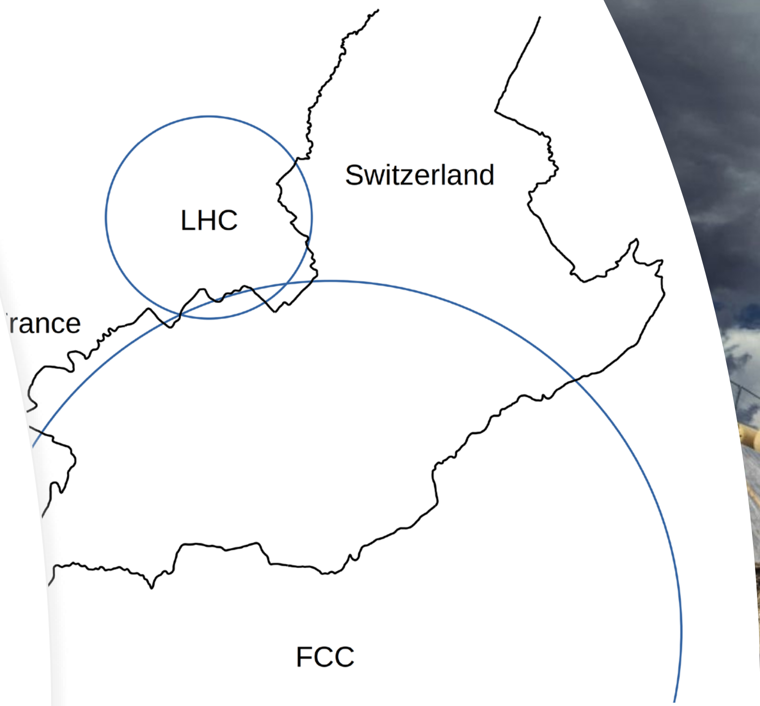
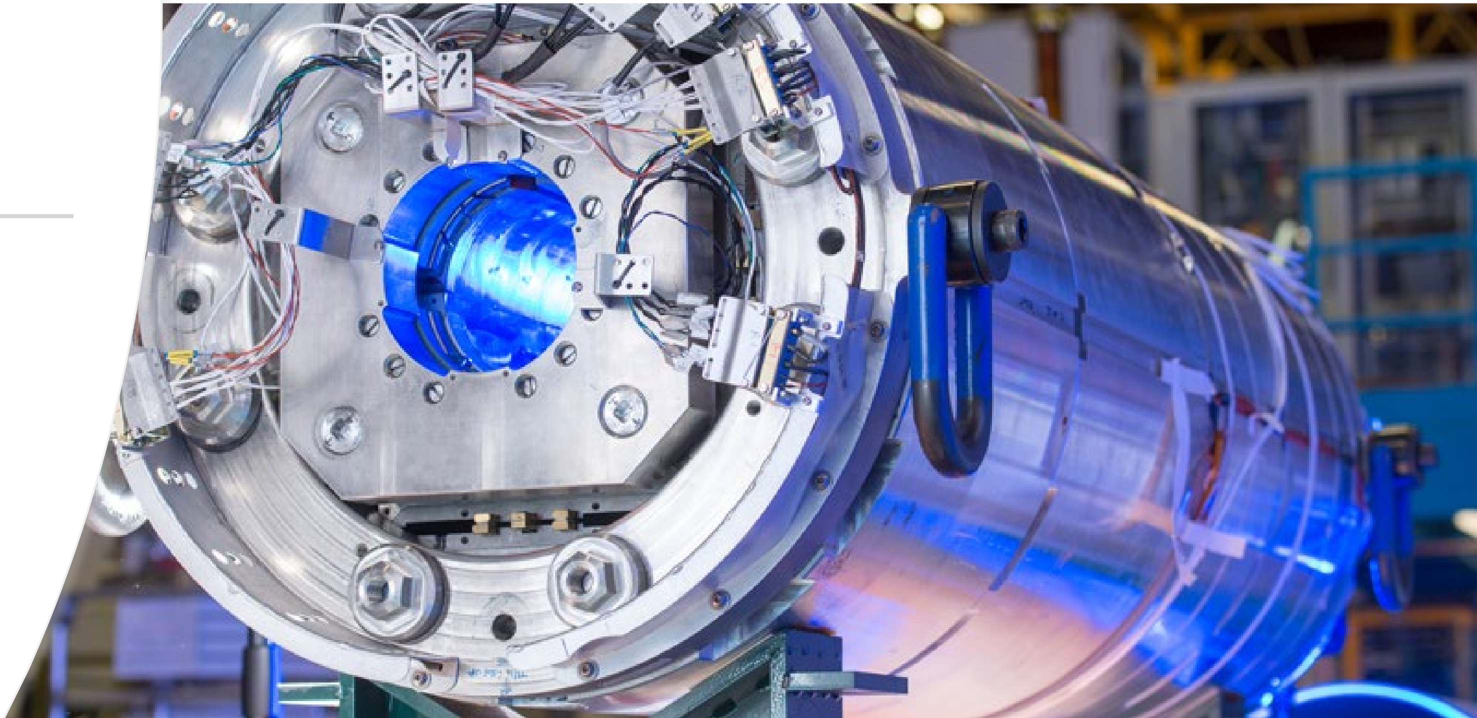
Model-specific BSM searches at future hadron colliders





Sarah Eno, U. Maryland

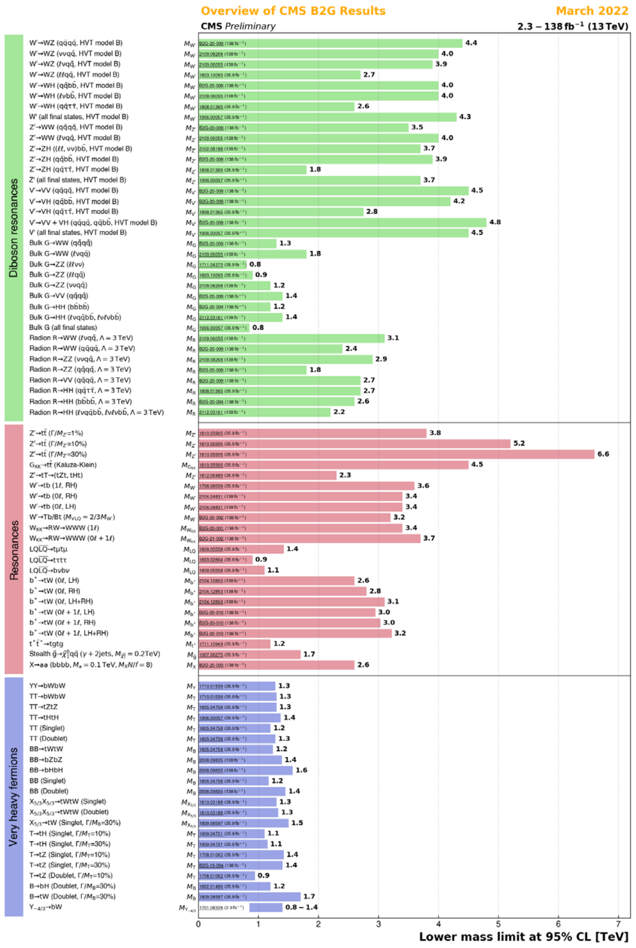
Snowmass Energy Frontier model-specific BSM subgroup session

