Physics at e^+e^- colliders

Rohini M. Godbole
Centre for High Energy Physics, IISc, Bangalore, India

- Introduction: The physics case for e^+e^- colliders.

- Which e^+e^- colliders? Only high energy ones!

- Physics possibilities:

1. Precision Higgs studies as a portal to BSM

2. Examples for SUSY

3. **CP violation in the Higgs sector, precision t studies as probe of BSM, self coupling λ**

Particle physics finds itself in a very peculiar place.

To steal from 'A tale of two cities': (Apologies to Charles Dickens!)

It is the best of times , it is the worst of times

We have found the SM Higgs, proved the SM, we have no glimmer of BSM that the Higgs properties promises!

So we all can feel a bit like Lord Kelvin who thought that

" There is nothing new to be discovered in physics now, All that remains is **more and more precise measurement**."

Mere mortals today:

All that remains is **more and more precise measurement** of the Higgs and top properties! *OR Higher and higher energies?*

e^+e^- colliders are an integral part of this path ahead!

Traditionally we have been alternating between hadronic colliders to offer us broad sweep panorama of the particle physics terrain from the top of a hill and the e^+e^- colliders to grant a telescopic image of a some part of the terrain!

UA-1/UA-2 observed a handfull $\sim \mathcal{O}(10)$ W and Z. LEP-1 and SLC studied Millions of Z and LEP-2 thousands of W.

Recall also SLC with its 60000 Z's offered a comparable precision on $\sin^2\theta_W$ as LEP-1 with its Millions of Z's because of **Beam Polarisation!**

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

H^0

$J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^\pm$ and $H^{\pm\pm}$)", respectively.

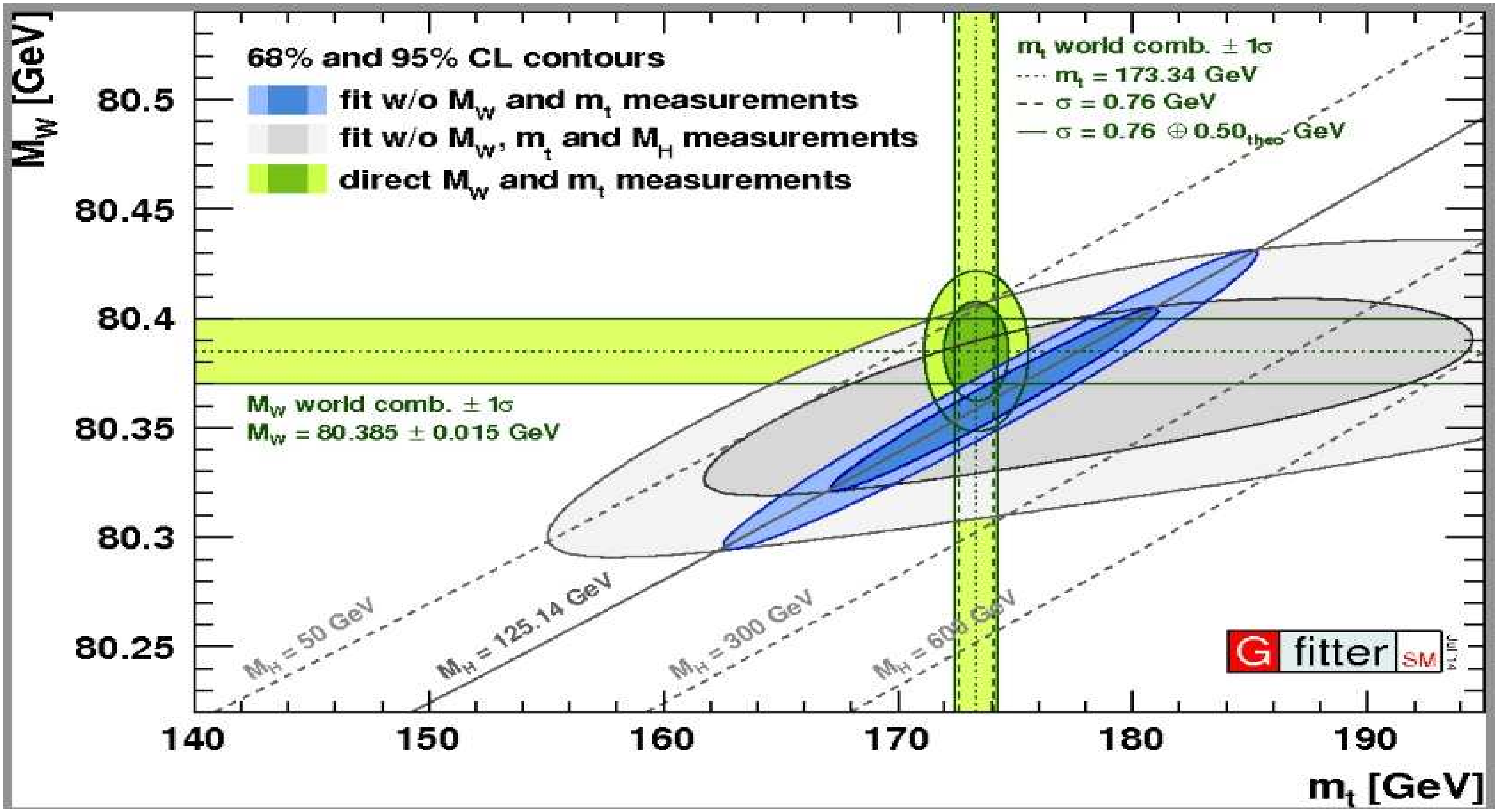
H^0 MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.09±0.21±0.11	[1,2] AAD	15B	LHC	pp, 7, 8 TeV

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.7 $\times 10^{-12}$	95	[1] KHACHATRY...	15AM	CMS	pp, 7, 8 TeV
>3.5 $\times 10^{-12}$	95	[2] KHACHATRY...	15BA	CMS	pp, 7, 8 TeV, flight distance
<5.0 $\times 10^{-12}$	95	[3] AAD	14W	ATLS	pp, 7, 8 TeV, $\gamma\gamma$
<2.6 $\times 10^{-12}$	95	[3] AAD	14W	ATLS	pp, 7, 8 TeV, $ZZ^* \to 4\ell$

HTTP://PDG.LBL.GOV Page 4 Created: 10/1/2016 20:06

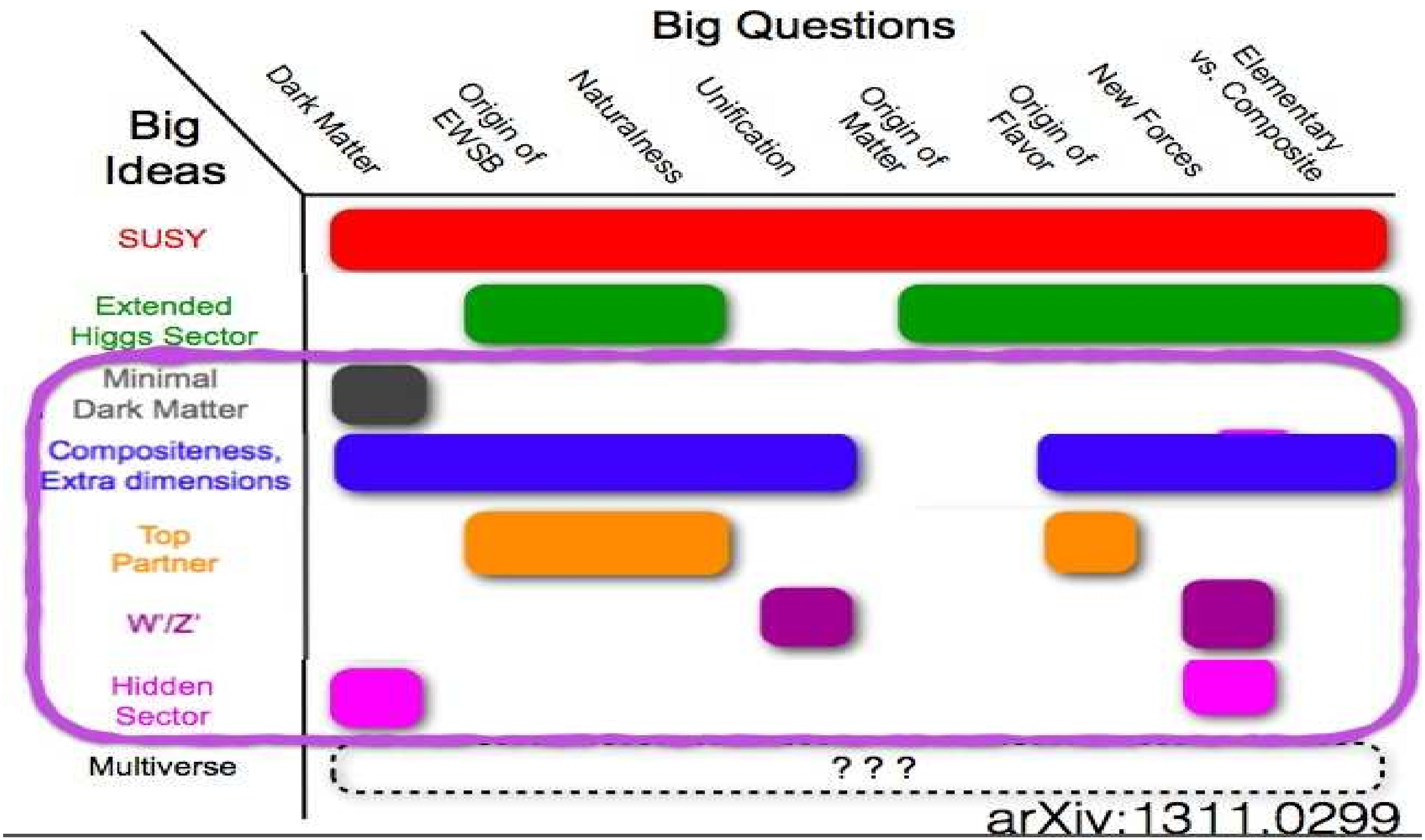
Next steps: couplings and CP! Still not in the PDG!



SM rocks! *At LOOP level* Role played by precision measurements!

LHC Seems to have found the light Higgs consistent with the top mass implied by EW precision tests

BUT So far no evidence/indication for the different BSM particles that one expected!



ICHEP 2016 talk!

One way ahead has to be through a precision study of the two heaviest particles the top and the Higgs that the nature has provides us!

The mass and the couplings of this light state and top might be the window through which we can get a view of BSM at present!

Model independent analyses the best story of the day! (Data driven!) e^+e^- colliders with beam polarisation great for this!

Remember the SM started its life as an effective theory: Fermi's theory of β decay!

Peeping through the Higgs and the top window!

The statement from European Strategy Group :

- **Reminder: European Strategy statement (2013)**

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

The physics case of the e^+e^- colliders was made long time back and for two decades people have been working hard to make them a reality.

When Higgs mass was not known the generic energy being considered was $\sqrt{s} = 500$ GeV and extendable to 1 TeV to cover the case of WW scattering!

It had to be a linear collider. International Linear Collider (ILC) was the only kid on the block!

Low mass of the observed Higgs gave rise to idea of 'Higgs factories' which can actually be realized in the circular mode, though the linear machines are still 'greener'

As of today three e^+e^- colliders under discussion.

The International Linear Collider : ILC 250 with a lumi upgrade, extendable to higher energies.

"The effort by the Japanese HEP community to realise the 250 GeV ILC, upgradable, has been intensified right now and it is at the most crucial phase whether the Japanese government could be persuaded to take an initiative for realising the ILC250GeV as an international project with a major investment from Japan."

