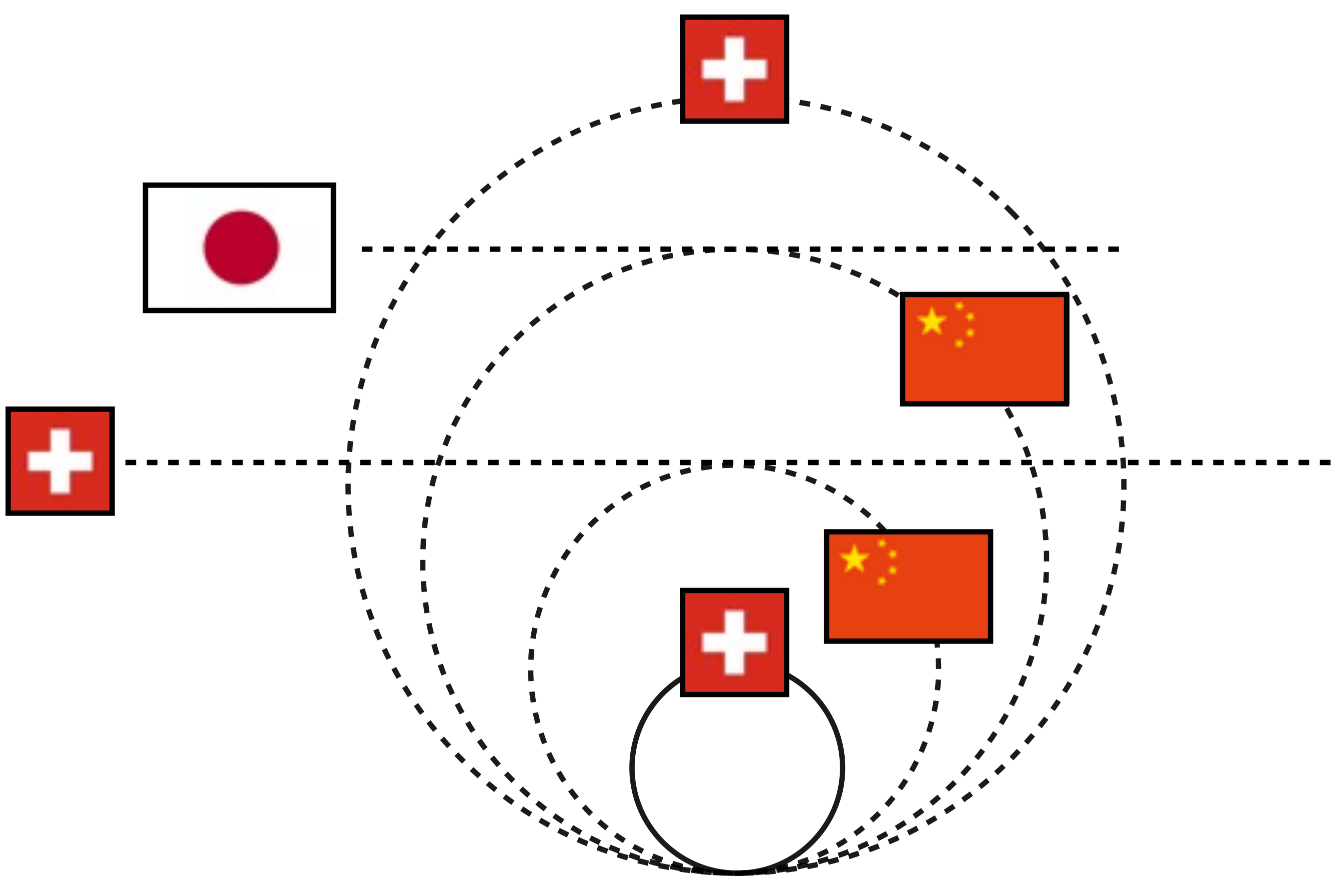
Physics Highlights of future ee colliders

98th Plenary ECFA meeting
CERN, November 19, 2015



Christophe Grojean
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HEP landscape after the Higgs discovery

The Higgs discovery has been a great success...

...but the experimentalists haven't found what the BSM theorists told them they will find in addition to the Higgs boson:

no susy, no BH, no extra dimensions, nothing ...

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Furthermore we are left with big questions that the SM cannot address

1) Origin of quark and lepton flavor, origin of neutrino masses
2) Only a description of EW symmetry breaking, not an explanation
3) No place for the particle(s) that make up the cosmic DM
4) Does not explain the asymmetry matter-antimatter

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   ➠ Are there some global flavor symmetry (incl. lepton #)?
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   ➠ What separates the EW scale from the Planck scale?
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   ➠ What are the DM particles?
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   ➠ Are the conditions realized to allow for EW baryogenesis?

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Where and how does the SM break down?

Which machine(s) will reveal (best) this breakdown?

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

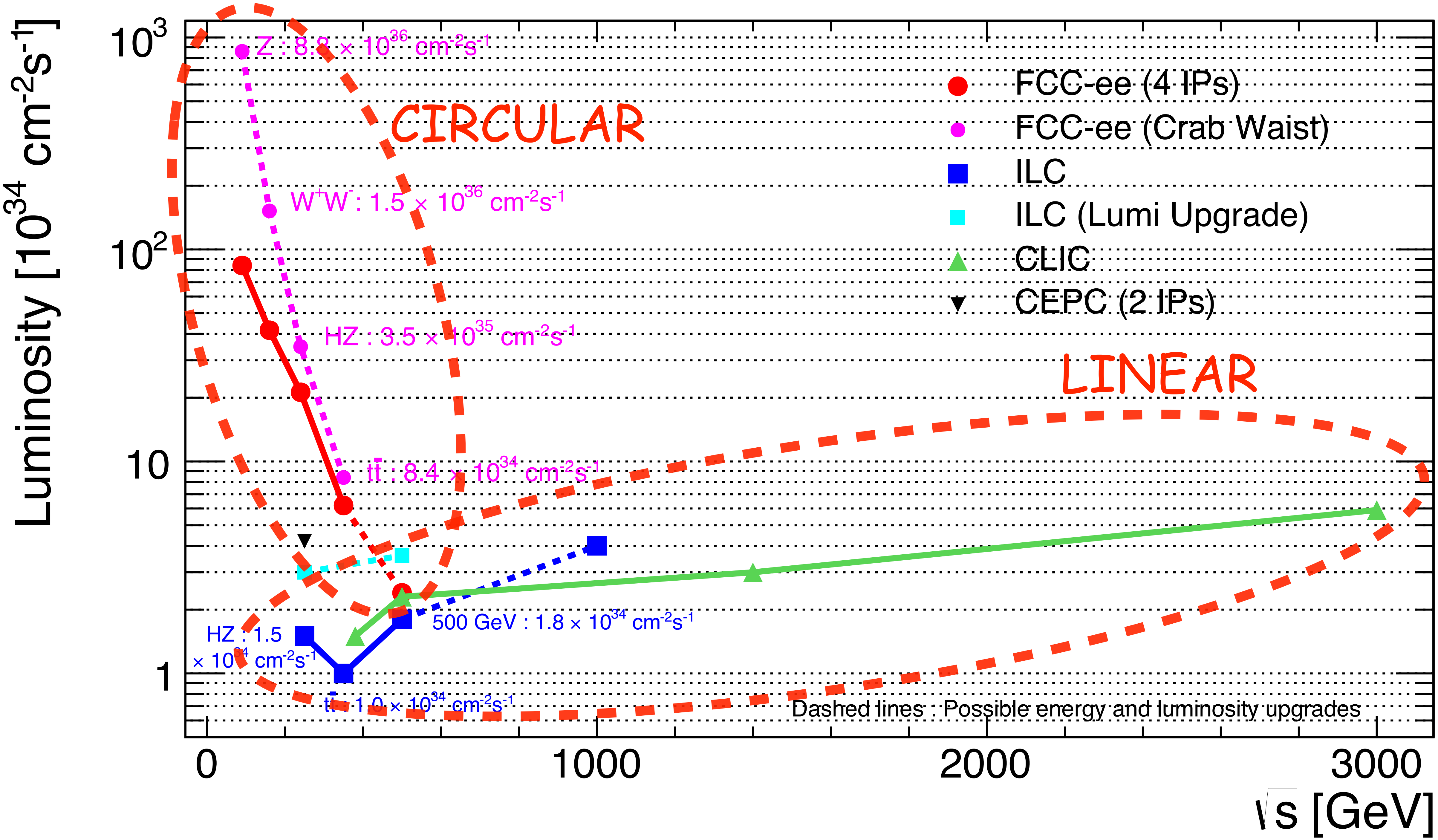
Circular

- $\sqrt{s}$ limited by synchroton radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) @ FCC-ee via resonant depolarization)

Linear

- easier to upgrade in energy
- easier to polarize beams
- large beamsthralung
- greener: less power consumption

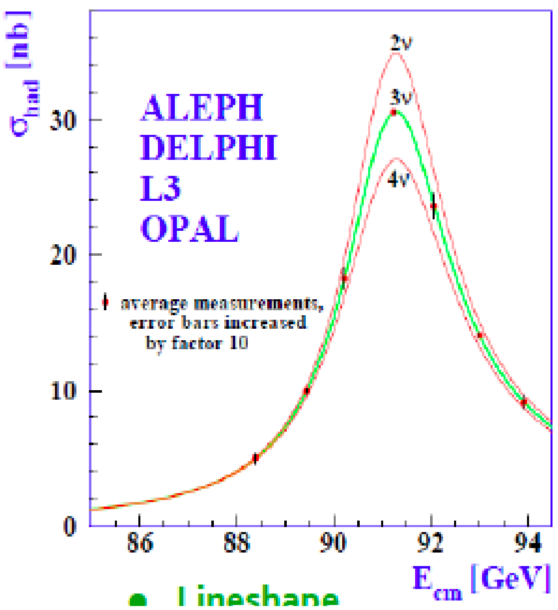
Energy vs. Luminosity



Test of SM bones

d'Enterria Lomonosov '15

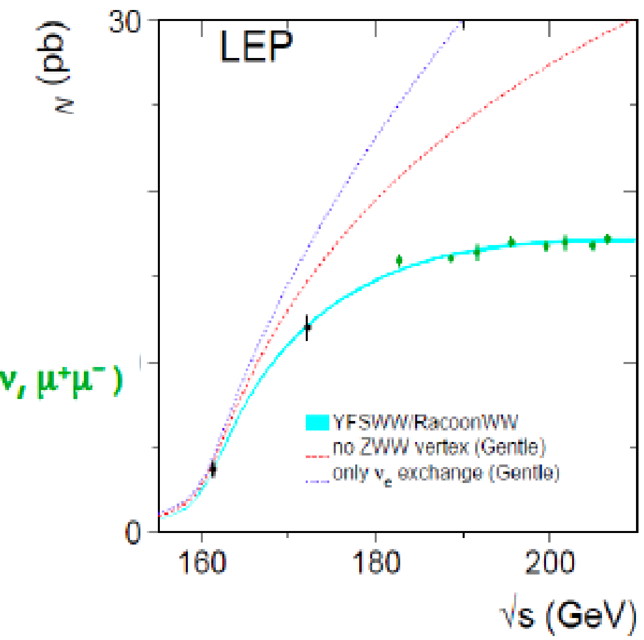
Z resonance: TeraZ



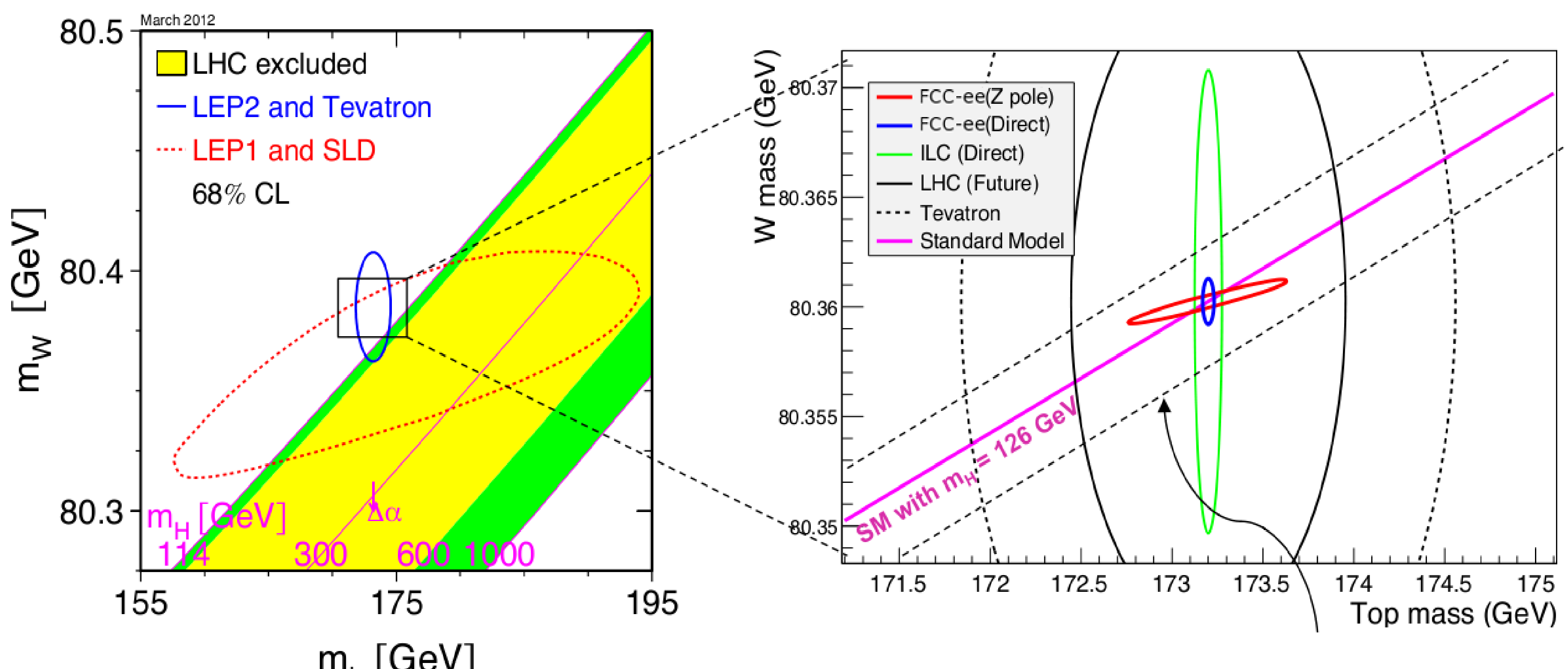
- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to 10 keV
- Asymmetries
  - $\sin^2\theta_W$ to 2×10^{-6}
- Branching ratios, R_l, R_b
  - $\alpha_S(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

WW threshold scan: OkuW

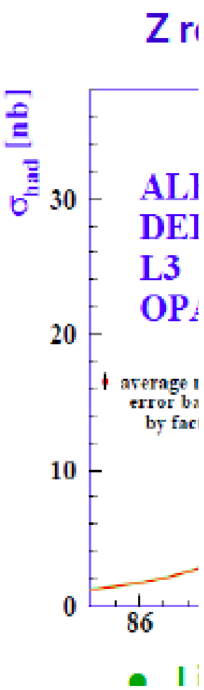
- Threshold scan
  - m_W to 500 keV
- Branching ratios R_l, R_{had}
  - $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$ $(Z\to\nu\nu, \mu^+\mu^-)$
  - N_ν to 0.0004



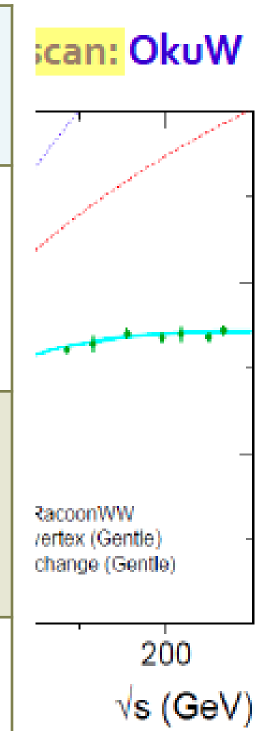
best test of QM beyond QED (and indirect probe of new physics up to ~ 30 TeV)



Test of SM bones



	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z [MeV]	91187.5 ±2.1	Z Line shape scan	0.005 MeV <±0.1 MeV	E_cal	QED corrections
Γ_Z [MeV]	2495.2 ±2.3	Z Line shape scan	0.008 MeV <±0.1 MeV	E_cal	QED corrections
R_l	20.767 ± 0.025	Z Peak	0.0001 ± 0.002 - 0.0002	Statistics	QED corrections
N_ν	2.984 ±0.008	Z Peak Z+γ(161 GeV)	0.00008 ±0.004 0.0004-0.001	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	0.21629 ±0.00066	Z Peak	0.000003 ±0.000020 - 60	Statistics, small IP	Hemisphere correlations
A_{LR}	0.1514 ±0.0022	Z peak, polarized	±0.000015	4 bunch scheme	Design experiment
M_W [MeV]	80385 ± 15	Threshold (161 GeV)	0.3 MeV <1 MeV	E_cal & Statistics	QED corections
M_{top} [MeV]	173200 ± 900	Threshold scan	10 MeV	E_cal & Statistics	Theory limit at 100 MeV?



bes

TeV)

Klute @ LCWS'15

Requires a significant theory program

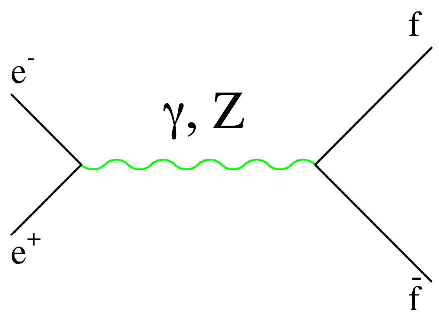
m_t [GeV]

Accessing SM input parameters

$\alpha_{QED}(m_Z)$

Janot '15

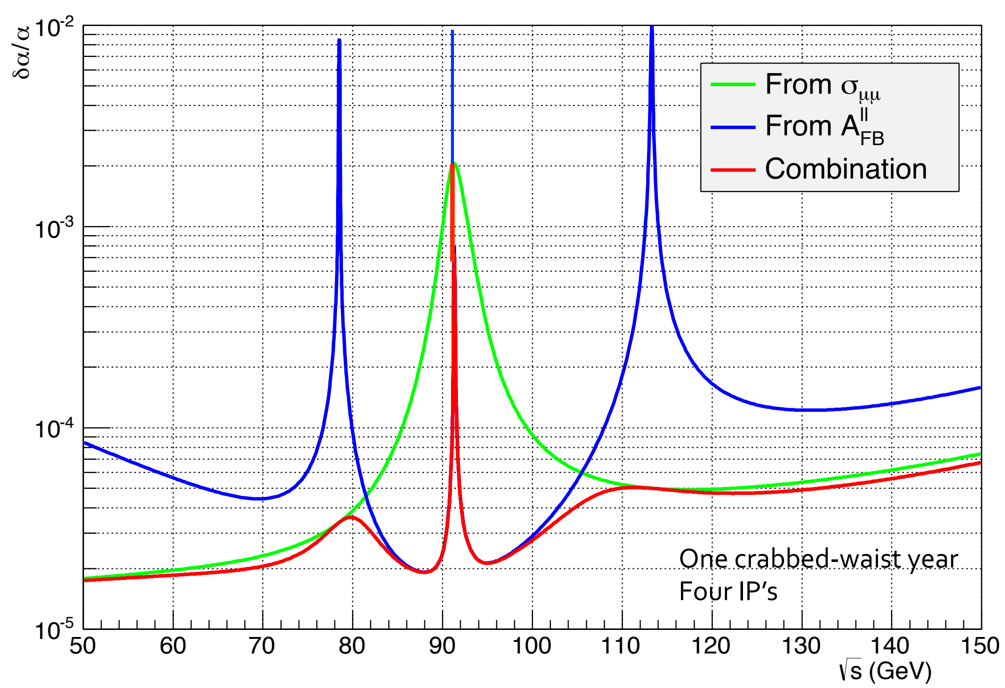
measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$

