Future circular colliders

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Lect 3,4

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Table 2.1: Machine parameters of the FCC-ee for different beam energies.

		Z	WW	ZH	$t\bar{t}$	
Circumference	[km]	97.756				
Bending radius	[km]	10.760				
Free length to IP ℓ^*	[m]	2.2				
Solenoid field at IP	[T]	2.0				
Full crossing angle at IP θ	[mrad]	30				
SR power / beam	[MW]	50				
Beam energy	[GeV]	45.6	80	120	175	182.5
Beam current	[mA]	1390	147	29	6.4	5.4
Bunches / beam		16640	2000	328	59	48
Average bunch spacing	[ns]	19.6	163	994	2763[a]	3396[??]
Bunch population	[10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x	[nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y	[pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances	[deg]	60/60		90/90		
Momentum compaction α_p	[10^{-6}]	14.8		7.3		
Arc sextupole families		208		292		
Horizontal β^*_x	[m]	0.15	0.2	0.3	1.0	
Vertical β^*_y	[mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ^*_x	[µm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ^*_y	[nm]	28	41	36	66	68
Energy spread (SR/BS) σ_δ	[%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z	[mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Piwinski angle (SR/BS) ϕ		8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0
Length of interaction area L_i	[mm]	0.42	0.85	0.90	1.8	1.8
Hourglass factor R_{HG}		0.95	0.89	0.88	0.84	0.84
Crab sextupole strength[b]	[%]	97	87	80	40	40
Energy loss / turn	[GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency	[MHz]	400			400 / 800	
RF voltage	[GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Synchrotron tune Q_s		0.0250	0.0506	0.0358	0.0818	0.0872
Longitudinal damping time	[turns]	1273	236	70.3	23.1	20.4
RF bucket height	[%]	1.9	3.5	2.3	3.36	3.36
Energy acceptance (DA)	[%]	$\pm$1.3	$\pm$1.3	$\pm$1.7	-2.8 +2.4	
Polarisation time t_p	[min]	15000	900	120	18.0	14.6
Luminosity / IP	[10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55
Horizontal tune Q_x		269.139	269.124	389.129	389.108	
Vertical tune Q_y		269.219	269.199	389.199	389.175	
Beam-beam ξ_x/ξ_y		0.004/0.133	0.010/0.113	0.016/0.118	0.097/0.128	0.099/0.126
Allowable e^+e^- charge asymmetry	[%]	$\pm$5	$\pm$3			
Lifetime by rad. Bhabha scattering	[min]	68	59	38	40	39
Actual lifetime due to beamstrahlung	[min]	$>$ 200	$>$ 200	18	24	18

FCC-ee run plan

phase	Run duration (yrs)	√s (GeV)	L_{int} (ab^{-1})	Event stats
ee→Z	4	88-95	150	$3x10^{12}$ had Z decays
ee→WW	2	158-192	12	$3x10^{8}$ WW
ee→ZH	3	240	5	10^{6} ZH
machine modification for RF installation and rearrangement: 1 year				
ee→tt	5	345-365	1.5	10^{6} tt + $4x10^{4}$ Hνν
ee→H	(3)	(125)	(21)	(H resonance)

Total programme duration: 14 years (including machine modifications)
plus optional 3years @ H resonance

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

Goal: 20-30 ab^{-1} during the collider lifetime

FCC-he & HE-LHC-ep parameters

parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	**3.5**	**1.7**	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\varepsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} cm^{-2}s^{-1}]	**11**	**9**	8	1.3

Event rates: examples

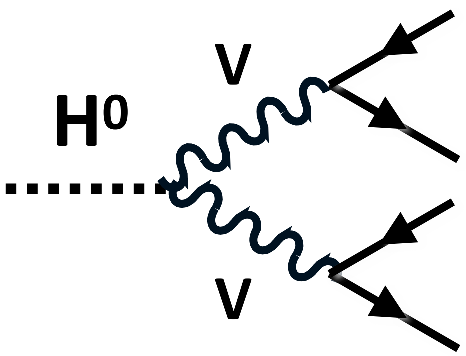
FCC-ee	H	Z	W	t	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
	10^6	5×10^{12}	10^8	10^6	3×10^{11}	1.5×10^{12}	10^{12}

FCC-hh	H	b	t	$W(\leftarrow t)$	$\tau(\leftarrow W \leftarrow t)$
	2.5×10^{10}	10^{17}	10^{12}	10^{12}	10^{11}

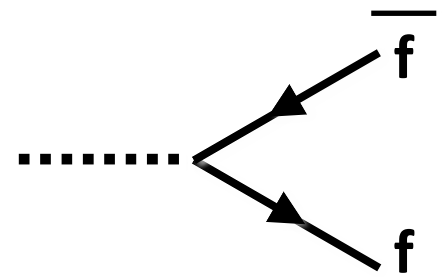
FCC-eh	H	t
	$2.5\ 10^6$	$2\ 10^7$

Higgs observables: decay BRs

Tree-level couplings



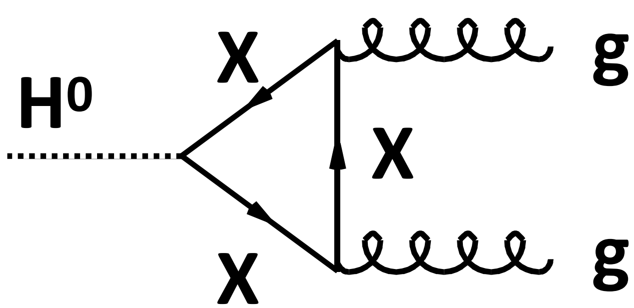
coupling to EW gauge bosons $\Rightarrow$ g,g'



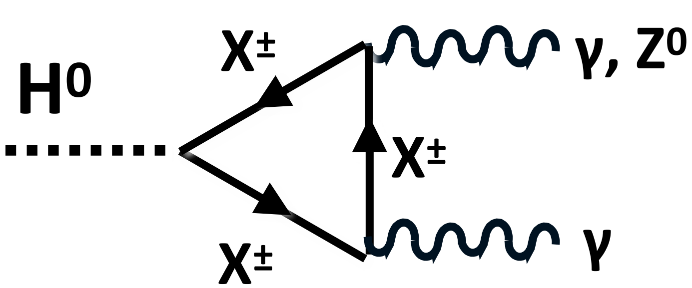
coupling to fermions
$\Rightarrow m_f / v$

$m_f < m_H / 2$

Loop-level couplings



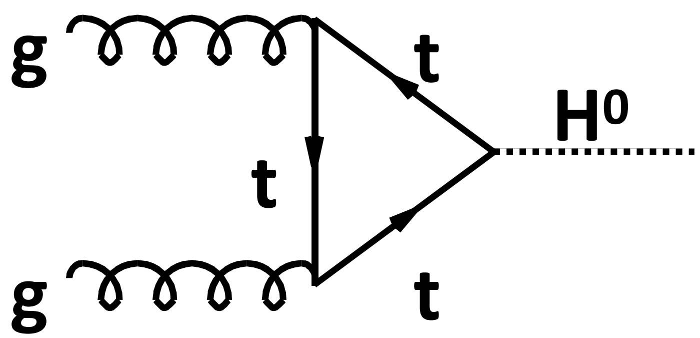
X_{SM} =t,b,c X_{BSM} = T, stop, ...?

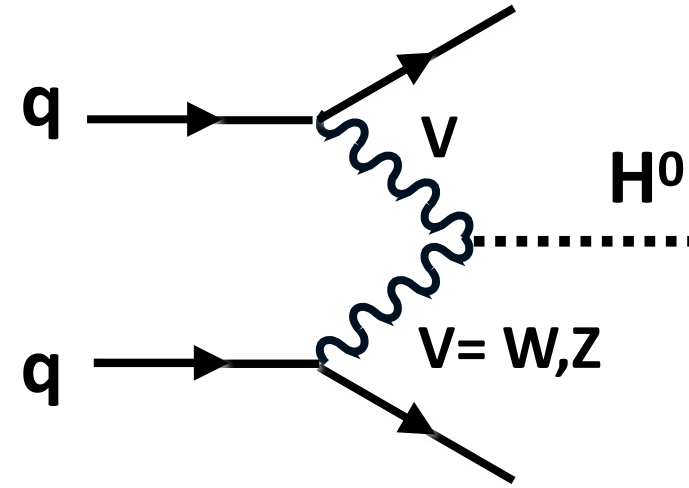


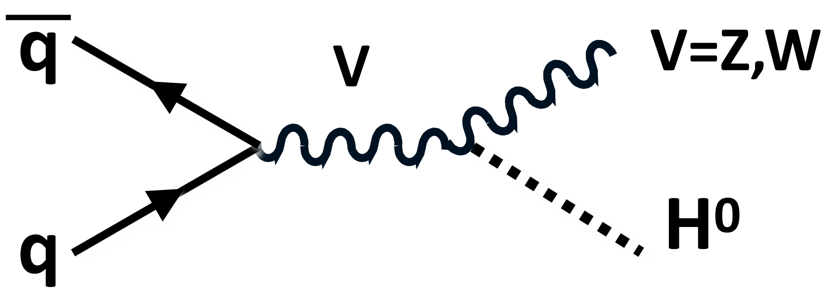
X_{SM} =t, $W^{\pm}$ X_{BSM} = T, stop, chargino, ...?

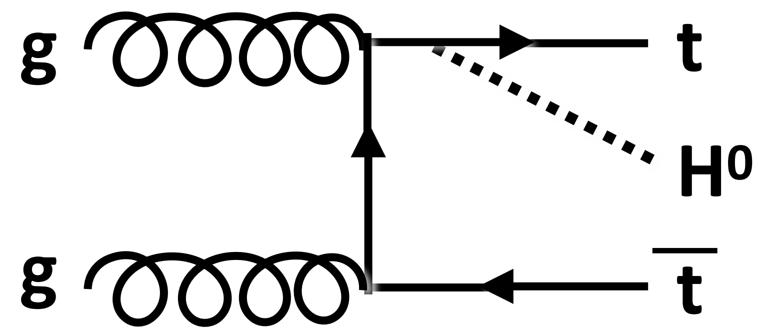
Higgs observables: production rates

Hadronic collisions

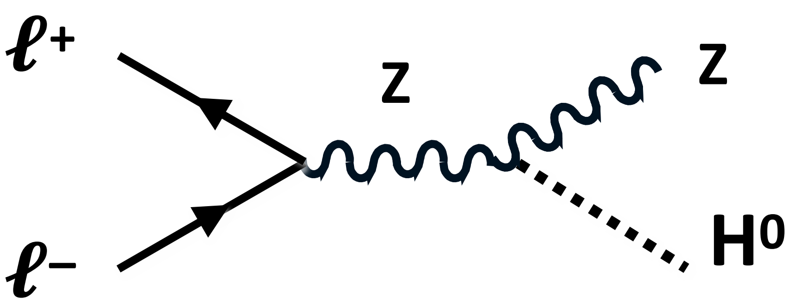


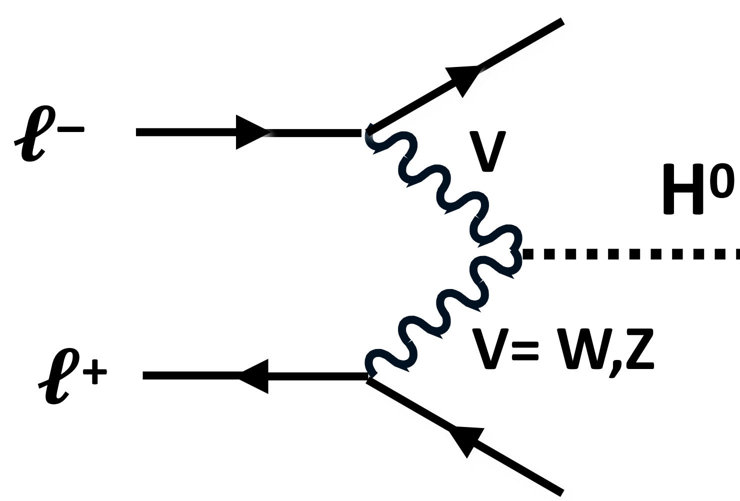


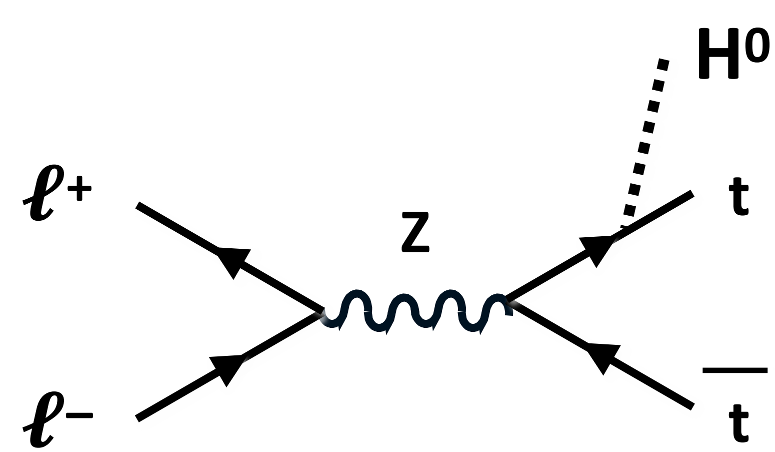




Laptonic collisions







Sensitivity of various Higgs couplings to examples of beyond-the-SM phenomena

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arXiv:1310.8361

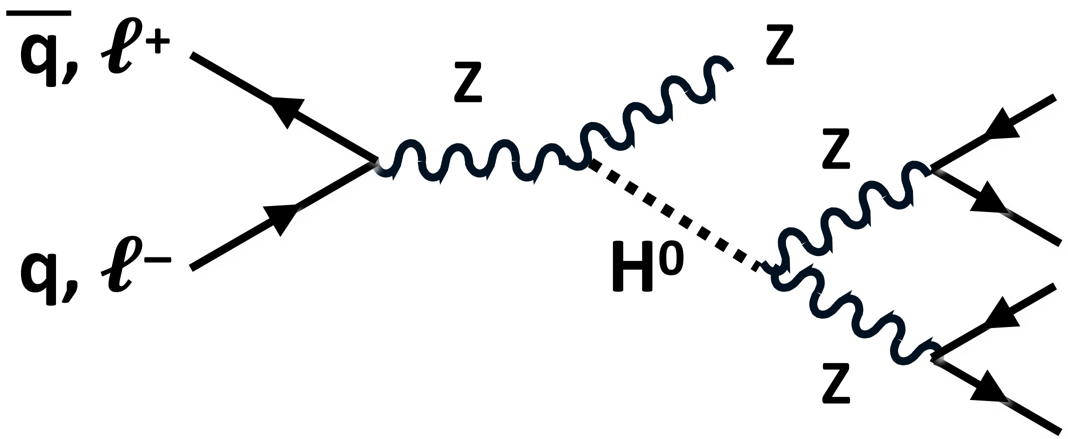
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

=> the goal should be (sub)percent precision!

Extracting couplings from measurements

Example

(A)

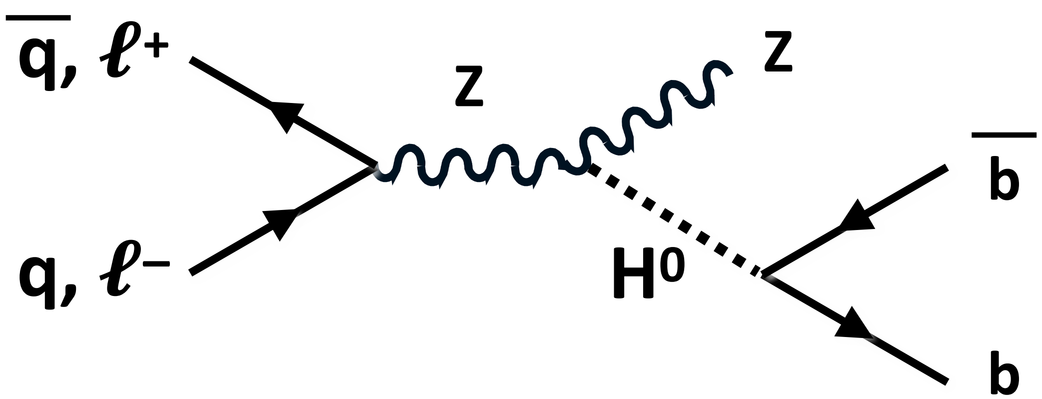


$$\sigma\left(pp/ee \to ZH[\to ZZ^*]\right) \propto g^2_{HZZ} \times \boxed{\frac{g^2_{HZZ}}{\Gamma_H}}$$

1 measurement, 2 parameters!

$B(H \to ZZ^*)$

(B)



$$\sigma\left(pp/ee \to ZH[\to b\bar{b}]\right) \propto g^2_{HZZ} \times \boxed{\frac{g^2_{Hbb}}{\Gamma_H}}$$

1 new measurement, but
1 more parameter…

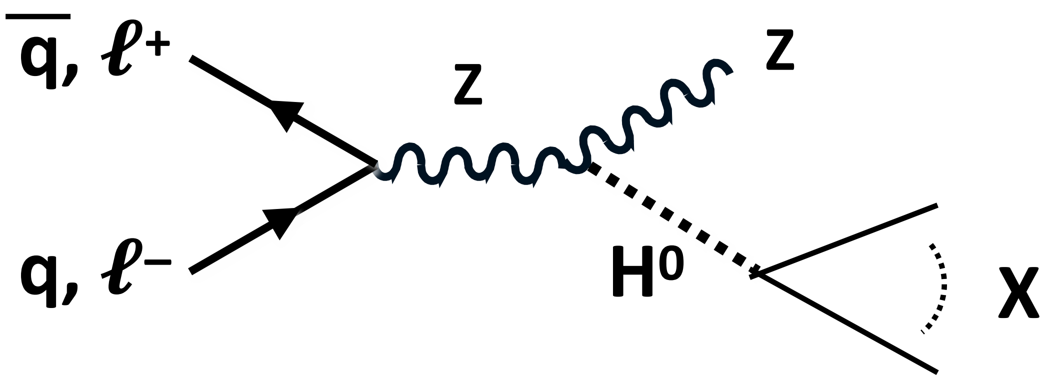
$B(H \to b\bar{b})$

… little progress, except we now know $$\frac{g^2_{HZZ}}{g^2_{Hbb}} = \frac{\sigma_A}{\sigma_B}$$

Overall constraint: $$\sum_X B(H \to X) = 1$$

Therefore:

$$\sum_X \sigma\Big($$

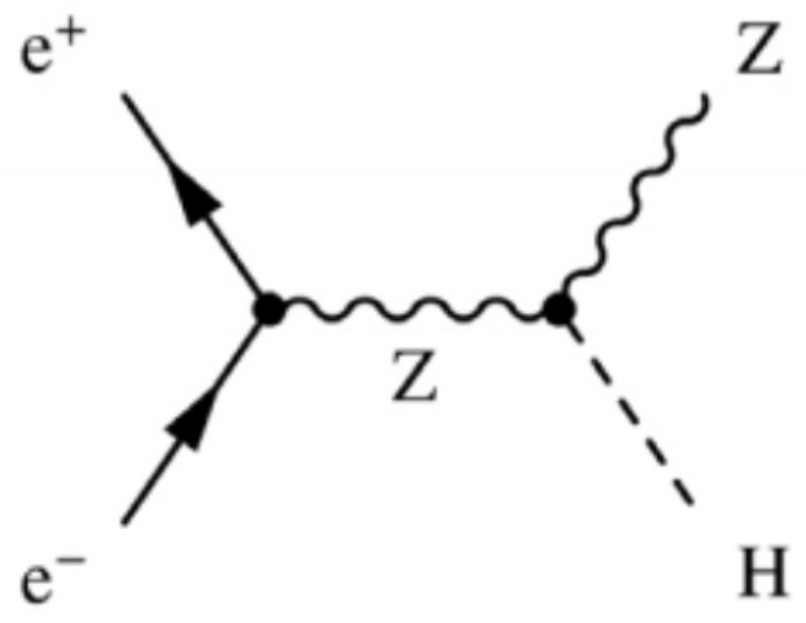


$$\Big) = \sigma(ZH) \propto g_{HZZ}^2$$

How can we hope to detect ALL possible decays of the Higgs boson??

If the goal is to test its properties, we cannot make assumptions, and must be open to possible unexpected decays, possibly invisible, like H→dark matter…

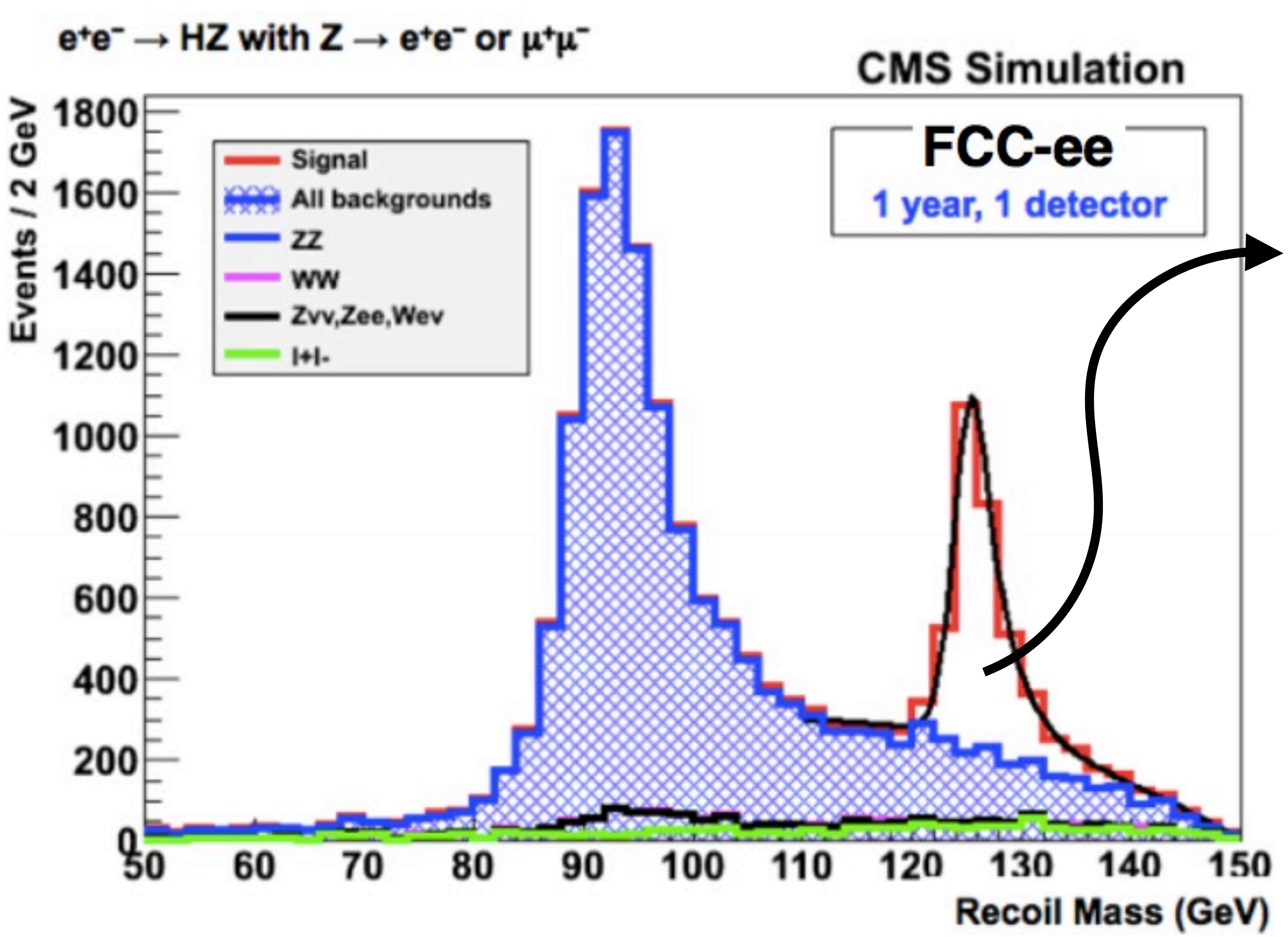
An $\ell^+\ell^-$ collider provides the solution ….



