The Higgs self-coupling at future colliders

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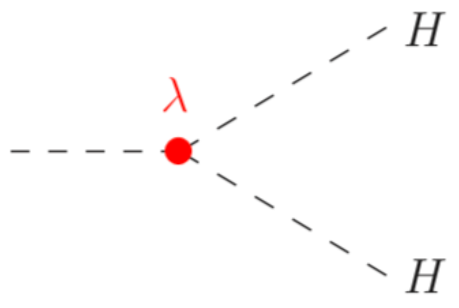
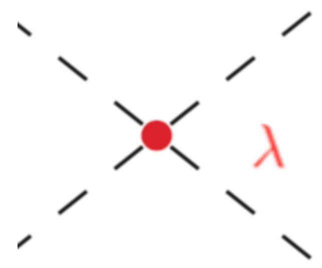
Higgs Pairs mini-workshop 2021- 30/09/2021

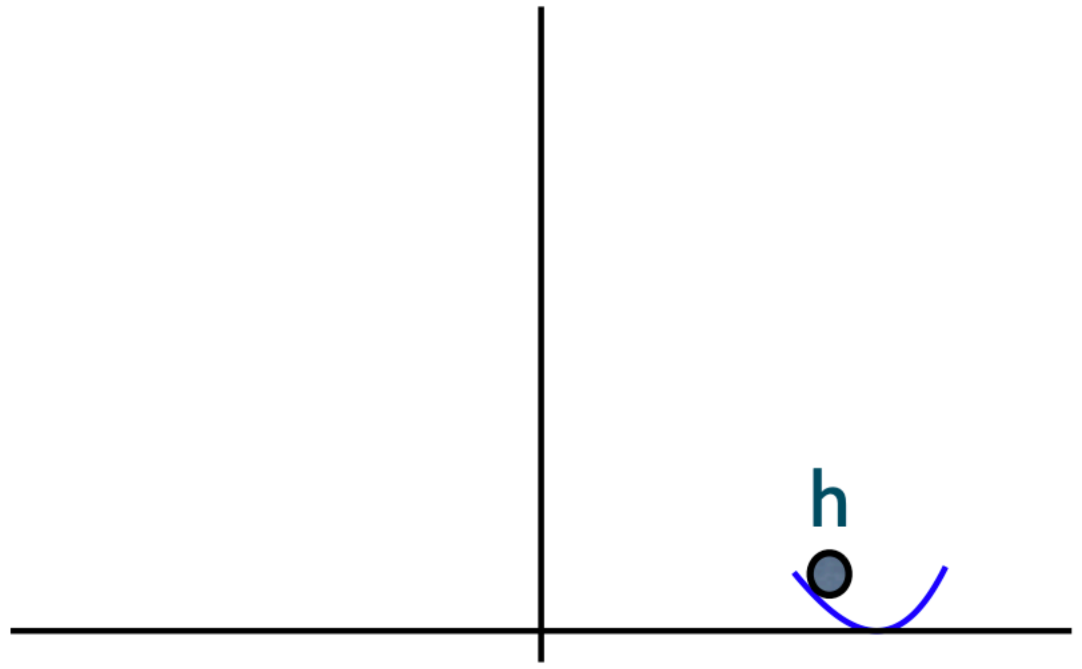
Why?

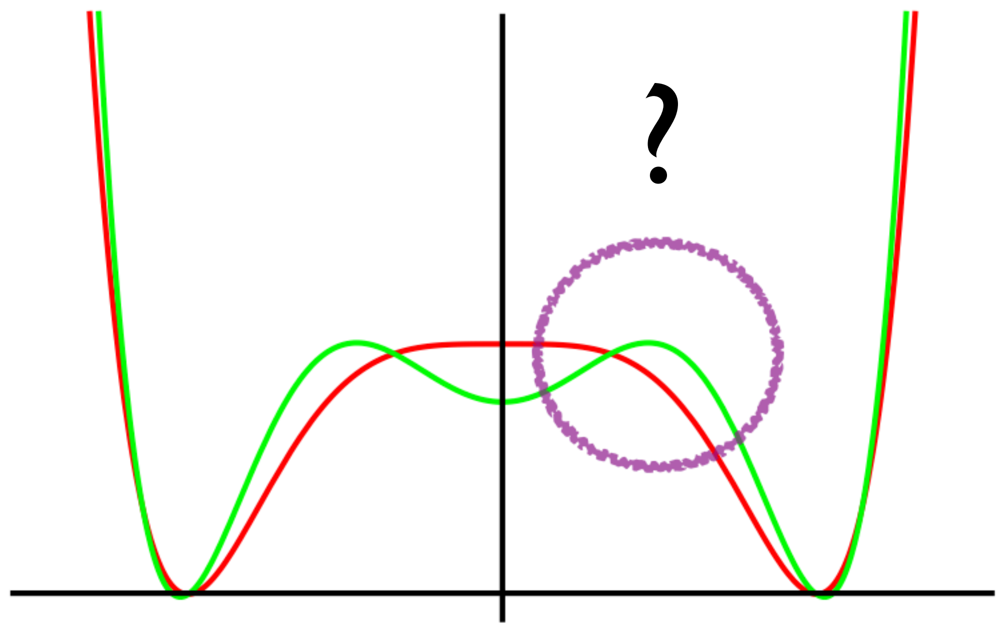


$$\mathcal{L}_h = m_h^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$



- In the SM, EWSB and λ_3 and λ_4 purely determined by the **shape of the Higgs potential**
- However, Higgs potential could be different (required by some scenarios of EWK baryogenesis) → **has barely been measured**
- Measuring the Higgs self-couplings gives a handle on the Higgs potential is determined by the self coupling value





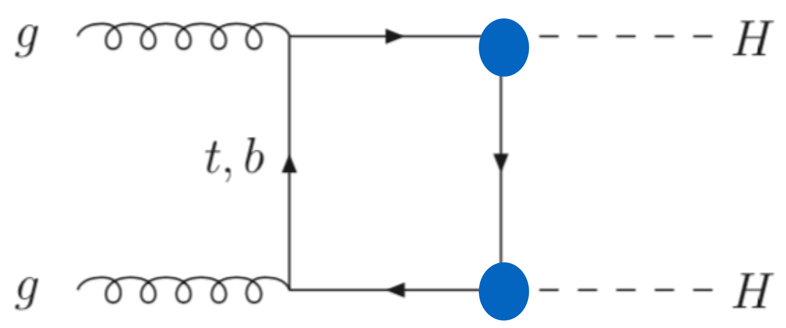
How?

HH pair production

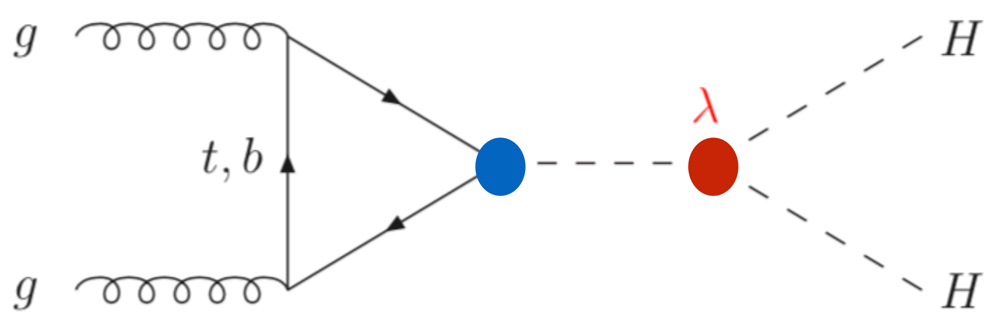
gluon fusion | top associated pair production

p-p

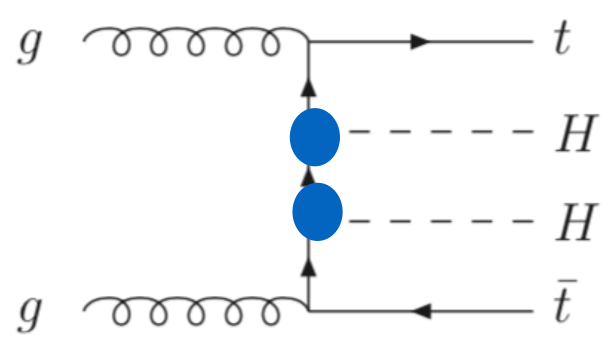
LHC
FCC-hh



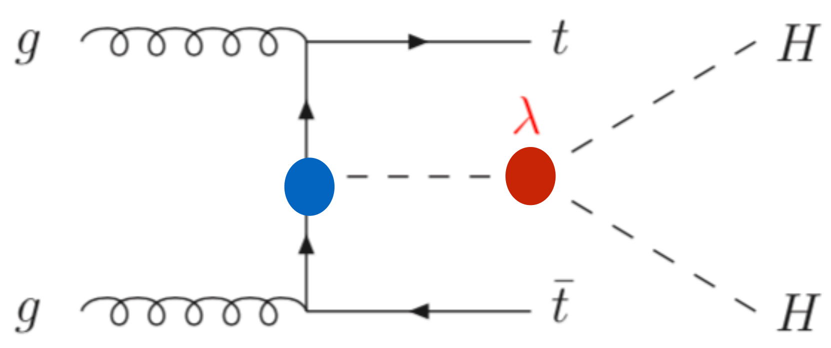
y_t



y_t , λ_3



y_t



y_t , λ_3

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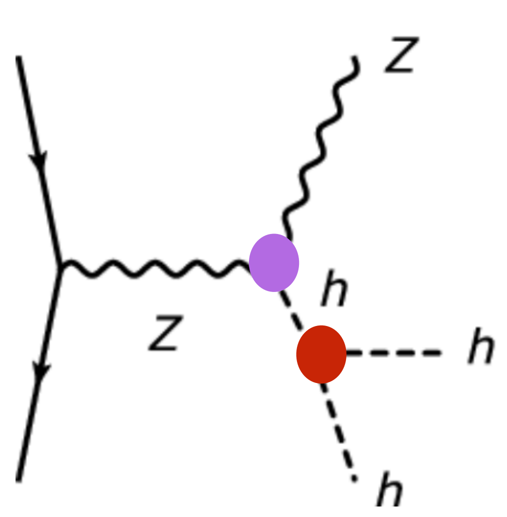
double Higgs-strahlung ($\sqrt{s}$ < 1 TeV) | weak boson fusion ($\sqrt{s}$ > 1 TeV)

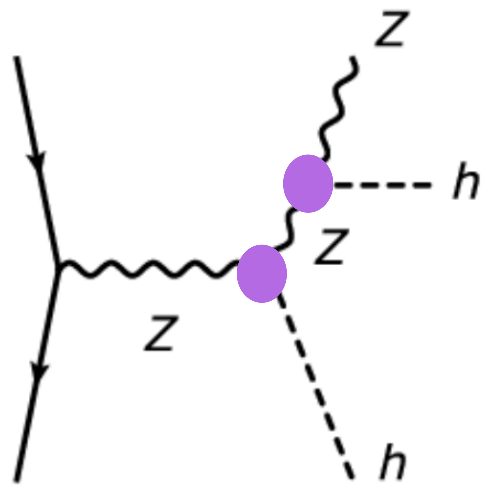
e^+e^-

$\mu^+\mu^-$

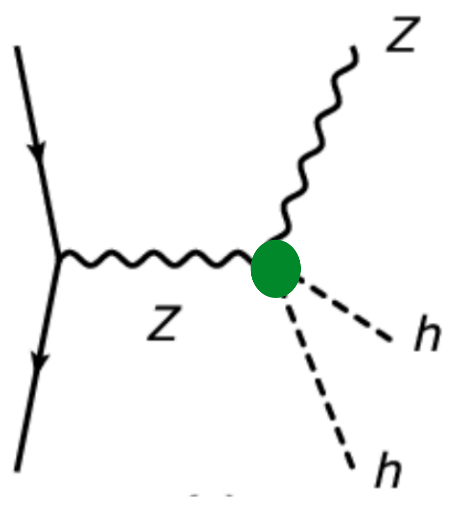
ILC
CLIC
Muon Collider



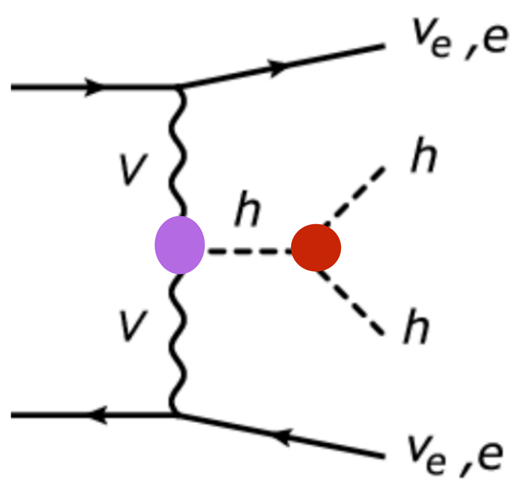
g_Z , λ_3



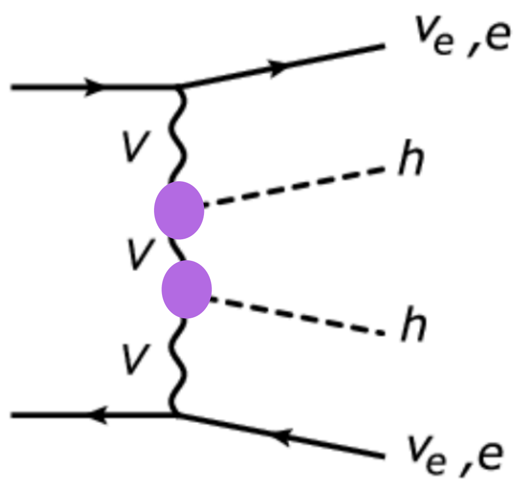
g_Z



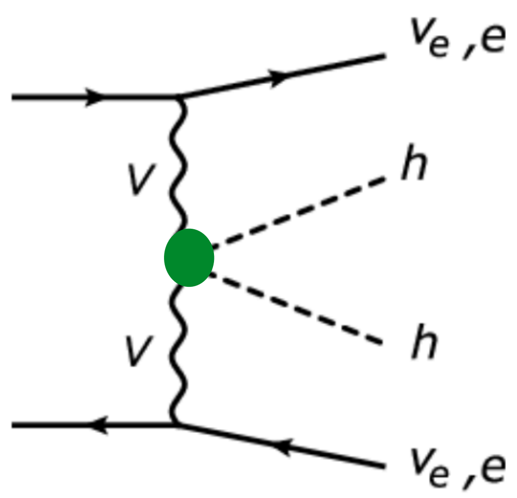
λ_{VVHH}



g_Z , λ_3



g_Z



λ_{VVHH}

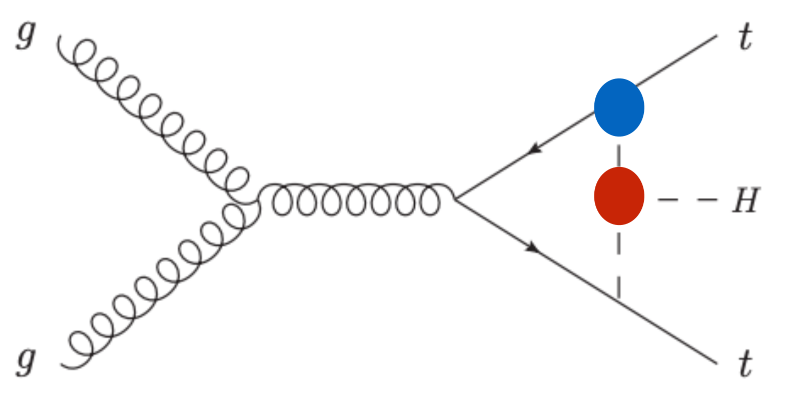
How?

single H production

p-p

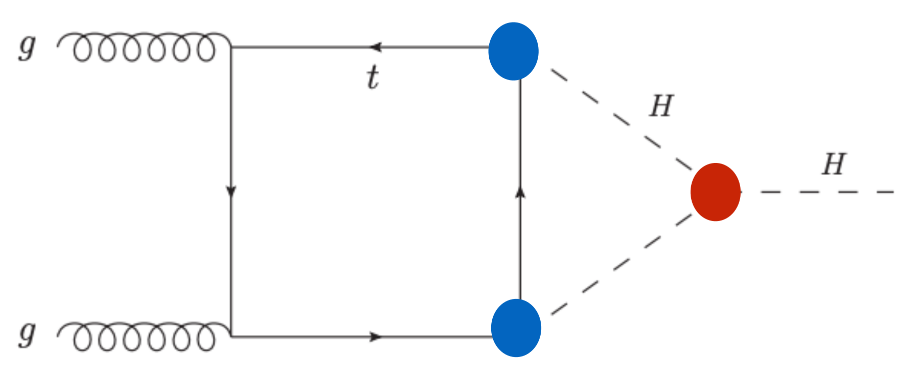
LHC
FCC-hh

ttH

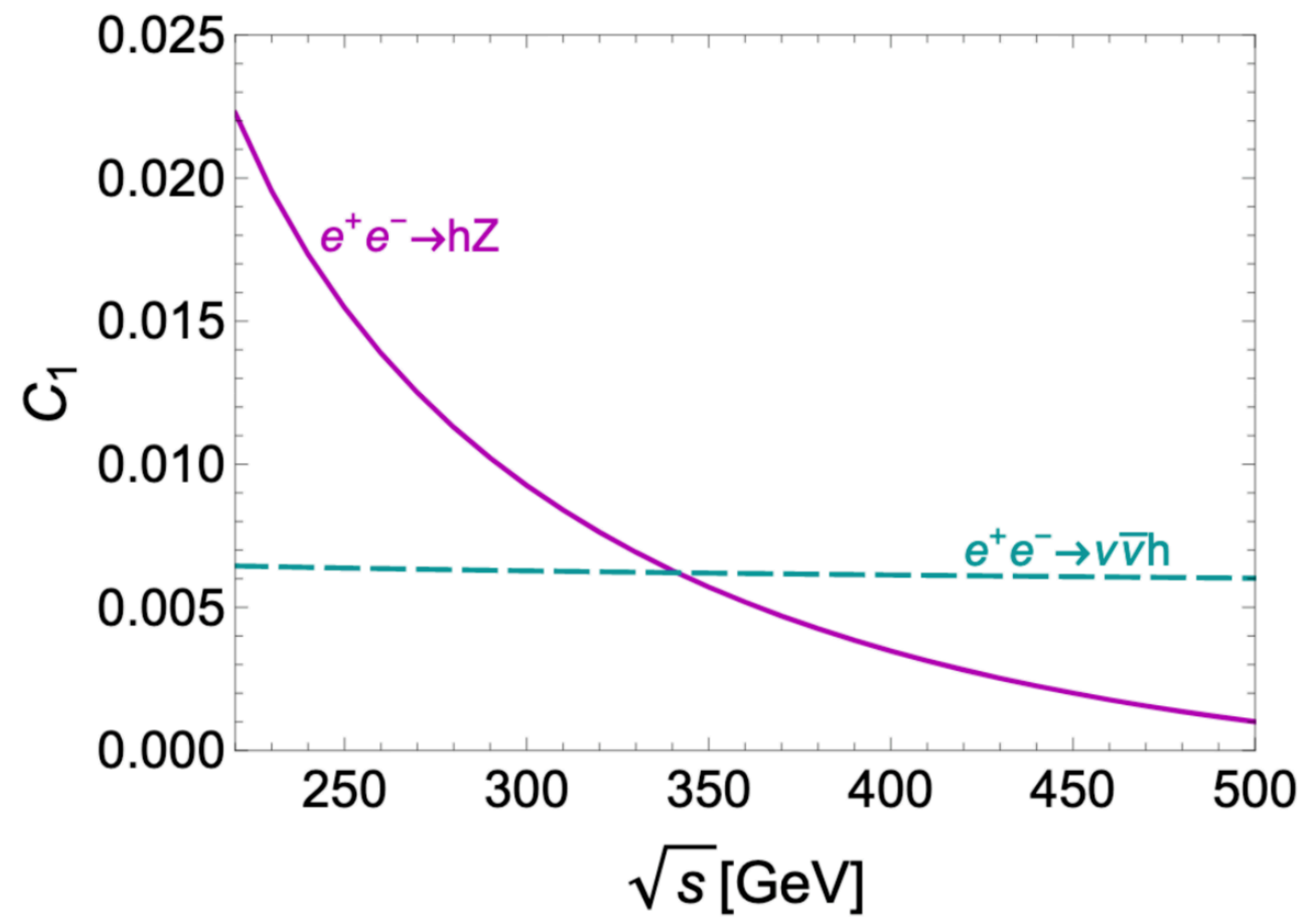


y_t

gluon fusion



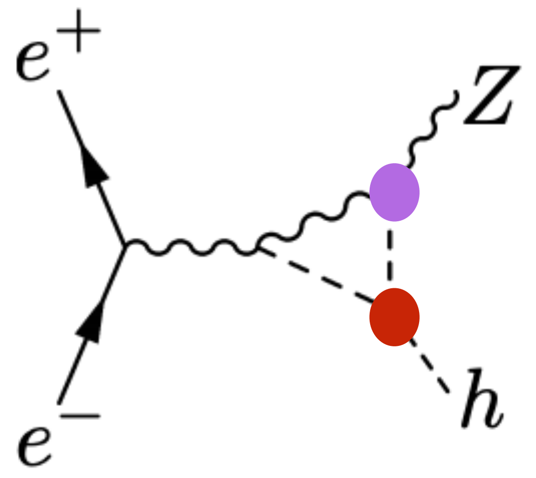
y_t , λ_3



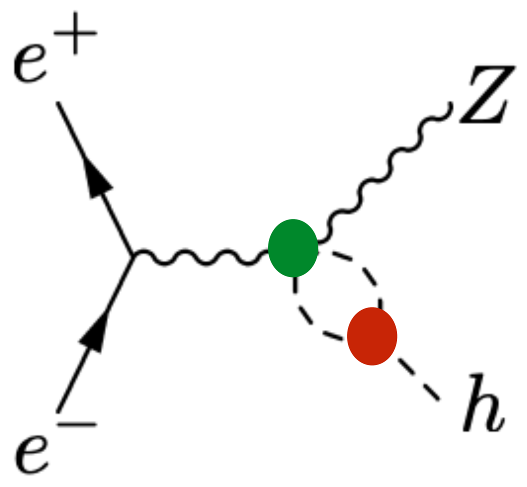
e^+e^-
$\mu^+\mu^-$

ILC
CLIC
Muon Collider

Higgs-strahlung

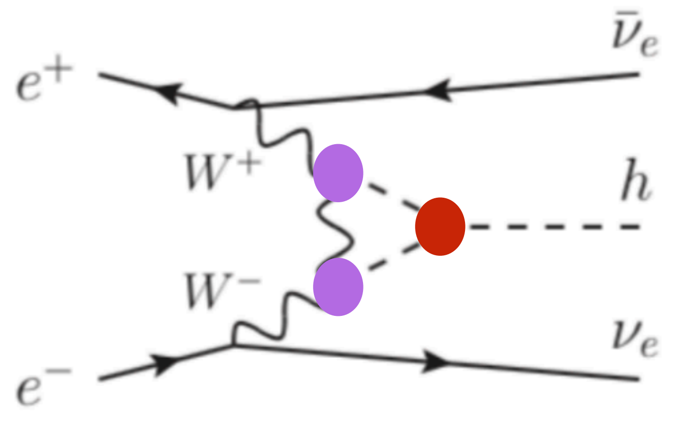


g_Z , λ_3

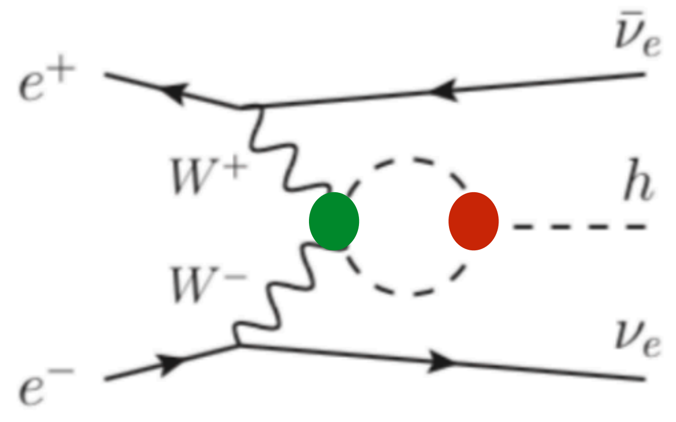


λ_3 , λ_{VVHH}

weak boson fusion



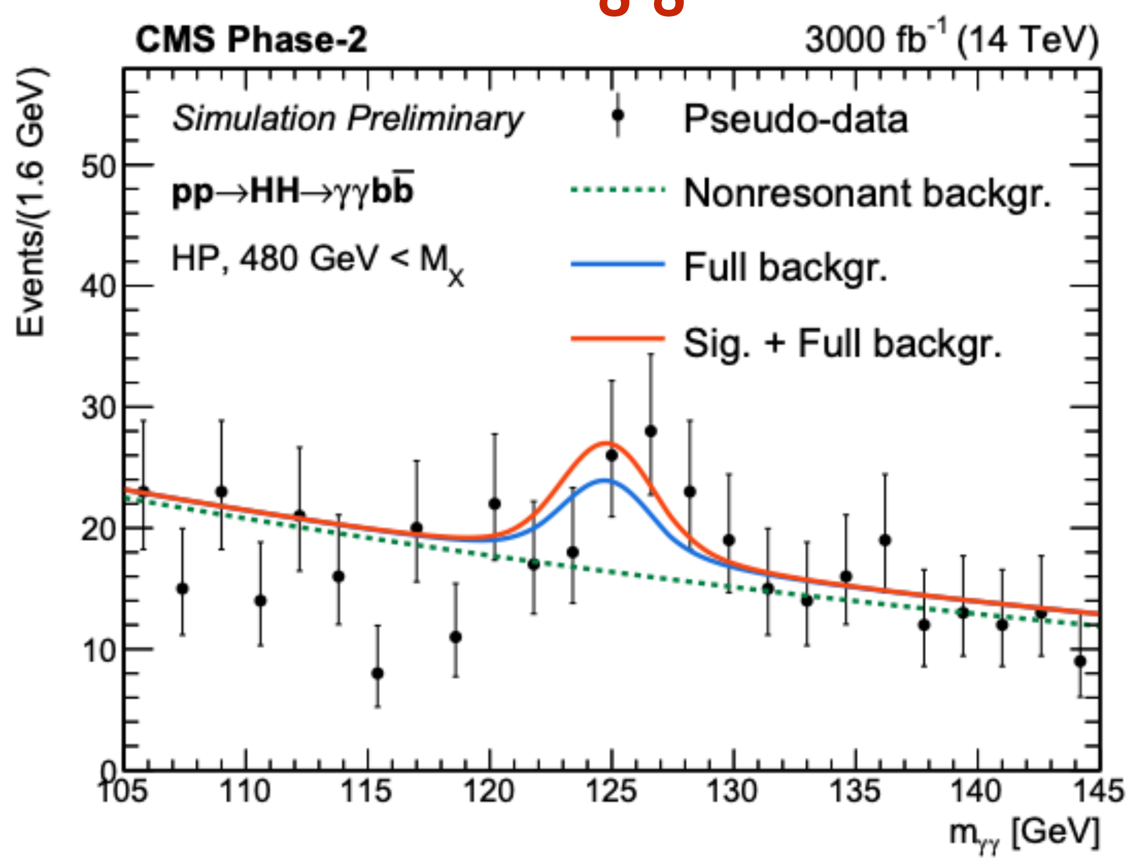
g_Z , λ_3



λ_3 , λ_{VVHH}

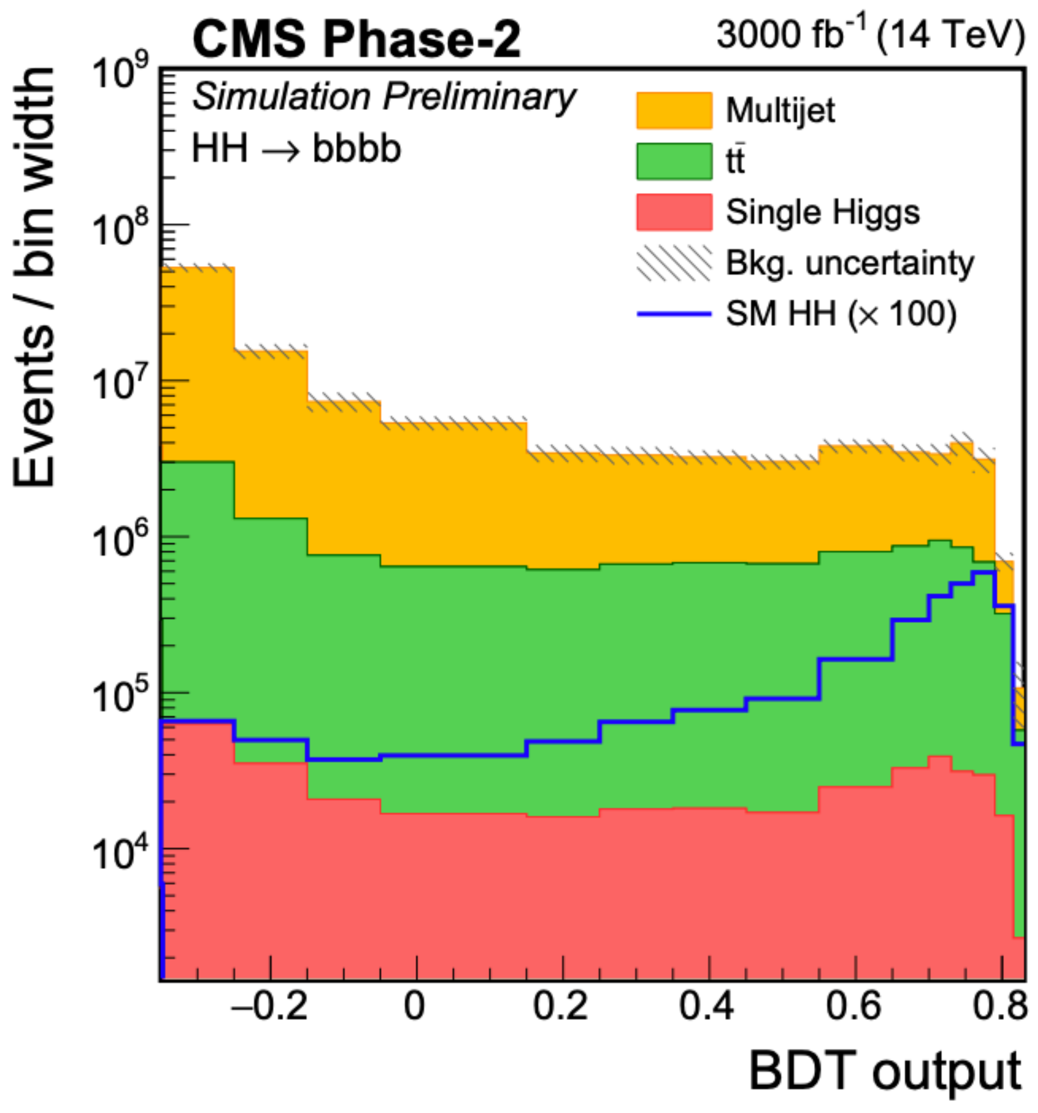
Self coupling @ HL-LHC measurements

bbγγ

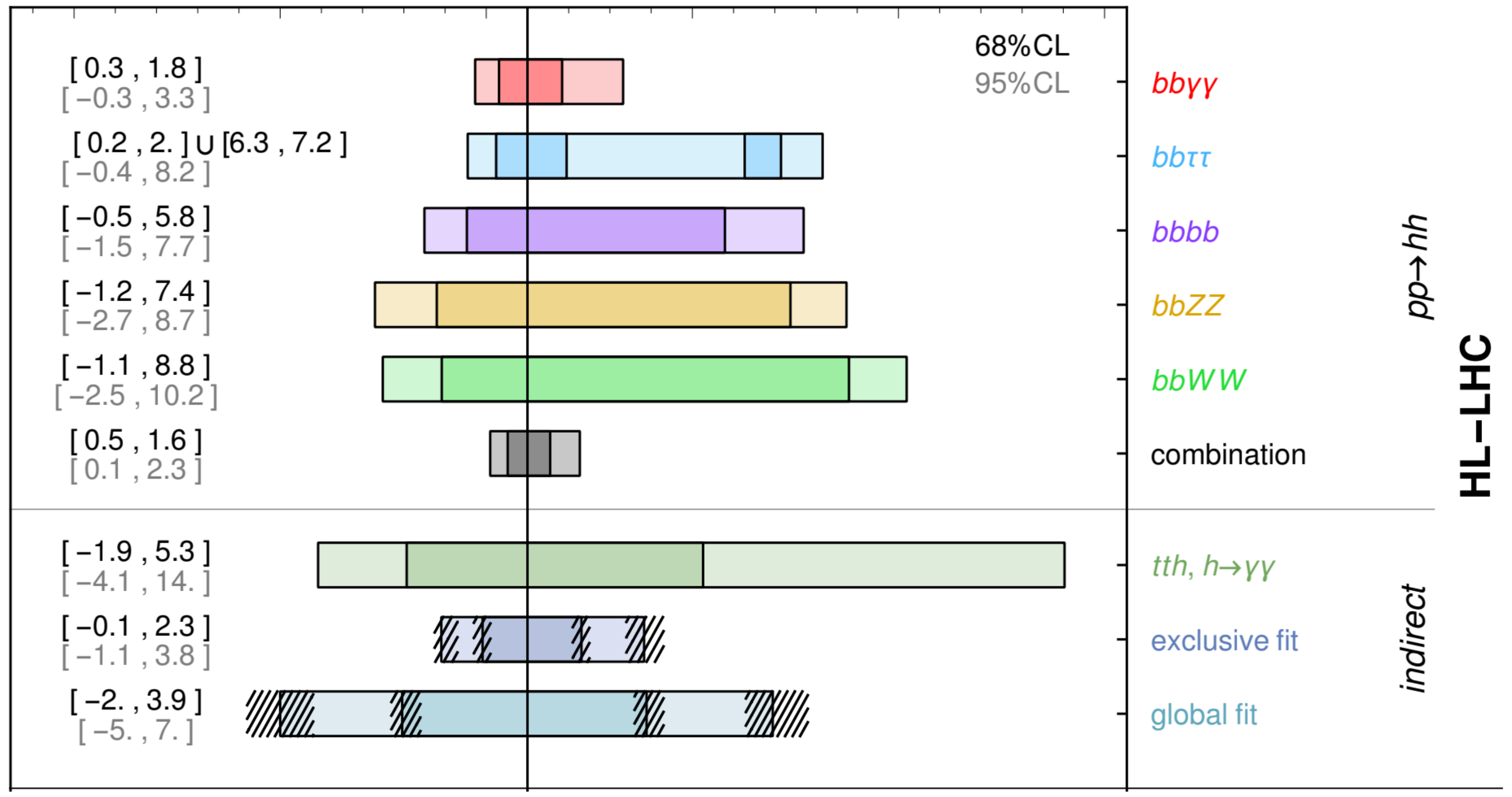


- At the (HL-)LHC the self-coupling can be measured via both:
  - Higgs pair production
  - single Higgs production
- Indirect constraint from ggH and ttH:
  - $\delta\kappa_\lambda \approx 100\%$ (exclusive)
  - $\delta\kappa_\lambda \approx 200\%$ (global)
- Direct measurement:
  - $\delta\kappa_\lambda \approx 50\%$