The Z exchange term is proportional to G^2_F, hence independent of α_{QED}

The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$



By running six months at each of 88 and 95 GeV points:

➤ Could potentially reach a precision of : $\delta\alpha/\alpha = 2 \times 10^{-5}$

$\alpha_{QCD}(m_Z)$

Dam @ EPS'15

$$R_l = \Gamma_{had}/\Gamma_l$$

LEP measurements with

(1) new N^{3}LO results

(2) improved m_{top}

(3) m_{Higgs}

$\delta(\alpha_s(m_Z))_{LEP} = \pm 0.0038$ (exp.) ± 0.0002 (others)

stat. limited

TLEP statistics

$\delta(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm 0.00015$

Key goals of the ee machines as BSM probes

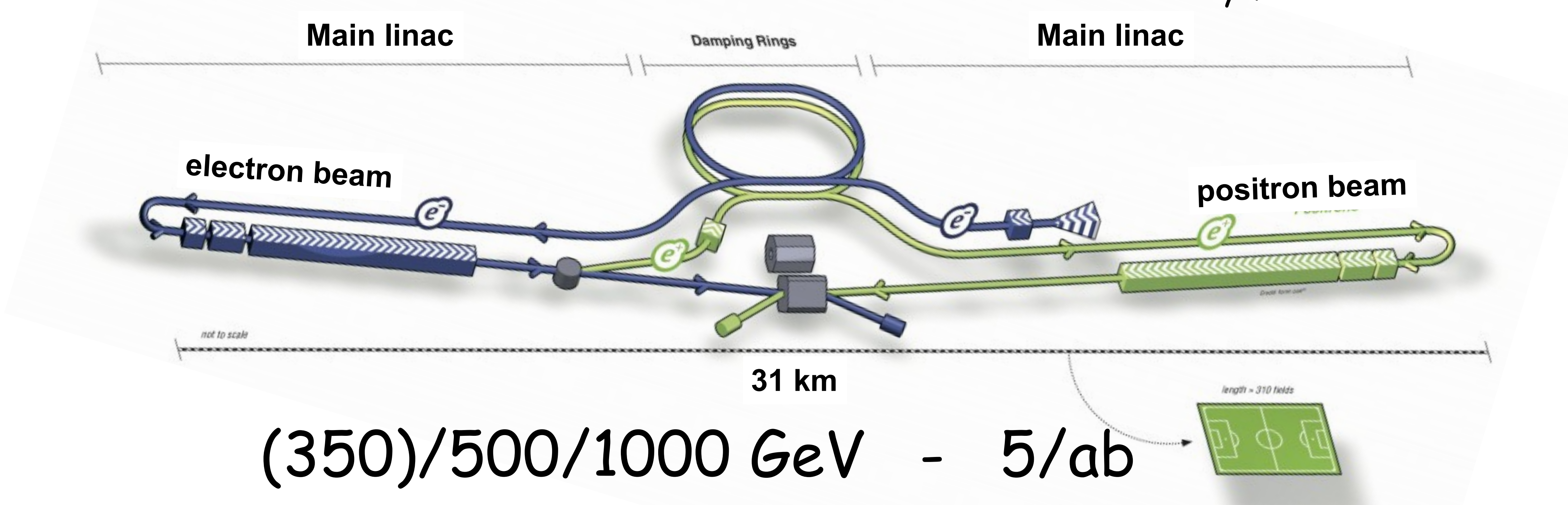
in order to address the physics questions outside the SM boundaries
the physics program of the future ee colliders is built around three key goals

1. Measurement of the properties of the newly-discovered **Higgs** boson with very high precision. ⇛ Is it elementary? Does it have siblings/relatives? What keeps it light? Why does it freeze in?
2. Measurement of the properties of the **top** quark with very high precision to indirectly constrain new physics
3. Direct searches for and studies of (uncolored) **new particles** expected in models of physics at the TeV energy scale. Complementary to LHC searches.

Higgs and top properties are fundamental SM input parameters
that need to be measured as precisely
to reduce theoretical systematics in searches for BSM

ILC (2027?*-2047?)

*ready for construction once approved



(350)/500/1000 GeV - 5/ab

+ Giga-Z for the measurement of polarization asymmetries

	Staged ILC		TDR			TDR
ECM [GeV]	**250**	**250**	**500**	**250**	**500**	**1000**
rep. rate [Hz]	5	10	**5**	10	5	**4**
N_{bunch}	1315	1315	**1315**	2625	2625	**2450**
inst. lumi [10^{34} / cm^2 / s]	0.75	1.5	**1.8**	3	3.6	**3.6-4.9**
total power [MW]	**100**	**160**	**160**	**190**	**200**	**300**

Stage	ILC500			ILC500 LumiUP		
$\sqrt{s}$ [GeV]	500	350	250	500	350	250
$\mathcal{L}$ [fb^{-1}]	500	200	500	3500	-	1500
time [a]	3.7	1.3	3.1	7.5	-	3.1

ILC Parameter WG '15, arXiv 1506.07830

- O(10^6) H
- O(10^6) top pairs

Giga-Z running precision Z-physics:

- ALR(e): 0.00008 (vs. 0.001 now)
- ALR(b): 0.001 (vs. 0.02 now)
- Rb: 0.00014 (vs 0.00069 now)

ILC (2027?*-2047?)

*ready for construction once approved

ILC Operating Scenarios

June 2015

arXiv:1506.07830

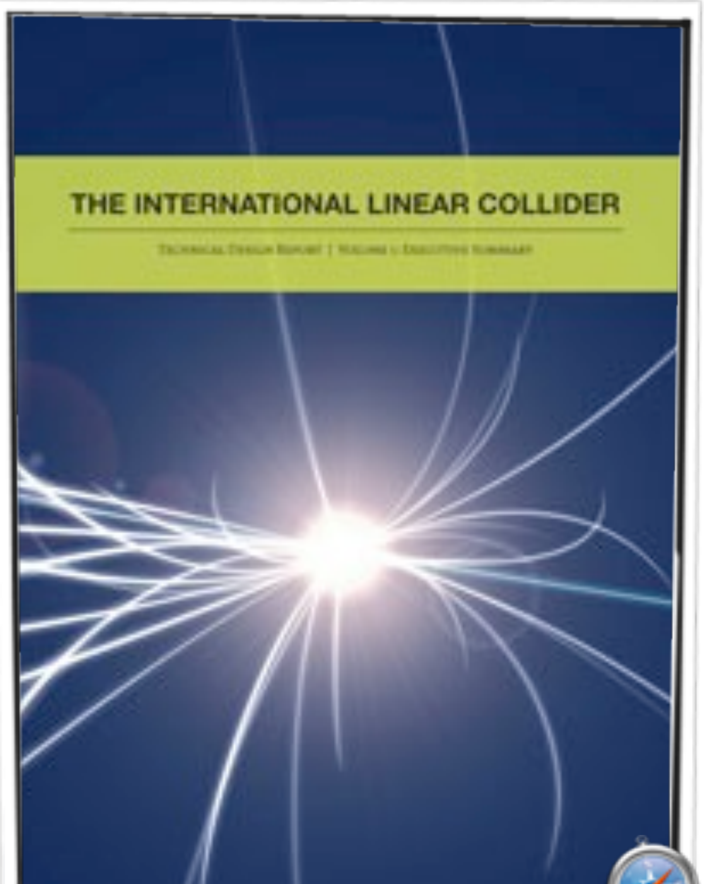
ILC Parameters Joint Working Group

Physics Case for the International Linear Collider

June 2015

arXiv:1506.05992

LCC Physics Working Group



The International Linear Collider

Jim Brau[†], Paul Grannis[‡], Mike Harrison[#], Michael Peskin[*], Marc Ross[*], Harry Weerts[§]
for the ILC Collaboration
April 9, 2013

submitted to the Community Summer Study (Snowmass on the Mississippi), July 2013

The Physics Case for an e^+e^- Linear Collider

James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d], Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]

A Report Commissioned by the Linear Collider Community[†]

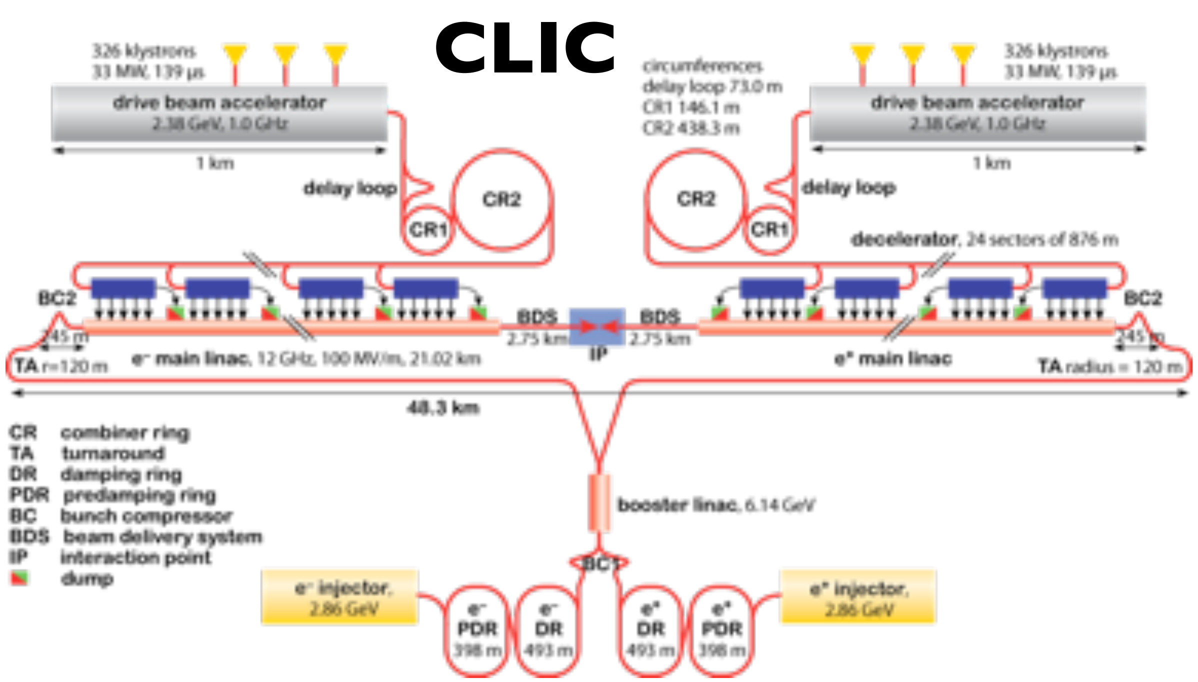
Physics Case for the ILC Project:
Perspective from Beyond the Standard Model

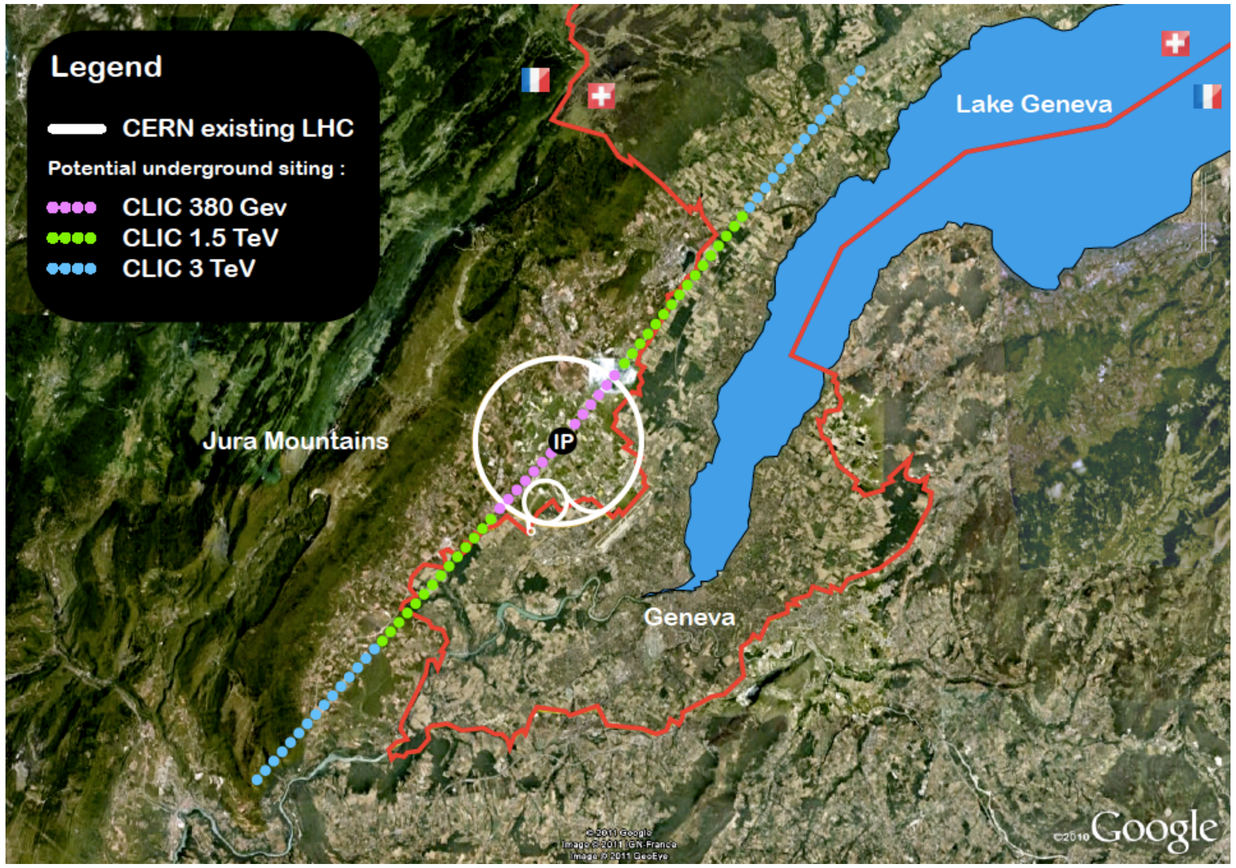
Howard Baer[1], Mikael Berggren[2], Jenny List[2], Mihoko M. Nojiri[3,4], Maxim Perelstein[5], Aaron Pierce[6], Werner Porod[7], Tomohiko Tanabe[8]

Physics at the e^+e^- Linear Collider

CLIC (post HL-LHC-x+20)

(350)/1000/3000 GeV - 5/ab





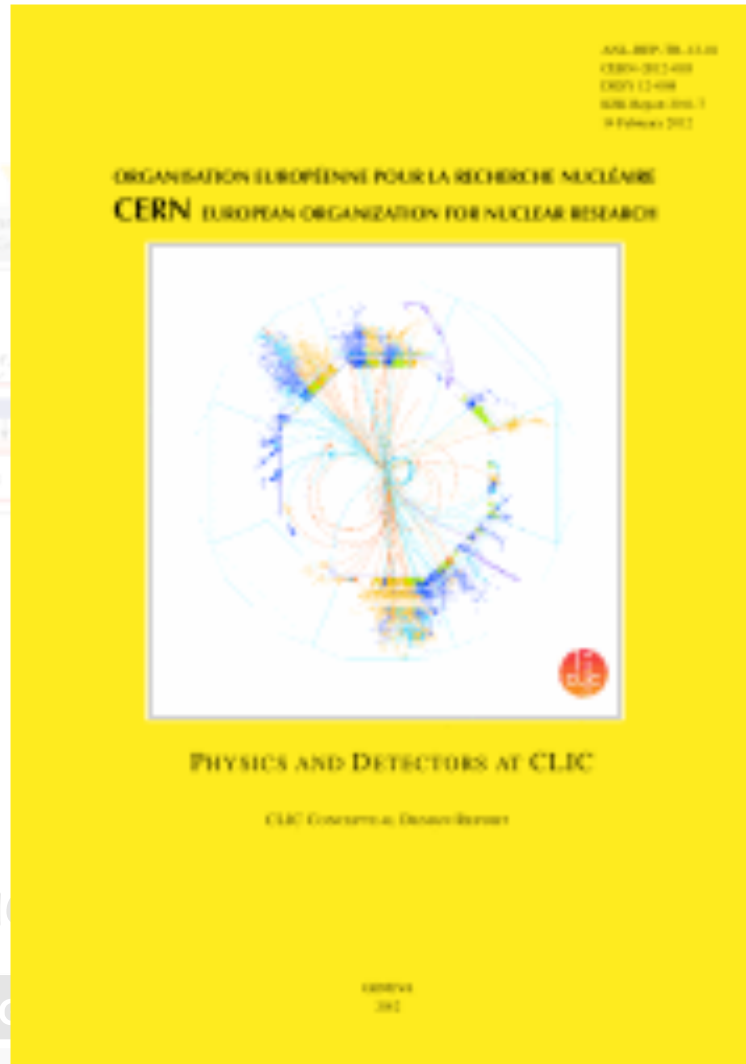
- cost review due in 2018

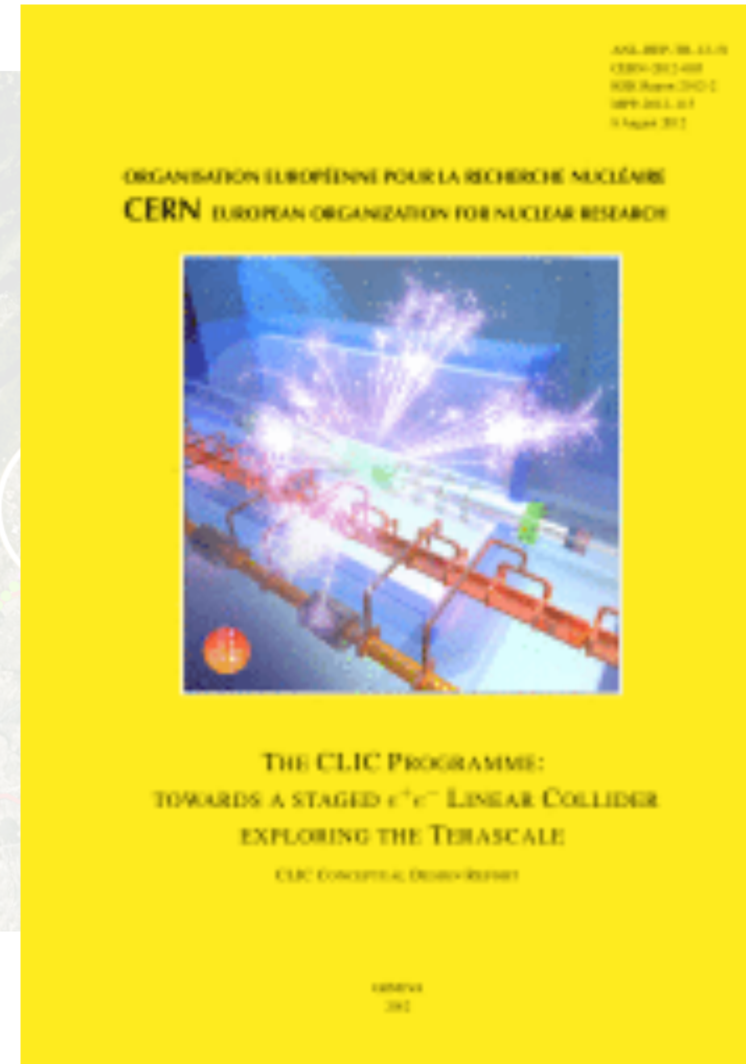
Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of $\sqrt{s}$	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

