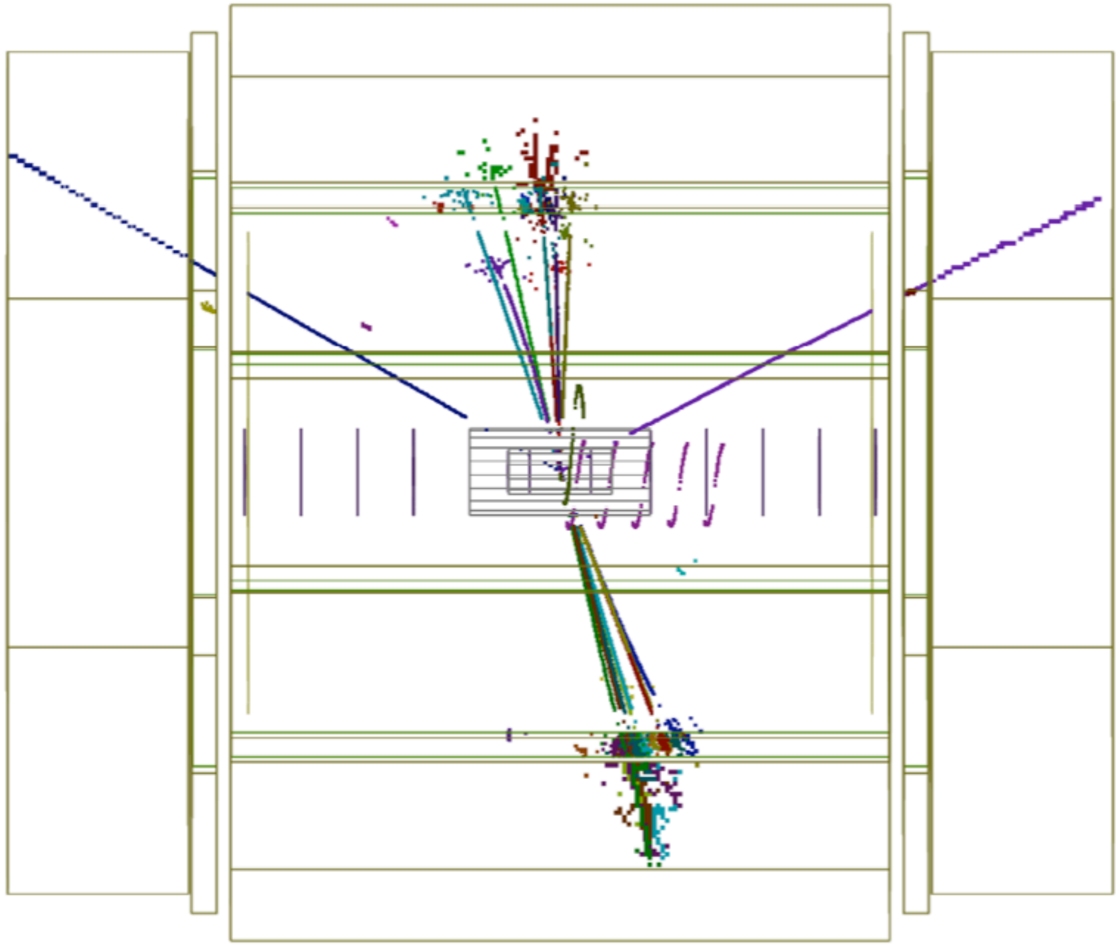
Linear Collider Physics



M. E. Peskin
LCWS 2013
November 2013

This talk will review the physics opportunities for Linear Colliders, with special emphasis on physics at the International Linear Collider.

This subject has been discussed for more than 25 years, since the first reports on physics at linear colliders from KEK, DESY, and SLAC.

The case for linear collider experiments has continually become stronger over that time.

Last year, the discovery of the Higgs boson at the Large Hadron Collider has brought the case for the Linear Collider to the front and center of the agenda for particle physics.

This is reflected in two important sets of Linear Collider physics documents written in the past year by a global cast of authors.

ILC TDR,
esp. Volume 2 (physics) and Volume 4 (detectors)

White Papers for the Snowmass 2013 study in the US:

ILC Higgs White Paper	arXiv:1310.0763
ILC Electroweak White Paper	arXiv:1307.3962
ILC Top Quark White Paper	arXiv:1307.8265
ILC BSM White Paper	arXiv:1307.5248
CLIC Physics White Paper	arXiv:1307.5288

I will review new results from these papers in this talk.

outline of this talk:

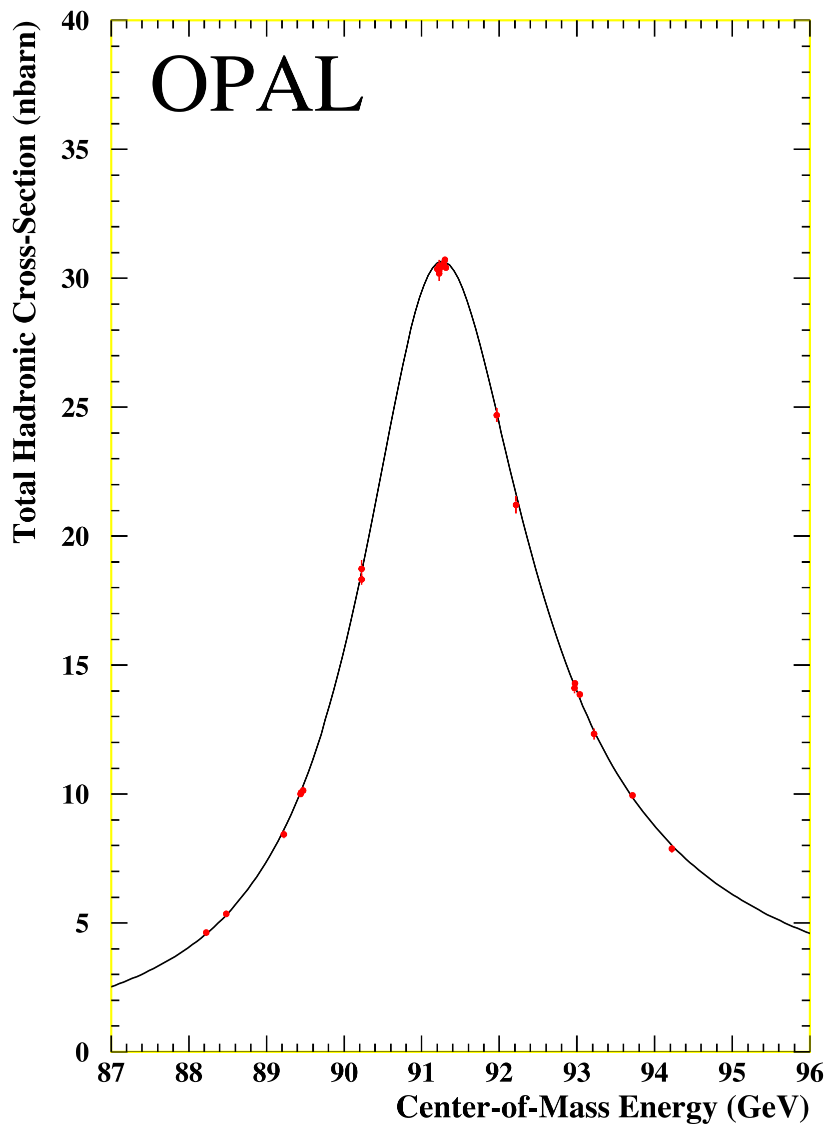
the central nature of mystery of the Higgs field

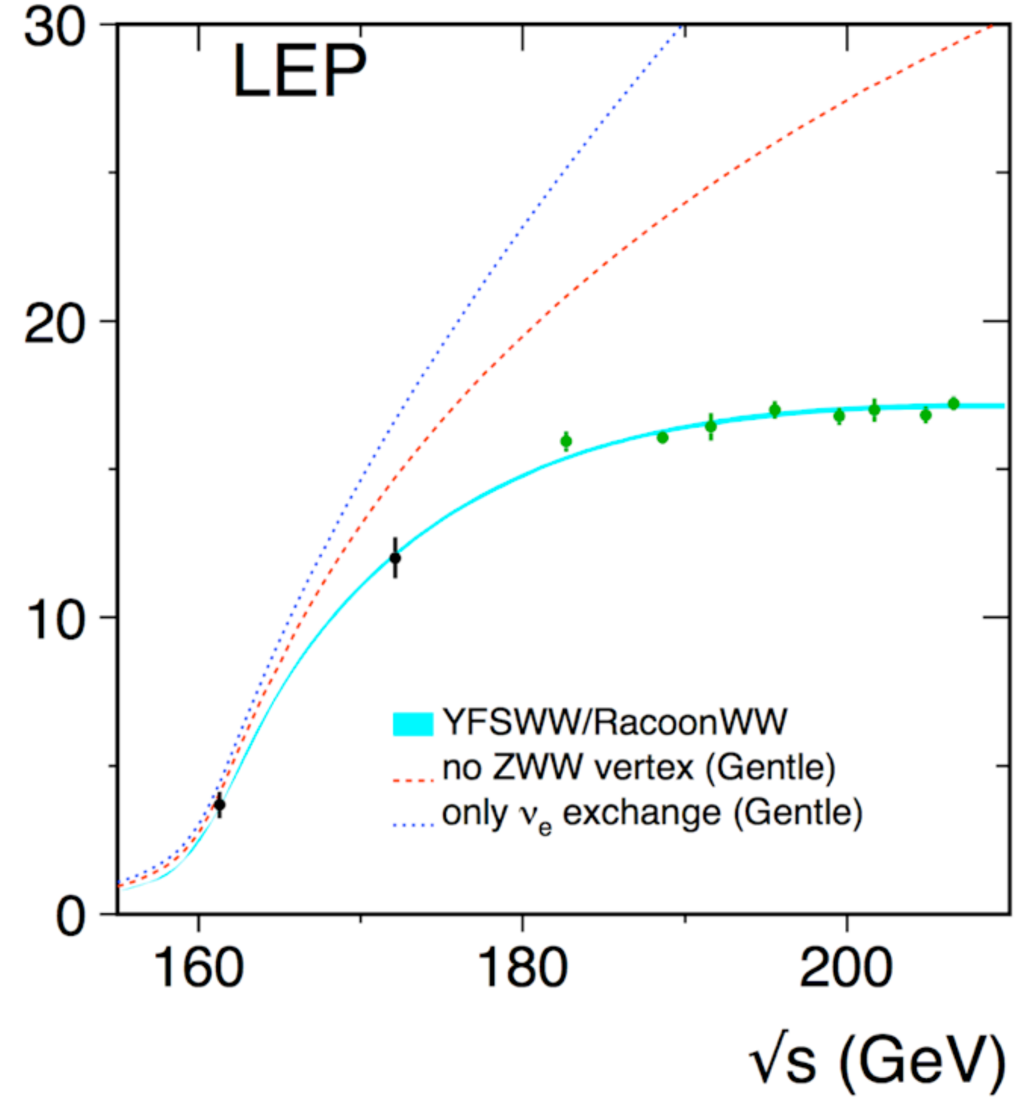
Higgs boson physics

top quark physics

searches for new physics

We particle physicists have been living for a long time with the Standard Model. This gives a simple and precise description of the strong, weak, and electromagnetic interactions. In the past 25 years, it has passed many stringent experimental tests.





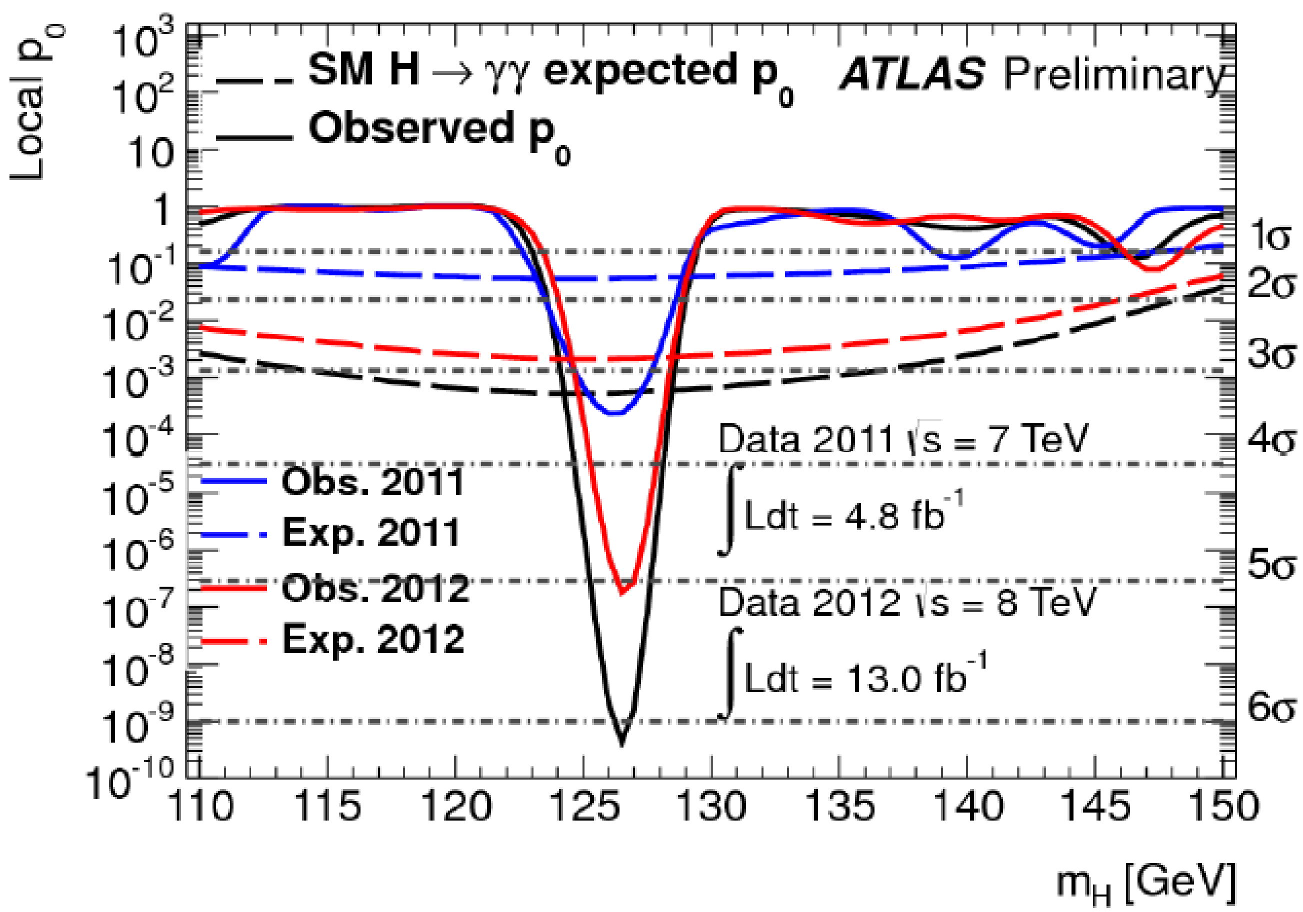
Yet there has always been mystery at the core of the Standard Model.

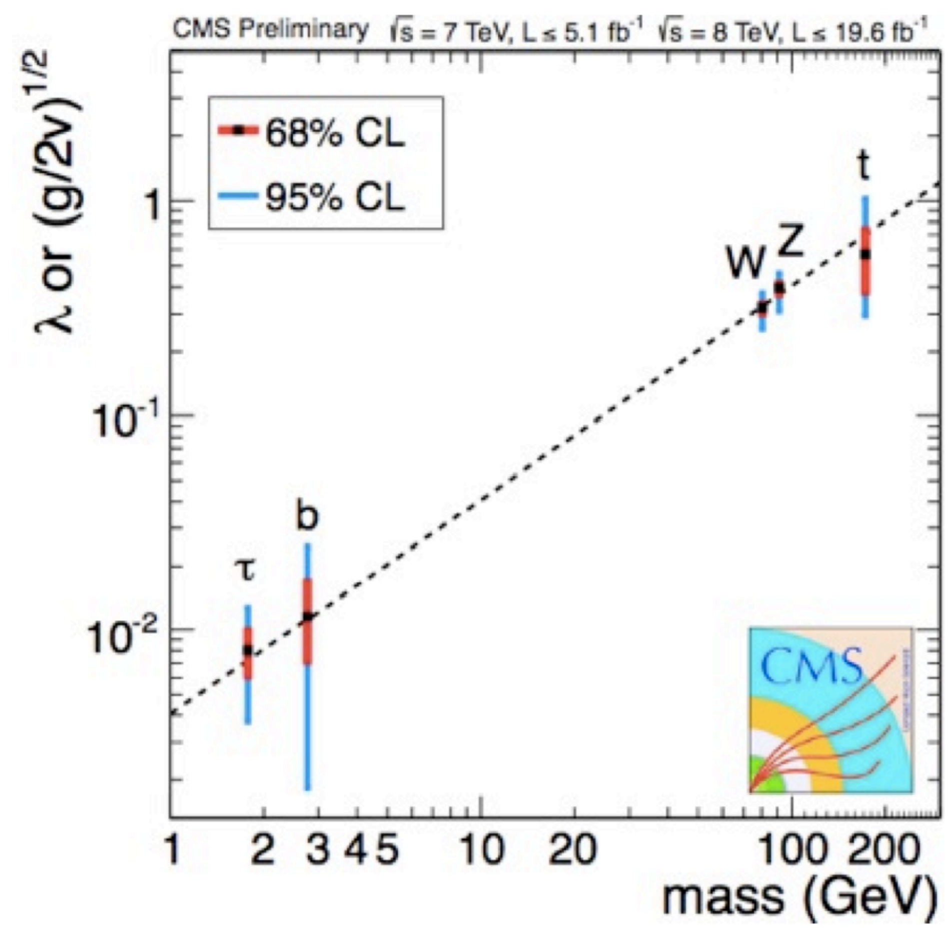
The model is based on spontaneous breaking of its fundamental SU(2)xU(1) symmetry.

The fields responsible for this symmetry breaking, the cause of their instability, and the physics of that couples them to quarks and leptons are all unknown.

Since Higgs, theorists have been troubled by these questions. And, experimenters have doubted that the story makes sense.

The discovery of the Higgs boson sheds light on these mysteries, but it also makes the questions sharper than ever.   Now we cannot avoid answering them.

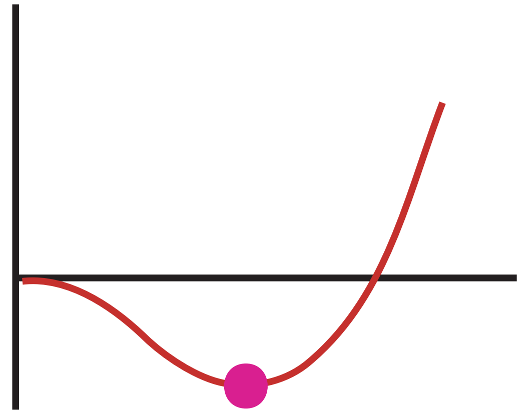




We now know that there is a scalar particle whose field has a vacuum value. It couples roughly according to mass.

In the Standard Model, symmetry breaking is the result of a fundamental scalar field with the potential

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$



The total of the Standard Model explanation for the phenomenon of symmetry breaking is

$$\mu^2 < 0$$

It is not possible to compute μ^2 within the Standard Model. The result contains quadratic divergences with competing signs.

