FUTURE COLLIDERS

Carleton University

DANIEL STOLARSKI

IPP 50th Anniversary Symposium — May 29, 2022

DISCLAIMERS

I am a BSM theorist giving a short talk:

- Will not discuss low energy or neutrino experiments.
- Will not discuss many interesting topics including QCD, heavy ions, etc.
- Incomplete list of physics opportunities.

See references in backup slides for much more.

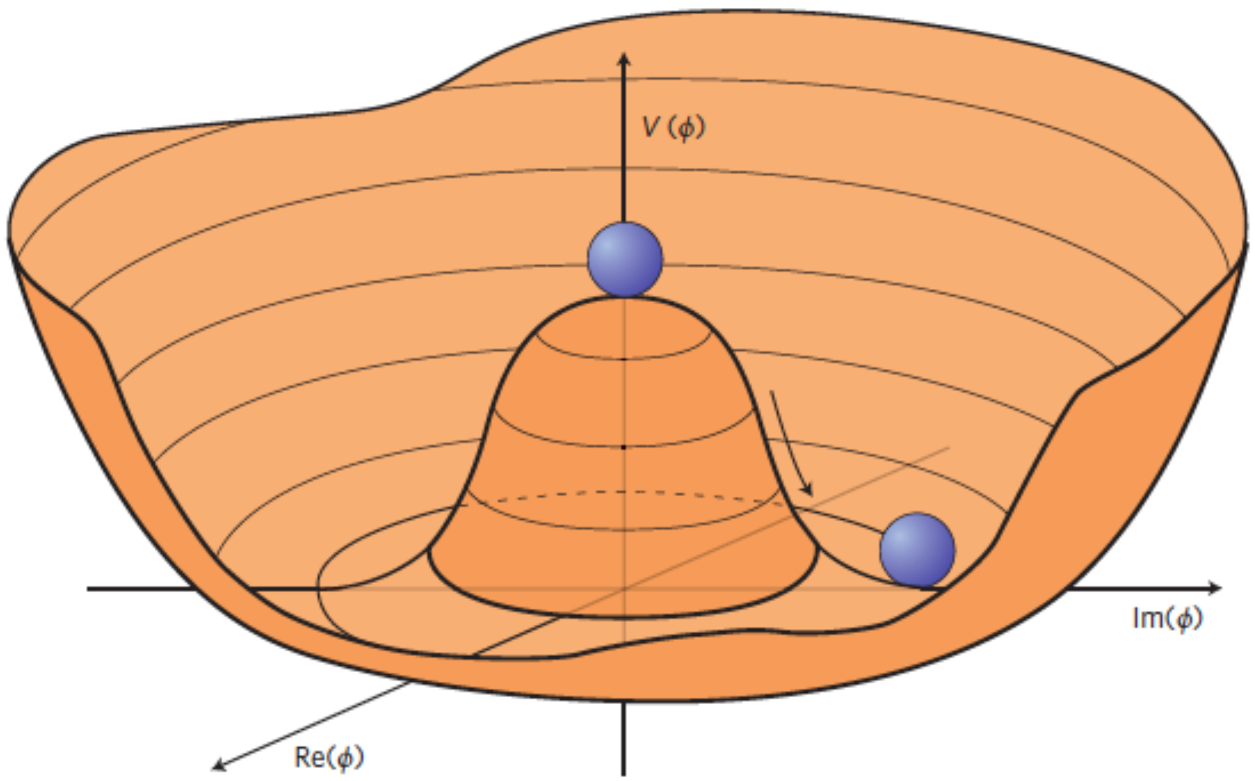
COLLIDER CONCEPTS

- e^+e^- machine: higher energy and/or luminosity than LEP. (CEPC, CLIC, FCC-ee, ILC)
- Hadron collider: higher energy than LHC. (FCC-hh, HE-LHC, SppC)
- Electron hadron collider, capture some of the advantages of both hadron and lepton machines.
- Muon collider, can achieve much higher energy than electrons, technology is unproven.

HIGGS POTENTIAL

SM says Higgs breaks electroweak symmetry with this potential.

No direct experimental evidence of this.