- sub-percent Higgs coupling measurements
- few percents Higgs width
- top mass, top EW couplings
- direct BSM sensitivity in the multi-TeV region (direct and indirectly via precision)

CLIC (post HL-LHC-x+20)

(350)/1000/3000 GeV - 5/ab





Physics at the CLIC e^+e^- Linear Collider

Input to the Snowmass process 2013

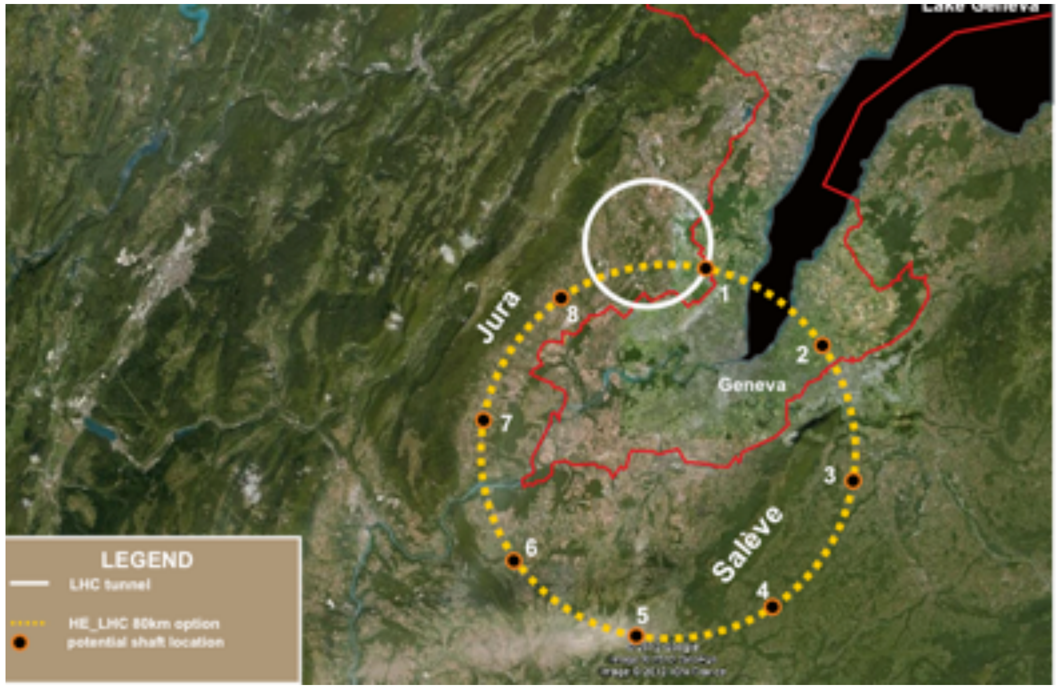
July 22, 2013

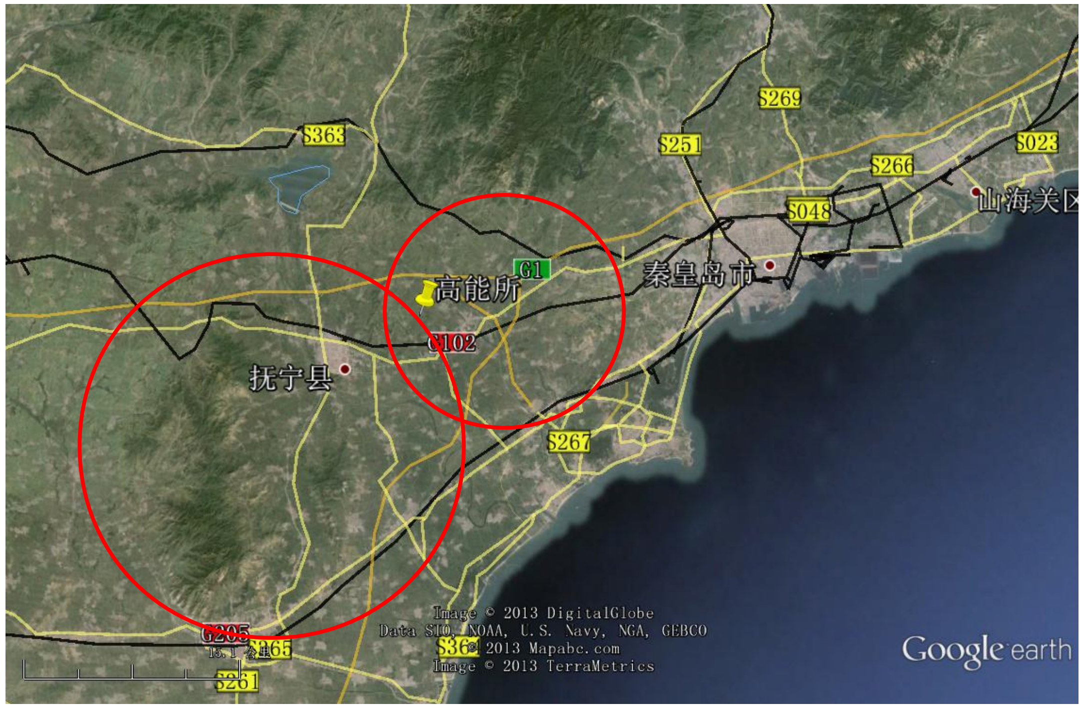
arXiv:1307.5288

post-Higgs discovery update

FCC-ee (post HL-LHC-x+20)/CepC (??-??)

240/350/(500) - 10/ab





FCC-ee (post HL-LHC-x+20)/CepC (??-??)

240/350/(500) - 10/ab

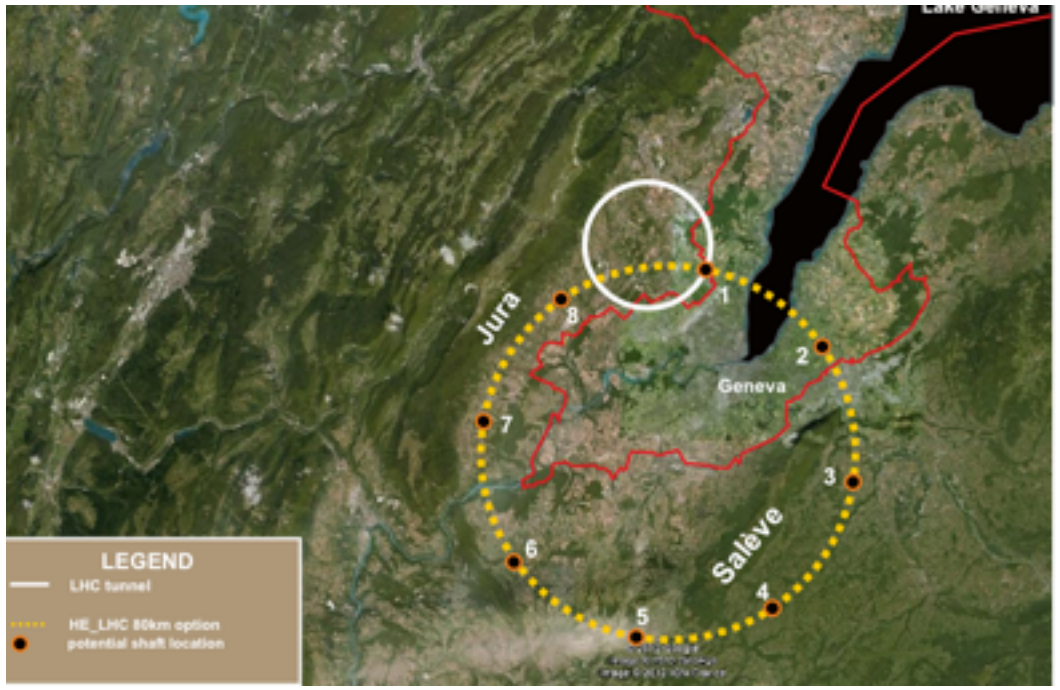
parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	13000-60000	500-1400	51- 98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	6.9	3.5

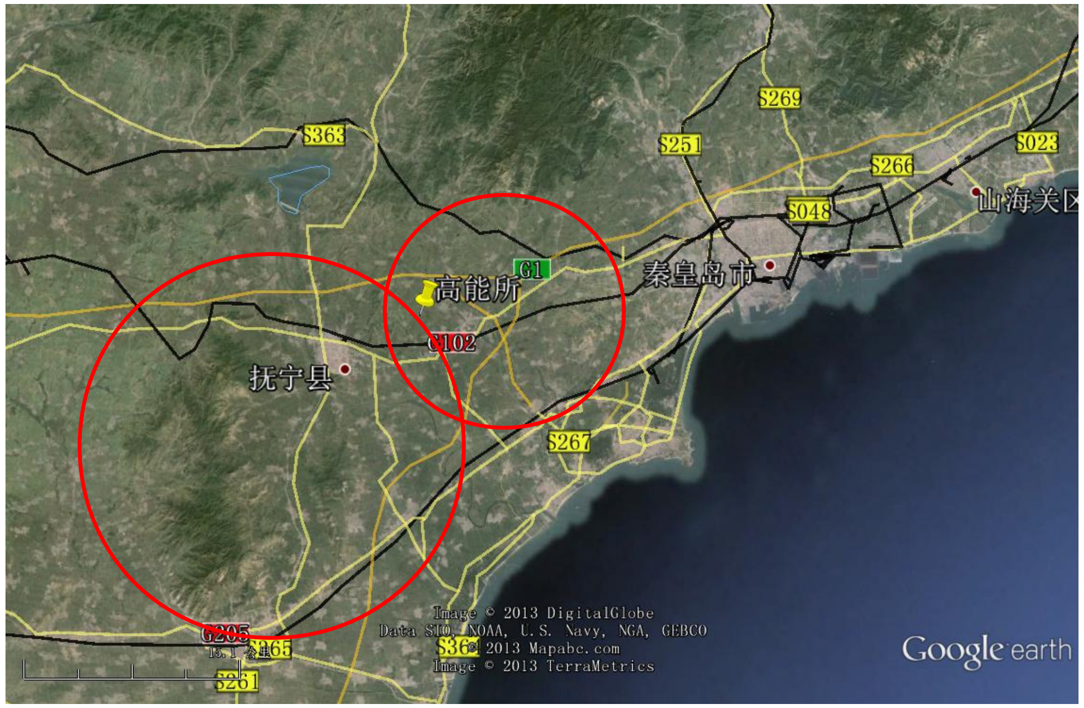
@FCC-ee

- 10^6 H
- 10^{12} Z possible upgrade to 10^{13} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^8 W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks ⇒ >20'000 $B_s\to\tau^+\tau^-$
- TLEP@340/500: 10^6 top pairs (pole mass, probe FCNC decays, top Yukawa)

FCC-ee/CepC (??-??)

240/350/(500) - 10/ab





- physics case: JHEP01(2014)164 arXiv:1308.6176
- CDR and cost review due in 2018

JHEP

PUBLISHED FOR SISSA BY SPRINGER

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ACCEPTED: *December 25, 2013*
PUBLISHED: *January 29, 2014*

First look at the physics case of TLEP

The FCC and CepC are essentially equivalent proposals with different emphasis; FCC – hadrons via e+e-, CepC – e+e- then hadrons

Mike Harrison , SPC meeting Sept. 2015

pre-CDR:

IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group

March 2015

IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

The CEPC-SPPC Study Group

March 2015

1

Higgs physics

Higgs boson & New Physics

The Higgs is related to some of the deepest problems of HEP

$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

- vacuum energy / cosmological constant: $V_0 \approx (2\times 10^{-3}\ \text{eV})^4 \ll M_{\text{PL}}^4$
- hierarchy problem: $m_H \approx 100\ \text{GeV} \ll M_{\text{Pl}}$
- triviality/stability of EW vacuum
- mass and mixing hierarchy
- flavour & CP

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cosmological constant
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triviality/stability
of EW vacuum

mass and mixing
hierarchy

flavour & CP

~~ Higgs interactions ~~

gauge symmetry is the organizing principle for interactions in the gauge sector
not in the Higgs sector ⇒ many free parameters!

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- $\mu^2 H^\dagger H$ → hierarchy problem: $m_H \approx 100\ \text{GeV} \ll M_{\text{Pl}}$
- $\lambda (H^\dagger H)^2$ → triviality/stability of EW vacuum
- y_{ij} → mass and mixing hierarchy
- $\bar{\psi}_{Li} \psi_{Rj} H + h.c.$ → flavour & CP

~~ Higgs interactions ~~

gauge symmetry is the organizing principle for interactions in the gauge sector

not in the Higgs sector ⇛ many free parameters!

but they obey 3 basic structures

(1) proportionality: $g_{hff} \propto m_f \qquad g_{hVV} \propto m_V^2$

(2) factor of proportionality: $g_{hff}/m_f = \sqrt{2}/v$

(3) flavor alignment: $g_{hf_if_j} \propto \delta_{ij}$

Higgs boson & New Physics

The Higgs is related to some of the deepest problems of HEP

$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

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- y_{ij} → *mass and mixing hierarchy*
- $h.c.$ → *flavour & CP*

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➠ test for extended Higgs sectors

(2) factor of proportionality: $g_{hff}/m_f = \sqrt{2}/v$

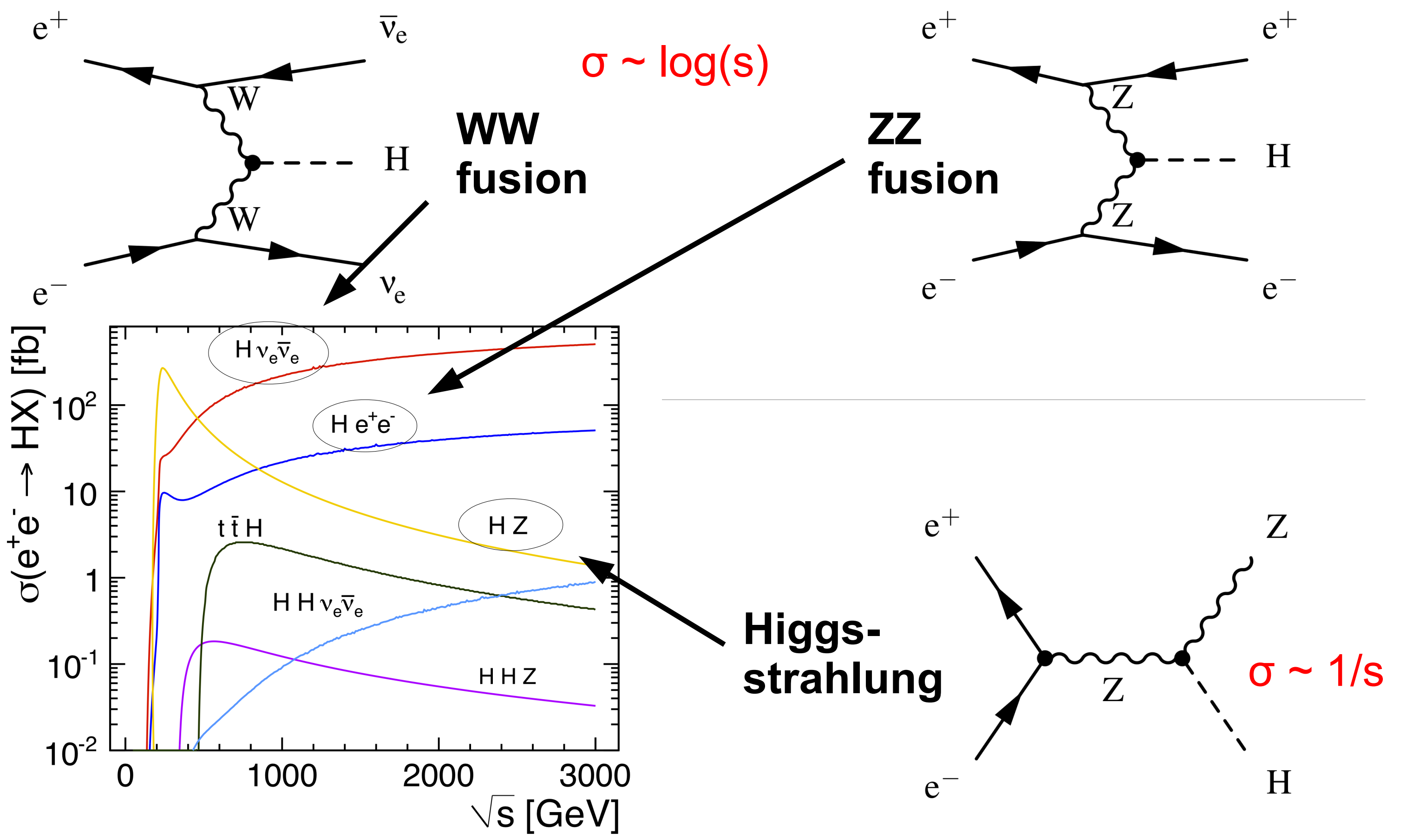
➠ test for extended Higgs sectors

➠ test for Higgs compositeness

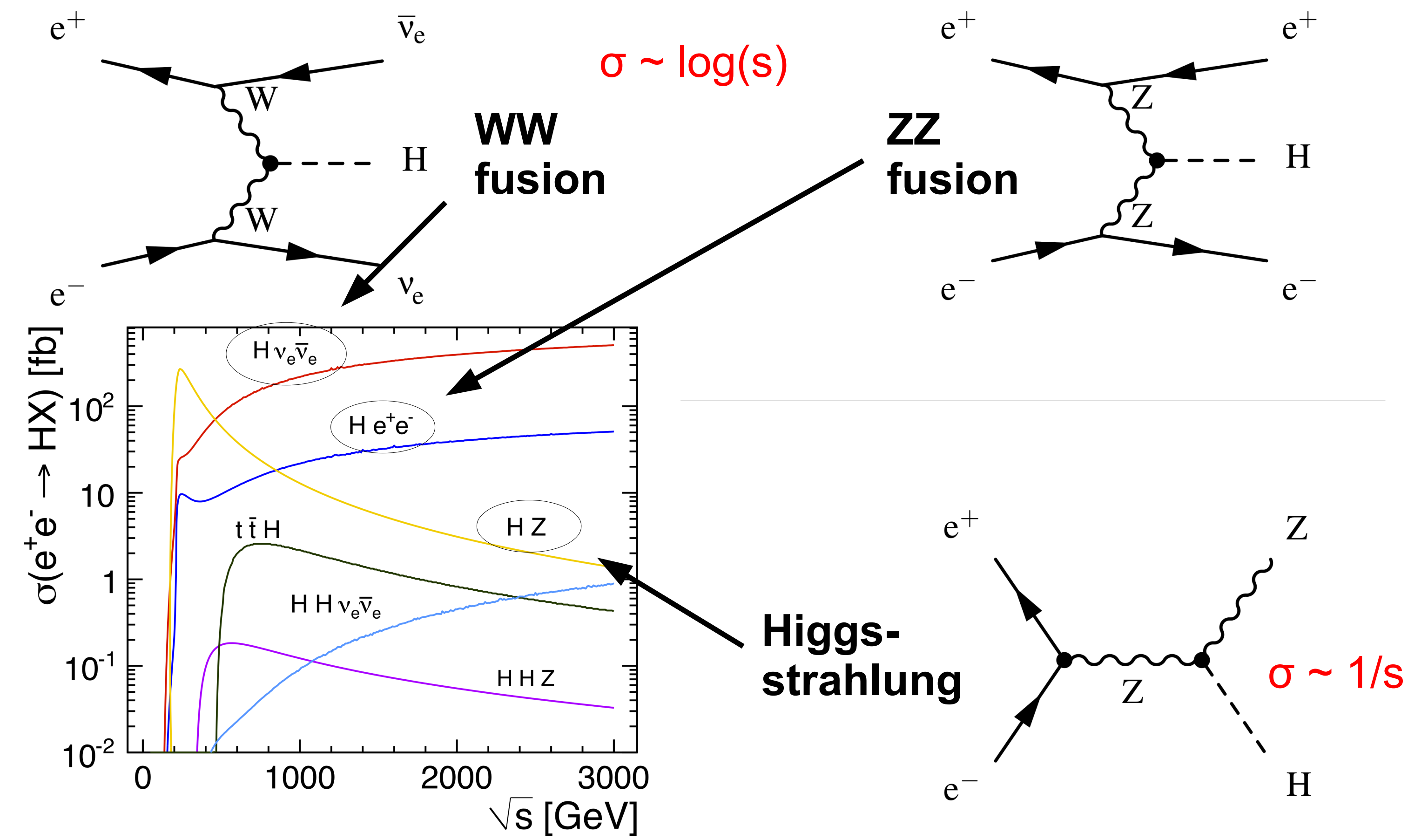
(3) flavor alignment: $g_{hf_if_j} \propto \delta_{ij}$