$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\ p(e^-e^+) - p(Z)\ ]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!

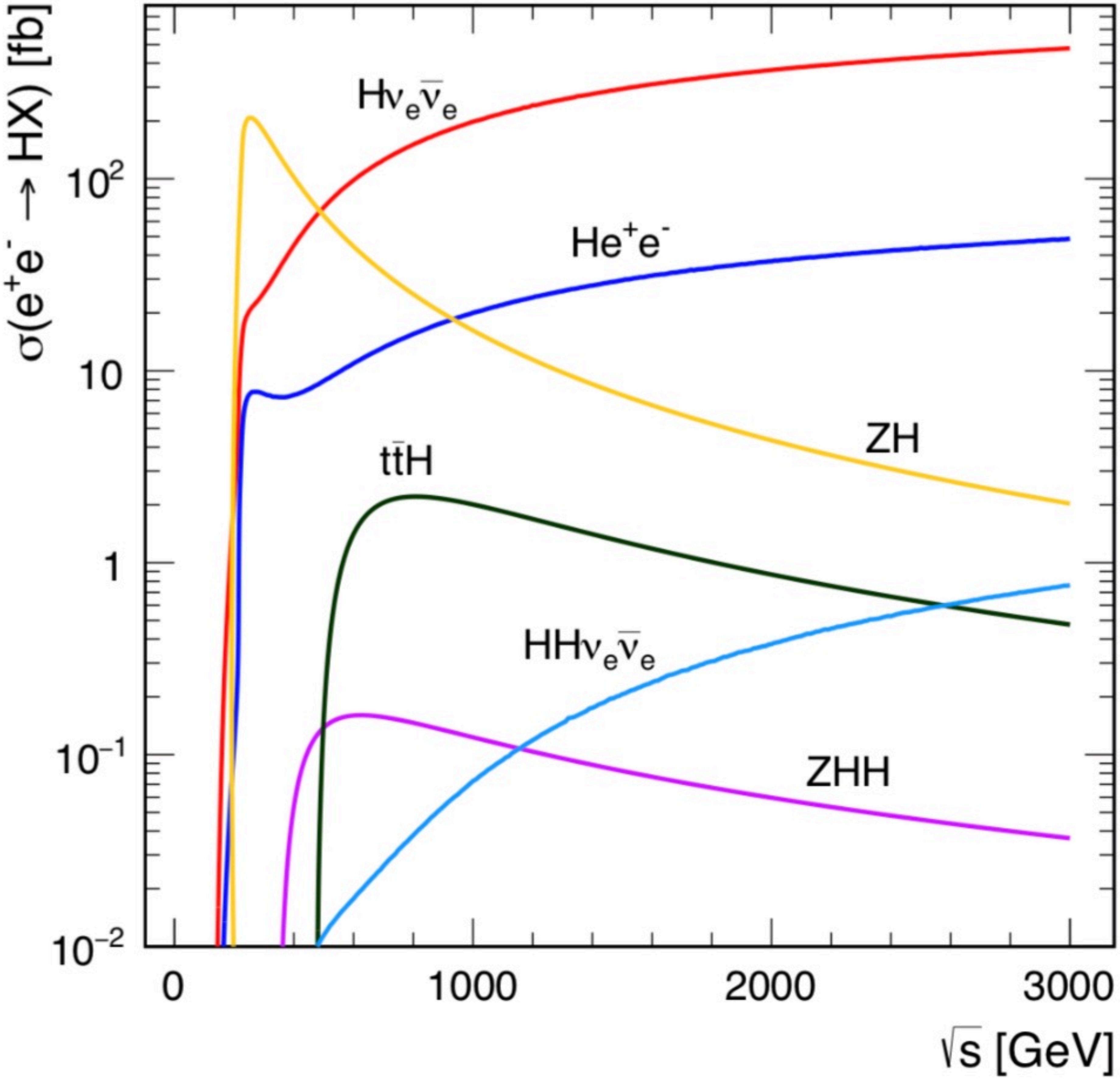


$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\rightarrow ZZ]) \propto$
$\sigma(ZH) \times BR(H\rightarrow ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

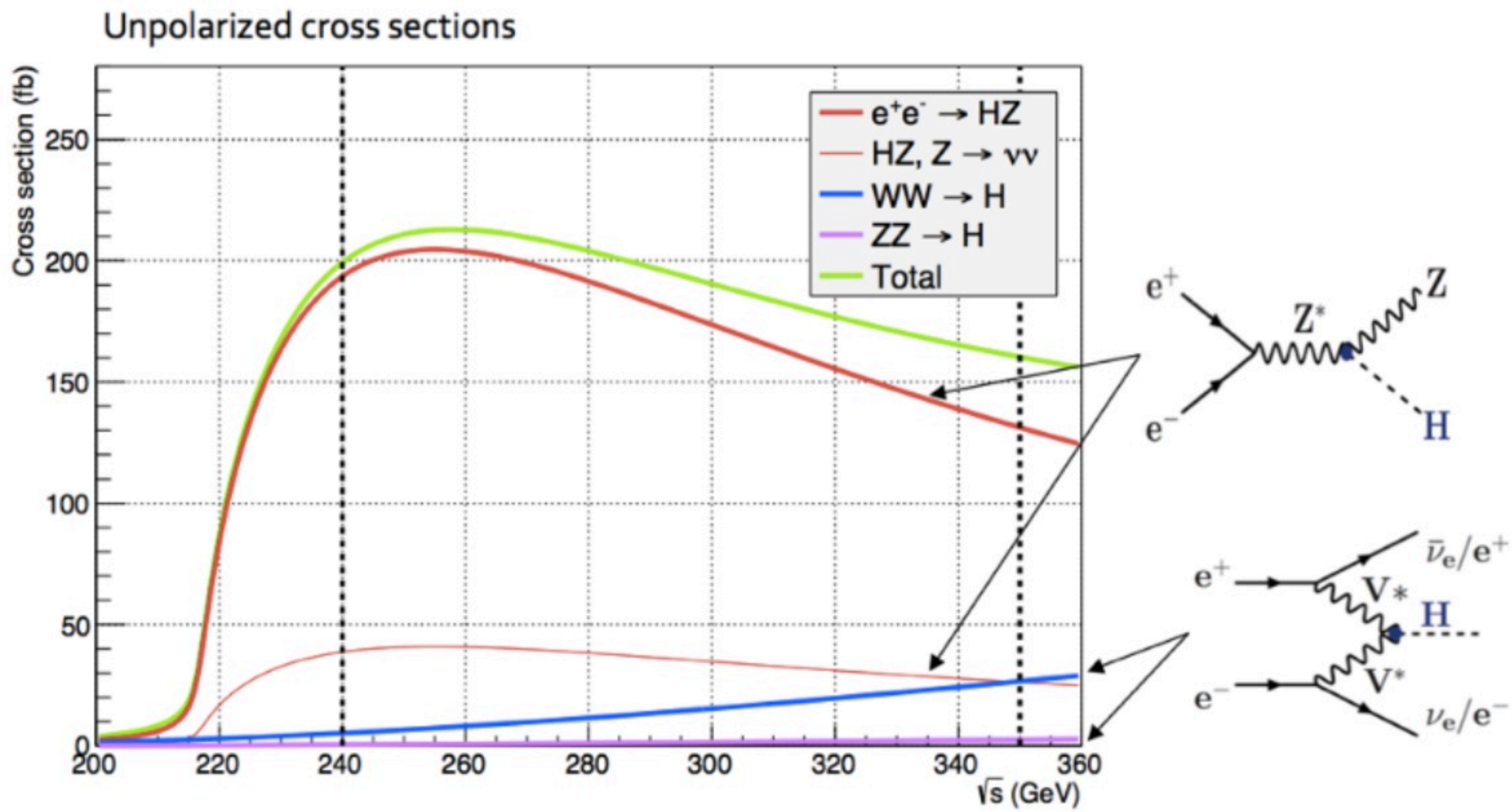
=> absolute measurement of width and couplings

$m_{recoil} = \sqrt{[\ p(e^-e^+) - p(Z)\ ]^2}$



σ(e⁺e⁻ → HX) [fb]
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000
√s [GeV]
$H\nu_e\bar{\nu}_e$
He^+e^-
ZH
$t\bar{t}H$
$HH\nu_e\bar{\nu}_e$
ZHH

FCC-ee



	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
# Higgs bosons from $e^+e^- \to HZ$	1,000,000	200,000
# Higgs bosons form fusion process	25,000	40,000

Higgs couplings: beyond the HL-LHC

Collider	HL-LHC	**HL-LHC update**	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\mathrm{FCC\text{-}ee}_{240+365}$		
Lumi (ab^{-1})	3	3	2	0.5	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	25	15	7	6	7	3	+4	
$\delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}$ (%)	SM	50	3.6	6.3	3.6	2.6	2.7	**1.3**	1.1
$\delta g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}$ (%)	3.5	**1.5**	0.3	0.40	0.32	0.25	0.20	**0.17**	**0.16**
$\delta g_{\mathrm{HWW}}/g_{\mathrm{HWW}}$ (%)	3.5	**1.7**	1.7	0.8	1.7	1.2	1.3	**0.43**	**0.40**
$\delta g_{\mathrm{Hbb}}/g_{\mathrm{Hbb}}$ (%)	8.2	**3.7**	1.7	1.3	1.8	1.3	1.3	**0.61**	**0.56**
$\delta g_{\mathrm{Hcc}}/g_{\mathrm{Hcc}}$ (%)	SM	**SM**	2.3	4.1	2.3	1.8	1.7	**1.21**	**1.18**
$\delta g_{\mathrm{Hgg}}/g_{\mathrm{Hgg}}$ (%)	3.9	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{\mathrm{H\tau\tau}}/g_{\mathrm{H\tau\tau}}$ (%)	6.5	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{\mathrm{H\mu\mu}}/g_{\mathrm{H\mu\mu}}$ (%)	5.0	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{\mathrm{H\gamma\gamma}}/g_{\mathrm{H\gamma\gamma}}$ (%)	3.6	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{\mathrm{Htt}}/g_{\mathrm{Htt}}$ (%)	4.2	**3.4**	–	–	–	–	–	–	**3.1**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	$< \mathbf{1.0}$	< 1.0

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other $\mathrm{e}^+\mathrm{e}^-$ colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with $5\ \mathrm{ab}^{-1}$ at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional $1.5\ \mathrm{ab}^{-1}$ at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $\mathrm{c\bar{c}}$ and into exotic particles are set to their SM values.

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

Remarks and key messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as $H\gamma\gamma$, $H\mu\mu$, $HZ\gamma$, Htt

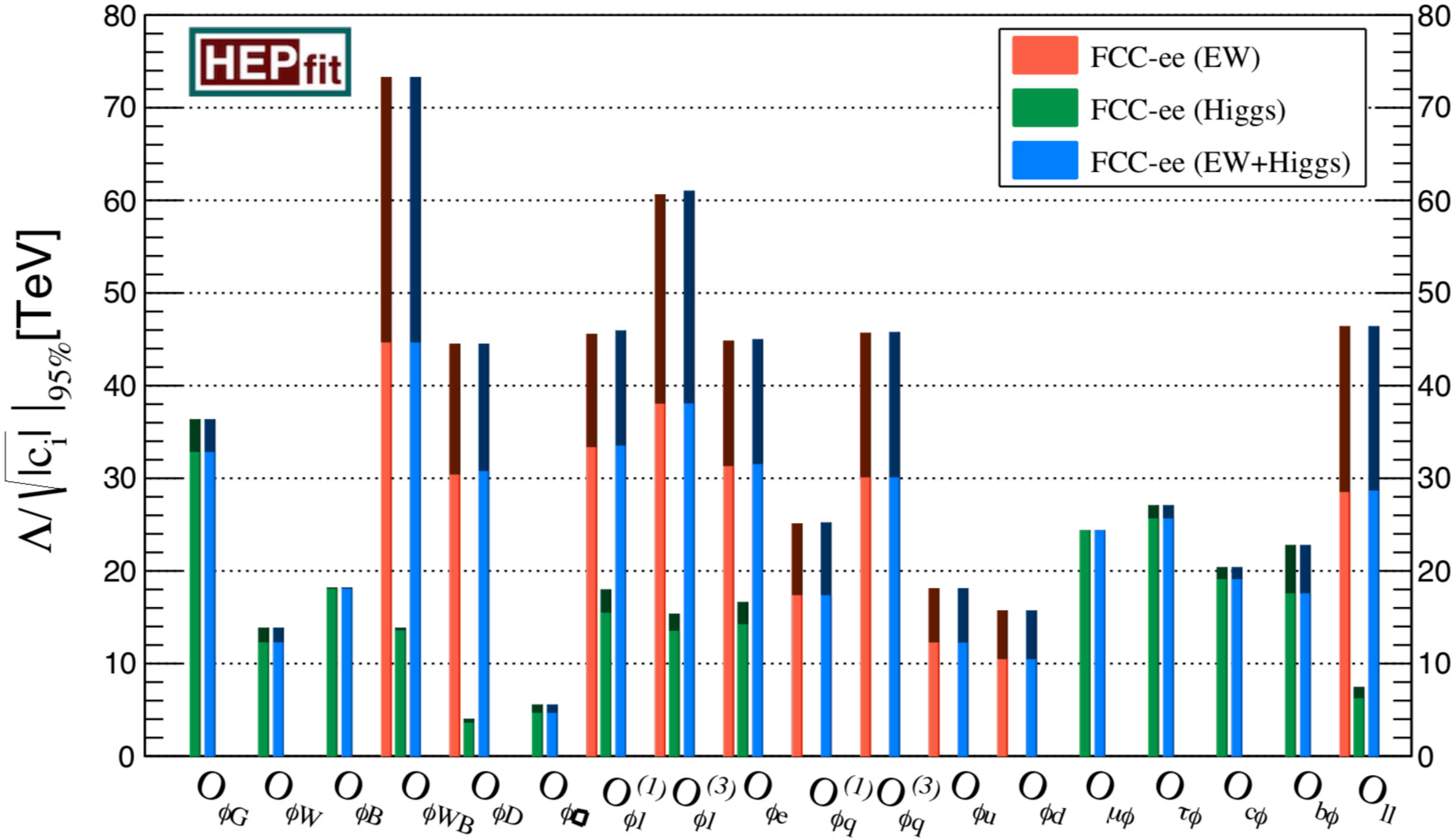
EW parameters @ FCC-ee

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z (×10³)	20767±25	0.06	0.2-1.0
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6
R_b (×10⁶)	216290±660	0.3	<60
σ^0_{had} (×10³) (nb)	41541±37	0.1	4
N_ν (×10³)	2991±7	0.005	1
$\sin^2\theta_W^{\text{eff}}$ (×10⁶)	231480±160	3	2-5
$1/\alpha_{\text{QED}}(m_Z)$ (×10³)	128952±14	4	Small
$A_{\text{FB}}^{b,0}$ (×10⁴)	992±16	0.02	1-3
$A_{\text{FB}}^{\text{pol},\tau}$ (×10⁴)	1498±49	0.15	<2
m_W (MeV)	80350±15	0.6	0.3
Γ_W (MeV)	2085±42	1.5	0.3
α_s (m_W) (×10⁴)	1170±420	3	Small
N_ν(×10³)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

On the role of measurement

- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, it's about finding out how things work
- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … but who knows how important a given measurement can become, to assess the validity of a future theory?
  - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

Global EFT fits to EW and H observables at FCC-ee



Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

Remarks and key messages

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations

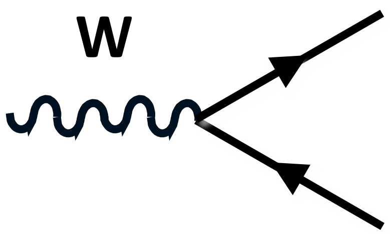
1. An ee Higgs factory needs to operate at the Z pole and WW threshold to maximize the potential of precision measurements of the EW sector

- EW&Higgs precision measurements at future ee colliders could probe scales as large as several 10's of TeV ($c_i \sim 1 \div 4\pi$)

2. To directly explore the origin of possible discrepancies, requires collisions in the several 10s of TeV region
3. A 100-TeV pp collider is a natural, and likely required, extension of an ee facility

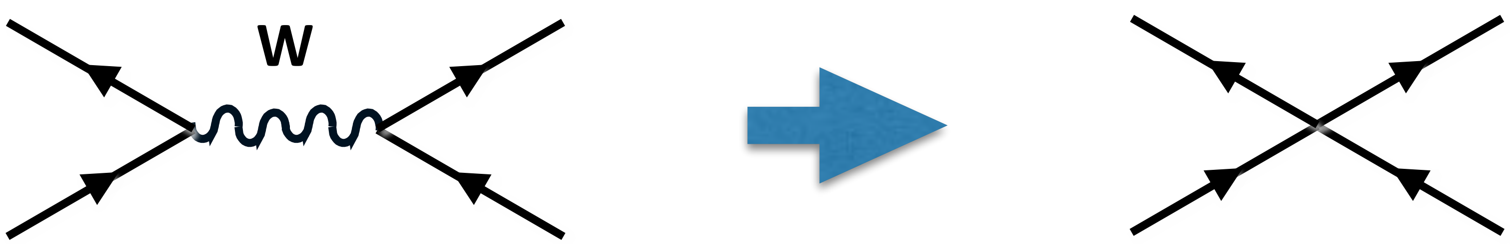
Remark on interpretation of EFT bounds

Example: weak interactions



$$\frac{g}{\sqrt{2}}\overline{\Psi}\gamma_\mu\Psi_L$$

At low energy:



$$\frac{g^2}{2M_W^2}\,\overline{\Psi}\gamma_\mu\Psi_L\;\overline{\Psi}\gamma_\mu\Psi_L$$

$$\frac{c}{\Lambda^2} = \frac{g^2}{2M_W^2} = 2\sqrt{2}G_F = \frac{2}{v^2} = \frac{1}{(174\,\mathrm{GeV})^2}$$

versus

$$M_W = 80\,\mathrm{GeV}$$

The limits on c/Λ² are typically larger than the mass scale at which new physics appears

