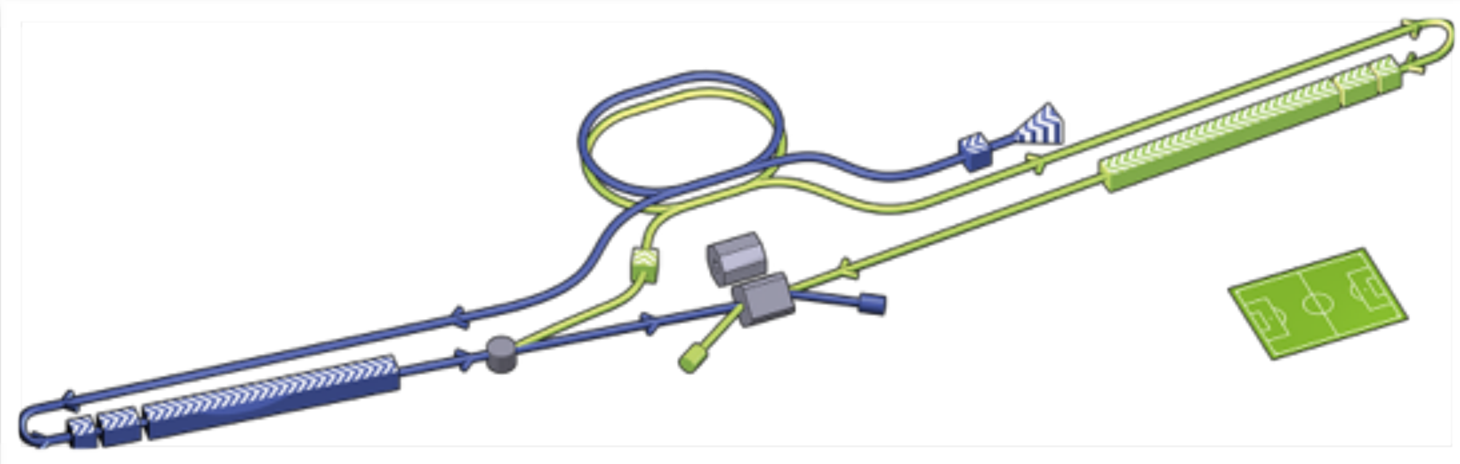
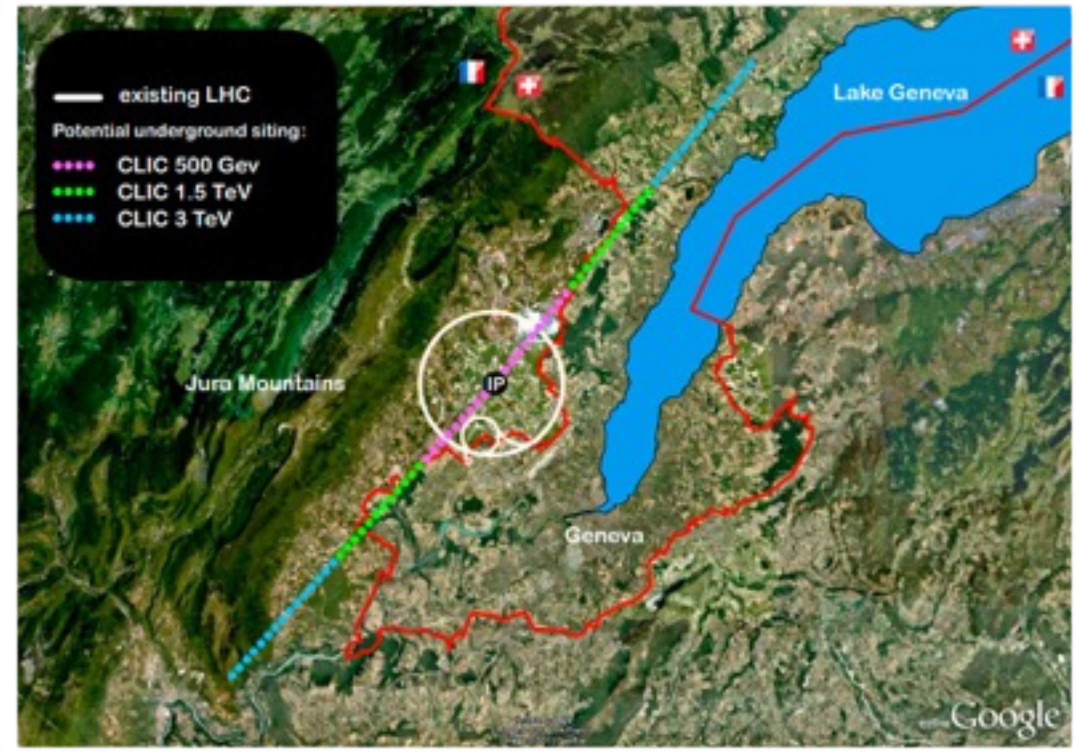
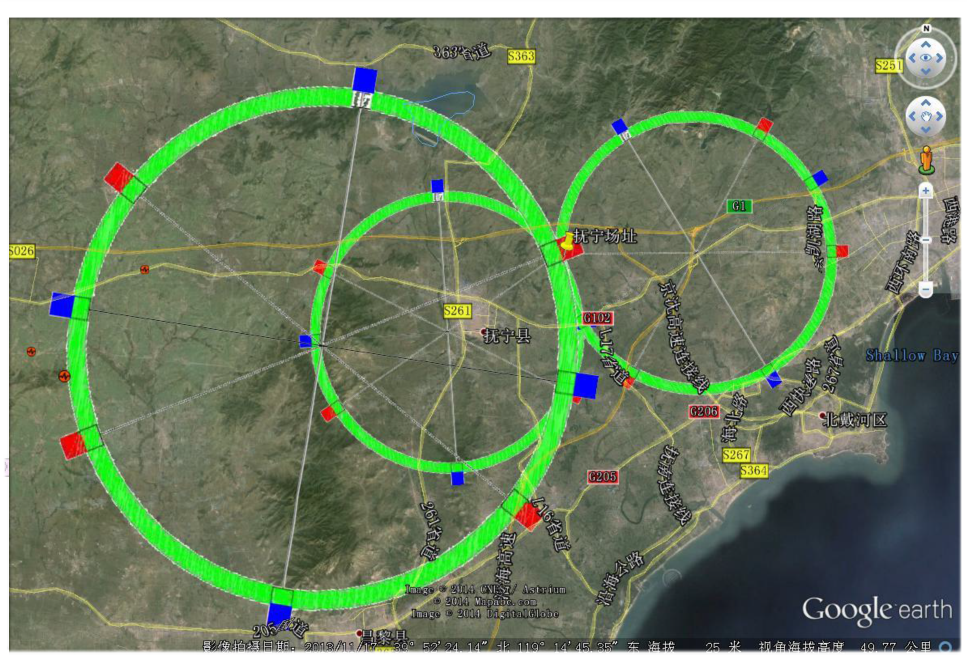
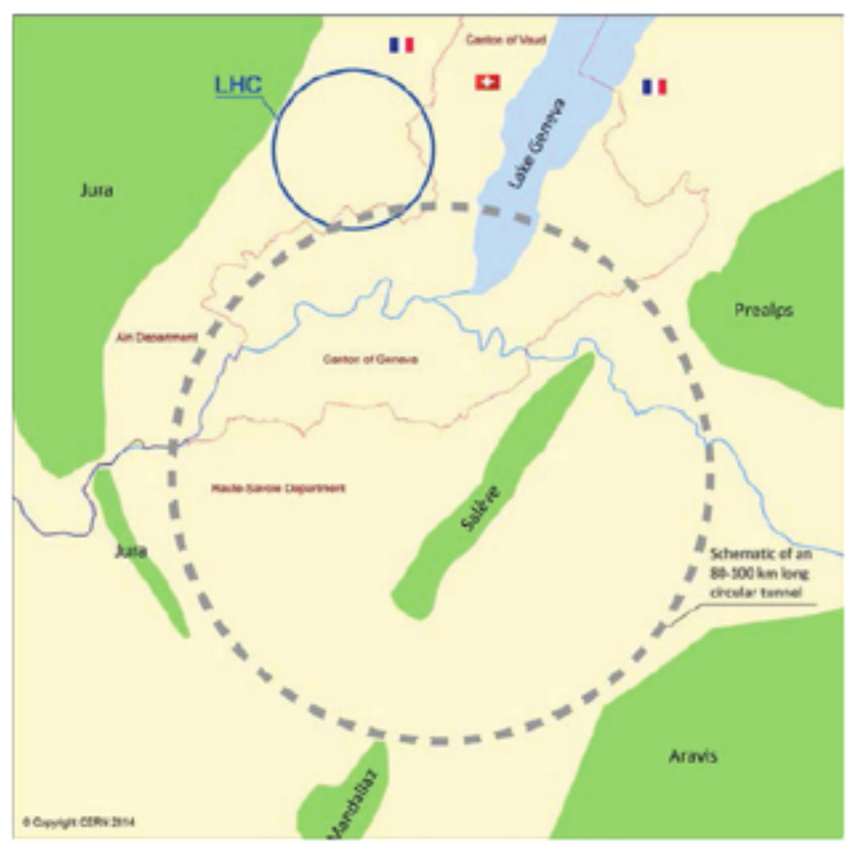