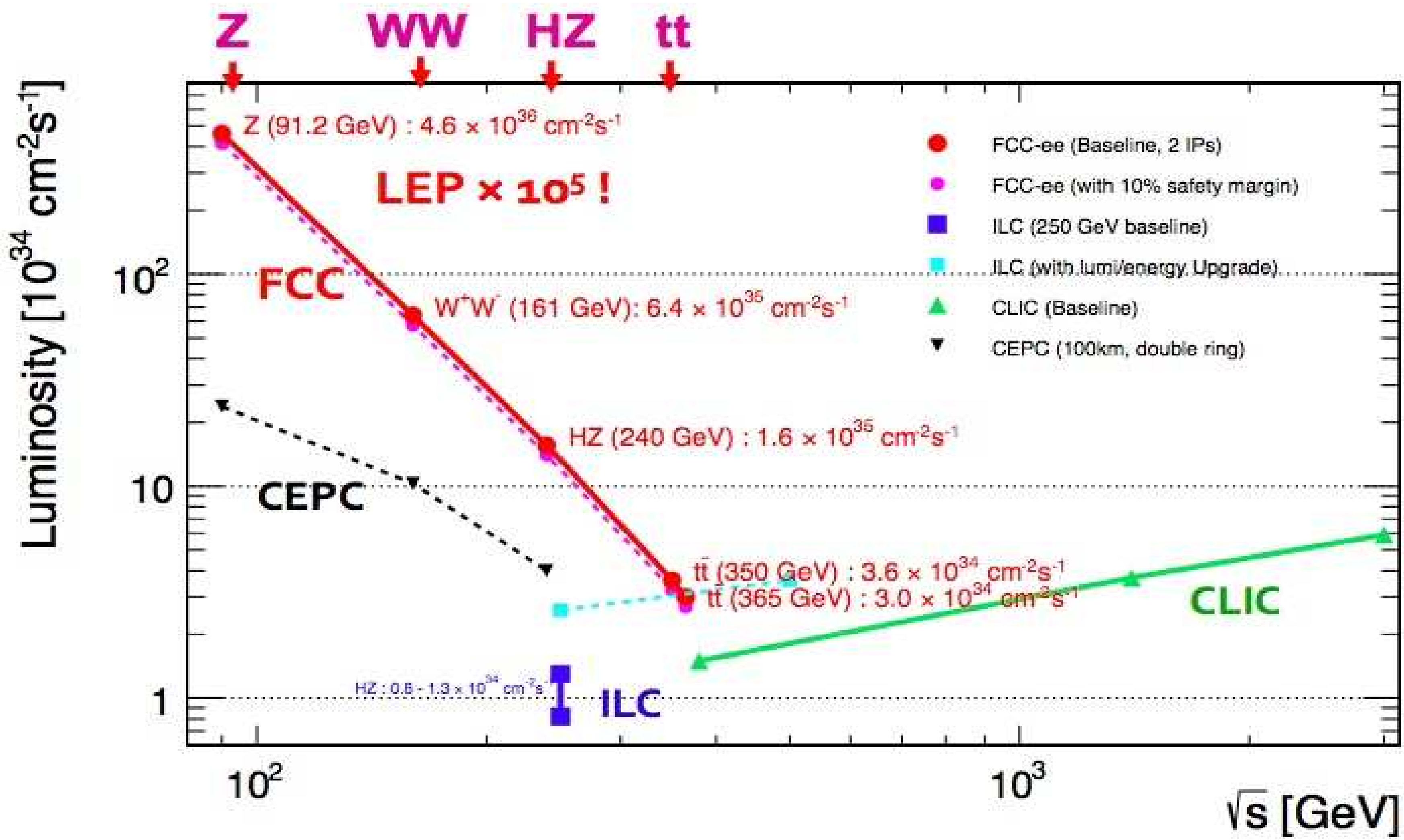
Discussions with the Japanese funding Agencies as well as with US and European community on going.

FCC (ee) 240 GeV, 380 GeV and Terra Z factory. CDR will be ready by end 2018 for the deliberations of the European Strategy Group

CEPC(China) $\sim$ 240GeV ($10^6 ZH$, $10^8 WW$ and as well as $10^{10} Z$): CDR to be ready April 2018, efforts by the Chinese Community full on. 100 km radius same as FCC(ee). Studies benefit from all the work done for the ILC.

CLIC : different acceleration technique, beam beam acceleration and can go up to 3 TeV.

Lot of work was done pre LHC with hopes of having a machine that can directly probe the high scale new physics for which LHC will give us hints. But now with the scales in question this plan looks questionable.



P. Janot: Academic Training Program CERN, Oct. 2017

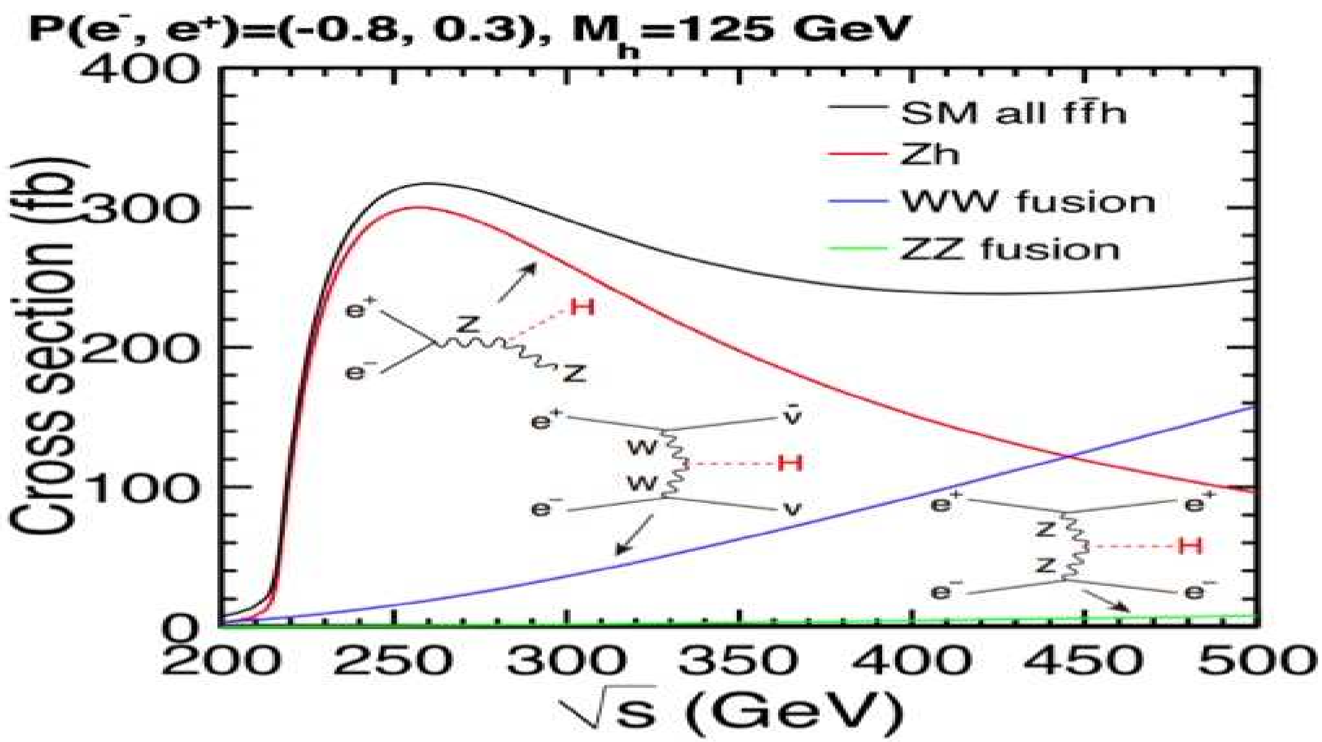
I will show you most of the results from ILC TDR as quite often they are with full simulations. Will also show comparisons with CEPC and FCC.

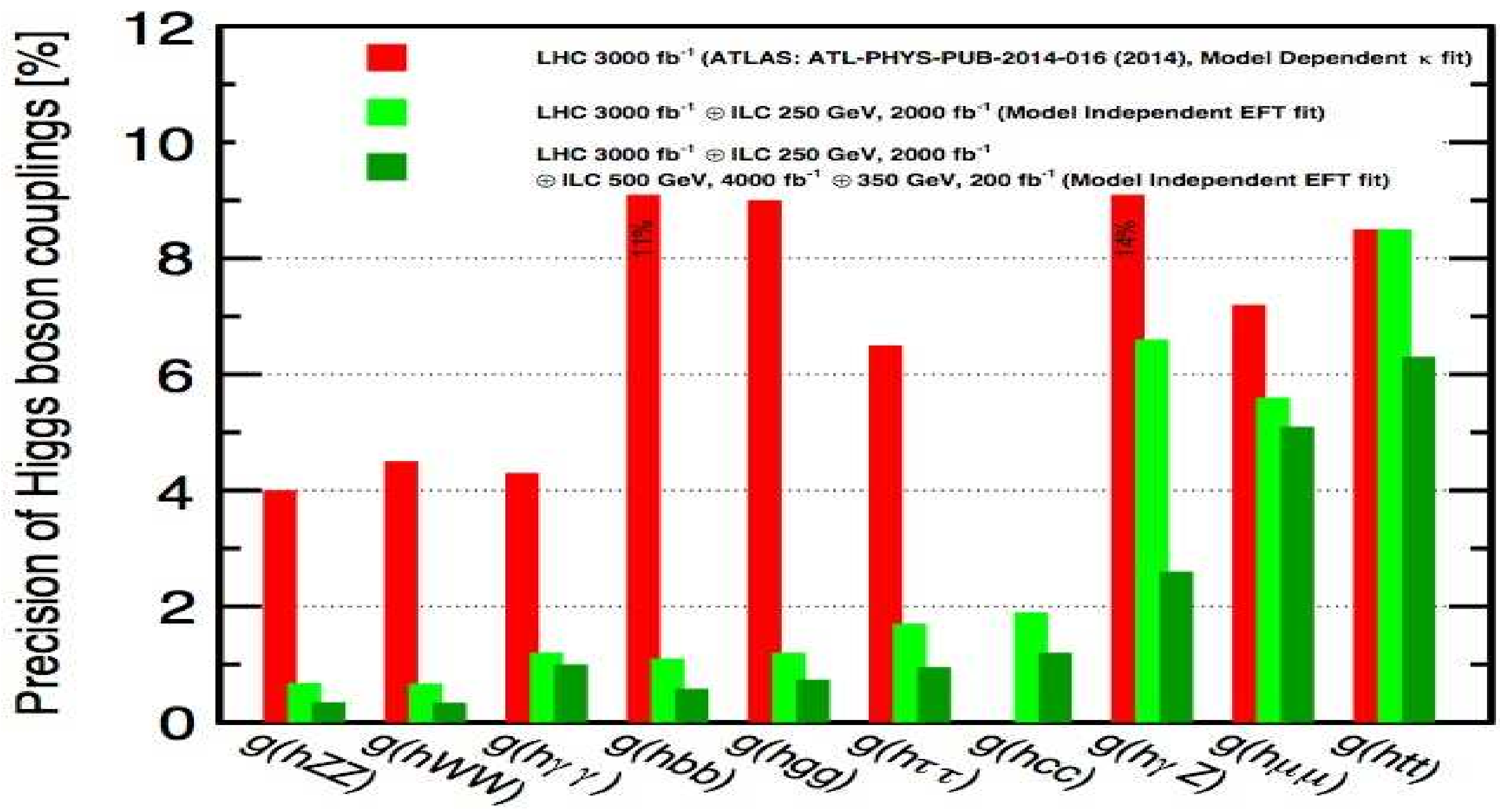
Major question to ask how does it complement information available from HL-LHC.