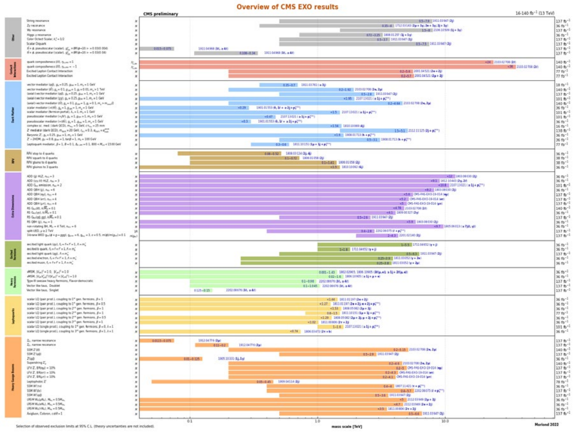
18 July 2022

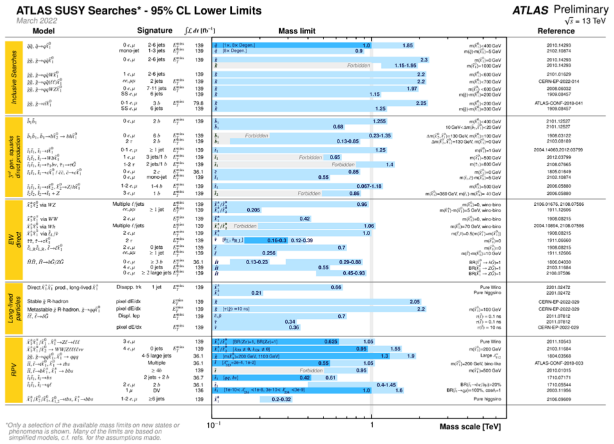
Hadron Colliders and model-specific BSM

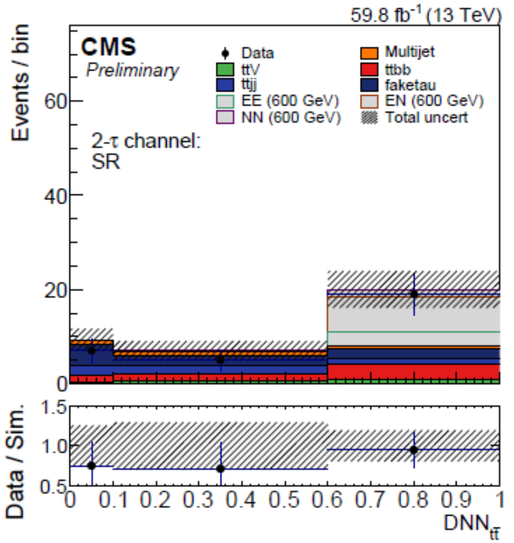
Most new particles are discovered at the current energy frontier machine (an exception is ν_τ). Since 2010, this has been the LHC. The LHC has discovered the Higgs boson and put strong constraints on popular, compelling BSM models such as Supersymmetry.

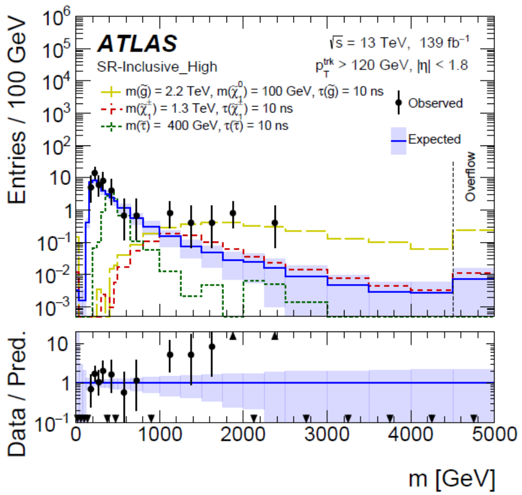
And who knows? Maybe some of the current hints won't go away with more statistics…





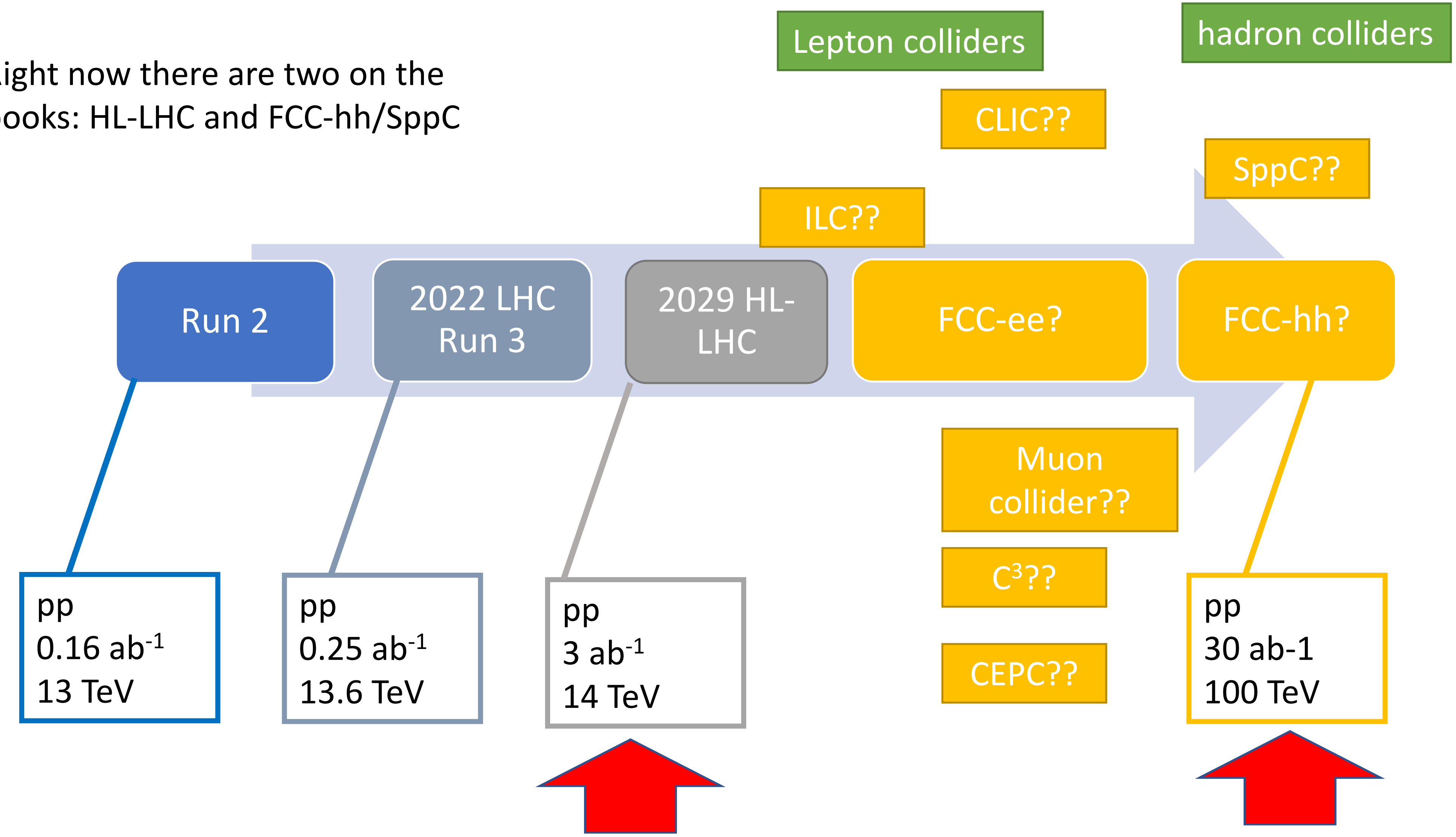






Future hadron colliders

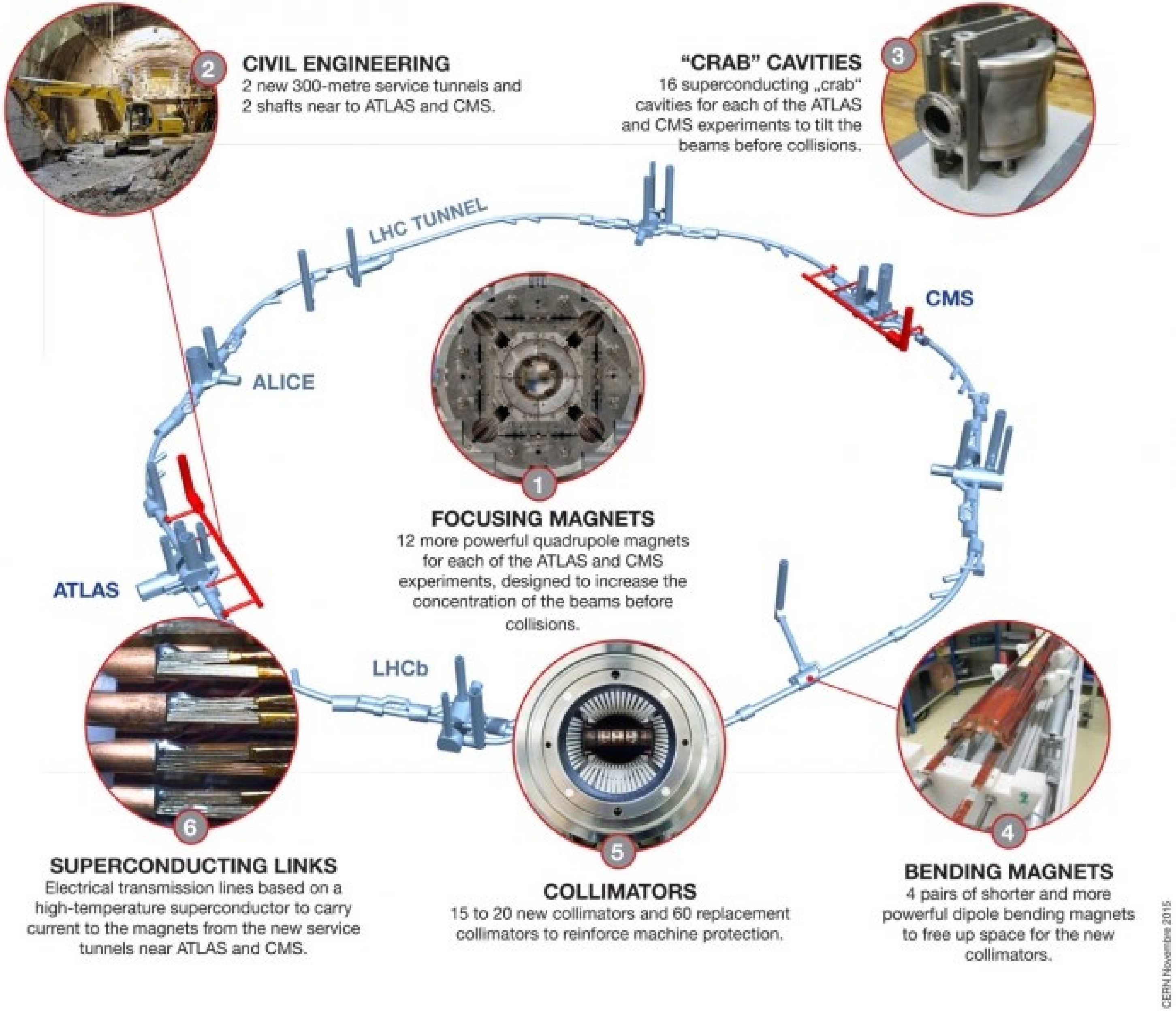
Right now there are two on the books: HL-LHC and FCC-hh/SppC



The role of LHC is our near-term future is exciting We have only 5% of the current data on tape.
In the long run, there are exciting prospects for a much higher center-of-mass energy and intense beams.

