How Should We Think about 10 TeV pCM Colliders ?

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A key recommendation of the recent P5 report is the visionary statement:

Recommendation 4: Support a comprehensive effort to develop the resources — theoretical, computational, and technological — essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

pCM = parton center of mass energy

Such a collider might be based on “proton, muon, or possible wakefield technologies”.

There are many challenges to be met for this program:

Energy: 10 TeV pCM exceeds the limits of all current accelerator technologies. Simply scaling up existing facilities is not an option.

Luminosity: Cross sections for producing new particles of mass M decrease as $1/M^2$. Thus, luminosities growing as E_{CM}^2 are needed. These are $\mathcal{L} \sim 10^{36}/\mathrm{cm}^2\mathrm{sec}$ $\quad 10\ \mathrm{ab}^{-1}/\mathrm{yr}$ for 10 TeV.

Backgrounds: Techniques to reach these high luminosities create very large backgrounds generated by beam particles.

Physics: Envisioned machines have price tags in the $ 10B range (many x LHC). Thus, a sharp physics case is needed: “curiosity” and “exploration” will not be enough.

Timescale: Developing solutions to the technical problems will take decades. Nevertheless, I think it is not too early for theorists to study the technical solutions and engage with the planning for physics.

Review the status and major issues of the 3 suggested technologies:

Protons: FCC-hh or SppS, 100 TeV pp colliders in ~ 100 km rings

Muons: Muon Collider

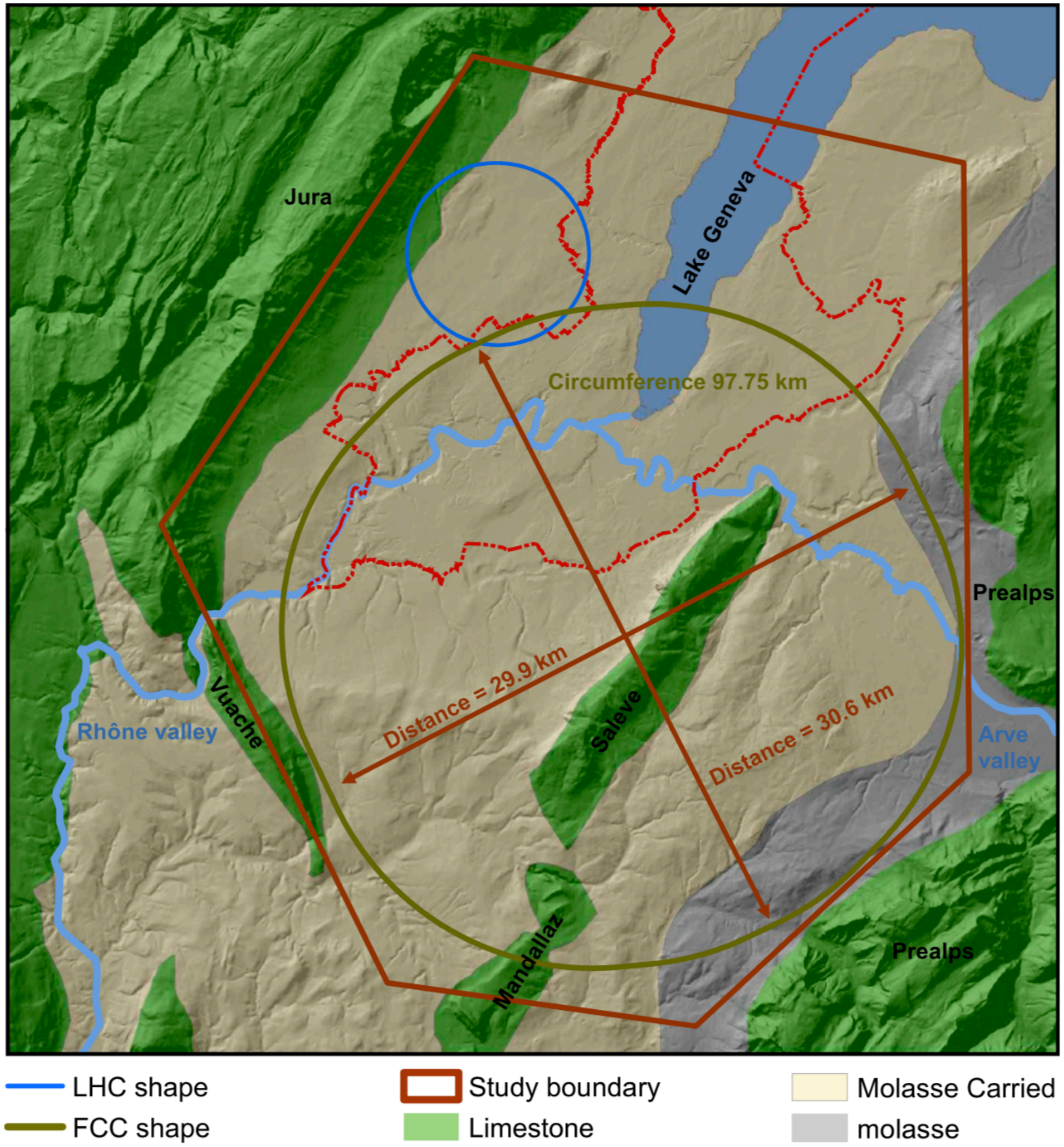
Electrons: beam- or laser-driven plasma wakefieild accelerators

I will quote costs from the report of the Snowmass Implementation Task Force (ITF), Roser et al, arXiv:2208.06030. These authors impressively evaluated and costed 30 future collider proposals. Costs are based on the current status of the accelerator design.

pp colliders — the unfortunate facts of life:

1. The proton is not an elementary particle, so $E(\mathrm{parton}) \sim 0.1E(p)$
2. Ring size is limited by the available magnetic bending field
3. $\sigma_{tot}(pp)$ is constant as production cross sections ~ $1/M^2$

This is the most conservative approach, but also, likely, the most expensive.

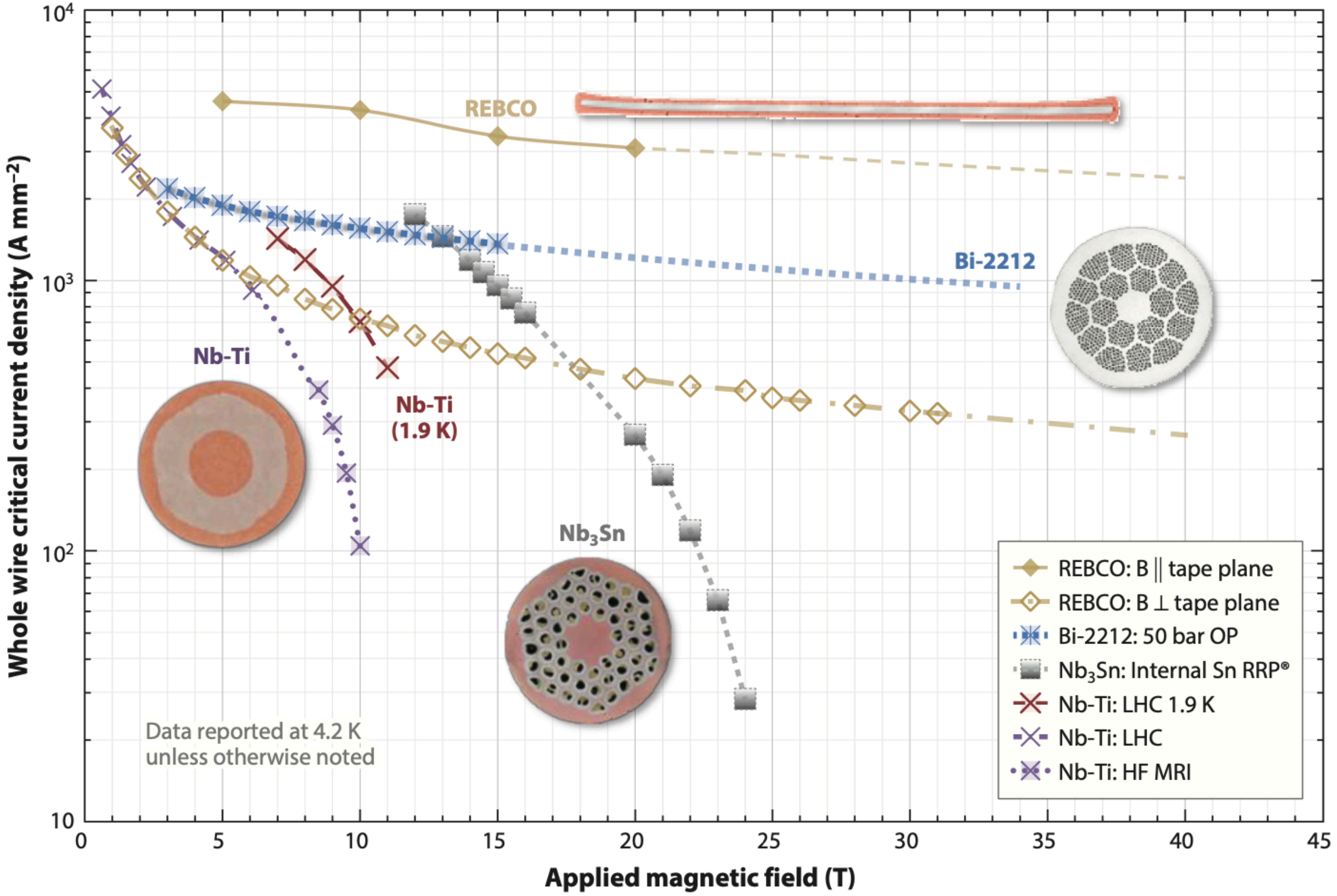


FCC-hh
CDR

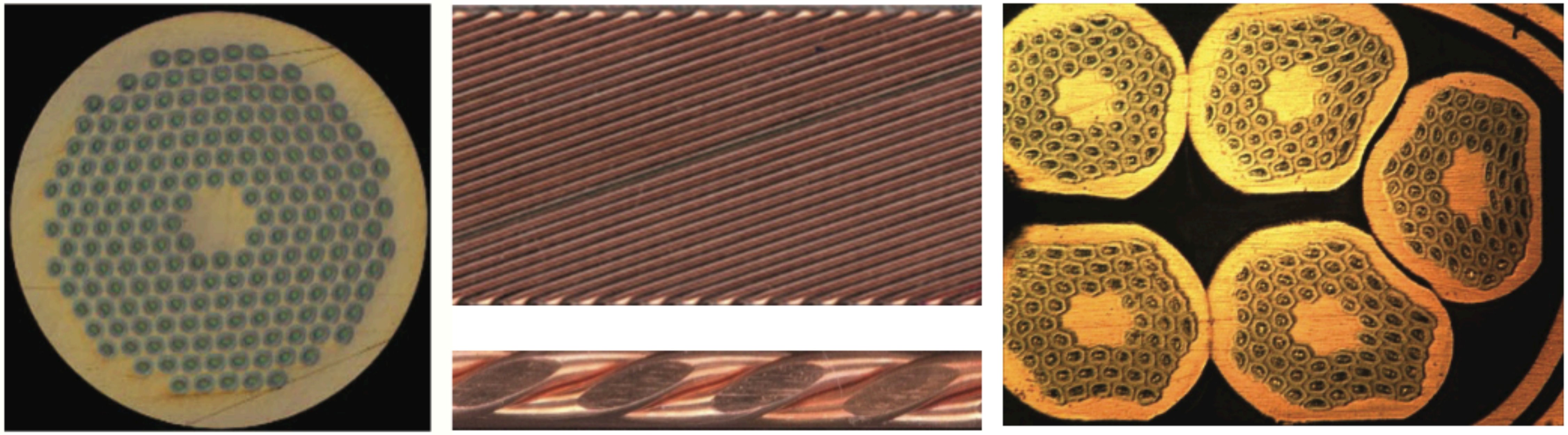
CERN-ACC-2018-0058

FCC-hh 91 km ring x 16 T -> 100 TeV in pp CM
estimated cost (Snowmass ITF panel) 20 - 60 B$

The current 8 T is close to the limit for the NbTi magnets used for LHC. For higher fields, new superconductors must be used.



