HIGGS BOSON SELF-COUPLING AT FCC-EE

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Outline of the presentation

- Importance of the Higgs self coupling
  - *Methods of measuring the self coupling and considered processes*
- Categorization
  - *240 GeV*
    - Discuss Z($\mu^+\mu^-$)H and Z($b\bar{b}$)H
  - *365 GeV*
    - Neutral VBF
- Combined analysis
- Conclusions and next steps

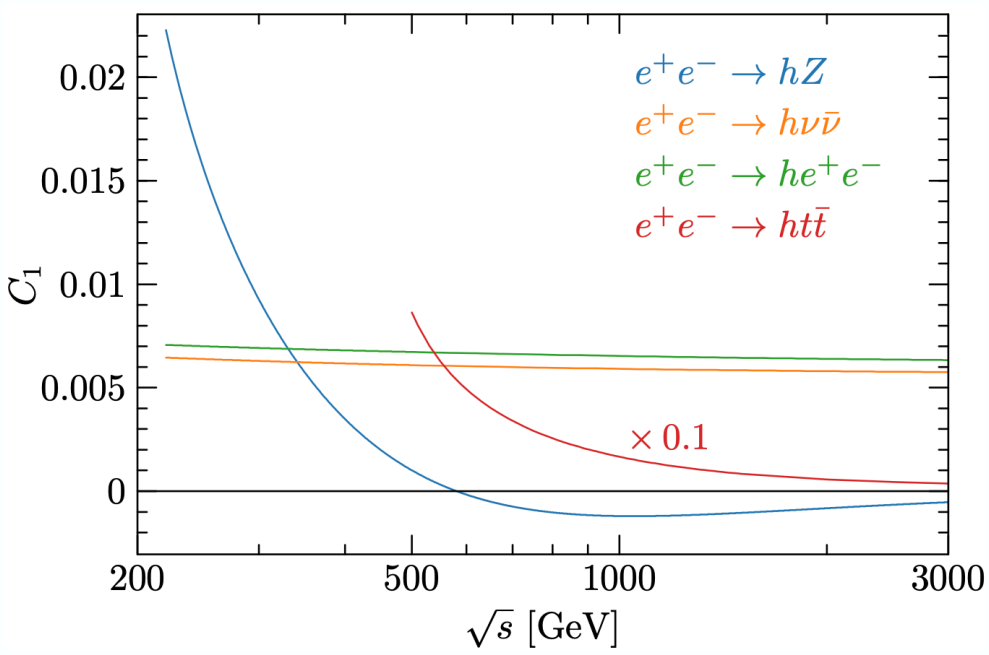
arXiv: 1711.03978
arXiv: 1607.04251

Importance of the Higgs self coupling

- Measuring the tri- and quadrilinear self coupling of the Higgs crucial to understand the EWSB
- Parametrize deviations from SM trilinear coupling with κ_λ
- At FCC-ee: Indirect access to κ_λ in ZH and VBF via NLO EWK corrections
- Consider two energy points (240 and 365 GeV) to improve precision on the deviation of κ_λ from the SM value and exploit high single-Higgs production cross section.

$$V^{\mathrm{SM}}(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

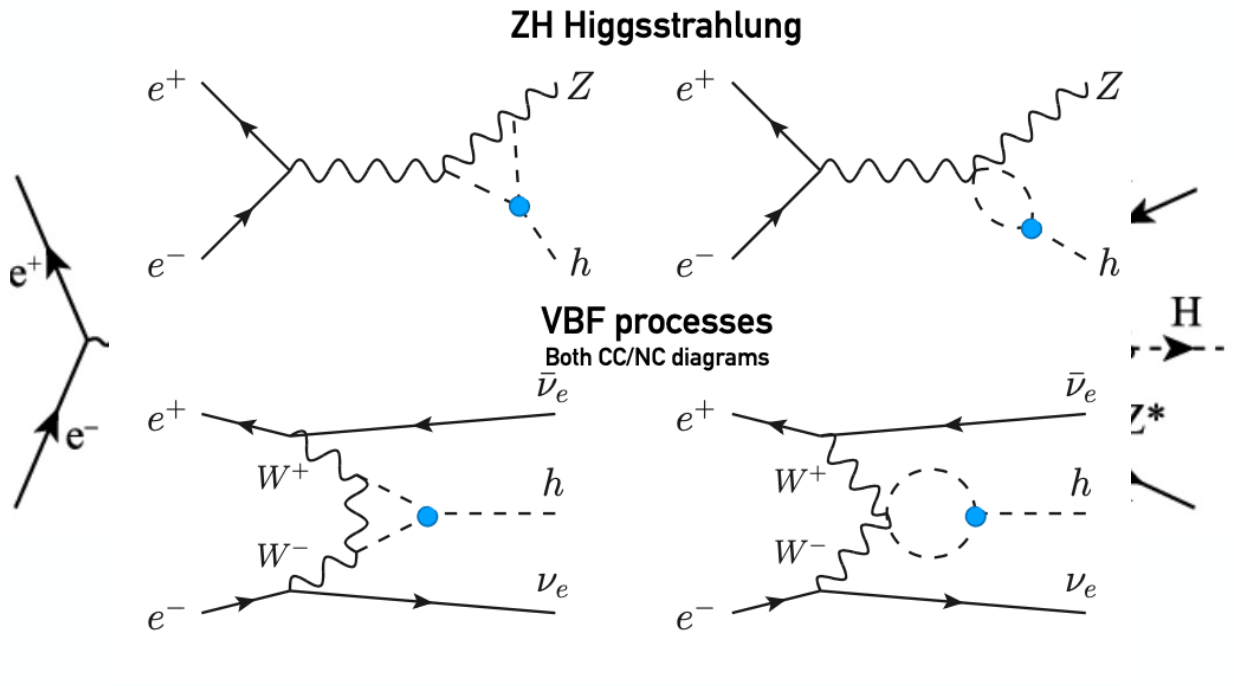
$$\Sigma_{\mathrm{NLO}} = Z_H\,\Sigma_{\mathrm{LO}}\,(1 + \kappa_\lambda C_1)$$



Methods

- Consider only single Higgs production => trilinear self coupling appear only at NLO

NLO



Considered processes

- Higgsstrahlung ($e^+e^- \rightarrow$ ZH) @ 240 and 365 GeV
  - *Inclusive Higgs decays: $Z(\mu^+\mu^-)H$, $Z(e^+e^-)H$, $Z(q\bar{q})H$*
  - *Extracted recoil mass distribution*

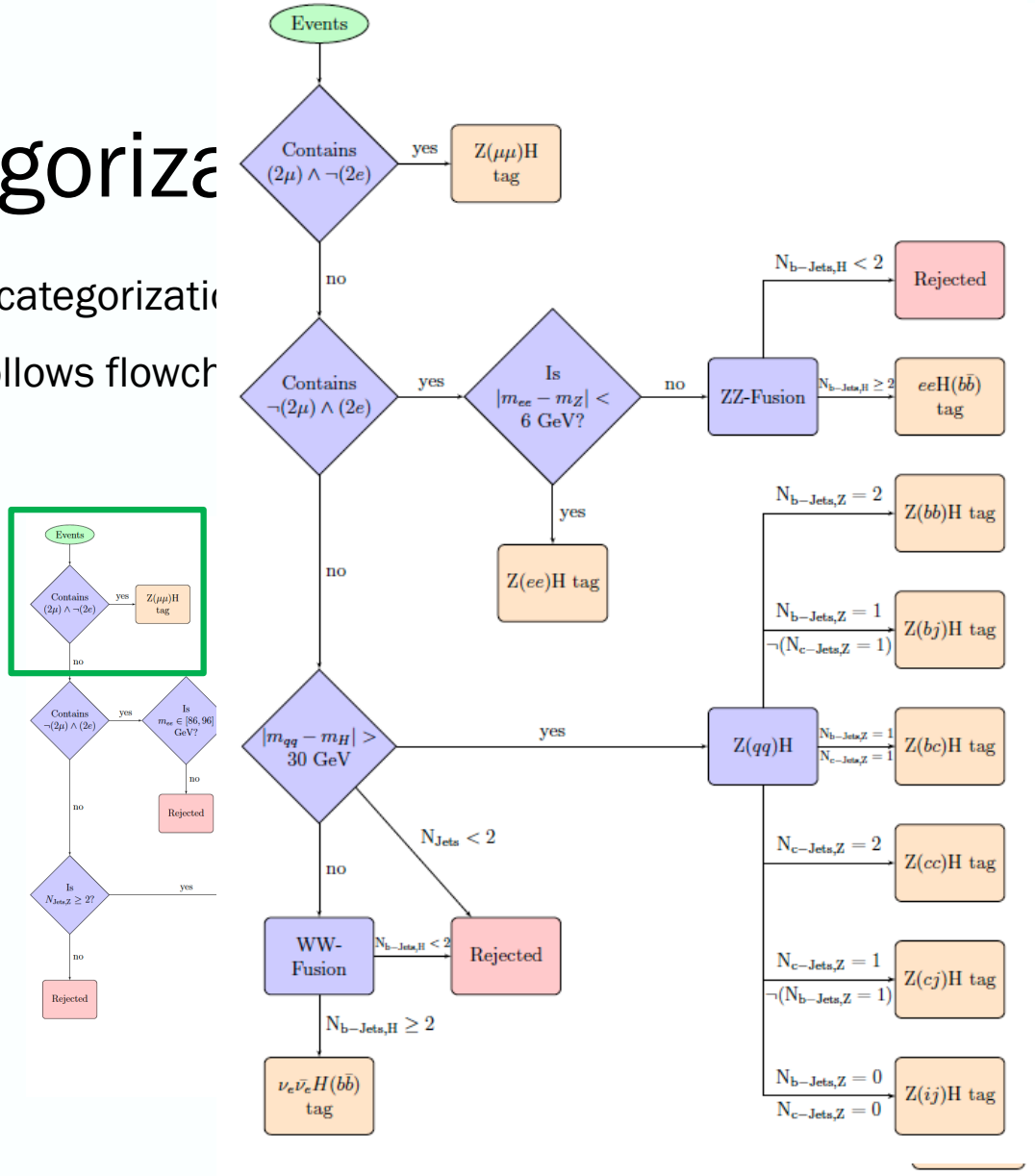
$$
\begin{aligned}
M^2_{\text{Rec}} &= p^2_H \\
&= \left(E_{\text{ff}} - \sqrt{s}\right)^2 - |\vec{p_{\text{ff}}}|^2 \\
&= s - 2E_{\text{ff}}\sqrt{s} + M^2_{\text{ff}},
\end{aligned}
$$