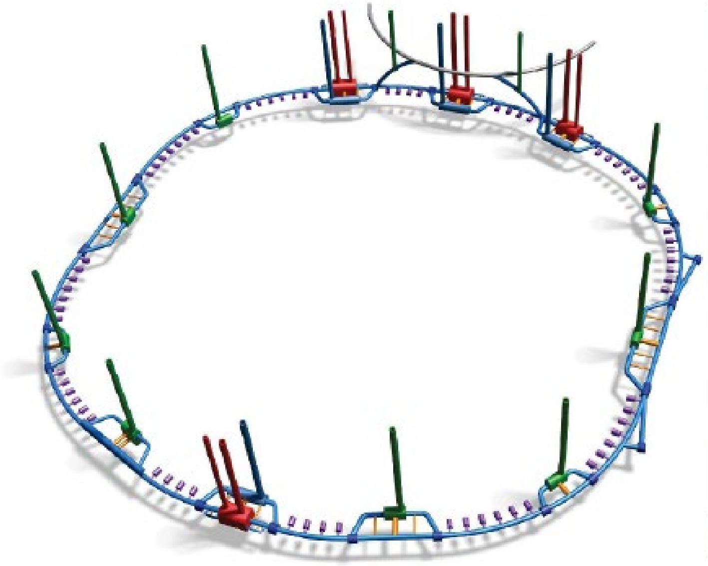
HL-LHC

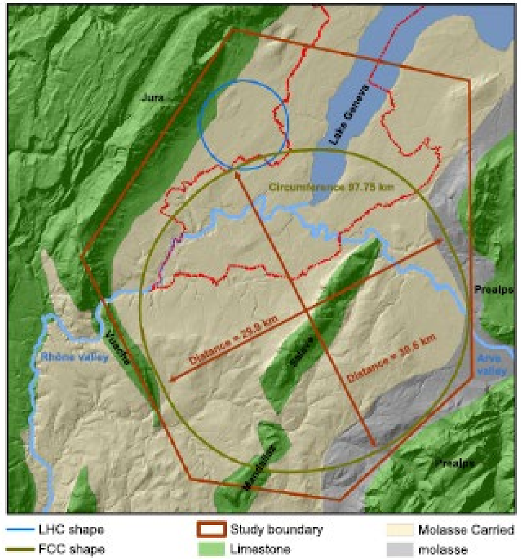
New 10T quadrupole magnetics, crab cavities, luminosity leveling and other upgrades will allow unprecedented beam intensity after “Long Shutdown 3”.

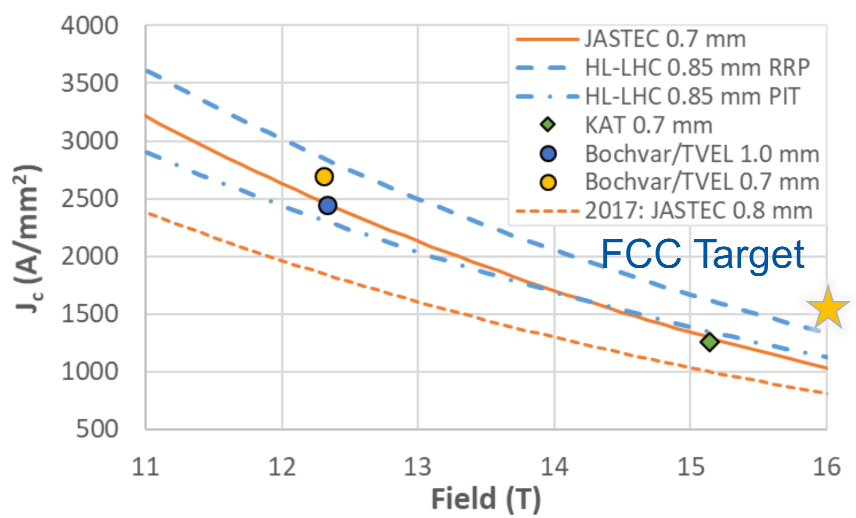


FCC-hh (SppC)

- Circumference of about 100 km
- Goal is an energy 7x higher than LHC peak luminosities initially similar to HL-LHC ($5x10^{34}$ $cm^{-2}s^{-1}$) with goal up to 6x higher.
- Key technological challenges if high-field accelerator magnets. Current LHC magnets are 8.33 T. FCC-hh needs 17 T with a current density of 1500 J/mm^2. R&D on Nb_3Sn superconducting wire. Magnet scientists at FSU and also a HyperTech/Ohio SU/FNAL have recently reached the current density spec. More long-term work high-temperature superconductor and hybrids may also help. China working on HTS iron-based magnets for 20T







Generic reaches

For e^+e^- collider, reach is typically $\frac{\sqrt{s}}{2}$ for pair produced particles that couple to the Z or photon with a coupling big enough to produce events for the given luminosity (or to the kinematic limit for production in association with other SM particles)

For hadron colliders it is more complicated.

Pros of hadron colliders:

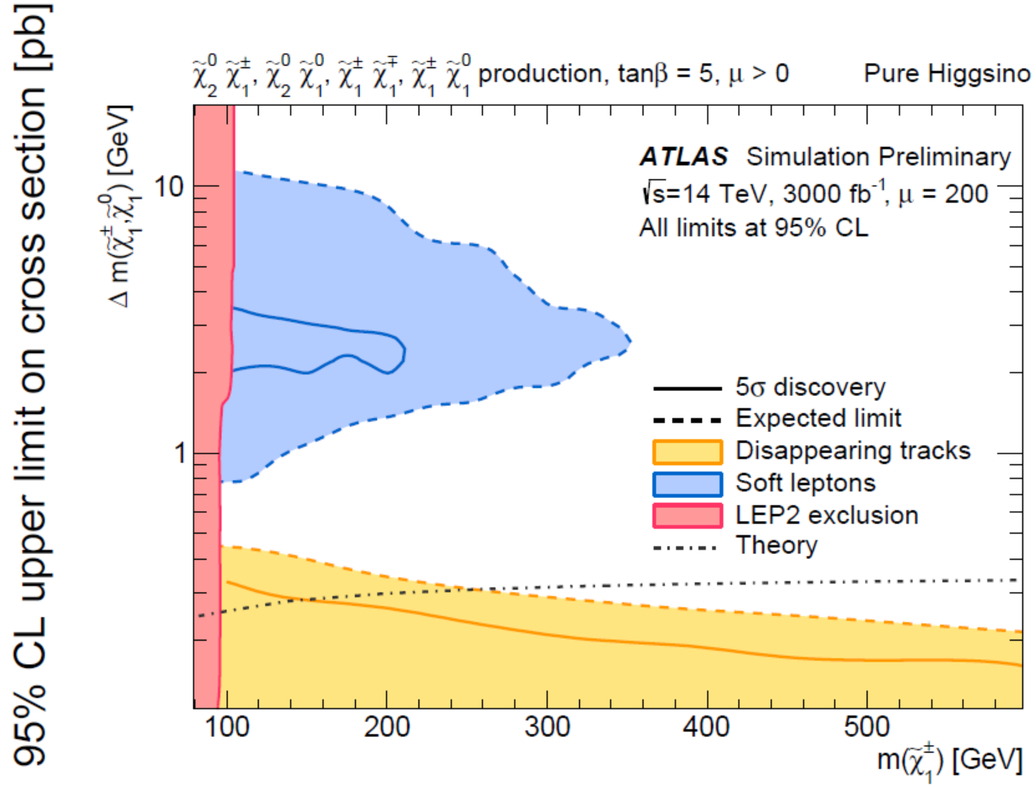
- Center of mass energy (although more innovative lepton colliders can also have impressive $\sqrt{s}$)
- Large BSM cross sections, especially for colored particles
- Variety of initial states

