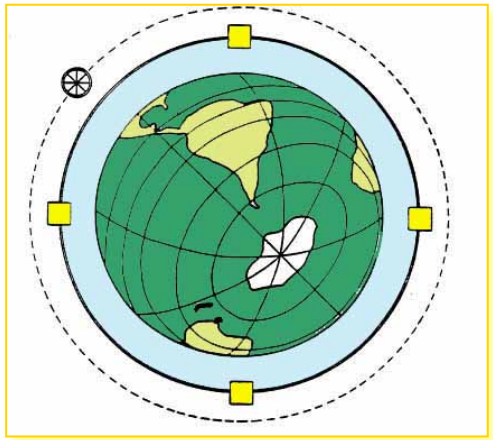
Physics Opportunities at Very High Energy Machines

S. Dawson, BNL

Presentation to P5

Dec 16, 2013



What is the Physics Case?

- 33, 70,…..,100 TeV pp
- 3 TeV e^+e^-
- Up to 10 TeV $\mu^+\mu^-$

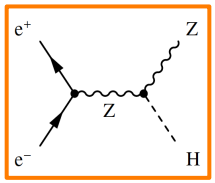
} + precision measurements at lower energies

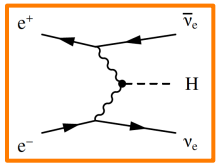
- ***After the Higgs, no guaranteed discoveries***
  - But many questions remain suggesting new physics beyond the SM (flavor, dark matter….)

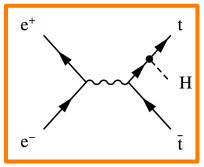
High energy machines are discovery machines

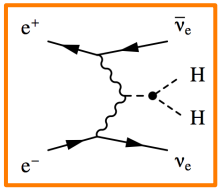
CLIC Physics in a Nutshell

- Staged approach:
  - 500 fb^{-1} @ 350 – 375 GeV : precision Higgs and top physics
  - 1.5 ab^{-1} @ ~1.5 TeV : precision Higgs, precision SUSY, BSM
  - ~2 ab^{-1} @ ~ 3 TeV : Higgs self-coupling, BSM









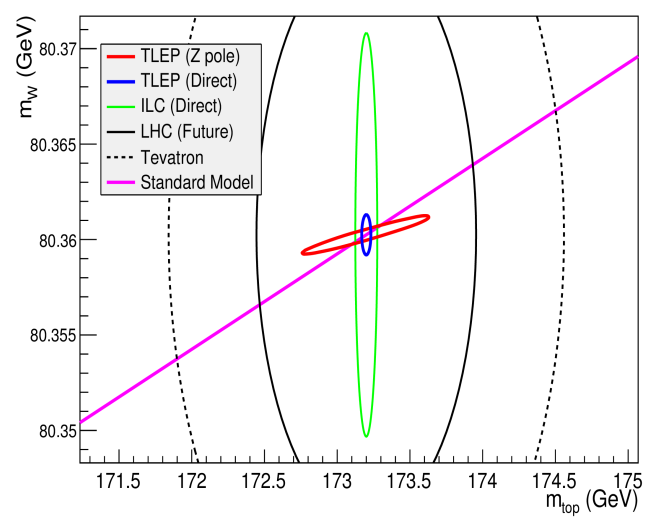
- Exact energy of TeV stages depends on LHC Results
- If LHC discovers new particle that is kinematically accessible, want to explore its properties

High energy pp, High Lumi e^+e^-, and μ Collider

- pp at high energy
  - Optimal energy for physics not yet determined
  - 100 km ring with 15 T magnets gives $\sqrt{s}$=100 TeV
  - Large cross sections for SM processes and BSM discovery
- e^+e^- as 1st step of circular high energy pp
  - High luminosity e^+e^- at $\sqrt{s}$ =90-350 GeV
  - Precision EW measurements and precision Higgs program
- μ collider
  - Run at M_H for precision Higgs mass measurement and subsequent high energy exploration of BSM

