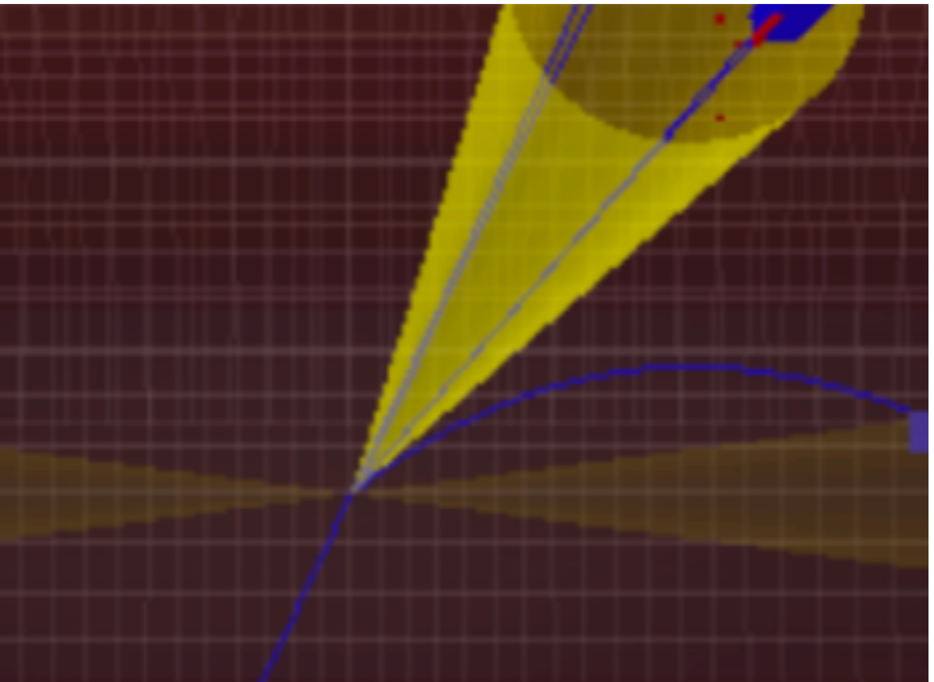
New Physics Goals for 10-100 TeV Accelerators



M. E. Peskin
Johns Hopkins Workshop, GGI
October 2018

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, a Higgs factory of a type described earlier this afternoon.

But maybe it is not too early to think about a lepton collider of the generation beyond this one. This capability could be provided by a muon collider, but here I will focus on a linear electron collider based on very high gradient acceleration using a new technology. Ideally, this technology will leapfrog proton colliders and represent the true energy frontier of its era.

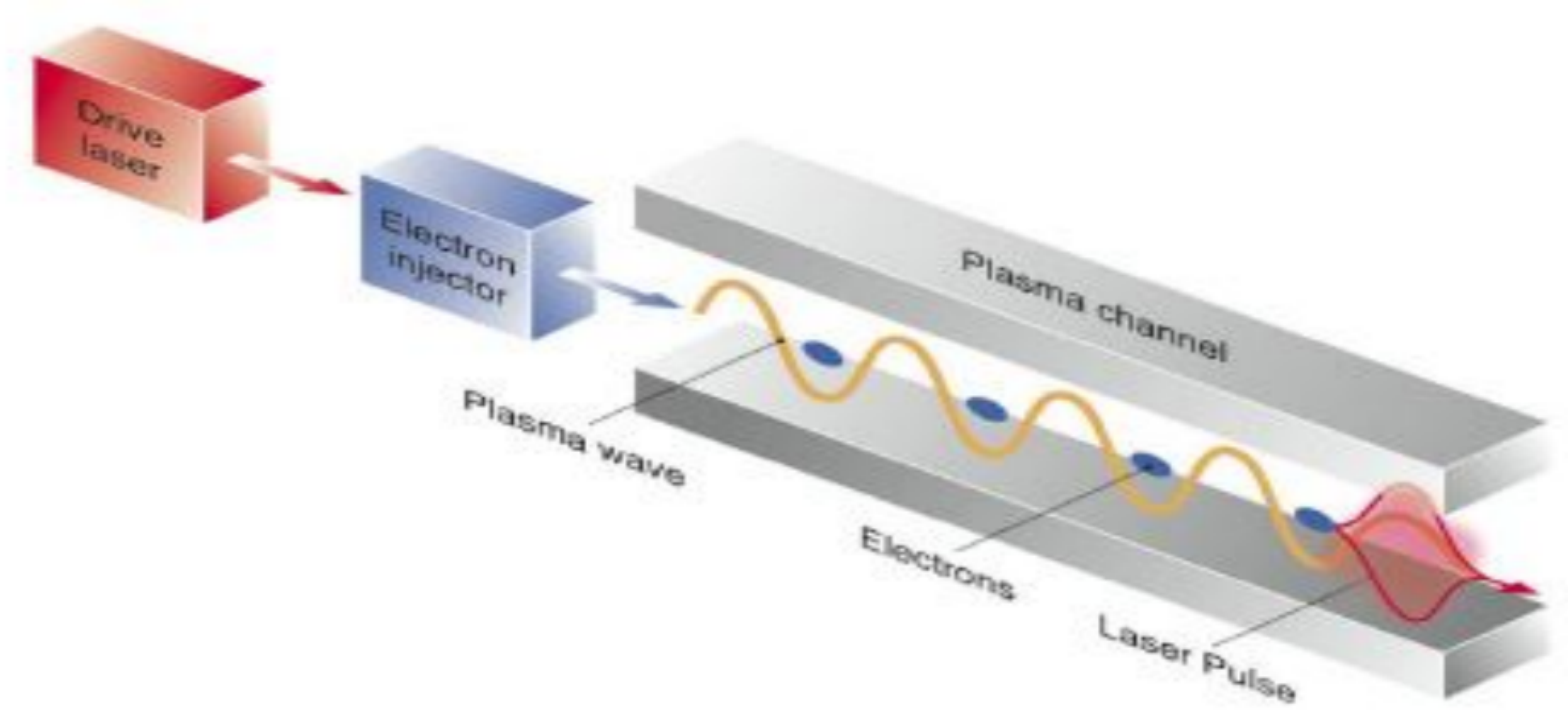
Methods for advanced electron acceleration:

	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. 4 GeV/m achieved
by several groups

but, no solution yet to the connection of multiple stages

Maybe it is interesting to point out that laser plasma acceleration is one of the technologies enabled by the work celebrated in the 2018 Nobel Prize in Physics (to Gerard Mourou and Donna Strickland). Here is a figure from the Nobel Prize announcement:



It seems possible at the end of a long research program to achieve 100 x the ILC gradient of 35 MeV/m over multiple stages.

Then, after the ILC phsics program is complete, we can have a 30 TeV electron collider in the ILC tunnel.

-> ALIC <-

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/

This paper discusses a roadmap to the ALIC collider.

The physics conveners are Junping Tian and MEP.

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,

$$\begin{aligned}\mathbf{R} &= \frac{100\ \mathrm{fb}}{(E_{\mathrm{CM}}\ (\mathrm{TeV}))^2} \\ &= 10^5\ \mathrm{events/yr}/10^{35}/(E_{\mathrm{CM}}\ (\mathrm{TeV}))^2\end{aligned}$$

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 discussing new physics at ALIC, we need to discuss the Standard Model at these energies. SM processes have new features.