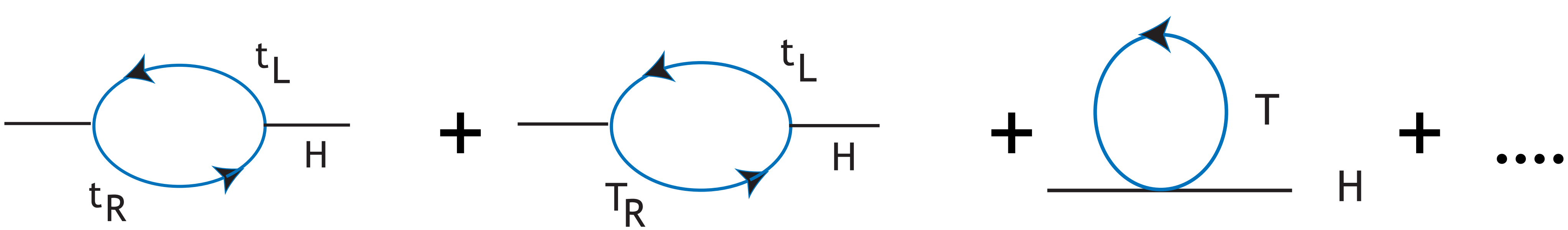
In condensed matter physics, there are many examples of spontaneous symmetry breaking

superconductivity, magnetism, binary alloys, ...

In each case, the instability to symmetry breaking occurs for a physics reason.

For this to be true also in particle physics, there must be new particles and interactions not found in the Standard Model.

$\mu^2 =$



Examples are found in theories of supersymmetry, extra dimensions, new forces at TeV energies, ...

We need more structure in particle physics to explain many phenomena that are outside the scope of the Standard Model

dark matter
baryogenesis
quantum numbers of quarks and leptons
neutrino mass
dark energy and cosmic inflation
...

All of these phenomena call for new particles and forces in nature. All are potentially affected by new structure at the Higgs boson energy scale.

Conclusions of the "Energy Frontier" study for Snowmass 2013:

The search for these new particles and forces at the TeV energy scale has a central role in the future of particle physics.

A 3-prong program is required:

- Study the Higgs boson in as much detail as possible.
- Search for the imprint of the Higgs on W, Z, and top.
- Search for new particles with TeV-scale masses.

Today, this program is driven by the experiments at the CERN Large Hadron Collider.

The EF study gave strong endorsement to the High Luminosity phase of the LHC in the 2020's.

However, the study also enunciated goals in precision measurement that go beyond the capabilities of the LHC. For this, lepton collider experiments are needed.

ILC, on the table today, meets these goals.

Higgs boson

What do we need from an experimental program on the Higgs boson ?

high precision

comprehensive, model-independent survey of couplings to SM particles

ability to detect invisible and exotic decay modes

A paradox of Higgs boson studies:

We know almost nothing about the Higgs boson sector. It could contain one or many doublet fields, and arbitrary additional content.

But, if all new particles except the known Higgs boson are at mass M or above, the lightest Higgs boson has Standard-Model-like couplings to the accuracy

$$m_h^2/M^2$$

by Haber's Decoupling Theorem.

Survey of effects in the EF report, for M = 1 TeV.

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Discovery is 5σ , so the goal is sub-percent accuracy.

Lepton colliders bring important advantages to the study of the Higgs Boson couplings:

Higgs rates are 1% of the total cross section, not 10^{-10}.

Low backgrounds and high flavor tagging efficiency make possible the direct observation of hadronic decay channels $h \to b\bar{b}, c\bar{c}, gg$.

The reaction $e^+e^- \to Zh$ provides tagged Higgs decay. This gives a tool for measuring branching fractions and a way to discover invisible and otherwise unexpected Higgs decays.

A comprehensive Higgs program requires running at multiple energies:

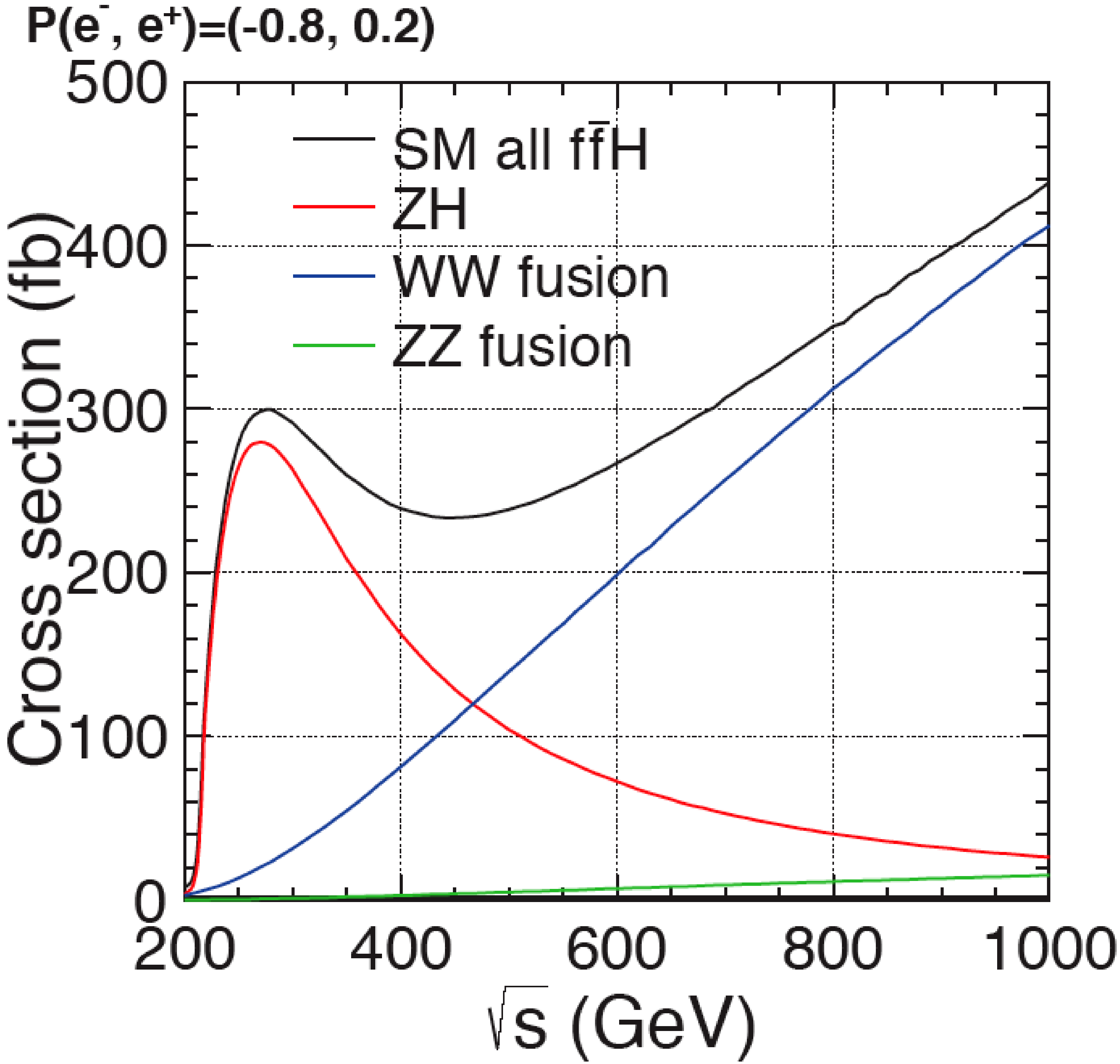
250 GeV: tagged Higgs, branching ratios

350-500 GeV: W fusion production, absolute normalization of the couplings

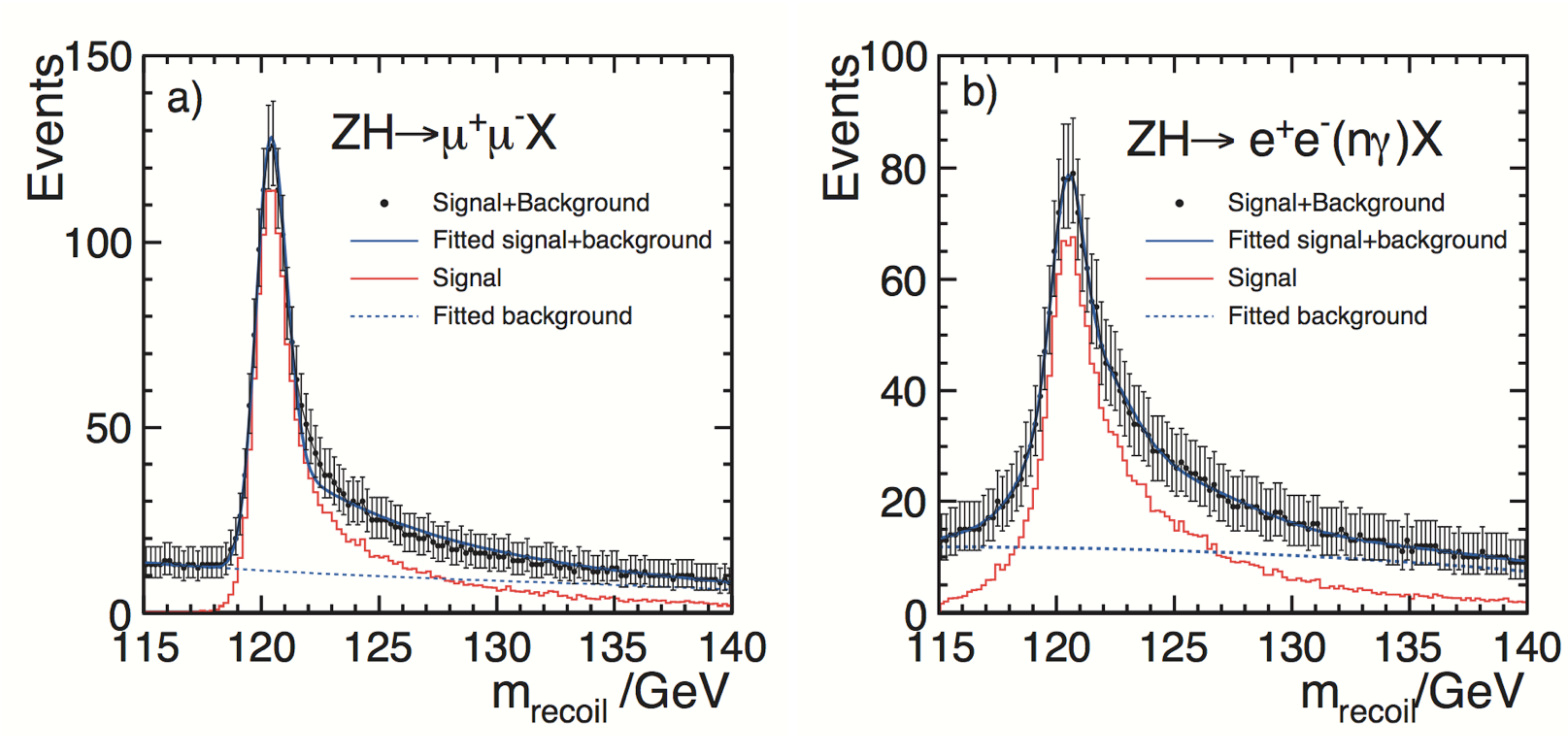
> 700 GeV: Higgs coupling to top

> 700 GeV: Higgs self-coupling

The energy stages of ILC will allow us to carry out this program.

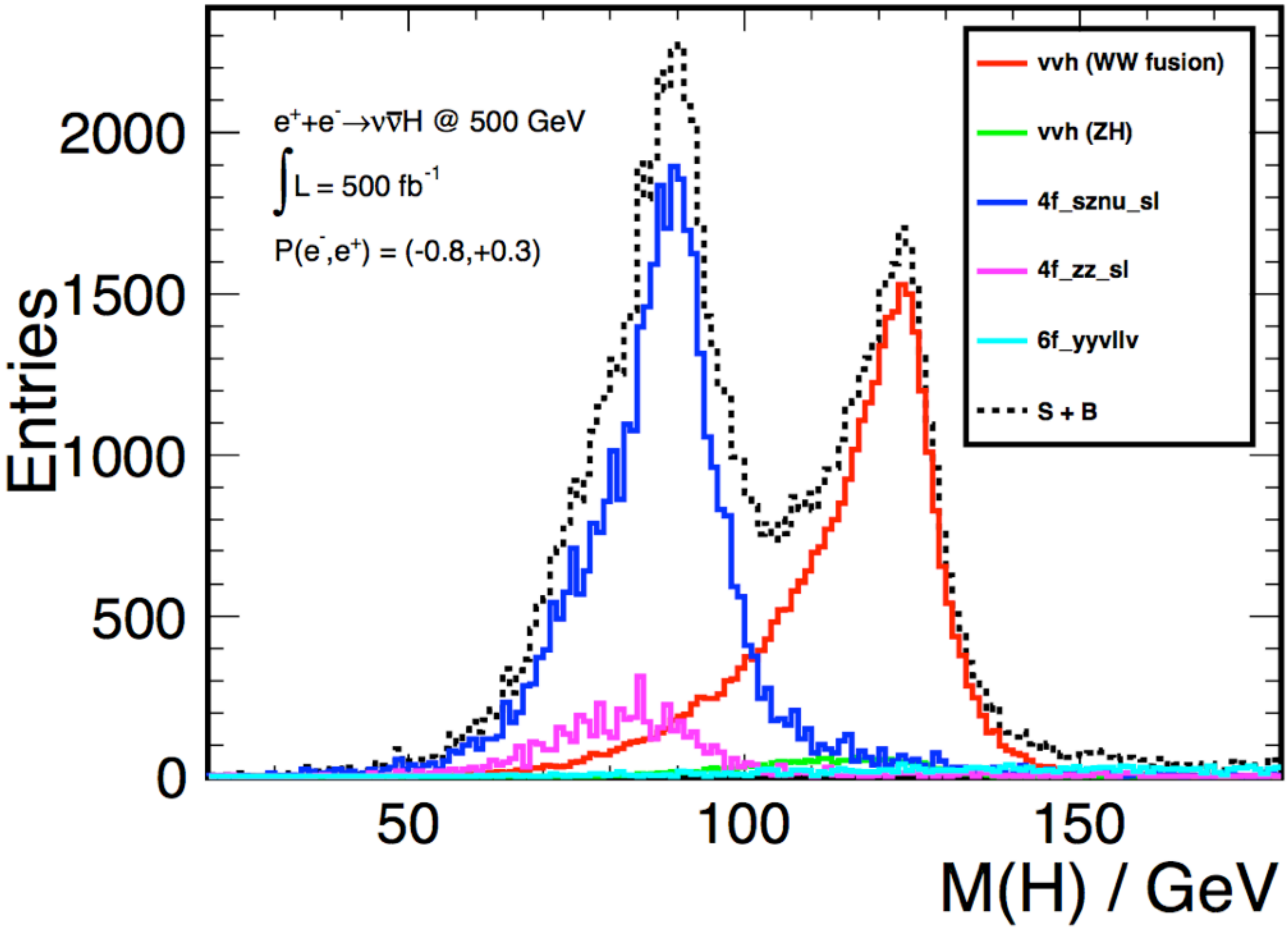


P(e⁻, e⁺)=(-0.8, 0.2)
SM all ff̄H
ZH
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
√s (GeV)



uncertainty in Higgs boson mass : 32 MeV

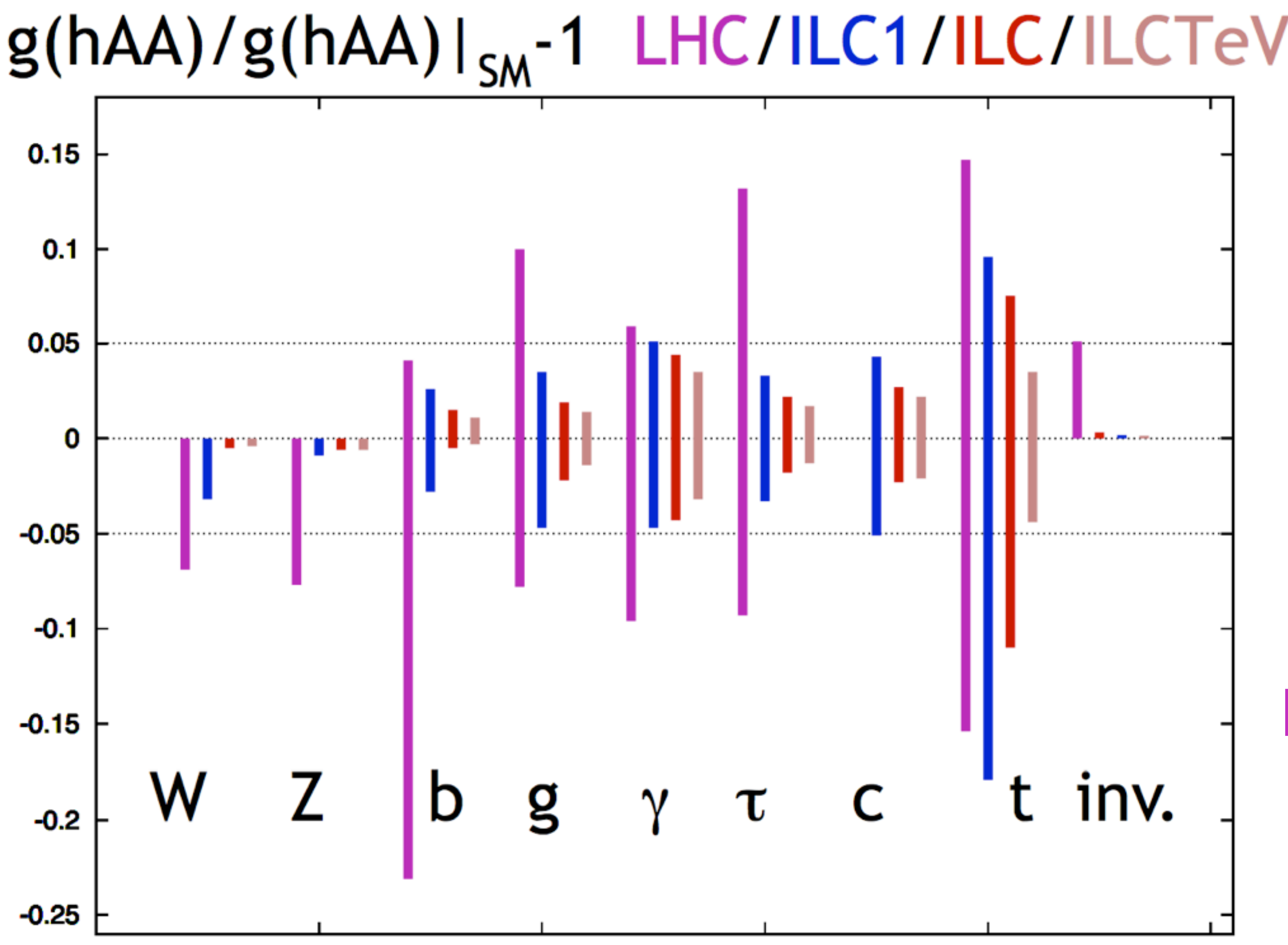
ILC TDR



ILC Higgs White Paper

Comparison of LHC and ILC Higgs coupling accuracies ?

Here is the figure from the ILC TDR:



LHC = 300/fb

ILC = TDR

Snowmass reconsidered this comparison using LHC projections for 300/fb and 3000/fb:

CMS approach:

Scenario 1: use current systematics and theory errors
Scenario 2: theory errors decrease by 2, experimental systematics by $\sqrt{N}$

This is an extrapolation into the high-pileup regime.

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

Scenario 2 quantifies the opportunity of the HL-LHC.

Can one comparably quantify the opportunity of the ILC ?