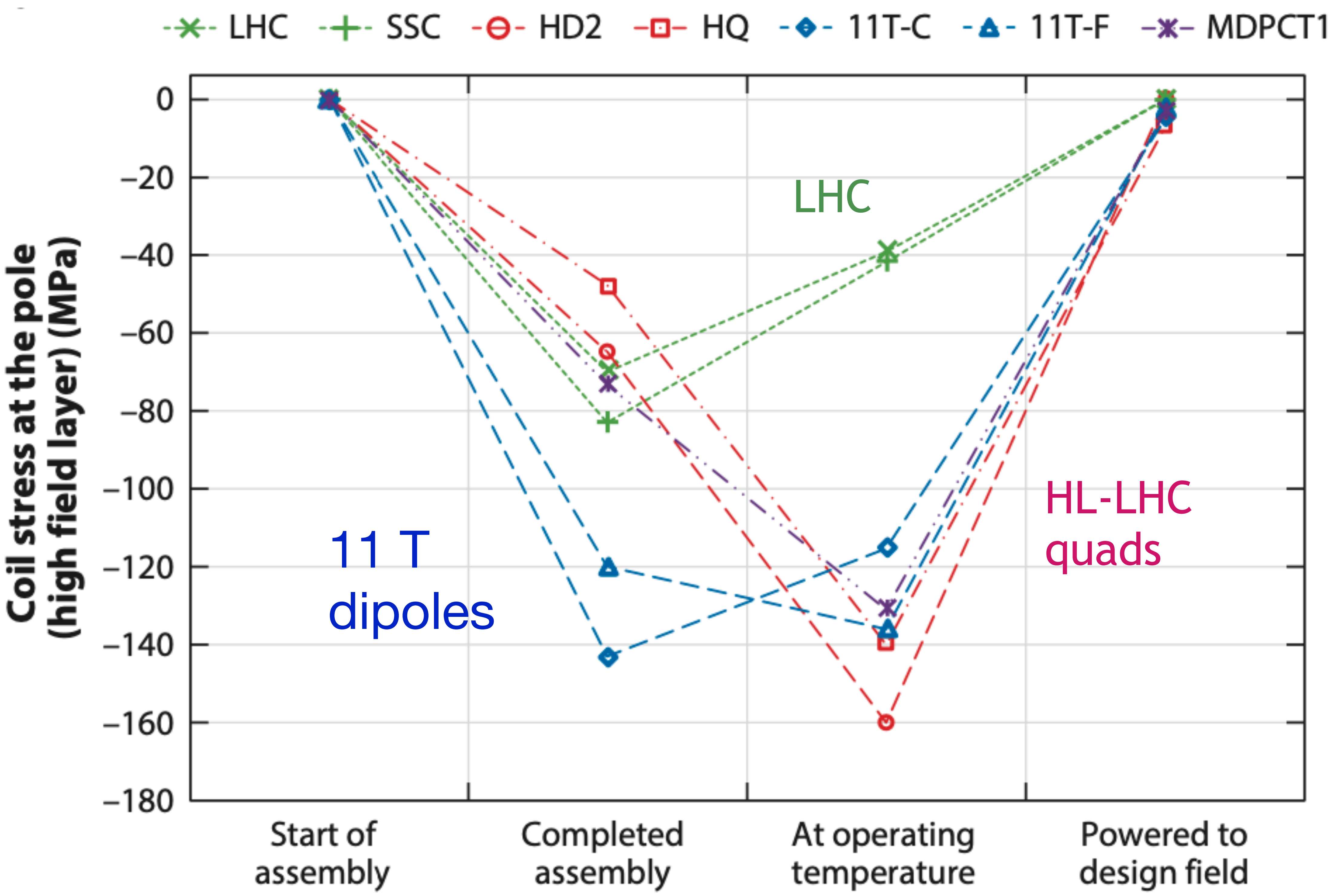
Nb3Sn and High-TC superconductors are brittle materials. To manufacture magnets, it is necessary to wind a precursor material, then heat-treat to make the final product.



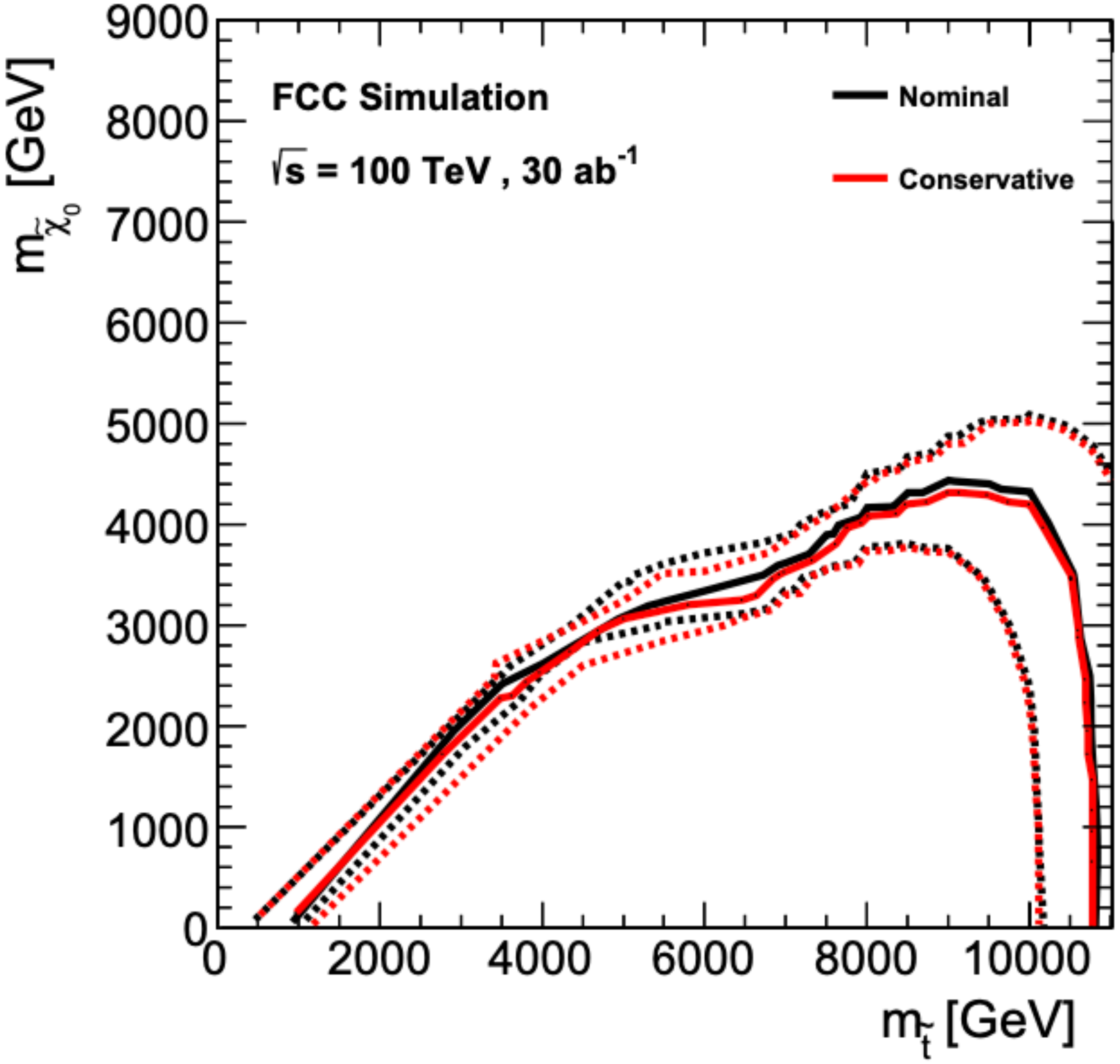
12 T Nb3Sn quadrupoles have been made for the HL-LHC final focus magnets. There are a few examples now of 14 T Nb3Sn. All of these are made 1-by-1. Industrialization of the manufacturing technique is well in the future.

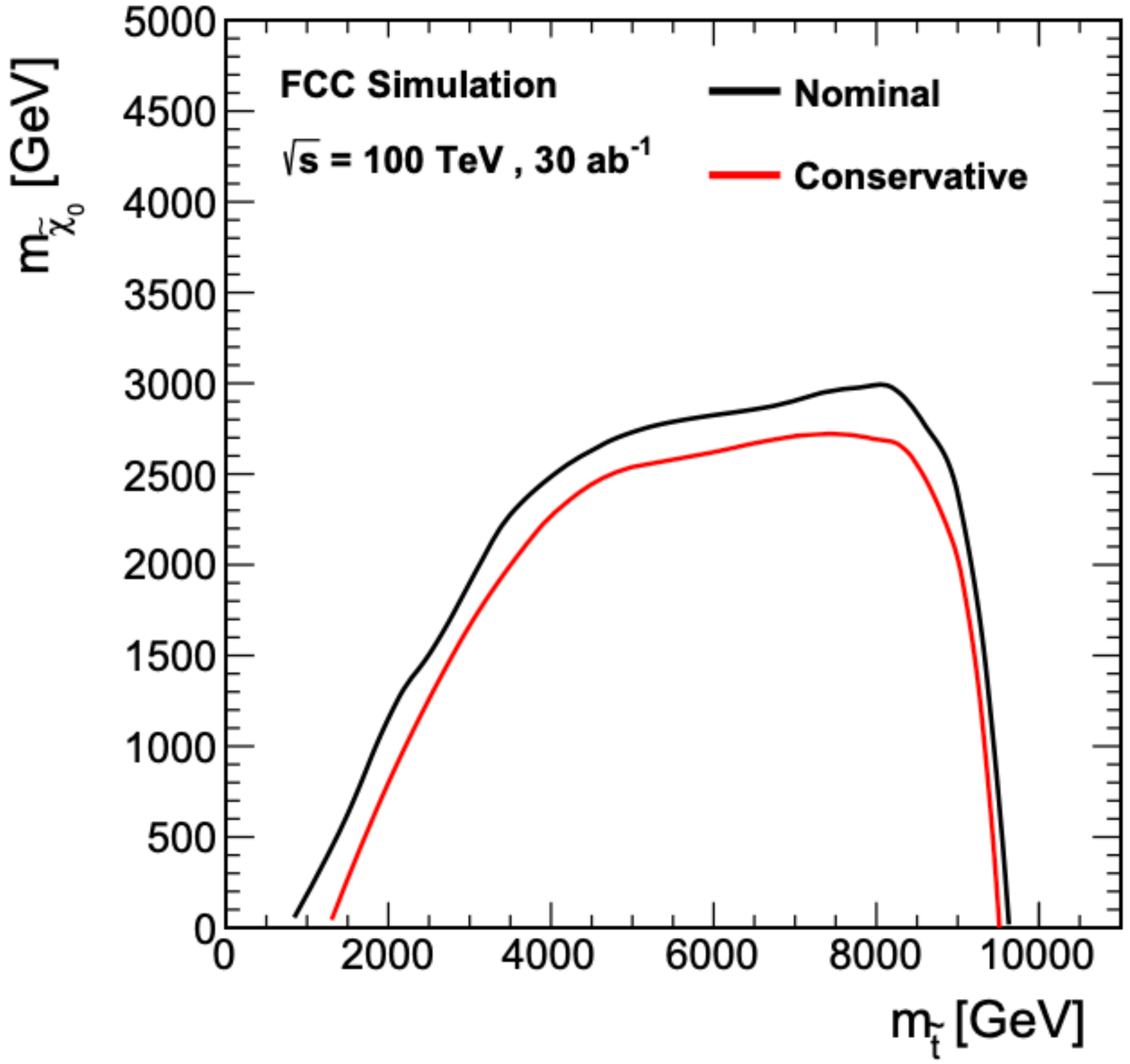
G. Sabbi, Ann. Rev. Nucl. Part. Sci. 74, 369 (2024)