FCC/TLEP Physics in a Nutshell

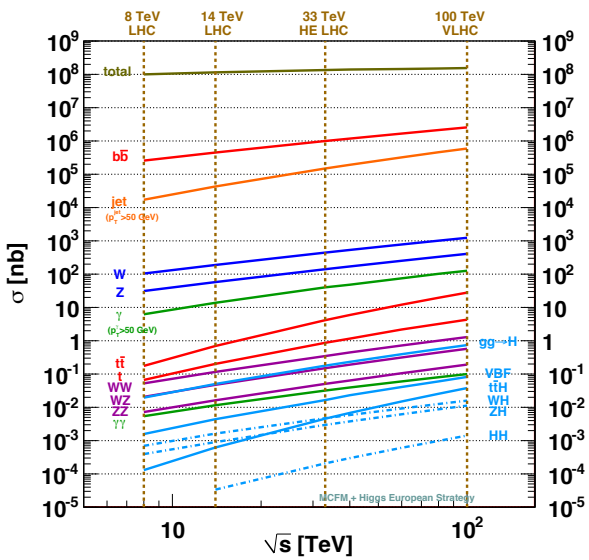
- 10^{12} Z, 10^8 WW, 2 x 10^6 ZH, 10^6 $t\bar{t}$
- Sensitivity to BSM physics through precision Z, W, H, t processes
  - Higgs invisible width to .16%, $g_{H\gamma\gamma}$ to 1.4%, g_{HZZ} to .05%, $g_{H\tau\tau}$ to .49%
  - ΔM_W = <.5 MeV, ΔM_Z < 100 KeV
- Search for rare processes



[TLEP physics, arXiv:1308.6176]

Bread and Butter SM Physics

- Large samples of W/Z/top/Higgs at high energy pp

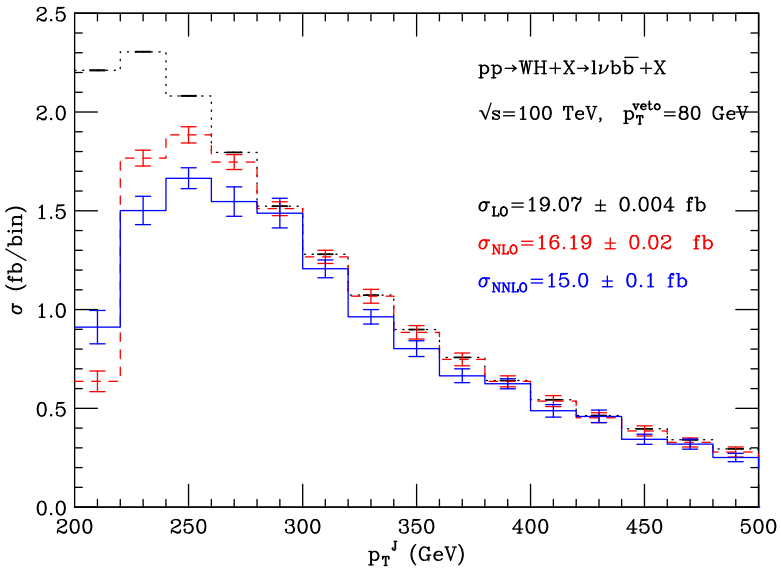


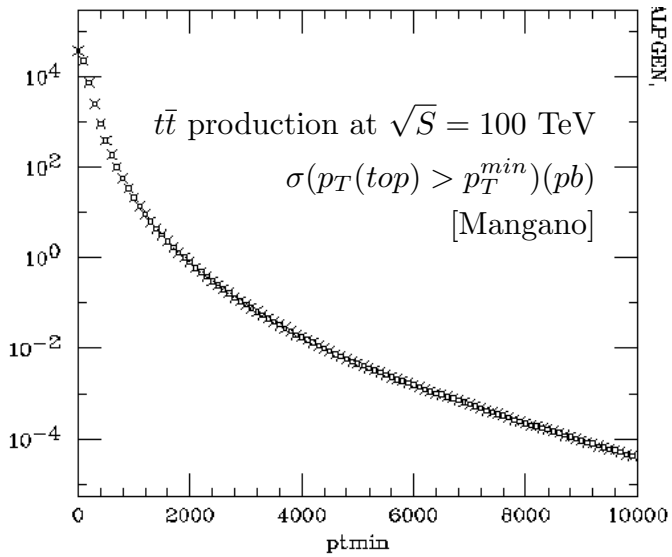
Process	σ(100 TeV)/σ(14 TeV)
W	7
Z	7
WW	10
tt	33