For ILC: 1708.08912, 1710.07621 (EFT Higgs fits), 1708.09079: Higgs self coupling, 1702.05377 (dark matter simplified models)

For CEPC: Upcoming TDR

Two ways: 1)κ formalism 2)EFT formalism Show results for EFT from 1710.07621. κ formalism neglects momentum dependent Higher dimensional operators in determining width of the Higgs. Additionally accuracy at 250 GeV limited by smallness of $h \to ZZ^*$ rates.





High accuracy measurements possible. Improvement over HL-LHC. ILC 250 GeV can in principle attain results similar to ILC 500. Polarisation plays important role. Comparisons with other machines?

With polarization one can have additional observables such that number of observables is bigger than the number of parameters. As a result one can test the EFT and this can yield information about light particles.

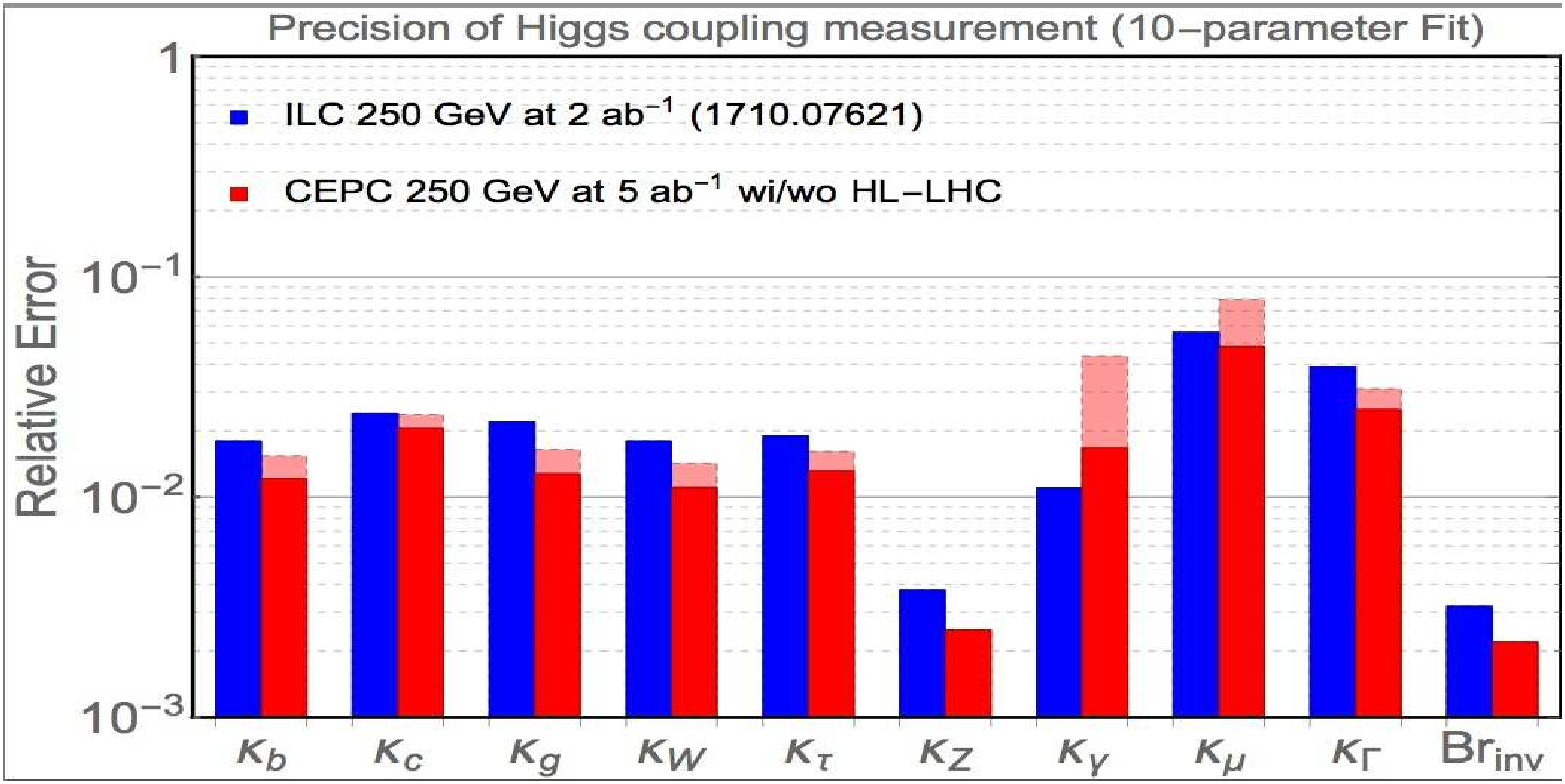
$$\Gamma_{\mu\nu} = g_V \left[a_V \; g_{\mu\nu} + \frac{b_V}{M_V^2} \; (k^1_\nu k^2_\mu - g_{\mu\nu} k^1 . k^2) + \frac{\tilde{b}_V}{M_V^2} \; \epsilon_{\mu\nu\alpha\beta} k^{1\alpha} k^{2\beta} \; \right]$$

Construct observables with definite $CP/\tilde{T}$ transformation properties using beam/final sate polarizations and other kinematic variables to probe the anomalous couplings (PRD 79, 035012, Biswal et al) Process $e^+e^- \to f\bar{f}h$

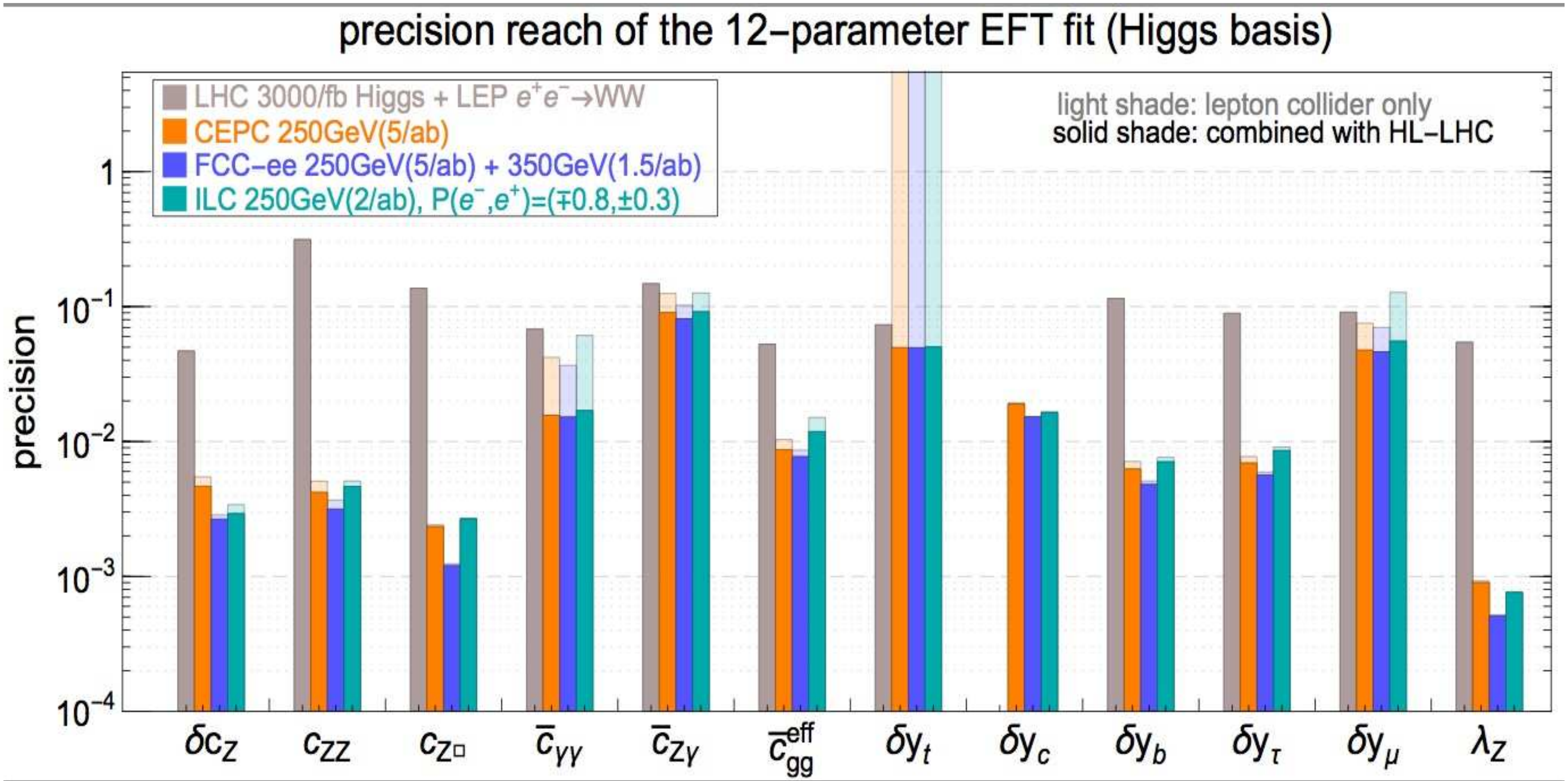
Combination	Asymmetry	Probe of
$\vec{P}_e \cdot \vec{P}_f^+$ (CP - , $\tilde{T}$ +)	$A_{FB}(C_H) = \frac{\sigma(C_H>0)-\sigma(C_H<0)}{\sigma(C_H>0)+\sigma(C_H<0)}$	$\Im(\tilde{b}_V)$

Polarised beams enhance the asymmetry.

Unpolarized Beam	Polarized Beam	Observable used
$\lvert\Im(\tilde{b}_z)\rvert \leq 0.042$	$\lvert\Im(\tilde{b}_z)\rvert \leq 0.0079$	$A_{FB}^{-,+}(R1; \mu, q)$



Courtesy : Lian Tao Wang , CEPC CDR (in preparation)



Courtesy : Lian Tao Wang , CEPC CDR (in preparation)

With this we can fingerprint the BSM. Will give example for SUSY. Complementary to direct searches at the LHC! (1308.0297)..Similarly probes for large m_A possible.

