Physics at Multi-10-TeV γγ Colliders

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The subject of physics in the multi-10-TeV (parton) energy region is a new one that we are just beginning to explore.

The study of this region is made difficult by two important features:

1. We have no idea how to get there.

2. We have no idea what we are looking for.

This talk is supposed to be about γγ colliders to explore this energy region.   In preparing it, I am impressed by how much work I still need to do to give a reasonable talk on that subject.

Instead, I am going to discuss:

1.   My motivations for going to multi-10-TeV and things that I, at least, hope to learn there.

2.   My motivation that γγ colliders provide a possible approach

I hope that I can fill in some of these ideas and return to give a more complete talk later in the Snowmass process.

There are three possible motivations for thinking about colliders reaching the multi-10-TeV scale.

1. Because it is there, and we are high-energy physicists

2. Because we did not find new particles at the LHC, so the next step should be a big one

3. Because there are specific targets that we would like to access

We have the difficulty that frontier colliders are very expensive.   You know better that I that it will be a challenge to design a 10-TeV-scale collider for the price close to that of the LHC.

Given this, the motivation cannot be a search for some hypothetical particles that may or may not be there. We need a concrete motivation to search in this region. And, our accelerator should give the expectation, not only that we will discover a particle, but that we will learn new laws of physics.

To discuss this in a serious way, we need to understand what is the nature of the new physics beyond the Standard Model.

Unfortunately, we know almost nothing about this. The Standard Model is self-consistent up to very high energy. The verification of the Standard Model is robust, even if some anomalies remain.

There are reasons to believe that the Standard Model is incomplete.   However, these do not give clear targets for higher-energy colliders:

Dark Matter:

Dark Matter could be a particle of GeV or even much smaller mass, accessible in fixed-target or non-accelerator experiments.   This is probably the main topic of interest today among particle theorists.

The idea that Dark Matter is a WIMP with a mass of 1 TeV or above, up to a unitarity limit of about 10 TeV, is still open.

Baryogenesis:

The baryon number of the universe must be generated by new CP-violating physics that operated after the end of inflation.

An interesting possibility is that it is generated at the electroweak phase transition, in a model with an extended Higgs sector. However, an alternative is leptogenesis, in the extended neutrino sector at $10^{10} - 10^{13} \ \mathrm{GeV}$.

Flavor:

The flavor structure of the SM comes from the fermion-Higgs Yukawa couplings.   These can be almost completely arbitrary.   The known flavor constraints (e.g., absence of flavor-changing neutral currents) come from the properties of the gauge sector of the SM.

The situation changes in physics beyond the SM. The SM uses up this freedom, so new physics interactions must be constrained to be flavor-conserving, or they must be at very high mass (well above 10 TeV).

If the current B anomalies hold up, they require new interactions.   A typical model involves a large multiplet of leptoquark bosons at 7 - 10 TeV.

The most robust expectation for new physics beyond the SM comes from a more theoretical idea:

We know that the weak interactions arise from an SU(2)xU(1) gauge theory that is spontaneously broken by the Higgs field.   But, we do not know why this breaking occurs.

The simplest models giving physical explanations for the Higgs spontaneous breaking contain new particles in the few-100 GeV mass region (e.g. top squarks)   or new strong interactions at 1 TeV (e.g. technicolor). Both are now excluded.

The idea that the magnitude of the Higgs field expectation value $v = 250$ GeV comes from physics, and that the new physics interactions must then be near the scale of 1 TeV, is called "naturalness".

This principle is now much derided by theorists:

Gian Guidice says that we live in the "post-naturalness era".

Nima Arkani-Hamed has given a talk with the title: "The World is not a Crappy Metal".

But I do not see an alternative to this idea.   This poses a serious question for theorists:

How do we explain that 250 GeV Higgs scale with new physics that is far above this scale? And, how far above will it be?

Here are some concrete ideas along these lines:

"Supersoft supersymmetry":

Suppress the feed-down of mass from the gauginos to the squarks and sleptons, for example, by giving gauginos Dirac-type masses. This can put gluinos above 10 TeV and top squarks at ~2 TeV, out of reach of LHC.

"Twin Higgs":

Postulate an extended Higgs sector with a Z_2 symmetry that forbids the generation of a mass for the standard Higgs field.   This is eventually broken, but the extended Higgs particles can be at multi-TeV. That theory has its own divergence problems, so more structure is needed at 10 TeV.

"Higgs as a Goldstone Boson":

The complete Higgs complex doublet Φ can be Goldstone bosons of a new strong interaction theory. The mass of the Higgs and other light states are generated by weak symmetry-breaking. It is possible, even straightforward, to avoid generating mass for the Higgs in leading order. Then we can have the new strong interactions at 10 TeV, some light partner particles at a 1- 3 TeV, and Higgs at 100 GeV.

Partners are constrained by LHC, so additional structure might be needed. Some ideas are

"neutral naturalness" — the partners are color-singlet
"competing forces" — some partners stabilize SU(2)xU(1)

The "Higgs as a Goldstone boson" models come in conventional strong interaction versions ("Little Higgs") and extra-dimensional versions (e.g., "Randall-Sundrum").

In the extra-dimension versions, the extra dimensions are expressed as s-channel resonances. The full problem is not to find the first resonance, but rather to find enough resonance to infer the underlying geometry.

