(New) Physics at Future Colliders

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TRIUMF

CAP 2022 Seminar Day

Future Colliders Types

- e^+e^- at a higher energy and/or more luminosity than LEP (FCC-ee, CLIC, CEPC, ILC, CCC)

- Hadron colliders at higher energy/more luminosity than LHC (HE-LHC, FCC-hh, SppC)

- eh can have some benefits of electron and hadron machines, useful for probing proton structure (LHeC)

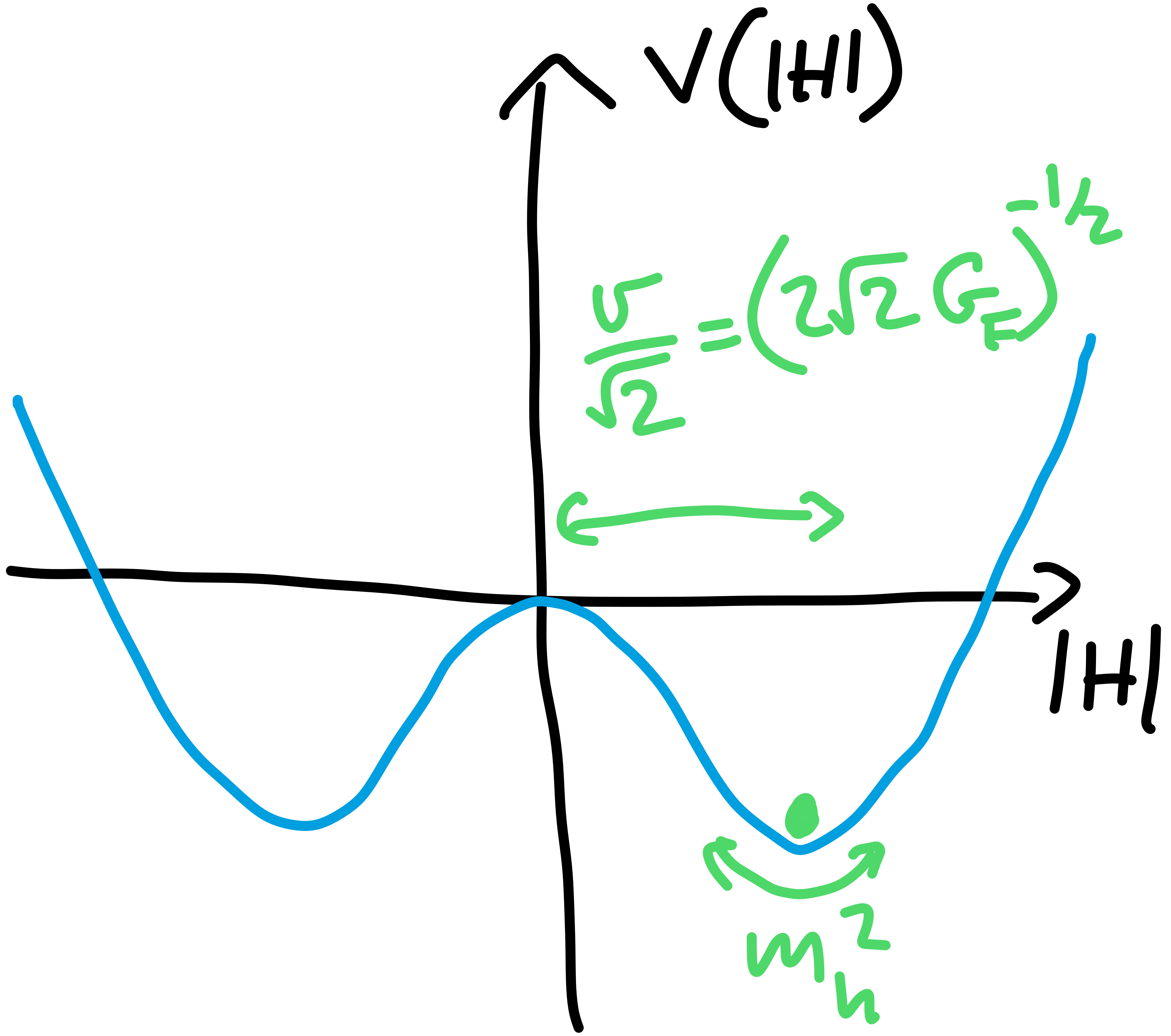
- $\mu^+\mu^-$ would be the best of all worlds…but requires a lot of work

- Won't discuss lower energy machines, e.g. Chiral Belle, Electron-ion Collider, DarkLight@ARIEL, etc.

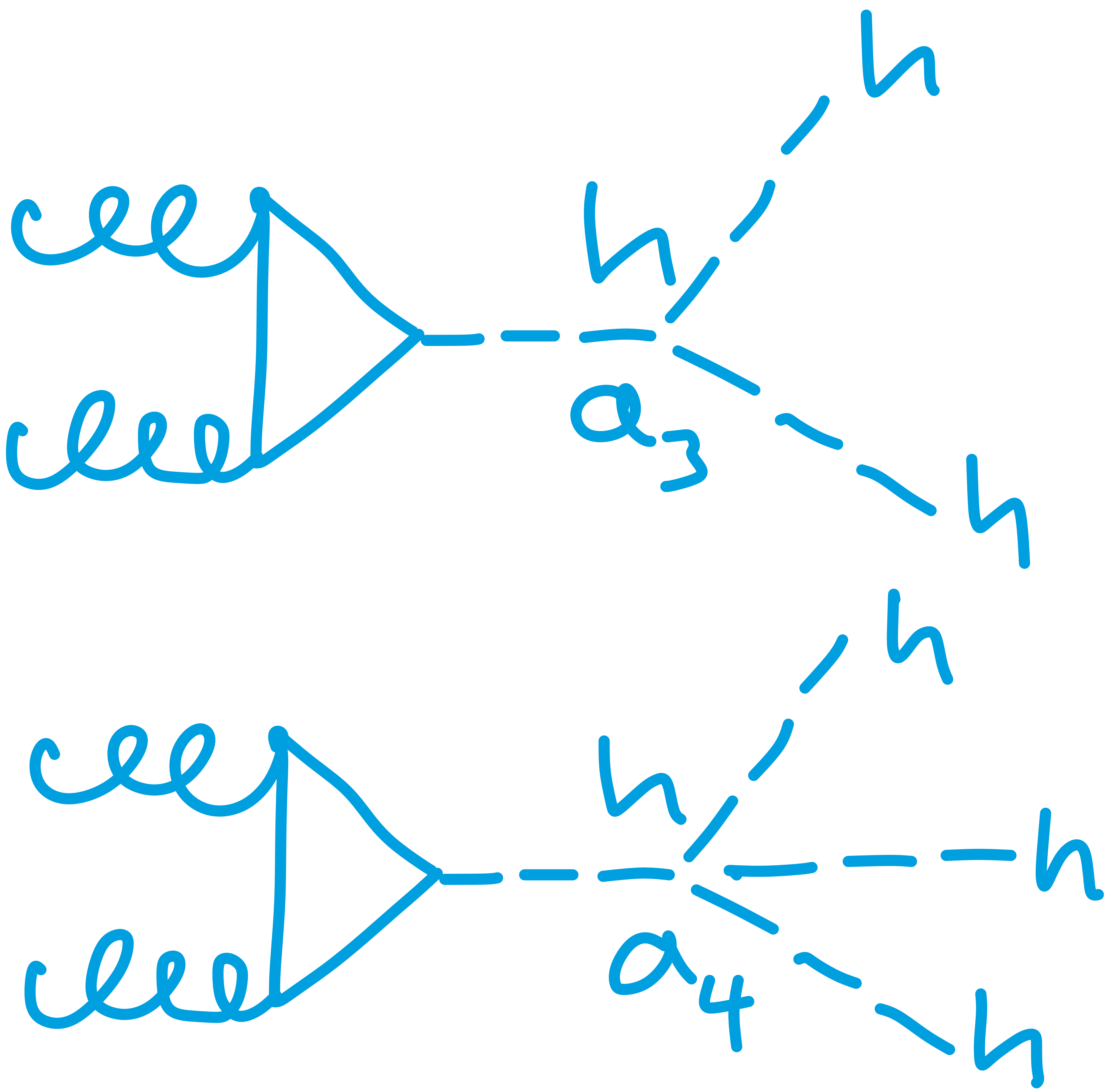
Higgs Potential

- So far we have measured just the position of the minimum of $V(h)$ and the curvature at that minimum (m_h^2)
- No other experimental information about the shape of the potential
- Multi-higgs production can probe other terms in Taylor series of

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{a_3}{3!} h^3 + \frac{a_4}{4!} h^4$$