The unique contributions of a *100 TeV pp collider to Higgs physics*

- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition
    - …

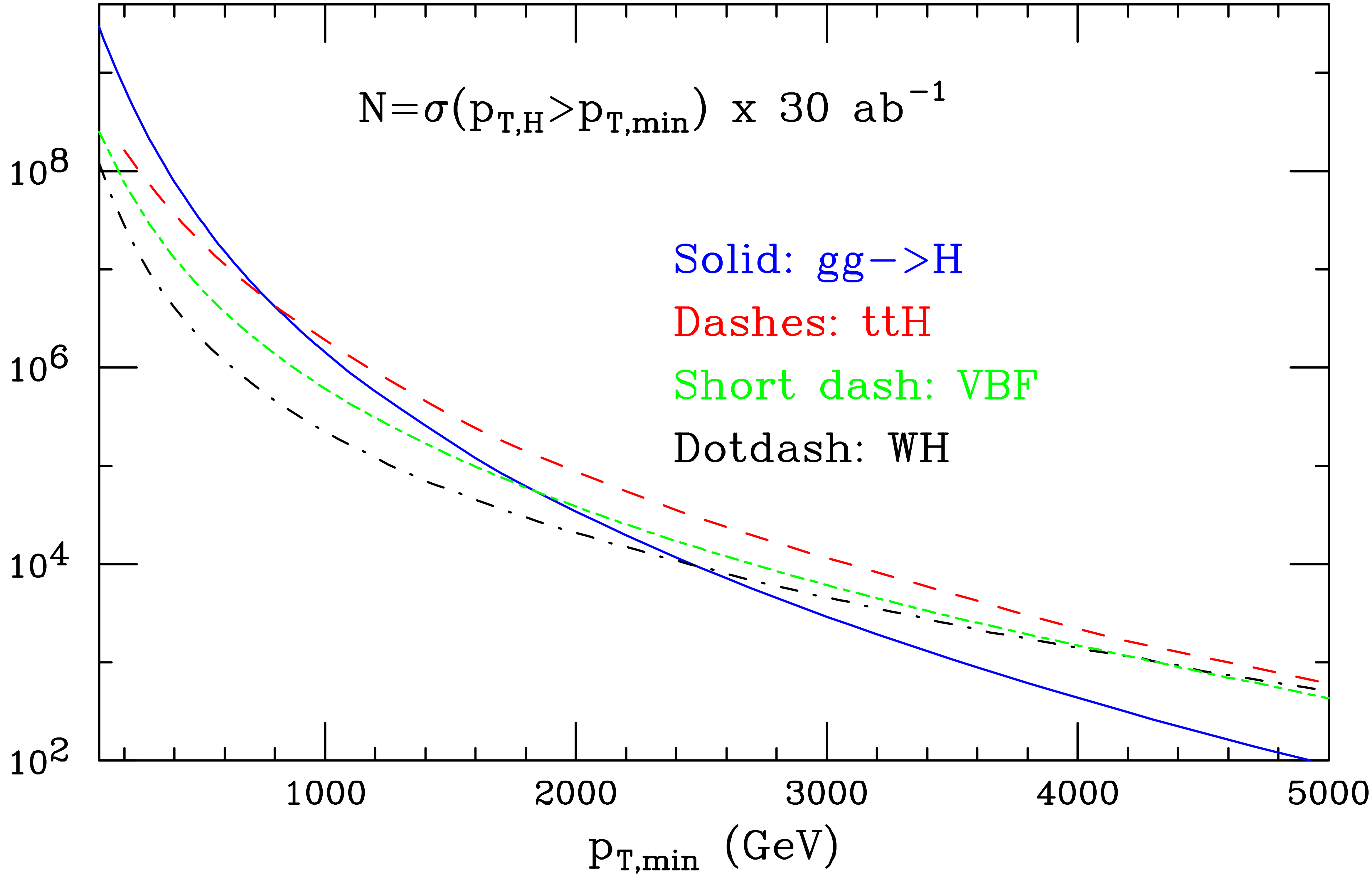
SM Higgs: event rates in pp@100 TeV

	$gg \to H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

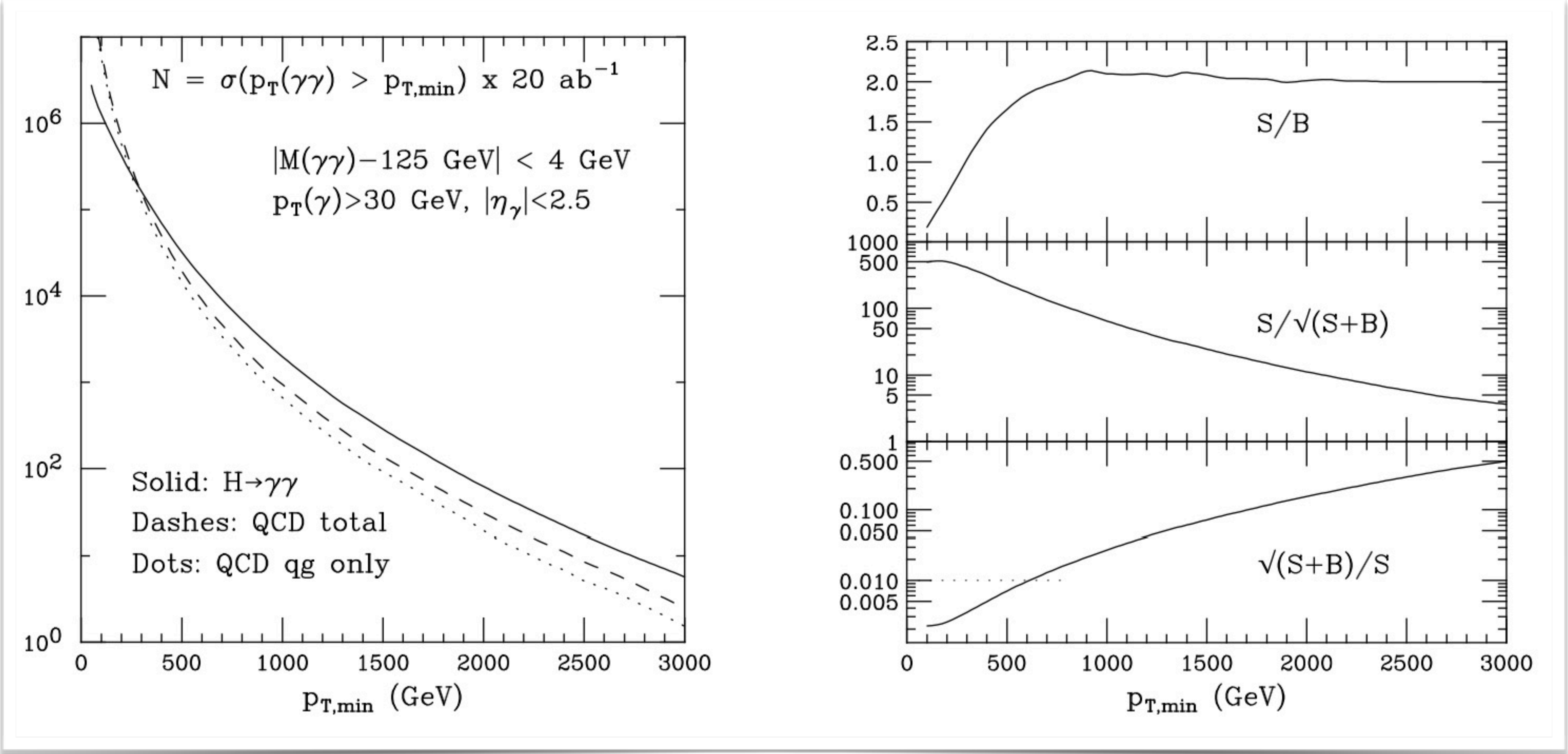
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg\to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg\to H)$ above 1800 GeV

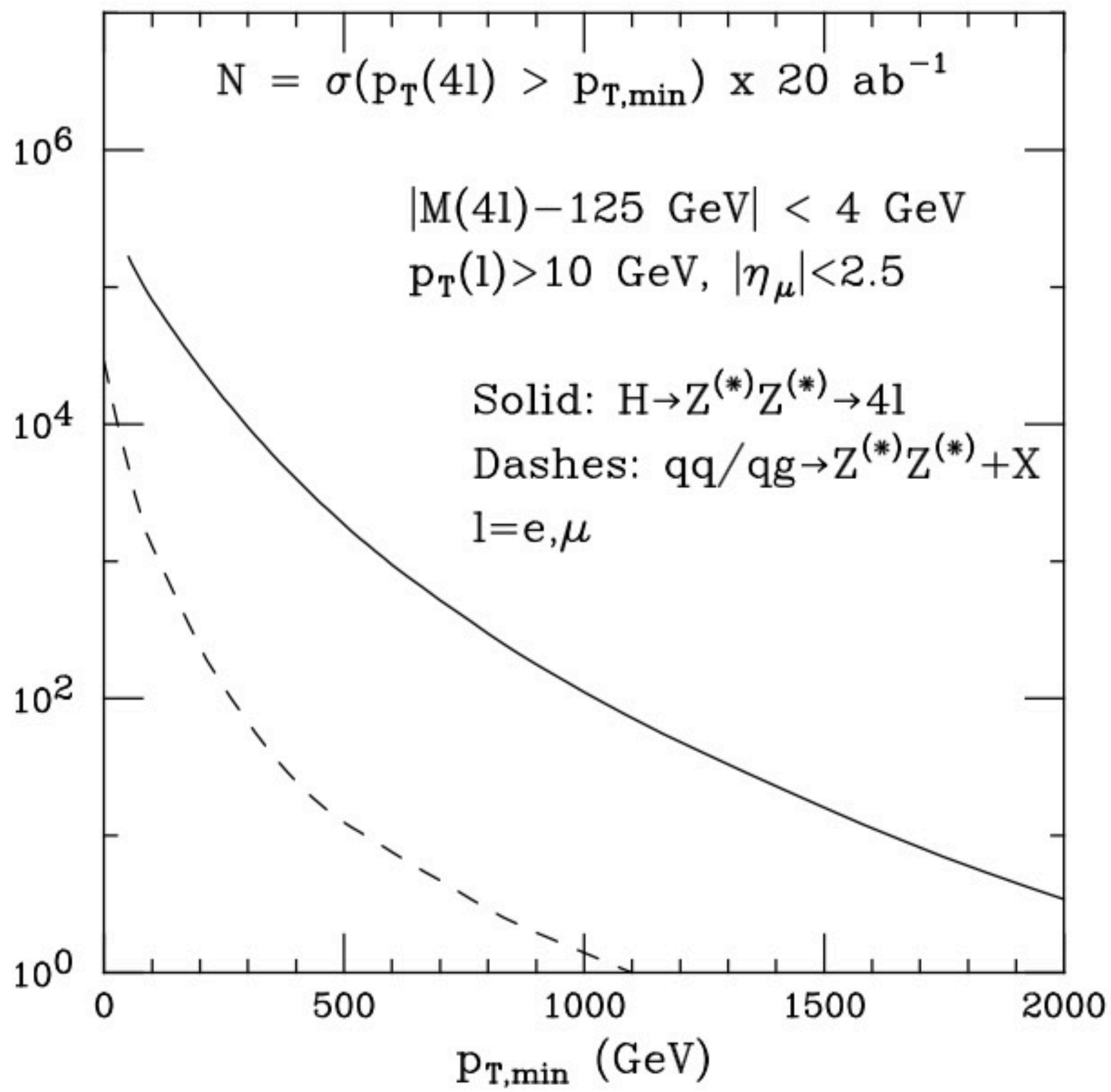
gg→H→γγ at large p_T

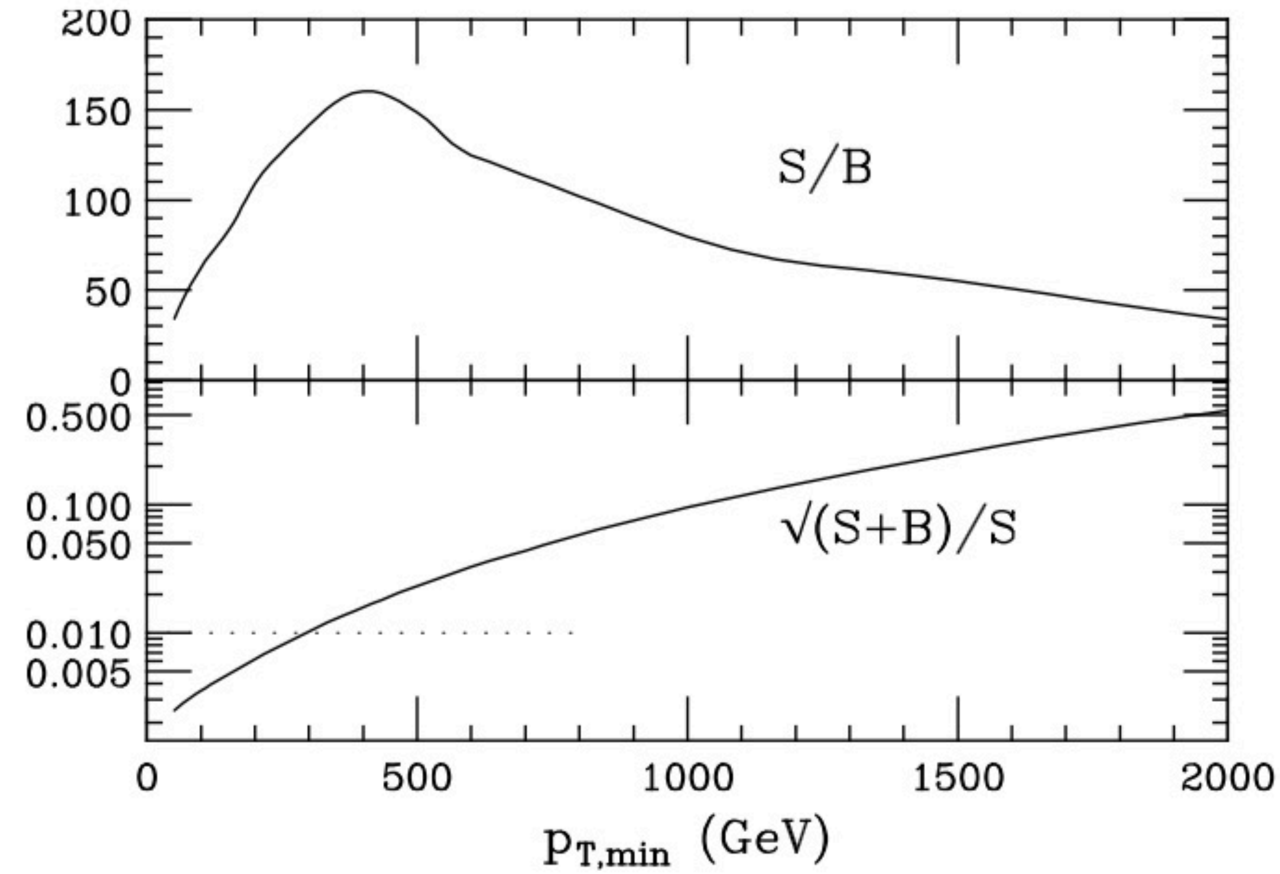


- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

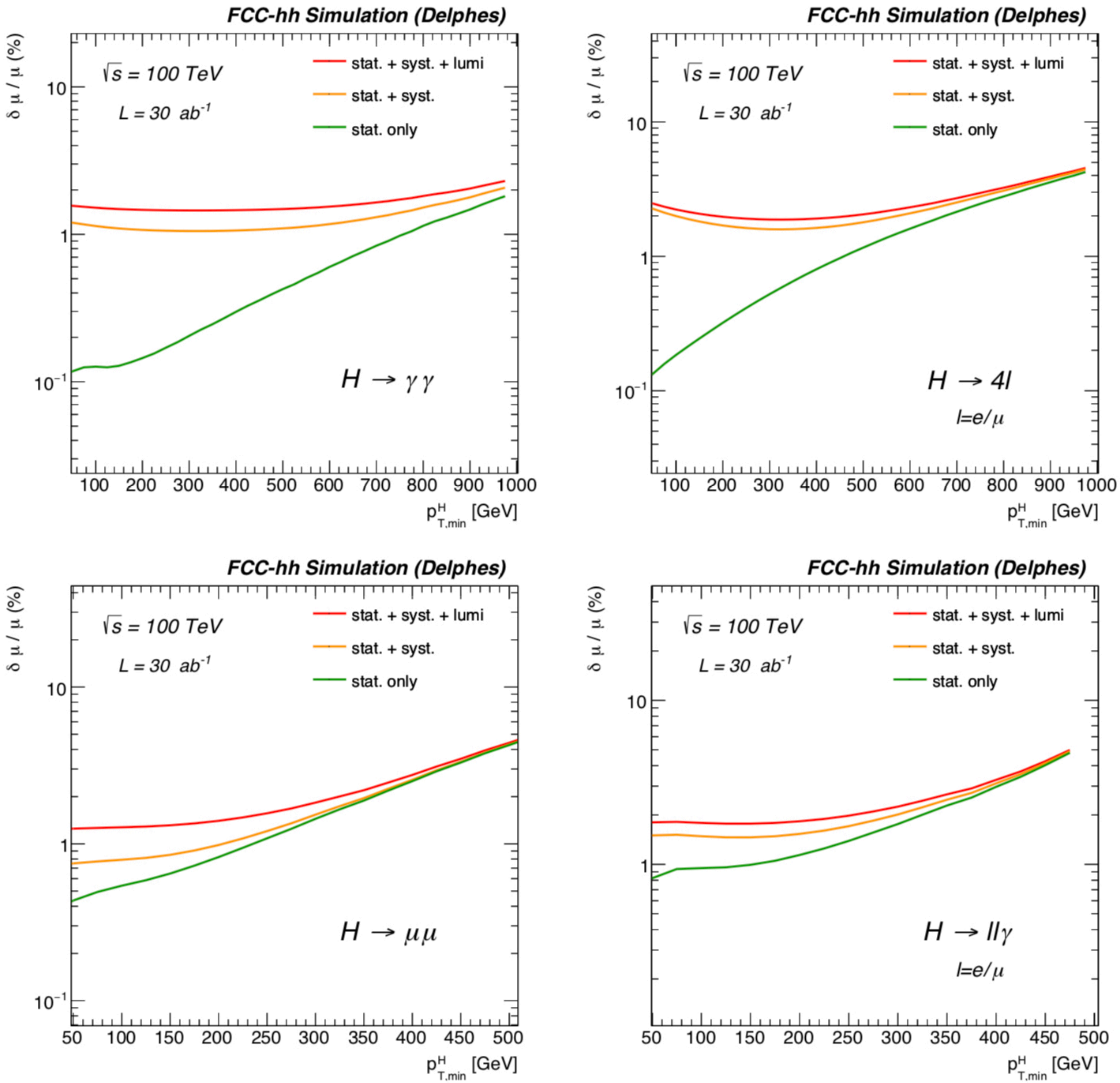
gg→H→ZZ*→4l at large p_T



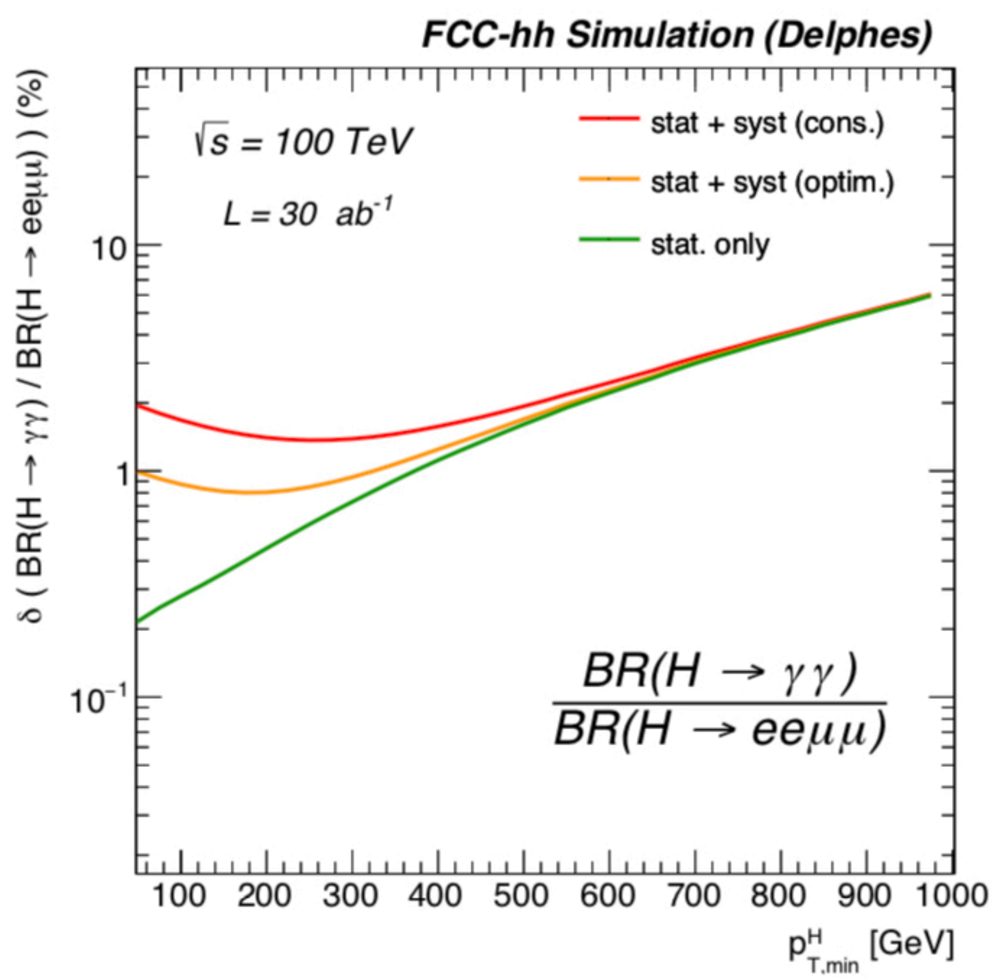


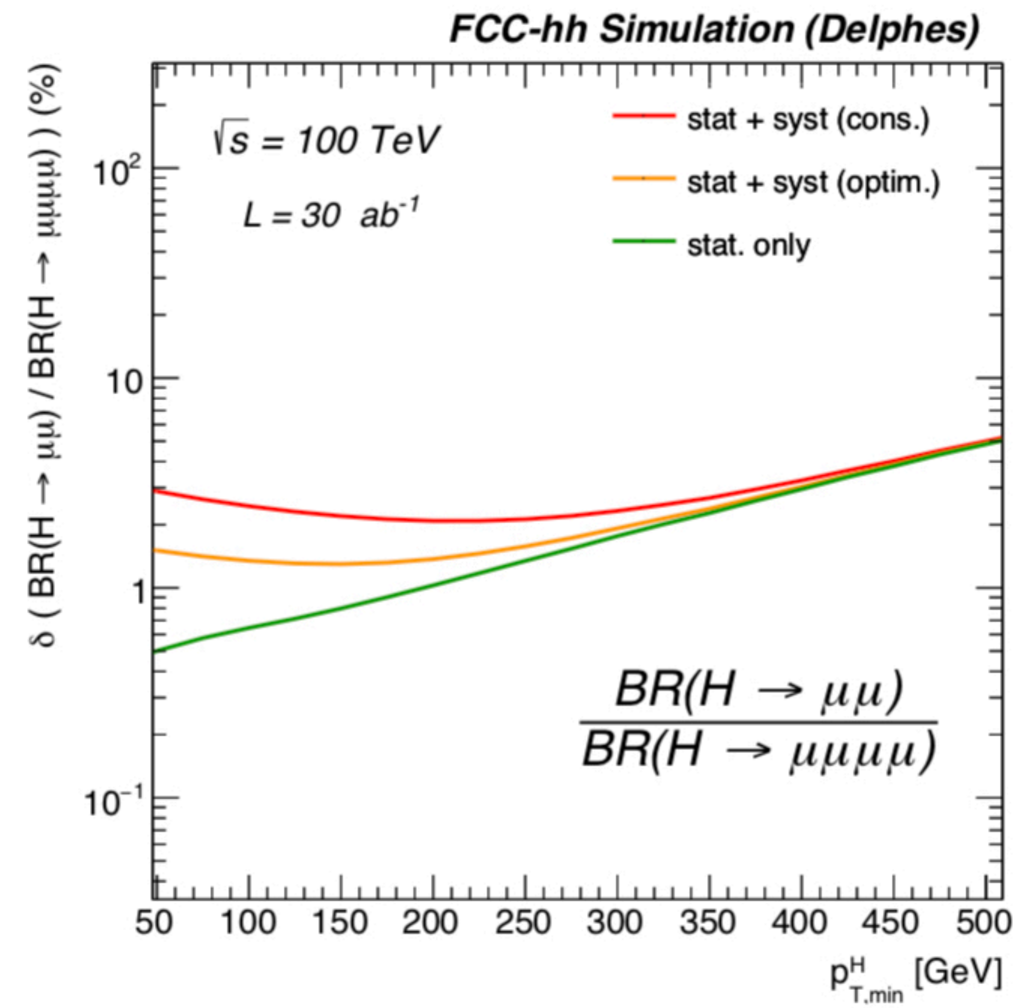
- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