SM and Higgs at future machines (both ee and pp)

Heather M. Gray, CERN





Thanks to Tim Barklow, Albert de Roeck, Markus Klute, Lucie Linssen, Michelangelo Mangano, Emmanuel Perez, Krisztian Peters, Philip Roloff

Future Collider Options

FCC-ee (CERN): 88-350 GeV CEPC (China): 240-250 GeV

CLIC (CERN): 350-3000 GeV ILC (Japan?): 250-1000 GeV

HE-LHC (CERN): 26-33 TeV *(not discussed here)*

SppC (China): 50-70 TeV FCC-hh (CERN): 100 TeV

See talks by Emmanuel Perez and Albert de Roeck for collider details

SM Physics at Future Colliders

- Future colliders provide higher **energies** and **luminosities**
  - Opportunity for a rich program in SM physics
- Electroweak Precision Measurements
  - Precision measurements of W, Z and top mass and width
  - Probe rare production and decay modes
- Higgs
  - Precision coupling measurements
  - t-H coupling
  - HH (self-coupling) production

Impossible to summarise such a rich program in such a short talk: selected highlights only !

Precision SM Physics

A. Freitas, arXiv: 1604.00406
Eur. Phys. J. C (2013) 73:2530

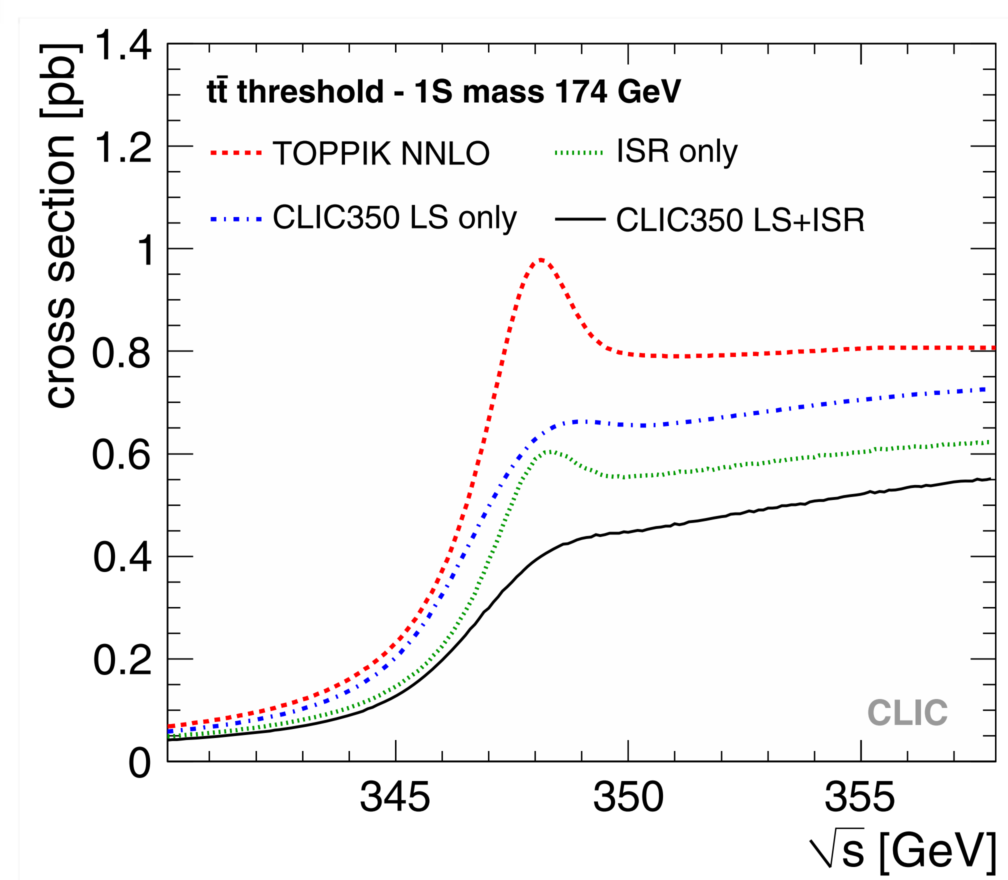
- ee machines provided opportunities for unparalleled **precision** measurements of EW observables
- Typically **order of magnitude improvement** over current results
- Top mass and width via energy scan: <50 MeV total uncertainty
    - Measure EW couplings of top to ~1% precision

Current

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2\theta^\ell_{eff}$ [10^{-5}]	4.5	16
Γ_Z [MeV]	0.5	2.3
R_b [10^{-5}]	15	66

