What future energy frontier colliders may teach us*

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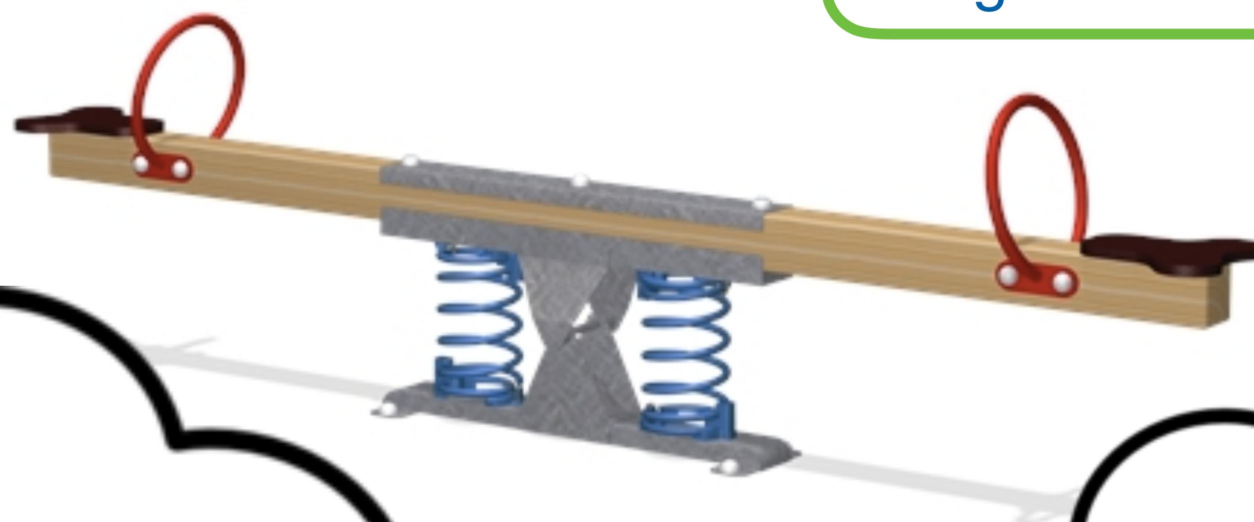
* It is impossible to capture immense effort and delicate subtleties in a brief overview. Apologies for painting with a broad brush!

Energy Frontier overview

Higher energy has always led to new discoveries

Concrete and well-articulated goals and benchmarks



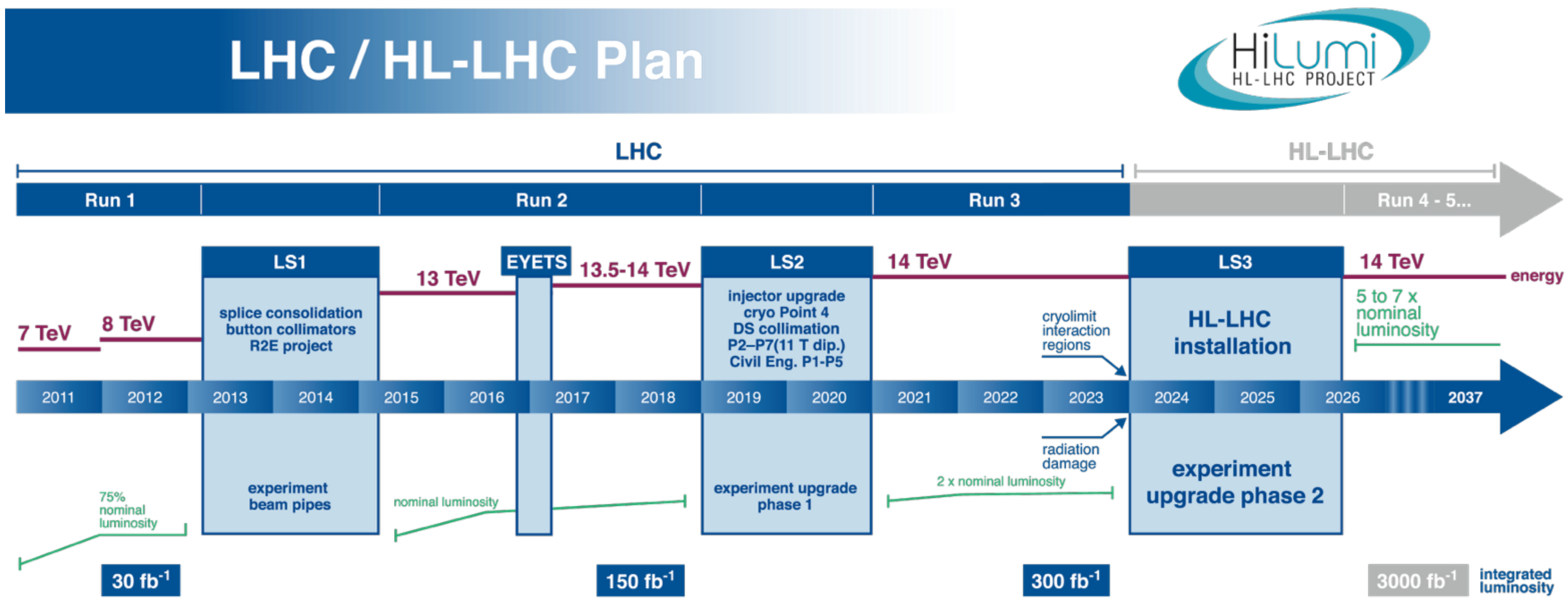
Where are the new particles responsible for explaining existing phenomena (DM, matter-antimatter asymmetry, ν masses, naturalness …)?