The first one is obvious. Displaced SM vertices are highly displaced:

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

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

So (as a first idea),

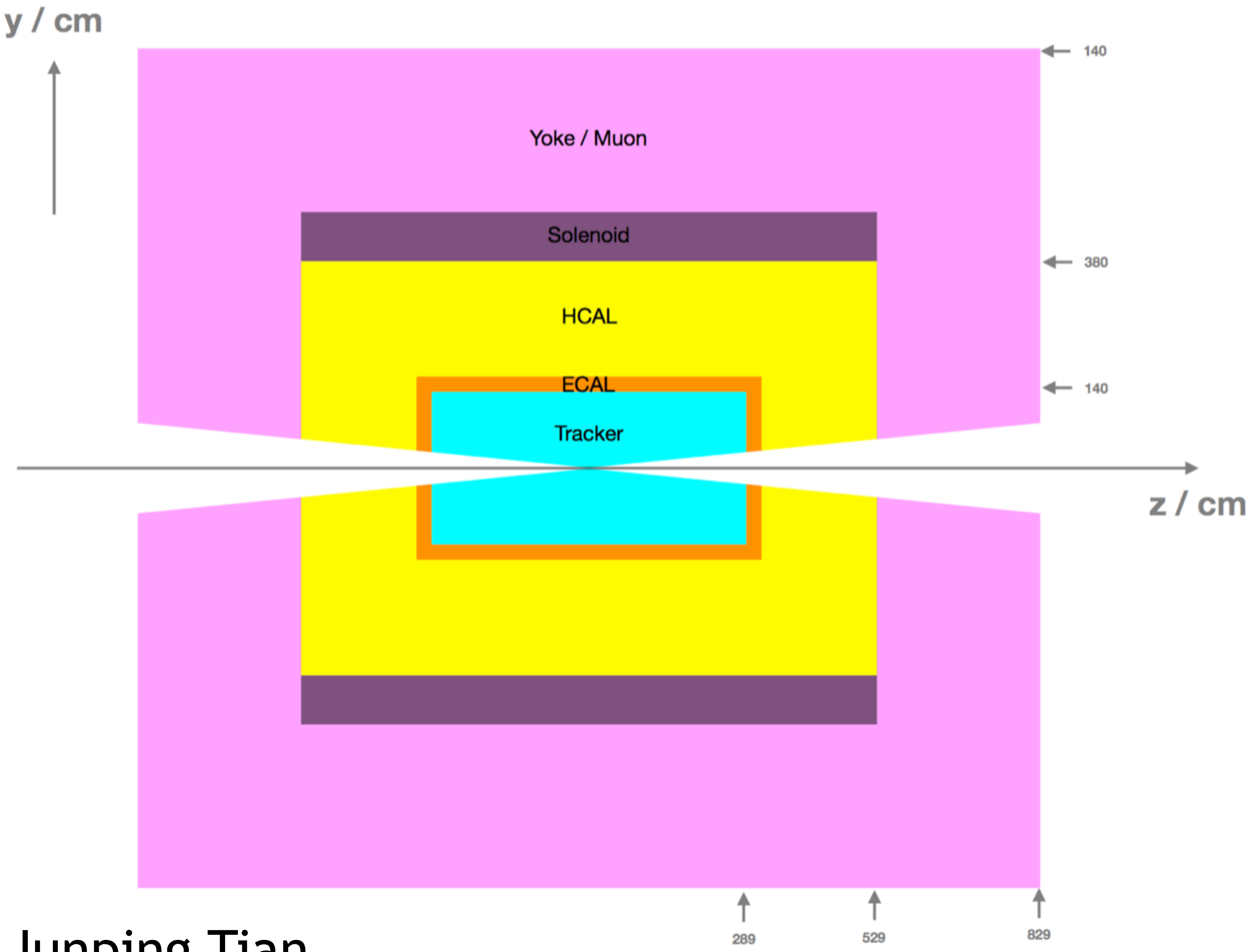
no vertex detector is needed

hermeticity is not an issue

the tracker will find SM vertices
and measure the sign of charged tracks

the burden of momentum/energy measurement
will be on a tracking calorimeter

ALIC Detector Envelop



Junping Tian

ballpark parameters

- Tracker: full silicon

  inner: pixel, σ~3- 5 μm
  outer: strip, σ~7-10 μm

  $\frac{\Delta P_t}{Pt} \sim 20\%$ (for Pt=10 TeV)

- ECAL: Silicon-Tungston

  longitudinal: 30 radiation length (X_0)

  $\frac{\Delta E}{E} \sim \frac{18\%}{\sqrt{E}}$ (E in GeV)

- HCAL: Scintillator-Iron

  longitudinal: 9 hadronic interaction length (X_0)

  $\frac{\Delta E}{E} \sim \frac{60\%}{\sqrt{E}}$

- Solenoid: 5T
- Return Yoke / Muon Chamber: 2.5T

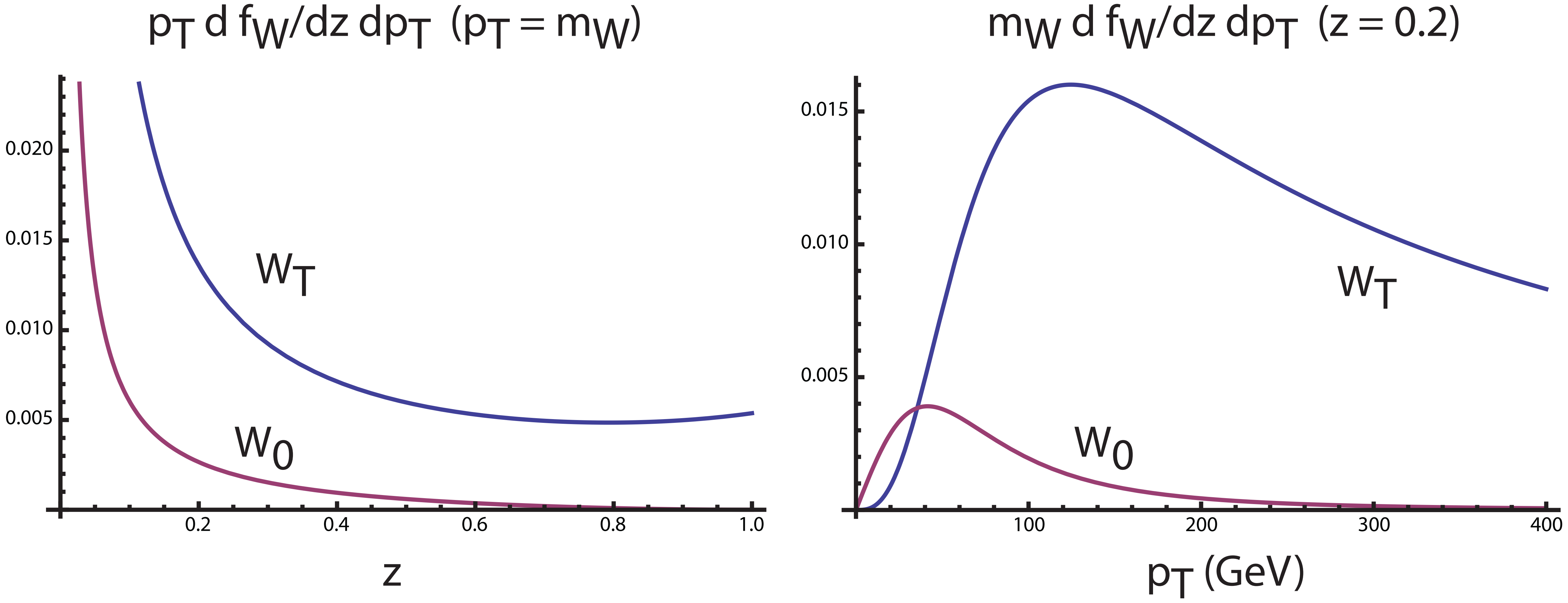
Electroweak ISR, FSR is an order-1 effect:

For μL (but not μR) the probability of radiating a W in the final state is

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

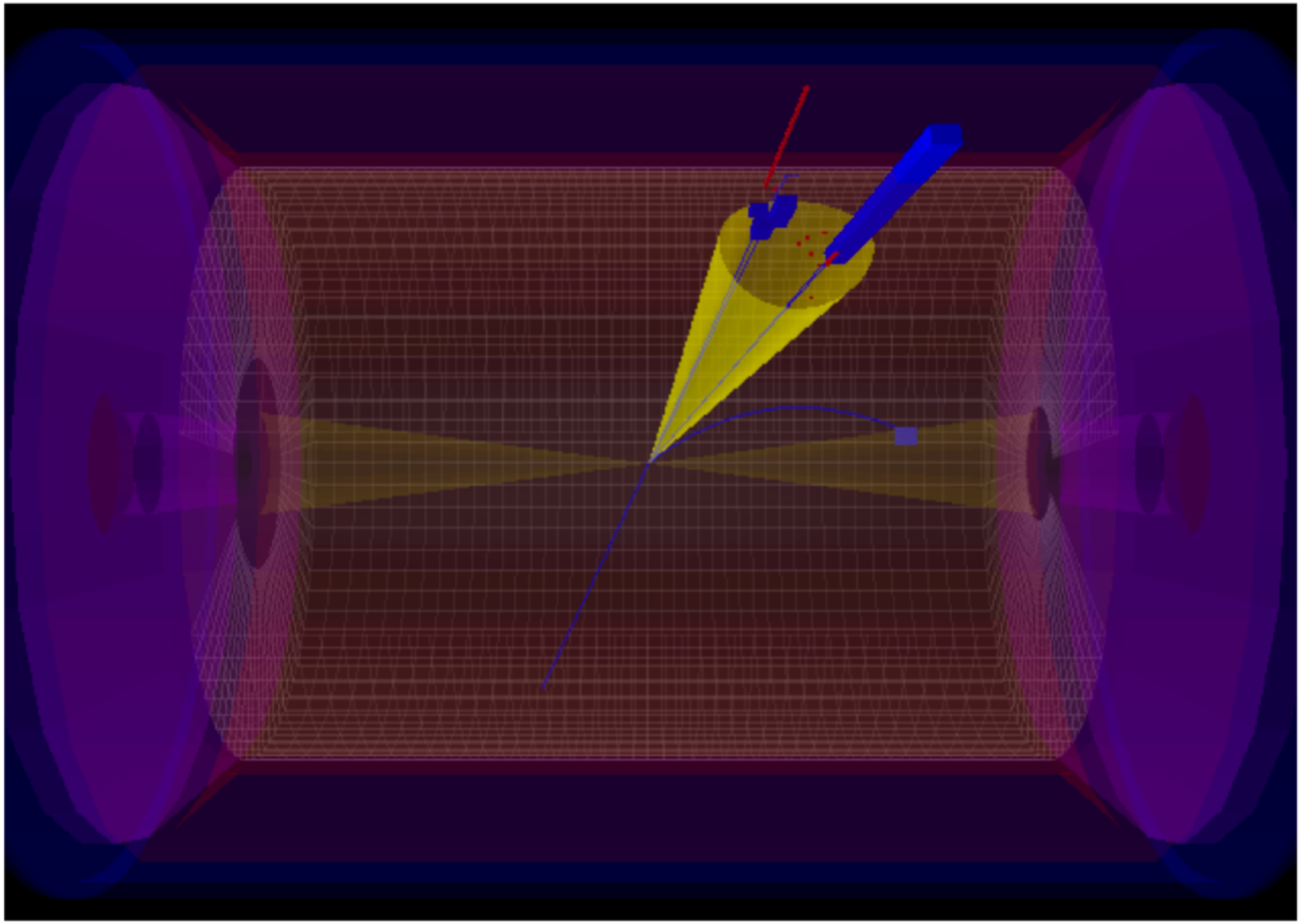
so muons are often seen as ν + (hadronic W)

similarly, WW scattering is an order-1 component of the menu of annihilation reactions


$p_T\, d\, f_W/dz\, dp_T$ ($p_T = m_W$)
0.020
0.015
0.010
0.005
0.2
0.4
0.6
0.8
1.0
z
W_T
W_0
$m_W\, d\, f_W/dz\, dp_T$ ($z = 0.2$)
0.015
0.010
0.005
100
200
300
400
p_T (GeV)
W_T
W_0

A typical event display in Delphes

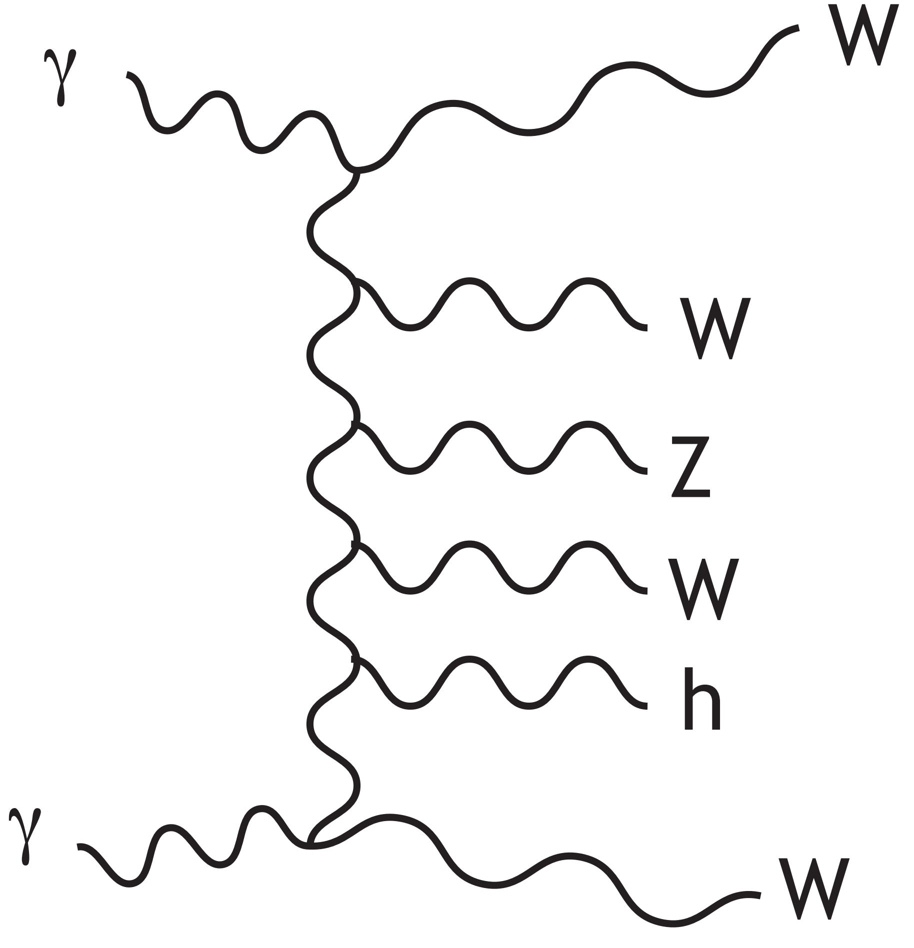
e+e- -> μ+ μ- @ 30 TeV, with final state electro-weak shower