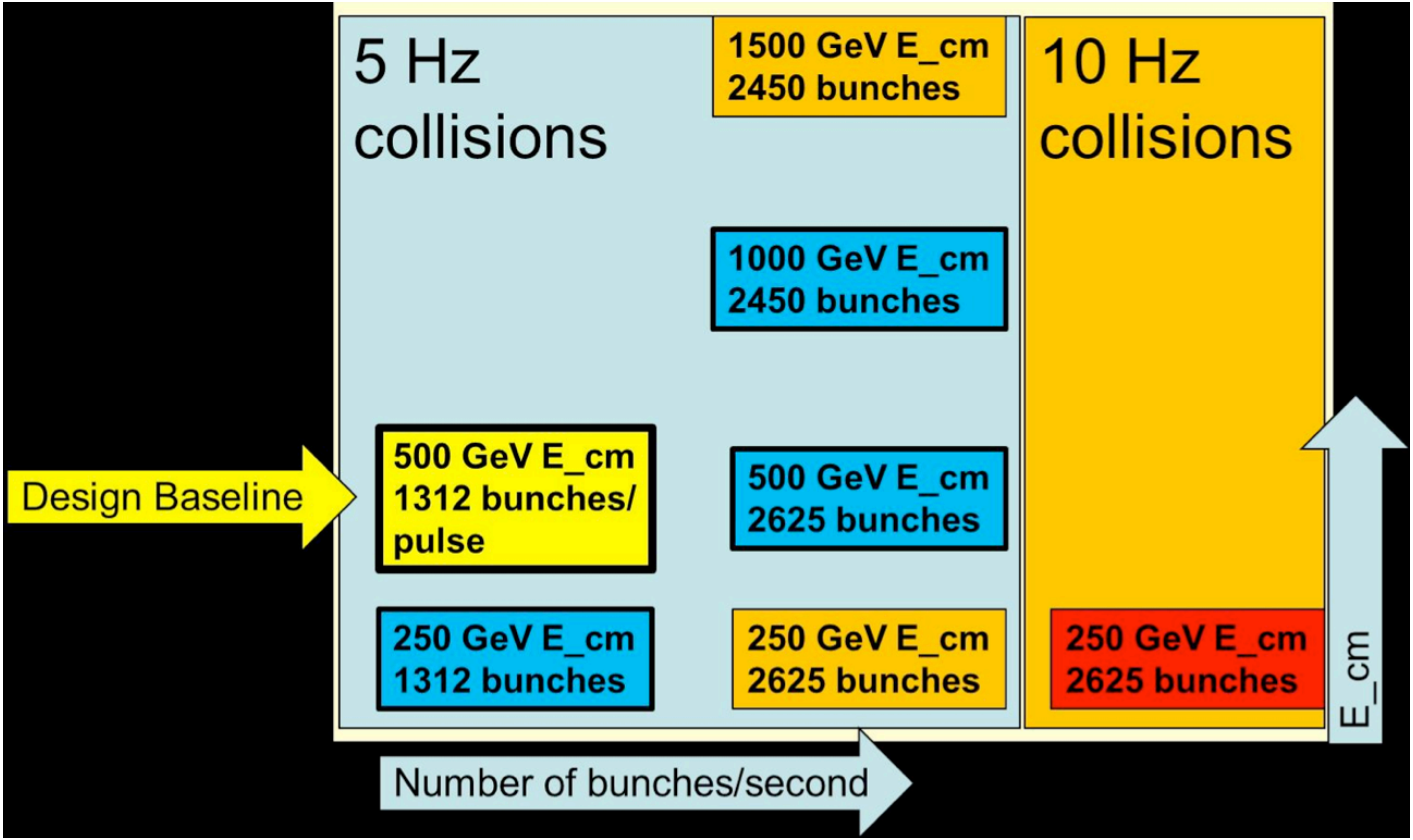
Attitude of the ILC Higgs White paper:

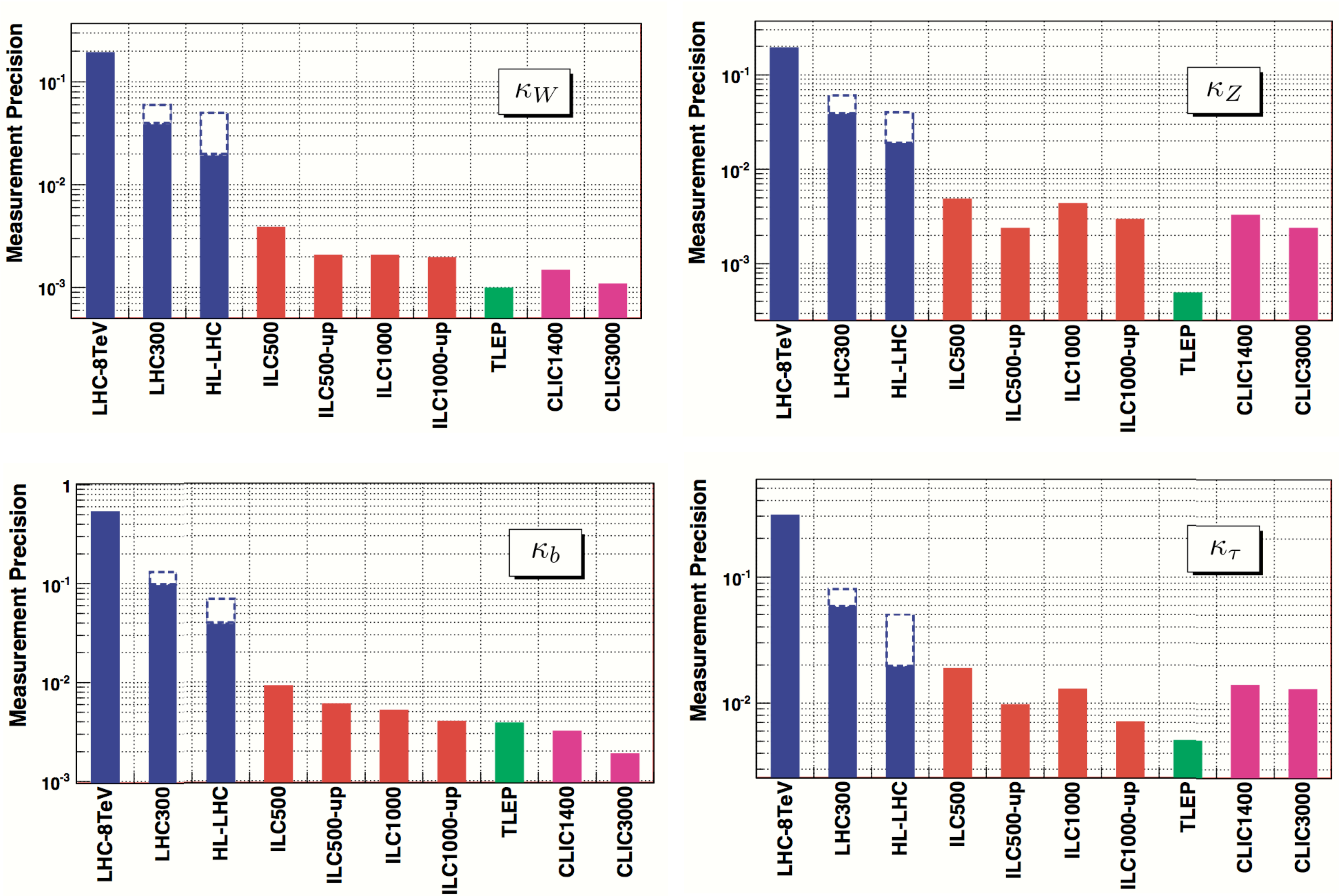
Consider the long-term ILC program.

The TDR is the beginning. It sets a new level of accuracy dominated by statistical errors.

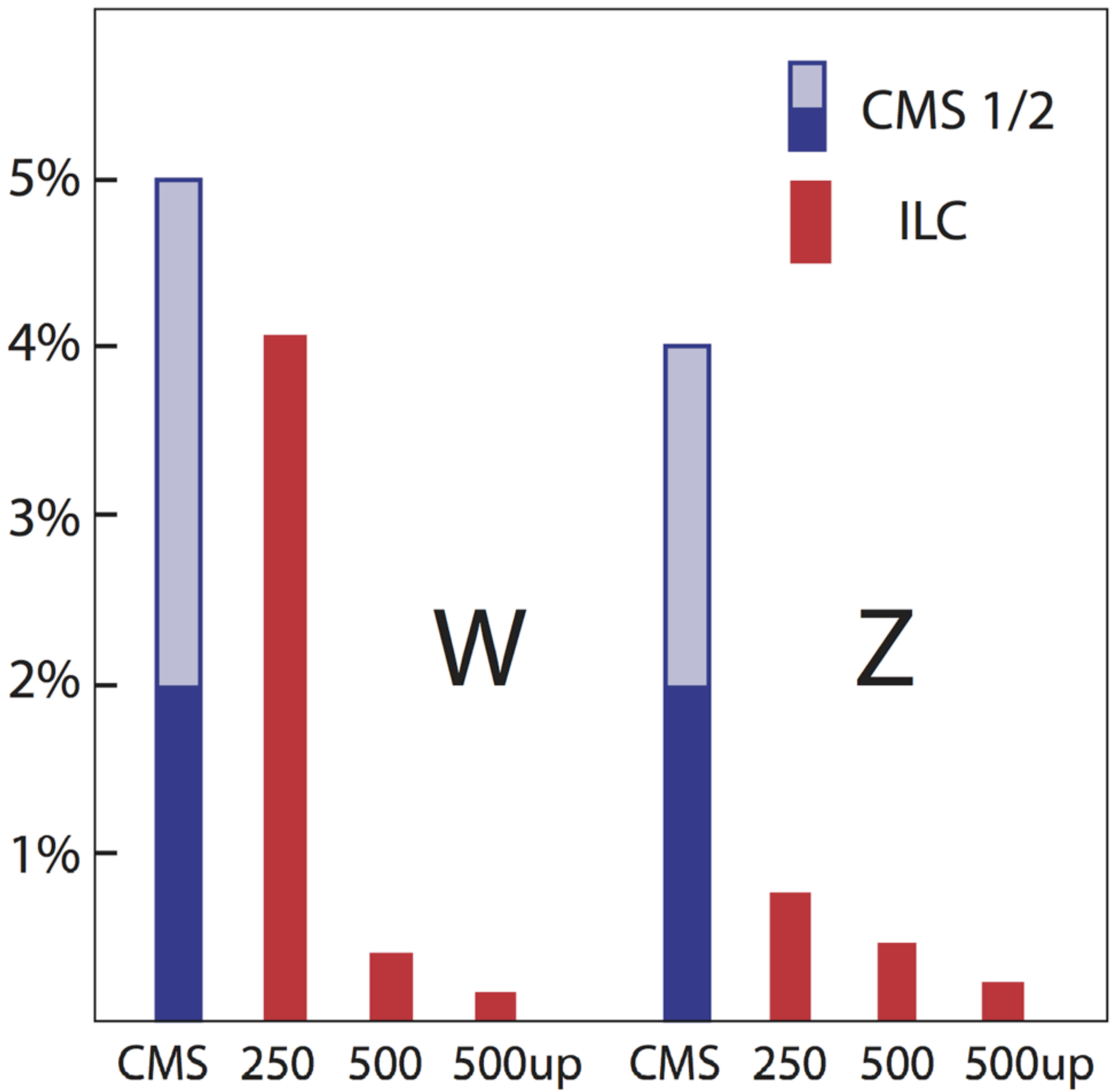
Improve the TDR uncertainties by more running, and by luminosity upgrades foreseen in the TDR.

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})
ILC(250)	250	250						
ILC(500)	250	250		500	500			
ILC(1000)	250	250		500	500		1000	1000
ILC(LumUp)	250	1150		500	1600		1000	2500

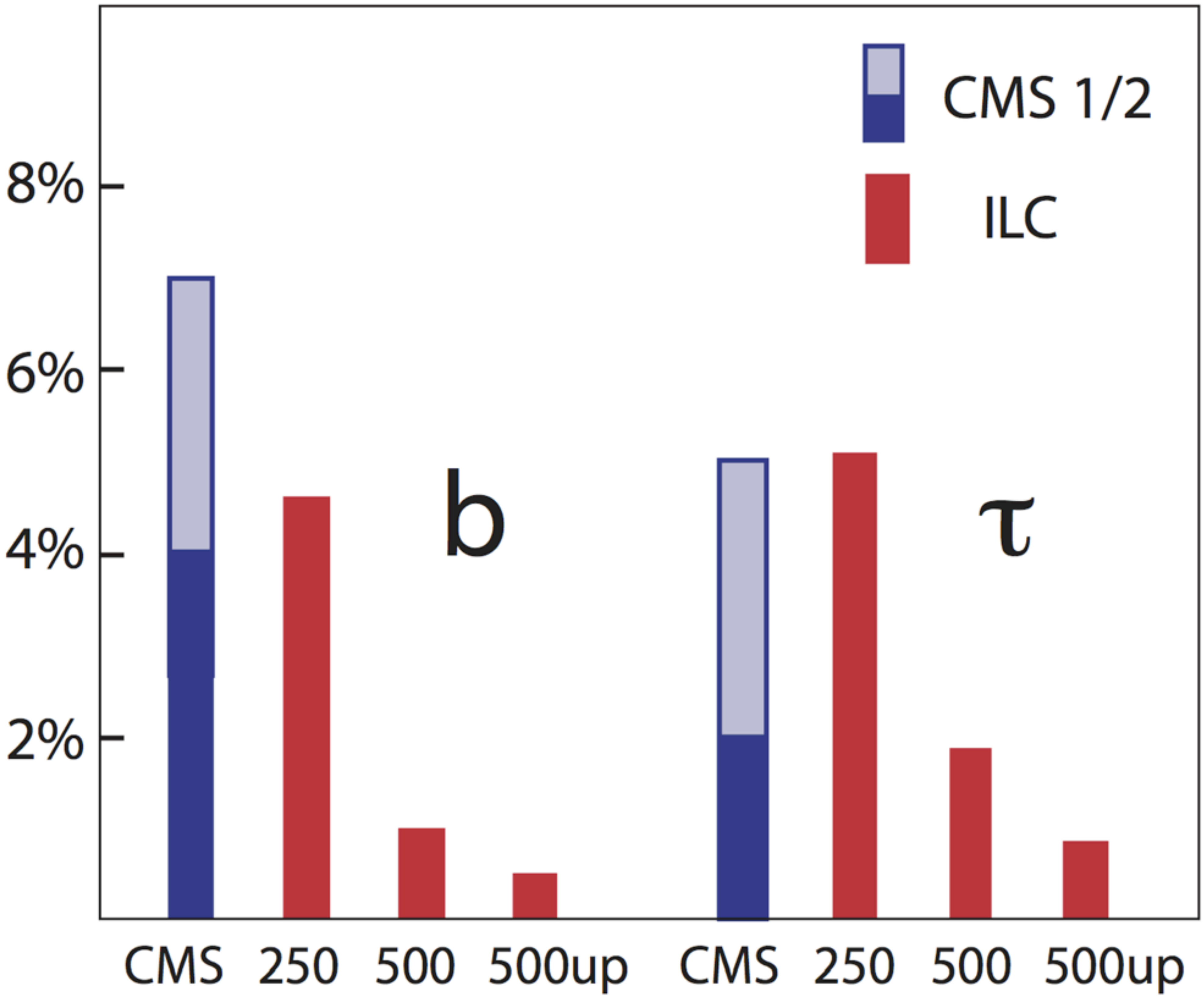

5 Hz collisions
1500 GeV E_cm 2450 bunches
10 Hz collisions
1000 GeV E_cm 2450 bunches
Design Baseline
500 GeV E_cm 1312 bunches/ pulse
500 GeV E_cm 2625 bunches
250 GeV E_cm 1312 bunches
250 GeV E_cm 2625 bunches
250 GeV E_cm 2625 bunches
E_cm
Number of bunches/second