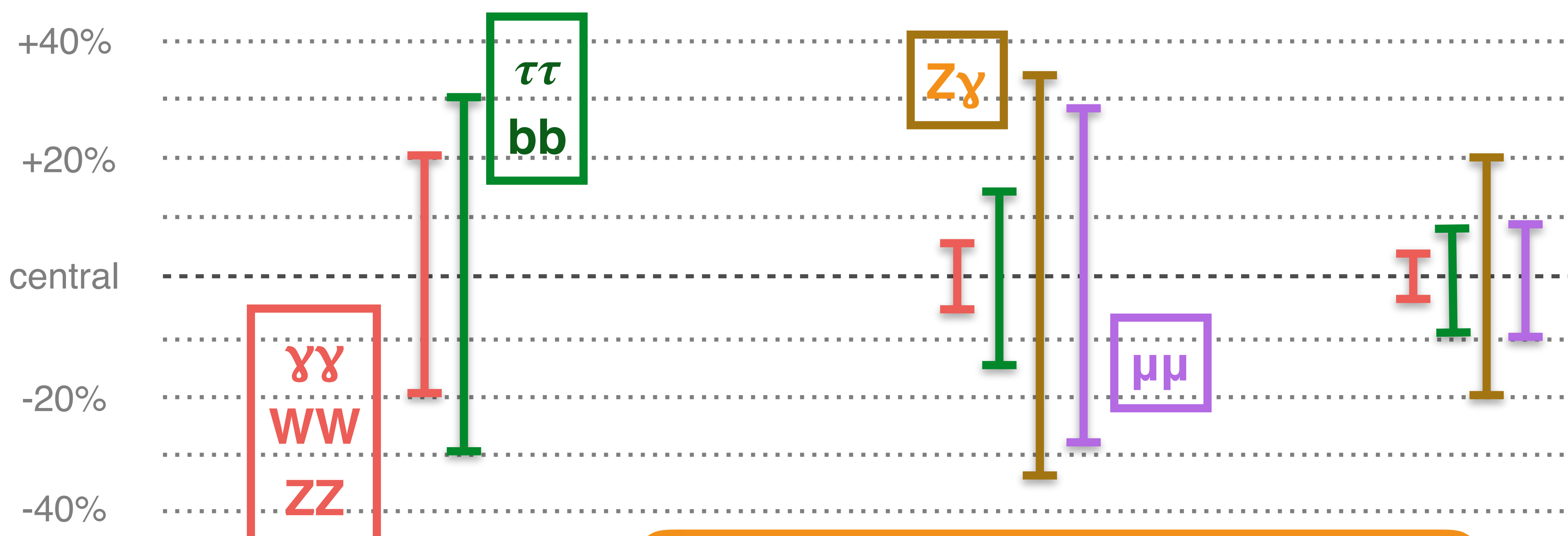
To what level of precision does the observed Higgs boson look like the SM one?

No guarantee of direct observation of new particles implies a program of precision measurements

[Adapted from Hadron Collider Study Group, Snowmass 2013]

HL-LHC evolution of Higgs measurements





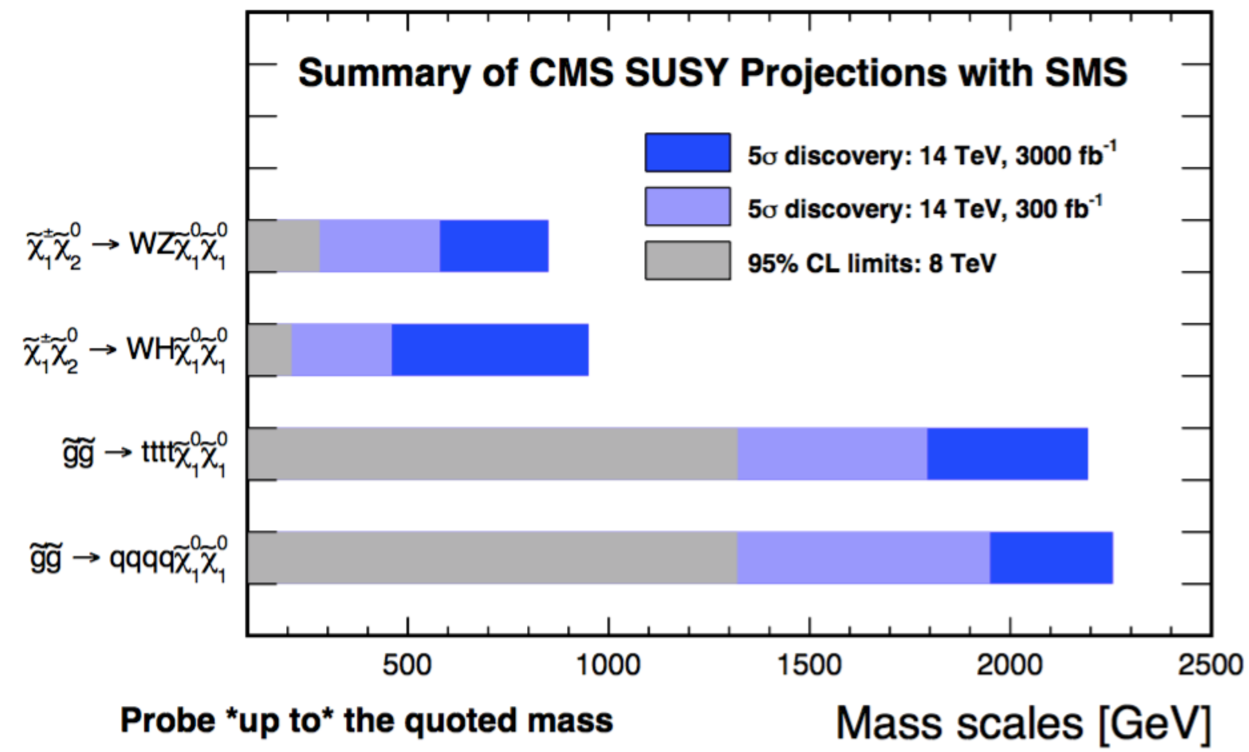
[approximate, based on combining ATLAS ECFA14 contribution and LHCC-P-008]

