Physics at a 30 TeV $e^+e^-/\gamma\gamma$ Collider

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It has been almost 30 years since the previous generation of energy frontier e+e- colliders - LEP and SLC - begin operation. We are eagerly awaiting the start of the next energy frontier electron machine - ILC .

But maybe it is not too early to think about colliders of the generation beyond this one.   These should be based on new technologies that provide much higher gradient electron acceleration. Ideally, these technologies will leapfrog proton colliders and represent the true energy frontier of their era.

Methods for advanced electron acceleration:

	beam-driven	laser-driven
plasma wakefield	FACET (SLAC) AWAKE (CERN)	BELLA (LBNL)
dielectric or W-band	(Argonne NL) (CERN: CLIC++)	"accelerator on a chip" (Stanford/SLAC)

record gradient: 45 GeV/m over 1 m (FFTB@SLAC)
controlled acceleration w. 1 GeV/m achieved by several groups

but, no solution yet to the connection of multiple stages

So we can think about a 30 TeV collider as the next accelerator in the ILC tunnel after ILC.

-> ALIC <-

FACET @ SLAC accelerated a positron bunch with 3 GeV/m using plasma wakefields. However, it is still in question whether there are robust solutions for positron acceleration. It might be that the primary collider at very high energies must be a $\gamma\gamma$ collider. Physics studies should acknowledge this.

ANAR report on technologies for high-gradient acceleration:

http://www.lpgp.u-psud.fr/icfaana/ANAR2017_report.pdf

A group called ALEGRO is writing a white paper for the 2019-20 European Strategy Study. See

http://www.lpgp.u-psud.fr/icfaana/alegro/

Your help with the physics chapter of this report would be welcome. The physics conveners are Junping Tian and Michael Peskin.

Luminosity is an issue for any future collider. Rates for new particle production — at any lepton or hadron collider — are set by the point cross section,

$$\mathbf{R} = \frac{100 \text{ fb}}{(E_{\rm CM} \text{ (TeV)})^2}$$
$$= 10^5 \text{ events/yr}/10^{35}/(E_{\rm CM} \text{ (TeV)})^2$$

so a luminosity of 10^{36} is the absolute minimum for any 30 TeV e+e-/γγ collider.

This luminosity is appropriate for new particle discovery and survey, not for precision experiments.

It will be technically very difficult to achieve such a high luminosity:

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

For ILC at 500 GeV, this formula is evaluated as

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

Scaling to a 30 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.

Please remember that such high luminosities are equally difficult for hadron colliders:

The point cross section decreases as $1/E^2$ while the pp total cross section slowly increases. This means that pileup will be 100 times larger than at LHC. More importantly, synchrotron radiation becomes important for pp colliders above 50 TeV and increases as E^4. Colliders will be limited by the ability to avoid synchrotron radiation quenching of superconducting magnets.

Before we begin discussing new physics, I should point to some interesting physics issues for a 30 TeV collider within the Standard Model:

importance of electroweak ISR, FSR:

probability of radiating a W in the final state is

$$2 \times \frac{\alpha_w^2}{2\pi} \log^2 \frac{E_{CM}}{m_W} \approx 0.4$$

so muons are often seen as ν + (hadronic W)

similarly, WW scattering is an order-1 component of the menu of annihilation reactions b, c, τ have macroscopic lifetimes ($z \sim 0.2$ for B, D)

b	c	τ
40 cm	20 cm	74 cm

on the other hand, opening angles are very small

$$\gamma(\tau) = 8500 \quad (0.12 \text{ mm} \ / \ 1 \text{ m})$$

Detector strategy:

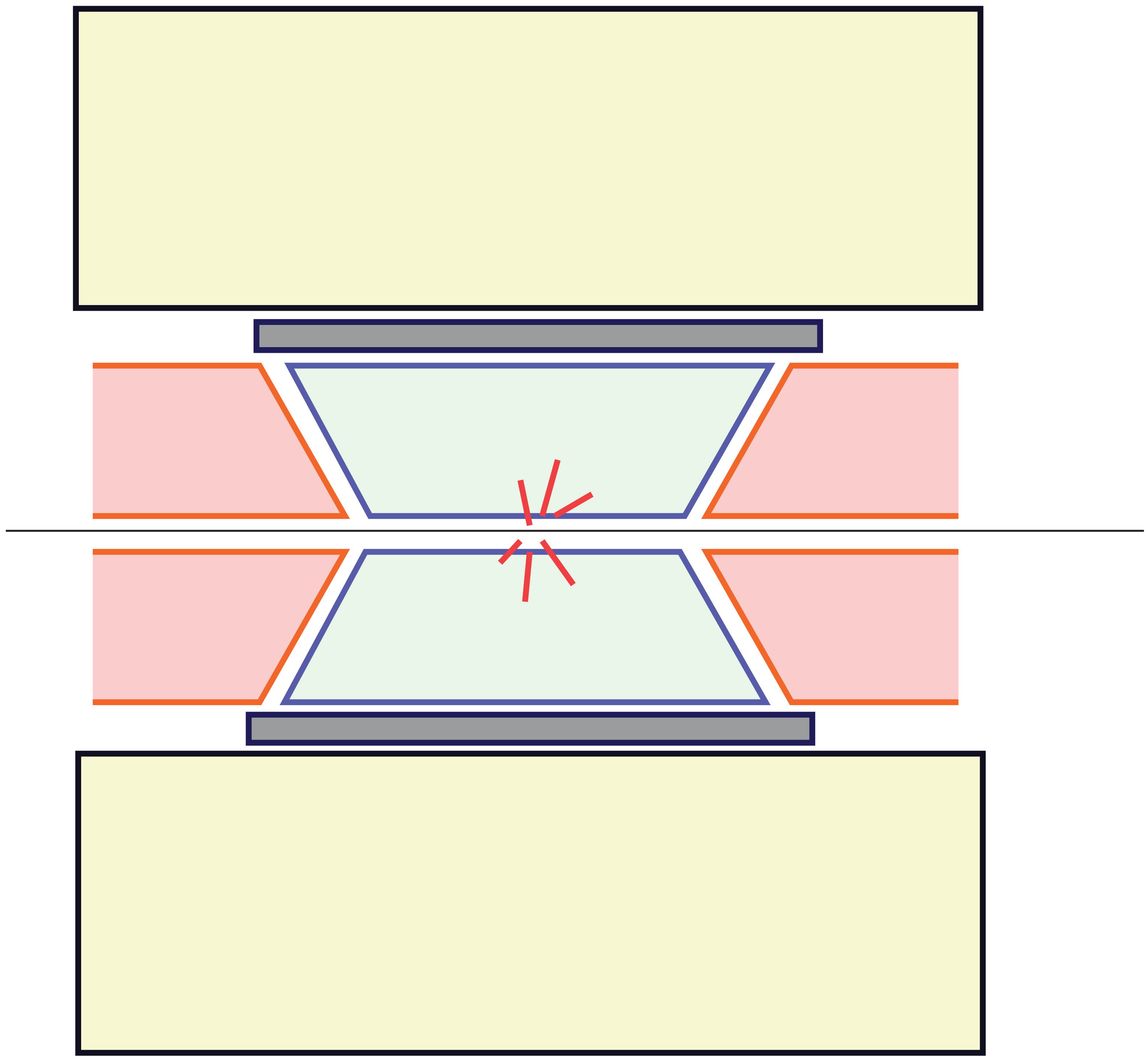
precision vertex detector is not needed (a big relief)

tracking volume scales as E, calorimetry as $\log E$

so consider a $\sim$ 1 m tracking volume w. goals to measure the signs of tracks and to resolve displaced vertices