Higgs Potential



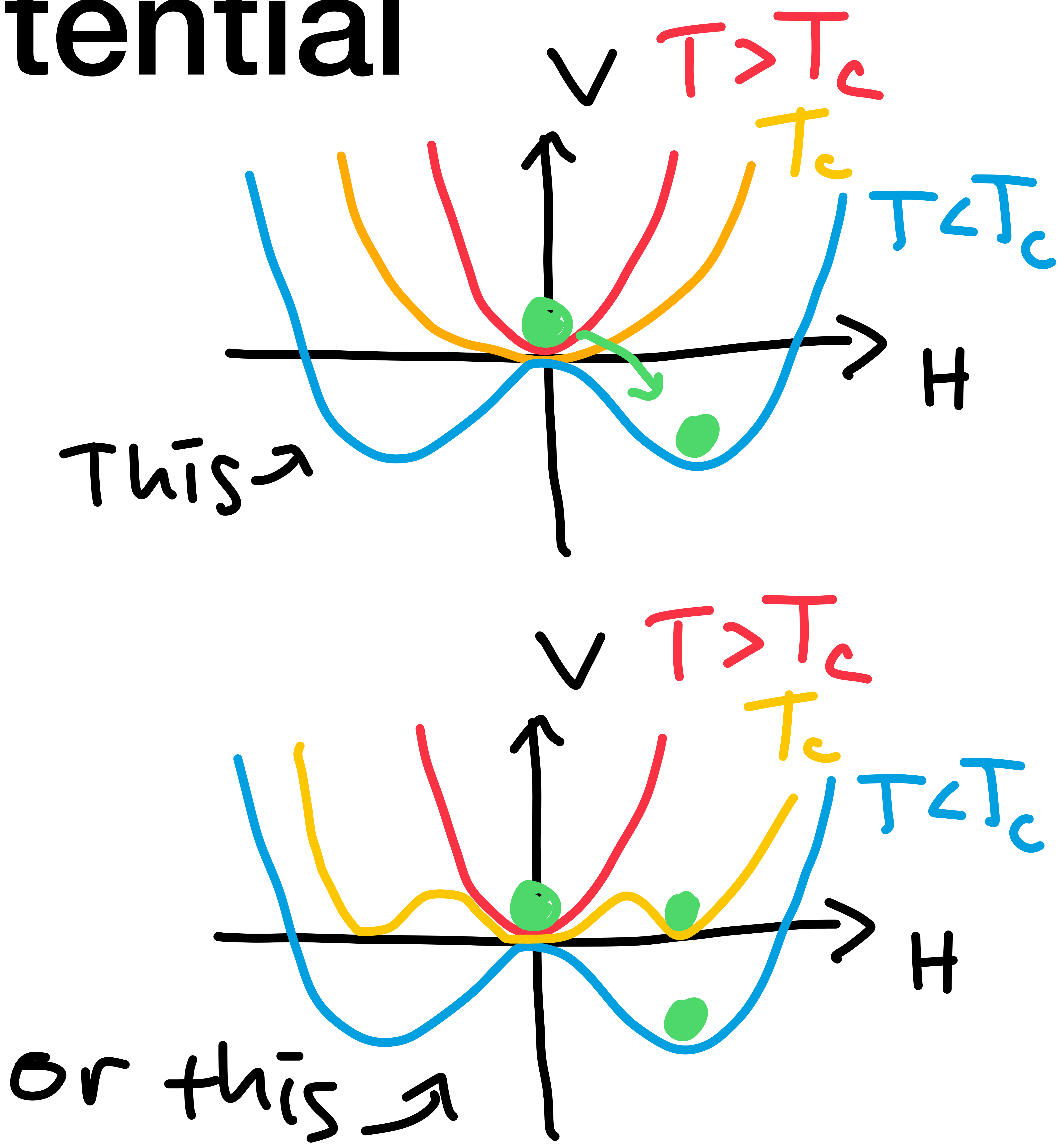
- SM makes definite prediction for higher order terms in

$$V(h) = \frac{1}{2}m_h^2 h^2 + \frac{a_3}{3!}h^3 + \frac{a_4}{4!}h^4 \simeq \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

- Test this with hh and hhh production (very difficult at LHC)

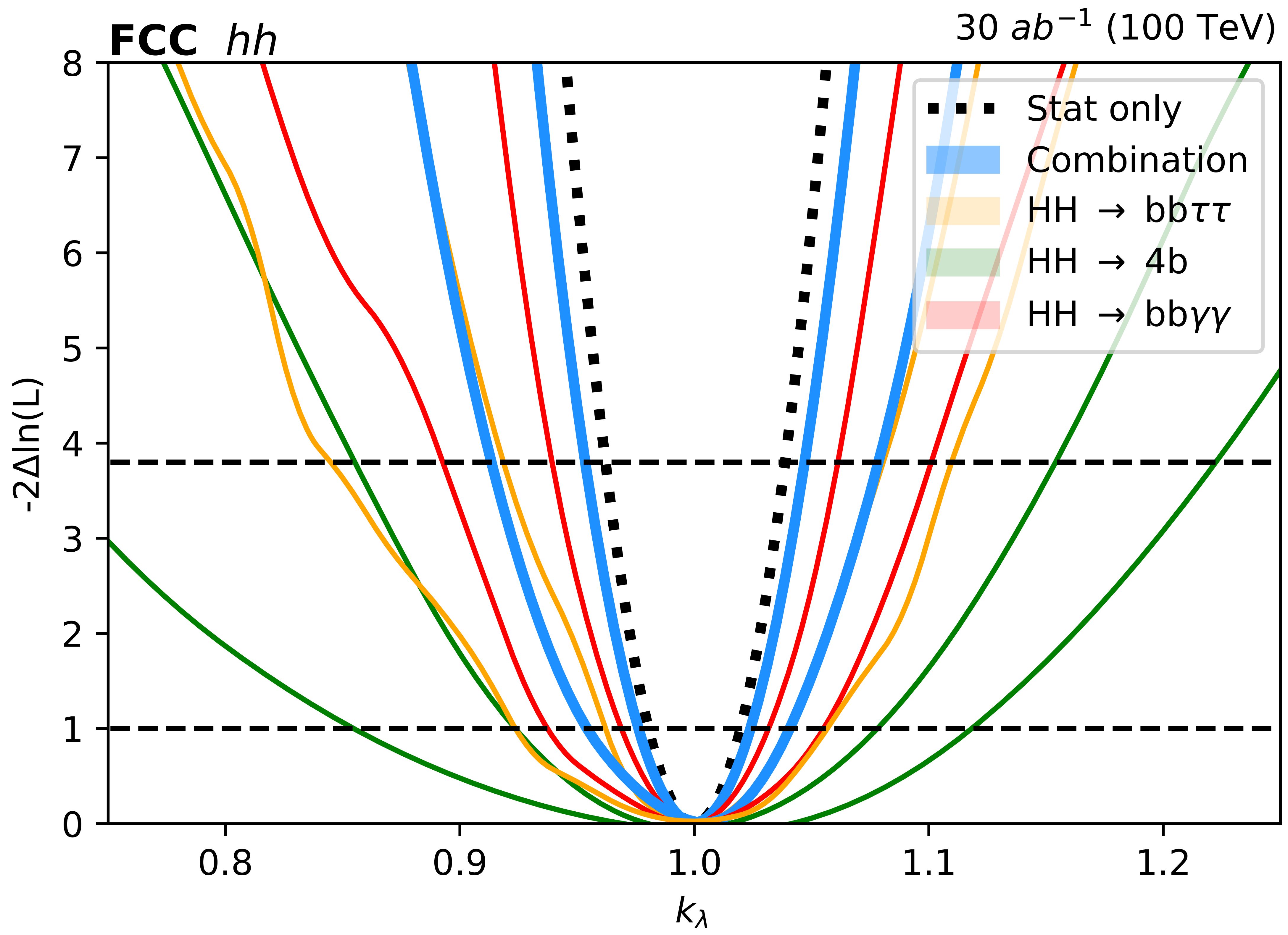
Higgs Potential

- Shape of potential very important in the early universe (is the electroweak phase transition 1st or 2nd order)
- New states can alter this shape
- Important consequences for matter asymmetry of the universe