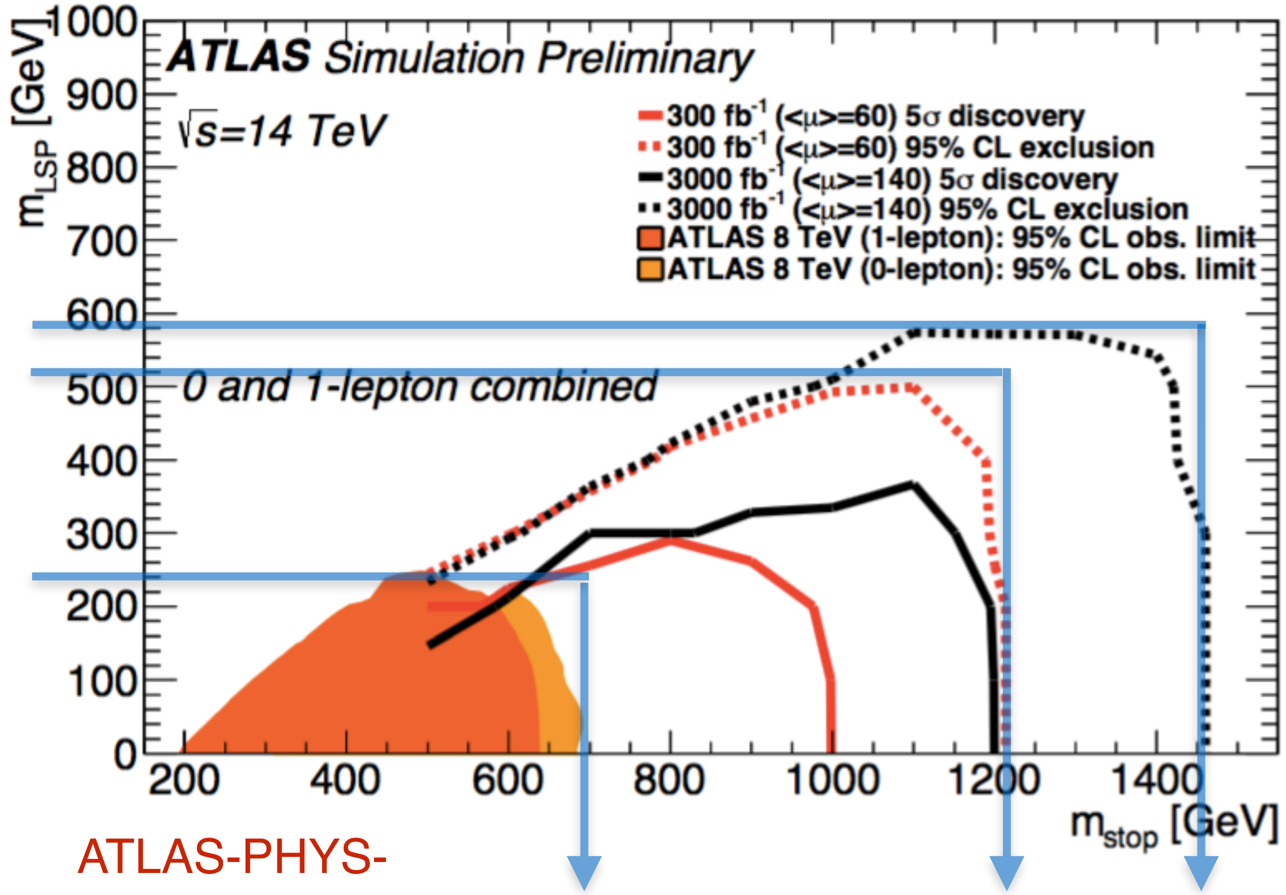
~ 10% precision, 2^{nd} gen. (charm?)

Fermilab

HL-LHC: searches and more

CMS Phase-II Upgrade Proposal, LHCC-P-008





ATLAS-PHYS-PUB-2013-011

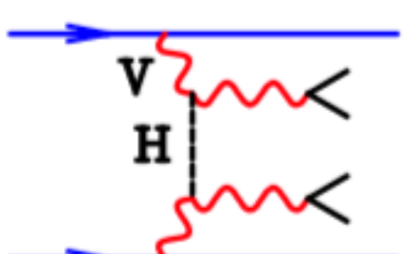
~ now

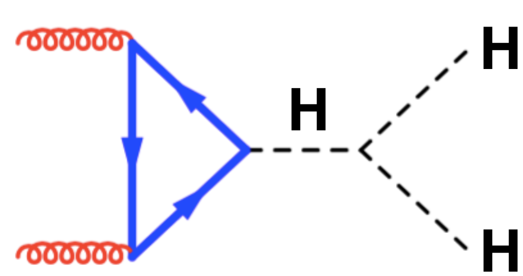
$300 fb^{-1}$

$3ab^{-1}$

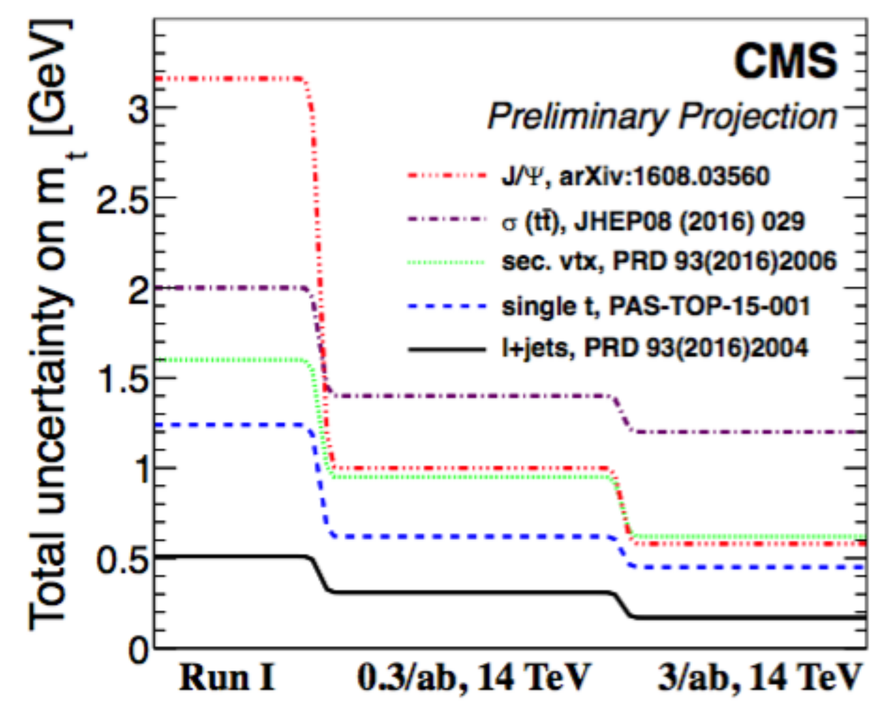
access to broad spectrum of channels key to uncovering subtle signals