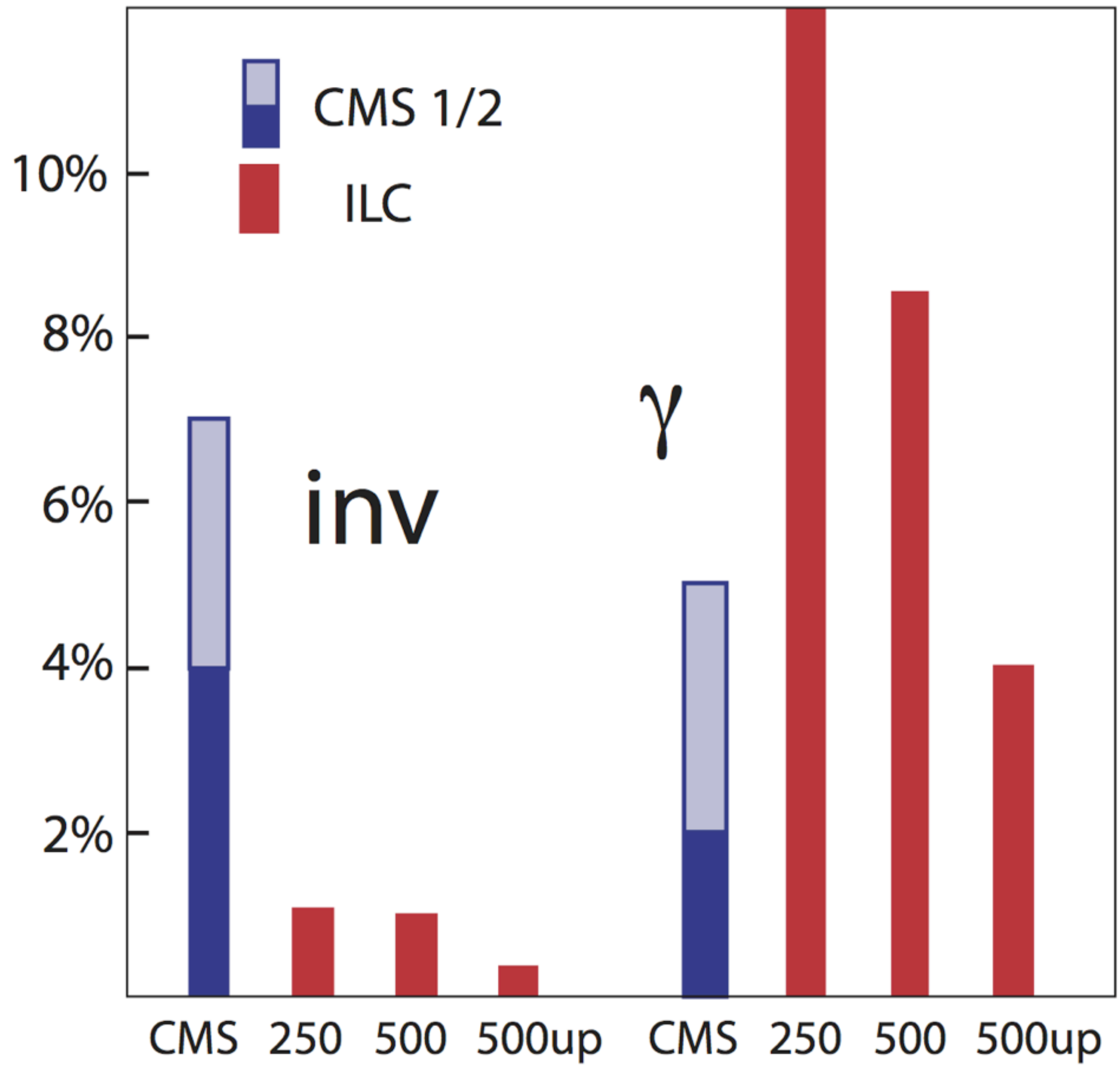
Snowmass Higgs report



CMS 1/2
ILC
5%
4%
3%
2%
1%
W
Z
CMS
250
500
500up
CMS
250
500
500up



CMS 1/2
ILC
8%
6%
4%
2%
b
τ
CMS
250
500
500up
CMS
250
500
500up


CMS 1/2
ILC
10%
8%
6%
4%
2%
inv
γ
CMS
250
500
500up
CMS
250
500
500up

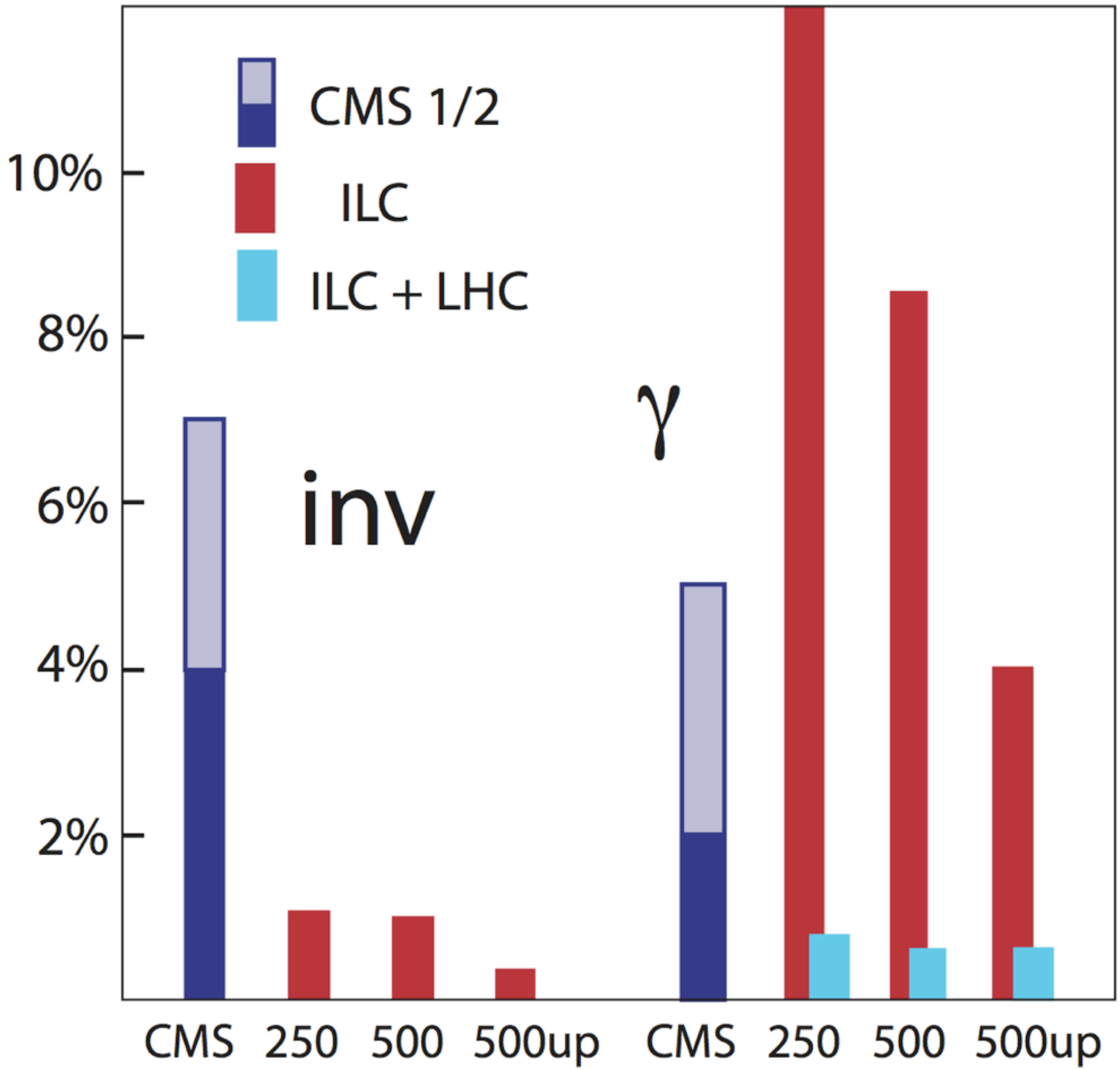
The advantage of the LHC is very high statistics -- 200 million Higgs bosons -- to measure rare modes.

ATLAS estimates a measurement uncertainty

$$\Delta[BR(h \to \gamma\gamma)/BR(h \to ZZ^*)] \sim 2.9\%$$

free of theoretical systematics, from the HL-LHC.

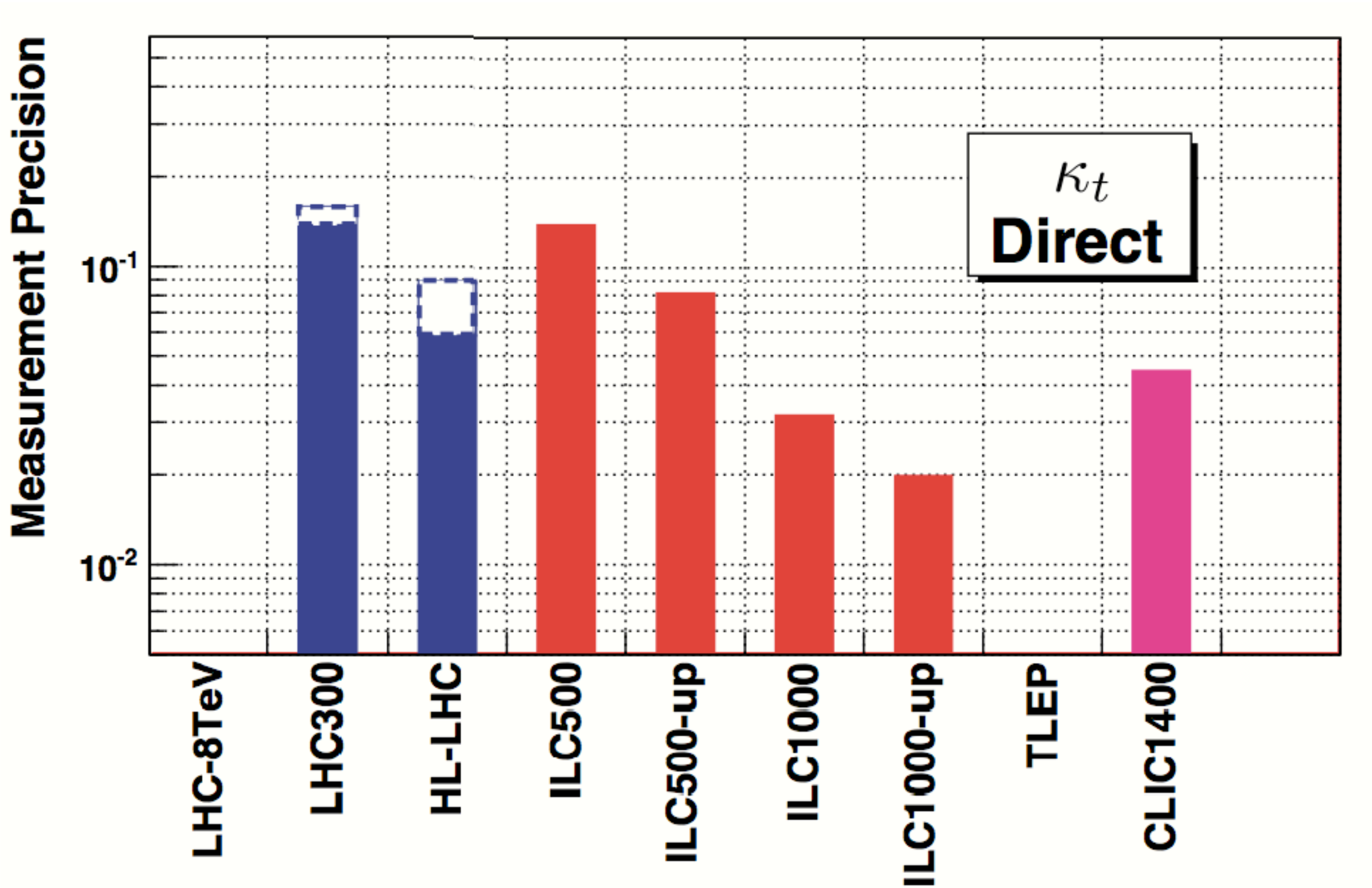
Add this one data point to the Linear Collider measurements:


CMS 1/2
ILC
ILC + LHC
10%
8%
6%
4%
2%
inv
γ
CMS
250
500
500up
CMS
250
500
500up

Experiments at higher energy give access to the Higgs coupling to top and the Higgs self-coupling

at 1 TeV: uncertainty for

	top	self
TDR (1/ab)	3.7 %	26 %
2.5/ab	2.0 %	13 %



Snowmass Higgs report

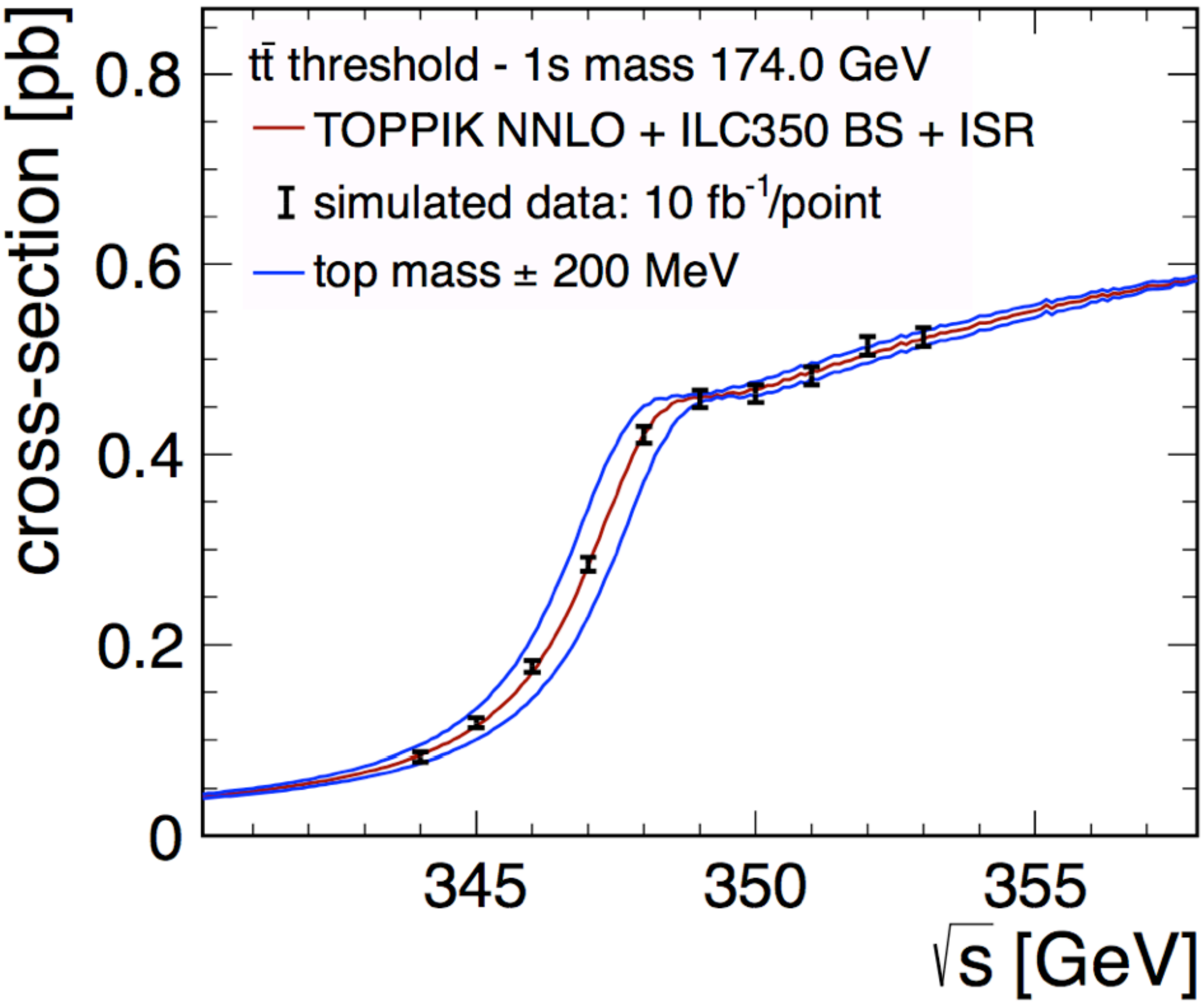
Top quark

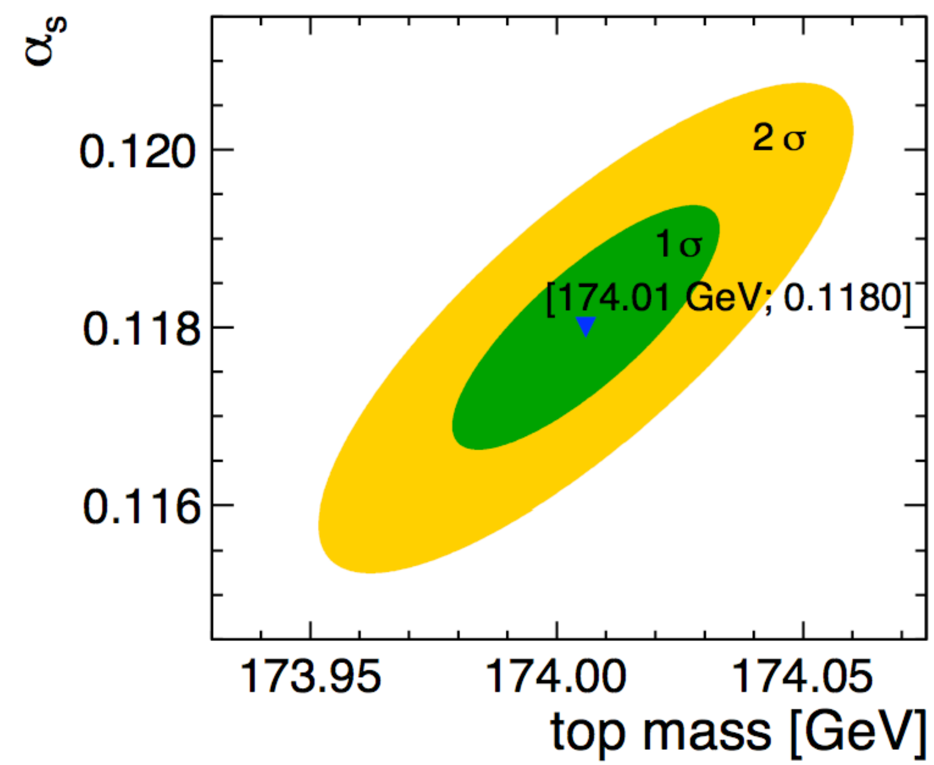
The two most important goals of the Linear Collider program on the top quark are:

to measure the top quark mass -- a fundamental parameter

to search for signals of top/Higgs compositeness

Similar opportunities are available, in both respects, for the W boson.





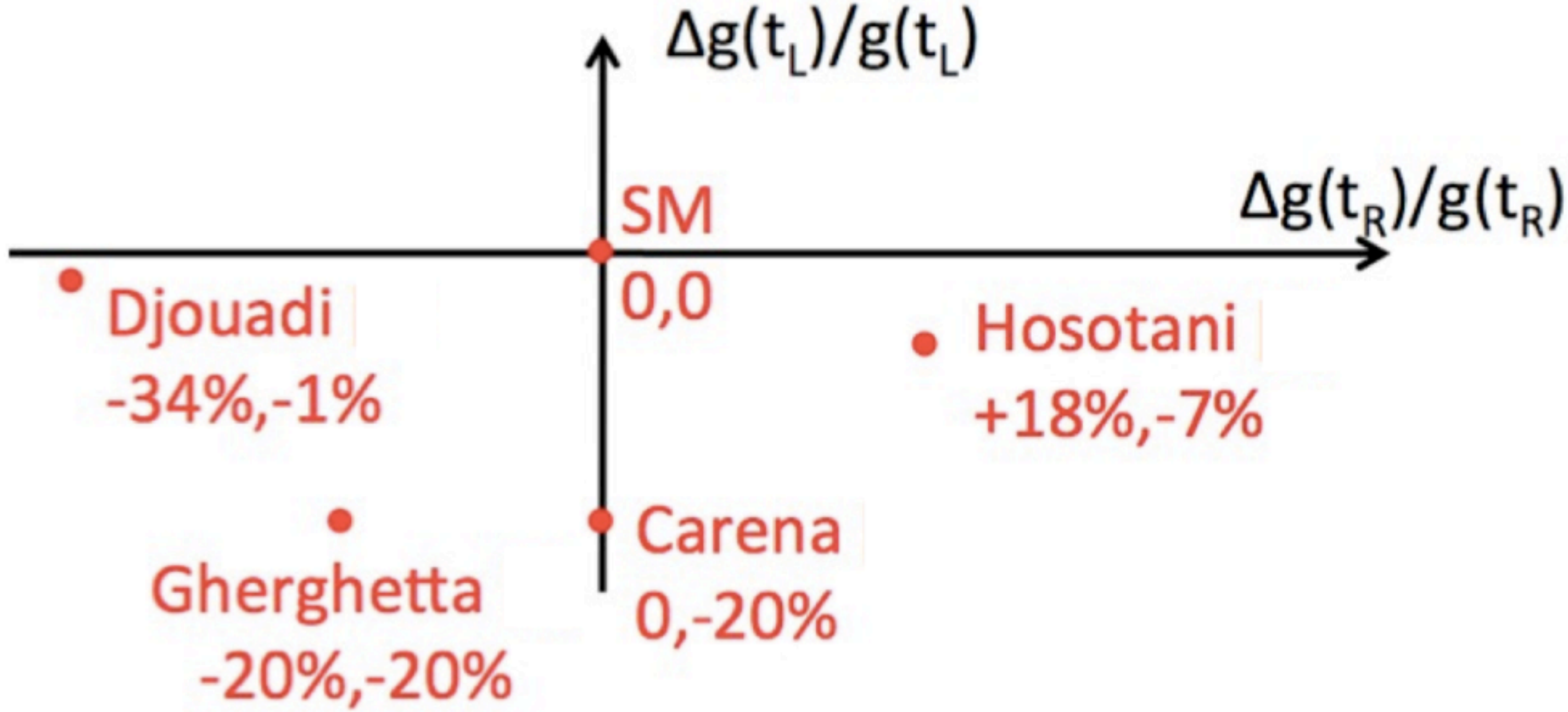
$$\Delta[m_t(\overline{MS}, m_t)] \sim 100 \text{ MeV}$$

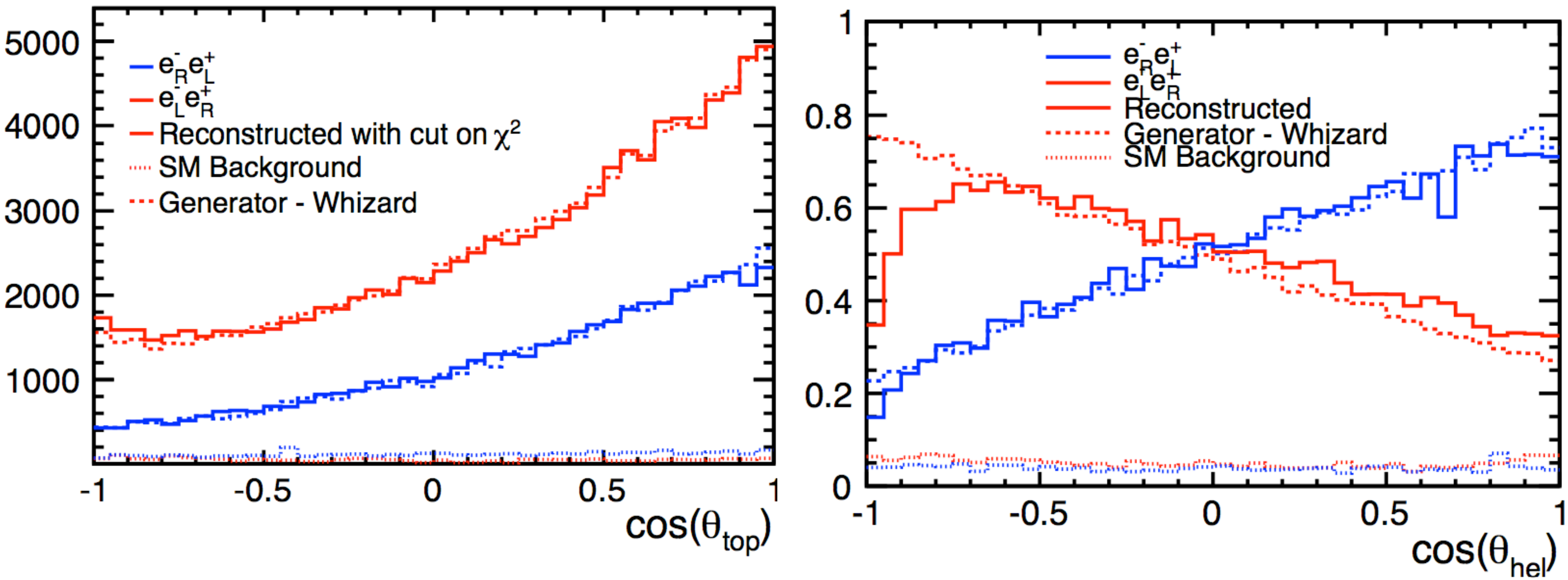
Because the top quark is the heaviest Standard Model particle, it is the one with the strongest coupling to the Higgs sector.