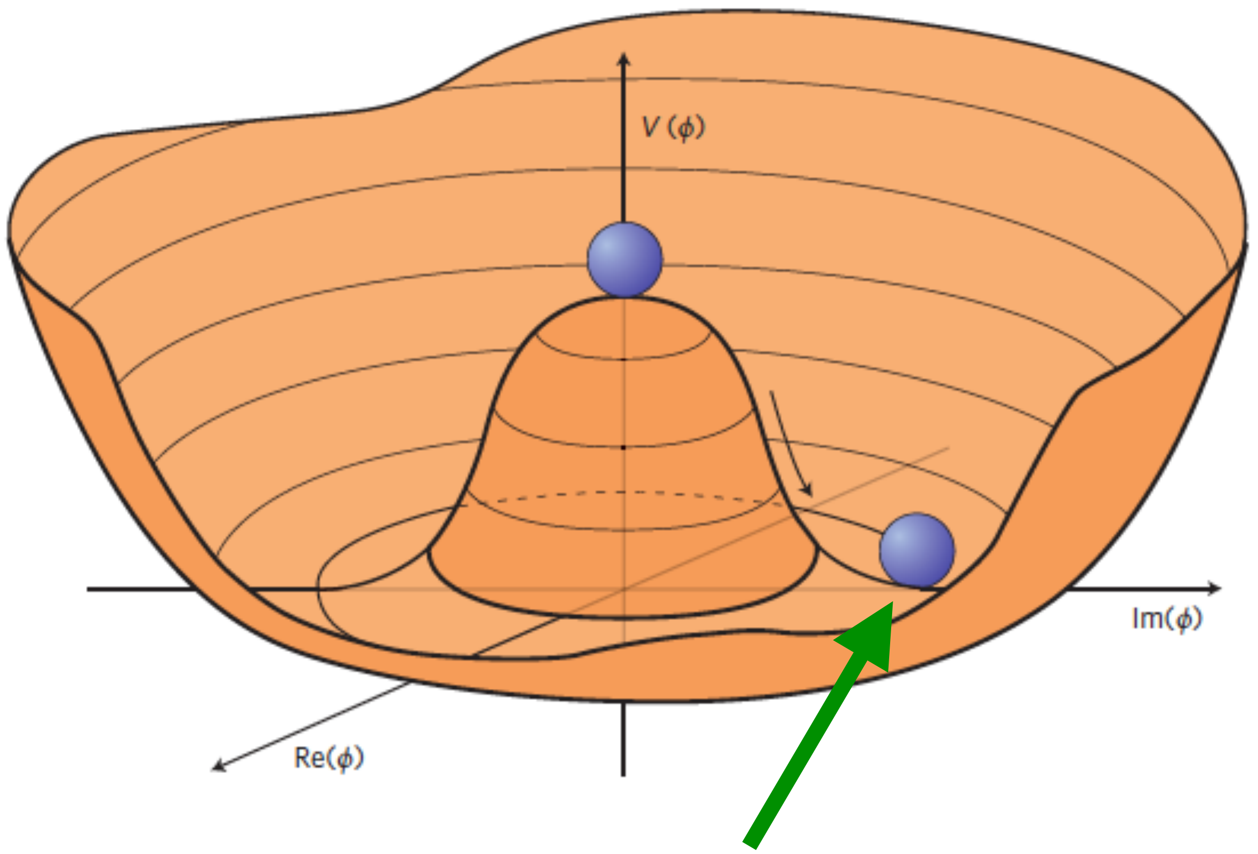


HIGGS POTENTIAL

SM says Higgs breaks electroweak symmetry with this potential.

No direct experimental evidence of this.

Can measure derivatives of potential.



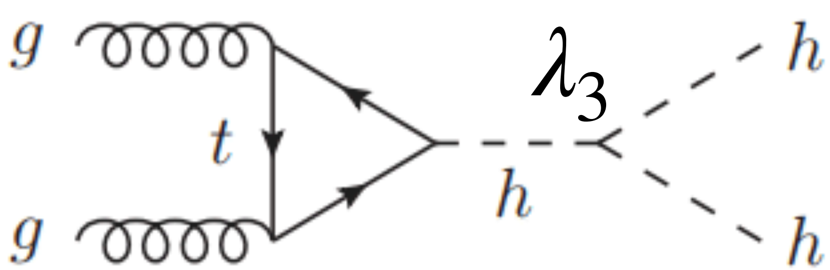
$$V(h) \sim \frac{1}{2} m_h^2 h^2 + \frac{1}{3!}\lambda_3 h^3 + \frac{1}{4!}\lambda_4 h^4 + \ldots$$

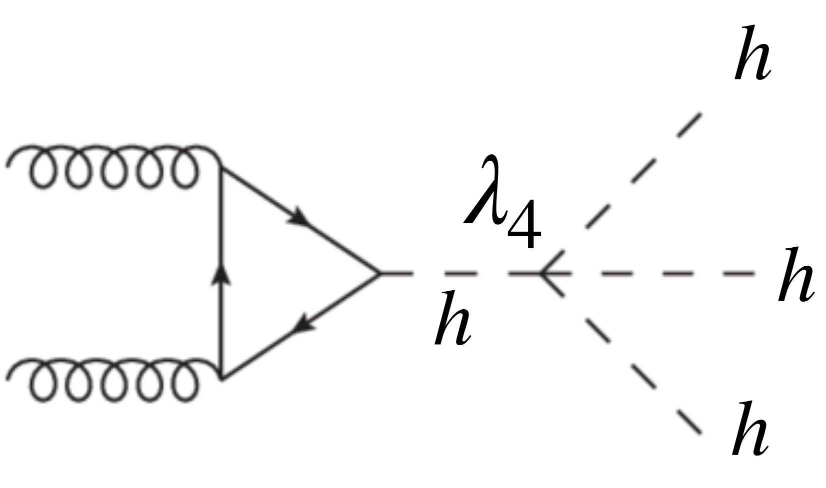
N-HIGGS PRODUCTION (hh/μμ)

SM makes definite predictions for these coefficients:

$$\lambda_3 \sim \frac{g\, m_h^2}{m_W} \qquad \lambda_4 \sim \frac{g^2\, m_h^2}{m_W^2}$$

