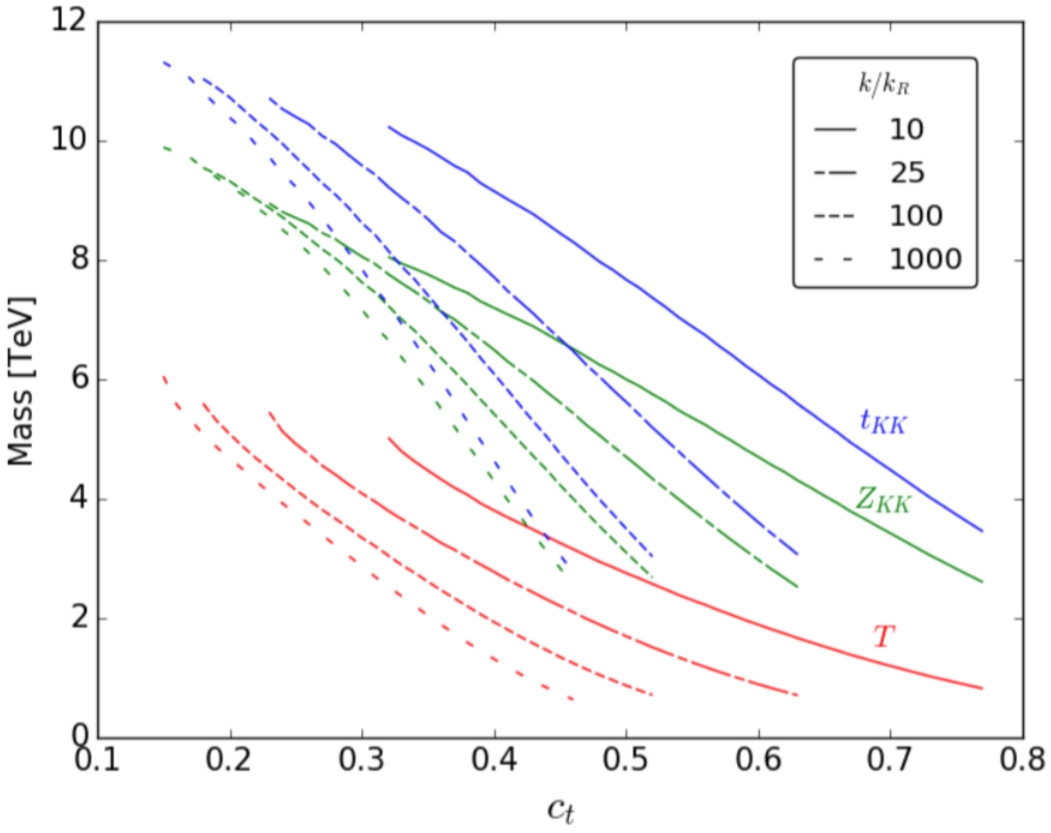
Physics Case for Advanced Linear Accelerators



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The purpose of this talk is to motivate novel, high-gradient linear acceleration technologies.

These might have application to pursue the current goals of high-energy physics or new goals appropriate to higher energies.

In this talk, I will briefly discuss the first topic (familiar physics), and then introduce the second topic (novel physics).

We hope to construct ILC at 250 GeV or CLIC at 380 GeV.

If these machines are built, we also hope to upgrade them to higher energy.

Why is this important ?

Precision study of Higgs:

The Higgs boson is at the center of the remaining mysteries of particle physics. We do not understand

why the Higgs boson condenses and acquires a nonzero vacuum expectation value

what explains the values of the quark and lepton masses

what explains flavor mixing and CP violation

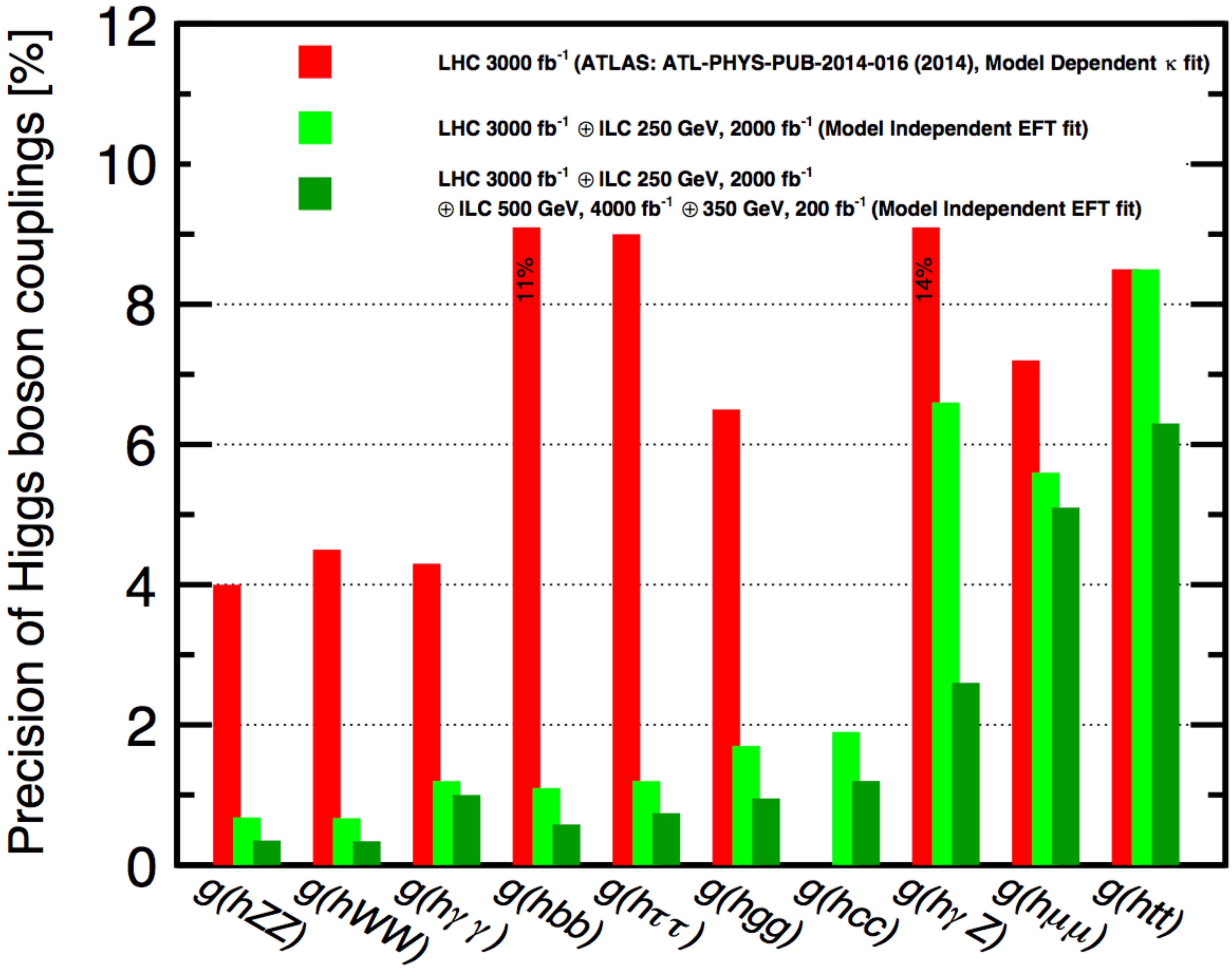
what additional sources of CP violation exist to explain the matter-antimatter asymmetry

All of these issues involve the physics of the Higgs field.

