Higgs physics at future machines: precision and discovery program

Zhen Liu (FNAL)

CPAD Instrumentation Frontier Meeting 2016

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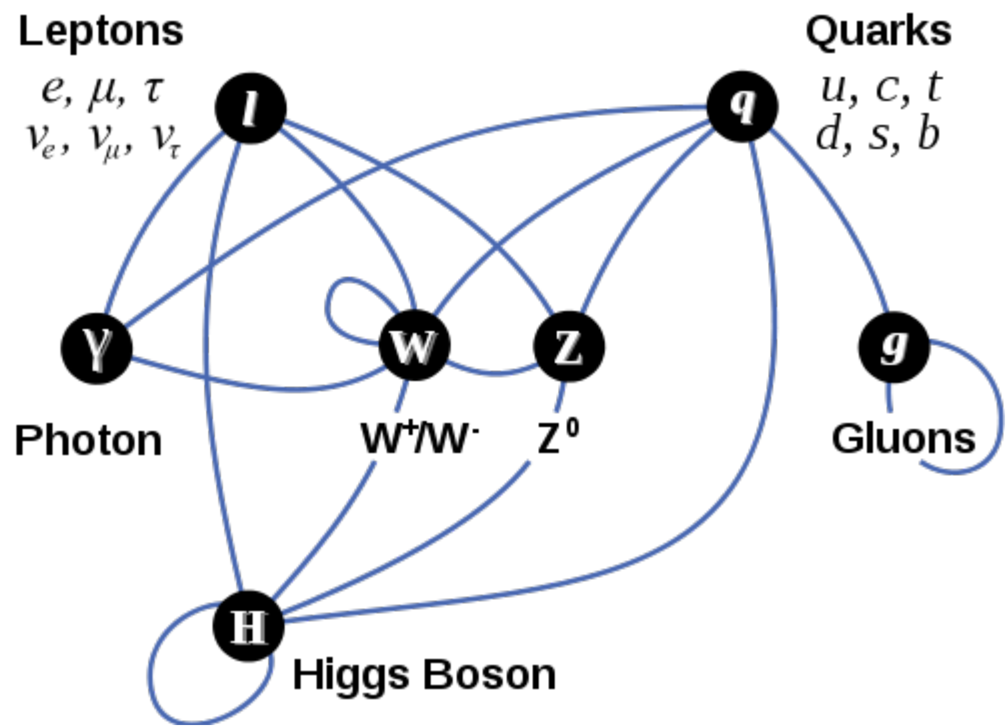
New Particle and New Forces

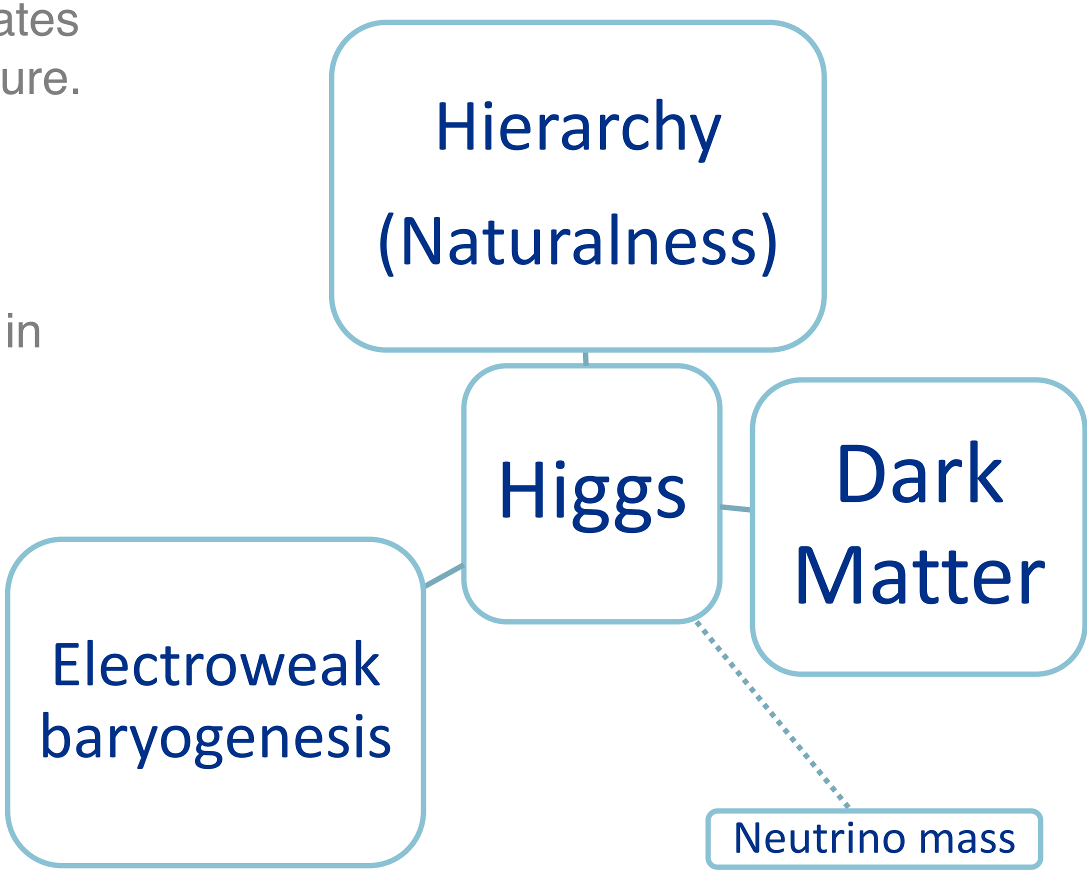
- Gauge coupling
- Yukawa coupling—new forces (9+ Yukawas)
- Self coupling—new force
- Derived couplings
  $H\gamma\gamma, Hgg, HZ\gamma, \ldots$



Key to many Puzzles

Higgs boson discovery substantiates (more) many big questions in nature. It could well be the key to unlock some of nature's secrets.

All connections may be revealed in Higgs measurements.