➠ test for flavor models, origin of fermion masses

The Higgs thresholds



The Higgs thresholds



~250 GeV | ~350 GeV | ~ 500 GeV | ~ 1 TeV | **Center of Mass Energy**

Zh

$t\bar{t}$
VBF Higgs

Zhh(DHS)
HHH opens up!
Top Yukawa via $t\bar{t}h$

VBF at 1 TeV
improves HHH coupling
by combining with Zhh

m_h
Γ_h
higgs couplings

m_t
top Yuk.
Γ_h

ZZhh coupling
h^3 coupling
direct top Yuk.

h^3 coupling
direct top Yuk.

Higgs: ee colliders vs. LHC

~~ significant steps in precision study of Higgs properties ~~

(1) Higgs kinematic parameters: m_H and Γ_H

- ↠ reduce parametric uncertainties in xs and BR
- ↠ control the fate of EW vacuum within the SM
- ↠ constrain new physics models (e.g. MSSM)

(2) Precise and model-independent access to Higgs couplings

- ↠ 1% level
- ↠ identification of correlation patterns among deviations
- ↠ indirect test of extended Higgs sectors/composite nature
- ↠ ultimate test of naturalness

(3) Access to decays modes that are background dominated @ LHC

- ↠ bb/cc/gg
- ↠ exotic decay modes (↳ portal models of Dark Matter)

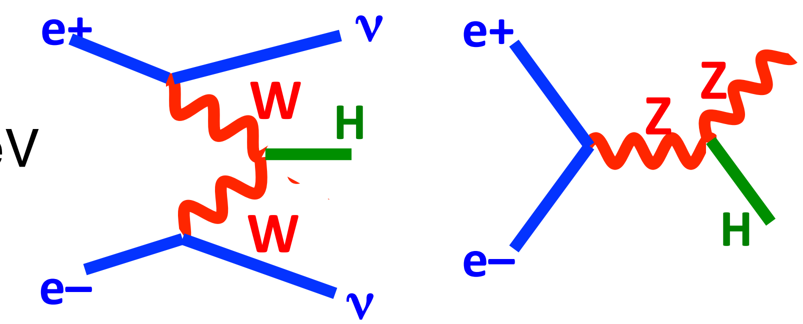
(4) Constraints on Higgs flavor violating couplings

- ↠ shed light on the origin of fermion masses and flavors

Higgs: ee colliders vs. LHC

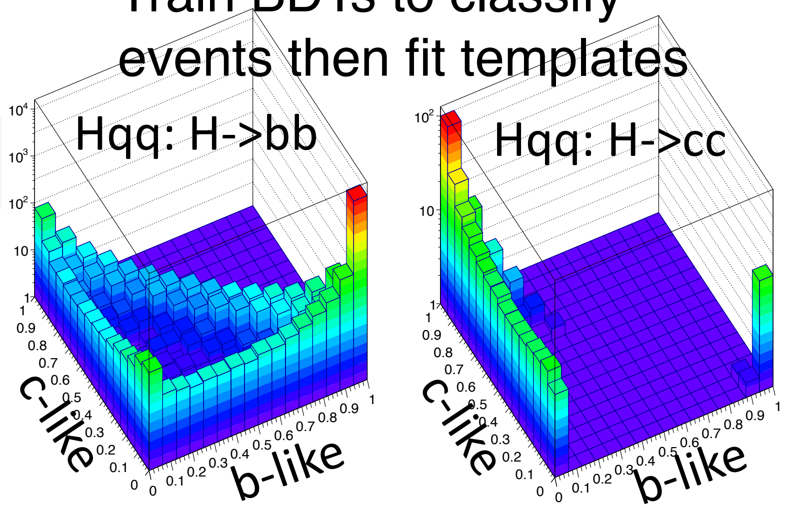
New analyses at 3TeV, 1.4TeV, 350GeV

2jets+missing energy



also 2 jets + 2 leptons, and 4 jets

Train BDTs to classify events then fit templates



CLIC

$\Delta(\sigma \times Br(H\to bb))$ <1%

$\Delta(\sigma \times Br(H\to cc))$ 6–10%

$\Delta(\sigma \times Br(H\to gg))$ 4–5%

A. Robson@LCWS15

ILC

Topic	Parameter	Initial Phase	Full Data Set	units
Higgs	m_h	25	15	MeV
	$g(hZZ)$	0.58	0.31	%
	$g(hWW)$	0.81	0.42	%
	$g(hb\bar{b})$	1.5	0.7	%
	$g(hgg)$	2.3	1.0	%
	$g(h\gamma\gamma)$	7.8	3.4	%
		1.2	1.0	%, w. LHC results
	$g(h\tau\tau)$	1.9	0.9	%
	$g(hc\bar{c})$	2.7	1.2	%
	$g(ht\bar{t})$	18	6.3	%, direct
		20	20	%, $t\bar{t}$ threshold
	$g(h\mu\mu)$	20	9.2	%
	$g(hhh)$	77	27	%
	Γ_{tot}	3.8	1.8	%
	Γ_{invis}	0.54	0.29	%, 95% conf. limit

arxiv:1506.05992

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
γγ	1.7%	<1% ?
Zγ	?	1% ?
tt		1% ?
bb	0.42%	
ττ	0.94%	
cc	1.0%	
ss	H→Vγ, in progr.	
μμ	6.4%	2% ?
uu,dd	H→Vγ, in progr.	
ee	$e^+e^-\to H$, in progr.	
HH		5% ?
BR_{exo}	0.48%	< 10^{-6} ?

adapted from M. Mangano, HXSWG '15

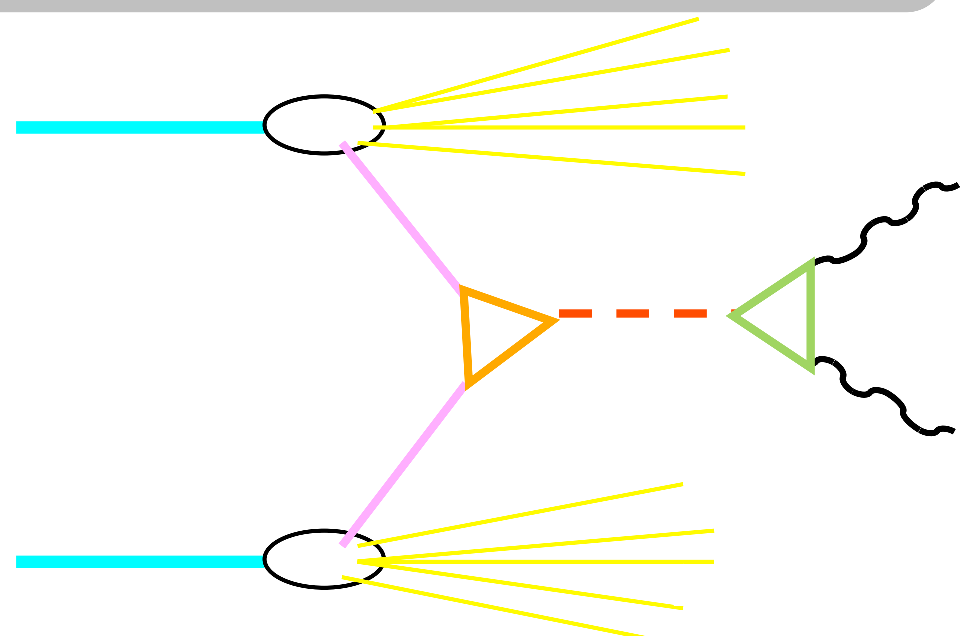
Higgs mass

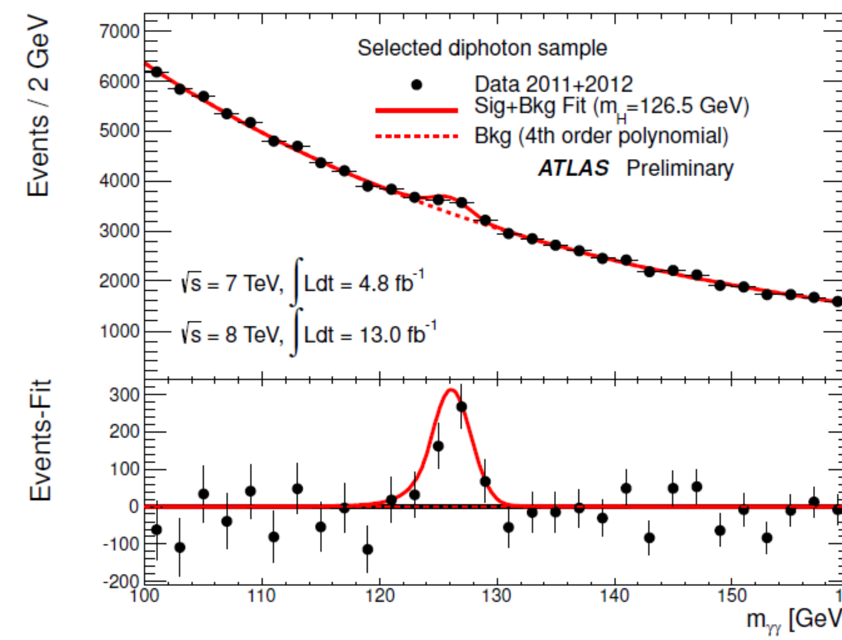
Remember that Δm_H = 200 MeV shifts prediction for BR($H \to VV$) by 2%

LHC $H \to \gamma\gamma$ Invariant mass of $\gamma\gamma$

now
$\Delta m_H \sim 240$ MeV

14Tev/3ab^{-1}
$\Delta m_H \sim 40$ MeV (tbc)