Superconducting magnets undergo high stress at various stages of their construction. This is also an issue for the manufacturing process:



FCC-hh plans for luminosities up to 3×10^{35} , corresponding to 1000 pileup events per bunch crossing. Physics studies assume that future detectors will resolve this. Then the physics reach for new particles is impressive. Example: stop search:





A. Abada, et al. Eur. Phys. J C 79, 474 (2019)

muon colliders $-$ the unfortunate facts of life:

1. Muons are unstable, $\tau = 2\ \mu\text{sec}$
2. Muons are produced in a large phase space that must be reduced by a factor 10^6.
3. When muons are guided to the collision point, their decay products are guided there also.

This approach is the most power- and cost-efficient, if it can work at all.

Muons have a number of advantages for a high-energy collider. Electron synchrotrons are limited to energies below 200-300 GeV because of synchrotron radiation. At the highest energies of LEP, each electron would lose ~1% of its energy every time it went around the ring.   For muons, this effect is smaller by

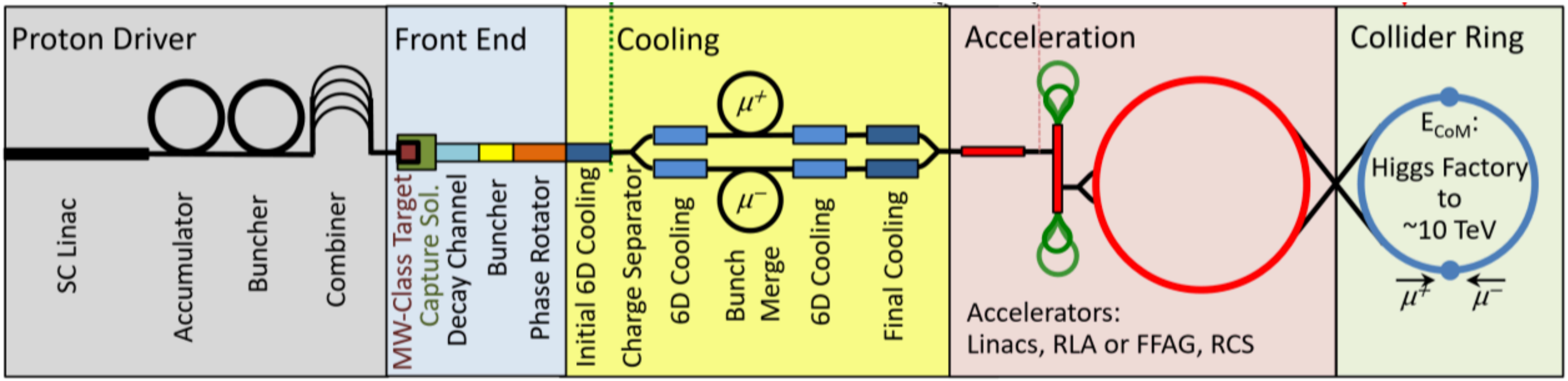
$$(m_e/m_\mu)^4$$

enabling muon colliders in the 10s of TeV range.

In a synchrotron, the luminosity typically increases as $\mathcal{L} \sim E_{cm}$

However, in a muon collider, because the muons live longer, one can have $\mathcal{L} \sim E_{cm}^2$, as we really wish.

The difficulty is that muons must be made on the spot, and then "cooled" to reduce their phase space enough to inject into a synchrotron.



layout for the ionization cooling scheme of muon production

Snowmass Muon Collider Forum report,
Black et al, arXiv:2209.01318

estimated cost for a 10 TeV collider
Snowmass ITF panel: 12-20 B$

idea: 10% reduction per stage x 120 stages = 10^{-6}

but, muon cooling is subtle:

Cooling affects the longitudinal phase space, but we need to reduce the transverse phase space.

Phase space increases in the absorber; eventually, there is an equilibrium. This must be postponed as long as possible.

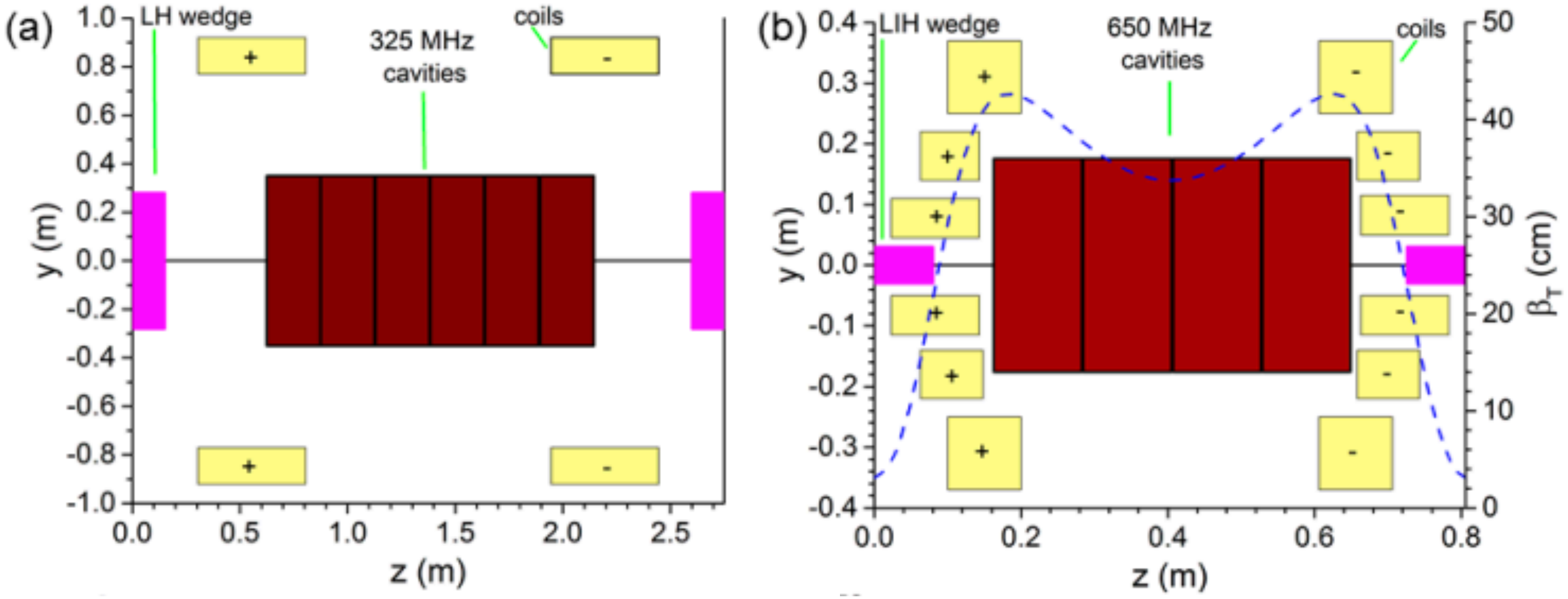
For a total efficiency of 10^{-3}, require only 4% loss per stage.

This gives $\mathcal{L} = 2 \times 10^{35}$ at 10 TeV.