Emerging colliders

Proposals and studies are under fast development, under various timelines, CERN (HL-LHC, FCC, CLIC), Japan (ILC), China (CEPC/SPPC)

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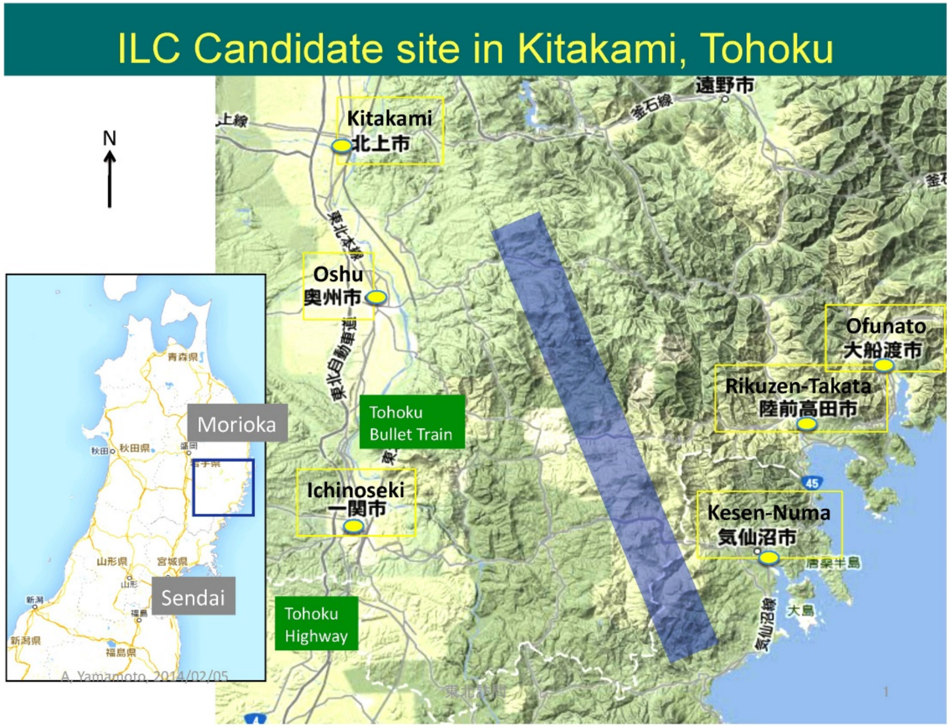

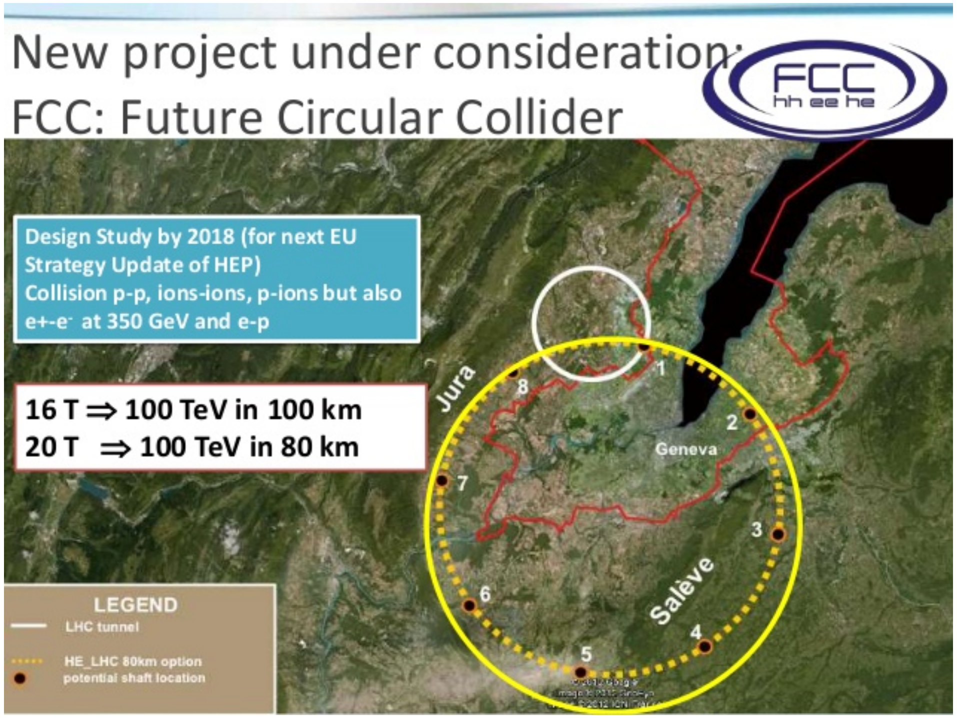

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Proposals and studies are under fast development, under various timelines, CERN (HL-LHC, FCC, CLIC), Japan (ILC), China (CEPC/SPPC)

- Higgs physics could directly probe new physics
- New physics can easily couples to Higgs, linking to hierarchy problem, electroweak baryogenesis, naturalness, dark matter, etc.
- Next generation “Higgs factories” are to explore this opportunity.

Too ambitious to cover all the aspects, and the answer would be clear from theoretical perspective,

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Too ambitious to cover all the aspects, and the answer would be clear from theoretical perspective,

High luminosity, high energy
Triggerless data acquisition
Perfect heavy jet flavor tagging
Excellent momentum resolution
Forget about pile-up, radiation damage, etc.

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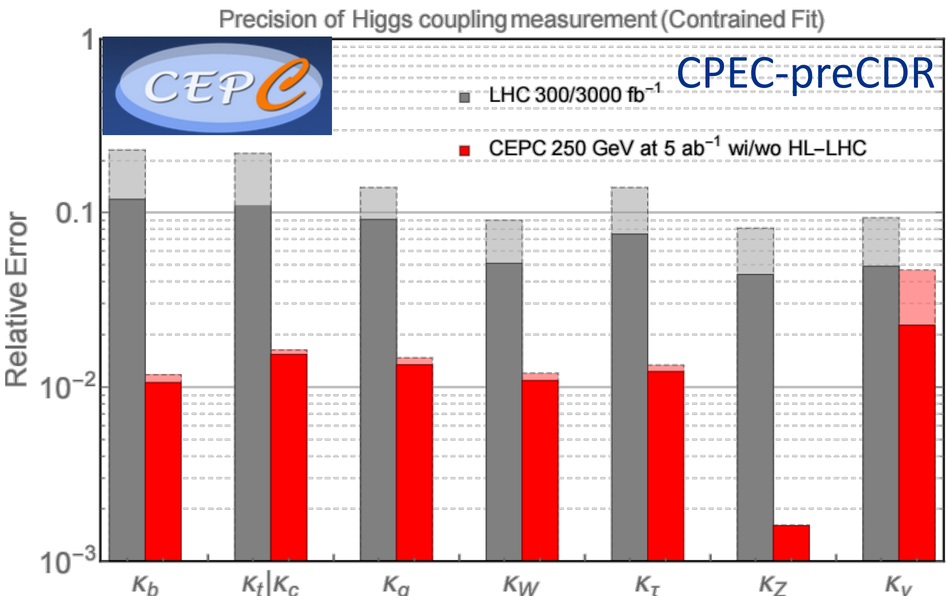
- New physics can easily couples to Higgs, linking to hierarchy problem, electroweak baryogenesis, naturalness, dark matter, etc.
- Next generation "Higgs factories" are to explore this opportunity.

Too ambitious to cover all the aspects
Instead, I will provide several representative examples for Higgs as a tool for discovery from three different perspectives:

Precision
Exotic Decay
Exotic Production

Precision—couplings

The Higgs physics potential is an essential physics piece for any proposal for future colliders, e.g.