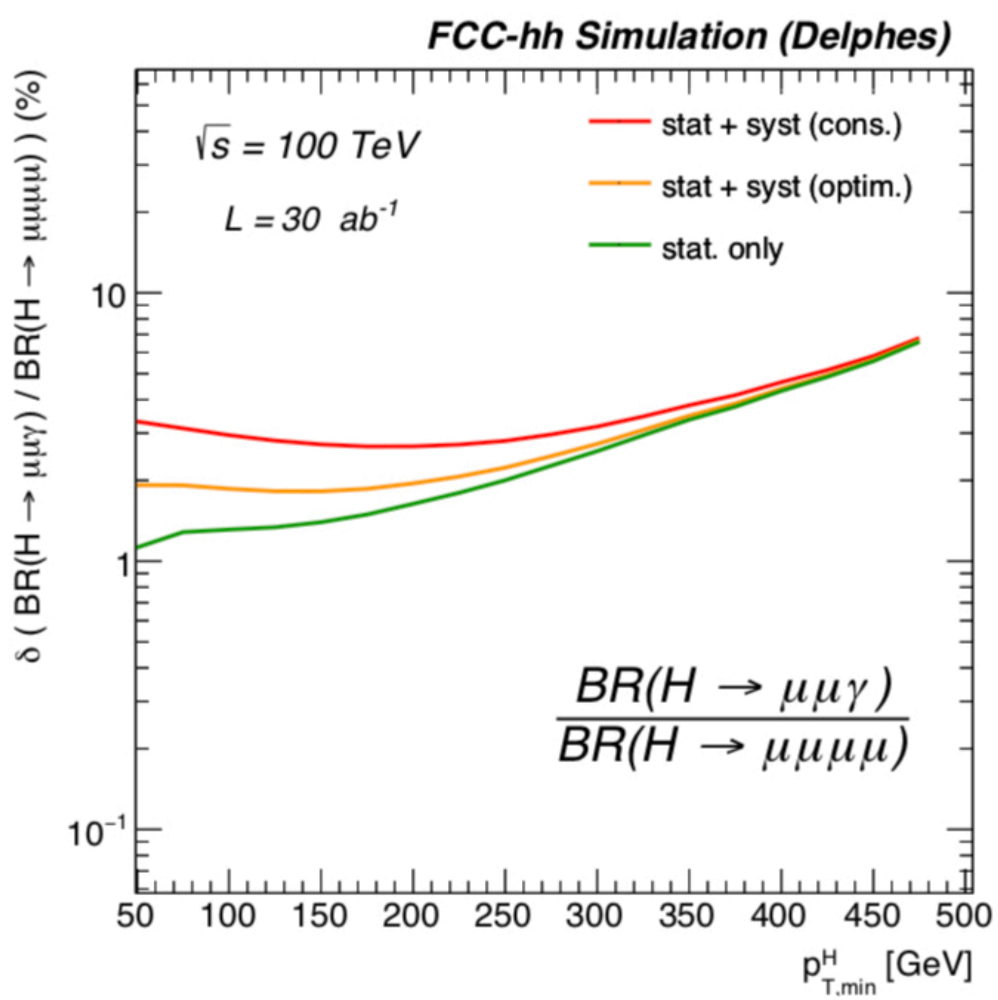
$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%



FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat. + syst. + lumi
stat. + syst.
stat. only
$H \rightarrow \gamma\gamma$
$H \rightarrow 4l$
$l=e/\mu$
$H \rightarrow \mu\mu$
$H \rightarrow ll\gamma$
$l=e/\mu$
$\delta\mu / \mu$ (%)
$p^{H}_{T,min}$ [GeV]

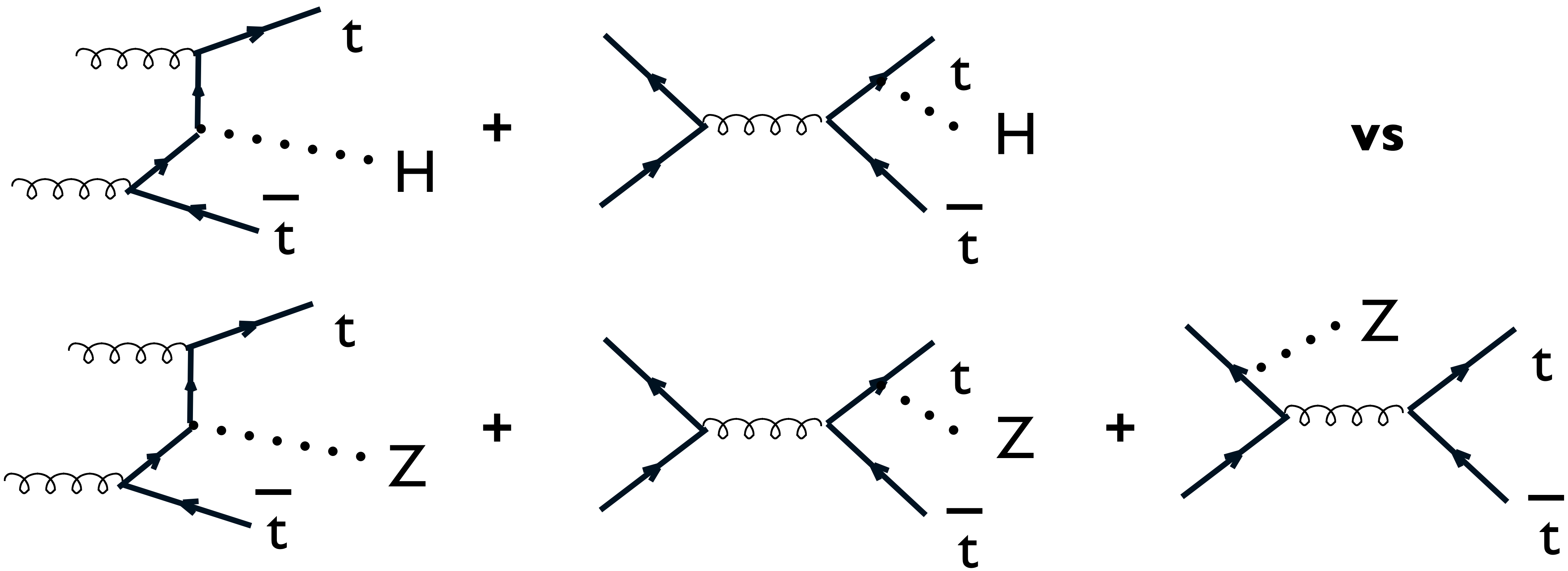

FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \gamma\gamma)}{BR(H \to ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu\gamma)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
$p_{T,min}^{H}$ [GeV]

Top Yukawa coupling from σ(ttH)/σ(ttZ)

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:

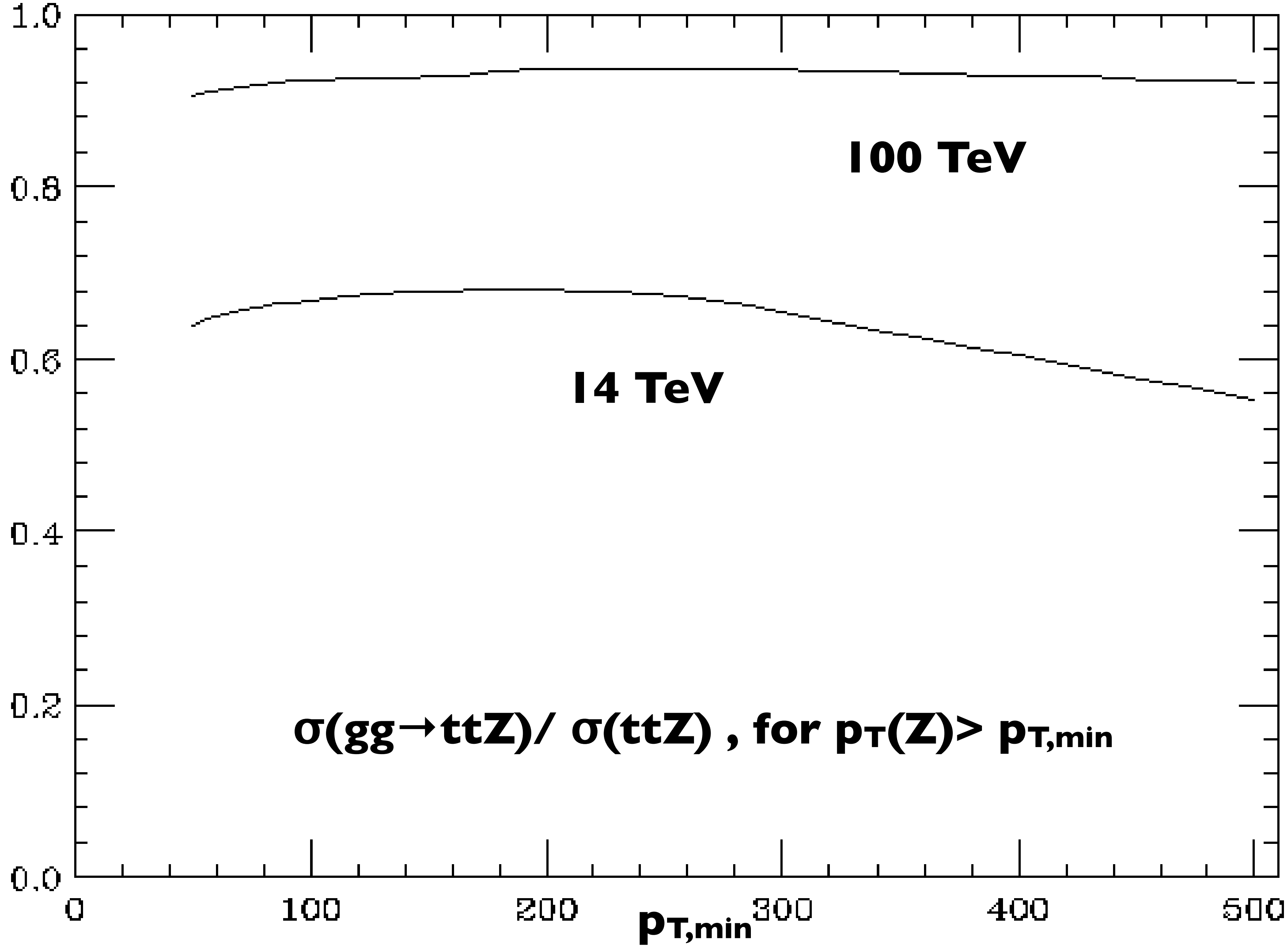
o correlated QCD corrections, correlated scale dependence
o correlated α_S systematics

- $m_Z \sim m_H$ ⇒ almost identical kinematic boundaries:

o correlated PDF systematics
o correlated m_{top} systematics

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

At 100 TeV, gg→tt X is indeed dominant ....



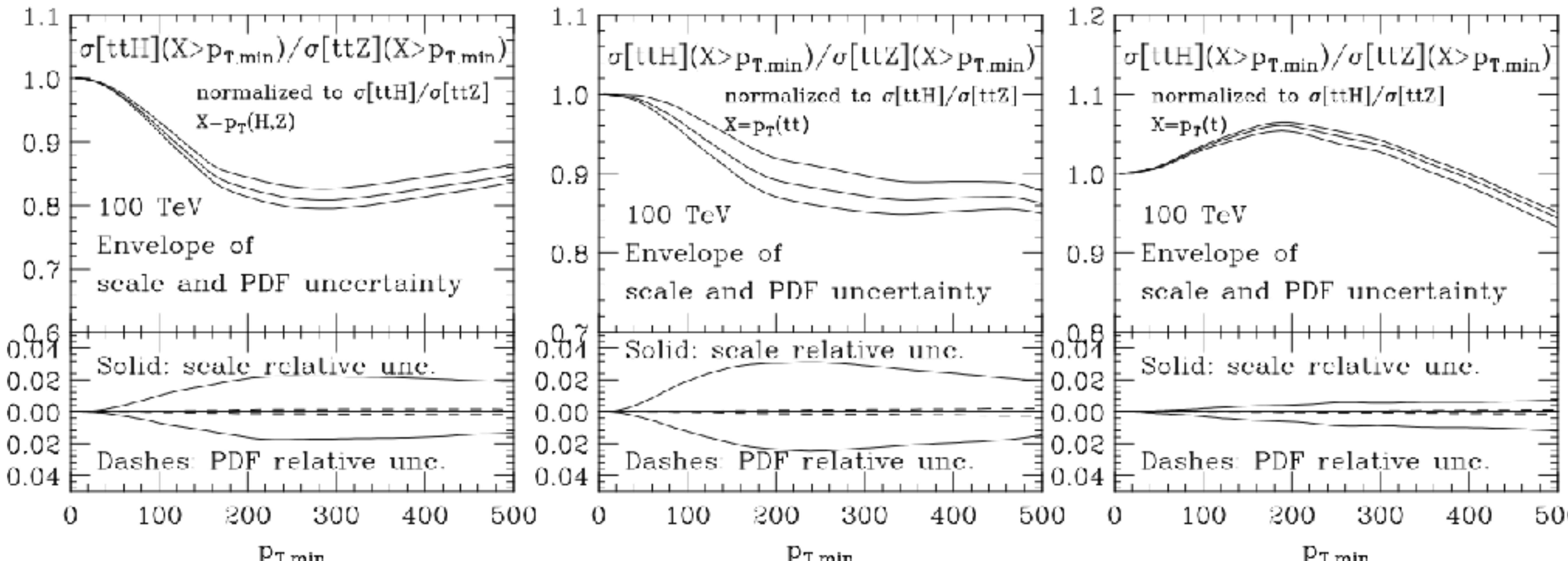
NB: At lower p_T values, gg fraction is slightly larger for ttZ than for ttH, since $m_Z < m_H$

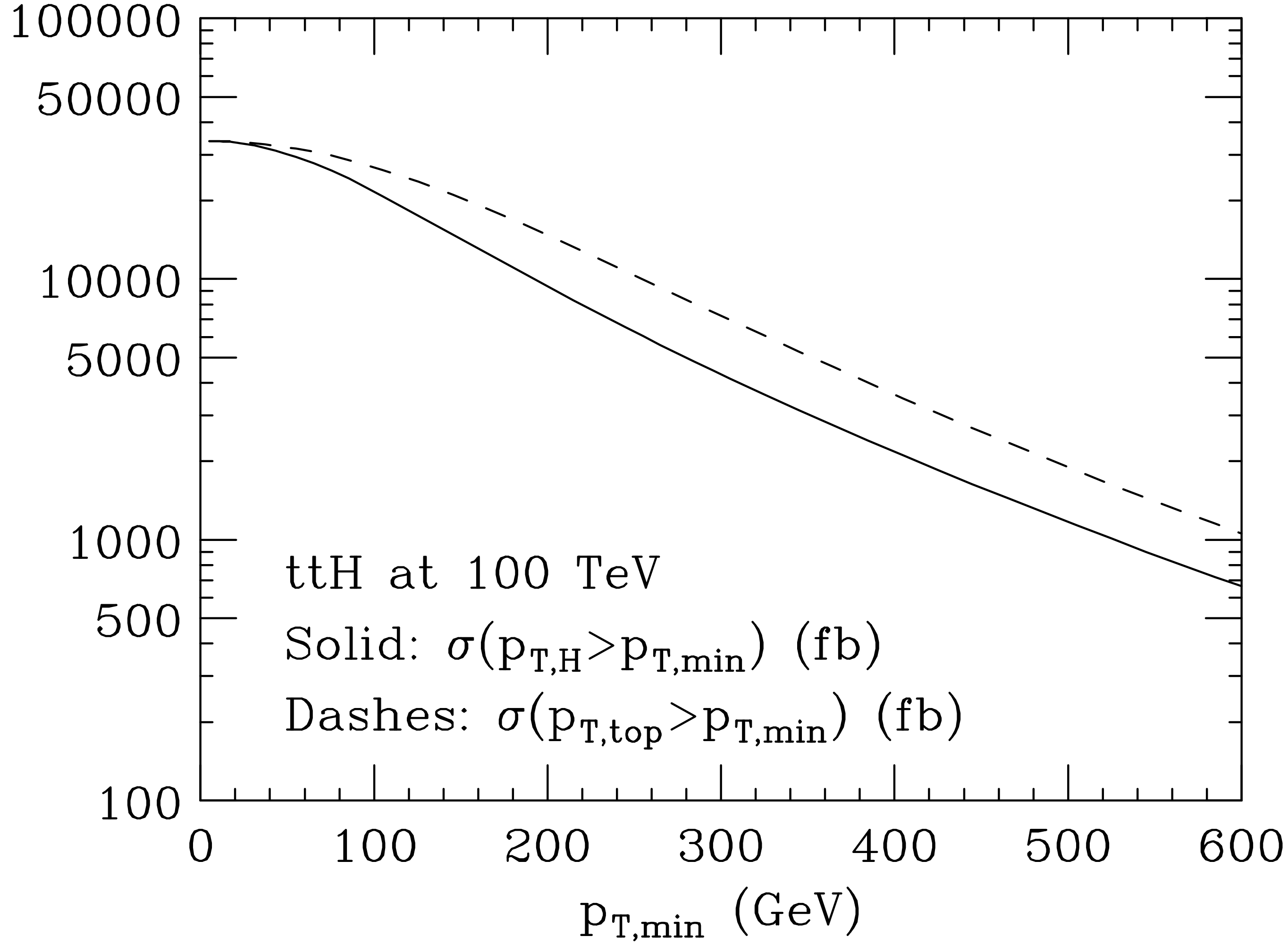
Cross section ratio stability

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

scale PDF

Production kinematics ratio stability





$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

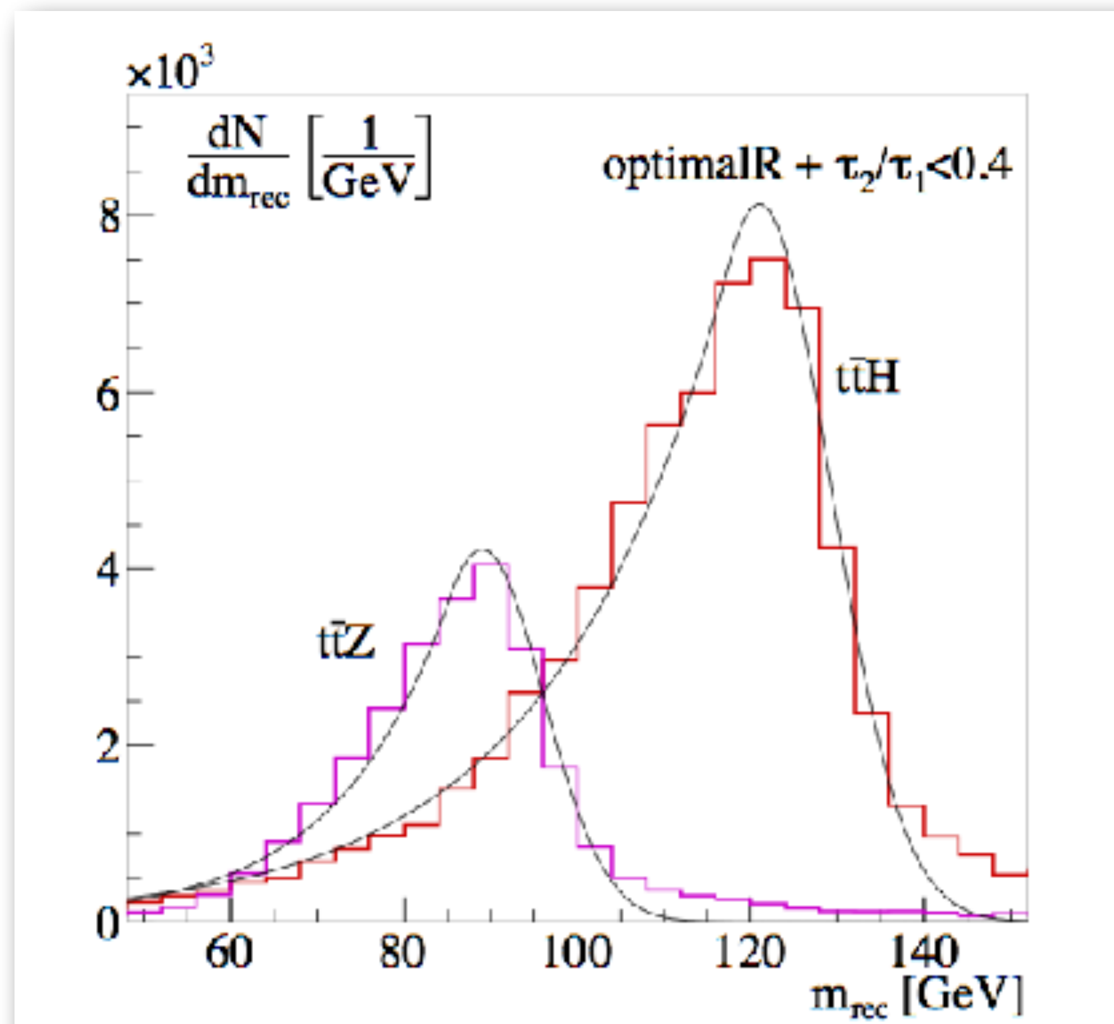
Events/20ab^{-1} , with tt→$\ell\nu$+jets

⇒ huge rates, exploit boosted topologies

Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

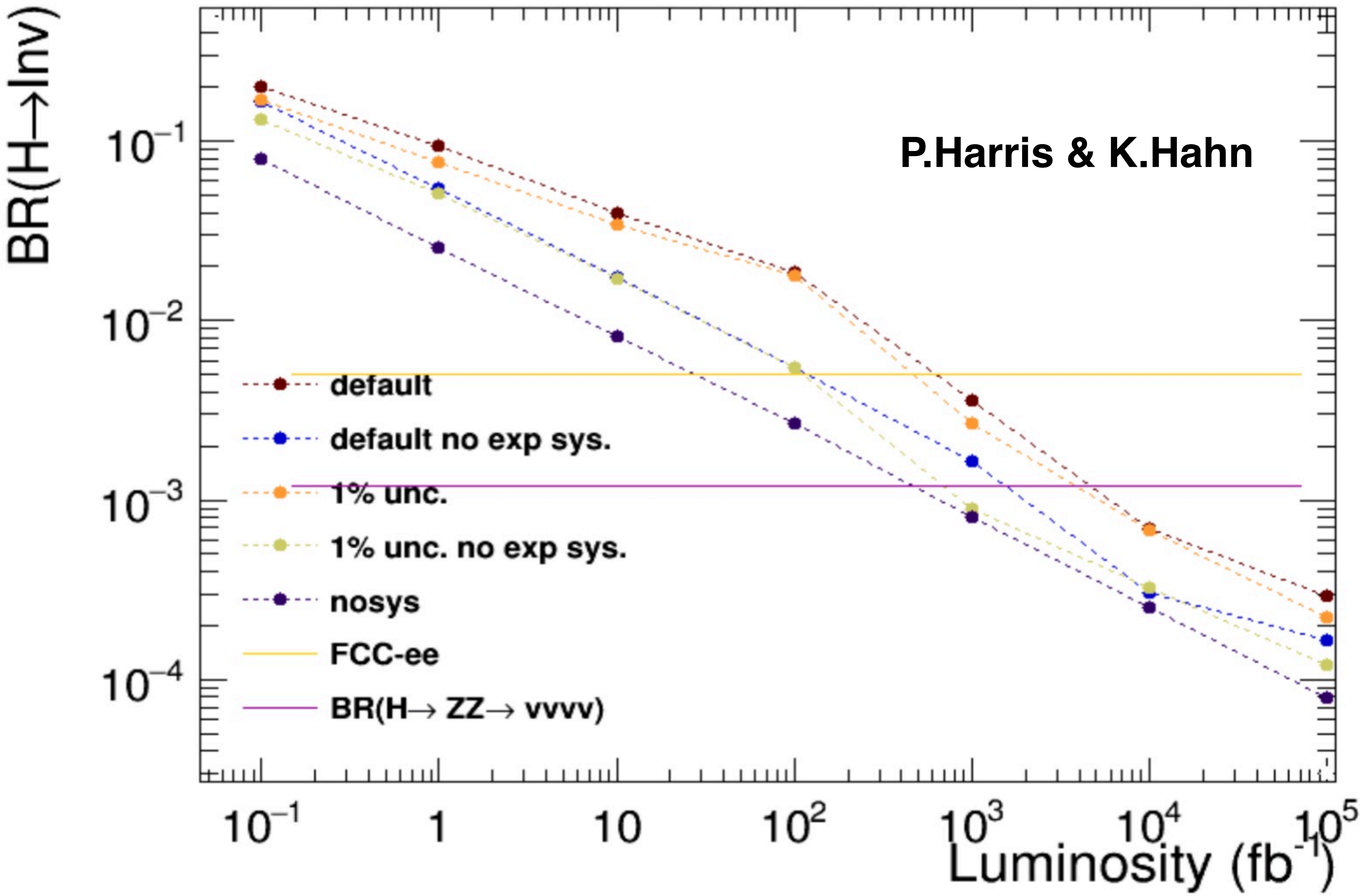
- δy_t (stat + syst $_{TH}$) ~ 1%

- great potential to reduce to similar levels $\delta_{exp\ syst}$
- consider other decay modes, e.g. 2l2nu



BR(H→inv) in H+X production at large $p_T(H)$

Constrain bg pt spectrum from $Z \to \nu\nu$ to the % level using NNLO QCD/EW to relate to measured $Z \to ee$, W and γ spectra



SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

Higgs couplings (κ fit): HL-LHC → FCC-ee → hh

	HL-LHC(§)	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM(§§)	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**6.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

§ M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, Higgs Physics at the HL-LHC and HE-LHC, arXiv:1902.00134

§§ SM width assumed in the global fit. Will be measured to ~20% (68%CL) via off-shell H->4l, to ~5% (95%CL) from global fit of Higgs production cross sections.

* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Importance of standalone precise "ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

$BR(H\to\gamma\gamma)/BR(H\to ZZ^*)$

loop-level tree-level

$BR(H\to\mu\mu)/BR(H\to ZZ^*)$

2nd gen'n Yukawa gauge coupling

$BR(H\to\gamma\gamma)/BR(H\to Z\gamma)$

different EW charges in the loops of the two procs

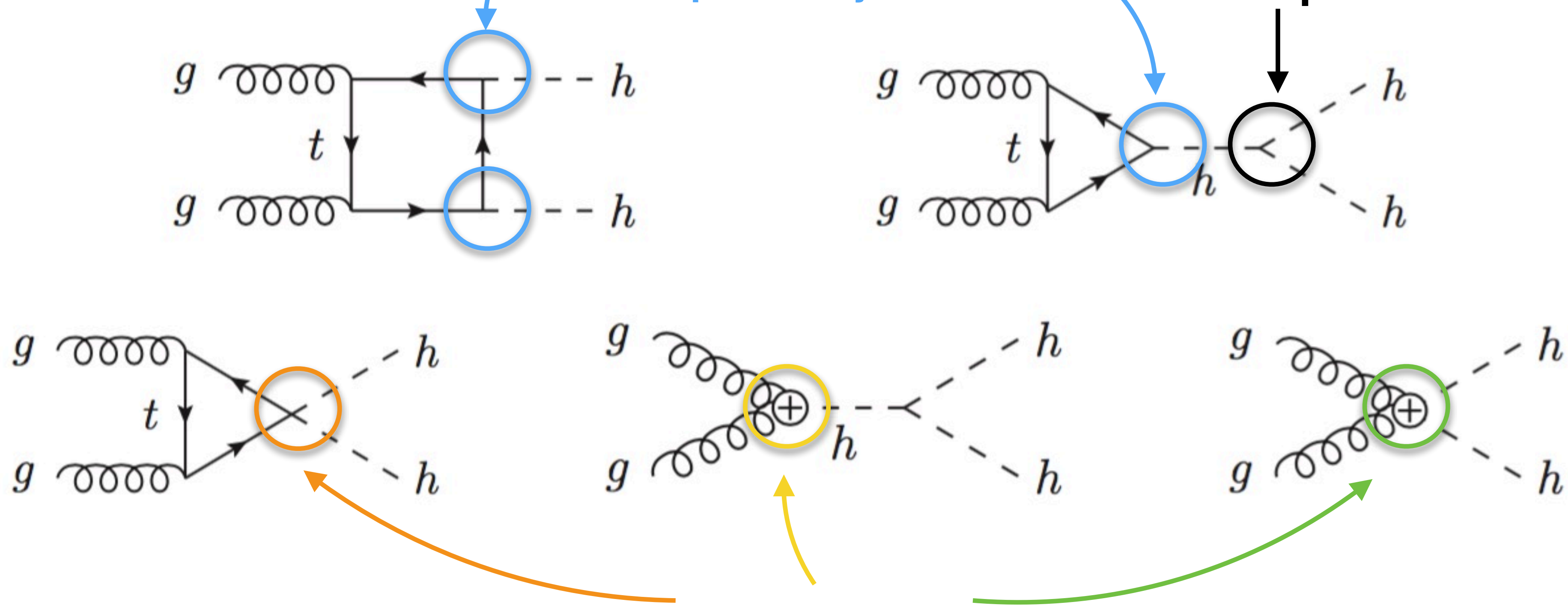
$BR(H\to inv)/BR(H\to\gamma\gamma)$

tree-level neutral loop-level charged

Extracting Higgs self-coupling from gg→HH at FCC-hh

… these we must assume, or measure independently

this we want to probe …

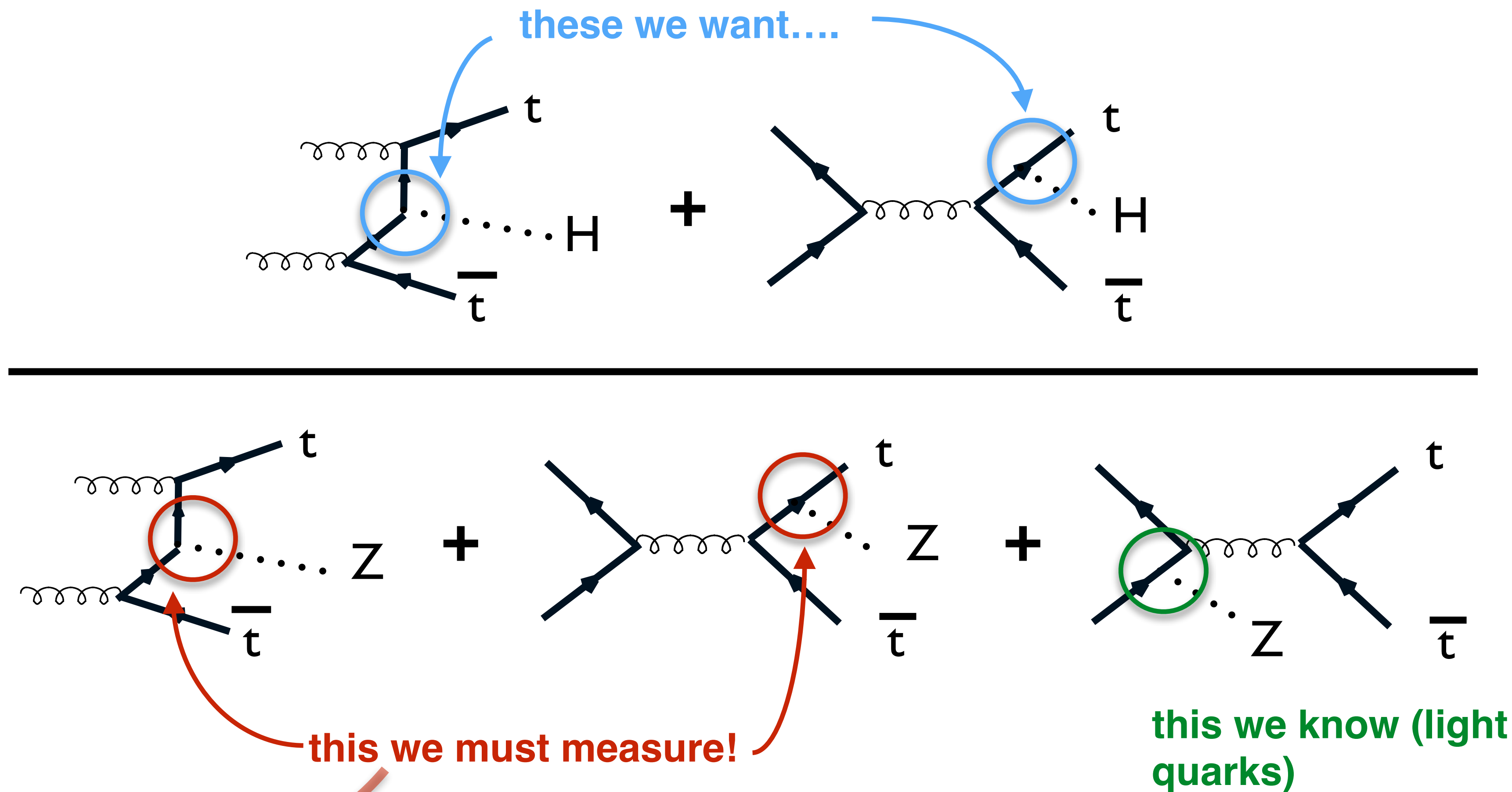


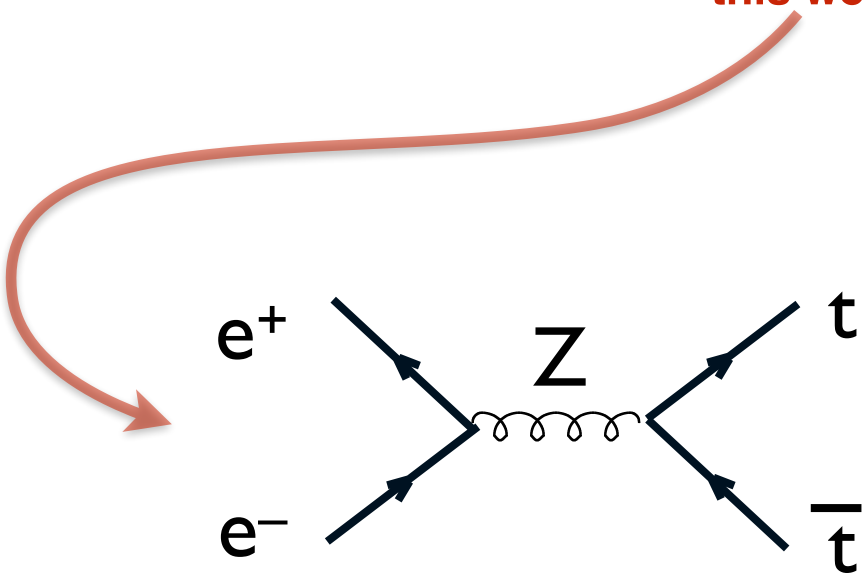
… these would come into play if we eventually need to decode the origin of a deviation, as possible alternative sources of new physics

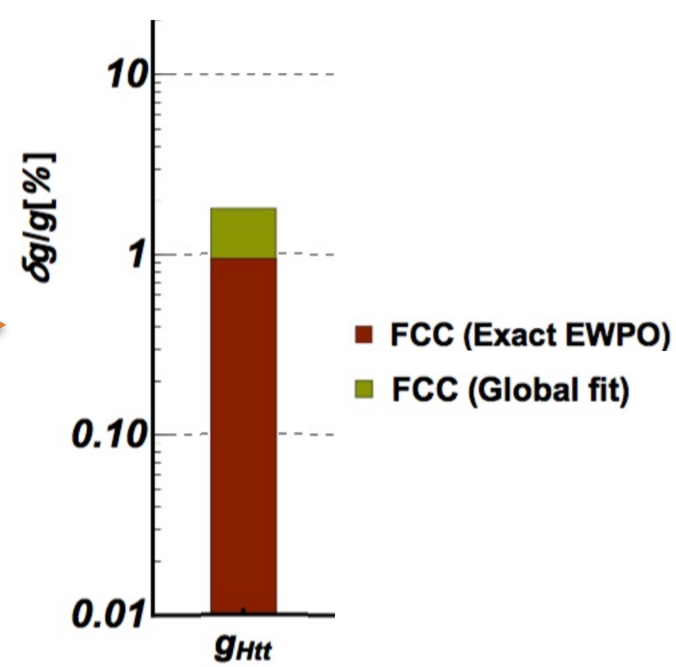
Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

FCC-hh can measure R_t with $\Delta R_t/R_t \sim 2\%$

$R_t =$







$\delta\lambda/\lambda$=5% from gg→HH assuming SM inputs

$\delta\lambda/\lambda$ ~ 10% from global fit

Higgs self-coupling, gg→HH

From the detector performance studies: | Pheno-level studies:

	bbγγ	bbZZ[→4l]	bbWW[→2jlν]	4b+j	2b2τ+j
$\delta\kappa_\lambda$ (%)	6.5	14	40	30	8

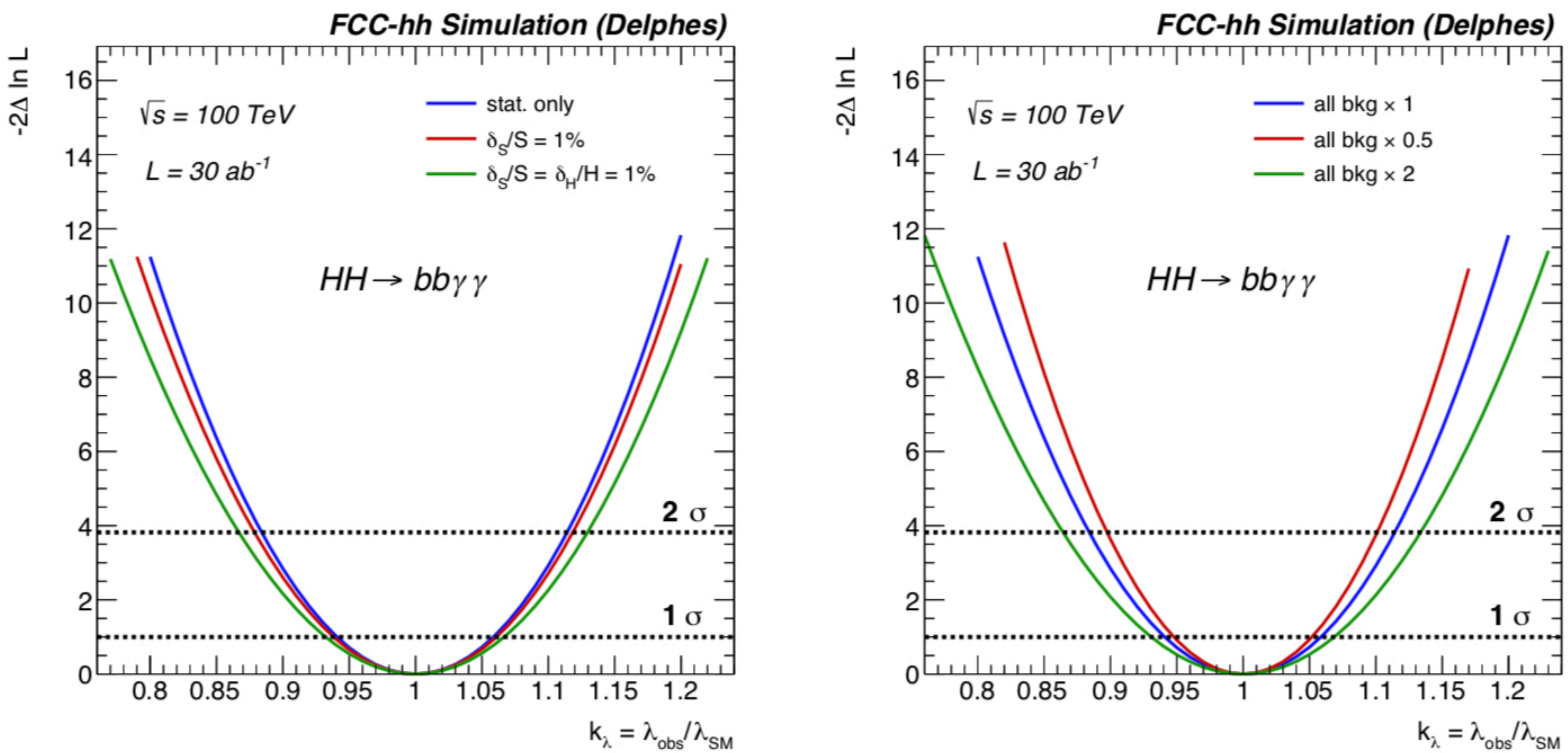
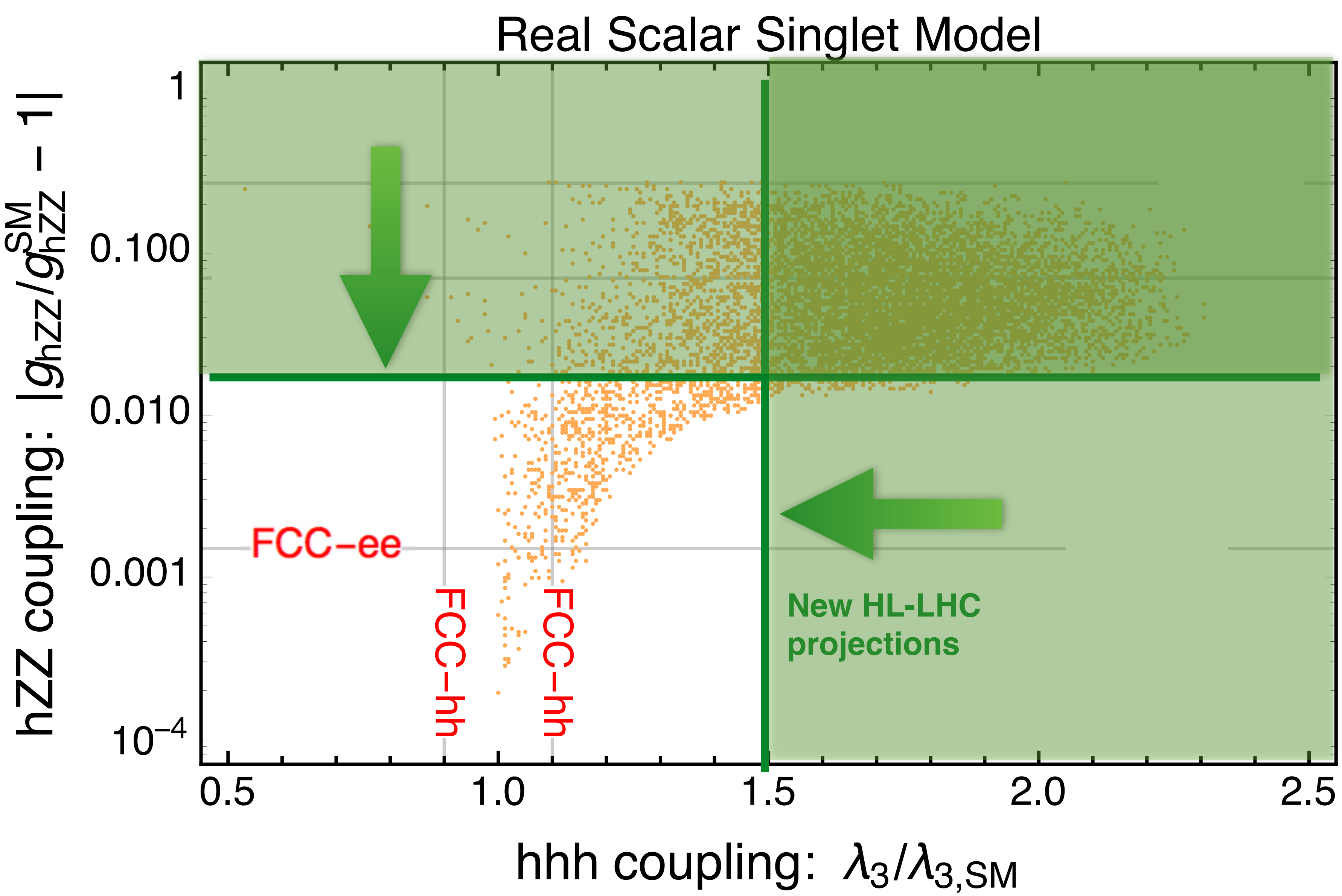


Figure 10.4: Expected precision on the Higgs self-coupling modifier κ_λ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively $\times 1$, $\times 2$, $\times 0.5$ background yields (right).)

Constraints on models with 1st order phase transition: after the HL-LHC

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

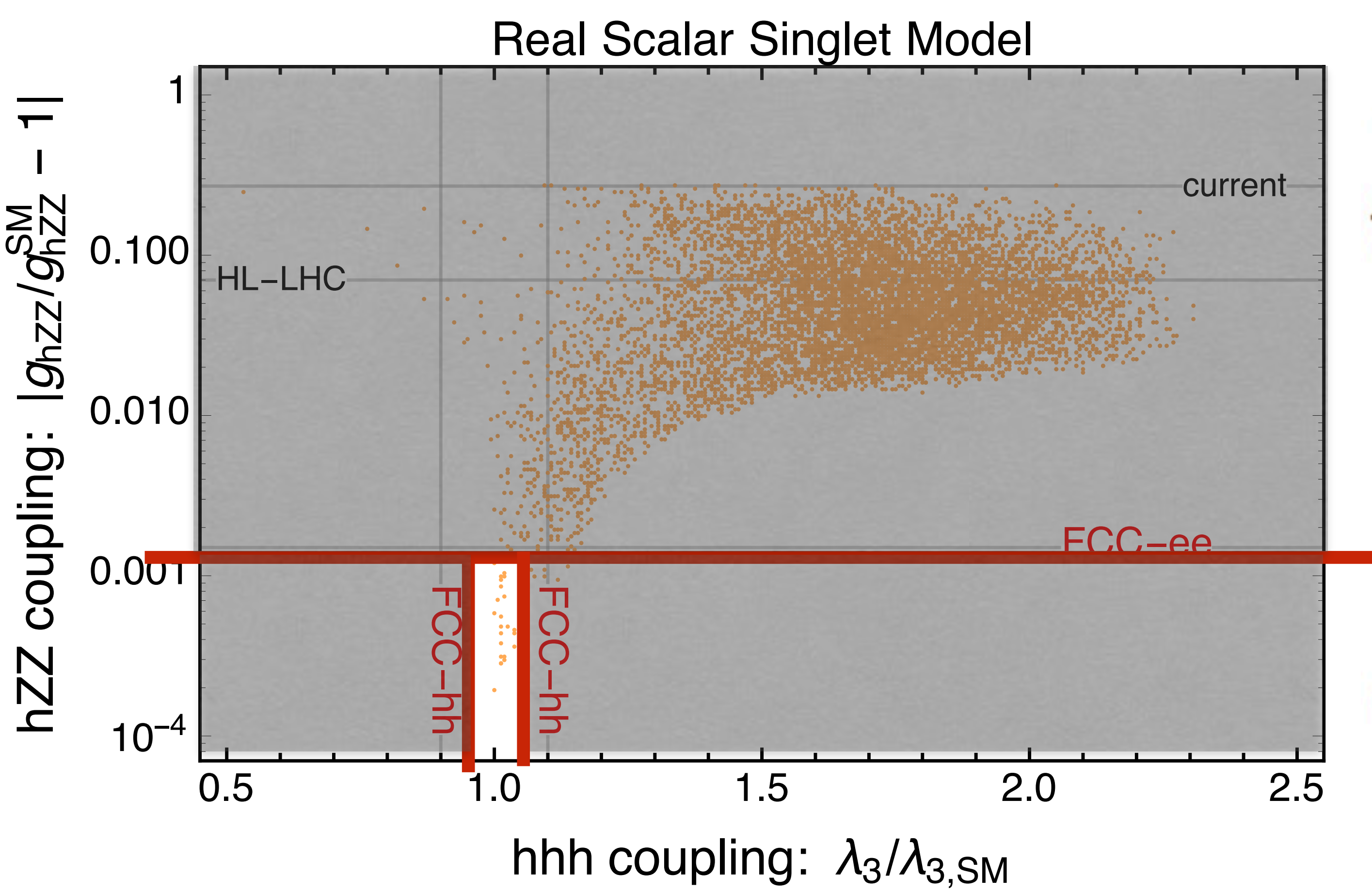


Bringing the HL-LHC sensitivity to the ±50% level, makes a big dent in this class of BSM models!

