New Physics at the Energy Frontier

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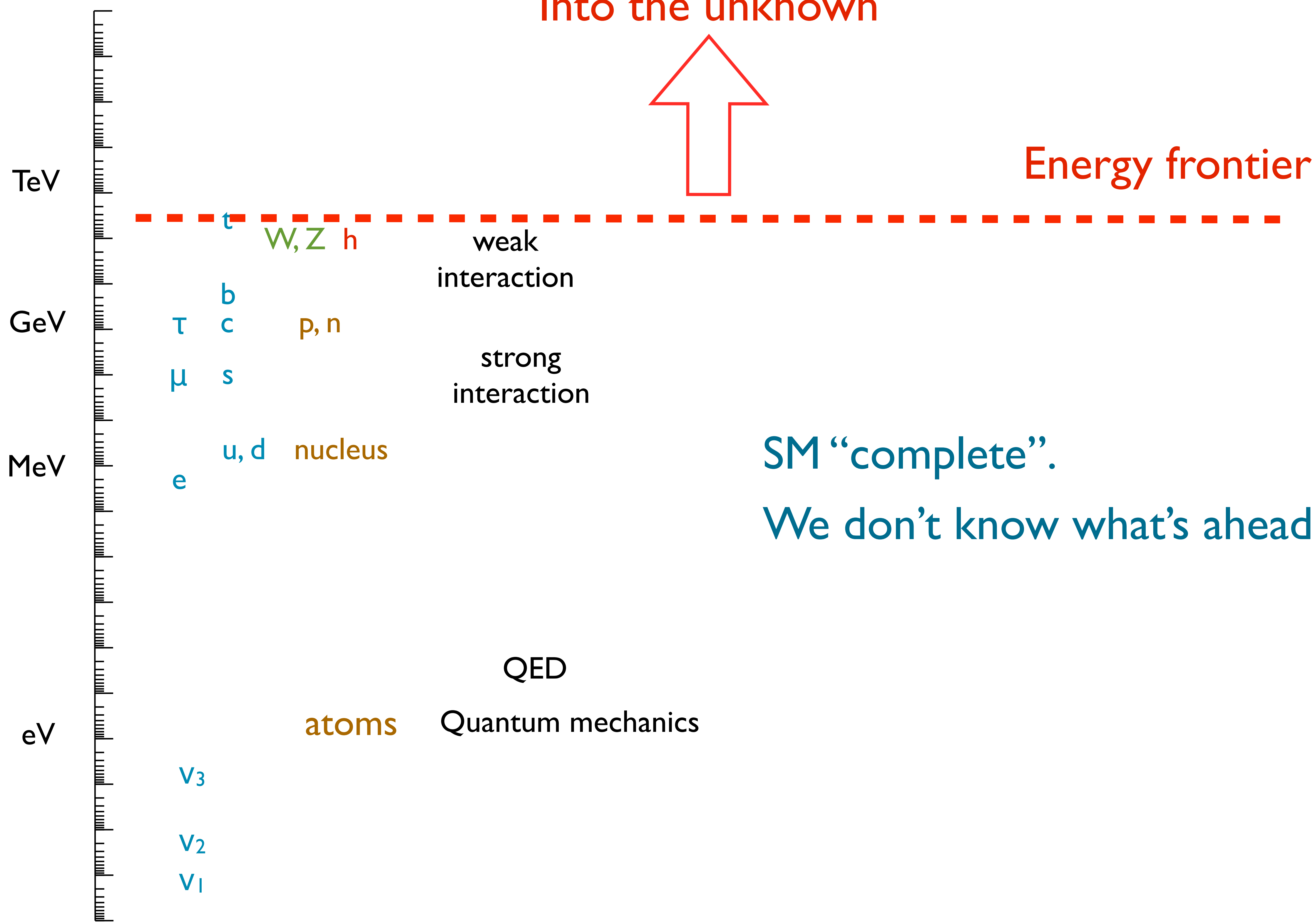
U. Chicago

PANIC 2017. Sept. 2 Beijing

Each new step ≡ new territory
Into the unknown



SM “complete”.

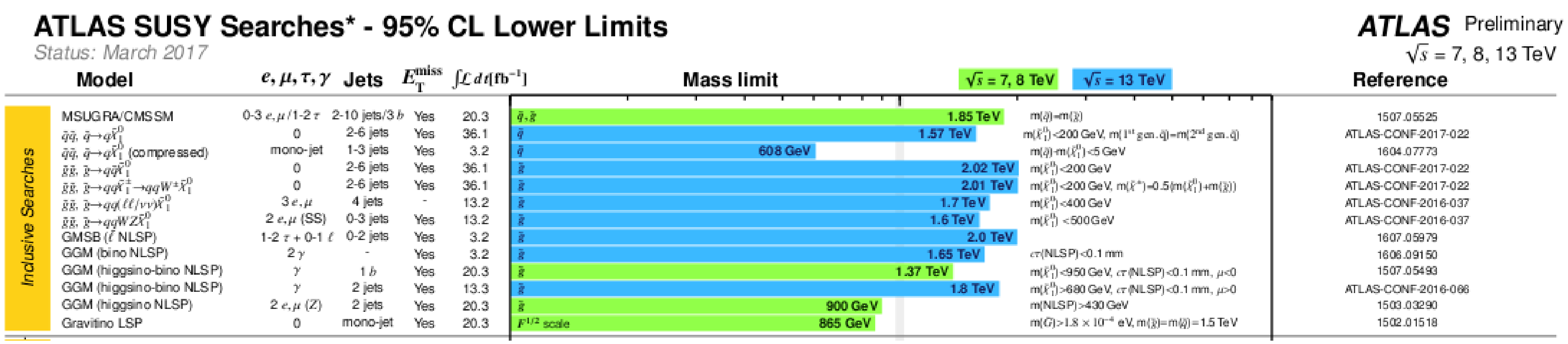
We don’t know what’s ahead.

News from Moriond 2017

52nd Rencontres de Moriond EW 2017

présidé par Lydia Iconomidou-Fayard (LAL), Jean Marie Frere (ULB Brussels)

de samedi 18 mars 2017 à **08:30** à samedi 25 mars 2017 à **12:00** (Europe/Paris)



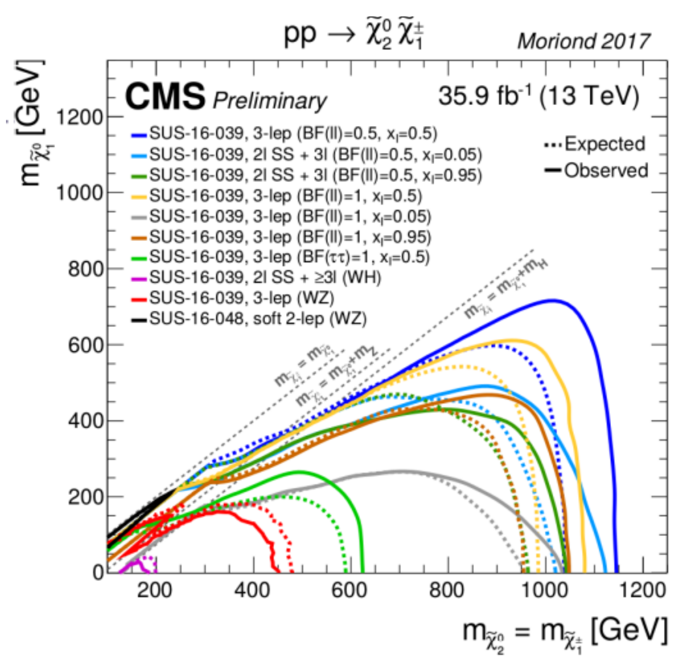
ATLAS SUSY Searches* - 95% CL Lower Limits

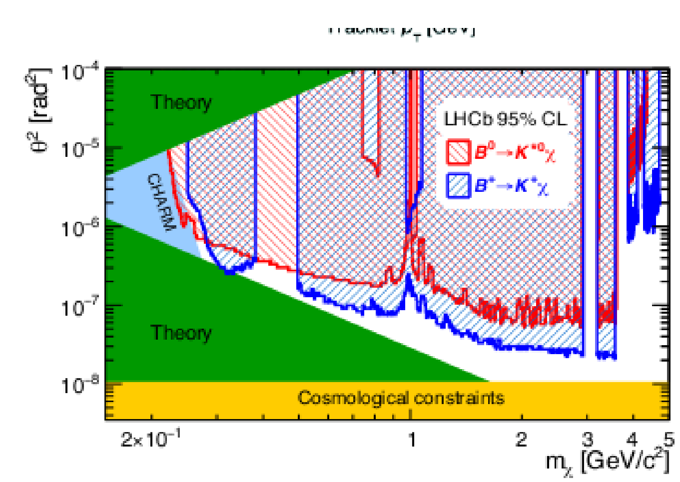
Status: March 2017

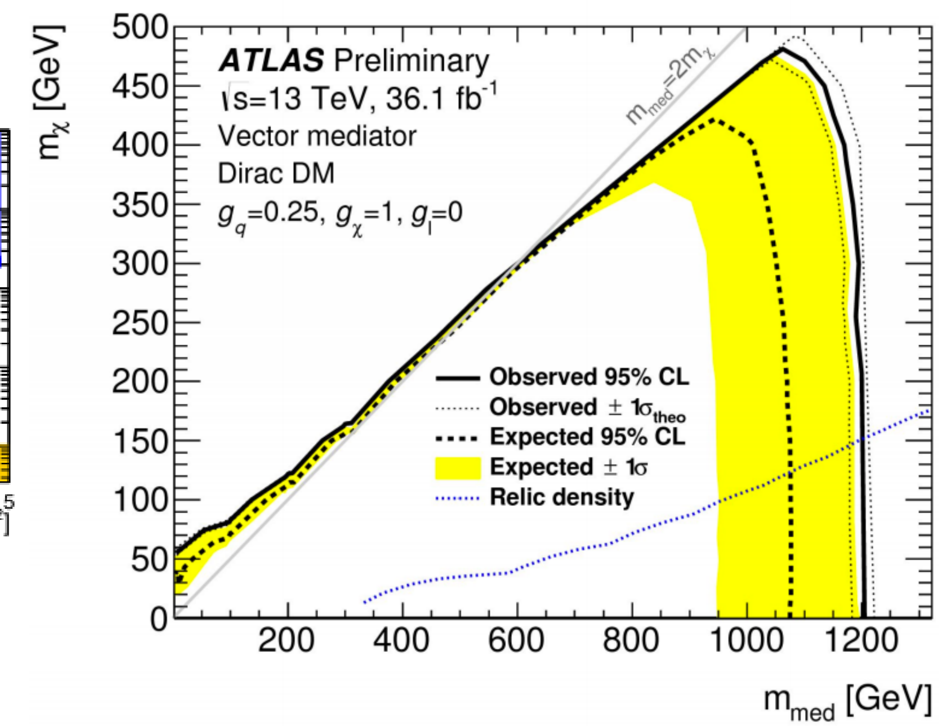
ATLAS Preliminary $\sqrt{s}$ = 7, 8, 13 TeV