New particles and forces affect the properties of the known Higgs boson, but at the 10% level or below.

The Higgs can be a window to the discovery of new fundamental interactions — but only if we can do experiments of sufficient precision.

The current agreement of the Higgs boson properties with the Standard Model is completely to be expected. We are not yet exploiting this method of searching for new physics. But we may need to, if other methods cannot break through.

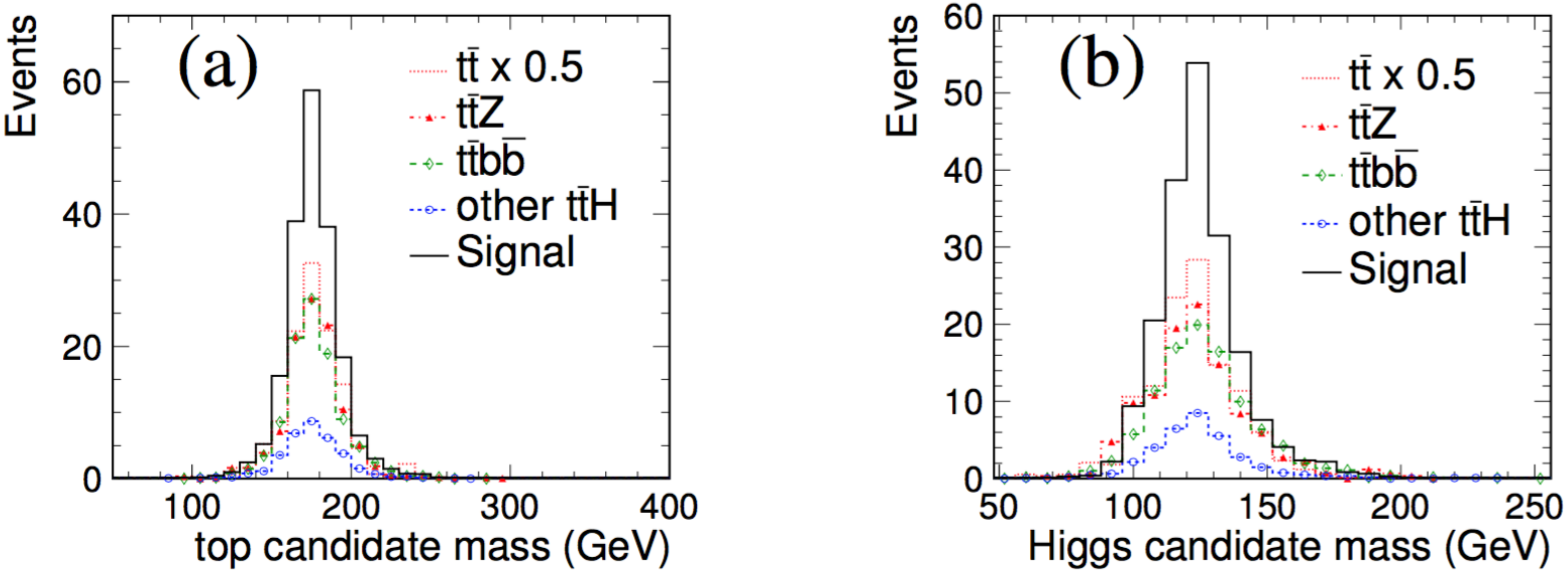


LCC Physics Working Group arXiv:1710.07621

Couplngs of the Higgs boson to heavy species:

Two of the most important parameters of the Higgs boson are the Higgs coupling to the top quark and the Higgs self-coupling.

These can only be addressed in e+e- at CM energies of 500 GeV and above.



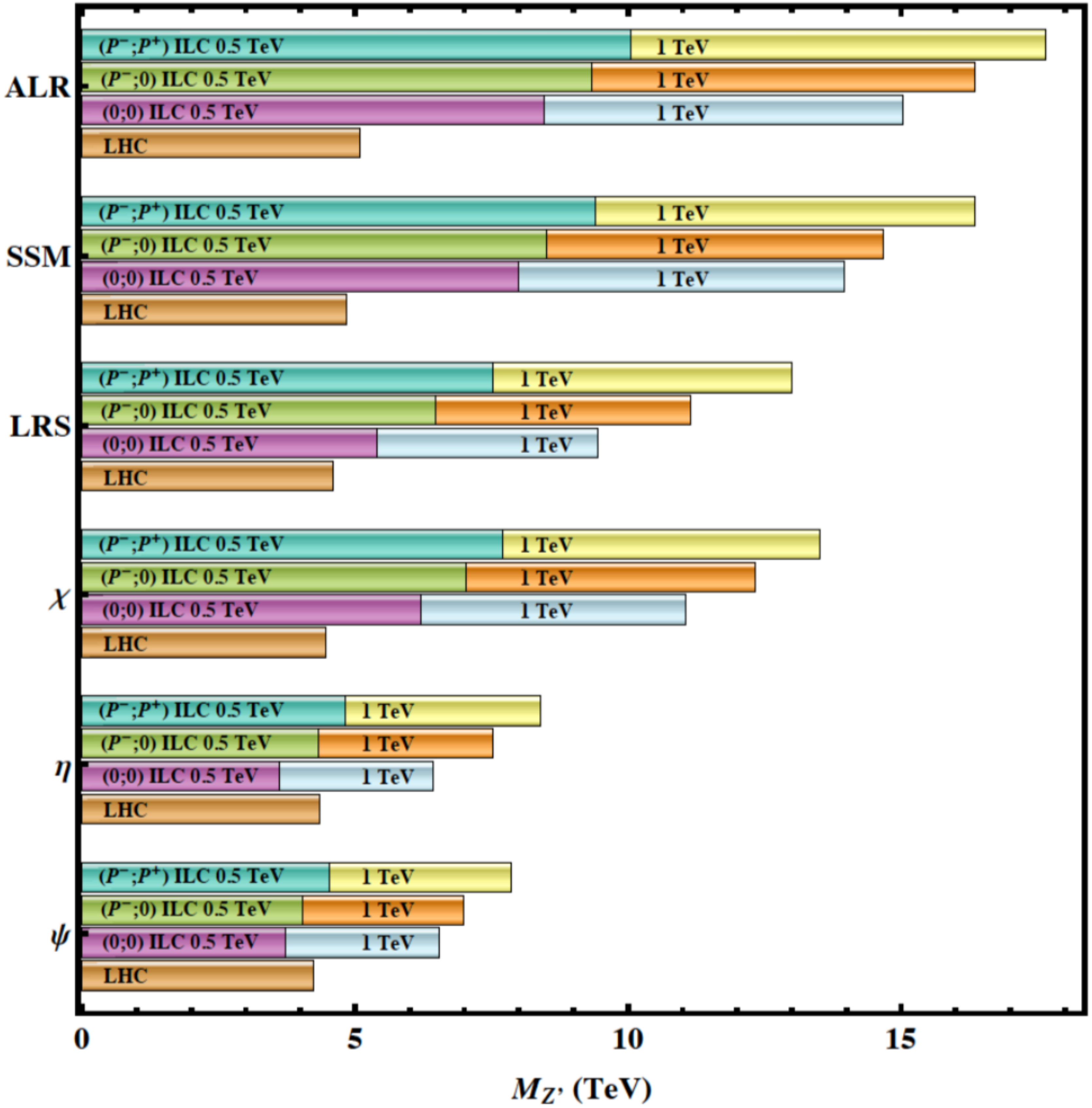
Price, Roloff, Strube, Tanabe, arXiv:1409.7157

