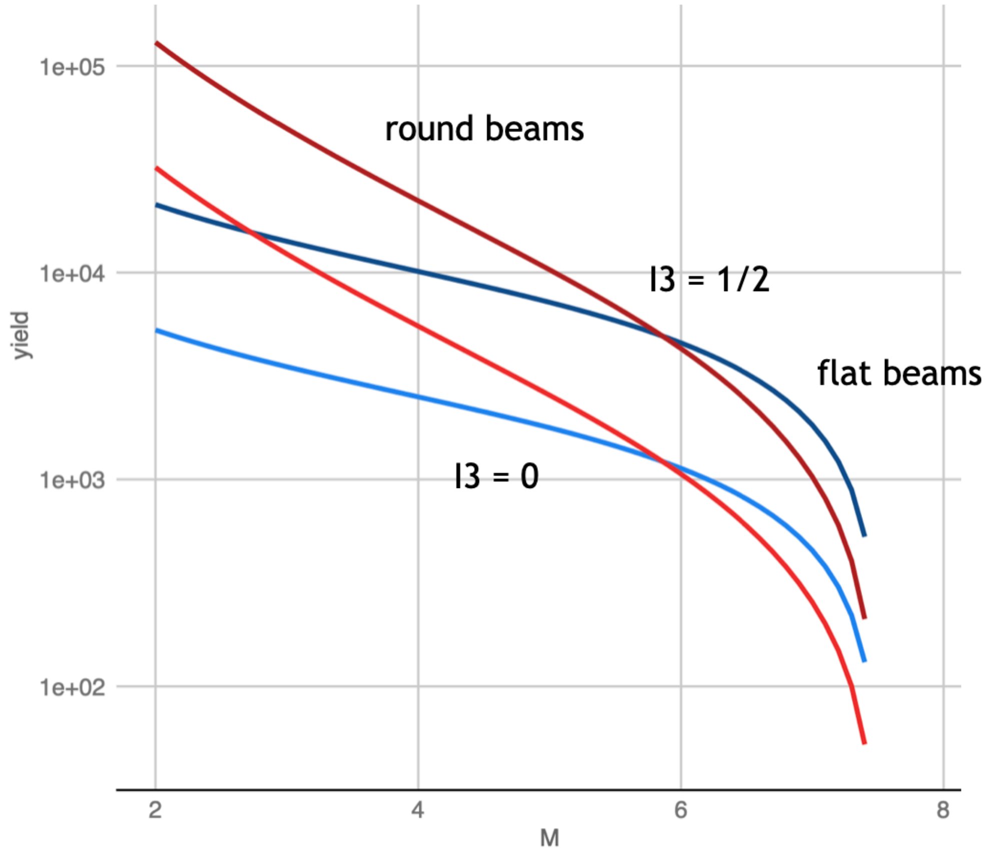
Physics Considerations for 10-30 TeV e+e-, γγ, and μ+μ- Colliders



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thanks to Kalyan Narayanan and to the SLAC-LBNL working group on 10 TeV physics organized by Spencer Gessner.

For future colliders, the next major step in energy will be to the 10 TeV parton energy scale. This is the goal of FCC-hh, SPPS, muon colliders, plasma wakefield electron colliders.

Today, there are no reasonable solutions to reach this energy scale:

High-field dipoles for pp colliders have cost/m >> NbTi LHC magnets.

Muon cooling is unproven; phase space compression of 10^6 is needed.

Plasma wakefield accelerators are not yet at the stage of consistent, reproducible operation.

Major R&D programs are needed to have such colliders in operation, even 30 years from now.

Still, it is likely that lepton colliders will win out and will be "energy frontier" or "discovery" machines in the usual sense.

In the meantime, we ought to discuss the physics motivation for these machines. As high-energy physicists, we feel that "exploration" is sufficient reason. However, for a multi - $B collider, we should have a more definite target.

We have a need for new fundamental interactions, and new particles, to give a physical model of electroweak symmetry breaking.

Before the LHC, the most attractive models of EWSB involved new particles with few-hundred GeV masses. Integrating these out gave the Higgs potential, unstable at the origin. Such models seem to be excluded by LHC searches. Still, there is room for more complex models with multiple stages of symmetry breaking. Such models are more complex, but there are actual models in this class. The alternative are less well formed ideas — anthropic arguments, appeals to cosmology, or other accidents of nature.

Thus, it is important to continue the search for pair production of new particles, and the search for s-channel resonances, even to the 10 TeV range of masses.

Pair-production cross sections for new heavy particles follow the law

$$\sigma \sim 1/M^2$$

and typically, for synchrotrons and linear colliders, $\mathcal{L} \sim E_{CM}$,

so it is an issue to maintain the required luminosity.

The one exception here is the muon collider. Since the muons live longer, proportional to E_{CM}/m_μ , the integrated luminosity goes as

$$\mathcal{L} \sim E_{CM}^2$$

The muon collider is, in this and other ways, an ideal machine for going to the highest energies.

Beam related backgrounds are difficult, but in the detectors of the future, timing in each cell will greatly assist with this problem. For a current review, see: Casarsa, Lucchesi, and Sestini, arXiv:2311.0380.

Of course, this all depends on whether one can cool muons with sufficient efficiency to get any luminosity at all.