If the Higgs is composite, the top quark must also have composite structure.

This is realized in a dual description in Randall-Sundrum theory. To obtain a large mass, the t_L and t_R must lie near the "IR brane". This alters the chiral gauge couplings to γ and Z .

There are only weak constraints on the t_R coupling to the Z. Sizeable corrections are predicted in these theories.

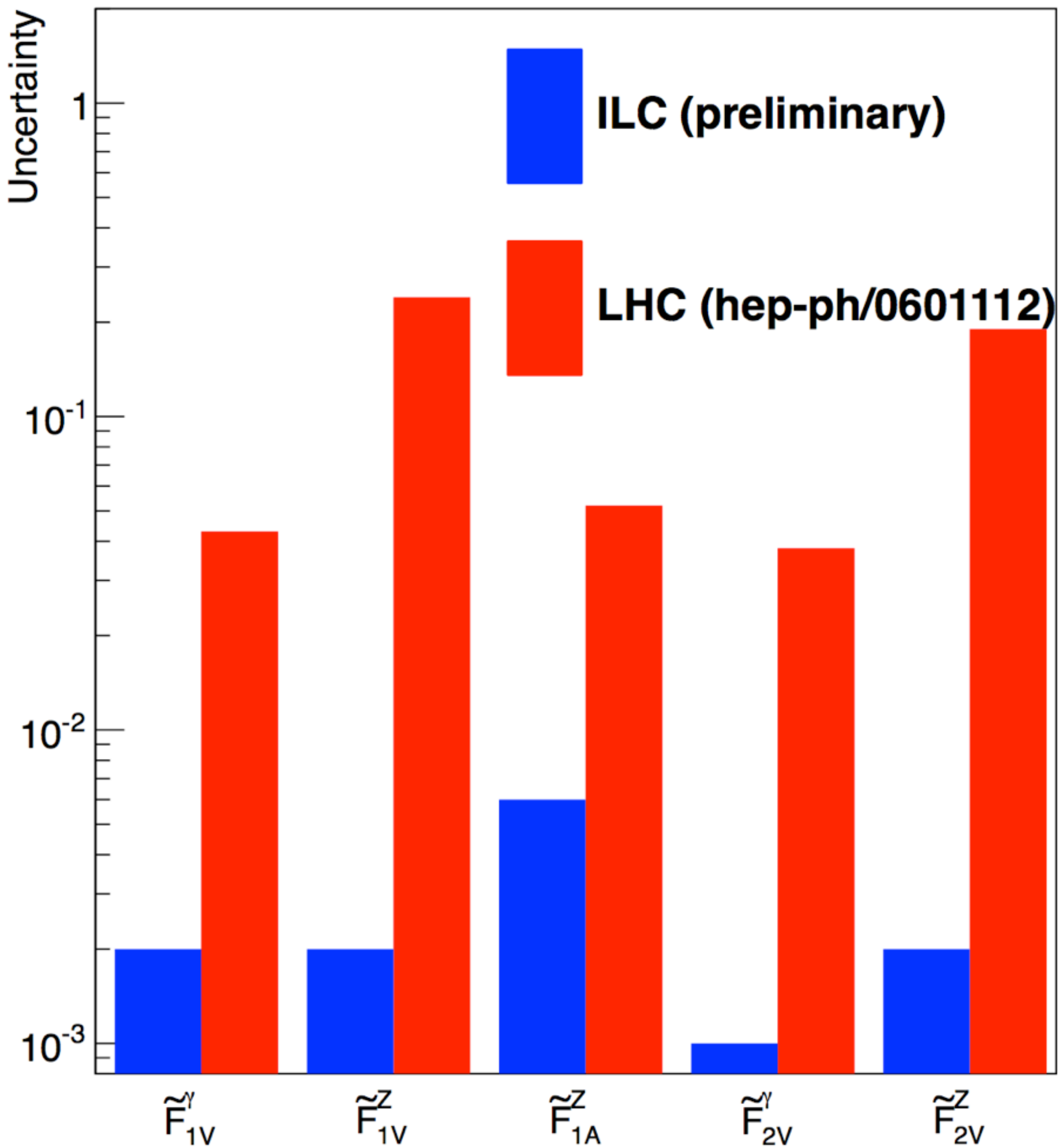

Δg(t_L)/g(t_L)
Δg(t_R)/g(t_R)
SM
0,0
Djouadi
-34%,-1%
Hosotani
+18%,-7%
Carena
0,-20%
Gherghetta
-20%,-20%



Beam polarization and final-state polarization asymmetries allow one to completely disentangle the terms in the top quark - gauge boson couplings.

$$
eA_\mu \; \bar{t}[\gamma^\mu P_L \cdot \frac{2}{3} F_L(q^2) + \gamma^\mu P_R \cdot \frac{2}{3} F_R(q^2)] t
$$

$$
+ \frac{e}{s_w c_w} Z_\mu \; \bar{t}[\gamma^\mu P_L \cdot (\frac{1}{2} - \frac{2}{3} s_w^2) F_L(q^2) + \gamma^\mu P_R \cdot (-\frac{2}{3} s_w^2) F_R(q^2)] t
$$


Uncertainty
1
10^{-1}
10^{-2}
10^{-3}
ILC (preliminary)
LHC (hep-ph/0601112)
$\tilde{F}^{\gamma}_{1V}$
$\tilde{F}^{Z}_{1V}$
$\tilde{F}^{Z}_{1A}$
$\tilde{F}^{\gamma}_{2V}$
$\tilde{F}^{Z}_{2V}$

ILC TDR

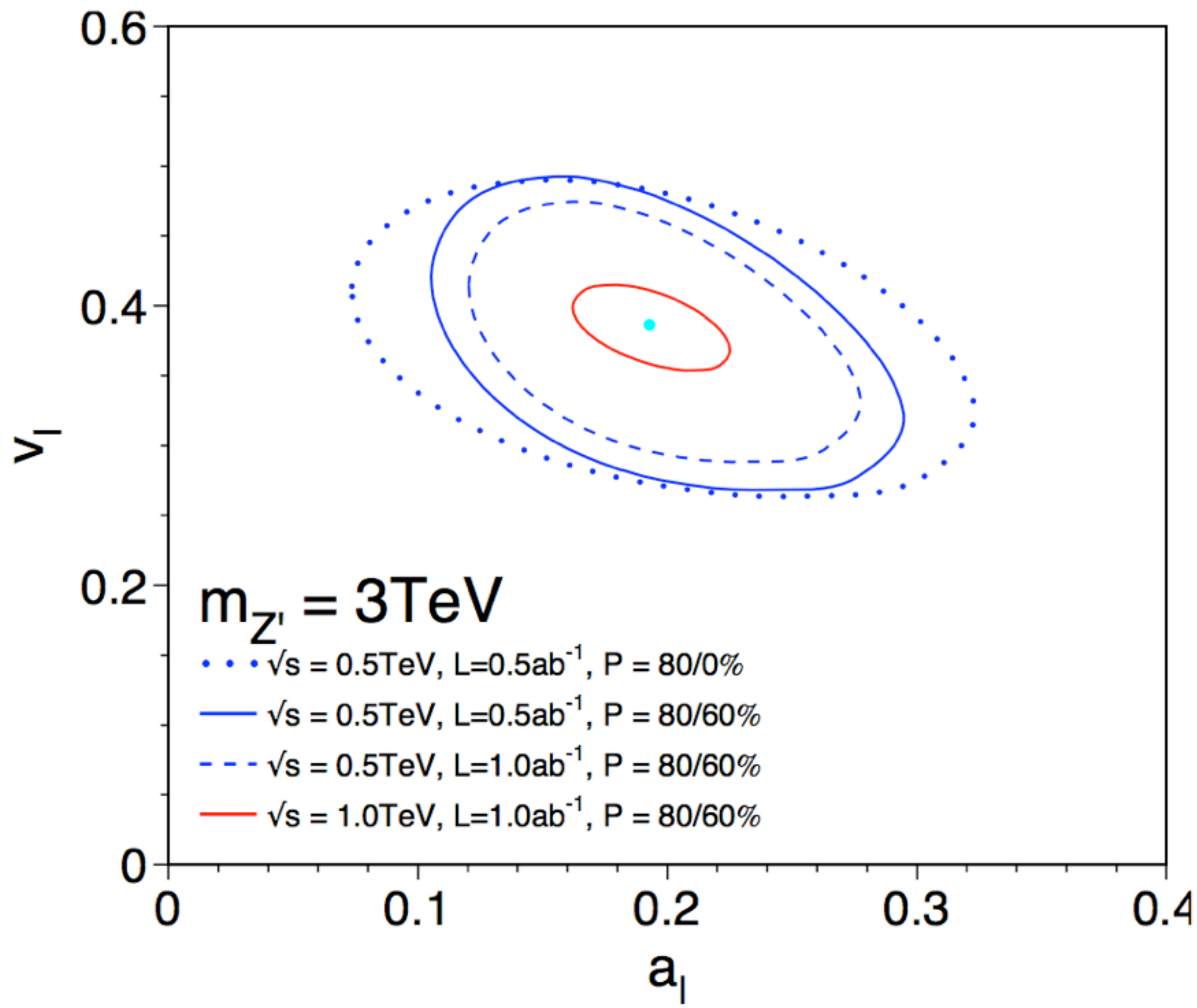
Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^{Z} (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	–	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	–	–
photon, F_{2V}^{γ}	0.037	0.025	0.003
photon, F_{2A}^{γ}	0.017	0.011	0.007
Z boson, F_{2V}^{Z}	0.25	0.17	0.006
Z boson, ReF_{2A}^{Z}	0.35	0.25	0.008
Z boson, ImF_{2A}^{Z}	0.035	0.025	0.015

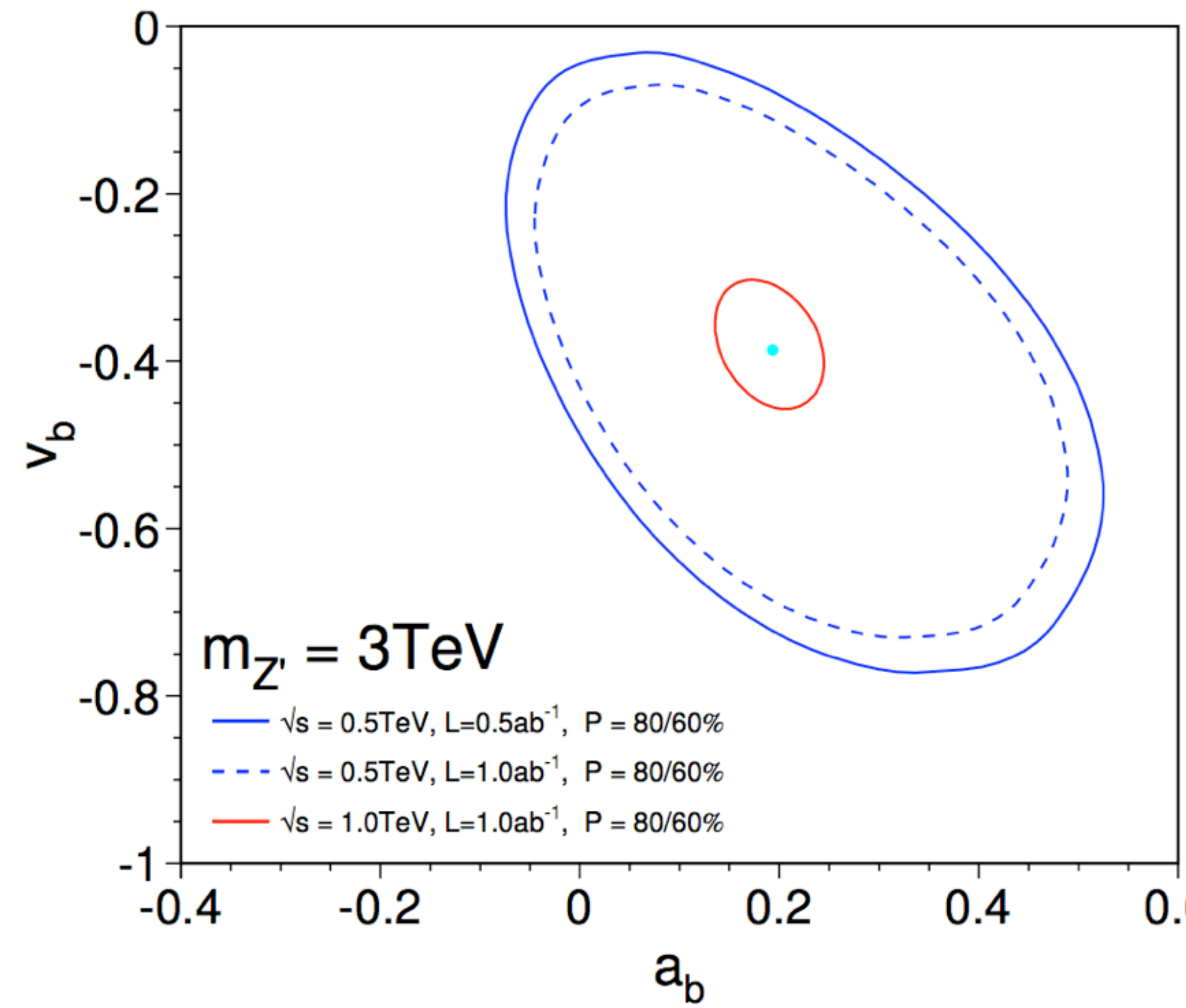
Snowmass Top report

New particle searches

Linear colliders have excellent capabilities to search for new particles. These can be sought directly in pair-production and indirectly, as contributions of s-channel resonances to Standard Model processes measured with high precision. The measurement of top quark couplings already gave an example of an indirect search for Higgs resonances coupling to top.

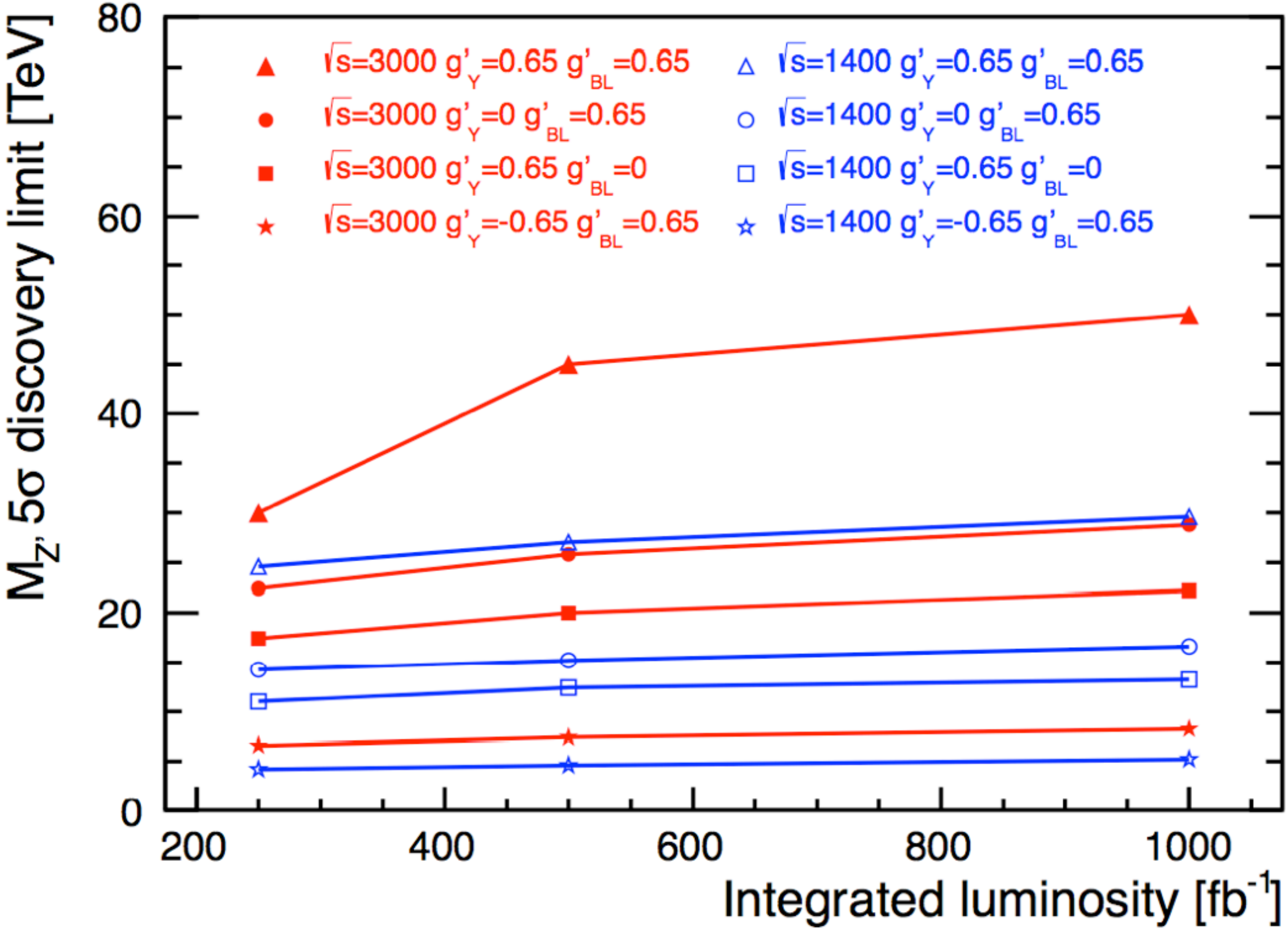
measurement of the properties of a 3 TeV Z'