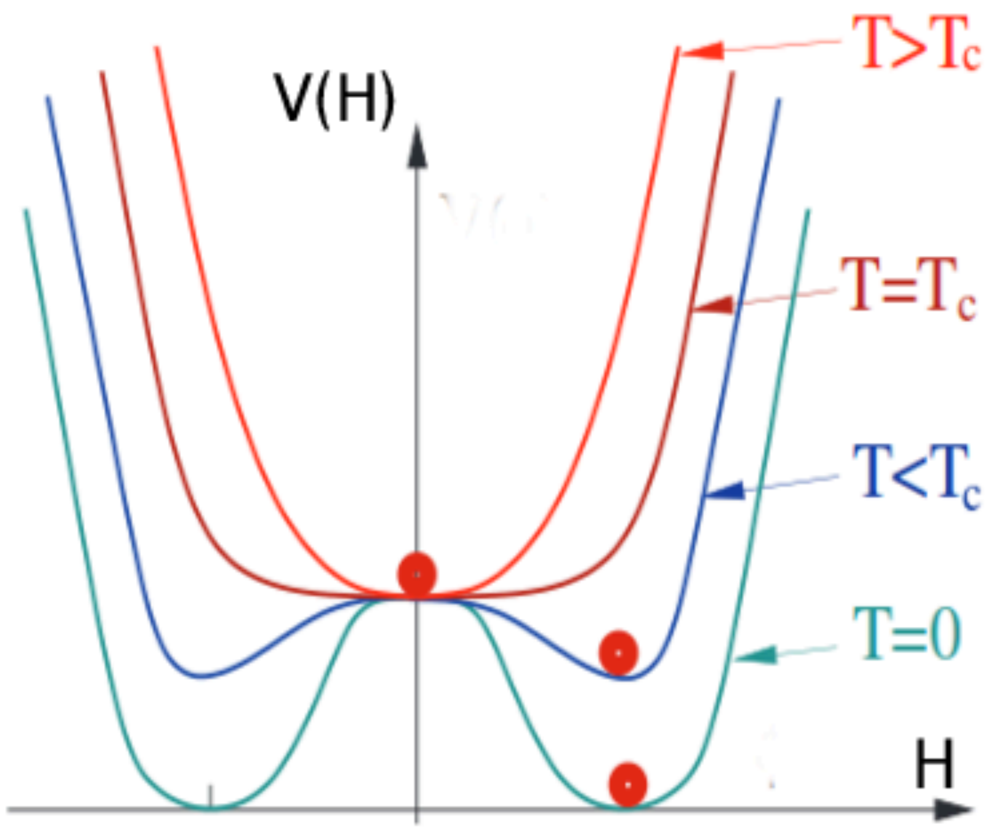
Can directly measure these couplings with multi-Higgs production (very hard at LHC).





ELECTROWEAK PHASE TRANSITION (hh/μμ)

In the early universe, electroweak symmetry is restored.



SM predicts smooth transition from unbroken to broken phase.

ELECTROWEAK PHASE TRANSITION (hh/uu)

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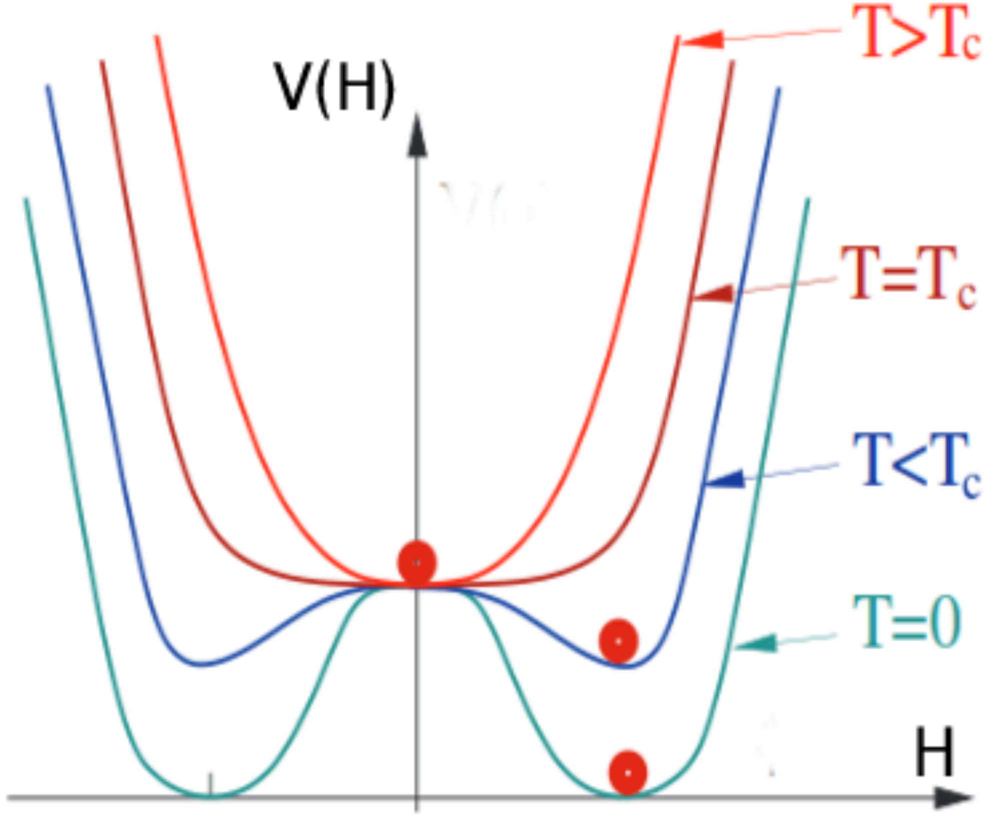
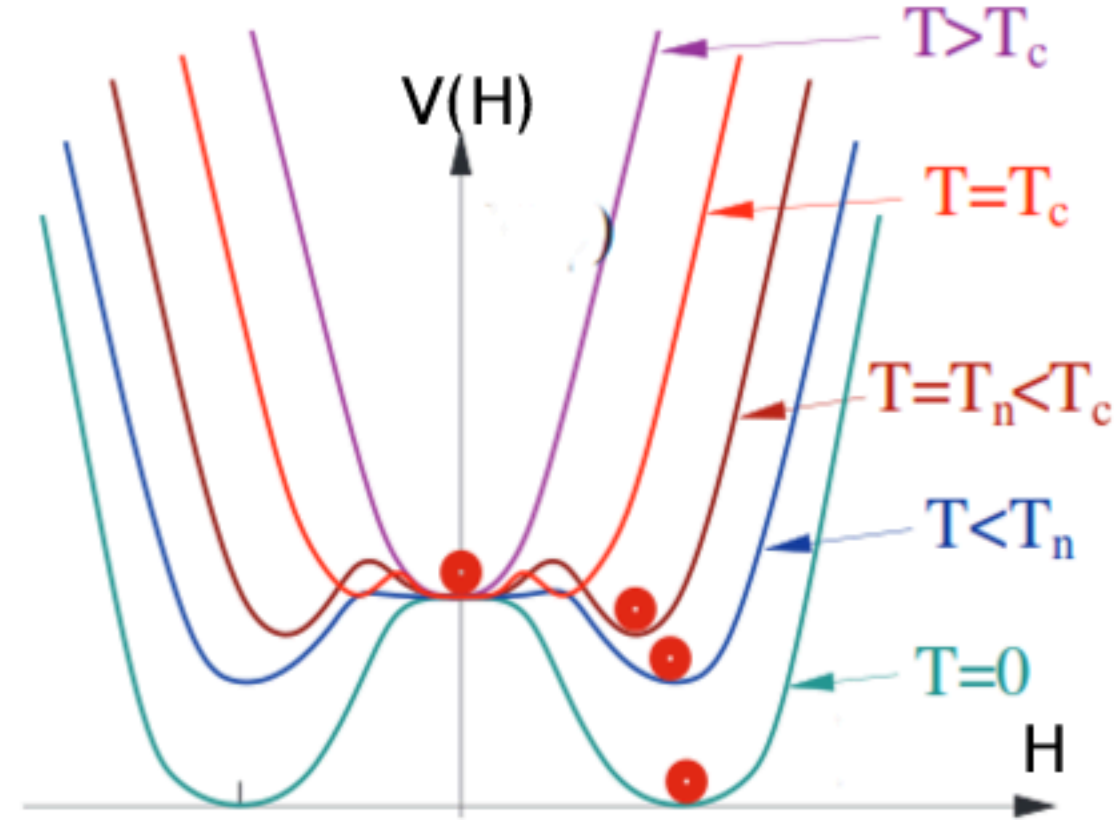


