5%	1%	2%	Signals, MC bkgs.	✓
Signal cross-section	0.5%	1%	1.5%	Signals, MC bkgs.	✓
$b\bar{b}\gamma\gamma$ systematics					
γ ID / γ	0.5%	1%	2%	Signals, 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%	$t\bar{t}$	✗

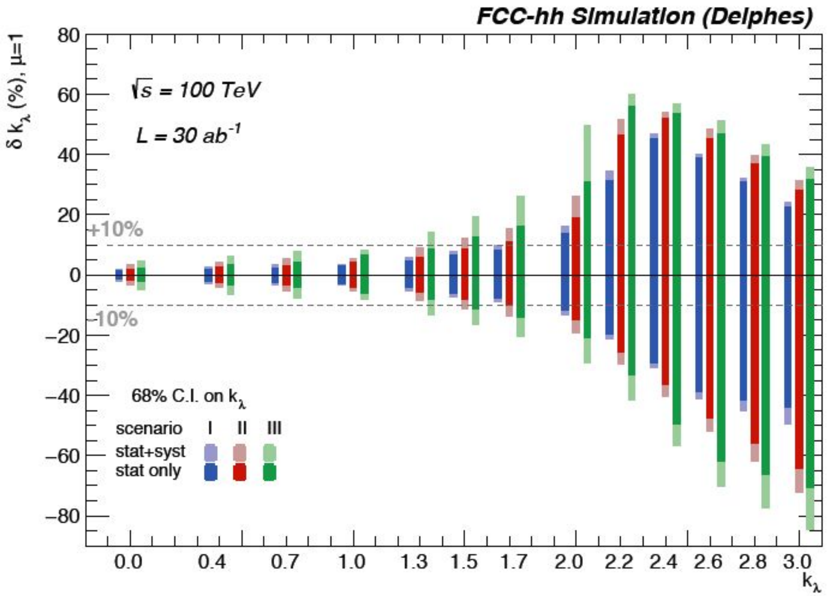
- Following previous di-Higgs studies@FCC-hh
- Applied as rate systematics only, no shape effect

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

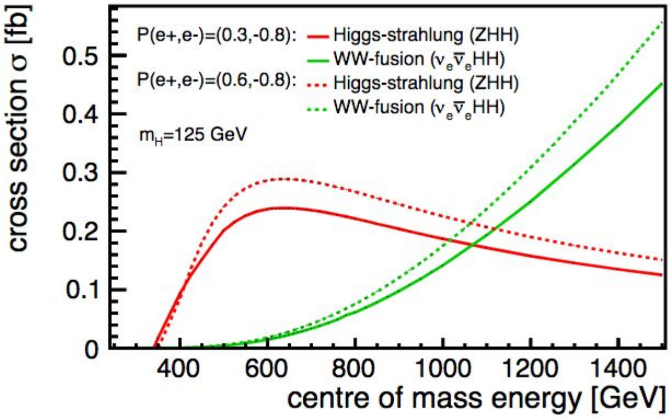
	80 TeV	100 TeV	120 TeV
No assumption on mbb	4.0% - st. only 3.6%	3.5% - st. only 3.4%	3.1% - st. only 2.8%
mbb res 10 GeV	2.5% - st. only 2.3%	2.2% - st. only 2.0%	1.9% - st. only 1.7%
mbb res 5 GeV	2.0% - st. only 1.9%	1.8% - st. only 1.6%	1.6% - st. only 1.4%
mbb res 3 GeV	1.8% - st. only 1.7%	1.6%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