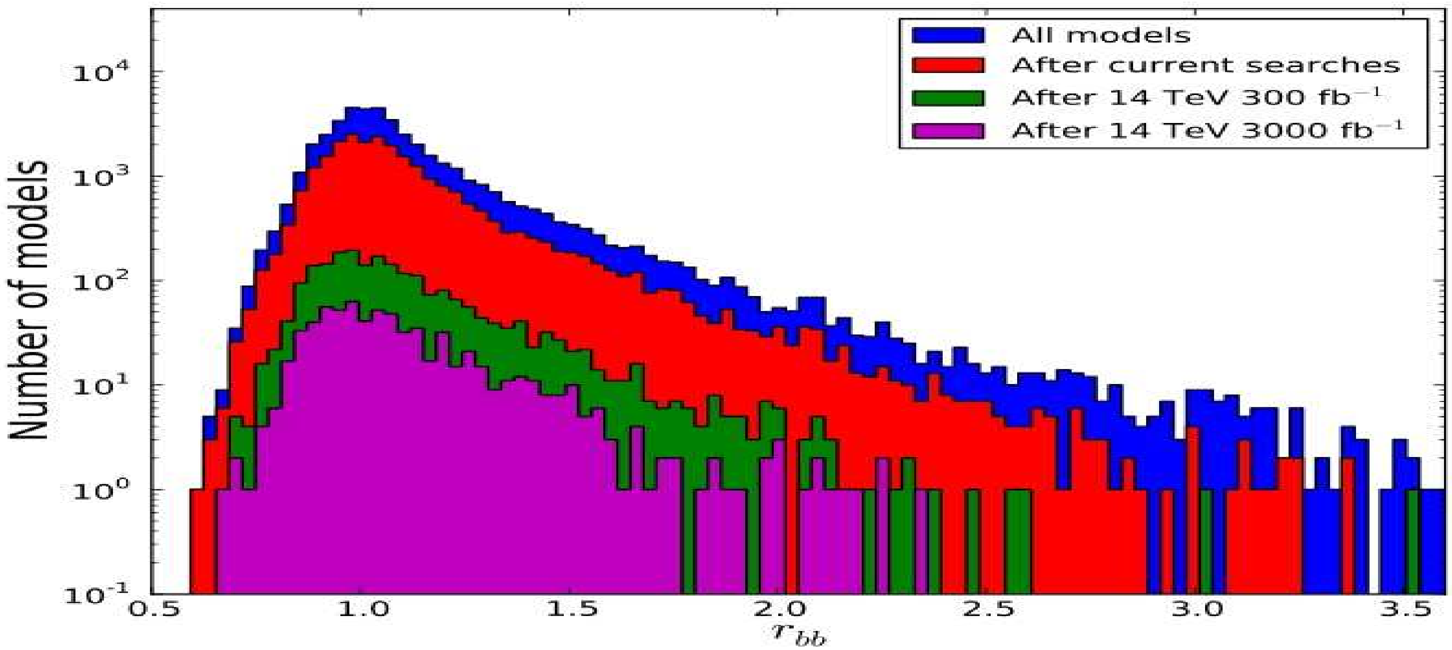
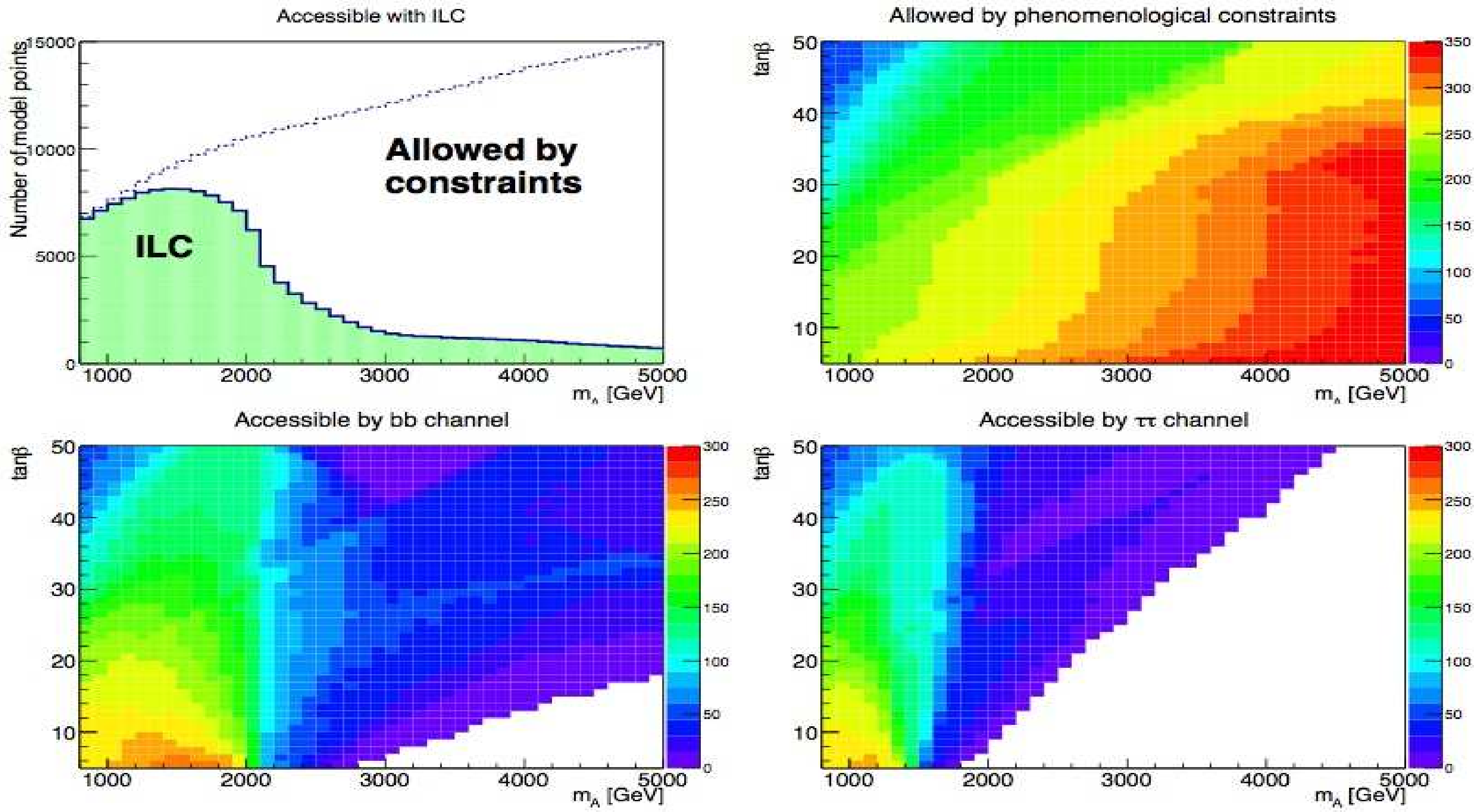


Figure 8: Histograms of the ratio $r_{bb} = \Gamma(h \to \bar{b}b)/\Gamma(h \to \bar{b}b)_{SM}$ within a scan of the approximately 250,000 supersymmetry parameter sets after various stages of the LHC, assuming the LHC does not find direct evidence for supersymmetry. The purple histogram shows parameter points that would not be discovered at future upgrades of the LHC (14 TeV and 3 ab^{-1} integrated luminosity). From [37].



1502.03959: Endo et al.

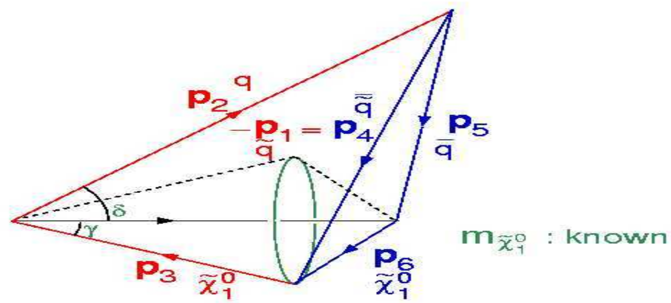
In the early explorations SUSY at ILC meant determinations of model parameters, precision determination of masses, use of polarization to determine the mixing in the stau sector, ...I show below some plots from a talk I gave on SUSY at LC in 2000!

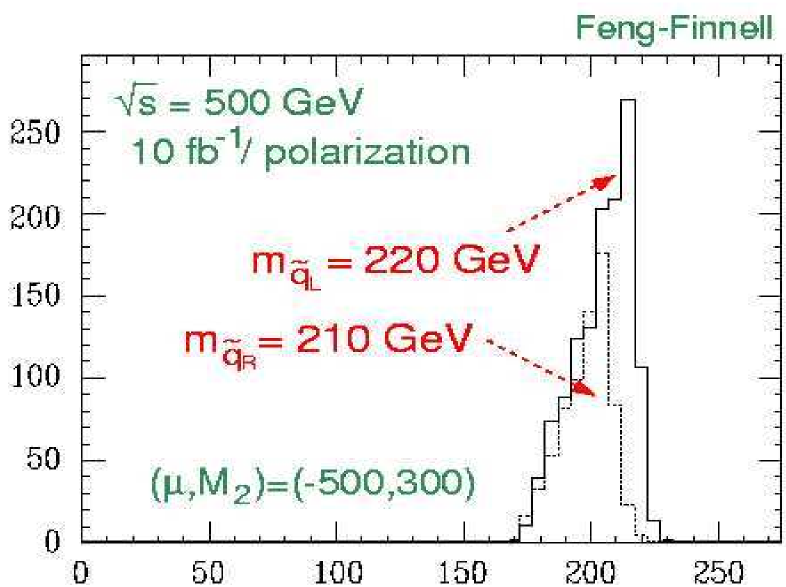
SUSY and SUSY Breaking Scale at the Linear Collider

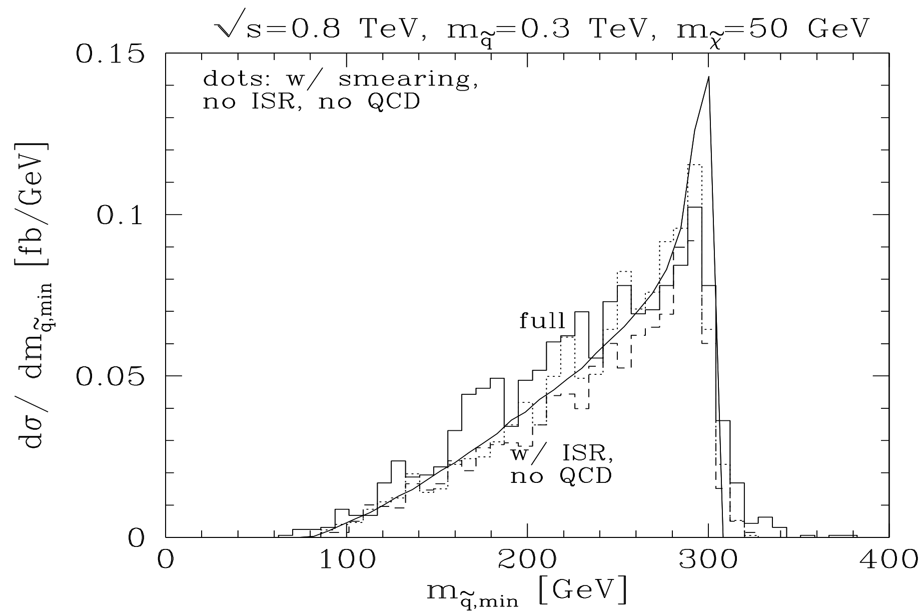
R. M. Godbole

Centre for Theoretical Studies,
Indian Institute of Science,
Bangalore, 560 012
INDIA

Abstract. After summarising very briefly the key features of different model predictions for sparticle masses and their relation with the supersymmetry (SUSY) breaking scales and parameters, I discuss the capabilities of an e^+e^- Linear Collider (LC) with $\sqrt{s} \geq 500$ GeV for precision measurements of sparticle properties. Then I focus on the lessons one can learn about the scale and mechanism of SUSY breaking from these measurements and point out how LC can crucially complement and extend the achievements of the LHC. I end by mentioning what would be the desired extensions in the type/energy of the colliding particles and their luminosity from the point of view of SUSY investigations.


p2 q
−p1 = p4 q̃
p5 q̄
q̃
δ
γ
p3 χ̃10
p6 χ̃10
mχ̃10 : known


Feng-Finnell
√s = 500 GeV
10 fb-1/ polarization
mq̃L = 220 GeV
mq̃R = 210 GeV
(μ,M2)=(-500,300)
0
50
100
150
200
250


√s=0.8 TeV, mq̃=0.3 TeV, mχ̃=50 GeV
dots: w/ smearing,
no ISR, no QCD
full
w/ ISR,
no QCD
dσ/ dmq̃,min [fb/GeV]
mq̃,min [GeV]
0
0.05
0.1
0.15
100
200
300
400