This list is certainly incomplete. It remains a challenge for theorists to add testable examples to this list.

resonance masses in a realistic RS composite Higgs model

Yoon + MEP
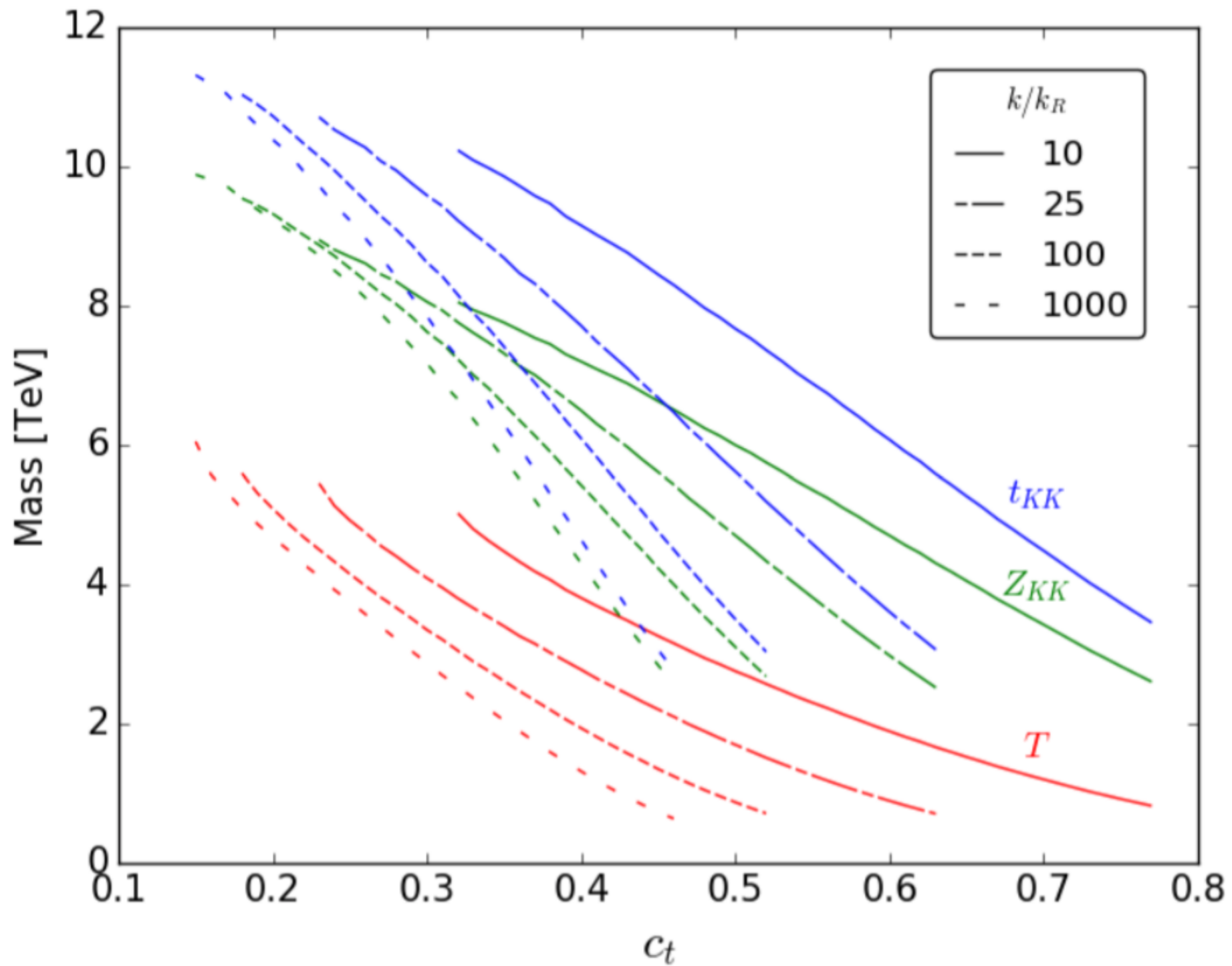
A general schema that appears in all of these models is the following:

new fundamental interactions are M^2

light partner or helper particles at $\left(\dfrac{\alpha_w}{4\pi}\right) M^2$

generate a Higgs potential at $\left(\dfrac{\alpha_w}{4\pi}\right)^2 M^2$

We can hope to discover the helper particles at the HL-LHC or, indirectly, through violation of the SM predictions for Higgs boson couplings. I am afraid that this is the only way we can build sufficient motivation to fund a multi-10-TeV scale collider.

From this perspective, the goals of a program of multi-10-TeV parton collisions are somewhat changed.

We expect to have some hints of the nature of the new physics that we expect to see in the high-energy region.

Thus our expectation for the accelerator is that it should explore this region and learn the nature of the new physics.   It is not enough just to discover individual particles.

As an analogy, think about the step in $\pi - \pi$ scattering or $e^+ e^- \rightarrow \mathrm{hadrons}$ from 400 MeV to 4 GeV in the CM.

Given the potential importance of exploring the multi-10-TeV scale and the issues with all current ideas, it seems important to pursue as many directions as possible.

So far, we have on the table:
    pp colliders, possibly with high-Tc magnets
    muon colliders

I would like to consider the alternative of γγ colliders. Photons are fundamental particles, like electrons and muons, with only electromagnetic interactions. Thus, ideally, they can probe up to the nominal CM energy and can provide a clean environment for experimental observations.