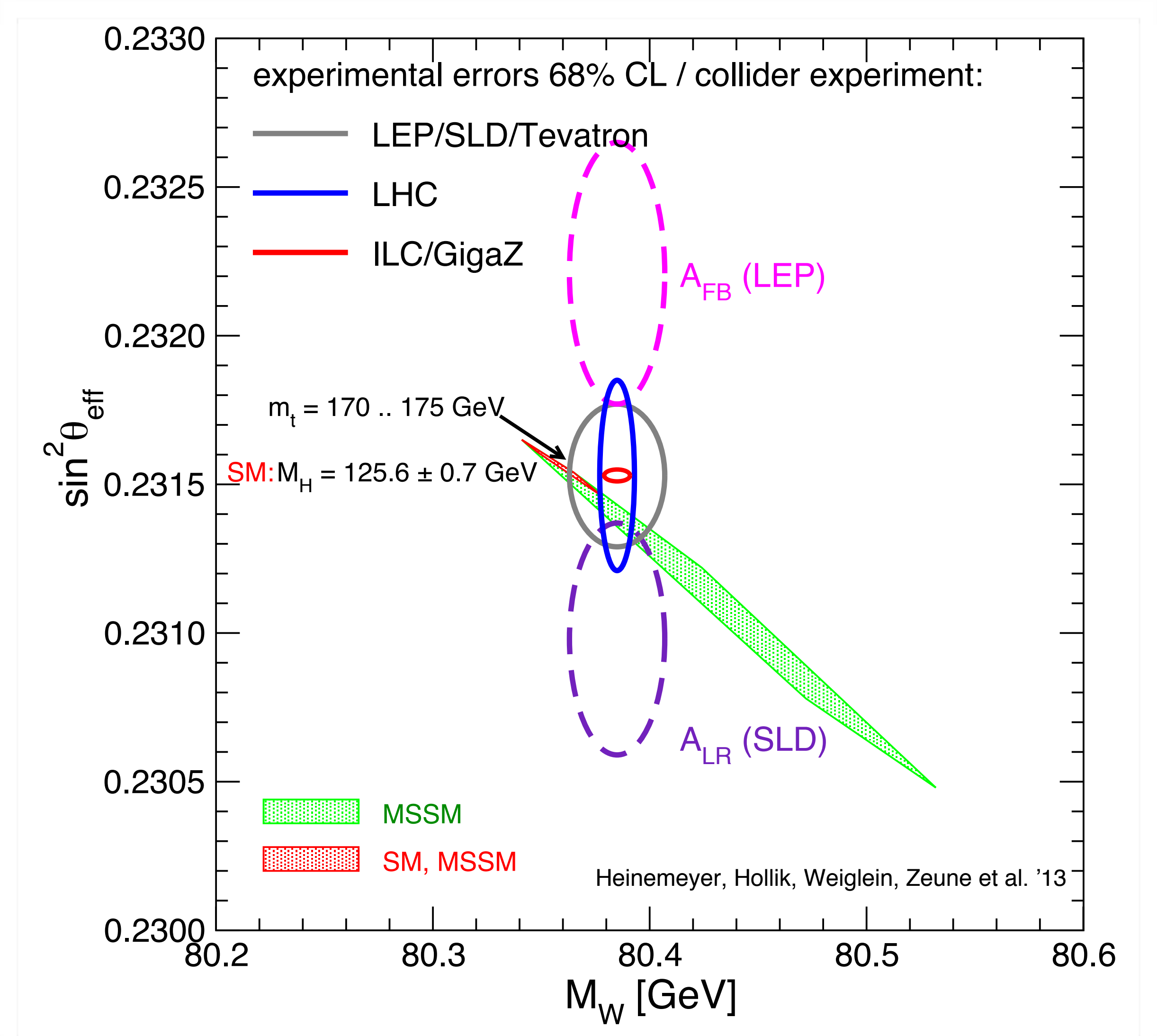
Future

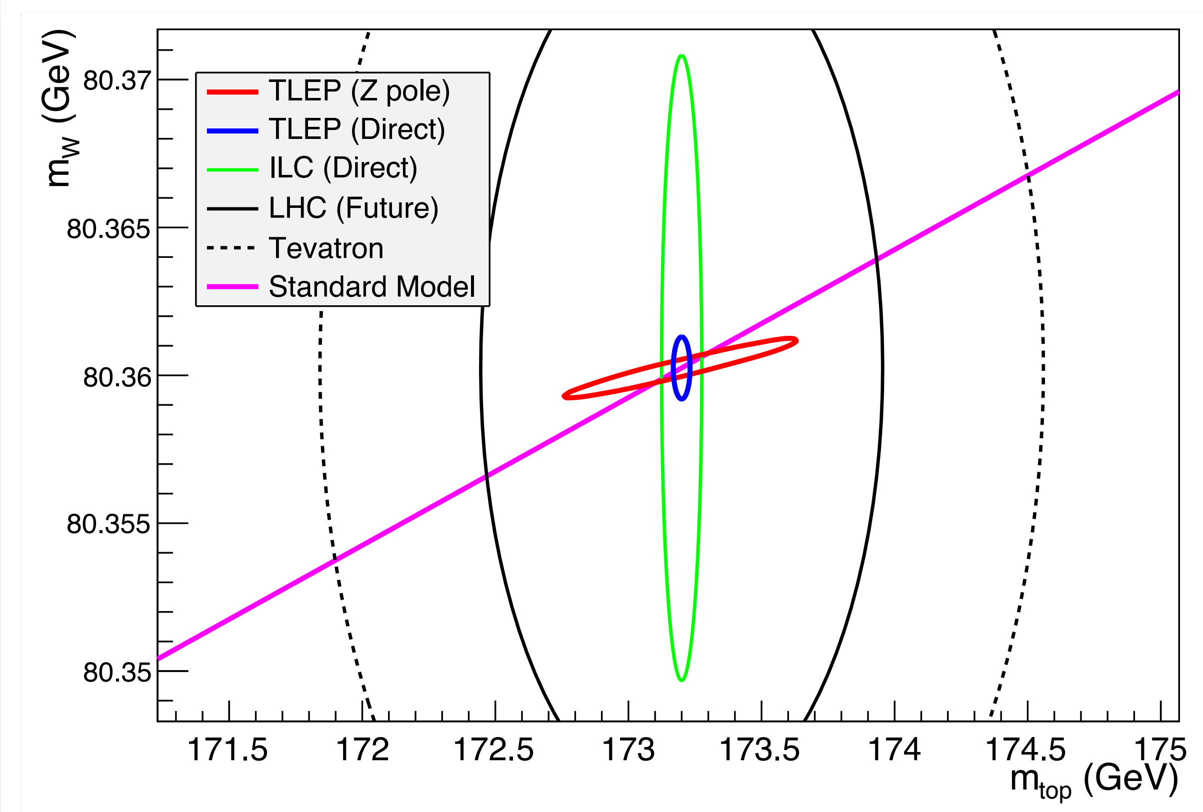
Quantity	ILC	FCC-ee	CEPC	Projected theory error
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^\ell_{eff}$ [10^{-5}]	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
R_b [10^{-5}]	14	6	17	5–10



Implications of Precision Measurements

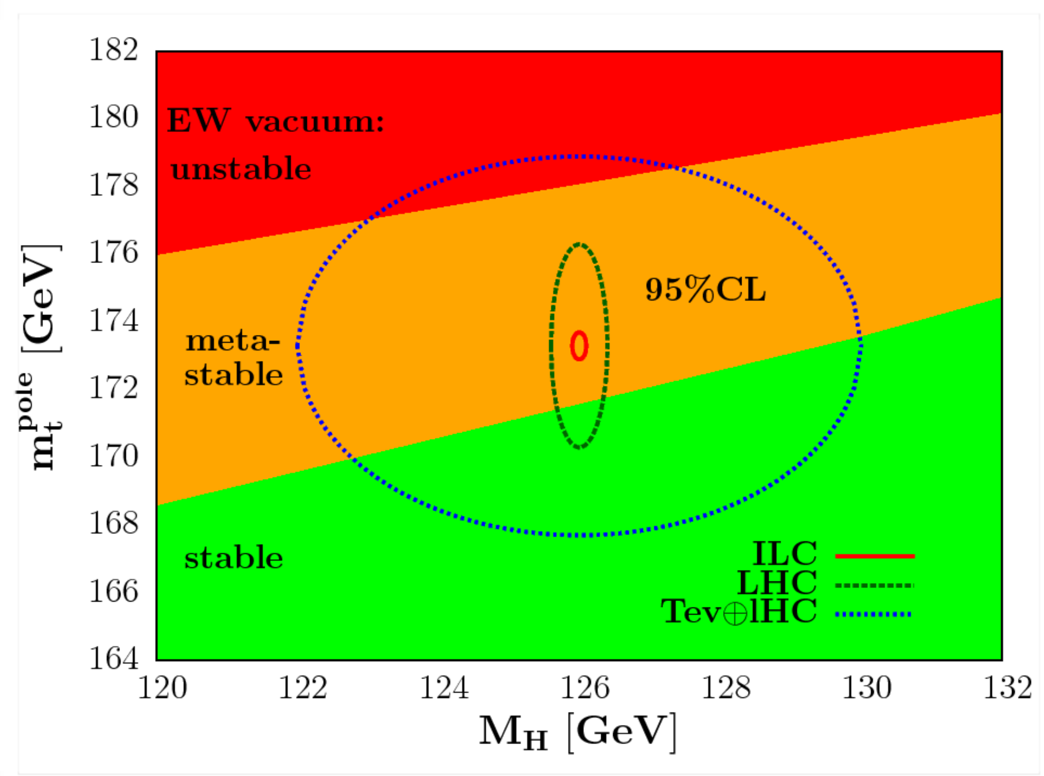
arXiv:1308.6176
Heinemeyer et al, 2013
PLB 716 (2012) 214–219