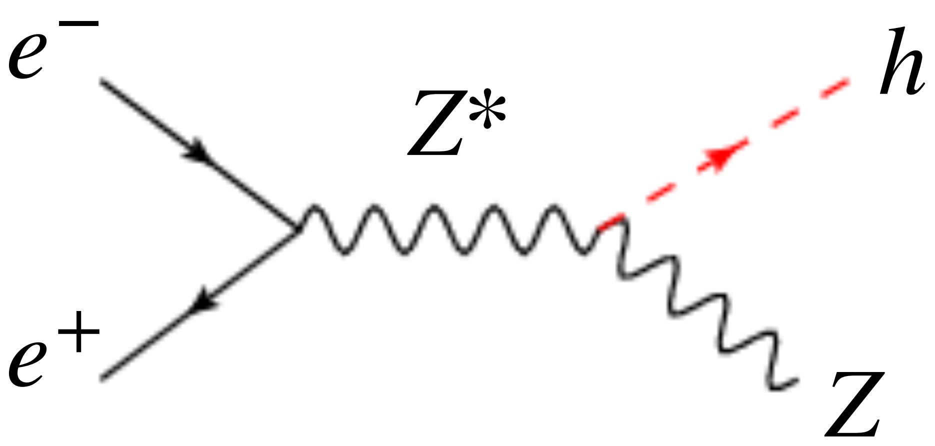


BSM theories (with new states) could have violent transition, possible baryogengesis mechanism.

Curtin, Meade, Yu, arXiv:1409.0005.

NEW LIGHT PARTICLES (ee/uu/he?)

In lepton collider, can use knowledge of initial state to detect that a Higgs was created without seeing it.



Search for Higgs decays to new particles.

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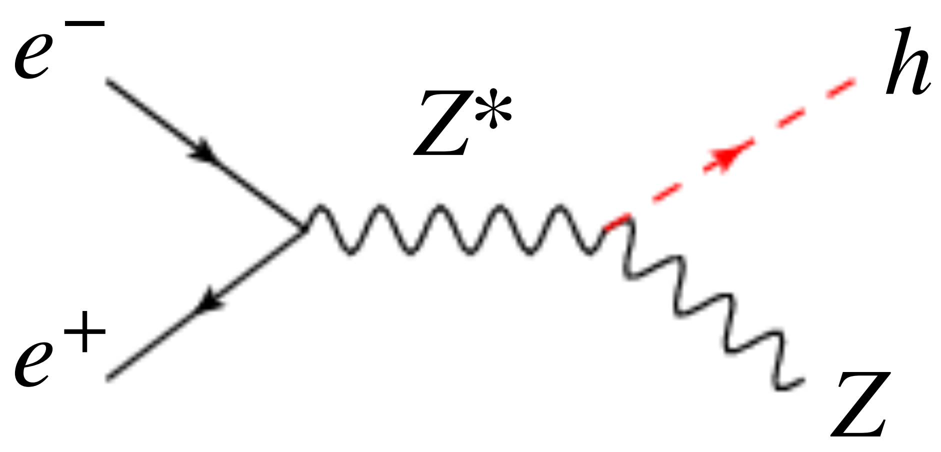
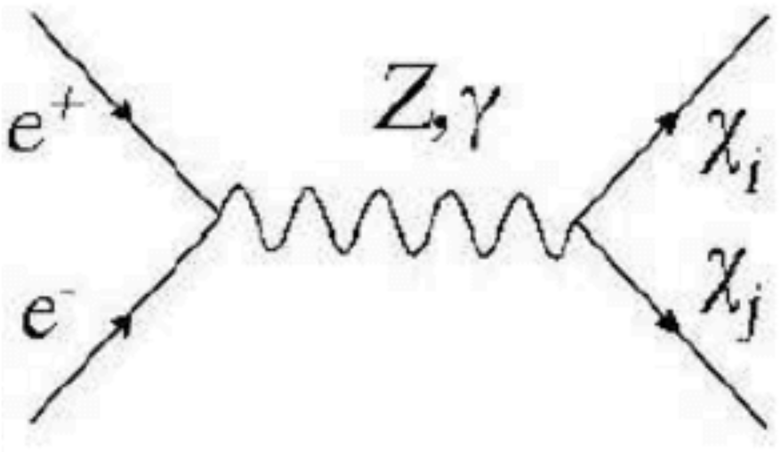


Search for Higgs decays to new particles.