Precision estimates from ILD full simulation:

	500 GeV, 4 ab^{-1}	1000 GeV, 5 ab^{-1}
g(htt)	6%	2%
g(hhh)	27%	10%

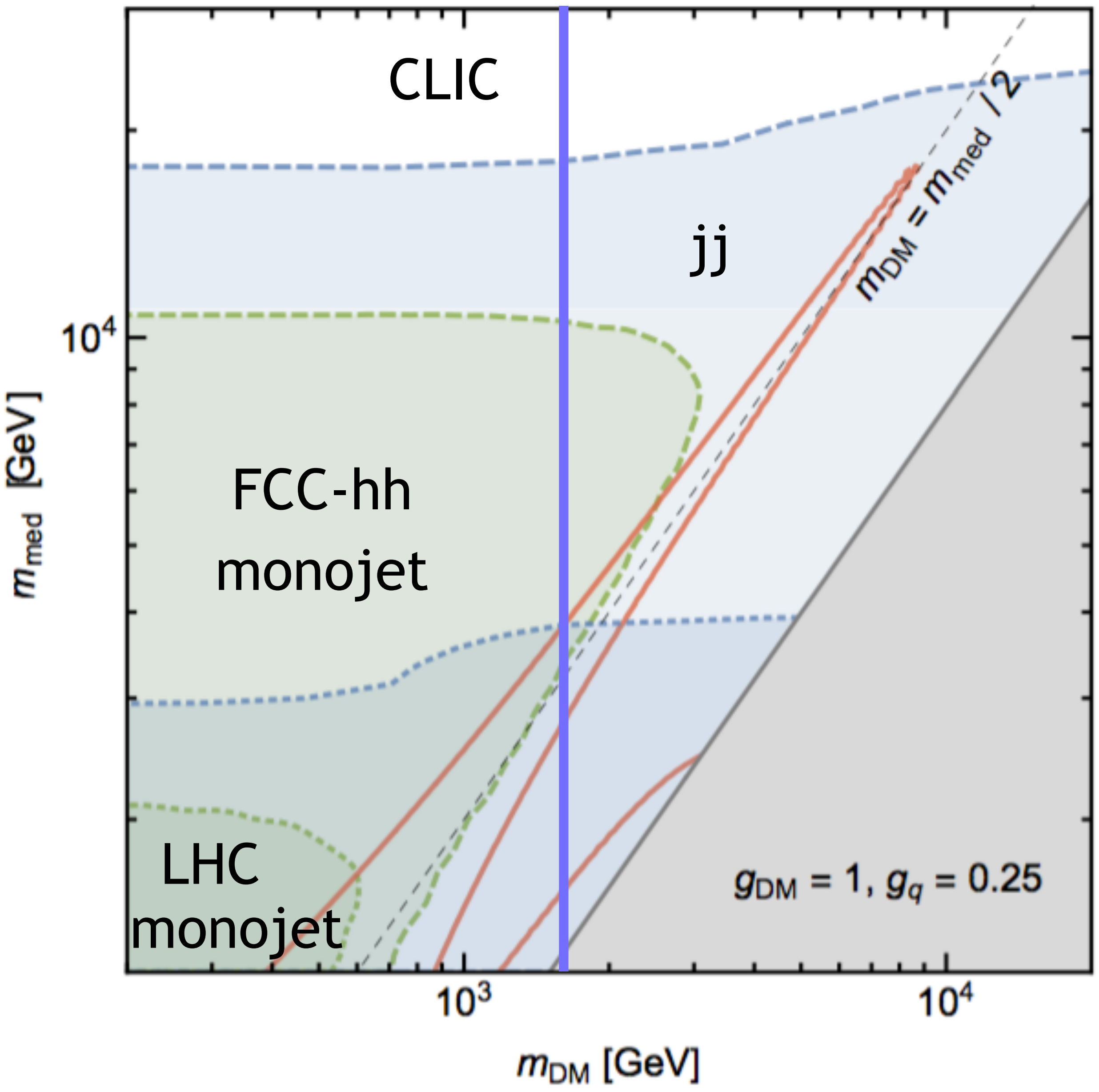
Search for new, heavy electroweak bosons:

This search uses precision measurements of $e^+e^- \to f\overline{f}$ making use of e-/ e+ beam polarization.



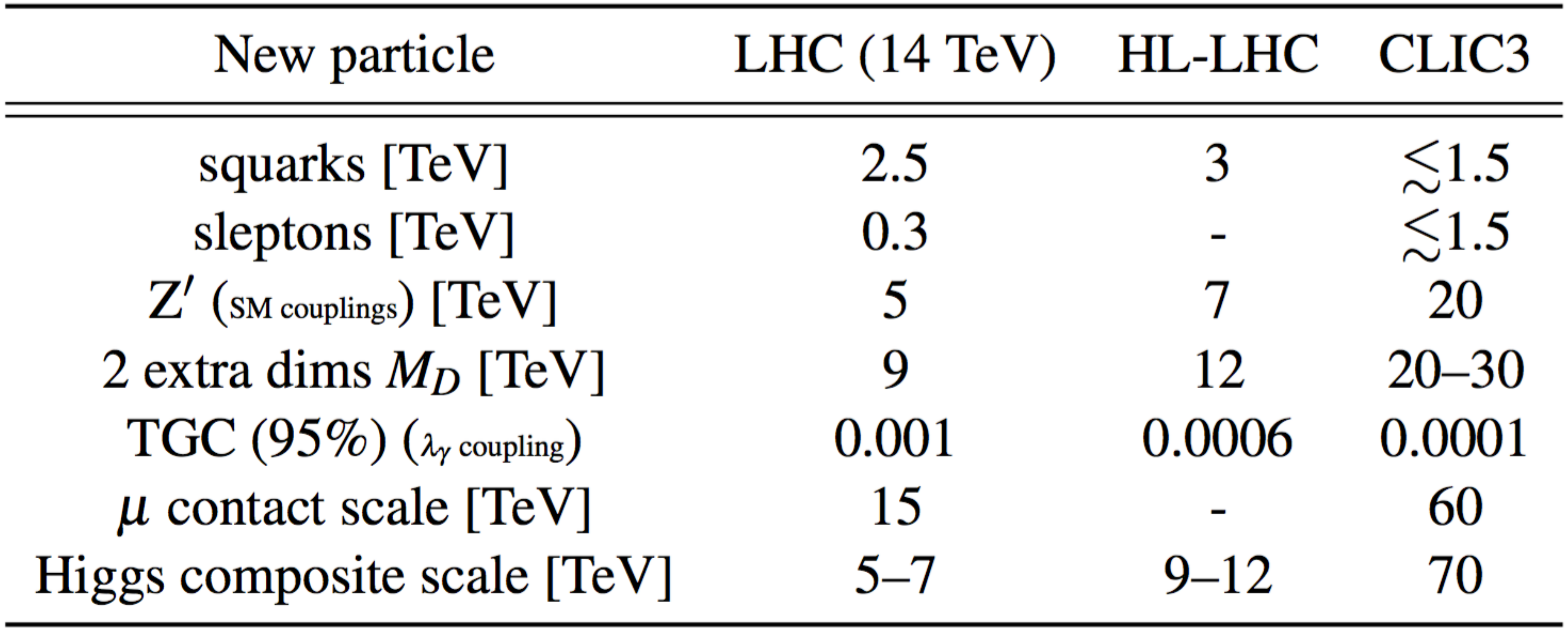
Search for invisible particles, dark matter:

from the Physics at 100 TeV CERN Yellow Report:



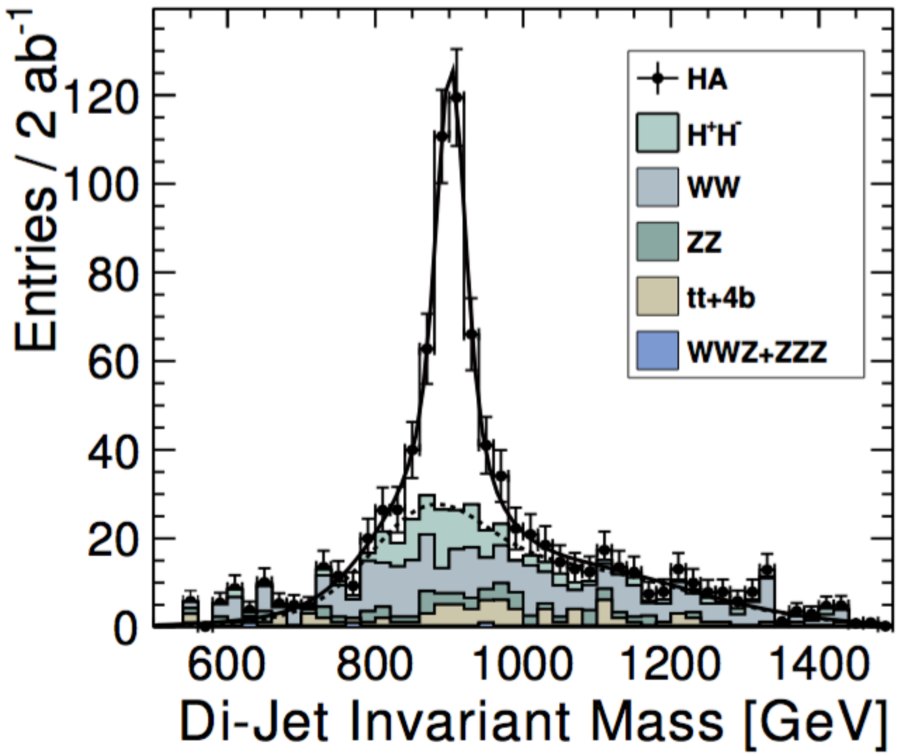
Search for new particles:

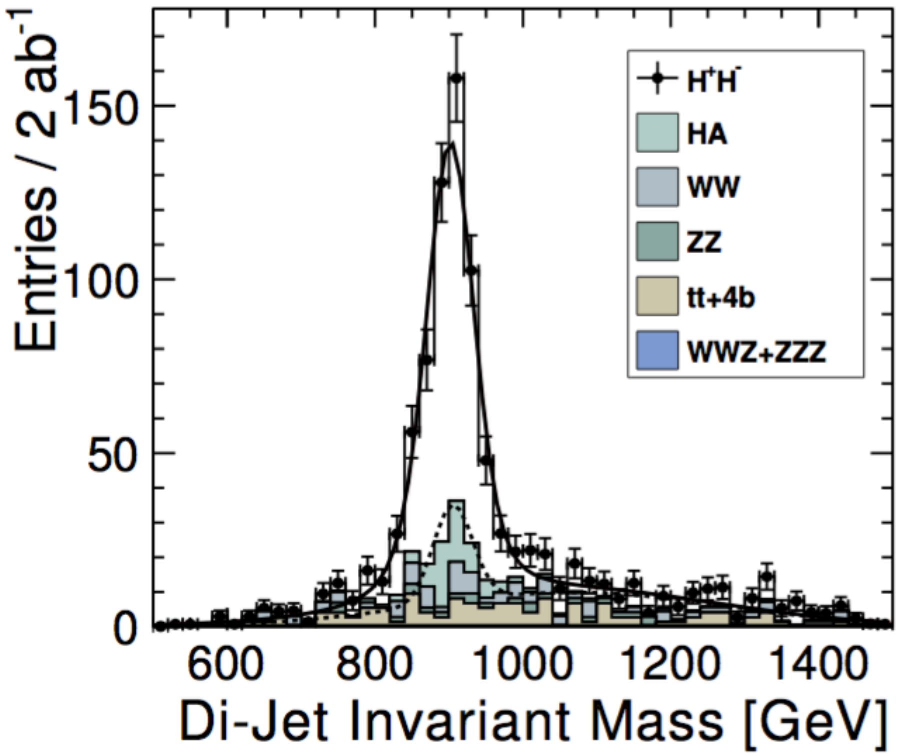
Summary table from the CLIC study report to Snowmass 2013:



New particle	LHC (14 TeV)	HL-LHC	CLIC3
squarks [TeV]	2.5	3	$\lesssim$1.5
sleptons [TeV]	0.3	-	$\lesssim$1.5
Z' (SM couplings) [TeV]	5	7	20
2 extra dims M_D [TeV]	9	12	20–30
TGC (95%) (λ_γ coupling)	0.001	0.0006	0.0001
μ contact scale [TeV]	15	-	60
Higgs composite scale [TeV]	5–7	9–12	70