Constraints on models with 1st order phase transition: after the FCC

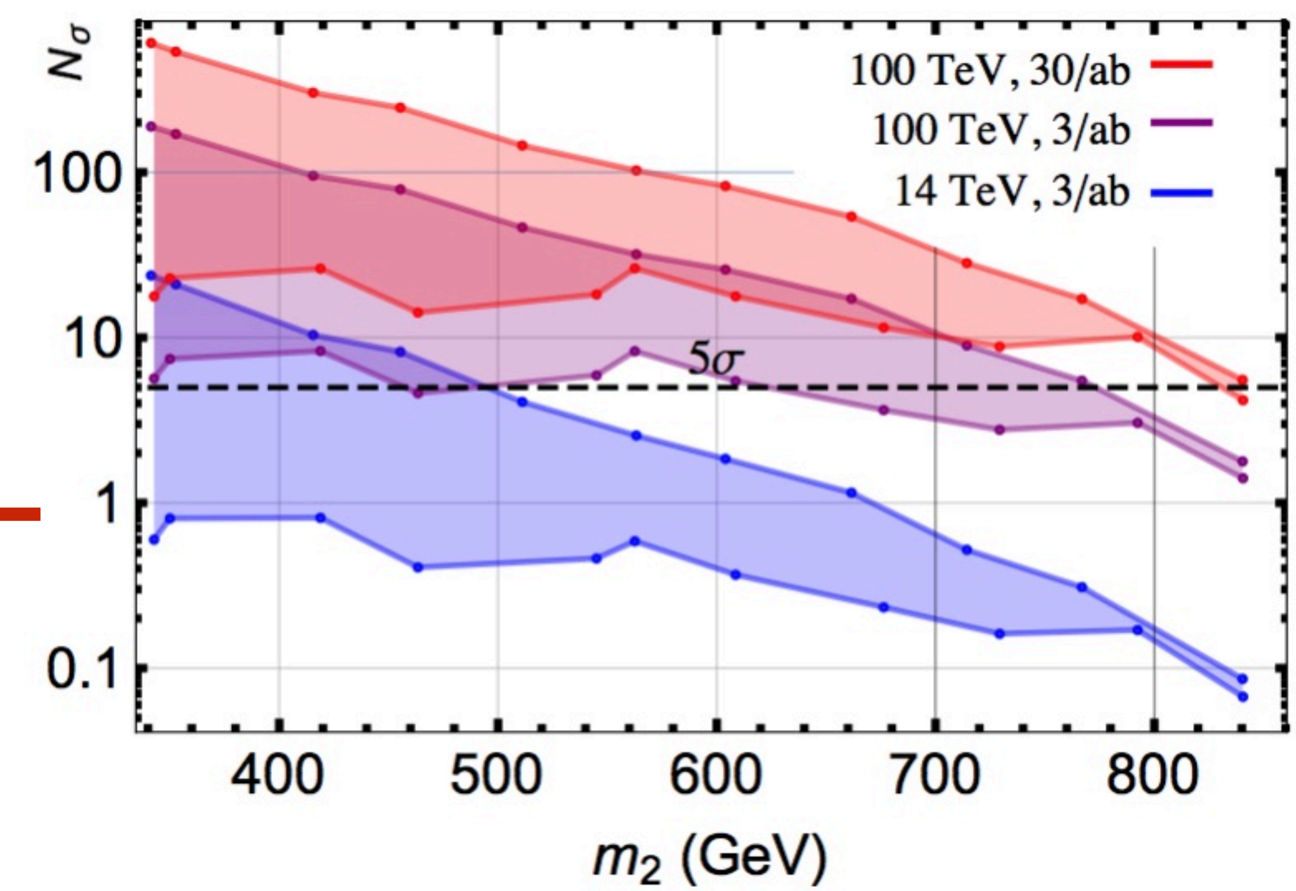
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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.

Direct detection of extra Higgs states at FCC-hh



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

$(h_2 \sim S, \quad h_1 \sim H)$

Precision vs sensitivity

- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- ***Sensitivity*** may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

High-Q^2 observables : precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = | \langle f|L|i\rangle |^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

$\Rightarrow$ **precision** probes large Λ

e.g. δO=1% $\Rightarrow$ $\Lambda \sim$ 2.5 TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

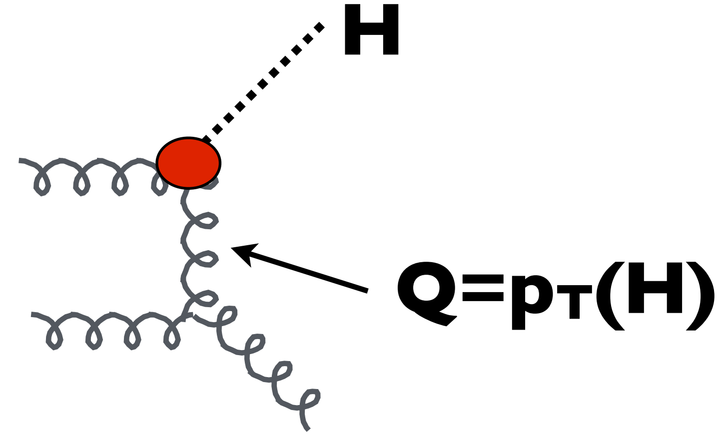
$\Rightarrow$ **kinematic reach** probes large Λ even if precision is "low"

e.g. δO=10% at Q=1.5 TeV $\Rightarrow$ Λ~5 TeV

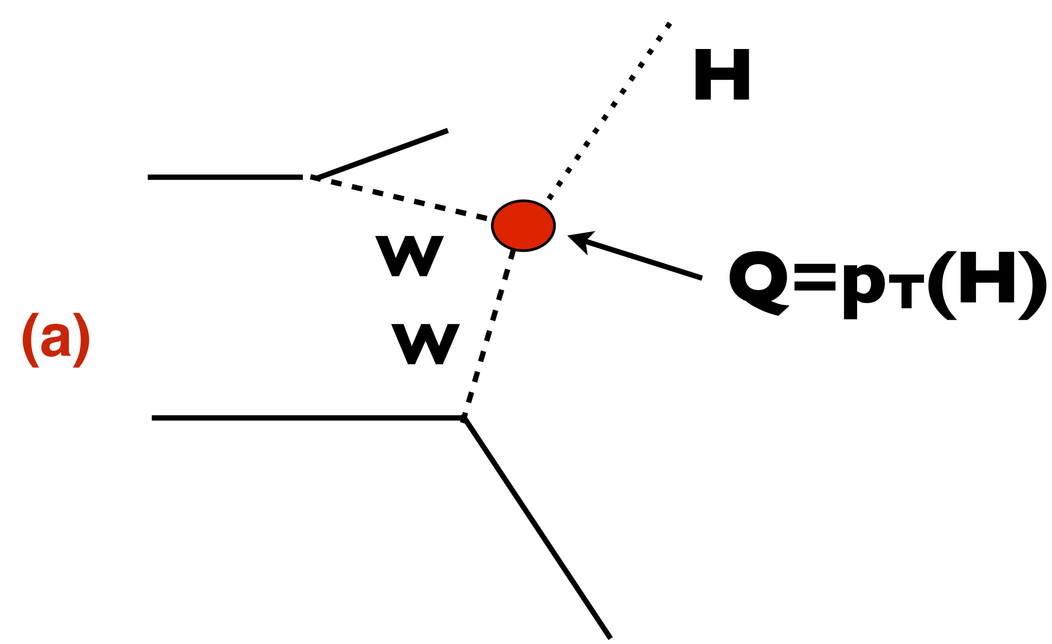
Complementarity between precise measurements at ee collider and large-Q studies at 100 TeV

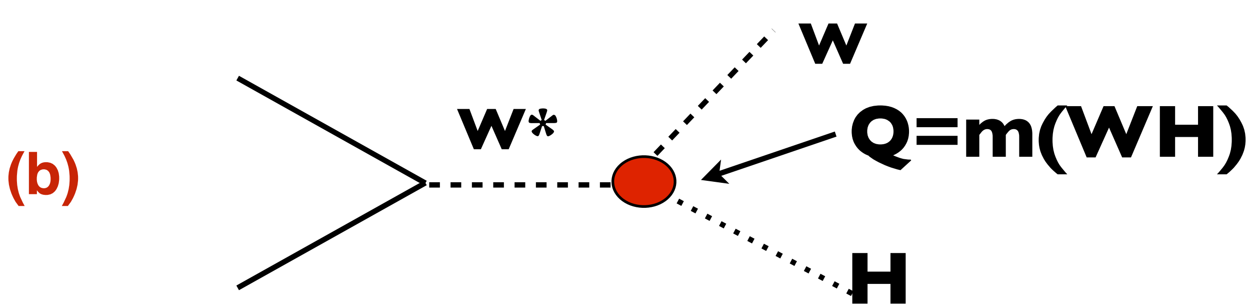
Examples

$\delta BR(H \to gg)$



$\delta BR(H \to WW^*)$

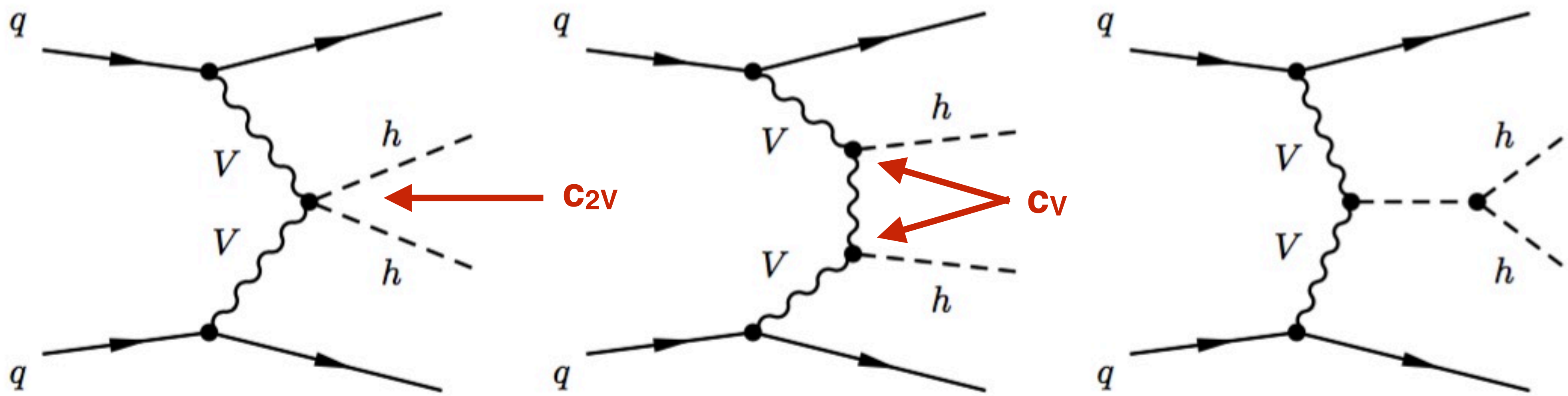




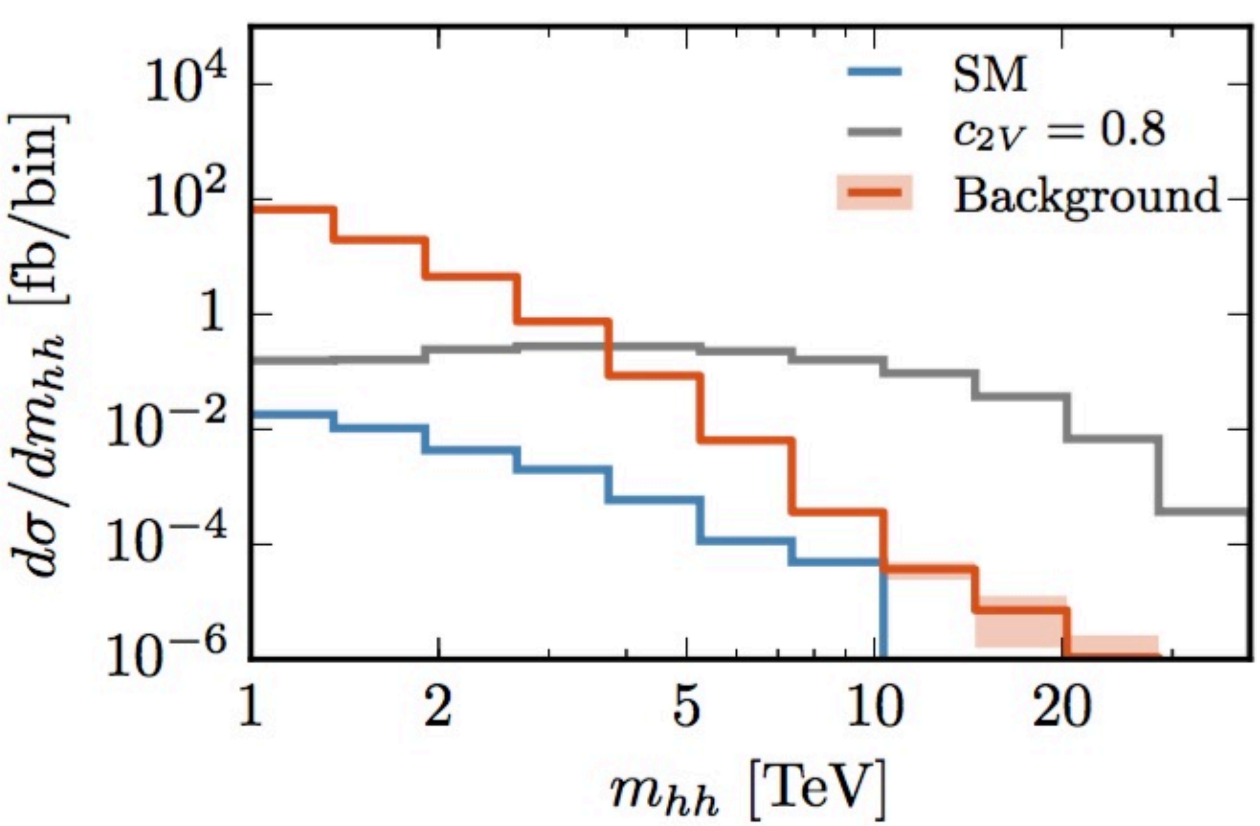
$$L_{D=6} = \frac{ig}{2} \frac{c_W}{\Lambda^2} \left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

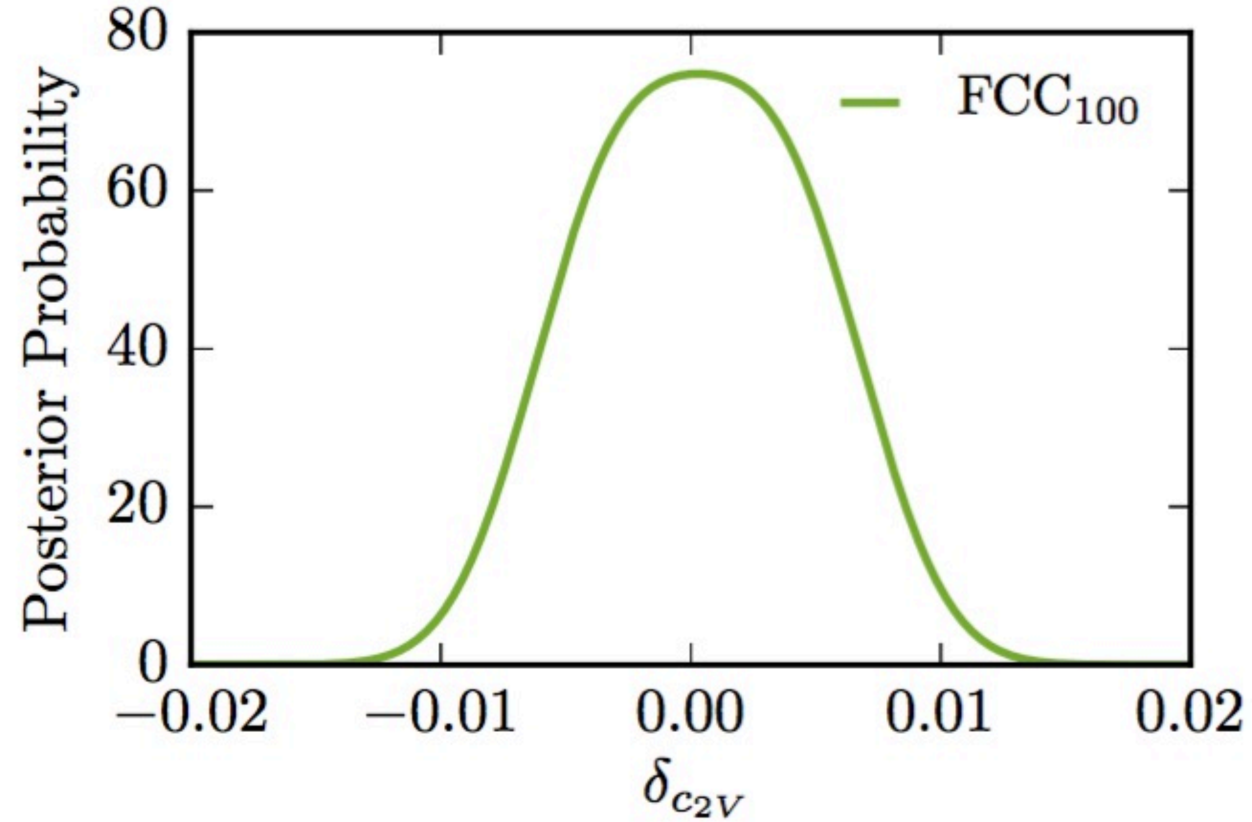
$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

Example: high mass VV → HH

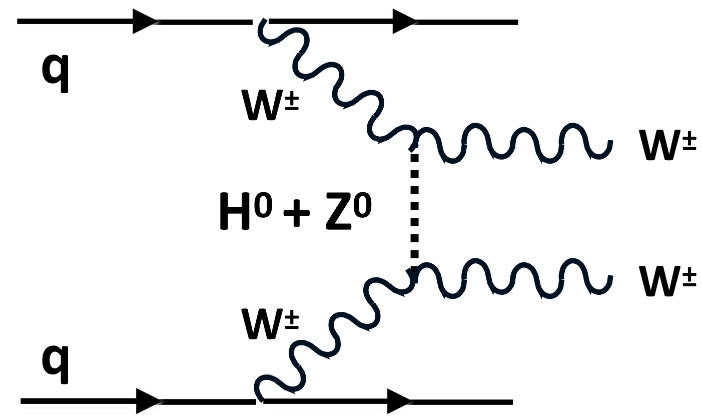


$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$ · **where** $$\begin{cases} c_V = g_{HVV}/g_{HVV}^{SM} \\ c_{2V} = g_{HHVV}/g_{HHVV}^{SM} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$$