An important new component of the SM background is the multiperpheral W exchange:

This generates multiple production of W, Z, h, at rates much higher than annihilation at the full energy.

Jongmin Yoon and I are writing a generator for this class of events.



(Marc Riembau)

e+e- or γγ ?

e+e- colliders have well known advantages, but

Beamsstrahlung in bunch collision gives a 1% energy spread at 250 GeV, 4% at 1 TeV, and limits luminosity above that energy.

Plasmas are not CP-symmetry; they are focusing for electrons, defocusing for positrons.

An alternative is to build an e-e- collider and convert e-s to γs near the interaction point.

The traditional idea of a γγ collider is to collide focused electron beams of high energy E with low-energy photon beams, mm in front of the collision point. The photons with the hardest Compton scatters follow the electron path and collide at energy close to 2E.

(Ginzburg, Kotkin, Serbo, Telnov)

Critical parameter: $x = \frac{s(e\gamma)}{m_e^2} = \frac{4E\omega}{m_e^2} = 15.3\ \frac{E}{\mathrm{TeV}}\ \frac{\omega}{\mathrm{eV}}$

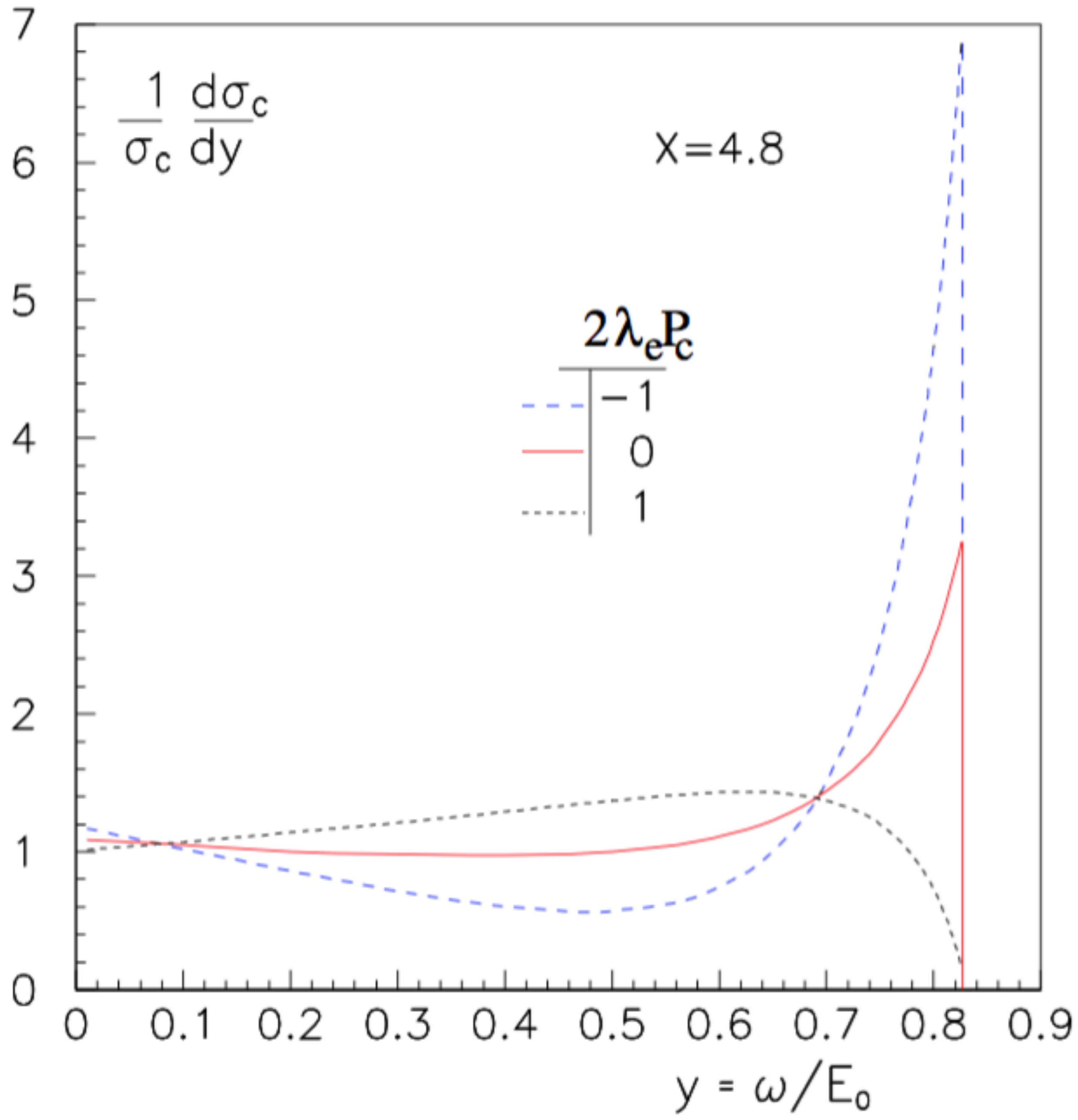
Maximum photon energy: $E_\gamma / E = \frac{x}{(1+x)}$