Future e+e- machines

allow "Model-Independent" extraction of the SM Higgs couplings;

improve the precision roughly by one-order of magnitude;

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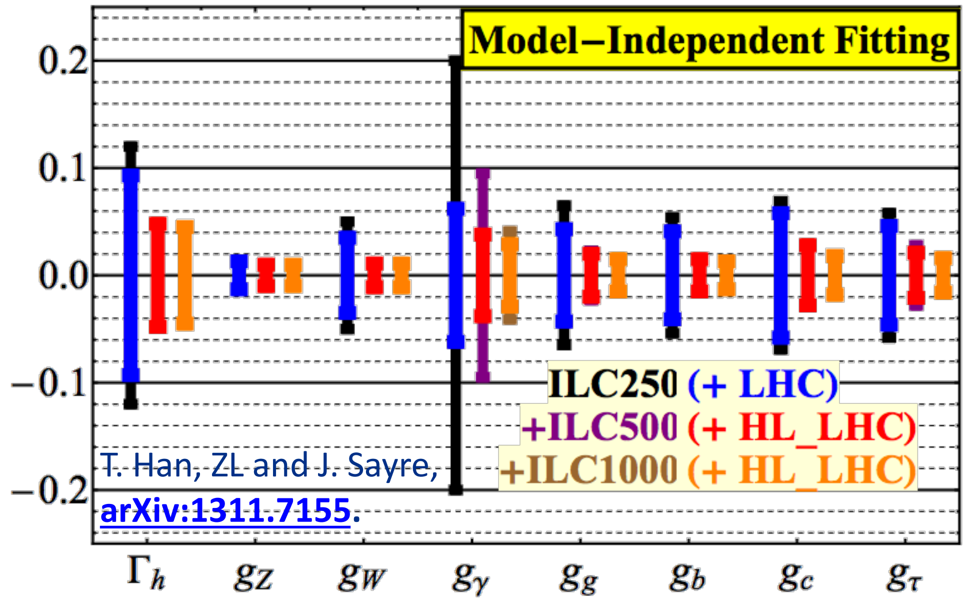
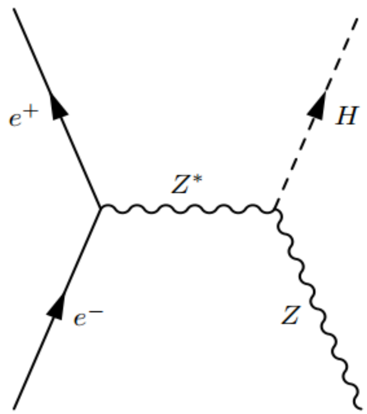


Future pp machines (including HL-LHC)
are good at measuring Higgs (EW) rare decays, H to $ZZ \rightarrow$4l, Zγ, $\mu\mu$, $\gamma\gamma$, etc.
improve the lepton colliders precision on these rare modes when combined
can measure the top Yukawa from the tth associated production.

Precision—beyond

The featured measurement at lepton collider are the HZZ precision from the inclusive ZH associated production using the ``recoil mass” technique.



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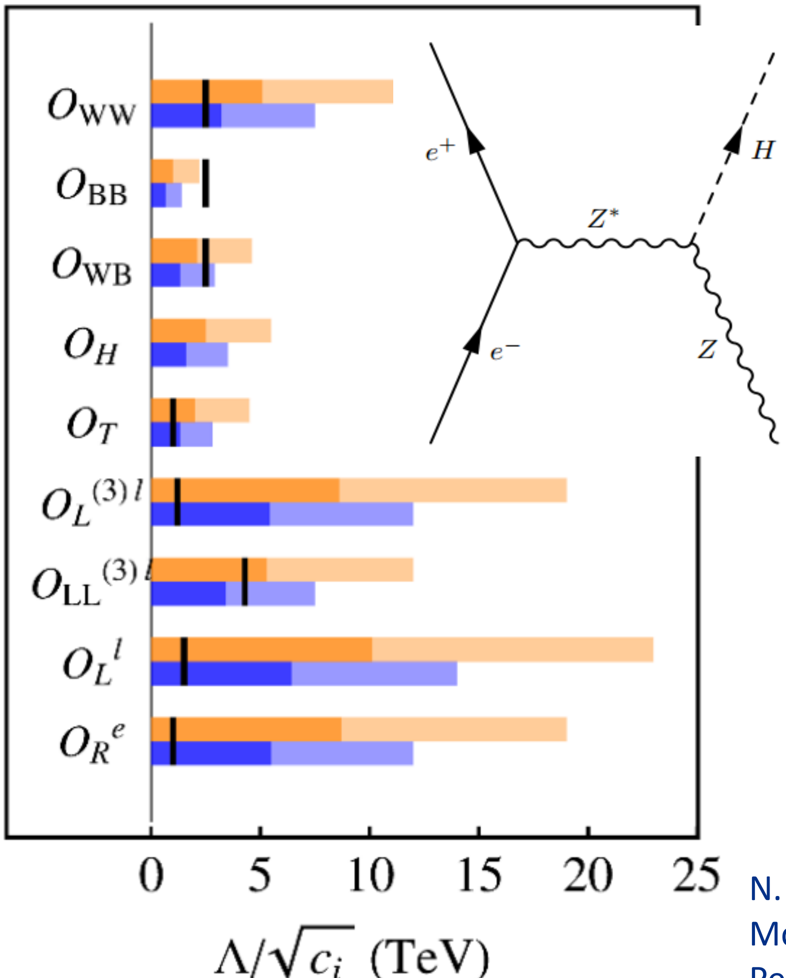

9 operators at dimension-six level contribute to this measurement, beyond our simple parametrization of rescaling HZZ coupling.