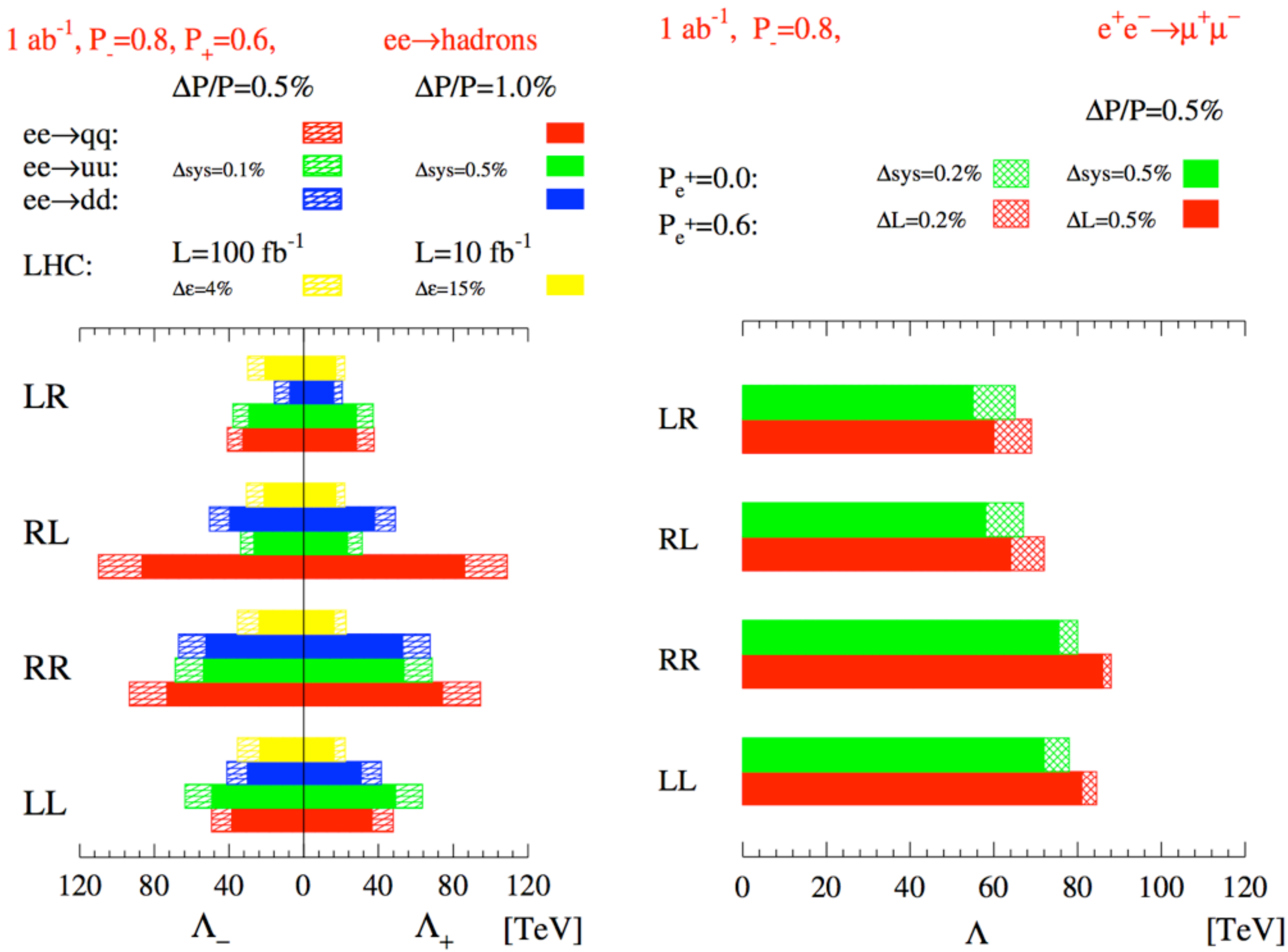
All polarized 2-fermion reactions $e^+_L e^-_R, e^+_R e^-_L \to f\overline{f}$ can contribute to this study.

S. Riemann ILC TDR



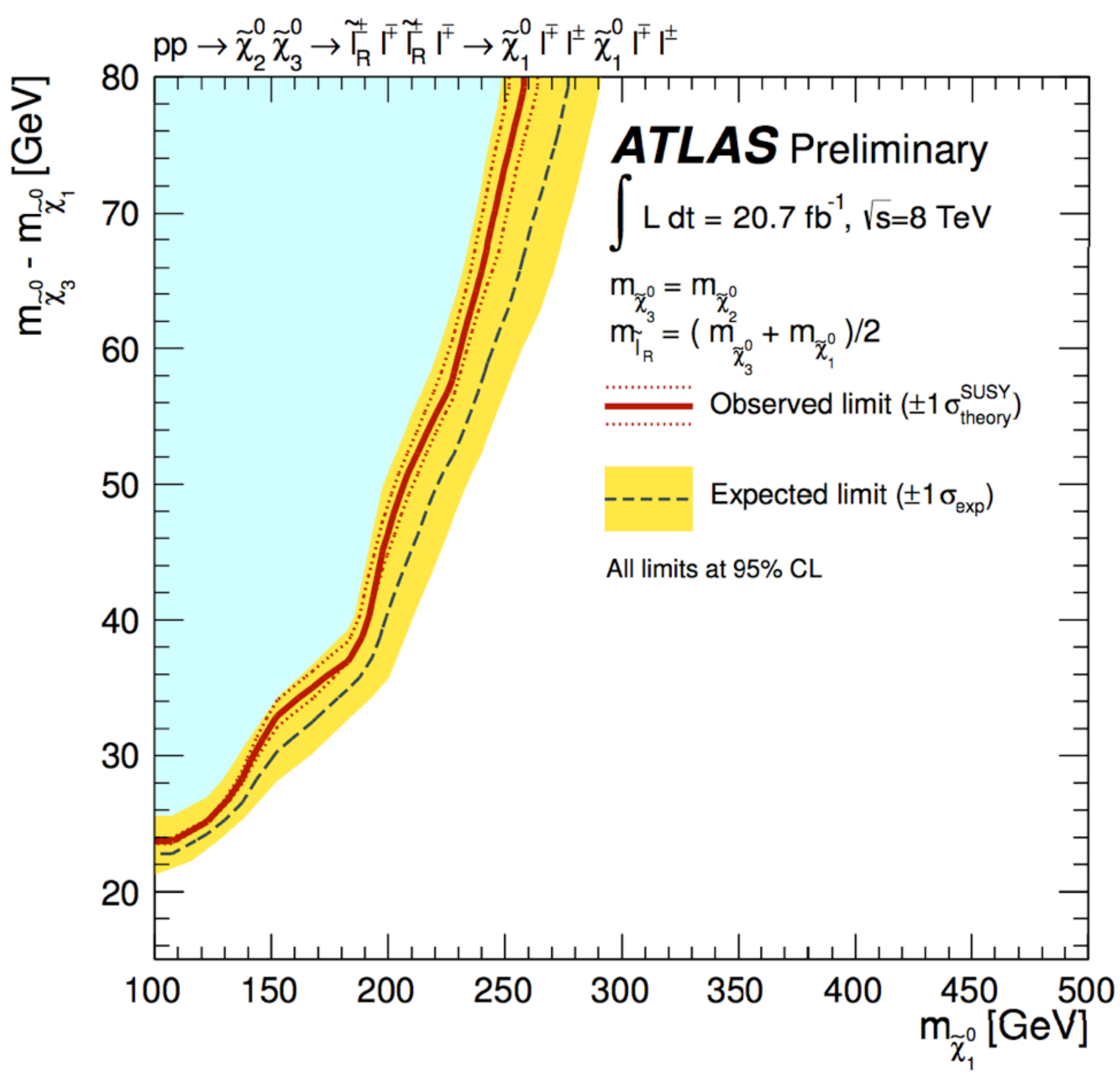
CLIC Snowmass White Paper

searches for lepton compositeness



ILC TDR

One often hears that new particle exclusions from the LHC imply that the ILC cannot discover new particles in direct pair production. That is not correct, especially for particles with only electroweak interactions. In those cases, the LHC is sensitive only when the energy release in particle decay is large.



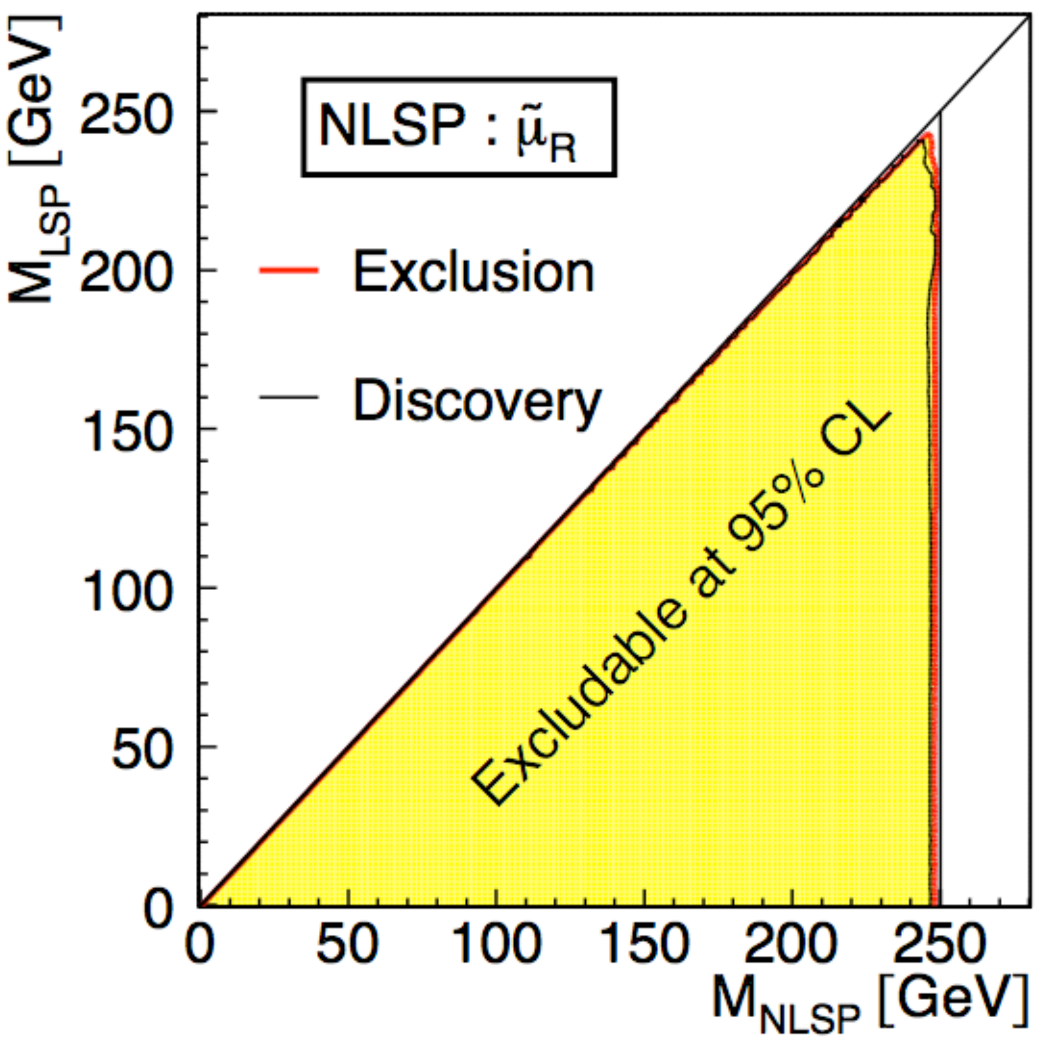
If there are no particle discoveries at the LHC at 14 TeV, it will be compelling to go to lower energies to find particles that the LHC might have left behind. There are well-motivated models:

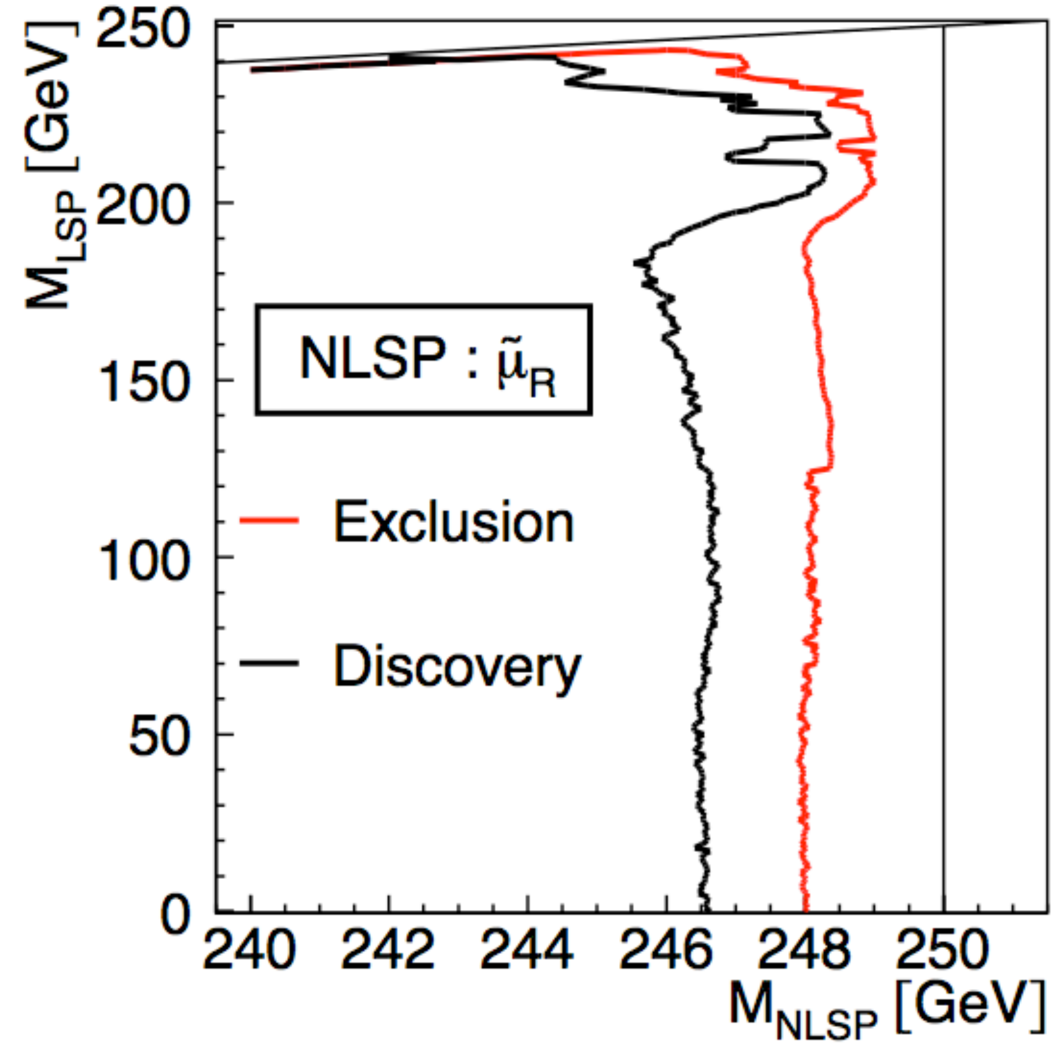
Higgsino sector in “natural supersymmetry”

stau or other particles in dark matter coannihilation scenarios

If the LHC at 14 TeV discovers new heavy particles -- especially colored particles that decay to lighter states -- this would add further motivation to the case for the ILC.

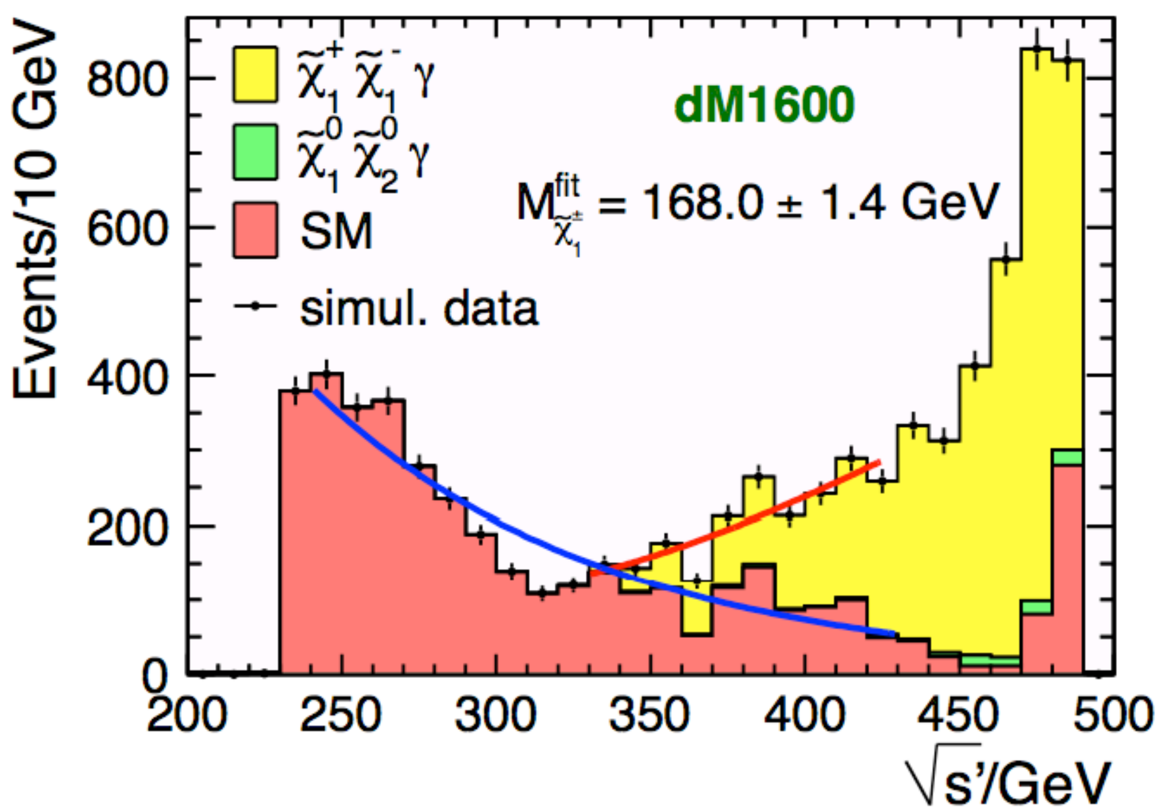
discovery up to $\sqrt{s}/2$ means ...