$\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518

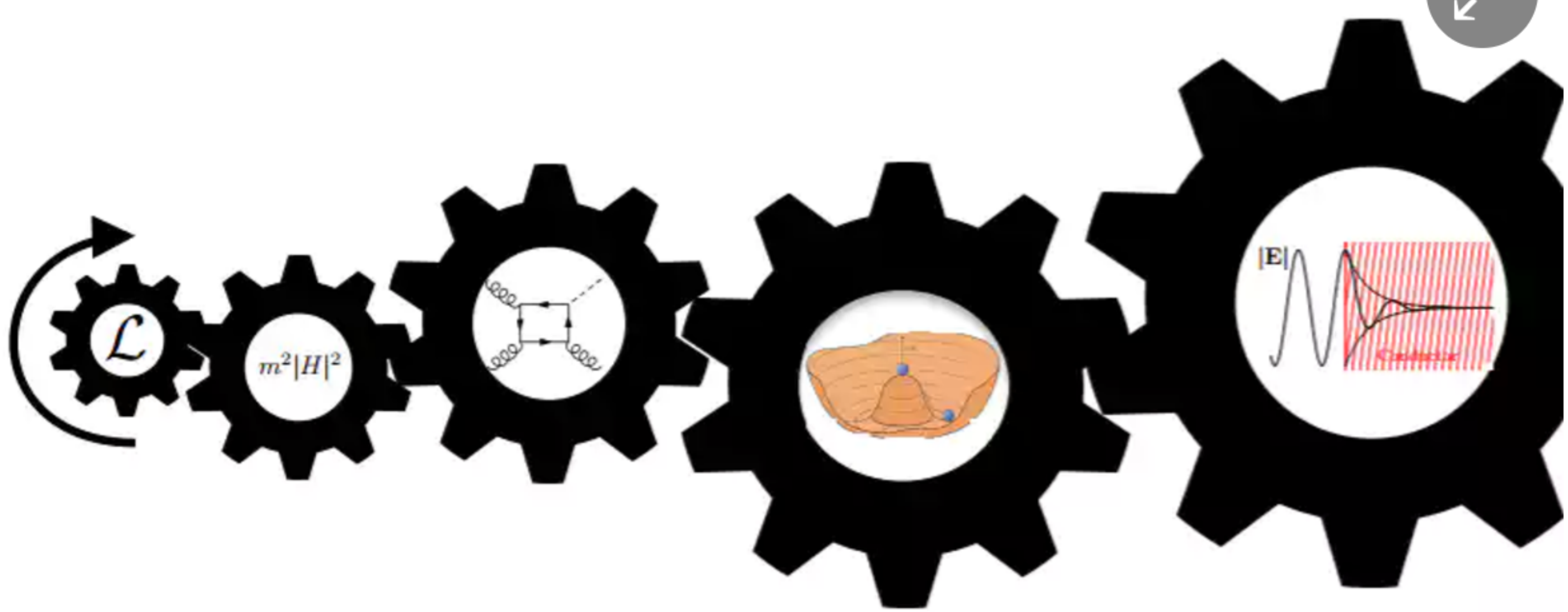






From gravity to the Higgs we're still waiting for new physics

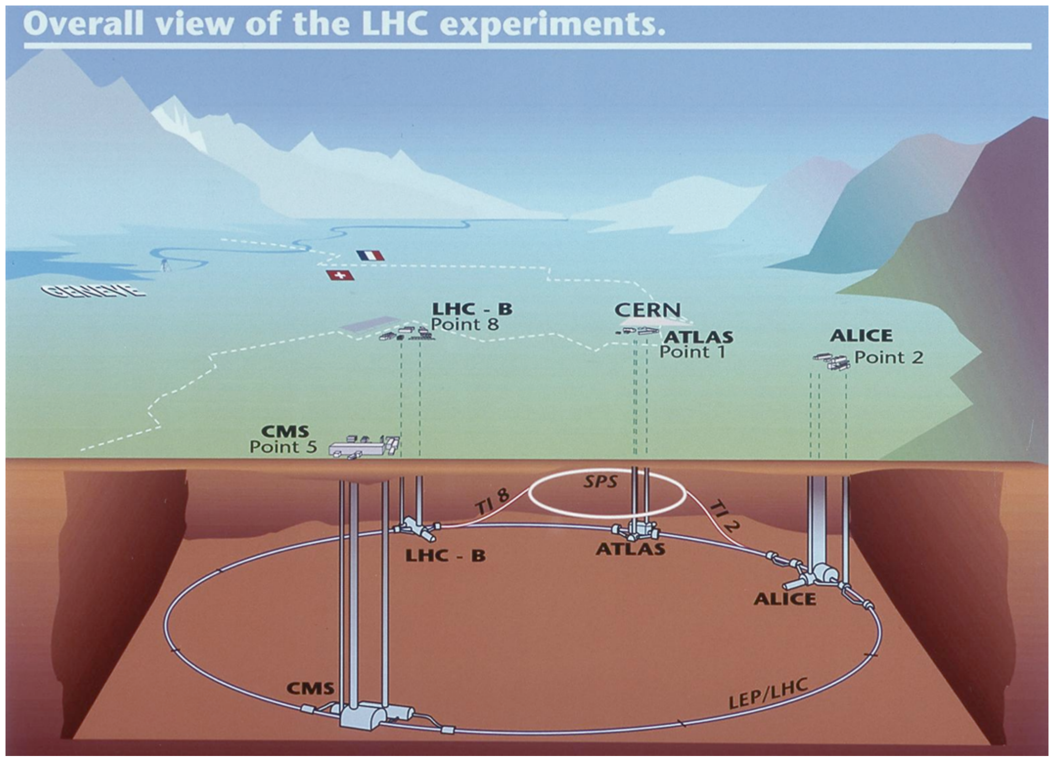
Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound

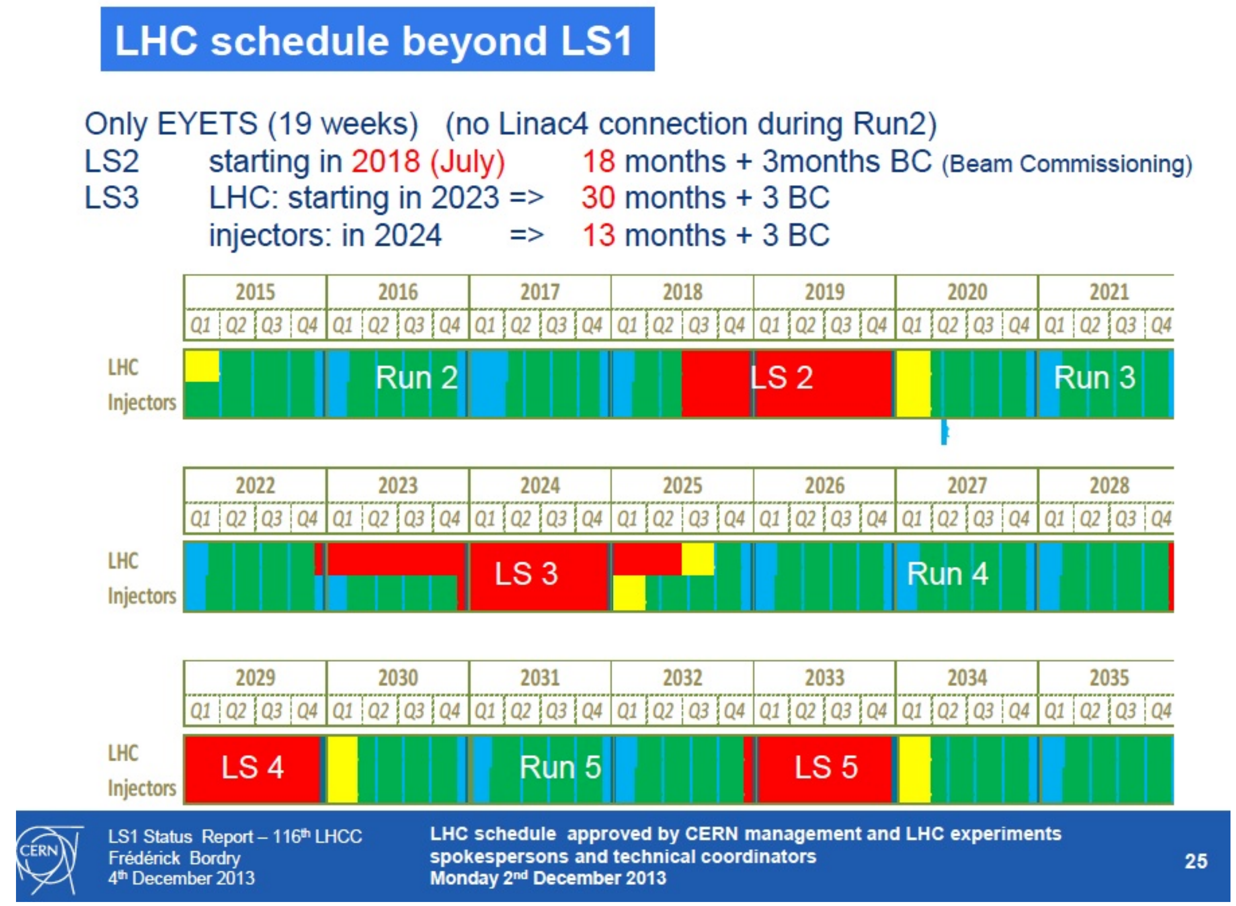


Guardian

Road ahead:

Immediate future: Large Hadron Collider

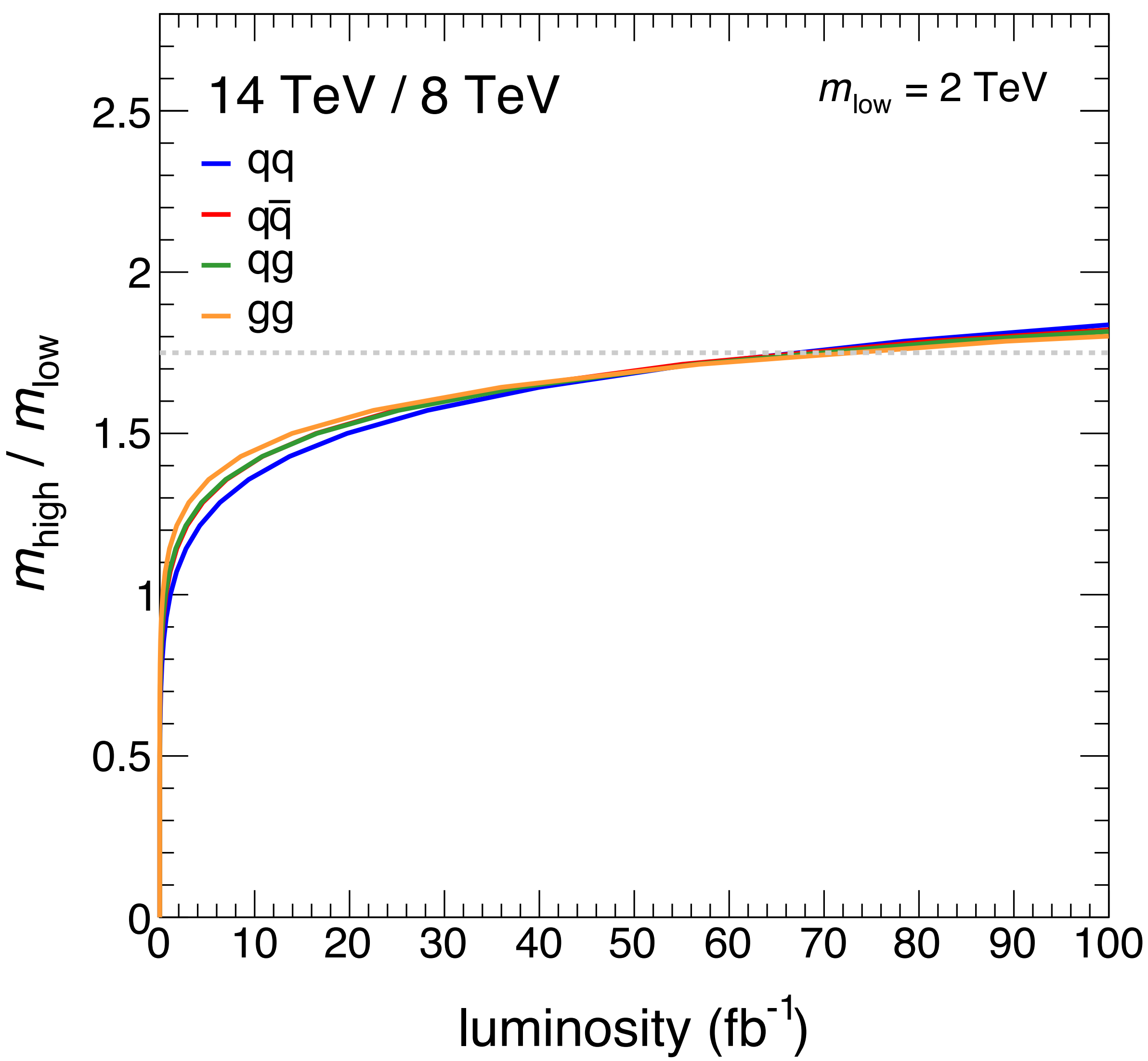




– Much more to come: 99% of the data to come

As data accumulates

Run 1 limit 2 TeV, e.g. pair of 1 TeV gluino.