900 GeV
SUSY Higgs
at 3 TeV CLIC,
2 ab-1





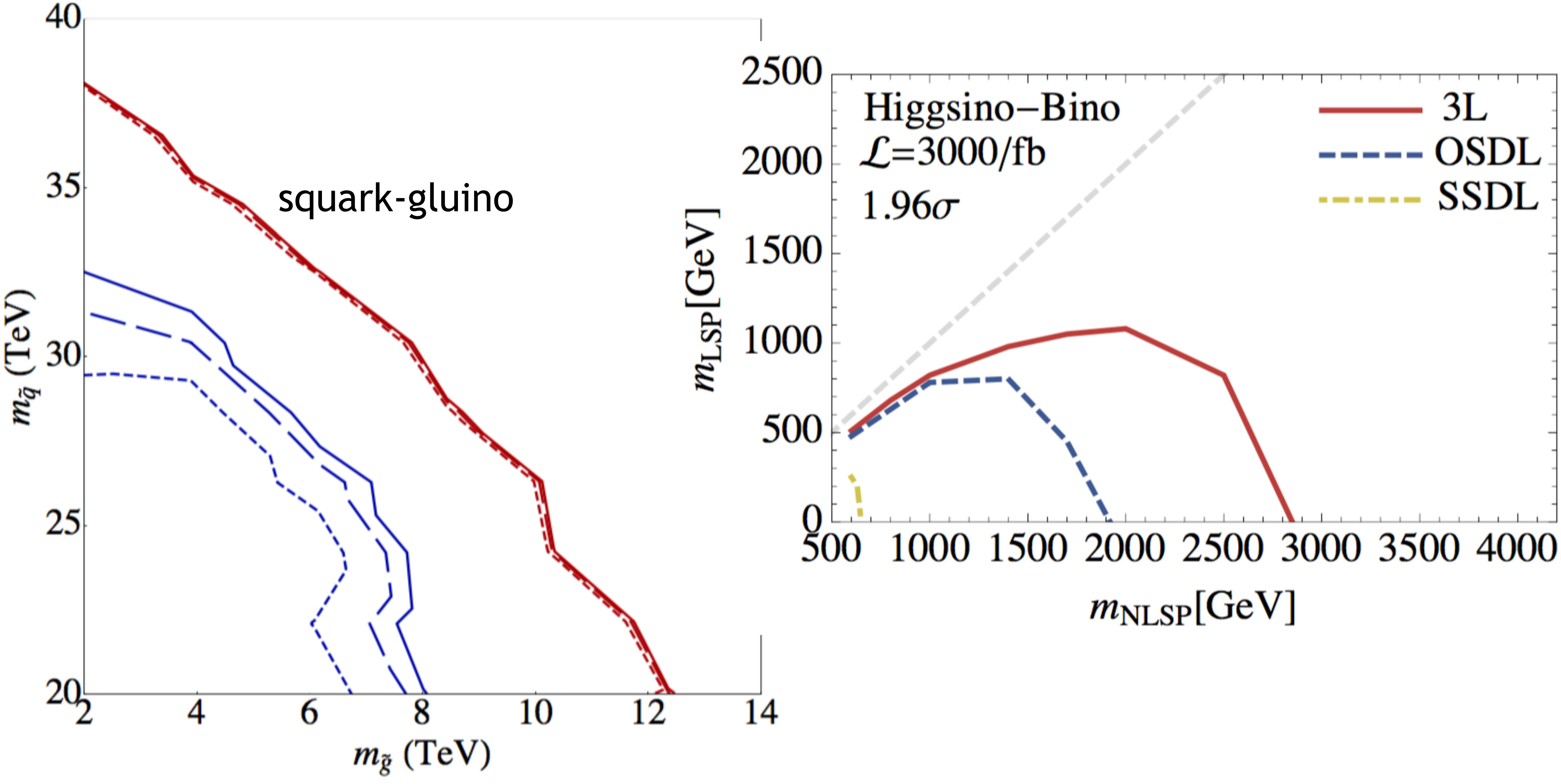
It is not surprising that high-energy extensions of e+e- collisions are highly motivated.

All studies that I have described so far are precision measurements.   Whatever the advanced accelerator technology is, one must take care not to spoil the clean environment in which these measurements are done.

We are concentrating on high precision for the following reason:

All of these accelerator proposals lie in the shadows of hadron colliders with much higher energy reach.

Here are some representative plots of SUSY discovery and exclusion limits from the FCC-hh 100 TeV collider study:



However, these approach the ultimate limits of circular hadron collider technology.

When we think about advanced linear accelerators, we could be thinking about even more ambitious discovery goals:

Imagine a 5 GeV/m effective gradient after staging.

This is SLAC in 10 m

— but a collider still requires a multi-km beam delivery region and final focus, 100 m detectors

So, better to imagine 10 km of accelerating structure.

This is a 50 TeV e+e- or γγ collider .

I believe that the ALEGRO white paper must include a vision that directly competes with — and even leaps over — the direct particle search reach of hadron colliders.

I will discuss the philosophy of this statement and its implications in some detail later in the talk.

But, first, let's discuss the basic challenges of e+e- experimentation at very high energy.

The most crucial challenge is that the scaling

$$\sigma(e^+e^- \to F\overline{F}) \sim 1/(E_{CM})^2$$

cannot be avoided.

High energy needs extremely high luminosity.

Pair production cross sections in e^+e^- and $\gamma\gamma$:

illustrative case of a vectorlike heavy lepton ($I^3 = Y = \frac{1}{2}$)

$$\sigma(e^-_L e^+_R \to L\overline{L}) = \mathbf{R} \cdot (4.0) \cdot (\frac{p}{E}) \cdot (1 + \frac{m^2}{2E^2})$$

$$\sigma(e^-_R e^+_L \to L\overline{L}) = \mathbf{R} \cdot (0.85) \cdot (\frac{p}{E}) \cdot (1 + \frac{m^2}{2E^2})$$

$$\sigma(\gamma\gamma \to L\overline{L}) = \mathbf{R} \cdot (6) \cdot (\frac{p}{E}) \cdot (\frac{(E^2+p^2)^2}{4E^2} \log\frac{E+p}{m} - \frac{1}{2}(1 + \frac{m^2}{E^2})$$

with

$$\mathbf{R} = \frac{100 \text{ fb}}{(E_{\text{CM}} \text{ (TeV)})^2}$$

$$= 10^5 \text{ events/yr}/10^{35}/(E_{\text{CM}} \text{ (TeV)})^2$$

These cross sections are simple, model-independent functions of electroweak quantum numbers.

Luminosity is at a premium when we go above 1 TeV.

Beam polarization is not a luxury. It is an important diagnostic, and it has a qualitative effect on rates.

Photon-photon collisions are naturally present from initial state radiation.   The spectrum of high-energy photons in each e-/e+ beam is

$$\frac{\alpha}{\pi}\log\frac{E_{CM}}{m_e}\ dz\,\frac{1+(1-z)^2}{z} = 0.04\ dz\,\frac{1+(1-z)^2}{z}$$

At energies of 10 TeV and above, initial state radiation of W bosons is also a major effect. For an e-L beam, the spectrum of high-energy W’s is

$$\frac{\alpha_w}{2\pi}\log\frac{E_{CM}}{m_W}\ dz\,\frac{1}{z} = 0.03\ dz\,\frac{1}{z}$$