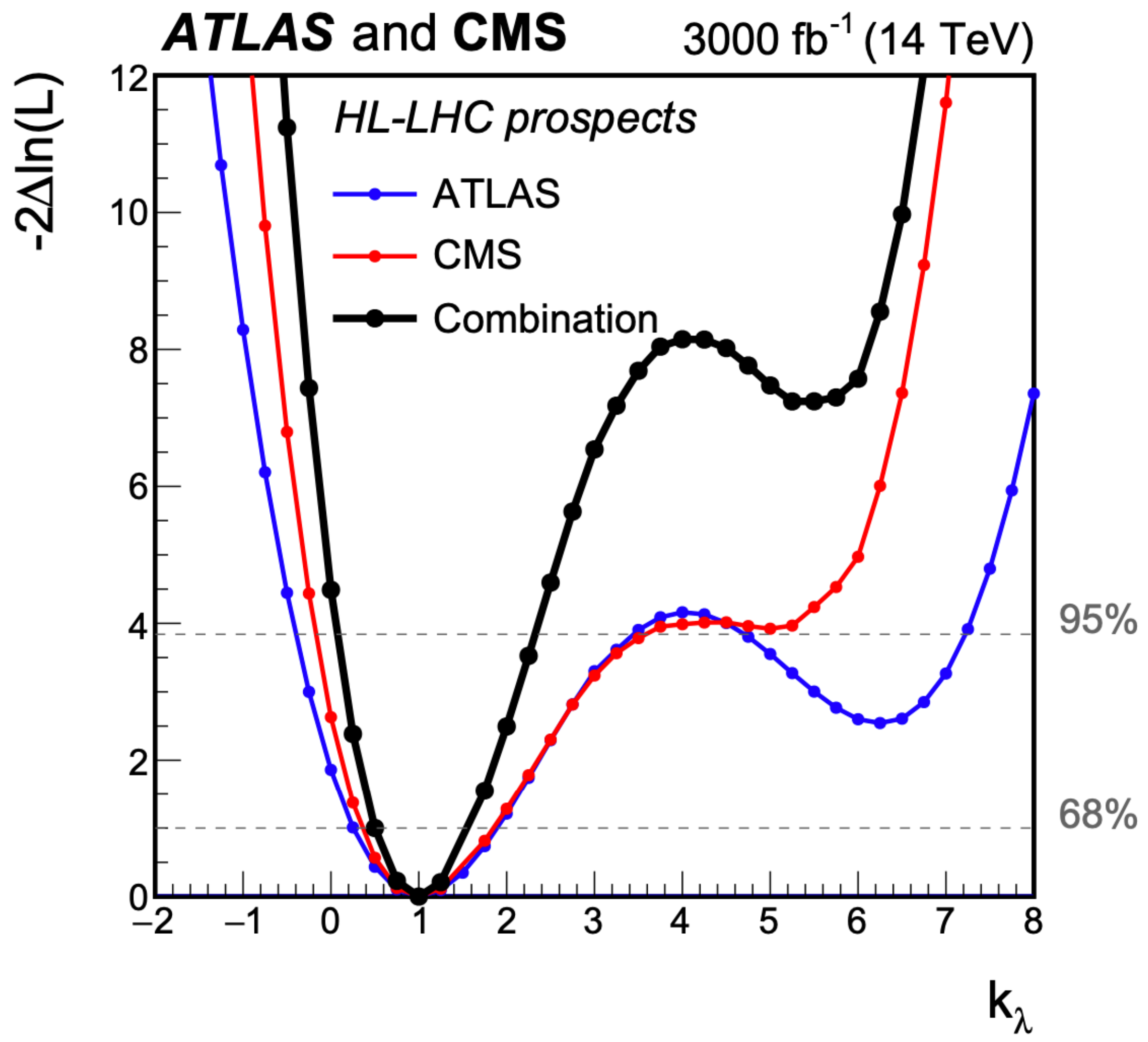
bbbb



combination HL-LHC

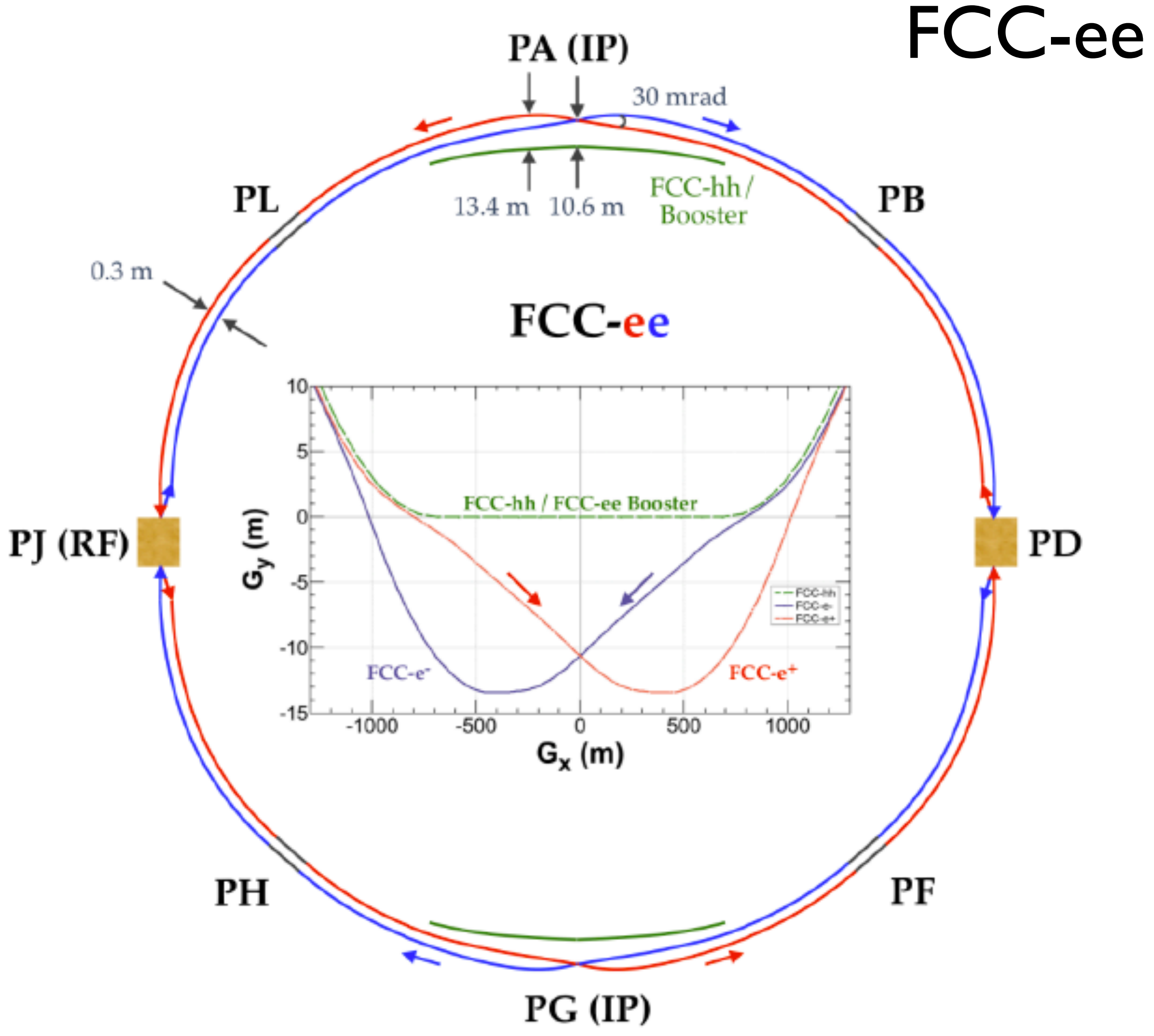


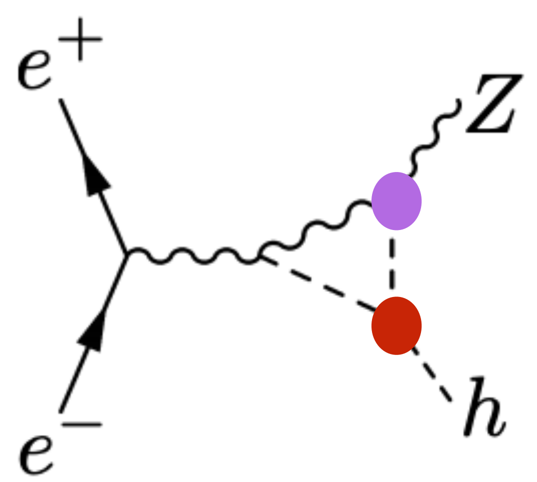
combination HL-LHC

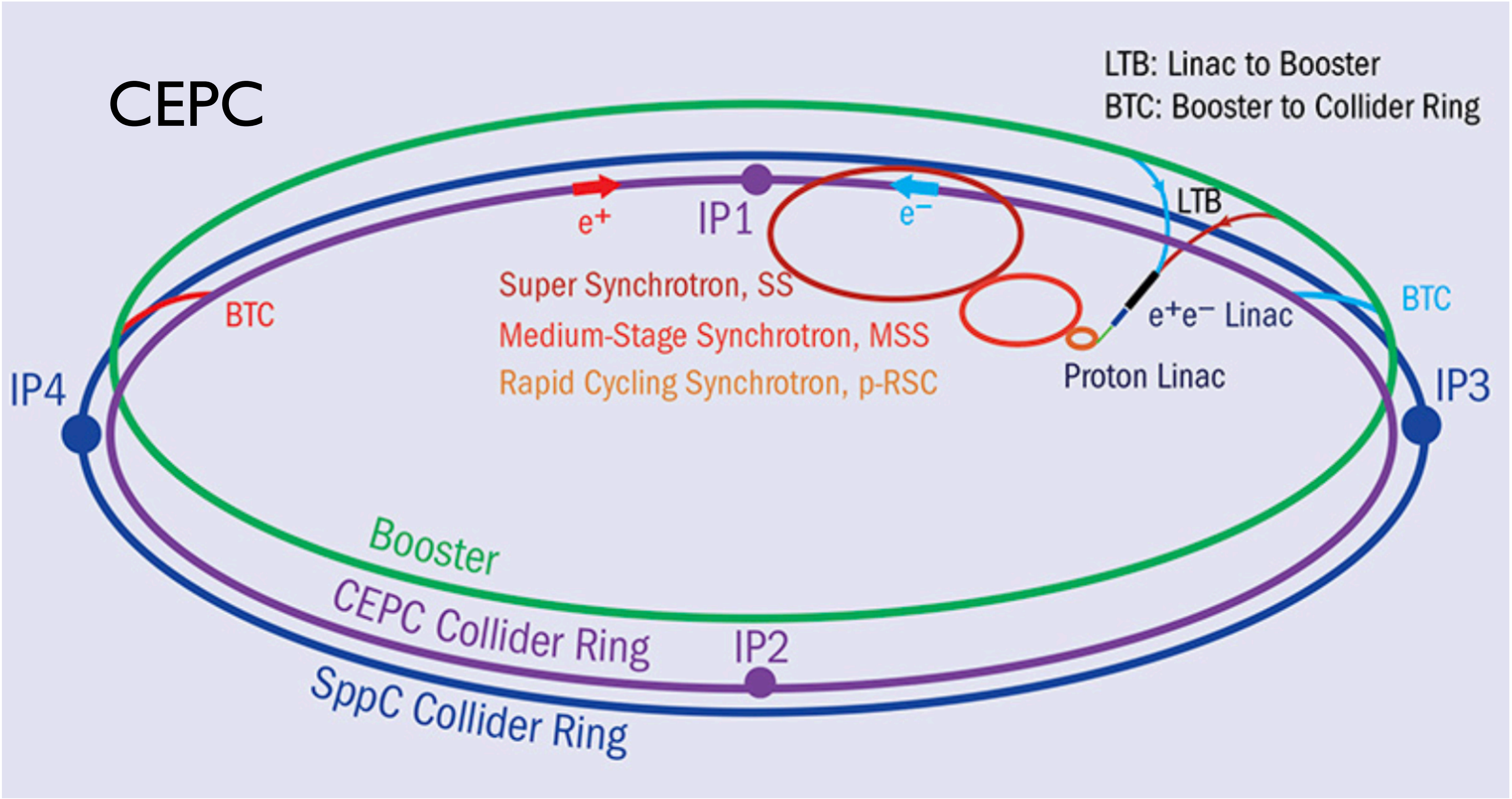


Circular e+e- machines

FCC-ee

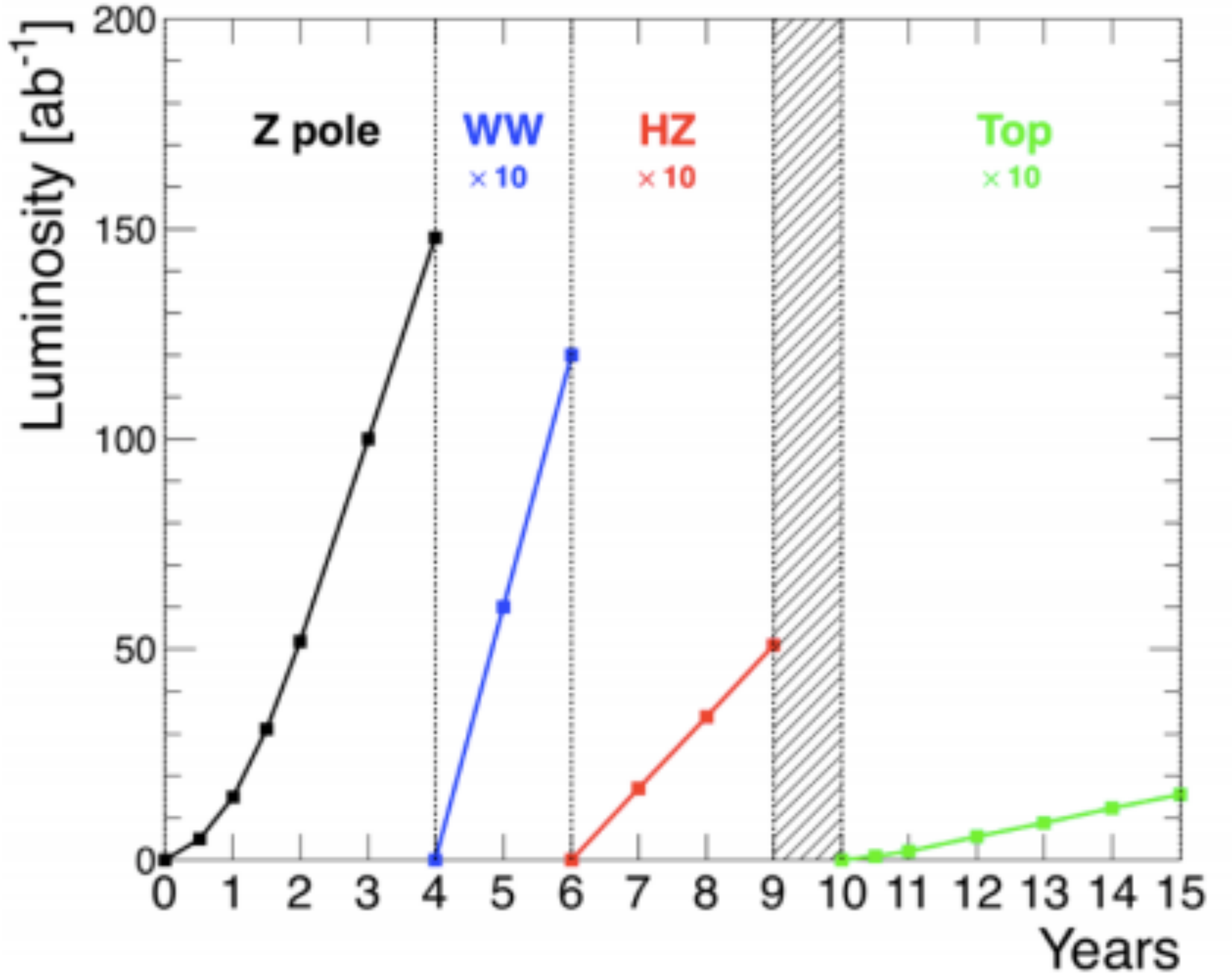




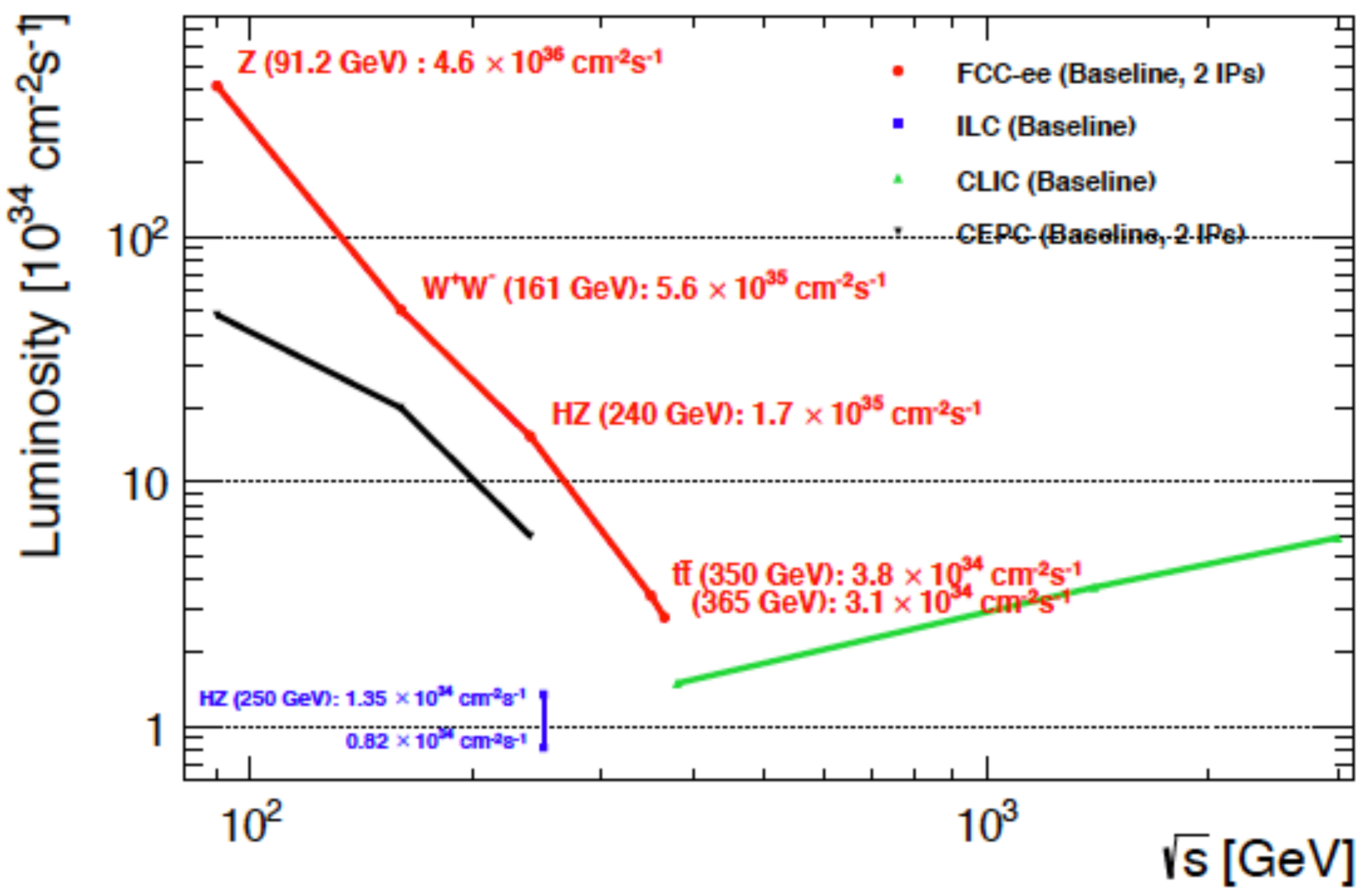


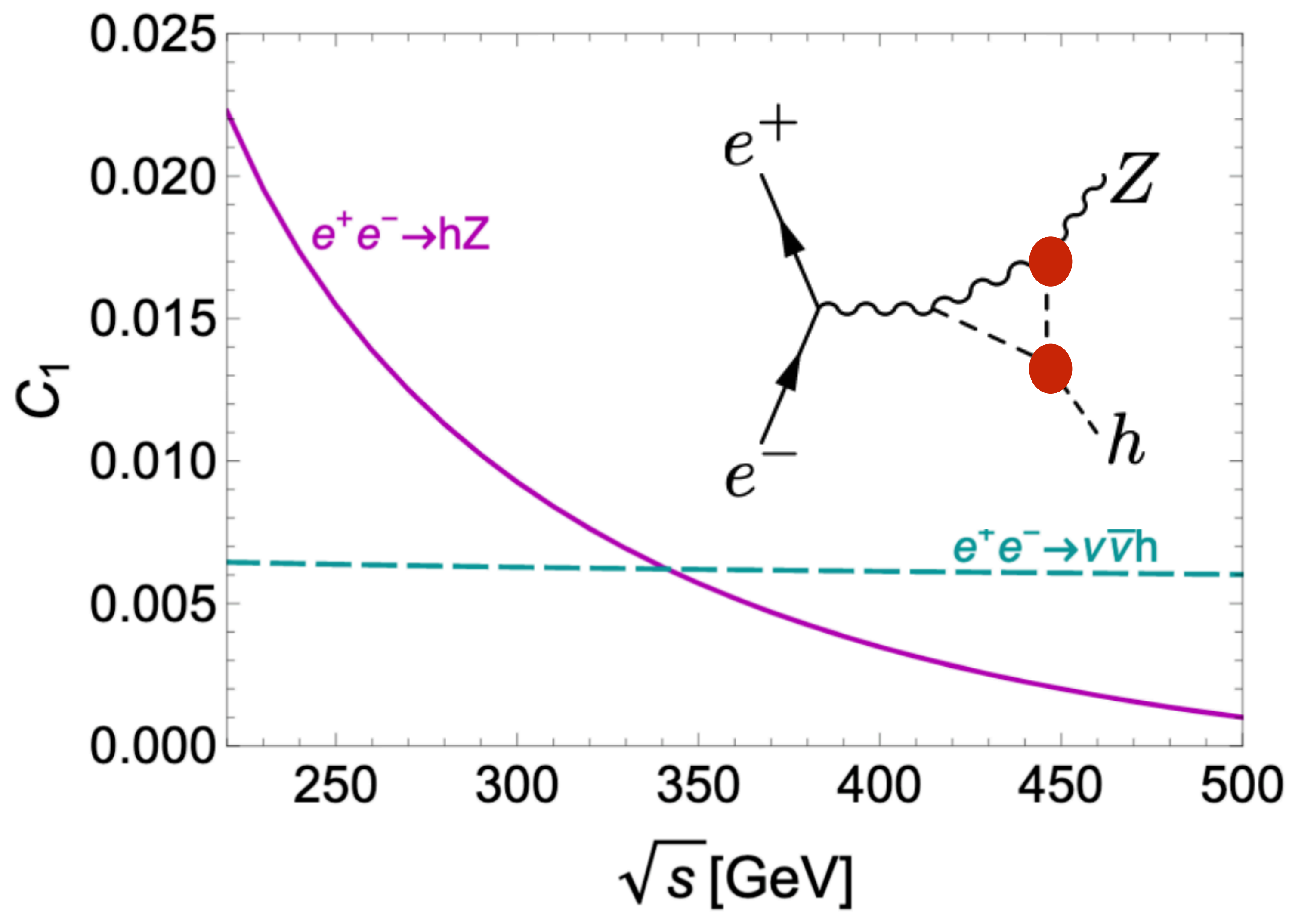
Parameter	Z	W	H	t
Cm E [GeV]	91.2	160	240	350
FCC-ee				
L [10^{34} $cm^{-2}s^{-1}$]	200	28	8.5	1.8
Years op.	4	2	3	5
Int. L / 2 IP [ab^{-1}]	150	10	5	1.5
CEPC				
L [10^{34} $cm^{-2}s^{-1}$]	32	10	3	
Years op.	2	1	7	
Int. L / 2 IP [ab^{-1}]	16	2.6	5.6	

- Maximum ECM ~ 350 GeV
- Limited by synchrotron radiation

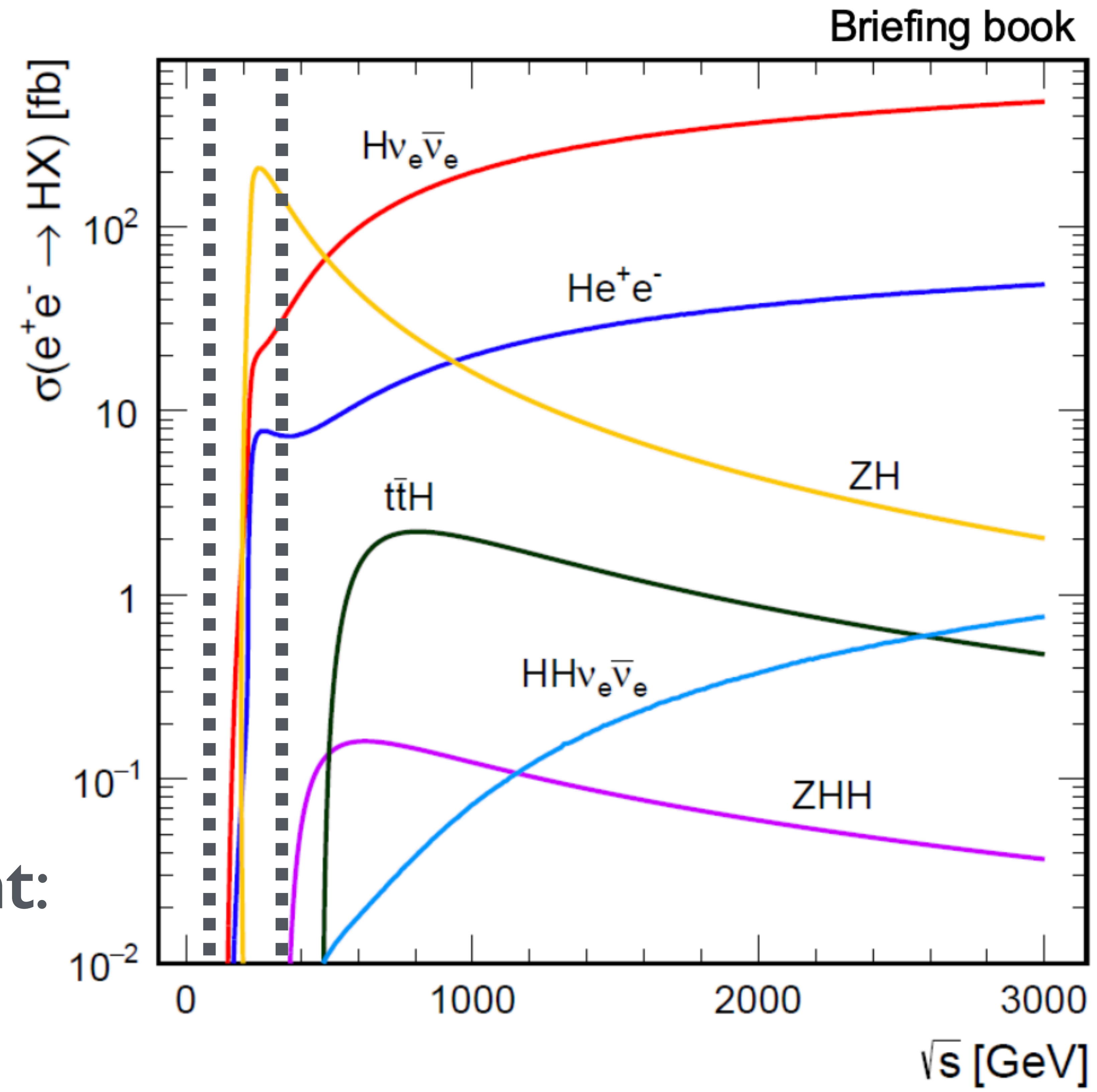


Self-coupling at circular e^+e^- colliders





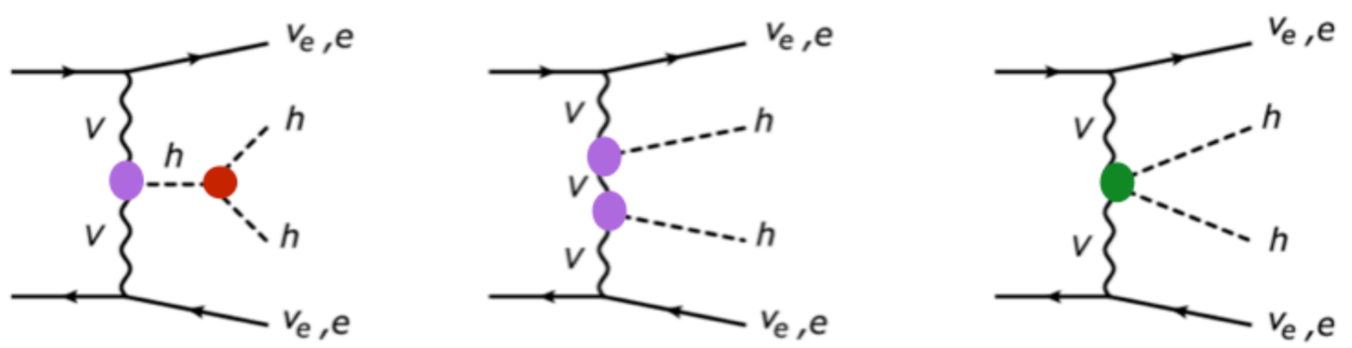
- At **low energy √s < 500 GeV** the self-coupling is measured via **single Higgs production** (FCC-ee)
- Precise ZH, ννH cross-section measurement at various energies:
  - sqrt(s) = 240, 365 GeV
- can resolve λ_3, λ_{VVHH}
- **FCC-ee provides best measurement:**
  - $\delta\kappa_\lambda$ = 33% (2 IPs)
  - $\delta\kappa_\lambda$ = 24% (4 IPs)



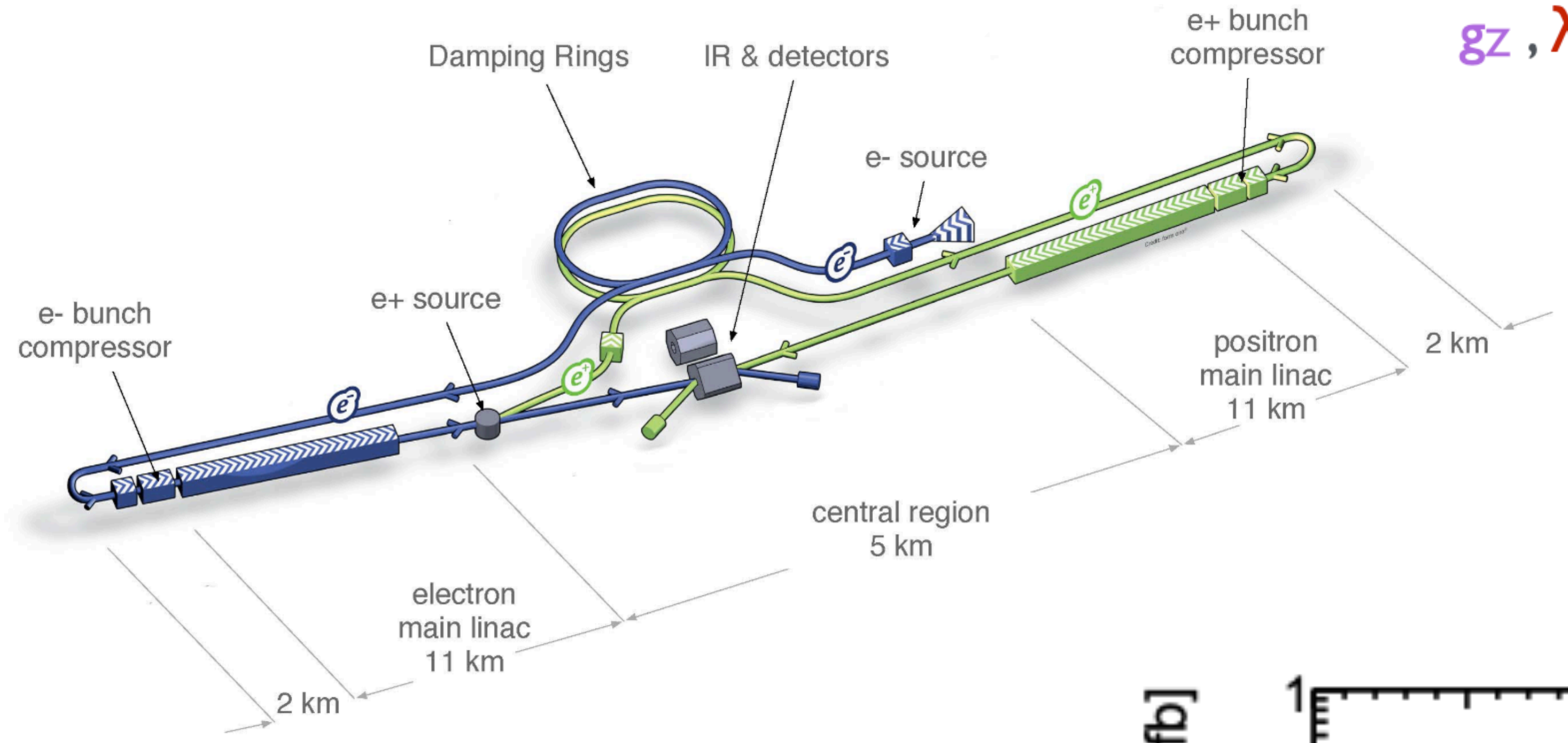
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 2IP 27./24. 4IP