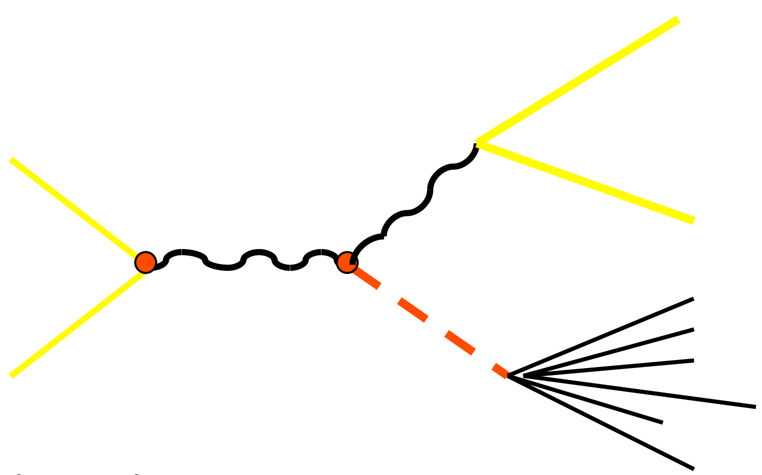


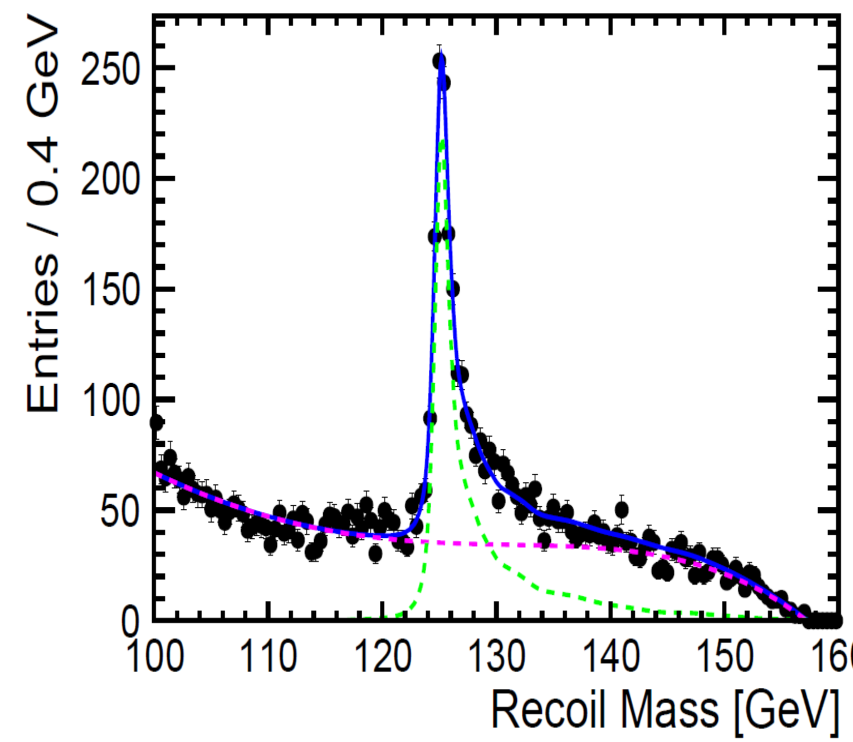


ee Recoil mass of $Z(\mu^+\mu^-)$

H20@20years
$\Delta m_H \sim 15$ MeV

ILC+FCC/CepC
$\Delta m_H < 10$ MeV



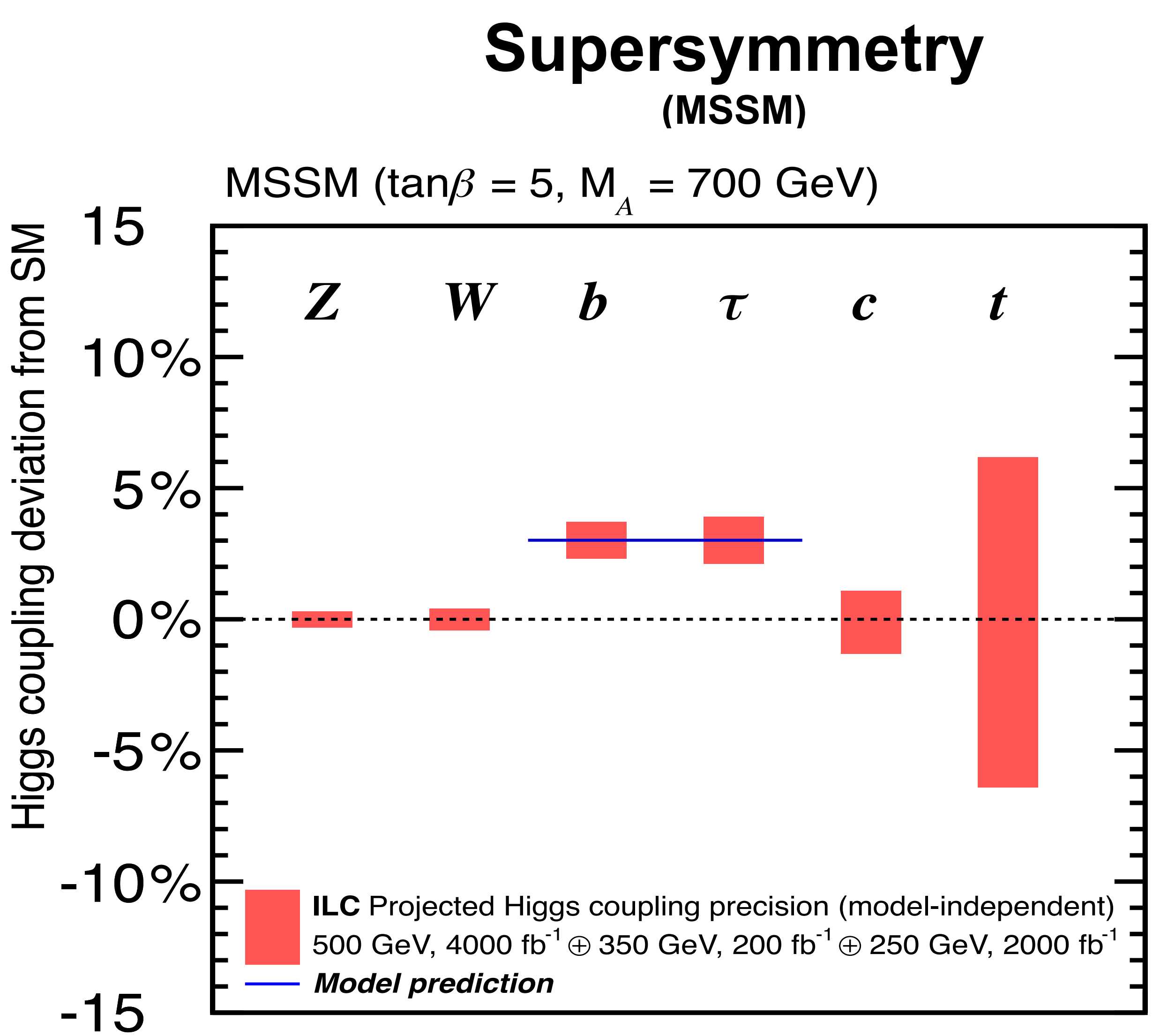


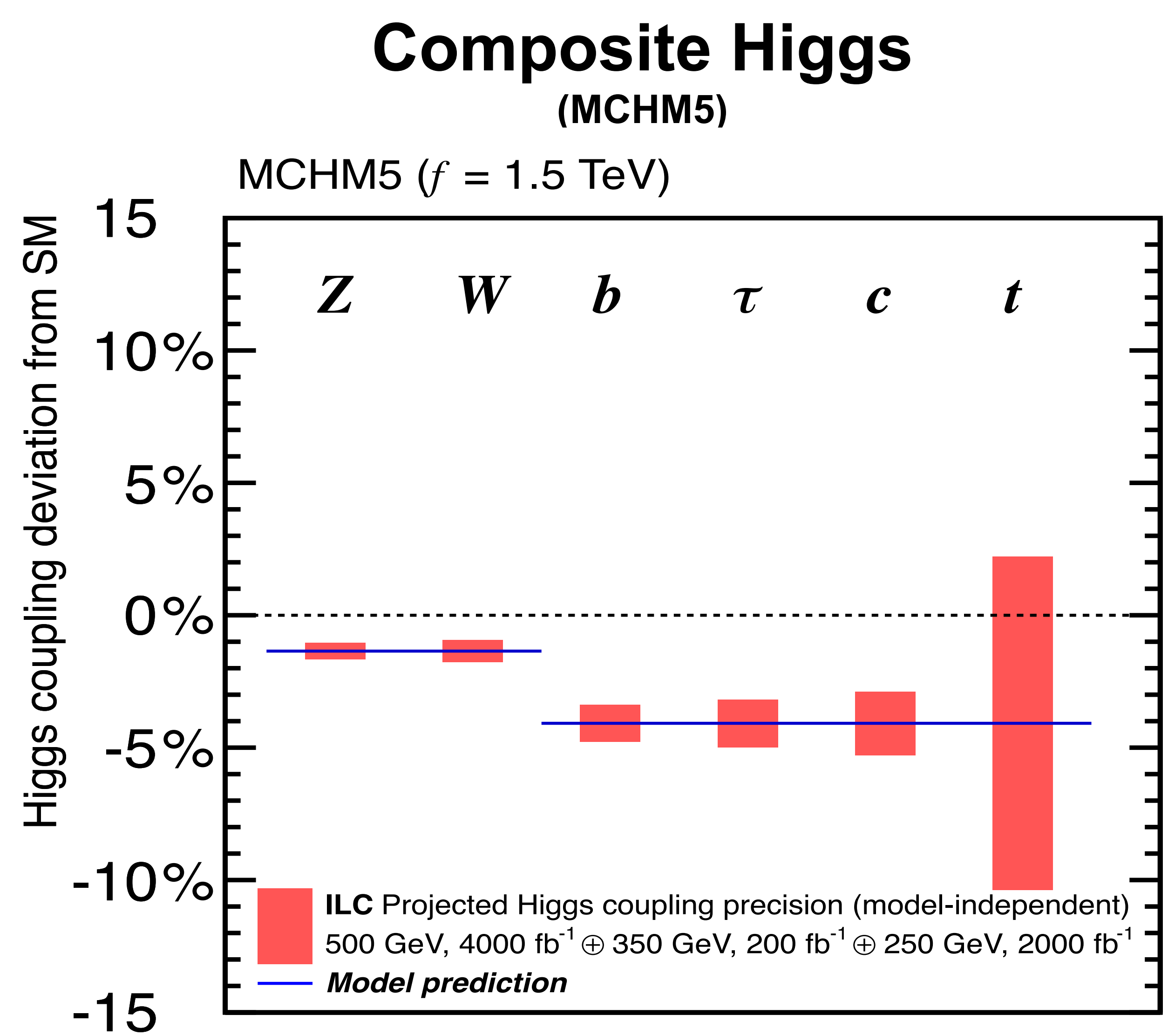
350Gev/0.5ab^{-1}
$\Delta m_H \sim 120$ MeV (30 MeV with VBF and bb mass distribution)

$\Rrightarrow$ ZH @ee: tag Higgs events independently of its decay modes

Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model





ILC Physics WG, '15
arXiv:1506.05992

Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying
~~ expected largest relative deviations ~~

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

A. Pomarol, Naturalness ’15

Higgs couplings measurement projections

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

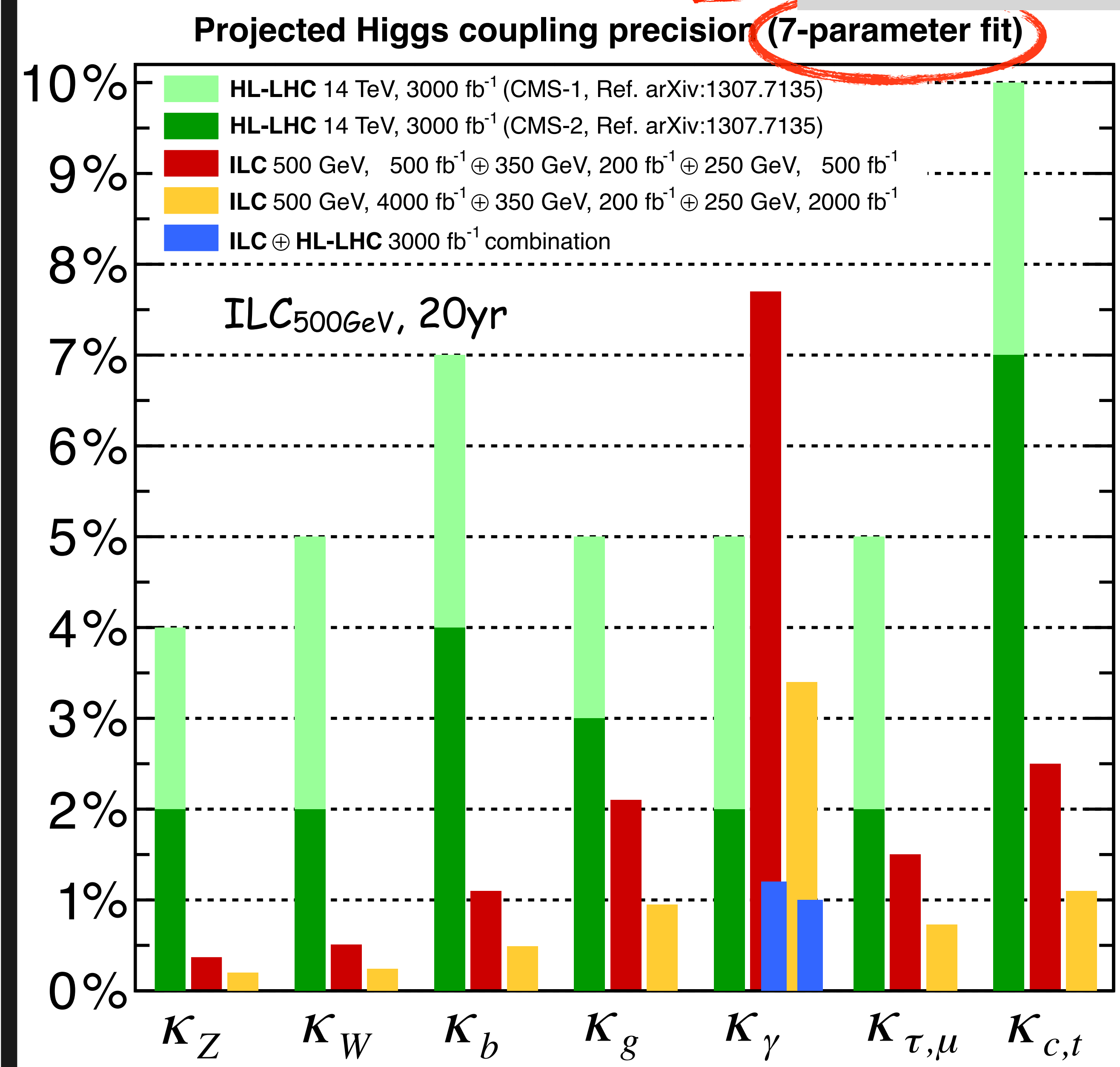
estimates done soon after Higgs discovery, a lot of work since then and results have been refined

Rich experimental program of (sub)percent precision

Higgs couplings measurement projections

ILC500GeV, 20yr ~ 100 HL-LHC
(apart for $h\gamma\gamma$)

assumption about Higgs width



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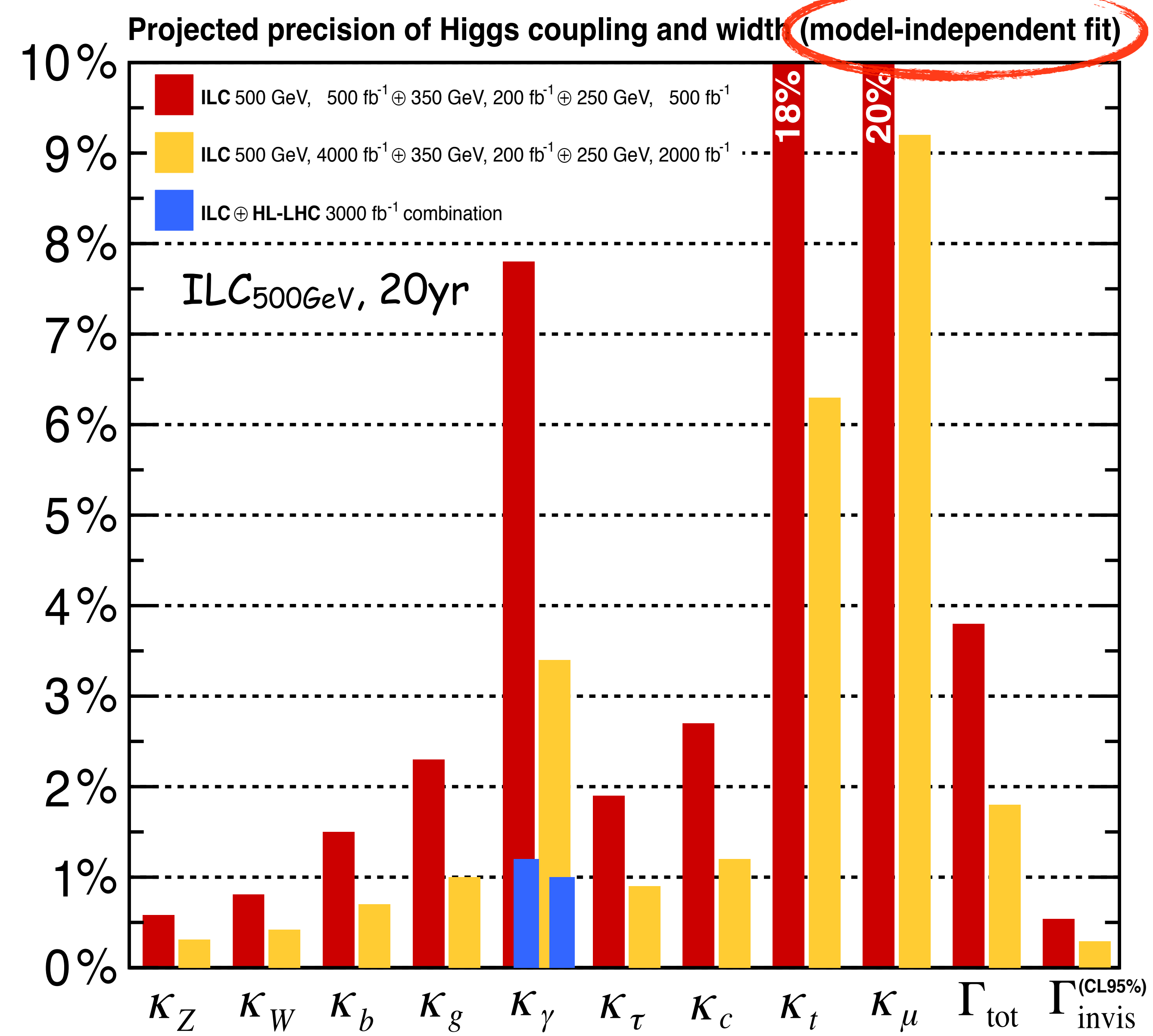


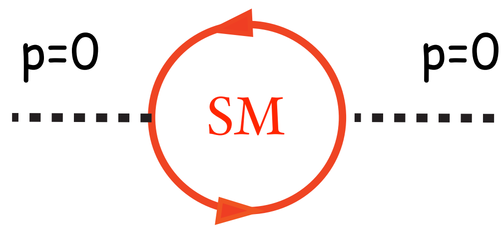
Rich experimental program of (sub)percent precision
Nice synergy/complementarity LHC-ILC ($h\gamma\gamma$)

use BR ratios from hh with absolute precise BR from ee
to export ee precision to Higgs decays that are limited by statistics in ee

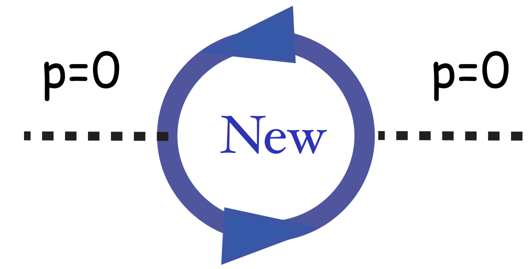
Higgs couplings as a test of naturalness

$$-(125\ \text{GeV})^2 \left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 =$



$+$



$\sim m_H^2$

generically

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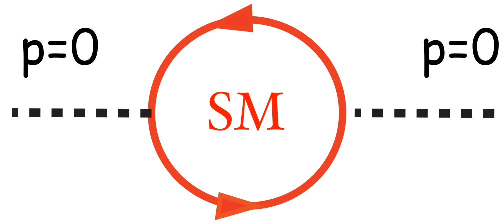
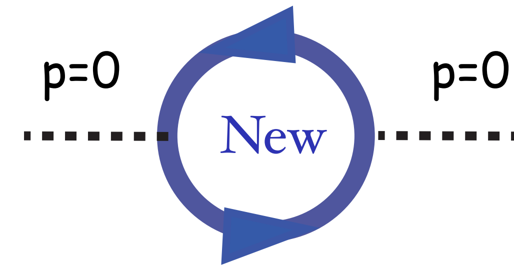
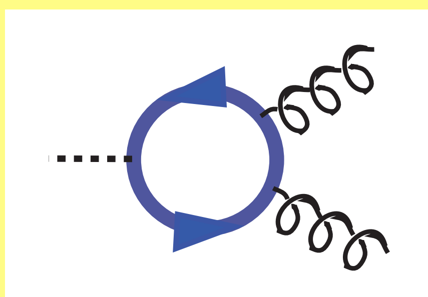
$\delta m_H^2 =$  $+$  $\sim m_H^2$

charged particles

generically



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad\qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$

Colorful naturalness probed @ LHC

Higgs couplings as a test of naturalness

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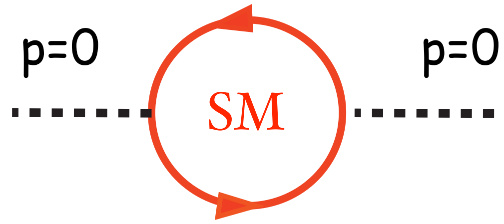
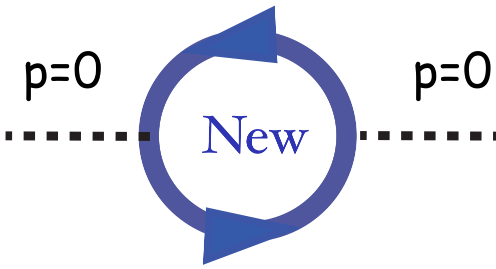
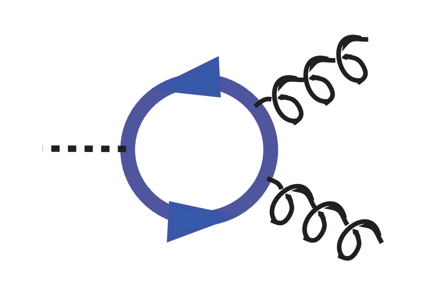
$\delta m_H^2 =$ 

$+$ 

$\sim m_H^2$

charged particles — *generically* — neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

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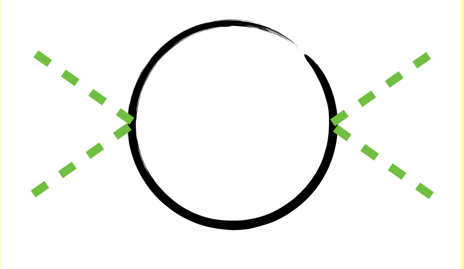


$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

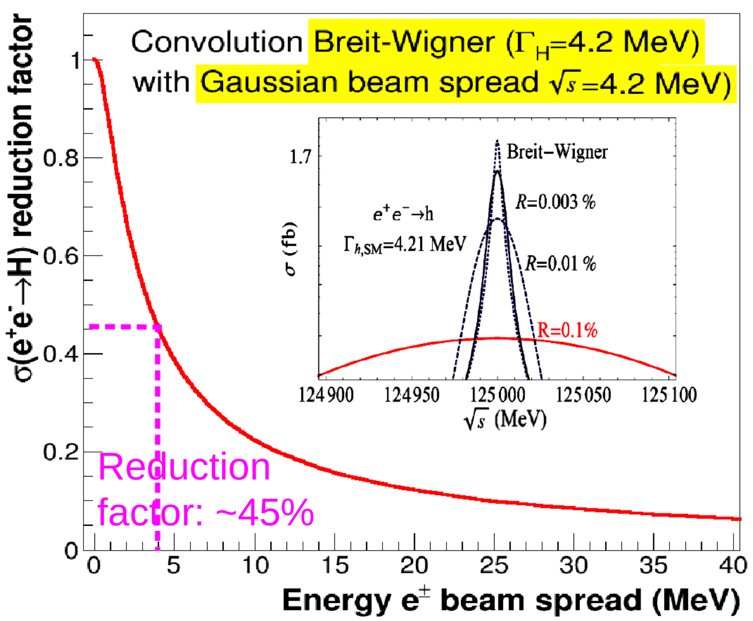
Neutral naturalness (invisible?) @ LHC

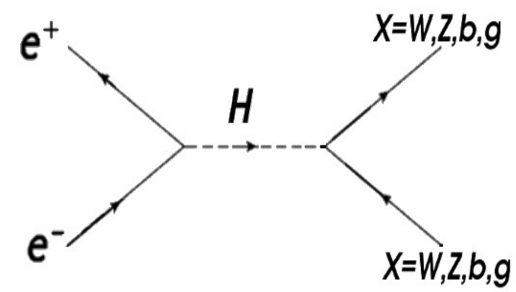
Higgs couplings to electrons (unique to FCC-ee)

- Higgs-e$^{\pm}$ Yukawa g_{Hee} unobservable via decay: BR(H→e^{+}e^{-})~5.3·10^{-9}
- Resonant s-channel production considered so far only for μμ collider ($\sigma_{\mu\mu\to H}$ ~ 70 pb). $\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$ ⇒ Tiny σ(ee→H)

$$\sigma(e^+ e^- \to H) = \frac{4\pi\Gamma_H^2 Br(H \to e^+e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} = 1.6 \text{ fb}$$

d'Enterria Lomonosov '15





Including ISR + $\sqrt{\sigma_{spread}} \sim \Gamma_H$ = 4.2 MeV:

σ(ee→H) = 280 ab

Analysis of 7 Higgs decay channels:
L_{int} = 10 ab^{-1}, S=0.65:
BR(Hee) < 4.6×BR_{SM} (3σ)
g_{hee} < 2.2 × $g_{Hee,SM}$ (3σ)

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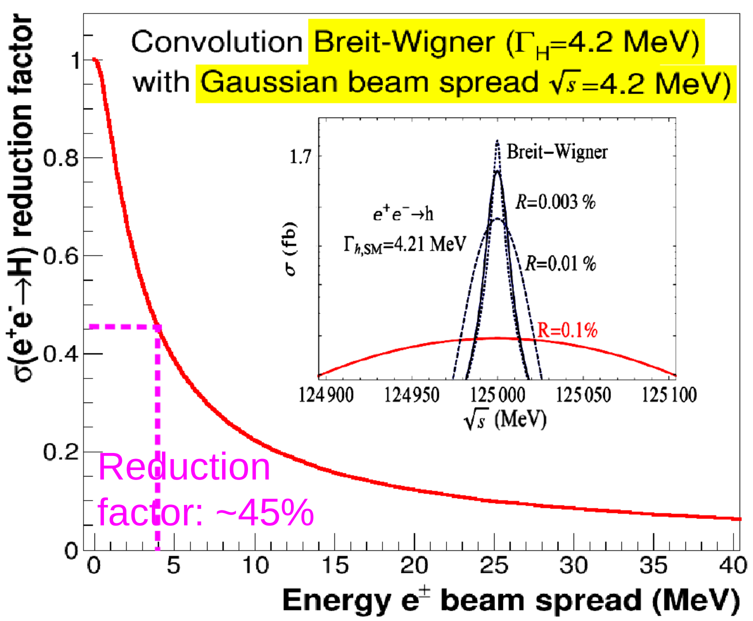

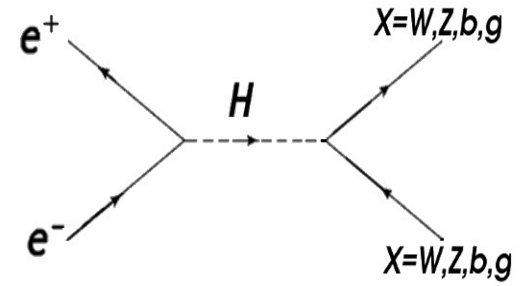

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- invaluable info on mass generation of light particles
- indirect stringent bounds on Higgs CP-violating couplings

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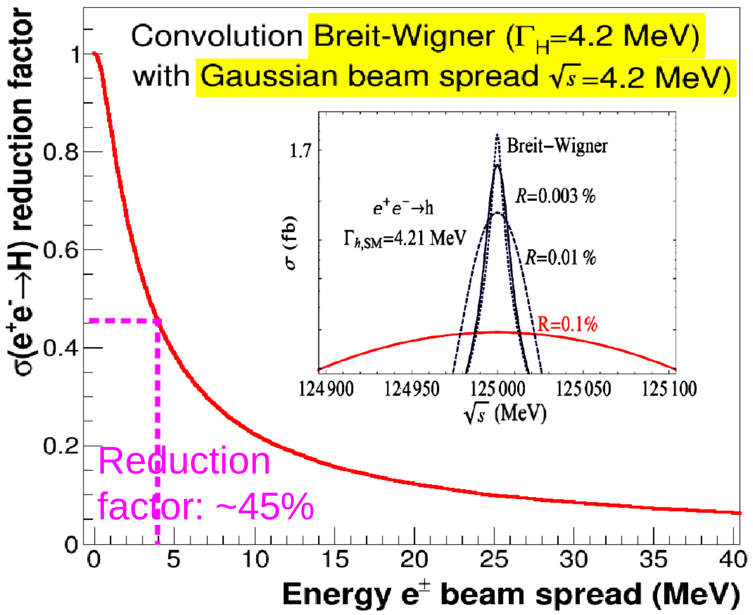

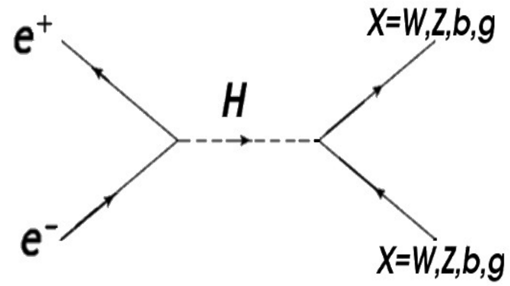

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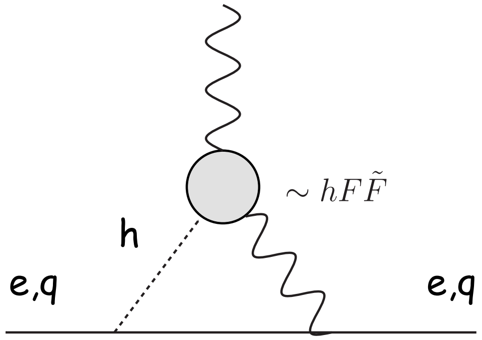
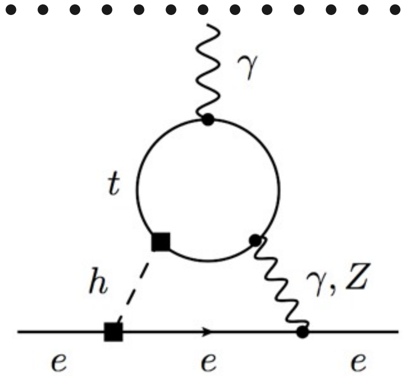
operators with γ:
already severely constrained by e and q EDMs
McKeen, Pospelov, Ritz '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \le 10^{-4}$$

Λ_{CP} > 25 TeV

operators with top:
already severely constrained by e and q EDMs
Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \le 0.01$$

Λ_{CP} > 2.5 TeV

Higgs portals and Higgs exotic decays

$|H|^2$ and HL are SM-singlet of low dimension

they can have large (renormalizable) couplings to hidden/dark sector that could

(i) make up the DM relic abundance

or (ii) be key agents in models of neutral naturalness

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new exotic/invisible decay modes: ee sensitivity $BR_{exo}<1\%$

(if $m_{NP} < m_H/2$, possible production via off-shell Higgs but limited reach Craig et al '14)

$Z_{\mu\nu} Z_D^{\mu\nu}$	$\|H\|^2 \|S\|^2$	HLN
$H \to Z Z_D$	$H \to ss$	$H \to LN$
new force	new Higgses	new matter

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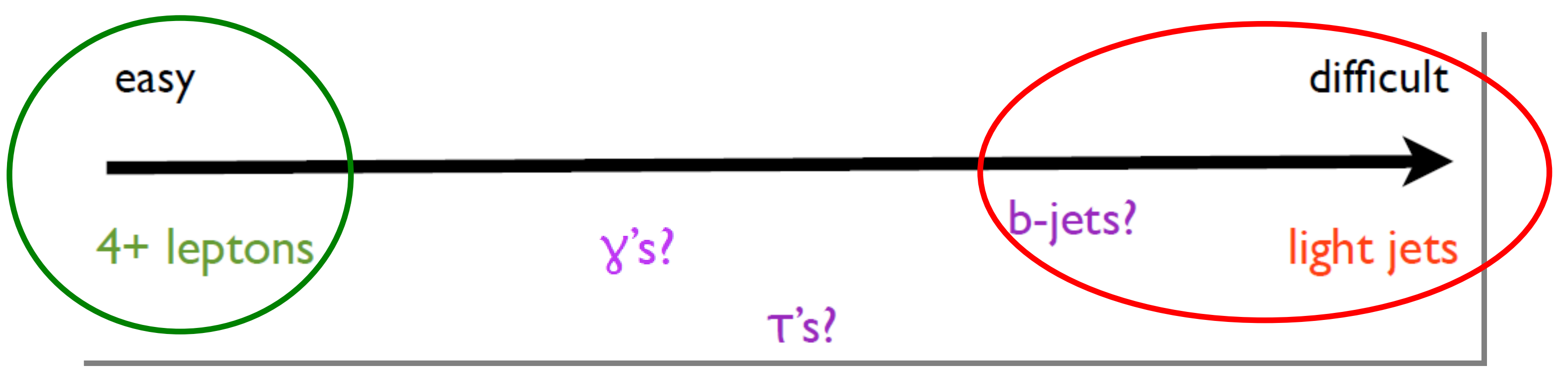
Gori @ LCWS'15



Complementarity with LHC searches

Example:
h ⟶ ZZ_D ⟶ 4l

These can be seen by the LHC pretty easily:
BRs ~ 10^{-6} – 10^{-7} can be probed by the HL-LHC

Curtin, Essig, SG, Shelton 1412.0018

See Liu, Potter, 1309.0021 for a ILC h ⟶ 4τ analysis

Example: (as in the NMSSM)
h ⟶ ss ⟶ 4b

Background limited at the LHC.
Theory studies show that BRs ~ 0.1 might be reached Cao et al, 1309.4939

Higgs and Flavor Origin

it is core property of the origin of fermion masses in the SM
that the Higgs doesn't mediate FCNC at tree-level
Seeing any large flavor violating Higgs channels, we'll have unique implications

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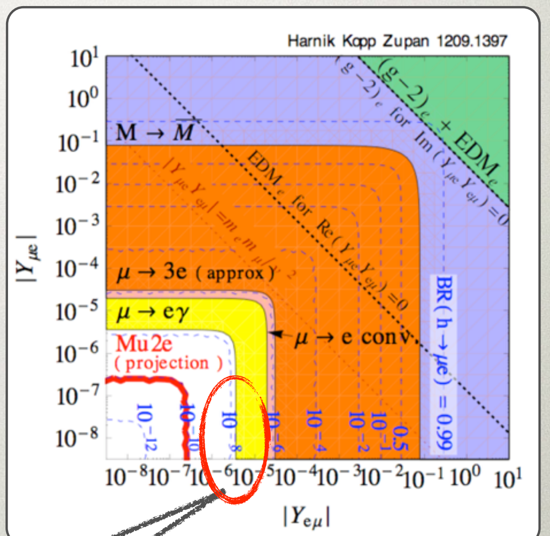
Zupan @ FCC Washington '15

$h \to \mu e$

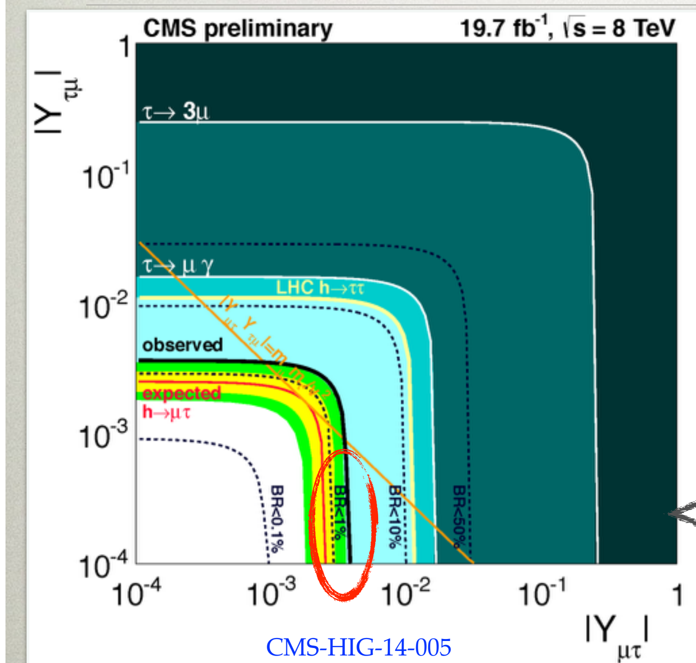
- indirect bounds better than LHC
- $h \to \mu e$ very clean channel



- what can one do with 10^9 Higgses @100TeV?

FCC week, Mar 26 2015, Washington DC

$h \to \tau\mu$



- right now: 2j channel statistics limited, 0j+1j not
- how about with $\sim 10^9$ h? *LHC8* $\Rightarrow$ ***100 TeV 3 ab^{-1}***
- assume same scaling for signal and bckg
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-4}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 2$TeV
- if bckg free
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-6}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 20$TeV
  - $(Y_{\mu\tau} Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2)$

Higgs and Flavor Origin

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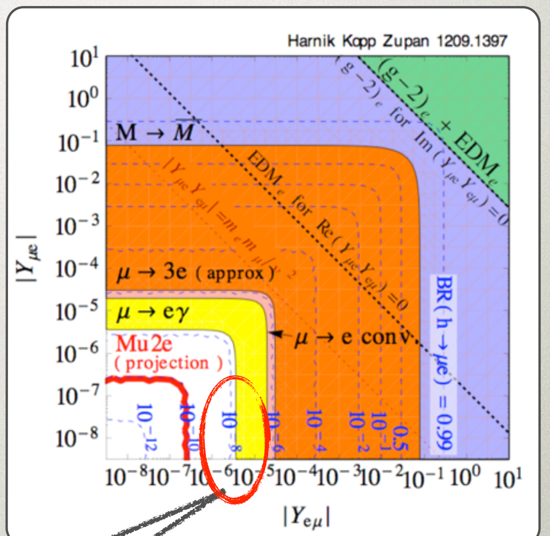

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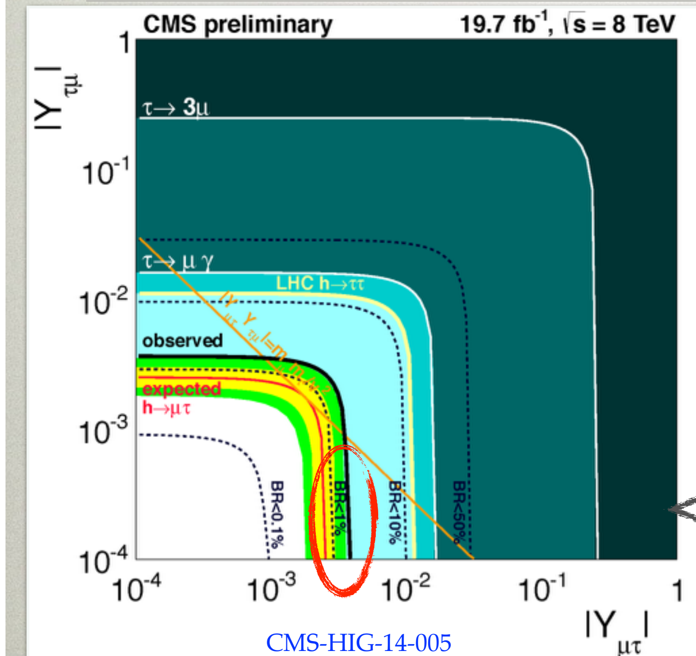

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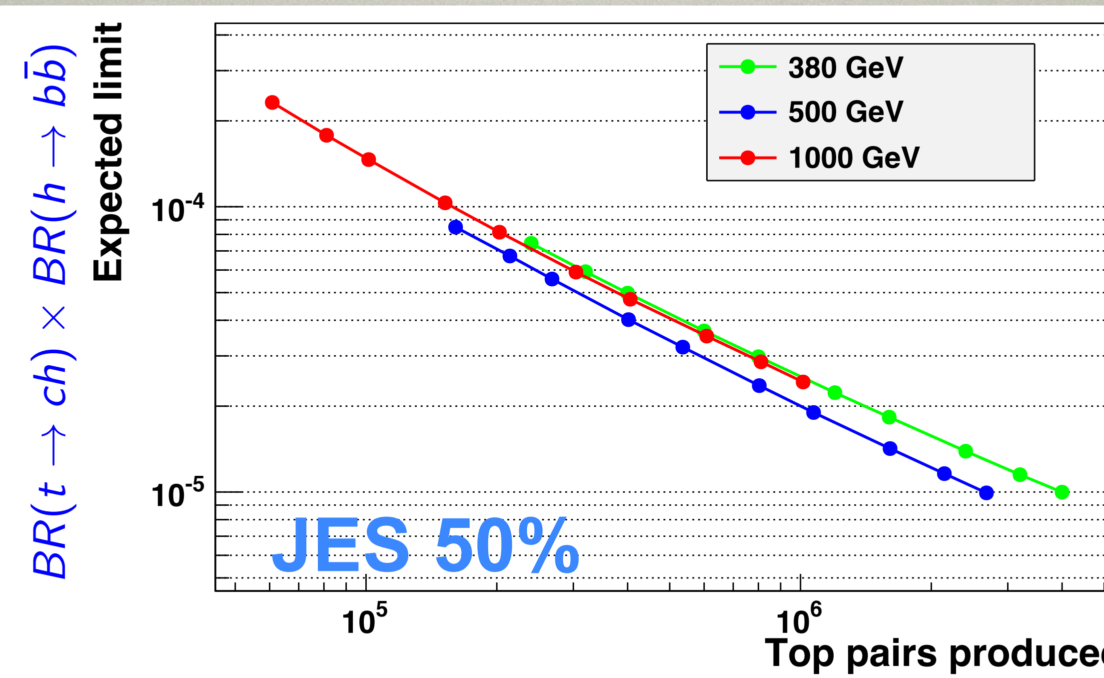
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 20$TeV
  - $(Y_{\mu\tau} Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2)$

ee prospects on t→ch

Basic event selection:

- 1 lepton + Etmiss + 4 jets, among which 3 b-jets
- 0 lepton, no Etmiss, 6 jets, among which 3 b-jets

F. Zarnecki, Valencia'15



Higgs @ high thresholds (unique to ILC/CLIC)

ttH

direct access to top Yukawa coupling

(vacuum stability, Higgs mass hierarchy)

final states analyzed:

"*8 jets*": $t(\to qqb)\bar{t}(\to qq\bar{b})H(\to b\bar{b})$
"*6 jets*": $t(\to qqb)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$
["*4 jets*": $t(\to l\nu b)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$]

crucial assets of ee colliders:

- jet reconstruction in complex final states
- flavor tagging
- charged lepton identification
- missing energy reconstruction

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	$(14-15)\%$	$(7-10)\%$	10%	4%	4%

- 6.3% (update)
- 3% if $\sqrt{s}\nearrow$550GeV

top WG @ Snowmass'13 arXiv:1311.2028

Higgs self-coupling

Higgs potential

(dynamics of phase transition, baryogenesis)

ILC current studies:

(4b and 2b2W modes)

29%@4/ab, 500GeV

16%@2/ab, 1TeV

10%@5/ab, 1TeV

CLIC studies:

(VBF w/ 80% e^--pola)

24%@1.5/ab, 1.4TeV

12%@2/ab, 3TeV

need to disentangle λ_{HHH} and g_{HHVV}

Can high thresholds be probed by combining LHC+low threshold ee?