For electron linear colliders, the small size of bunches leads to a strong beam-beam interaction and beamstrahlung, and this produces a substantial spread in the effective CM energy. To judge the physics of e+e- colliders at 10 TeV, one must understand the properties of the luminosity function

$$\mathcal{L}(z, ECM)$$

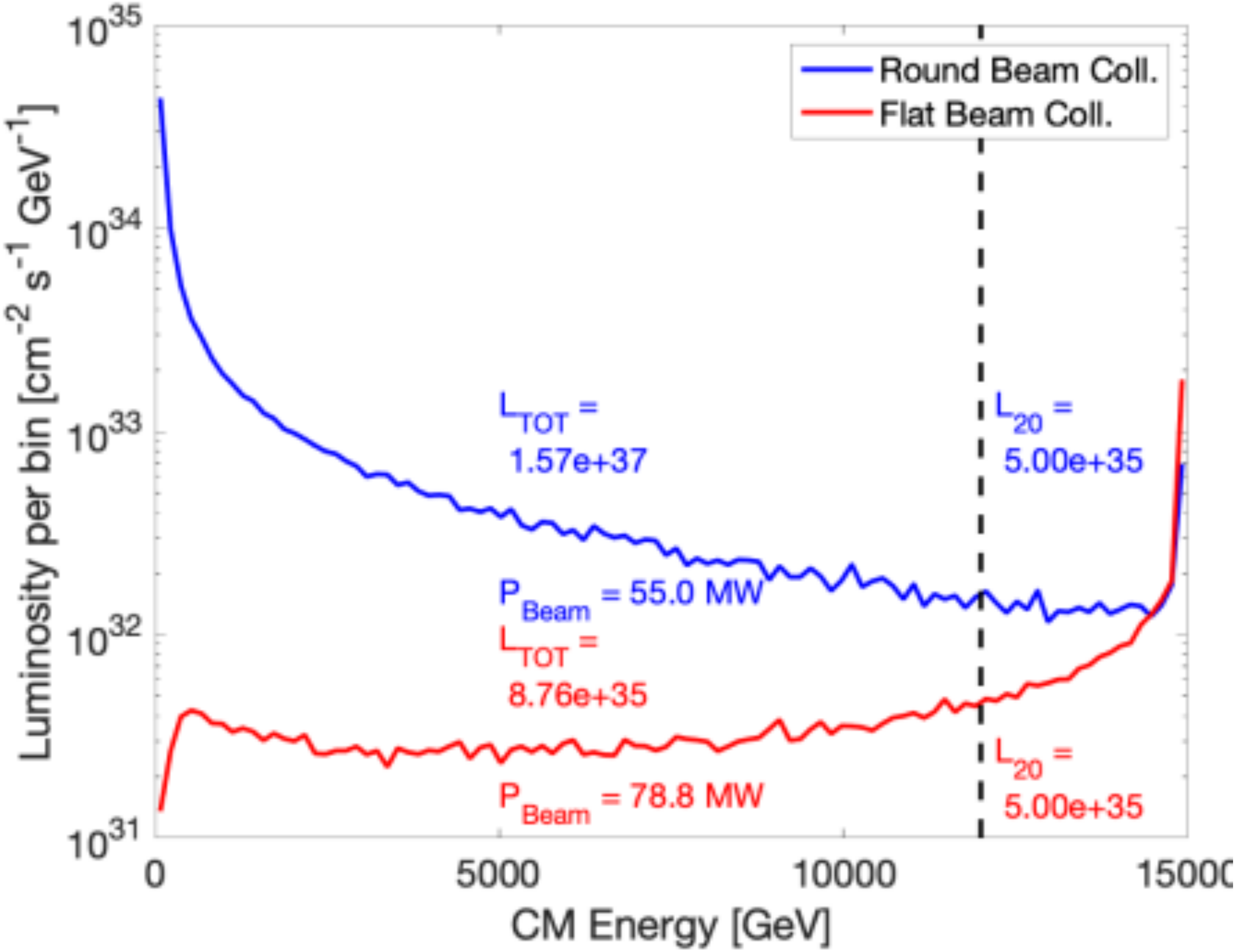
Currently, this is computed from codes such as Guinea-Pig and CAIN.

It is often said that this physics makes e+e- colliders ineffective above CM energies of 3 TeV. I feel that this is an exaggeration.

For new particle pair-production, it is not necessary to have all of the luminosity concentrated within 1% of z =1. As a rule of thumb, it is the luminosity within 10-20% of the nominal CM energy that is important.

Also, beamstrahlung-generated luminosity spectrum peak near z = 1 and also contain a contribution proportiaonal to $\delta(z-1)$, so even narrow resonances can be visible.

Gessner and Cao used Guinea-Pig to compute some sample luminosity functions for 15 TeV e+e- colliders.   These have rather aggressive parameters, see Barklow et al., arXiv:2305.00573.