MICE experiment: 7% reduction in 1 stage with 10% efficiency.
arXiv:1907.08562

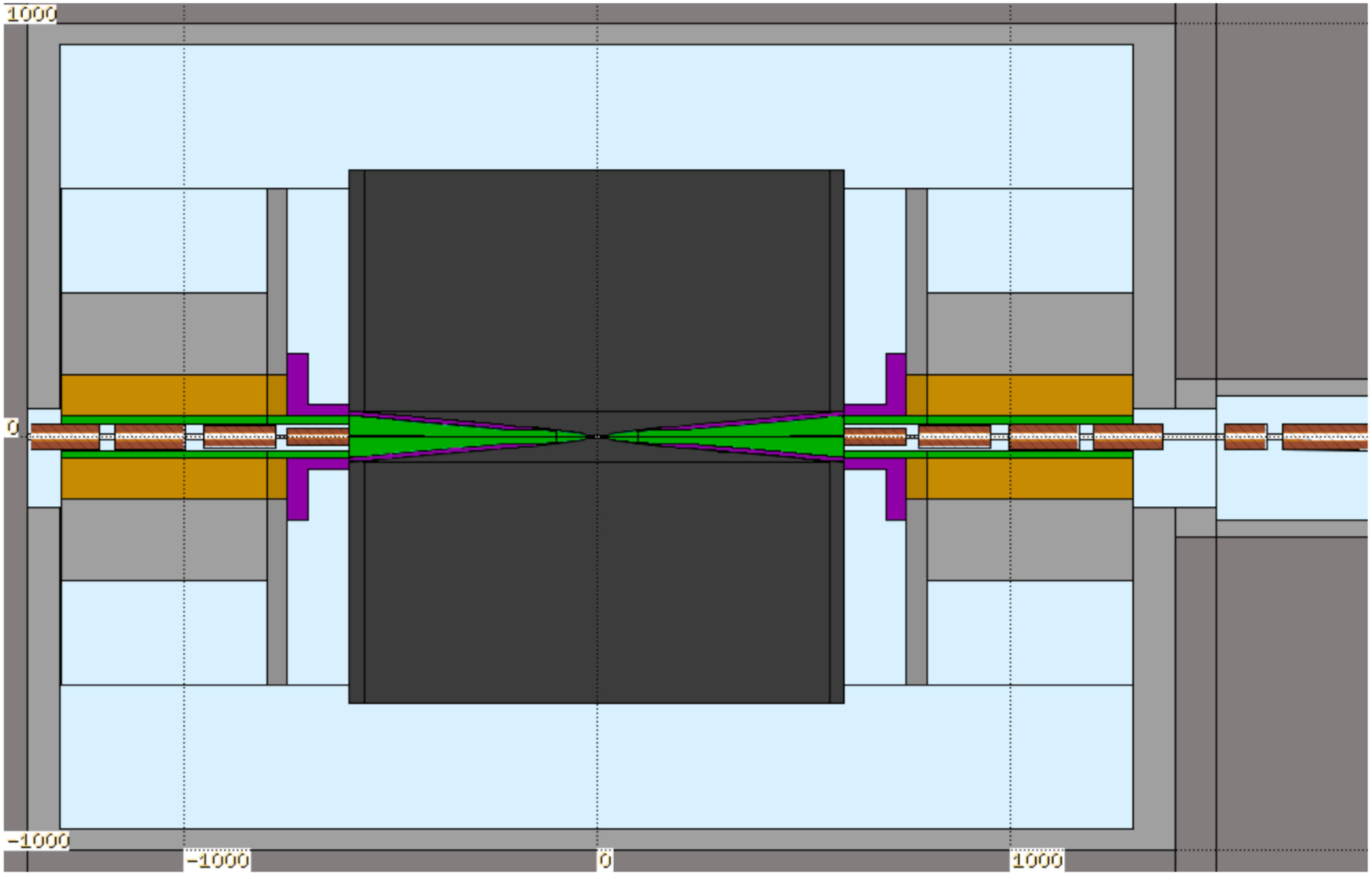
initial stage

final stage



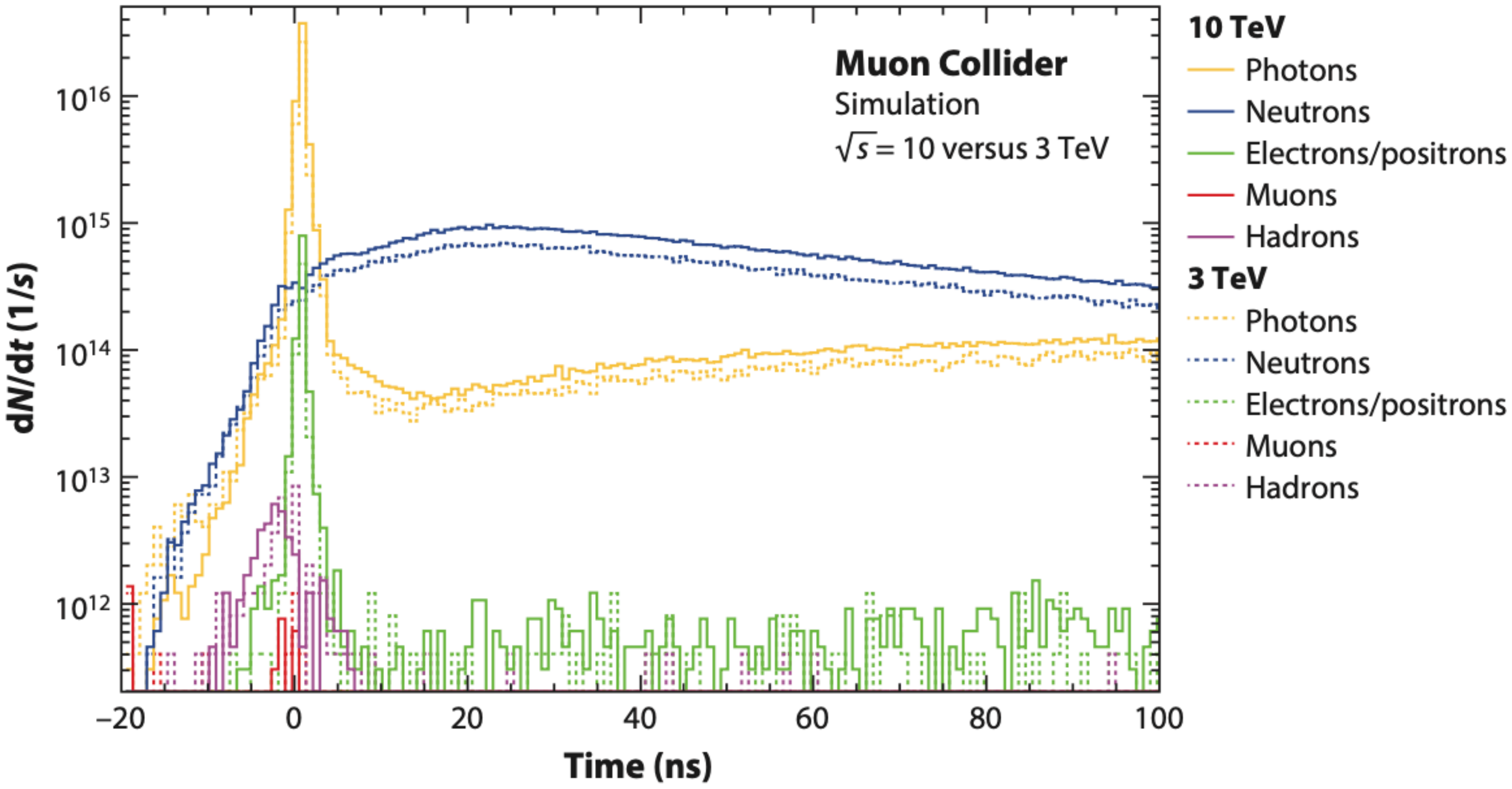
Stratakis and Palmer, Phys. Rev. ST AB 18, 3 (2015)

On the collision path, muons will decay into the detector. This must be considered in the evaluation of physics capabilities.



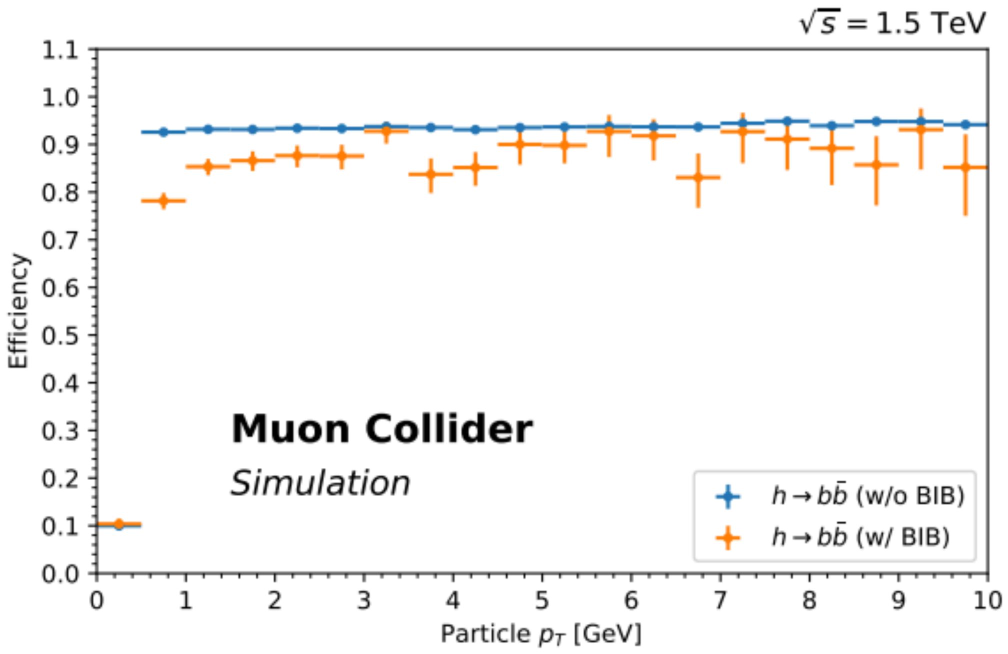
green: Tungsten beam shields (6 m)

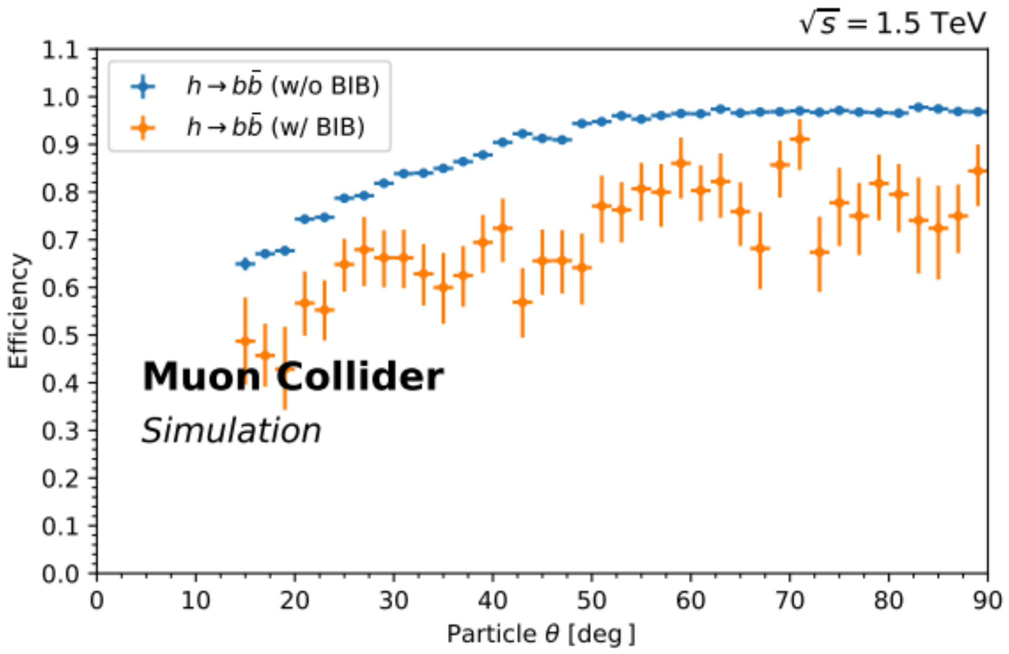
Beam induced background particle fluxes

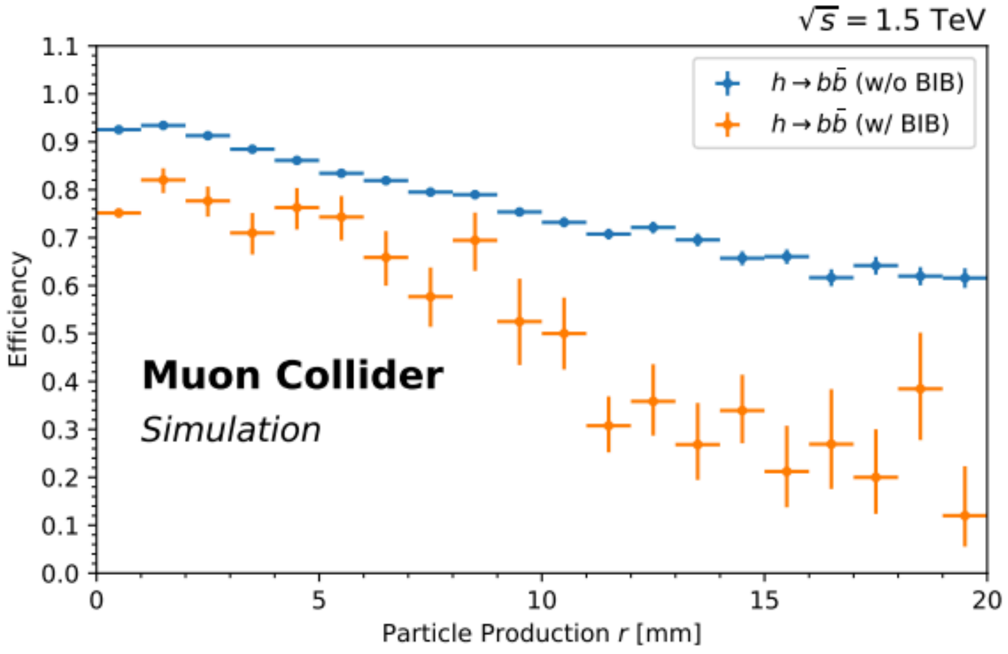


Casarsa, Lucchesi, Sestini, arXiv:2311.03280

efficiency for reconstruction of $h \to b\bar{b}$ events
at 1.5 TeV without/with BIB (Bartosik et al arXiv:2203.07964)







benefits greatly from 30 ps timing on tracker hits, and general LHC experience on pileup mitigation

e+e- colliders — the unfortunate facts of life:

1. Due to synchrotron radiation, circular colliders cannot be used above 350 GeV.

2. For linear colliders, $\mathcal{L} \sim P/\sigma_x\sigma_y$, so power efficiency is crucial.

3. With small spot sizes, the beam-beam interaction reaches extreme conditions for $E > 3$ TeV

Plasma wakefield acceleration gives very high accelerating fields, so this approach minimizes facility size, if not cost.

ALEGRO collaboration (B. Cros et al) arXiv:1901.10370

For linear colliders,

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 10 TeV collider

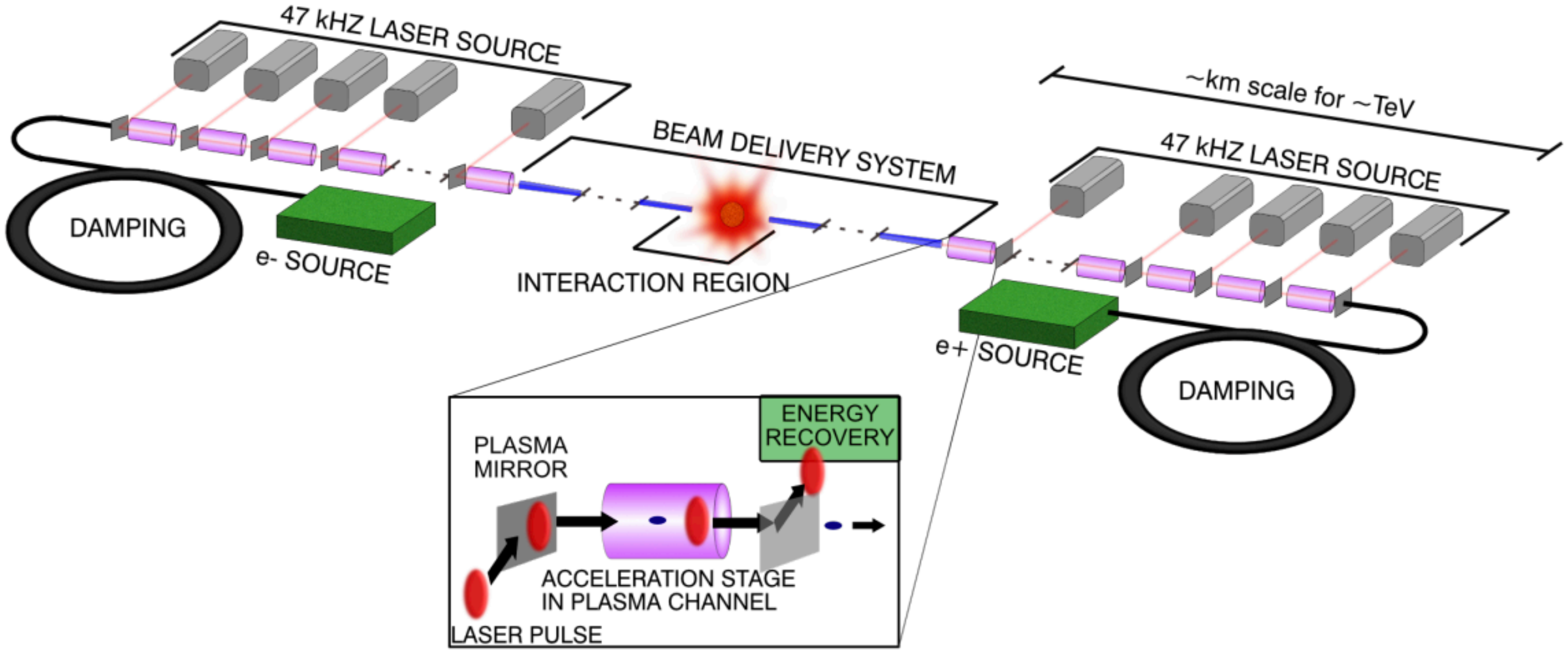
$$10^{36} \sim \frac{10 \text{ MW/beam}}{2 \text{ nm}^2}$$

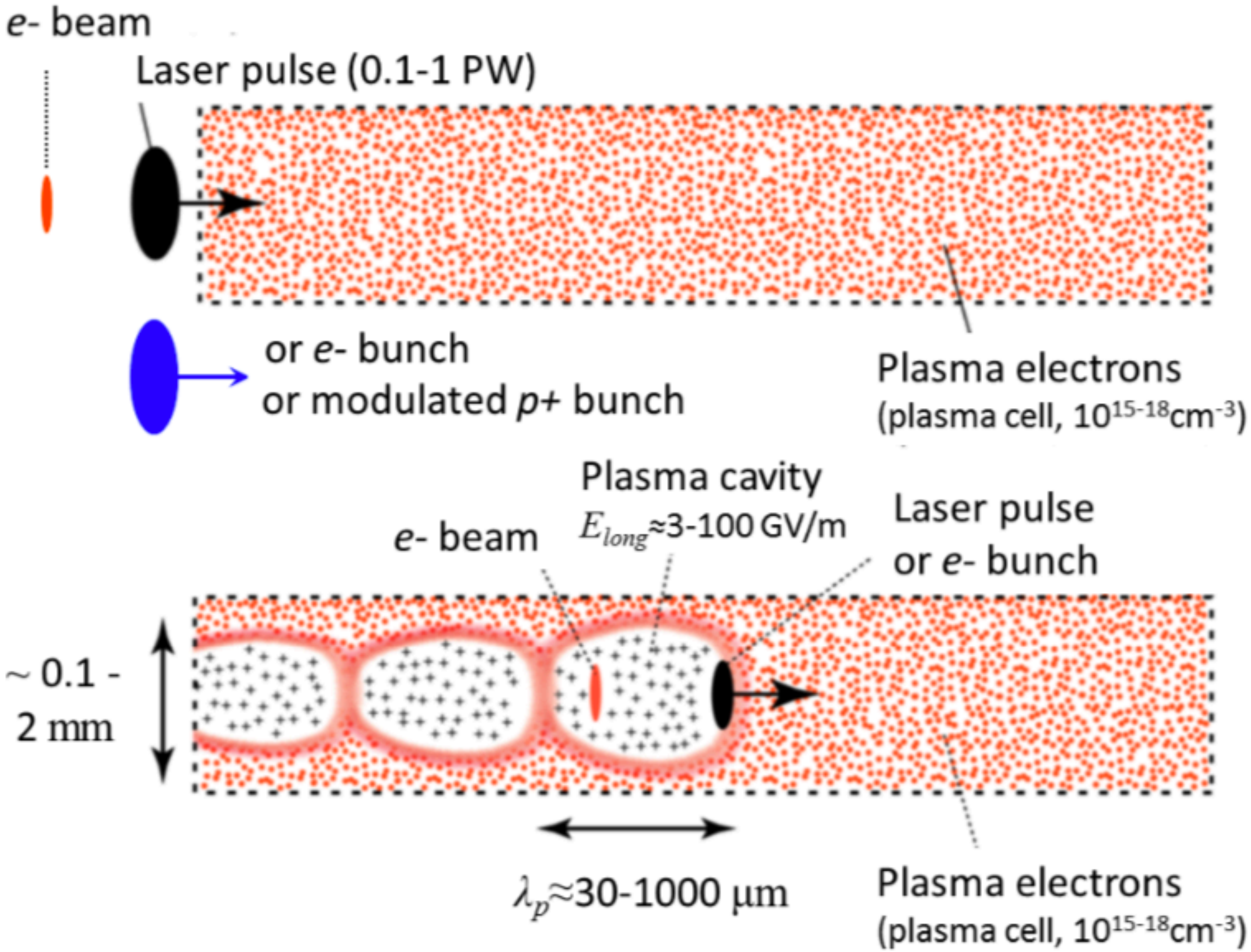
It is already understood how to produce beams of few-nm vertical size for the next-generation ILC and CLIC e+e- colliders.

Wakefields in a plasma can be driven by beams (e- or proton) or by lasers. The central idea is that an electromagnetic pulse ejects electrons from its path, creating a cavity and longitudinal accelerating fields dynamically.

A pulse that is small transversely leads to a narrow active region, with efficient energy transfer.

The method naturally produces high gradients; gradients of 150 GeV/m have been observed. Controlled acceleration has been achieved with gradients of ~ 5 GeV/m. In contrast, SLAC is 17 MeV/m.