- Exclusive VBF @ 365 GeV
  - *WW-Fusion: $e^+e^- \rightarrow \nu_e\bar{\nu}_e H(b\bar{b})$ and ZZ-Fusion: $e^+e^- \rightarrow e^+e^- H(b\bar{b})$*
  - *Extracted missing mass and invariant electron mass respectively*
- Used the Delphes spring 2021 samples in our analysis

CATEGORIZATION

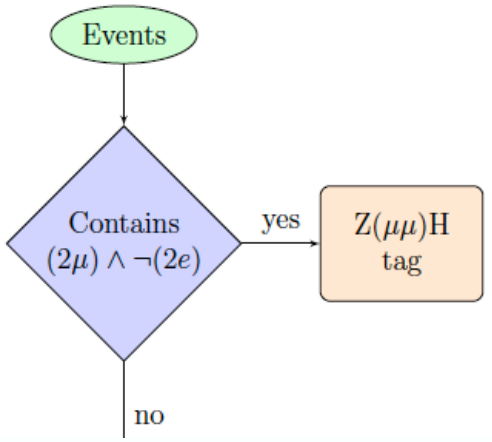
Categoriza

- Introduced categorizati… significance.
- Selection follows flowch…

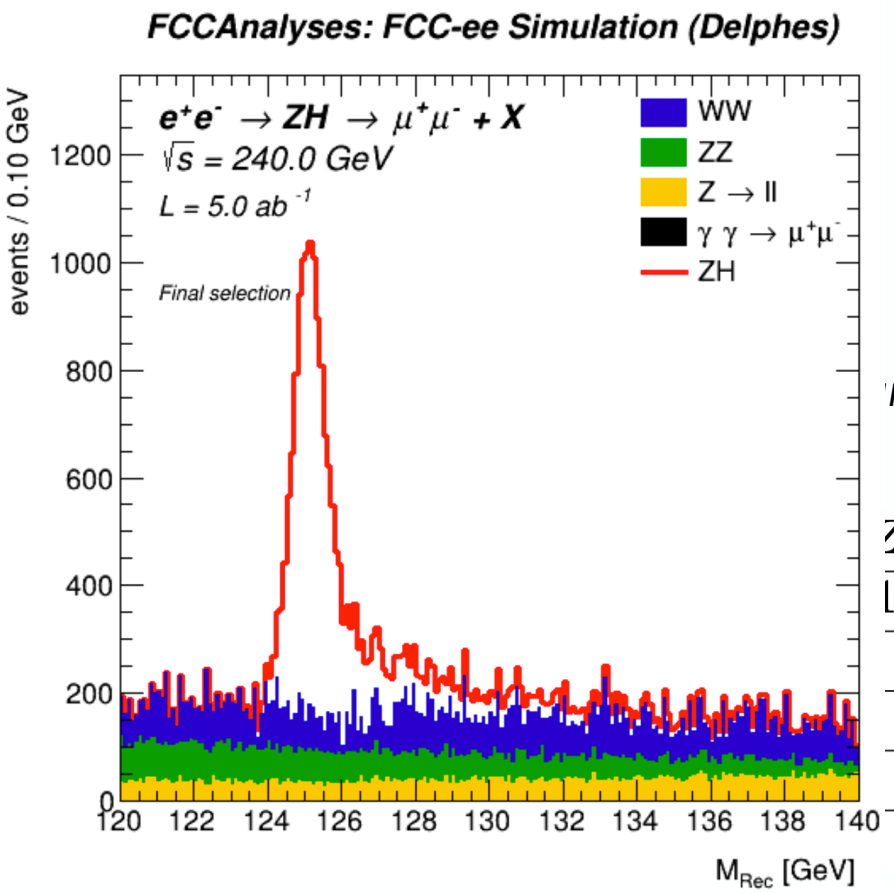


365 GeV

$Z(\mu^+\mu^-)H$ @ 240 GeV, L = 5 ab^{-1}



- Samples:
  - $e^+e^- \to Z(\mu^+\mu$
  - $e^+e^- \to ZZ, e^+$
    $e^+e^- \to \mu^+\mu^-,$
- Cutflow:

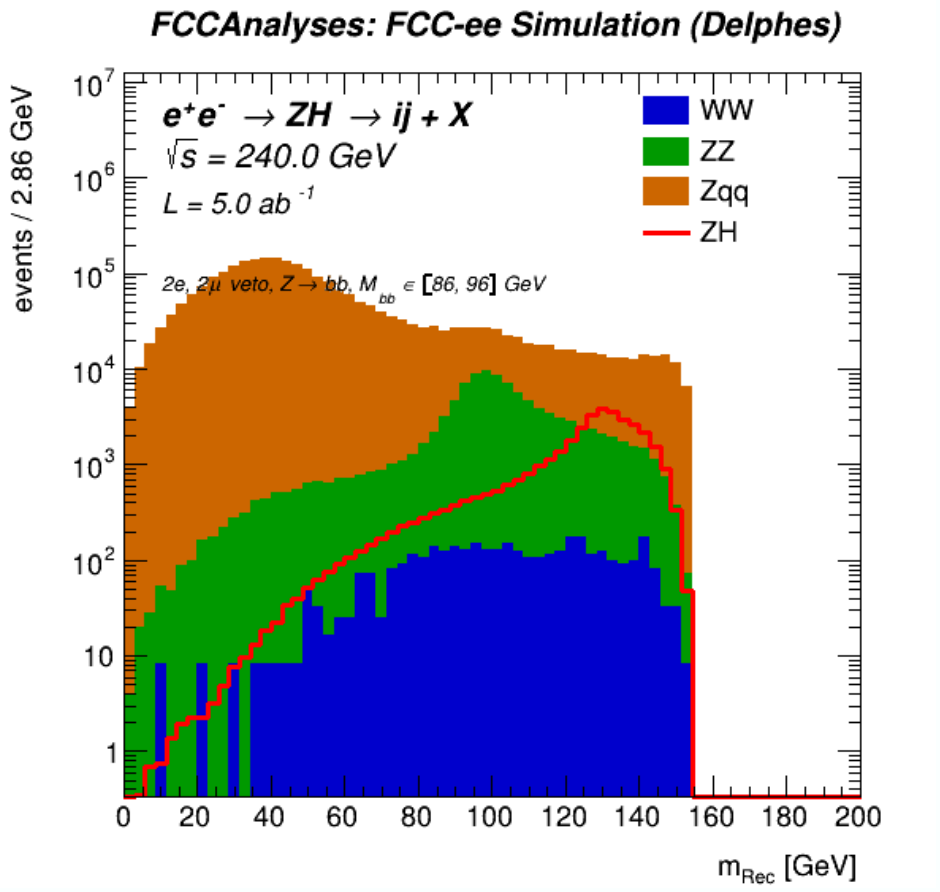


nd)

Number of events (Yield)	$Z \to \mu^+\mu^-$	$\gamma\gamma \to \mu^+\mu^-$
$Z(\mu\mu)H$ tag, $N_Z = 1$	18'115'143	1'309'126
$+ M_{\mu\mu} \in [86, 96]$ GeV, M	100 %	100 %
$+ p_T^{\mu\mu} \in [20, 70]$ GeV	0.93 %	2.74 %
$+ \lvert\cos(\theta_{\text{miss}})\rvert < 0.98$	0.20 %	$4.12{*}10^{-3}$ %
	0.05 %	$1.53{*}10^{-4}$ %