Cons of hadron colliders:

- Trigger
- Large SM process cross sections give large backgrounds

In general you need a simulation to estimate the reach, and often even a full analysis design

And this is why reach curves comparing electron with hadron tend to look like this (and also any reach plot compressed to 1D is generally hiding a missing phase space):

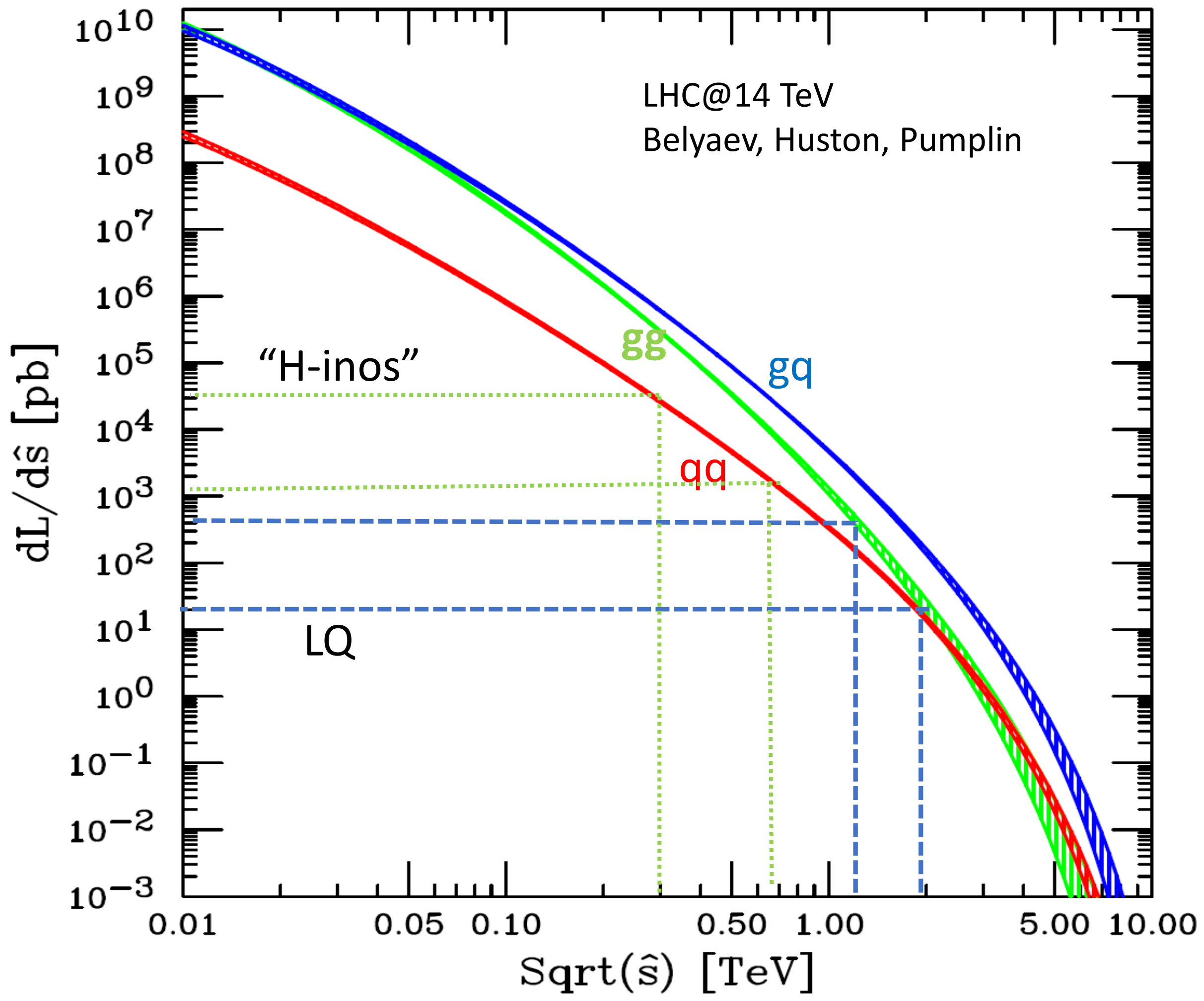


(d)

However, if you have an existing search, and the backgrounds/signal cross sections have similar scalings with energy, can do a rough reasonable estimation (although as the left figure shows, this can be rough. But even so the big picture comes through)

Reach for HL-LHC

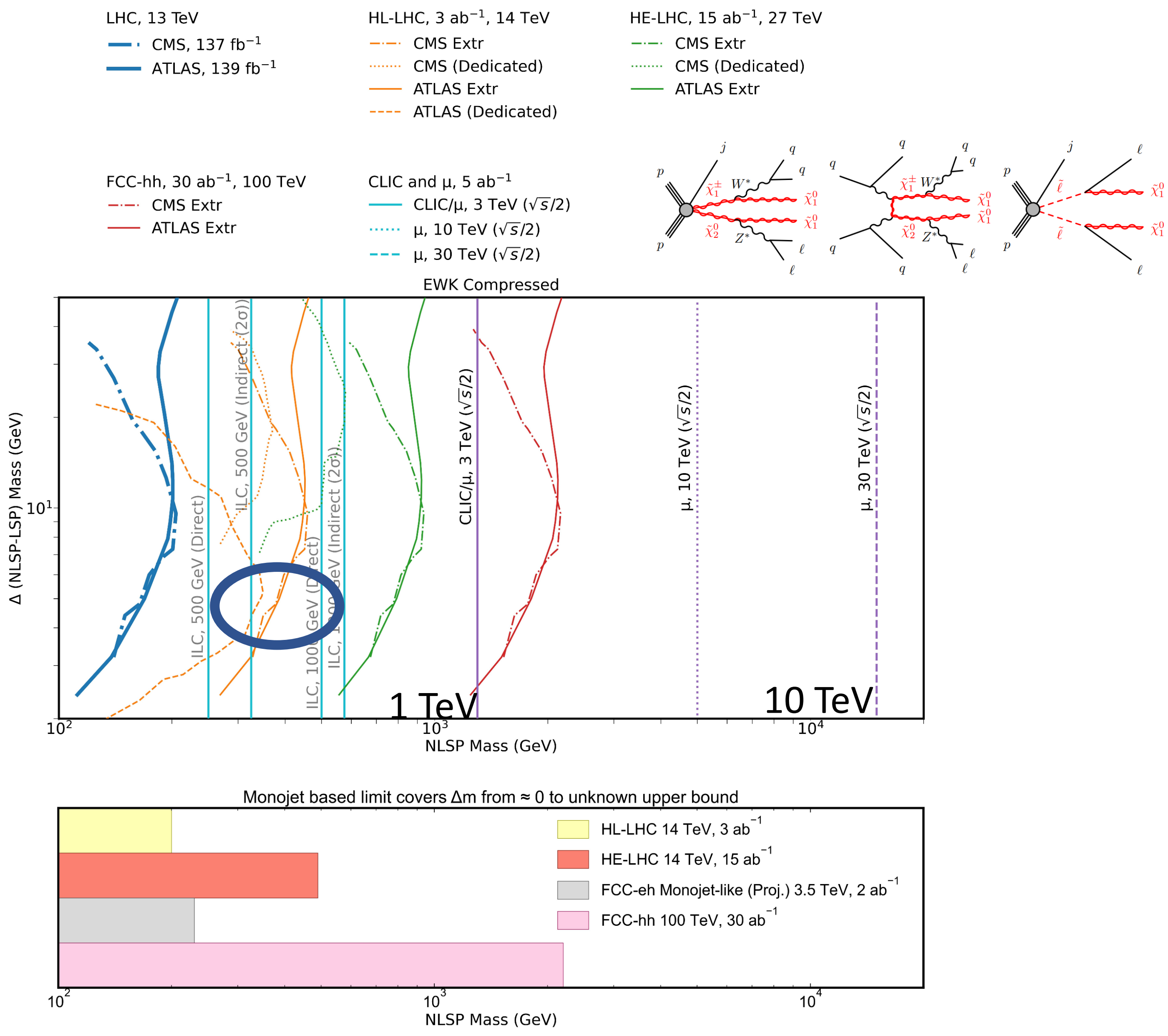
Can roughly estimate reach of a factor 20 more data from parton luminosity or you can do a more precise estimate with full simulation



Particle	Current limit (TeV)	Reference (arXiv)	Reach (TeV)	reference
MSSM H→ττ, tanβ=26	1.25	1803.06553	2.0	CMS-PAS-FTR-18-017
Heavy composite majorana neutrino	4.6-4.7	1706.08578	8.0	CMS-PAS-FTR-006
Randall-Sundrum gluon	4.55	1810.05905	6.6	CMS-PAS-18-009
Higgsino-like charginos,neutralinos	O(160)	1801.01846	O(0.35)	CMS-PAS-18-001
Leptoquark → te and tμ	1.4	1809.05558 1803.02864	1.8	CMS-PAS-18-008