Physics case for using these large samples is in its infancy

SM Physics at High Energy pp Machine

- Large samples at high p_T where new physics might be more readily visible





[QCD Snowmass Report, arXiv:1310.5189]

Precision Measurements of Higgs Properties

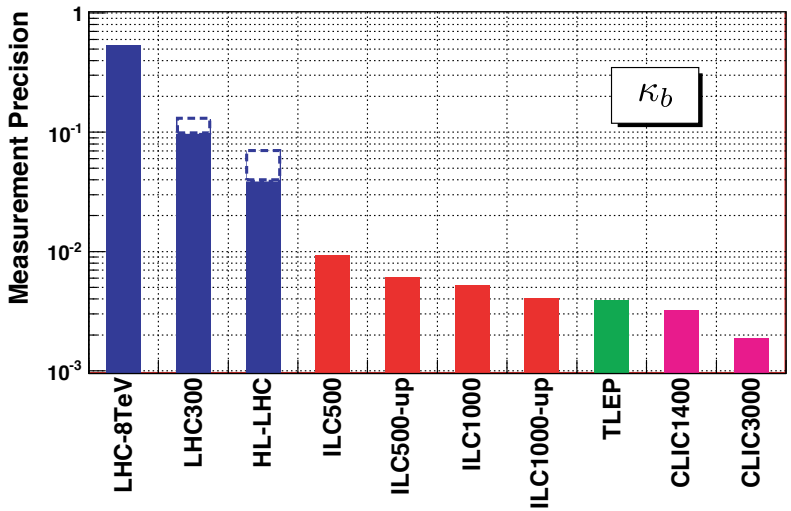
- Large cross sections at high energy pp
- Precision measurements at e^+e^- colliders
- Example: Higgs couplings

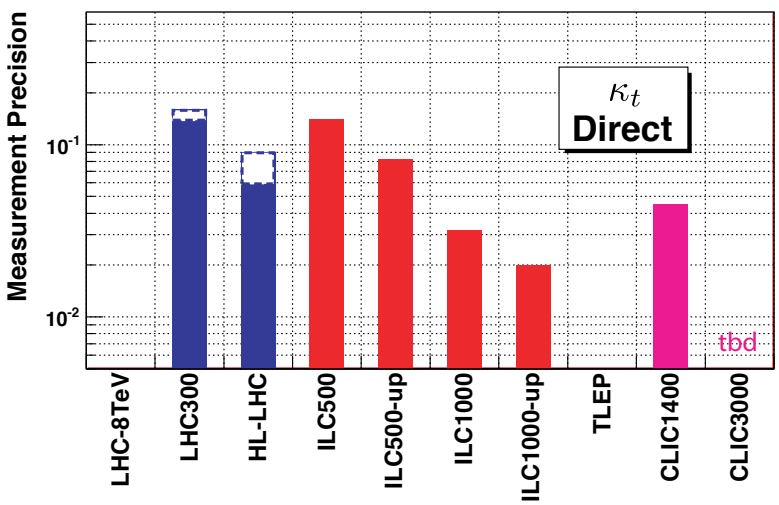
	√S=14 TeV	√S=33 TeV	√S=100 TeV
ggF	50.4 pb	178 pb	740 pb
VBF	4.4 pb	17 pb	82 pb
WH	1.6 pb	4.7 pb	16 pb
ttH	.62 pb	4.6 pb	38 pb
HH	.034 pb	.2 pb	1 pb

[Higgs cross section working group]

Effective Higgs Couplings to Fermions

Does the Higgs have SM couplings?





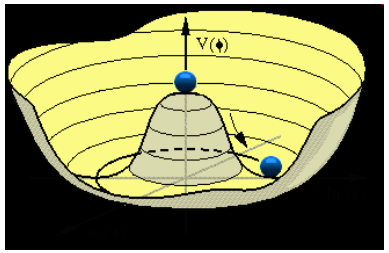
Measurements at the sub-percent level possible

*See Bagger talk for complete set of coupling measurements

[Snowmass Higgs Report, arXiv:1310.8361]

Does the Higgs come from the SM Potential?

$$V = \frac{M_H^{\ 2}}{2} H^2 + \frac{M_H^{\ 2}}{2v} H^3 + \frac{M_H^{\ 2}}{8v^2} H^4$$