Z($b\bar{b}$)H @ 240 GeV, L = 5 ab^{-1}

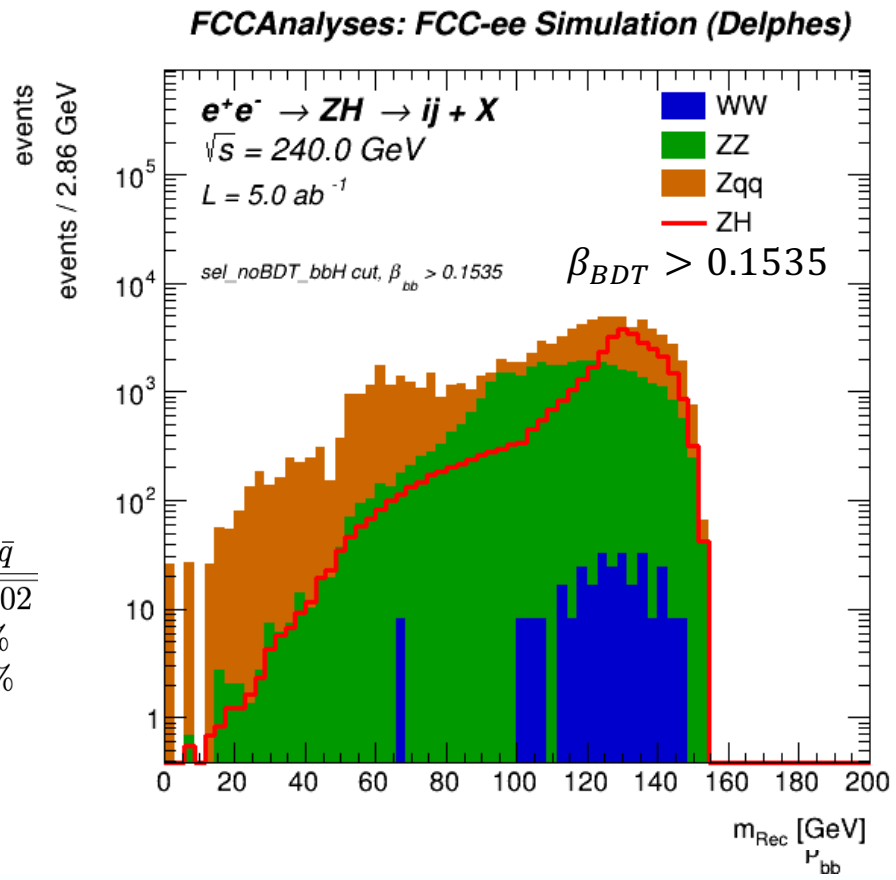
- Category requirement:
  - $\neg(\neg(2\mu) \wedge (2e))$ *in final state*
  - $N_{b-Jets,Z} = 2$
- Samples:
  - $e^+e^- \rightarrow q\bar{q}H$ *(Signal)*
  - $e^+e^- \rightarrow ZZ$, $e^+e^- \rightarrow WW$, $e^+e^- \rightarrow q\bar{q}$ *(Background)*
- Additional selection cuts:
  - $M_{bb} \in [86, 96]\ GeV$



Z($b\bar{b}$)H @ 240 GeV, L = 5 ab^{-1}

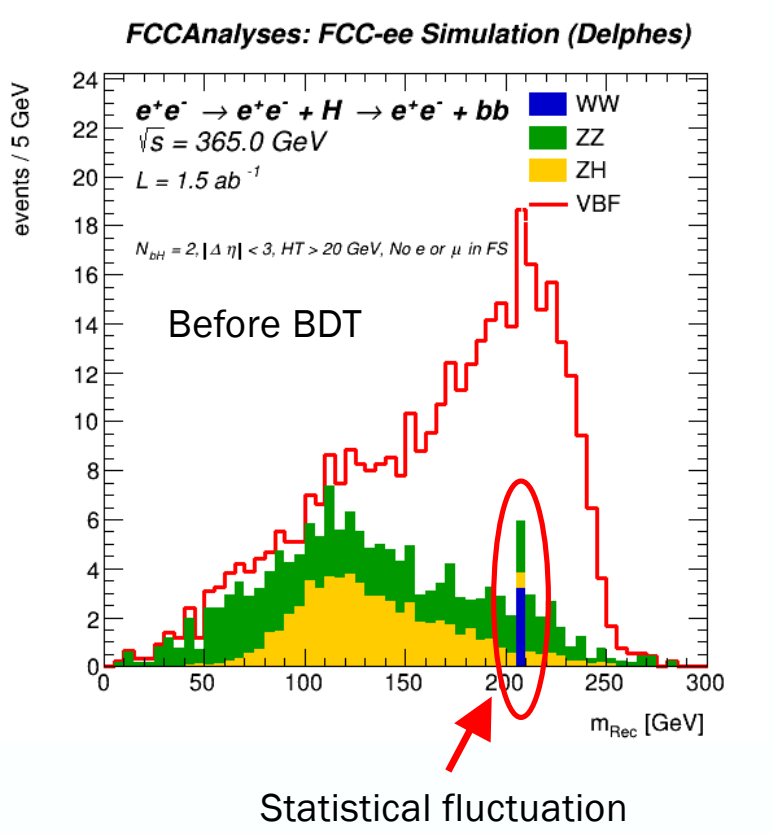
- Use adaptive Boosted Decision Trees (BDTs) to cut down $q\bar{q}$ background
- Input variables related to Z system:
  - $N_{b\ Jets}, M_{bb}, N_{Jets}, etc.$
- Cutflow:

	Z($q\bar{q}$)H	ZZ	WW	Z→ $q\bar{q}$
Number of bb events (Yield)	35'980	102'058	3'657	2'749'902
Z(bb) tag, $M_{bb} \in [86, 96]$ GeV	100 %	100 %	100 %	100 %
$+ \beta_{bb} > 0.1535$	91.46 %	33.82 %	7.85 %	1.86 %



$e^+e^-\mathrm{H}(b\bar{b})$ @ 365 GeV, L = 1.5 ab^{-1}

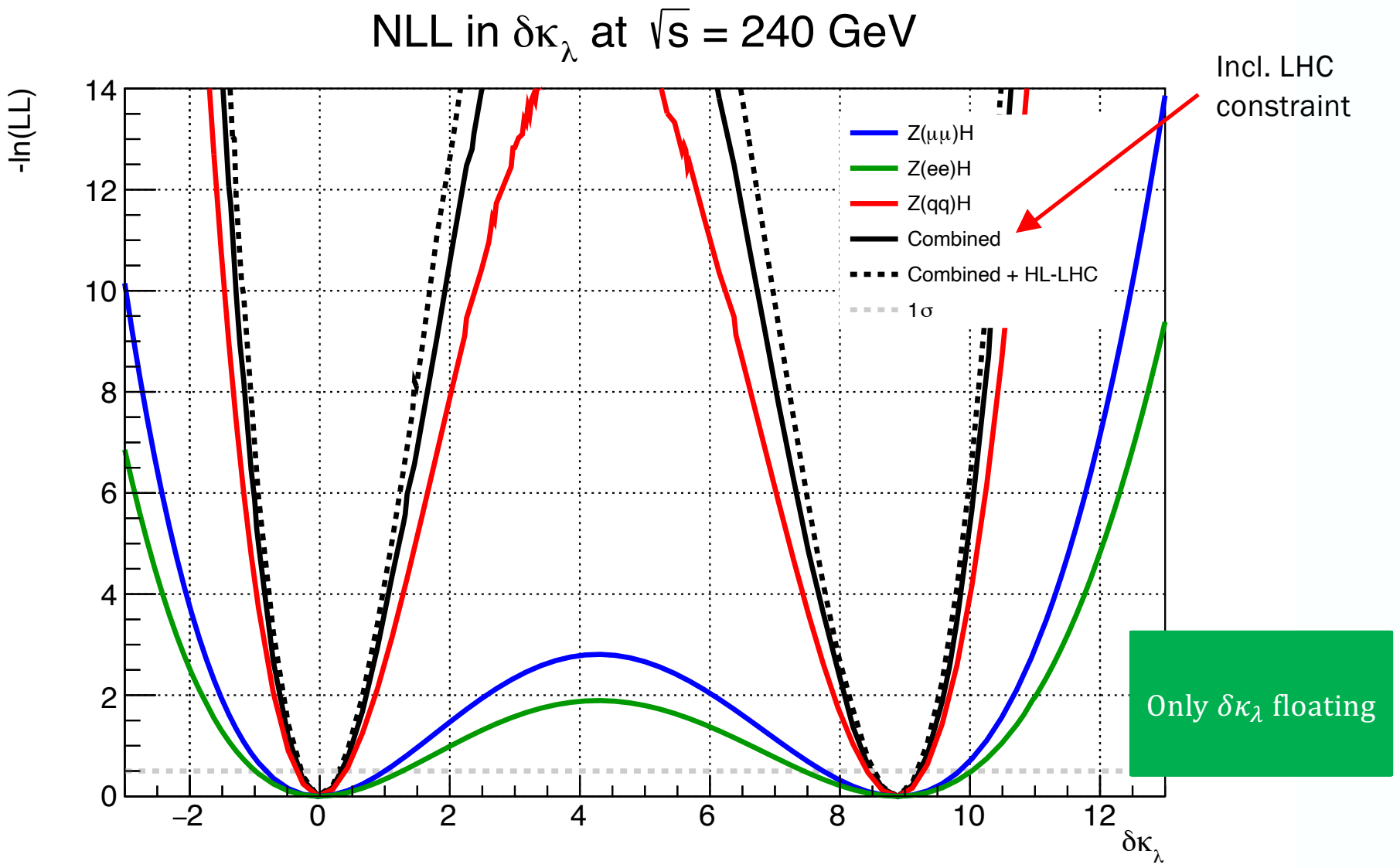
- Category requirement:
  - $\neg(2\mu) \wedge (2e)$ *in final state*
  - $|M_{ee} - M_Z| \geq 6$ *GeV*
  - $N_{b\text{–}Jets,\,H} \geq 2$
- Samples:
  - $e^+e^- \rightarrow e^+e^-H(b\bar{b})$ *(Signal)*
  - $e^+e^- \rightarrow ZZ$, $e^+e^- \rightarrow WW$, $e^+e^- \rightarrow ZH$ *(Background)*
- Additional selection cuts:
  - $|\Delta\eta_{bb}| < 3$, $H_T > 20$ GeV, $\beta_{BDT} > -0.1034$