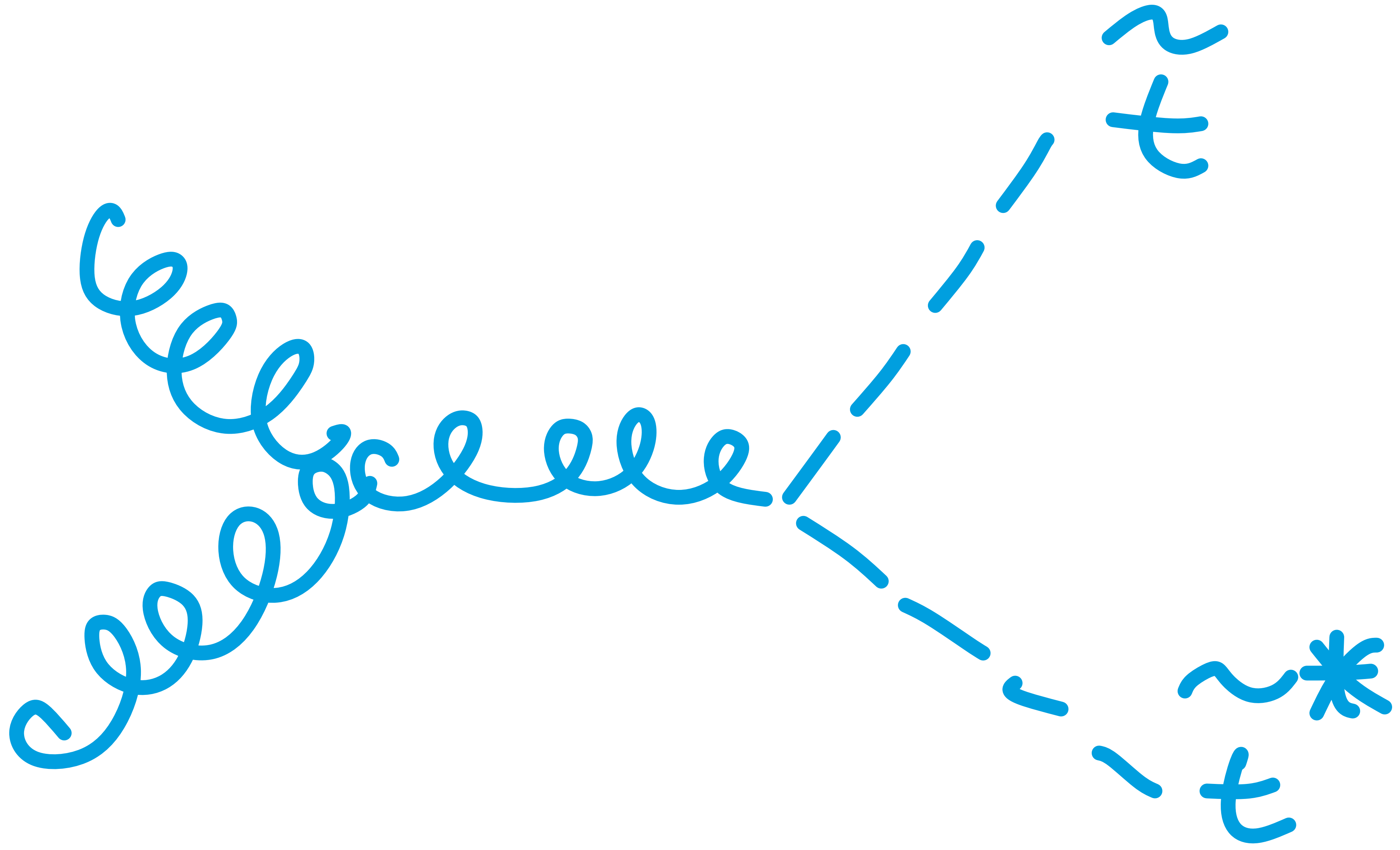
Di-Higgs at FCC-hh

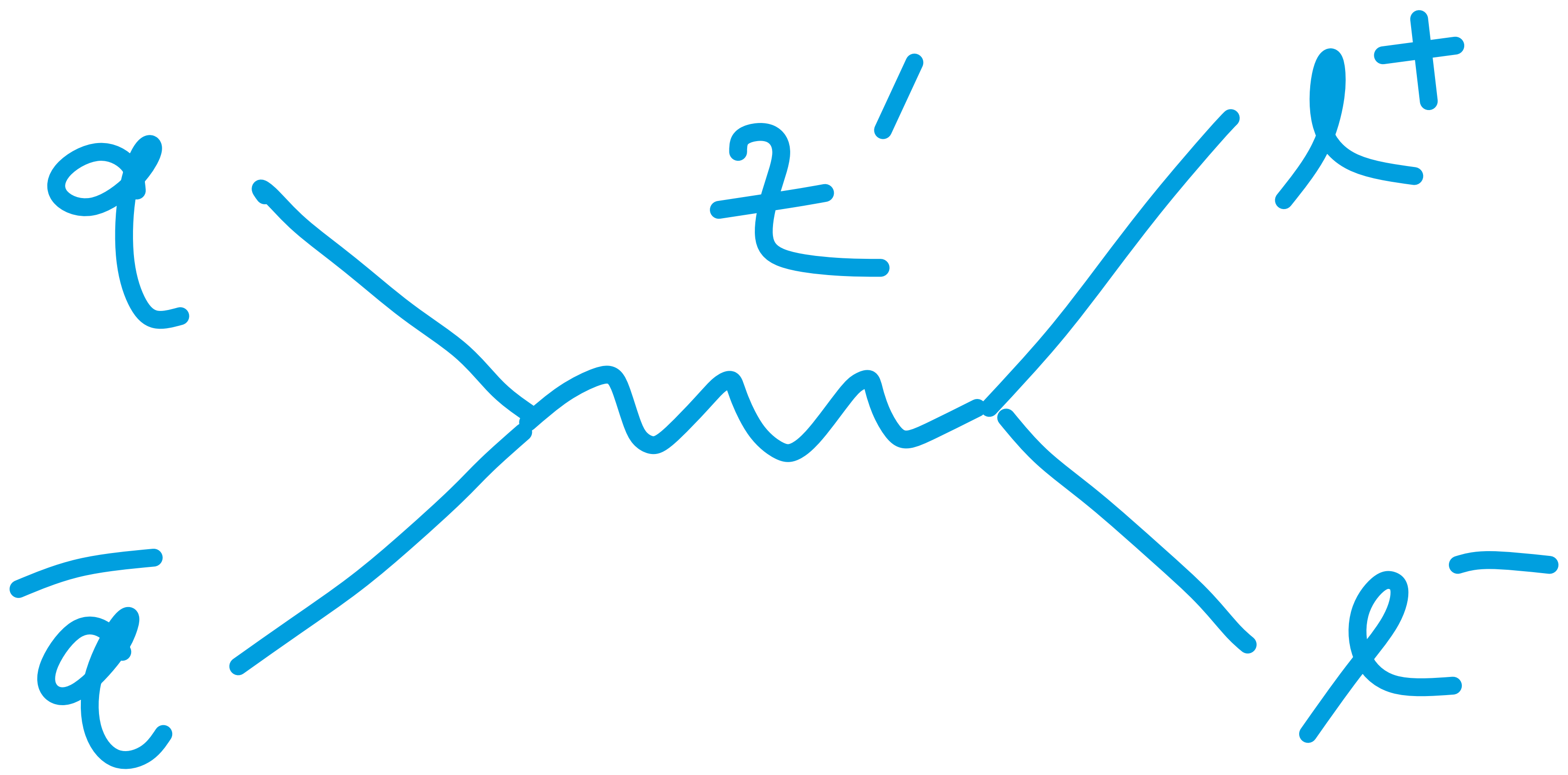
- Potential to constrain cubic coupling to $\mathcal{O}(10\%)$ at $100\ \mathrm{TeV}\ pp$ machine with $30\ \mathrm{ab}^{-1}$