Shiltsev-Zimmermann RMP review - arXiv:2003.0984 issues for PWFA:

energy efficiency: wall plug to drive beam or laser

reproducibility shot to shot, needed to maintain
small emittance by feedback control

control of beam instabilities

transport of the accelerated beam from each
stage to the next with emittance preservation

10,000 / 10 = 1000 stages

acceleration of e+
(observed at FACET in a special configuration)

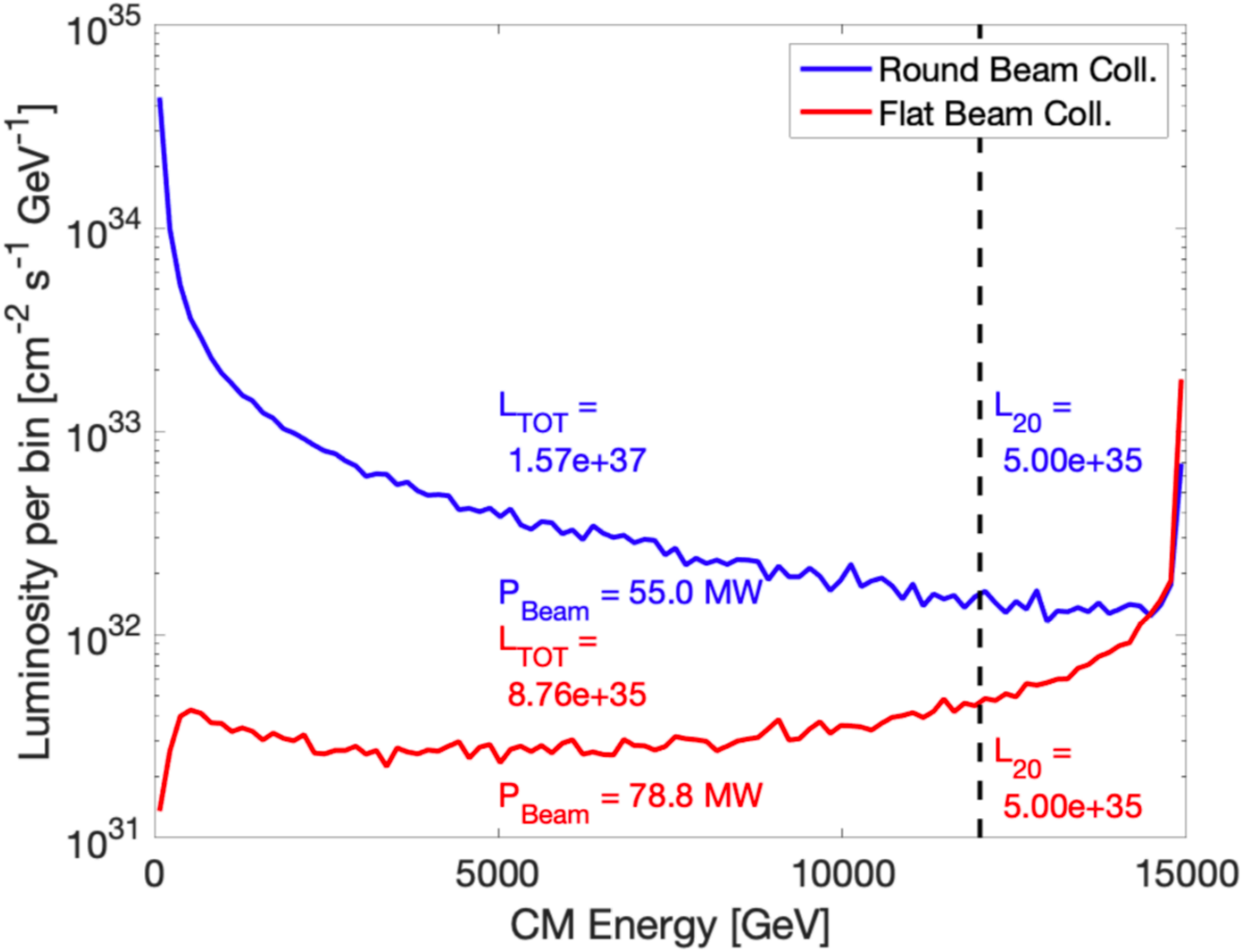
In e+e- collisions with very small, intense spot sizes, the charge of each bunch has a strong effect on the particles of the other bunch.

This leads to hard synchrotron radiation (beamstrahlung) and additional forward pair creation during the bunch-bunch collisions.

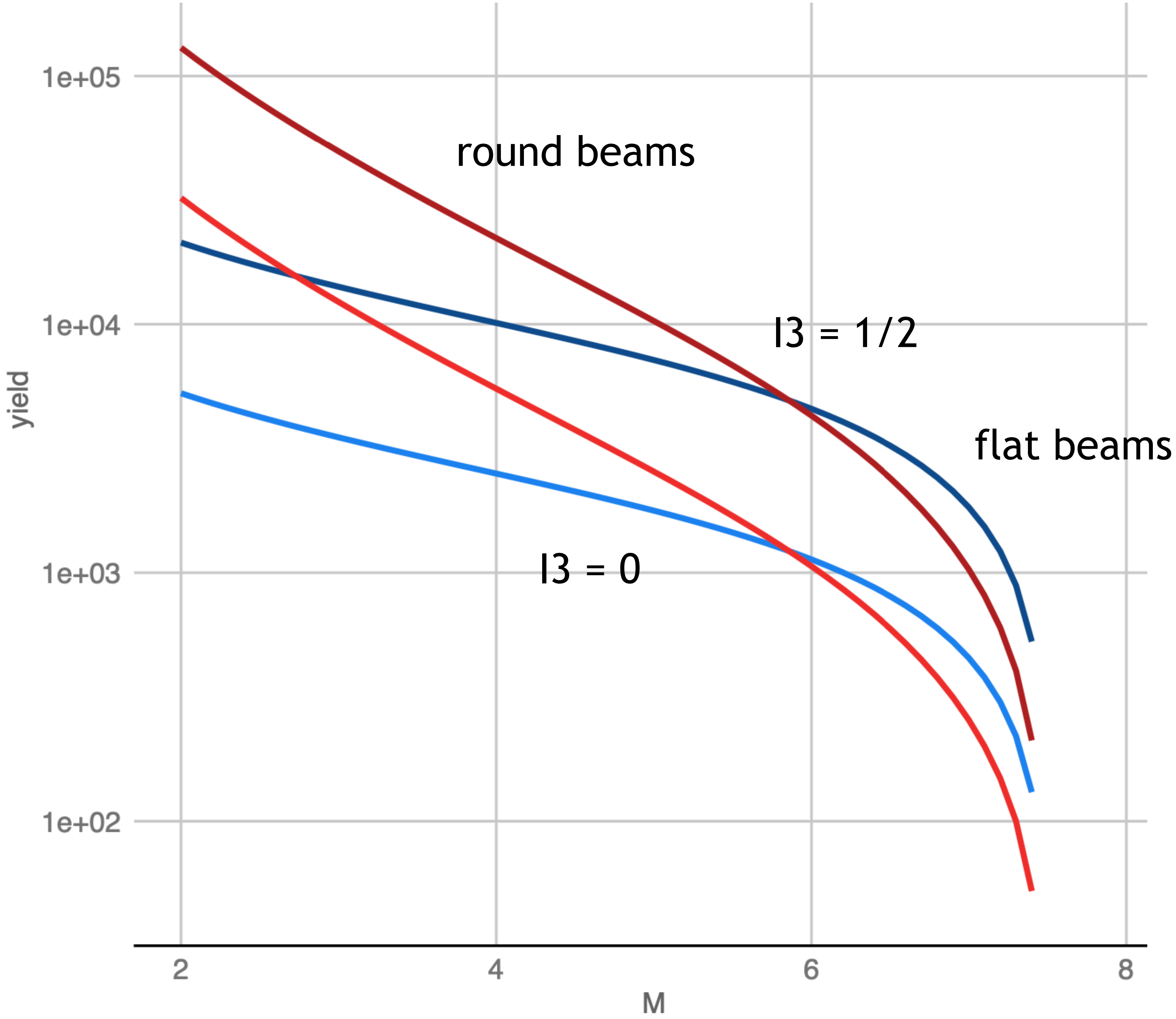
The electromagnetic fields are strong enough that Nonlinear QED effects must be taken into account.

simulation of the e+e- collision CM energy spectrum for 15 TeV colliders,

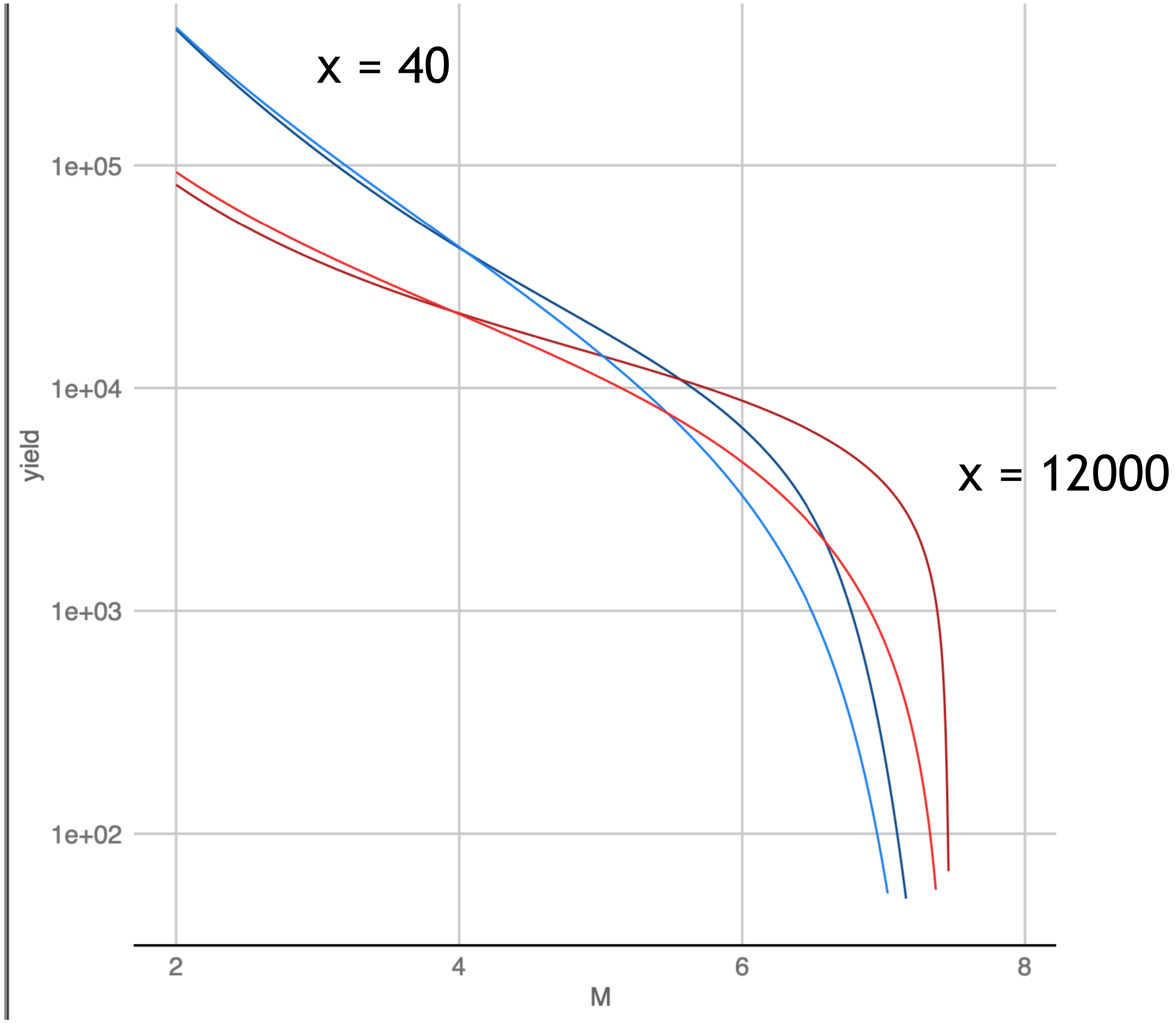
assuming β function and normalized emittance comparable to ILC designs, the scaling up the beam energies.



Cao and Gessner, in Barklow et al   arXiv:2305.00573 as an exercise, use these spectra to compute the yield/yr for pairs of heavy leptons:



For comparison with the e+e- distributions, consider γγ colliders with, similarly, 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)

Tim Barklow is investigating new ideas for the backscattered Compton source.

Finally, what is the physics program of these colliders ?