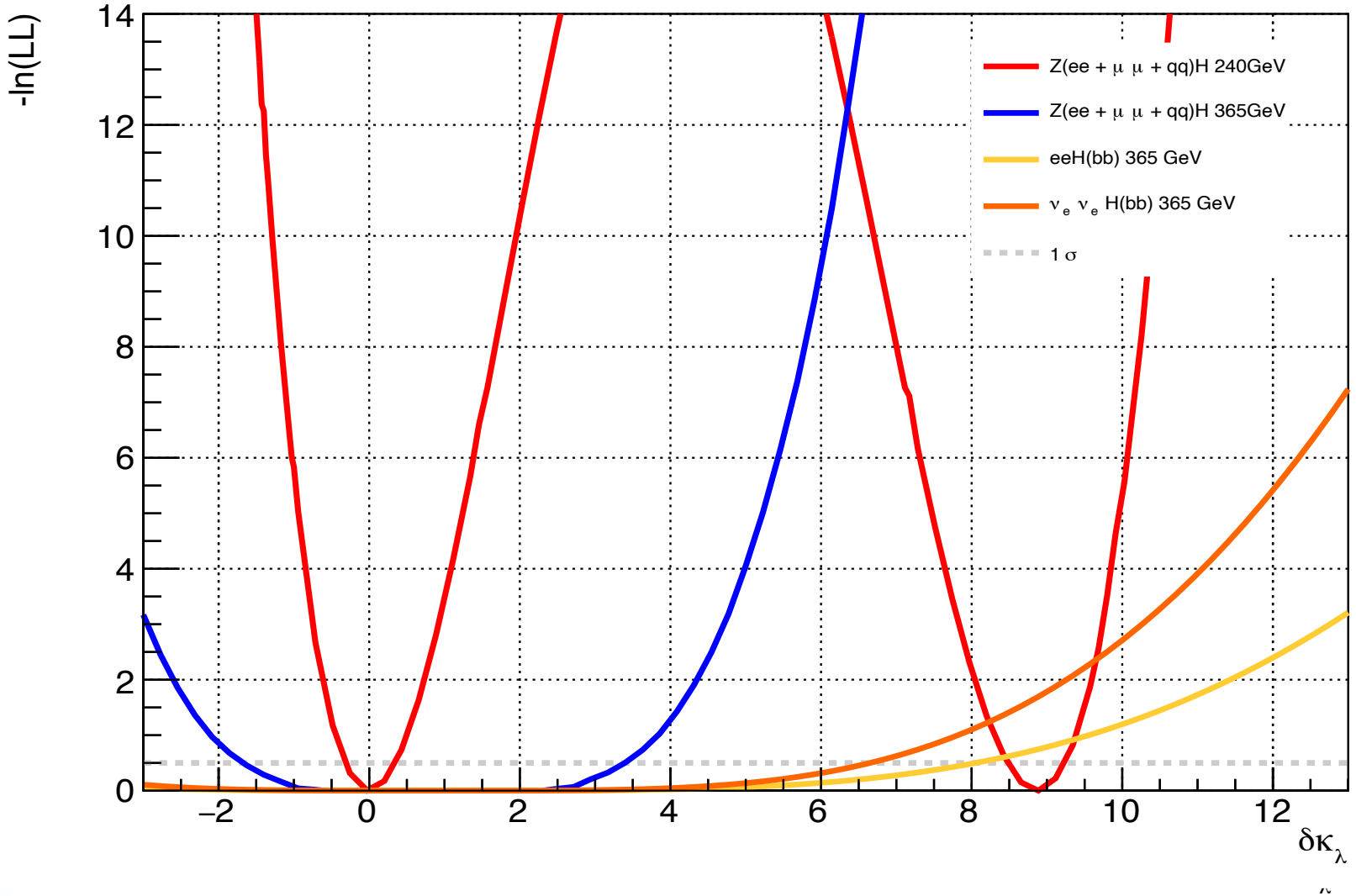
COMBINED ANALYSIS

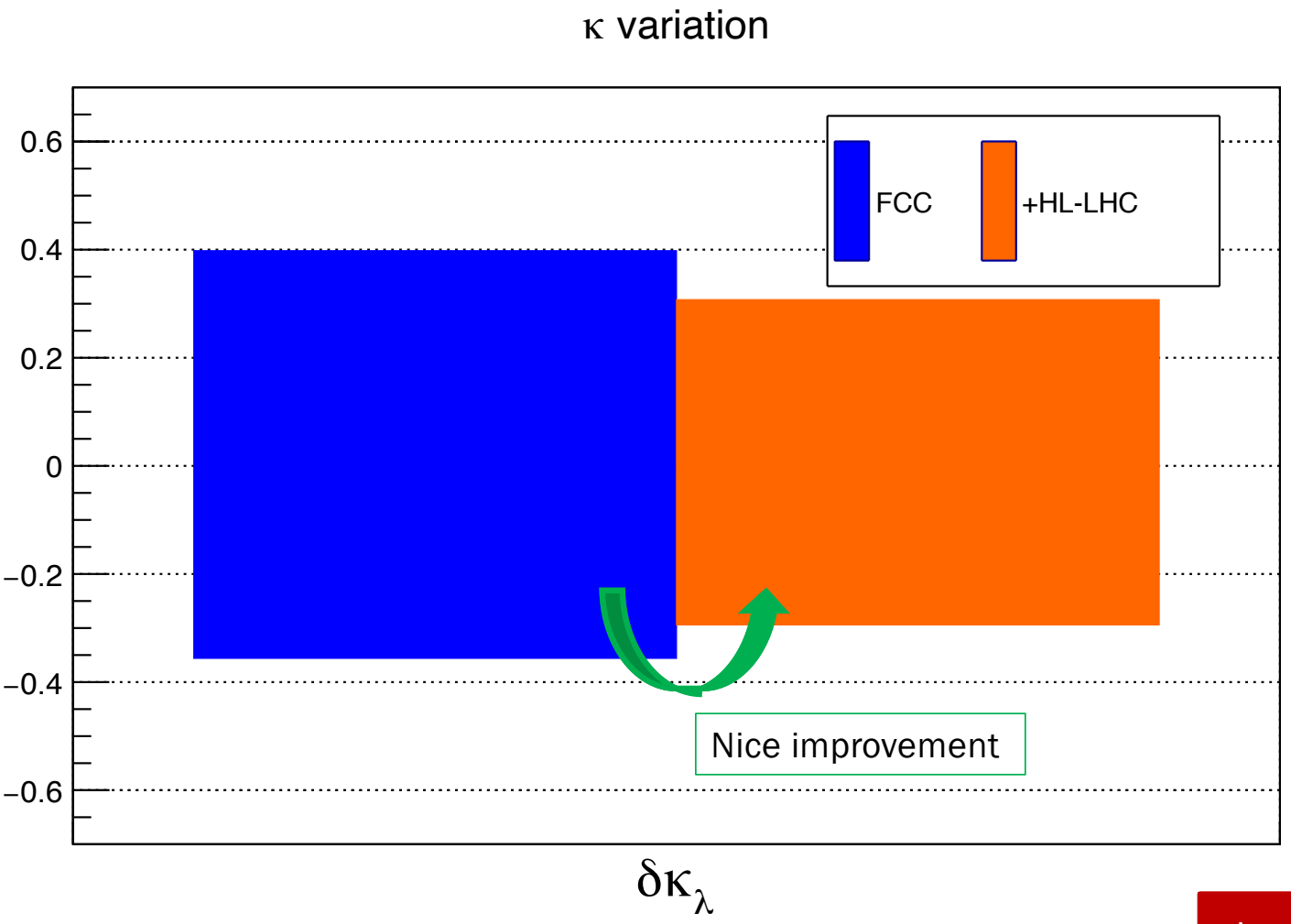
Combined analysis

- Fit all channels using parametric and non-parametric distributions
  - *Experimental systematics: Integrated luminosity measurement O(0.1%) and signal selection efficiency O(1%)*
- Construct Asimov dataset with original dataset and post-fit parameters
- Simultaneous fit of $\delta\kappa_\lambda$ to combined dataset
- Global assumption:
  - *Higgs decays as predicted in SM*


NLL in δκλ at √s = 240 GeV
-ln(LL)
δκλ
Z(μμ)H
Z(ee)H
Z(qq)H
Combined
Combined + HL-LHC
1σ
Incl. LHC constraint
Only δκλ floating