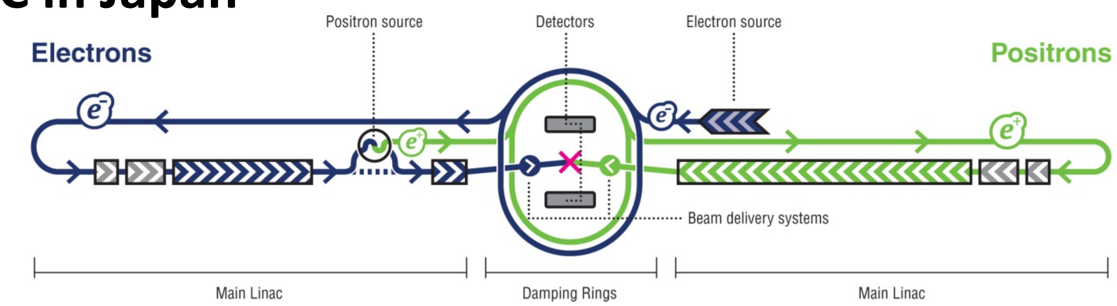


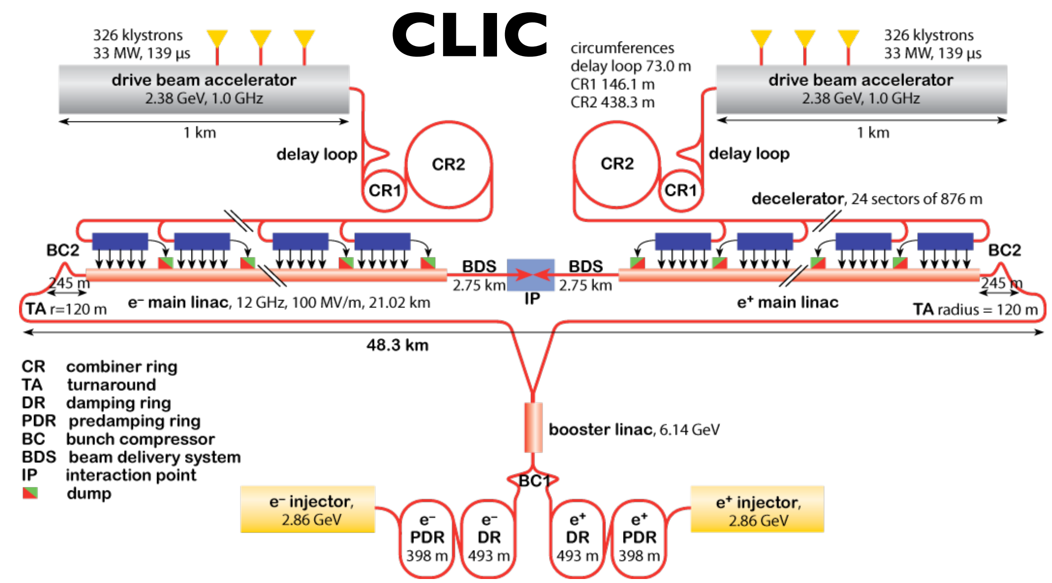
Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

Reaching the "slow" phase after Moriond 2017

Beyond the LHC, future facilities

ILC in Japan



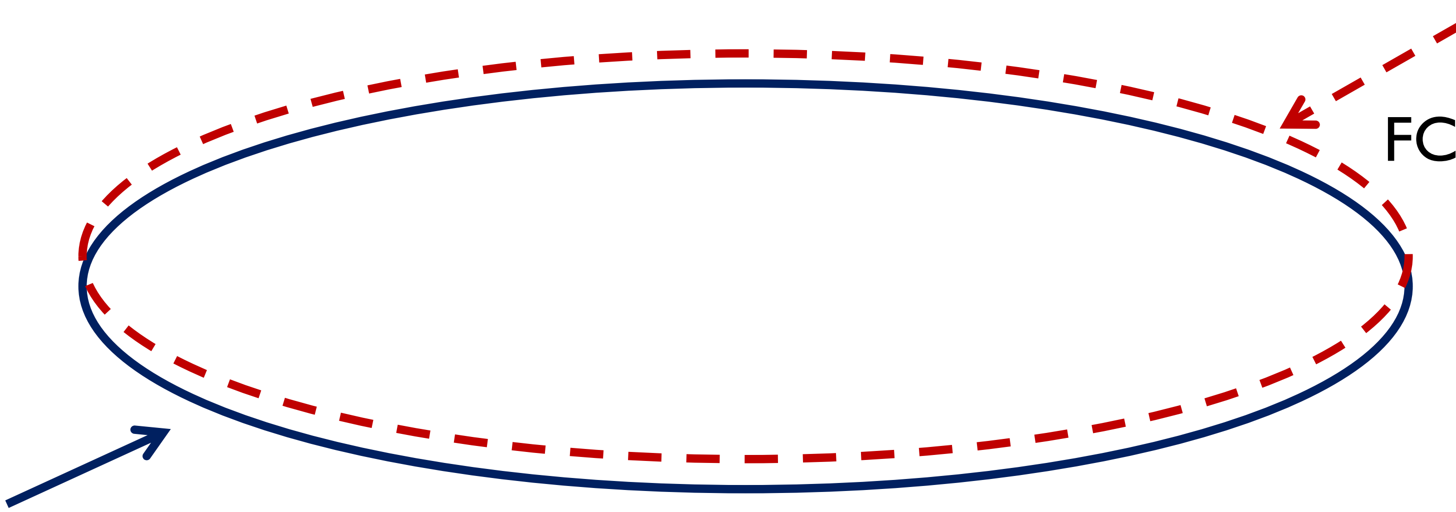


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

FCC-hh (CERN), SppC(China)



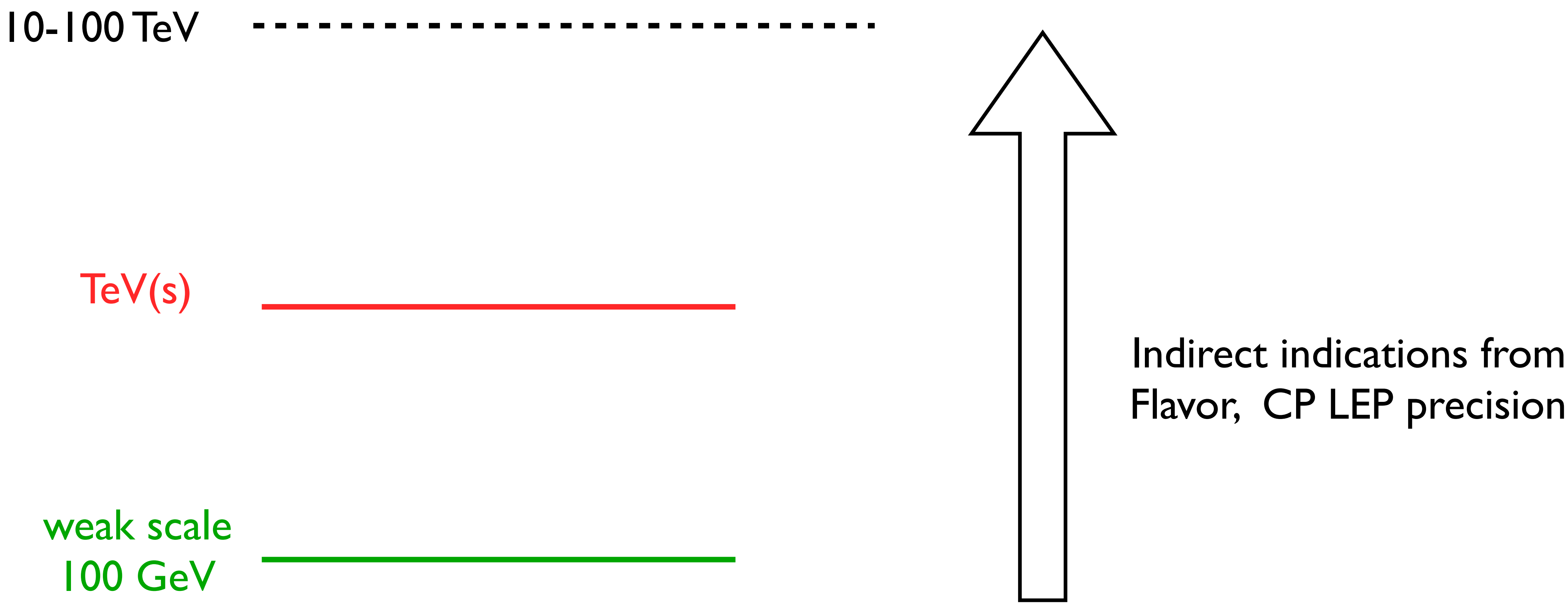
250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

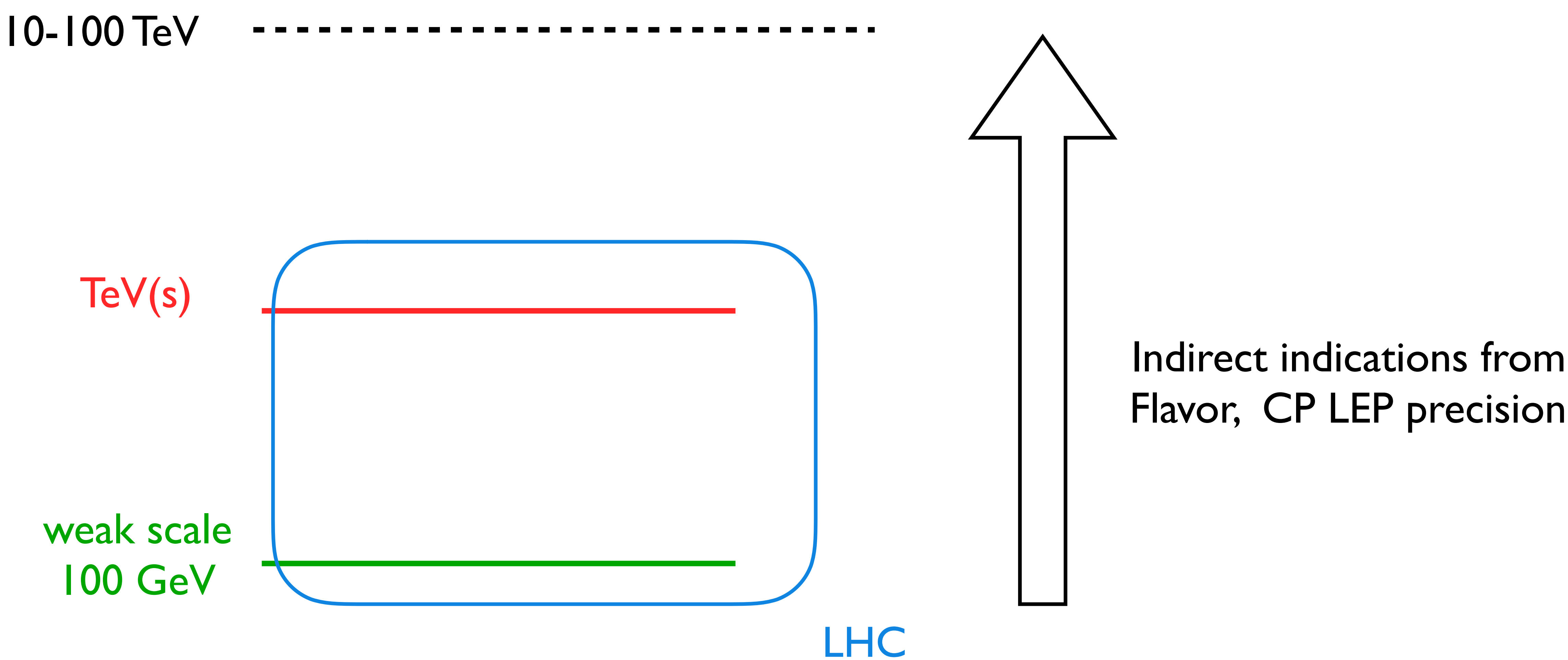
HE-LHC, "double" LHC energy

Muon collider, perhaps more down the road

Our expectation

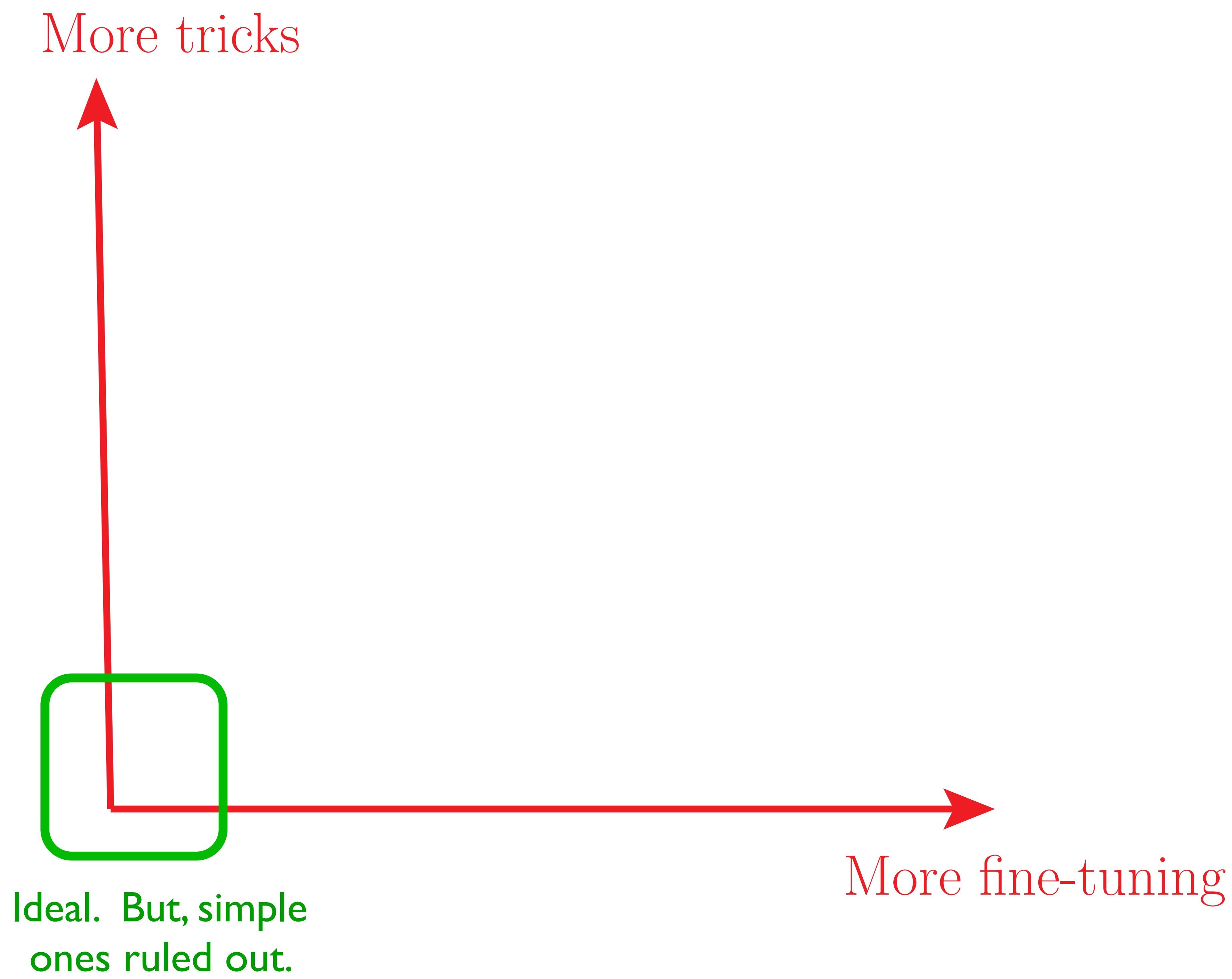


Our expectation



- Not too surprised that nothing has turned up yet.
- LHC may still bring surprises. Future colliders can probe 10s TeV regime.
- We don't know where new particles might be.