For linear colliders, $\mathcal{L} \sim \dfrac{P}{\sigma_x \sigma_y}$

For ILC at 500 GeV, this scaling is

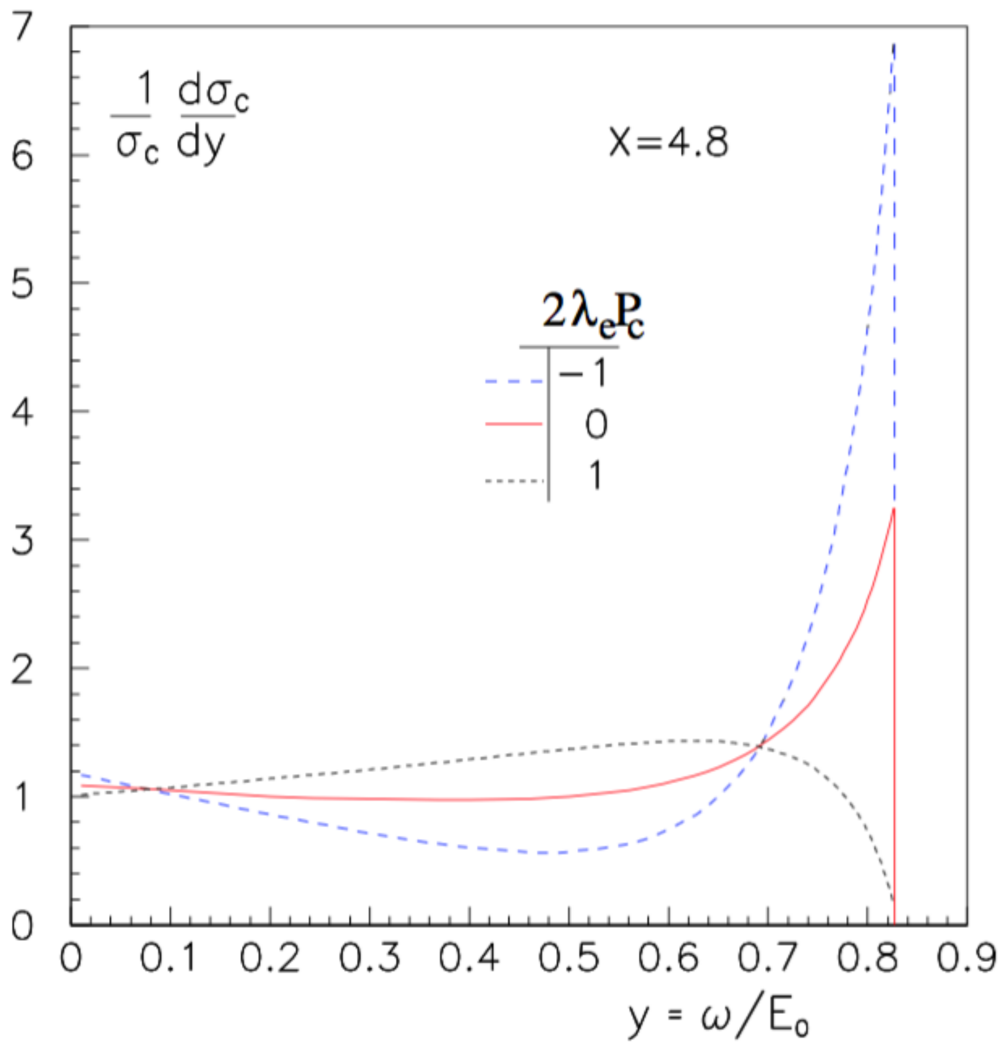
$$2 \times 10^{34} \sim \frac{10 \text{ MW/beam}}{500 \times 6 \text{ nm}^2}$$

Scaling to a 50 TeV collider at 10^{36}

$$10^{36} \sim \frac{10 \text{ MW/beam}}{0.6 \text{ nm}^2}$$

The small beam sizes might be achievable, but the large power/beam will be an issue for high-gradient technologies. Also, we are necessarily in the nonlinear regime for beamstrahlung.

On paper, luminosities comparable to e+e- luminosities are possible. The γ energy spectrum might well be sharper toward the endpoint that that in e+e-.



However, this requires handling very high power both the electron beams and in the laser/maser beams. The preferred γ wavelength is 0.1 mm.

Now I will turn to some philosophy.

What, exactly, do we hope to achieve with higher-energy colliders?

To answer this question, we must understand what lesson we have learned from the LHC.

There are many different opinions on this issue, but here is mine.

from the SLAC Theory Group bet book, 1988:

Lev Okun:
When the SSC runs, supersymmetry will be discovered.

Volodya Gribov:
When the SSC runs, supersymmetry will not be discovered.

Sid Drell:
When the SSC runs, supersymmetry will be forgotten.

Before the LHC ran, the dominant expectation among theorists was that new particles would be discovered there. Here is the logic:

The Higgs boson must exist. The unsolved problem of the Higgs boson is the origin of its spontaneous symmetry breaking, ie., the calculation of the Higgs field potential.

To solve this problem, find a theory whose symmetries require the Higgs potential to be zero. If this symmetry is broken, there are calculable corrections to the potential. Often, these destabilize $\langle h \rangle = 0$.

If the calculation is weak-coupling and has no unexpected cancellations, the new particles should have mass in the 100 GeV region.

Often, the symmetry-breaking terms come from loops with the top quark and its symmetry partners. Thus, the new particles should have QCD interactions and large production cross sections at the LHC.

Supersymmetry — the theoretically most beautiful extension of the Standard Model — has all of these ingredients and also attractive candidates for dark matter.

The simplest SUSY models have a “desert” with no new particles or forces between the TeV scale and the GUT scale.

Nature could still work this way, but the current exclusions of SUSY particles at the LHC are very discouraging. Current limits, in particular,

$$m(\widetilde{g}) > 1.9 - 2.0 \text{ TeV}$$

are 2 x the previously expected upper bounds.

The expected 5σ discovery limit for HL-LHC is 2400 GeV (ATLAS ATL-PHYS-PUB-2014-010).

[If gluinos were discovered at the LHC in its later stages, the ideal next accelerator would be one that could make precision measurements of the electroweakinos. CLIC at 3 TeV would fill the bill.]

If not SUSY, what then? The problem of explaining the Higgs potential has not gone away.

Another route to solving this problem is to assume that the Higgs boson is composite. Composite Higgs models also had the expectation of new particles below 1 TeV, but the estimated bound is much less precise.

More importantly, the discovery of the first new particle would be only the tip of the iceberg. In these models, there are new strong interactions at very high energy.

Evidence for compositeness of the Higgs boson would motivate accelerator experiments at 10 TeV and above. In this case, we will need a technology that can reach these energies.

Higgs Compositeness gives a model in which the qualitative nature of final states in e+e- annihilation is qualitatively different from the Standard Model expectation at energies above 10 TeV.

Are there other examples?

What does this require from our accelerators?

Thermalization:

Even within the Standard Model, it has been conjectured that e+e- annihilation can produce classical field configurations (sphalerons, Higgs sector solitons). These would have mass

$$\langle h \rangle / \alpha_w \sim 10 \text{ TeV}$$

They would decay to large numbers of Higgs, W, and Z bosons with momenta of order m_W in the frame of the classical object.

These objects certainly exist, but simple estimates of their production cross sections give small numbers.

However, see the talk of V. Khoze on Tuesday afternoon.