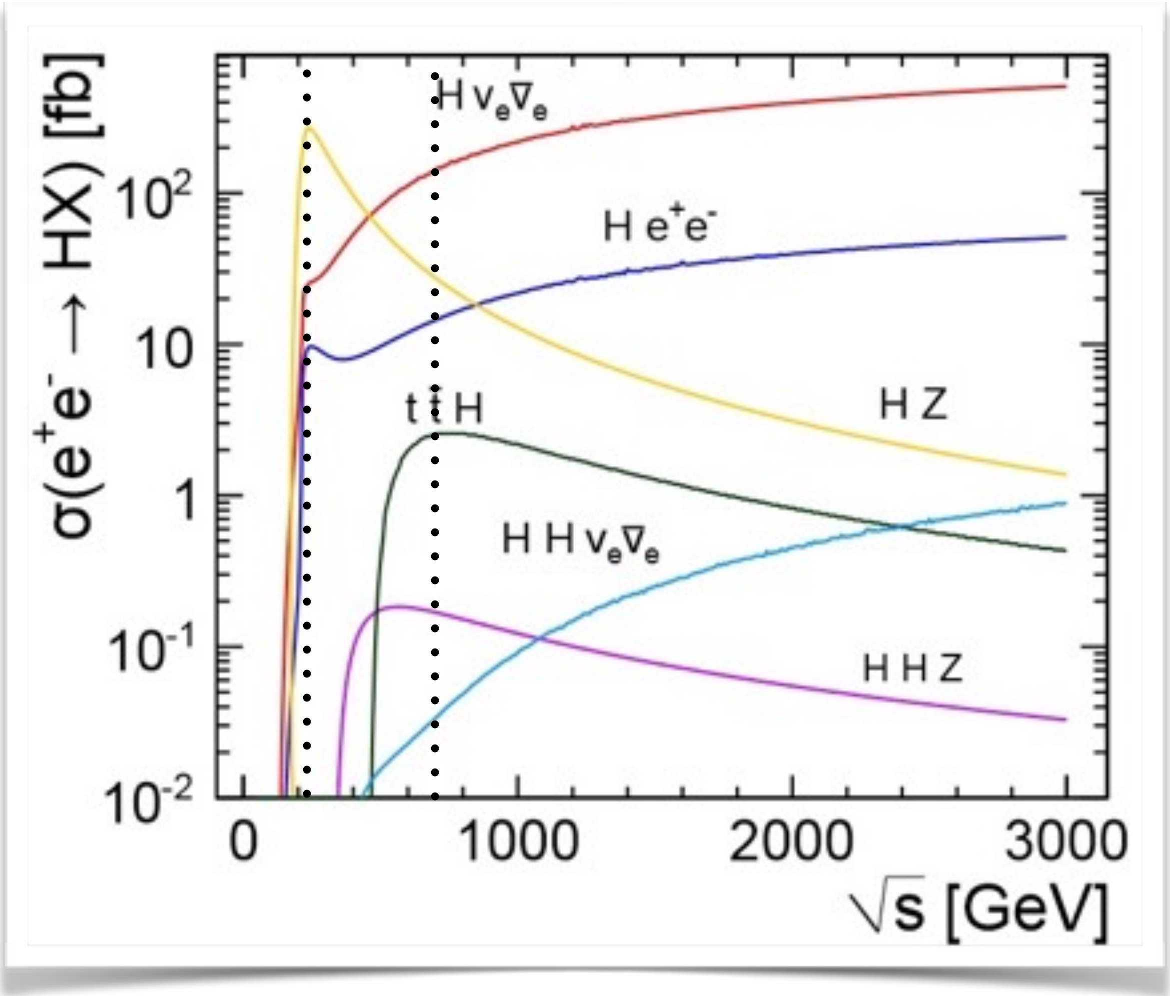
Strong constraints on SUSY

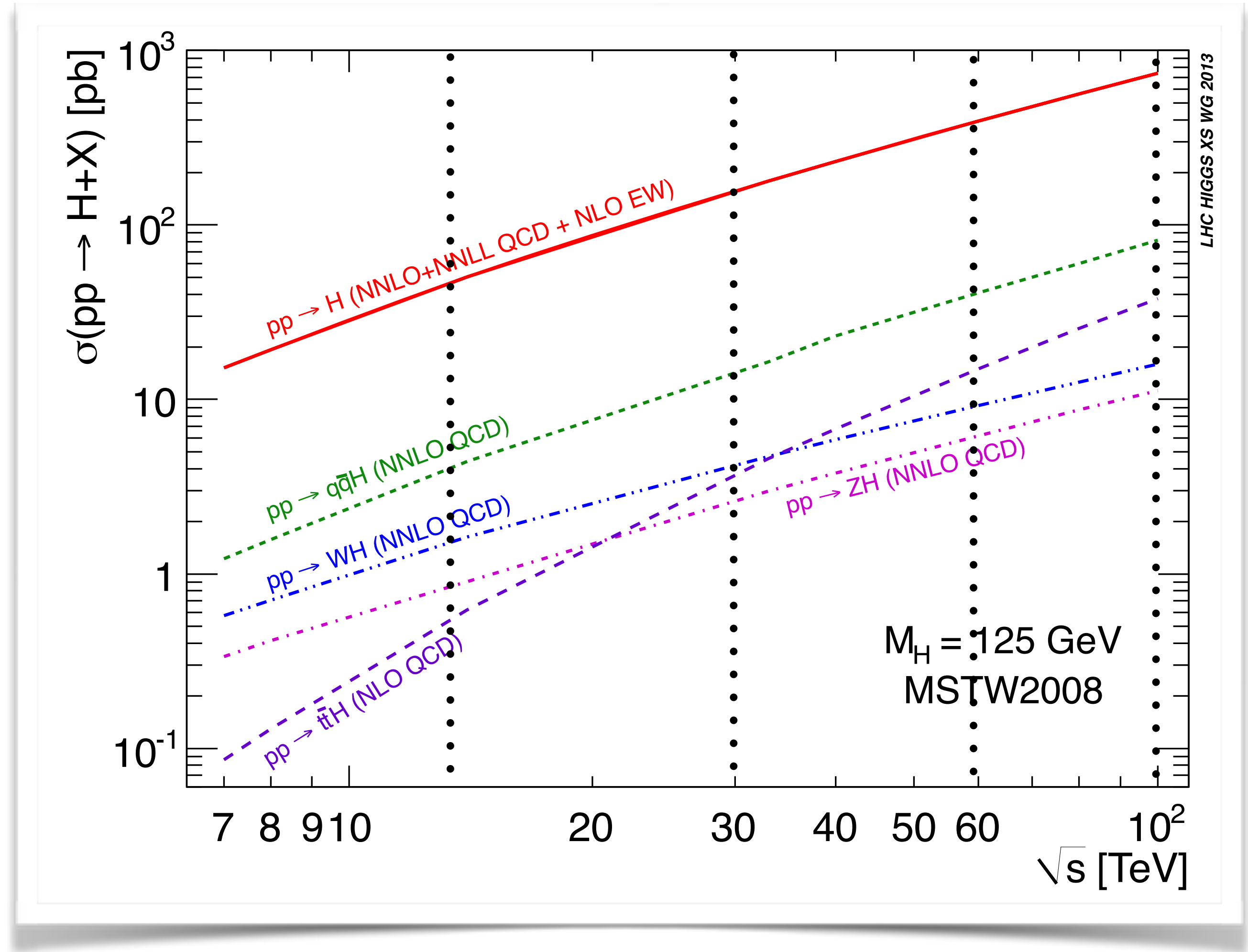
Stability of the Higgs potential
(and the universe) ?



Higgs Production

XSect WG
FCC-hh wiki





- Low backgrounds: all decay modes are accessible
- Model independent coupling measurements
- $\sqrt{s}$ > 500 GeV for ttH and HH production

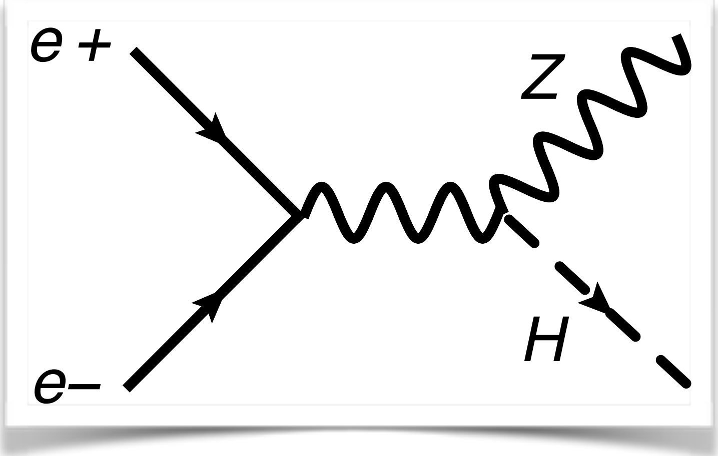
- High energy, huge cross-sections
- Rare decays, heavy final states (ttH, HH)
- Huge backgrounds: not all channels are accessible
- Model dependent coupling measurements

	gg→H	VBF	WH	ZH	ttH
σ_{100} [pb]	802	69	16	11	32
σ_{100}/σ_{14}	17	16	10	11	52

Model-independent Higgs Coupling

FCC-ee
CEPC, ILC
CLICdp - to be published soon

- Lepton colliders provide a unique opportunity to make model independent measurements of Higgs couplings via the measurement of $\sigma(e^+e^- \to ZH)$