explicit test of Higgs unitarity role and evidence for pair production

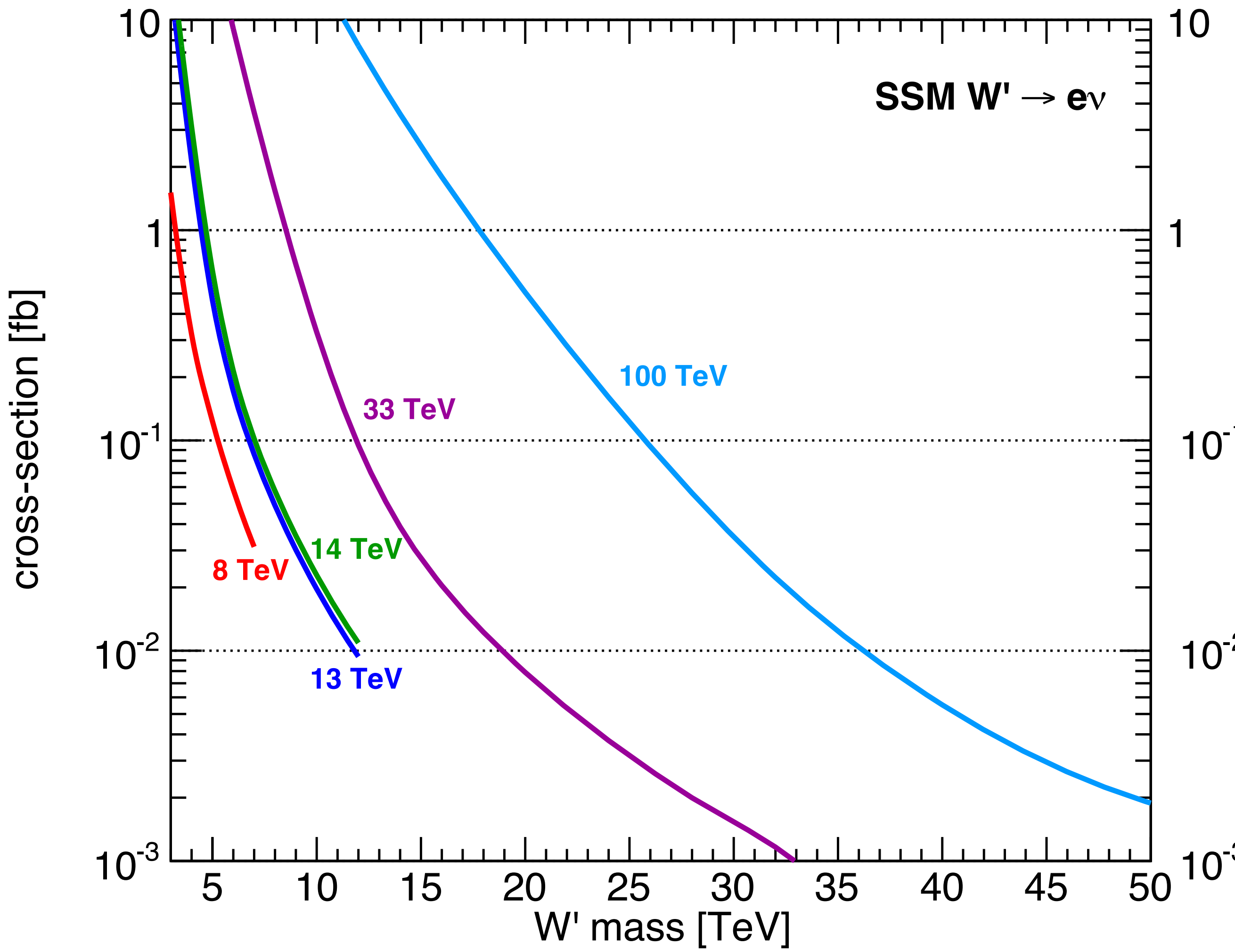


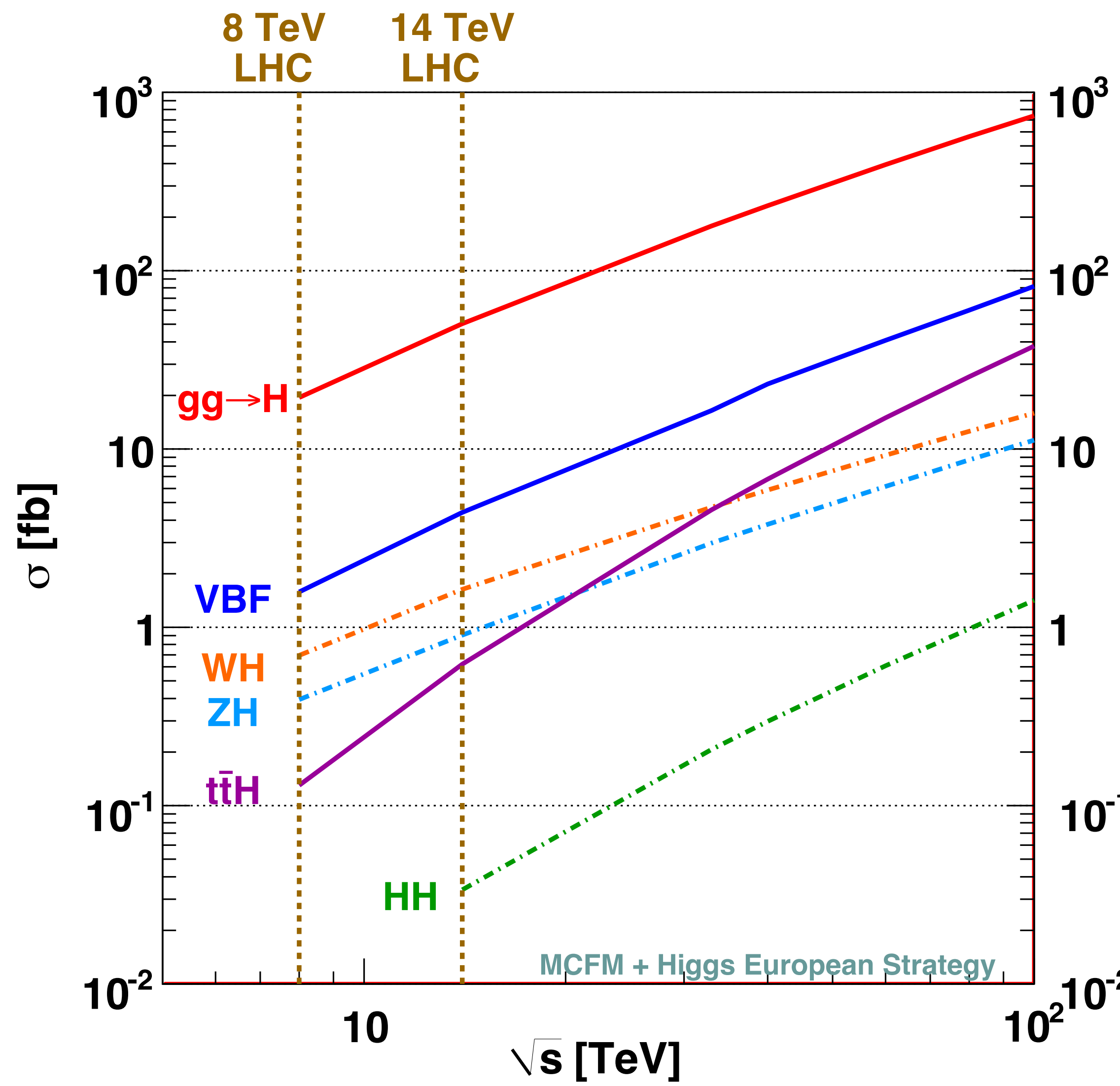


~ 0.2–0.5% top mass



Hadron colliders up to 100 TeV





begin precision test of Higgs potential

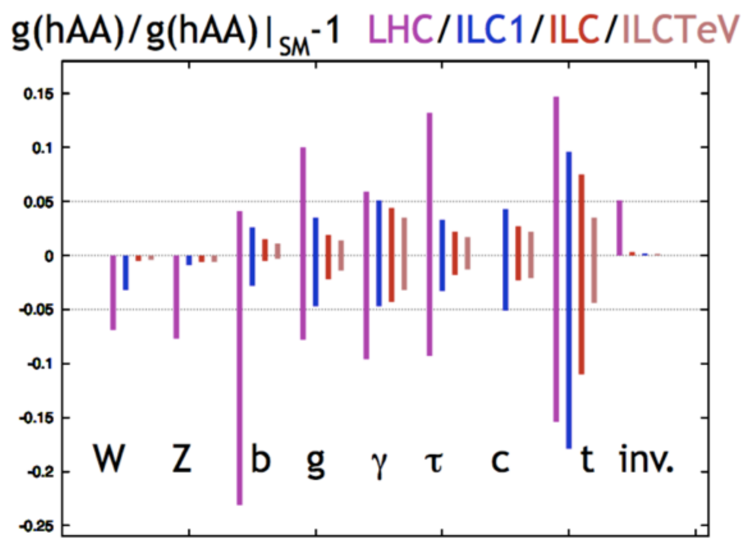