N. Craig, M. Farina, M. McCullough and M. Perelstein **arXiv:1411.0676**

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu} W^{a,\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_L^{(3)\ell} = \left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)\left(\bar{L}_L \gamma^\mu \sigma^a L_L\right)$$
$$\mathcal{O}_{LL}^{(3)\ell} = \left(\bar{L}_L \gamma_\mu \sigma^a L_L\right)\left(\bar{L}_L \gamma^\mu \sigma^a L_L\right)$$
$$\mathcal{O}_L^{\ell} = \left(iH^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{L}_L \gamma^\mu L_L\right)$$
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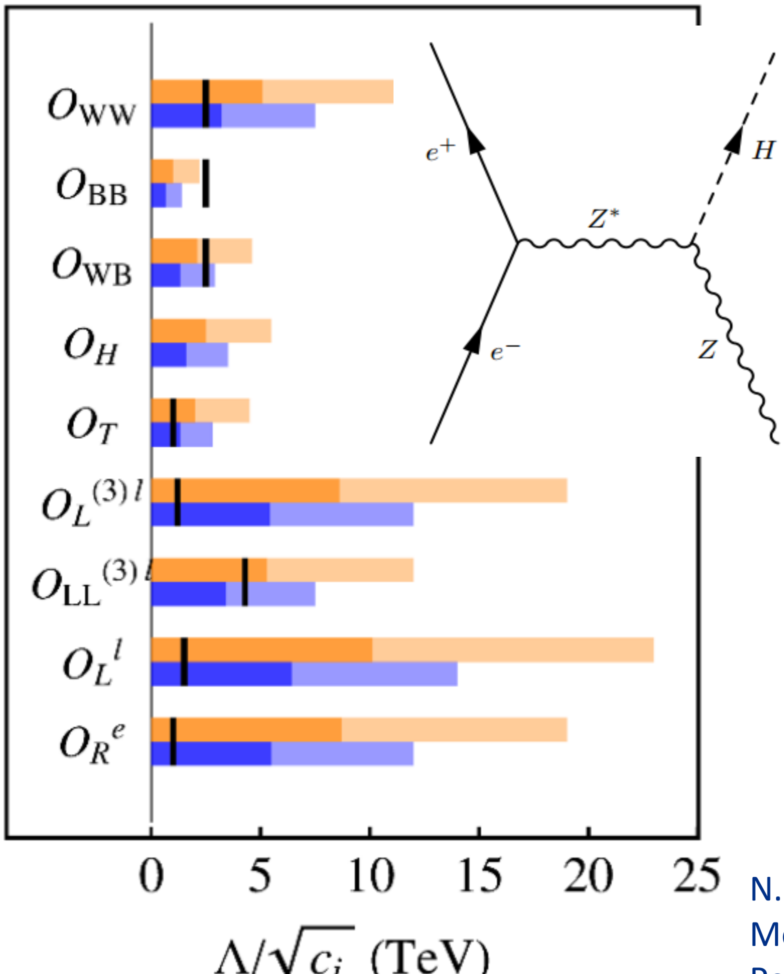

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e+e- machines and pp machines have different solutions

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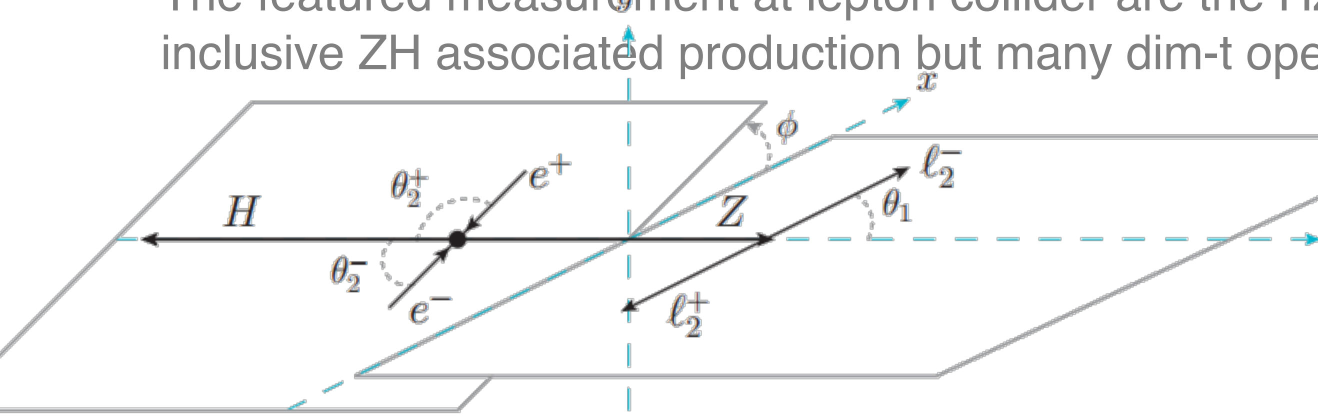
Precision—beyond (e+e-)

The featured measurement at lepton collider are the HZZ precision from the inclusive ZH associated production but many dim-t operators contribute.



$$\mathcal{A}_{\theta_1} = \frac{1}{d\Gamma/dq^2} \int_{-1}^{1} d\cos\theta_1 \; \mathrm{sgn}(\cos(2\theta_1$$

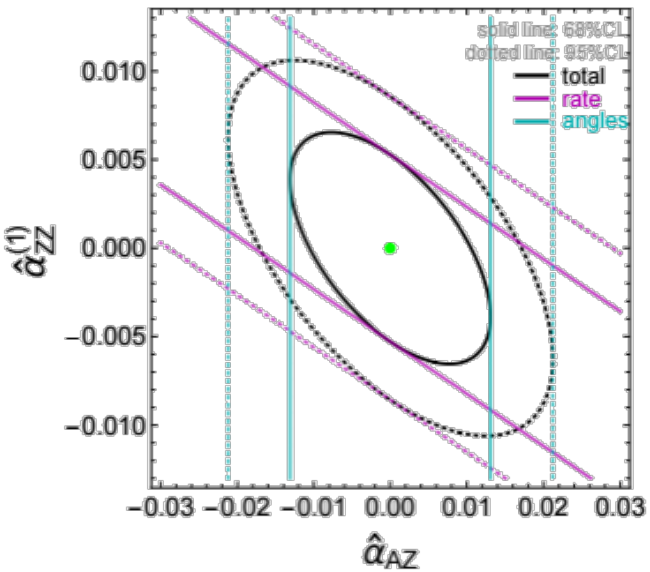
$$\mathcal{A}_{\phi}^{(1)} = \frac{1}{d\Gamma/dq^2} \int_{0}^{2\pi} d\phi \; \mathrm{sgn}(\sin\phi) \frac{d^2\Gamma}{dq^2 d\phi} =$$

$$\mathcal{A}_{\phi}^{(2)} = \frac{1}{d\Gamma/dq^2} \int_{0}^{2\pi} d\phi \; \mathrm{sgn}(\sin(2\phi)) \frac{d^2\Gamma}{dq^2 d\phi}$$

$$\mathcal{A}_{\phi}^{(3)} = \frac{1}{d\Gamma/dq^2} \int_{0}^{2\pi} d\phi \; \mathrm{sgn}(\cos\phi) \frac{d^2\Gamma}{dq^2 d\phi} =$$

$$\mathcal{A}_{\phi}^{(4)} = \frac{1}{d\Gamma/dq^2} \int_{0}^{2\pi} d\phi \; \mathrm{sgn}(\cos(2\phi)) \frac{d^2\Gamma}{dq^2 d\phi}$$

$$\mathcal{A}_{c\theta_1,c\theta_2} = \frac{1}{d\Gamma/dq^2} \int_{-1}^{1} d\cos\theta_1 \, \mathrm{sgn}(\cos\theta$$



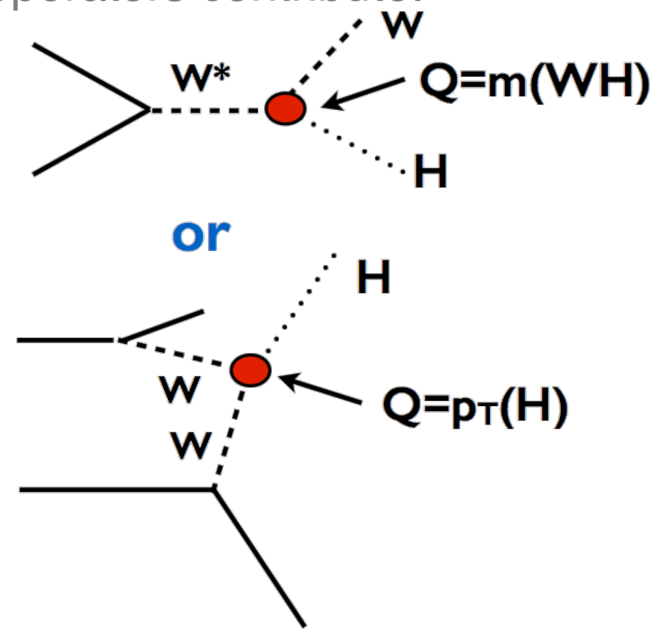
Angular asymmetries for the same process probes the physics of underlying operators with different Lorentz structure.