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

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

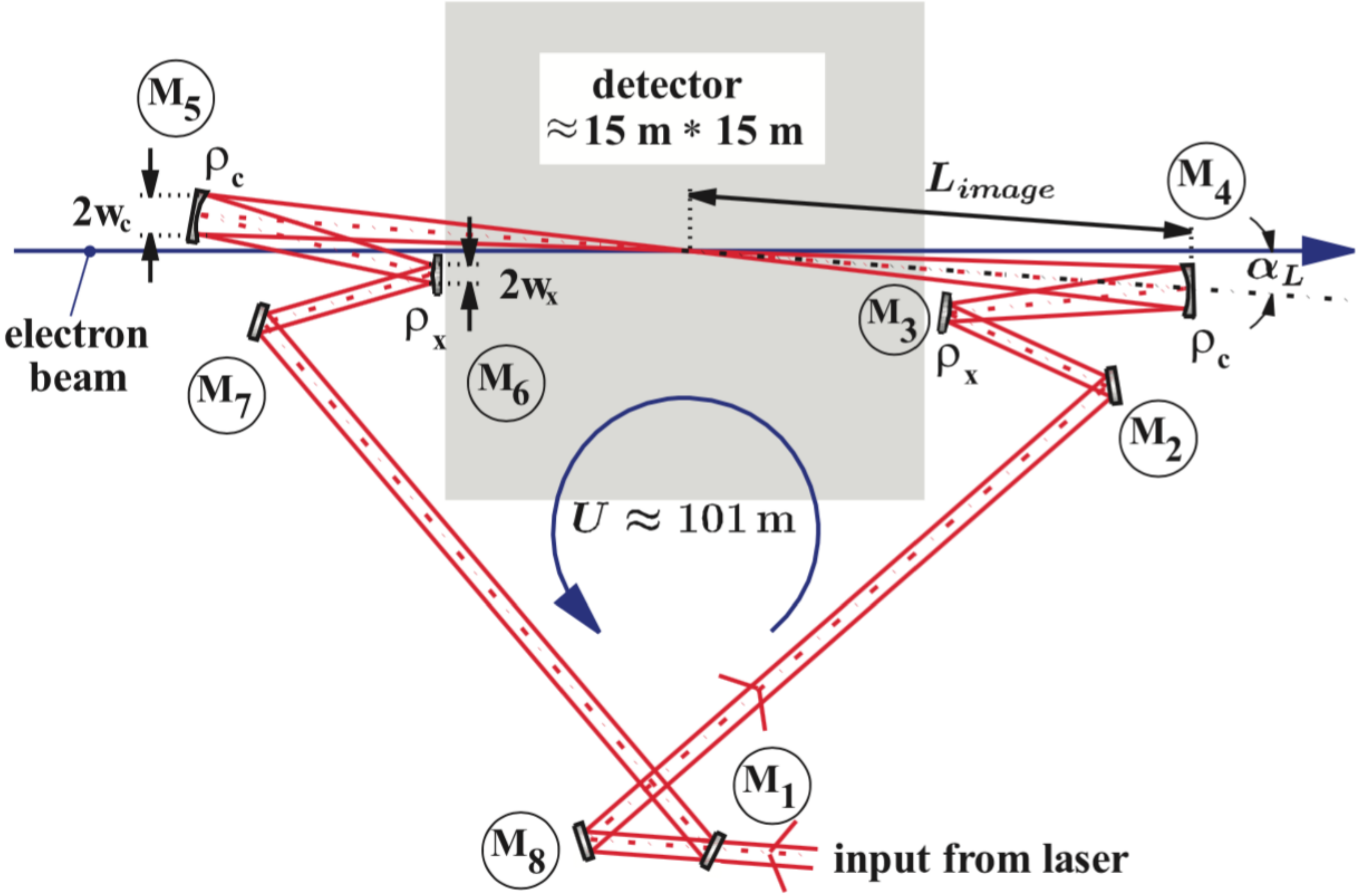
but it is possible to work above this boundary.

The sharpness of the γ energy spectrum is controlled by beam and laser polarization.



The produced γs are highly polarized, so all polarization observables are accessible.

For ILC applications, we envisioned near-IR photon pulses of 10 J / pulse, to achieve about 10% of the nominal e+e- luminosity. Higher luminosity is possible with round beams (Telnov). The correct format of γ pulses would supplied by an optical cavity that surrounds the detector (Monig)



It would be very interesting if an FEL-driven optical system could be integrated with a plasma-based collider.

A γγ collider has the disadvantage that γγ cannot couple to s-channel vector resonances.

However, it is typical in extra-dimensional and RS models that the electron wavefunction also has small overlap with vector resonances.

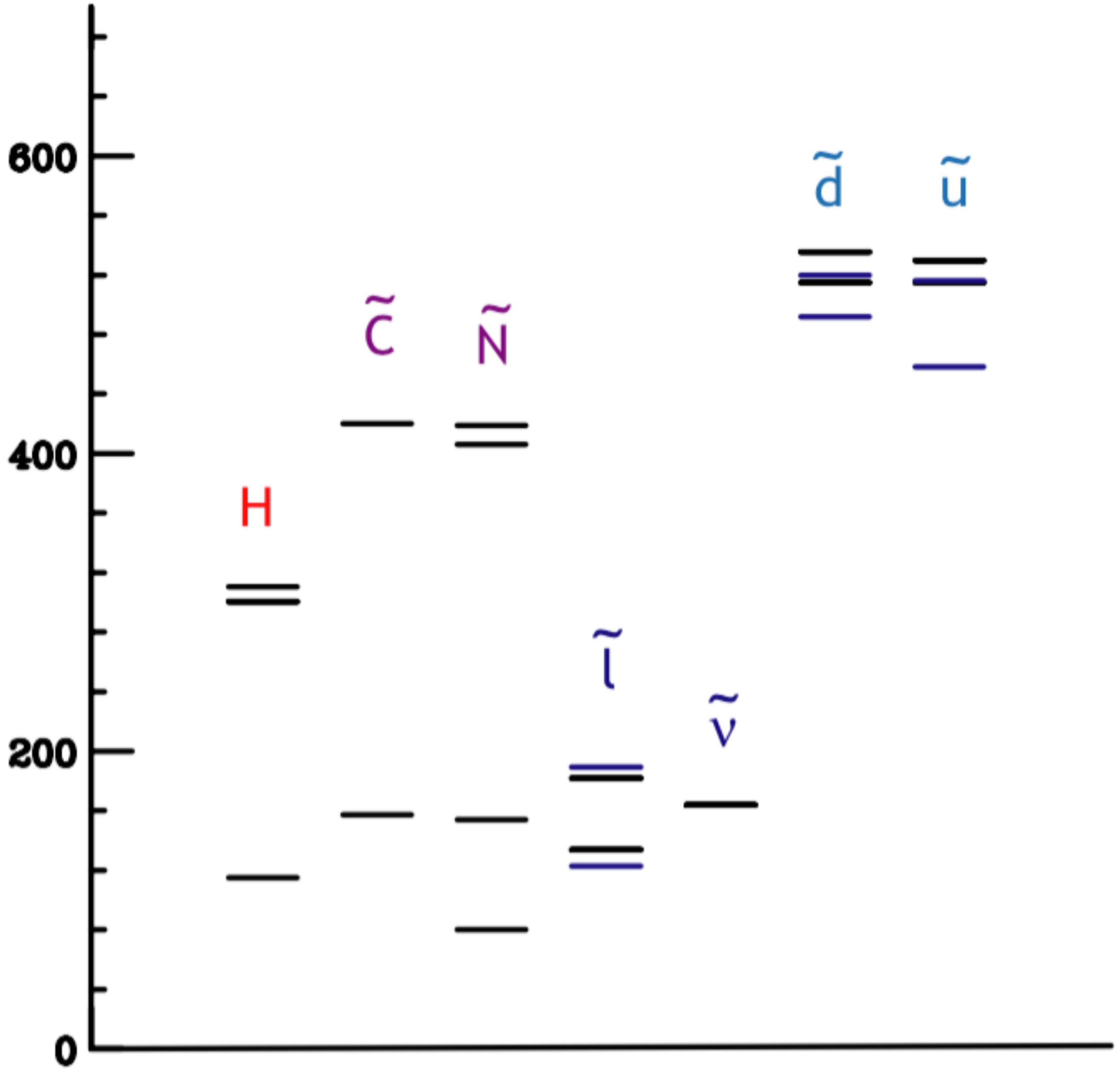
For new particle pair production,

γγ couples to all states with nonzero electric charge.