$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

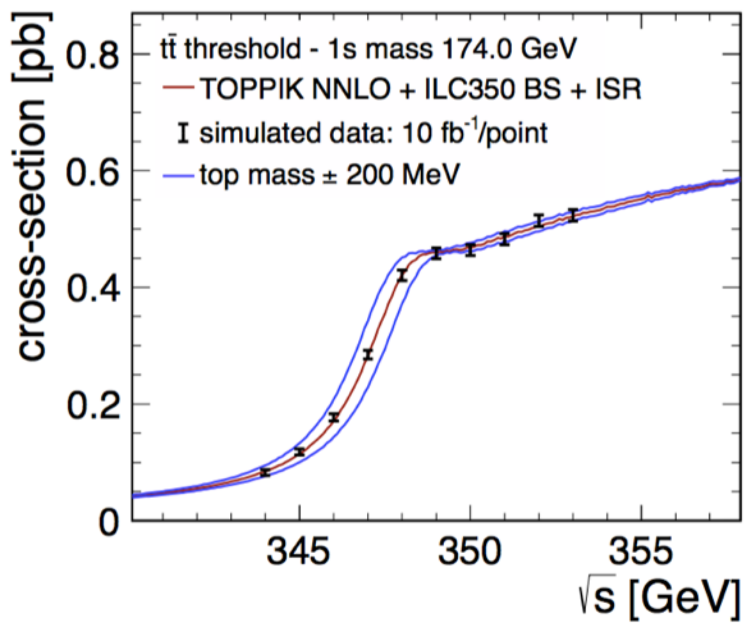
few % | O(500%)

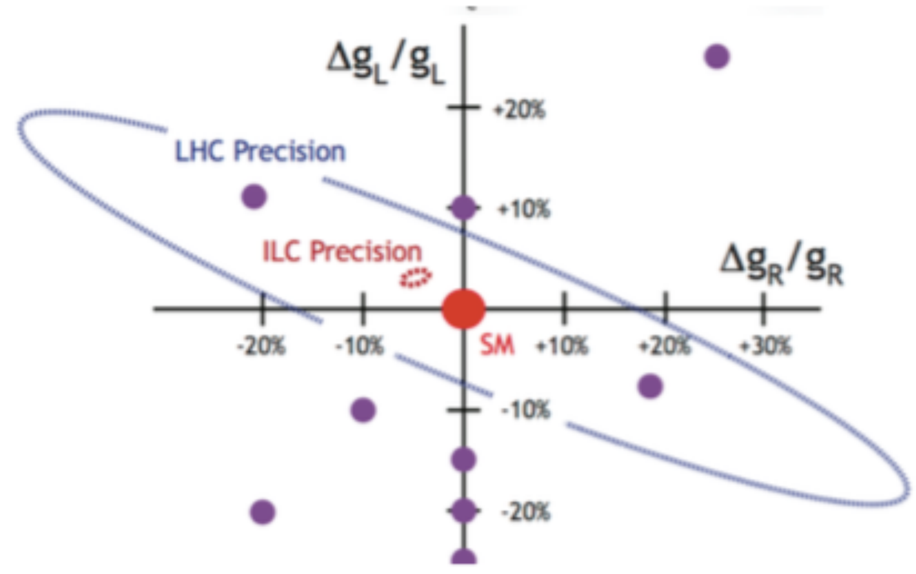
process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$

Physics at a 100 TeV pp collider: Higgs and EWSB studies

Lepton colliders up to a TeV (ILC)







Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

ILC TDR - Physics

"Giga-Z" EW precision x 10
"Mega-W" W mass ~ MeV

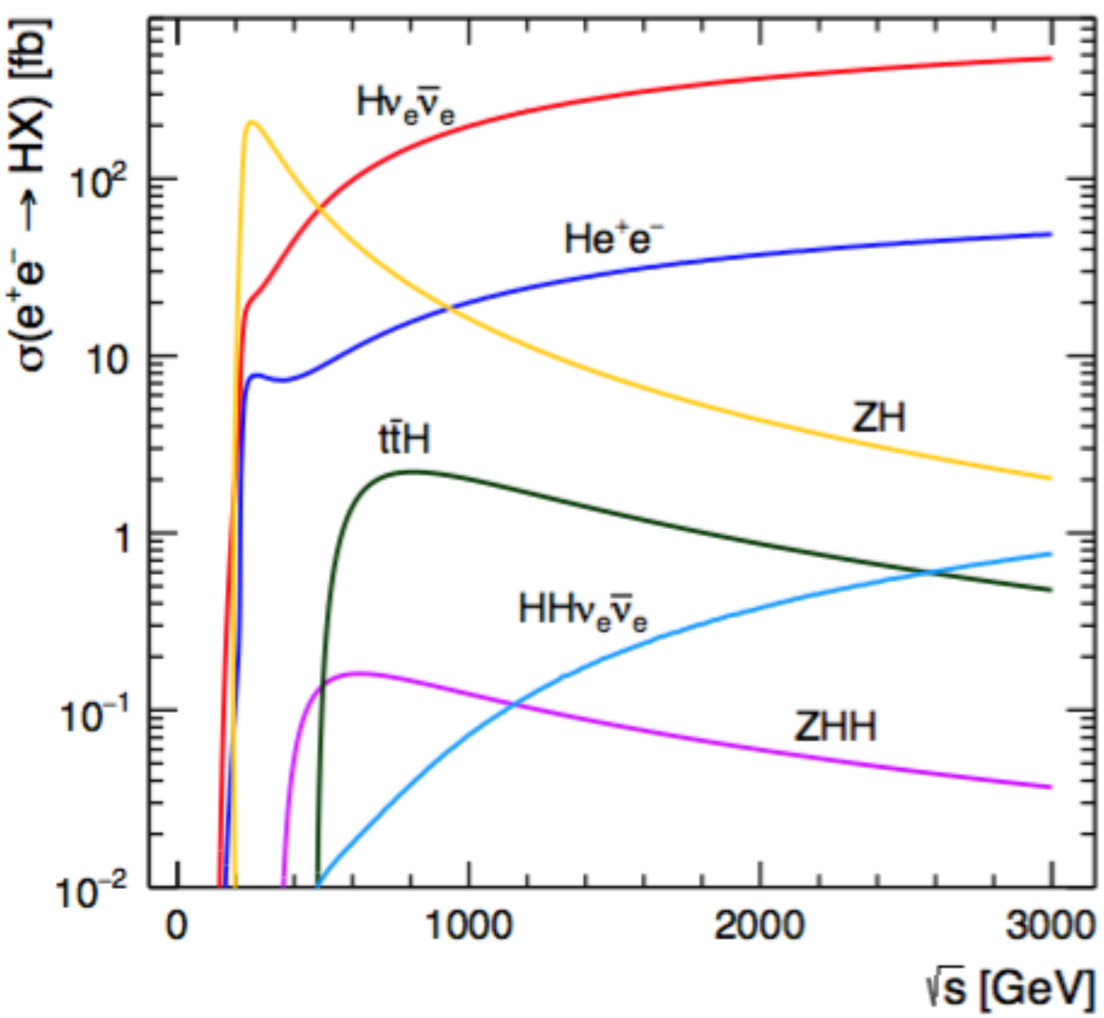
top mass O(100 MeV)

Higgs couplings 1-7%, width 2-5%
self coupling (λ_3) ~ 20-100%,

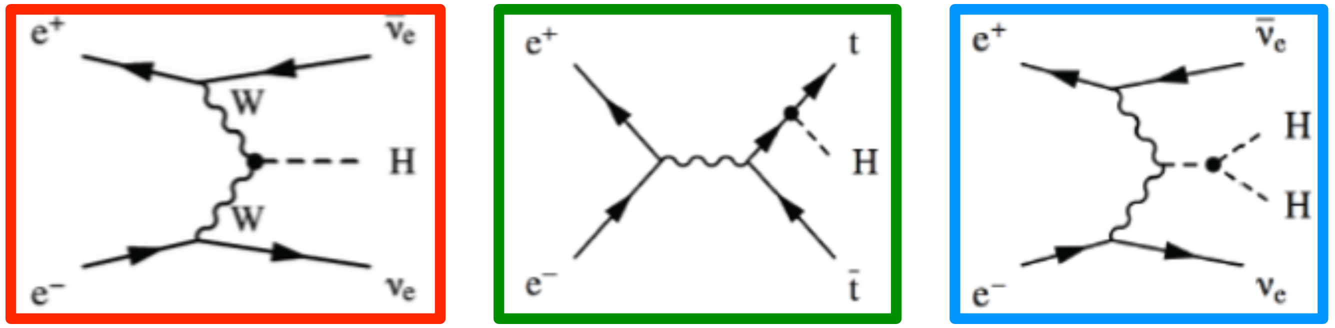
unprecedented precision studies of any newly-discovered particles

Multi-TeV lepton colliders (CLIC, muon collider)

- Many physics processes blind to difference between electrons and muons.
- Staging scenarios of CLIC can give similar physics as ILC, but gain new sensitivity in TeV range.