Of course, this is only in theory; reality might be different.

First, a remark on needed luminosity.

We need to face up to the tyranny of

$$\sigma \sim \pi\alpha^2 / E_{CM}^2$$

If we wish to access new particles at the 10 TeV scale, this is the magnitude of the cross sections.

Lighter particles (top, W, Z, Higgs) are produced with much larger cross sections through W fusion. We should not consider these the ultimate benchmarks for collider luminosity. Actually, they provide an interesting new source of background − multiple production due to the W Regge pole.

Study of 1 resonance can relax this requirement; search for multiple resonances does not.

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

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

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

So for electron, muon, γγ colliders, in the multi-10-TeV region, we must consider as a minimum a luminosity of order

$$10^{36} \text{cm}^{-2} \text{sec}^{-1}$$

(The one exception: If we have Arkani-Hamed-Dimopoulos-Dvali low-scale gravity with a Planck scale of 5 TeV, cross sections have a minimum at that scale.)

Some experimental aspects do become easier

b, c, τ   have macroscopic lifetimes   ($z \sim 0.2$ for B, D)

$$\frac{b \qquad\qquad c \qquad\qquad \tau}{40 \text{ cm} \qquad 20 \text{ cm} \qquad 74 \text{ cm}}$$

on the other hand, opening angles are very small

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

and bending of the highest energy particles is very small

This requires rethinking the detector design.

Detector strategy:

precision vertex detector is not needed. This is a relief; the interaction region will be filled with focusing magnets and machine protection.

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

so consider a ~ 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

Plasma wakefield and dielectric accelerators promise extremely high accelerating gradients (3 GeV/m). This is SLAC in 10m or 30 TeV in 10 km.

The ALEGRO report to the European Strategy Study (arXiv:1901.10370) gives straw-man designs for 30 TeV and $10^{36} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$ luminosity (ALIC).   Much R&D is needed, of course, to demonstrate the principles and reduce the power bill.

Why can't we then add $e^+ e^-$ collisions to the list?

There are two major problems.

One is the difficulty of accelerating positrons. Plasma colliders are not particle-antiparticle symmetric. This issue is being pursued at SLAC's FACET II facility.

The second problem is more intrinsic. In e+e- collisions with very small, intense spot sizes, the charge of each bunch has a strong effect on the particles of the other bunch. This leads to synchrotron radiation(beamstrahlung) and forward e^+e^- pair creation.

CLIC (3 TeV) is already close to the limit.