NLL in $\delta\kappa_\lambda$





$\delta\kappa_\lambda$: [-0.36, 0.40] (FCC only) ⟼ [-0.29, 0.31] (+HL-LHC)

Interval @ 68% CL

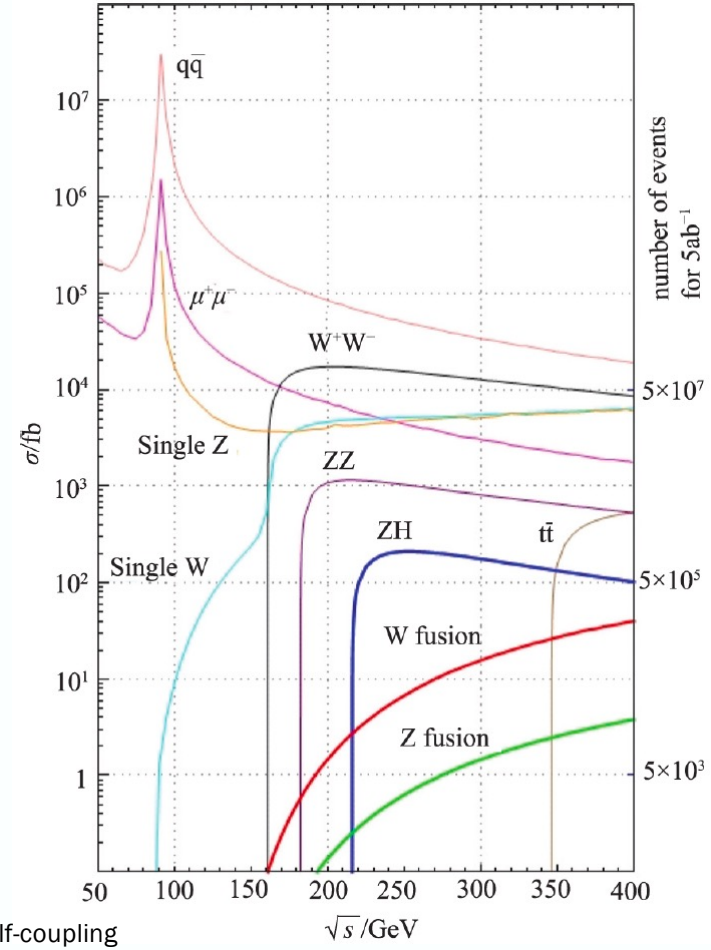
Conclusions and next steps

- Analysis involving almost complete ZH and VBF
  - *1D precision on $\delta\kappa_\lambda$: ~30% with HL-LHC*
- Next steps:
  - Add more systematics and their correlations between channels
  - Drop assumption: Higgs decays as predicted in SM
  - Probe more global scenarios (e.g. include more Higgs couplings to fermions)