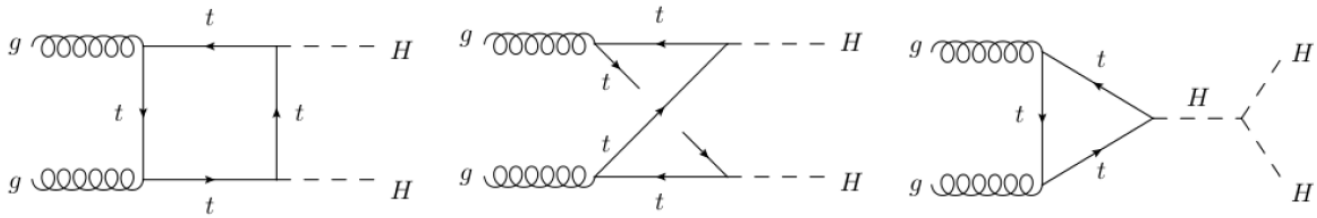


- Need to measure HHH and HHHH couplings
- HHH coupling can be measured with HH production

BSM models can change the HHH and HHHH couplings by factors ~ 10-20%*

*Models are restricted by requiring single H production to have experimentally measured value

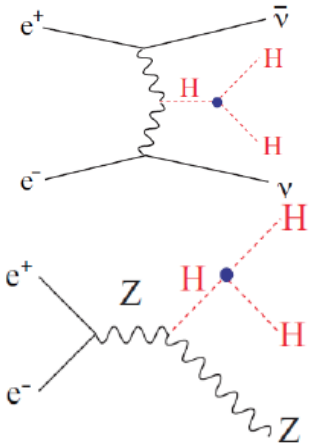
Higgs Self Coupling

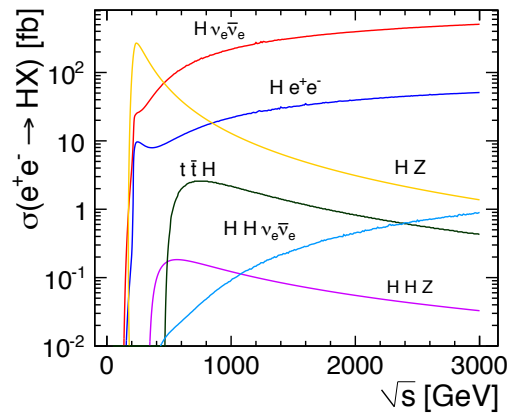


- Sensitive to HHH coupling and new particles in loops
  - Cancellation between box and triangle reduces sensitivity
- Small rates at LHC:
  - $bb\gamma\gamma$ gives 3σ with 3 ab^{-1} (270 events with 3 ab^{-1})
  - 30% measurement of λ_{HHH} with 2 experiments for SM
  - 8% with 100 TeV pp

[Guesstimate from Snowmass Higgs Report, arXiv:1310.8361;
Yao, Snowmass study, arXiv: 1308.6302]

e^+e^- machines also have low rates for HH





	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0, 0)/(-0.8, 0)$	$(0, 0)/(-0.8, 0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

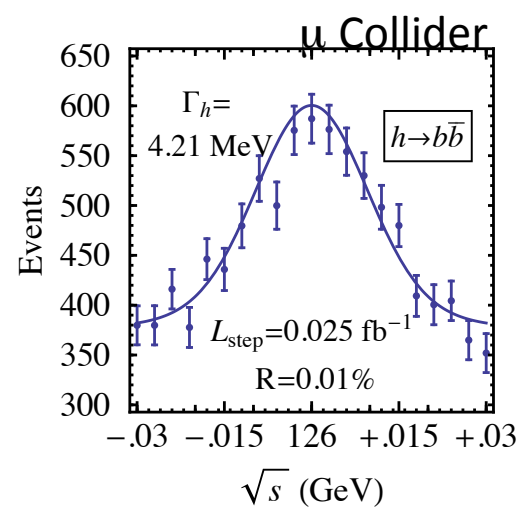
μ Collider δλ < 10% at 6 TeV

Higgs Width/Mass Measurements

	ILC1000	CLIC	TLEP (4 IP)	μC
√S (GeV)	250/500/1000	350/1400/3000	240/350	126
L (fb^{-1})	250+500+1000	500+1500+2000	10,000+2600	
ΔM_H (MeV)	32	20*	7	.06
Γ_H	5.6%	4%*	0.6%	4.3%