Can also look for new electroweakly charged particles with difficult decays.



Could be connected to dark matter or SUSY.

NEW HEAVY PARTICLES (hh/uu/he?)

With 100 TeV CM, could discover:

- ~10 TeV coloured particles
- ~2 TeV electroweak particles
- ~20 TeV resonances

Probing 10 TeV scale increases required tuning of weak scale from 1/100 to 1/10,000.

PROBING HIGH SCALES (ee/hh/he/μμ)

Precise measurements can be translated to limits (or discoveries!) of new physics at high scales.

Parameterize via effective field theory (very general).

Example: $\frac{\delta\Gamma_Z}{\Gamma_Z} \sim \frac{1}{500{,}000} \Rightarrow \Lambda \sim 50\,\mathrm{TeV}$

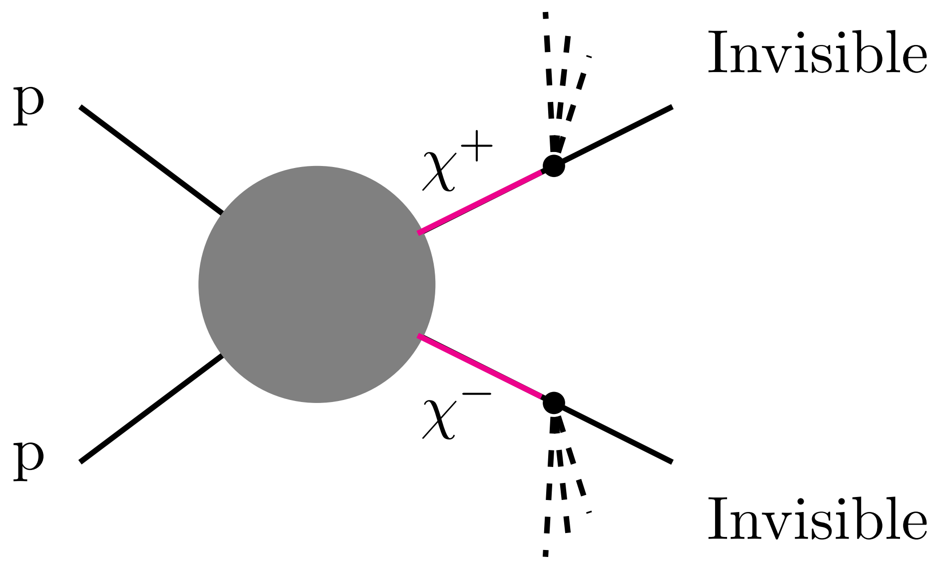
Can also do with W, Higgs, leptons, quarks…

DARK MATTER (hh/μμ)

WIMP classic (pure electroweak state) prefers a mass of 1-3 TeV.

Disappearing track search can probe cosmologically relevant parameters.

Also significant reach in mono-jets, mediator models, co-annihilation, asymmetric DM...



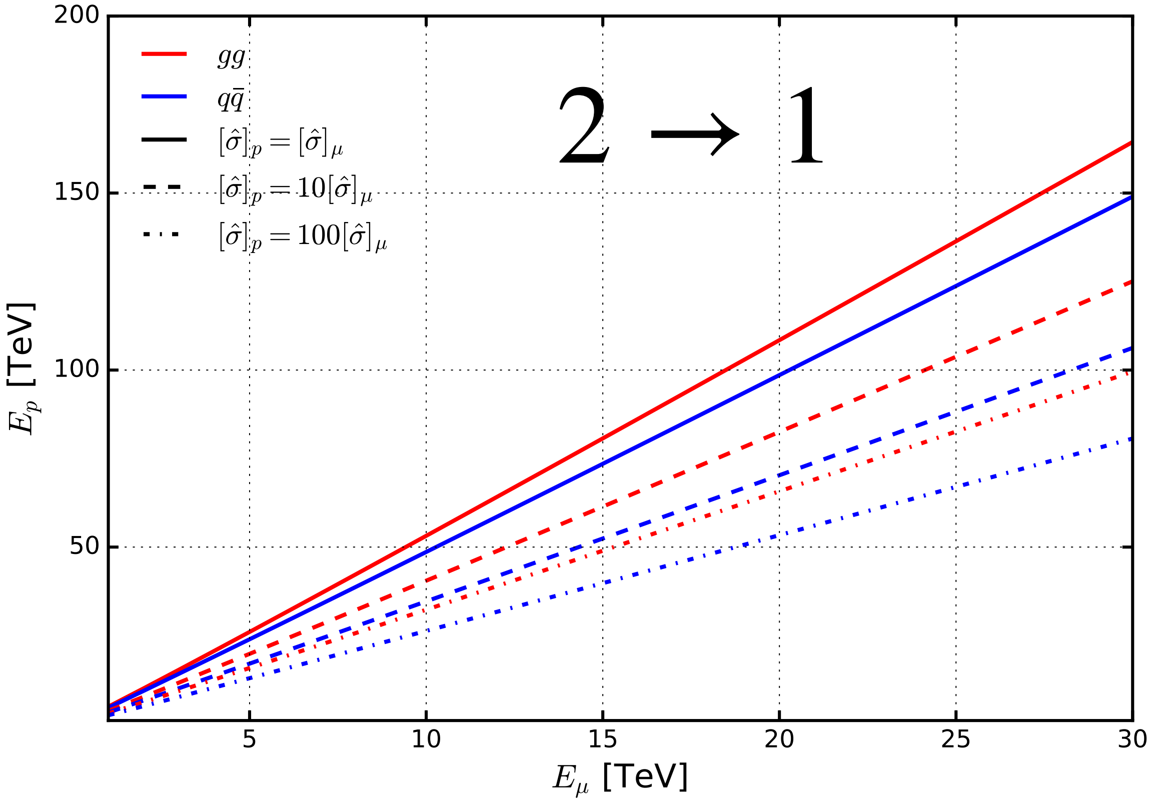
Mahbubani, Schwaller, Zurita, arXiv:1703.0532