comparison of 1 TeV and 3 TeV collider designs
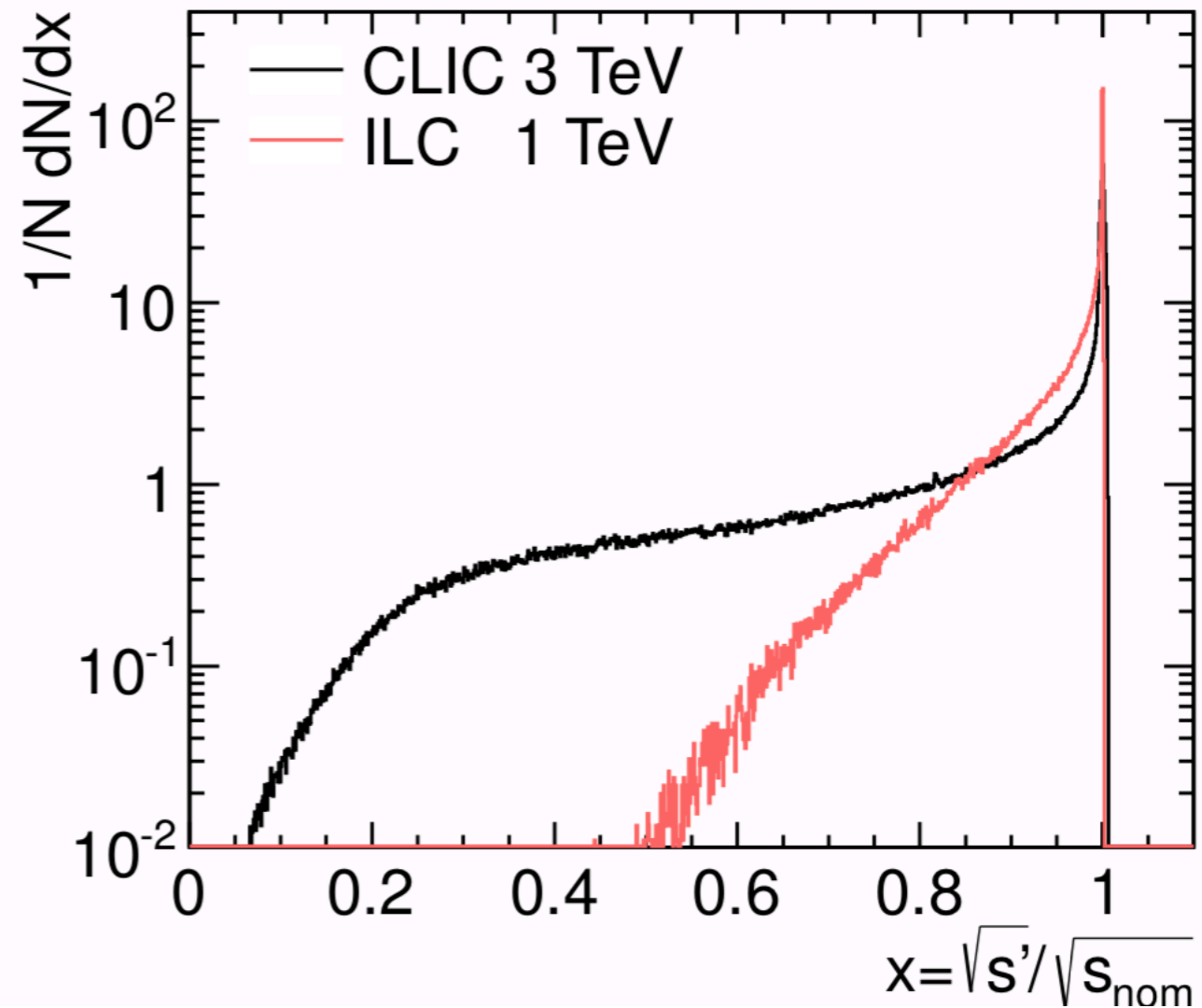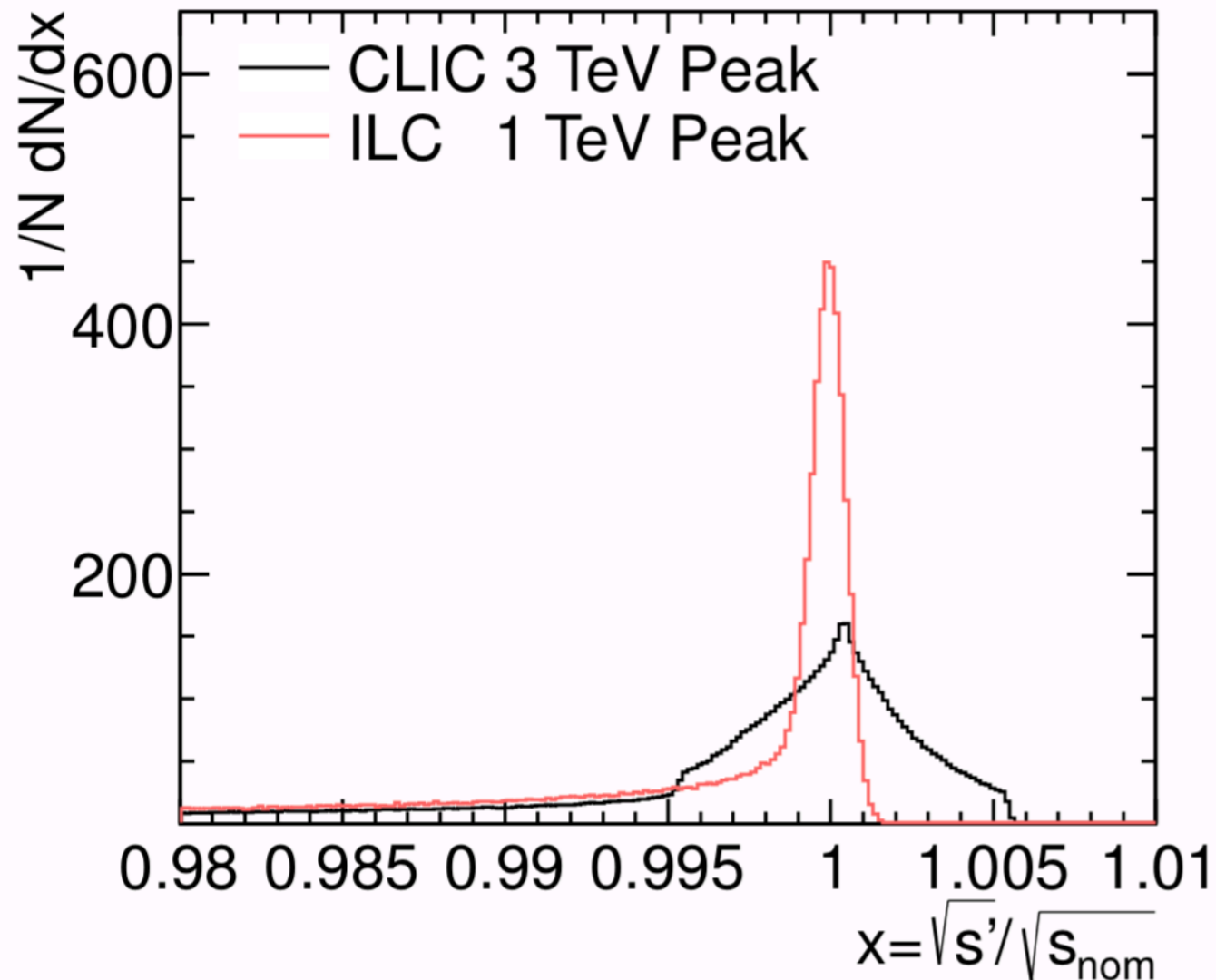
Sailer and Poss

At 30 TeV with $\mathcal{L} \sim 10^{36}$, this gives 100% smearing of the collision energy.

We can circumvent both problems by colliding photon beams.

Photon beams can be generated from accelerated e- beams. The photons follow the e- trajectories. A photon collider can be based on a e-e- accelerator.

Photons have higher backgrounds than e+e- by a factor of 100, but still small compared to pp collisions.