Taliercio *et al*. 2203.08042

New Heavy Particles

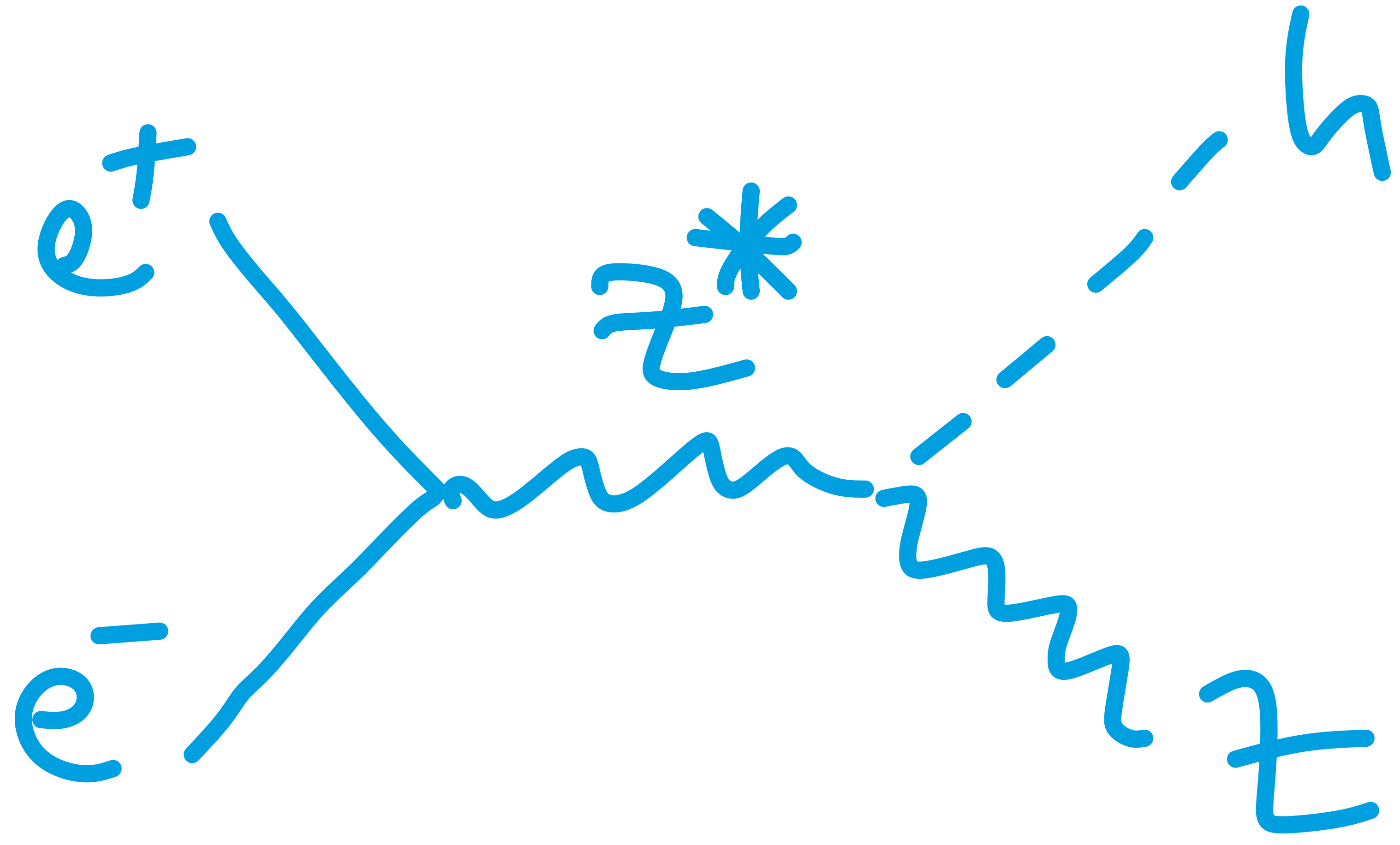


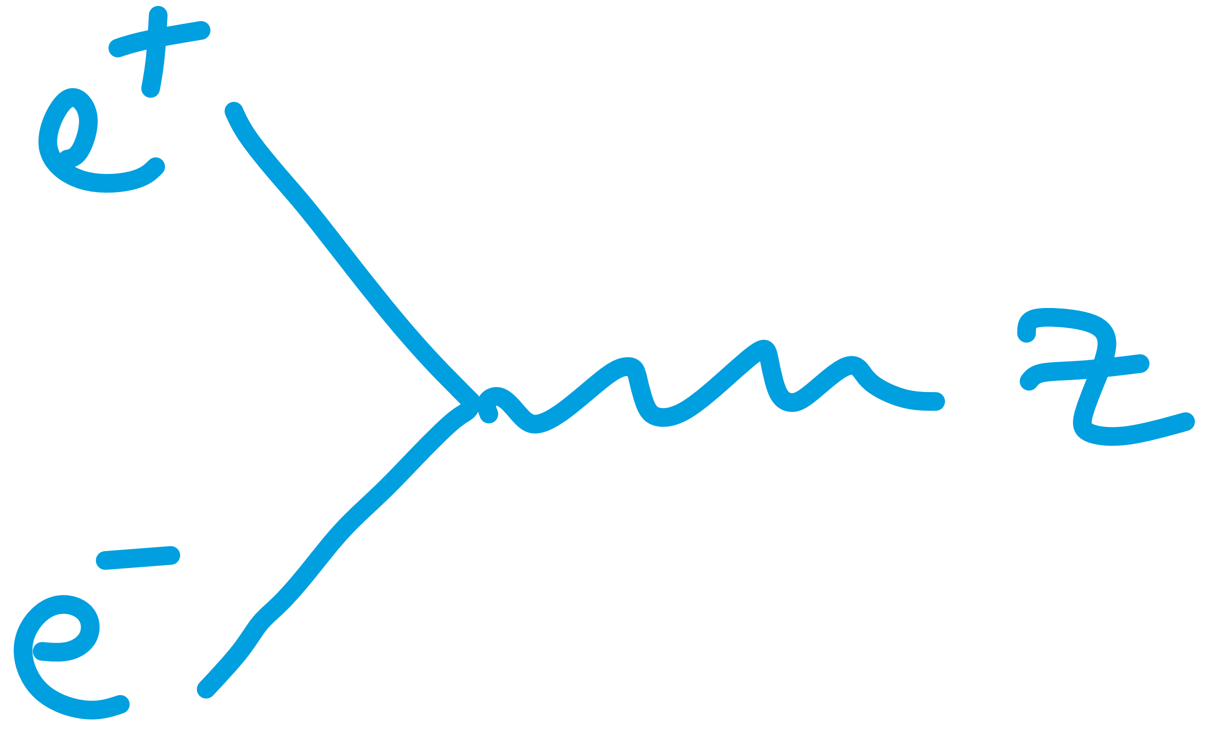


Hadron collider with 100 TeV c.o.m. energy can discover

- ~ 10 TeV coloured particles— would probe tuning of Higgs $\sim 100 \times$ LHC
- ~ 2 TeV electroweak particles
- ~ 20 TeV Z' resonances