- $\mu^+\mu^-$ collider: Energy scan gives M_H, Γ_H
  - s-channel with 4.2 fb^{-1}

    ΔM_H = .06 MeV, $\Delta\Gamma_H$ = .18 MeV



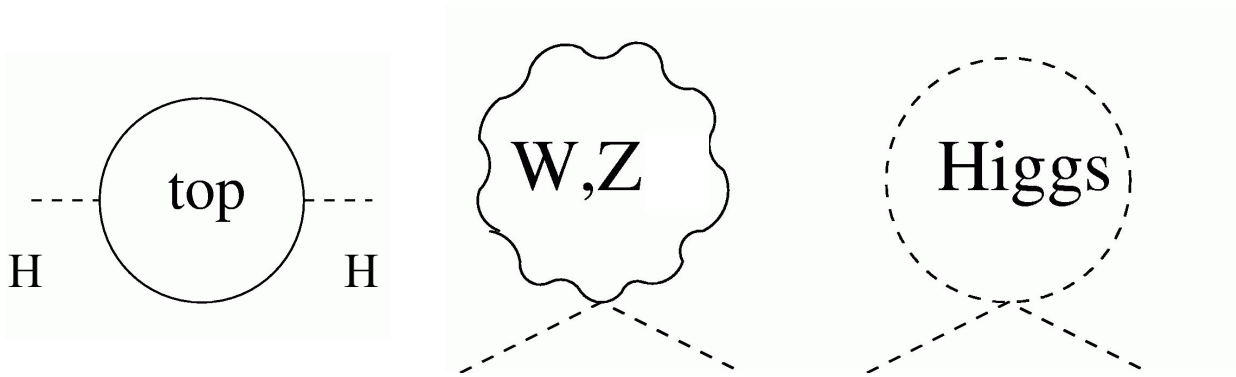
[Table from Snowmass Higgs Report, arXiv:1310.8361; Figure from Han, Liu, arXiv: 1210.7803]

*New since Snowmass

Precision Measurements and BSM Physics

- Precision measurements can point to the existence of new physics, but can't tell you what it is
  - SM framework allowed predictions for m_t and M_H in terms of well defined theory and observables
  - Different case now: Pattern of deviations from SM can suggest possibilities, but there is no standard BSM
  - In some cases, sensitivity to very high scales, but not guaranteed
- High energy machines directly produce particles associated with new physics

Pinpointing the Scale of New Physics



- Higgs mass grows with high scale, Λ (*a priori* $\Lambda = M_{pl}$)

$M_H \leq 200$ GeV requires $\Lambda \sim$ TeV

- Naturalness suggests new physics at (?) TeV scale
- Is scale 1,2,….10 TeV?

Flavor Physics Suggests High Scales

- Δm_K , ε_K probe $(s_L\gamma^\mu d_L)^2$ interaction to ~100 TeV for strength O(1)
- Δm_B probes $(b_L\gamma^\mu d_L)^2$ interaction to ~60-70 TeV