2

Top physics

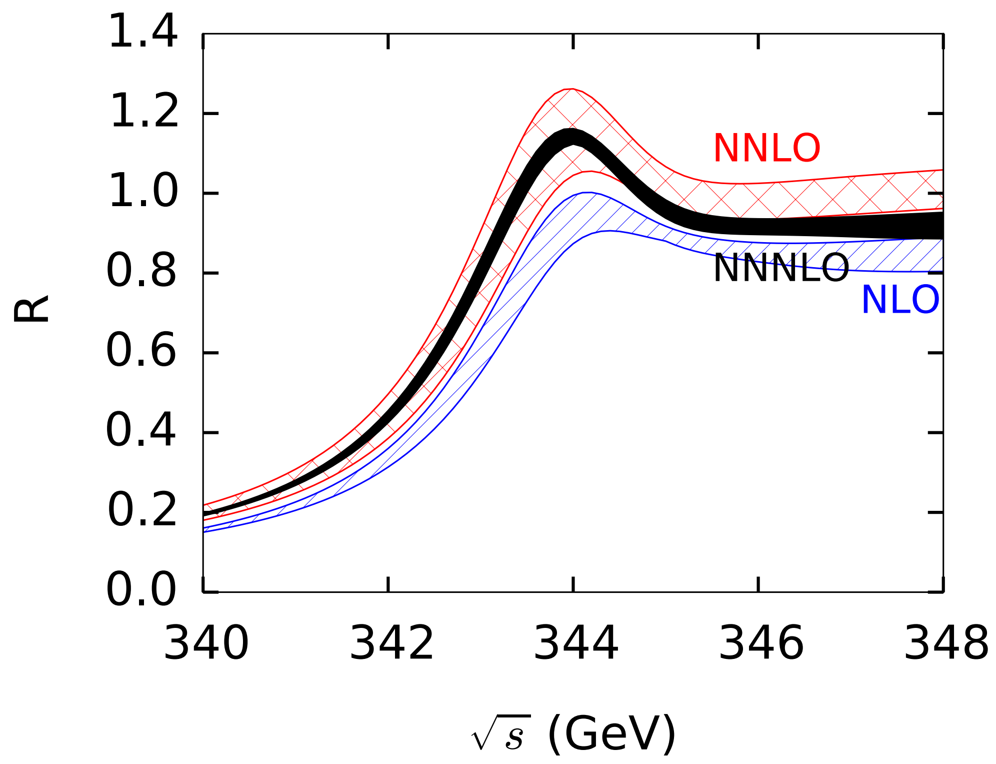
Top programme @ ee colliders

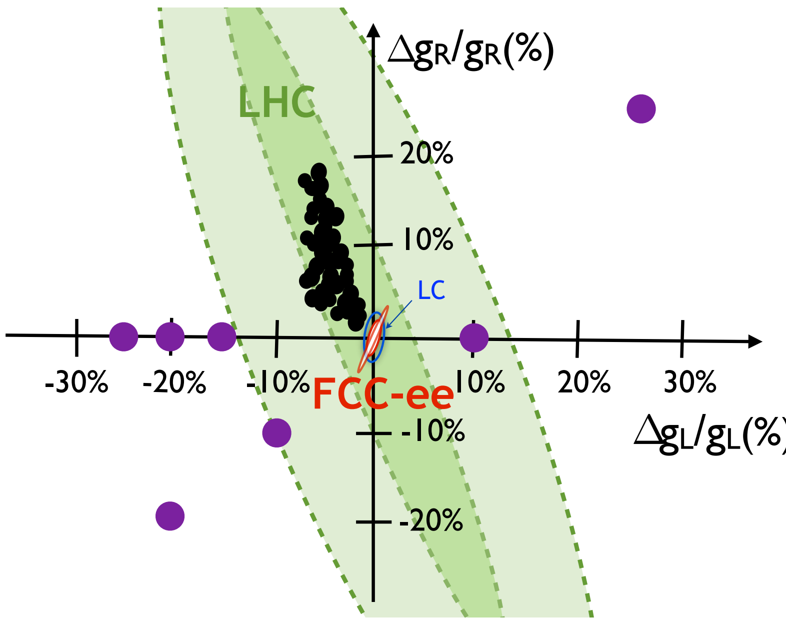
three-fold programme

(1) study of the threshold for $t\bar{t}$ production around 350 GeV = "hydrogen atom for strong interactions", i.e. bound state free of nonperturbative quark confining interactions

(2) measure the top-Higgs coupling (see ttH discussion in Higgs chapter)

(3) study of top quark production and decay (at high energy) to access top EW couplings

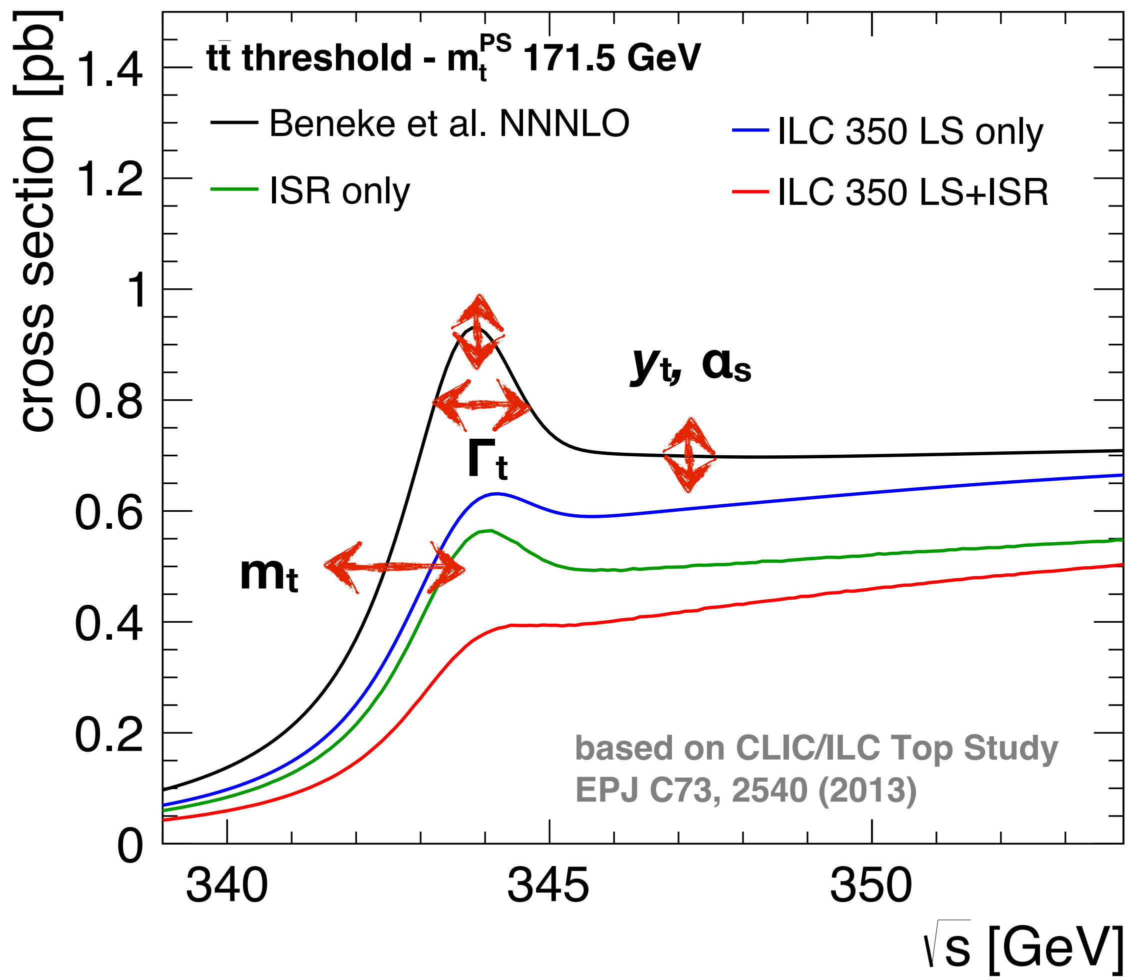




Top pair production @ threshold

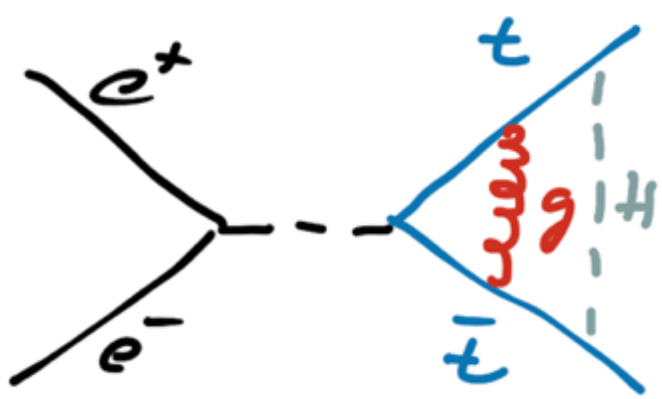
- Two key steps forward this year:
  - Conversion of pole / 1S / PS mass to msbar mass at NNNNLO QCD   Marquard et al '15
  - NNNLO QCD calculations of threshold   Beneke et al '15

F. Simon @LCWS'15



- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak - precise external α_s helps

- The cross-section around the threshold is affected by several properties of the top quark and by QCD
  - Top mass, width, Yukawa coupling
  - Strong coupling constant



$$\delta m_t \sim 30 \text{ MeV}$$

to be compared to HL-LHC prospect

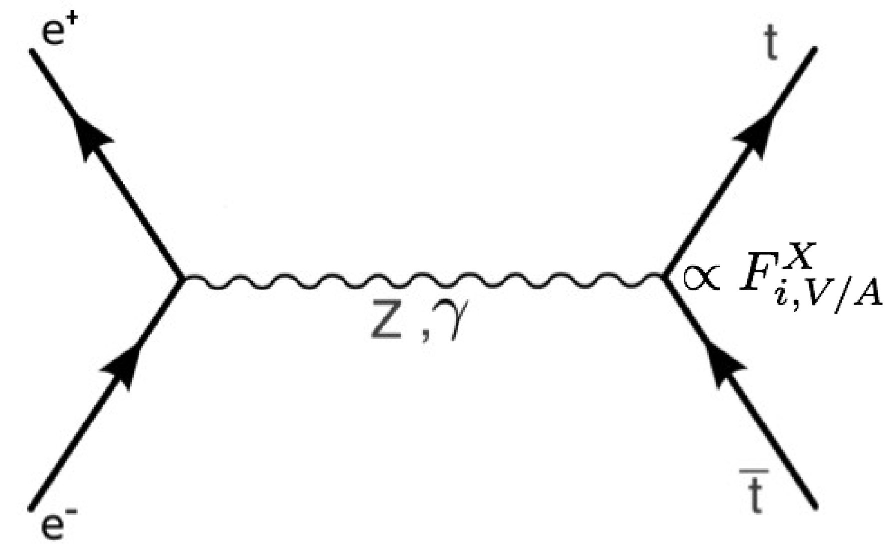
$$\delta m_t \sim 500 \text{ MeV}$$

Top EW couplings

Important properties of tt production above threshold

- events are fully reconstructable,
  all final parton angles can be measured
- production is from γ-Z interference,
  asymmetries are of order 1
- decay is by weak interactions,
  asymmetries are of order 1

M. Peskin @LCWS'15



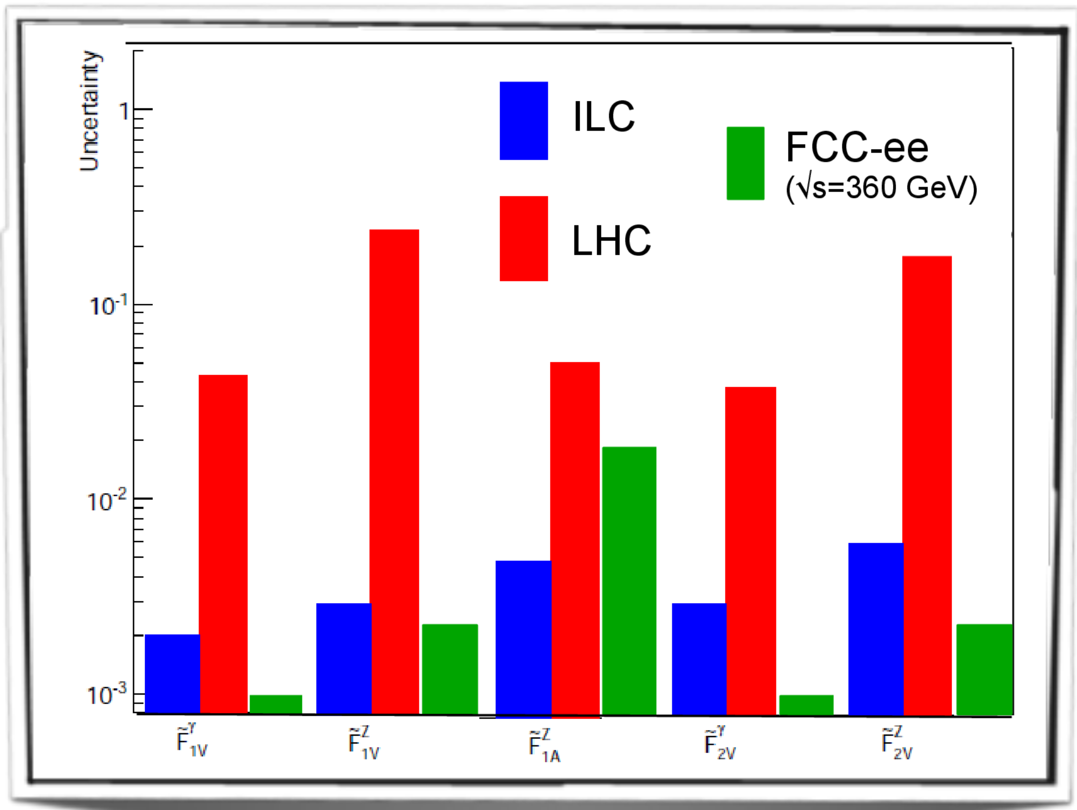
$$\Gamma^{ttX}_\mu(k^2,q,\bar{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5 F^X_{1A}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu\left(iF^X_{2V}(k^2)+\gamma_5 F^X_{2A}(k^2)\right)\right\}$$

Khiem et al '15,
arXiv:1503.04247

. syst. error included

. show feasibility of kinematic reconstruction of the di-lepton final state: $e^+e^- \to tt \to 6f$

. extract all ten form factors simultaneously using ME method



Janot '15,
arXiv:1503.01325

. stast. error only

. no beam polarization

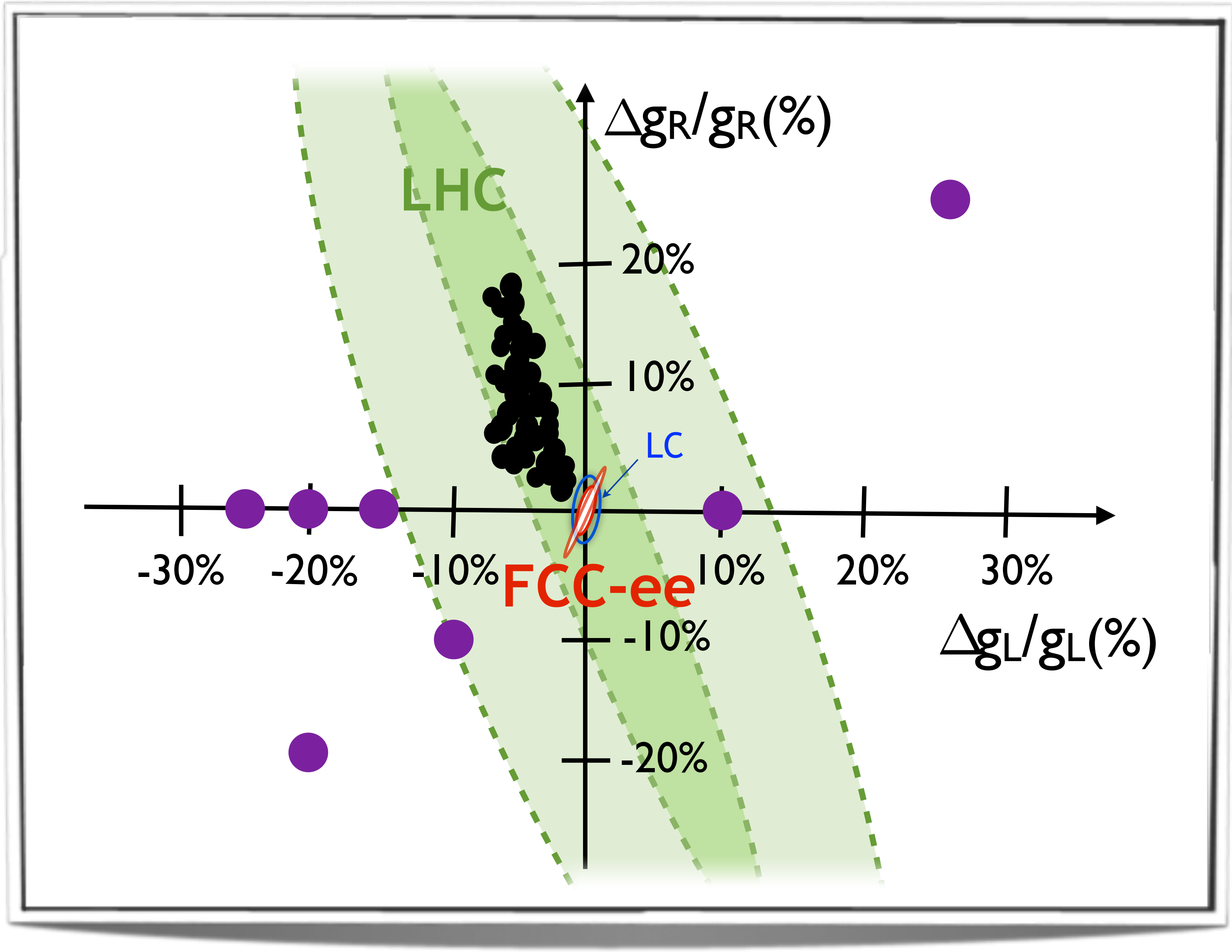
. use final-state polarization instead

. cross-over region (365GeV) well under control?