Where we are in theory space



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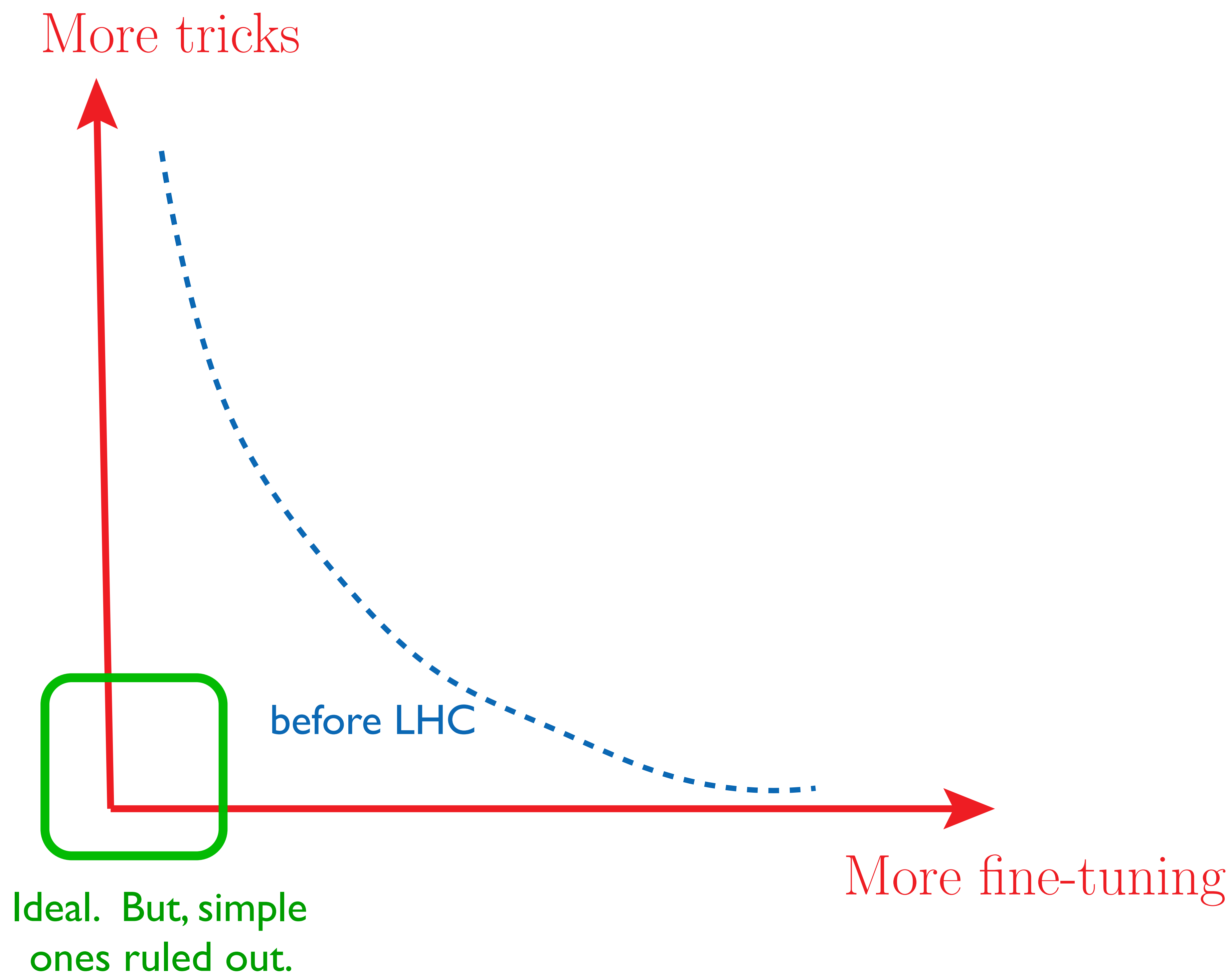

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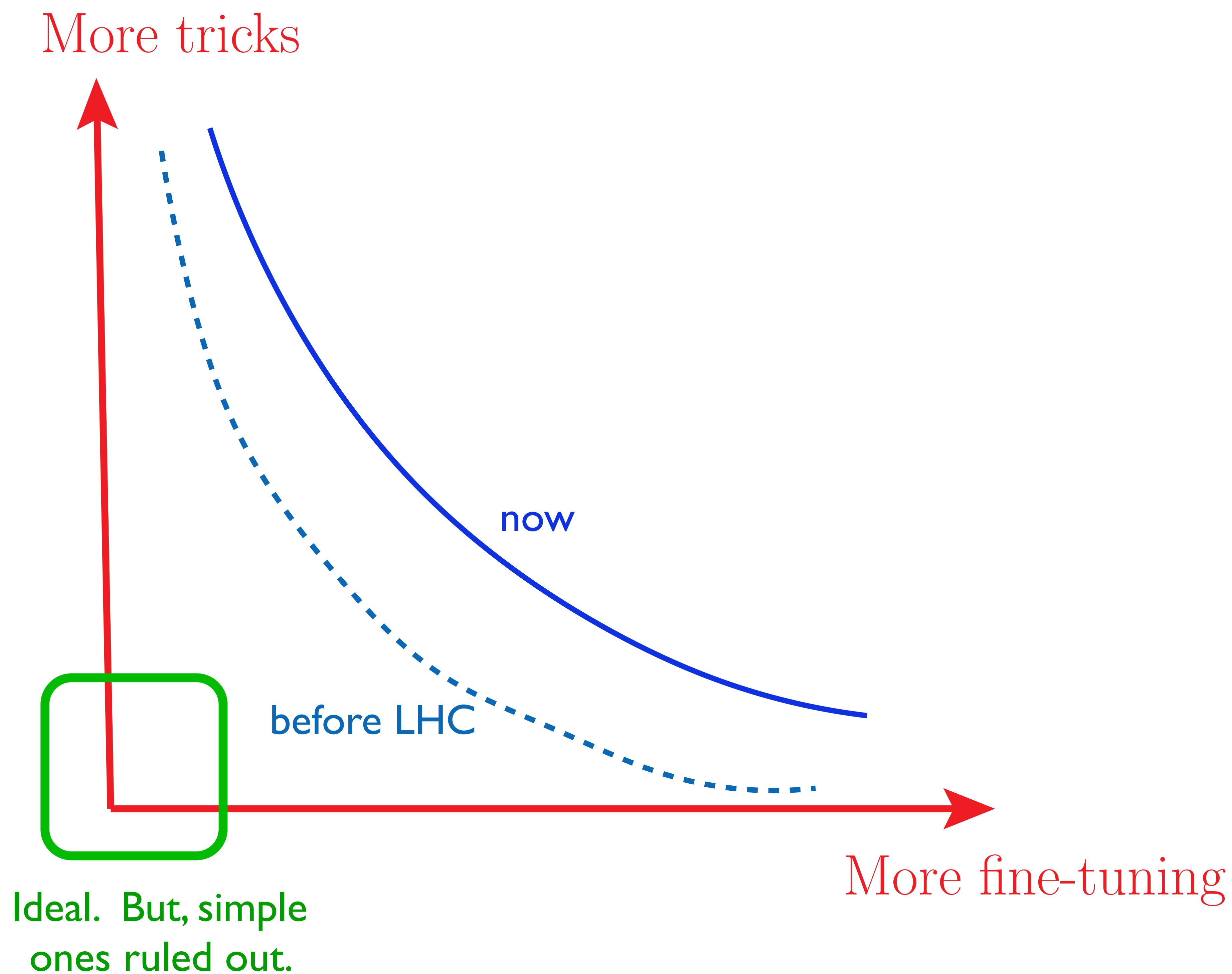

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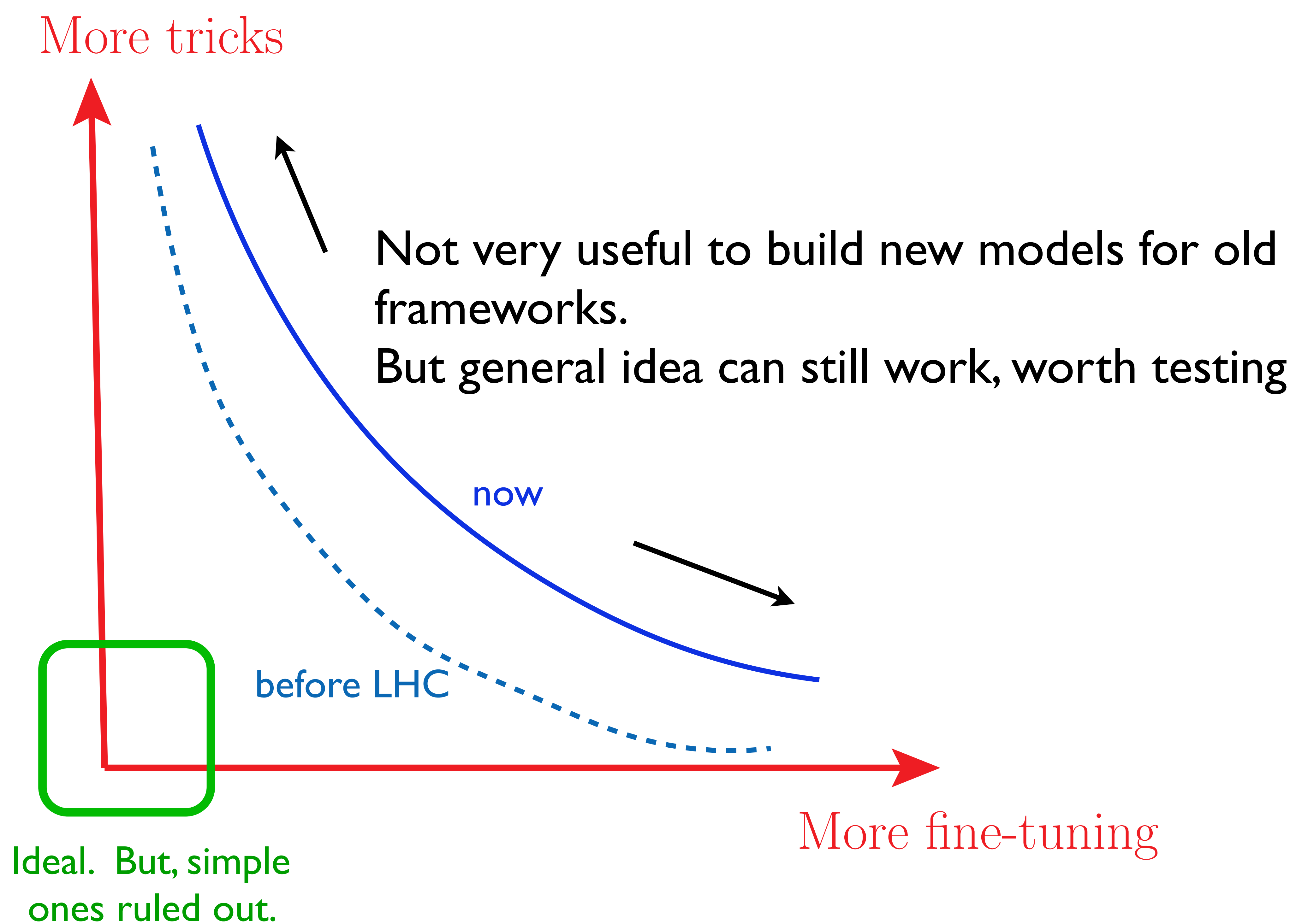
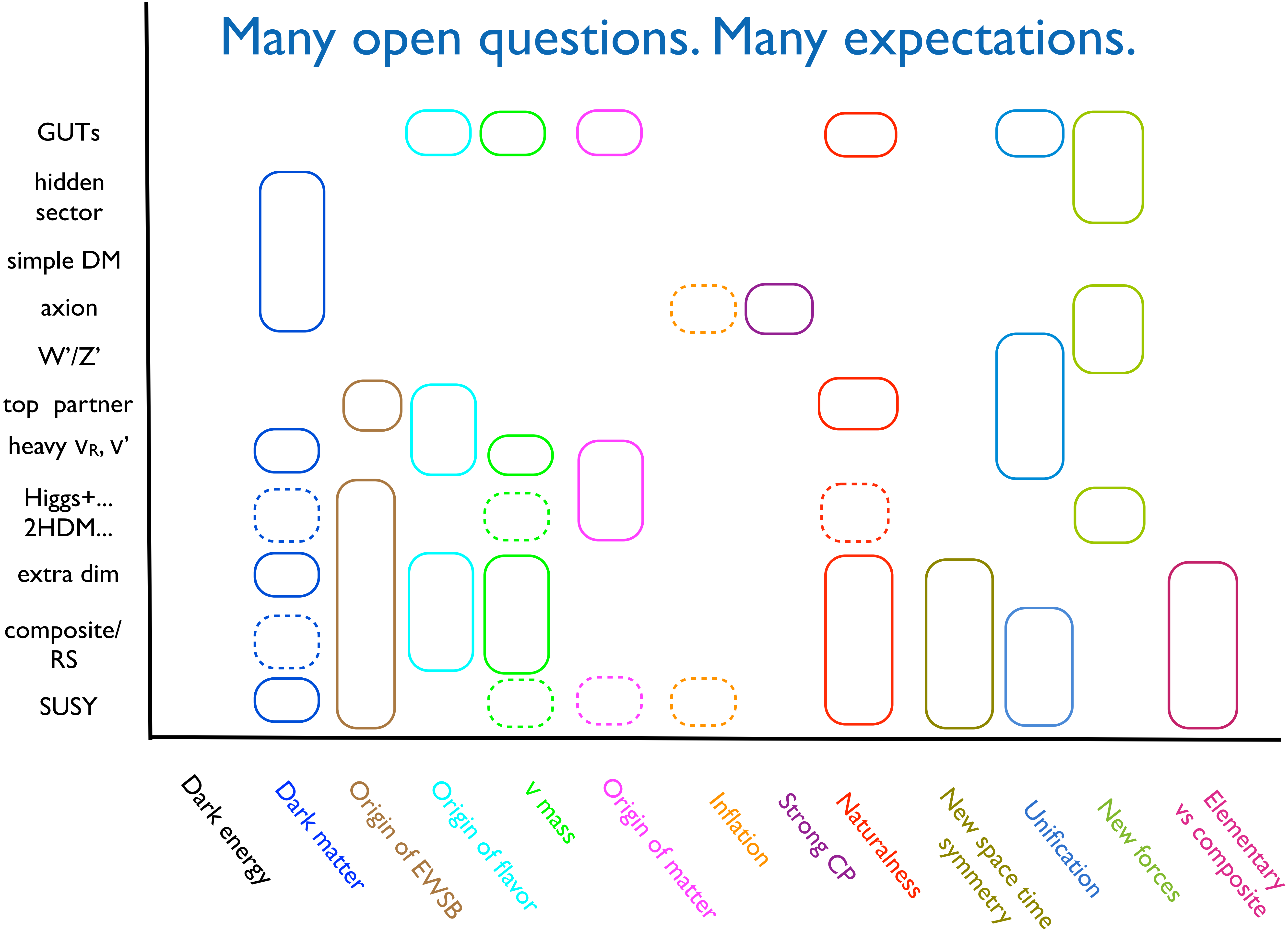