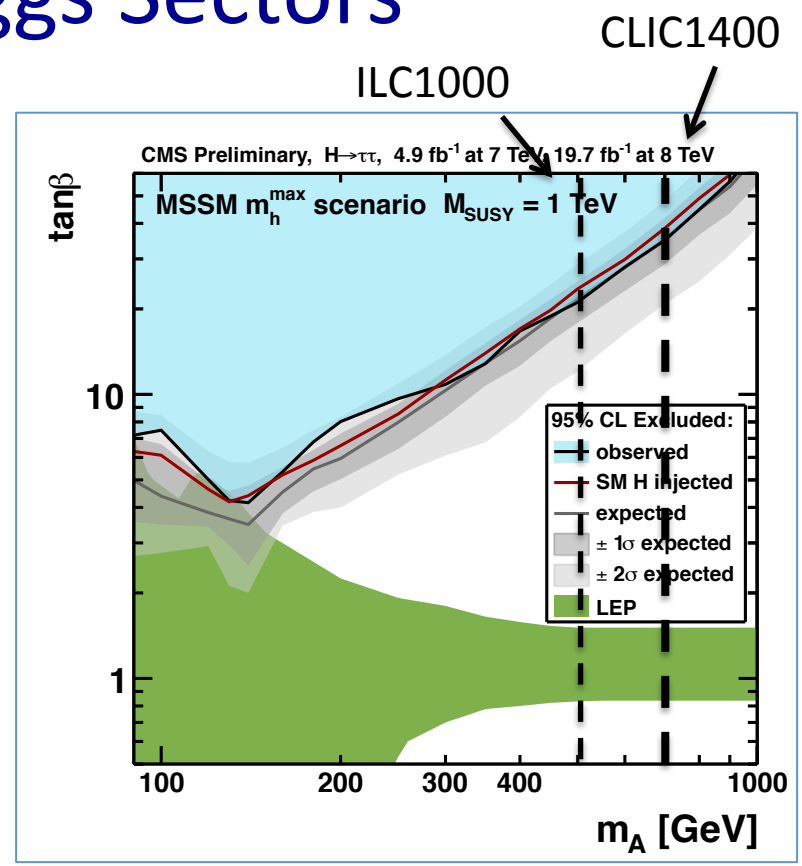
New physics in flavor sector at ~1-10 TeV implies new principles

Discoveries in flavor sector could motivate high energy machines

Extended Higgs Sectors

- MSSM (motivated by naturalness arguments) has 5 Higgs particles
- $e^+e^- \rightarrow AH$ gets to roughly kinematic limit with few assumptions

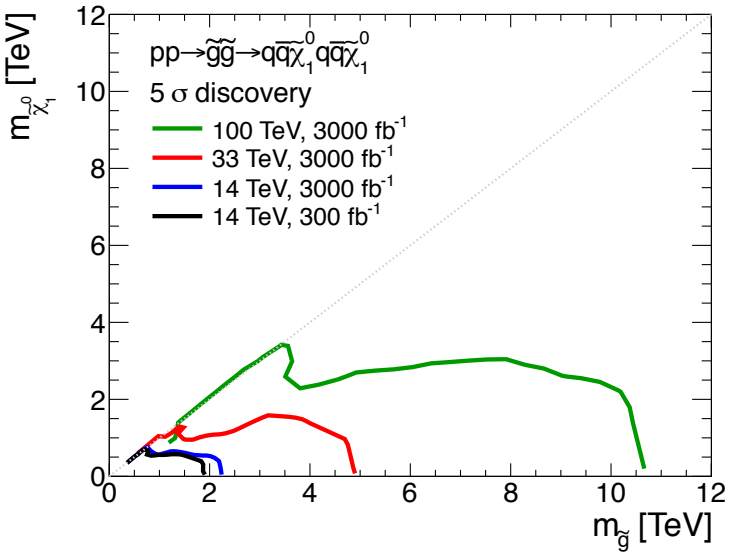
CLIC3000, $\Delta M_{A,H} \sim .3\%$



[CMS PAS HIG-13-021]

Heavy SUSY Searches

- Hadronic cross sections increase rapidly with √s
- Example: Gluino pair production with prompt decay to $q\bar{q}\tilde{\chi}^0$
  - Reach significantly extended at high energy pp



- Discovery of some SUSY particles at LHC motivates higher energy machine to complete exploration of SUSY spectrum
- 100 TeV has discovery reach far beyond LHC

[Cohen et al, arXiv:1310.0077, 1311.6480]

Searches for Weakly Interacting SUSY

- CLIC 3000 discovers squarks, sleptons to ~1.5 TeV
- Precision measurements of charginos/neutralinos
  - For neutralino/chargino masses ~ 650 GeV :