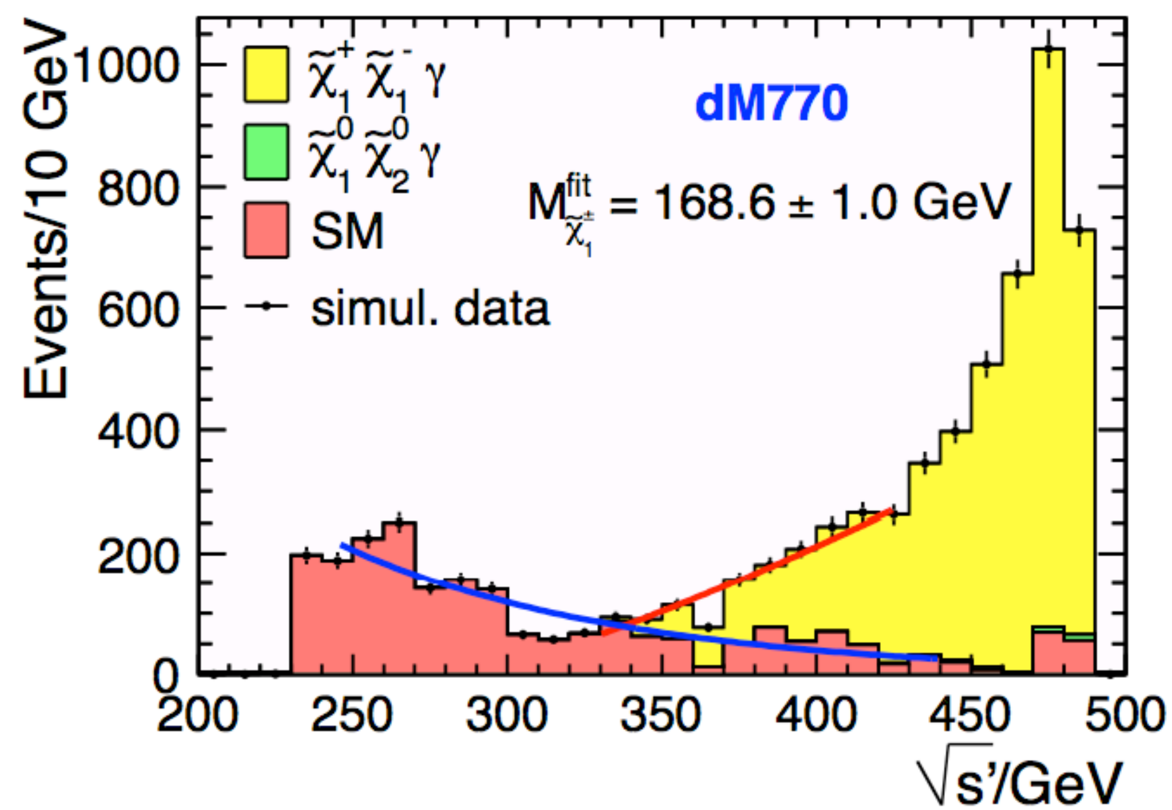




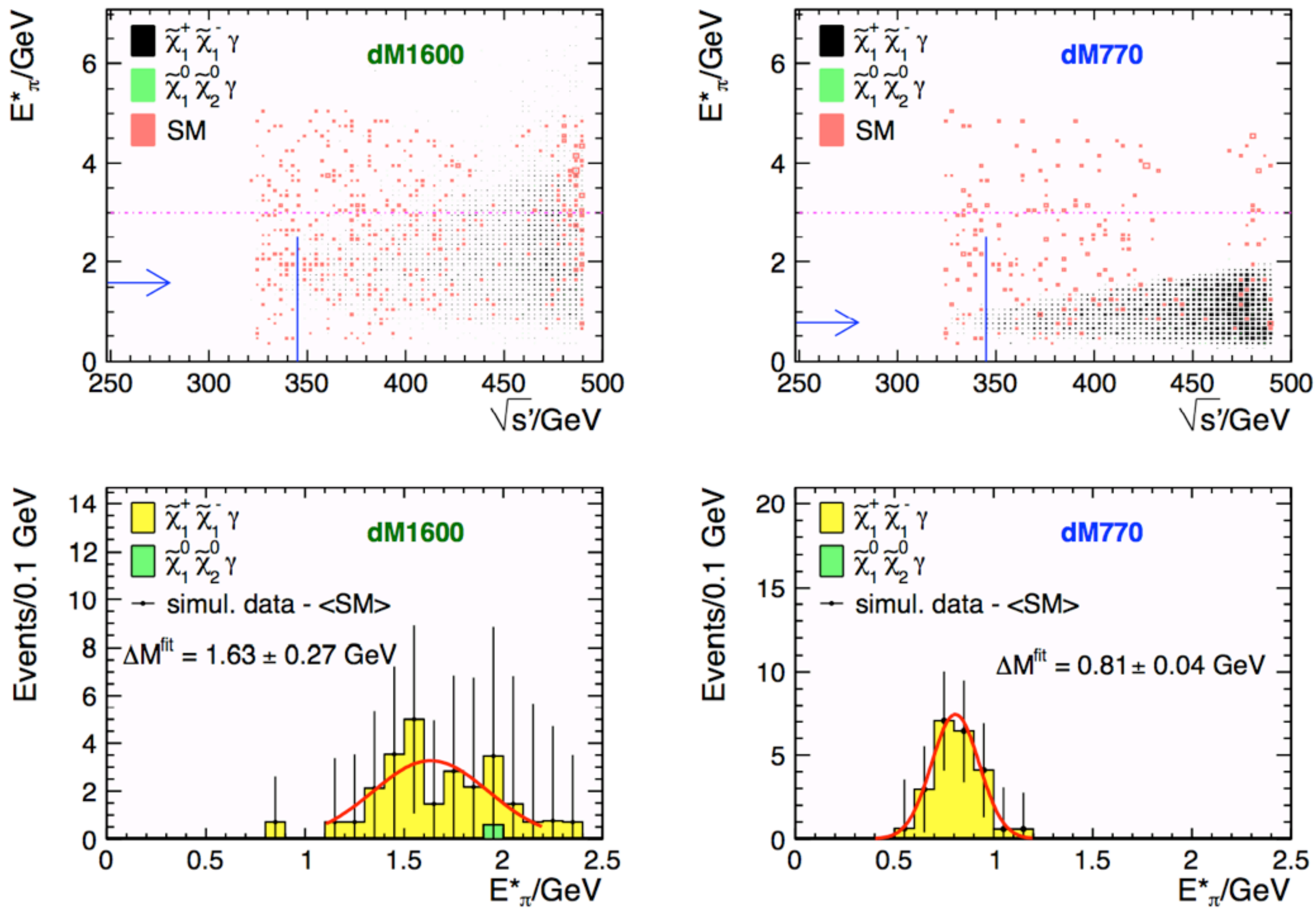
ILC BSM White Paper

study of Higgsino pair production tagged by an ISR photon

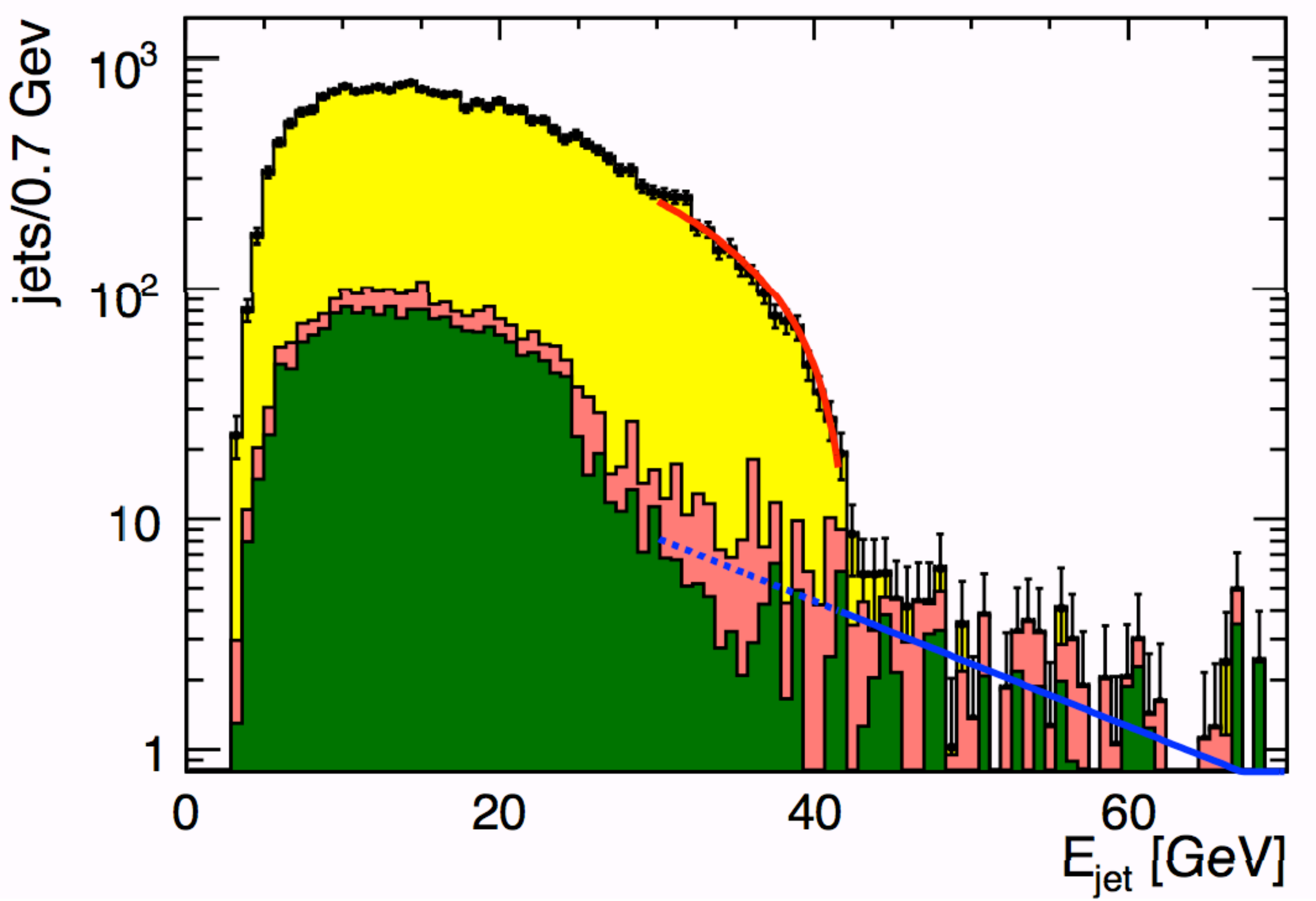




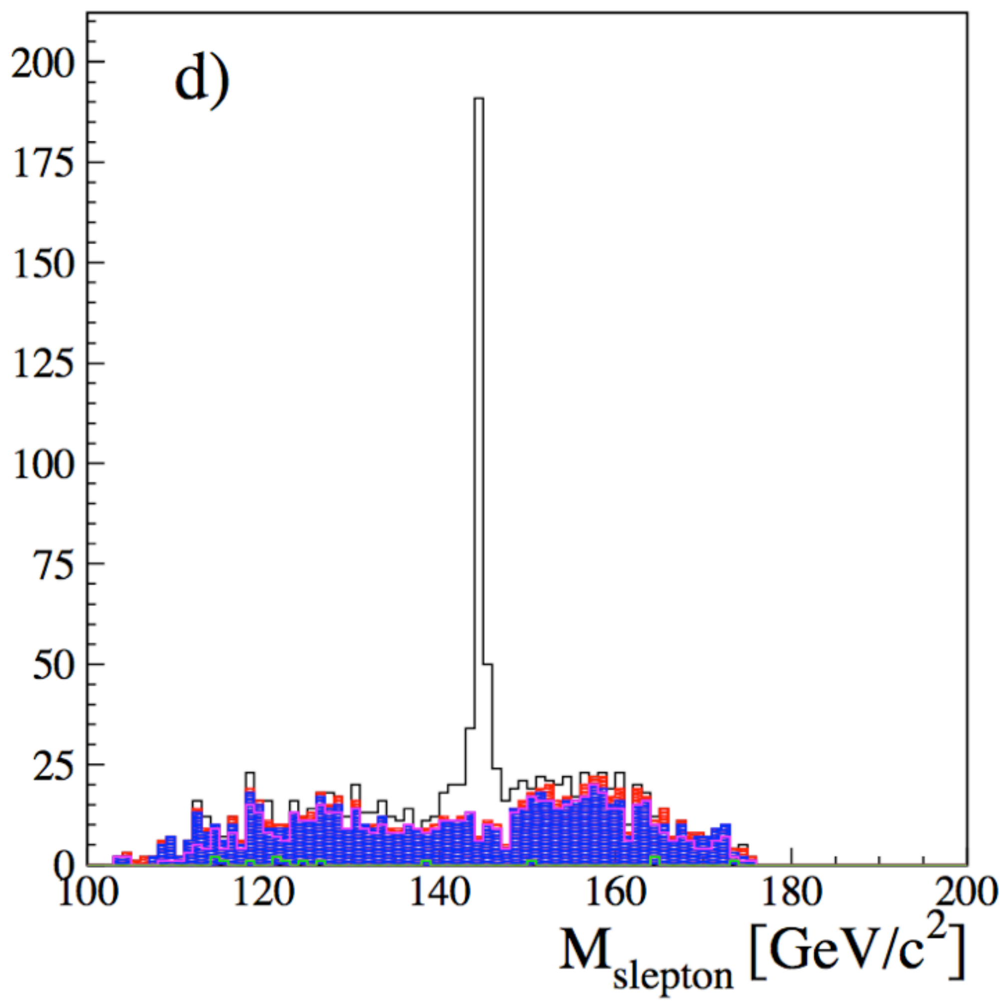
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert

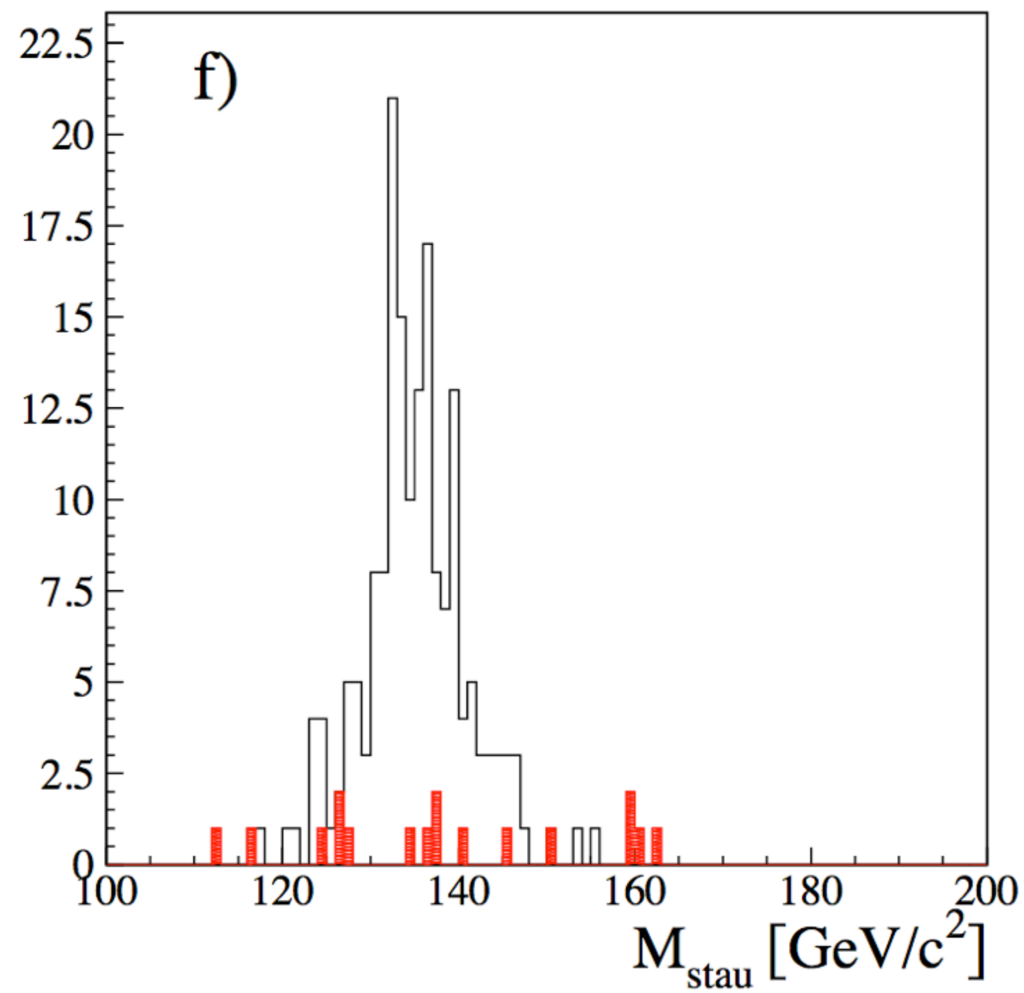


dM1600
dM770
SM
simul. data - <SM>
ΔM^{fit} = 1.63 ± 0.27 GeV
ΔM^{fit} = 0.81 ± 0.04 GeV
E^*_π/GeV
$\sqrt{s'}$/GeV
Events/0.1 GeV



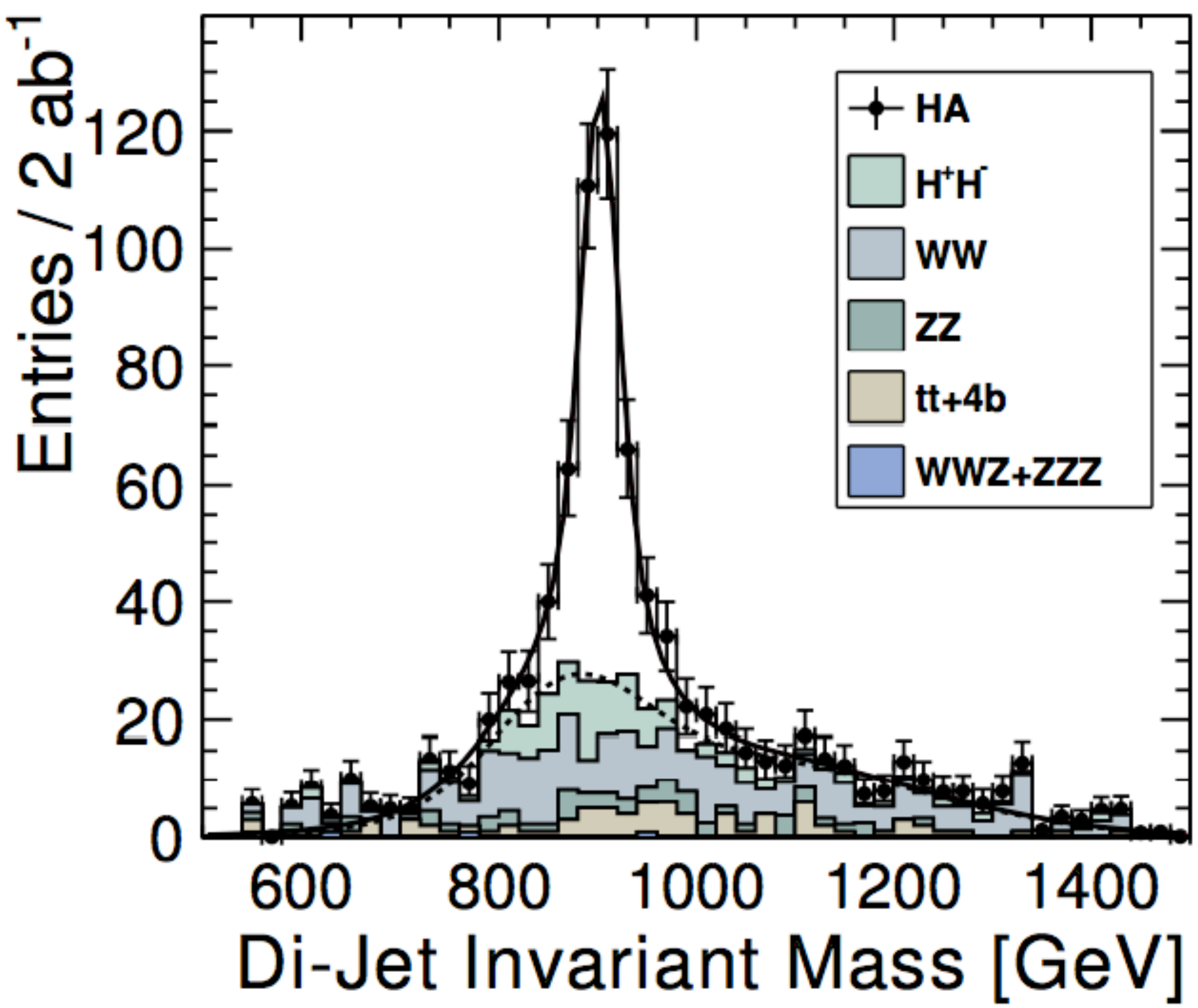
stau mass measurement from kinematic endpoint slepton mass reconstruction in the ILC environment