THANK YOU FOR YOUR ATTENTION

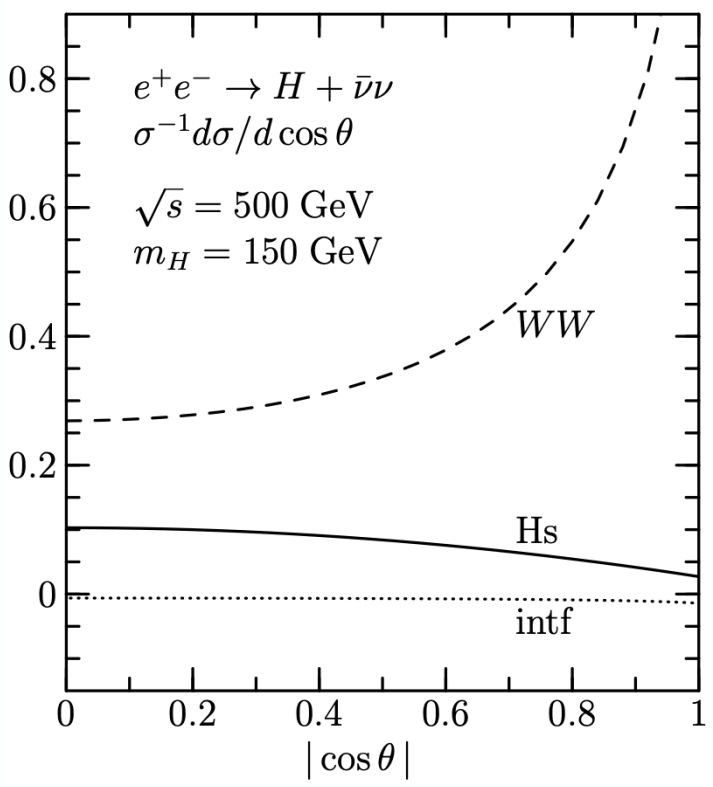
BACKUP SLIDES

Production cross sections



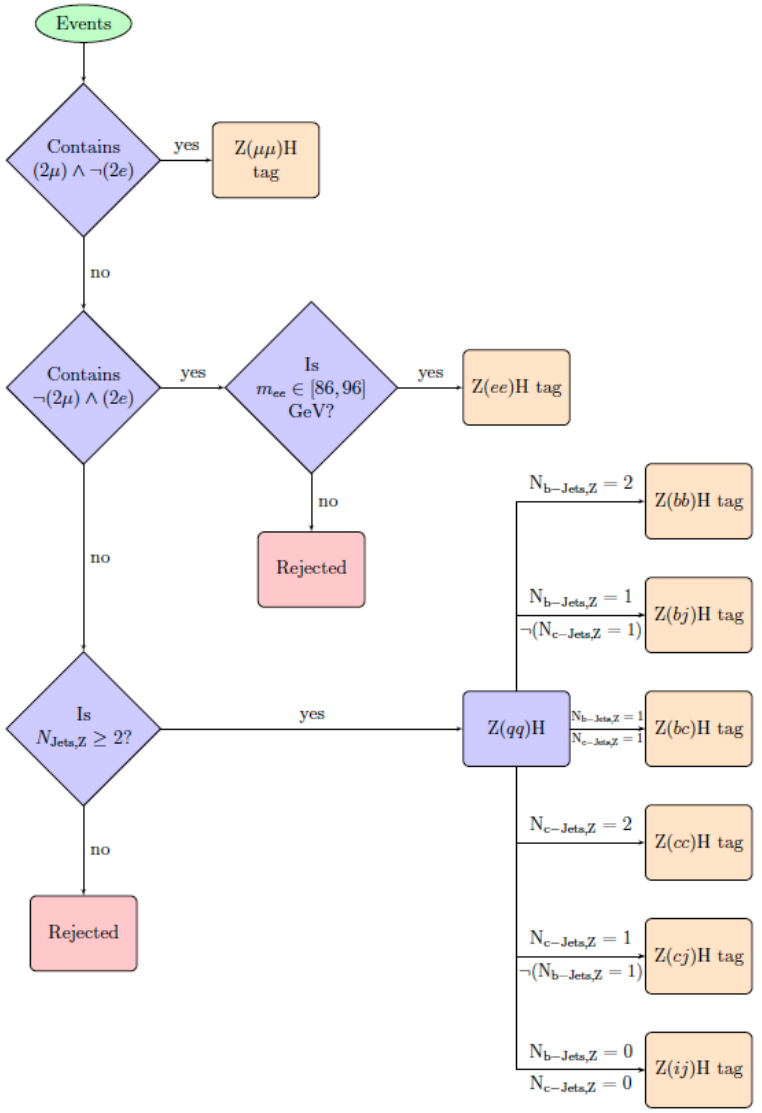
arXiv: 9512355

Separation of ZH and VBF



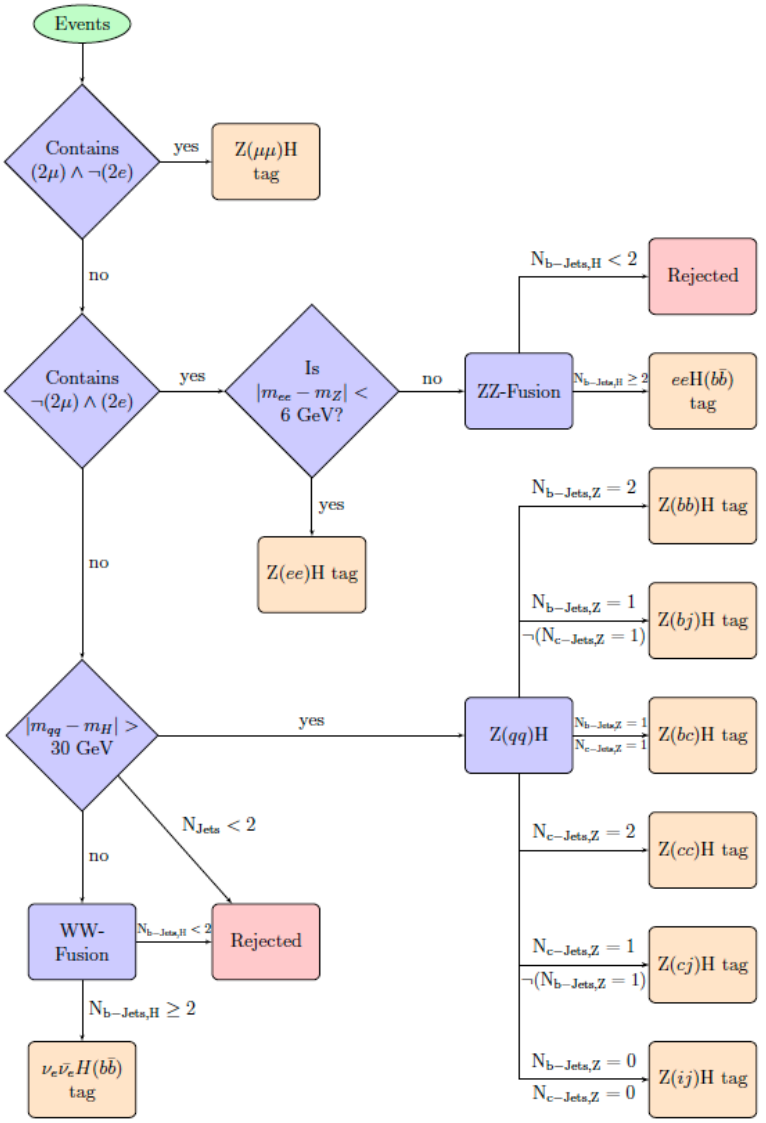
Categorization flowcha

- 240 GeV

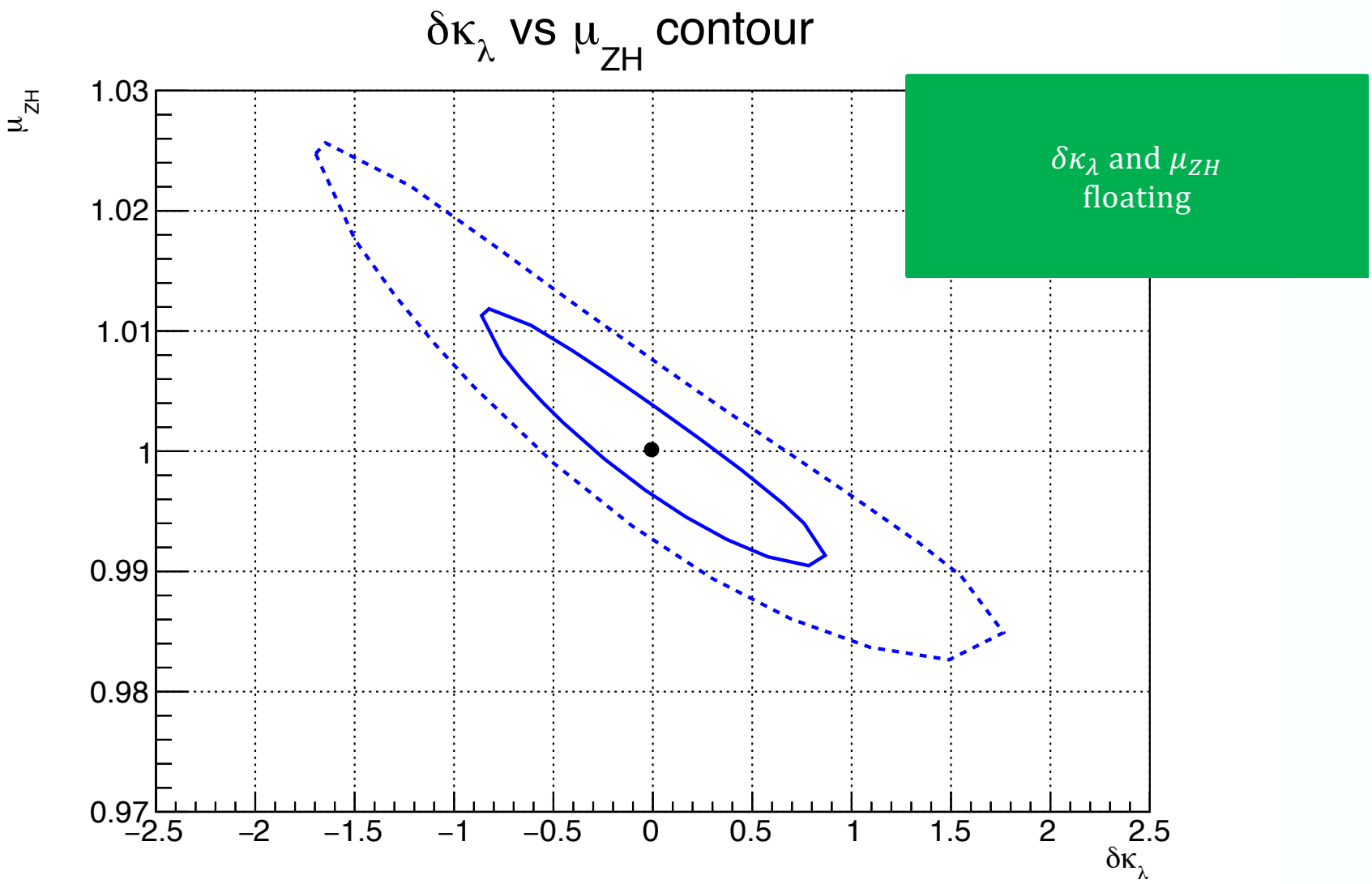


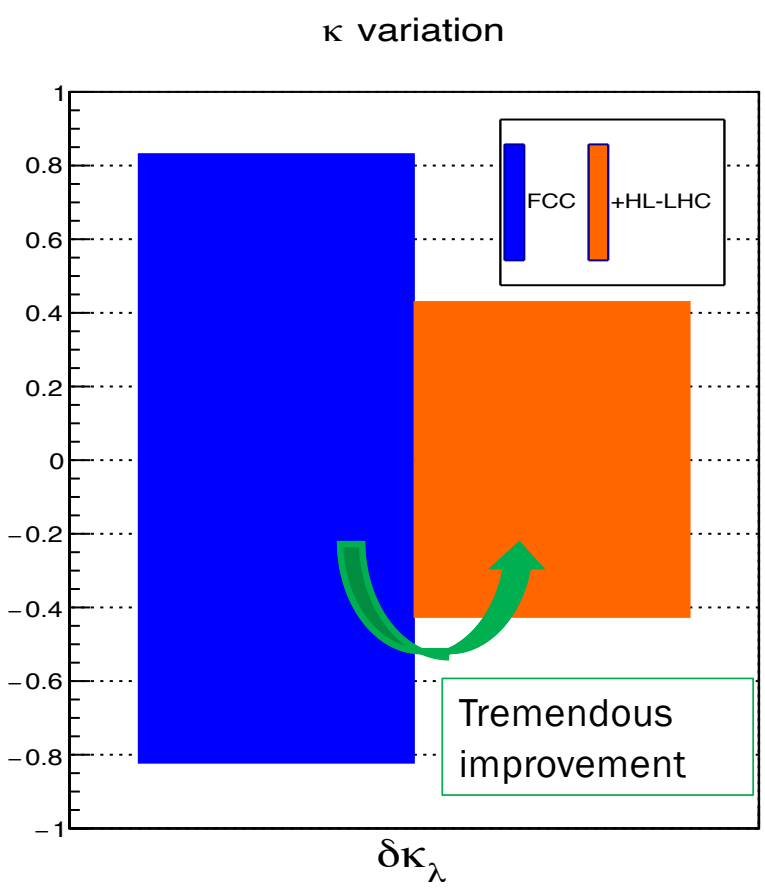
Categorization flowcha

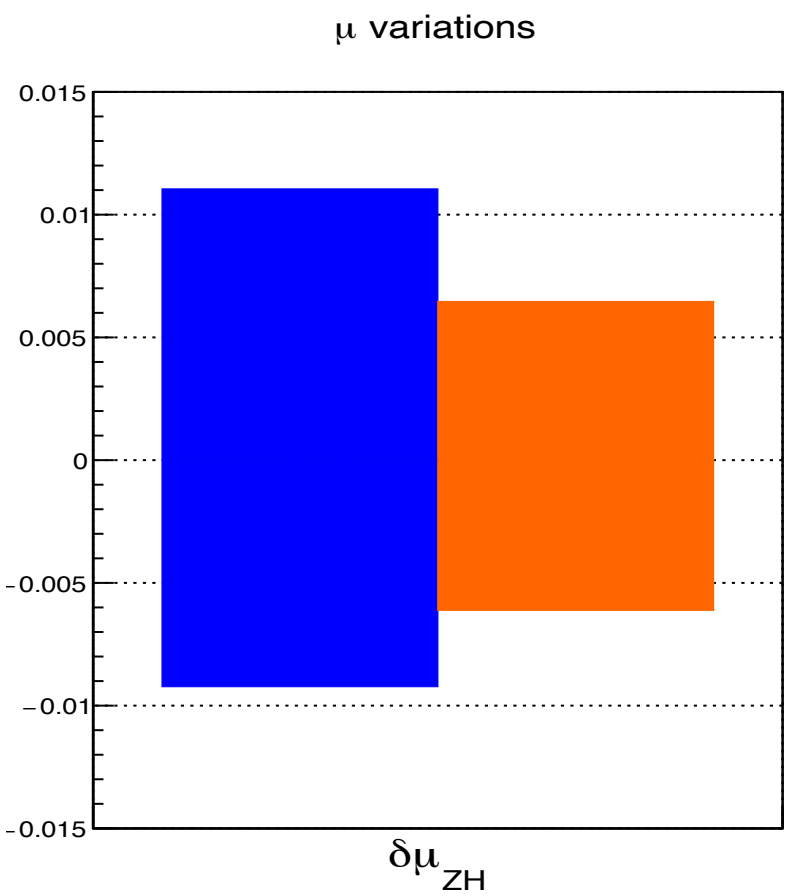
- 365 GeV



2D FIT


δκλ vs μZH contour
μZH
1.03
1.02
1.01
1
0.99
0.98
0.97
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
2.5
δκλ
δκλ and μZH floating