Photon Collider systematics
(Ginzburg, Kotkin, Serbo, Telnov)

Critical parameter: $\quad x = \dfrac{s(e\gamma)}{m_e^2} = \dfrac{4E\omega}{m_e^2} = 15.3 \; \dfrac{E}{\text{TeV}} \; \dfrac{\omega}{\text{eV}}$
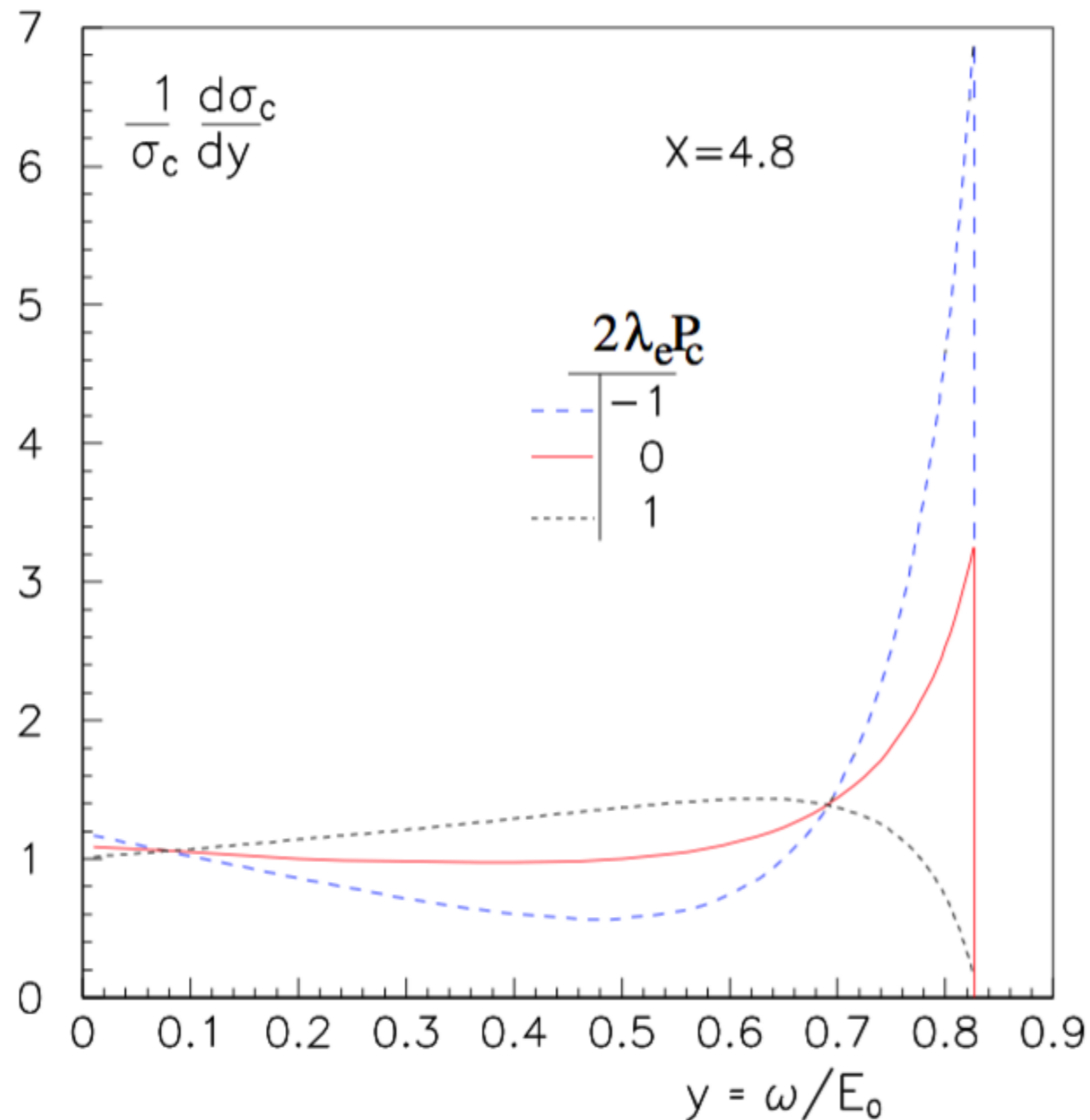
Maximum photon energy: $\quad E_\gamma/E = \dfrac{x}{(1+x)}$

Pair production $\gamma + \gamma \to e^+ e^-$ is forbidden if

$$x < 2(1+\sqrt{2}) = 4.8$$

but it is possible to work above this boundary.

It is possible to obtain a photon spectrum sharply peaked at high energy by matching the e- and laser γ polarizations.