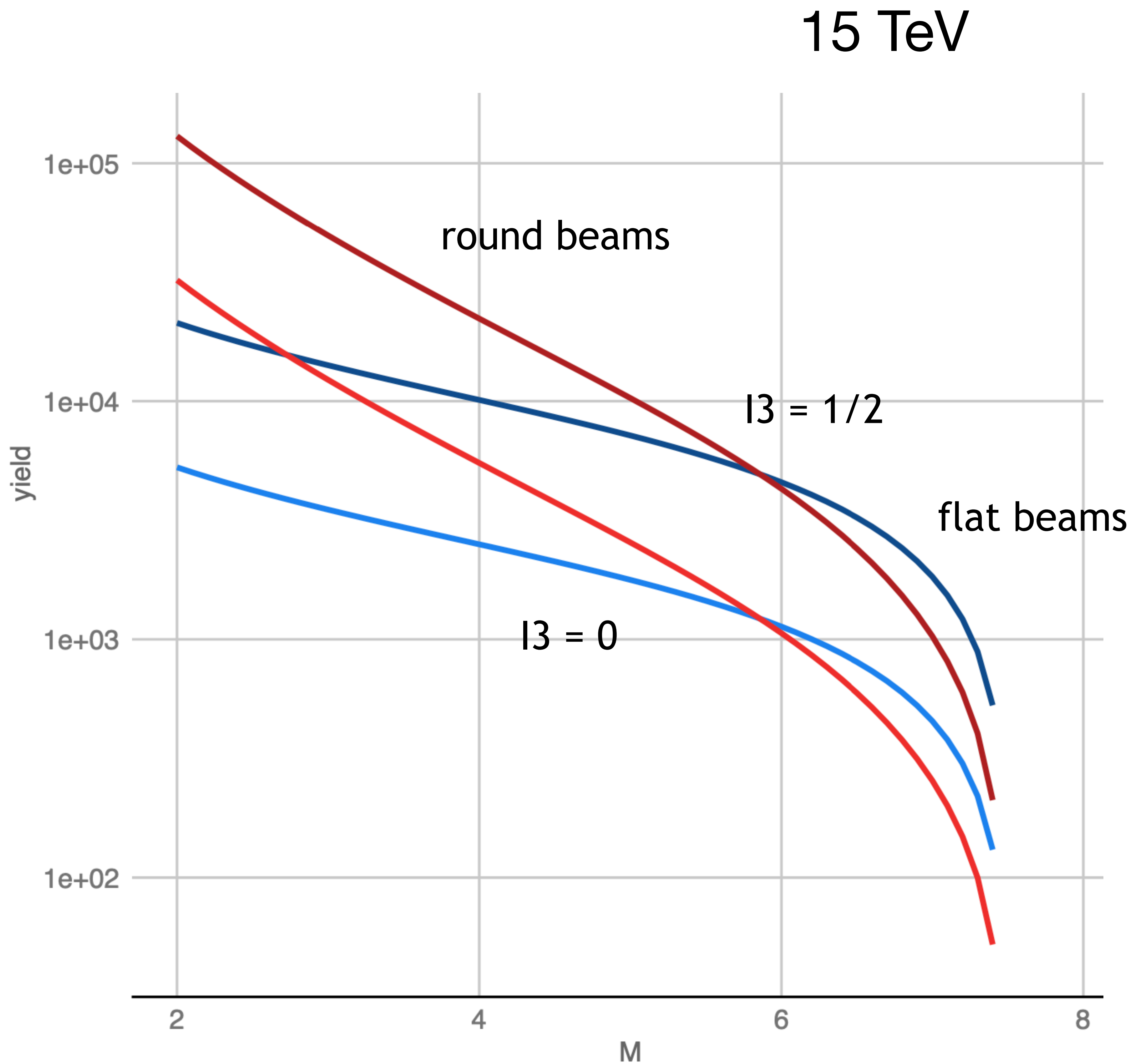
Their goal was to have the lumi within 20% = $5 \times 10^{35} = 1\ \mathrm{ab}^{-1}/\mathrm{yr}$

Using these functions and the SM cross sections for vectorlike fermion production, we can compute the yield of fermion pairs, assuming their SM quantum numbers:

$I^3 = -1/2, Y = -1/2$ or $I^3 = 0, Y = -1$

An important question is, how many pair events do we want? A simple answer (L-T Wang) is 20 signal events for discovery. I assume that we would like to study the new particles. For this, ~ 10,000 events would be needed.

The determination of the mass of the produced particles falls mainly on the detector, as at a hadron collider.