Precision Higgs/Z



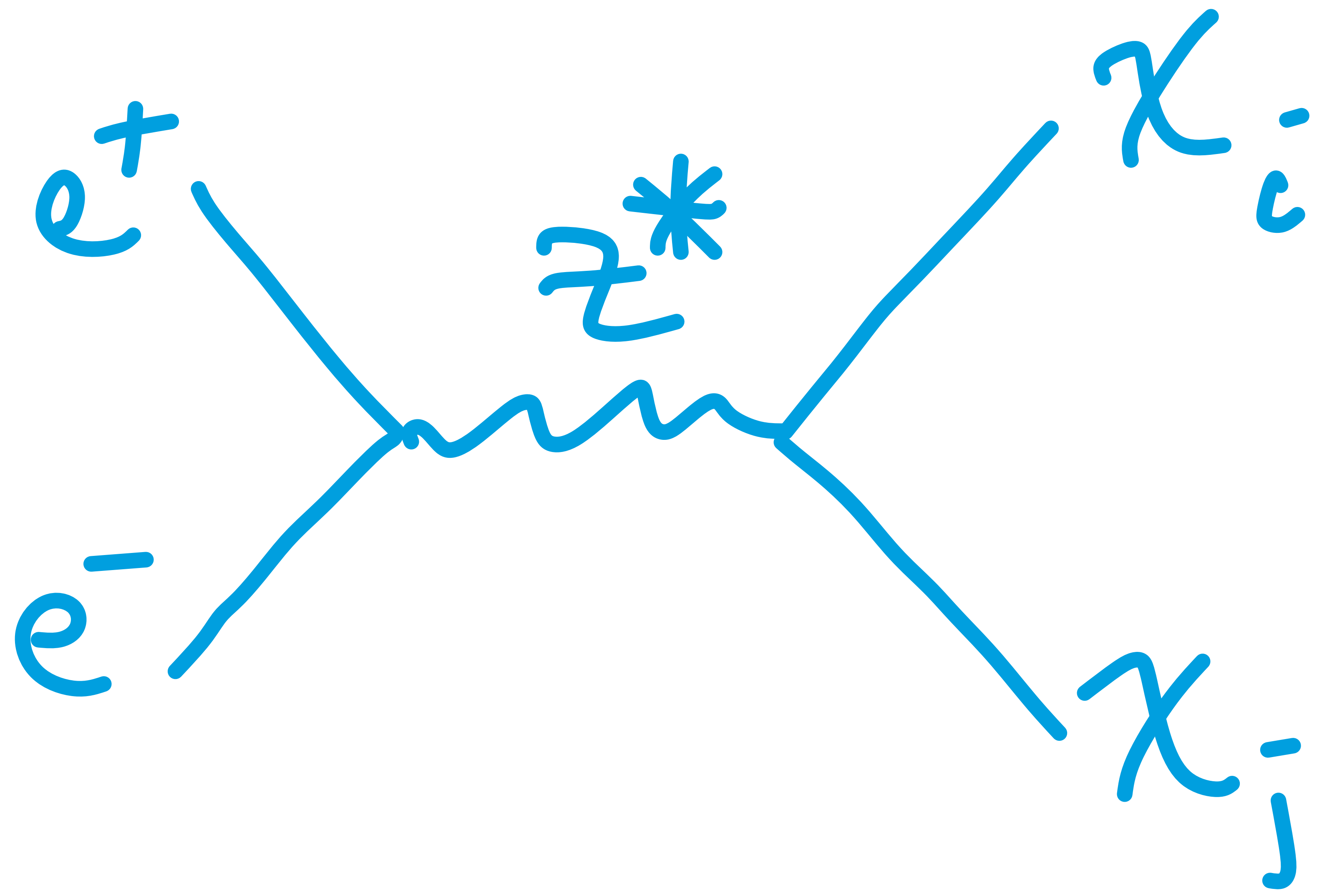


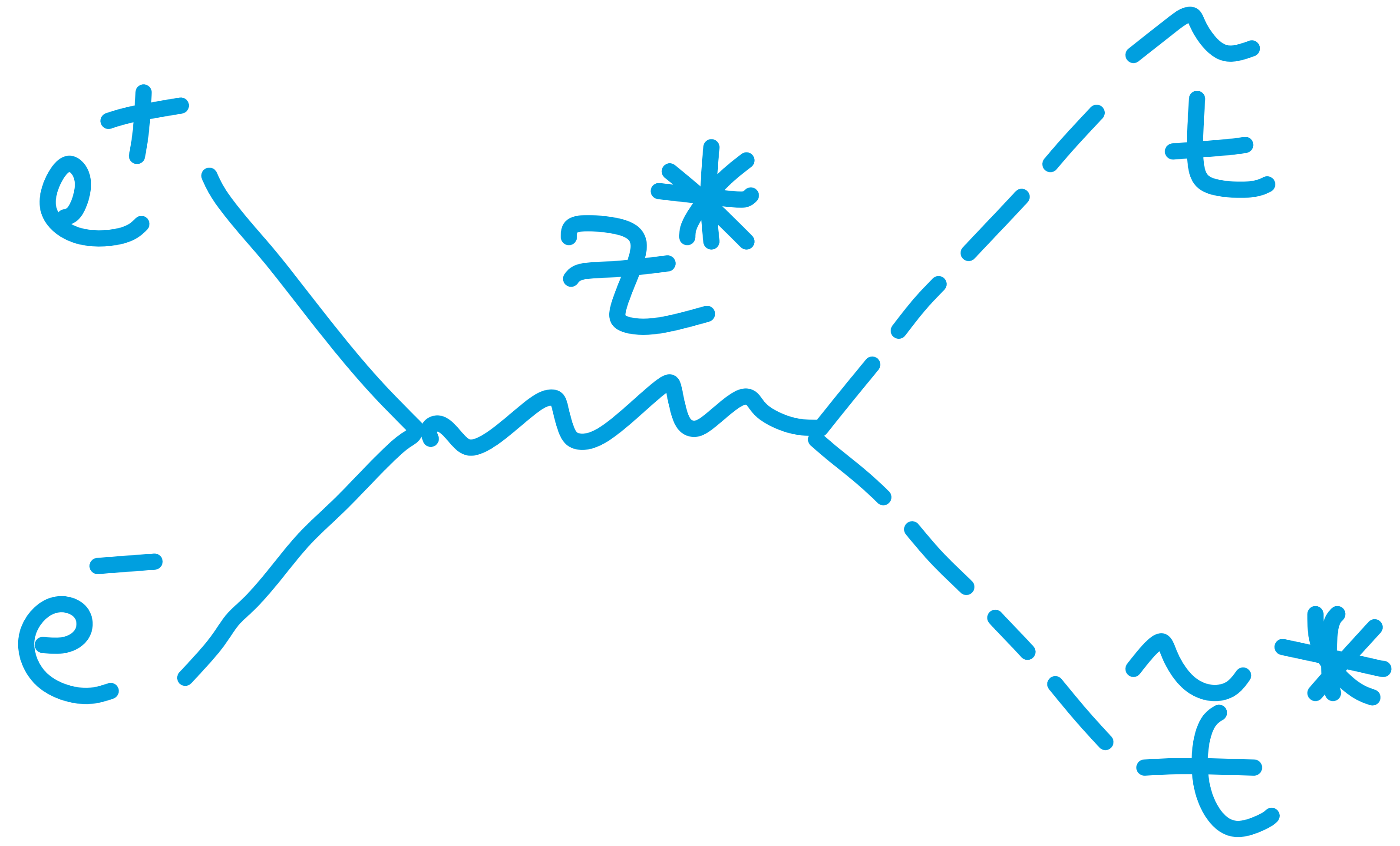
- New physics at scale Λ generically changes Higgs properties at the $\mathcal{O}(v^2/\Lambda^2)$ level
- e^+e^- machines allow for precise study of Higgs, helped by knowledge of initial state
- Circular e^+e^- colliders can produce $\sim 10^9$ or more Z bosons ($100\times$ more than LEP)$\Rightarrow$probe $\Lambda \sim \mathcal{O}(\text{10s of TeV})$

Electroweak States

- e^+e^- colliders also provide clean environment for producing electroweakly-charged states (could be connected to dark matter, higgsino/wino in SUSY)

- Can also search for states connected to hierarchy problem —e.g. top partners ($\tilde{t}$, T') through their electroweak couplings