most of the information will come from high-granularity calorimetry

ALIC detector



Junping Tian is preparing a MadGraph/DEPHES model

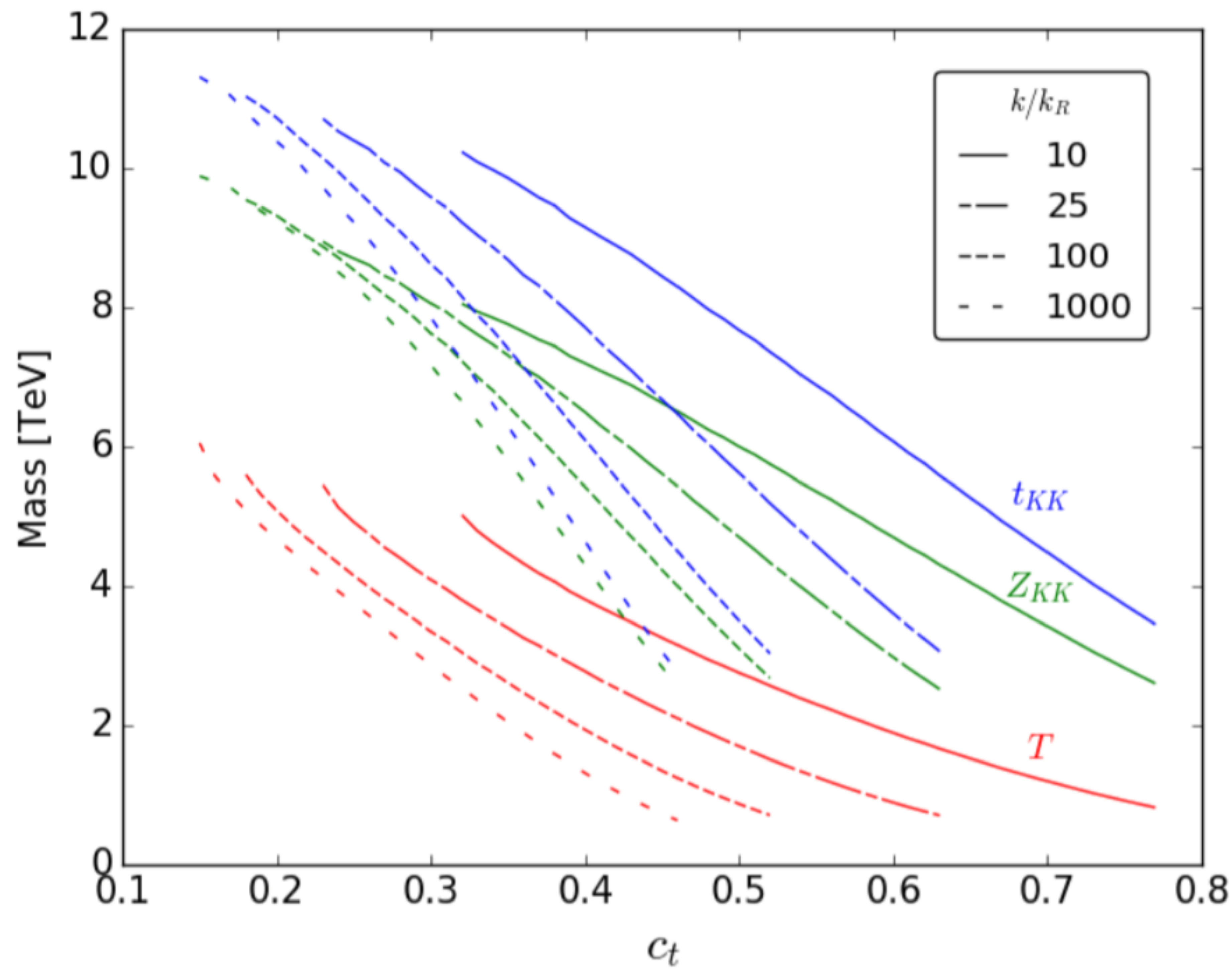
Physics issues for 30 TeV e+e- / γγ

Composite Higgs:

Models with Higgs as a Goldstone boson have their first new particles in the few TeV region, but their true strong interaction scale is typically in the tens of TeV region.

The full understanding of these models will require mapping the spectrum of strong interaction resonances.

resonance masses in a realistic RS composite Higgs model



Yoon + MEP ; see also Hosotani's talk this morning

Extra space dimensions:

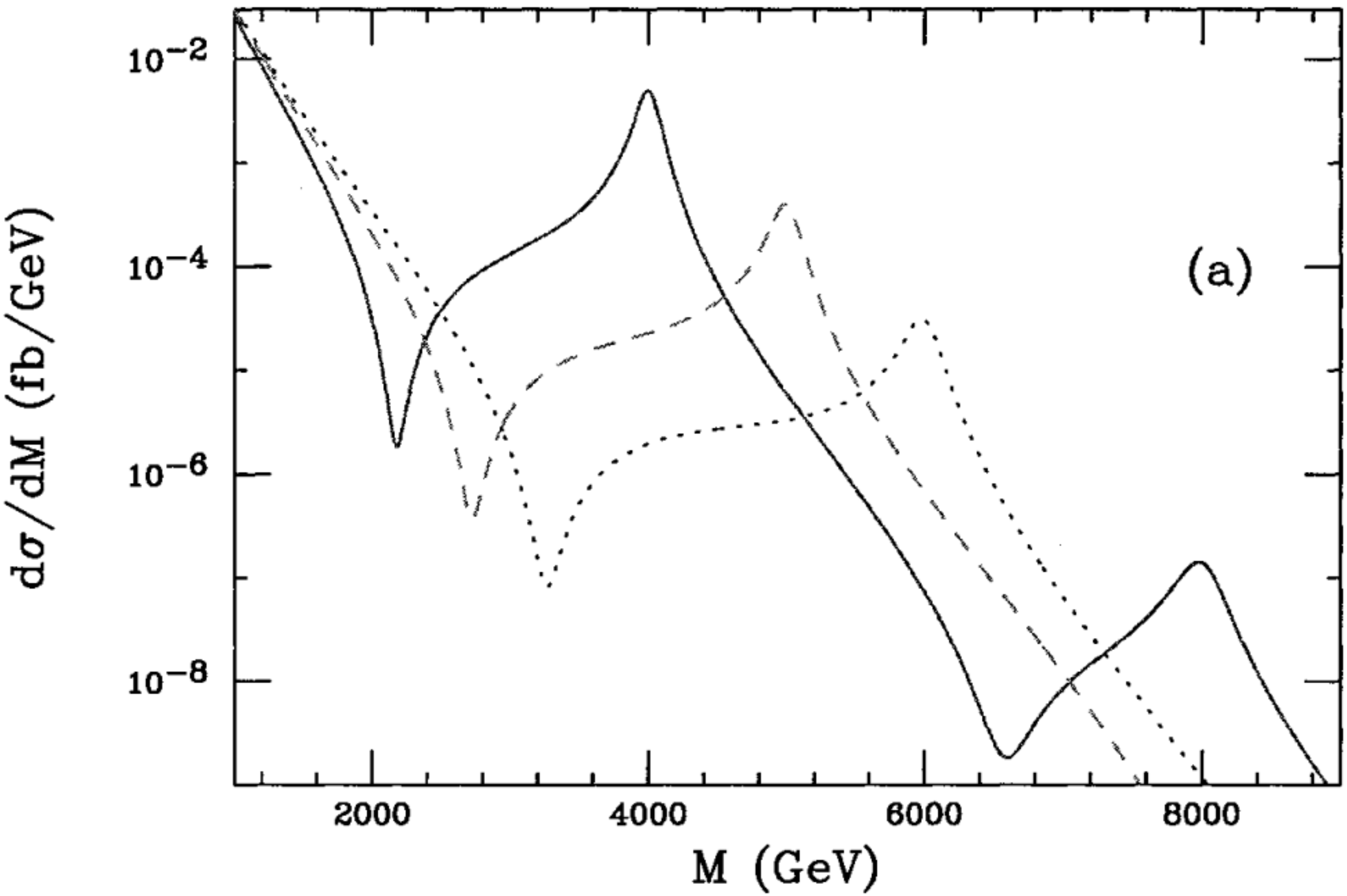
Often, we analyze composite Higgs models using a dual (Randall-Sundrum) 5-dimensional picture. There are more general models with TeV-scale extra dimensions.

In these models, the minimal mass of KK states is ~TeV. We must go much higher in energy to see the pattern of KK resonances,

linear in n ?

zeros of Bessel functions ?