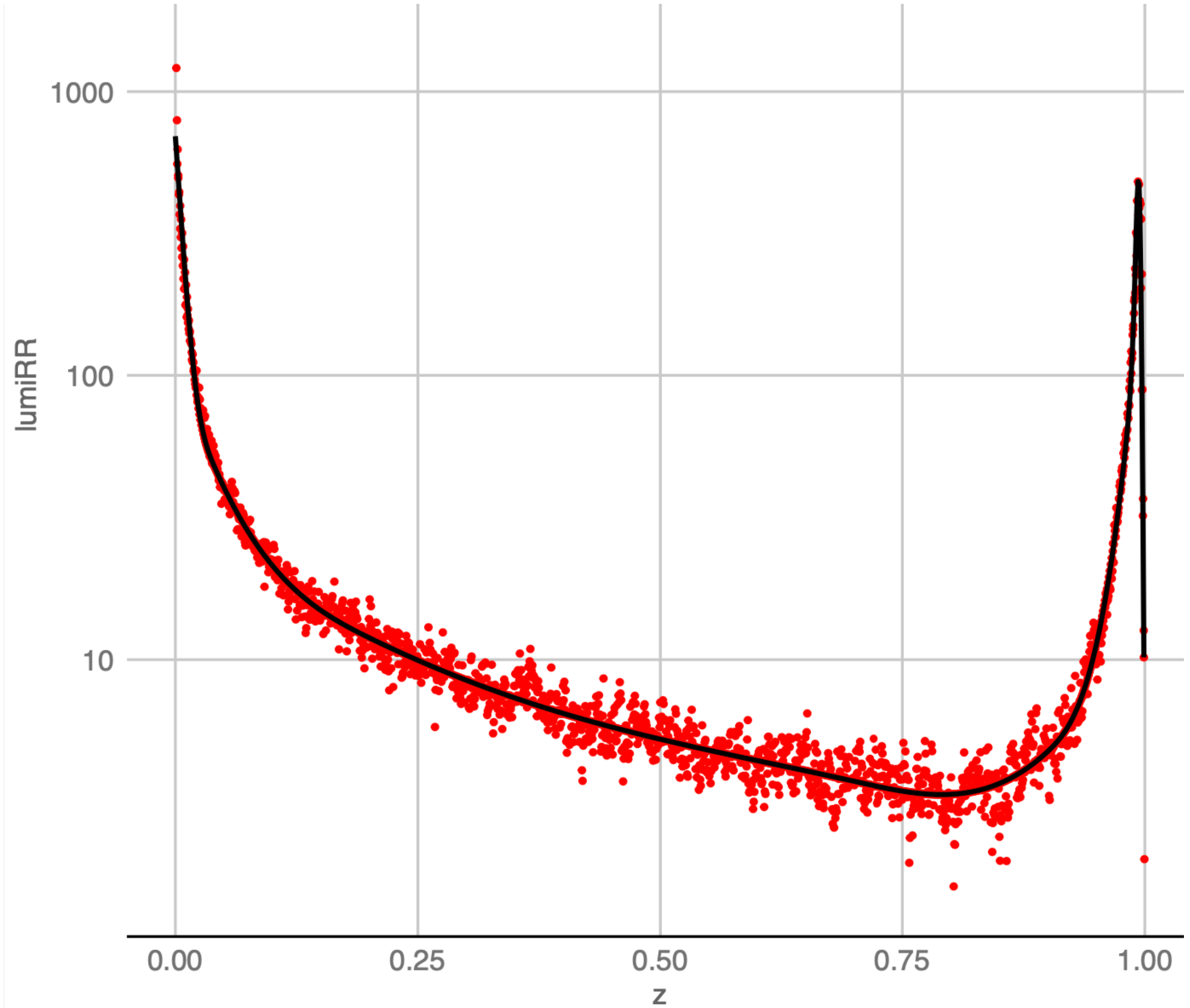


15 TeV
round beams
I3 = 1/2
flat beams
I3 = 0
1e+05
1e+04
1e+03
1e+02
yield
2
4
6
8
M

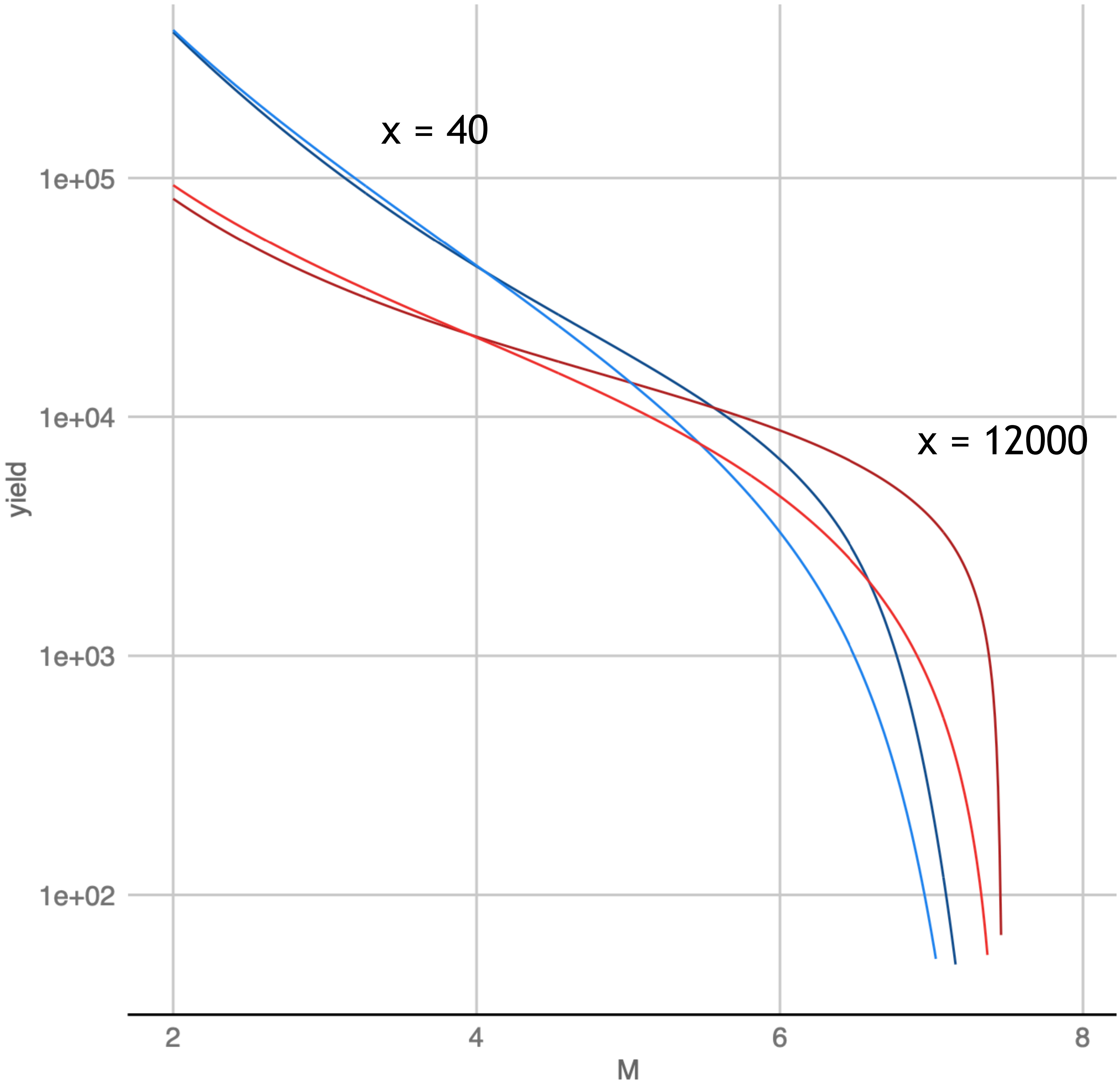
An alternative idea is to convert e- beams to γs using Compton backscattering.   Here the luminosity spectrum is shaped by the Compton cross section (which depends on polarizations), and by the residual electrons in the bunch-bunch collisions.