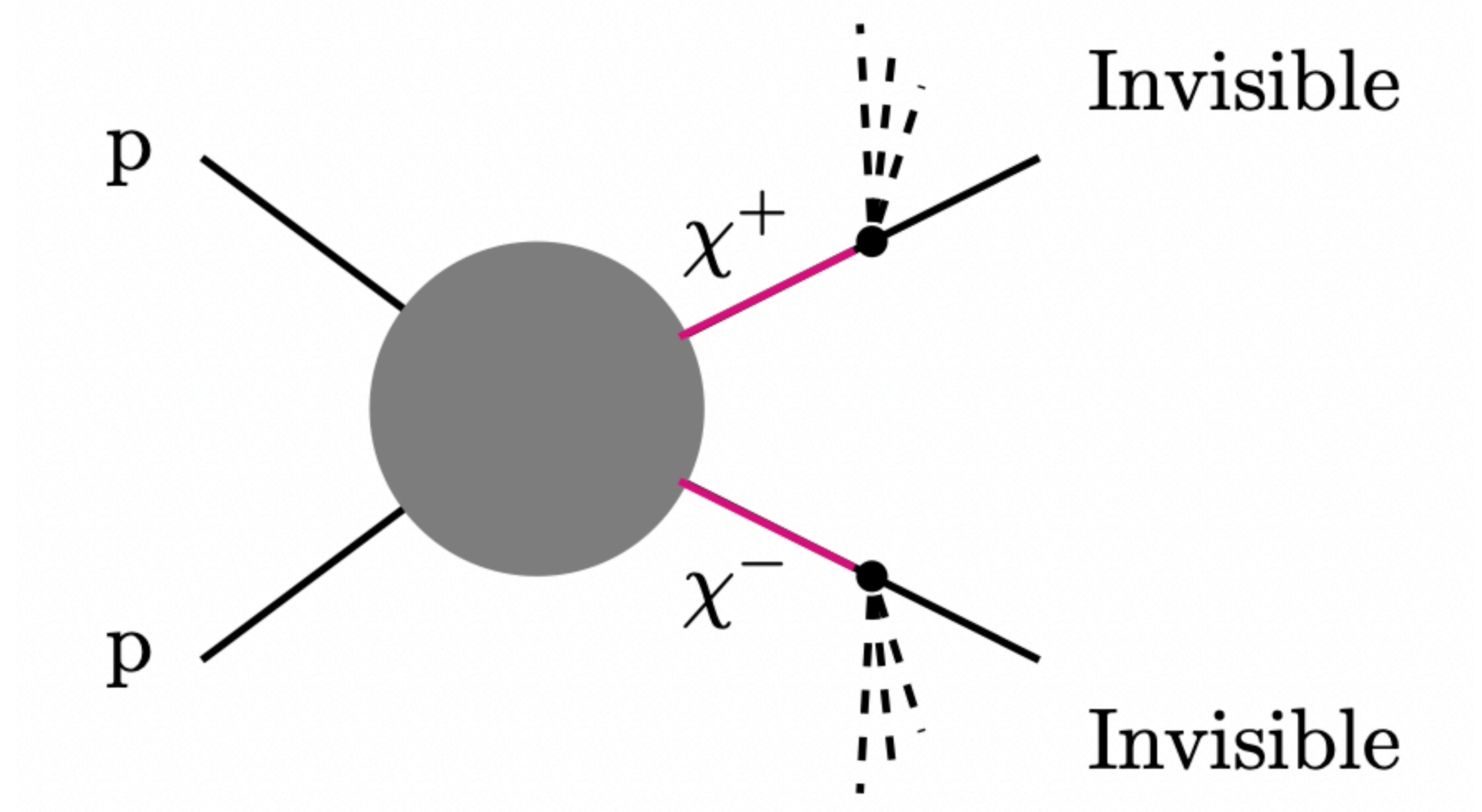




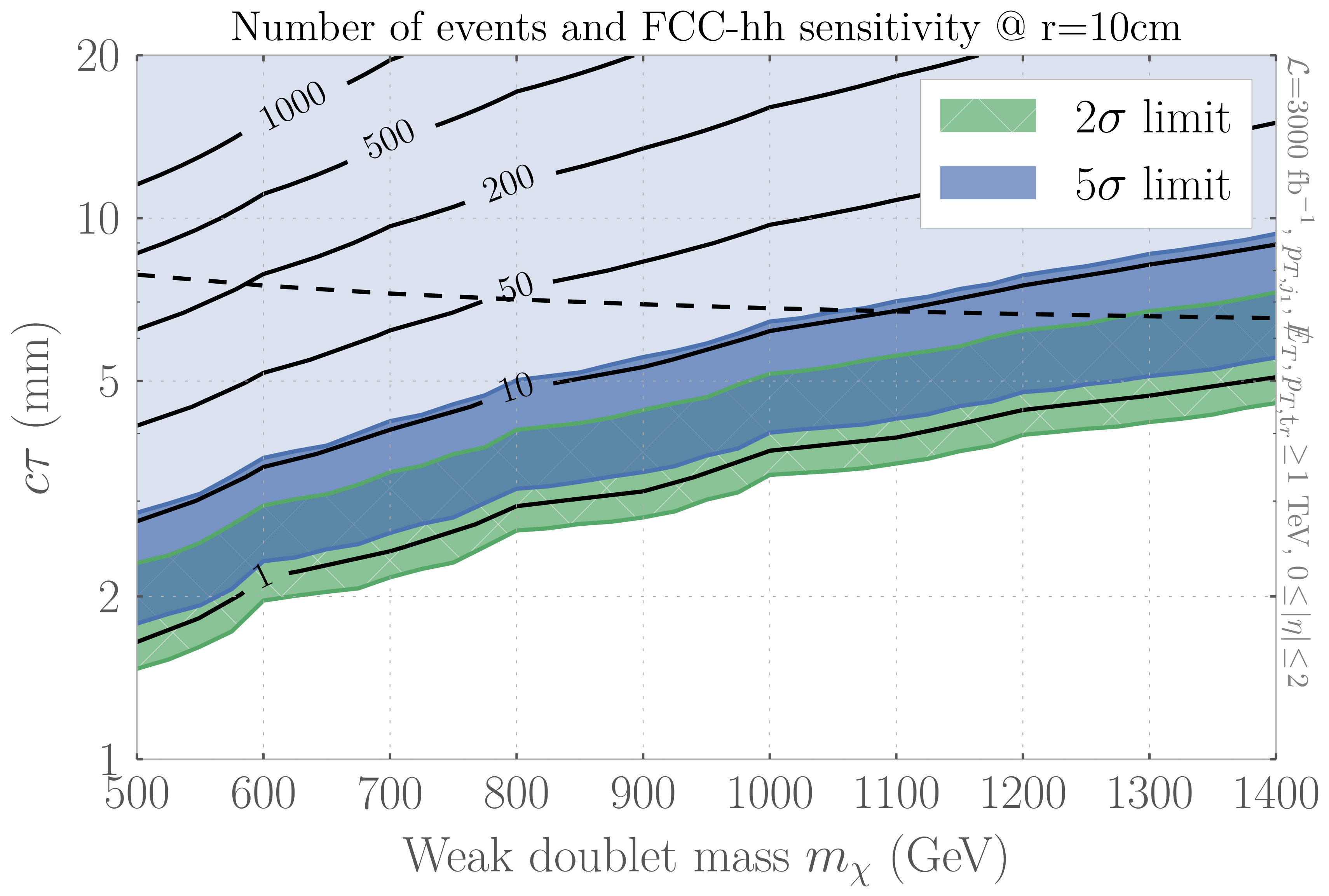
Disappearing Tracks and Pure WIMPs

- Pure electroweak state (higgsino/wino) DM favours mass of around a TeV, tiny splittings

- Can be probed at high energy hadron colliders using “disappearing tracks”