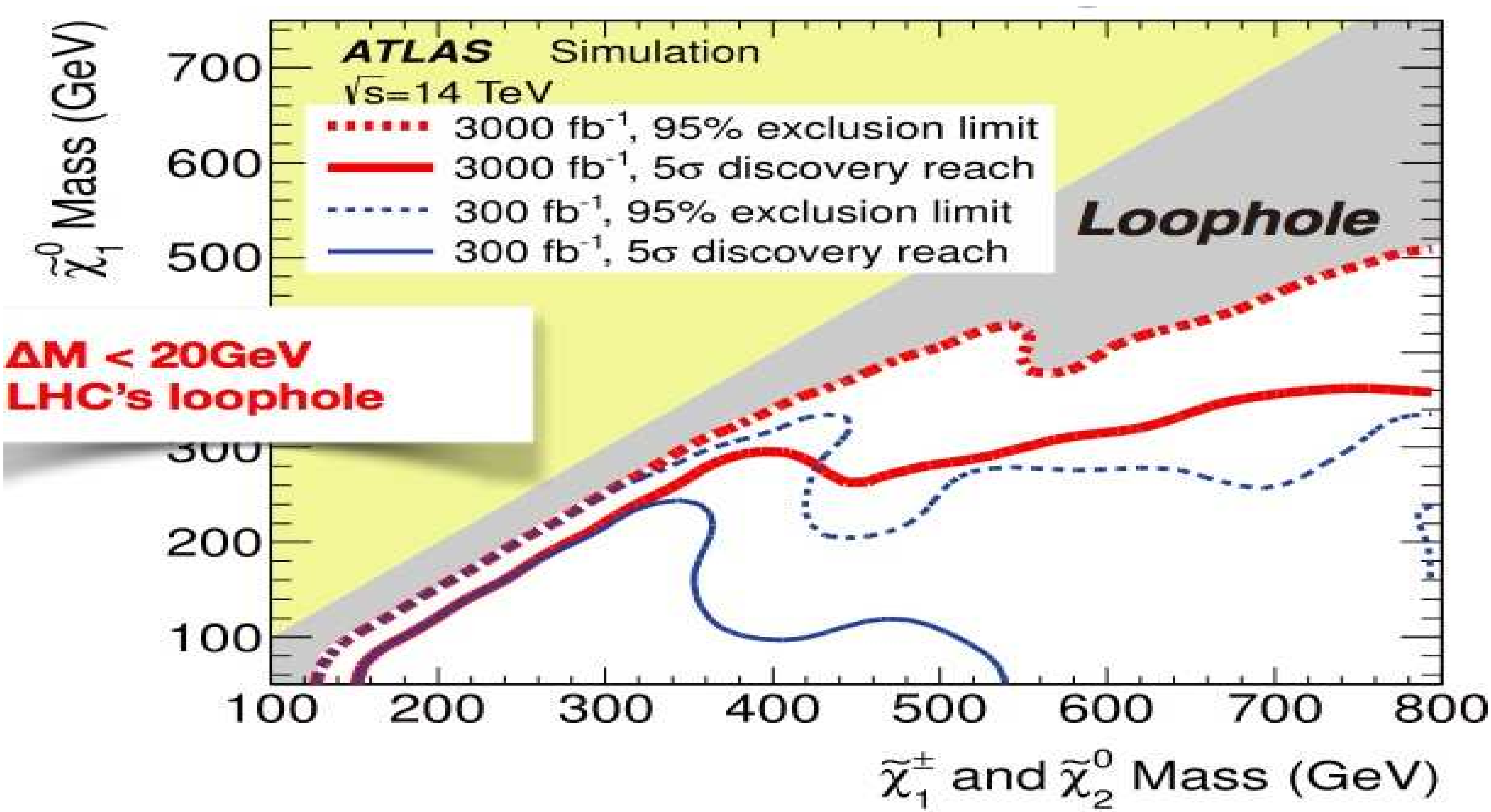
Fermion branching ratios a good 'indirect' probe and can probe large M_A, possible at ILC 250!

Want to discuss one more interesting case where lepton colliders can play an interesting role, ie. light Electroweakinos.

1)Light electro weakinos in particular light higgsinos which will allow low Δ_{EW} of X. Tata's talk. Direct production of Higgsinos.

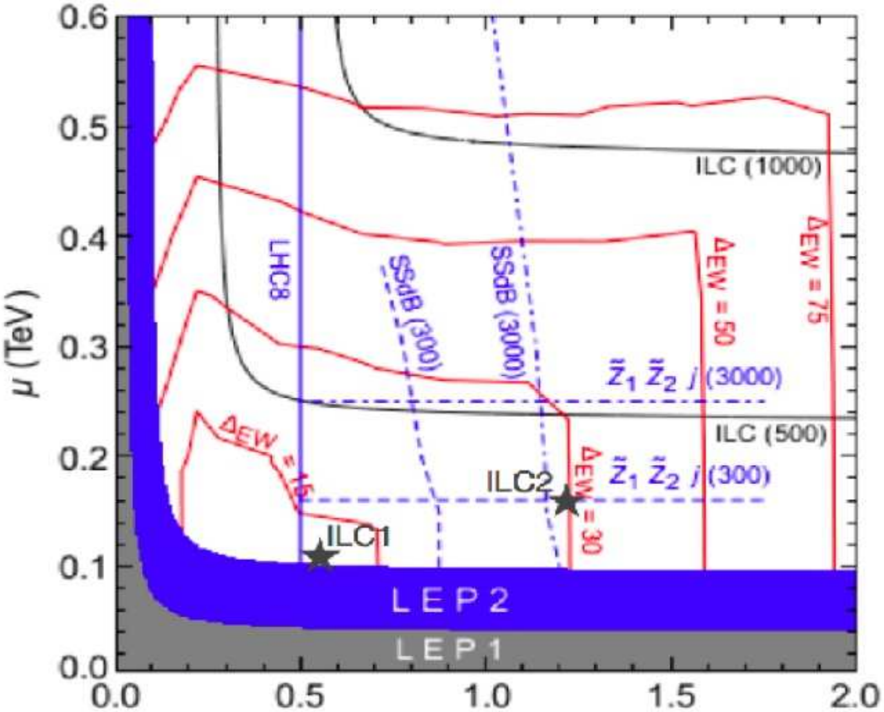
2) Invisible decay of the H (125) into neutralinos, requires light neutralinos.

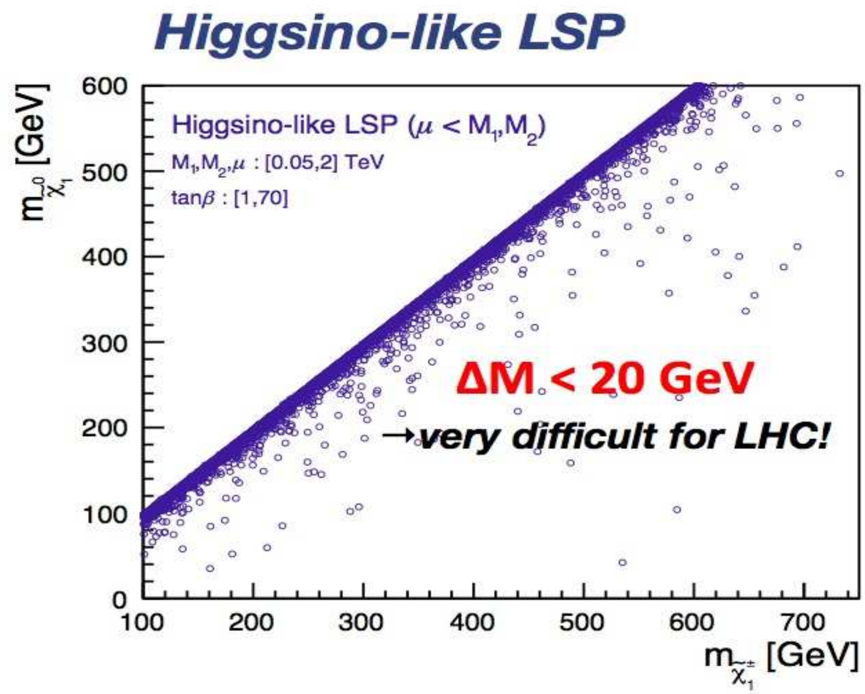
Small mass differences difficult for LHC . A hole in the EW searches. (From a slide from K. Fujii from a talk in NTU, Taiwan.)



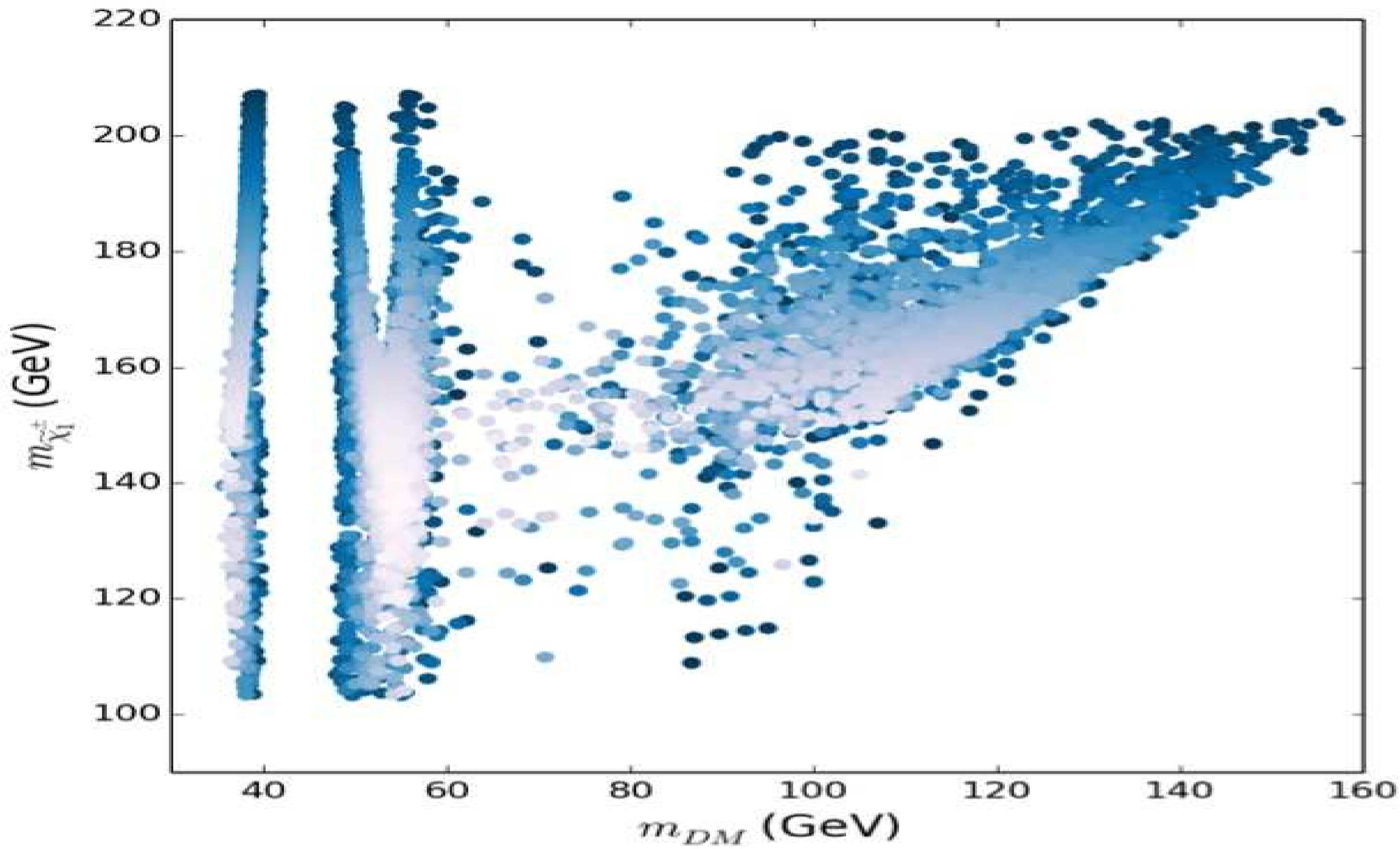
Analysed at ILC including full detector simulation for ILD for few benchmark points, Hale Sert (Ph.D. thesis). Plot from the talk by K. Fujii.