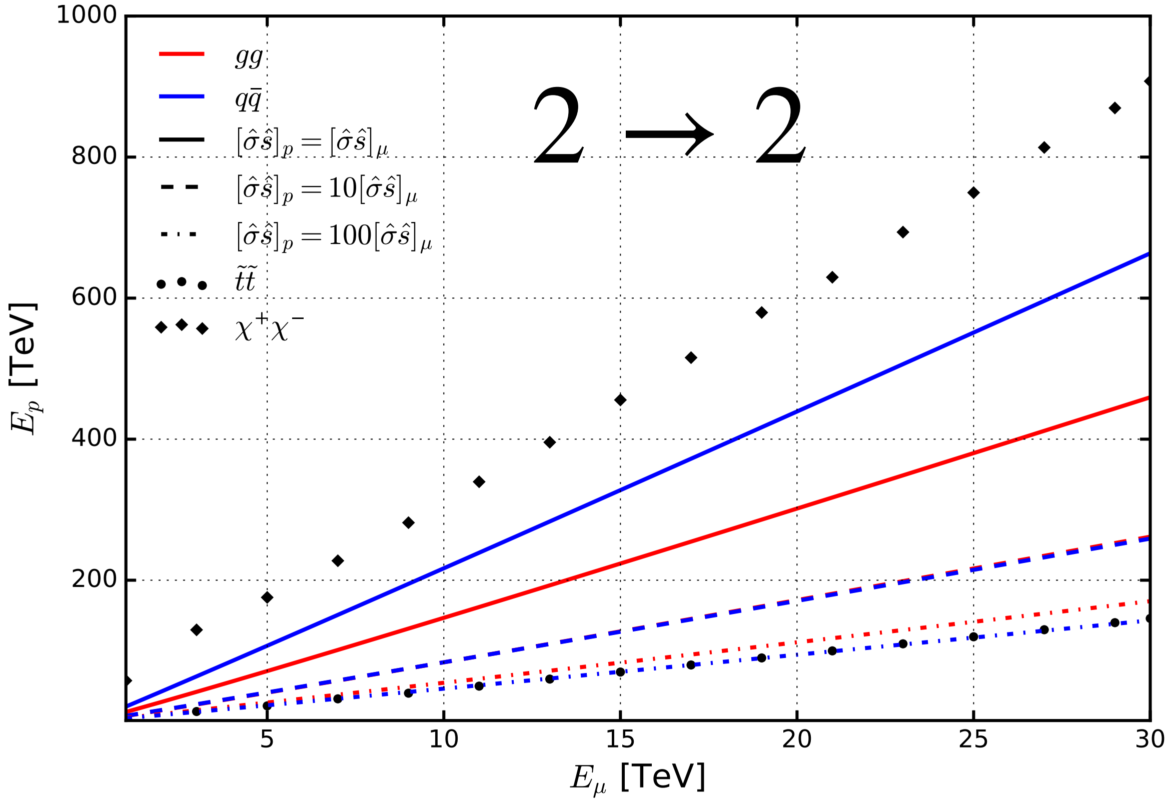
MUON COLLIDERS

Muon colliders can do it all!

Can reach much higher energies than electron collider.

Effective energy much higher than pp.