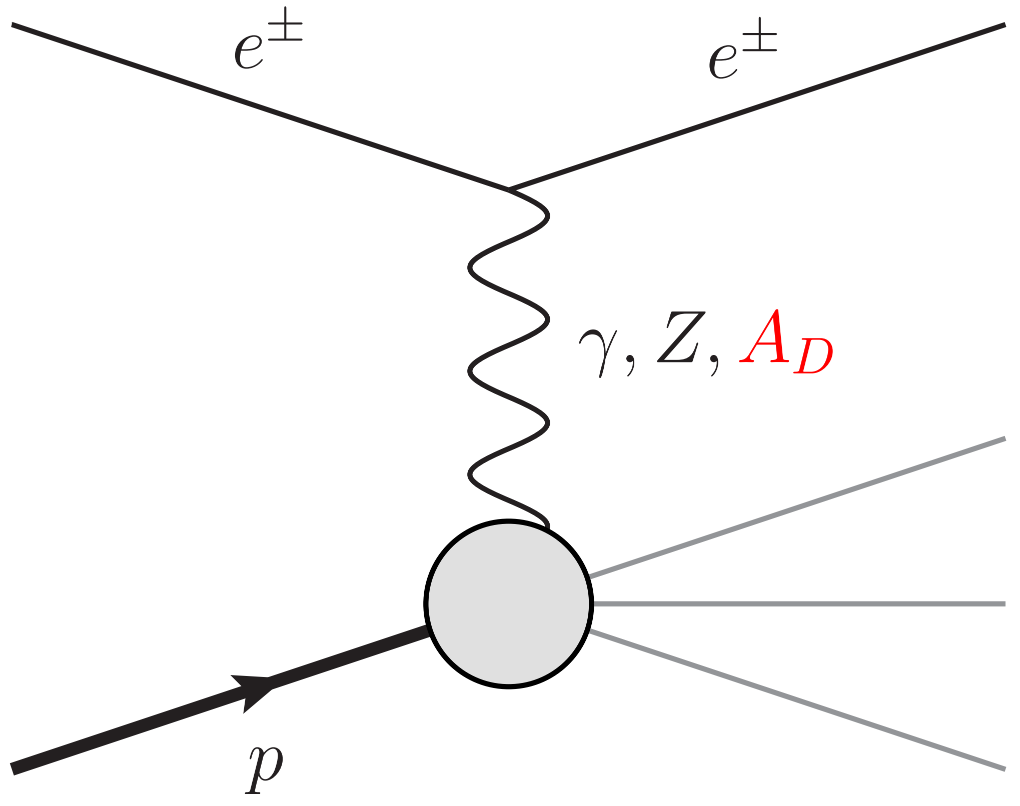
Mahbubani *et al*. 1703.05327

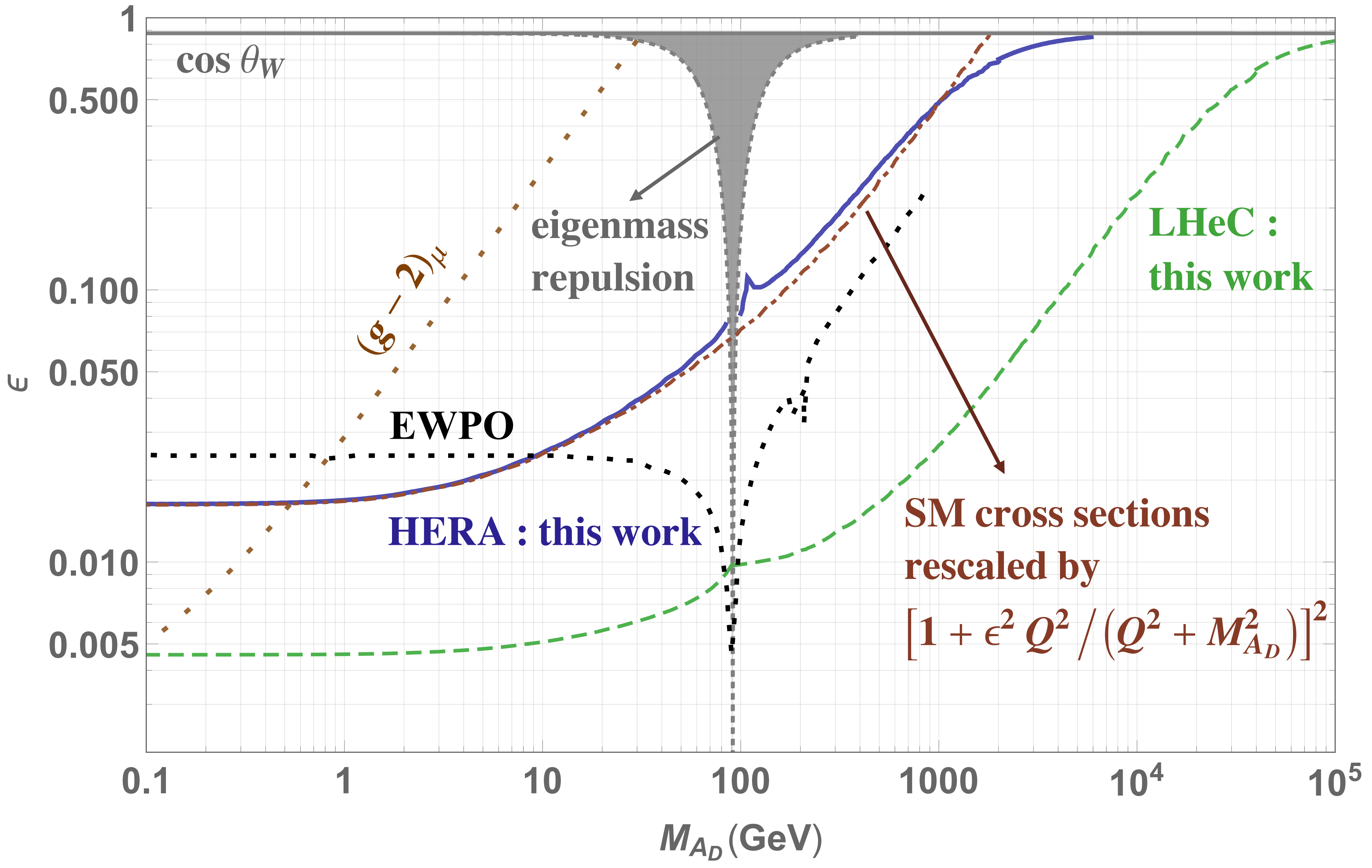


LHeC and Dark Photons

- $e^{\pm}p$ colliders are sensitive to dark photon exchange

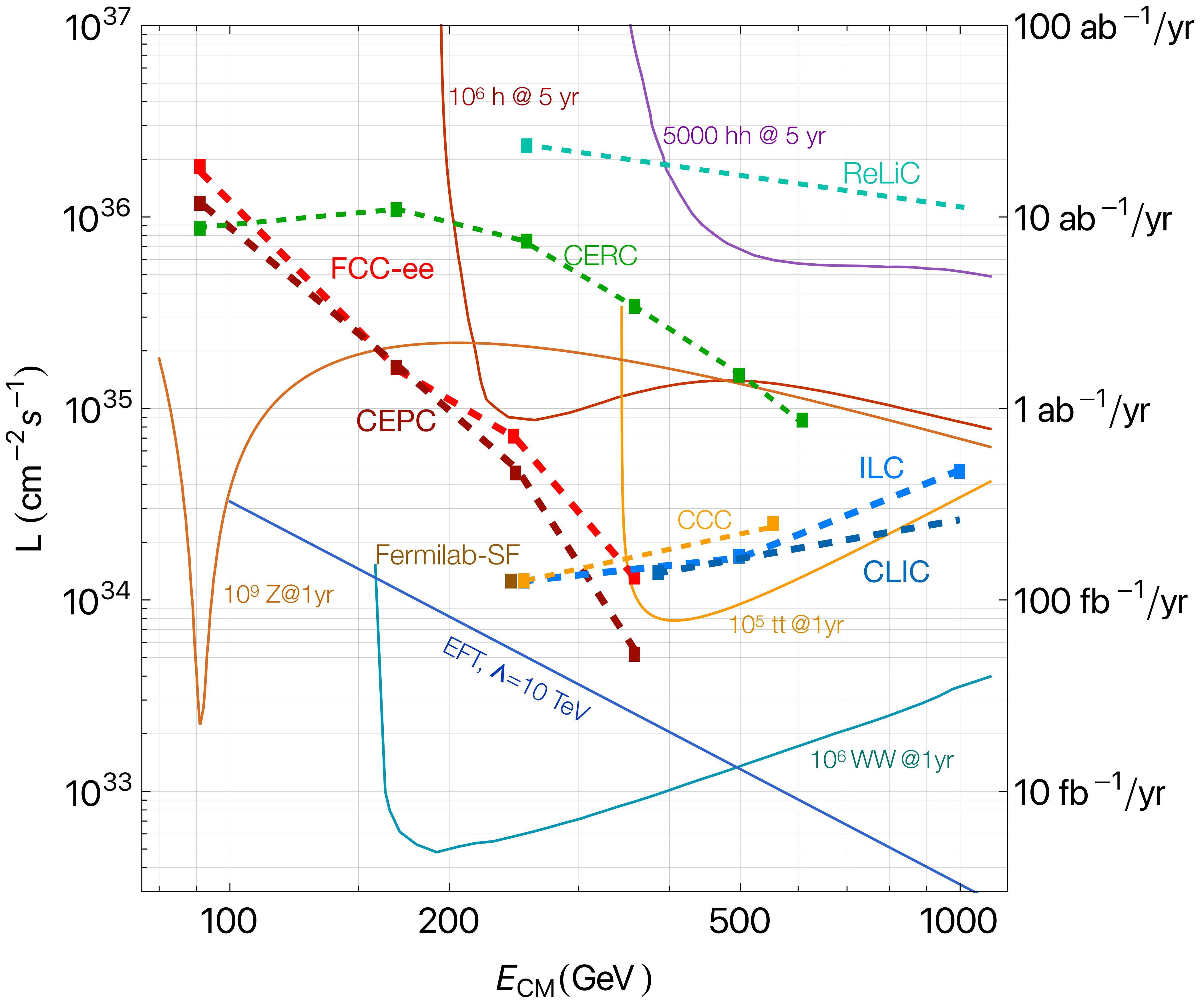
- Modifies parton distribution functions extracted from data in (Q, x_{Bj}) in a correlated way