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$





1612.06333v1: a light EW sector is 'natural' in this sense. 1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Austri. light to dark, Δ varies from 4 to 10.



A light LSP is still allowed in PMSSM, along with the relic constraints. For example, see R.K. Barman, G. Belanger, B. Bhattacharjee, R.G., D. Sengupta, G. Mendiratta,: PRD 95, 095018. Difft. from 1612.06333v1, **considered non thermal DM as well**.

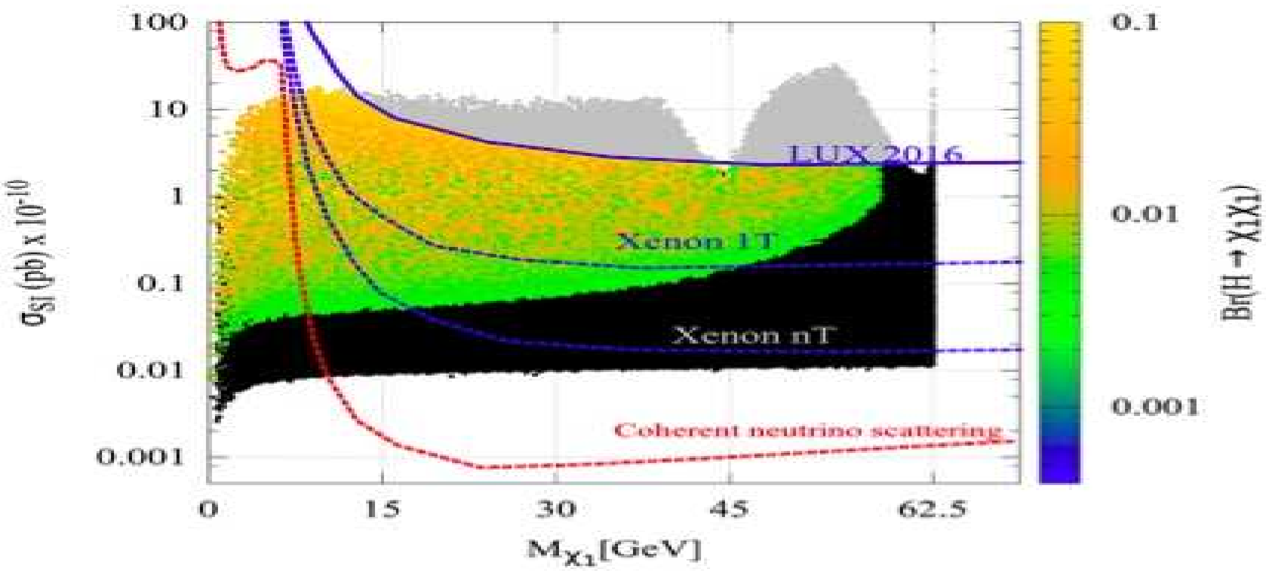
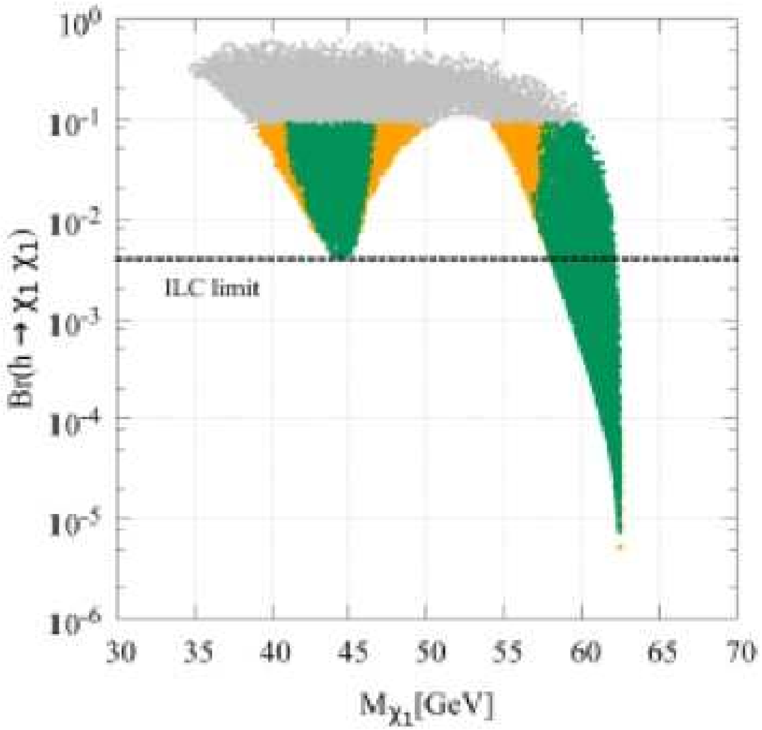


FIG. 7. SI WIMP-nucleon cross section vs $M_{\tilde{\chi}_1^0}$ for all points allowed by collider and relic density constraints. The color code characterizes the value of Br($h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$), while black points have Br($h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$) $< 0.4\%$. The blue-solid line shows the current limit from LUX-2016 [109], and the blue-dashed line shows the reach for Xenon-1T [110] and Xenon- nT [110].

This light LSP will mean invisible decay of the Higgs. Possible to probe it at LHC and future colliders. For example, D.Ghosh, R.G., M. Guchait and K. Mohan, PLB 725, 344, 2013 .



Projection for 13/14 TeV: 1310.8361 + HL LHC CMS/ATLAS studies:
300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.
Our scan allows relic to be less than observed. Most of the times one needs additional DM component.
Searches for invisibly decaying Higgs hold promise. Green(orange) (dis)allowed by LUX. (from PRD 95, 095018)

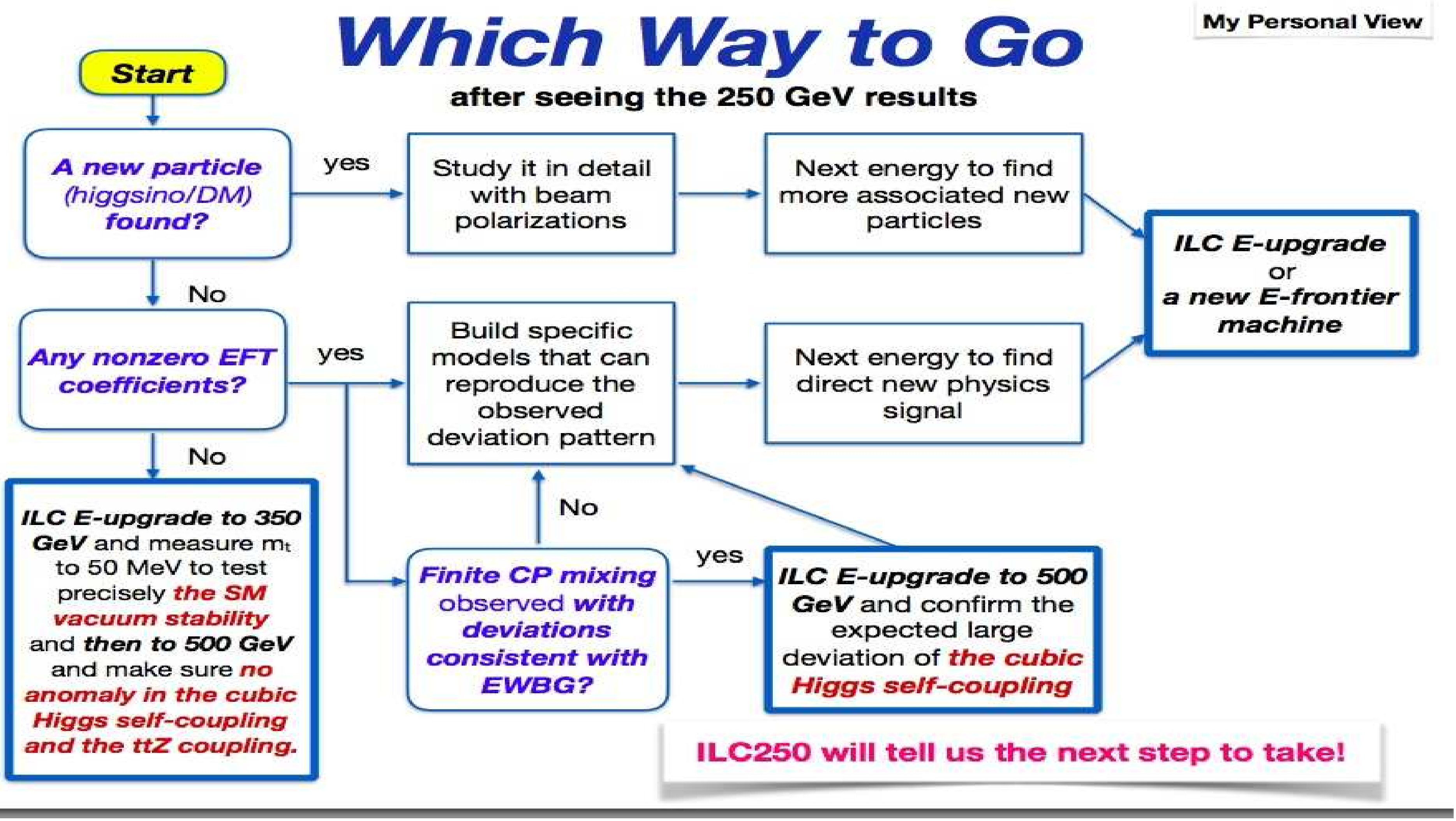
From K. Fujii

What we might lose

by staying at 250 GeV for long time

Challenging Tasks for ILC250	Issues	Possible Solutions/Measures
Higgs cubic self-coupling	A new interaction at the heart of EWSB, important in its own right. Large enhancement expected for models of EWBG. ***500 GeV needed for $e^+e^- \to ZHH$.***	Models of EWBG often predicts ***shifts in other Higgs couplings***, too. ***Synergy with HL-LHC, SuperKEKB, GW.***
Precision top mass	A parameter of SM, important in its own right. O(50) MeV desirable for vacuum stability test. ***Theoretically cleanest measurement requires ttbar threshold scan at around 350 GeV.***	***Direct top reconstruction at LHC with possible future theoretical progress*** to relate MC mass to pole mass (~200-300 MeV?).
Anomalous Top Couplings	Being heaviest in SM, top couples to new physics that caused EWSB. ***Needs at least 350 GeV, the best sensitivity expected at around 500 GeV.***	Most models of EWSB often predicts ***shifts in various Higgs couplings*** as well. ***Use the b-quark ($e^+e^- \to$ bbbar) as another 3rd generation quark.***
Top Yukawa coupling	6 (3)% at 500 (550) GeV, ***not available at 250 GeV.***	***Synergy with HL-LHC (~7%).***
New Particles	***Direct search limited by $m_X < E_{cm}/2$.***	Natural SUSY prefers ***light higgsinos.*** Indirect search through oblique correction may reach ~200GeV ***($e^+e^- \to$ ffbar)***. DM searches by ***$h \to$ invisible. Exotic higgs decays. Synergy with HL-LHC.***