global fit, with/without HL-LHC input

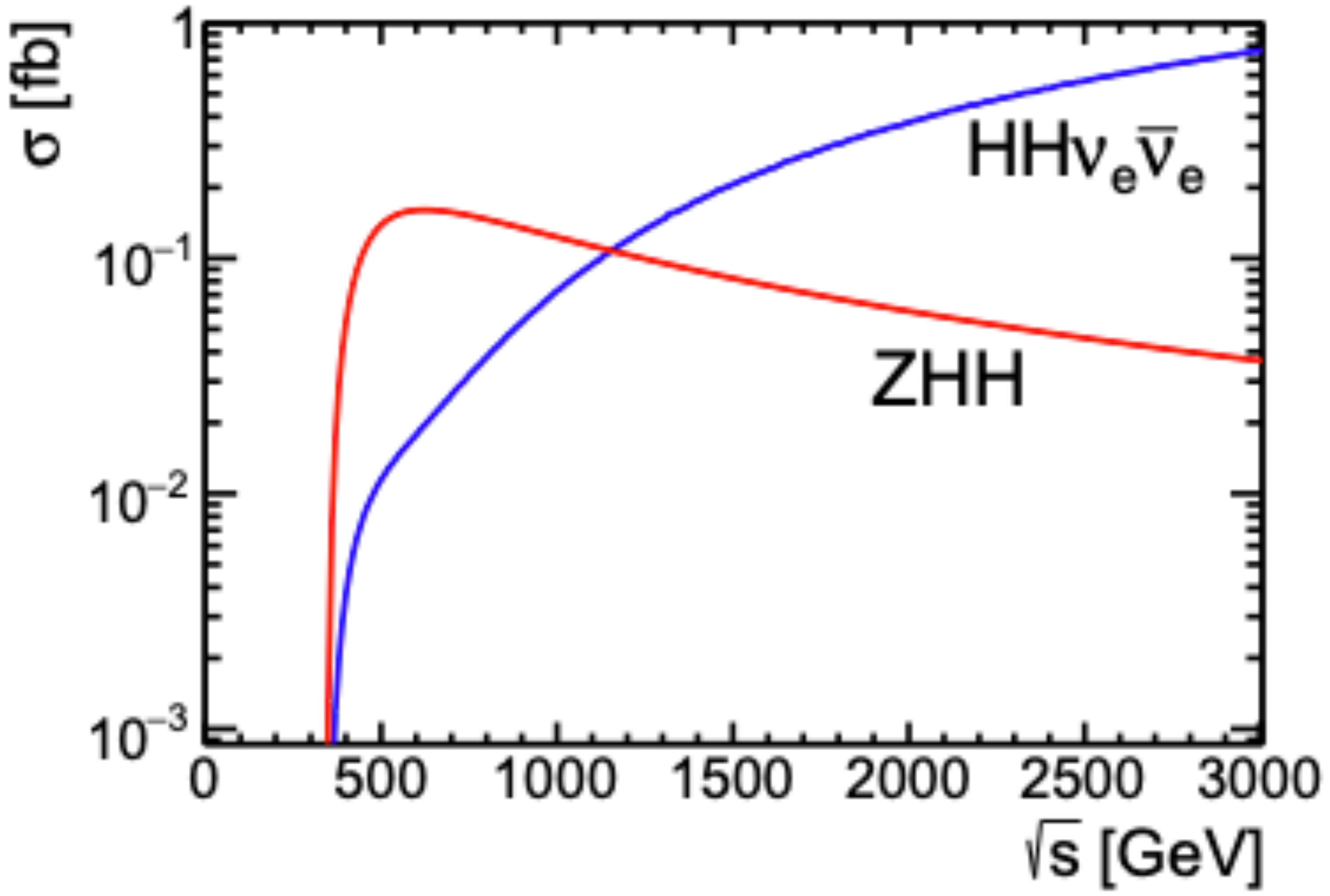
Linear e+e- colliders

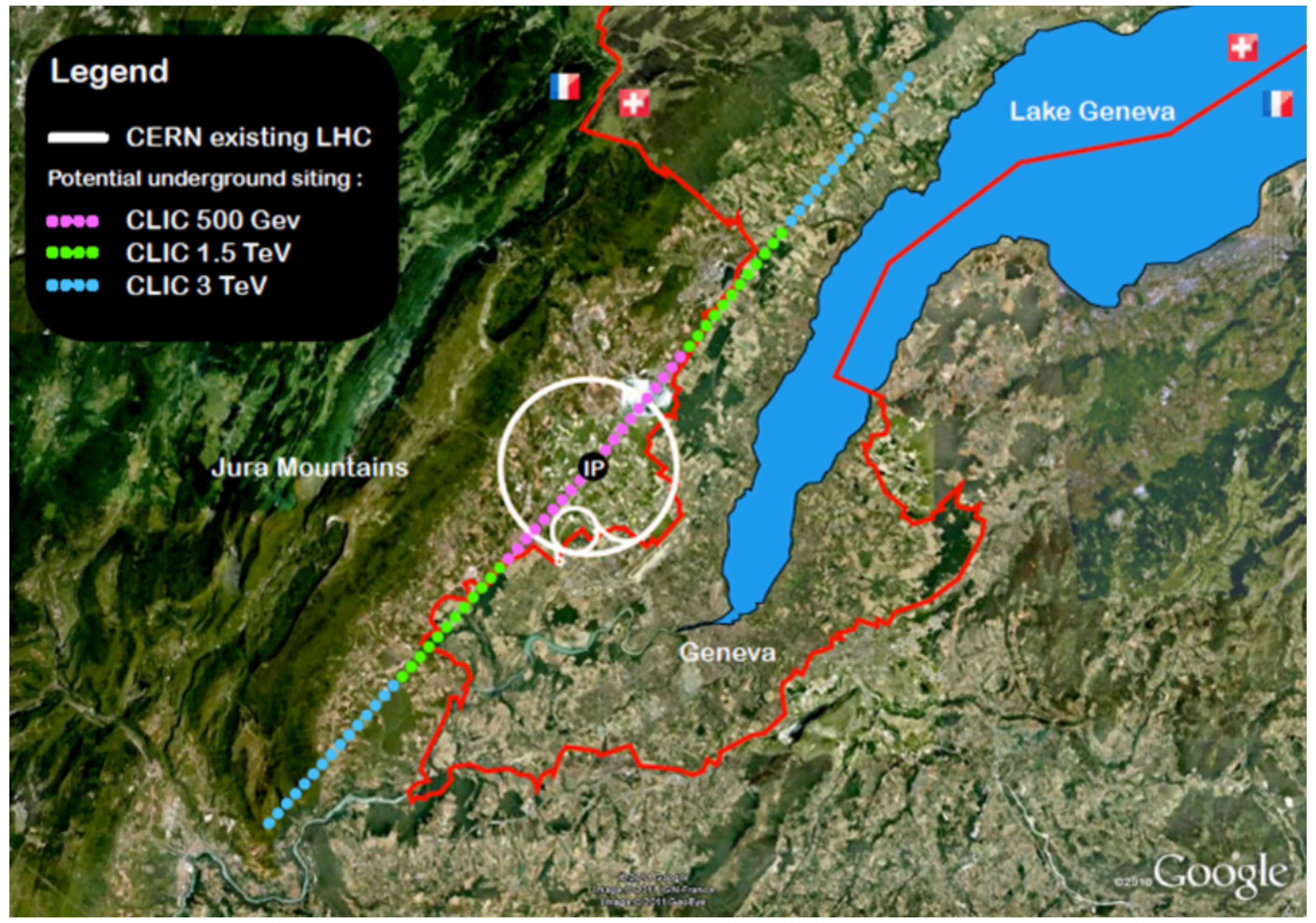


g_Z , λ_3 | g_Z | λ_{VVHH}



ILC



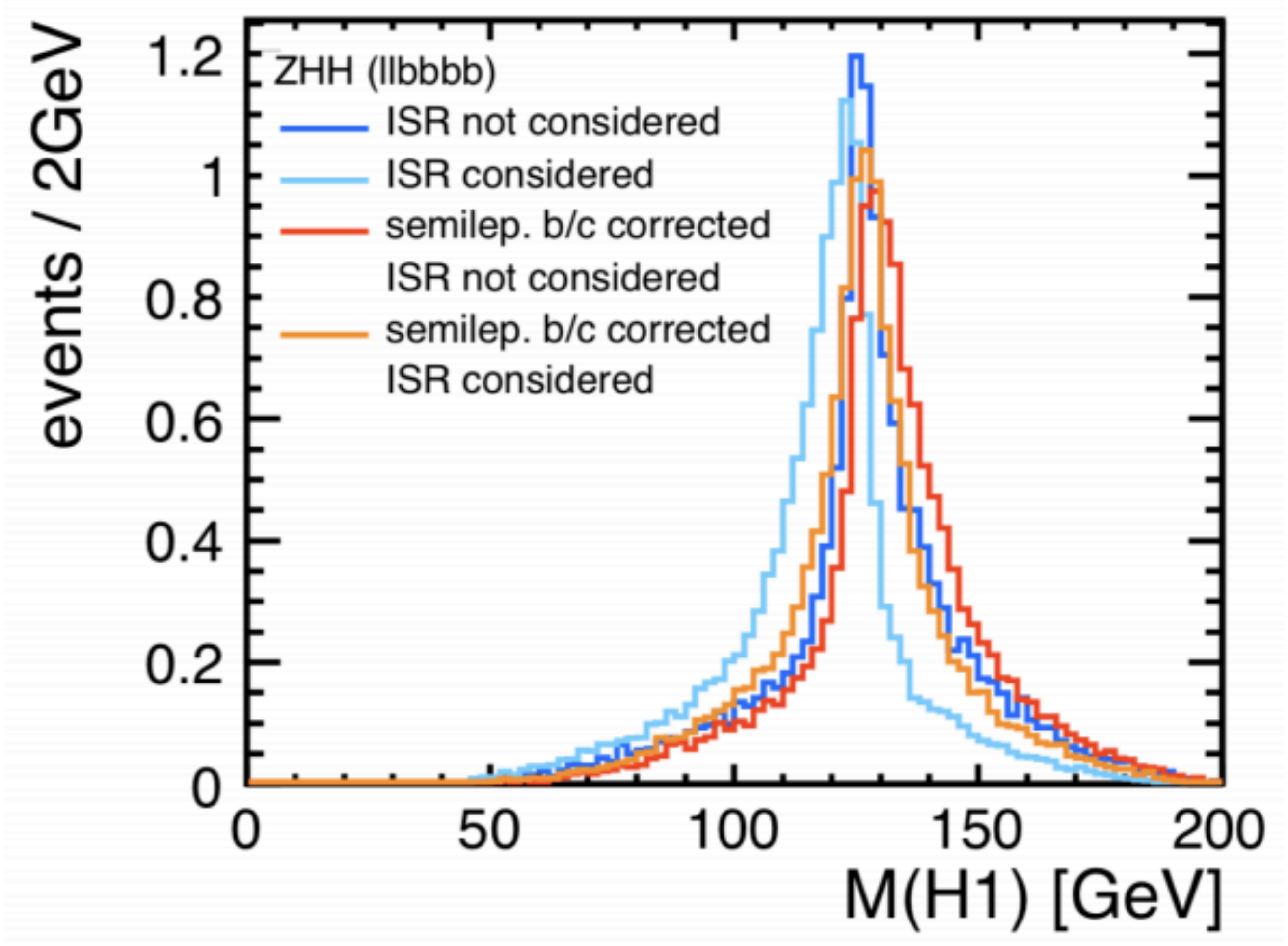


CLIC

sqrt(s)	500 GeV	1 TeV
Lumi	4 ab^{-1}	8 ab^{-1}

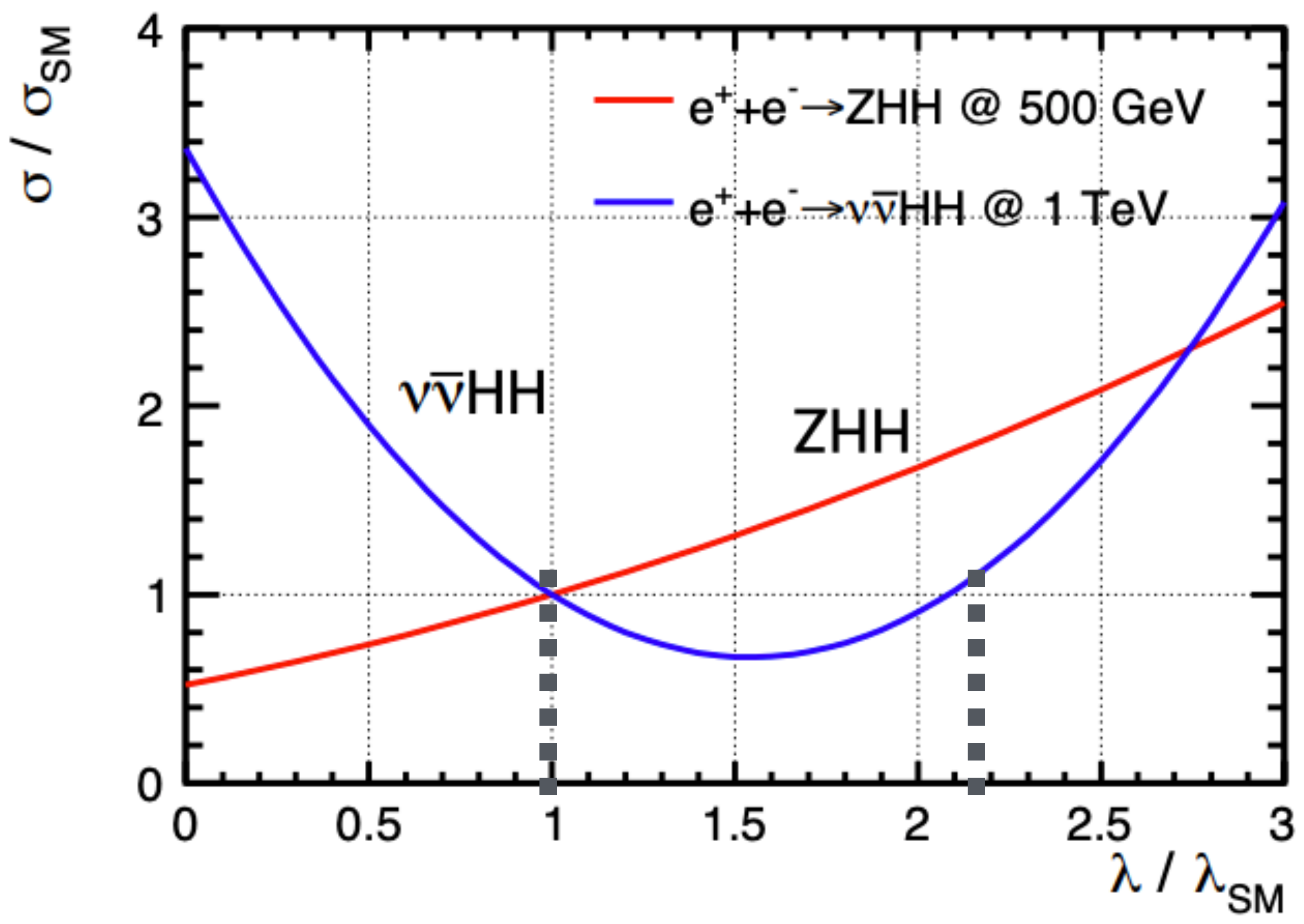
sqrt(s)	1.5 TeV	3 TeV
Lumi	2.5 ab^{-1}	5 ab^{-1}

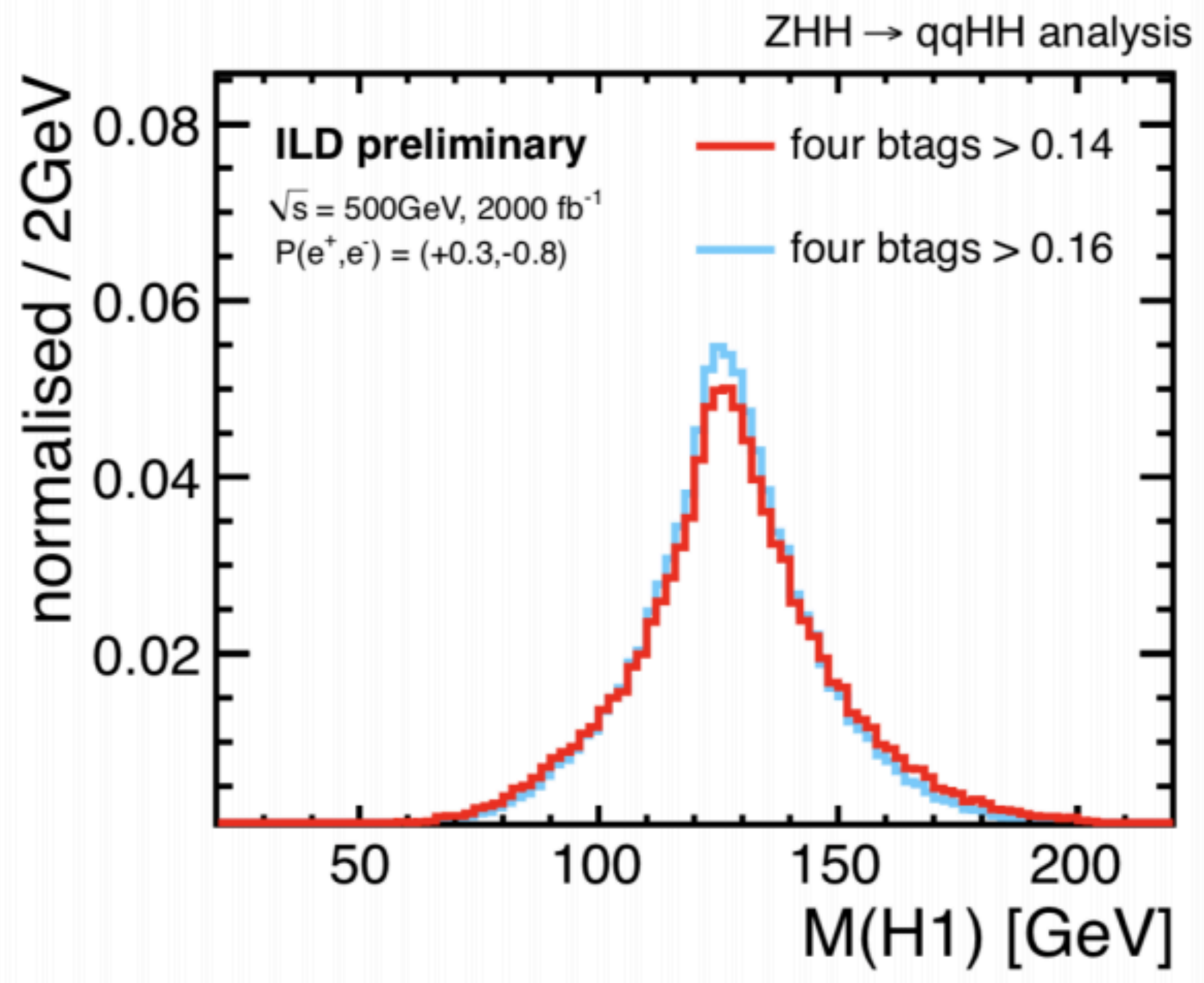
Self-coupling at ILC



- At high **energies √s > 500 GeV** self-coupling is measured via double Higgs production (ZHH and ννHH)
- ZHH/ννHH constructive/destructive interference
  - cross-section at various energies depends on λ_3 and λ_{VVHH}
- Polarisation **(80% LR/RL,20% LL/RR)** enhances ννHH production by x2

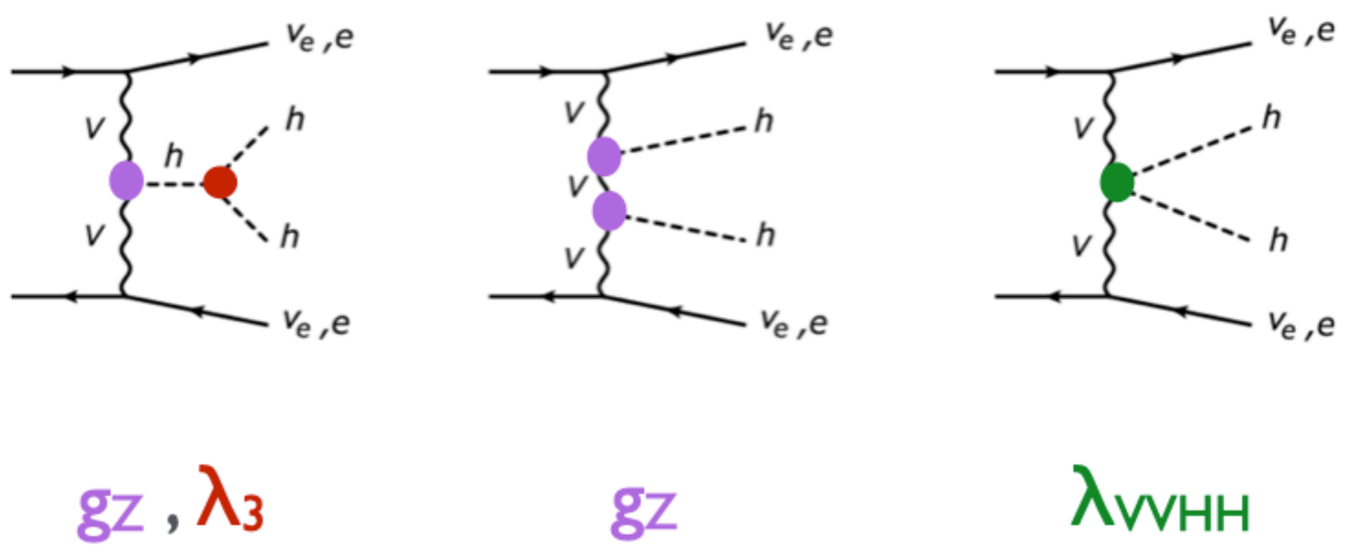
[1903.01629]

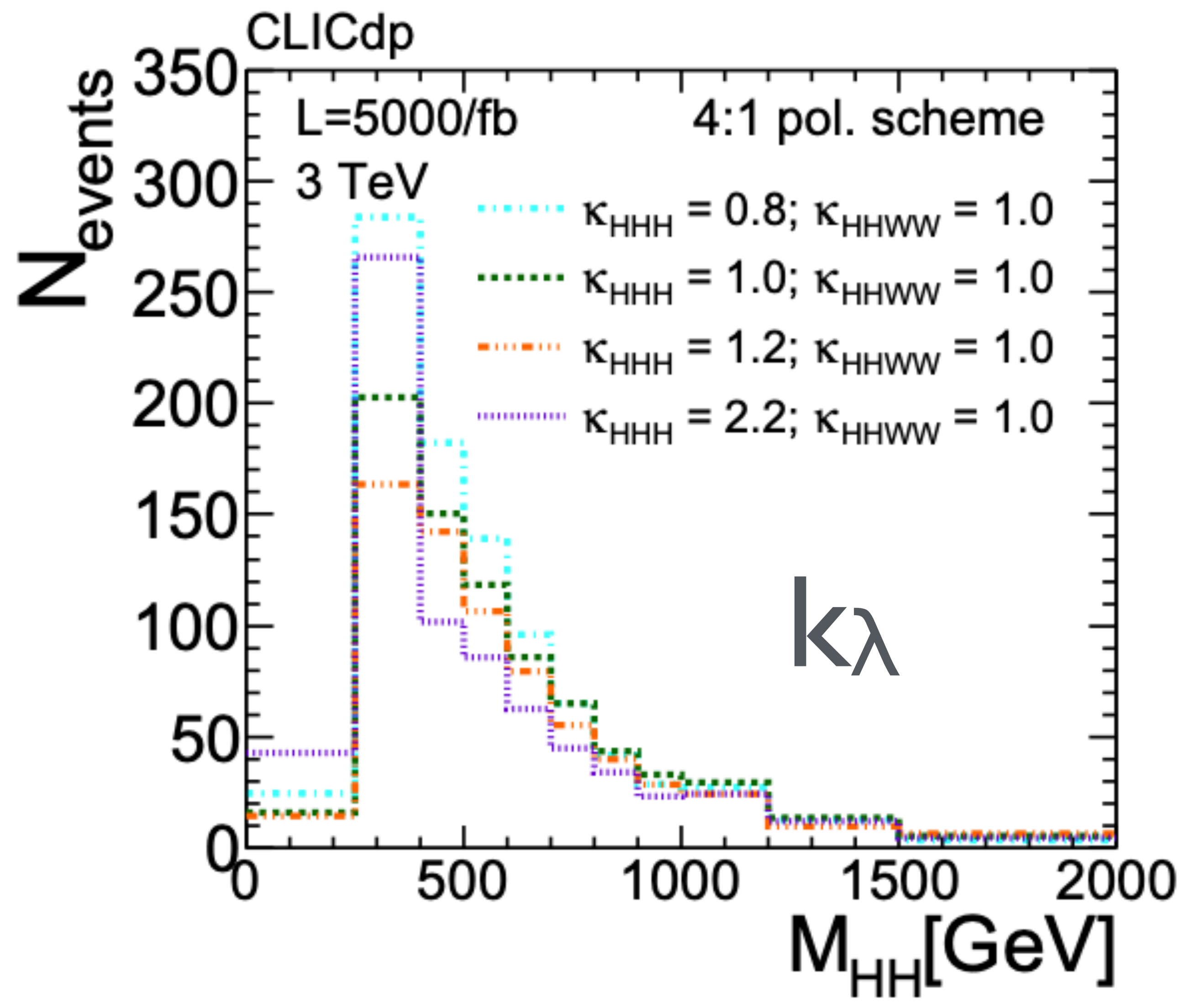




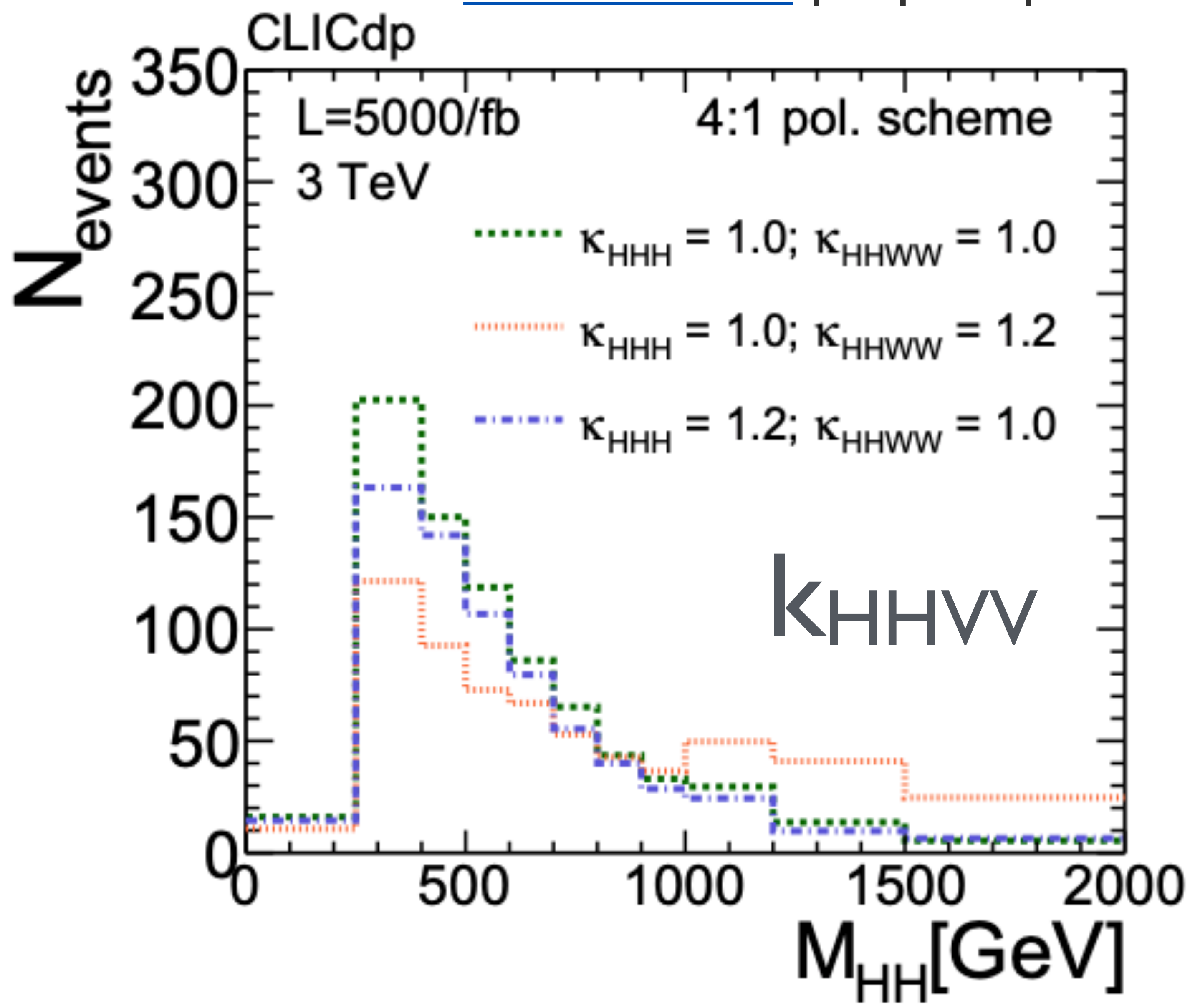
- **√s =** 500 GeV
  - Measured in ll(νν/jj) bbbb , bbWW (ZHH)
  - backgrounds: ZZZ, ZZH, bbqqqq
  - **$\delta k_\lambda / k_\lambda$ = 27%**

Self-coupling at CLIC

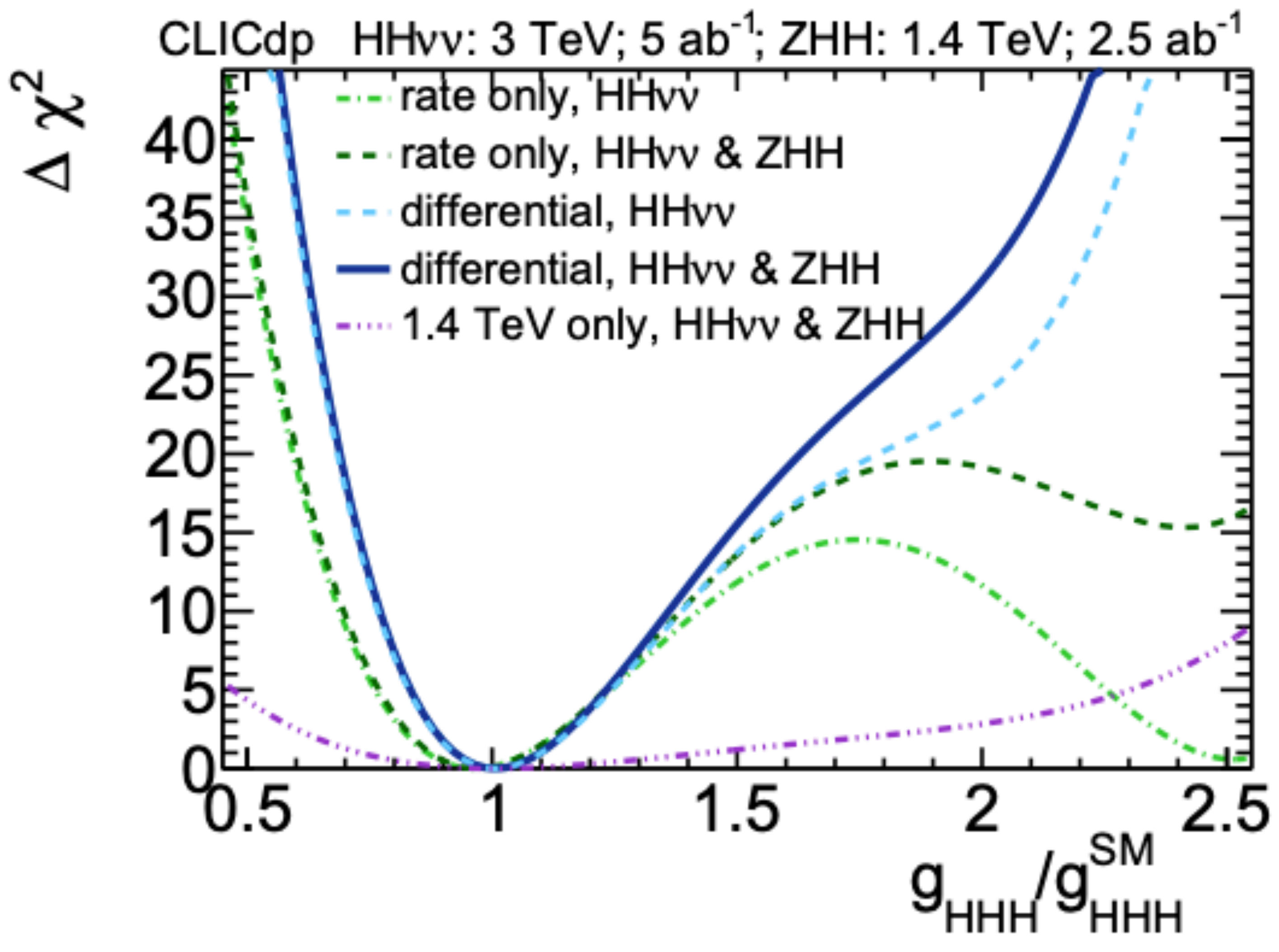


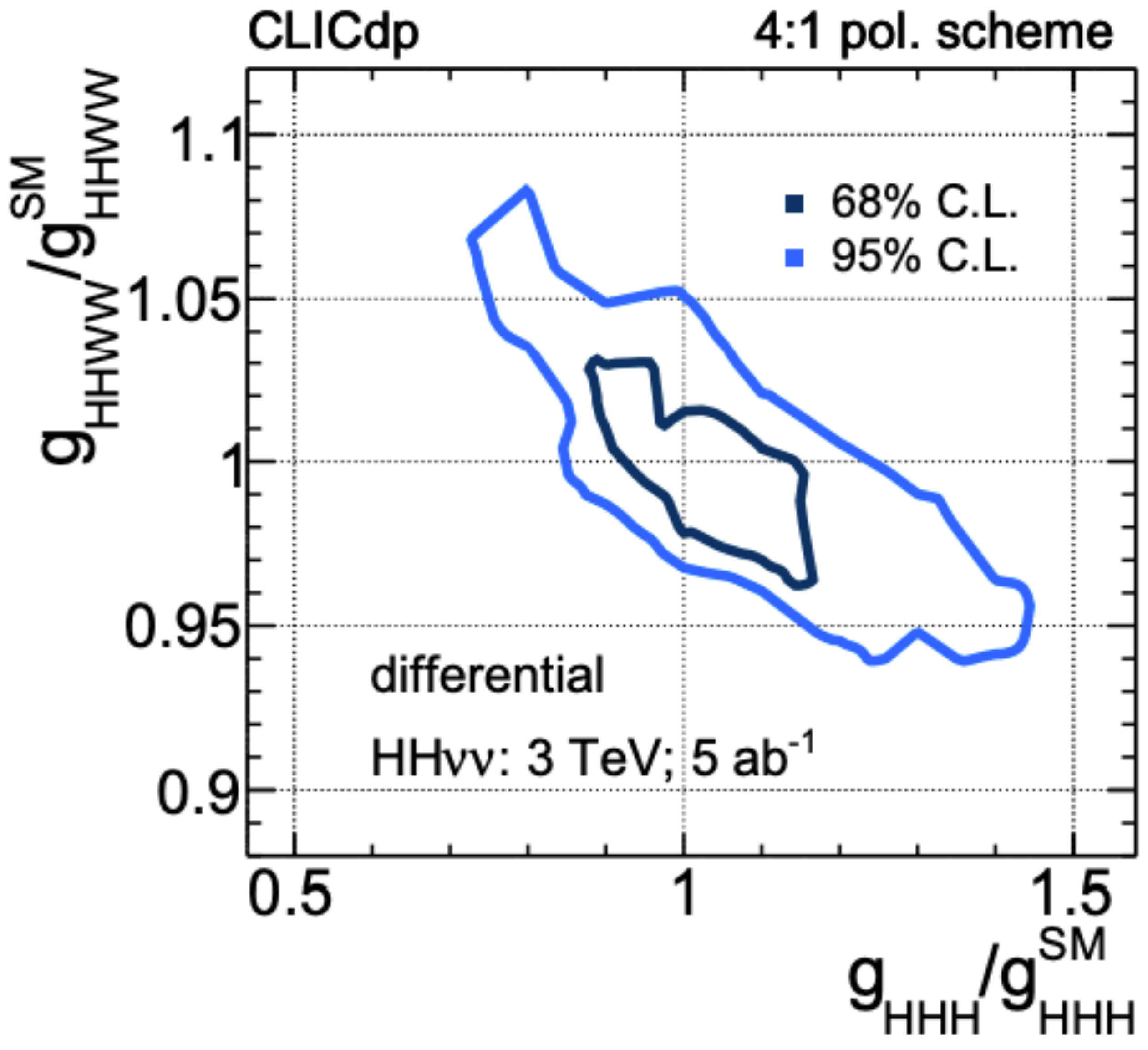


1901.05897 [hep-ex]

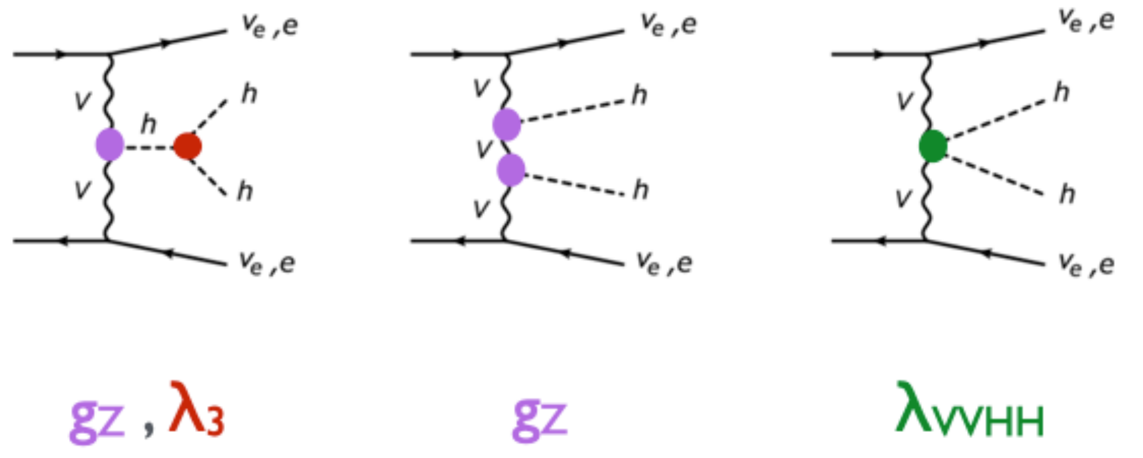


- 4:1 pol scheme 80% LR: 20% RL
- $\sqrt{s}$ = 1.4 TeV (early stage)
  - ννHH → 3.6σ evidence
  - ZHH → 2.1σ evidence
- $\sqrt{s}$ = 3 TeV (late stage)
  - Precision dominated by ννHH, but ZHH helps
  - Template fit on **differential** m_{HH} shape to resolve degeneracy at kλ = 1 and 2.2
  - **$\delta k_\lambda / k_\lambda$ = 8-11% with 5 ab^{-1}**