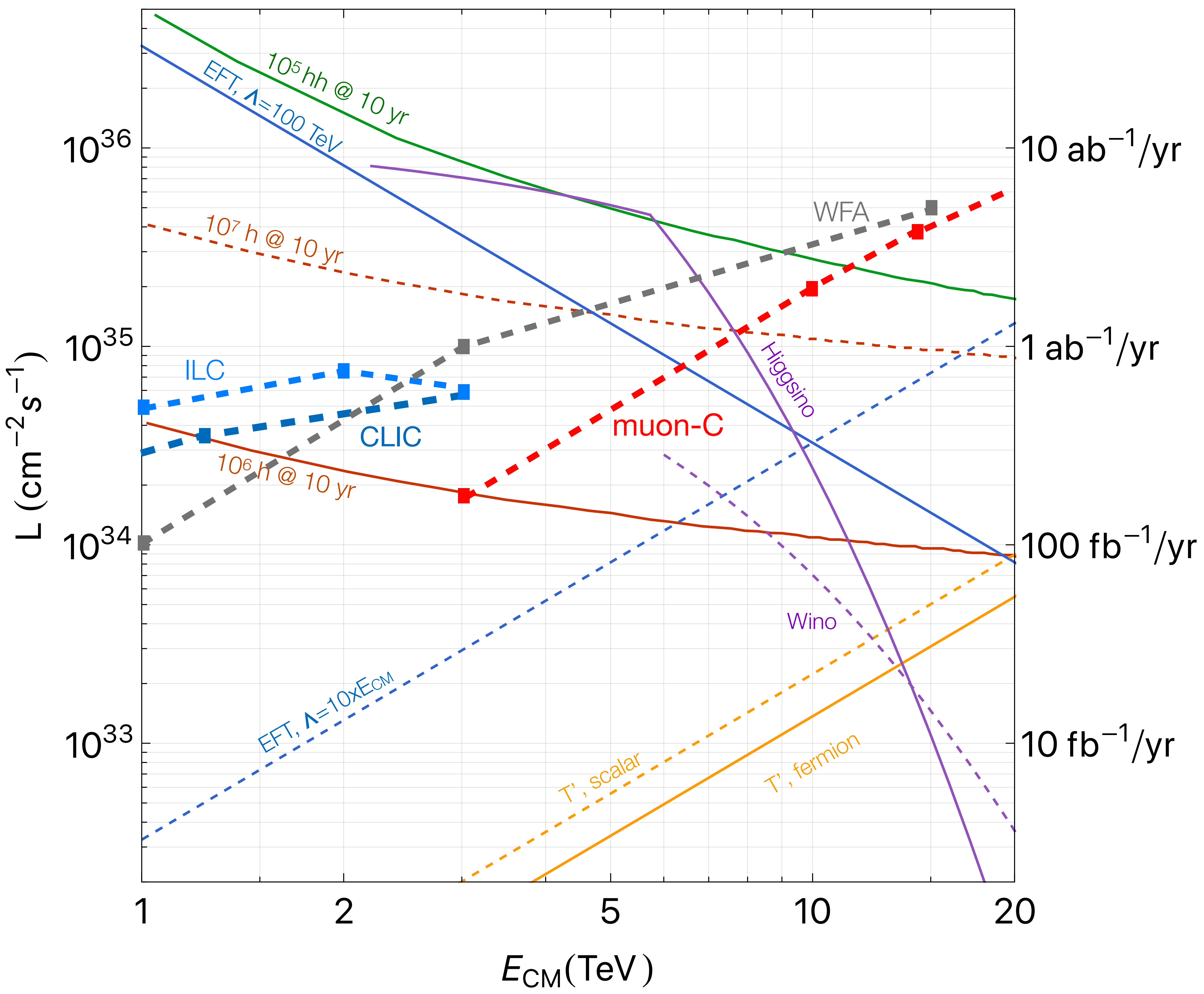




Kribs, DM, & Raj 2007.15655

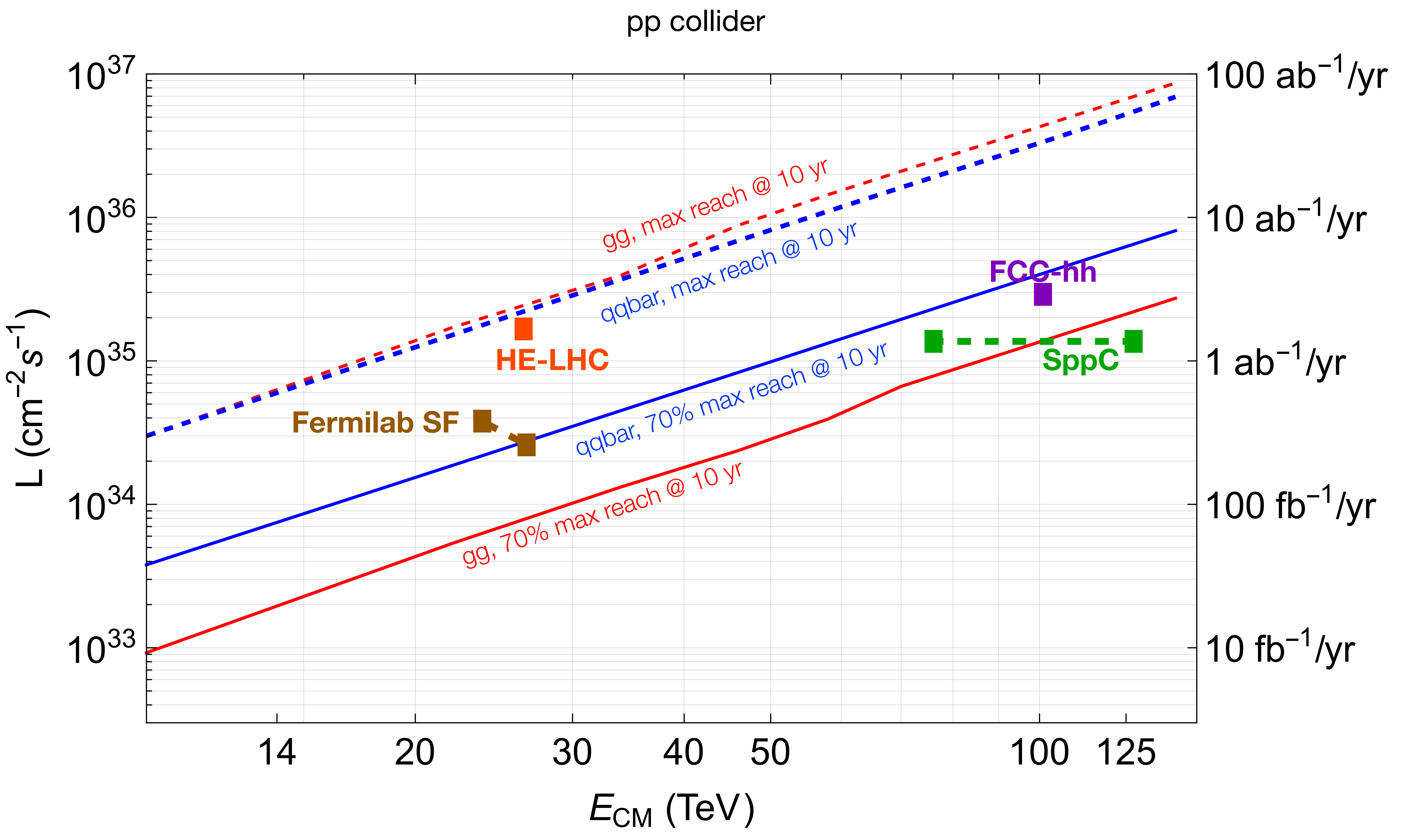
e^+e^- Energy vs. Luminosity





Liu & Wang 2205.00031

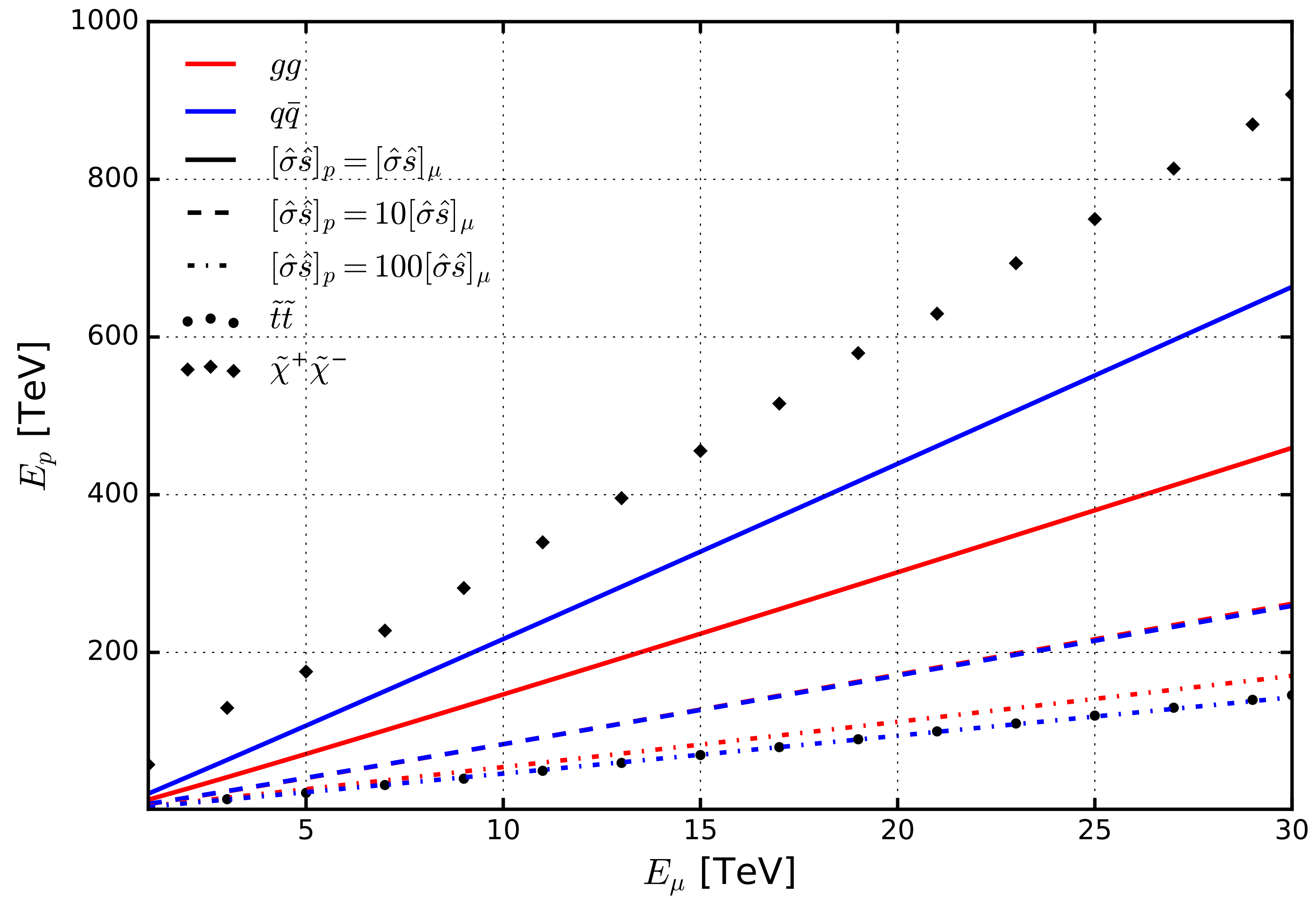
pp Energy vs. Luminosity



Liu & Wang 2205.00031

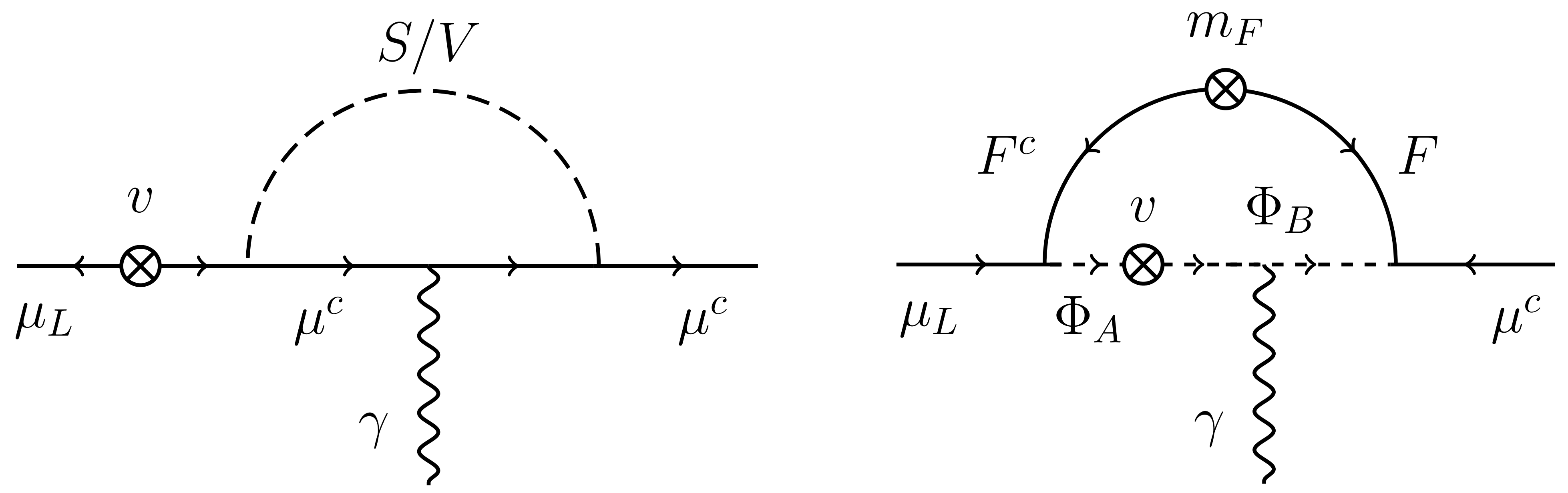
Muon Colliders

Costantini *et al*. 2005.10289



- Can reach higher energy than e^+e^-
- Higher effective energy than hadron collider
- Technologically challenging
- Connection to $(g-2)_\mu$

Capdevilla *et al*. 2006.16277



Conclusion

- The physics case for future colliders is clear
- Which is built depends on many factors outside physics
- Technological improvements are necessary on the accelerator and detector side
- Theory also needs to keep up