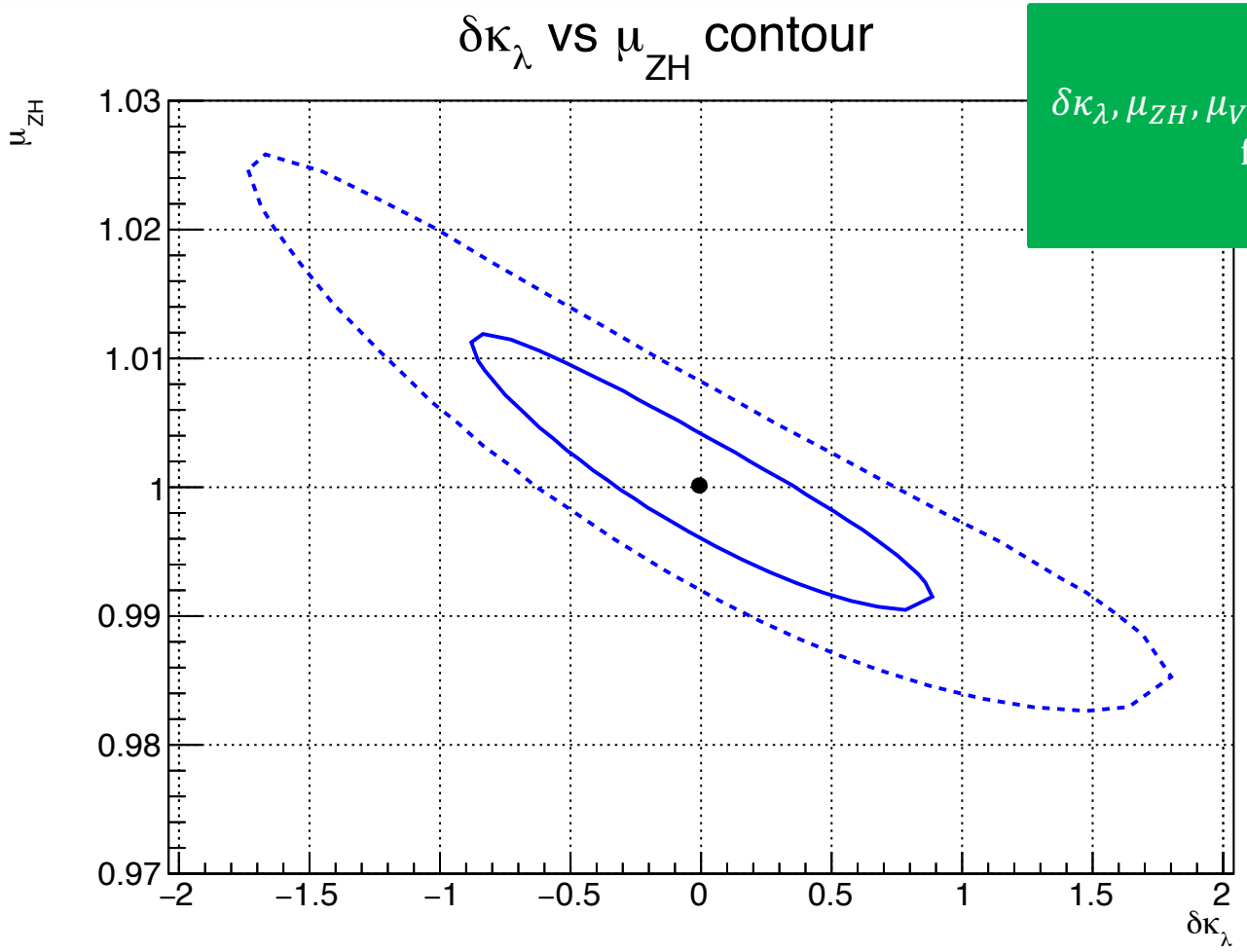


- 1D $\delta\kappa_\lambda$: [-0.36, 0.40] (FCC only) ⟼ [-0.29, 0.31] (+HL-LHC)
- 2D $\delta\kappa_\lambda$: [-0.83, 0.83] (FCC only) ⟼ [-0.43, 0.43] (+HL-LHC)

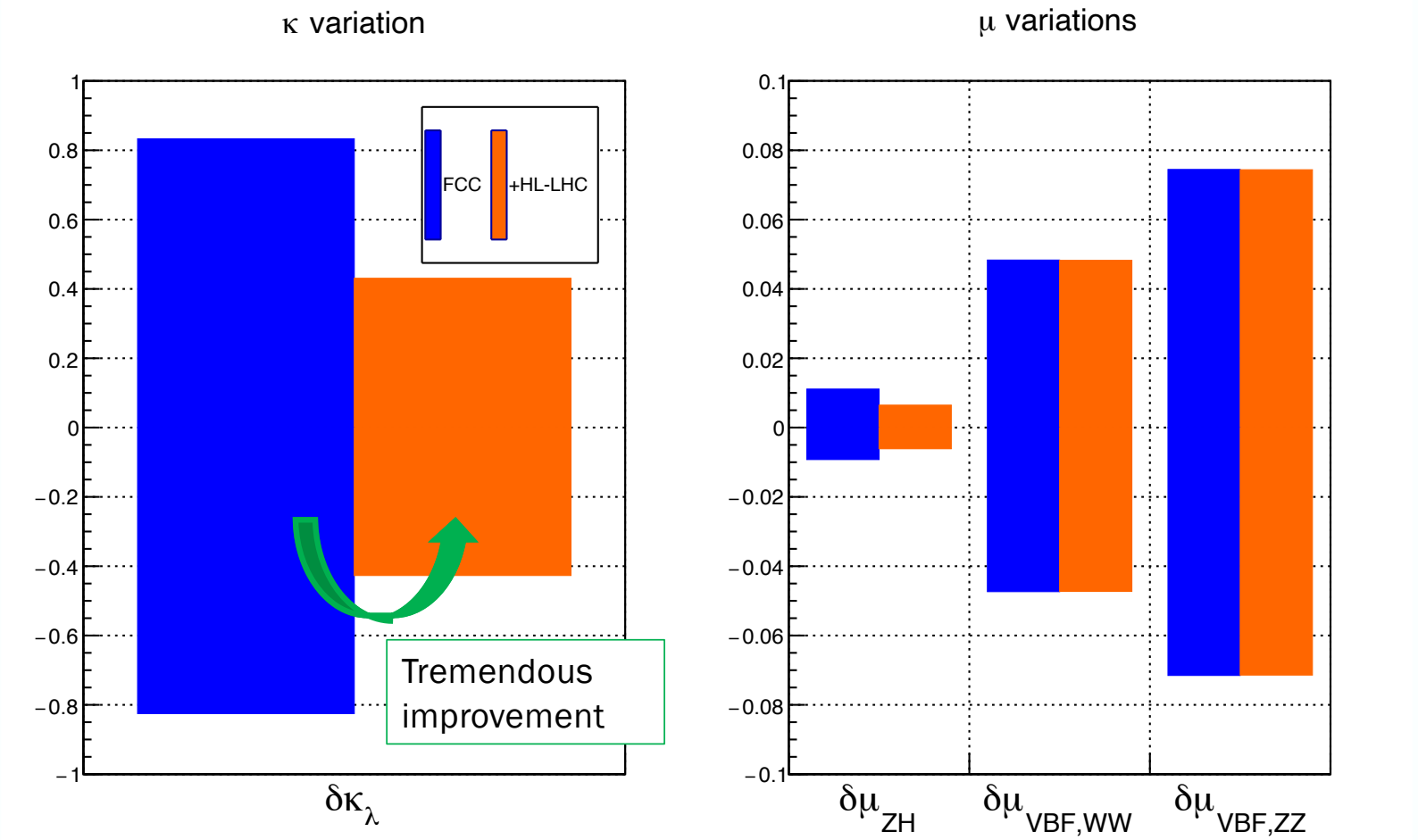
  $\delta\mu_{ZH}$: [-9.22, 11.1] $* 10^{-3}$ ⟼ [-6.12, 6.46] $* 10^{-3}$

Intervals @ 68% CL

4D FIT



$\delta\kappa_\lambda, \mu_{ZH}, \mu_{VBF,WW}$ and $\mu_{VBF,ZZ}$ floating


κ variation
μ variations
FCC
+HL-LHC
Tremendous improvement
δκλ
δμZH
δμVBF,WW
δμVBF,ZZ