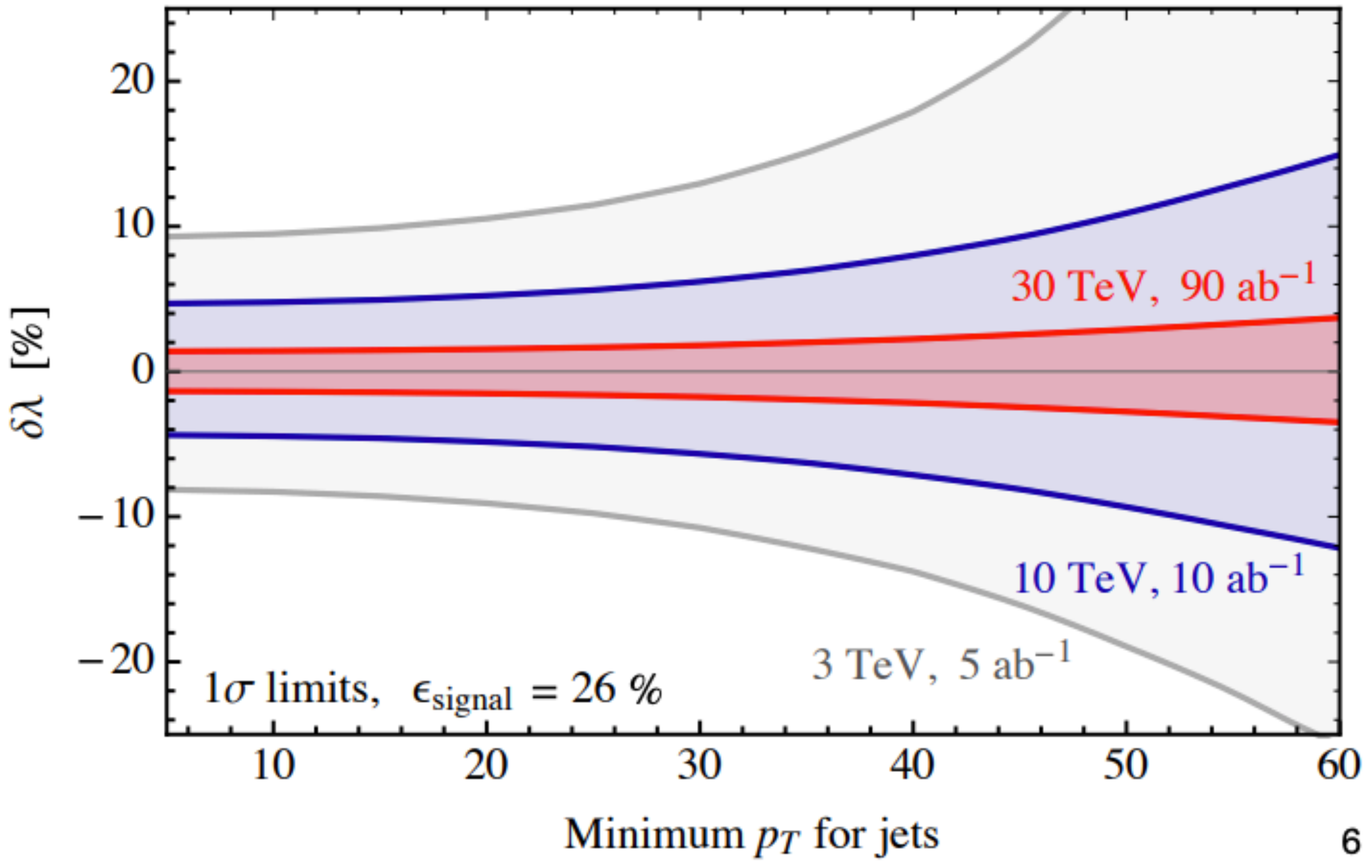




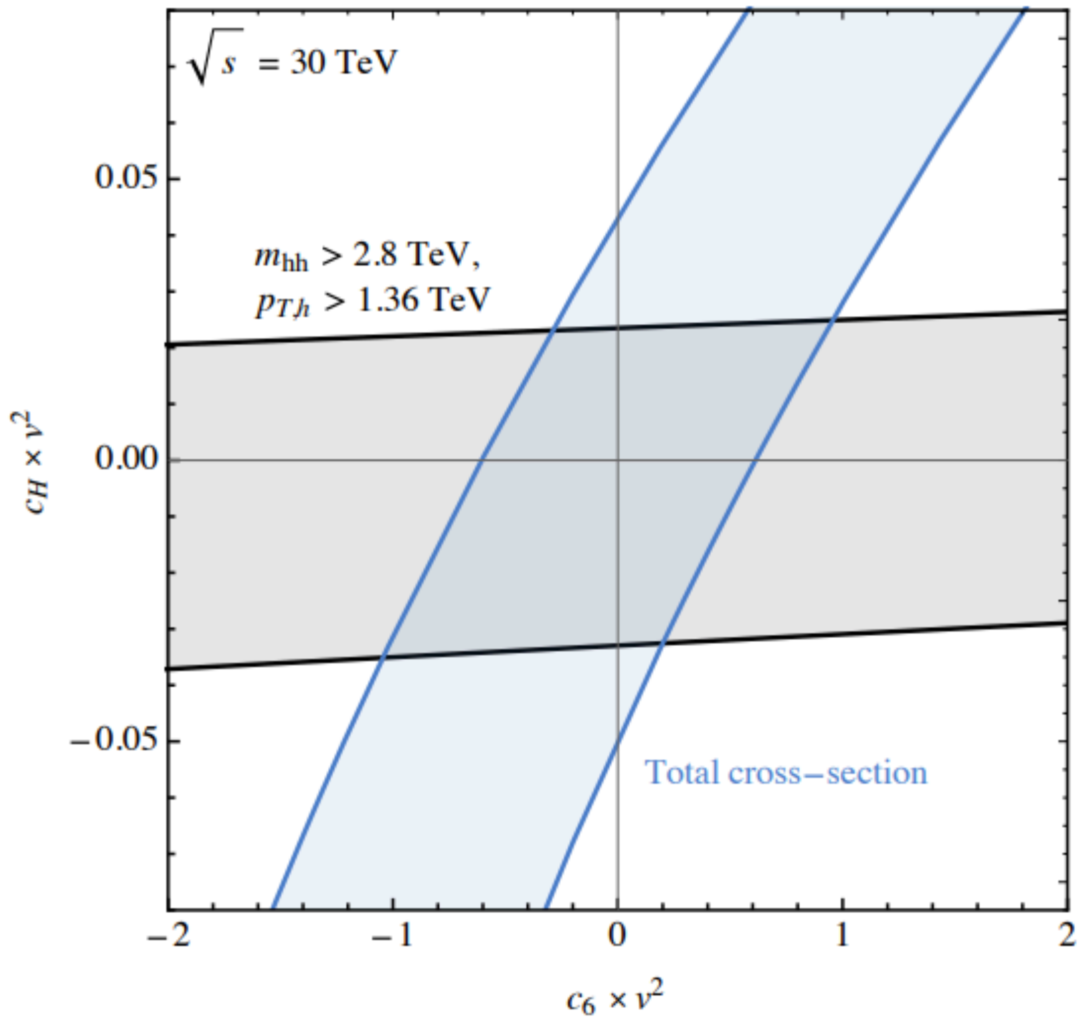
Self-coupling at the Muon Collider

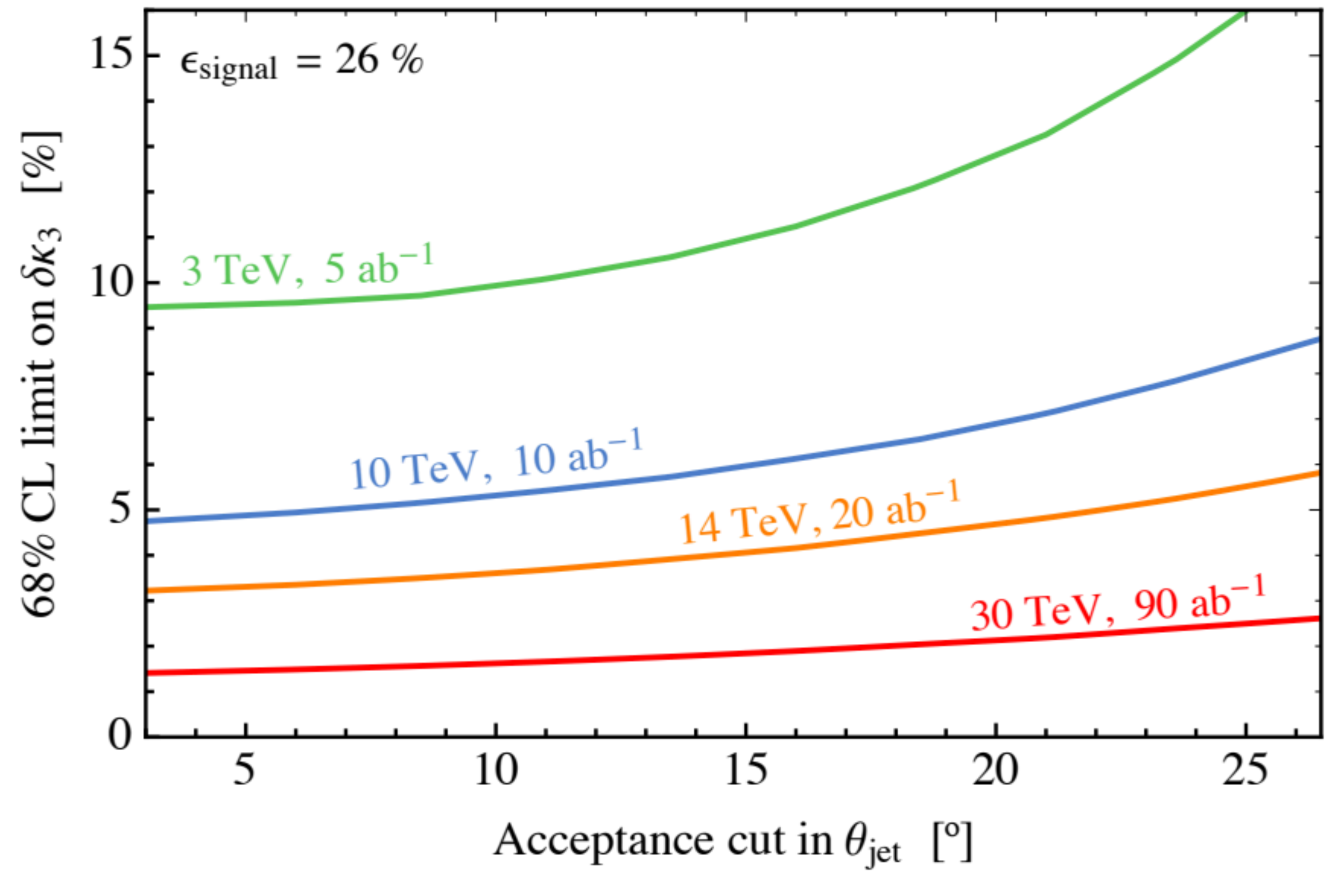


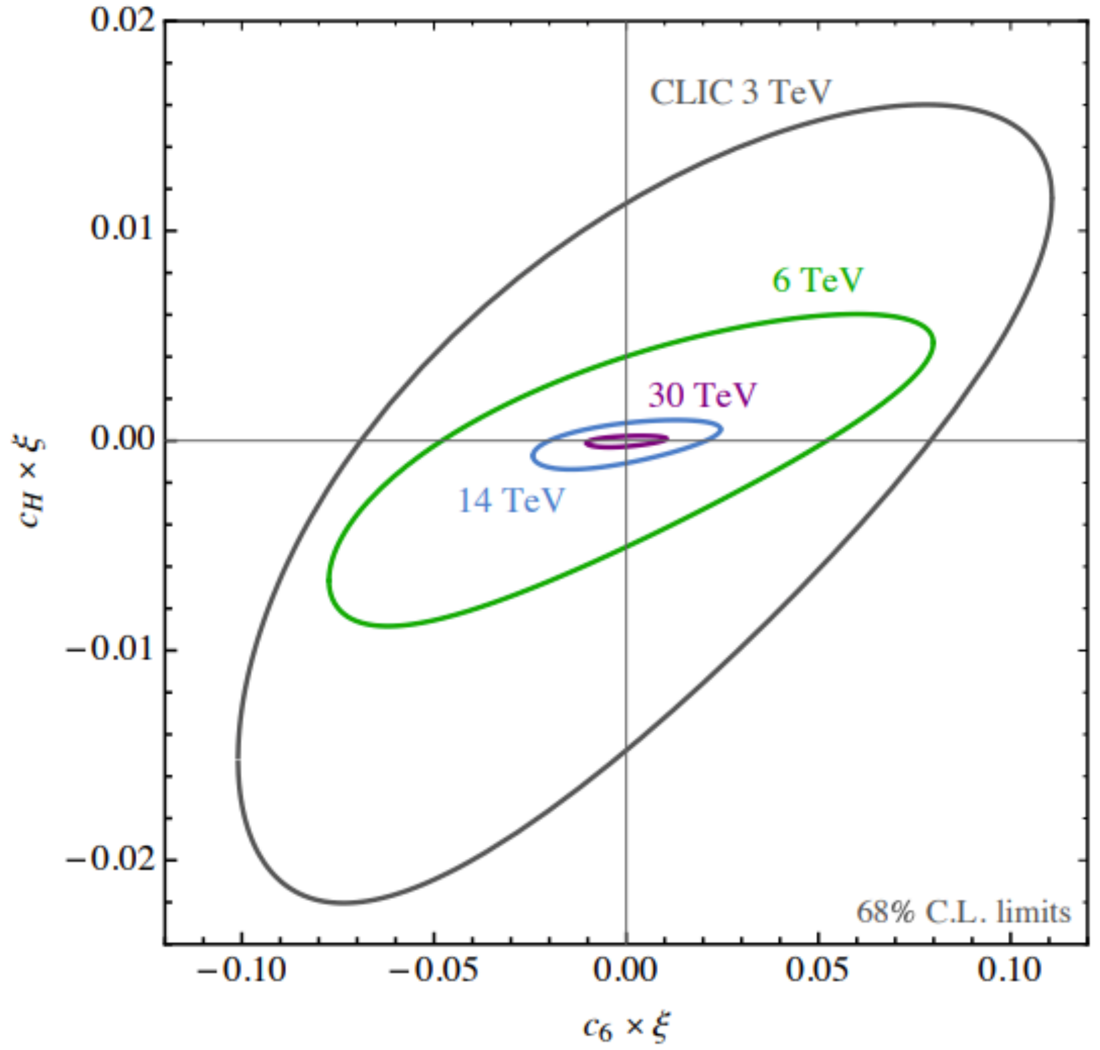
Buttazzo, Franceschini, Wulzer [2012.11555]



- Muon collider can potentially reach the highest energies (up to 30 TeV)
- At sqrt(s) >> 3 TeV muon collider, the VBF pair production dominates (~ CLIC)
- vvbbbb final state (4jets + ME)
- Muon collider could potentially provide the best precision at 30 TeV **~2-3% (stat only)** ?
- More studies needed, **parton level** only for now

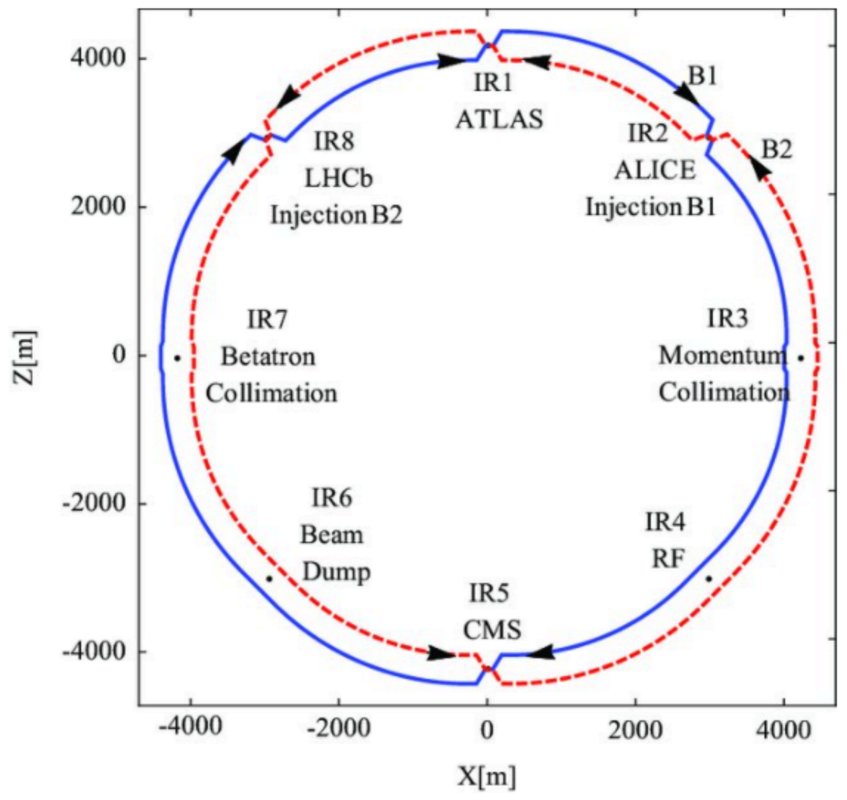




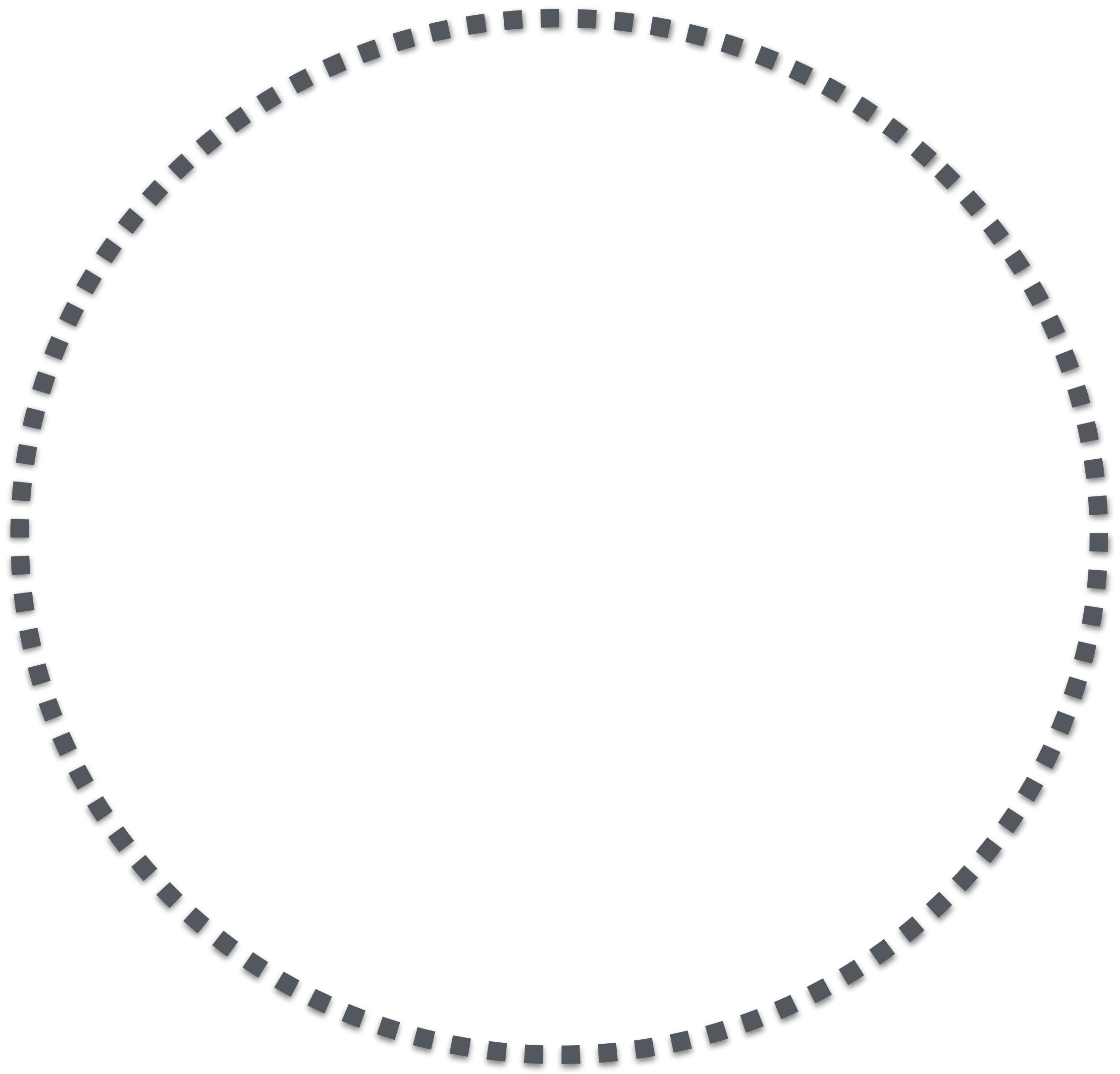


Apply gaussian smearing to jets, assuming 15% energy resolution

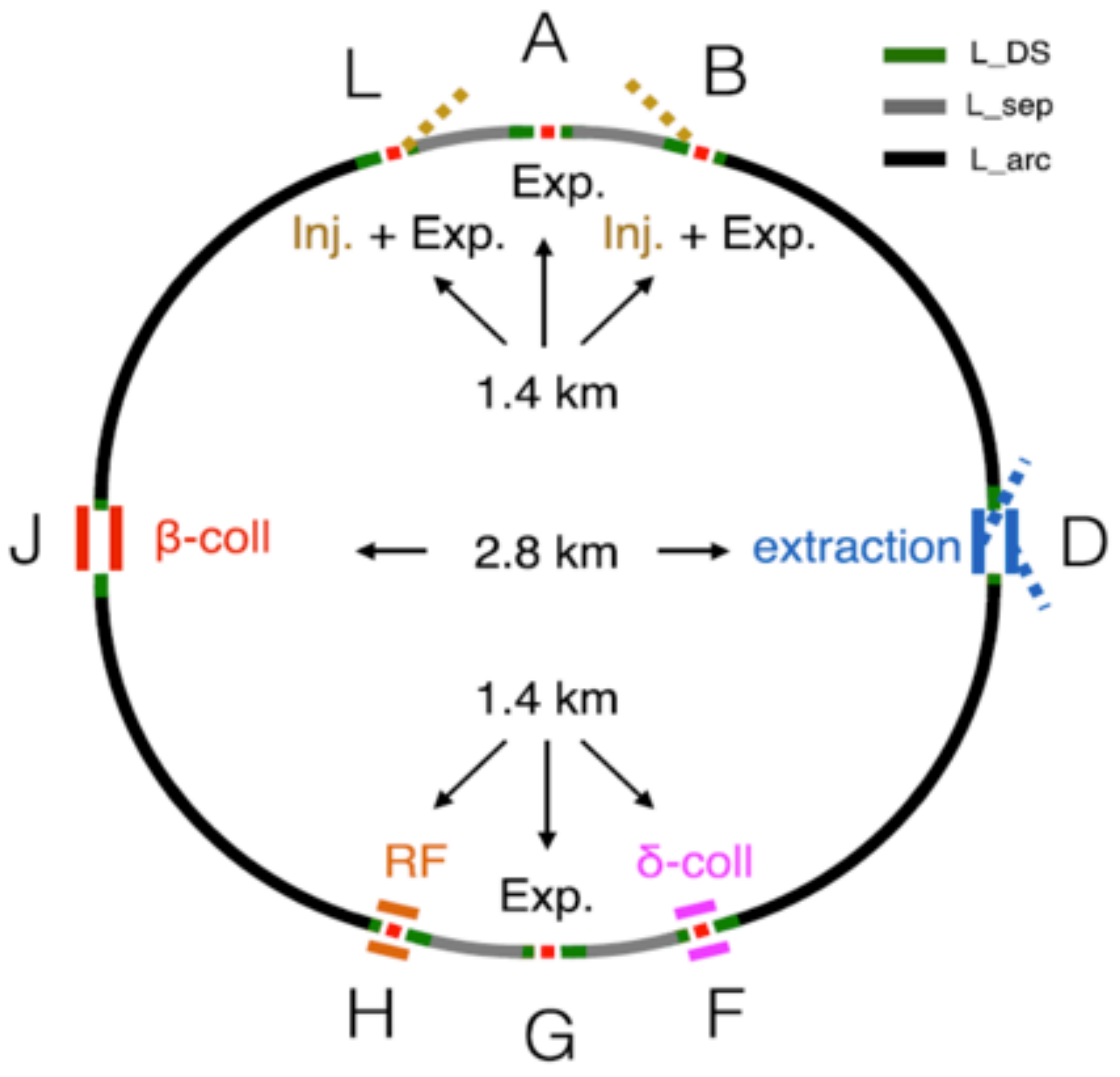
High energy hadron machines



HE-LHC



LE-FCC



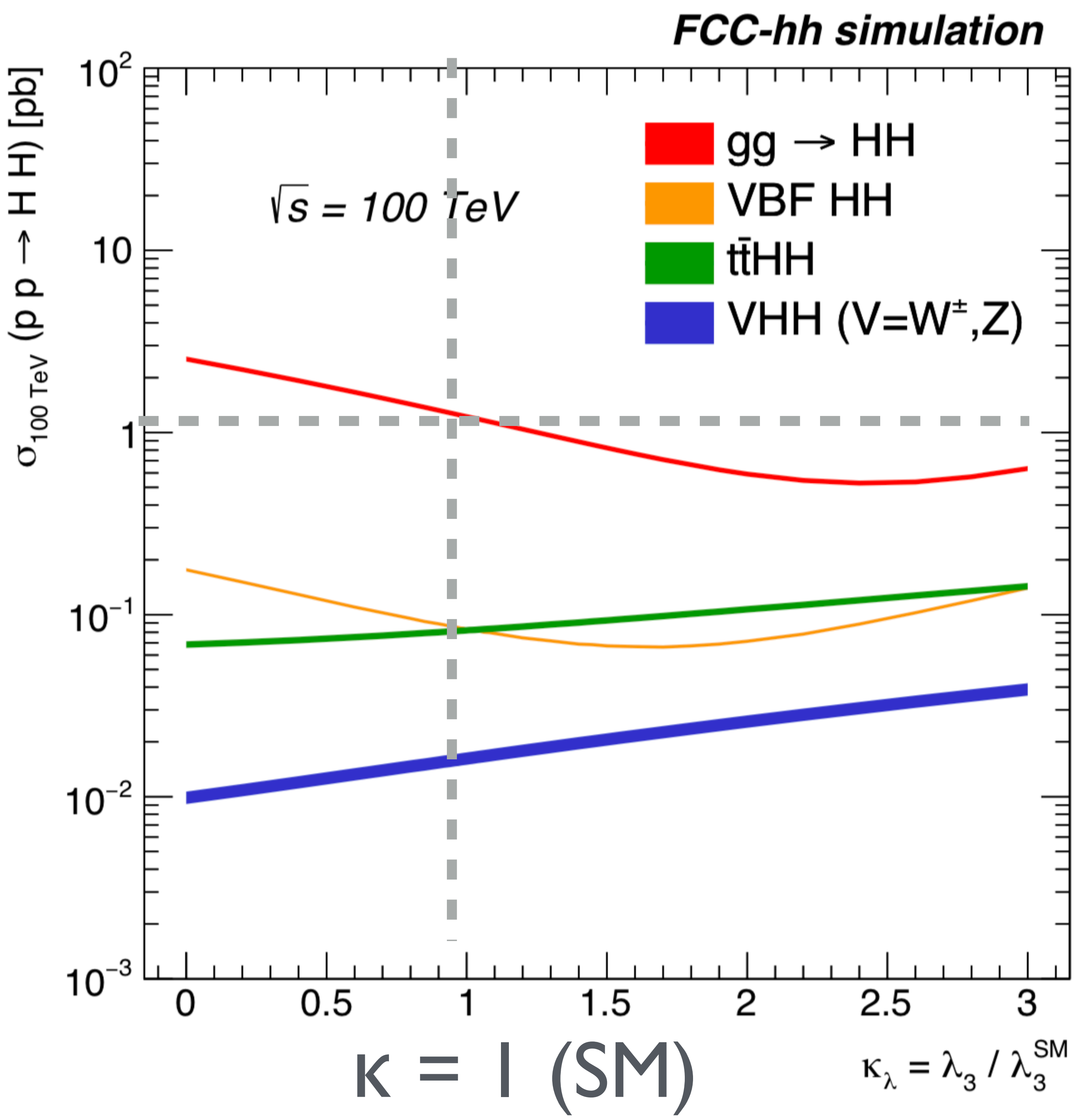
FCC-hh

sqrt(s)	27 TeV
Lumi	15 ab^{-1}
B	16 T
circ.	27 km

sqrt(s)	37 TeV
Lumi	15 ab^{-1}
B	6 T
circ.	100 km

sqrt(s)	100 TeV
Lumi	30 ab^{-1}
B	16 T
circ.	100 km

Higgs pair production at the FCC-hh

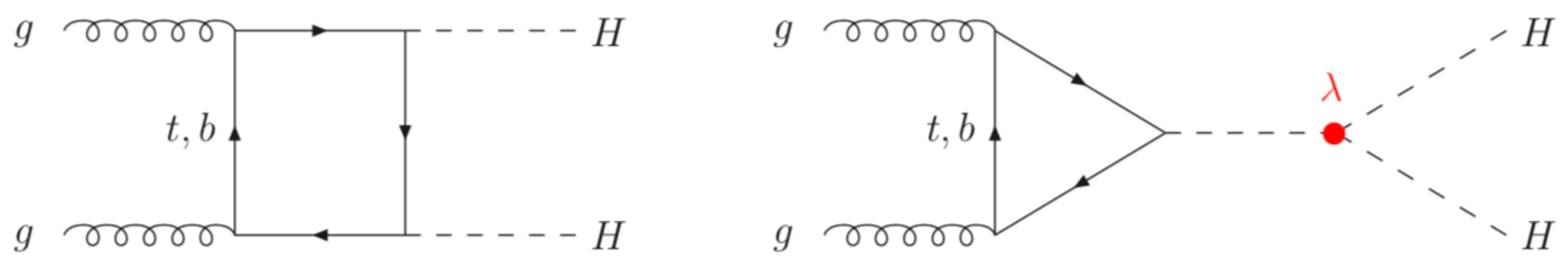


$\sigma \approx 1$ pb

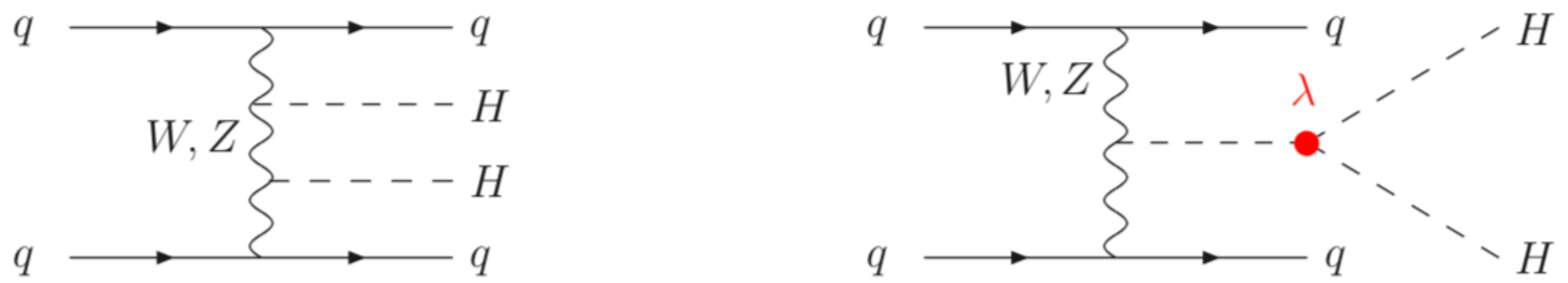
$\kappa = 1$ (SM)

≈ 15 %

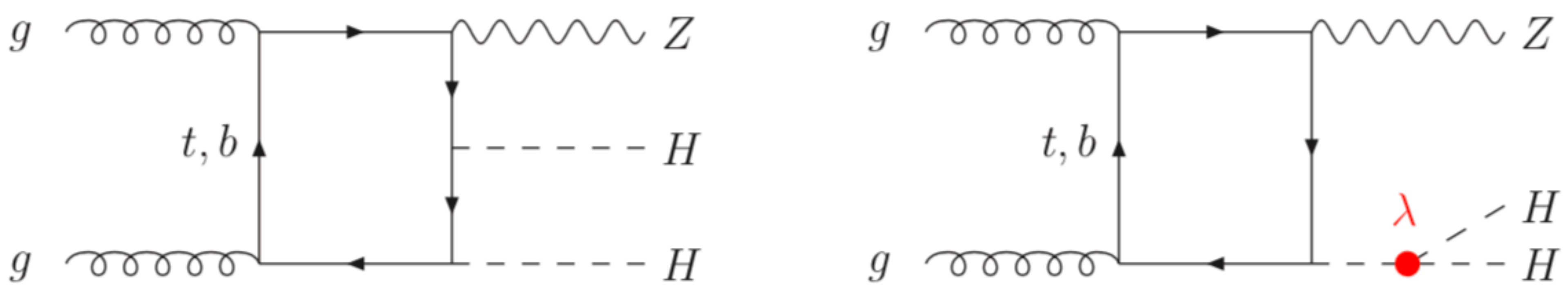
gluon fusion:



vbf HH:



VHH:



ttHH:

Expected precision:

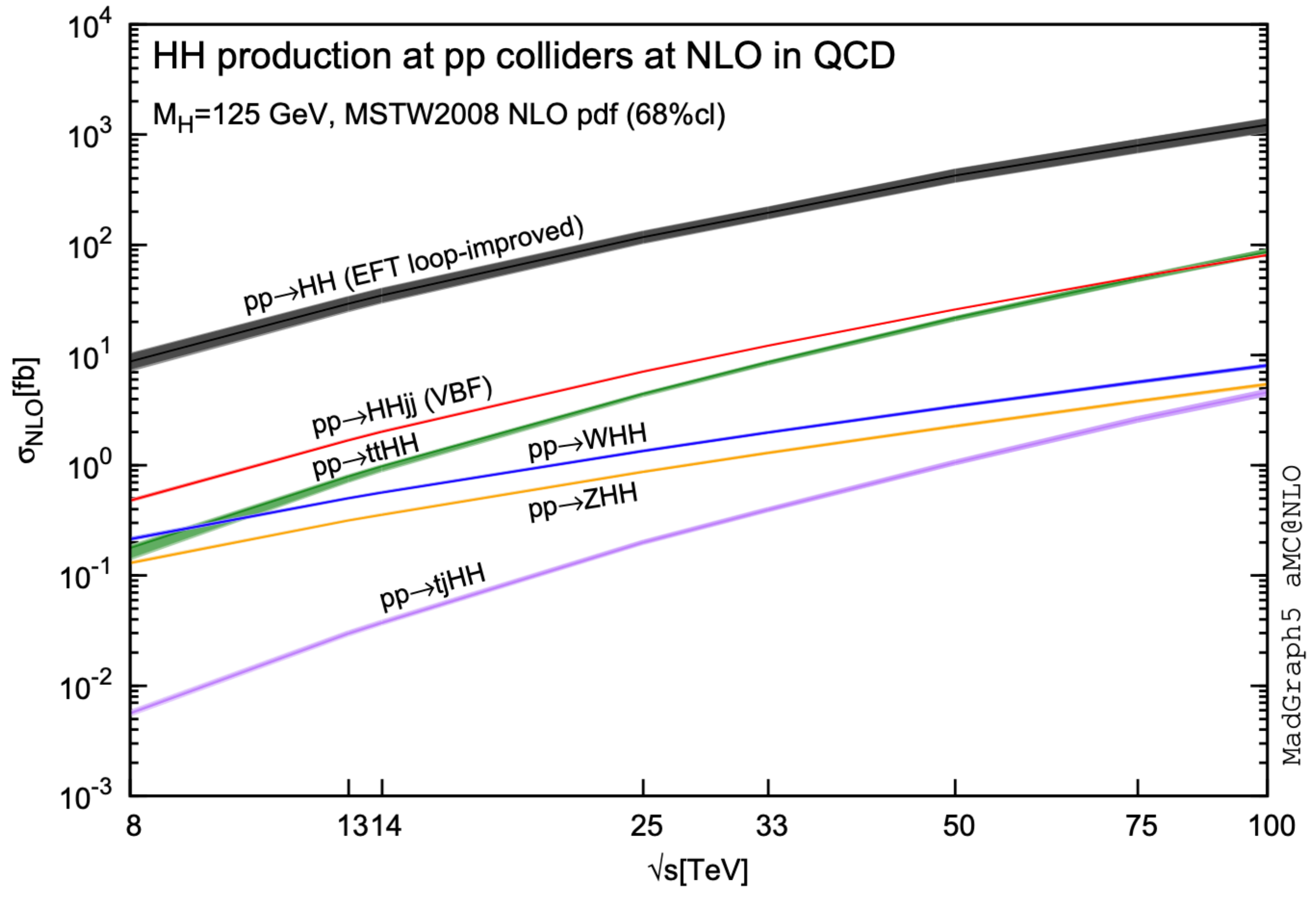
$$\delta_{\kappa_\lambda} = \frac{\delta_\mu}{\left.\frac{d\mu}{d\kappa_\lambda}\right|_{SM}}$$

where:

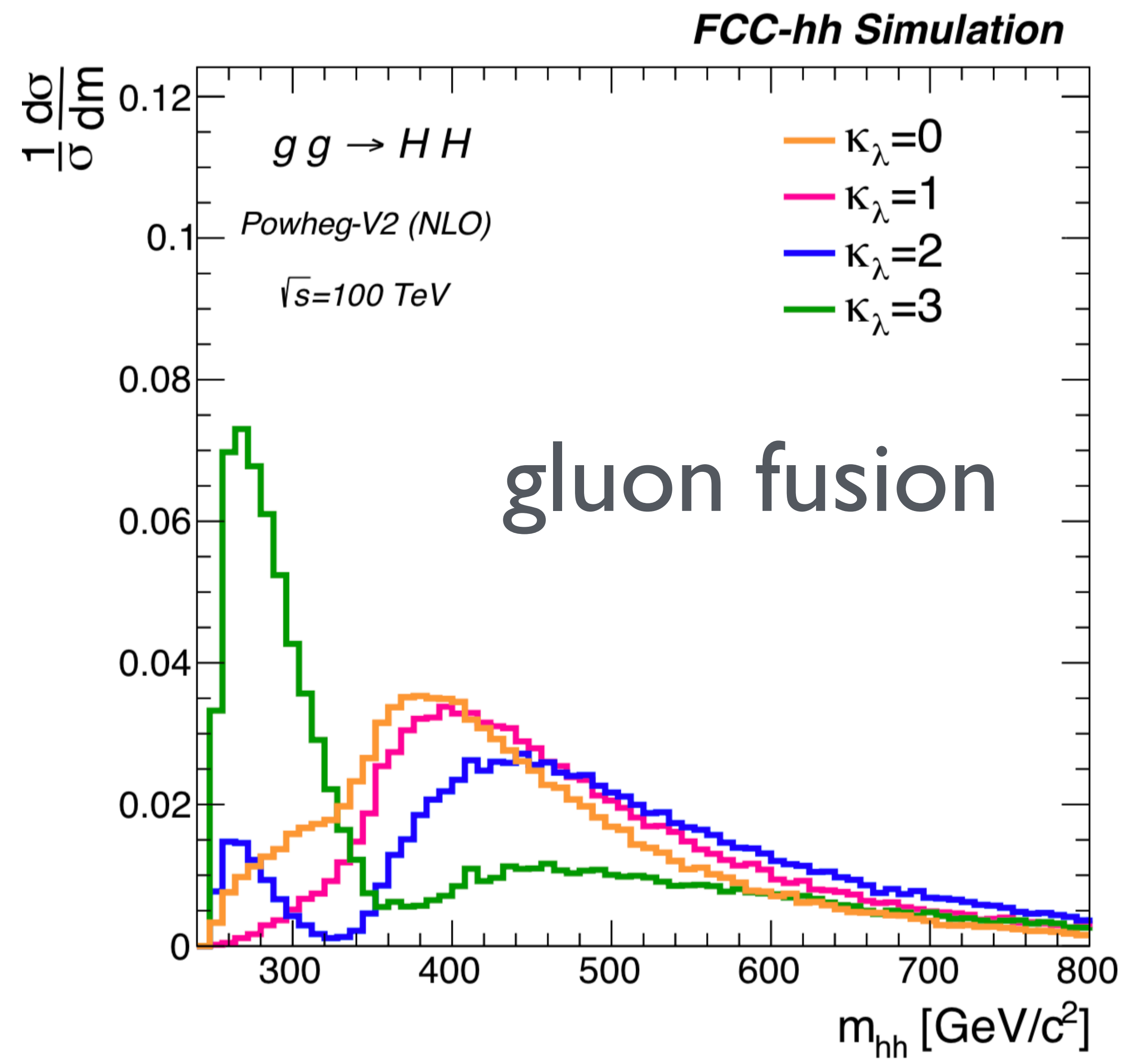
$$\kappa_\lambda = \lambda_3/\lambda_3^{SM}$$

$$\mu = \sigma/\sigma_{SM}$$

HH production@100 TeV



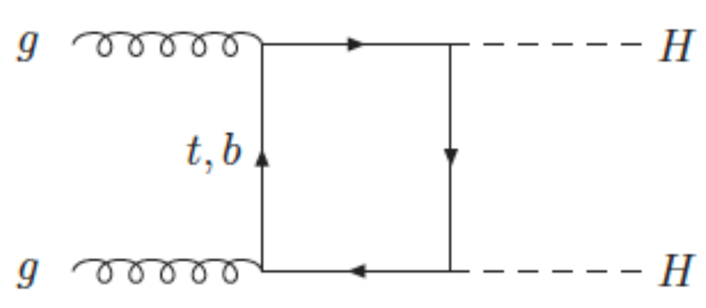
cross-section (fb)	σ(14 TeV)	σ(100 TeV)	accuracy	K-factor
ggHH	$36.69 \pm 4.6\%$	$1224 \pm 3.2\%$	$\mathrm{NNLO_{FTapprox}}$	1.08
VBF HH	$2.05 \pm 2.1\%$	$82.8 \pm 2.1\%$	NNLO	1.15
$t\bar{t}$HH	$0.949 \pm 2.9\%$	$82.1 \pm 4.2\%$	NLO	1.38
VHH	$0.982 \pm 4.4\%$	$16.23 \pm 7.8\%$	NNLO	1.40

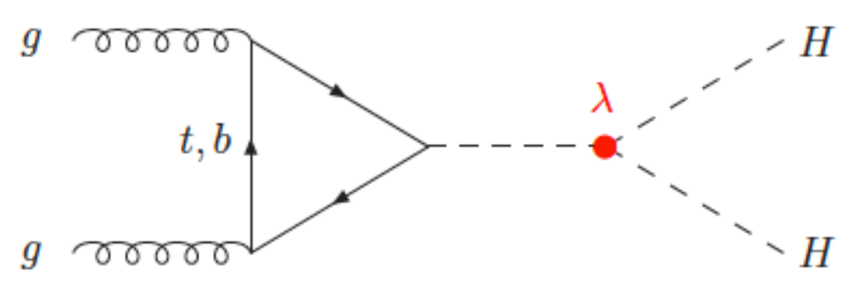


- Expect **large improvement** at FCC-hh wrt to LHC:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10 with 30 ab^{-1})
  - x400 in event yields and x20 in precision

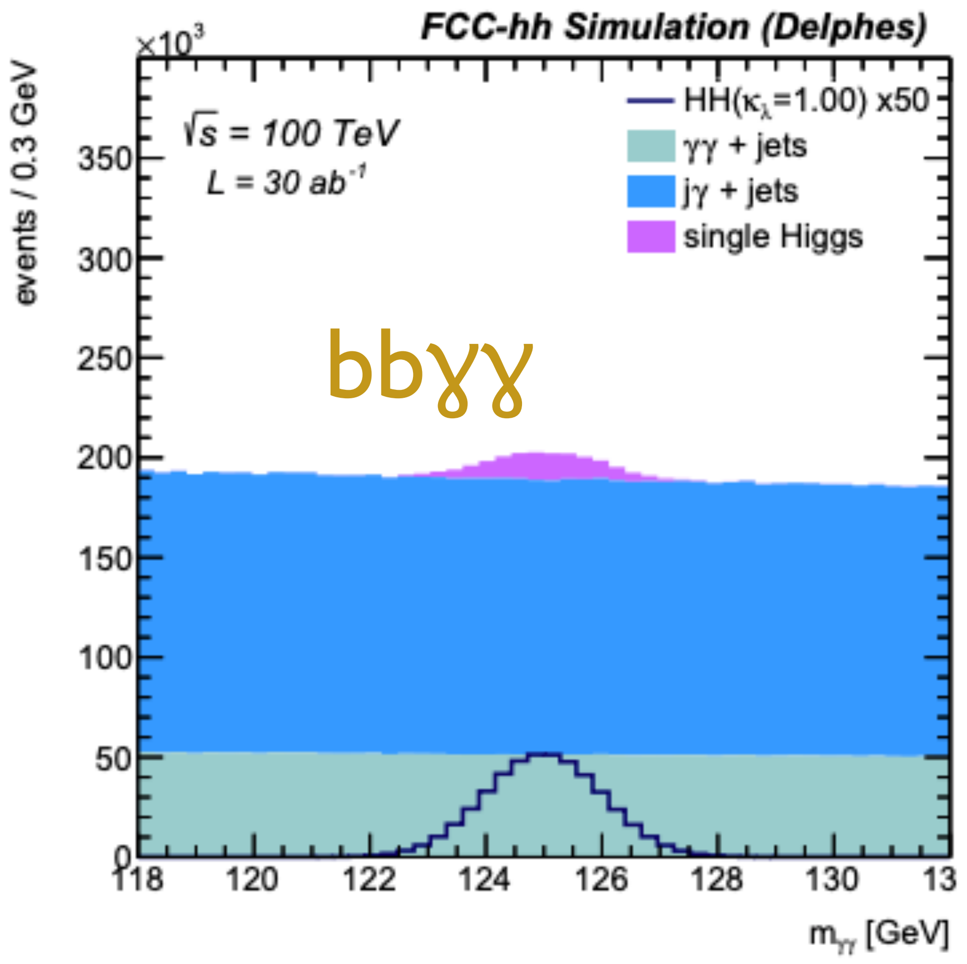
Sub-dominant production modes are included as part of the signal, but **no categorisation** has been made.

Self-coupling at the FCC-hh

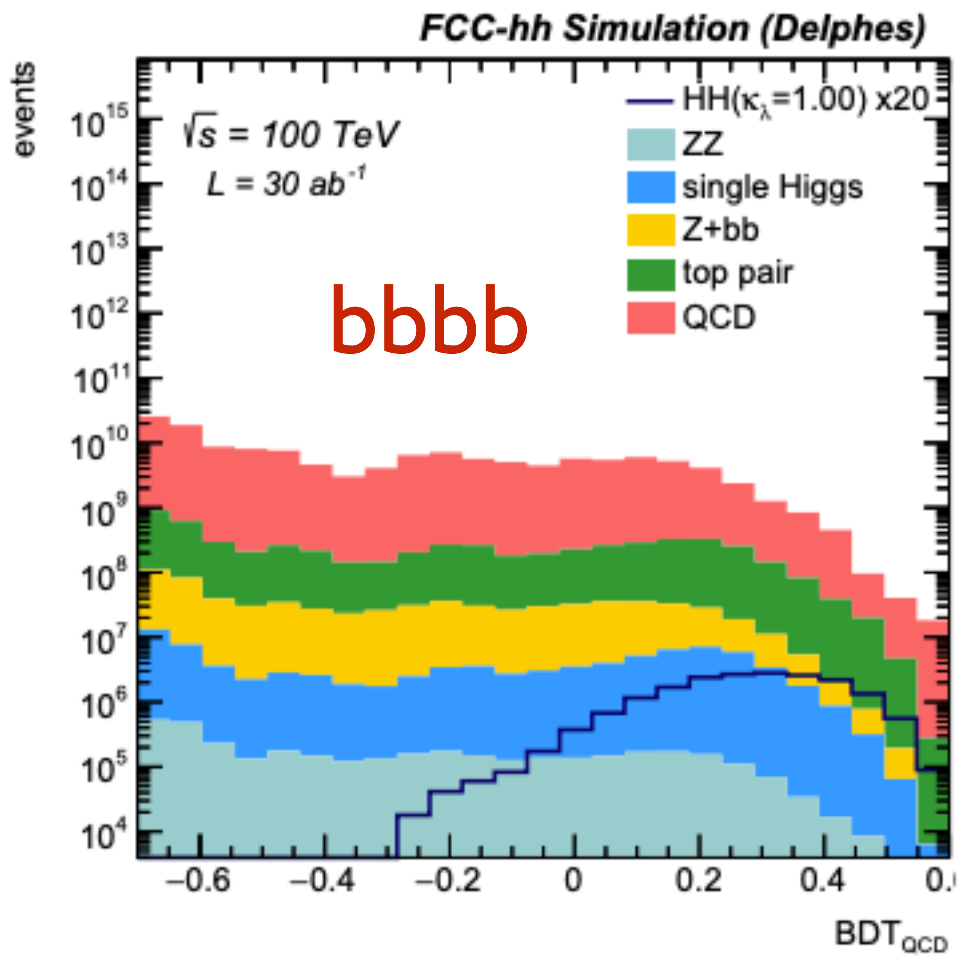




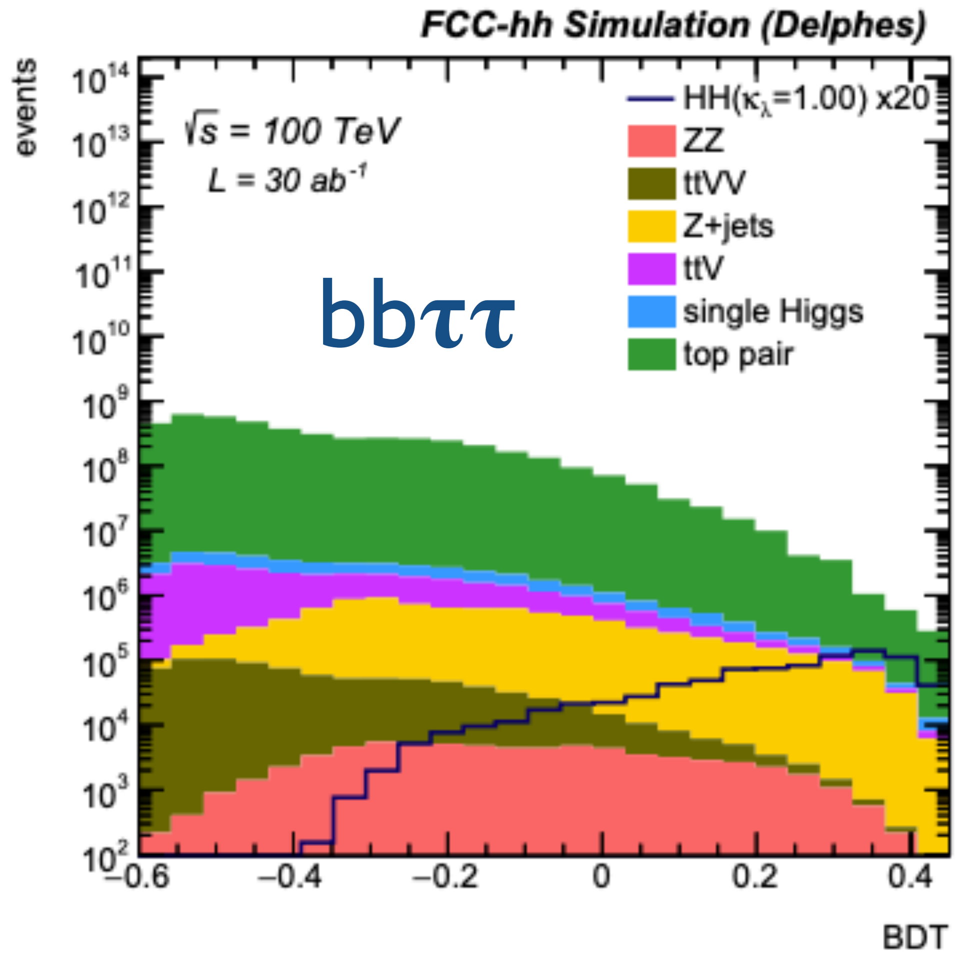
2004.03505



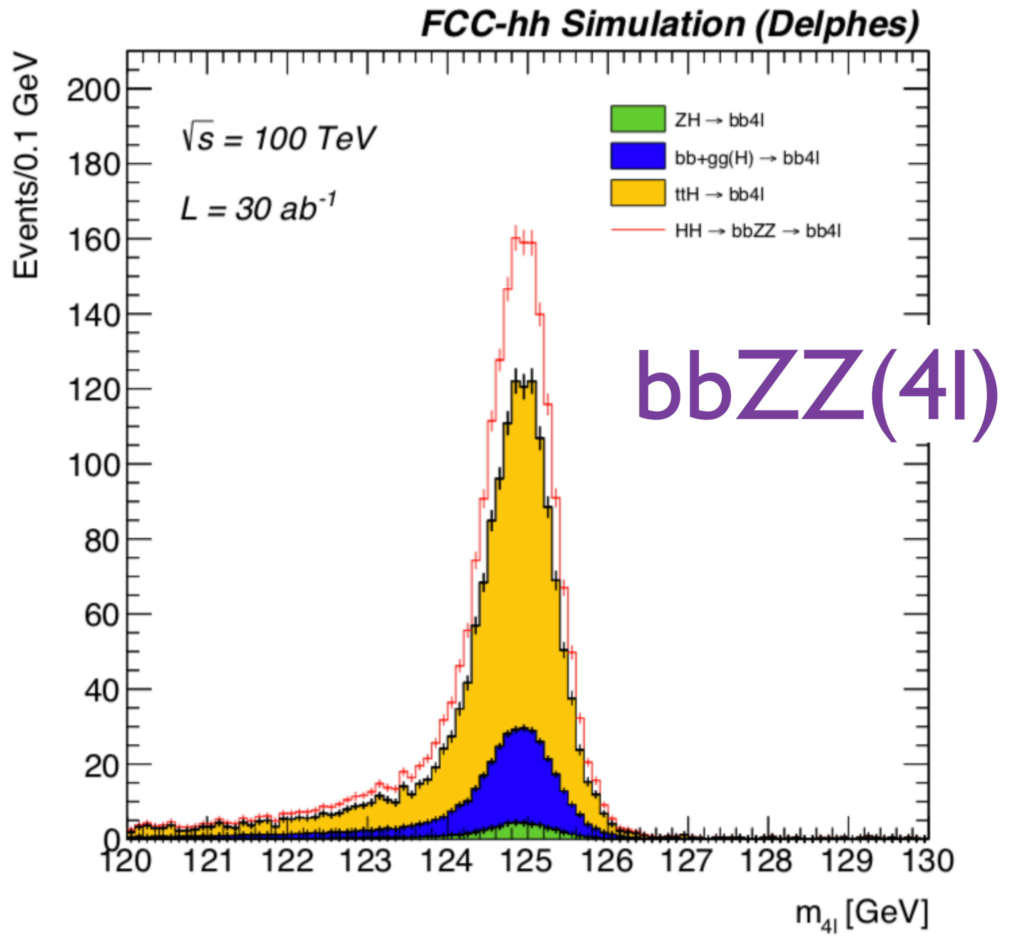
- Channels:
  - bbγγ (golden channel)
  - bbττ
  - bbbb
  - bbZZ(4l)



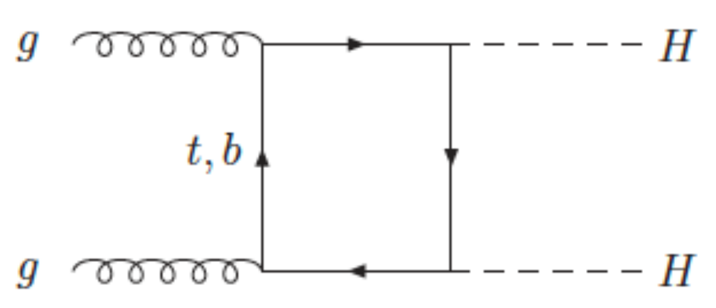
- Defined 3 scenarios with various detector assumptions and systematics:

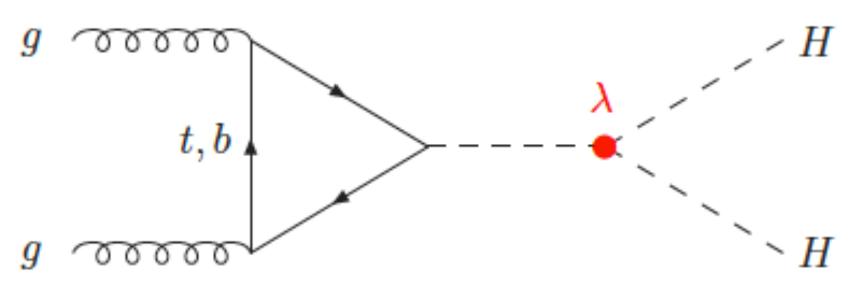


parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

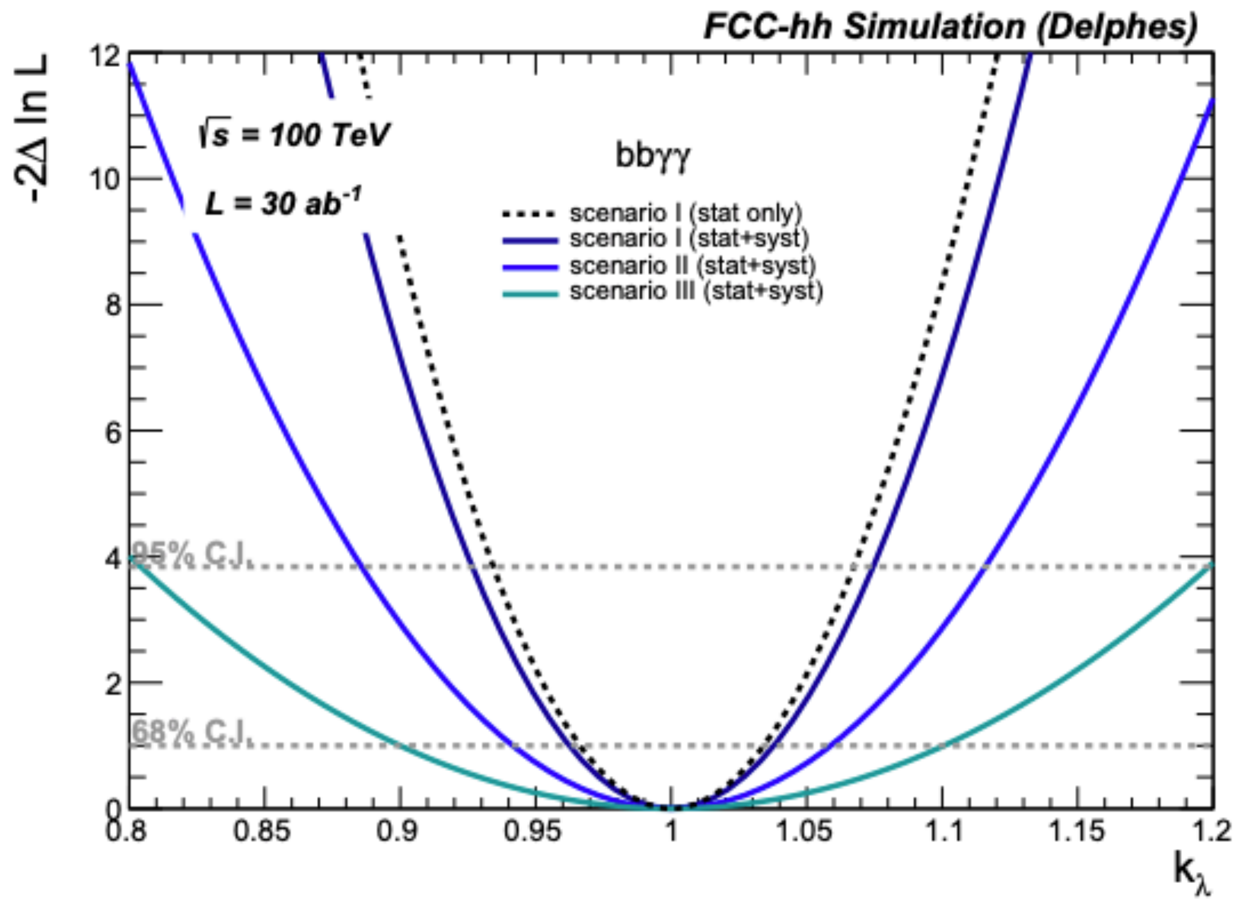


Self-coupling at the FCC-hh



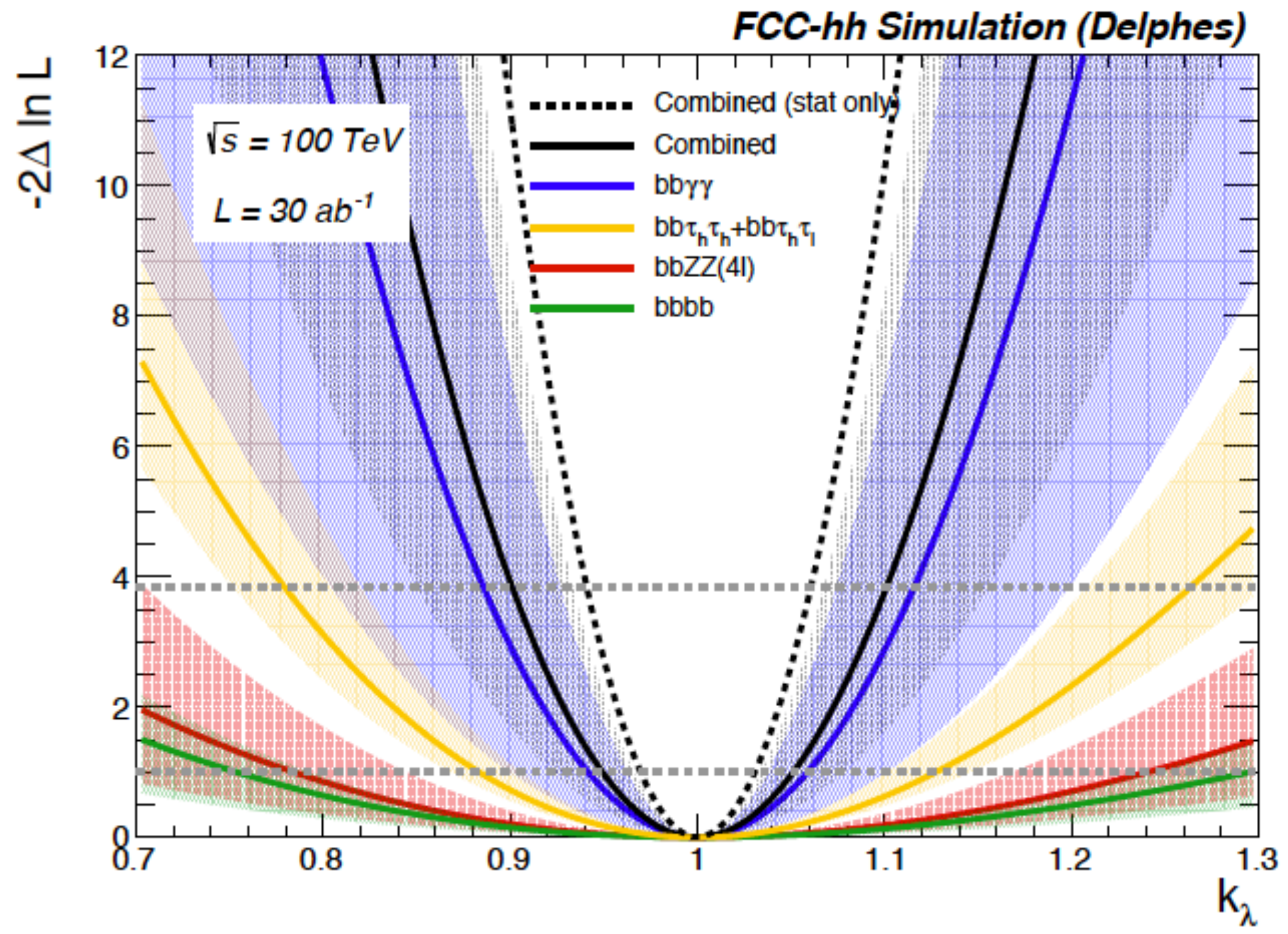


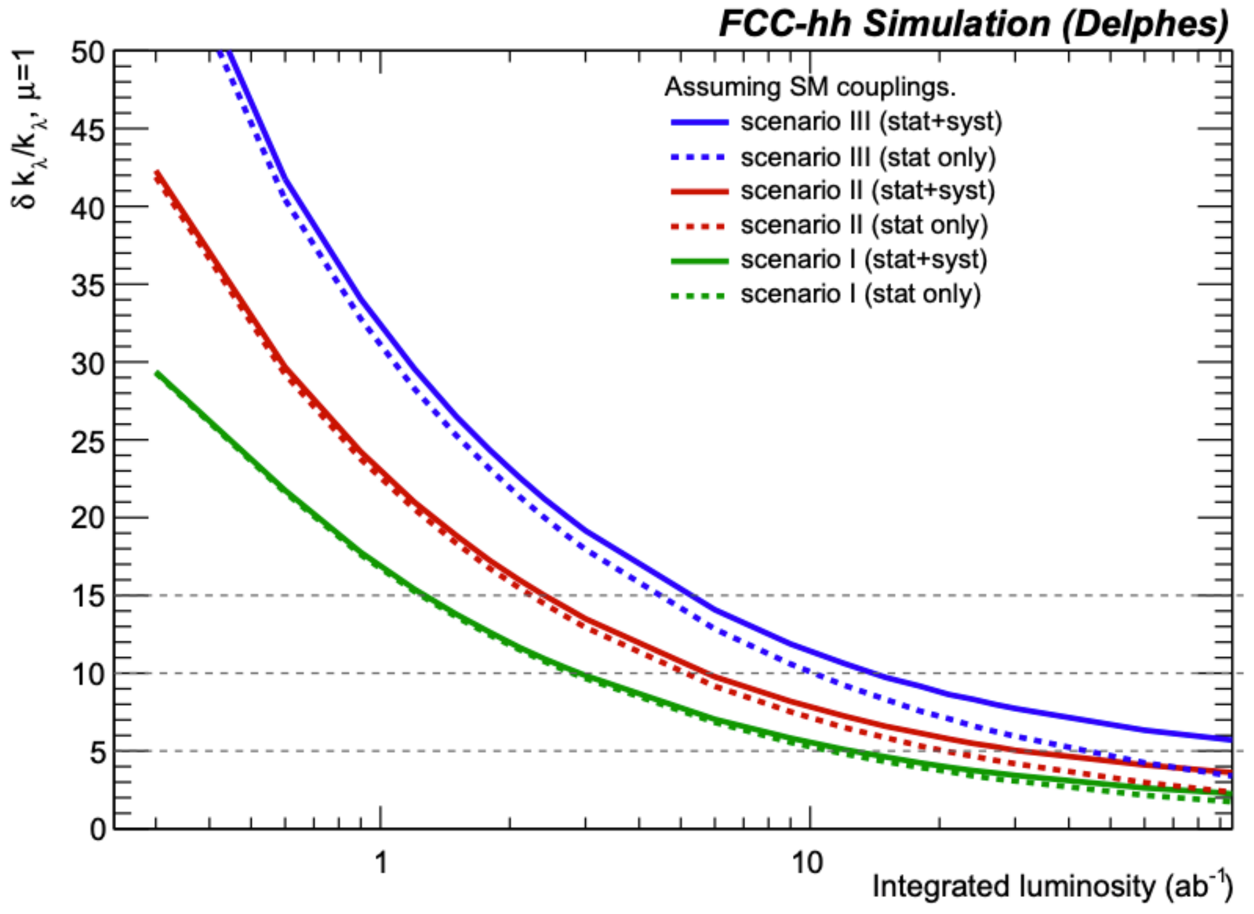
2004.03505 [hep-ph]



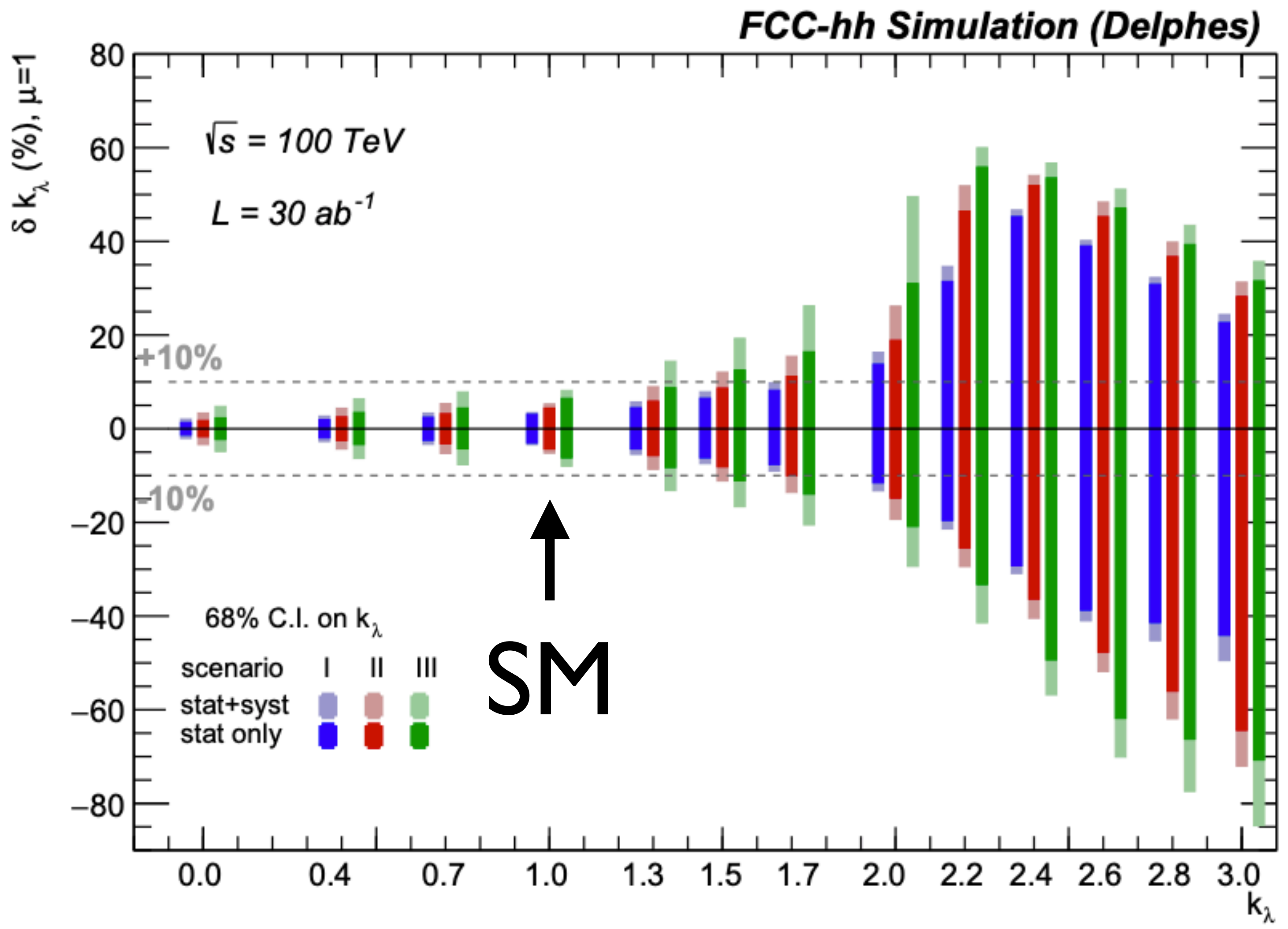
- Expected precision:

@68% CL	scenario I	scenario II	scenario III
bbɣɣ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8





- Combined precision:
  - **3.5-8%** for SM (3% stat. only)
  - **10-20%** for $\lambda_3 = 1.5 * \lambda_3^{SM}$



Precision vs. Time

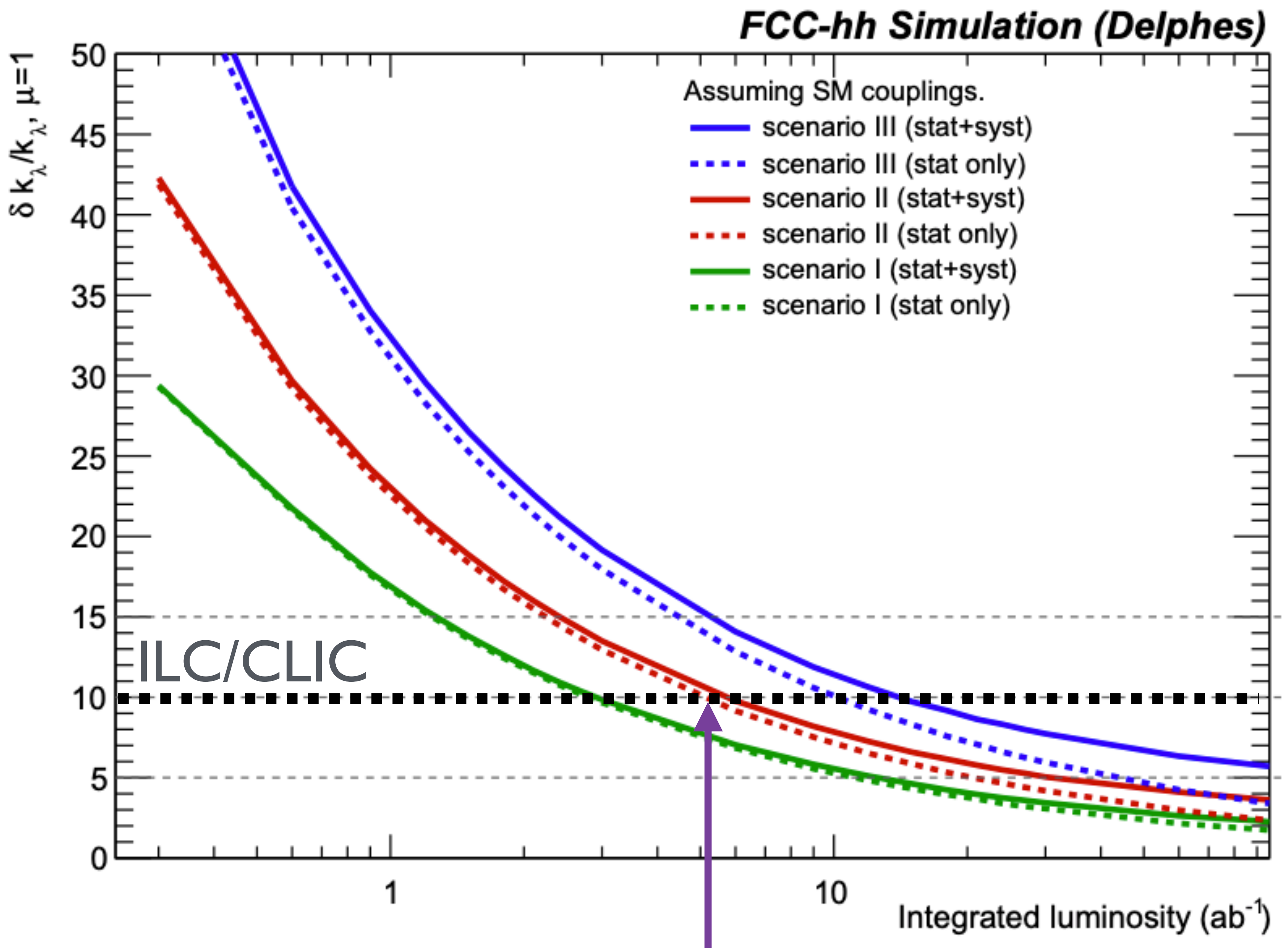
Briefing book

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	N_{Det}	$\mathscr{L}_{\text{inst}}$/Det. [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	pp	14 TeV	–	2	5	6.0	12
HE-LHC	pp	27 TeV	–	2	16	15.0	20
FCC-hh	pp	100 TeV	–	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
		(1y SD before $2m_{top}$ run)					(+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
		(1y SD after 250 GeV run)					(+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
		(2y SDs between energy stages)					(+4)
LHeC	ep	1.3 TeV	–	1	0.8	1.0	15
HE-LHeC	ep	1.8 TeV	–	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	–	1	1.5	2.0	25