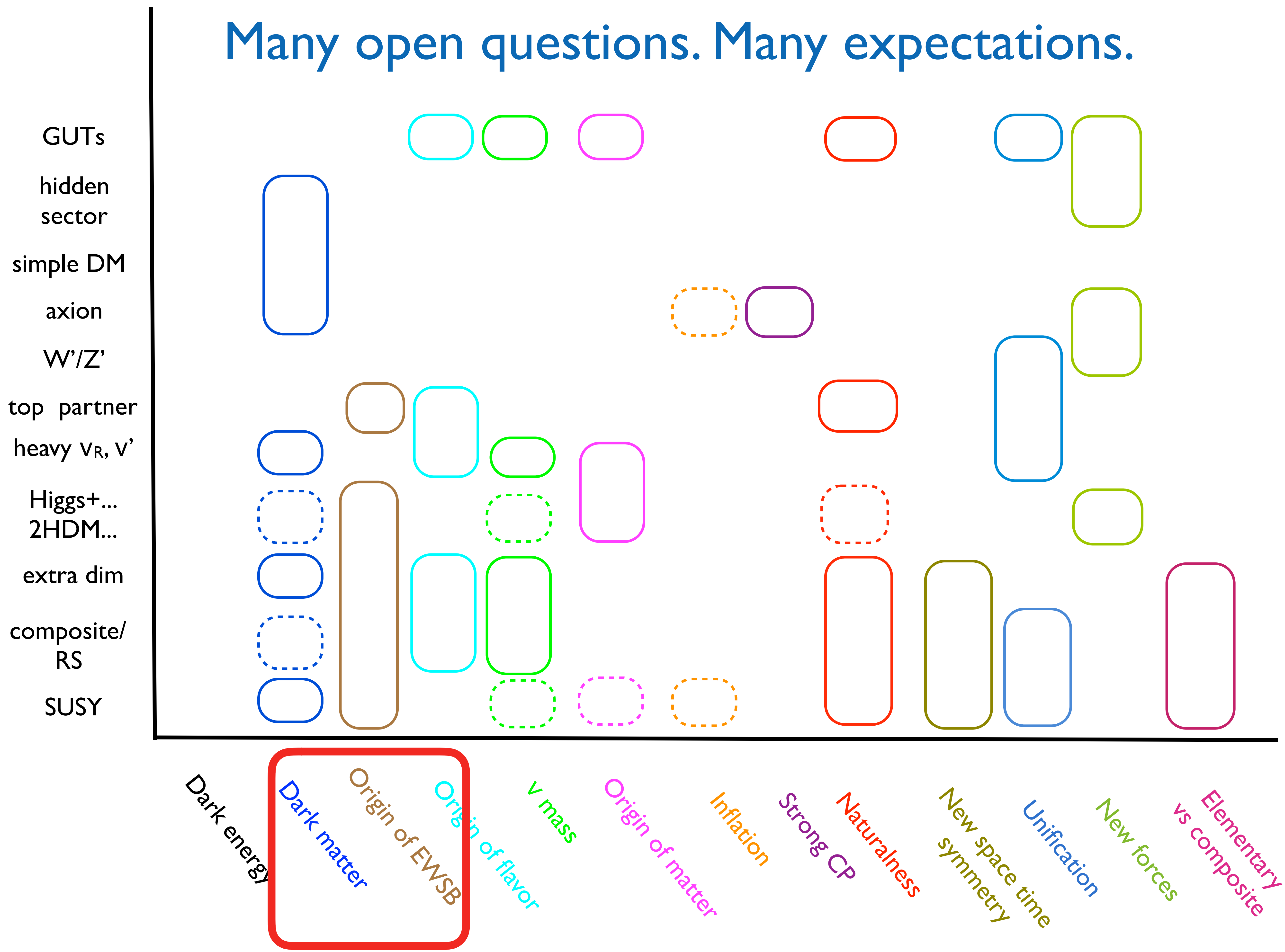
However, keep in mind:

- This is not a fishing expedition just to find new particles.
- Standard Model is not complete. Many open questions.
- The goal of particle physics is to answer these questions! We will keep trying.

Many open questions. Many expectations.

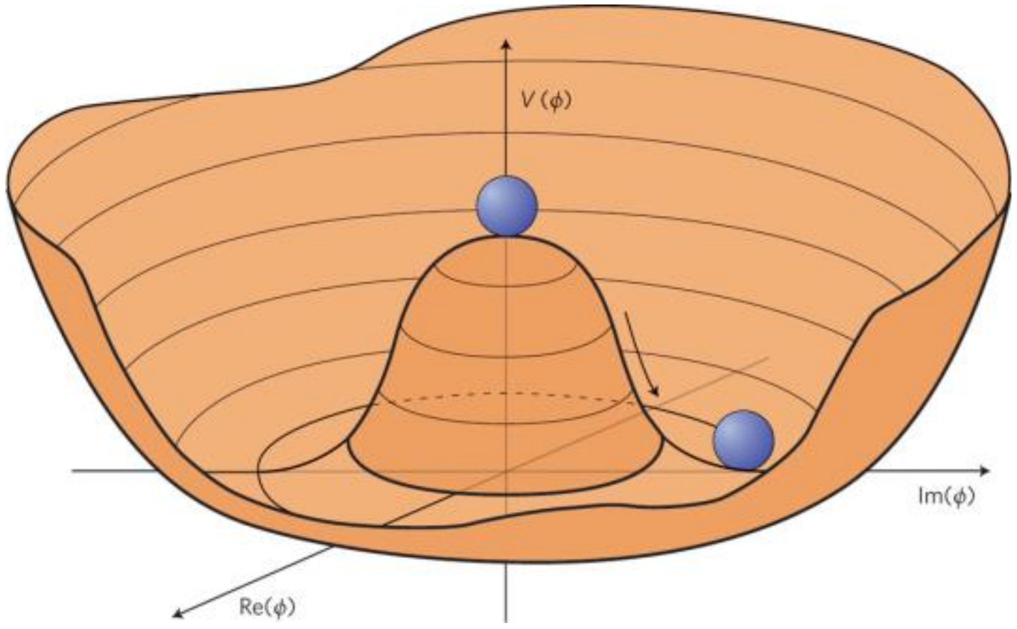


Many open questions. Many expectations.



Electroweak scale:
Naturalness and beyond

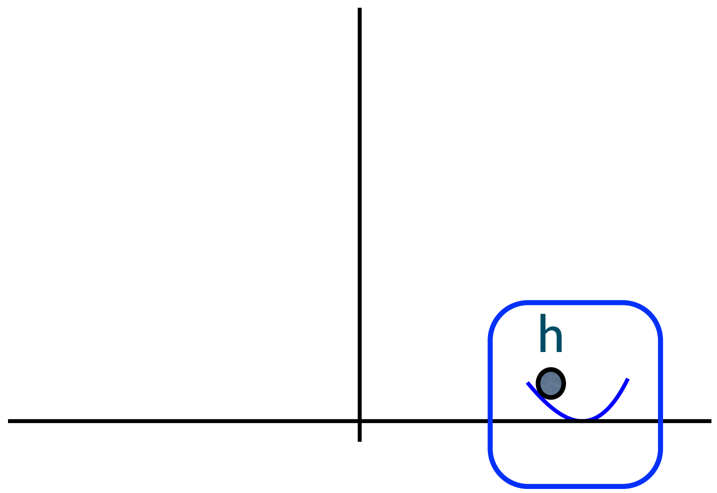
Mysteries of the electroweak scale.



$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \ \rightarrow \ m_W = g_W \frac{v}{2}$$

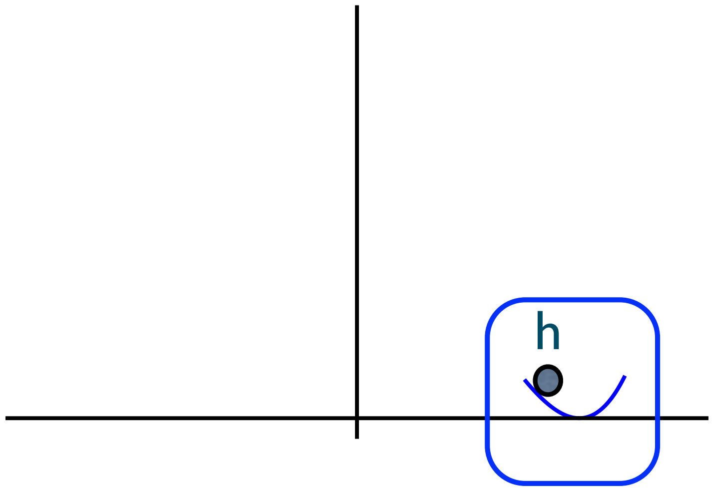
Mysteries of the electroweak scale.



What we know now

- How to predict/calculate Higgs mass?
- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.

Mysteries of the electroweak scale.