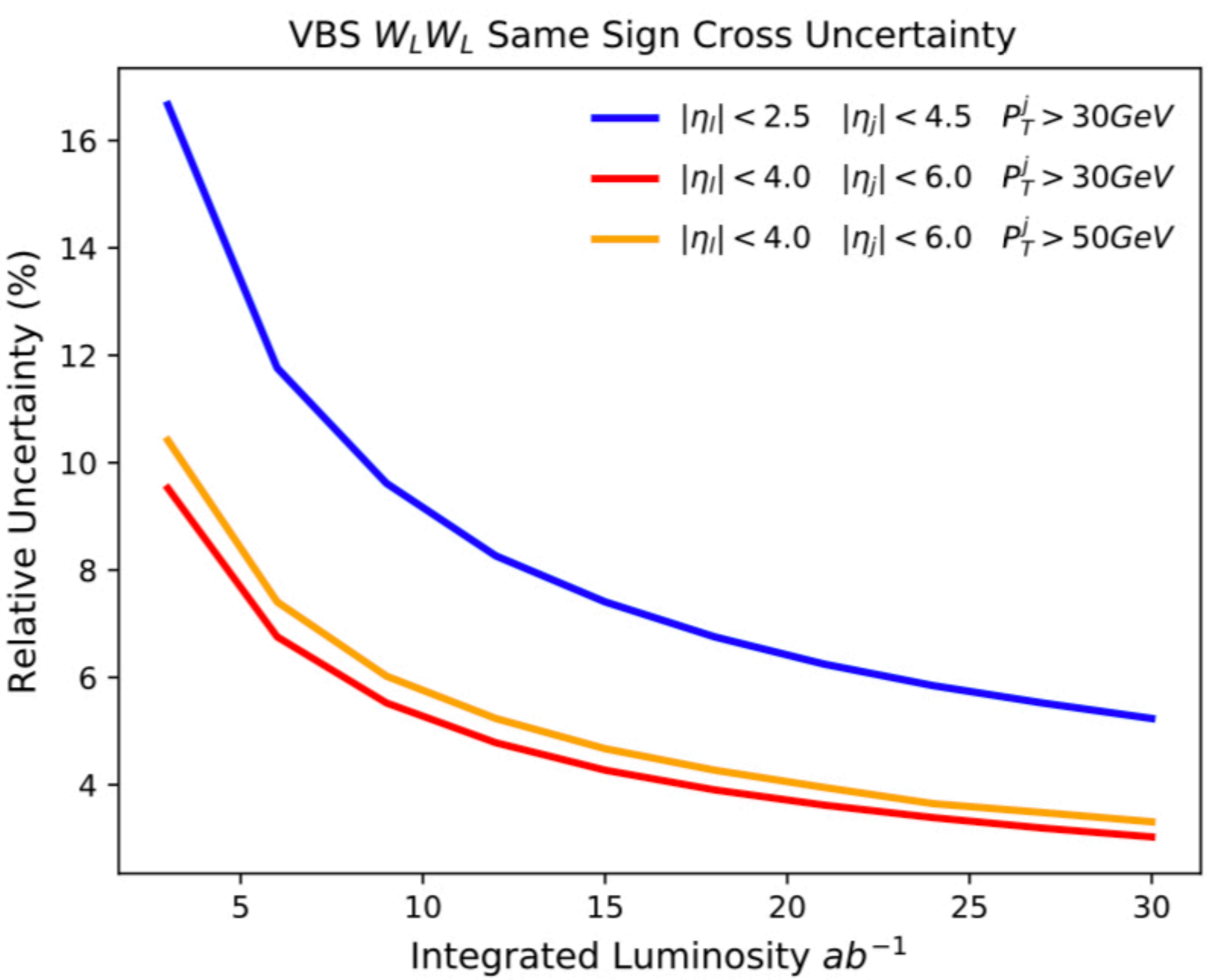




$W_L W_L$ scattering



large m_{WW}



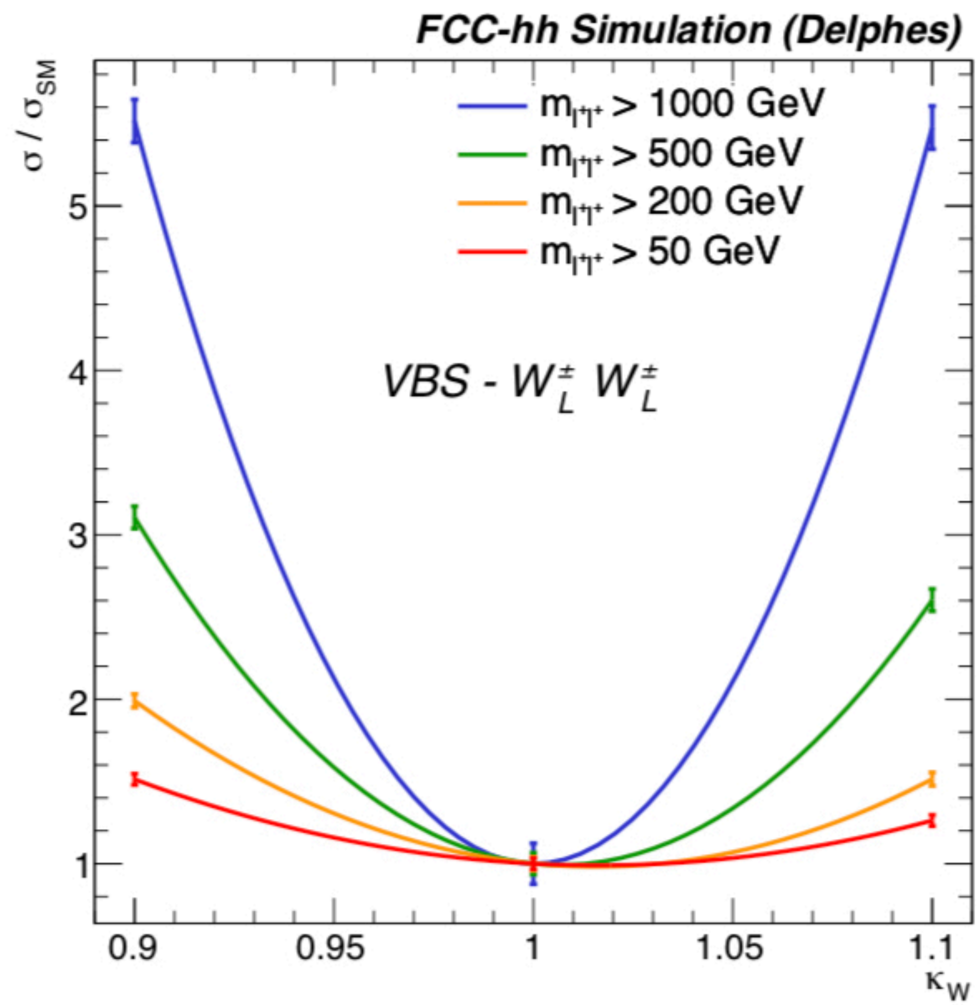


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

$$\kappa_W = \frac{g_{HWW}}{g_{HWW}^{SM}}$$

Example: high mass DY

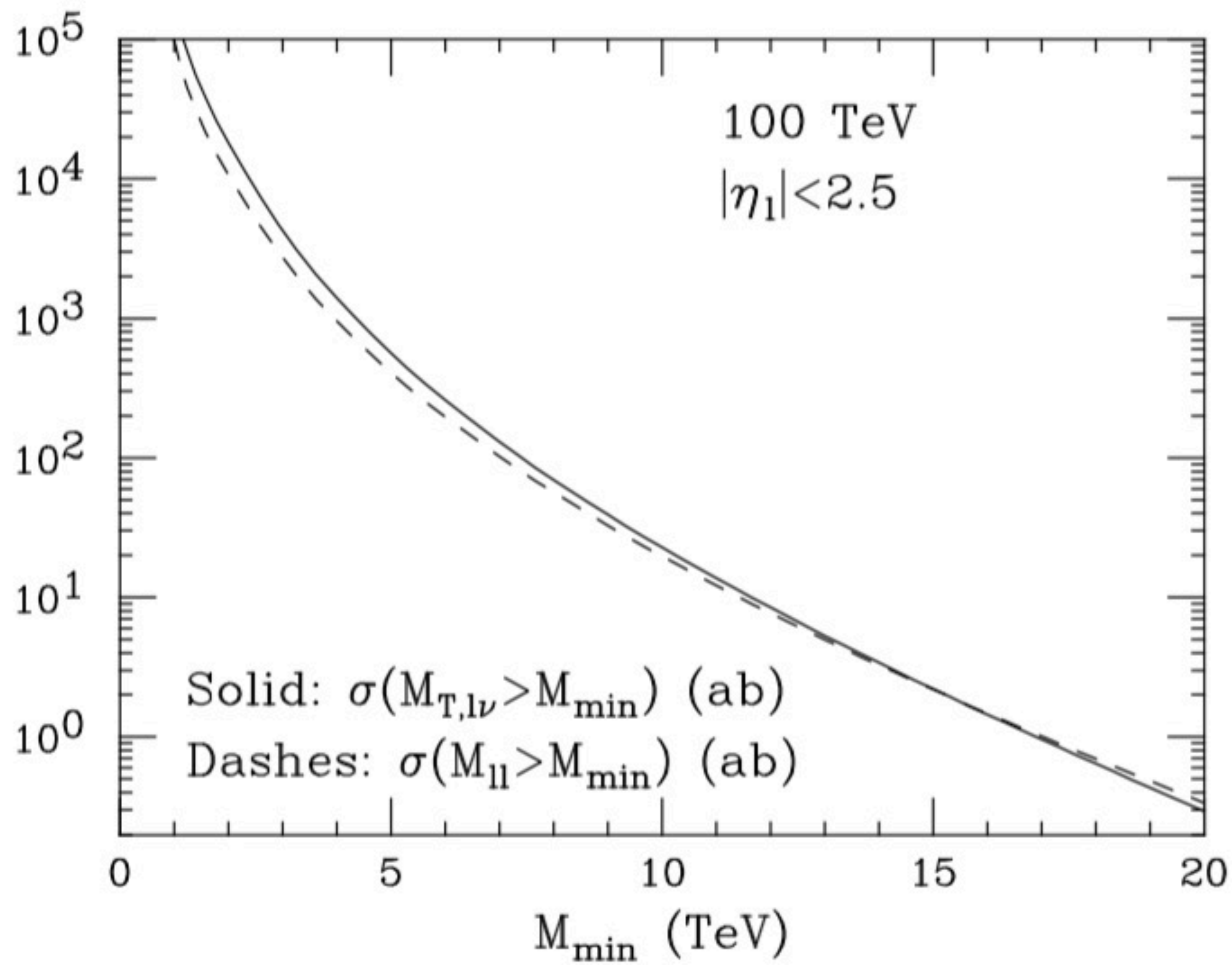
Farina et al, arXiv:1609.08157

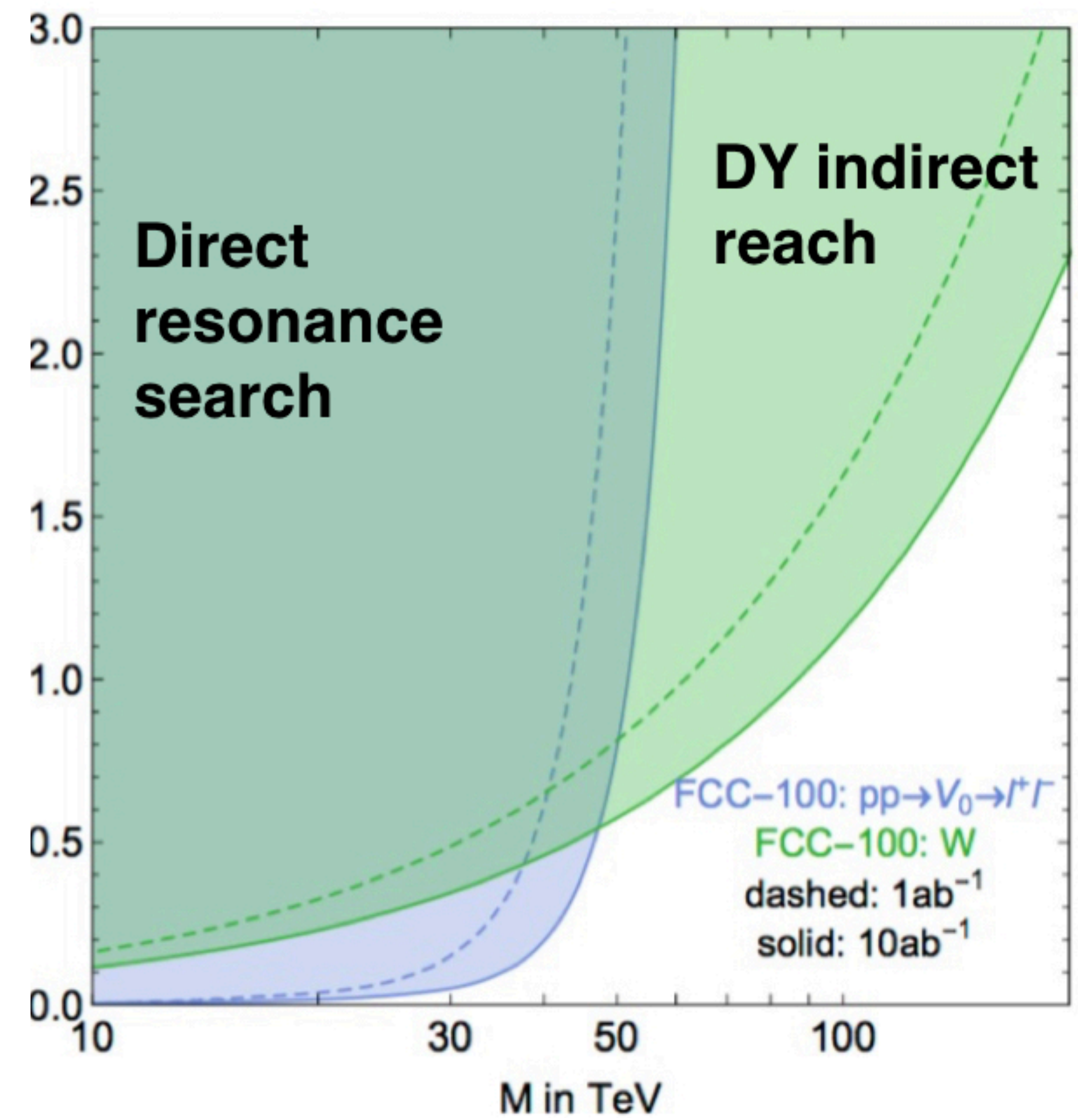
Constraints on Higher-dim op's

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

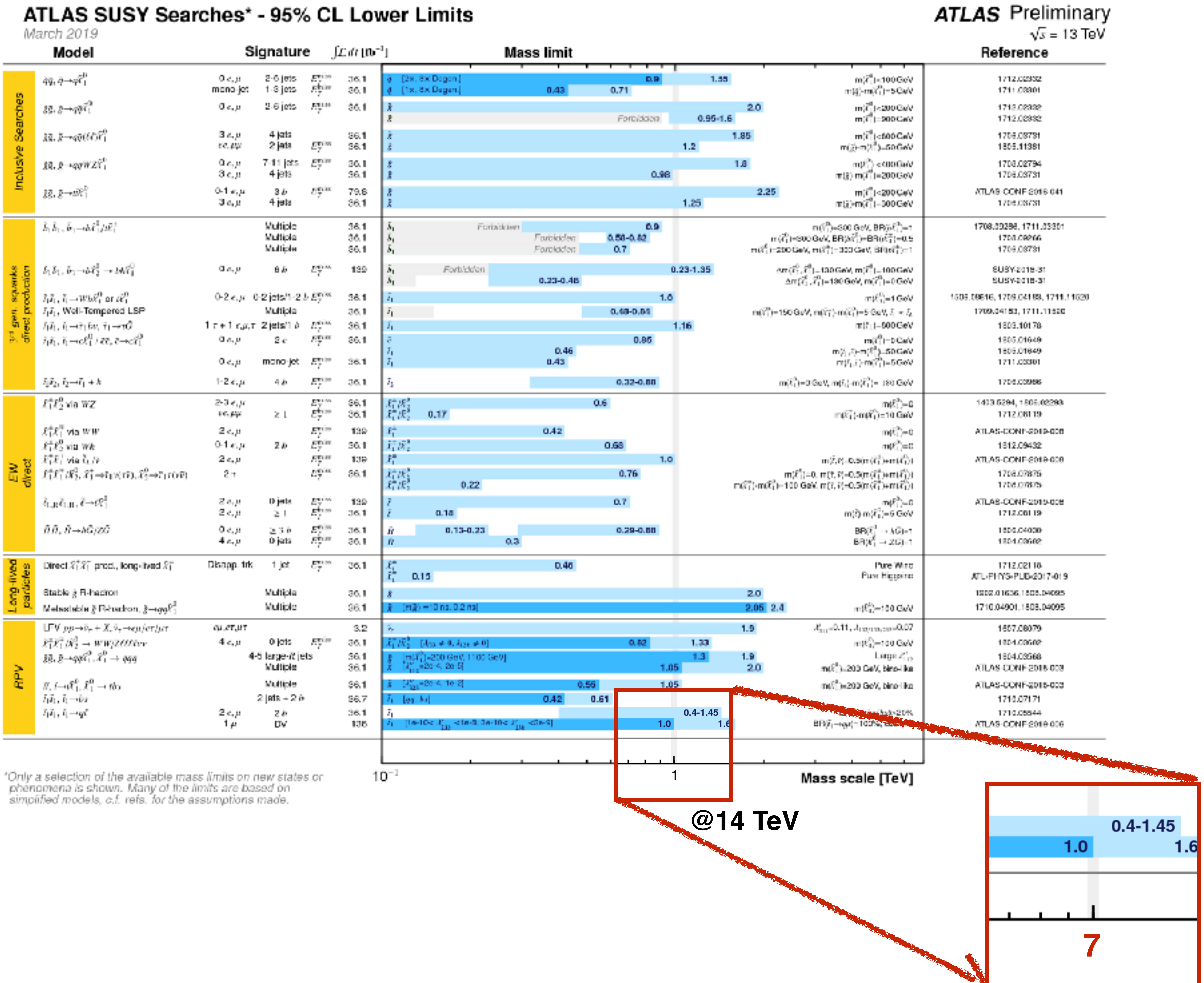
	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2\times10^7\,Z$	0.3/ab	3/ab	10/ab	$10^9\,Z$	$10^{12}\,Z$	$10^{10}\,Z$	3/ab	1/ab	1/ab
$W\ \times10^4$	$[-19,3]$	±0.7	±0.45	±0.02	±4.2	±1.2	±3.6	±0.3	±0.5	±0.15
$Y\ \times10^4$	$[-17,4]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2	$\sim\pm0.5$	$\sim\pm0.15$

$W / 4m_W^2 \;<\; 1/(100\text{ TeV})^2$



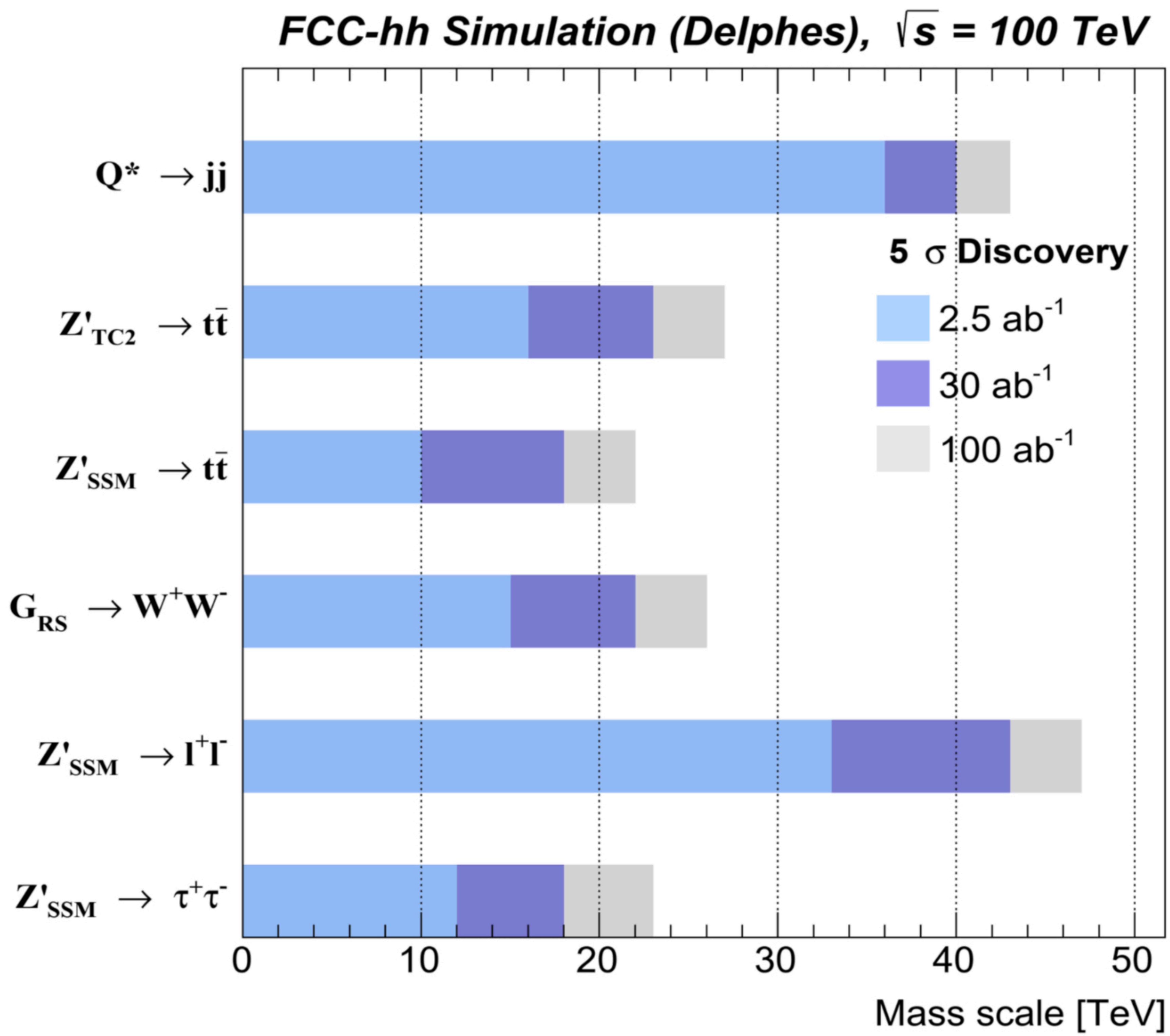


Direct discovery reach: the power of 100 TeV


ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
@14 TeV
0.4-1.45
1.0
1.6
7

@100 TeV

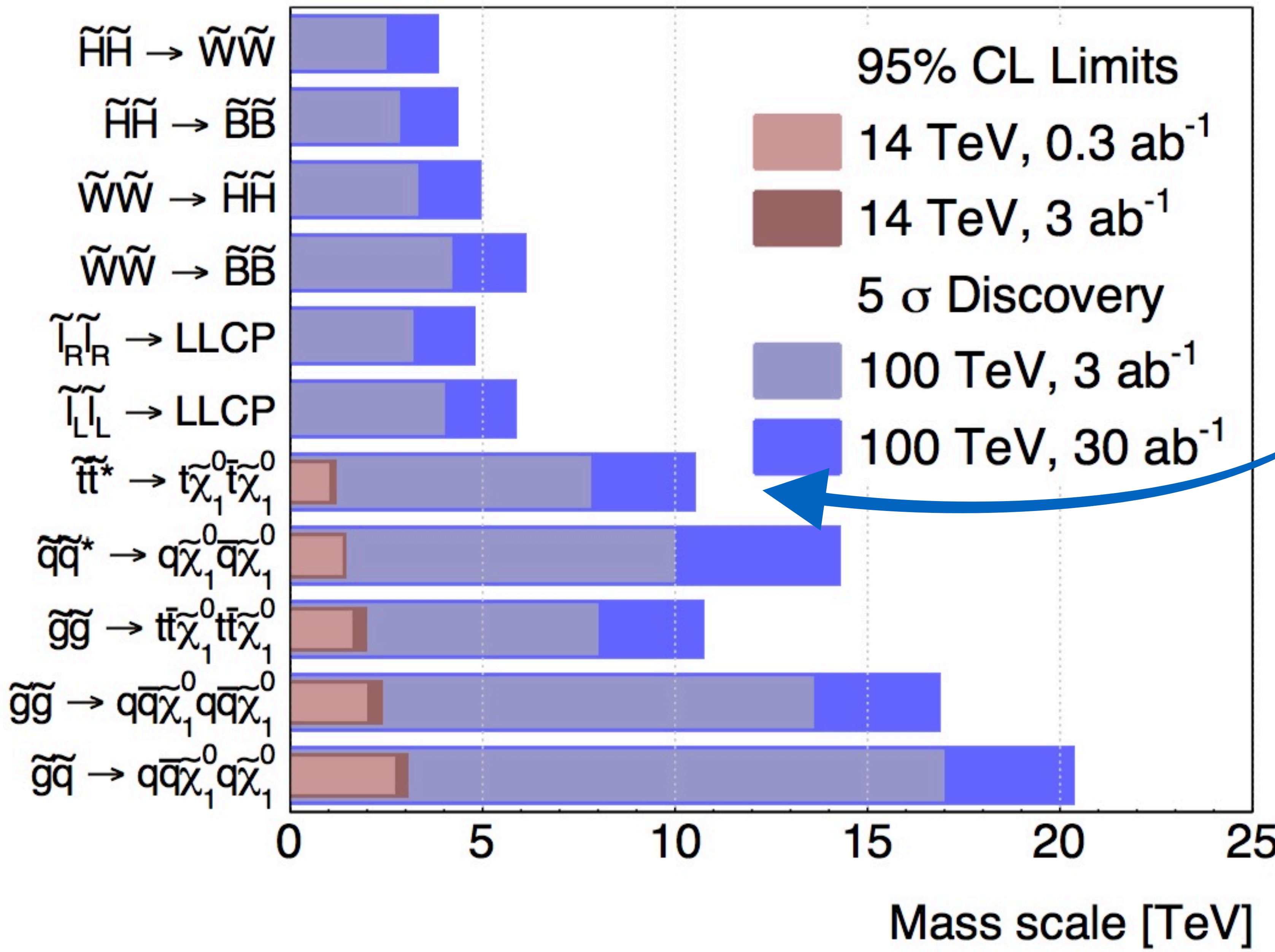
s-channel resonances



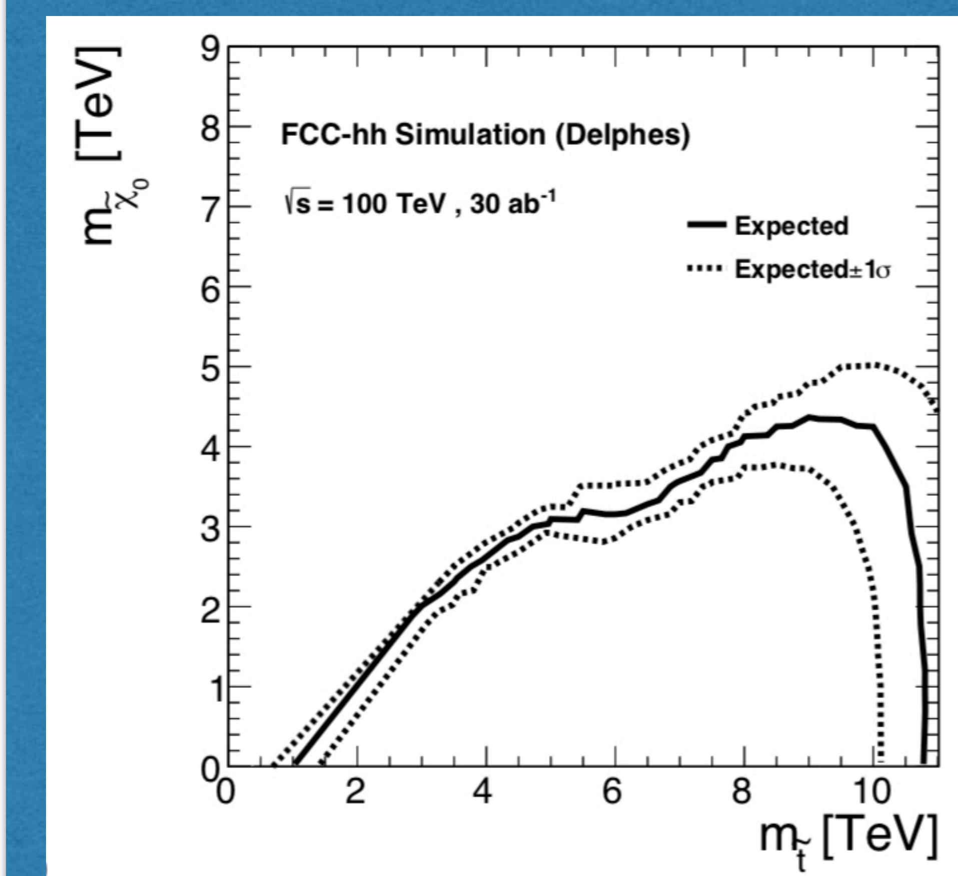
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies



New detector performance studies



Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question "what is DM?"
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
  - do WIMPS contribute to DM?
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders? Is there sensitivity to the explicit detection of DM-SM mediators?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\rm DM} h^2 \sim \frac{10^9 {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

$$\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

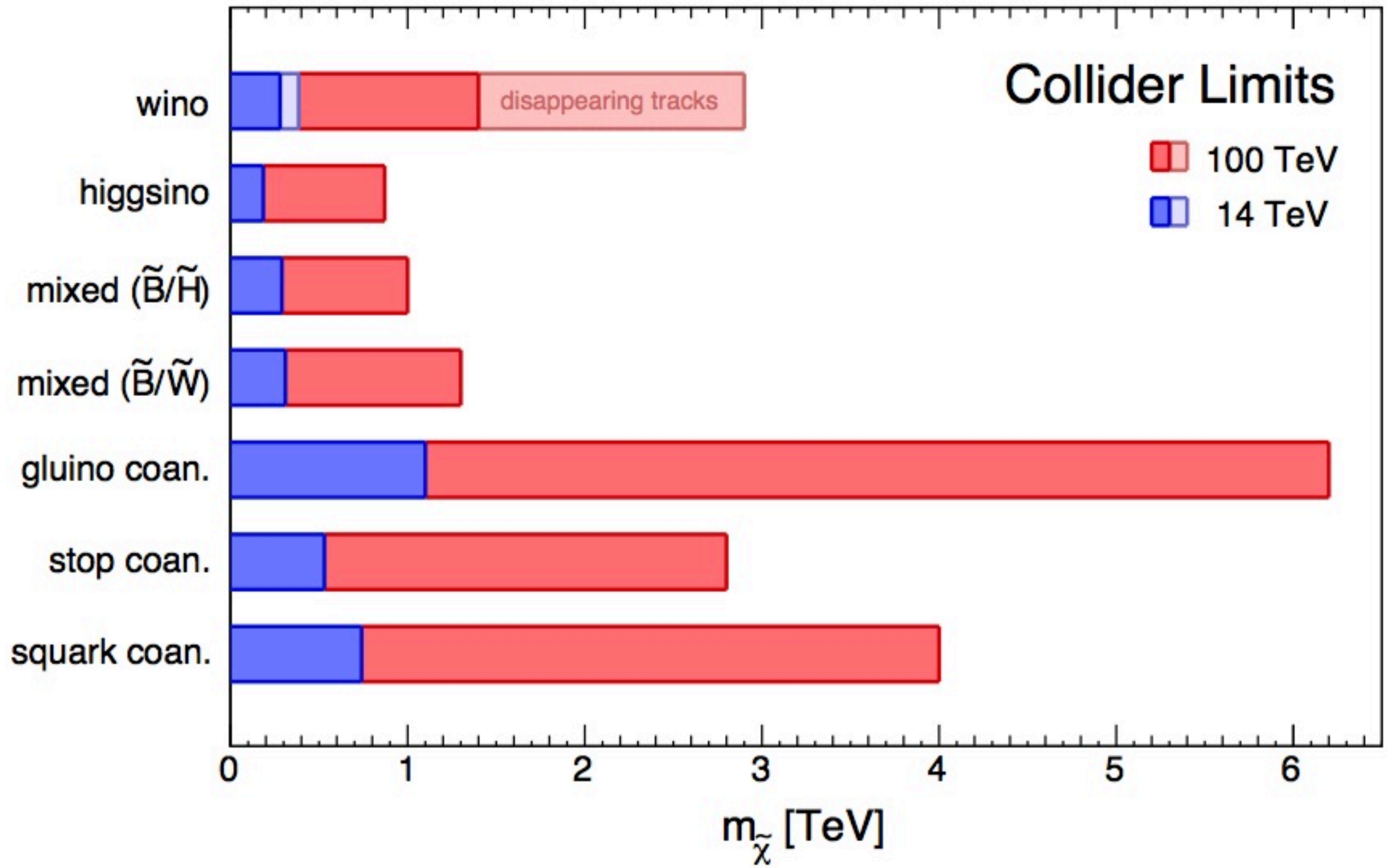
$$\Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}} \right)^2 \left(\frac{0.3}{g_{\rm eff}} \right)^4$$

$$\Omega_{wimp}\, h^2 \lesssim 0.12$$

$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3} \right)^2$$

DM reach at 100 TeV

Early phenomenology studies

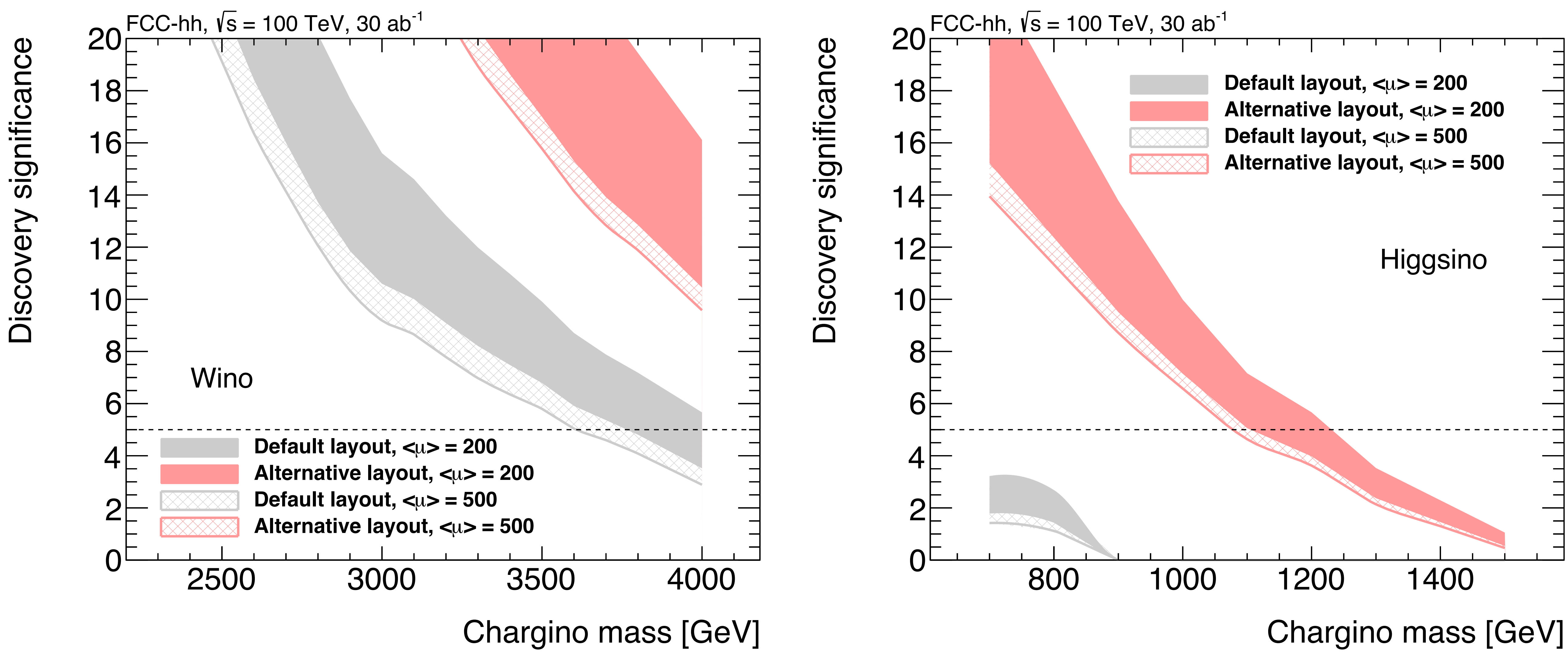


K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

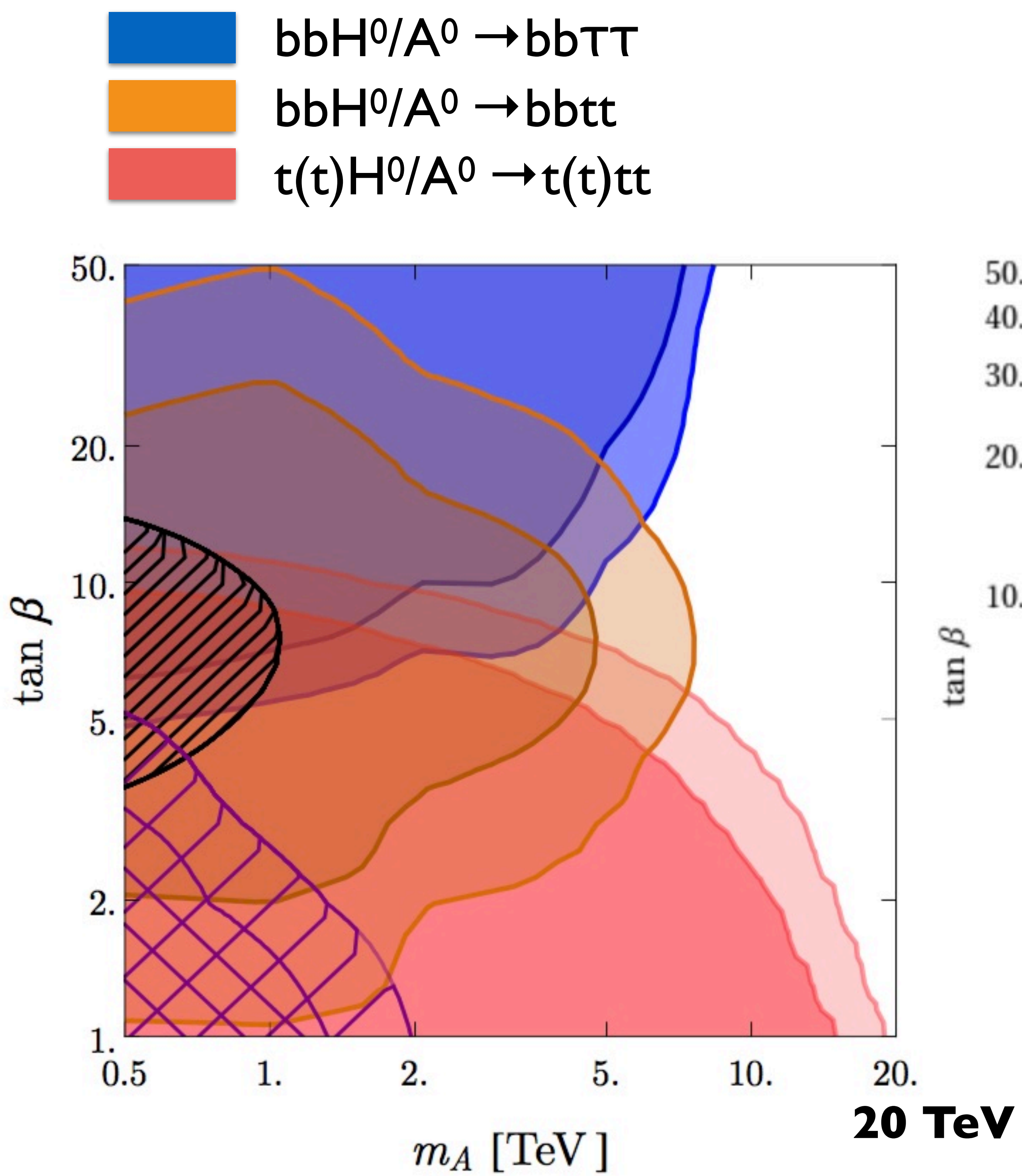
(at ~full pileup)

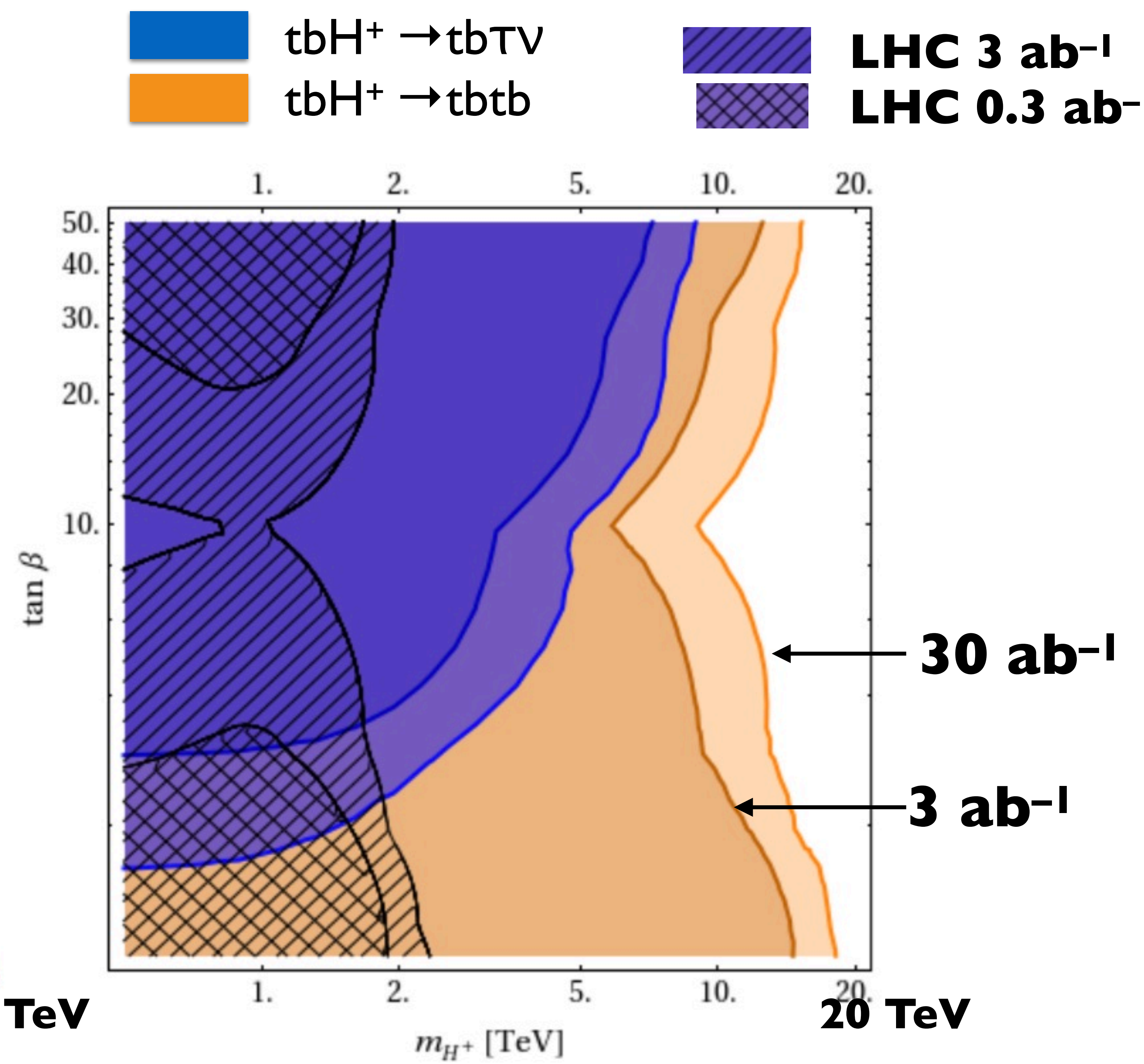


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{wimp} \lesssim 2\ \text{TeV} \left(\frac{g}{0.3}\right)^2$$

MSSM Higgs @ 100 TeV





N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

additional opportunities

- Flavour physics at the Z pole

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)

- eh collisions
- Heavy ion collisions
- Dedicated detectors for flavour physics (like LHCb)
- Forward physics (LHCf, TOTEM)
- Dedicated detectors for long-lifetime particles (like FASER, Mathusla)

Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- Unique among the proposed projects for future colliders, the FCC builds on the tried and tested format forged by the LEP-LHC experience, integrating the well-established and complementary qualities of circular e^+e^- and pp colliders within a largely common, and partly existing, infrastructure.
- The sequence of FCC-ee and FCC-hh provides the most complete, detailed and accurate picture of Higgs properties achievable with the currently planned facilities, and gives direct access to the largest mass scales allowed by foreseeable technology
- Flavor factory at the Z pole, heavy ions and ep collisions: extremely diversified program => broad community engagement

FCC-ee + FCC-hh, project timeline

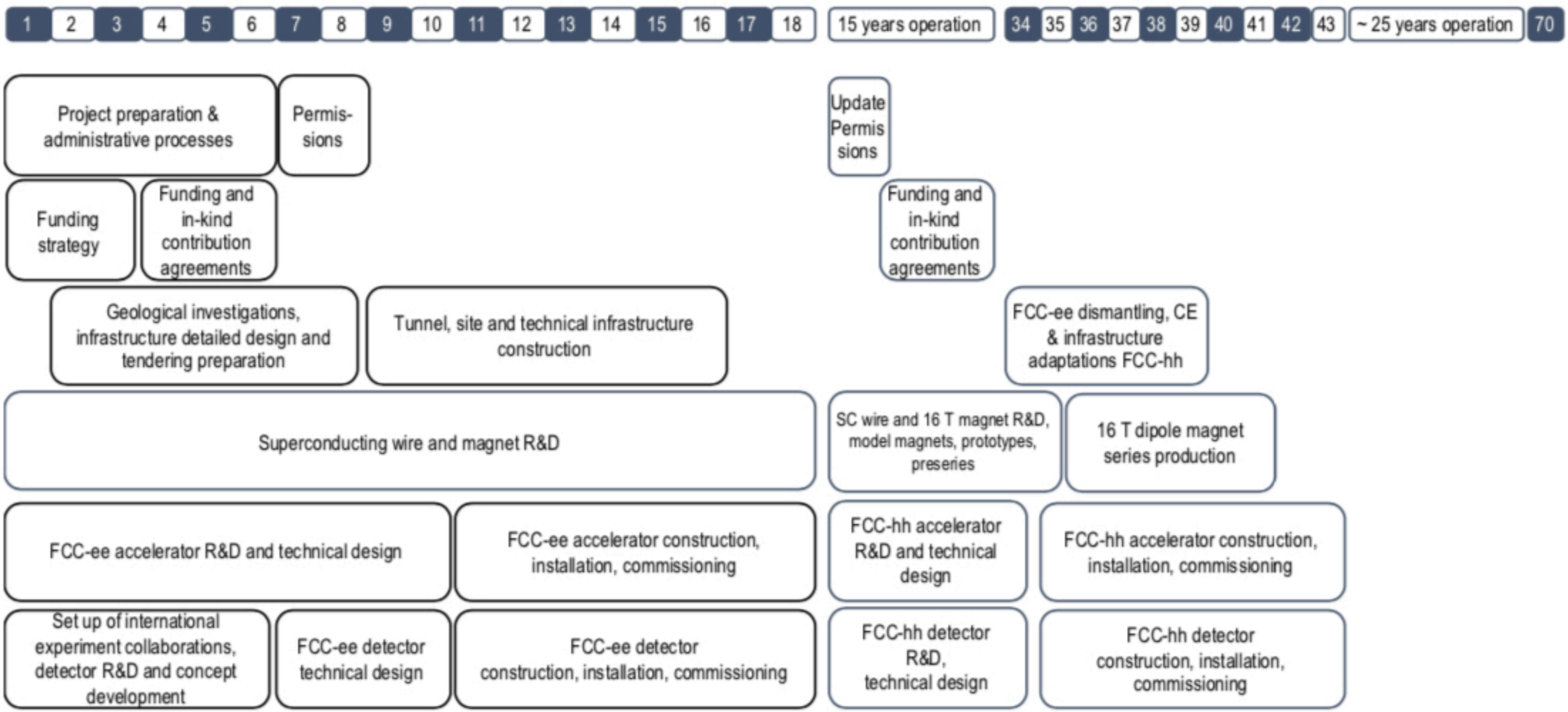


Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

Domain	**Cost in MCHF**
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**