Higgs Physics at the CLIC Electron-Positron Linear Collider



Higgs mass ~ 40 MeV

Top Yukawa ~ 5%

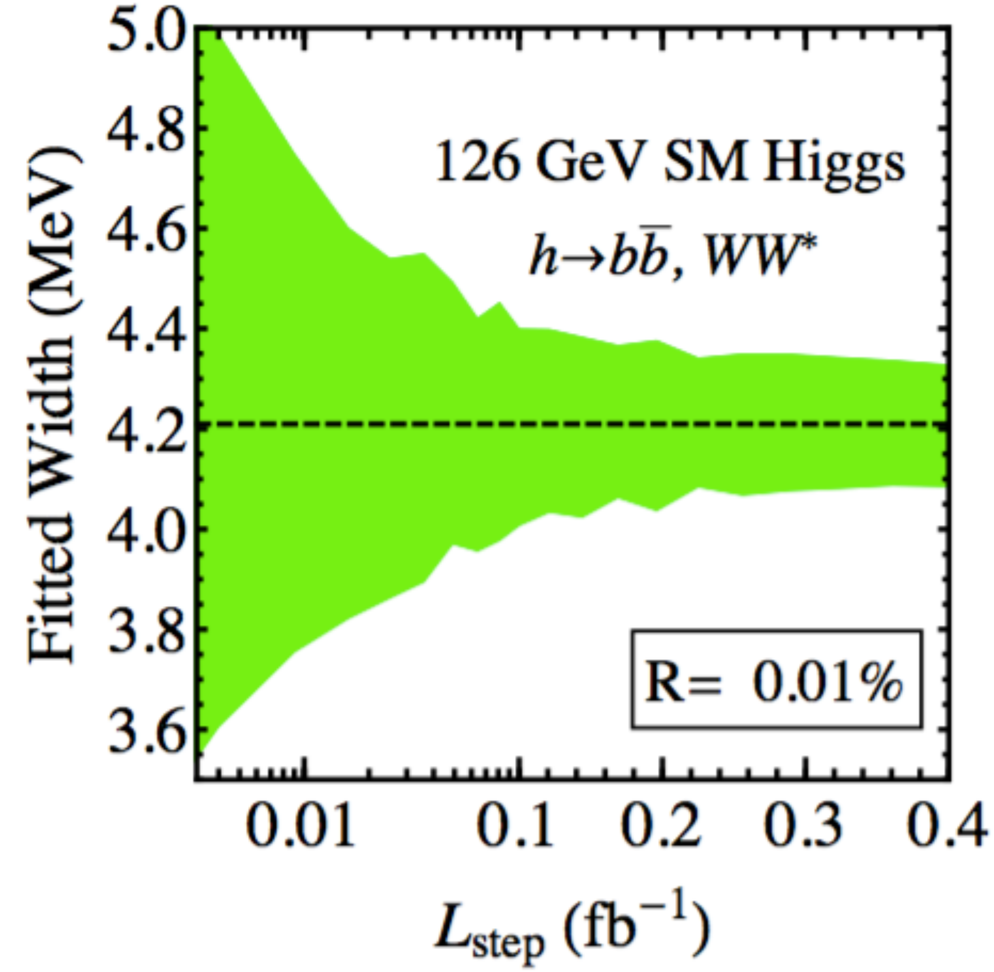
Trilinear Higgs coupling ~ 10%

O(1%) precision on “typical” BSM (supersymmetry) cross-sections and masses in 0.5 – 1 TeV range

Muon collider

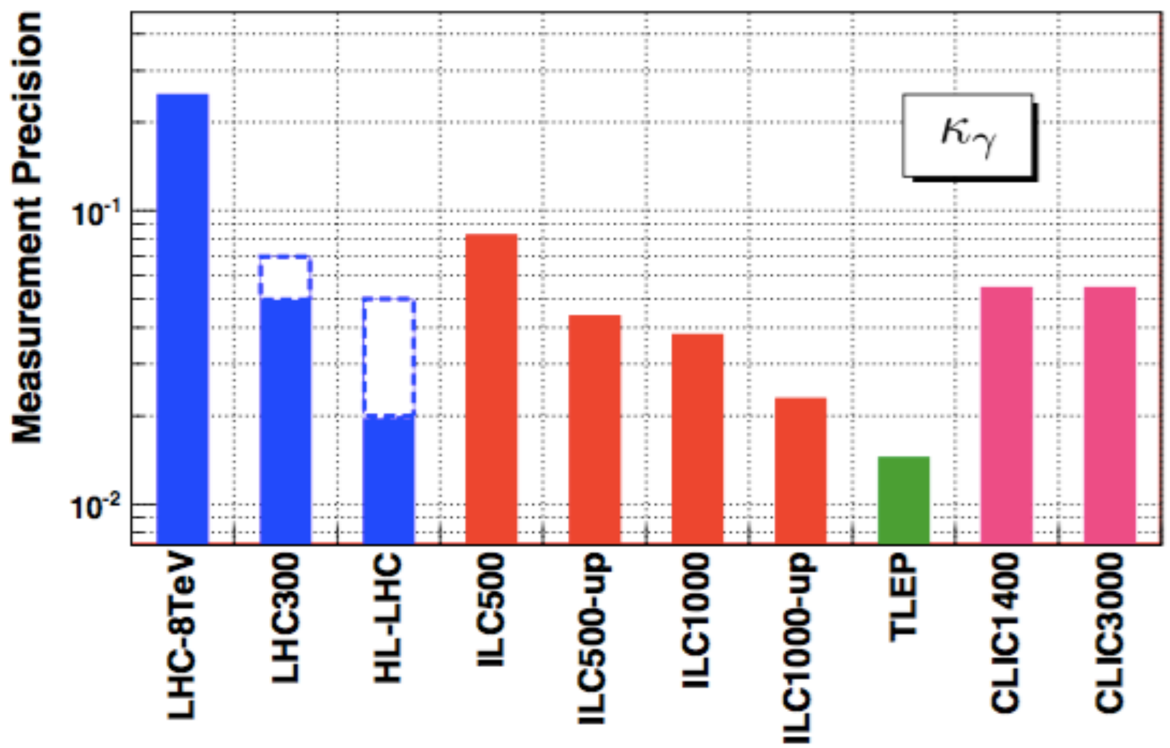
- Unique aspect of a muon collider is clearly precision probe of Higgs coupling to muons.
- Possibility to stage as a Higgs factory, for precision measurement of Higgs boson mass and width by line-shape scan.
- Special synergy: exploit similarity in front-end facilities to stage as neutrino factory for oscillation program (c.f. nuSTORM).