Tim Barklow will describe this analysis in the next talk.

Lumi functions that are highly peaked appear in some polarization states.



For comparison with the e+e- distributions, I have rescaled Tim's plots to luminosity within 20% of the nominal ECM = $5 \times 10^{35} = 1 \text{ ab}^{-1}/\text{yr}$



(σ depends only on the electric charge Q)

What about models with new physics characterized by narrow s-channel resonances, such as extra-dimensional or Randall-Sundrum models? Are these resonances still visible with strong beamstrahlung effects.

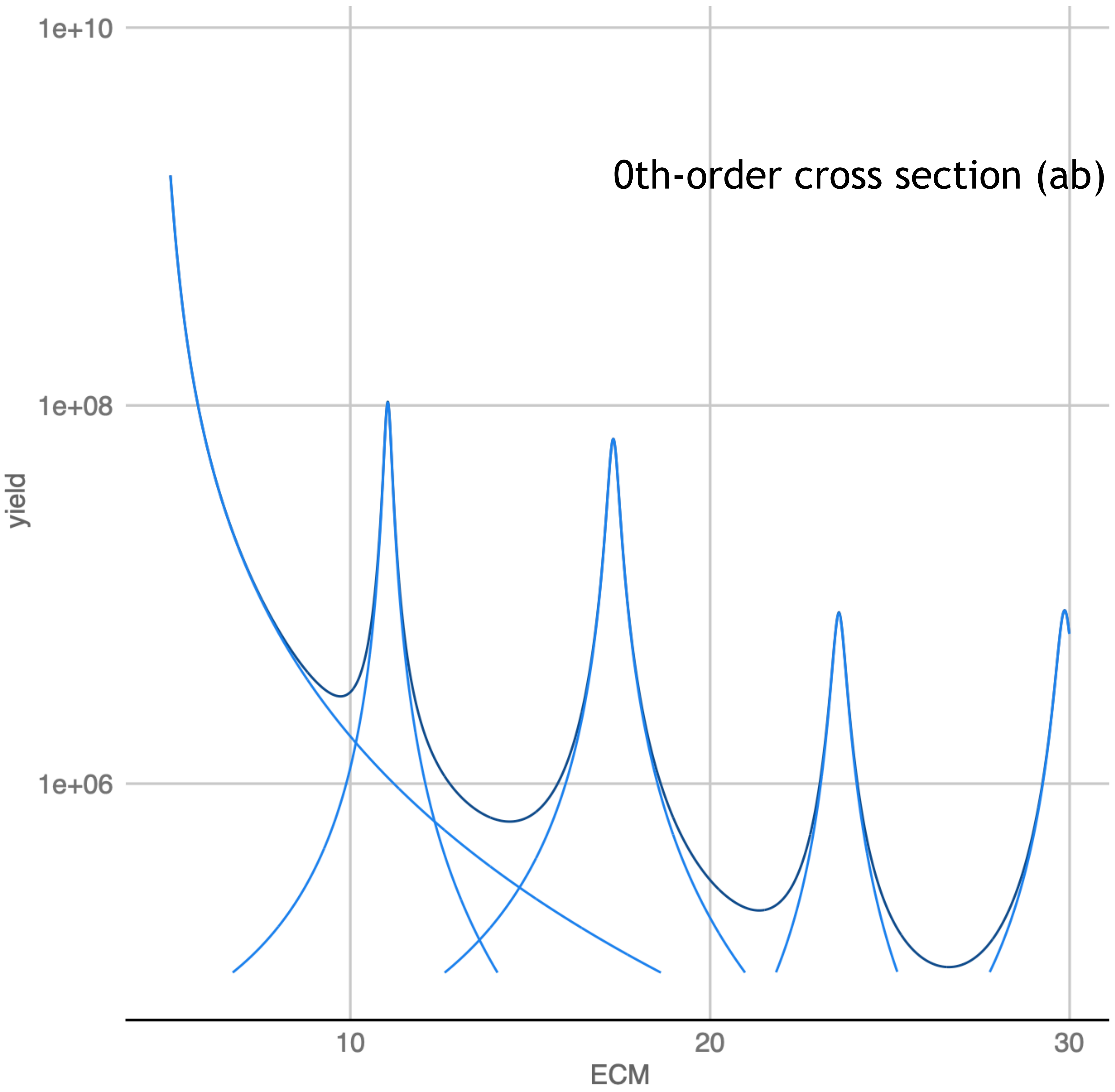
I'll show some results for a simple RS model that I have been studying with Kalyan Narayanan.