M. Benekea, D. Boitoa, and Y.-M. Wang, **arXiv:1406.1361**
N. Craig, J. Gu, ZL. K. Wang **arXiv:1512.06877**

Precision—beyond (pp)

The featured measurement at lepton collider are the HZZ precision from the inclusive ZH associated production but many dim-t operators contribute.

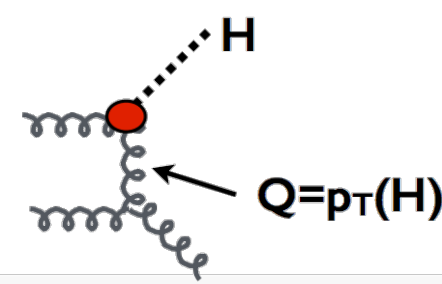
$\delta BR(H \to WW^*)$



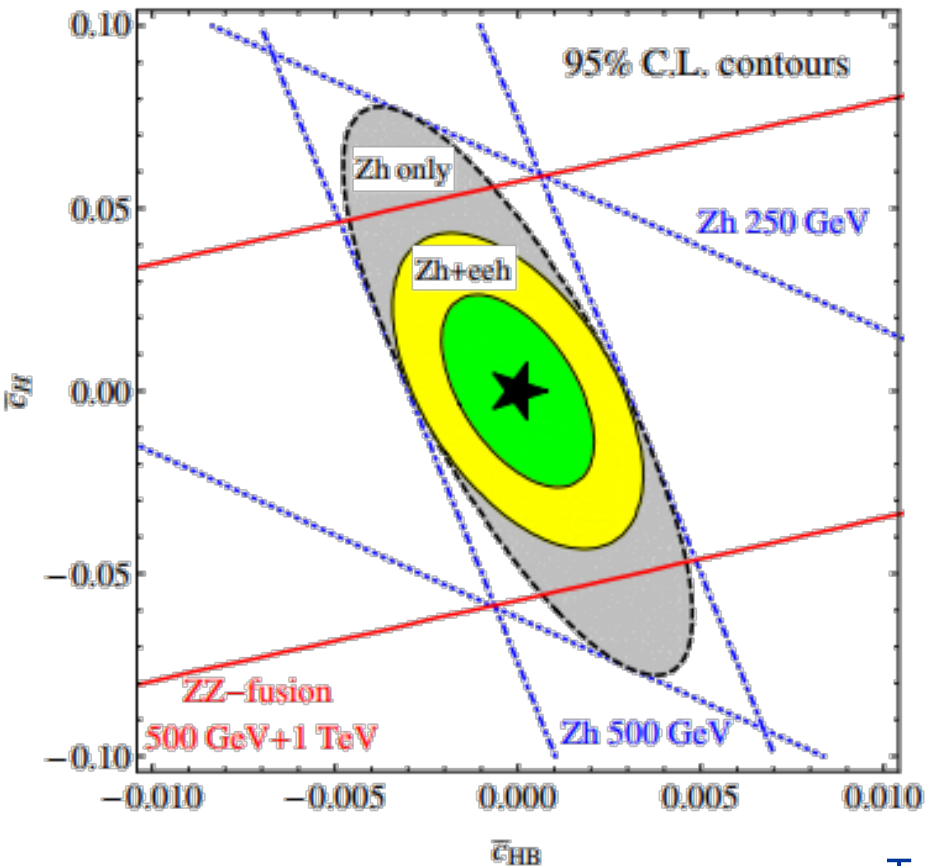
At pp machines, instead, we can go beyond the simple scaling of the couplings via the differential distribution of various Higgs production mechanism.

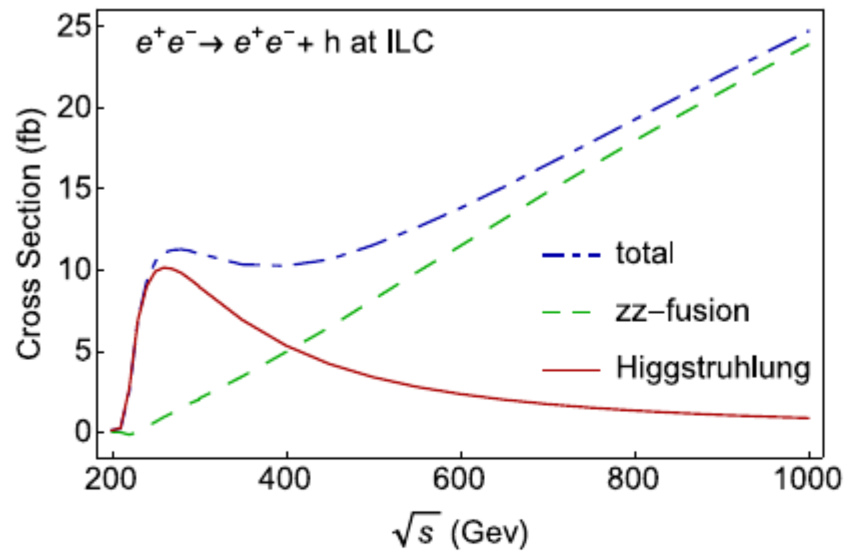
Picture from M. Mangano's 100 TeV talk at ICHEP 2016

$\delta BR(H \to gg)$



Precision—beyond (ee)





To gain more from going to higher energies, we propose to study the ZZ-fusion channel for inclusive measurement. ZZ-fusion break degeneracy and improve sensitivity.

T. Han, **ZL**, Z. Qian and J. Sayre, **arXiv:1504.01399**.

Similar to pp-machines, e+e- machines with higher energy runs probes the interactions at different energies, and thus can be used to probe different Lorentz structures.

Exotic Decays

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most search focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.
- Moreover, the precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass.

Exotic Decays

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most search focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.
- Higgs has tiny width ~4 MeV

$$\frac{\Gamma}{M} = O(10^{-5})$$

- *all* its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.

e.g., dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$

➔

- Any couplings could have sizable width, e.g.,

e.g. L $= \frac{\zeta}{2} s^2 |H|^2$ (common building block 2 in extended Higgs sectors) can give BR(h→ss)~O(10%) for ζ *as small as* 0.01 !