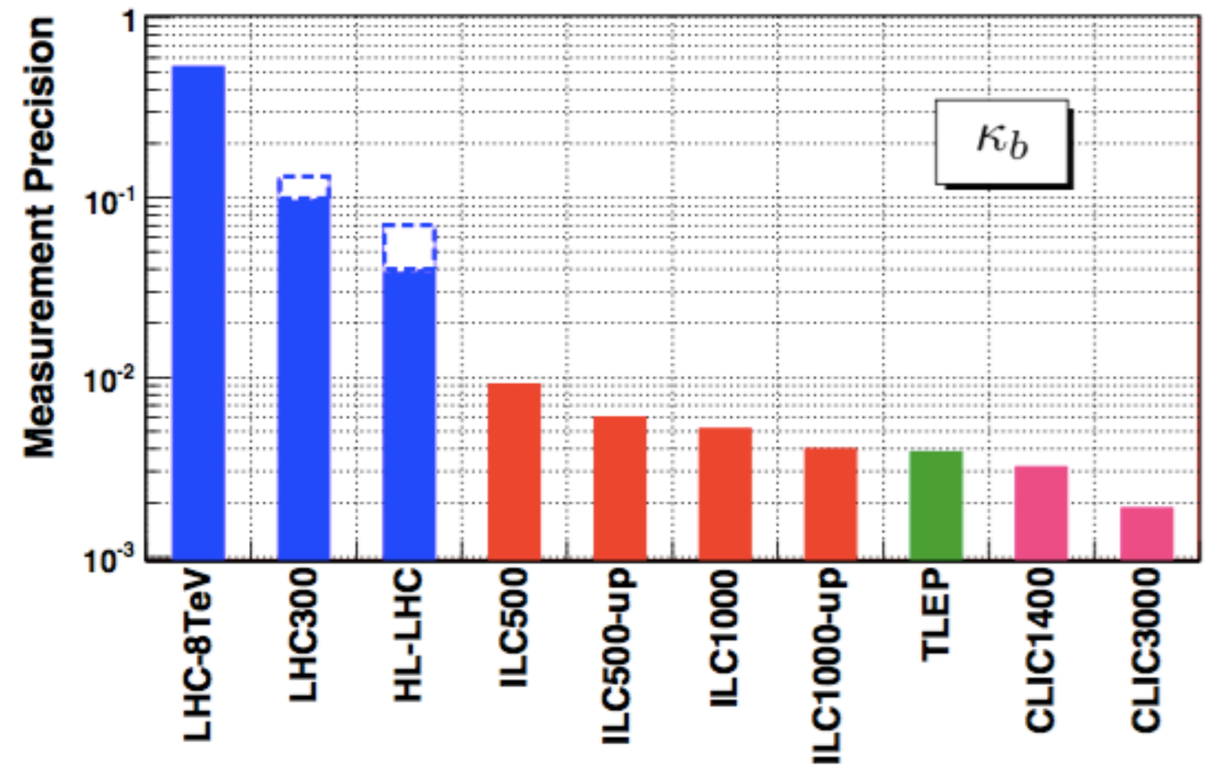
Han and Liu, arXiv:1210.7803



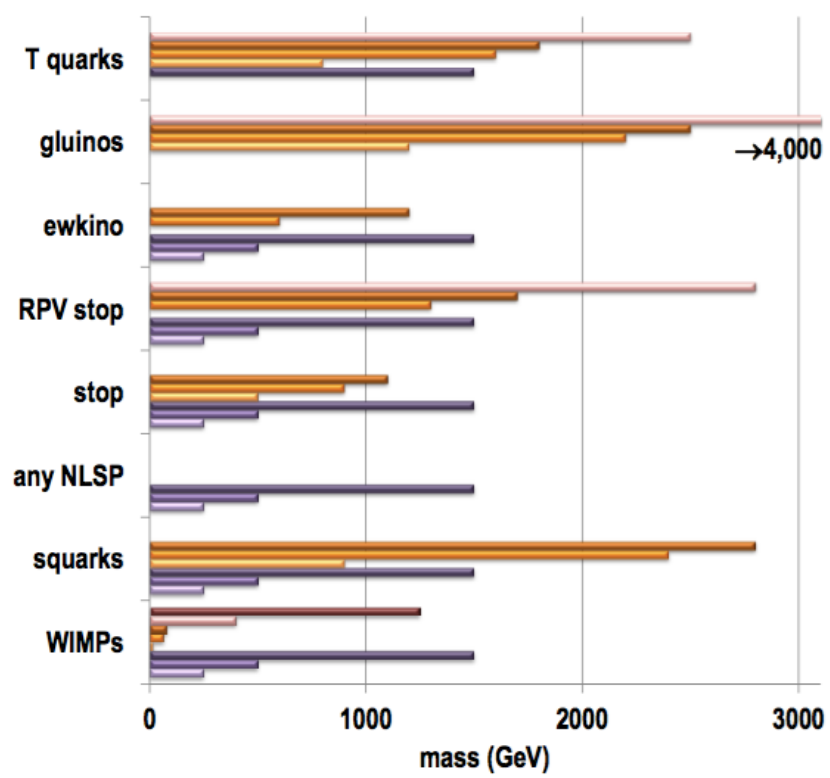
Higgs mass ~ 0.1%, width 2—5%

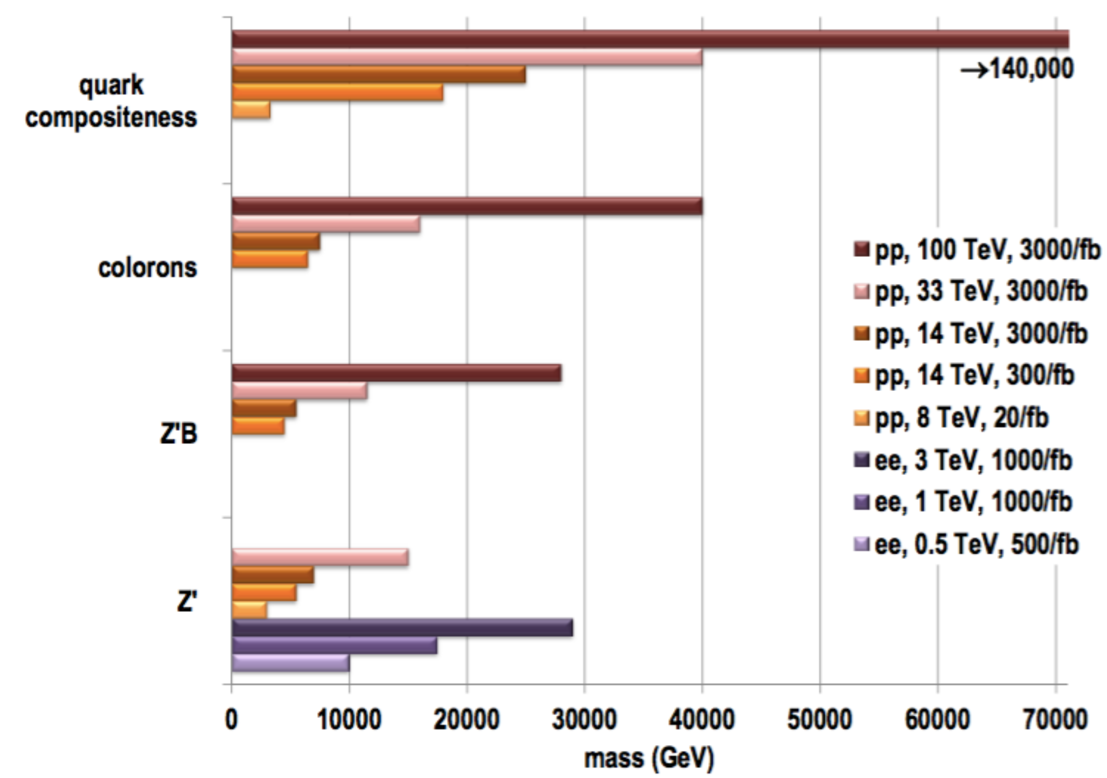
Discussion!





Snowmass summary of Higgs and BSM reach





Snowmass 2013 Energy Frontier summary report, arXiv: 1401.6081