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



Rizzo

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 V. Khoze and M. Spannowsky, “Higgsplosion”

Quantum gravity:

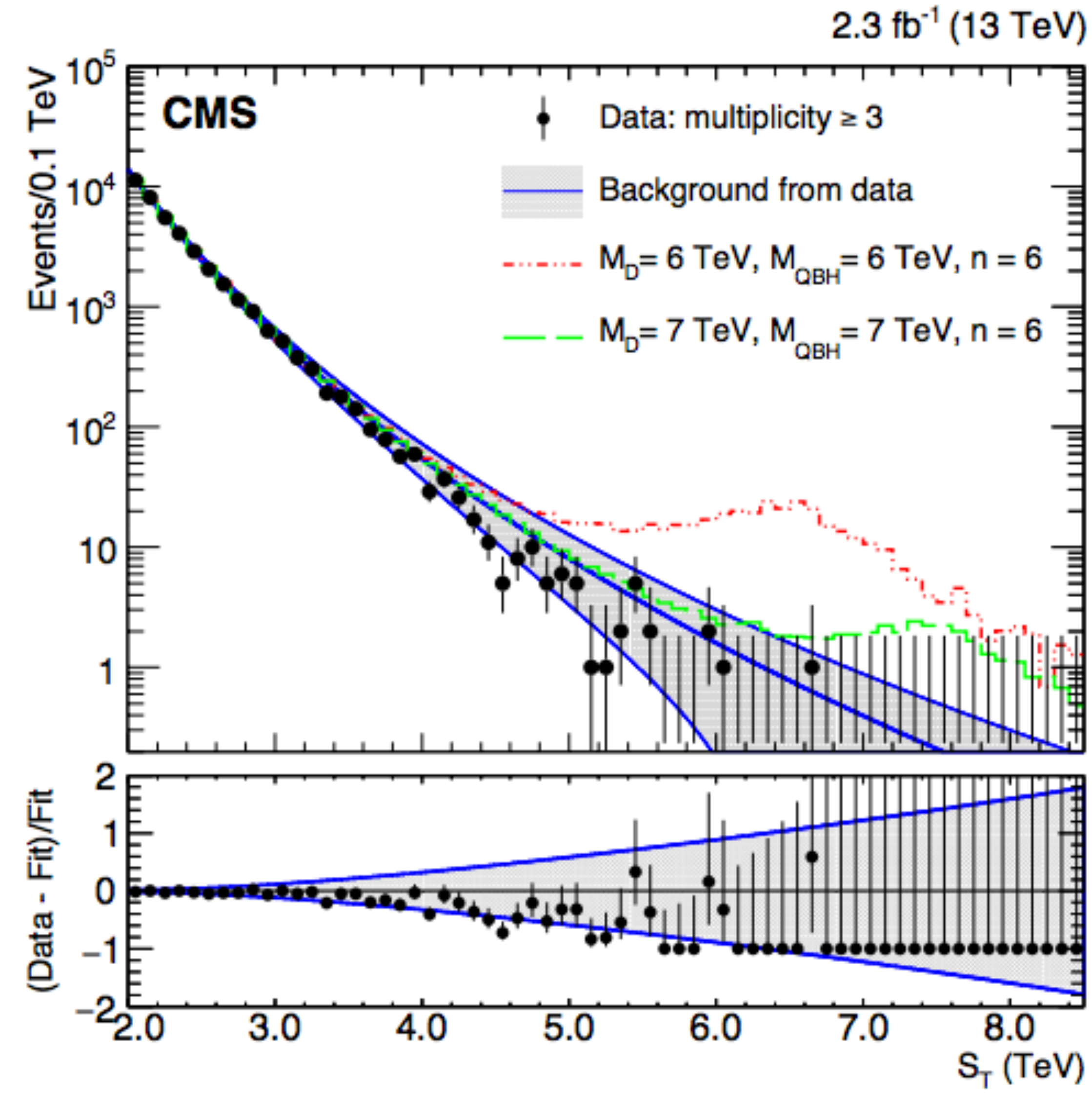
There is a variant of extra-dimensional models (Arkani-Hamed-Dimopoulos-Dvali) in which Standard Model particles are restricted to a 3-d “brane” while gravity can fill the extra dimension.