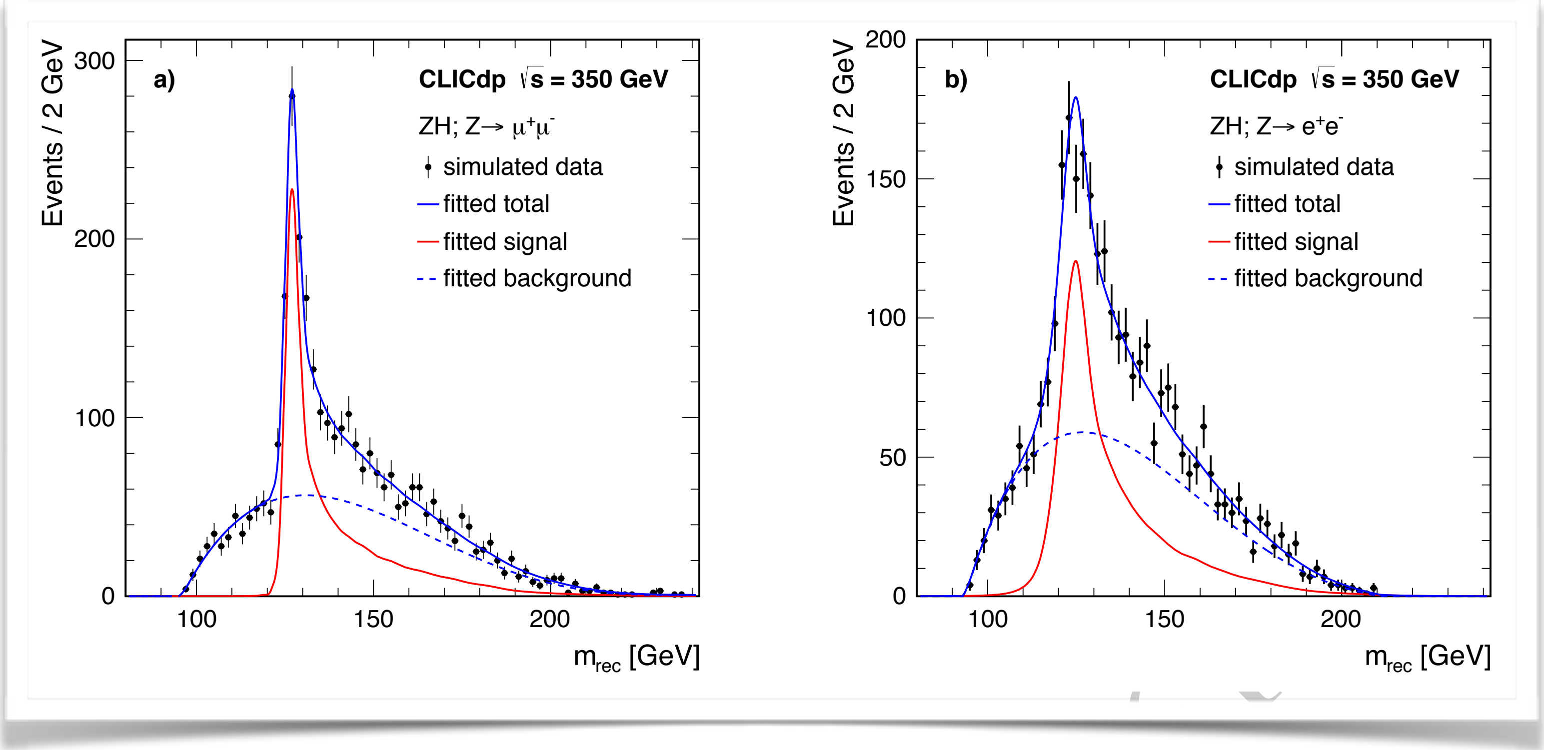


- Z is reconstructed independently of Higgs decay
- 4-momentum of the Higgs obtained from

$$E_{rec} = \sqrt{s} - E_Z \qquad \vec{p}_{rec} = -\vec{p}_Z$$

- Obtain a model independent measurement of g_{ZZ} of ~1%
- Higgs mass from recoil mass

	ILC	CLIC	FCC-ee	CEPC
Δm_H (MeV)	150	44	-	5.9
Γ_H	1.8%	3.6%	1%	2.8%



Precision Higgs Couplings

FCC-ee: http://arxiv.org/pdf/1308.6176.pdf
CLICdp - to be published soon
CEPC, ILC

- More than an order of magnitude improvement in coupling precision compared to HL-LHC
  - Use most optimistic scenario in each case
- FCC-ee has typically highest precision (see FCC-hh ttH/HH later)

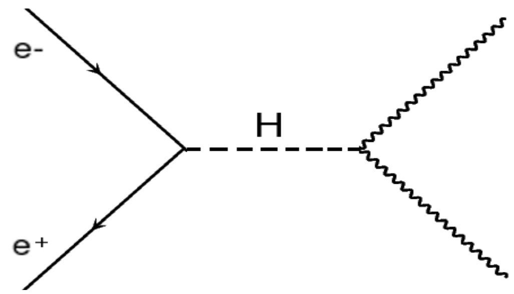
	ILC	FCC-ee	CEPC	CLIC
$\sigma(ZH)$	0.7%	0.4%	0.51%	1.65%
g_{bb}	0.7%	0.42%	0.57%	0.9%
g_{cc}	1.2%	0.71%	2.3%	1.9%
g_{gg}	1.0%	0.80%	1.7%	1.4%
g_{WW}	0.42%	0.19%	1.6%	0.9%
$g_{\tau\tau}$	0.9%	0.54%	1.3%	1.4%
$g_{\mu\mu}$	9.2%	6.2%	17%	7.8%
g_{inv}	<0.29%	<0.45%	<0.28%	<0.97%

~1% with hh? (← $g_{\mu\mu}$ row)

H→e coupling?

d'Enterria et al

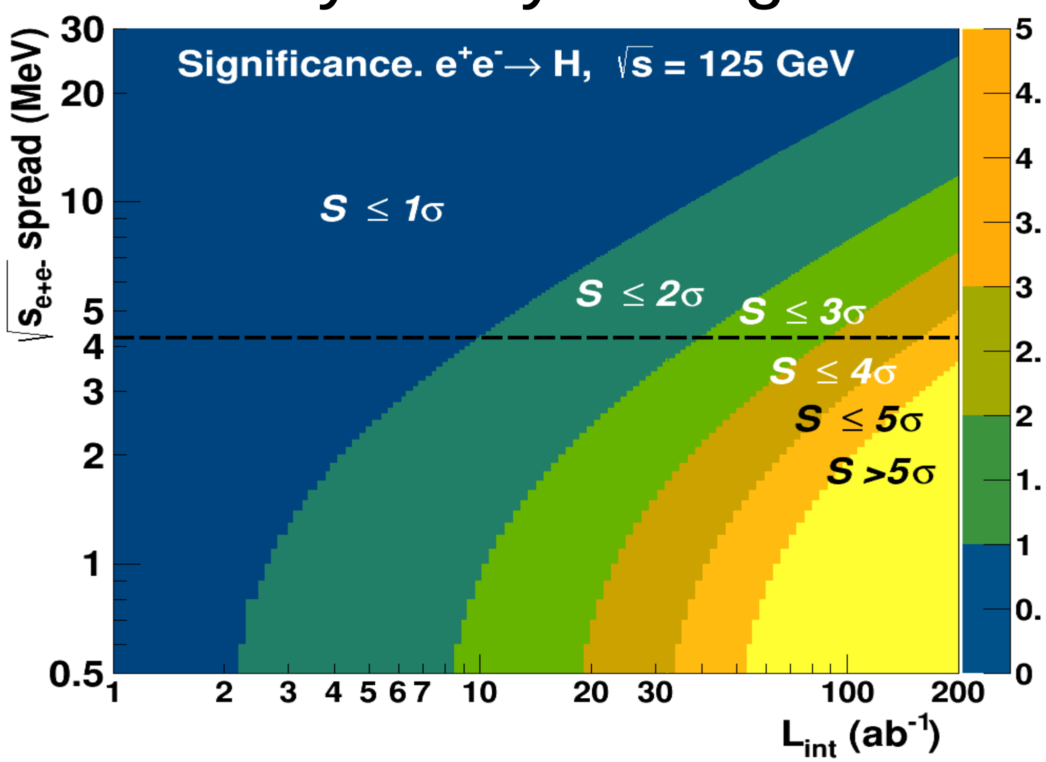
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):