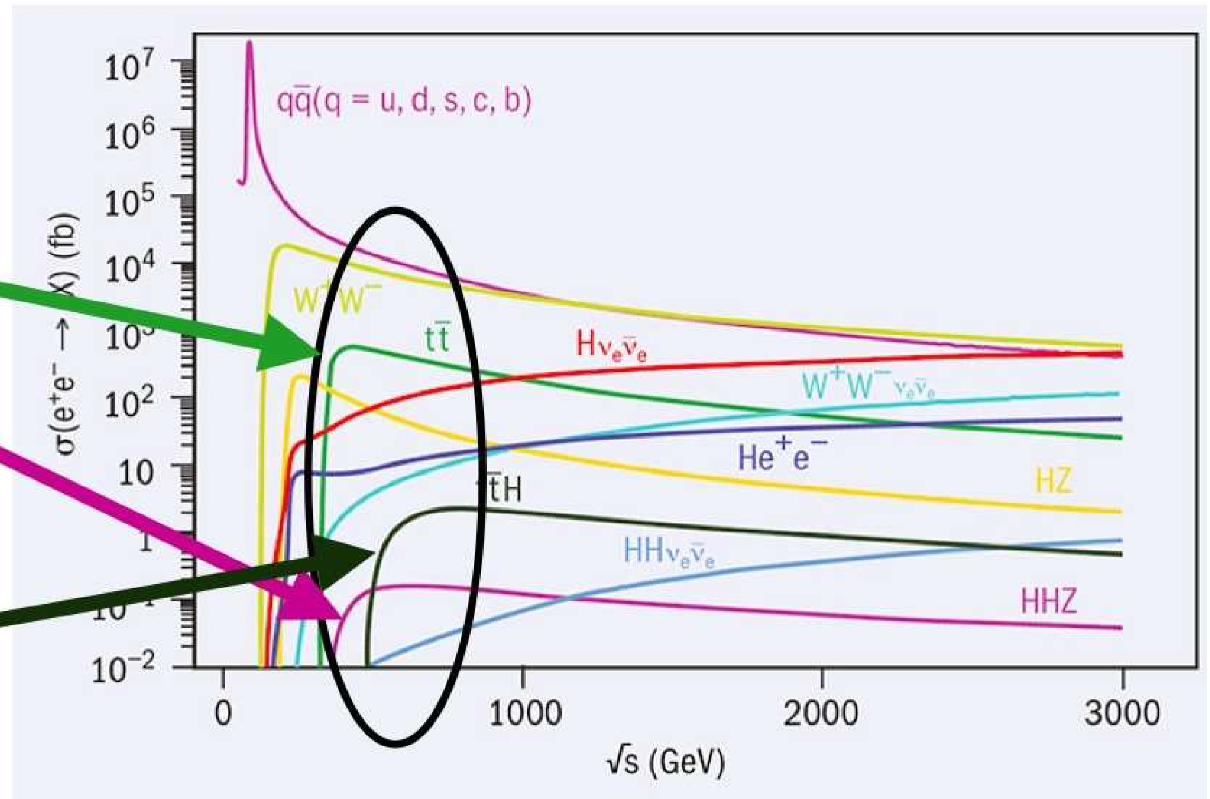
From K. Fujii


Which Way to Go
after seeing the 250 GeV results
My Personal View
Start
A new particle (higgsino/DM) found?
yes
Study it in detail with beam polarizations
Next energy to find more associated new particles
ILC E-upgrade or a new E-frontier machine
No
Any nonzero EFT coefficients?
yes
Build specific models that can reproduce the observed deviation pattern
Next energy to find direct new physics signal
No
ILC E-upgrade to 350 GeV and measure mt to 50 MeV to test precisely the SM vacuum stability and then to 500 GeV and make sure no anomaly in the cubic Higgs self-coupling and the ttZ coupling.
No
Finite CP mixing observed with deviations consistent with EWBG?
yes
ILC E-upgrade to 500 GeV and confirm the expected large deviation of the cubic Higgs self-coupling
ILC250 will tell us the next step to take!