PHYSICAL REVIEW D **90,** 075004 (2014)

Exotic decays of the 125 GeV Higgs boson

David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

- survey, systematize, prioritize exotic decays
  extensive literature exists, but models need reassessment:
- what BR can be probed? how maximize sensitivity?
  to some extent, develop search strategies, provide viable
- benchmark models/points, inform LHC14 trigger selection
- provide website that will be updated regularly (exotichiggs.physics.sunysb.edu)

Figure credit: S. Gori

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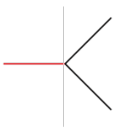
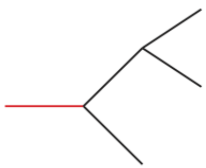
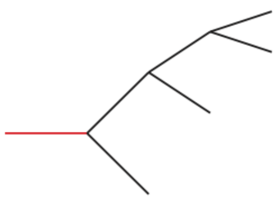
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
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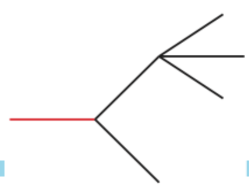
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
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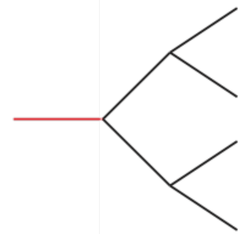
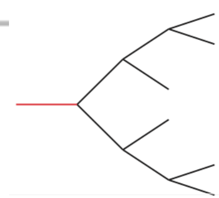
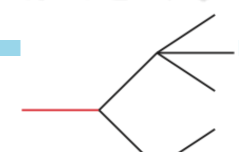
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Fermilab

Figure credit: S. Gori

Exotic Decays

pp machines great at EW final states, as they produce huge amount of Higgs bosons

ee machines great at (semi-)hadronic final stages, as they enjoy low background

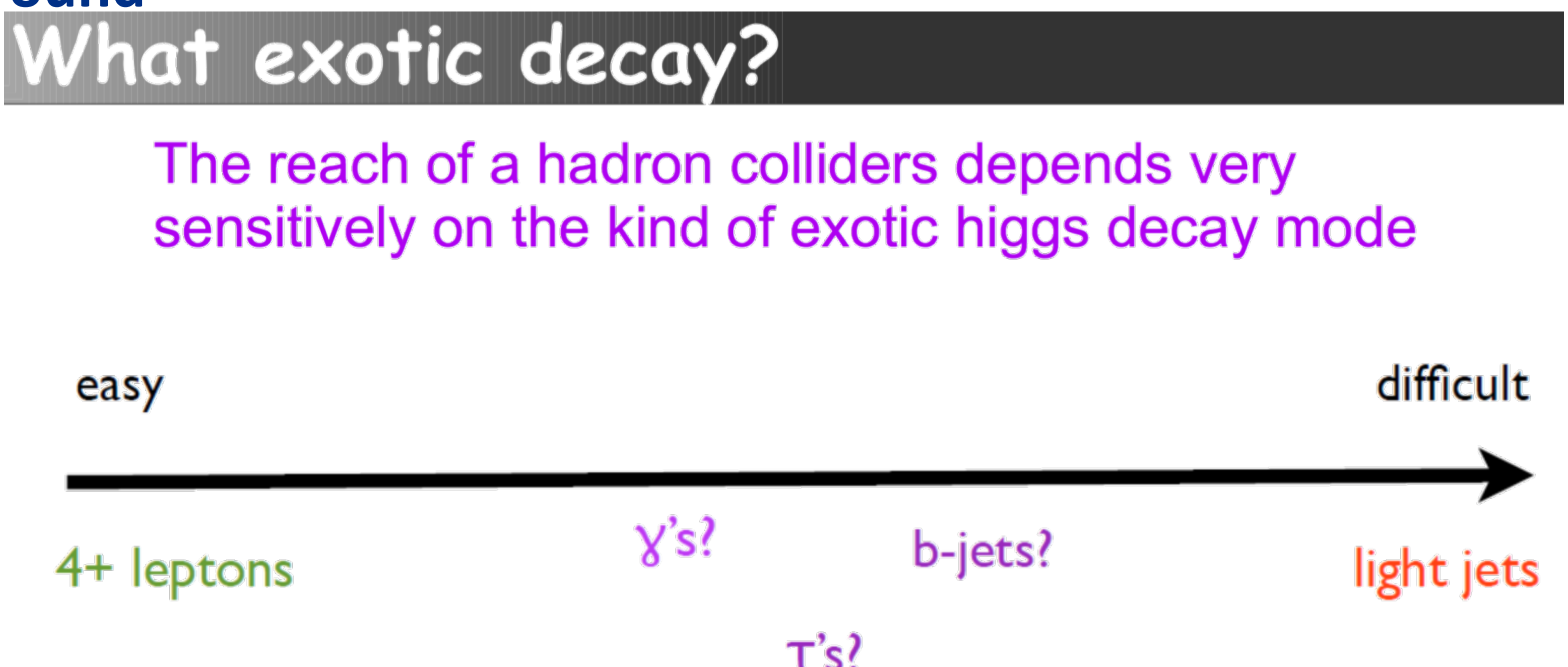
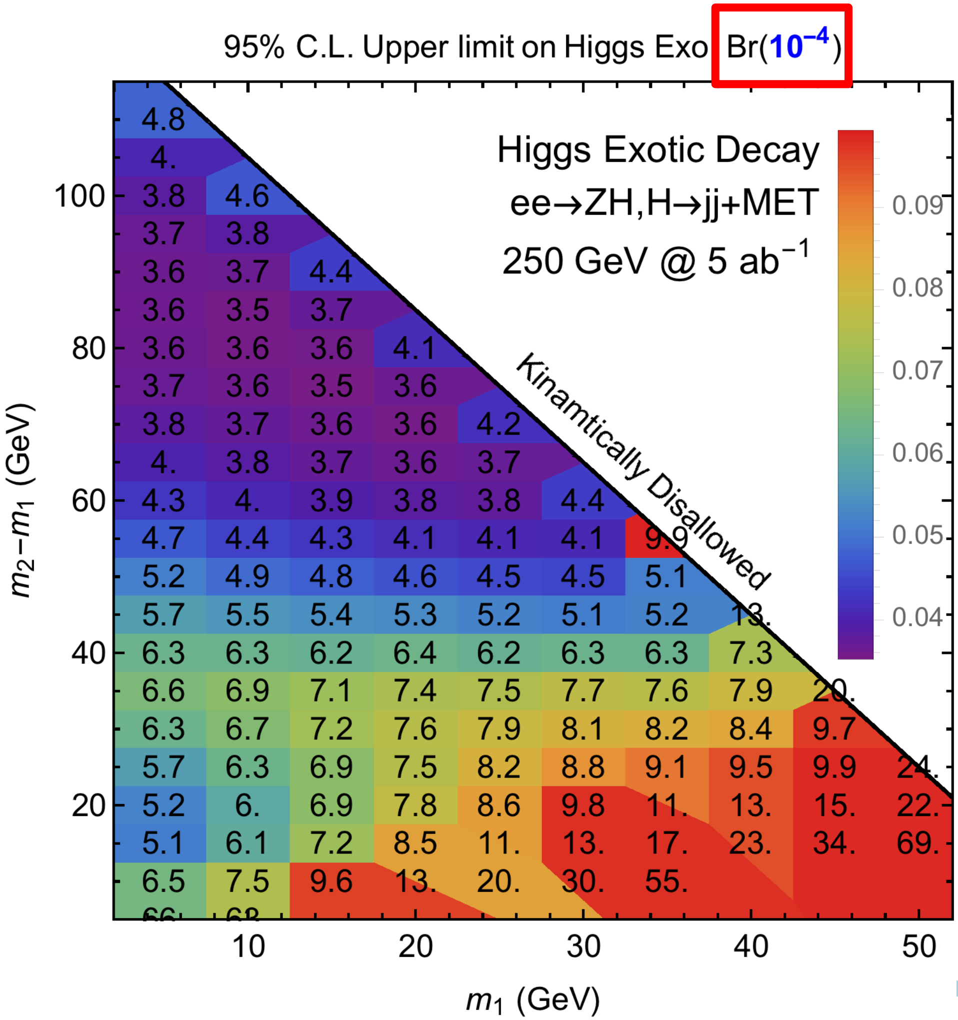