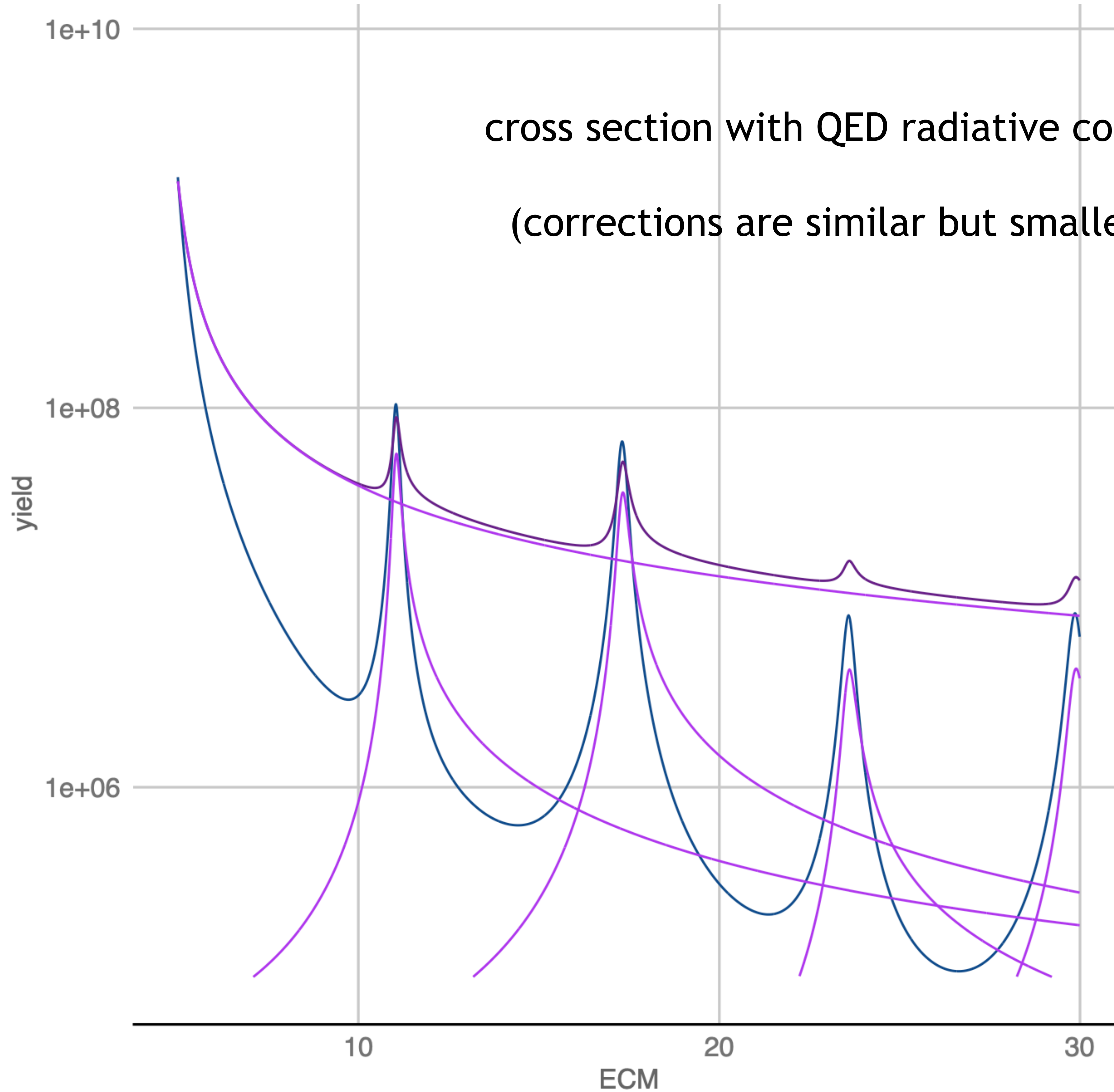
In e+e-, the main feature is strong s-channel resonances, with masses at

$$M_n \approx k_R z_n \qquad z_n = n\text{th zero of } J_0(z)$$

The cross=sections for producing these resonances, and their branching ratios, depend on the "compositeness" of the electron (or muon). There are additional resonances, crucial to the structure, that cannot be produced from l+l- but can be seen in resonance decays. These include excited states of the electron.