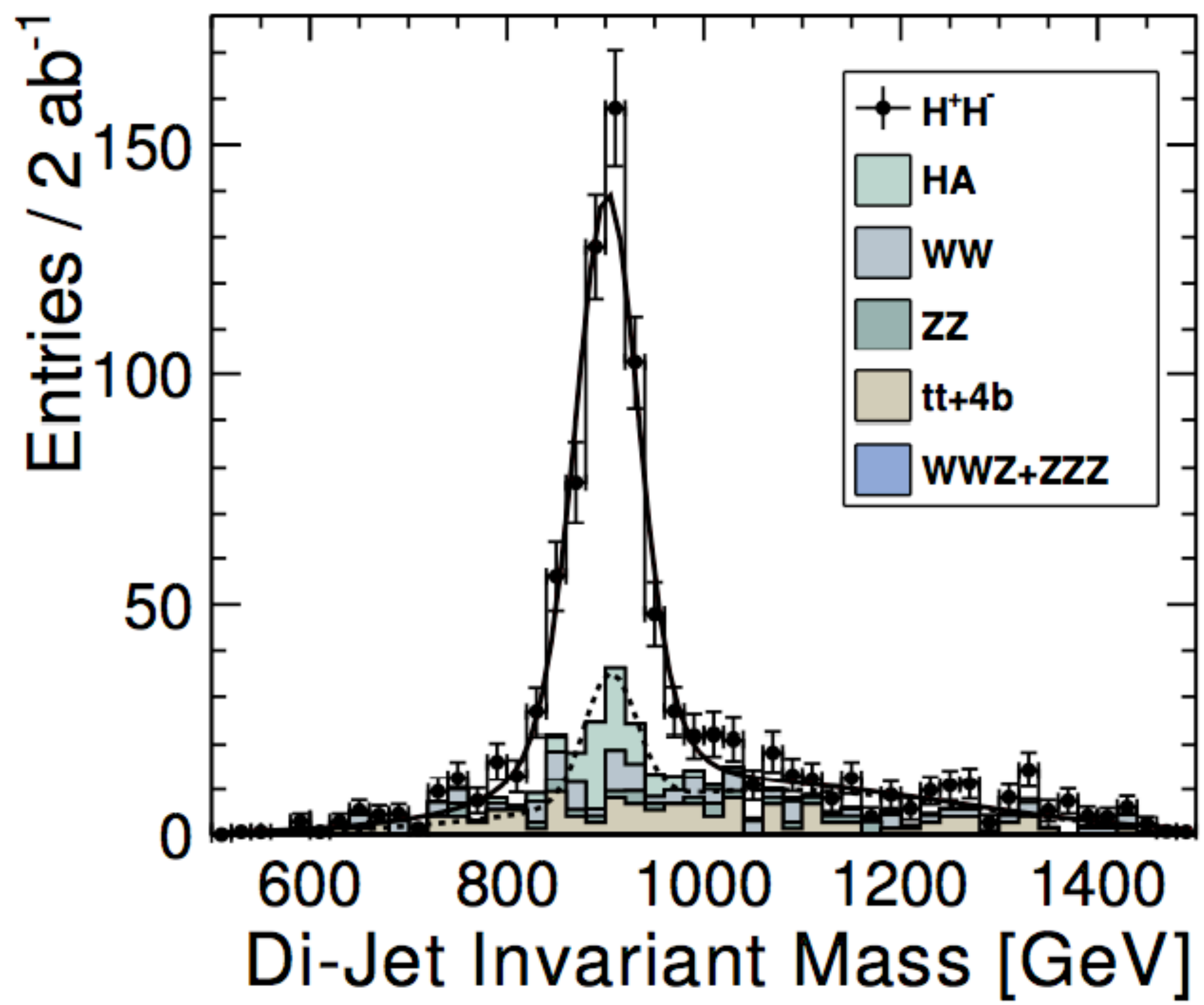




Berggren, Cakir, Kruecher, List,
Lobanov, Melzer-Pellmann

measurement of extended Higgs boson masses at CLIC

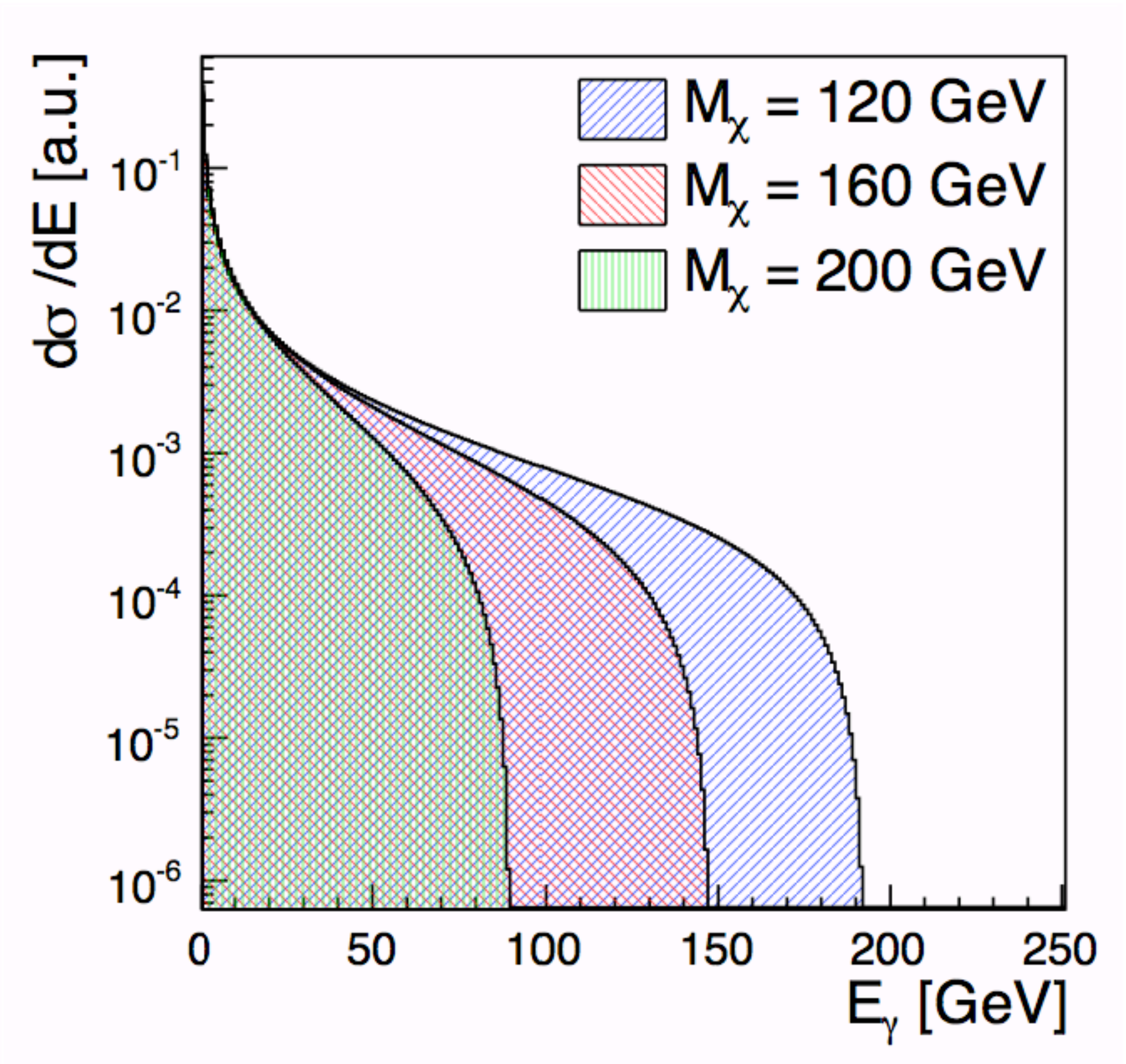


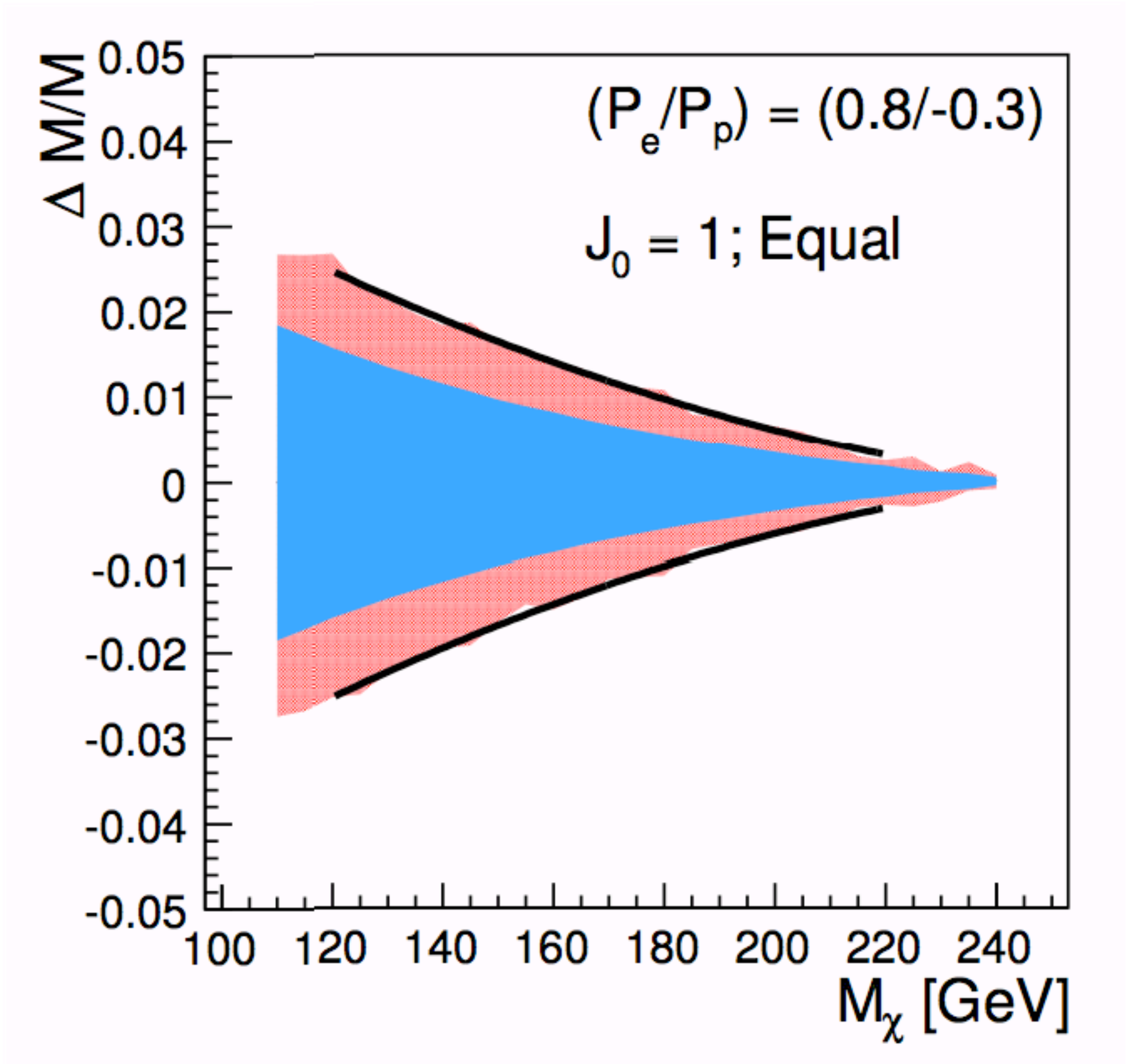


CLIC would probe for extended Higgs bosons, electroweakinos, to 1.5 TeV.

CLIC Snowmass White Paper

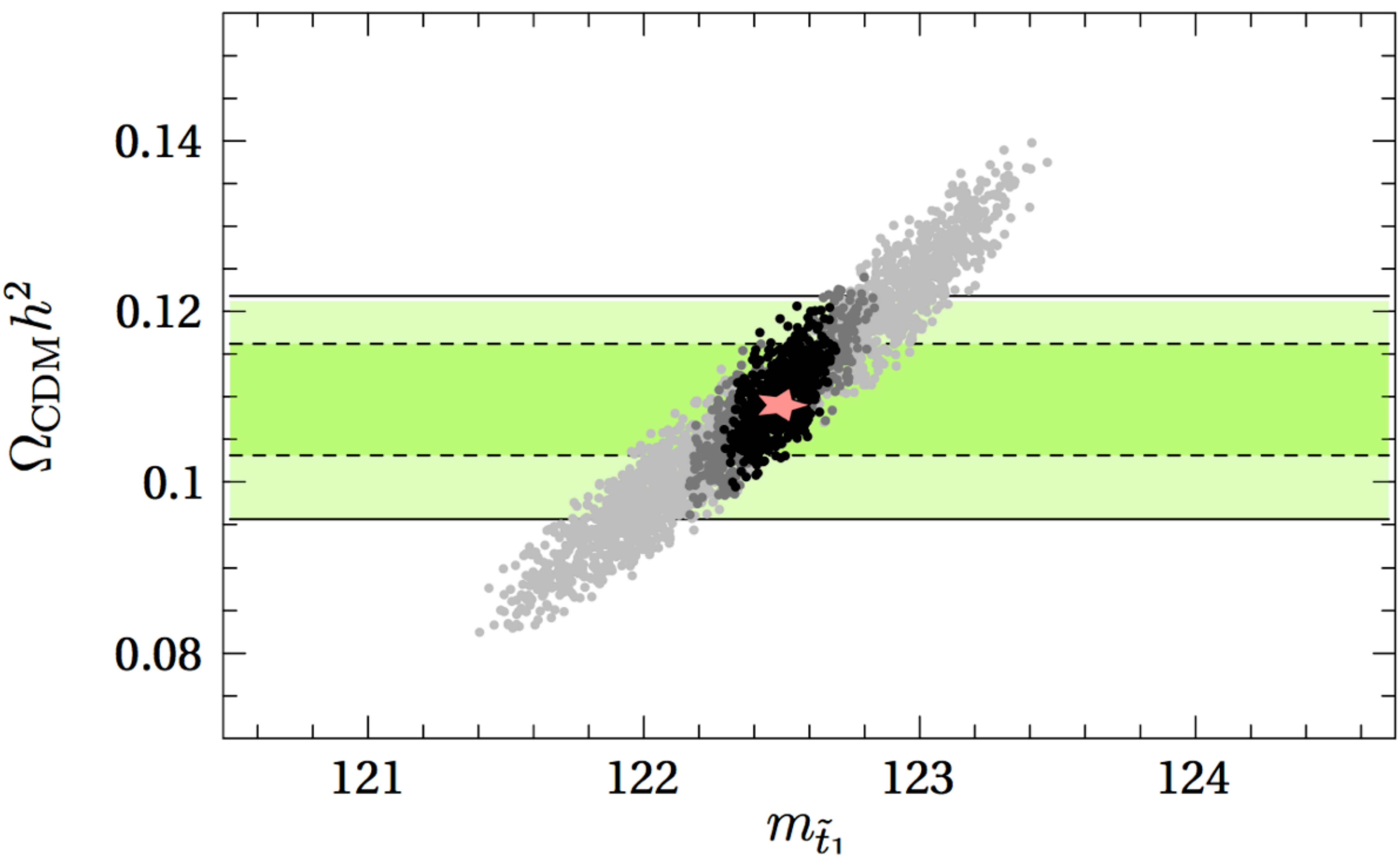
mass measurement of a dark matter particle from the photon recoil in $e^+e^- \to \chi\chi\gamma$





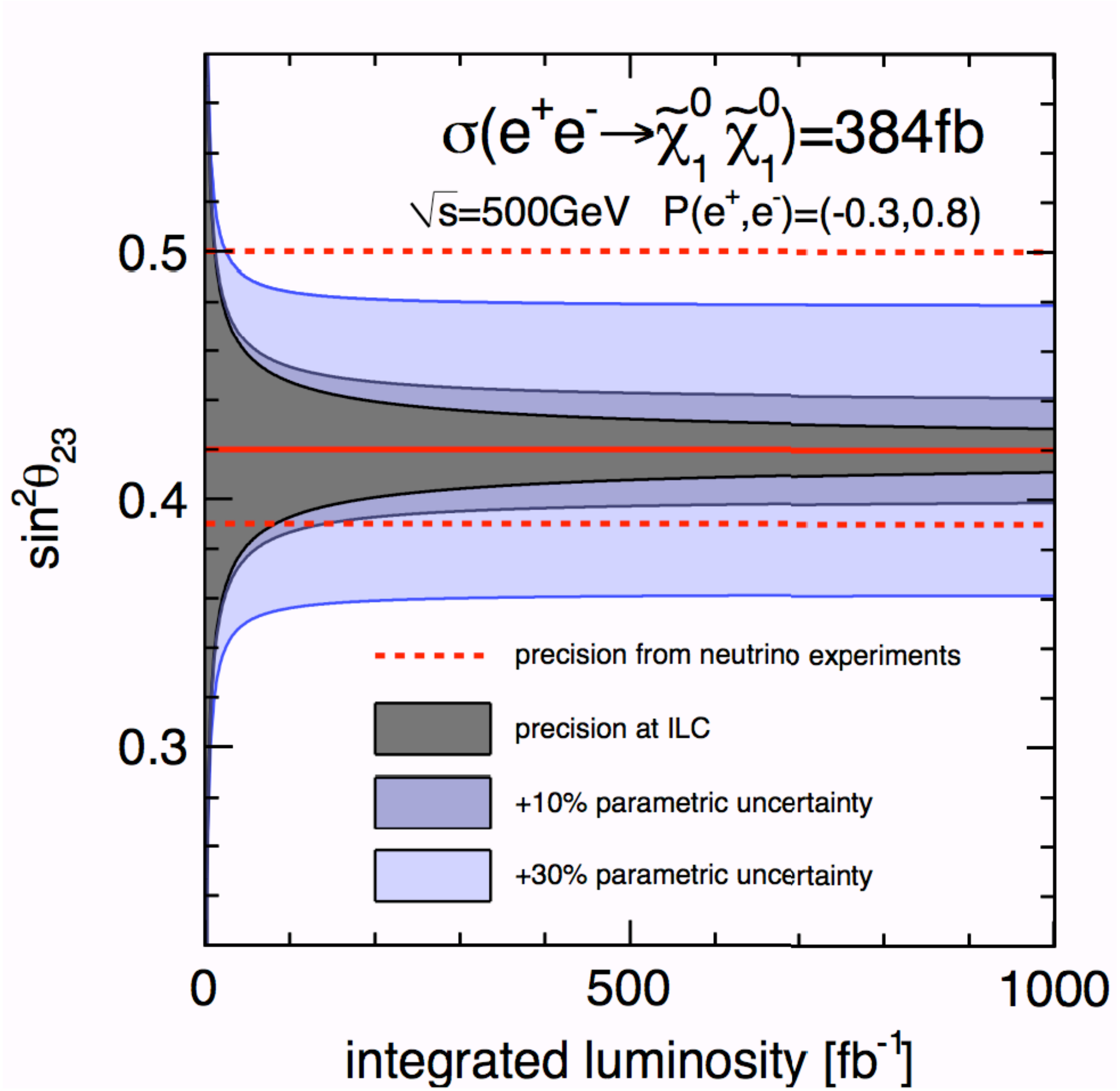
Bartels, Berggren, List

stop coannihilation model, with dark matter density predicted and compared to CMB measurements



ILC TDR

type III neutrino see-saw: stau decay rates measured and compared to a PMNS mixing angle



Vormwald and List

Conclusions:

The case for lepton collider experiments beyond the LHC is manifest.   LHC has an excellent window for discovery, but the goals of precision measurement lie beyond the LHC capabilities. ILC, on the table now, can achieve these goals.

Negative results from the LHC at 14 TeV will require that we probe the Higgs boson and the top quark with ILC precision.

Positive results from the LHC at 14 TeV -- and, in particular, the discovery of new particles at 14 TeV -- will make the case for ILC even stronger.

It is time to begin the Linear Collider Physics program !