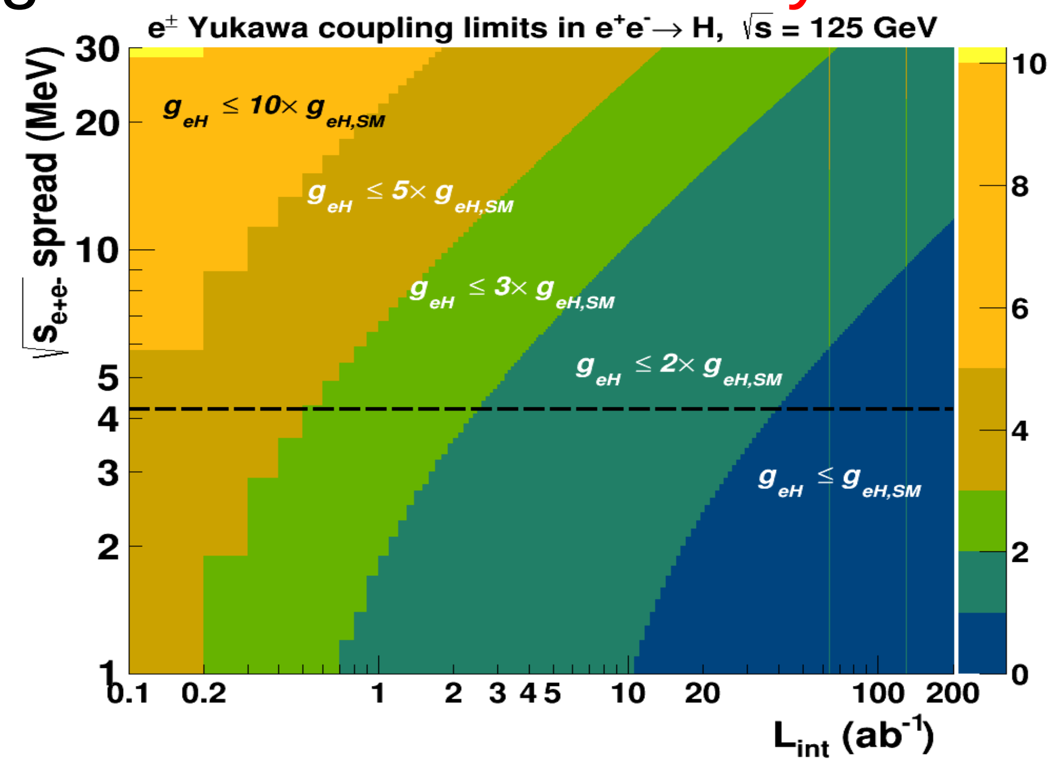


$\sigma(e^+e^-\to H)_{B\text{-}W}$ = 1.64 fb

$\sigma(e^+e^-\to H)_{visible}$ = 290 ab (ISR + $\sqrt{s}_{spread} = \Gamma_H$ = 4.2 MeV)

- Preliminary study for signal + background for "all" 10 decay channels.





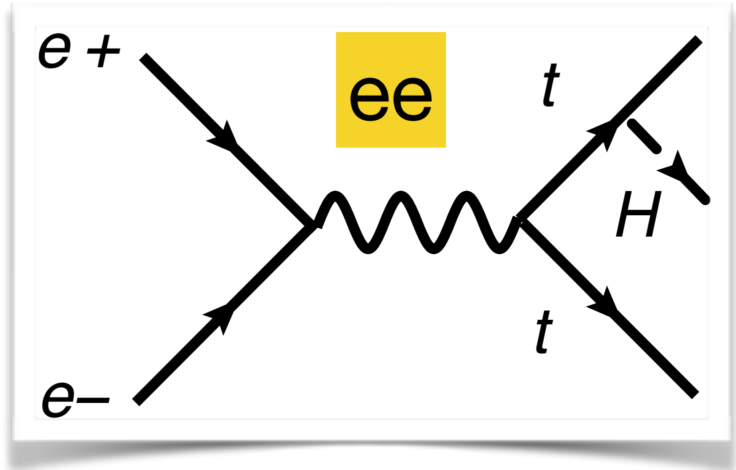
$\sqrt{s}_{spread} = \Gamma_H$, L_{int} = 10 ab^{-1}: S ≈ 0.7, BR(Hee) < 2.8×BR_{SM}, $g_{eH} < 1.7\times g_{eH,SM}$ (95% CL)

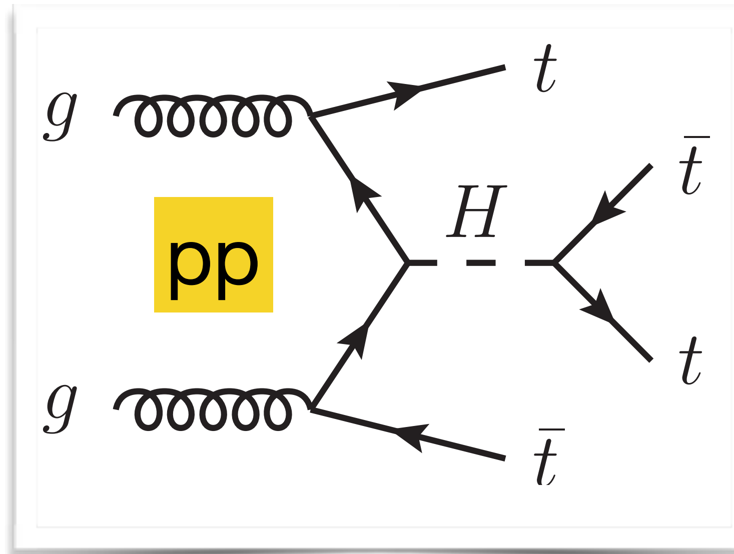
- Challenging performances: Mono-chromatization to achieve $\sqrt{s}_{spread} \sim \Gamma_H$
- Fundamental & unique physics accessible:
  - → Electron Yukawa coupling
  - → Higgs width measurable ("natural" threshold scan)?