→ 16 yrs (FCC-hh / FCC-ee)

→ 22 yrs (ILC)

→ 27 yrs (CLIC)



FCC-hh:

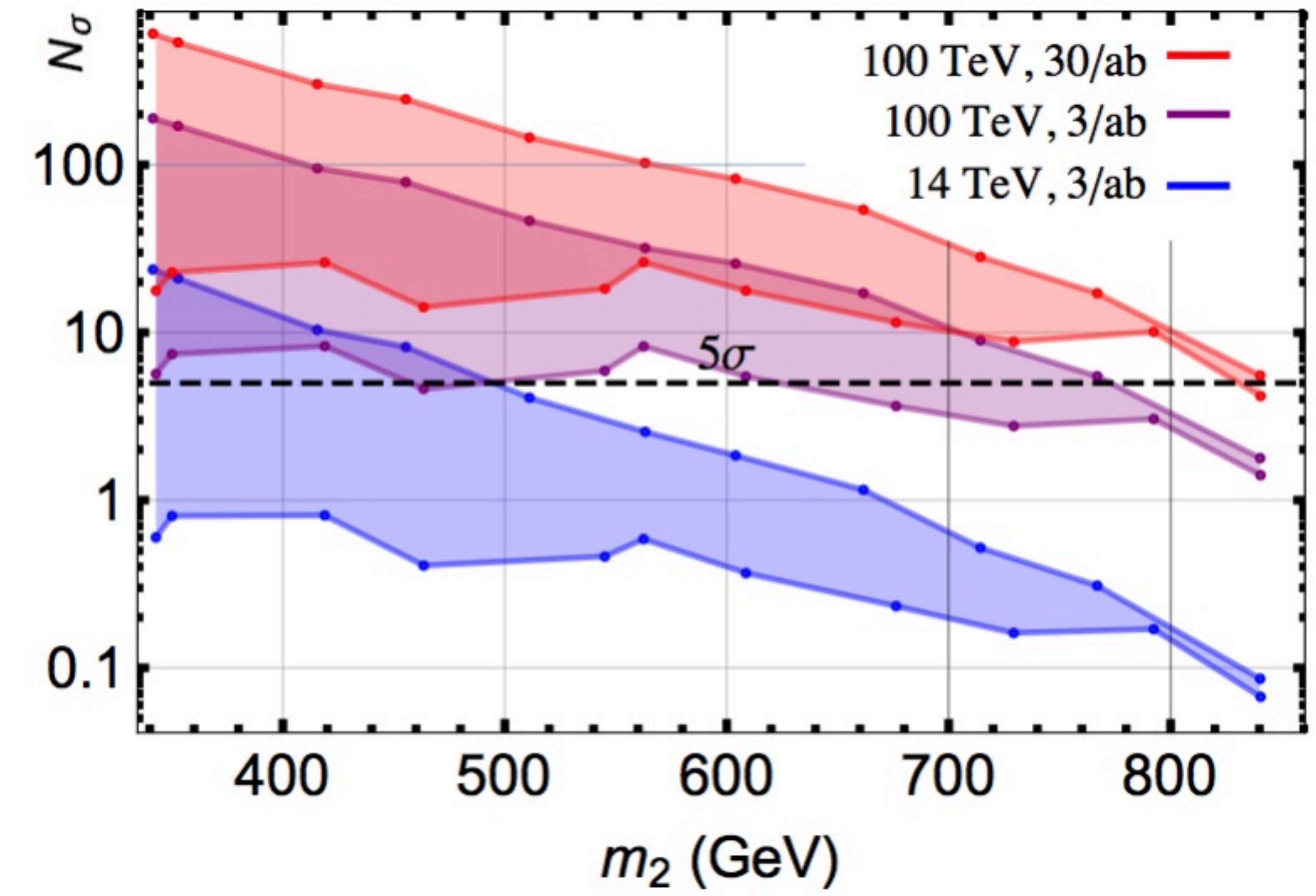
- 5 ab-1 during the first 10 years
- assuming 2 IPs:
  - **2.5 yrs / 2.5 ab^{-1}**

→ Can reach expected precision of ILC/CLIC with 5 ab^{-1}

Higgs Self-coupling and constraints on models with 1st order EWPT

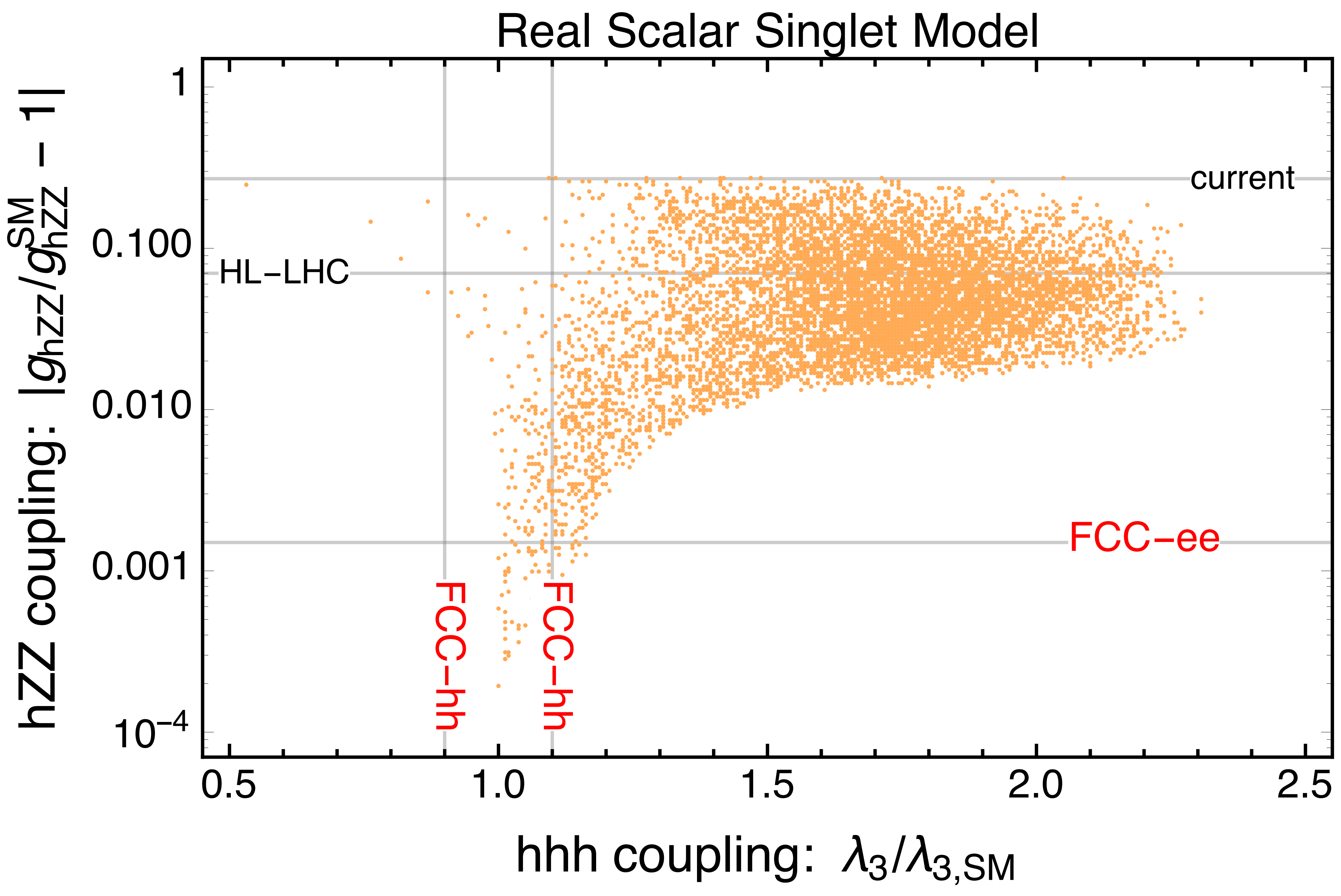
- **Strong 1st order EWPT** needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

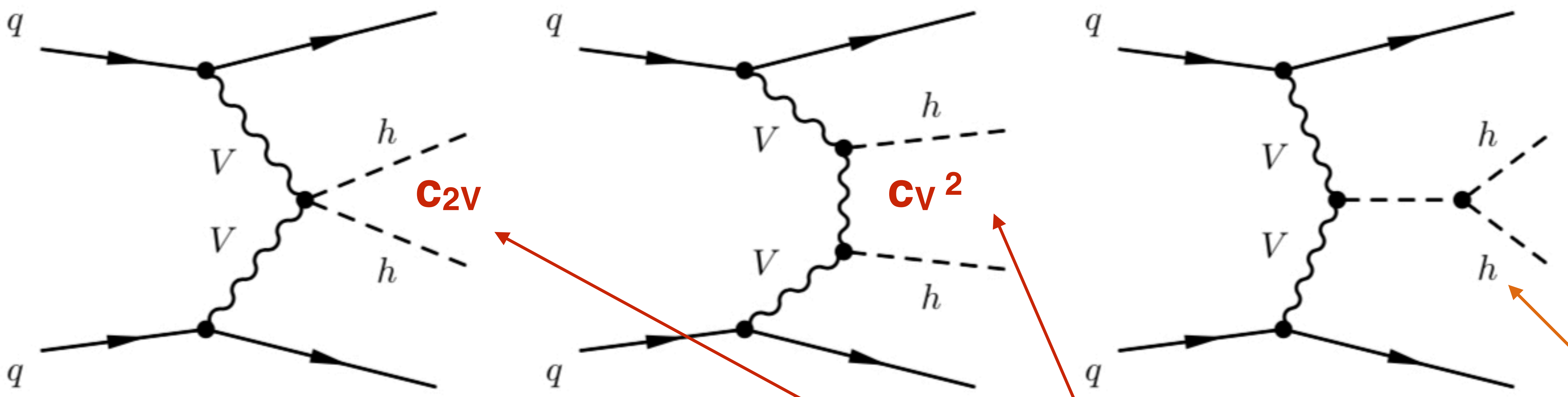
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

$V_LV_L \to HH$

[1611.03860]

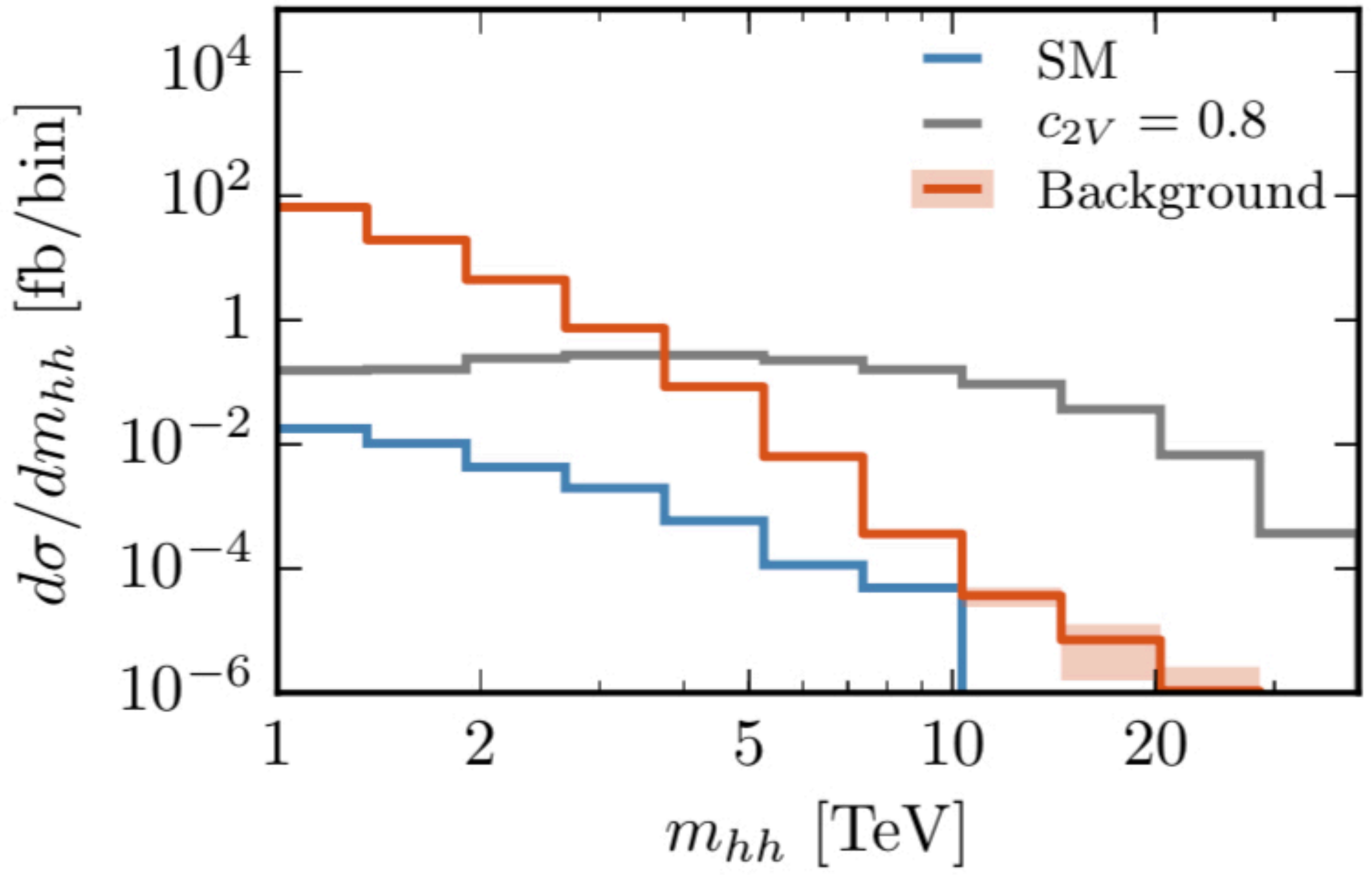


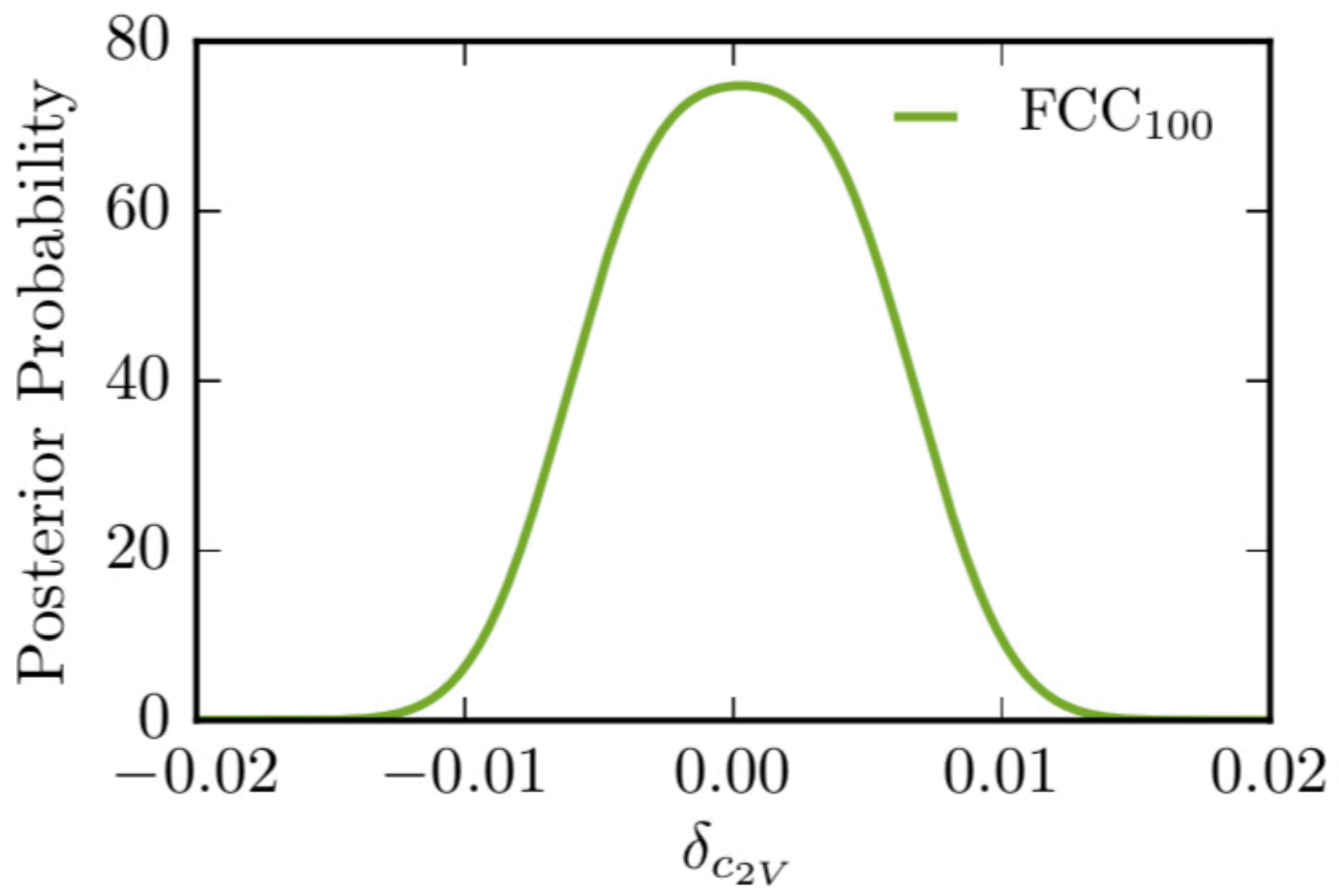
negligible at large m_{HH}

$$A(\mathrm{V_LV_L \to HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$

0 in the SM

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E

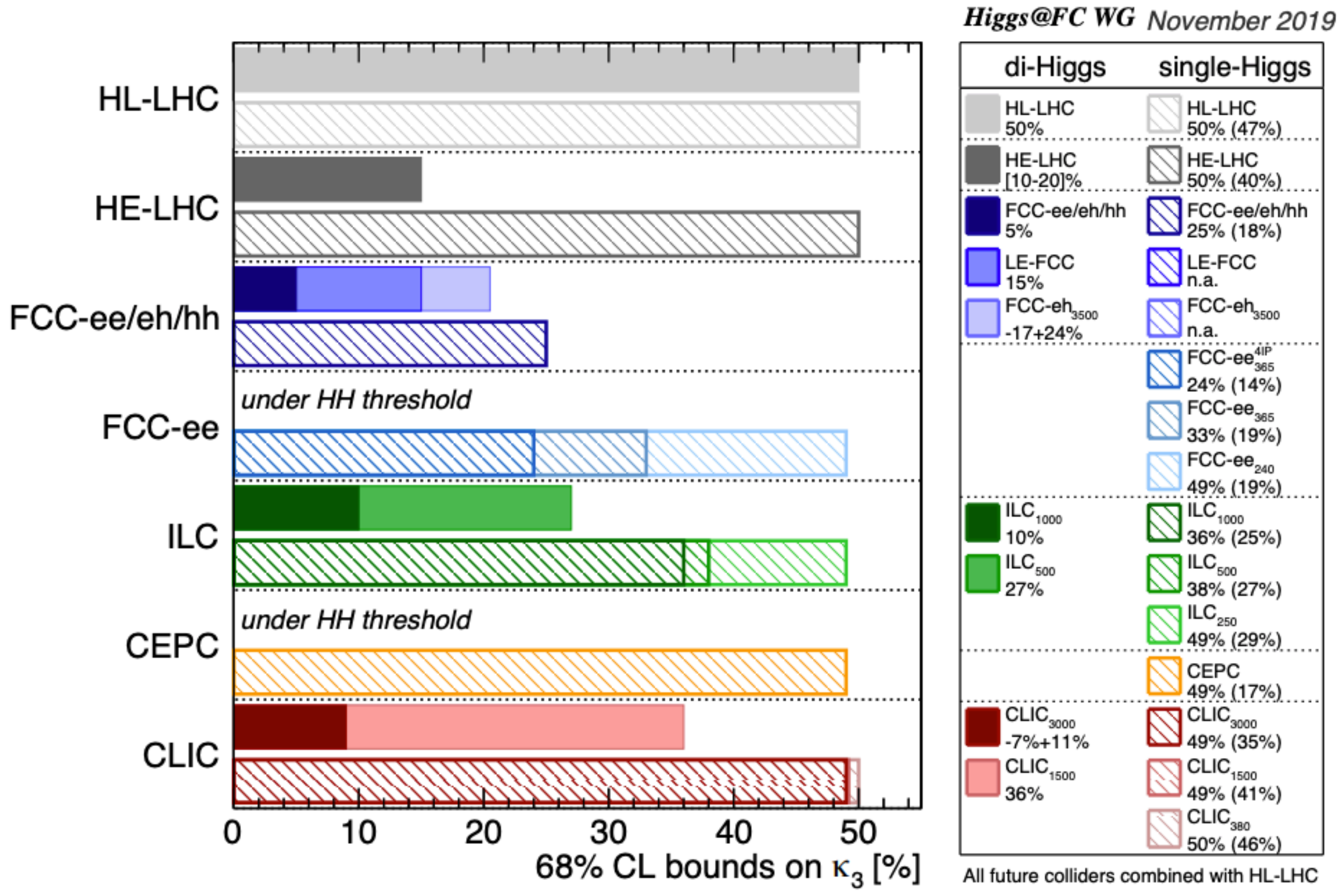




With c_V from FCC-ee, $\delta c_{2V} < 1\%$

Summary

- A precise measurement of the Higgs self-coupling can contrain the shape of the Higgs potential:
  - **LHC** can detect at best **O(10)-O(2)** deviations
  - **HL-LHC** can measure at **50 %** precision
  - **LE-FCC / HE-LHC** ~ 15% precision
  - **ILC/CLIC** can measure at best with **10%**
  - FCC can reach $\delta\kappa_\lambda \approx$ 5% using double Higgs production
  - Muon Collider @10 TeV ~ 5-7% ??
    @30 TeV ~ 2-3% ??



BACKUP

Prospects for HL-LHC measurements

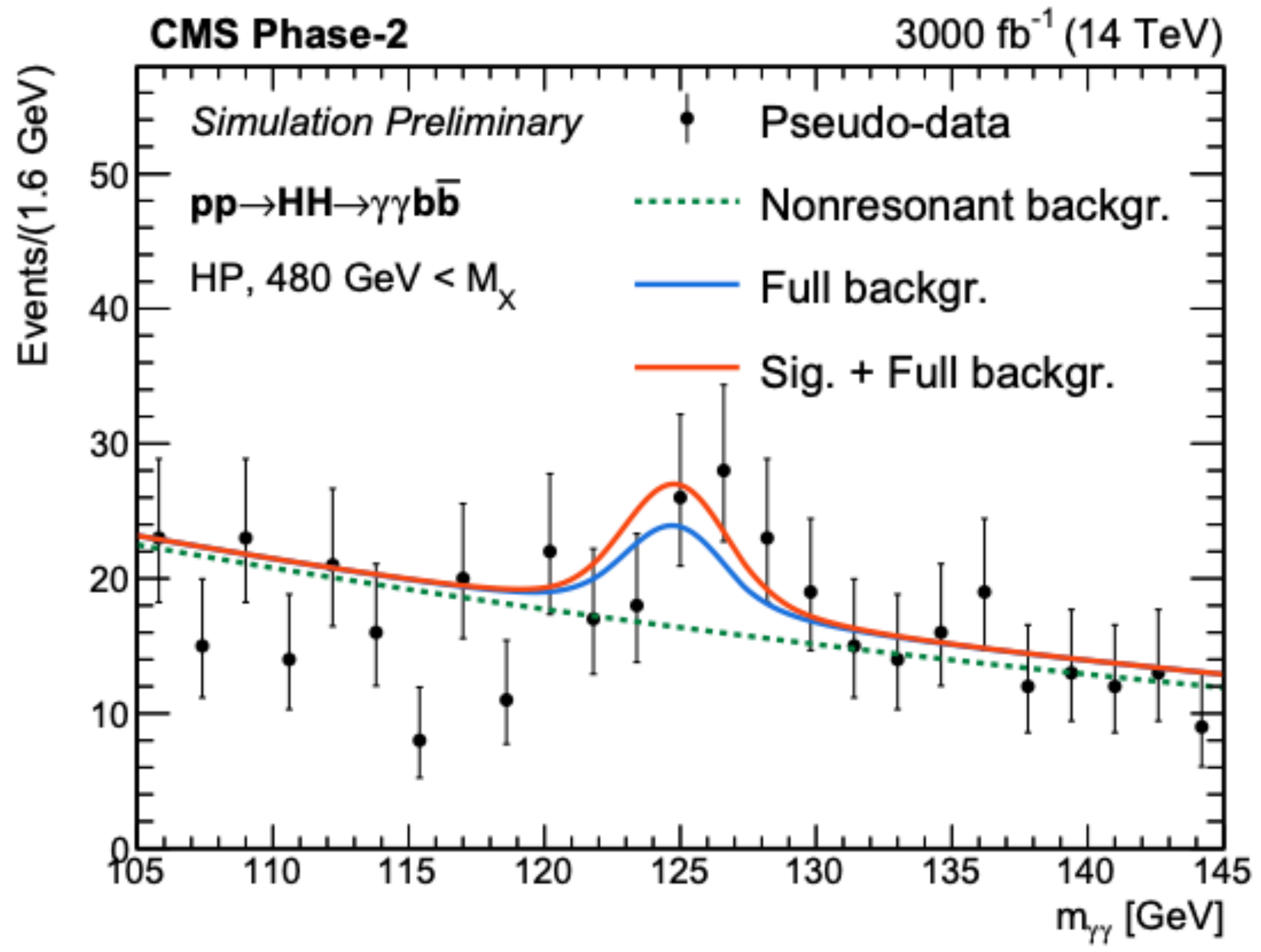
1) LHC
   - O(10)-O(2)
   - Could detect large anomalous coupling

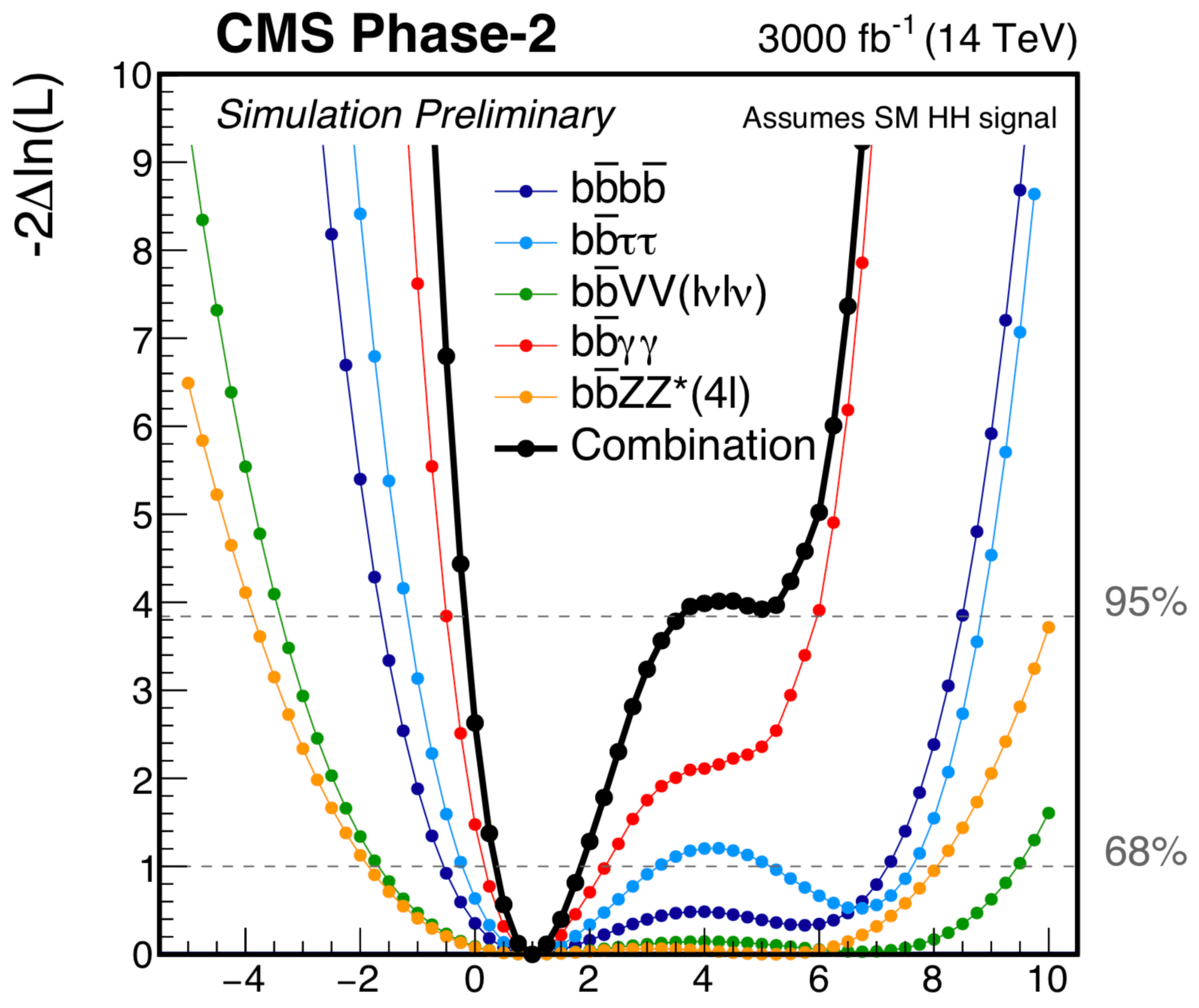
2) HL-LHC
   - O(1)
   - Potential for evidence (3σ precision)

3) FCC-ee : single H couplings + indirect measurement
   - Potential for observation (5σ precision)
   - δg_{ttZ} ~ 1%, allows for δy_t ~ 1% @FCC-hh

4) ILC/CLIC : ~ 10 % precision

5) FCC-hh : precision measurement



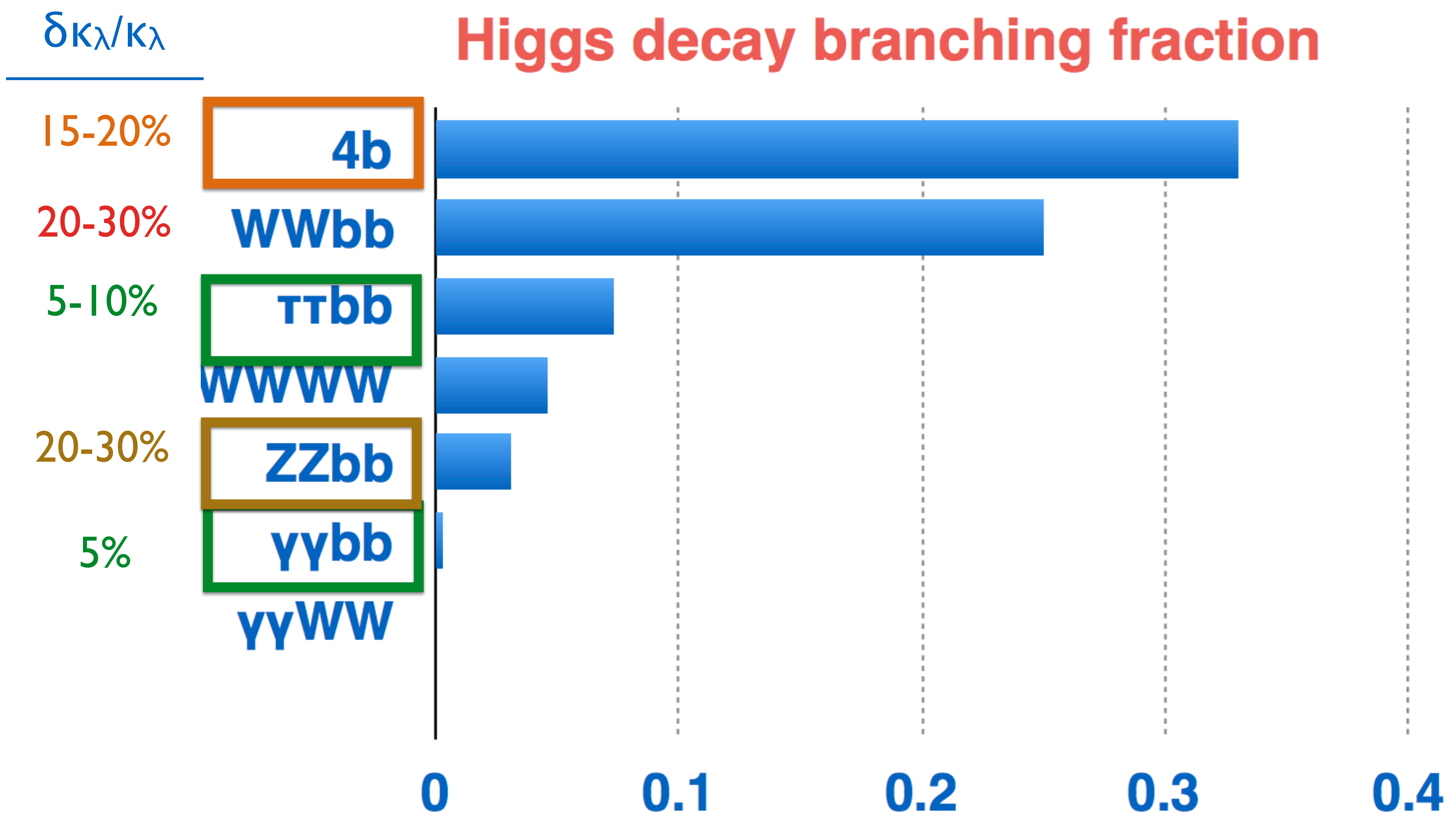


https://arxiv.org/abs/1902.00134

κλ

HH decays

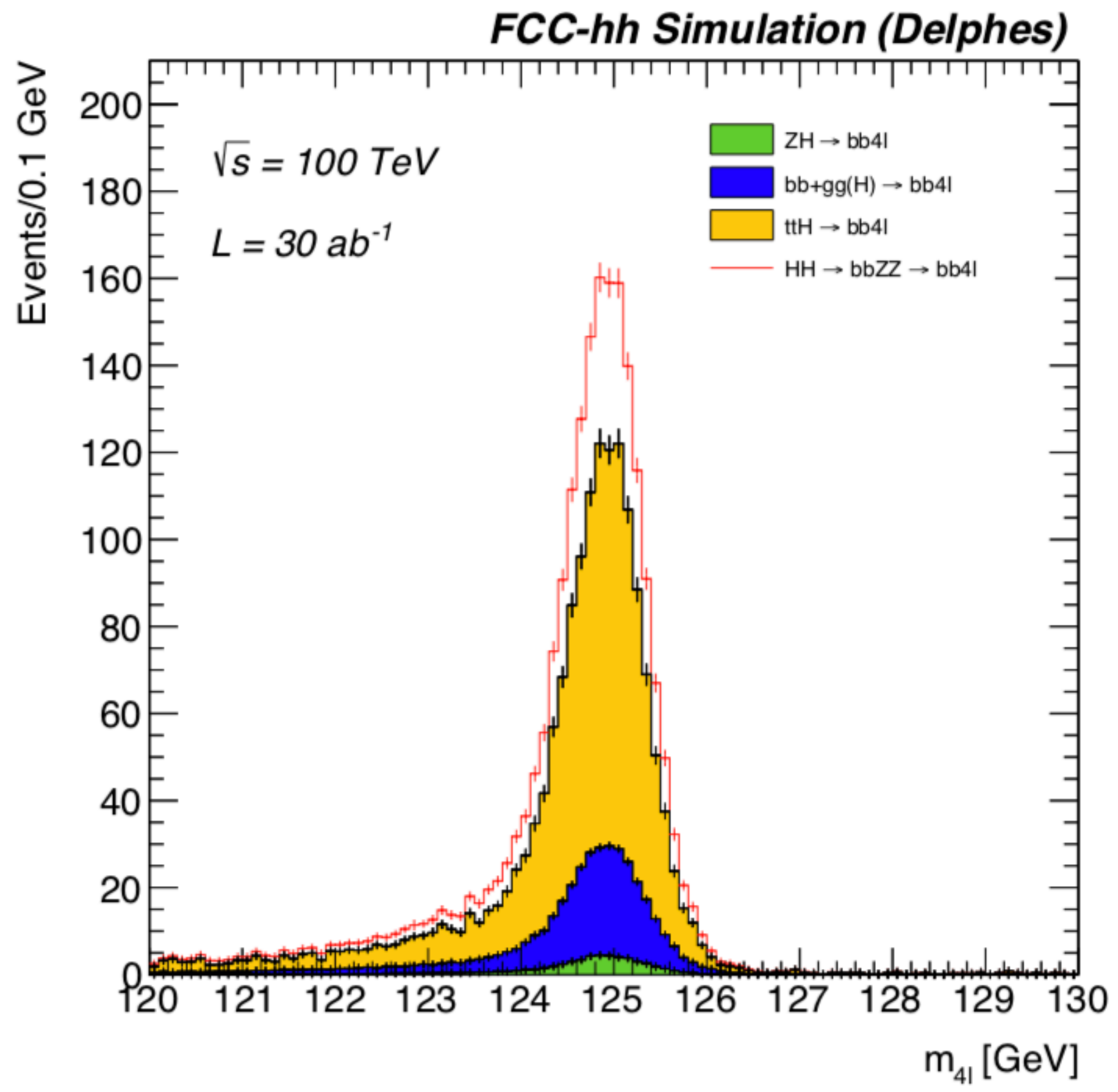
- Sensitivity driven by the following channels:
  - bbγγ (golden channel)
  - bbττ
  - bbbb
  - bbZZ(4l)