Confidence Intervals at 68% CL

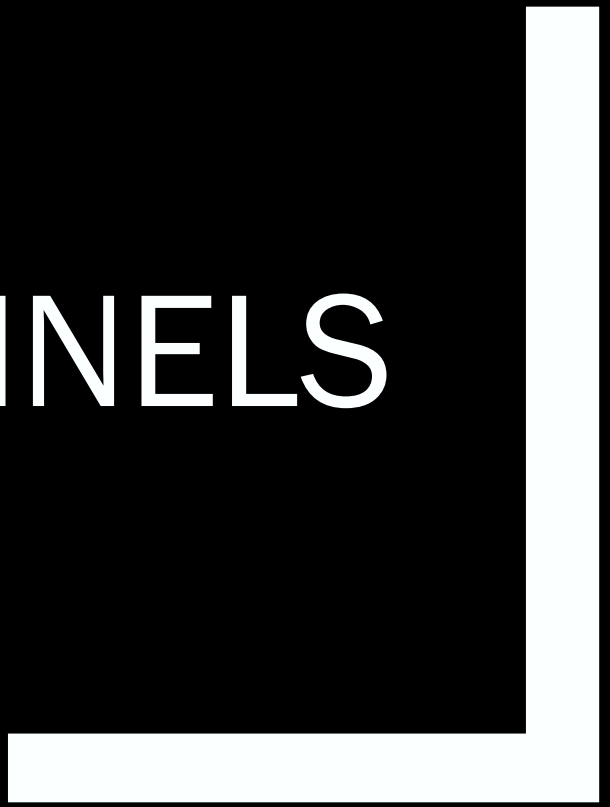
- 1D $\delta\kappa_\lambda$: [-0.36, 0.40] (FCC only) $\longmapsto$ [-0.29, 0.31] (+HL-LHC)
- 4D $\delta\kappa_\lambda$: [-0.83, 0.83] (FCC only) $\longmapsto$ [-0.43, 0.43] (+HL-LHC)

  $\delta\mu_{ZH}$: [-9.23, 11.1] $* 10^{-3}$ $\longmapsto$ [-6.11, 6.47] $* 10^{-3}$

  $\delta\mu_{VBF,WW}$: [-4.73, 4.83] $* 10^{-2}$ $\longmapsto$ [-4.72, 4.82] $* 10^{-2}$

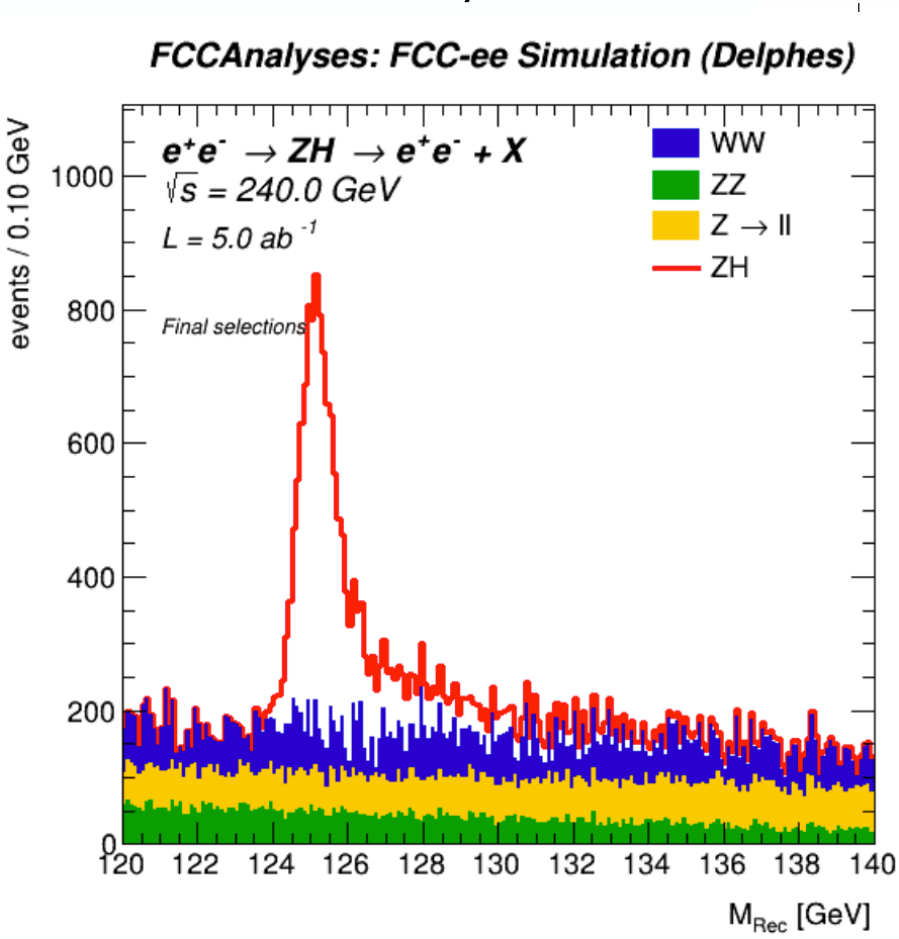
  $\delta\mu_{VBF,ZZ}$: [-7.15, 7.45] $* 10^{-2}$ $\longmapsto$ [-7.14, 7.44] $* 10^{-2}$

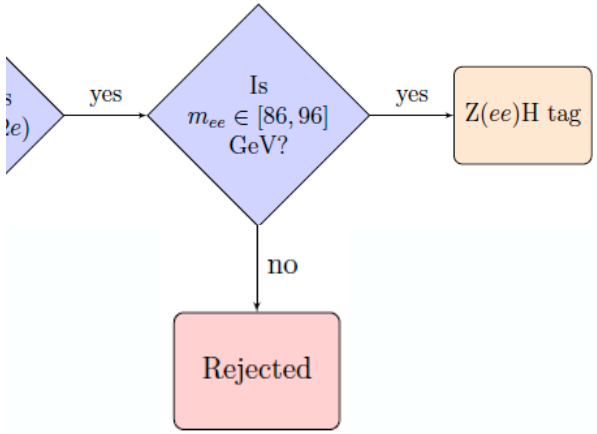
ADDITIONAL CHANNELS



$Z(e^+e^-)H$ @ 240 GeV, L = 5 ab^{-1}

- Samples:
  - $e^+e^- \to Z(e^+$
  - $e^+e^- \to ZZ, e$
    $e^+e^- \to e^+e^-$
- Cutflow:

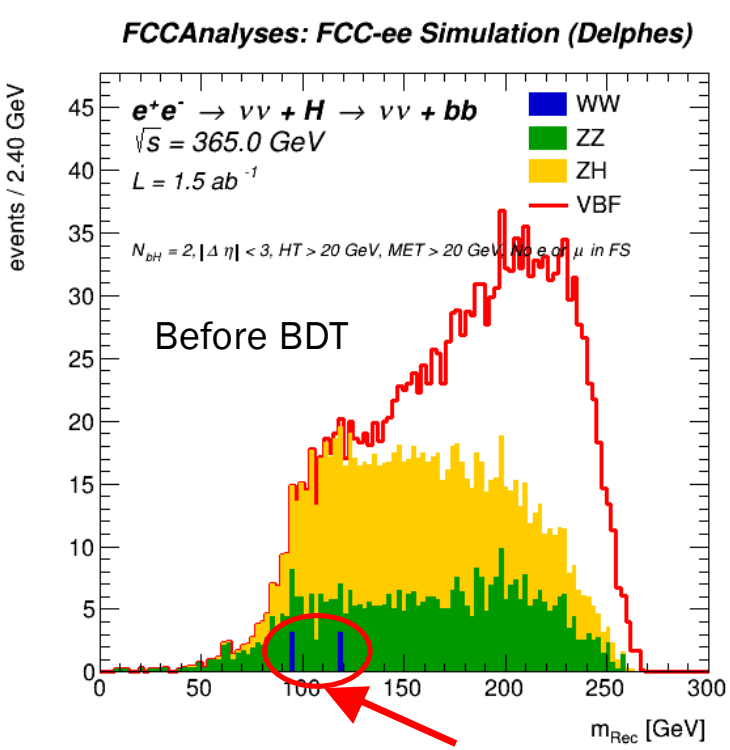




Number of events	WW	$Z \to l^+l^-$
Z(ee)H tag, $N_Z =$	745'609	27'171'720
$+ M_{ee} \in [86, 96]$ G	100 %	100 %
$+ p_T^{ee} \in [20, 70]$ Ge	6.60 %	1.02 %
$+ \lvert\cos(\theta_{\text{miss}})\rvert < 0.9$	1.68 %	0.24 %
	1.68 %	0.04 %

$\nu_e\bar{\nu}_e\mathrm{H}(b\bar{b})$ @ 365 GeV, L = 1.5 ab^{-1}

- Category requirement:
  - $\neg(\neg(2\mu) \wedge (2e))$ *in final state*
  - $|M_{qq} - M_H| \leq 6$ *GeV*
  - $N_{b,H} \geq 2$
- Samples:
  - $e^+e^- \to \nu_e\bar{\nu}_e H(b\bar{b})$ *(Signal)*
  - $e^+e^- \to ZZ$, $e^+e^- \to WW$, $e^+e^- \to ZH$ *(Background)*
- Additional selection cuts:
  - $|\Delta\eta_{bb}| < 3$, $H_T > 20$ *GeV*, $|\cos(\theta_H)| > 0.5$, $MET > 20$ *GeV*, $\beta_{BDT} > -0.0426$



Statistical fluctuations