The γγ pair production cross section is larger than that of e+e- by about a factor of 3.

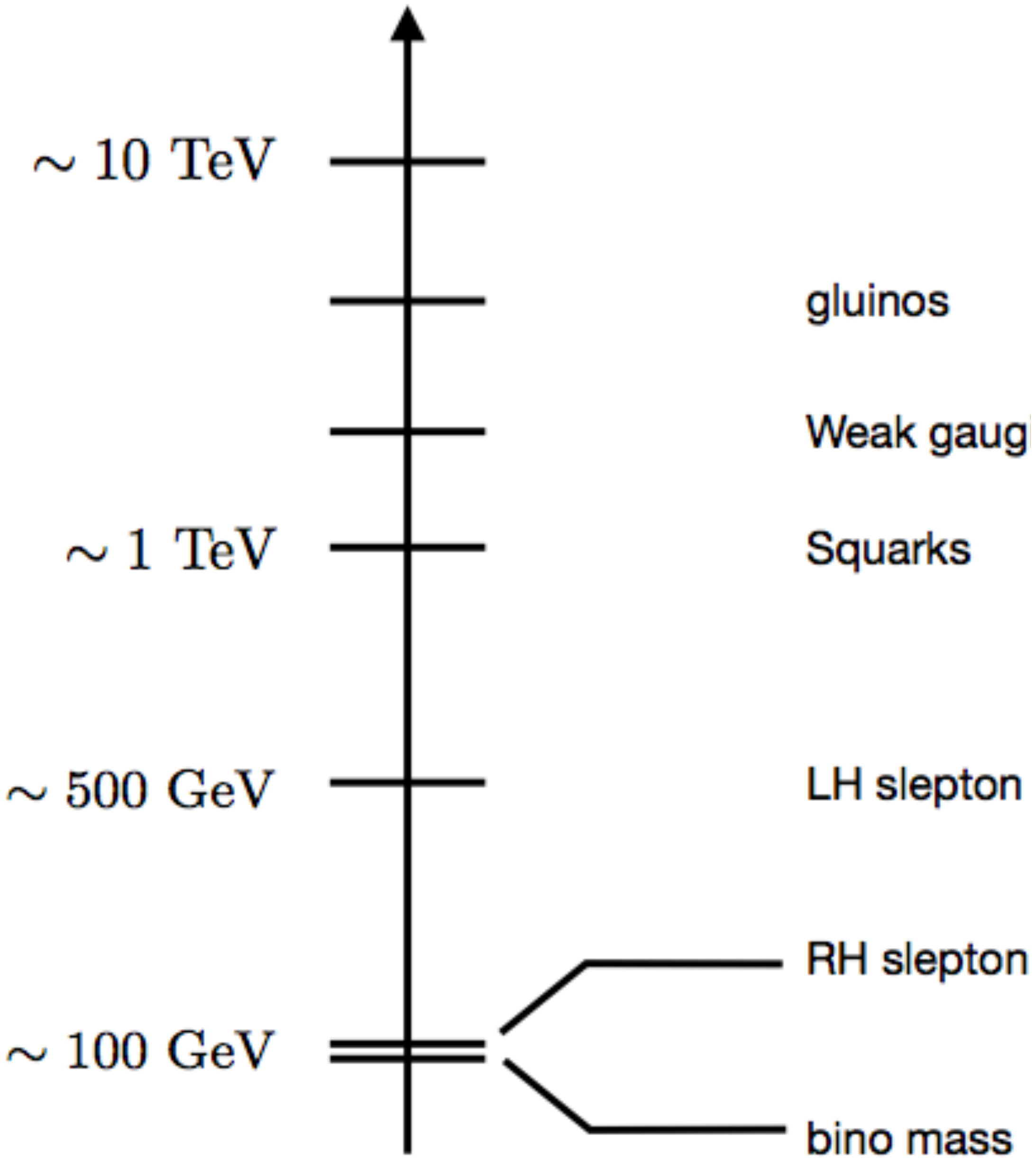
Physics goals of a 30 TeV γγ collider:

There is a straightforward story concerning searches for individual BSM particles. For the mass range, the bar has been raised. People used to show SUSY spectra like this one:

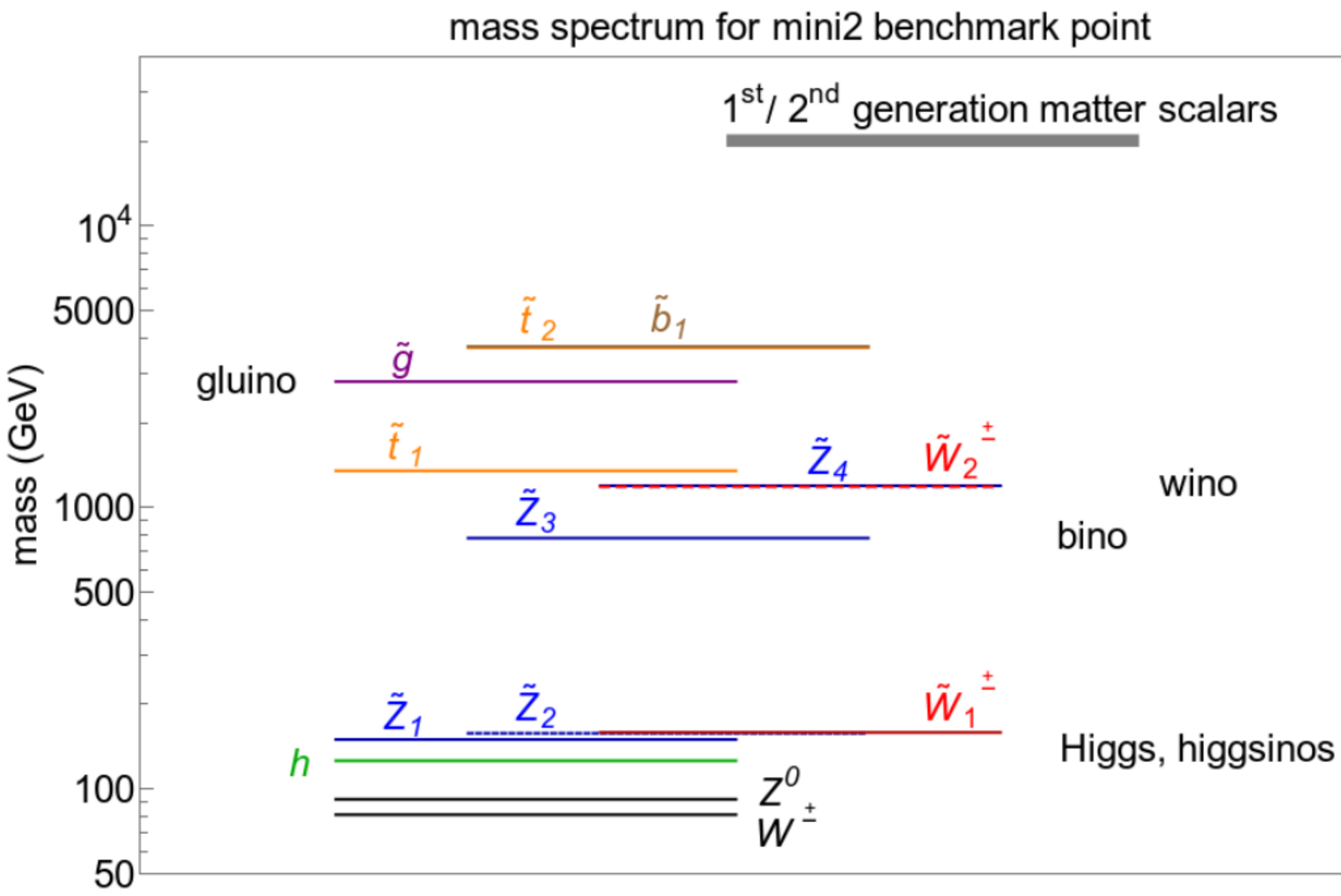


(from my TASI 2007 lectures)

Here is are 2 modern viewpoints (maybe still too conservative)



Chakraborty, Martin, and Roy



Baer, Barger, Savoy, Serse, Tata

However, I feel that the true value of thinking about these high energies comes not from the reach for single BSM particles but rather from access to the full structure of BSM concepts.

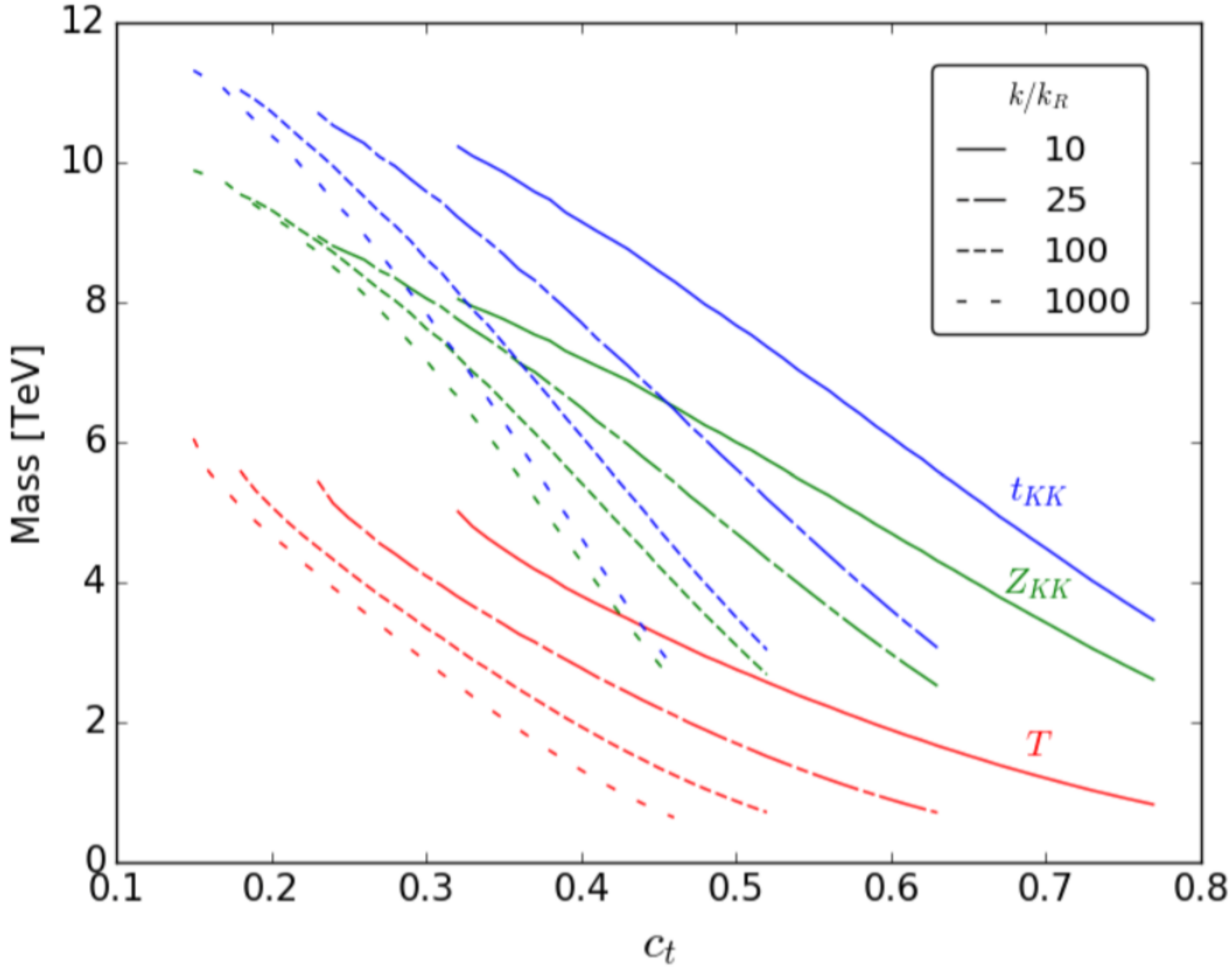
Composite Higgs:

The difficulties of building natural SUSY models gives new weight to the study of Composite Higgs models.

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 10-20 TeV region.

The full understanding of these models will require mapping the spectrum of strong interaction eigenstates, in the same way that we needed to meson/baryon spectrum to learn the structure of QCD.

eigenstate masses in a realistic RS composite Higgs model



Yoon + MEP

Extra space dimensions:

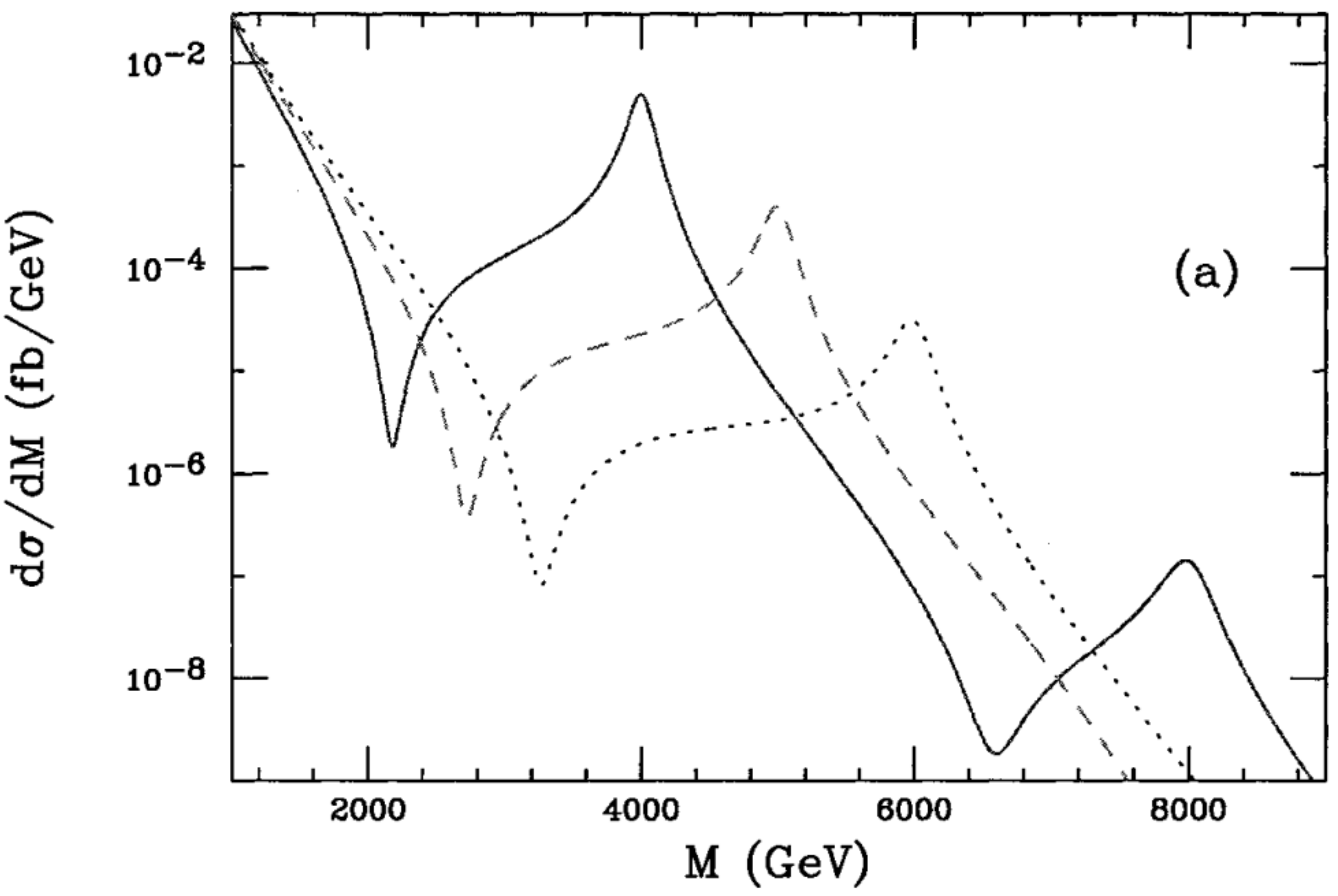
Often, we analyze composite Higgs models using a dual (Randall-Sundrum) 5-dimensional picture. There are more general models with TeV-scale extra dimensions.

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".

These authors argue that, above 30 TeV, typical SM final states in e+e- are dominated by threshold production of

$$W_0, Z_0, h$$

with typical CM energies near m_W, m_h. Then the typical event would have hundreds of heavy bosons.

(These authors make extravagant claims about solving the hierarchy problem, revising cosmology, etc. However, it is not necessary to accept those claims to believe that Higgsplosion takes place for timelike momenta.)

Quantum gravity:

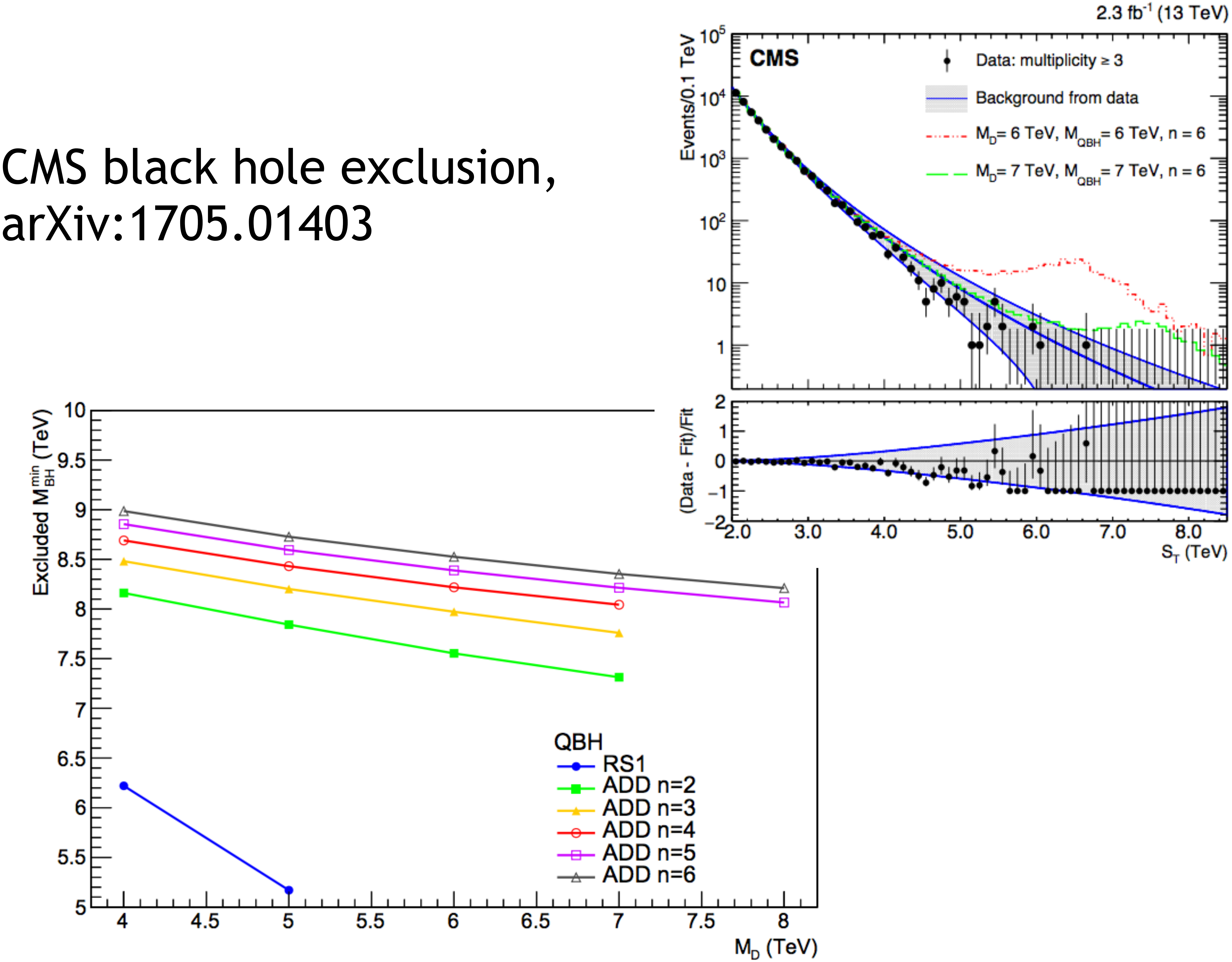
There is a variant of extra-dimensional models (Arkani-Hamed-Dimopoulos-Dvali) in which Standard Model particles are restricted to a 3-d “brane” while gravity can fill the extra dimension.

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.

It is attractive to guess that 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.   An especially appealing idea is that the vector leptoquarks form a non-Abelian gauge group, with only the lightest state being visible at LHCb.

(Allanach, Gripaios, You)

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.