HH →bb4l

[Borgonovi, Braibant, De Filippis, Fontanesi, GO, MS]

- **New channel** opening at FCC-hh !!
- clean channel with mostly reducible backgrounds (**single Higgs**)
- Simple cut and count analysis on (4e, 4μ and 2e2μ channels)

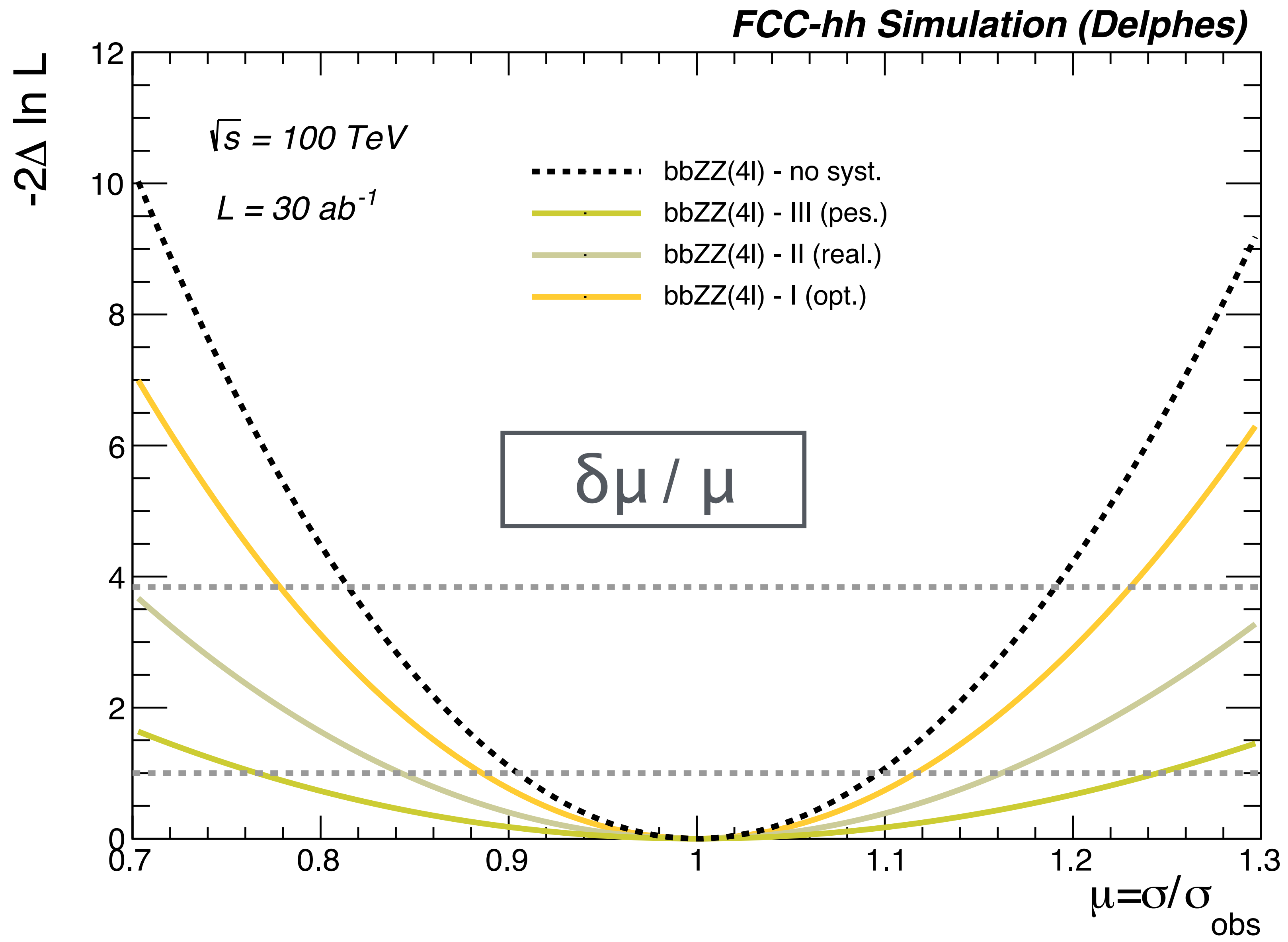


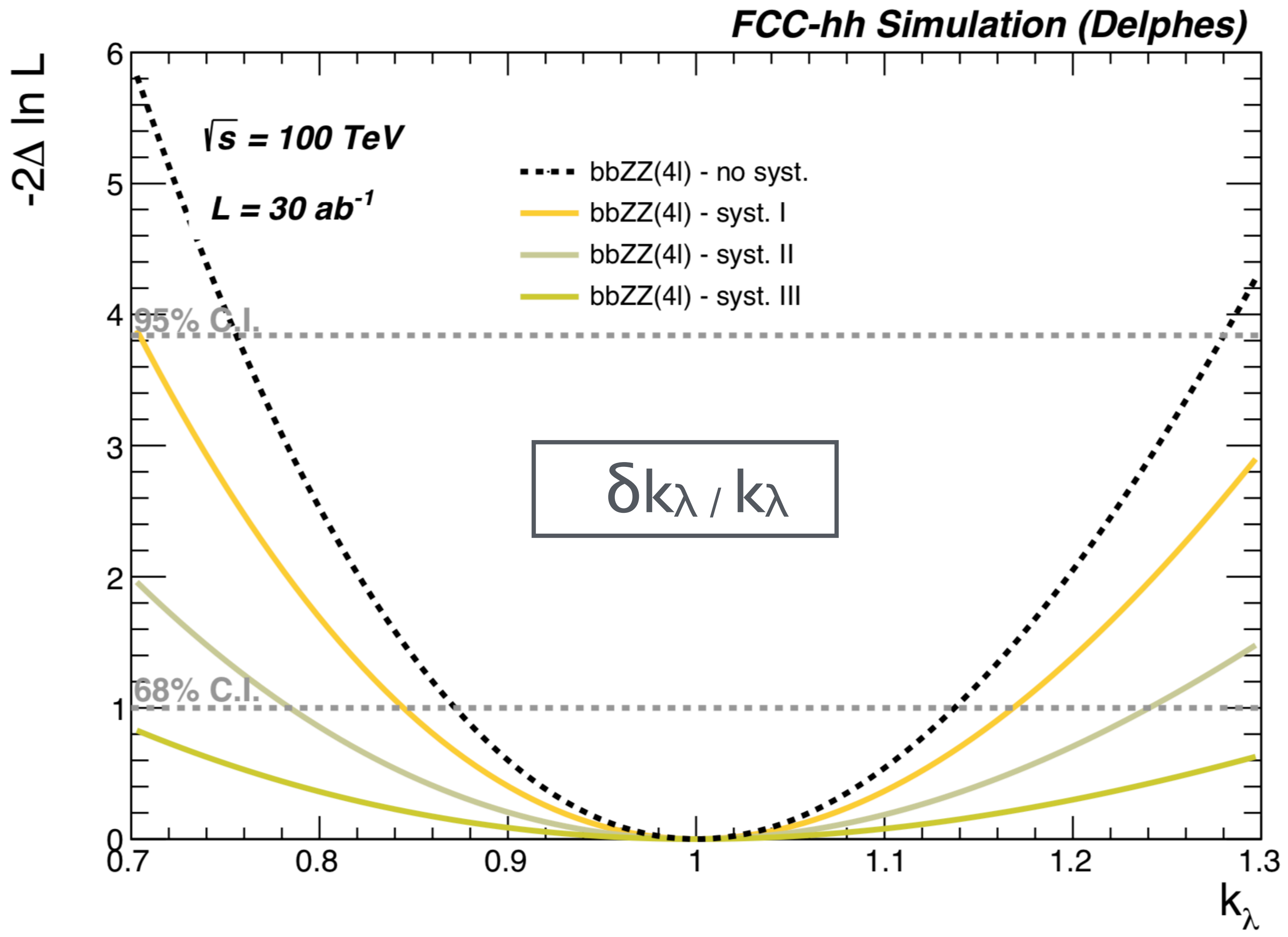
Backgrounds:

- ttH , H → 4 leptons
- 4l + jets (ZZ*, Z*Z*, ZZ) continuum
- p p → H b b →4l bb (gluon fusion)

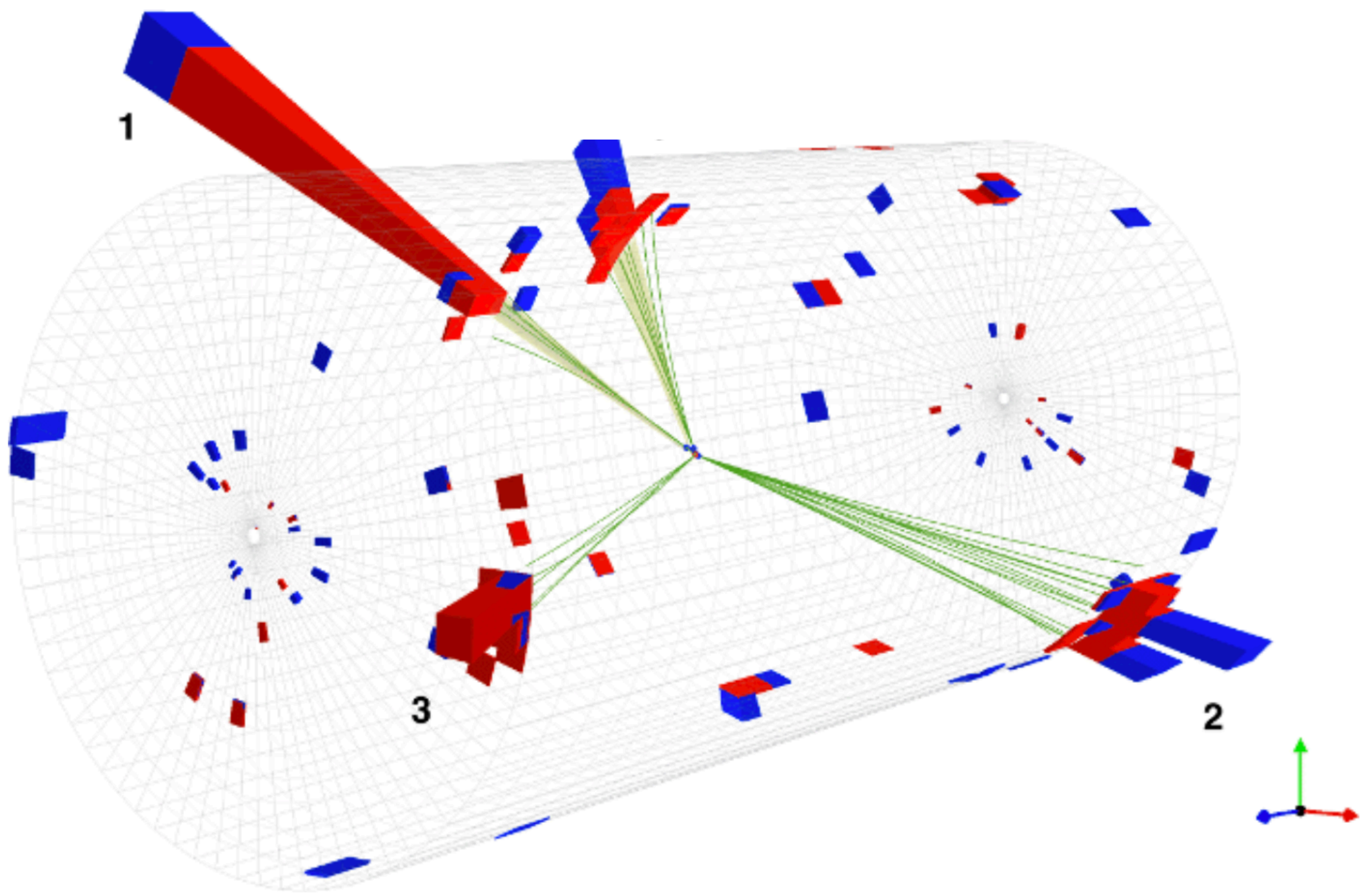
$\delta k_\lambda / k_\lambda$ = 15-30%

depending on systematics assumptions





The bbbb channel



Detector assumptions:

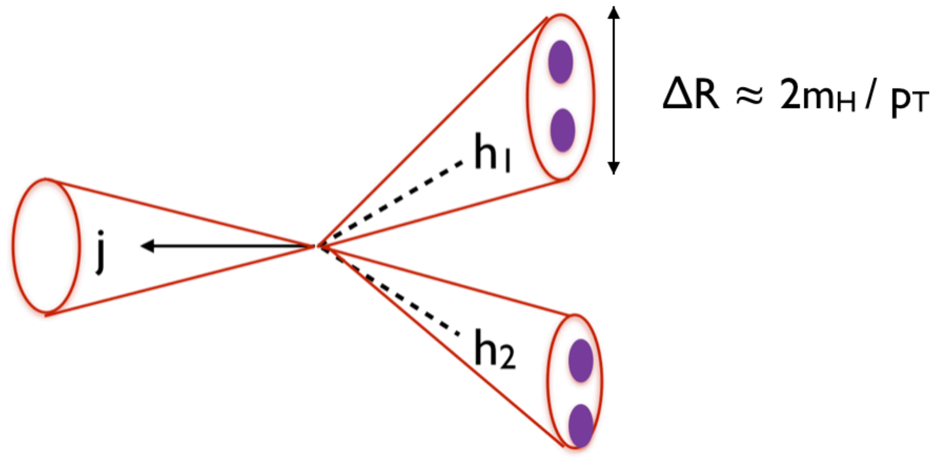
b-tagging : ε_b = 80%, $\varepsilon_{j\to b}$ = 1% (~ HL-LHC)

- **Largest branching ratio**
  BR(HH→bbbb) ≈ 31%

- Backgrounds:

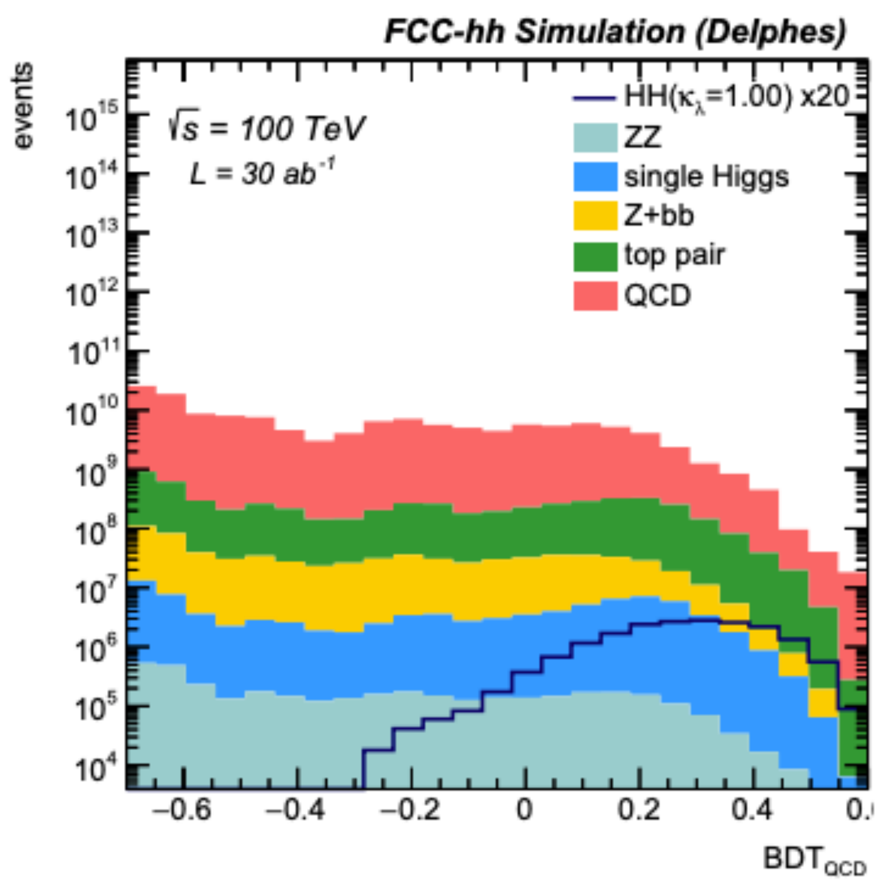
  - **QCD**
  - **Top pair**
  - **single Higgs (VH, ttH, ggH)**
  - Z + bb →bb + bb

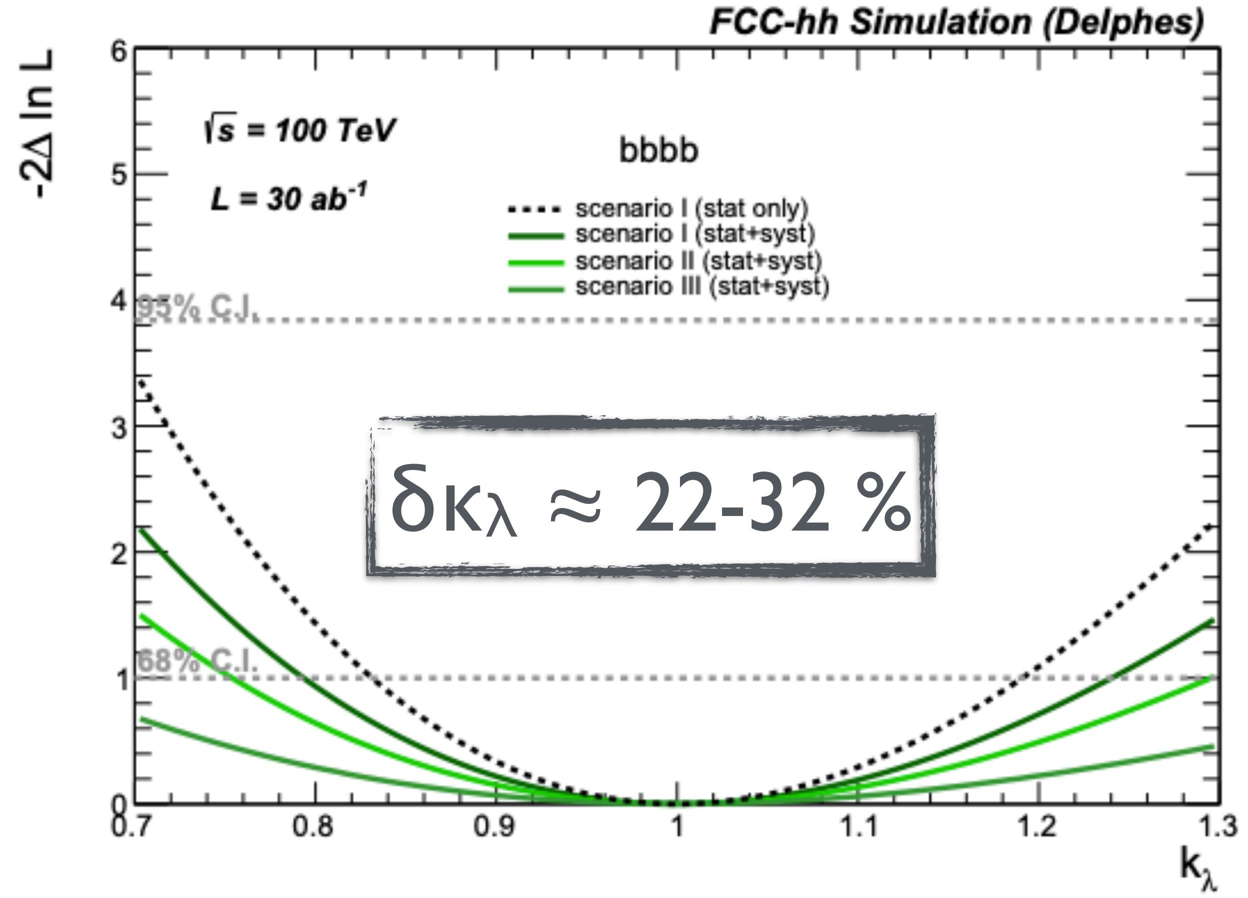
HH →bbbb



Resolved:

- Large combinatorial QCD background
- Select 4b-jets with p_T > 45 GeV
- Test all possible pairs among 4 b-jets (6 total), and rank them in ascending ascending **$|m_H$ - $m_{bb}|$** , keep first two pairs
- Use all kinematics available in the event to train a BDT discriminant

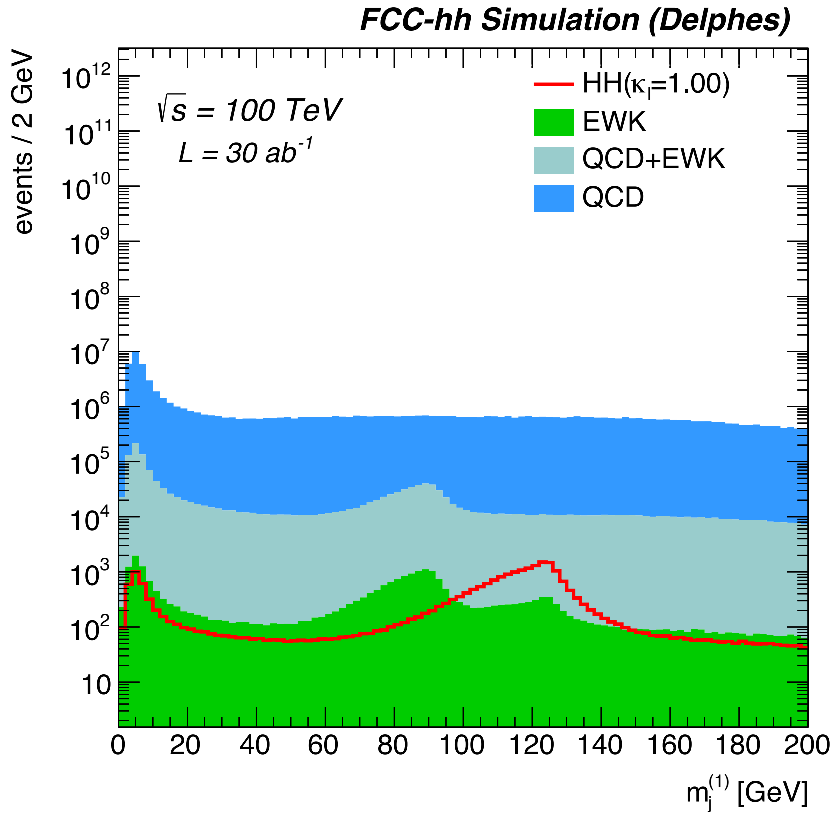




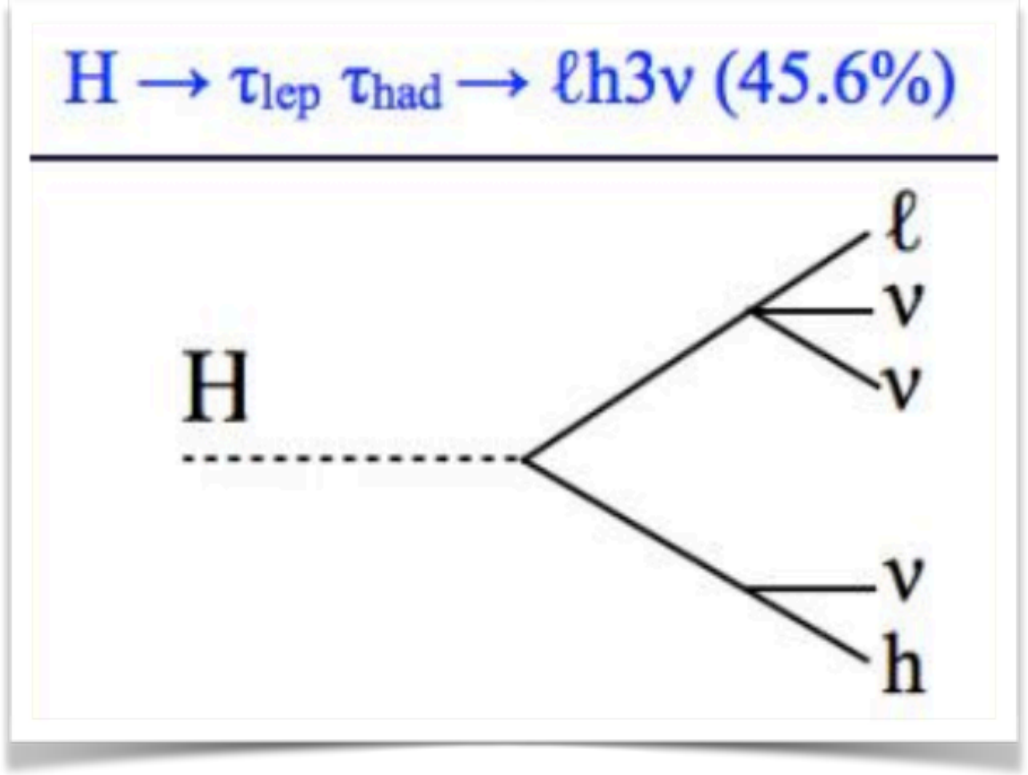
Boosted

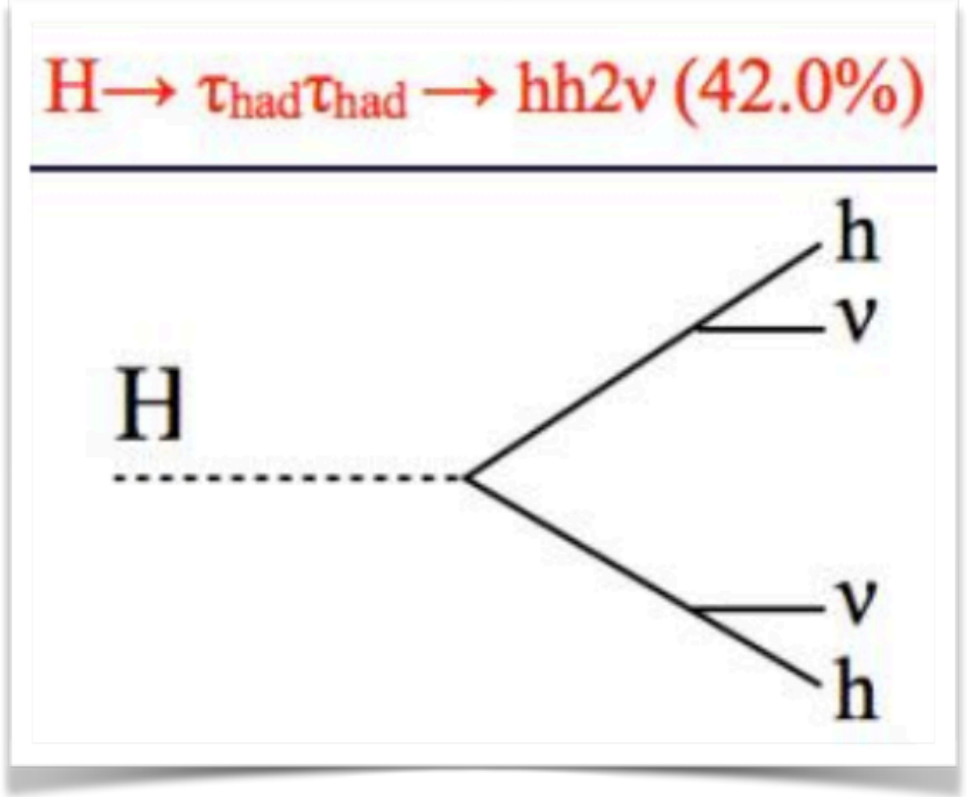
- Requiring a **boosted HH system recoiling against jet(s)**, contains the invariant mass to small values
  - → maintain sensitivity to the self-coupling
  - → reduce combinatorial background

$\delta\kappa_\lambda$(stat) ≈ 20 - 40 %



The bbττ channel





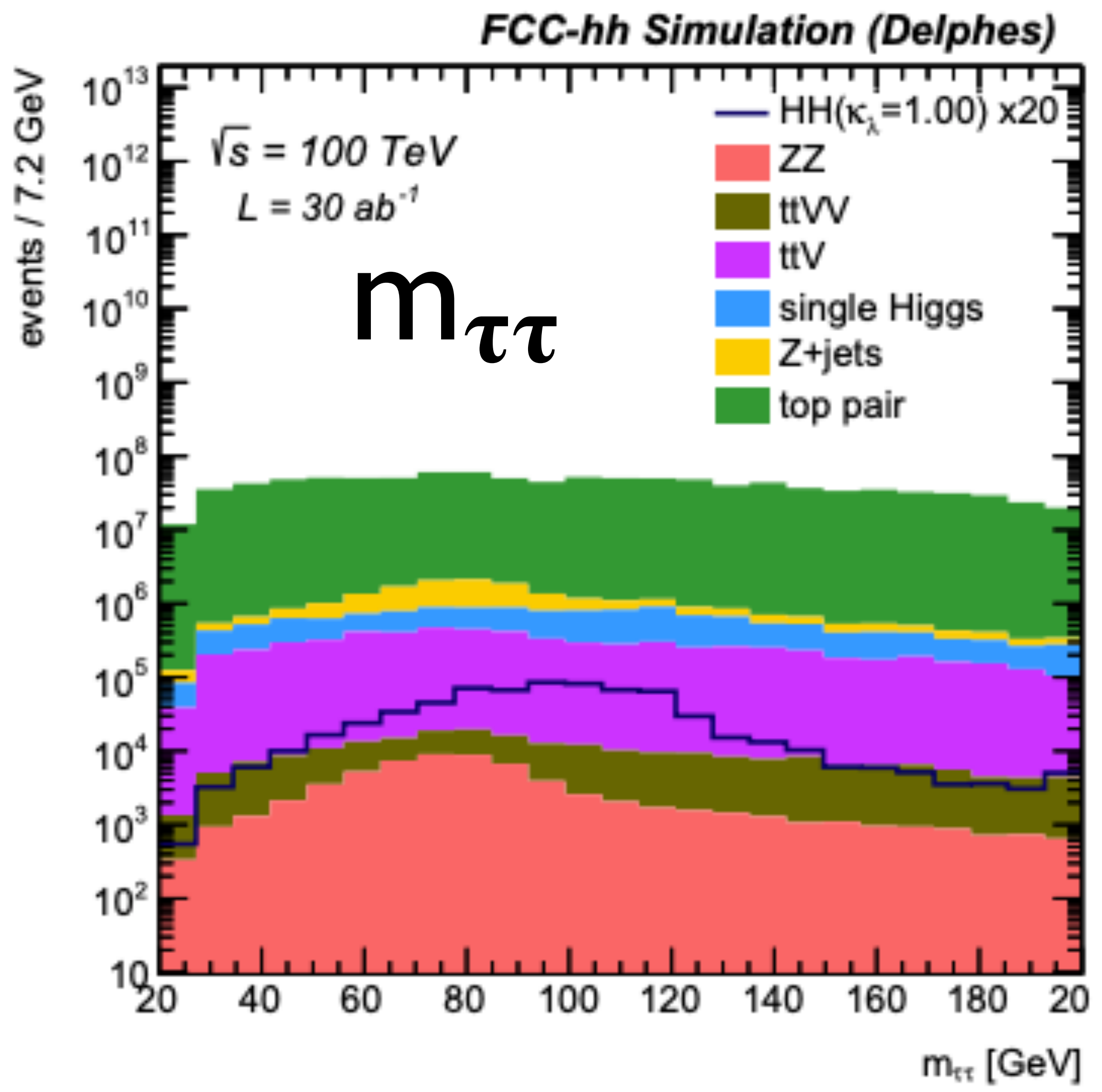
Detector assumptions:

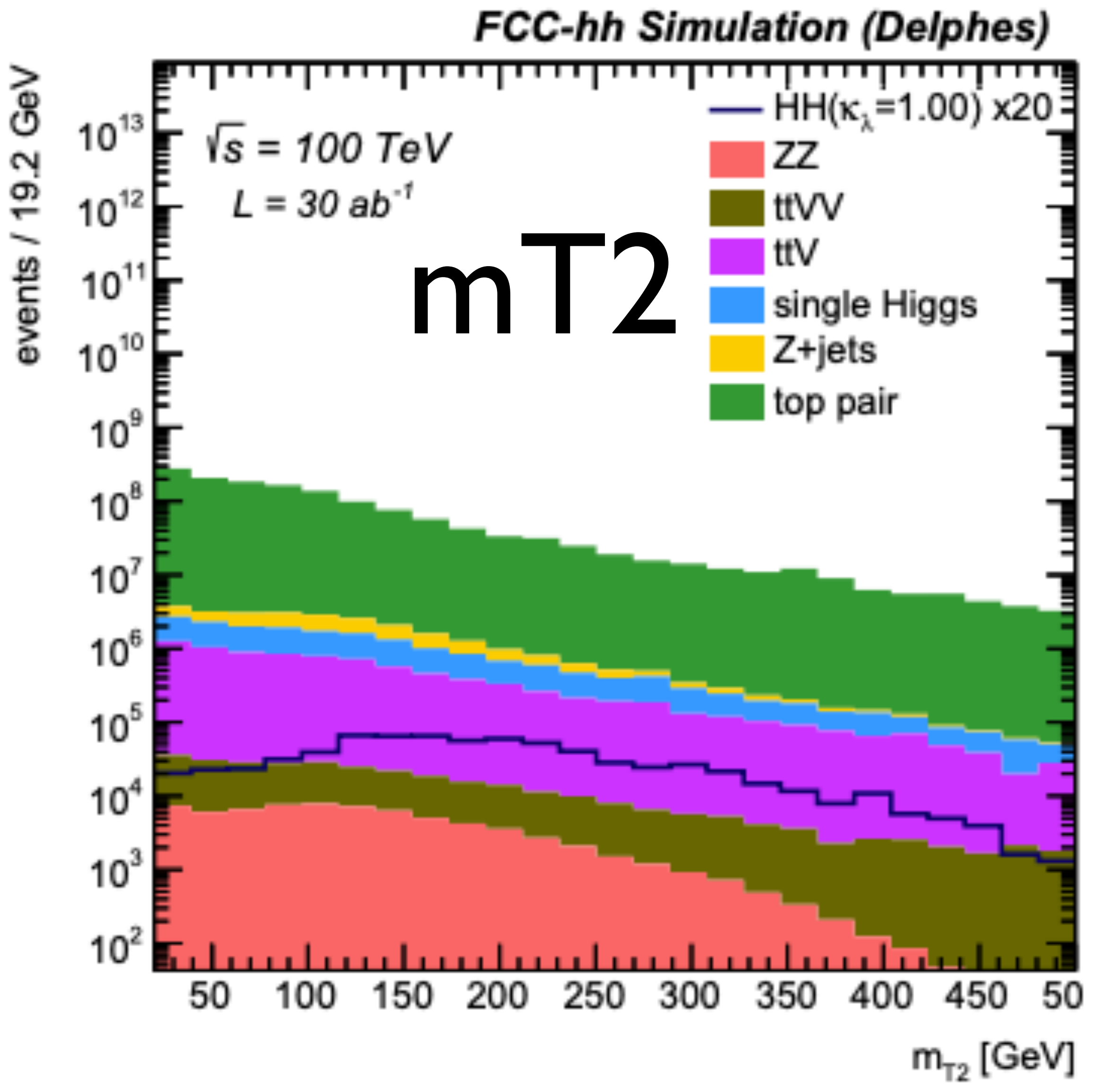
- b-tagging : ε_b = 85%, $\varepsilon_{j\to b}$ = 1% (~ HL-LHC)
- τ-tagging : ε_τ = 80%, $\varepsilon_{j\to\tau}$ = 1%. (~ HL-LHC)