Some example reaches estimated from full simulation from CMS (ATLAS reaches similar)

Caveat emptor

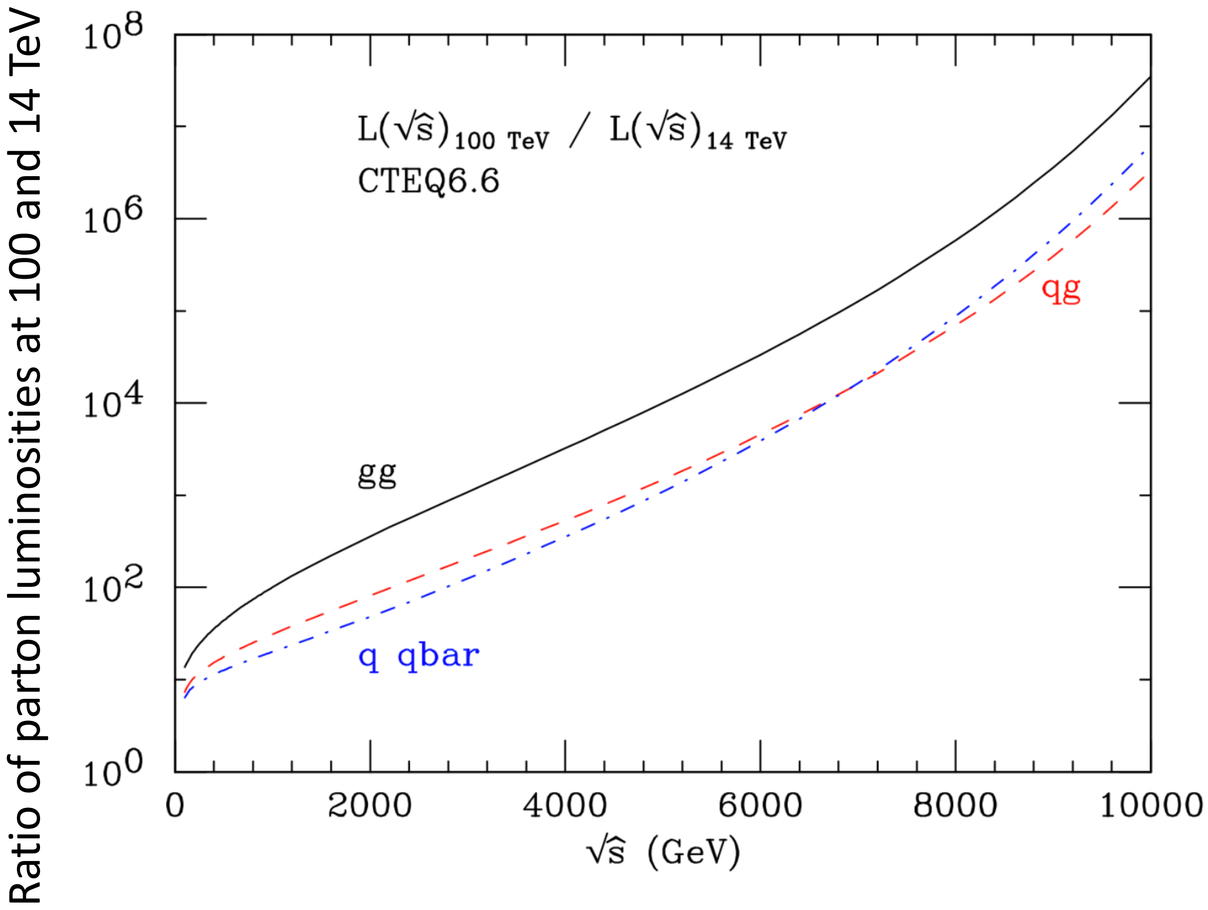


Because the backgrounds are larger, simple calculations/extrapolations are rougher than for lepton colliders. A simple analysis can be noticeably less efficient than an optimized one. Have to be cautious.

but the big picture comes through

Reach for FCC-hh

Can get a decent guess from current LHC results and this plot.



Connection to electron-positron Higgs factory

What if one of the current deviations from e.g. LHCb is confirmed at a future electron-positron collider? What if the CDF W mass measurement is confirmed by it? What if, when probed at the loop level, the Higgs branching fractions start to deviate from SM expectations?

Rule of thumb gives good guess at the energy needed for direct particle discovery for Higgs deviation

$$\Lambda \geq \frac{1\ TeV}{\sqrt{\frac{\delta g_{HXX}/\delta g_{HXX}^{SM}}{5\%}}}$$

$$\delta g_{HXX}/\delta g_{HXX}^{SM} = 0.15\%$$

Corresponds to 7 TeV. SUSY naturalness is also according to an educated guess to require new particles around 10 TeV, and the Higgs mass also points to a 10 TeV scale

Typical hadron collider reaches about a third to a half the center of mass energy

100 TeV should be safe. And this can probably be done with a hadron collider.

models

Look at more detailed simulated reach estimates
What are some models of interest?

- New bosons that produce resonances are a feature of many BSM models. Hadron colliders offer access to sensitivity to a wide variety of couplings, and is especially sensitive to bosons that couple to quarks/gluons. **Dijet resonances of interest to any DM model** that involves production in pp collisions via a mediator that couples to quarks/gluons.
- **SUSY** is still of interest as a solution, as it can still provide a dark matter candidate and a solution to naturalness. Hadron colliders provide access to most sparticles, with especially sensitivity to the stops curtail to the naturalness question. It also can capture the essence of many similar DM models.
- Heavy neutrinos are of interest to the solution to the neutrino mass question.

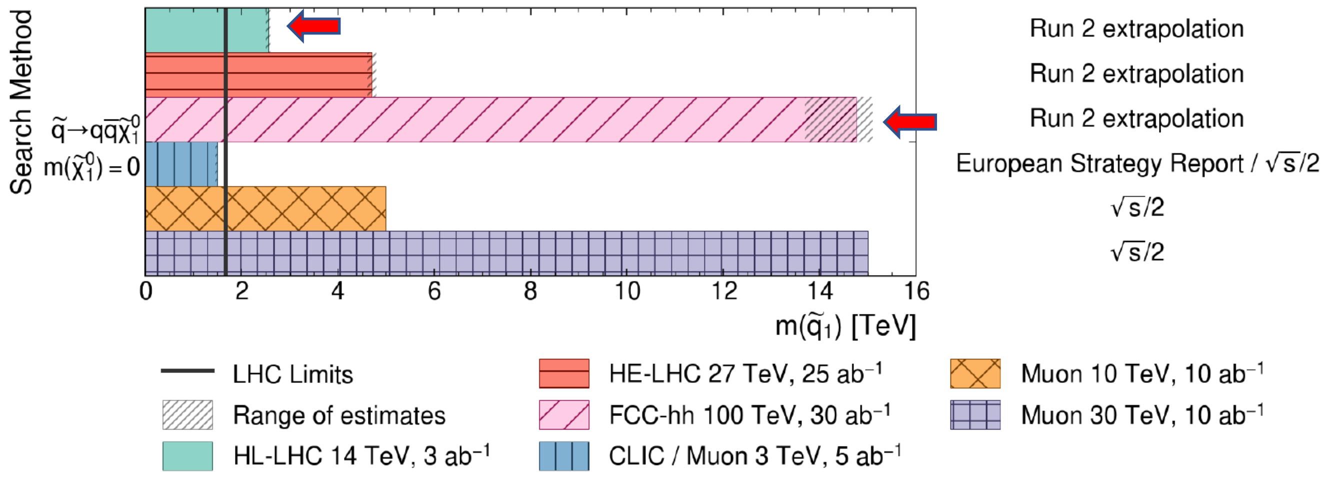
(of course many other compelling models. The collaborations welcome additional detailed reach estimates!)