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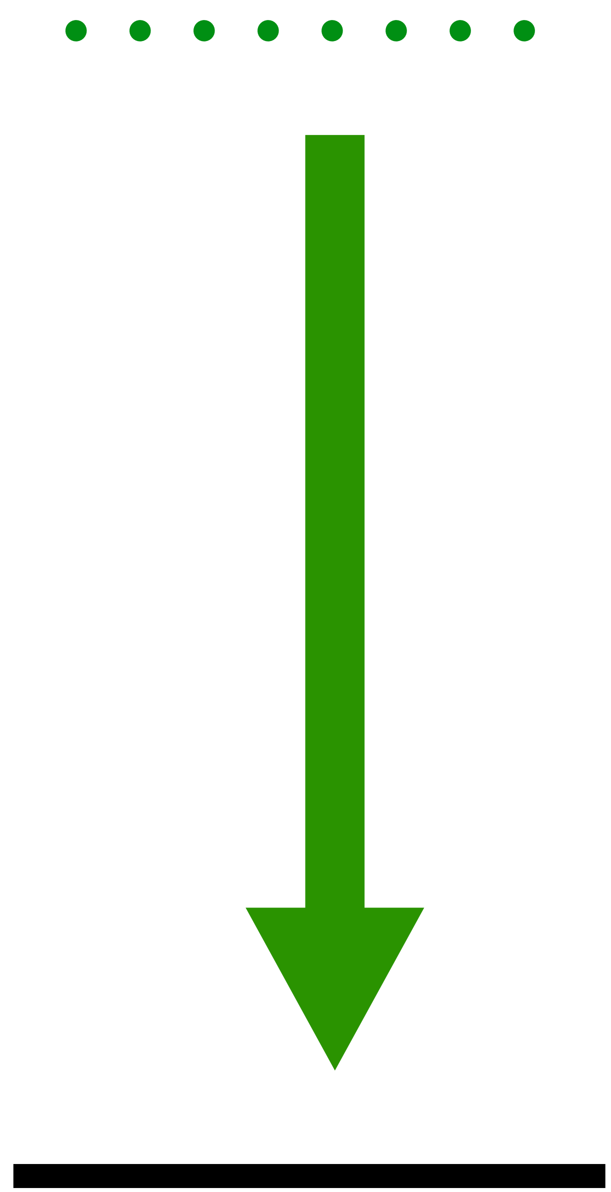
How to predict Higgs mass?



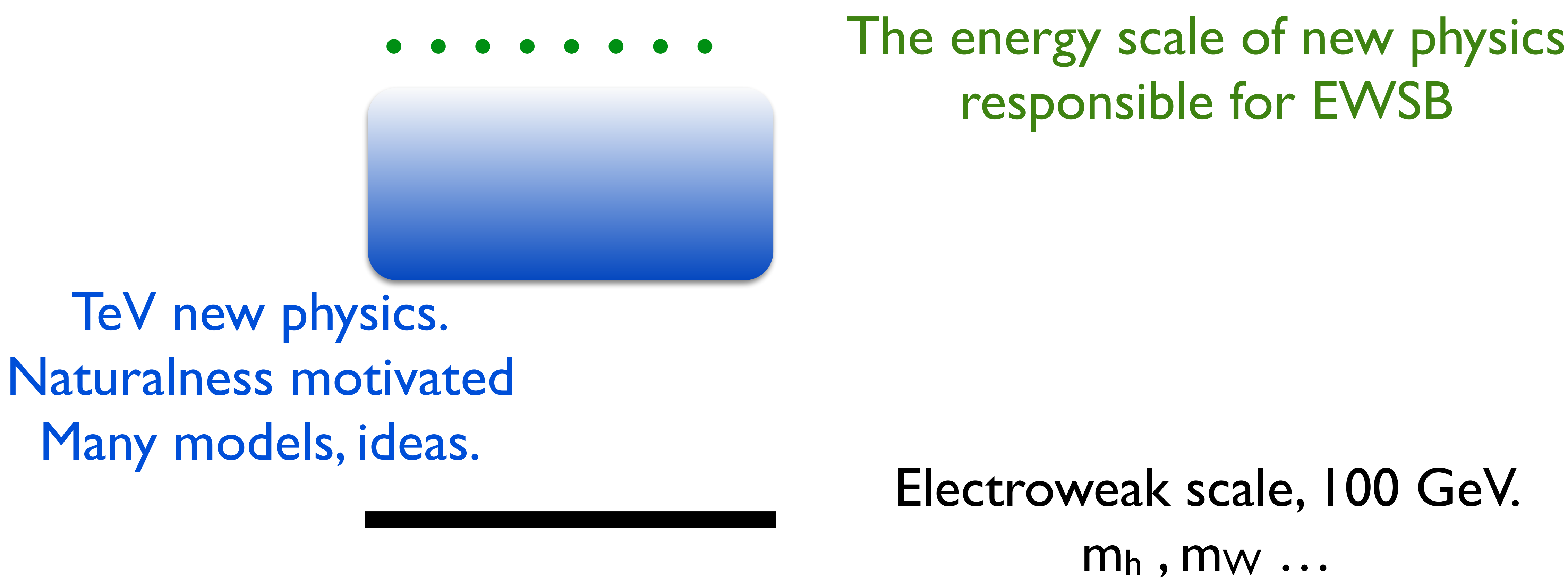
The energy scale of new physics
responsible for EWSB

What is this energy scale?
M_{Planck} = 10^{19} GeV, …?

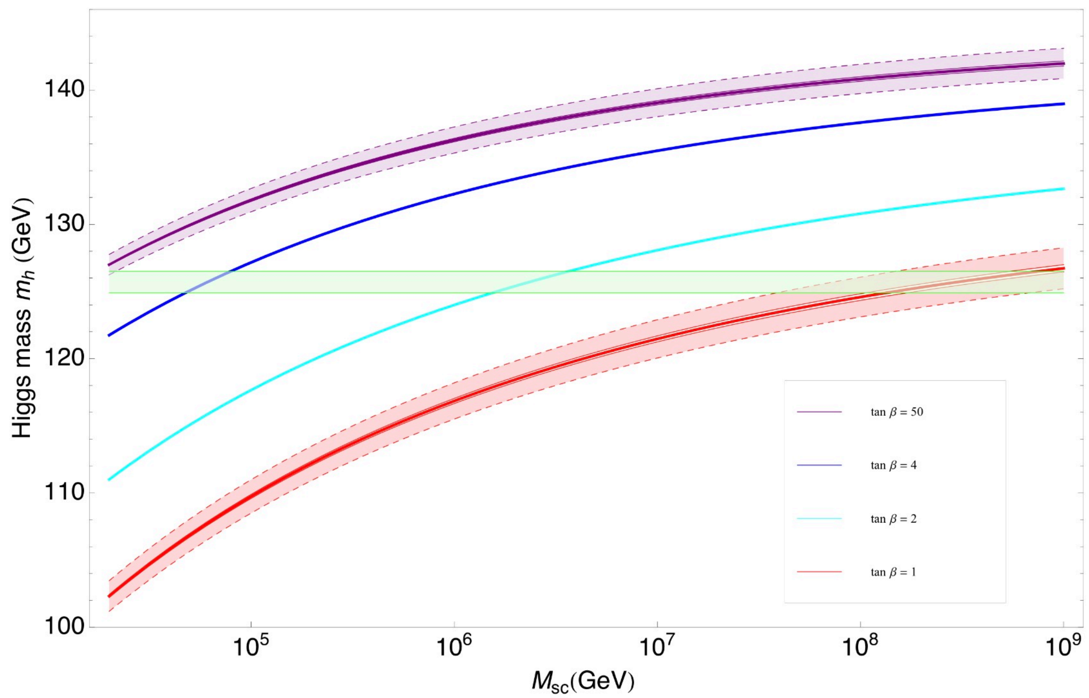
If so, why is so different from 100 GeV?
The so called naturalness problem

Electroweak scale, 100 GeV.
m_h , m_W …

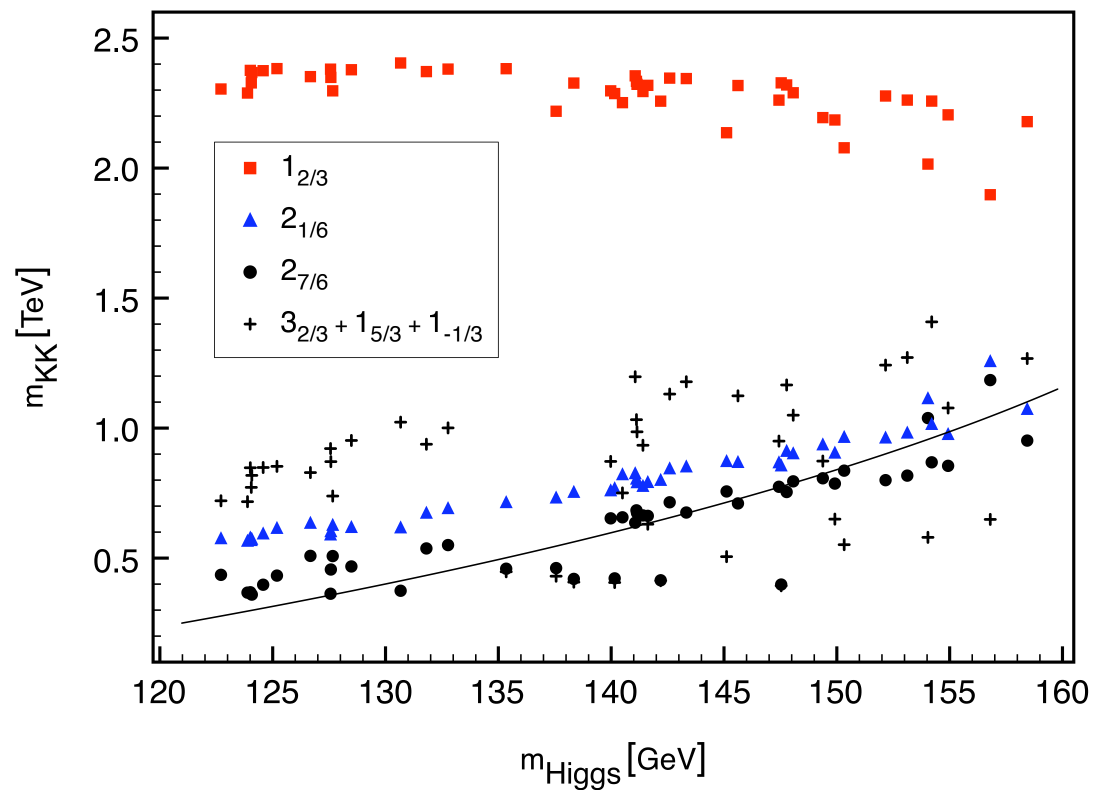
Naturalness of electroweak symmetry breaking