Extra dimensions:

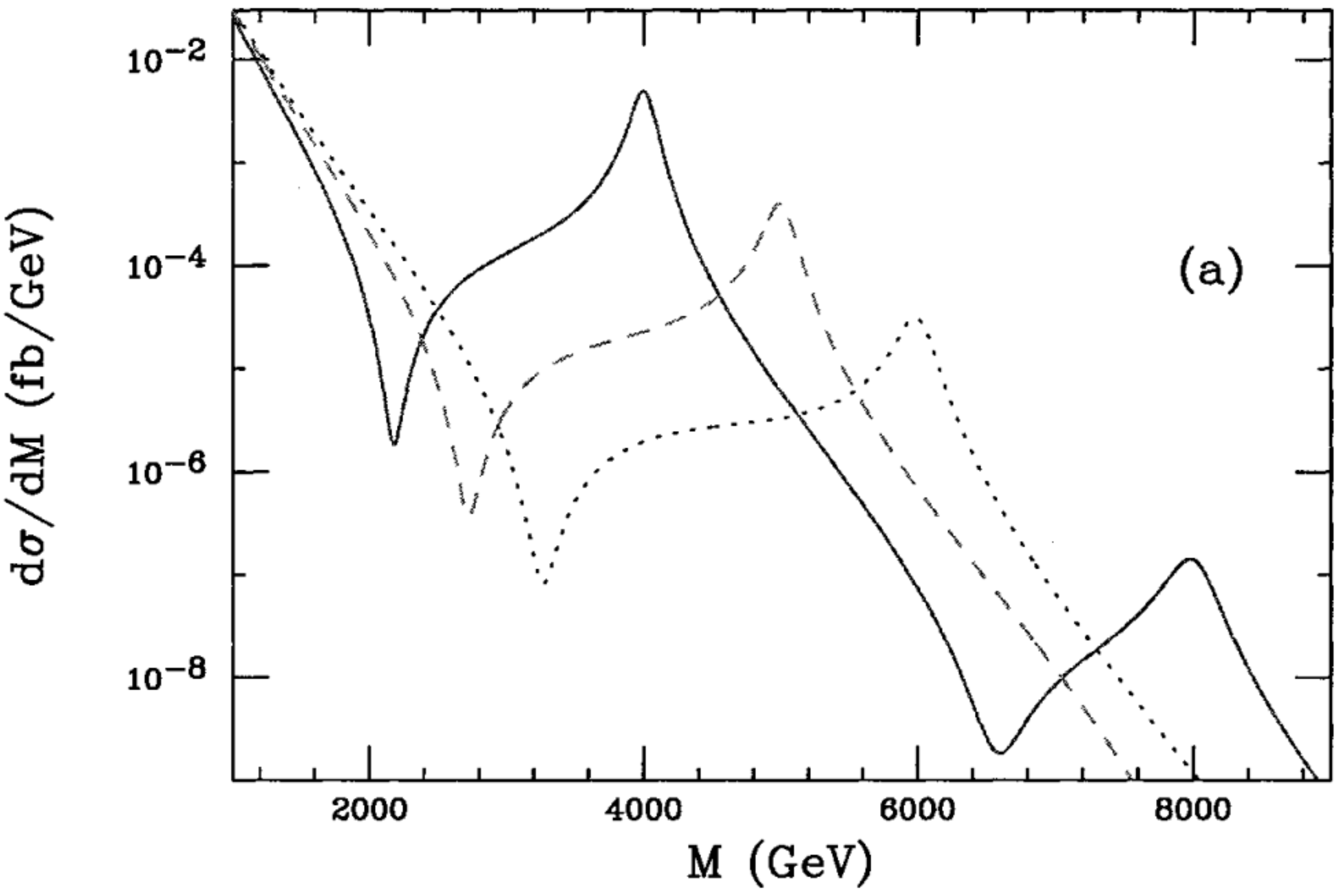
There are suggestions from many theoretical viewpoints that the universe has more than 3 space dimensions.

If this is true, there can be quantum state with nontrivial momenta or wavefunctions in the extra dimensions. These are called Kalusza-Klein (KK) states.

There is a spectrum of KK states extending to very high energy.

The KK excitation of the Z boson must have mass greater than ~3 TeV to avoid too large corrections to precision electroweak measurements.

$e^+e^- \to \mu^+\mu^-$



Rizzo

The position of the first resonance has some information, but the real information is in the pattern of resonance masses:

1 flat dimension	n/R
2 flat dimensions	$(m^2 + n^2)^{1/2}/R$
Randall-Sundrum	zeros of Bessel fncs.

To see the pattern, we must get well beyond the first resonance.

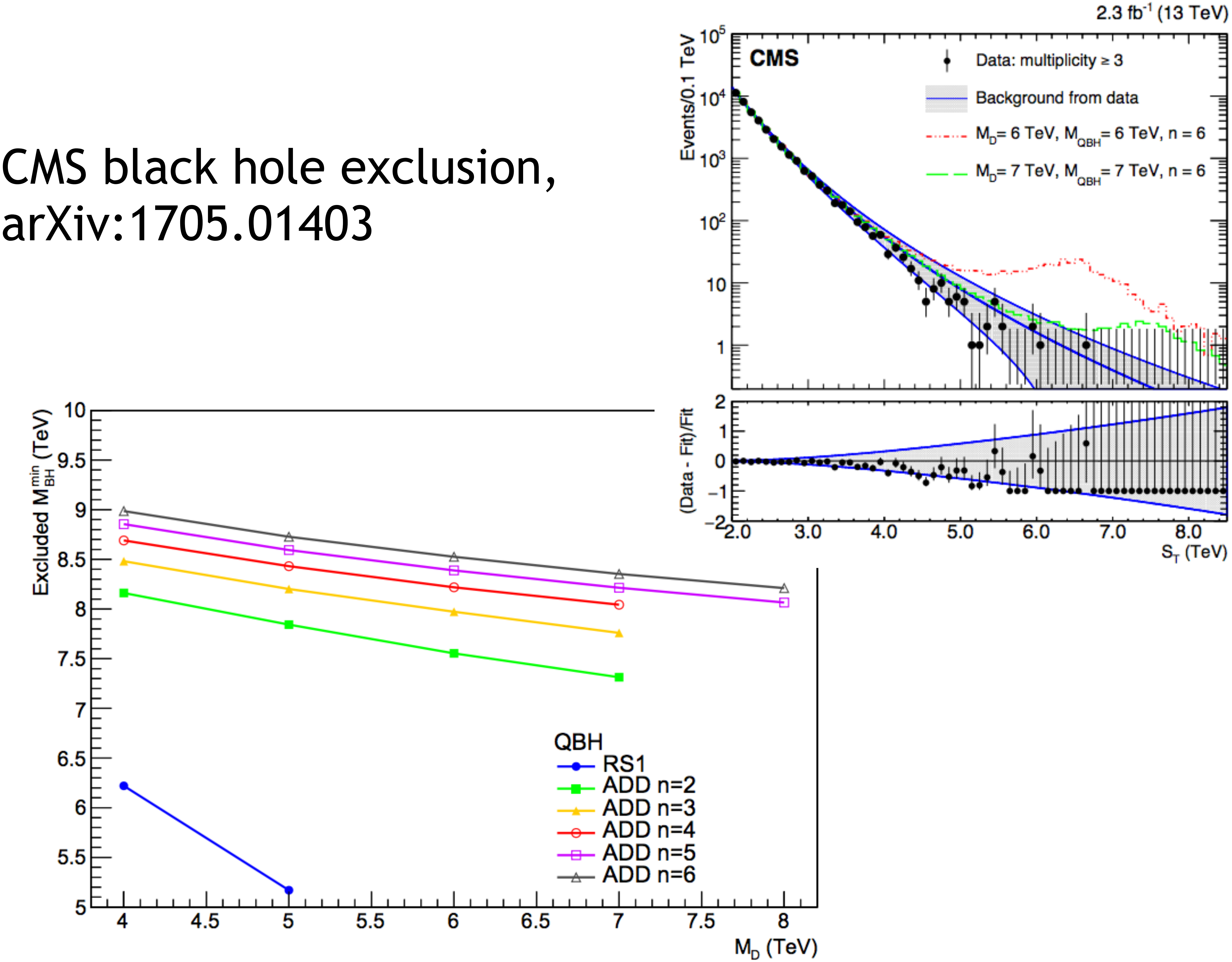
There is a variant of extra-dimensional models (Arkani-Hamed-Dimopoulos-Dvali) in which Standard Model particles are restricted to a 3-d “brane” while gravity can fill the extra dimension.