There are 3 possible paths to the creation of photons from an electron beam:

1. Compton scattering restricted to $x < 4.8$.

This requires a radiation field with 50 µm wavelength. Unfortunately, this is poorly matched to the nm size required for the electron bunches. So, high power must flow into the detector interaction region. This must be an optical cavity (Monig):
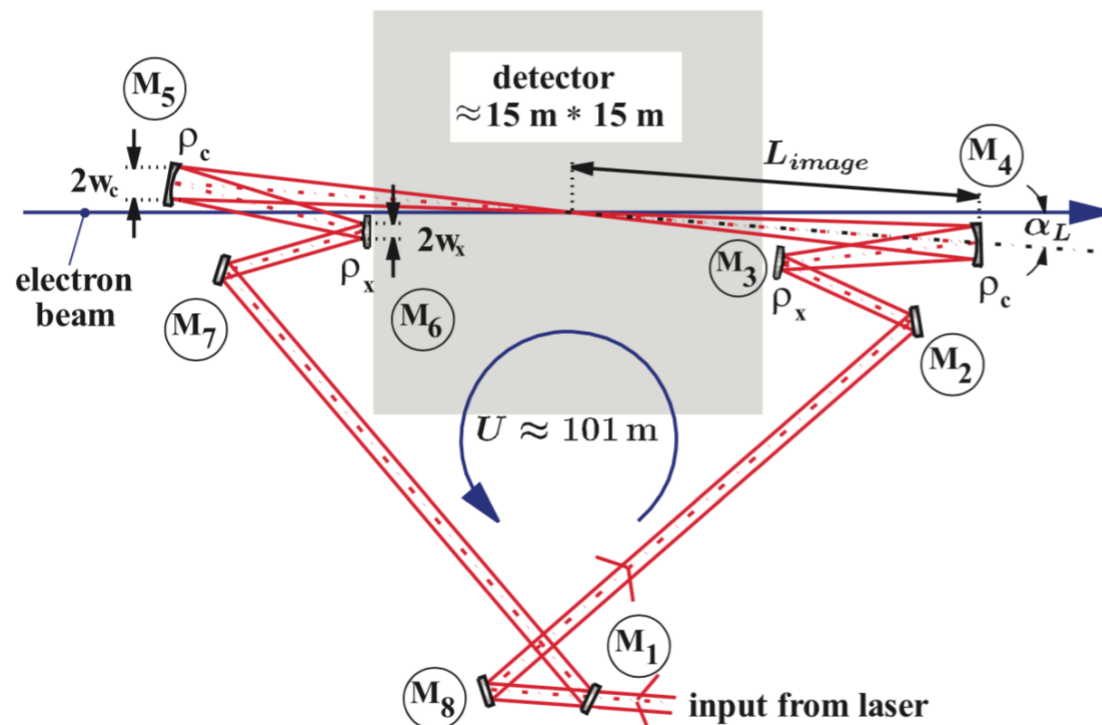
2. Compton scattering far above x = 4.8

Can we use an X-ray FEL to provide the photon beam for Compton scattering ?

This idea is the subject of a Snowmass LoIs by Tim Barklow, Zhirong Huang, et al. and Emanuela Barzi et al.