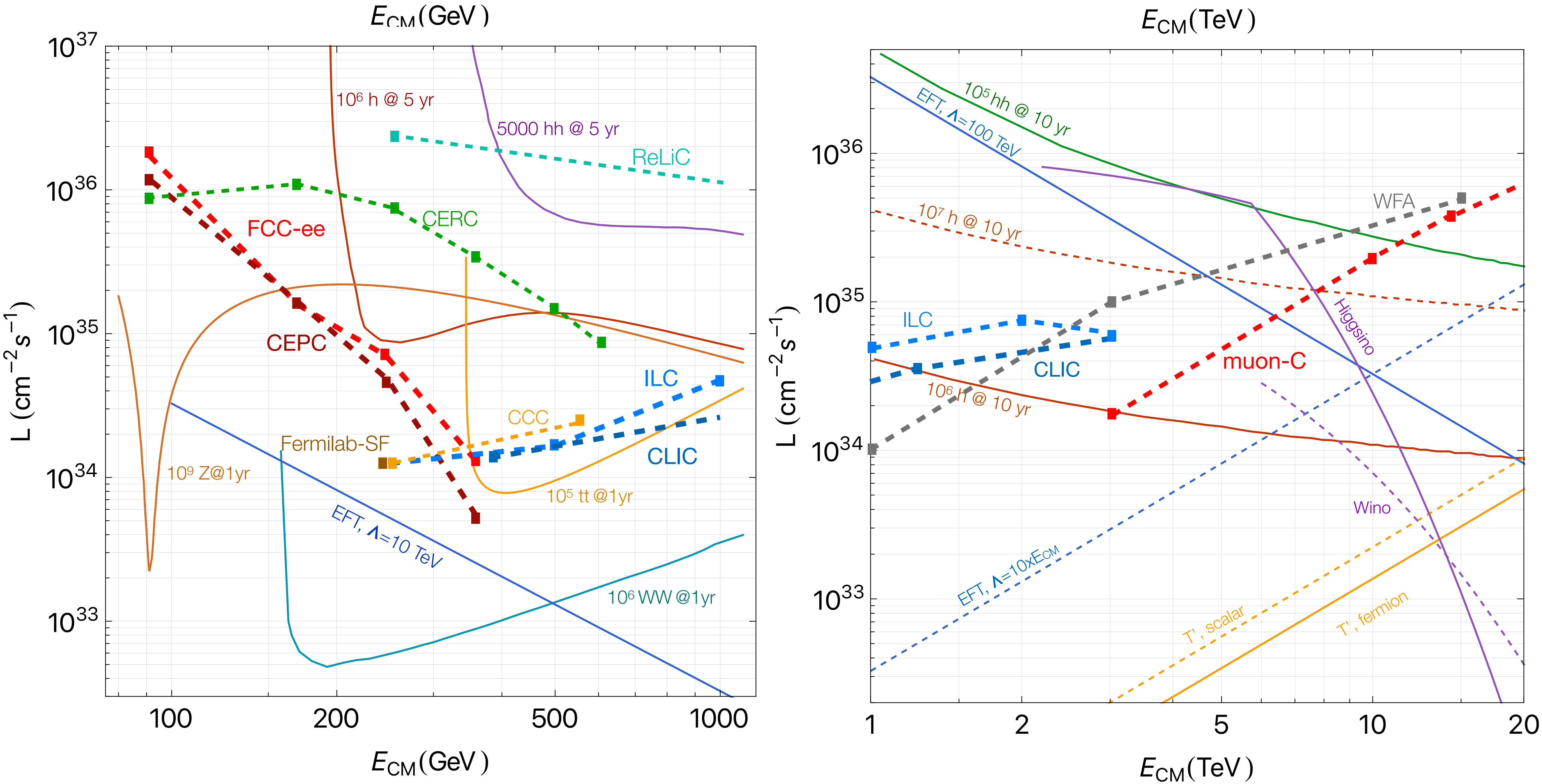




Costantini et al. arXiv:2005.10289

ENERGY VS LUMINOSITY

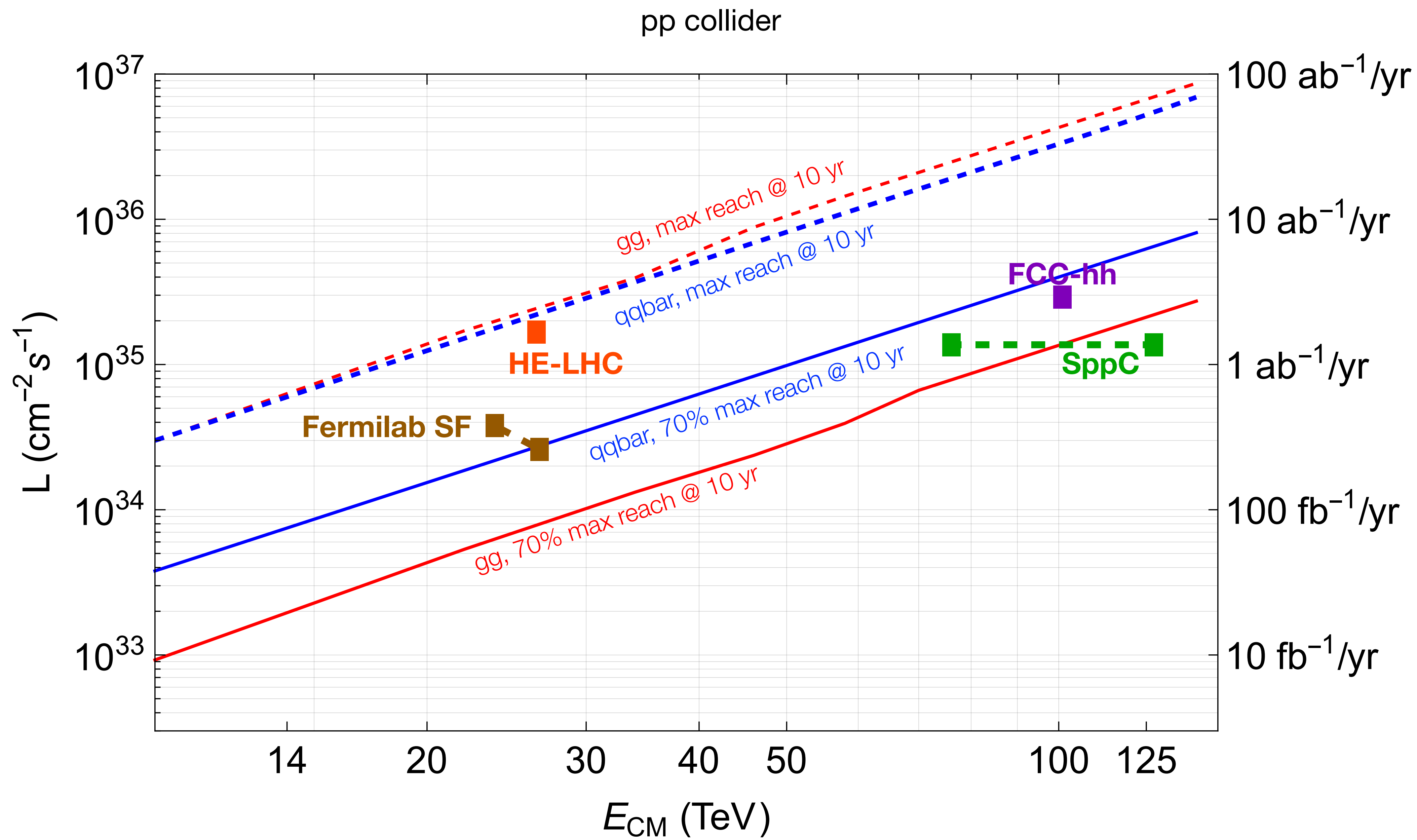
e+e- collider



Liu and Wang arXiv:2205.00031

E VS L HADRONS

Liu and Wang arXiv:2205.00031



CHALLENGES

The physics case is the easy part!