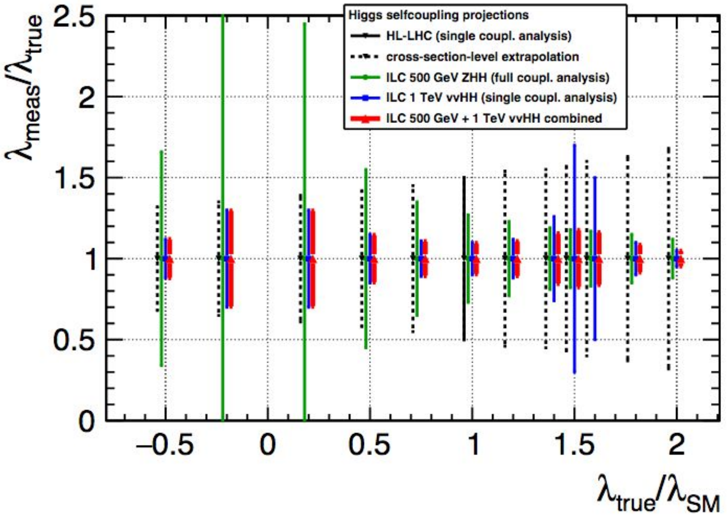
Di-Higgs cross-section dependance on κ_λ in pp-collisions





Higgs self-coupling @ ILC



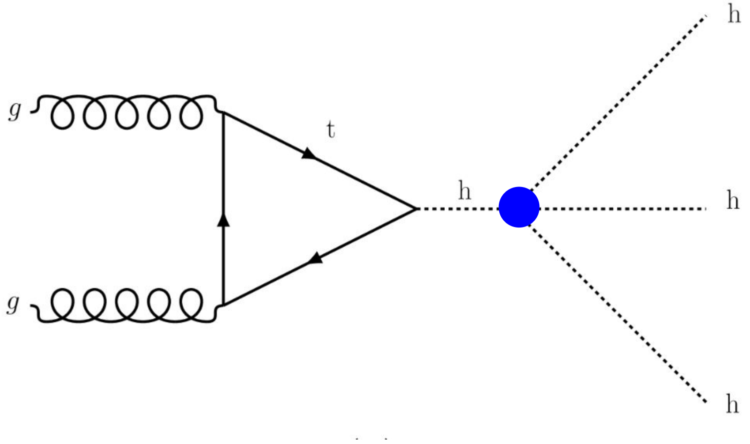


- Two production modes:
  - Higgsstrahlung, peaks ~500 GeV
  - WW-fusion, above ~1 TeV
  - → need runs at both energies for maximum κ_λ precision

- 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

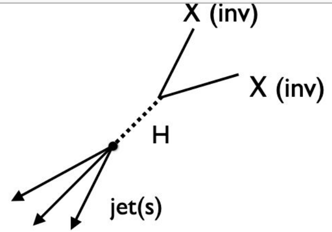
Again ~ O(100) smaller than the *HH* cross-section

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

Number of selected signal events ~O(100)

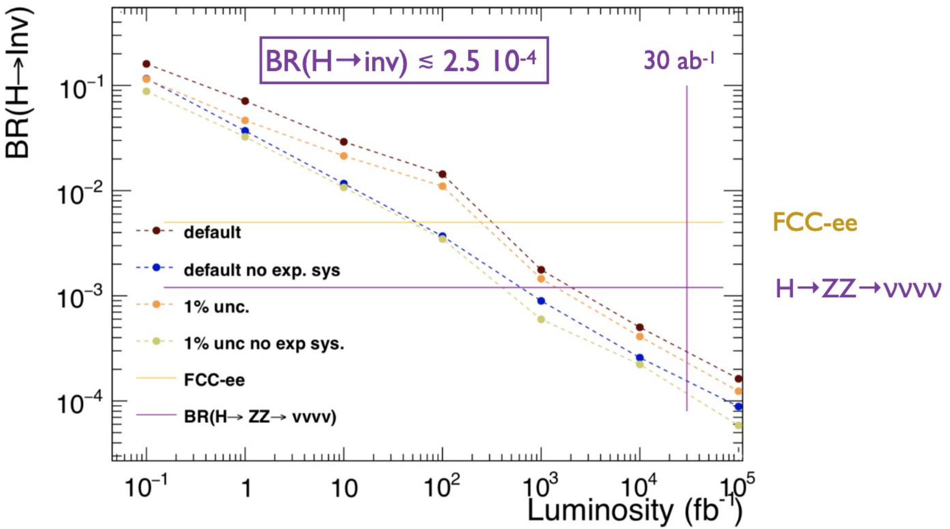
Combining several channels 3σ may be reached

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).

Phil Harris



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From M. Selvaggi