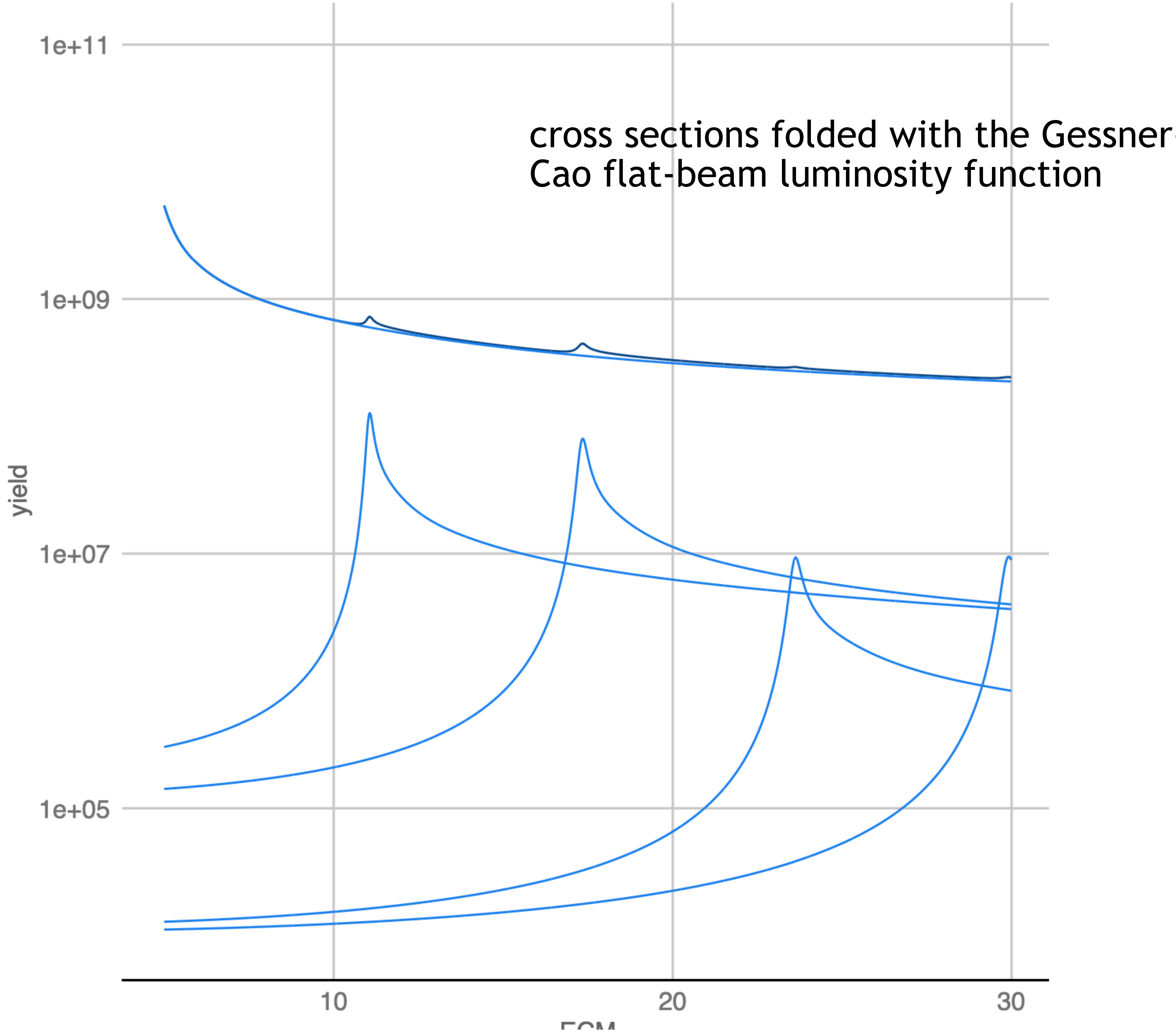
In γγ, the resonances are not accessible in the s-channel. But they will be pair-produced. The production cross section is the standard QED cross sections depending only on the mass and electric charge Q.


0th-order cross section (ab)
1e+10
1e+08
1e+06
yield
10
20
30
ECM



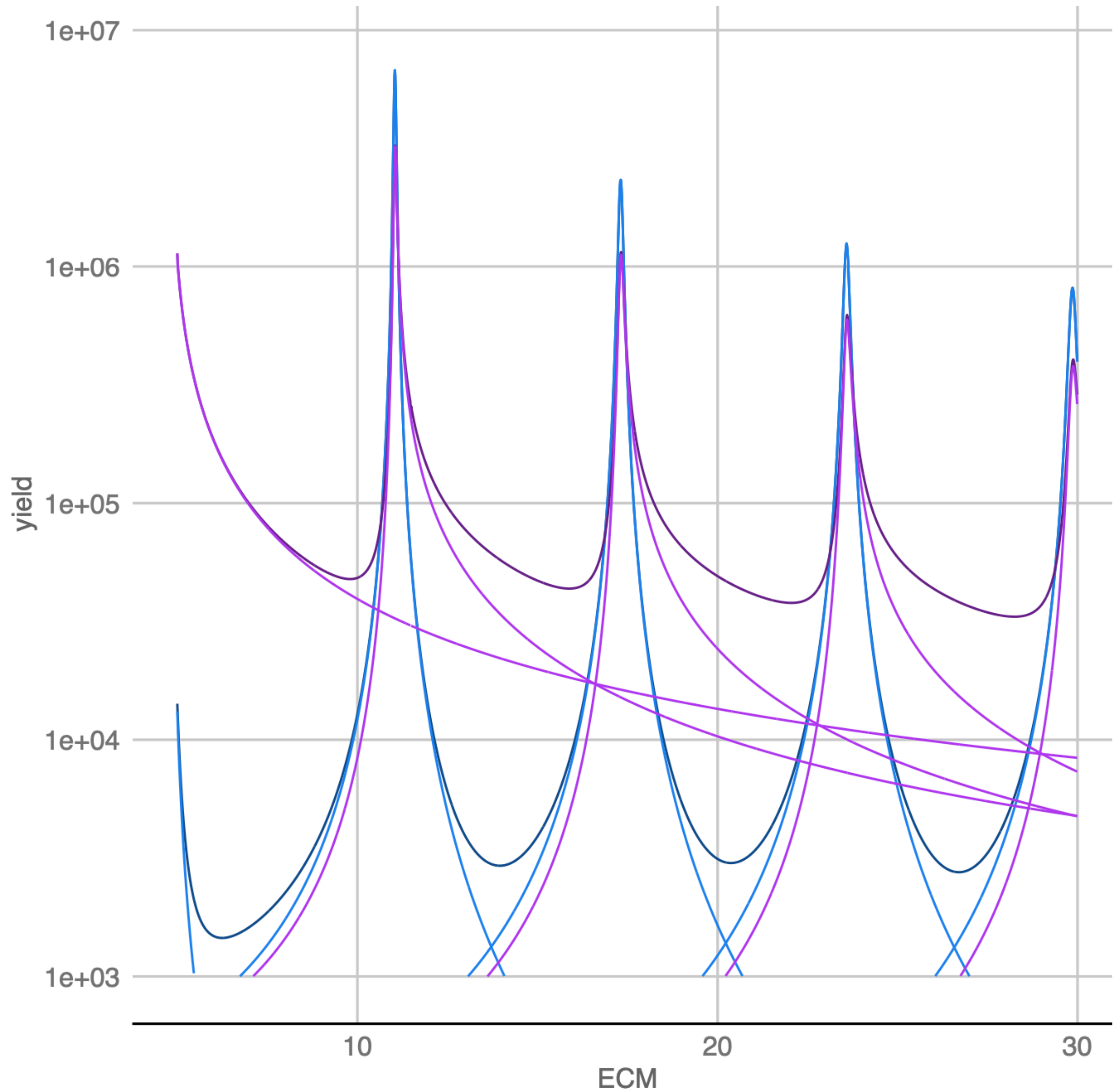
cross section with QED radiative corrections