In this theory, the minimum mass of a black hole can be much lower than the Planck scale (or, rather, the Planck scale is lowered to the TeV scale).

The signatures of black holes are similar to those of “thermalization”, except that most of the particles produced with high multiplicity are quarks and leptons.

If quantum gravity is string theory, then a series of resonances leads up to the black hole threshold.

CMS black hole exclusion, arXiv:1705.01403



Composite Higgs:

This is the most conservative set of models in this class. If there are new strong interactions coupling to the electroweak interactions, these have resonances, and those resonances can appear in e+e- annihilation.

A scenario that realizes the general framework for computing the Higgs potential is:

new strong interactions with $M_\rho \sim 10\ \mathrm{TeV}$

the Higgs multiplets are Goldstone bosons

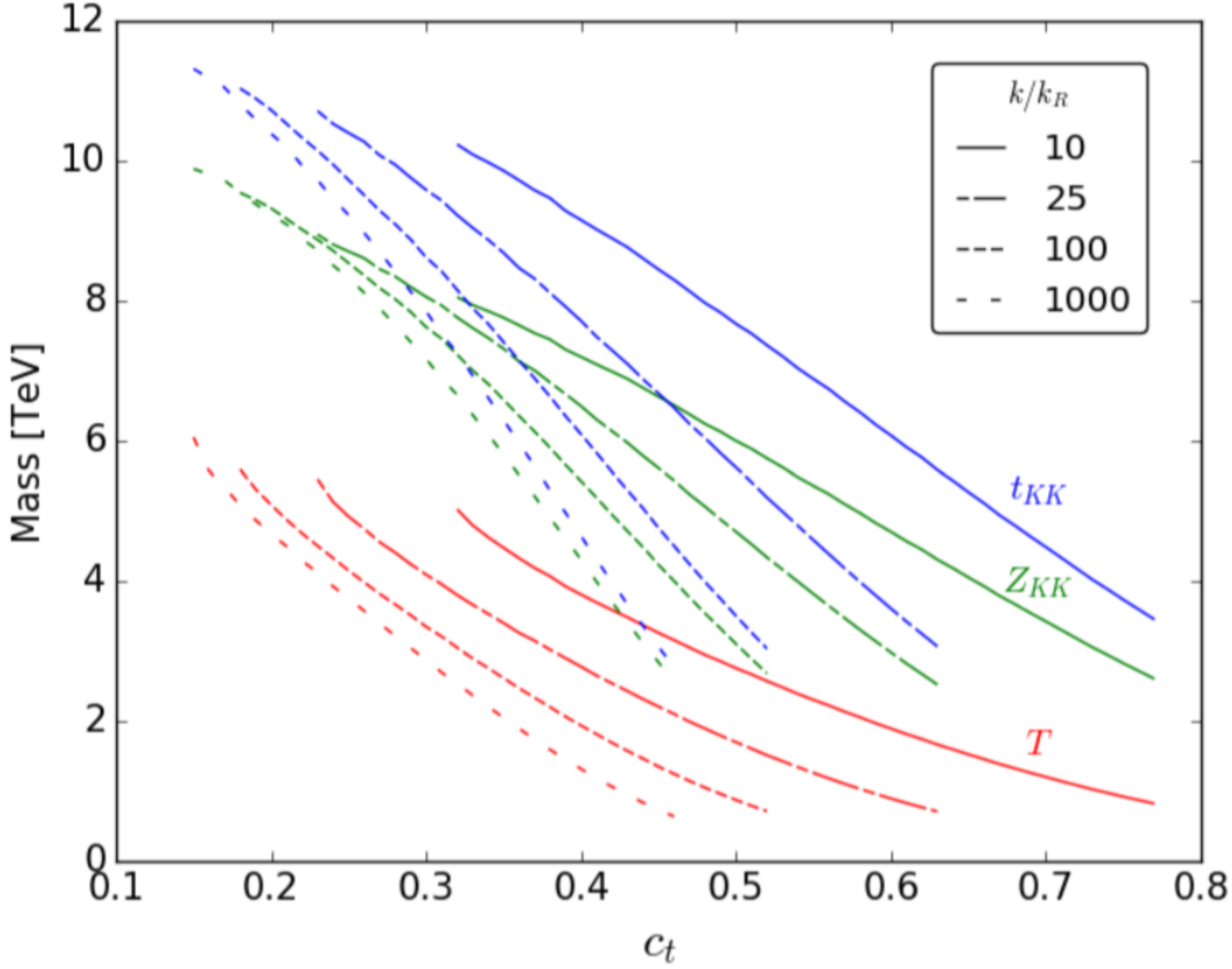
relatively light W, h, top partners with $M \sim \ \mathrm{TeV}$

radiative corrections from these generate m_h

There is a connection to extra dimensions. Through the AdS/CFT correspondence, this theory is related to a 4+1-d (Randall-Sundrum) theory with anti de Sitter metric in the extra dimension.

Again, the problem reduces to that of finding resonances, which appear now as KK states in the RS geometry.

resonance masses in a realistic RS composite Higgs model



Yoon + MEP

Wisdom from an Oxford don:

J. B. S. Haldane:

“My own suspicion is that the Universe is not only queerer than we suppose, but queerer than we can suppose.”

The real possibilities for 10 TeV scale physics may be even stranger and more complex than the examples I have given here.

We can only find out by doing the experiments.

For this, we rely on you to provide a robust, cost-effective accelerator technology.

Inevitably, high-energy physics will need to probe above 10 TeV. If your R&D will (uniquely) get us there, it must be supported.

From these examples, the goal would be to do systematic searches for resonances and thresholds in the 10 - 50 TeV energy region.

They give guidance that a narrow CM energy spectrum may not be needed. We can measure the resonance or threshold energies from calorimetry on the final state.

On the other hand, CM energy, luminosity, and beam polarization are crucial.

Can advanced acceleration technologies provide this?