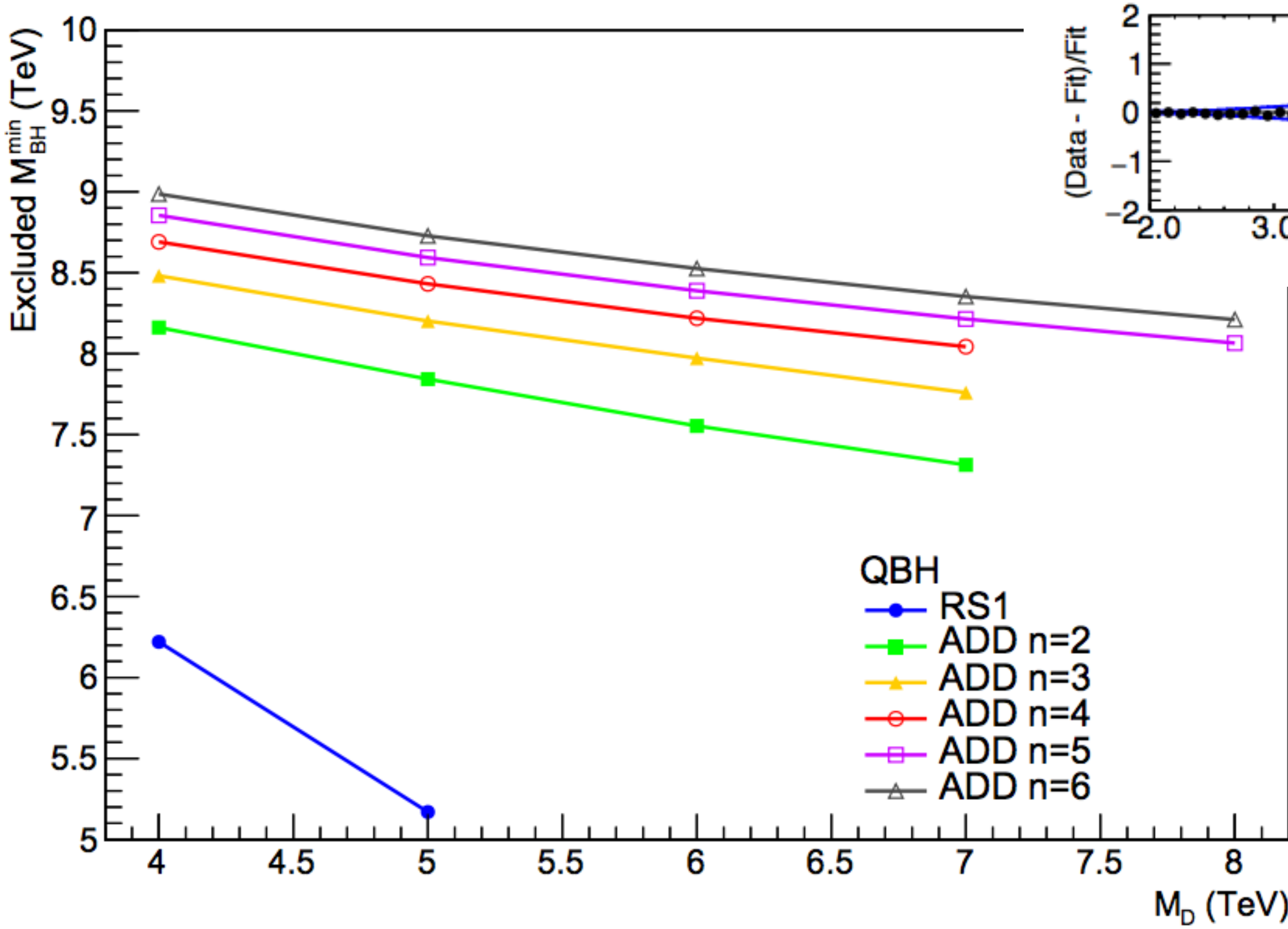
In this theory, the minimum mass of a black hole can be much lower than the Planck scale (or, rather, the Planck scale is lowered to the TeV scale).

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





Flavor dependence / anomalies :

New flavor-dependent interactions cannot be present at the TeV scale except with very small mixing angles.

Maybe the relevant mass scale for flavor physics is in the 10s of TeV.

Models of the LHCb flavor anomalies include leptoquark bosons with 10 TeV masses.

These fascinating physics issues have not been explored phenomenologically because theorists have not thought it realistic to reach the energies needed to perform the experiments.

I claim that we will see these experiments in your lifetime (maybe not in my lifetime).

Let's prepare the ground by analyzing these processes in detail. This will give our accelerator colleagues strong motivation (and funding) to make these accelerators real.