A confusing picture



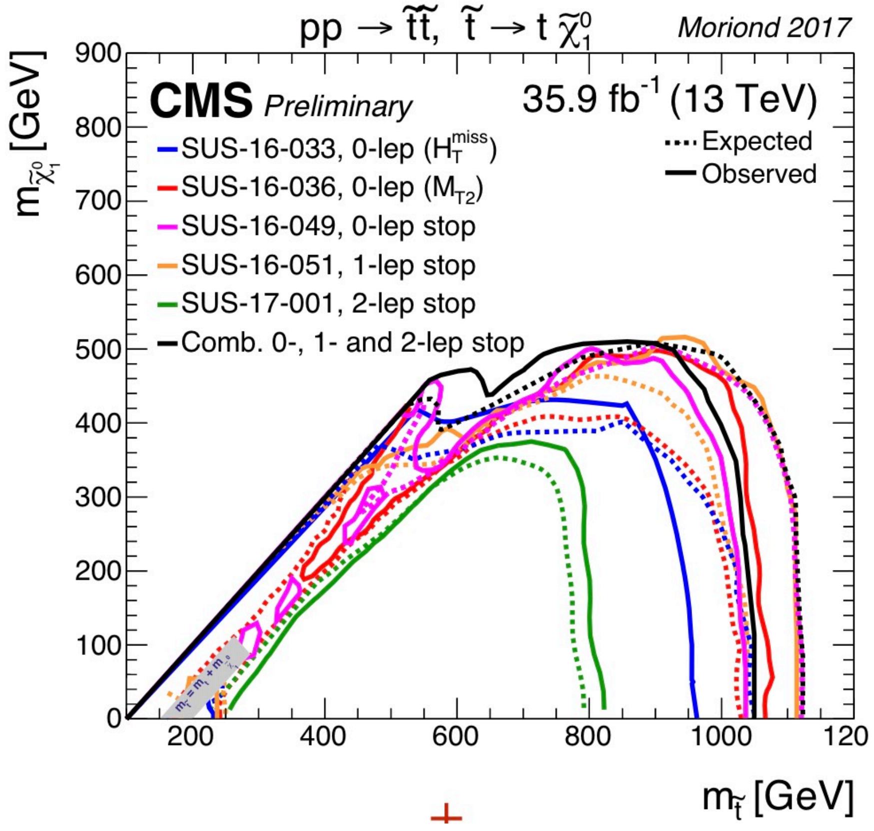
Stop too heavy to be natural

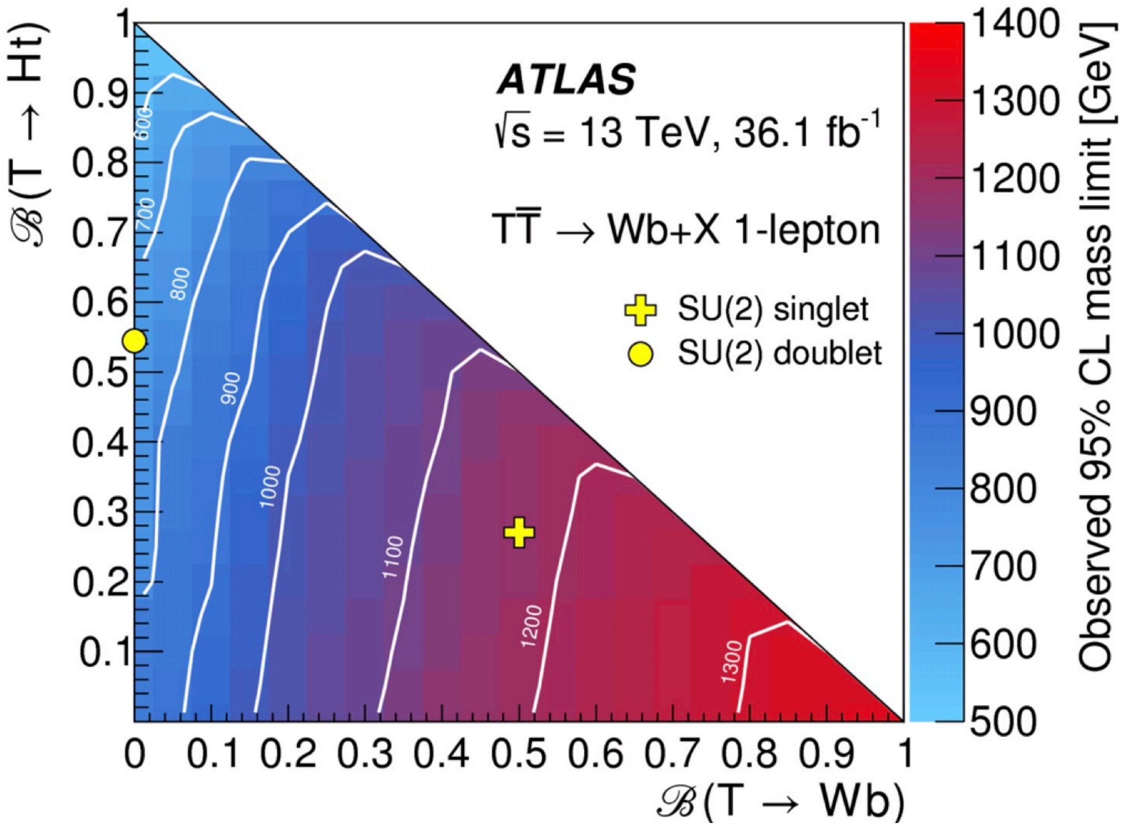


Composite top partner too light, excluded

Such conclusions too simplistic, "work around" available.
A bit uncomfortable, yes. Not time to give up just yet.

Direct searches



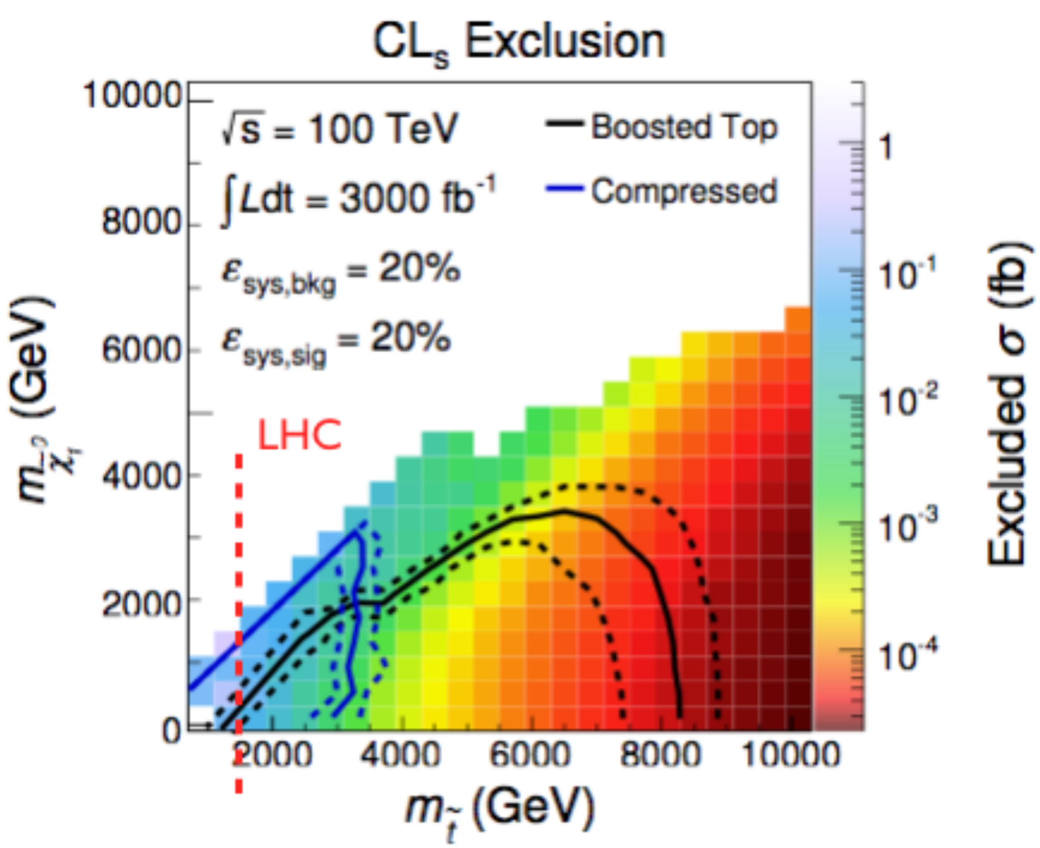


LHC will keep searching for such new particles

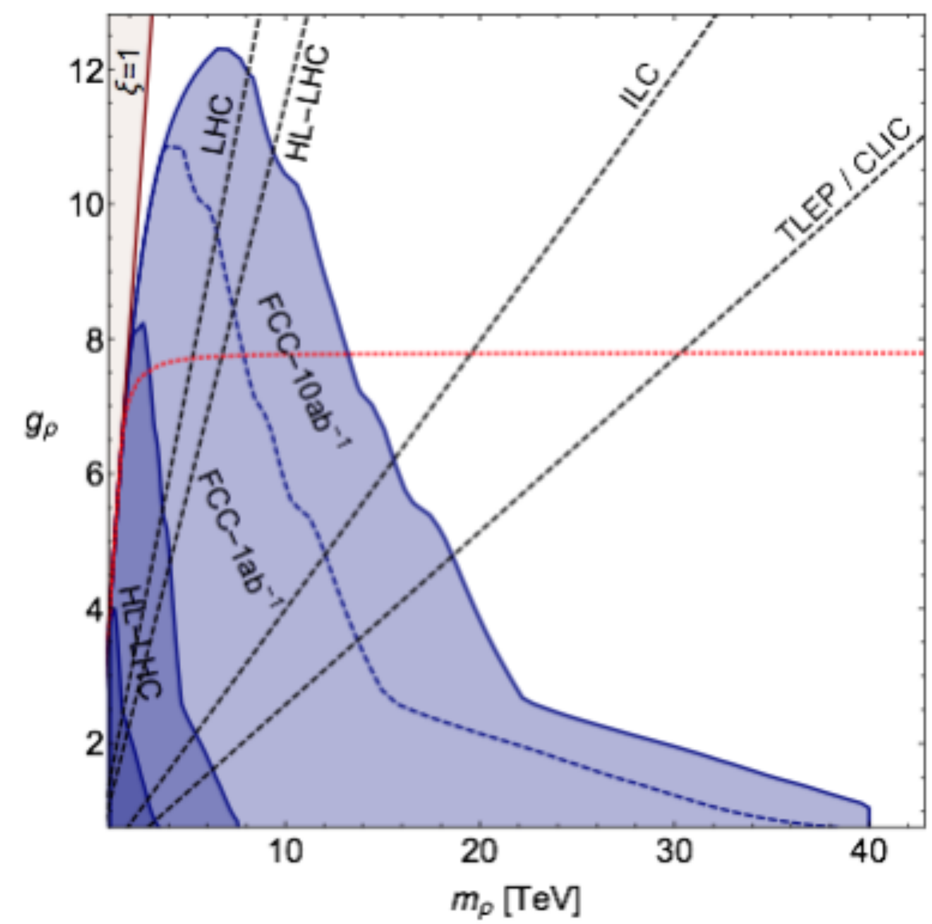
Future colliders, FCC-hh/SPPC, can continue the quest.

Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014

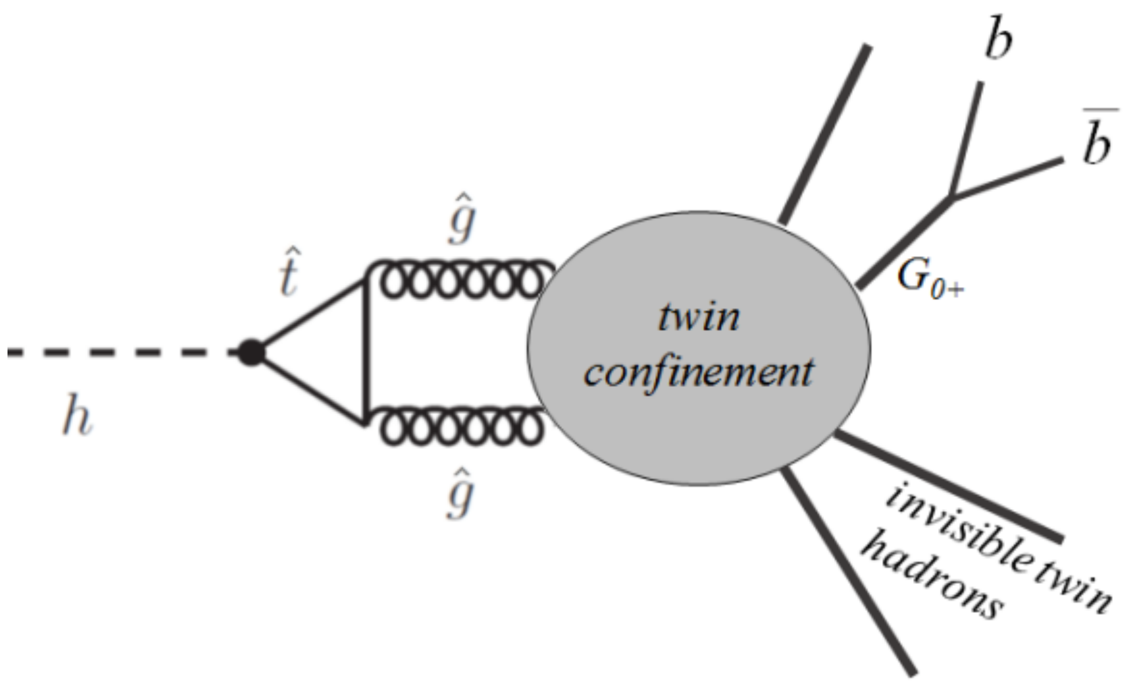


Fine tuning: $(M_{NP})^{-2}$

Stealthy top partner. "twin"