Top EW couplings

important to access the EW top couplings

1. chiral gauge symmetries are the only one to be spontaneously broken?
2. probe various scenarios of physics beyond the SM



adapted from Richard '14
see also Agashe et al '13
see also Janot '15

ILC sensitivity down to 0.5% (factor 10 improvement over TESLA estimates)

⇛ probe New Physics resonances up to 15-20 TeV, way above direct LHC access

3

New Physics Searches

ee colliders as NP discovery machines

no BSM particle discovered @ LHC: is it still worth searching?
LHC searches left territories unexplored
DM, neutral naturalness come with light uncolored particles
that are best searched for at ee colliders!
Even compressed gluinos are good ee-targets

ee colliders as NP discovery machines

no BSM particle discovered @ LHC: is it still worth searching?
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Even compressed gluinos are good ee-targets

~~ a few examples for illustration ~~

(1) compressed spectra (m_{LSP}~m_{NLSP})

- ↠ well-tempered neutralino DM
- ↠ weak LHC bounds (soft decay, small MET)

(2) light staus (similarly for higgsinos)

- ↠ weak LHC bound (~90GeV)
- ↠ DM with stau-neutralino co-annihilation
- ↠ enhance di-photon Higgs decay rate

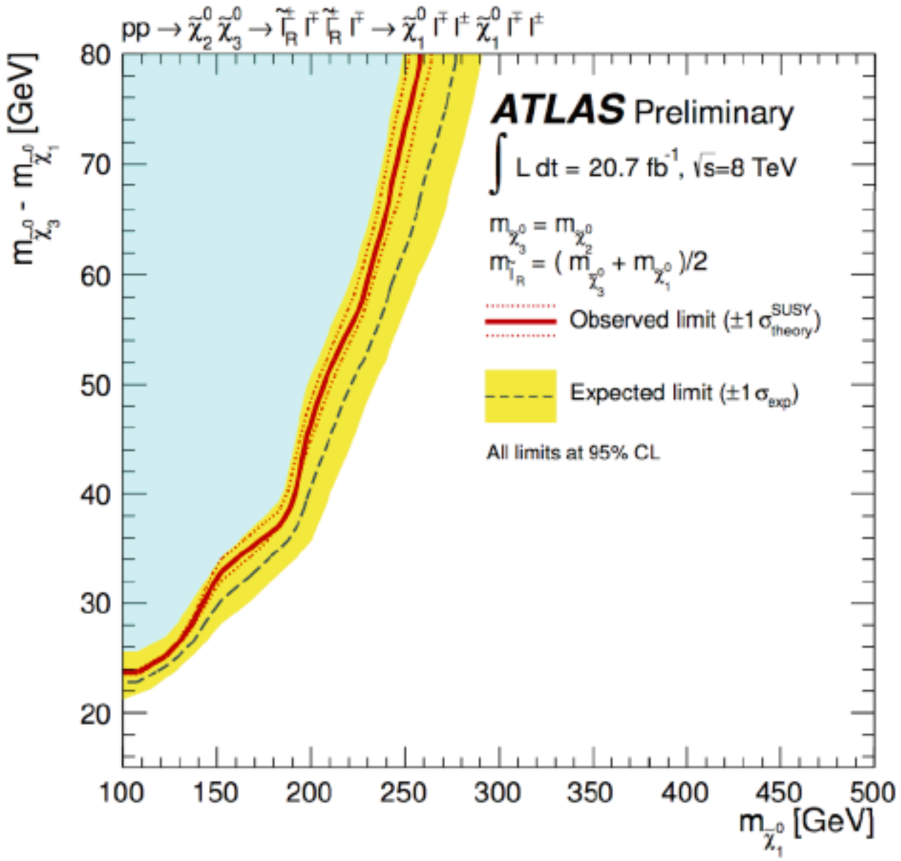
(3) heavy neutral leptons (aka as ν_R)

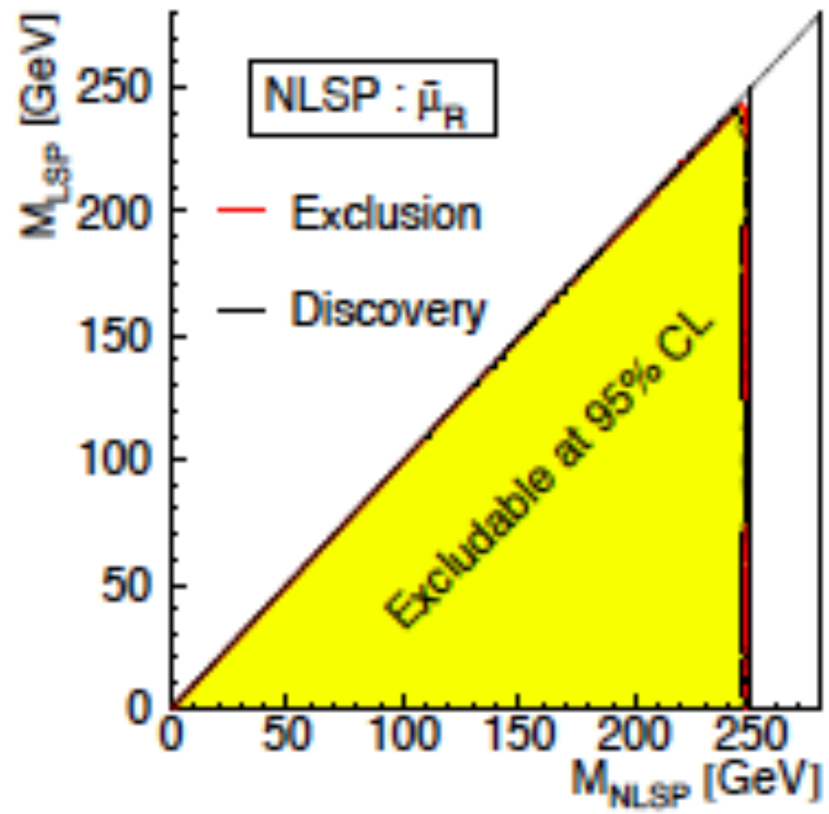
- ↠ neutrino masses
- ↠ possibly DM and matter-antimatter asymmetry

ee colliders as NP discovery machines

(1) compressed spectra ($m_{LSP} \sim m_{NLSP}$)

↠ well-tempered neutralino DM
↠ weak LHC bounds (soft decay, small MET)





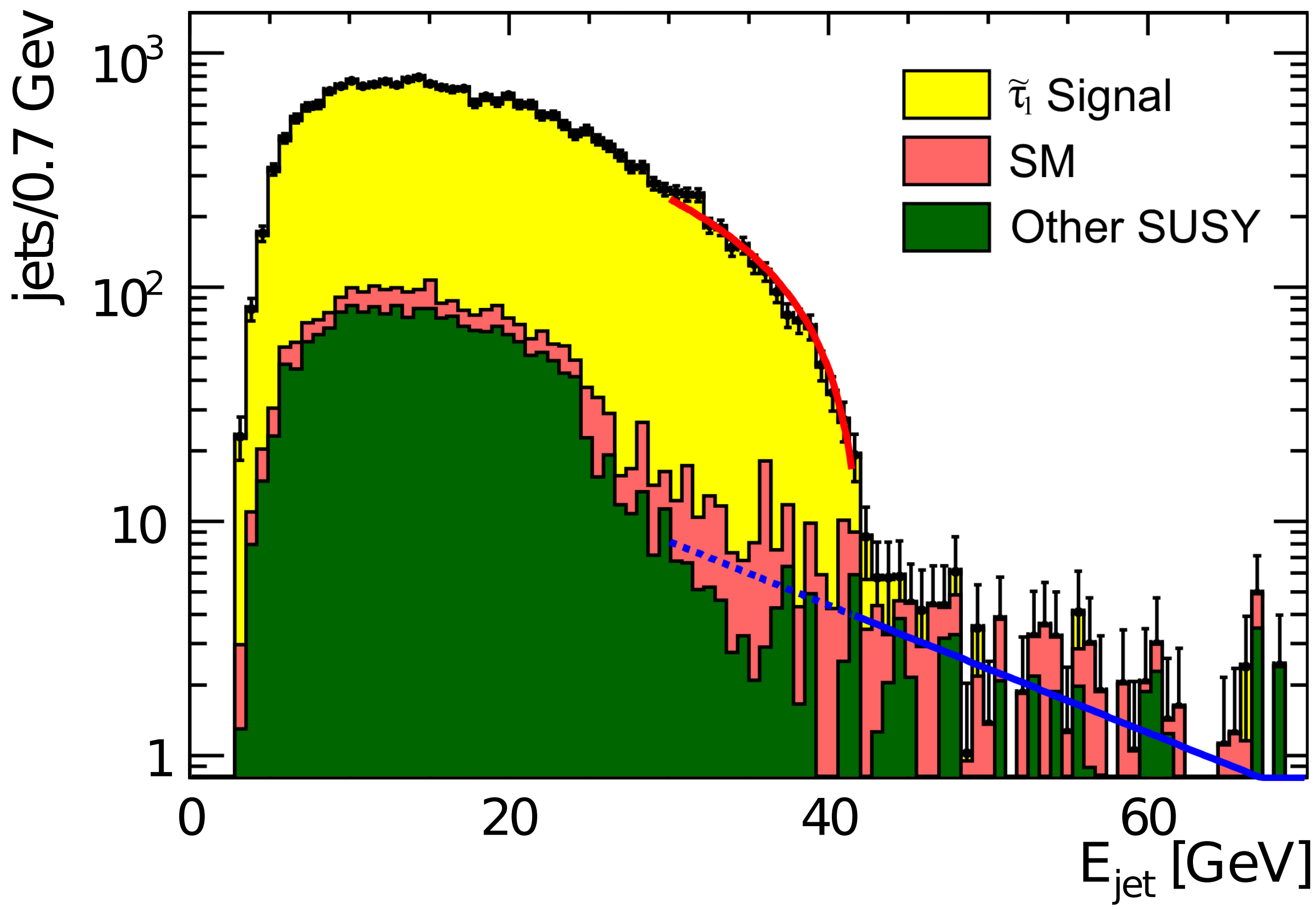
LHC:
Difficulty when mass difference is small

ILC:
Good sensitivity up to kinematic limit for (essentially) any mass difference

ee colliders as NP discovery machines

(2) light staus (similarly for higgsinos)

- ↠ weak LHC bound (~90GeV)
- ↠ DM with stau-neutralino co-annihilation
- ↠ enhance di-photon Higgs decay rate



stau pair production dominates over background

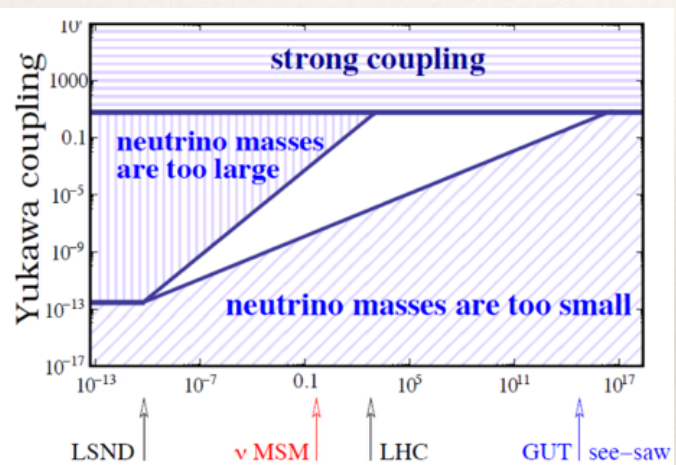
mass determination: stau~200 MeV, neutralino~400 MeV

EW quantum numbers of stau determined by production rates with polarized beams

ee colliders as NP discovery machines

(3) heavy neutral leptons (aka as ν_R)

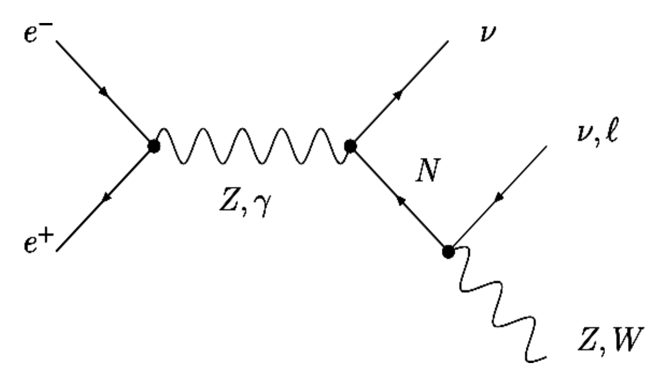
- ↠ neutrino masses
- ↠ possibly DM and matter-antimatter asymmetry



- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

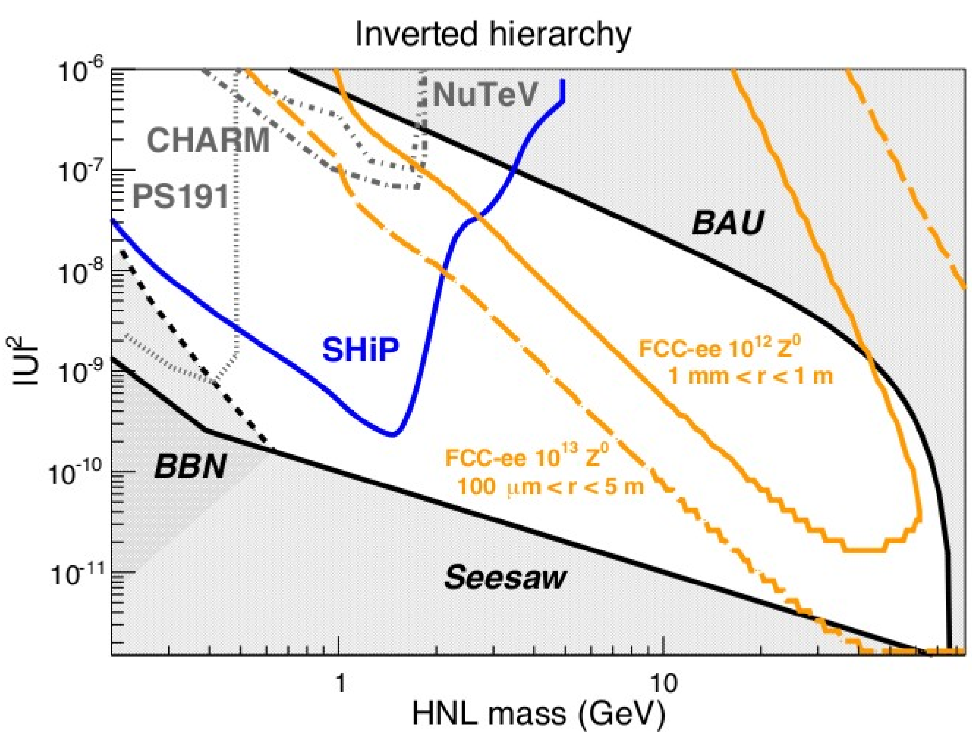
ν_R are produced in the 10^{12} TLEP Z decays



$N \to \ell^+ \ell'^- \nu$

or

$N \to \ell q \bar{q}$

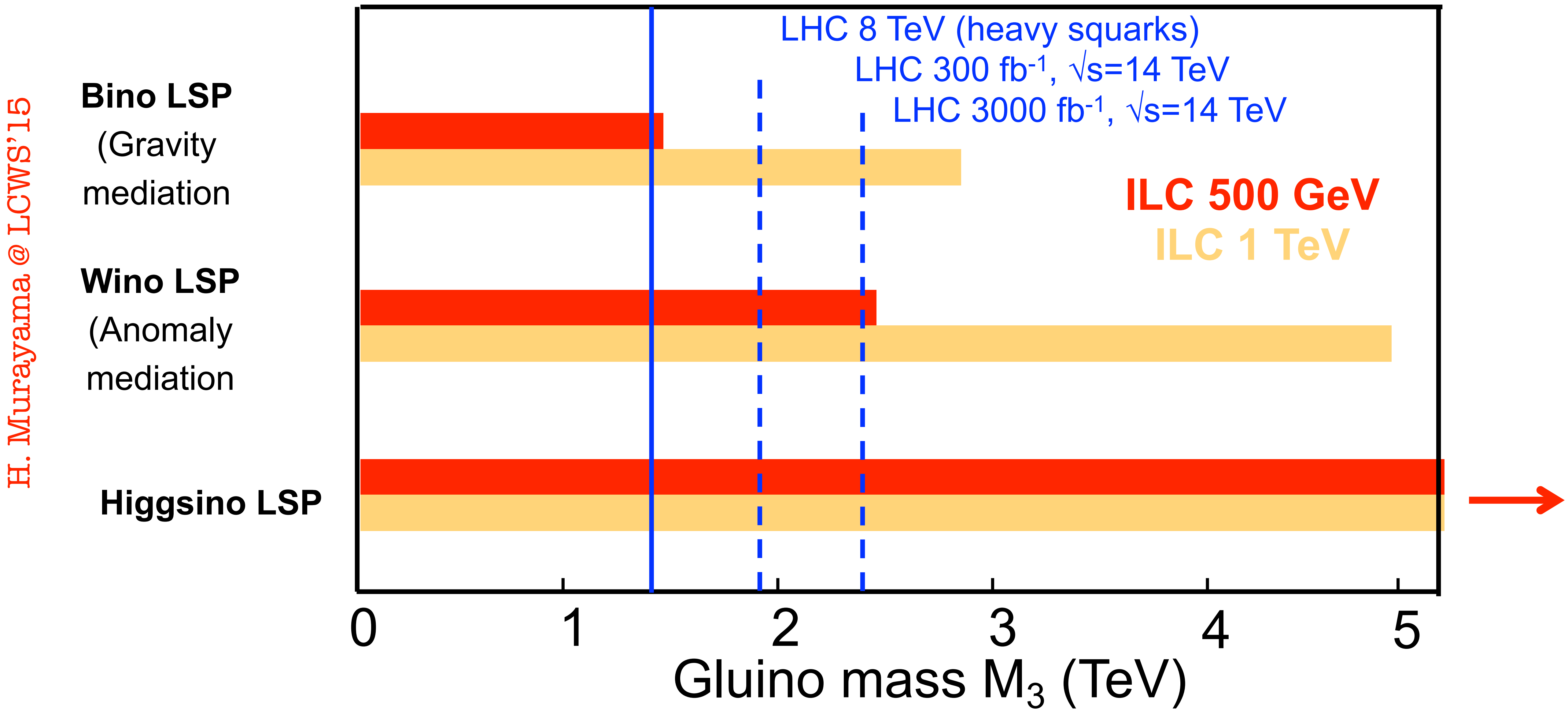


FCC-ee - SHiP
complementarity
to probe the interesting region

A. Blondel et al. '14

Probing heavy SUSY (model-dependent)

Gluino search at LHC
Chargino/Neutralino search at ILC
→ Comparison assuming gaugino mass relations



* Assumptions: MSUGRA/GMSB relation $M_1 : M_2 : M_3 = 1 : 2 : 6$; AMSB relation $M_1 : M_2 : M_3 = 3.3 : 1 : 10.5$

Probing high scale NP @ CLIC

Table 1.6: Discovery reach of various theory models for different colliders and various levels of integrated luminosity, $\mathscr{L}$ [73]. LHC14 and the luminosity-upgraded SLHC are both at $\sqrt{s}$ =14 TeV. LC800 is an 800 GeV e^+e^- collider and CLIC3 is $\sqrt{s}$ =3 TeV. TGC is short for Triple Gauge Coupling, and "μ contact scale" is short for LL μ contact interaction scale Λ with $g = 1$ (see Section 1.4).

New particle	collider: $\mathscr{L}$:	LHC14 100 fb^{-1}	SLHC 1 ab^{-1}	LC800 500 fb^{-1}	CLIC3 1 ab^{-1}
squarks [TeV]		2.5	3	0.4	1.5
sleptons [TeV]		0.3	-	0.4	1.5
Z' (SM couplings) [TeV]		5	7	8	20
2 extra dims M_D [TeV]		9	12	5-8.5	20-30
TGC (95%) (λ_γ coupling)		0.001	0.0006	0.0004	0.0001
μ contact scale [TeV]		15	-	20	60
Higgs compos. scale [TeV]		5-7	9-12	45	60

CLIC CDR arXiv:1202.5940

Conclusions

Conclusions

Main questions and main approaches to address them

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

F. Gianoti EPS '15

Combination of these complementary approaches is crucial to explore the largest range of E scales (directly and indirectly) and couplings, and properly interpret signs of new physics → hopefully build a coherent picture of the underlying theory.

⇓ ⇓ ⇓

there is a enticing case for Higgs/top factory
and we need a continuity in the field with a running machine
and more than ever importance of the synergy and
complementarity of experimental program