- Exploit **large branching ratio** 2*BR(H→bb)*BR(H→ττ) ≈ 7.3%
- Both states only $\tau_{had}\tau_{had}$ and $\tau_{had}\tau_{lep}$ considered
- $\tau_{lep}\tau_{had}$ has larger B contamination
  - ttbar with τ_{had} + e/mu (in addition to $\tau_{lep}\tau_{had}$)
- Backgrounds:
  - **Top pair**
  - **single Higgs (VH, ttH, ggH)**
  - Z + bb →ττ + bb
  - ttZ, ttW
  - ttZZ, ttWW, ttW

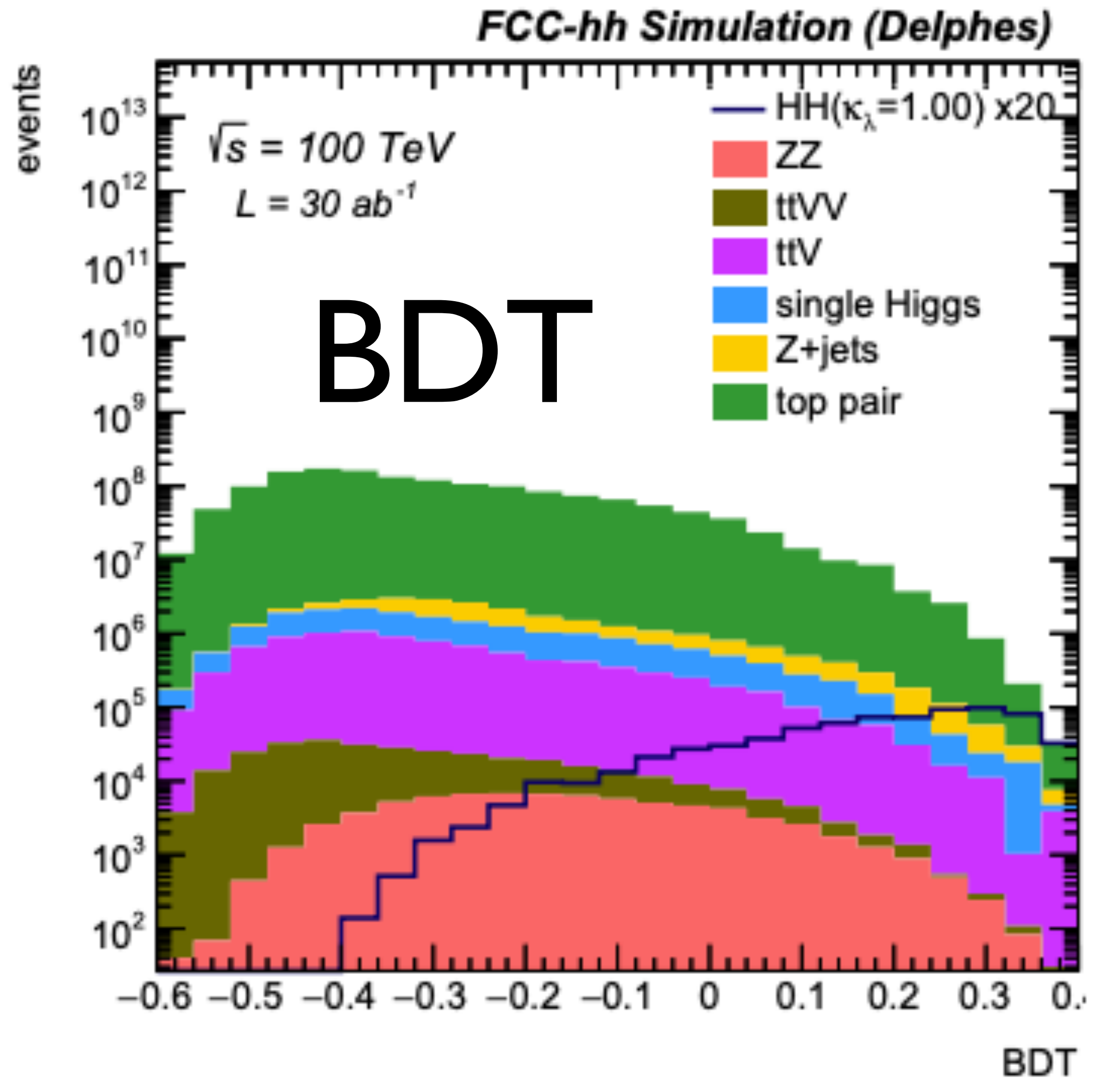
The bbττ channel

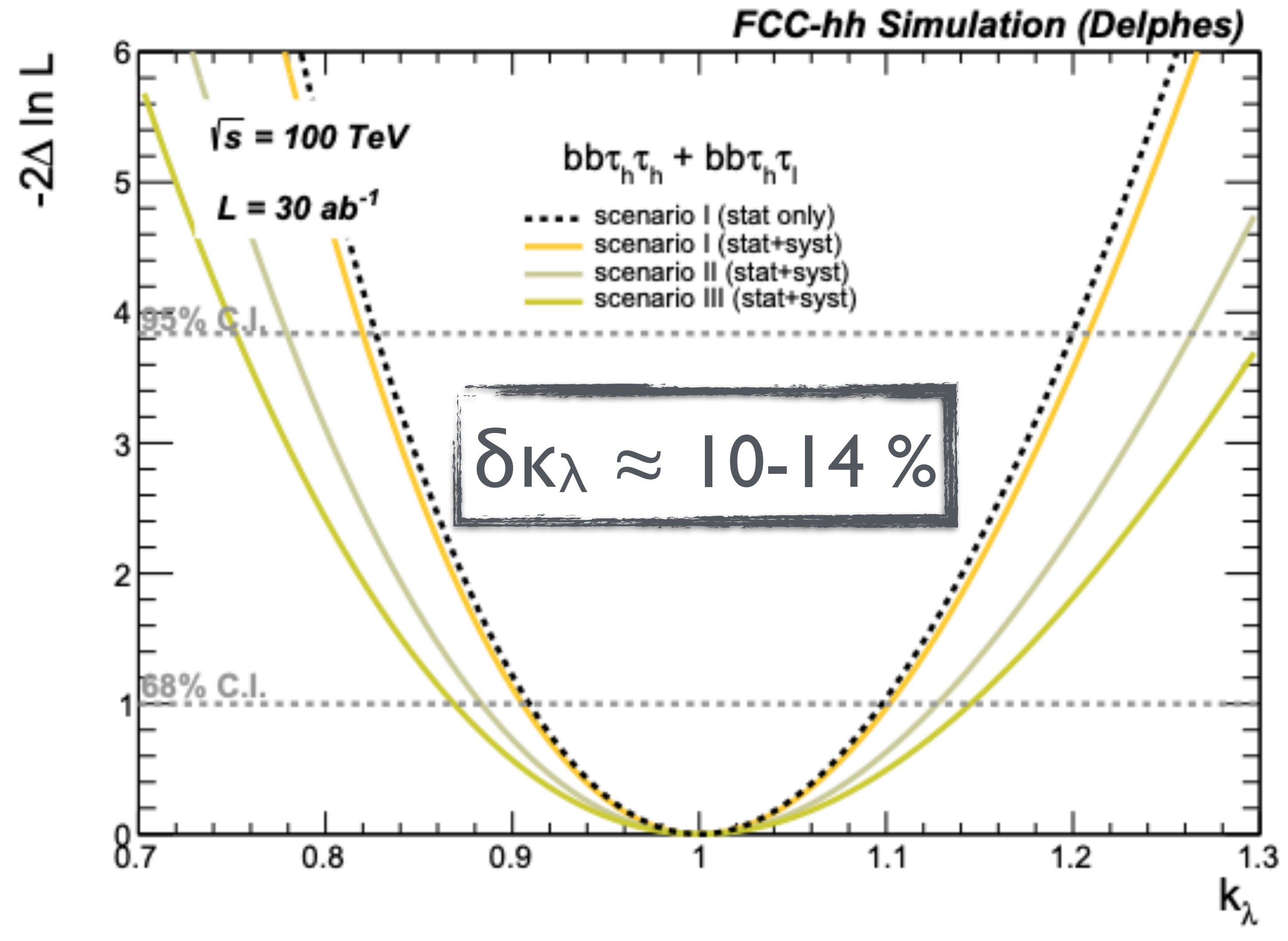
- Simple preselection $\tau_{had}\tau_{had}$/$\tau_{lep}\tau_{had}$:
  - **≥ 2 (1) τ-tagged jets** with:
    - $p_T(\tau_{had})$ > 45 GeV, $|\eta(\tau_{had})|$ < 3.0
  - **At least two b-tagged jets** with:
    - $p_T(b)$ > 30 GeV, $|\eta(b)|$ < 3.0
  - **< 1 lepton** $p_T(l)$ > 25 GeV, $|\eta(l)|$ < 3.0)
  - **≥ 1 lepton**





- BDT training input:
  - 3-vectors of τ_1, τ_2, b_1, b_2
  - 4-vectors of $H_{\tau\tau}$, H_{bb}, HH
  - E_T^{miss}
  - MT2, $m_T(\tau_1)$, $m_T(\tau_2)$, H_T

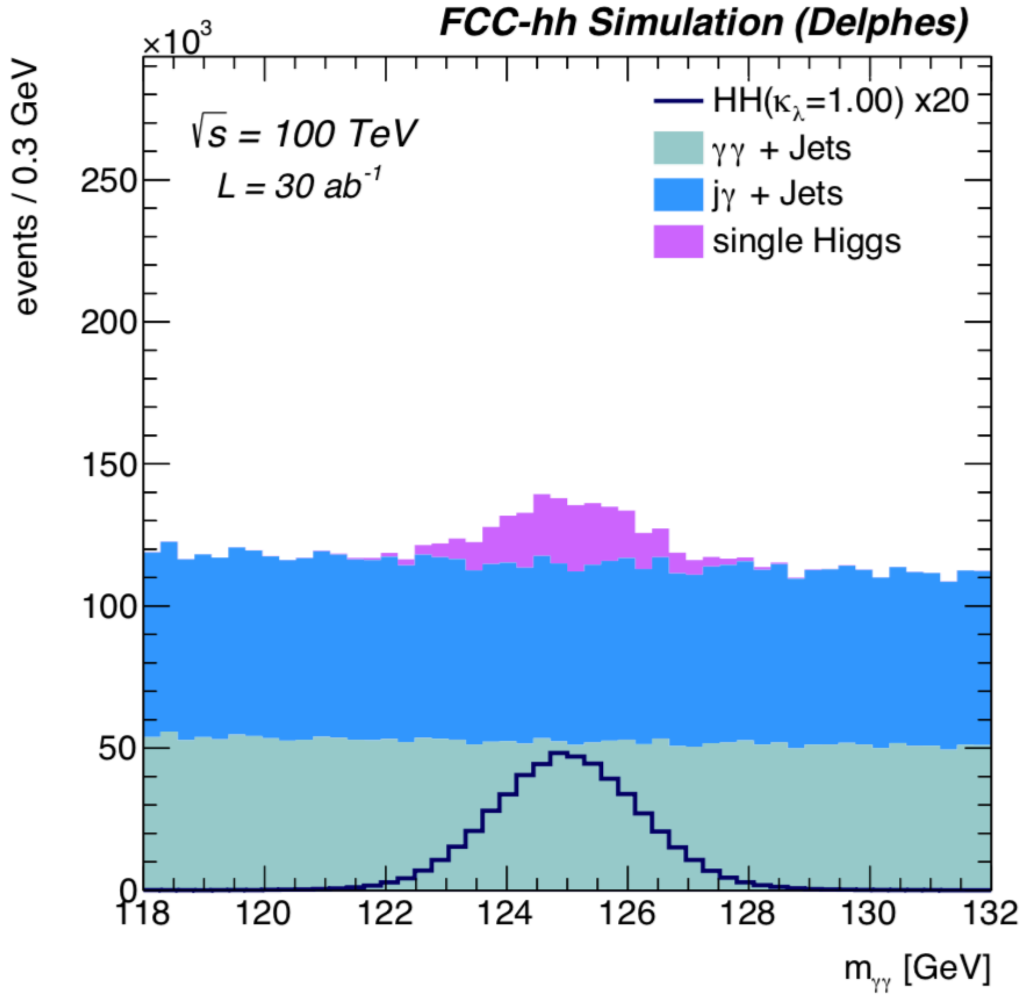


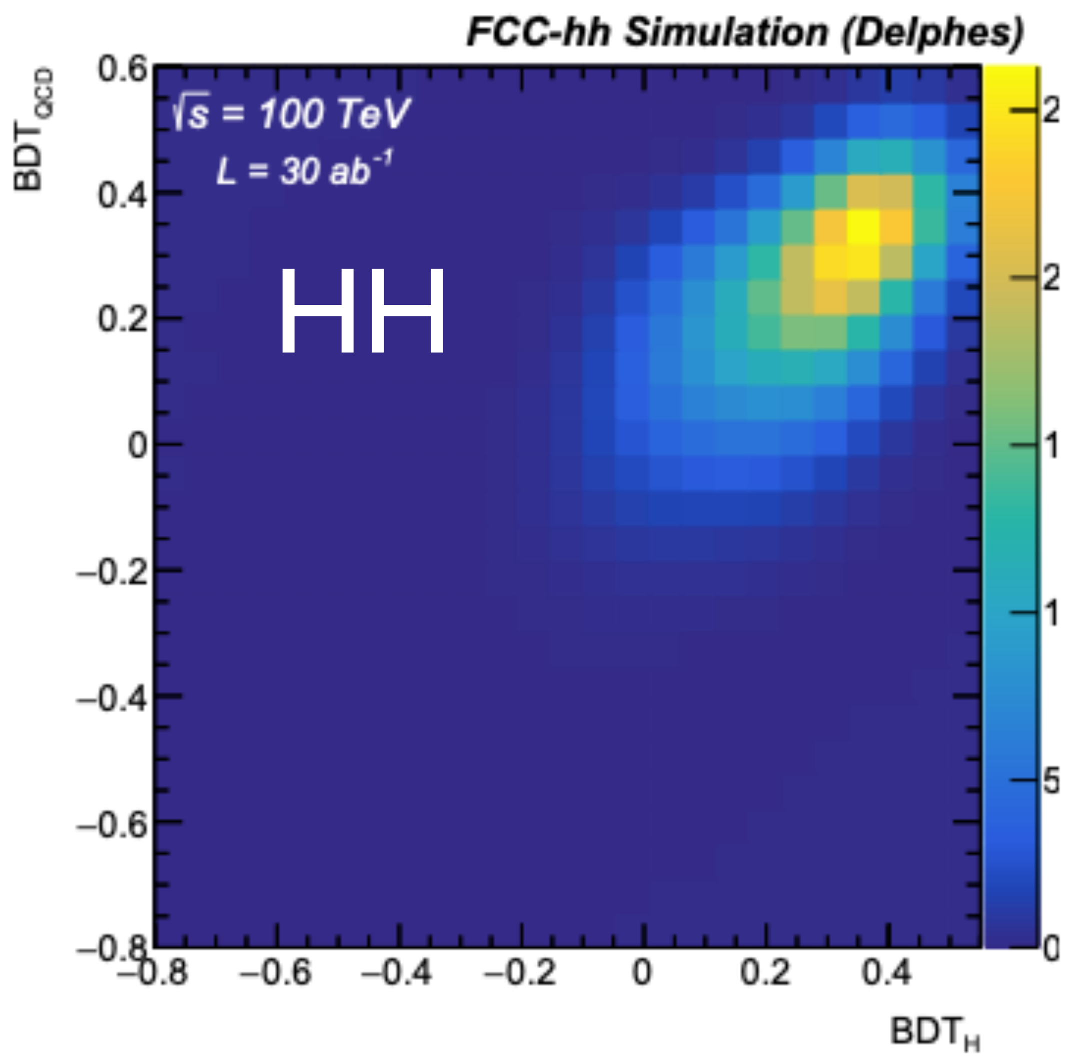


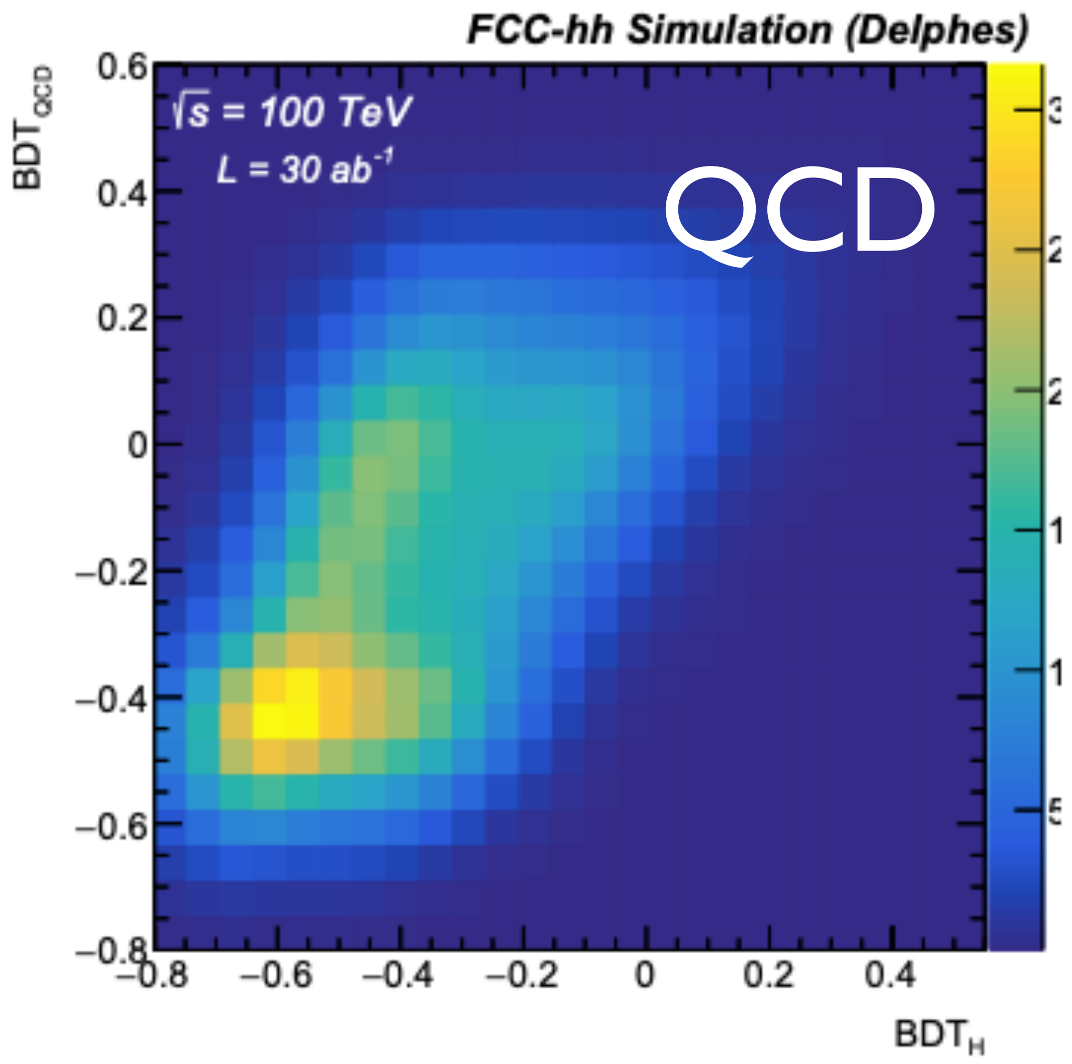
HH →bbγγ

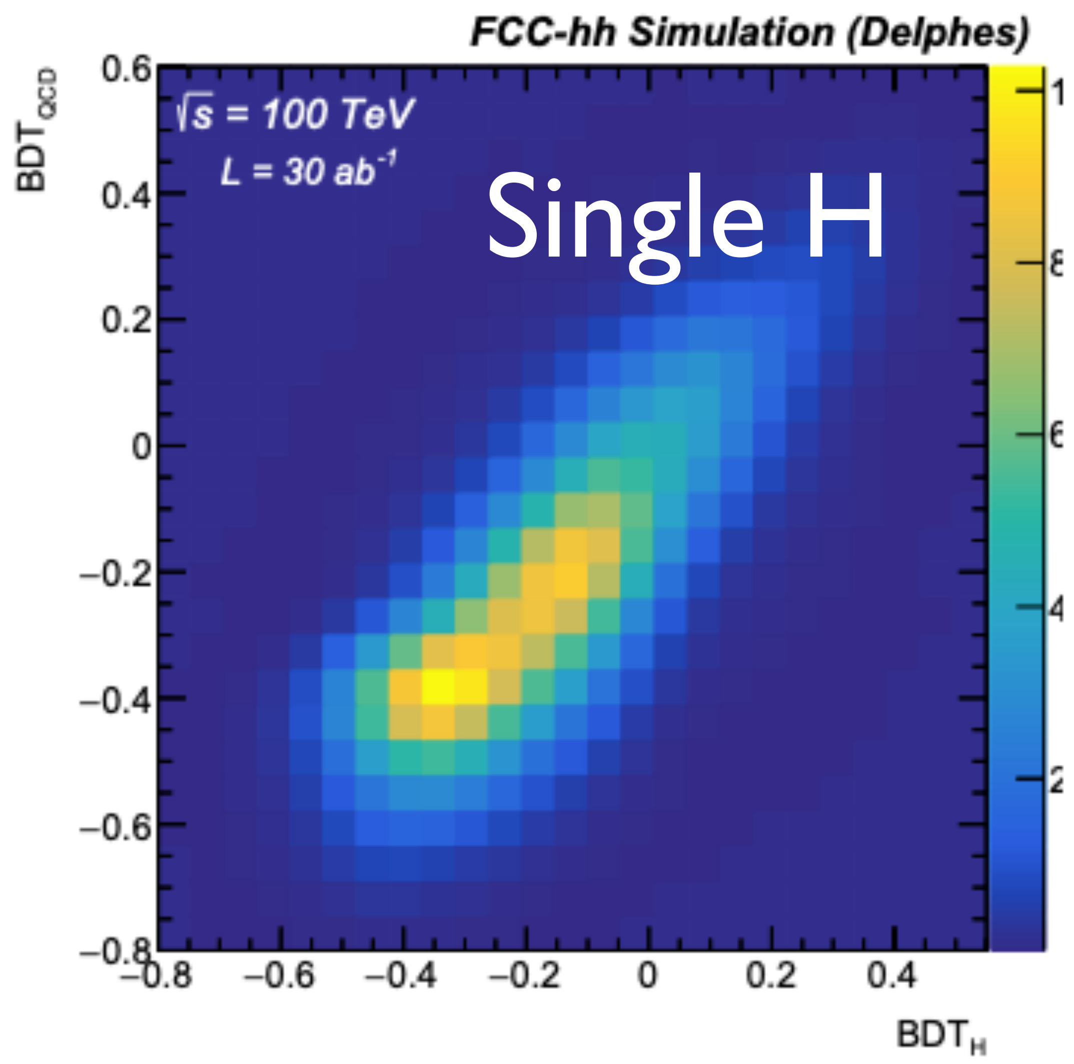
- Cleanest decay channel
- **Large QCD** backgrounds (jjγγ and γ+jets)
- Main difference w.r.t LHC is the very large single Higgs (mainly **ttH background)**

- <u>Strategy:</u>
  - Exploit full final state information and correlations $p_T(\gamma_i)$, $p_T(b_i)$, $\eta(\gamma_i)$, $\eta(b_i)$, etc… with a MVA
  - Single H and QCD trained separately
  - Fit 2D (BDT_H, BDT_{QCD}) spectrum

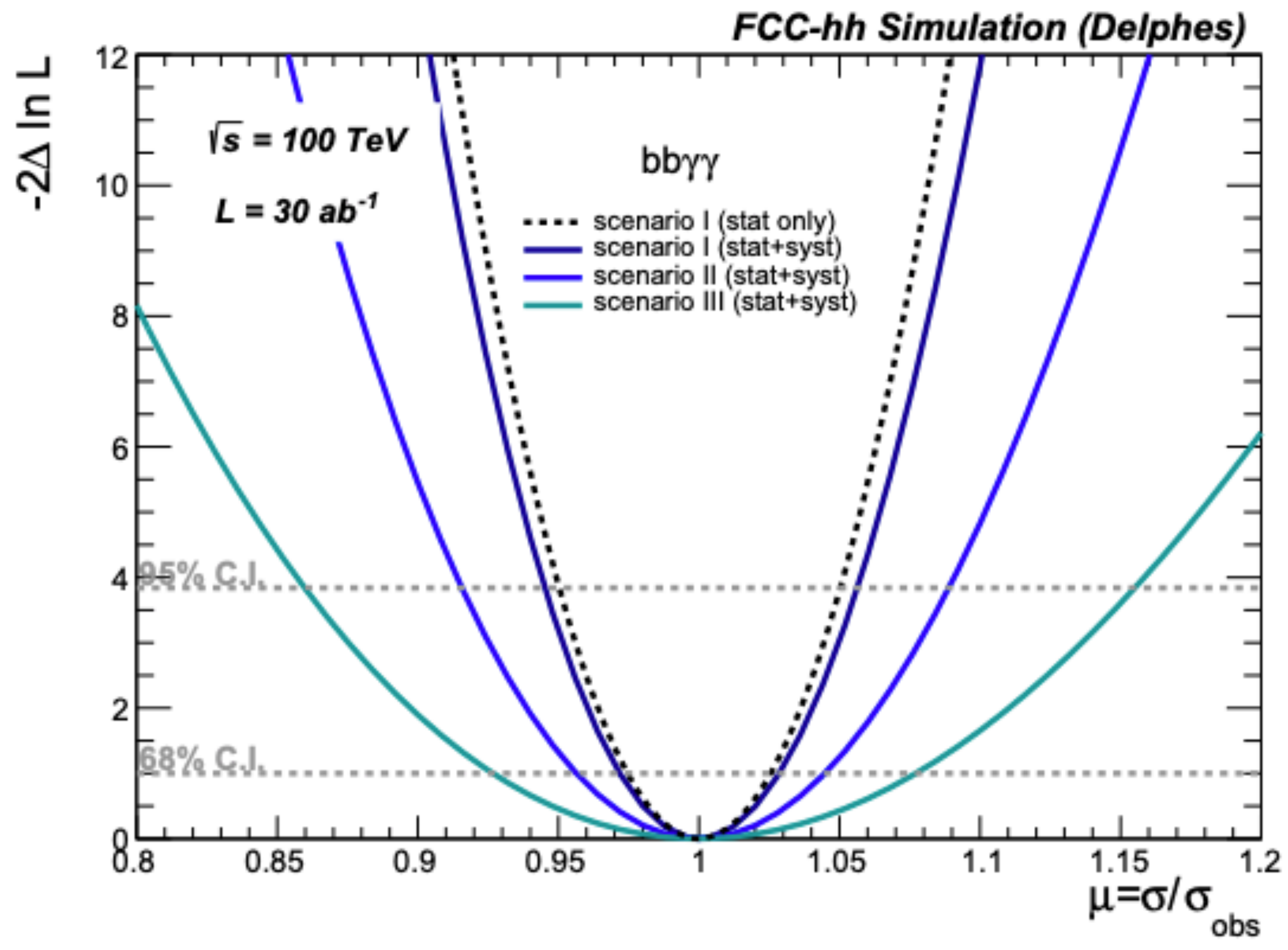


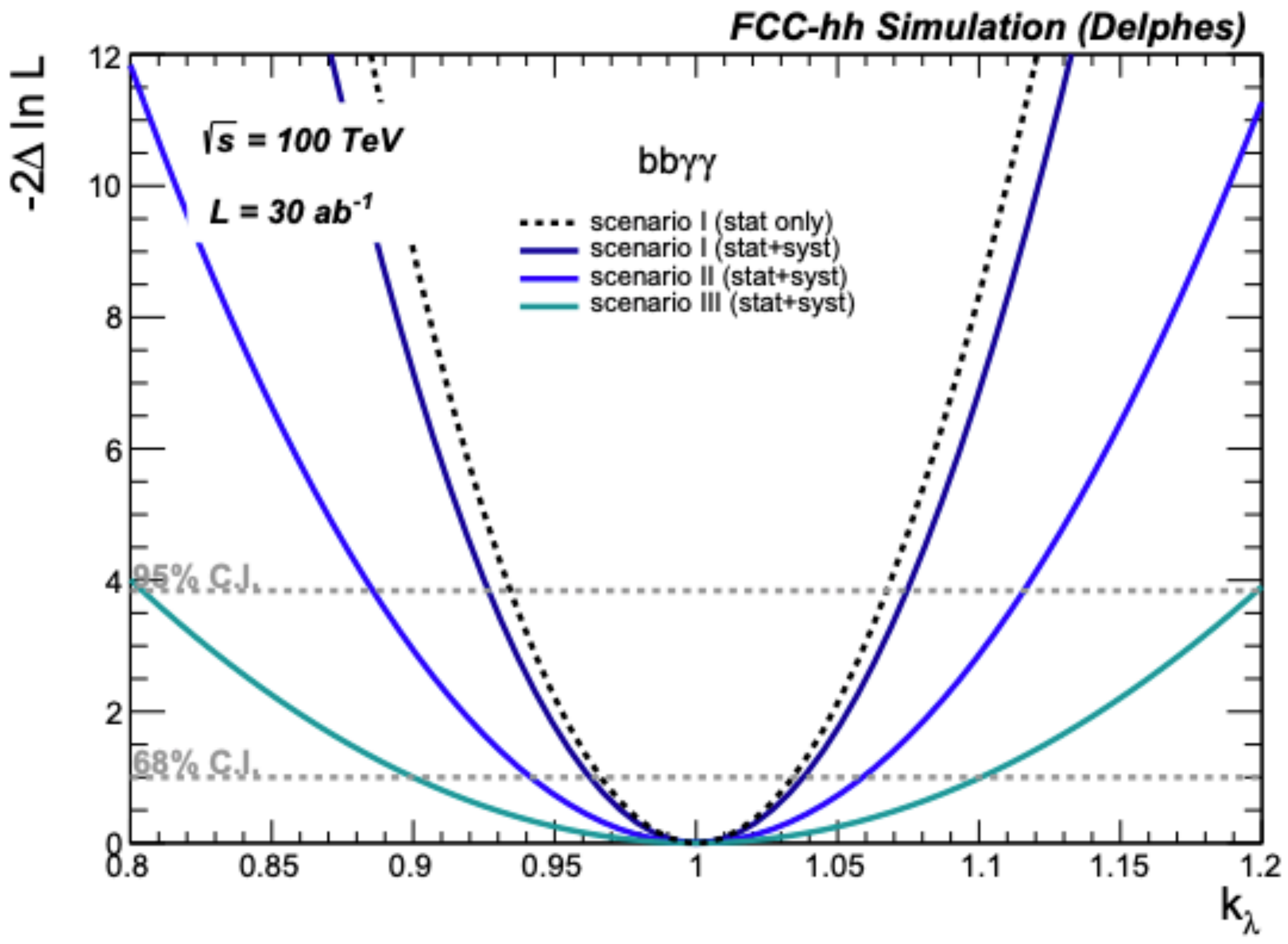






HH → bbγγ

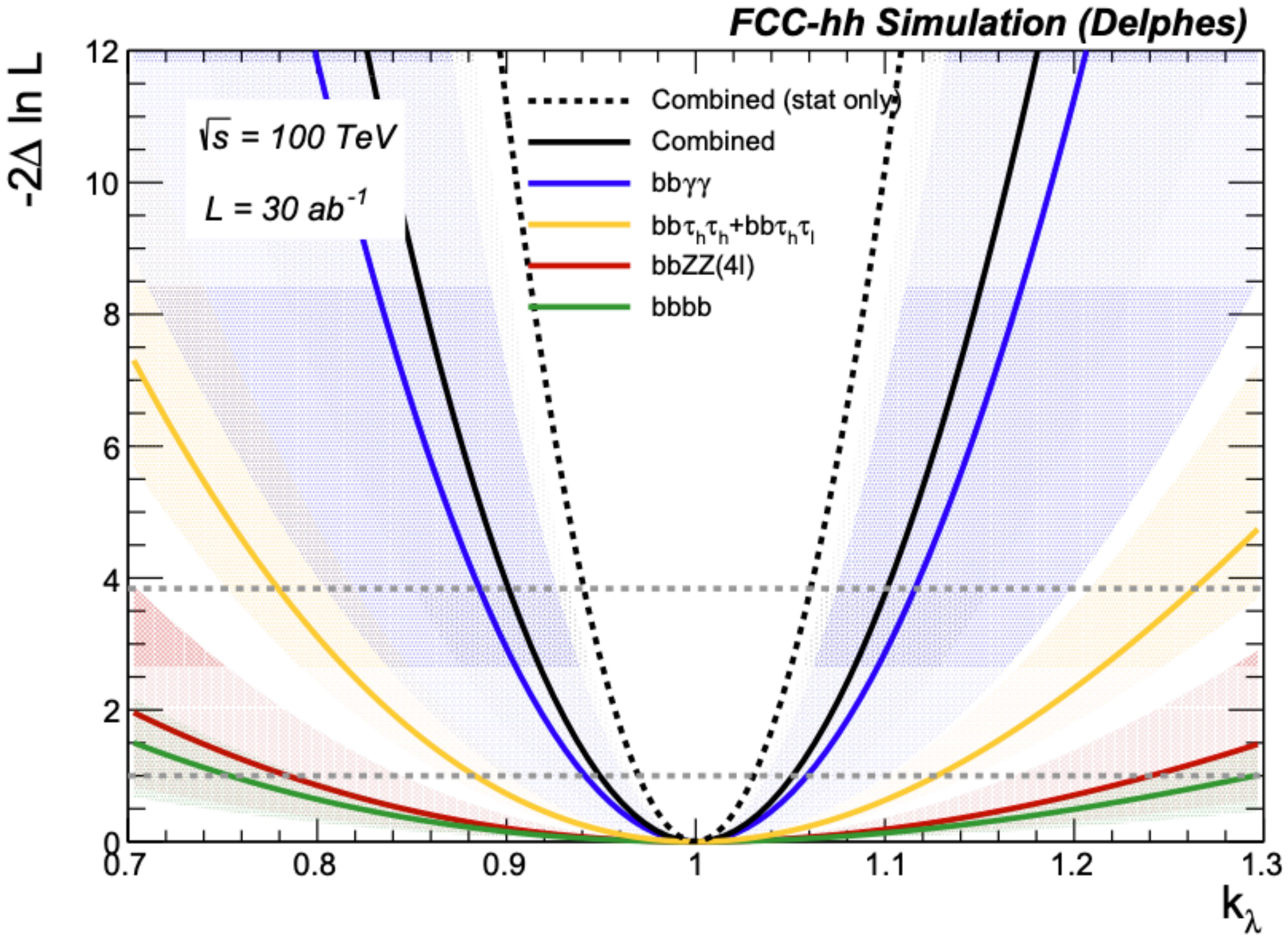




	@68% CL	scenario I	scenario II	scenario III
δ_μ	stat only	2.5	3.6	5.6
	stat + syst	2.8	4.4	7.5
δ_{κ_λ}	stat only	3.4	4.8	7.4
	stat + syst	3.8	5.9	10.0

Combination of all channels

w/ Giacomo Ortona



Combined sensitivity:

	@68% CL	scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8