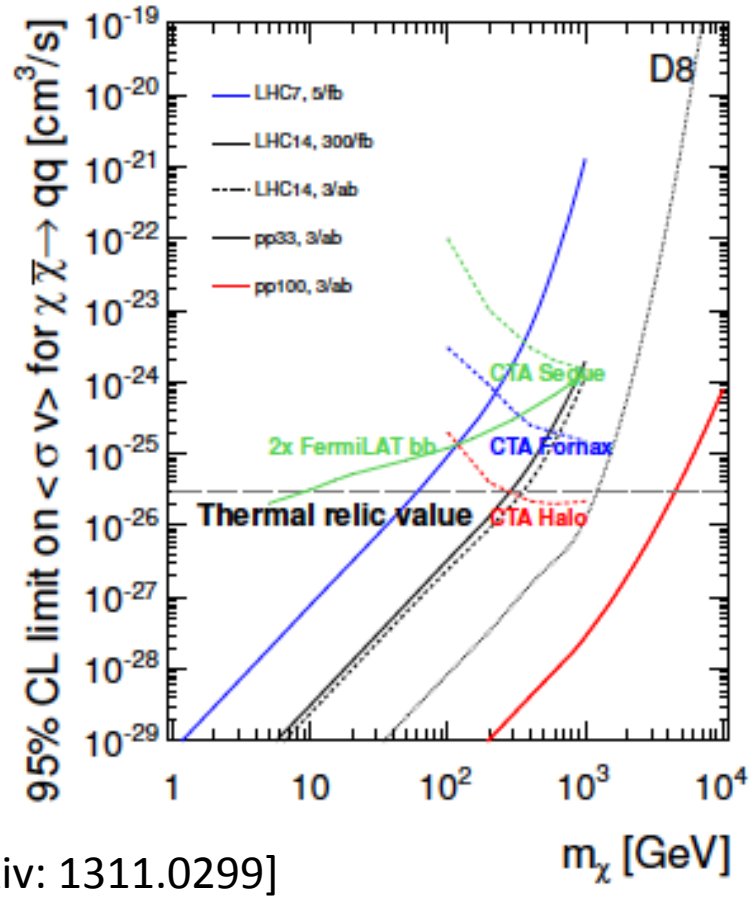
$$\Delta m(\tilde{\chi}^0) \sim \pm 3\ GeV$$
$$\Delta m(\tilde{\chi}^\pm) \sim (7-9)\ GeV$$

If kinematically accessible, precision SUSY program at CLIC (and also μ collider)*

* And also of course for ILC

WIMP Searches

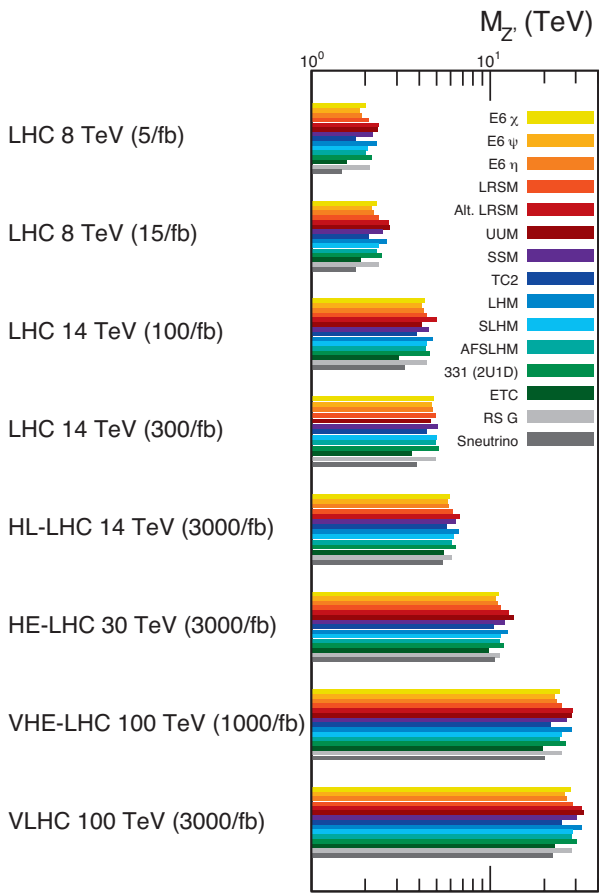
High energy gives large rates for dark matter + jet production