The three proposed accelerators share common goals. These are most clearly enunciated in the reports on muon colliders, e.g. Black et al, arXiv:2209:01318:

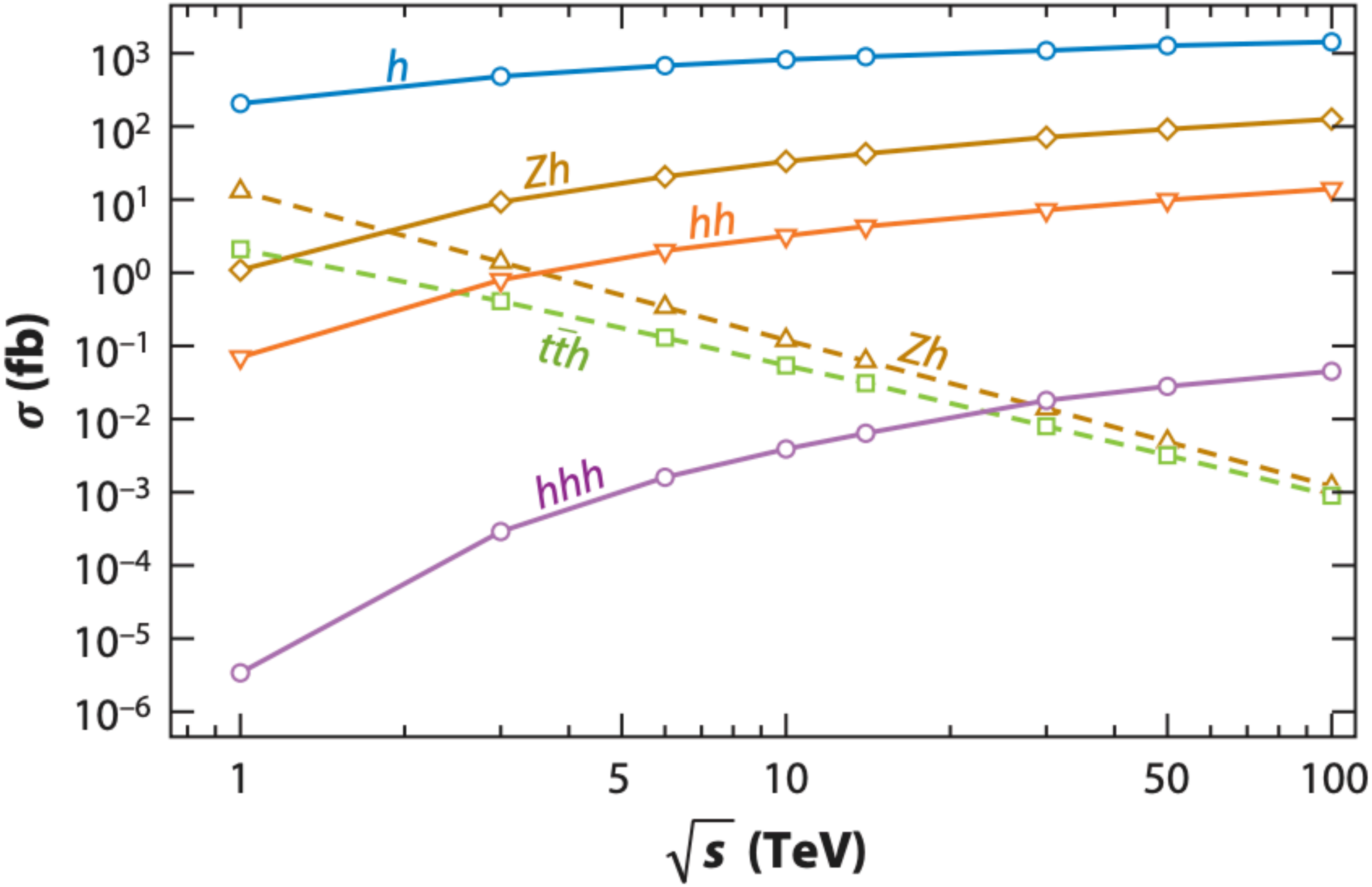
1. Higher precision tests of the Standard Model, especially, properties of the Higgs boson.

2. Production of TeV-mass WIMP dark matter candidates.

3. Pair production of new particles associated with Electroweak Symmetry Breaking.

Which goal is most important ? This shapes the form of the analyses and the requirements for luminosity.

There are two types of interesting electroweak cross sections at these colliders:

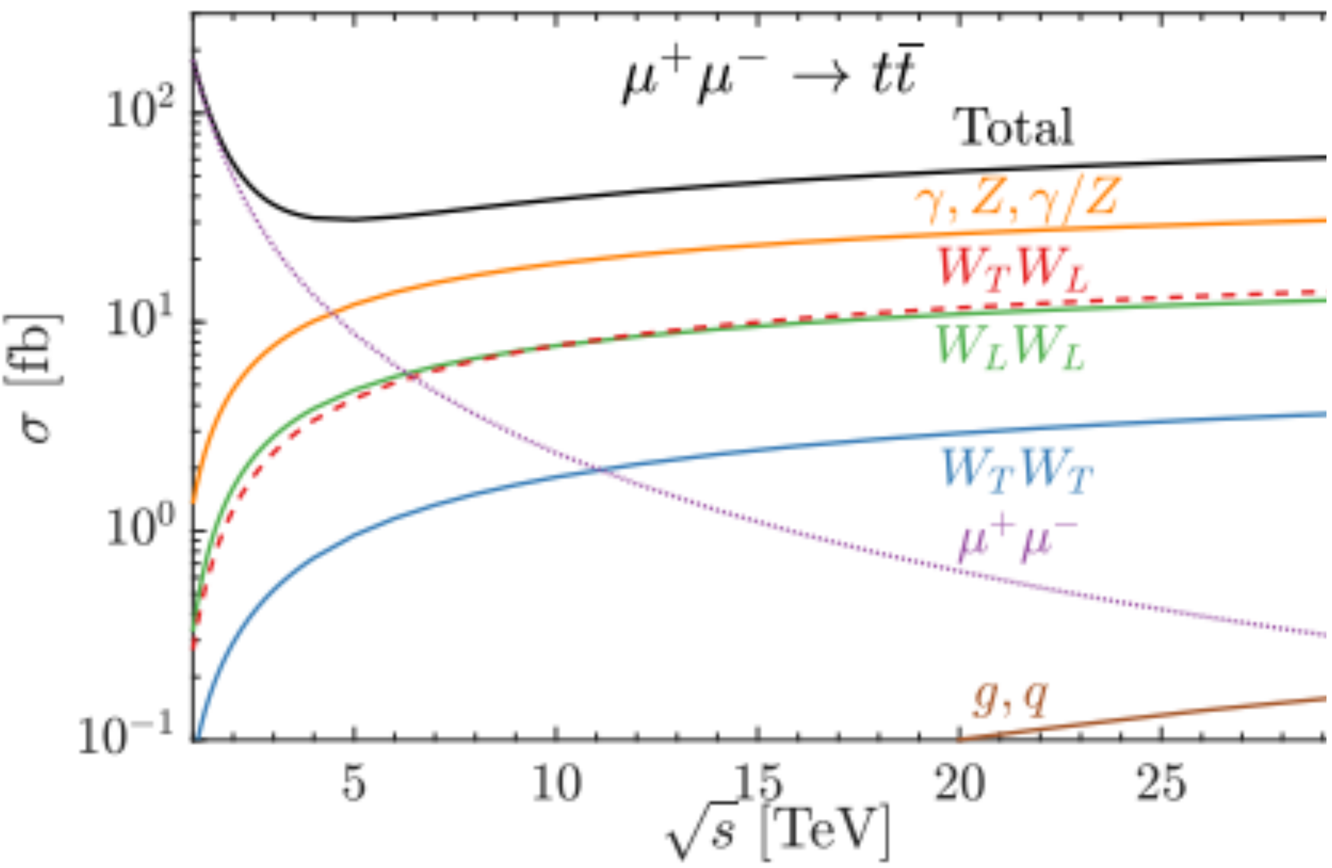


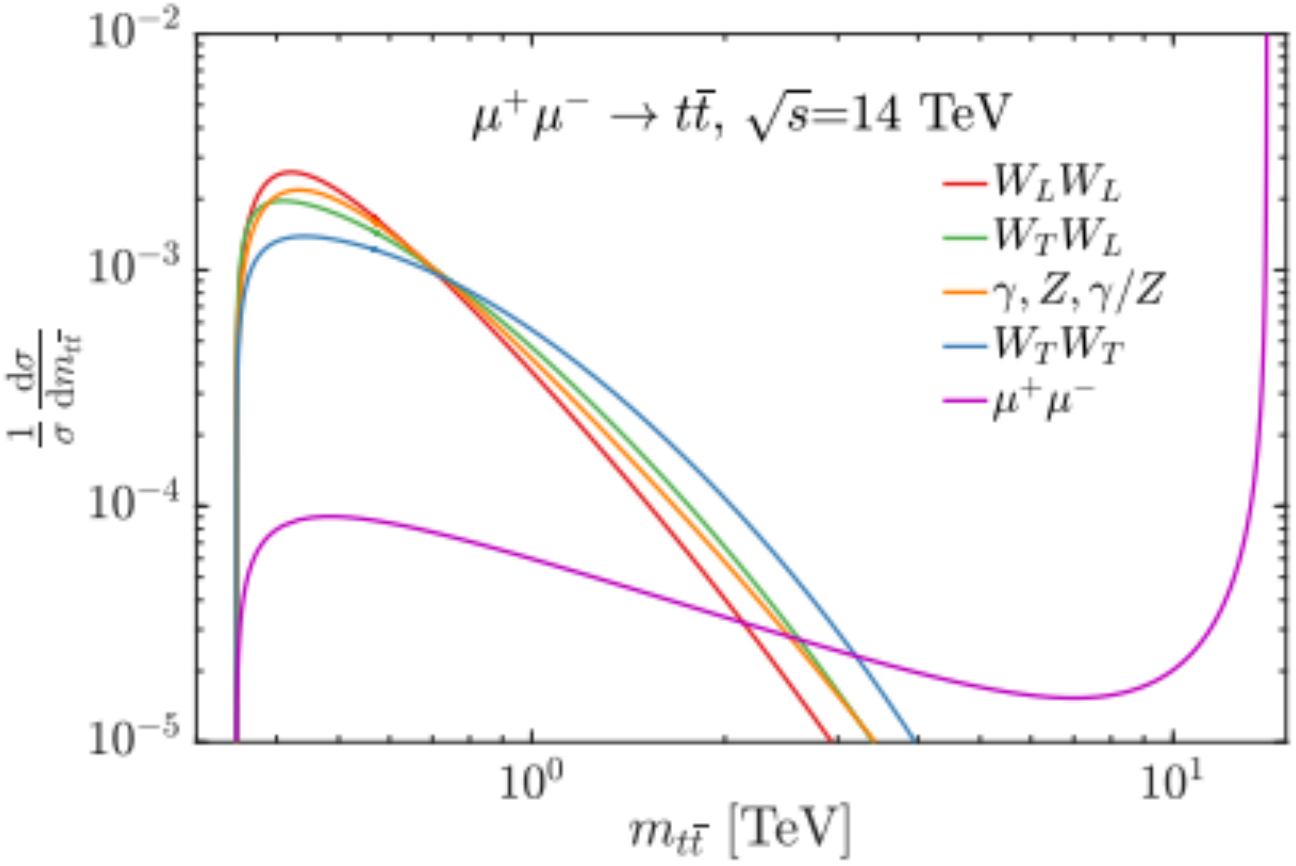
t-channel
W exchange

s-channel
annihilation

Here is a similar set of plots, associated with top quark production:

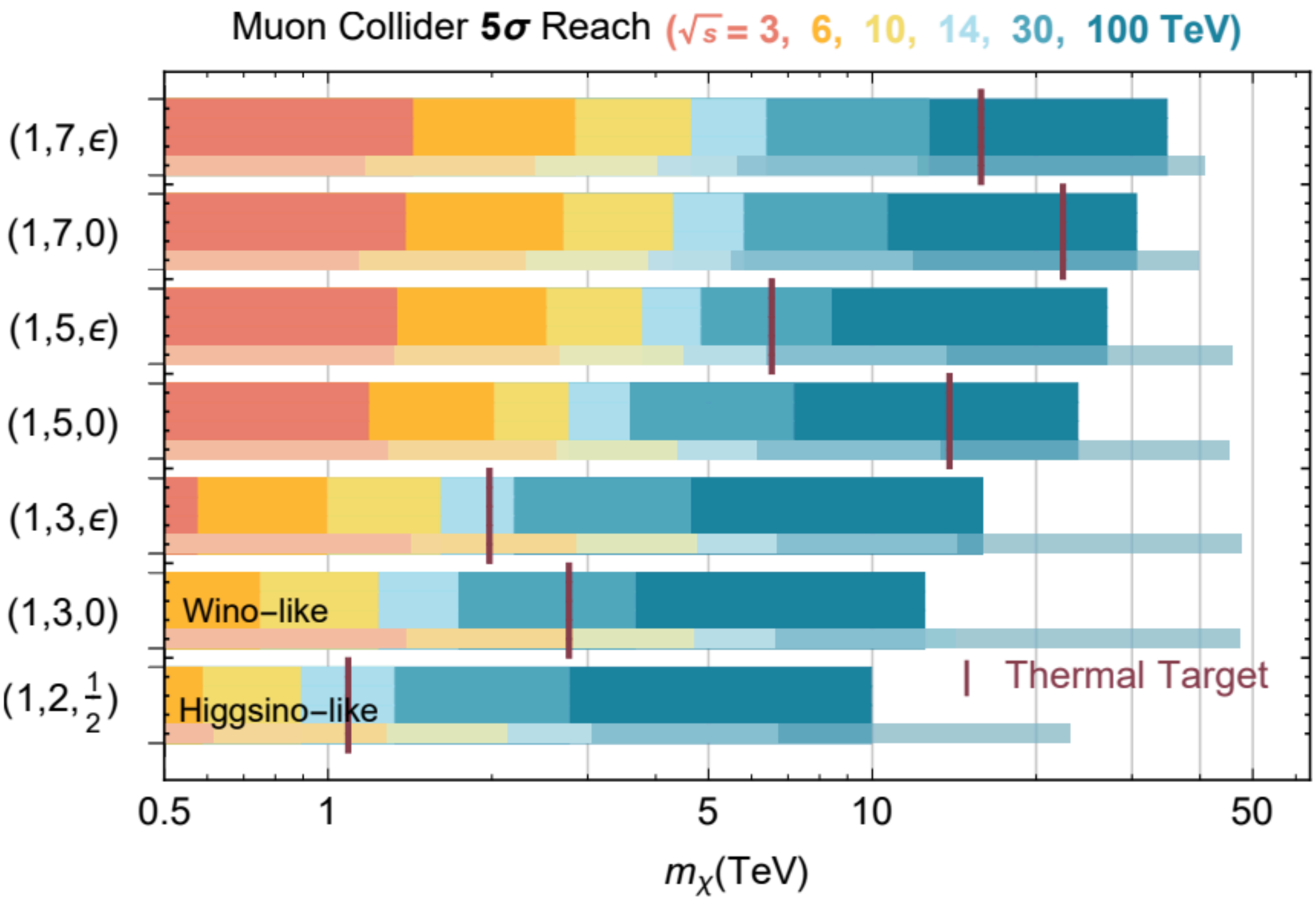
$$\mu^+\mu^- \to t\bar{t}$$





Han, Ma, Xie, arXiv:2007.14300

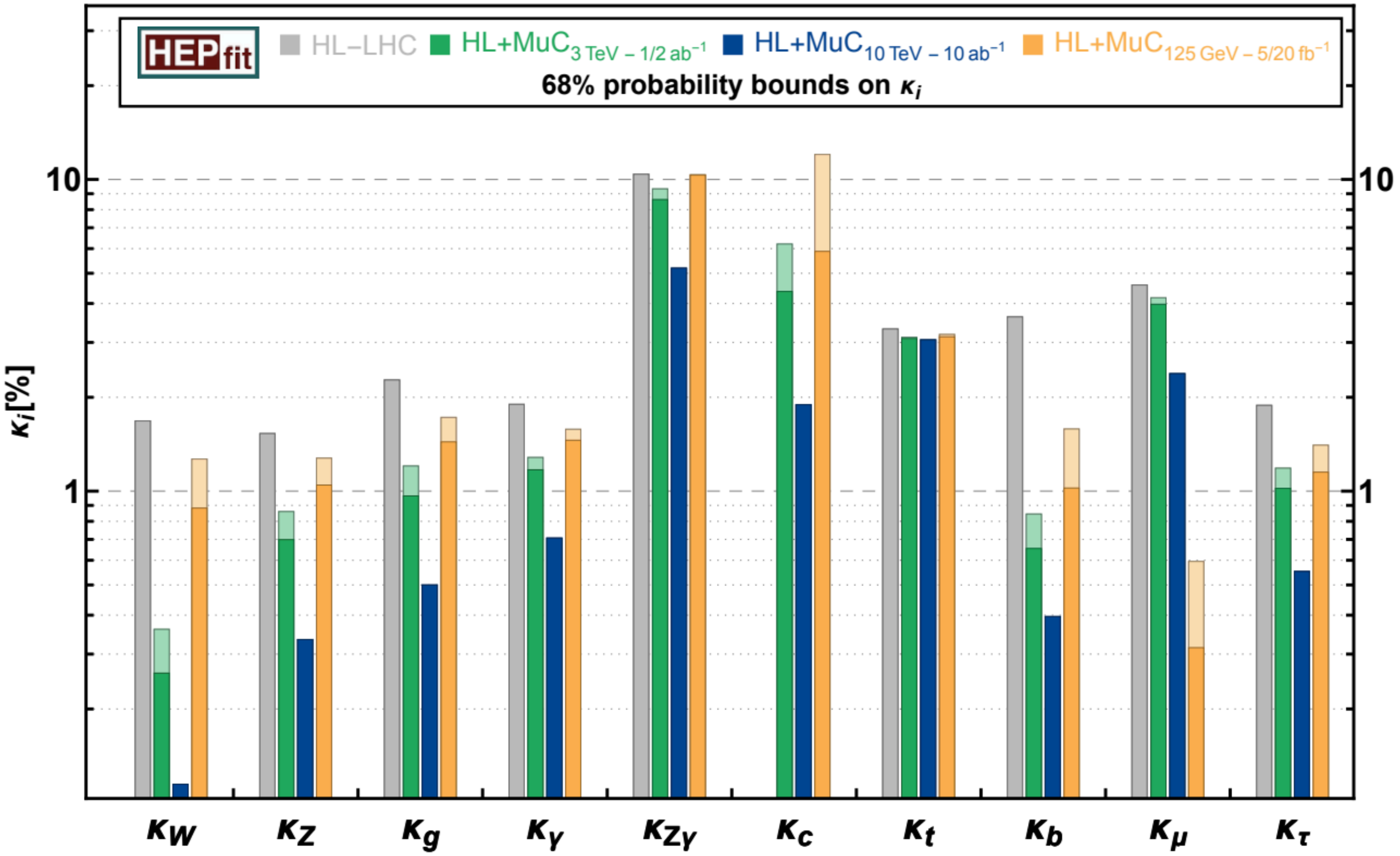
Here are some reach plots for heavy WIMPs. These models have small direct detection cross sections, below the neutrino floor. So high energy colliders close a relevant gap in dark matter searches.



Han, Liu, Wang, and Wang, arXiv:2203.07351

A 10 TeV lepton collider with $\mathcal{L} = 2 \times 10^{35}$ would produce 2 million Higgs bosons per year, mainly through WW fusion.

Assuming control of backgrounds (and a measurement of the Higgs total width from a Higgs factory), this facility would bring the precision on the leading Higgs couplings close to the part-per-mil level. This would be even more interesting for searches for rare Higgs decay modes.



Accettura et al, arXiv:2303.08533

Still, this study would use high energy to study physics at the m_h scale with high rates. A part-per-mil anomaly at the scale m_h would come from new physics at the scale

$$(v/\Lambda)^2 \sim 10^{-3} \quad \rightarrow \quad \Lambda = 8 \text{ TeV}$$

which is arguably within the direct reach of the collider.

This is a missing element in our thinking about 10 TeV pCM colliders, and also an element largely missing in our discussions of the future of particle physics.

It is the question of our attitude toward “naturalness”.   Or, I as I would rather put it, the question of why electroweak symmetry is broken.

Is there a mechanical theory of the electroweak symmetry breaking — in spite of exclusion of new particles at the 1 TeV energy scale — or do we need to go to UV/IR connection, cosmology, or even the anthropic principle to find the answer ?

There are theories of EWSB in which this phenomenon originates at the 10 TeV scale. For example, Little Higgs models, with hierarchies in the particle spectrum of order

$$m^2/M^2 \sim \alpha_w/\pi \quad \text{or} \quad m/M \sim 1/10$$

The spectrum contains:

New strong interactions at 10 TeV,

providing approximately massless composites at the TeV scale (but maybe above the reach of LHC,

in turn, radiatively generating the Higgs potential.

Models with Dirac gauginos and color-neutral top partners can have a similar structure.

Models of this type would be directly explored at 10 TeV pCM colliders.

However, to get the money to build such a collider, we would need

definitive proof of violation of the Standard Model from HL-LHC or Higgs factories

or

a clear and compelling model to be tested (as the MSSM was for LHC).

In my opinion, this puts a large burden on the theory community

1. To be sure that an e+e- Higgs factory actually is built

2. To put forward simple and attractive models of EWSB with a “little hierarchy”.

Conclusions:

10 TeV pCM colliders are more than a vision.   There are multiple strategies to reach the 10 TeV scale.   All of these have difficulties that may take decades of R&D to overcome.   But we can get there.

Are the secrets of electroweak symmetry breaking and the Higgs field to be found at 10 TeV ?   If we believe in this, we must still find arguments to convince our skeptical scientific colleagues. If we don't believe in it, we are believing that there is no point in making the next step in collider physics.

We cannot imagine the future of particle physics without grappling with this question.