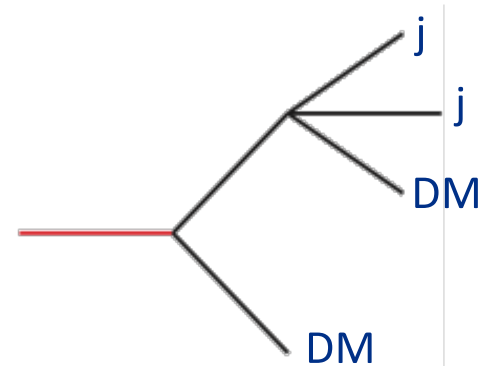
Figure credit: S. Gori

Exotic Decays—example:

$$H \to x_1, x_2 \to j\, j + MET$$



ZL, L-T. Wang, H. Zhang, to appear



Depending on the masses of the decaying particles, the exclusion reach on Higgs exotic BRs could be as low as 4×10^{-4} and remains at this order for large range, except kinematic edges.

The dijet invariant mass is a distribution since this topology explicitly forbids on-shell case.

Exotic Production

Higgs can act as taggers for new physics through exotic production mechanism, e.g.,

- Higgs Pair production as a probe for heavy scalar bosons;
- Higgs+ttbar+X production as probe for heavy top partners (stops or T’);
- Higgs+W/Z production as a probe for heavy gauge bosons (W’, Z’);
- Differential distribution of the Higgs+jets/W/Z/VBF as probes for heavy particles in the loop
- Off-shell Higgs effects as indirect probe of Higgs width and interactions
- …

Conclusion

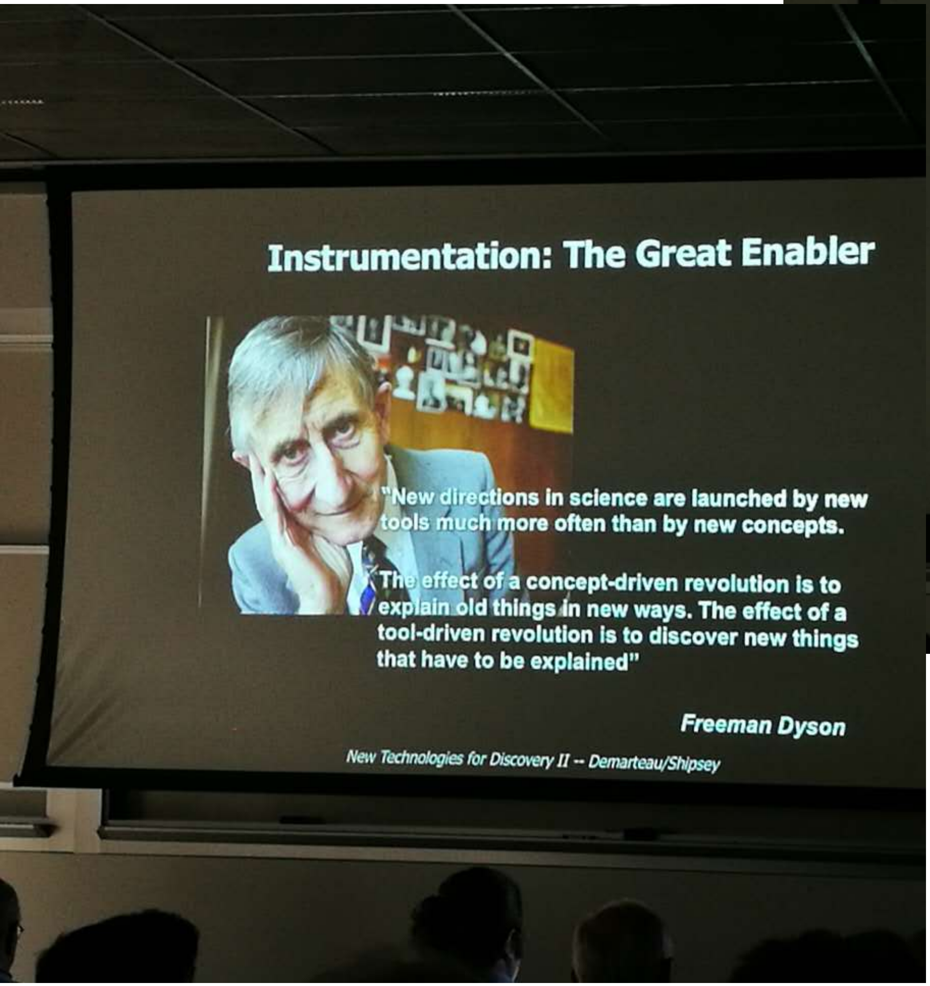
Higgs boson is the key to BSM physics and many puzzles of the SM
Higgs boson physics is essential for future programs