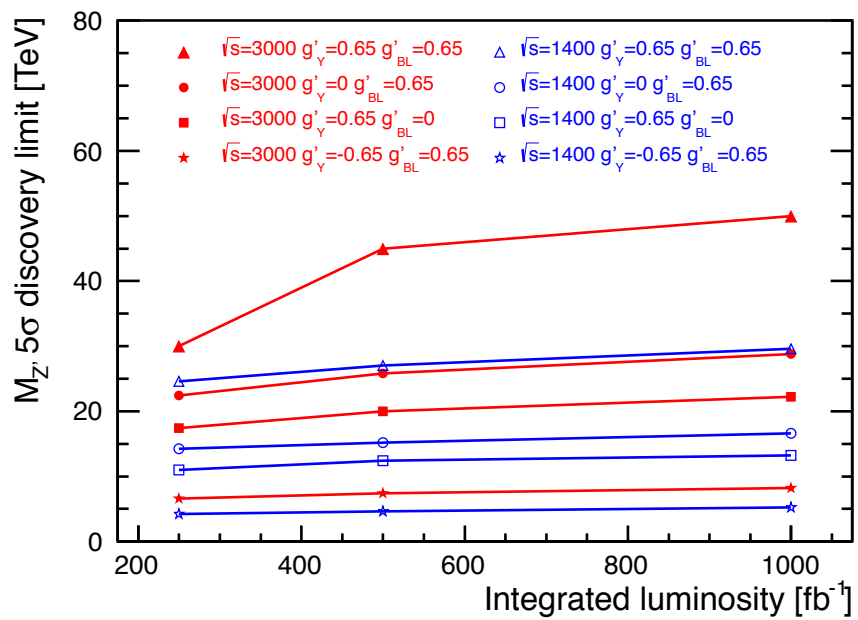
[Snowmass new phenomena report, arXiv: 1311.0299]

New Z' Searches

pp: Direct production of Z'



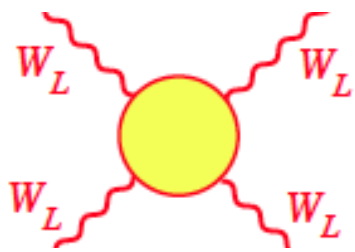
e^+e^-: Interference of Z' with SM



[Godfrey and Martin, arXiv:1309.1688; CLIC snowmass report, arXiv: 1307.5288]

If no new particles at LHC

- Effective Lagrangians can be used to describe physics
  - Construct interactions which respect SU(2) x U(1) symmetry
  - Expand in powers of s/Λ^2: $L \sim L_{SM} + \Sigma f_i O_i/\Lambda^2 + \ldots$
- Effects grow with energy
- Precision measurements of VBF at CLIC, high energy pp

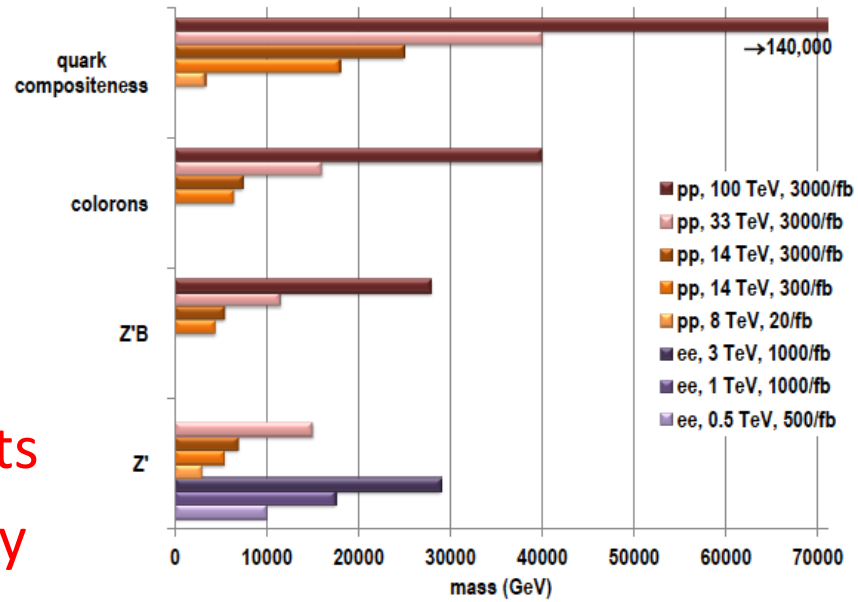


[Electroweak Snowmass Report, arXiv: 1310.6708]

Conclusion: The Case for Higher Energies

- Precision measurements of SM quantities
  - Window to BSM physics
  - λ_{HHH} is poster child
- Exploration of new heavy particles
  - Motivation from LHC results
  - 100 TeV has large discovery reach

Heavy Particle Reach



[New phenomena snowmass report, arXiv:1311.0299]