Have to find funding for these machines.

Significant technology development is necessary:

- Better accelerator technology
- Better detector technology

CAP SEMINAR DAY

Canadian Association of Physicists

Association canadienne des physiciens et physiciennes

2022 CAP Congress / Congrès de l'ACP 2022

Session

T1-3 New Directions in Accelerator-Based Experiments: Future Collider Experiments - Energy Frontier (PPD) | Nouvelles voies fondées sur des accélérateurs: expériences futures avec collisionneurs - frontière d'énergie (PPD)

T1-3

7 Jun 2022, 08:30

McMaster University

(I) Future Collider Pheno talk (invited talk by David McKeen) — *David McKeen*
MDCL 1105, McMaster University — 08:30 - 08:55

(I) Physics in the High-Luminosity Era with the ATLAS Detector — *Maximilian J Swiatlowski*
MDCL 1105, McMaster University — 08:55 - 09:20

(I) The ATLAS Detector Phase-II Upgrades for the HL-LHC — *Thomas Koffas*
MDCL 1105, McMaster University — 09:20 - 09:45

(I) Instrumentation and Accelerator Technologies for ILC and Other Future Colliders — *Alain Bellerive*
MDCL 1105, McMaster University — 09:45 - 10:10

(G*) Projection studies of non-resonant Higgs boson pair production in the bb¯bb¯ final state at the HL-LHC using the A...
Colm Sam

(I) The MoEDAL-MAPP Experiment – The Upgrade of the LHC's 1st Dedicated Search Experiment for LHC's Run-3 and B...
James Pinfold

(I) Prospects for Long Lived Particle searches with MATHUSLA — *Steven Robertson*
MDCL 1105, McMaster University — 11:25 - 11:50

(I) Chiral Belle: Upgrading SuperKEKB with a Polarized Electron Beam — *Michael Roney*
MDCL 1105, McMaster University — 11:50 - 12:15

(I) Measurement of Beam Polarization at an e^+e^- B-Factory with New Tau Polarimetry Technique — *Caleb Miller*
MDCL 1105, McMaster University — 13:15 - 13:30

(I) Hunting for new particles at TRIUMF with the DarkLight experiment — *Katherine Pachal*
MDCL 1105, McMaster University — 13:30 - 13:55

(I) The cyclotron based high-yield ultracold neutron source and neutron electric dipole moment experiment
Dr Rüdiger Picker

(I) The Electron-Ion Collider: A New Microscope for Nuclear Matter — *Wouter Deconinck*
MDCL 1105, McMaster University — 14:20 - 14:45

(I) The MOLLER experiment — *Prof. David Armstrong*
MDCL 1105, McMaster University — 15:15 - 15:40

(I) Proton Driven Plasma Wakefield Acceleration Experiment at CERN — *Victor Verzilov*
MDCL 1105, McMaster University — 15:40 - 16:05

(I) DUNE and PIP-II — *Lia Merminga*
MDCL 1105, McMaster University — 16:05 - 16:30

(I) Neutrino Physics and Beyond at T2K and Hyper-Kamiokande — *Mark Patrick Hartz*
MDCL 1105, McMaster University — 16:30 - 16:55

(I) Photogrammetry Calibration of the Super-Kamiokande and Hyper-Kamiokande Detectors — *Rhea Gaur*
MDCL 1105, McMaster University — 16:55 - 17:10

THANK YOU

RECENT REPORTS

Snowmass 2022 white papers (arXiv numbers):

- FCC-hh: 2204.10029
- FCC-ee: 2203.08310
- ILC: 2204.13627
- ReLiC: 2203.06476
- CERC: 2203.07358
- CEPC: 2205.08553
- CLIC: 2203.09186
- Electron ion: 2203.13199
- Muon collider: 2203.07361

OLDER REPORTS

Some reports from earlier (arXiv numbers):

- 100 TeV pp BSM: 1606.00947
- 100 TeV pp Higgs: 1606.09408
- FCC-ee: 1308.6176
- ILC: 1306.6352
- CEPC: 1811.10545
- CLIC: 1812.07986
- LHeC and FCC-he: 2007.14491
- Muon Collider: 2005.10289

MUON COLLIDERS

arXiv:2006.16277

A Guaranteed Discovery at Future Muon Colliders

Rodolfo Capdevilla[a,b,*] David Curtin[a,†] Yonatan Kahn[c,‡] and Gordan Krnjaic[d§]
[a] *Department of Physics, University of Toronto, Canada*
[b] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada*
[c] *University of Illinois at Urbana-Champaign, Urbana, IL USA and*
[d] *Fermi National Accelerator Laboratory, Batavia, IL USA*

(Dated: July 1, 2020)

The longstanding muon $g-2$ anomaly may indicate the existence of new particles that couple to muons, which could either be light ($\lesssim$ GeV) and weakly coupled, or heavy ($\gg$ 100 GeV) with large couplings. If light new states are responsible, upcoming intensity frontier experiments will discover further evidence of new physics. However, if heavy particles are responsible, many candidates are beyond the reach of existing colliders. We show that, if the $(g-2)_\mu$ anomaly is confirmed and no explanation is found at low-energy experiments, a high-energy muon collider program is guaranteed to make fundamental discoveries about our universe. New physics scenarios that account for the