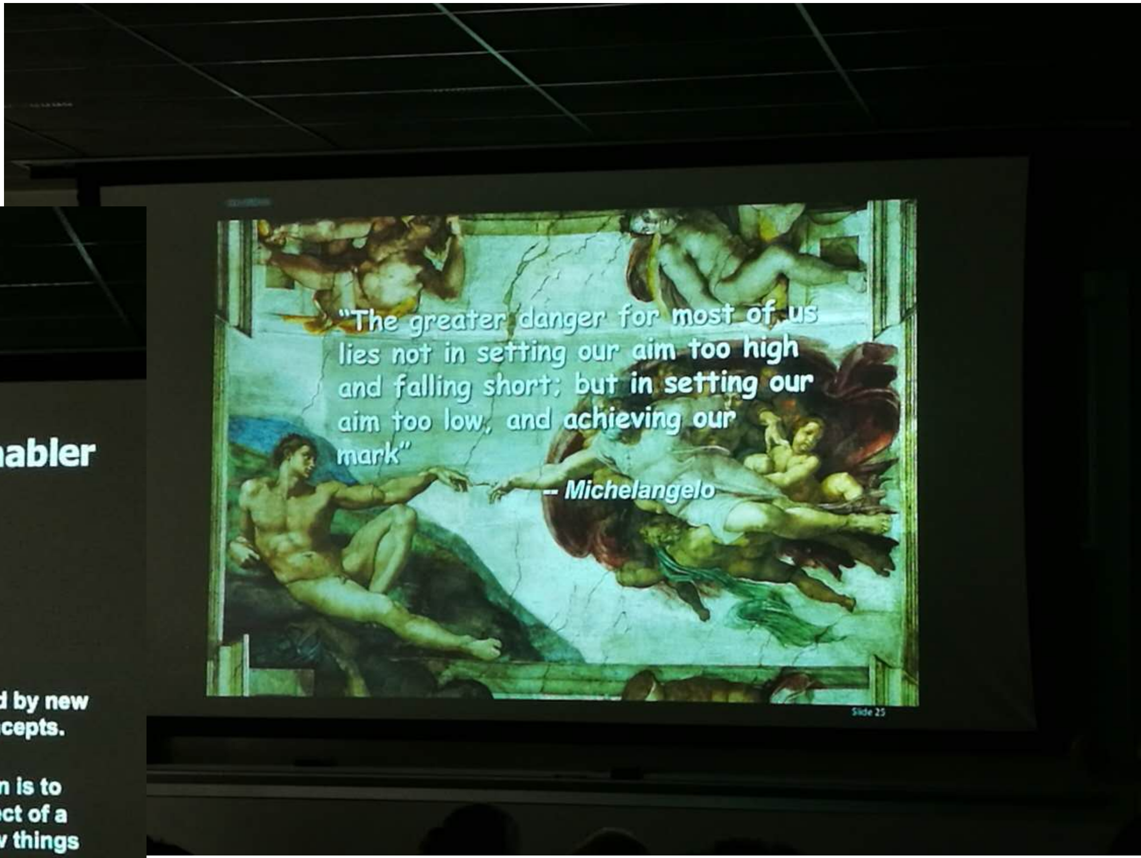
I provide representative examples from different perspective of Higgs as a tool for BSM physics at different colliders: precision, exotic decay and production

Different designs of the colliders as some fundamental advantages in certain directions, and they are also complementary:
e.g. 1, for charm-Yukawa,
pp could do J\ $\psi + \gamma$ while ee could do good charm tagging
e.g. 2, for EBPT,
pp and high energy ee could do double Higgs production, ee could do precision measurement of the loop-corrections in ZH production rate and Higgs exotic decays into light scalar pairs

Before going to an all-purpose perfect detector, we need to first ensure all the signature channels performs well

Outlook





Inspired by the opening talk
U.S. has long been the land of dreamers making breakthroughs.

What would the role be played by the U.S?

New technology breakthrough, weak-field acceleration, future muon collider?

Precision—couplings

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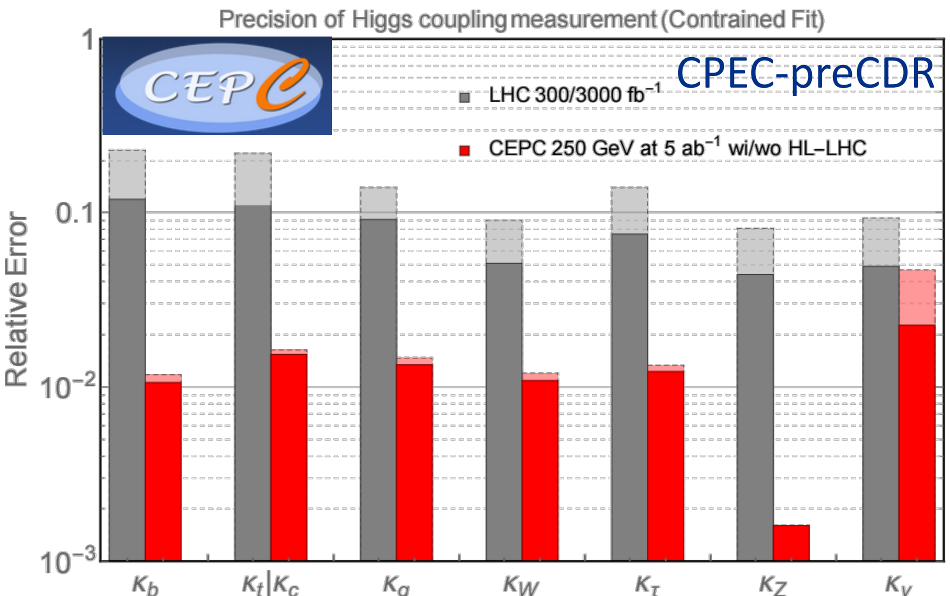

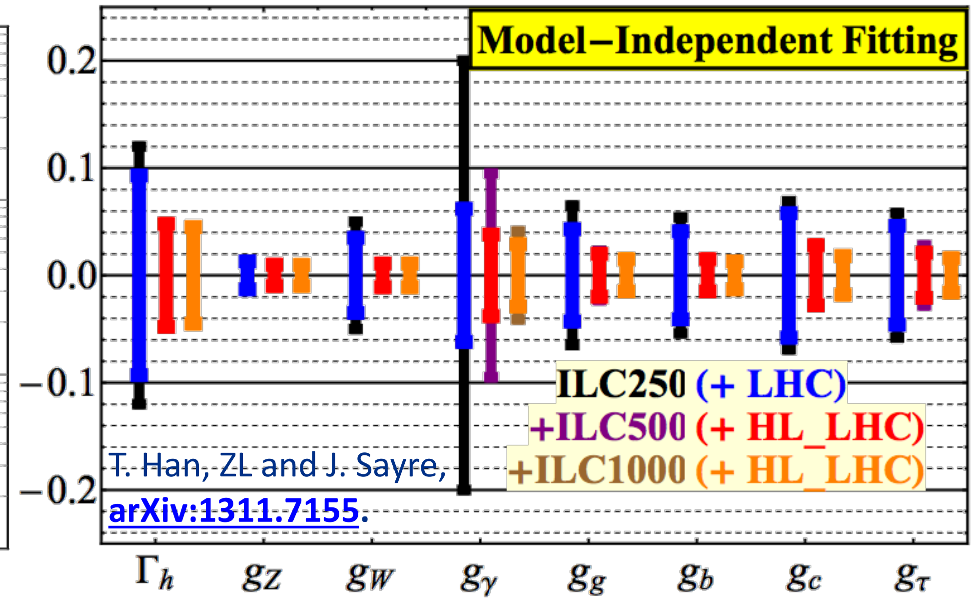

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improve the lepton colliders precision on these rare modes when combined
can measure the top Yukawa from the tth associated production.