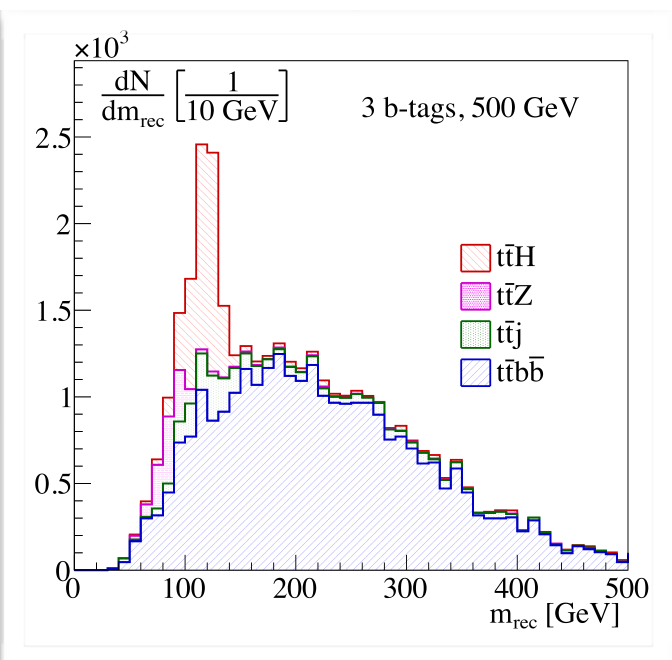
Top Yukawa Coupling

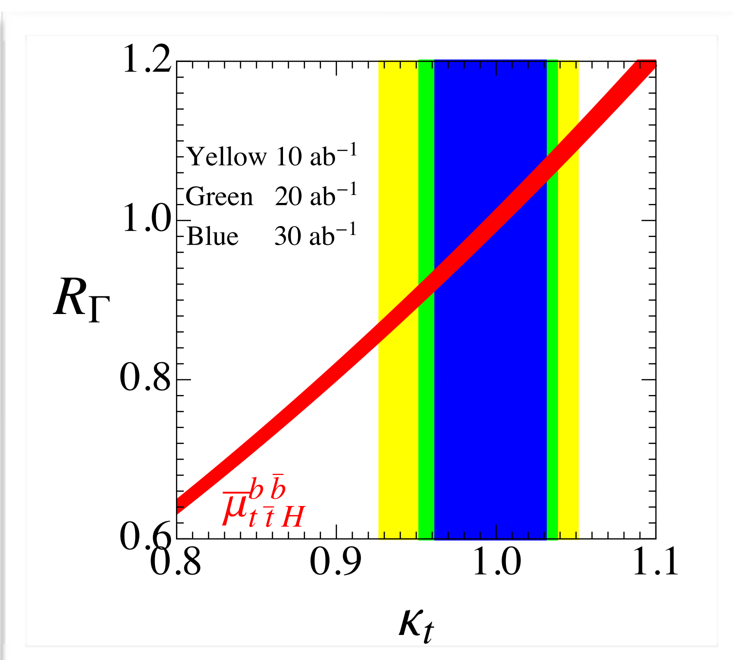
FCC-hh wiki

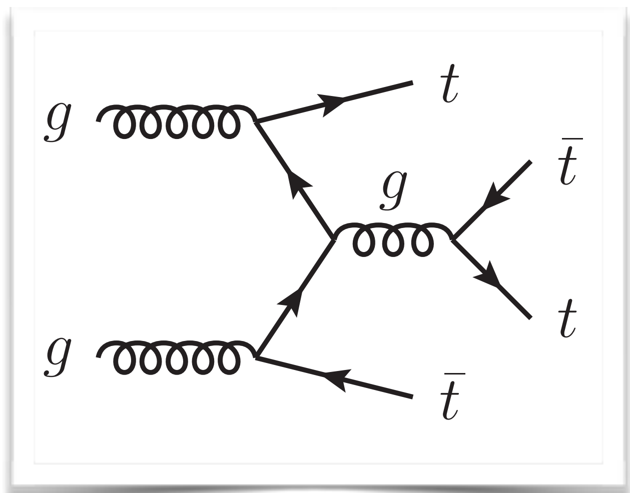
- Likely measured to ~10% by HL-LHC
- Need √s > 500 GeV to be accessible for lepton colliders
  - CLIC: 3.1%, ILC: 6.3%
- 60x cross-section increase from 13-100 TeV
  - Cut on Higgs p_T to reduce backgrounds
- Ratio of ttH/ttZ to cancel theory uncertainties: 1%?
- tttt production to make width independent measurement of κ_t











Rare modes

FCC-hh wiki

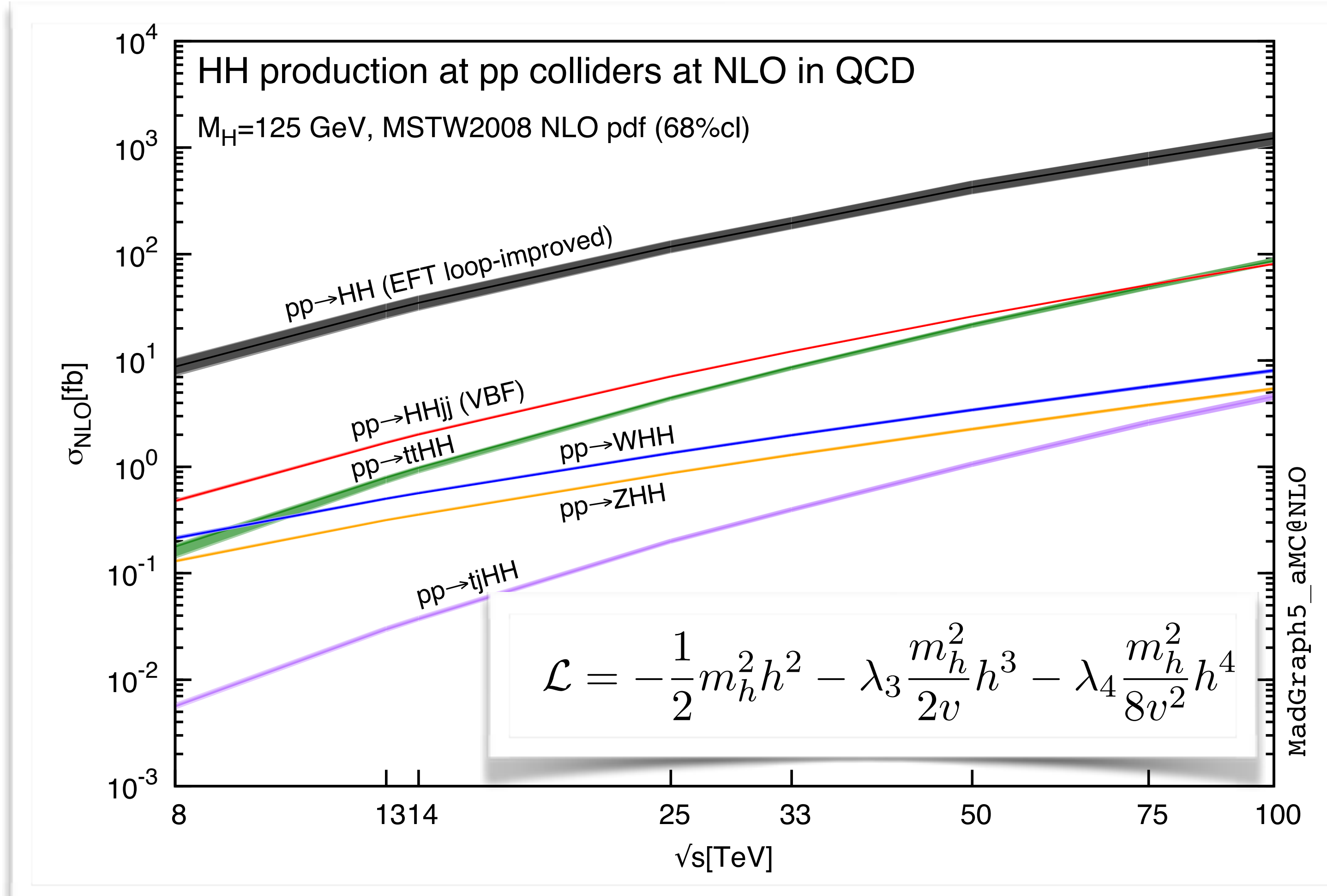
- At 100 TeV, production cross-sections for very **rare modes** become non-negligible
- Huge increase for pp→Htj: 250x 8 TeV (no cuts)
- Could use HVV to constrain possible anomalous Higgs couplings to vector-boson (and fermion) pairs?,
    - perturbative unitarity at high energy
    - anomalous triple-vector-boson vertices