New resonances to dijets

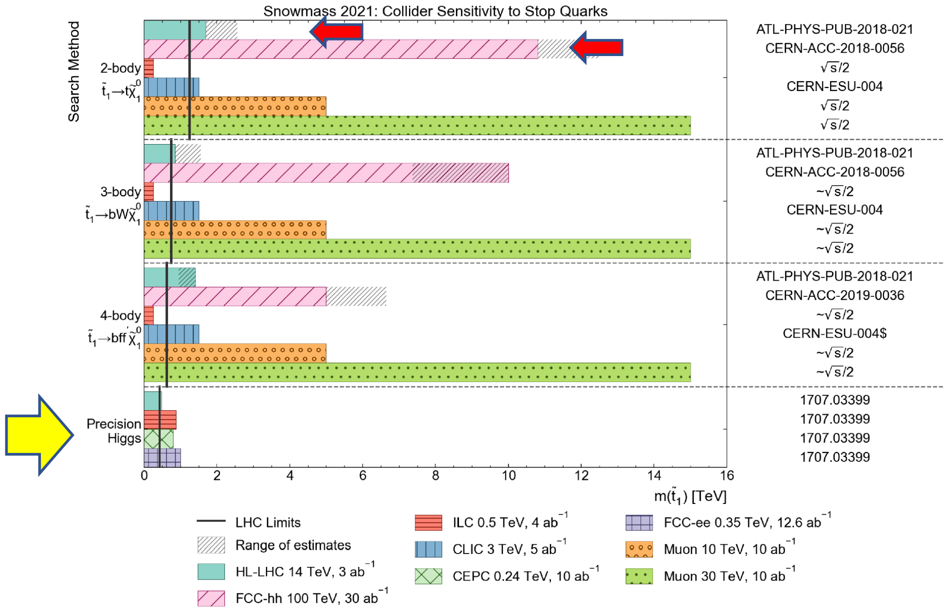
Rule of thumb is that the reach for a strongly coupled new boson is about half the center of mass energy

Model	HL-LHC $\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3 ab^{-1} 5σ [TeV]	HL-LHC 95% CL [TeV]	FCC-hh $\sqrt{s}$ = 100 TeV, $\int Ldt$ = 30 ab^{-1} 5σ [TeV]	FCC-hh 95% CL [TeV]
Strongly Produced Dijet Resonances				
Diquark	8.7	9.4	57	63
Coloron	7.1	7.8	45	51
q*	7.0	7.9	44	50
Weakly Produced Dijet Resonances				
W'	4.8	5.6	29	36
Z'	4.2	5.2	25	32
RS grav.	3.5	4.4	21	27
Top Squark $\tilde{t}_1\tilde{t}_1 \rightarrow (t\,\tilde{\chi}_1^0)\,(t\,\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0) = 0$				
$\tilde{t}_1$	1.3	1.7	9.6	10.8

SUSY: squarks including stop

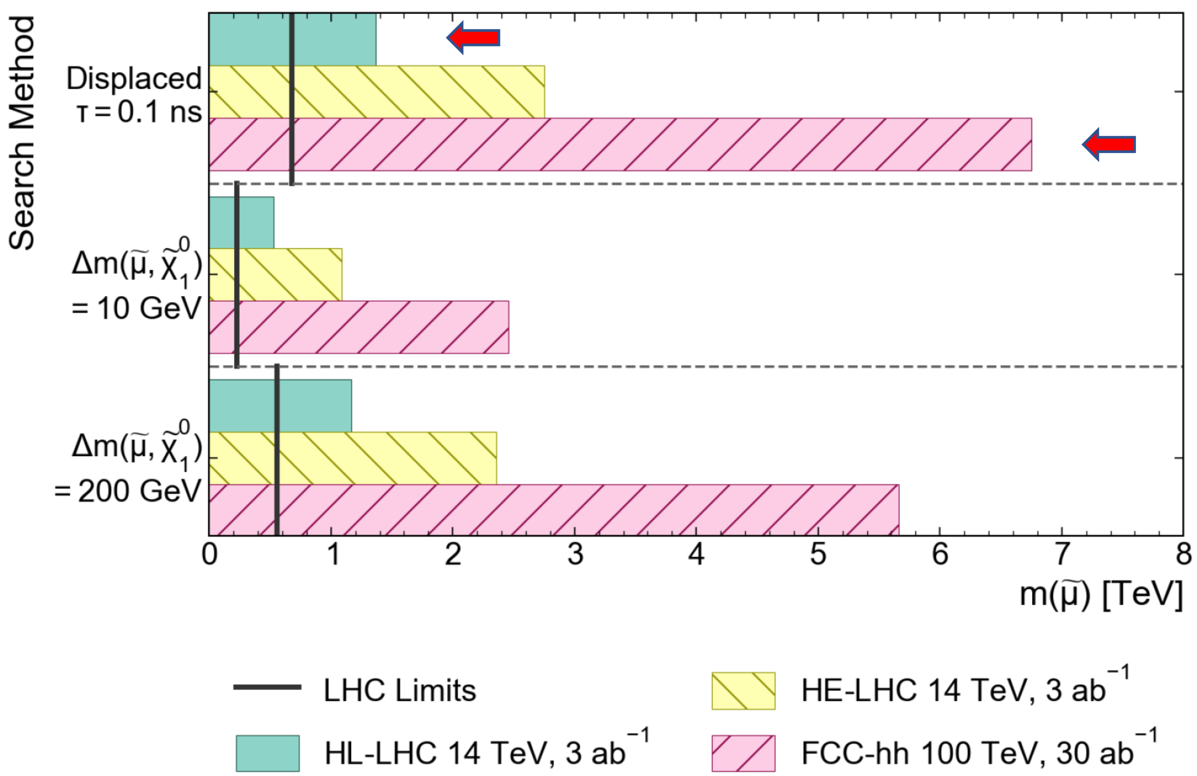


Hadron colliders are excellent places to look for colored particles like squarks/gluinos.



The reach even for HL-LHC is comparable to precision Higgs studies. FCC-hh will cover the full range for these decay modes.

SUSY: sleptons



Light sleptons are interesting in the neutralino-stau coannihilation region of SUSY DM solution
Perhaps related to g-2 anomaly

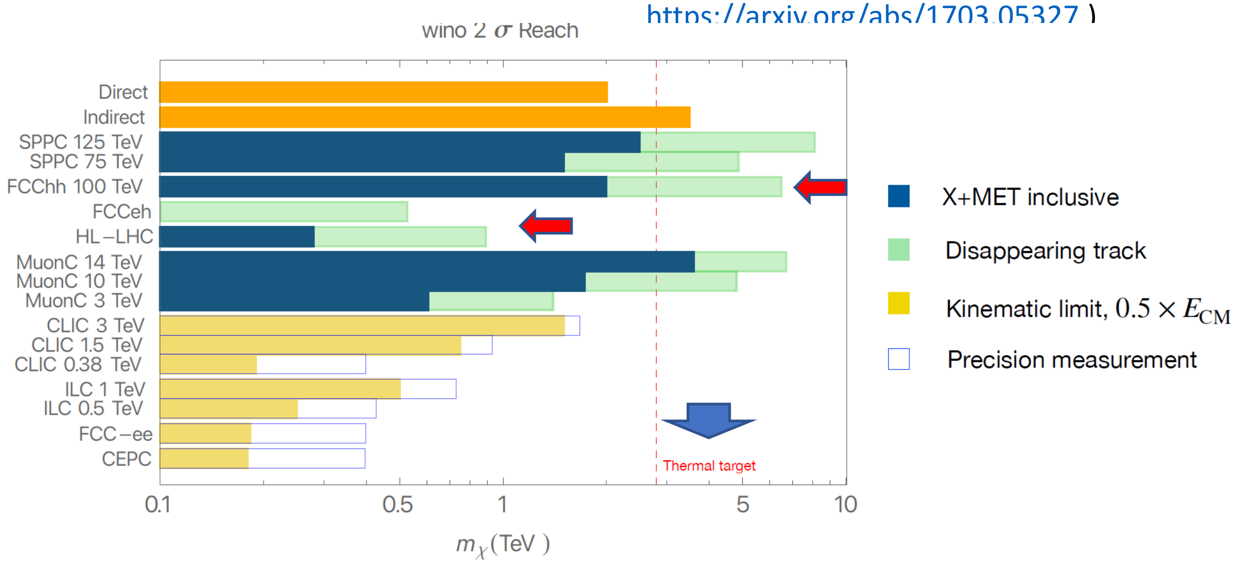
Dark Matter (SUSY-like)

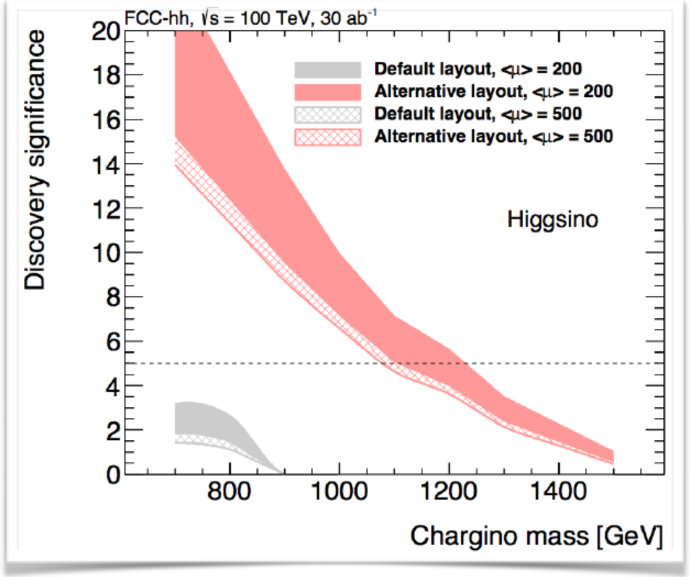
There are dark matter models with DM masses of on TeV scale (up to 100 TeV) that are consistent with cosmological measurements that can only be explored at a very high energy machine.