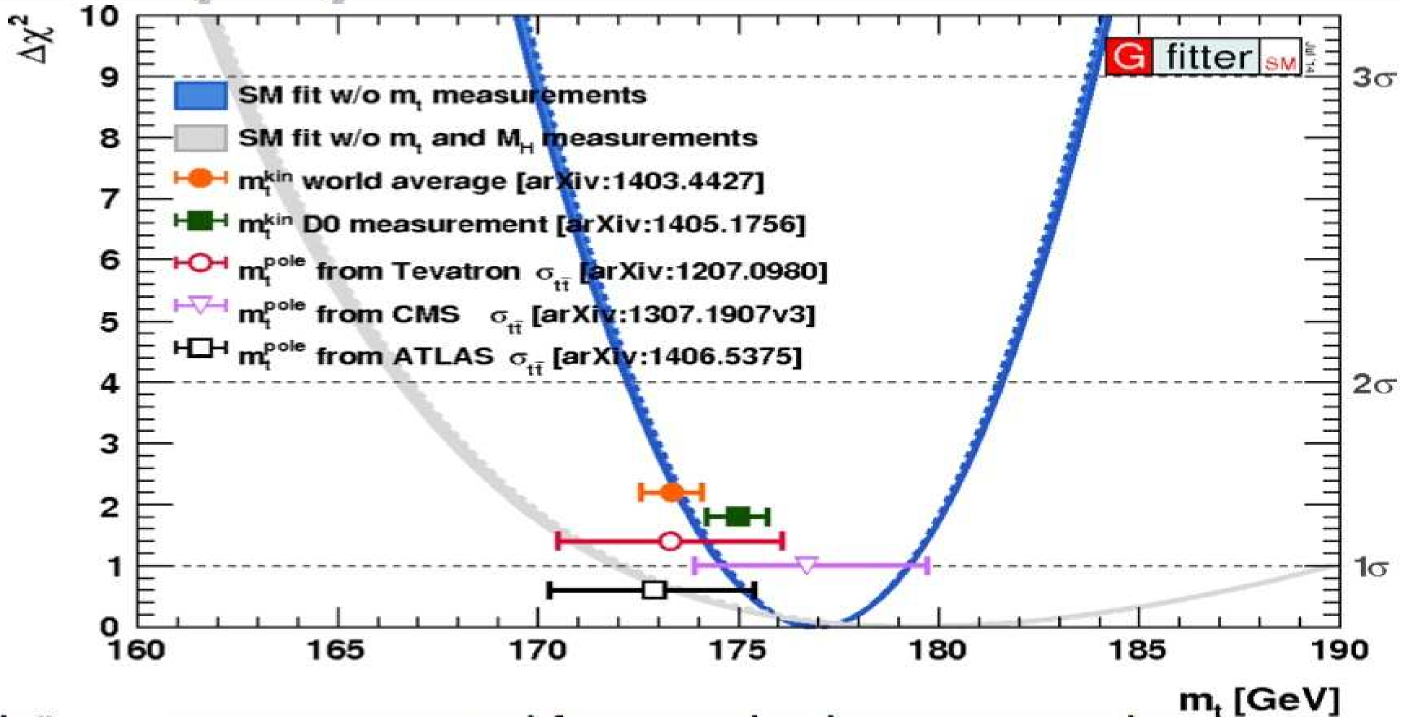
BACKUP

From J. List's talk at LCWS2017

- tt : ≳ 350 GeV
- ZHH : ≳ 450 GeV
- ttH : ≳ 500 GeV

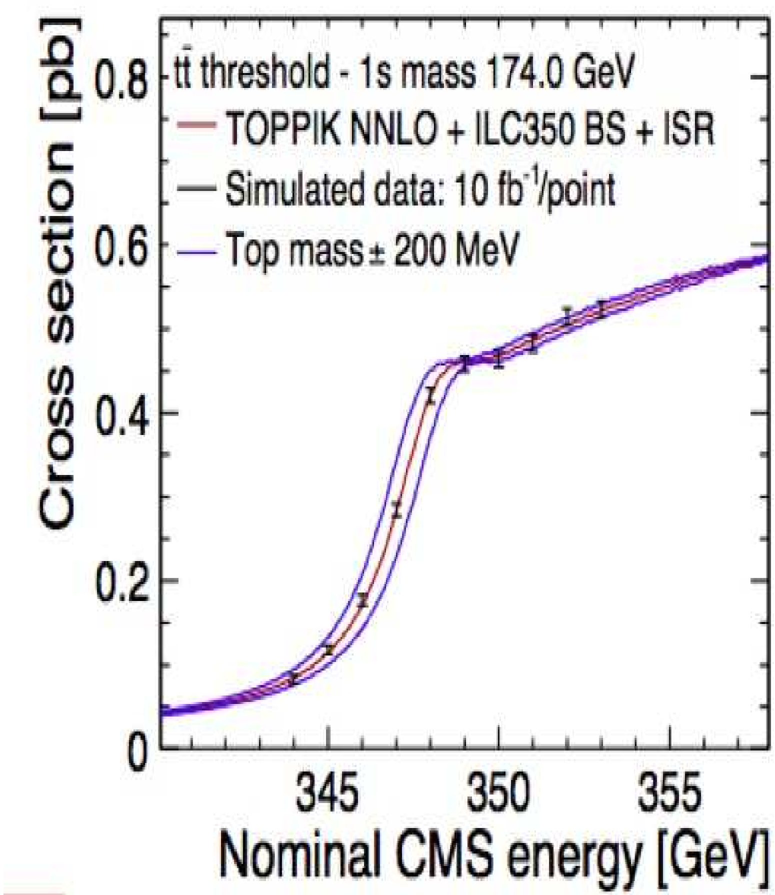


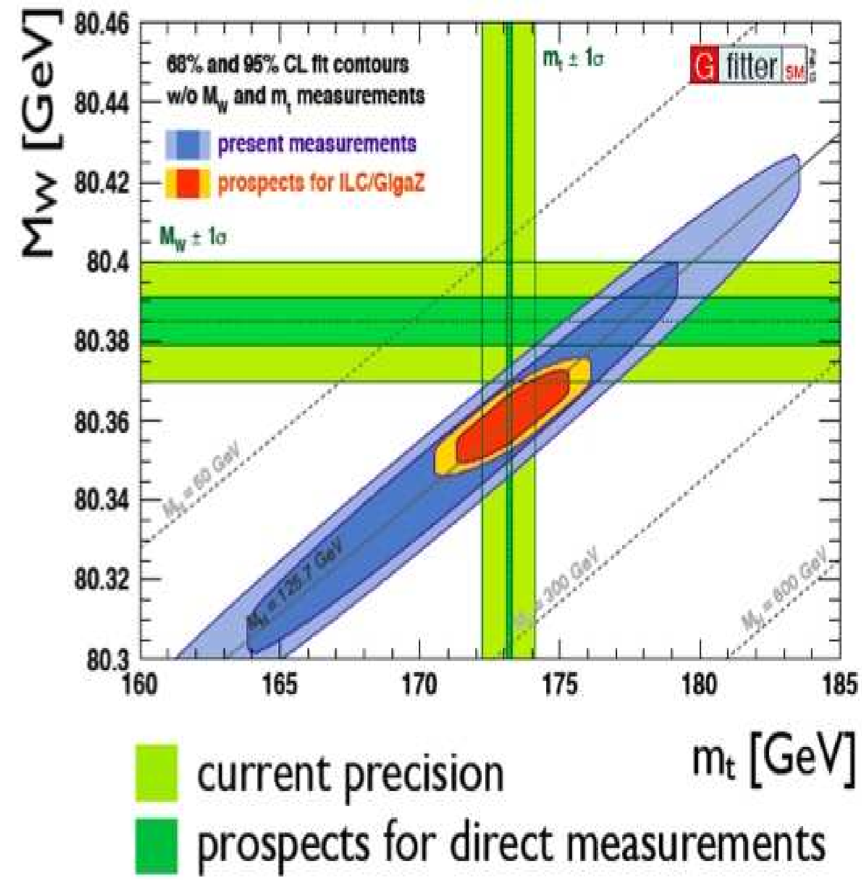
Top quark mass



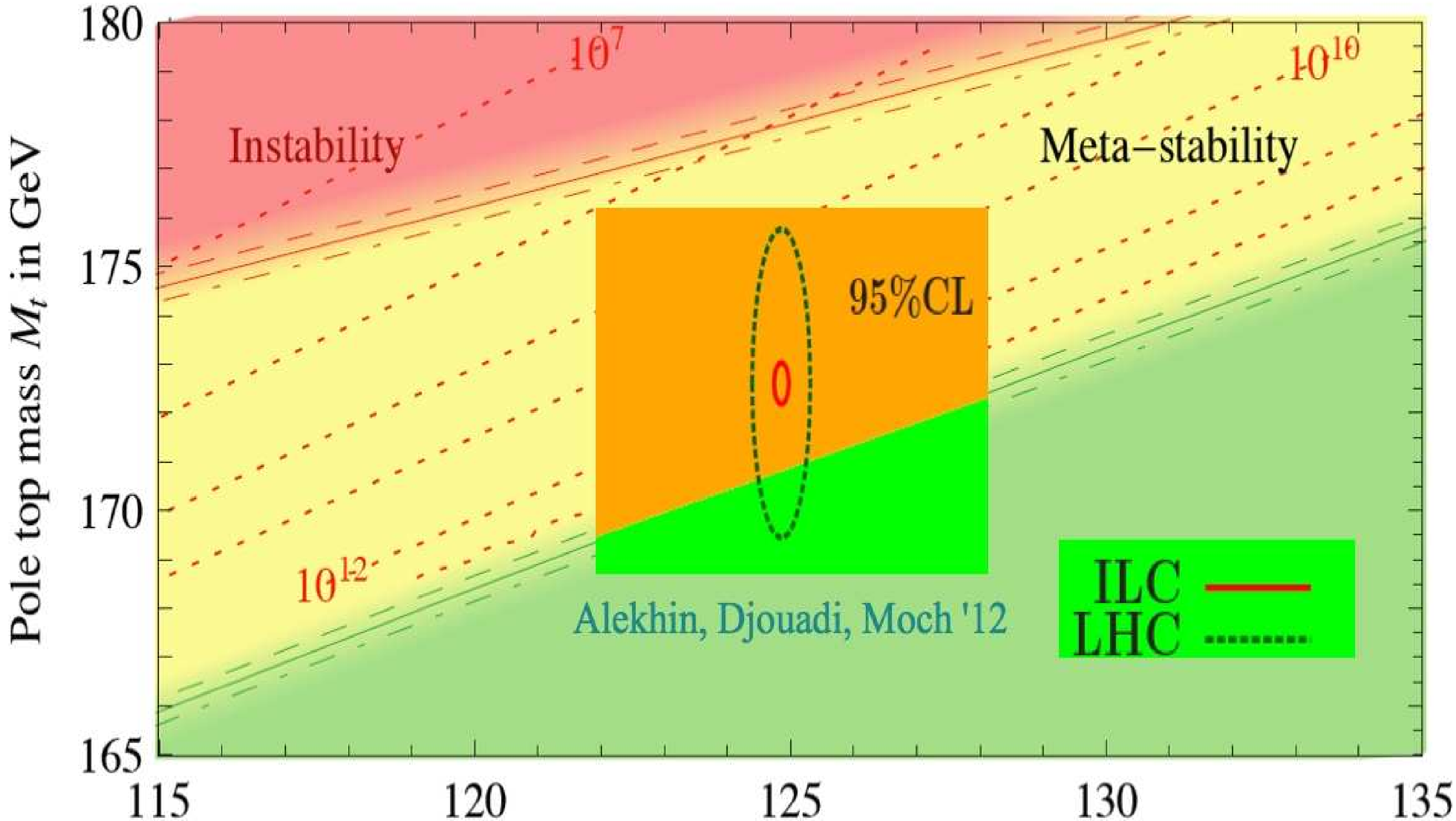
→ "pole" means extracted from production cross sections
→ "kin" means direct measurements, e.g. matrix element method

Precision at LHC (With 80 million top pairs) : 500 MeV, Ultimately 200 MeV may be possible!





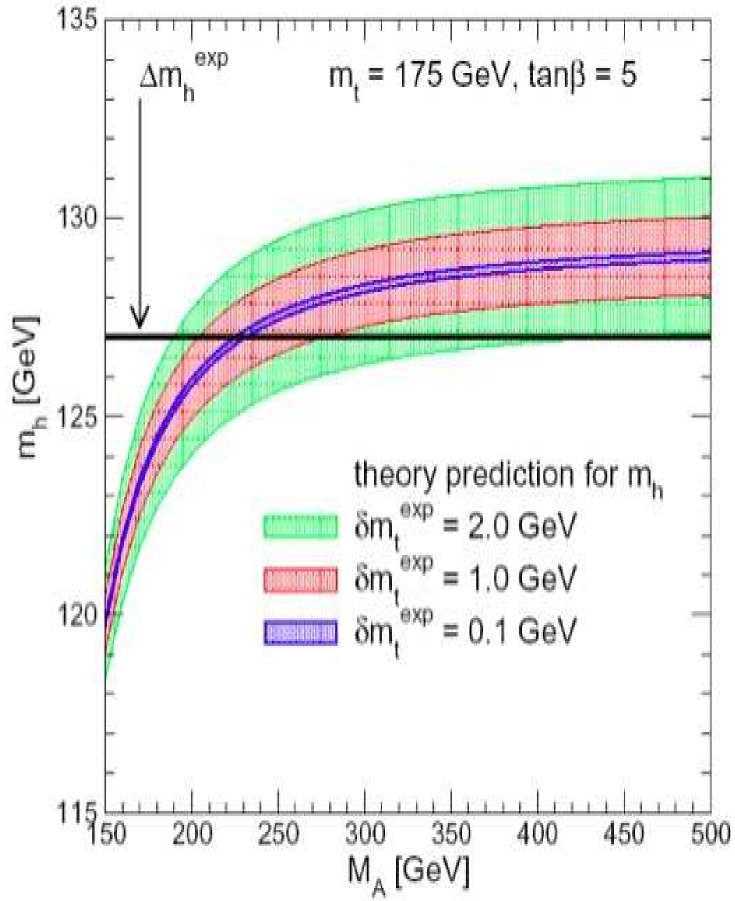
Precision: $\simeq$ 100 MeV!


180
175
170
165
115
120
125
130
135
Pole top mass M_t in GeV
10^7
10^{10}
10^{12}
Instability
Meta−stability
95%CL
Alekhin, Djouadi, Moch '12
ILC
LHC

In fact this can be an excellent way to look for BSM!

100 MeV precision on M_t would be required to match the precision on $\sin^2\theta_W$ and M_W at ILC/Giga Z.

100 MeV precision on M_t can be used to better exploit the LHC (and ILC) precision measurement on M_h.



Determination of self coupling λ! (talk by J. List LC2017)

e^+e^- at 500 GeV, ZHH, full simulation:

1. Observation of HH with ~8σ ✔
2. extract $\lambda|_{SM}$ with 27% uncertainty
3. recent demonstration that parametric uncertainties from other couplings well under control with full ILC Higgs program

arXiv:1708.09079

- **e^+e^- at > 500 GeV, ννHH, full simulation:**
  - 1 TeV, 4ab^{-1}: $\delta\lambda/\lambda\,|_{SM}$ = 10%
  - 1.4 TeV, 1.5ab^{-1}: $\delta\lambda/\lambda\,|_{SM}$ = 40%
  - + 3 TeV, 3ab^{-1}: $\delta\lambda/\lambda\,|_{SM}$ = 16%
  - upcoming improvement: exploit differential distributions at 3 TeV: expect ~ 10%

Thesis: C. Dürig, Hamburg University, Also EPJC 77(2017) no.7 475

Determination of self coupling λ! (talk by J. List LC2017)

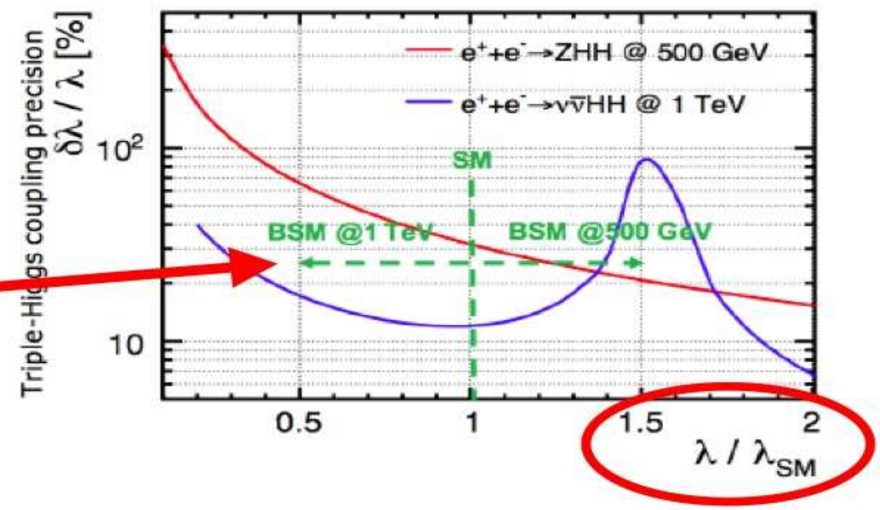
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2017-001/

In any case: e^+e^- offers significant added value w.r.t. HL-LHC

Important: achievable precision depends strongly on actual value of λ!

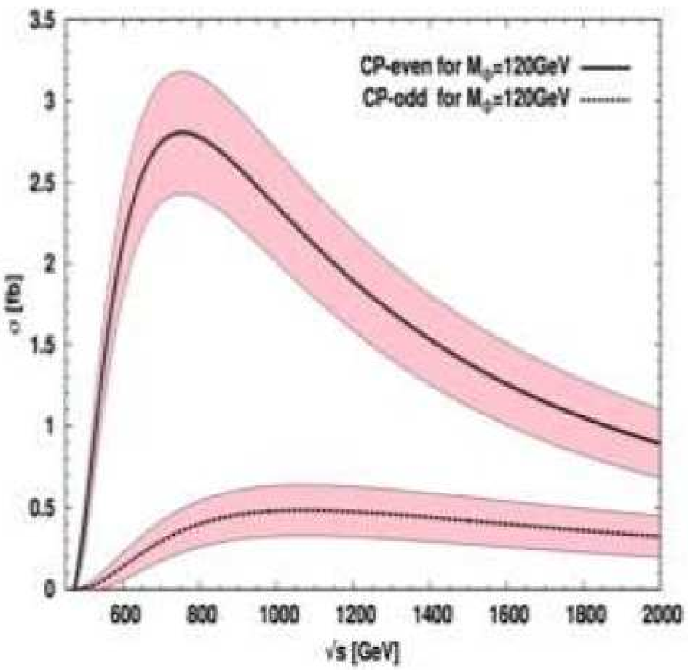
=> BSM can change the picture

=> with combination of ZHH and ννHH we're always on the safe side!



Thesis: C. Dürig, Hamburg University, Also EPJC 77(2017) no.7 475

At energies still higher (with CLIC) top yukawa measurement at 1.5% and possible determination of CP in the $ht\bar{t}$ coupling is possible.



The energy dependence of cross-section depends on a and b

Top curve a =1, b=0, Pure Scalar
Bottom curve a=0, b=1, pure pseudoscalar.

Phys. Rev. Lett. 100 (2008) 051801
(Bhupal Dev, A.Djoaudi, R.G. et al)

and

EPJC, 71 (2011) 1681
(C. Hangst, R.G., Margarete Muehelleitner et al)