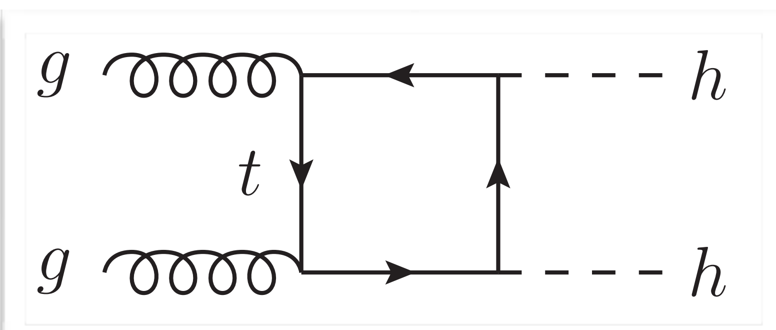
100 TeV/8 TeV

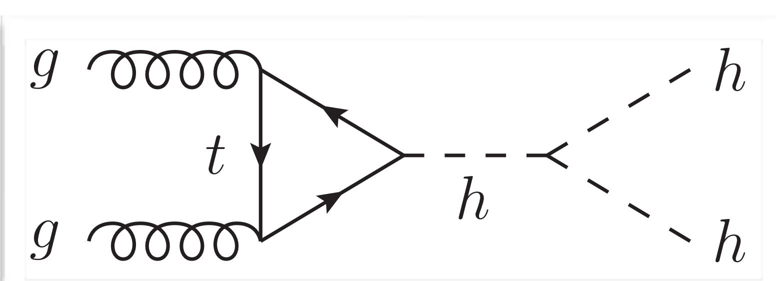
Process	σ_{NLO}(8 TeV) [fb]	σ_{NLO}(100 TeV) [fb]	ρ
$pp \rightarrow Htj$	$2.07 \cdot 10^{1}\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21 \cdot 10^{3}\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \rightarrow HW^{+}W^{-}$ (4FS)	$4.62 \cdot 10^{0}\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^{2}\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \rightarrow HZW^{\pm}$	$2.17 \cdot 10^{0}\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94 \cdot 10^{1}\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \rightarrow HW^{\pm}\gamma$	$2.36 \cdot 10^{0}\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75 \cdot 10^{1}\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \rightarrow HZ\gamma$	$1.54 \cdot 10^{0}\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29 \cdot 10^{1}\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \rightarrow HZZ$	$1.10 \cdot 10^{0}\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^{1}\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38

HH Production

- Measure Higgs potential to study EW symmetry breaking
- Not just enough to measure HH; need to extract self-coupling
  - Destructive interference between diagrams
- Need high energy and high luminosity







process	σ(14 TeV) (fb)	σ(100 TeV) (fb)	accuracy
HH (ggf)	$45.05^{+4.4\%}_{-6.0\%} \pm 3.0\% \pm 10\%$	$1749^{+5.1\%}_{-6.6\%} \pm 2.7\% \pm 10\%$	NNLL matched to NNLO
$HHjj$ (VBF)	$1.94^{+2.3\%}_{-2.6\%} \pm 2.3\%$	$80.3^{+0.5\%}_{-0.4\%} \pm 1.7\%$	NLO
HHZ	$0.415^{+3.5\%}_{-2.7\%} \pm 1.8\%$	$8.23^{+5.9\%}_{-4.6\%} \pm 1.7\%$	NNLO
HHW^+	$0.269^{+0.33\%}_{-0.39\%} \pm 2.1\%$	$4.70^{+0.90\%}_{-0.96\%} \pm 1.8\%$	NNLO
HHW^-	$0.198^{+1.2\%}_{-1.3\%} \pm 2.7\%$	$3.30^{+3.5\%}_{-4.3\%} \pm 1.9\%$	NNLO
$HHt\bar{t}$	$0.949^{+1.7\%}_{-4.5\%} \pm 3.1\%$	$82.1^{+7.9\%}_{-7.4\%} \pm 1.6\%$	NLO
$HHtj$	$0.0364^{+4.2\%}_{-1.8\%} \pm 4.7\%$	$4.44^{+2.2\%}_{-2.6\%} \pm 2.4\%$	NLO
HHH	$0.0892^{+14.8\%}_{-13.6\%} \pm 3.2\%$	$4.82^{+12.3\%}_{-11.9\%} \pm 1.8\%$	NLO

Current projections for HH

FCC-hh wiki
CLICdp - to be published soon

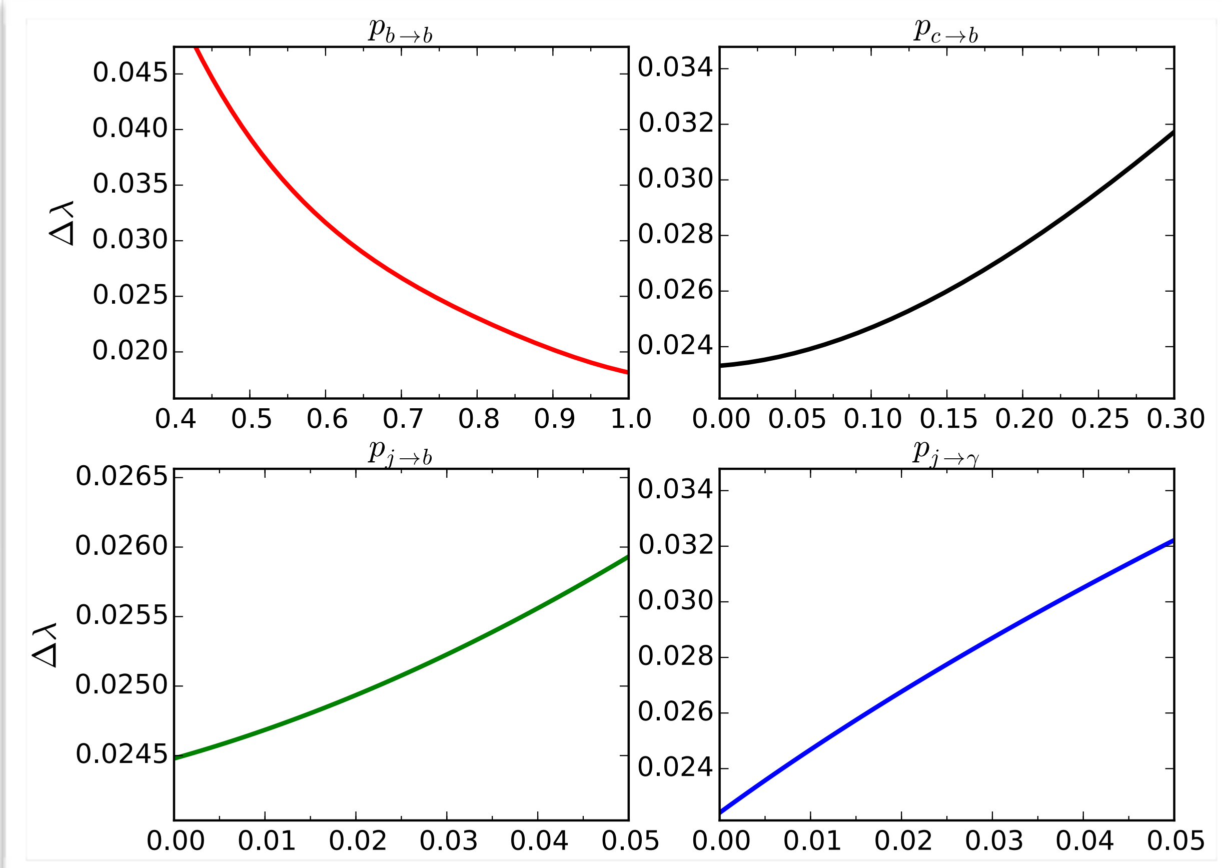
- HH is a benchmark process for pp colliders: bbɣɣ is most sensitive channel: many channels needed
- Depends on detector performance assumptions (e.g. flavour tagging performance)
- CEPC ~35% (radiative corrections at 240 GeV)
- ILC ~27% with √s = 500 GeV (ZHH)
- CLI: WW fusion (vvHH) at √s = 1 TeV and polarised beams

	√s=1.4 TeV	√s=3 TeV
Unpolarised	32%	16%
P(e⁻)=-80%	24%	12%

FCC-hh

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

bbɣɣ



Conclusion

- Exciting time to think about the future of collider physics
  - **Many options** are currently being discussed
- **Lepton colliders** (ILC, CLIC, CEPC, FCC-ee) would provide Standard Model and Higgs coupling measurements to unparalleled precision
  - Typically <1%
  - Indirect sensitivity to new physics
- **Hadron colliders** (HL-LHC, SppC, FCC-hh)
  - Obvious discovery potential
  - High energy and luminosity allow accurate measurements of rare modes, e.g. ttH, HH, H→μμ
- **High complementarity** between different options
  - Looking forward to a rich future !

Back up