The biggest question is whether the hard photons will be eaten up by conversion on low-energy photons before exiting the FEL beam.
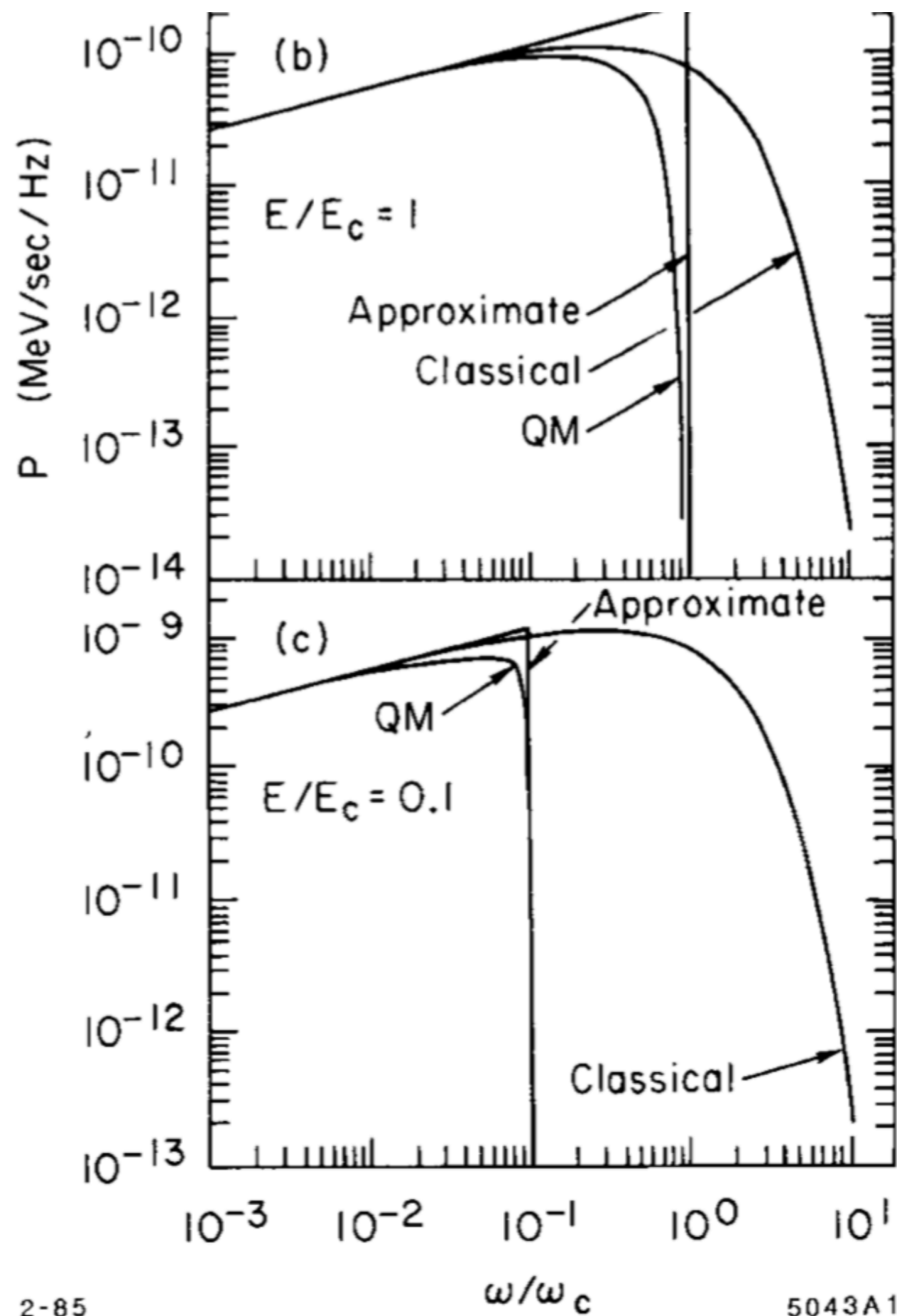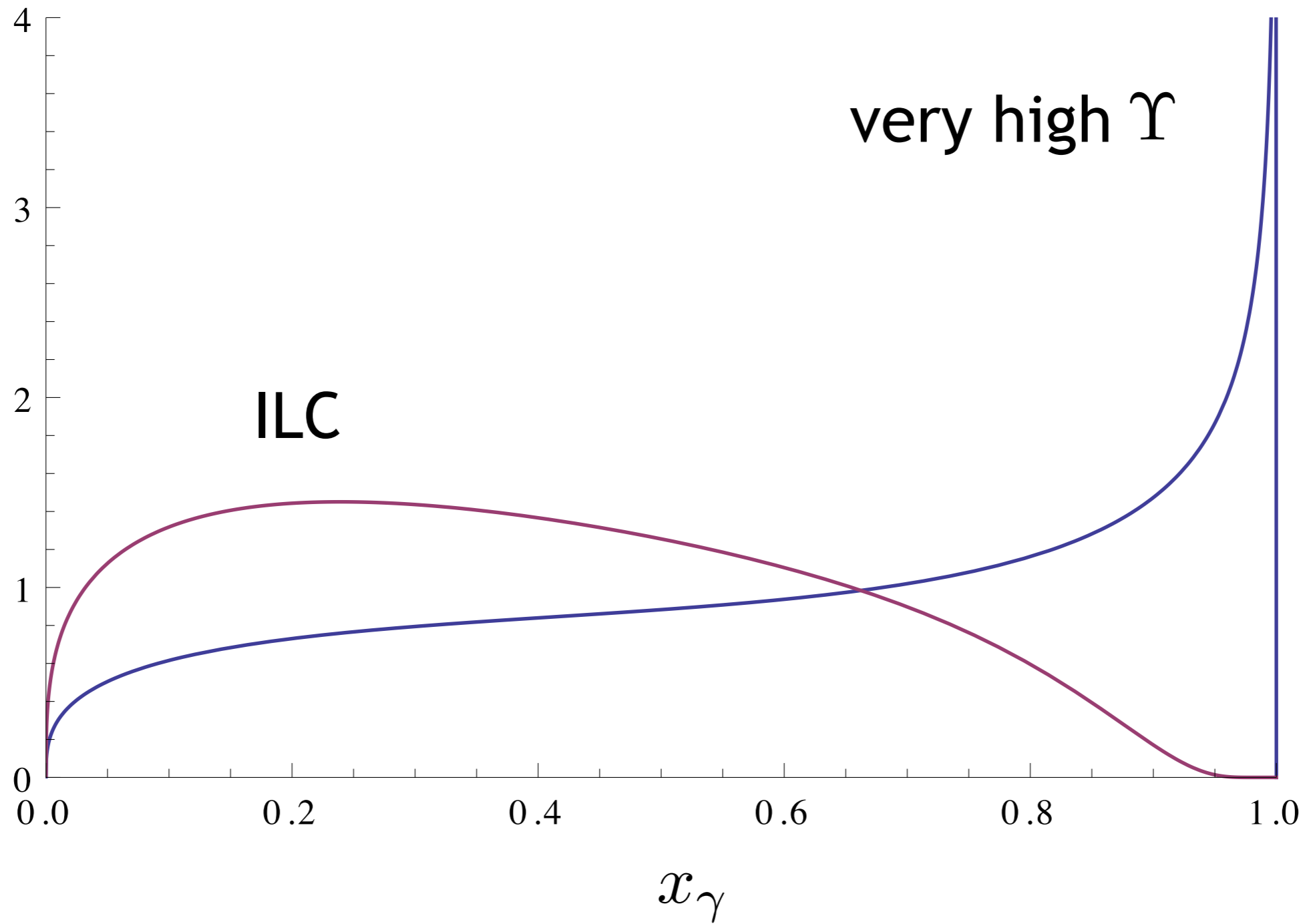
3. Beamstrahlung as a source of hard photons

(Blankenbecler and Drell; Yakimenko)

Shortening the e- bunch length and going to round bunches, approach the extreme quantum limit of beamstrahlung.

Then the beamstrahlung photon spectrum becomes hard, and an e-e- collider automatically becomes a γγ collider.

Himel and Siegrist

very high Υ

ILC

x_γ

This idea is the subject of a Snowmass LoI by Sebastian Meuren, Glen White, Vitaly Yakimenko, and me.