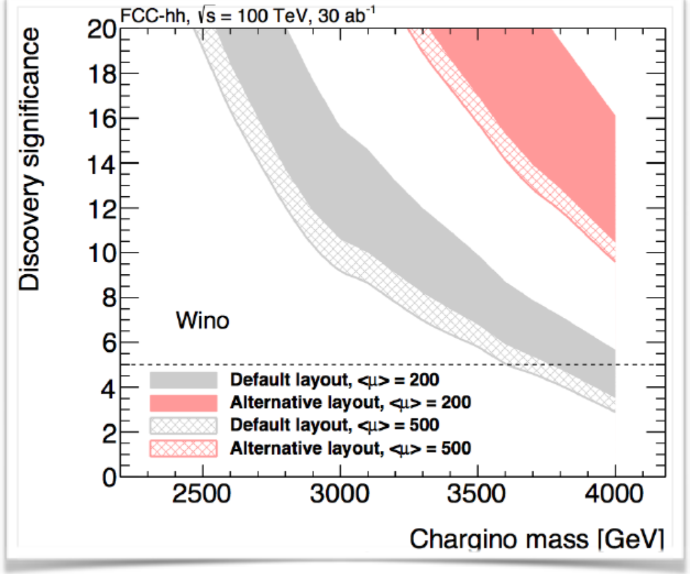
One example is SUSY-like DM models, with DM in an electroweak multiplets ("Higgsino" "wino") are compelling with DM candidates in the TeV region for correct abundance.

Capable of discovery of US(2) triplet DM ("wino") in the cosmologically interesting value of 2-3 TeV (https://cds.cern.ch/record/2642474)

Higgsino dark matter with cosmologically interesting masses 1-1.2 TeV can also only be found at FCC-hh (https://cds.cern.ch/record/2642474, https://arxiv.org/abs/1703.05327)







pMSSM

Only the red-ish points excluded by a lepton collider

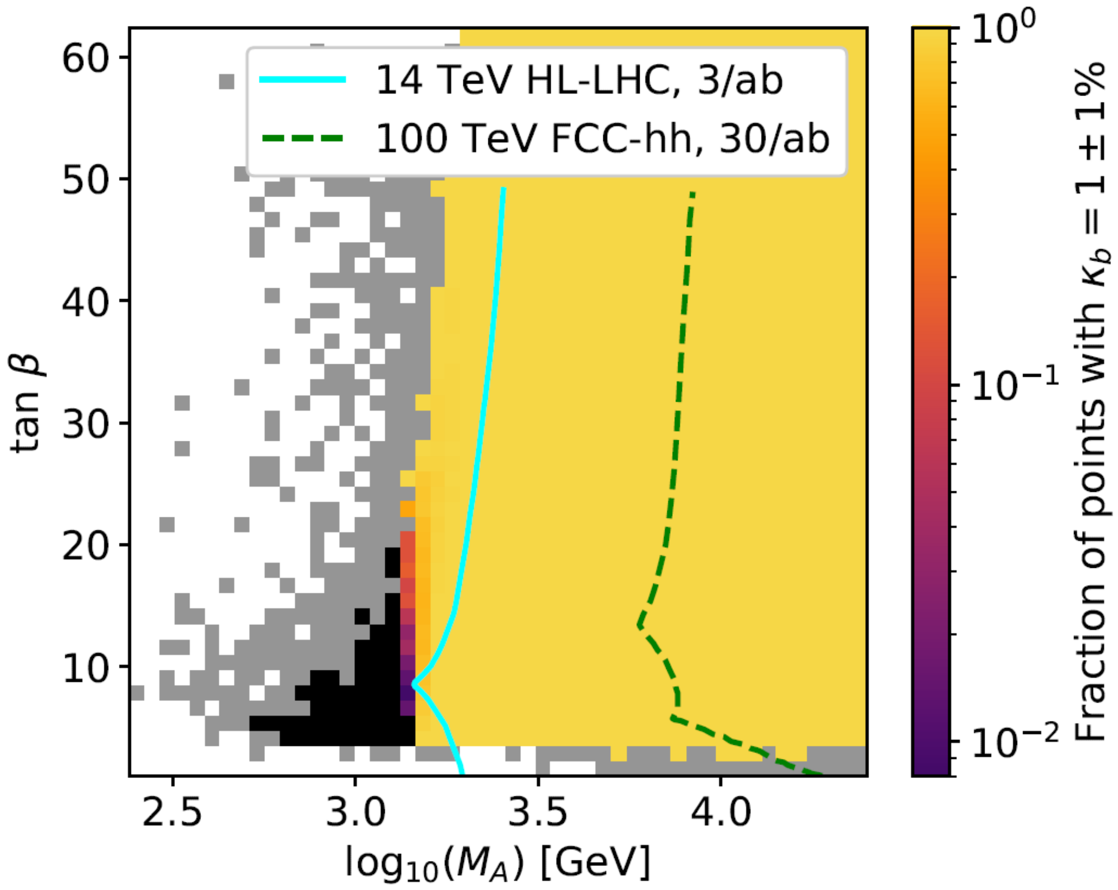


FIG. 10. The fraction of pMSSM scan points with κ_b within 1% of the SM expectation of unity as a function of $\tan\beta$ and M_A. The range of 1% is chosen to approximately reflect the 95% CL corresponding to the 0.48% precision on κ_b expected from the FCC-ee/eh/hh combination [216]. Expected 95% CL exclusions from HL-LHC [220, 222] and FCC-hh [220] are overlaid for reference. White bins include no scan points generated by the Markov chain Monte Carlo (McMC) procedure. Gray bins include scan points generated by the McMC, but rejected at a later step because of lack of consistency with current precision measurements and direct searches.

Version of SUSY that captures most phenomenology with 19 instead of 120 parameters (https://cds.cern.ch/record/2047040?ln=en, https://arxiv.org/abs/1606.03577, https://arxiv.org/abs/1206.4321)

Markov chain MC scan including physics observables like g-2, DM relic density, Higgs properties (especially couplings to b and tau) (https://arxiv.org/abs/2207.05103)

Of interest here is the direct search for the pseudoscalar Higgs boson A reach for HL-LHC and FCC-hh, which greatly extends the sensitive over the indirect searches.

Heavy neutrinos

The "Seesaw mechanism" is an appealing explanation for the lightness of the neutrinos.
Type-1 seesaw models have single HNL (typical decays $N \to eW$, $N \to \nu Z$, with long lifetime possible) and type-2 have a triple of heavy leptons (1 neutral).
If the HNL mix with the neutrinos, production and detection is possible.