(corrections are similar but smaller for muons)



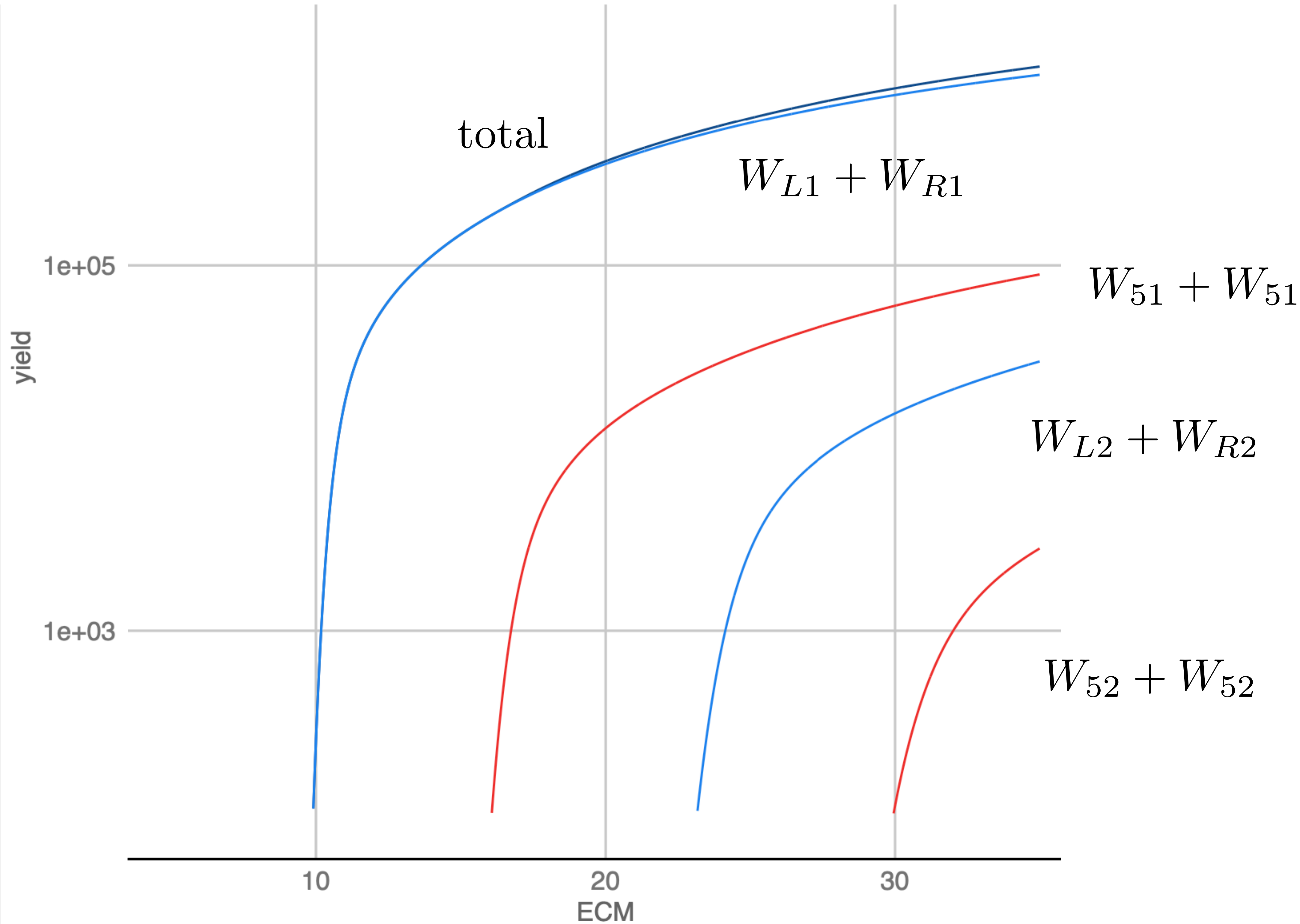
There are plenty of events! The detector will separate the various resonances.

The cross sections do depend strongly on compositeness of the electron or muon. Compare to another parameter setting:



If the μ or e masses are explained by RS dynamics, these cross sections are suppressed by m_ℓ^2/m_t^2 .

In this case, we will still learn much from γγ production, for which the cross section depends only on QED.



It would be wonderful to have a 10’s-TeV linear e+e- collider for which also the γγ option would be available.

If there is no method to accelerator e+ in plasmas, the γγ collider is an alternative that might be the most practical.

To make this available, we need a demonstration of a Compton backscattering collider.   This is another motivation for XCC.

One further note:

It is doubtful that the beam-beam physics in Guinea-Pig and CAIN is actually a precise prediction. The treatment of nonlinear QED processes and beamstrahlung is based on the assumption of a constant background field. This is strongly violated in cases with large disruption (ie. in all cases of 10 TeV colliders).

It is my belief (hope?) that a proper treatment of nonlinear QED will lead to smaller beamstrahlung effects and energy spread.

The laboratory for nonlinear QED available now is electron-laser scattering (SLAC-320 and LUXE at DESY). We need to follow this program very carefully.