The major question is whether the hard photons will survive interaction with softer photons and electrons generated in the bunch, even with the very short bunch lengths.

I feel that the exploration of the multi-10-TeV parton energy scale is an imperative for particle physics.

The experiments are 20-30 years away, but they require new accelerator ideas that are not yet developed.

We need to open our minds to all possibilities so that at least one can eventually be realized.

Einstein Offers New Theory To Unify Laws of the Cosmos

$$g_{ik;s} = 0, \qquad \Gamma_i = 0$$
$$+-$$
$$R_{ik} = 0, \qquad R_{ik,l} + R_{kl,i} + R_{li,k} = 0$$

Einstein's latest equations for a United Field Theory. These formulas are known as tensors. They are highly condensed mathematical shorthand, representing relationships between the forces of gravitation and electromagnetism in their relationship to space, time and physical forces.

By WILLIAM L. LAURENCE

Albert Einstein, named by George Bernard Shaw as one of the eight "Universe Builders" in recorded history, has returned from a three-year sojourn on the lonely summit of his scientific Sinai with a new set of laws for the cosmos.

These laws, embodied in a few mathematical formulas, will, he believes, reduce the physical universe in its totality to a few simple, fundamental concepts that will unify all its multifarious and seemingly unrelated manifestations into one all-embracing intellectual synthesis.

He calls this all-embracing concept, which he has been seeking with the consecrated devotion of a high priest of science for more than half of his seventy-four years,

universe, and ultimately permit admittance to its very sanctum sanctorum.

Dr. Einstein's latest concepts of the fundamental laws governing the cosmos are published today by the Princeton University Press as an appendix to the fourth edition of his famous book, "The Meaning of Relativity," originally published in 1922. The appendix, headed "Generalization of Gravitation Theory," is a radically revised version of an appendix to the third edition of the book, published in 1950.

His concept of 1950, he says, left one serious difficulty to be solved. This "last step in the theory," he adds, "has been fully overcome in the last few months."

In his quest for a new understanding of the fundamental laws
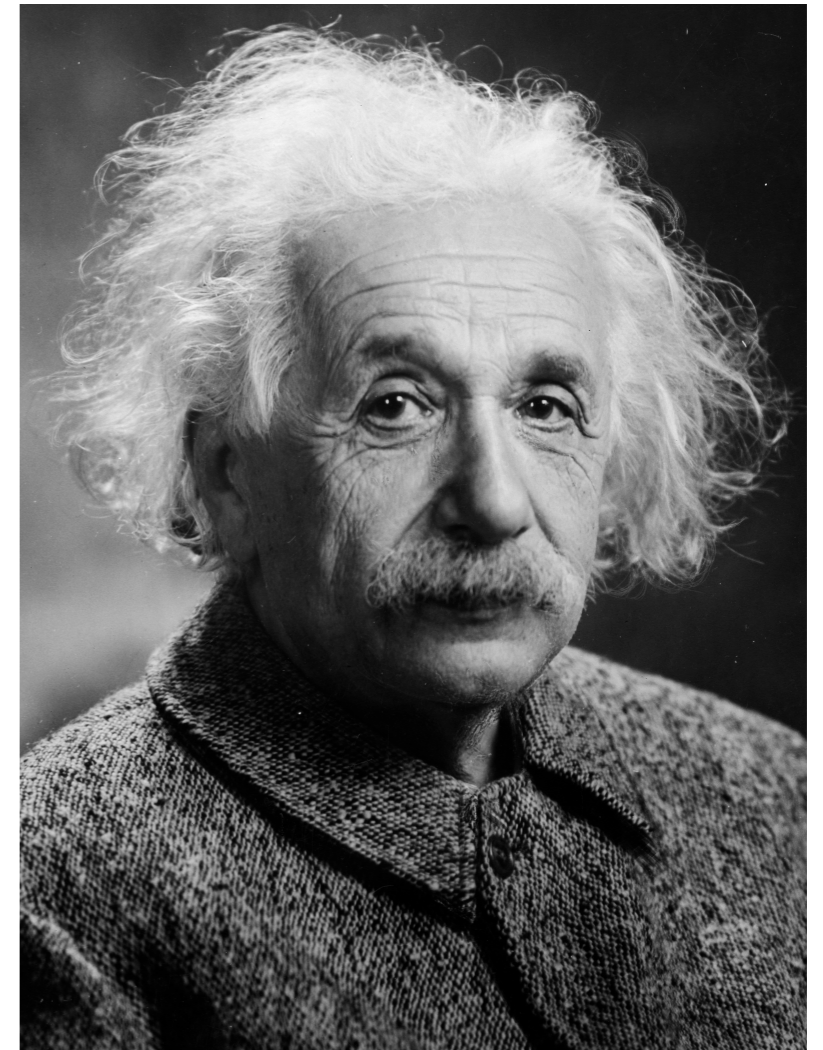
New York Times
March 1953

I have one more important message for this group:

To keep accelerator based particle physics alive to explore the multi-10-TeV region, we need a new, highly motivated frontier accelerator as soon as possible.

It is fun to think about the future, but let's not lose sight of this.

ILC is the only proposal on the table now.

I fear: No ILC, no community, no future.

Snowmass and P5 need to make a yes or no decision on the ILC. Let's not lose sight of this. Let's help to get the right answer.