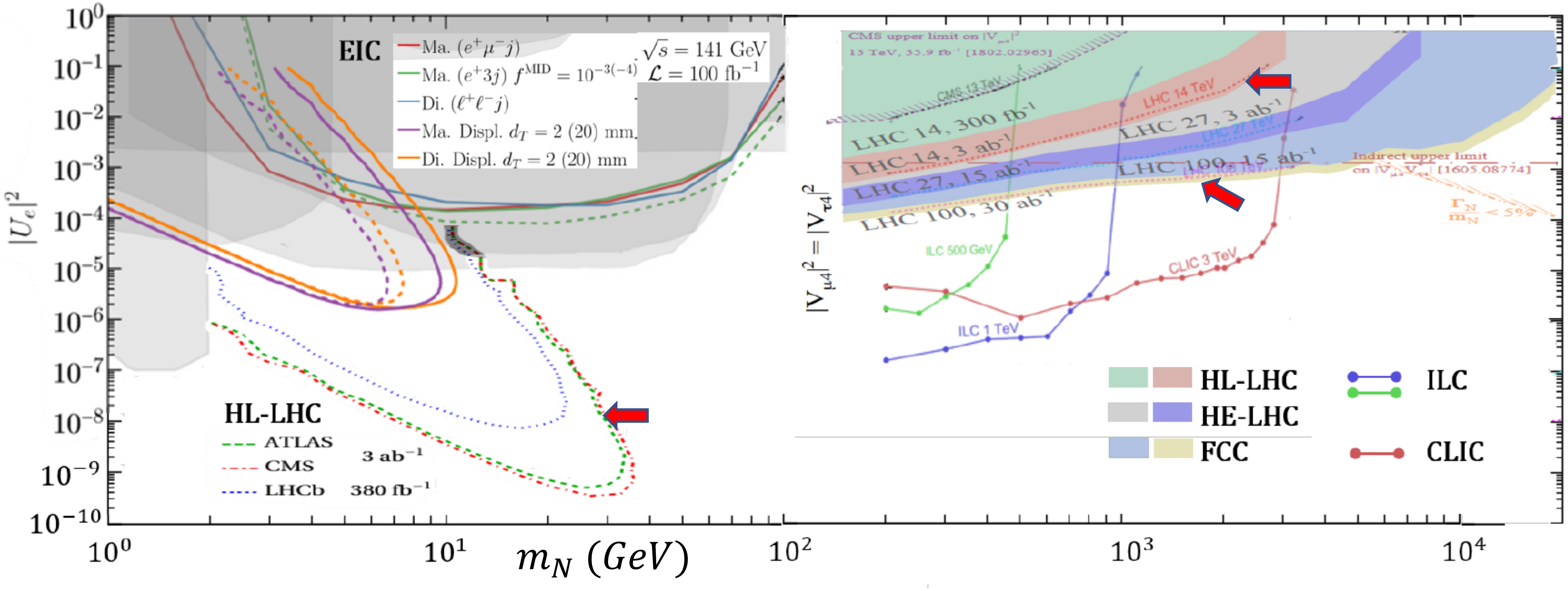
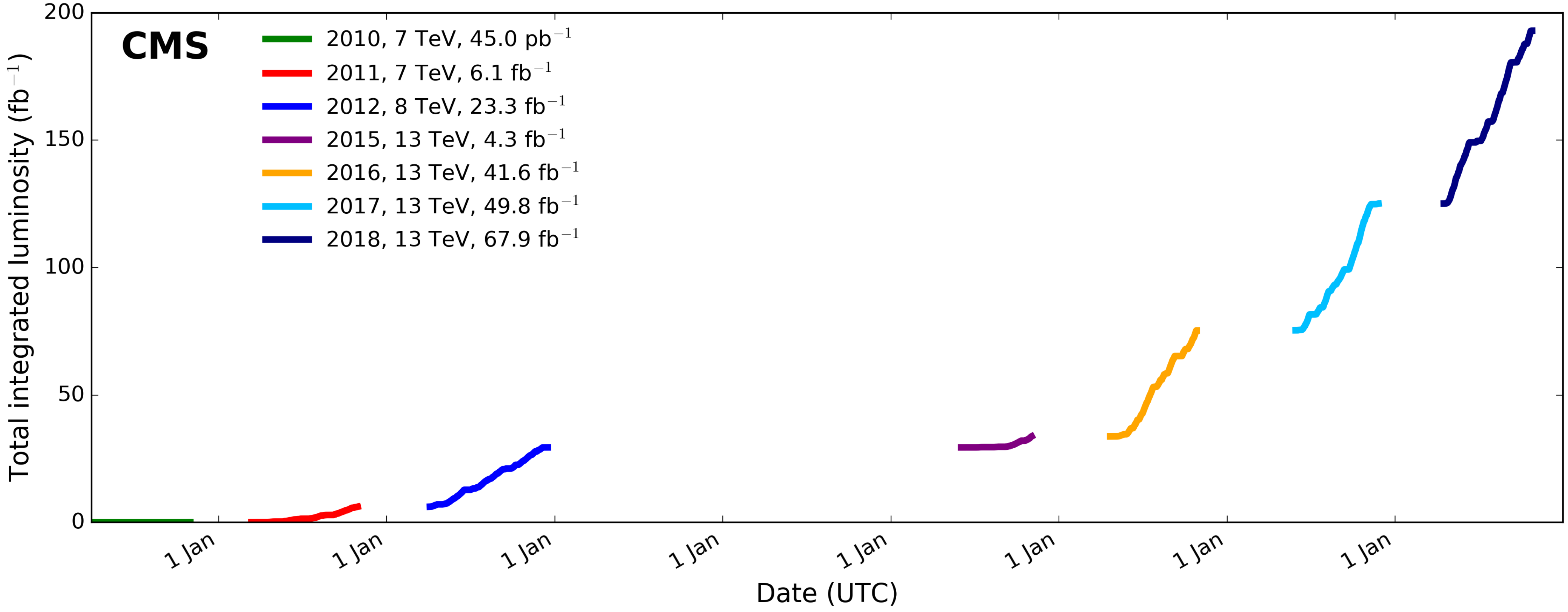
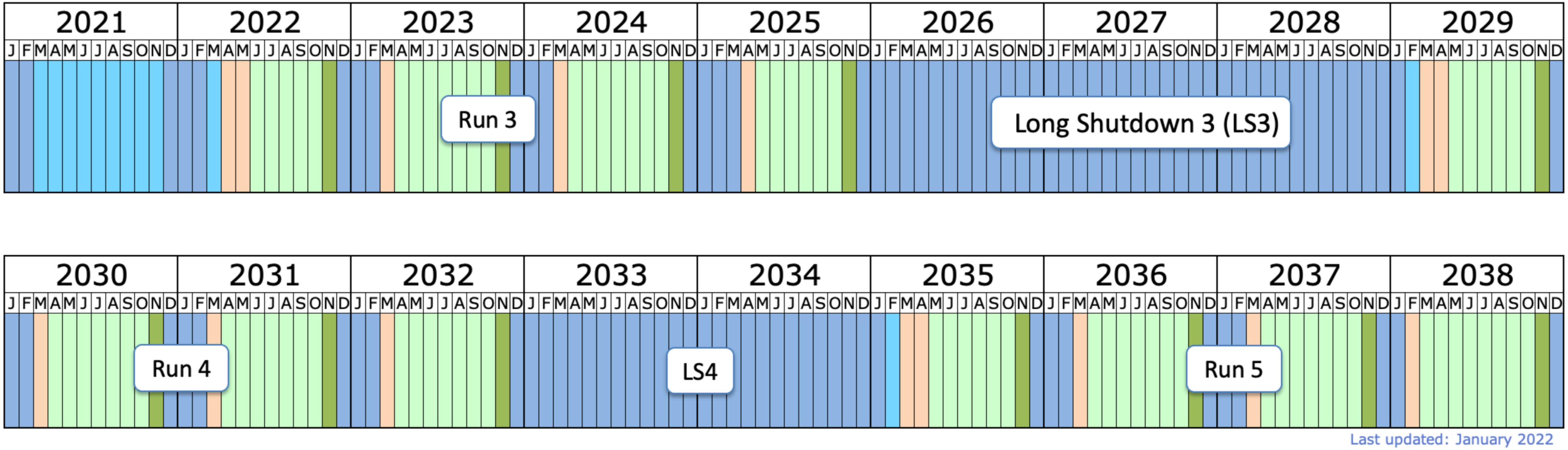


FIG. 15. Expected bounds for HNLs in the type-1 Seesaw model. Low mass constraints on the coupling of the HNL to electrons are set for the EIC and HL-LHC [244, 245]. High mass constraints from the HL-LHC, HE-LHC, FCC-hh, ILC, and CLIC assume either two (hadron colliders) or three (lepton colliders) non-zero couplings between the HNL and SM leptons [245, 247].

conclusions

Hadron colliders will provide exciting opportunities for new particle discovery!


CMS
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.3 fb⁻¹
2016, 13 TeV, 41.6 fb⁻¹
2017, 13 TeV, 49.8 fb⁻¹
2018, 13 TeV, 67.9 fb⁻¹
Total integrated luminosity (fb⁻¹)
200
150
100
50
0
1 Jan
Date (UTC)


2021
2022
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Run 3
Long Shutdown 3 (LS3)
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Run 4
LS4
Run 5
Last updated: January 2022

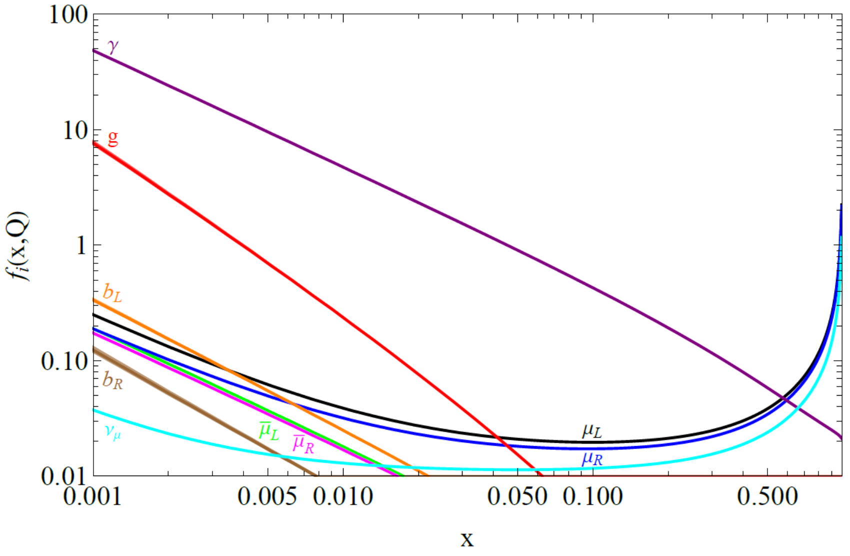

Figure 17. Muon PDFs including the full unbroken SM interactions for $Q = 3$ TeV. The thickness of the gluon and b quarks PDFs is obtained by varying the μ_{QCD} scale from 0.5 to 1 GeV.