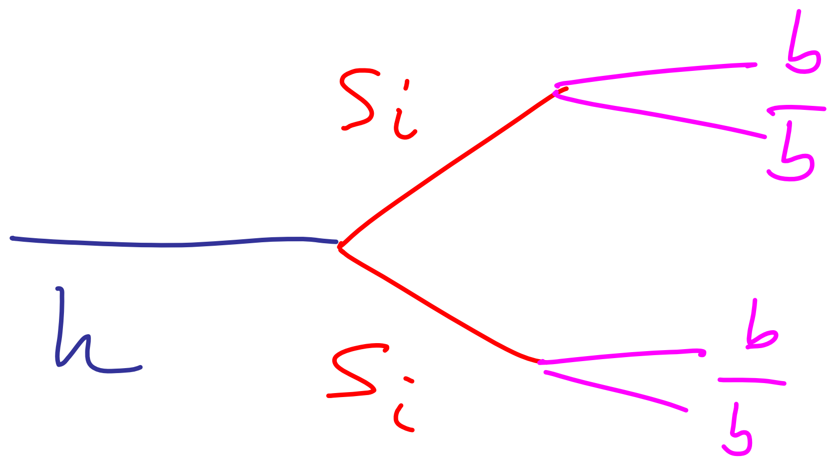
Chacko, Goh, Harnik

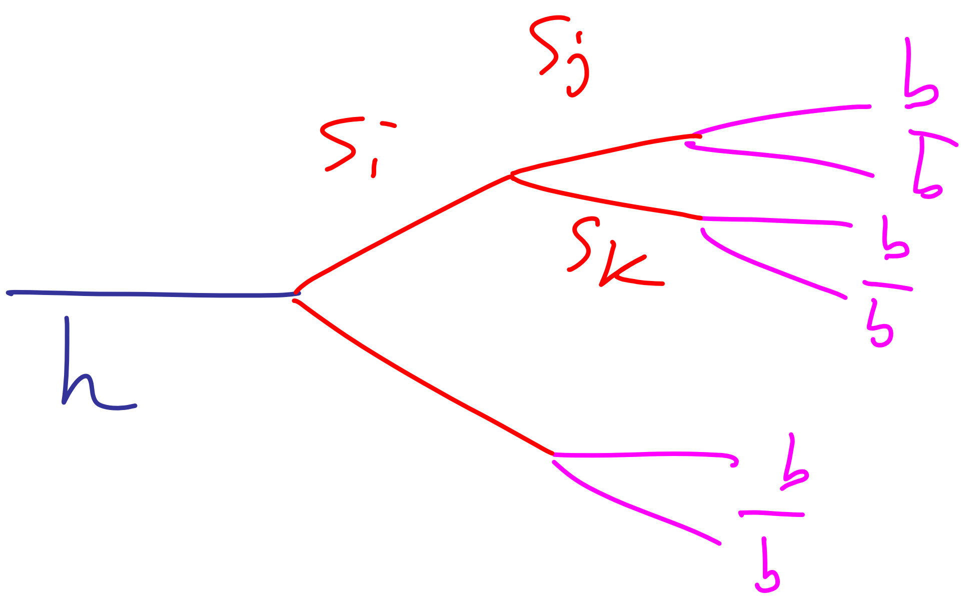
Craig, Katz, Strassler, Sundrum



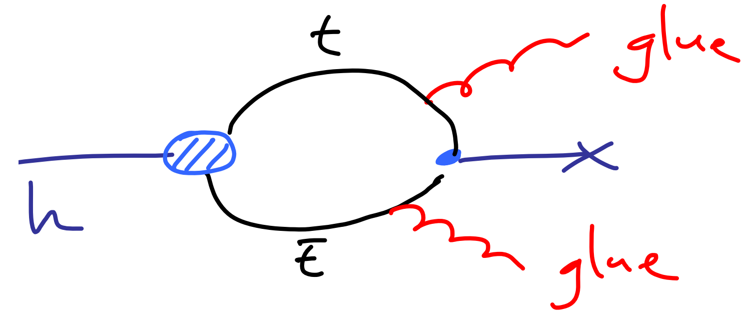
- Top partner not colored. Higgs decay through hidden world and back.
- Lead to Higgs rare decays.

More exotic ideas





Indirect: CEPC



$K_g \sim \left(\frac{m_t^2}{\Lambda^2}\right) \sim 10\%$ Easy @ CEPC

$K_\gamma \sim$ few % Possible @ CEPC

Low scale landscape

Higgs rare decay.

"fat" Higgs

Higgs coupling

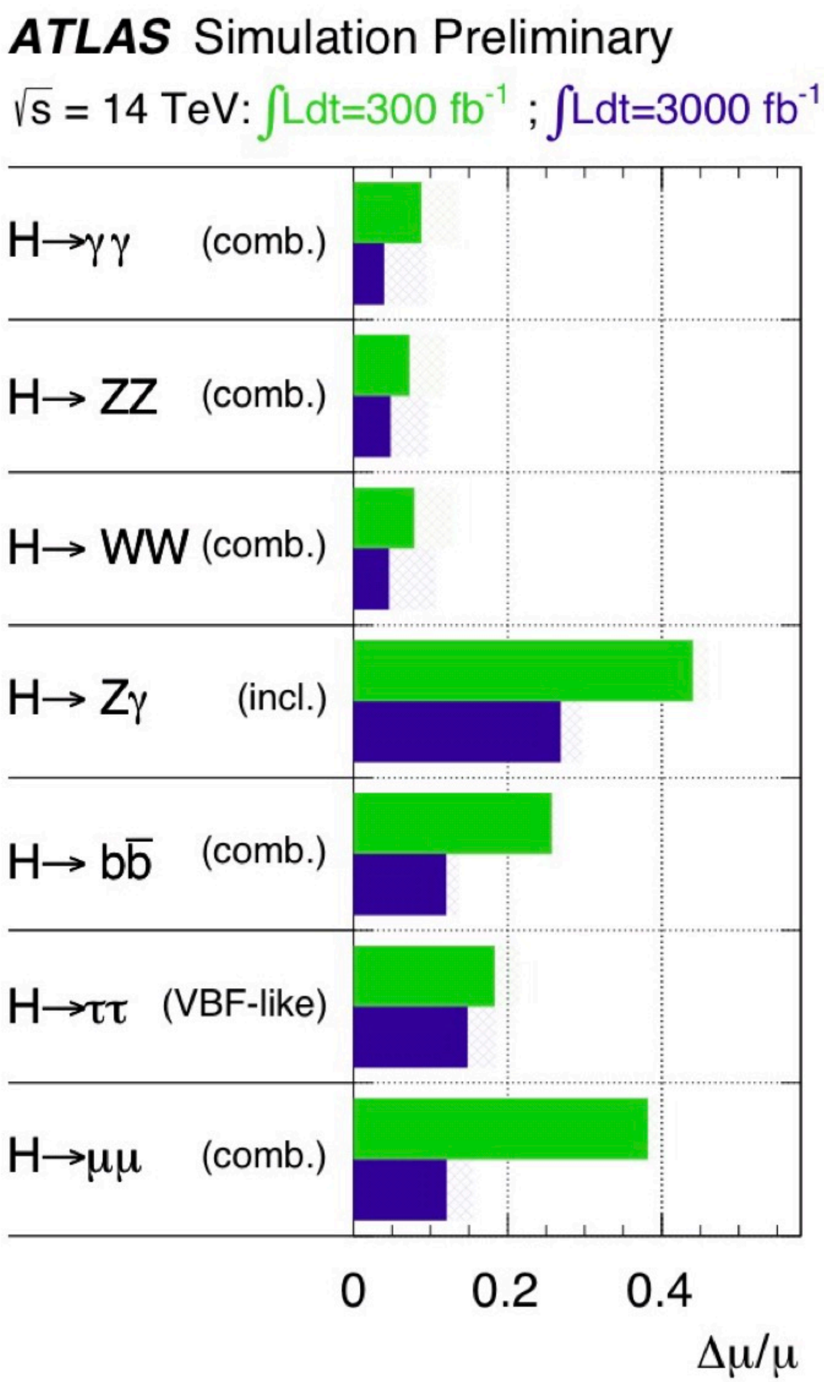
Can't hide from the Higgs.

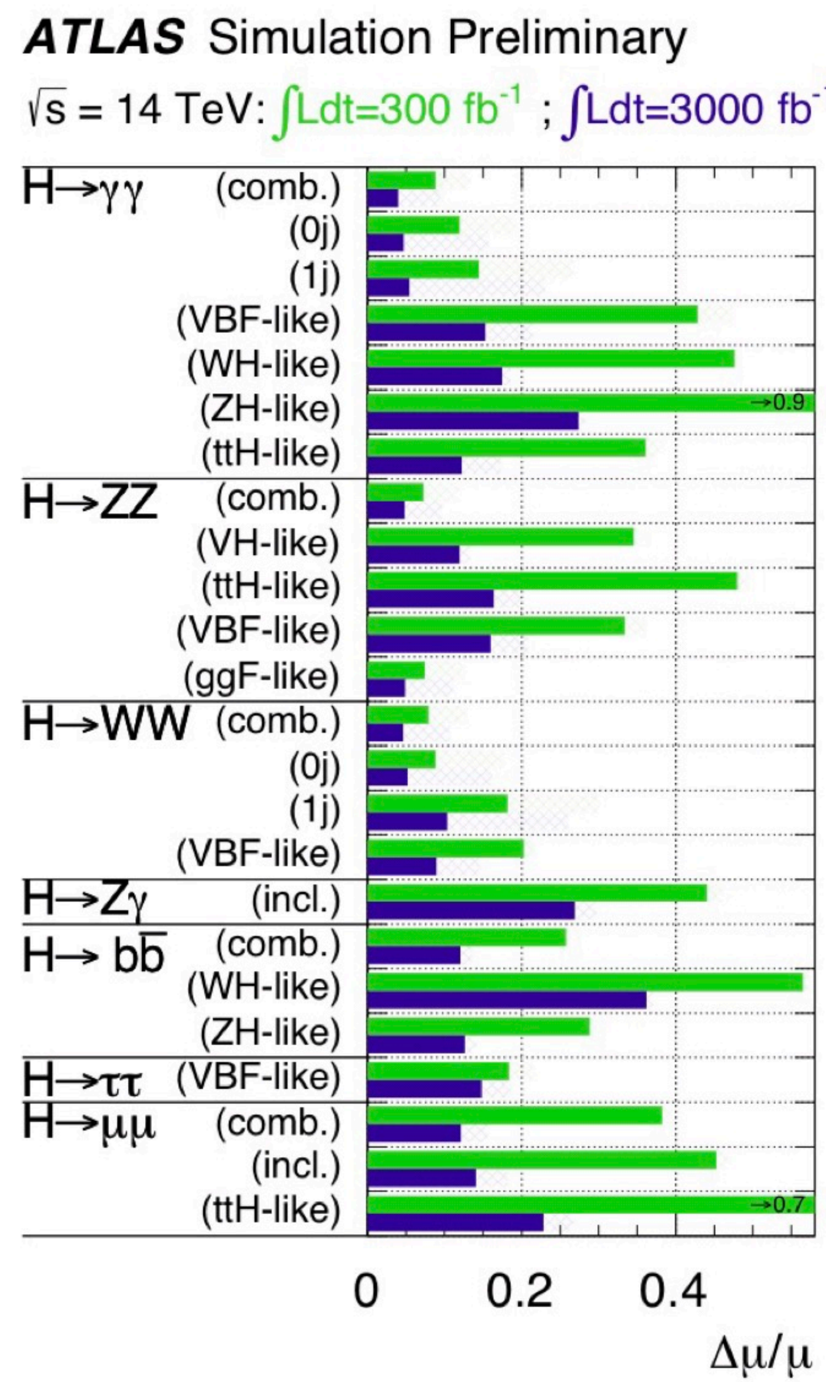
Talk by Arkani-Hamed CEPC workshop Sept. 2016

Bottom line on naturalness

- It is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We have ideas, but maybe not the right one.
  - No confirmation of any of the proposed models.
  - Confusion is good for physics. Challenging the foundation of our understanding of Quantum Field Theory.
  - Need experimental guidance.
- Fortunately, with Higgs, we know where to look.
  - Clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

LHC entering precision measurement stage

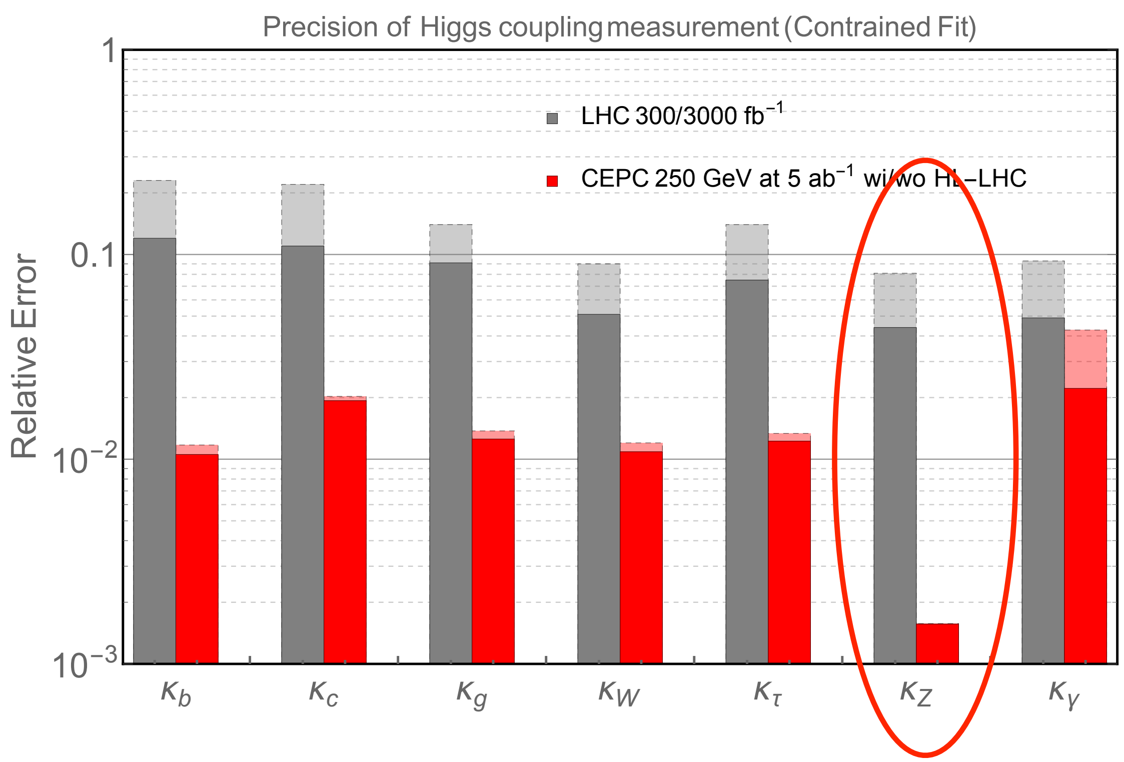


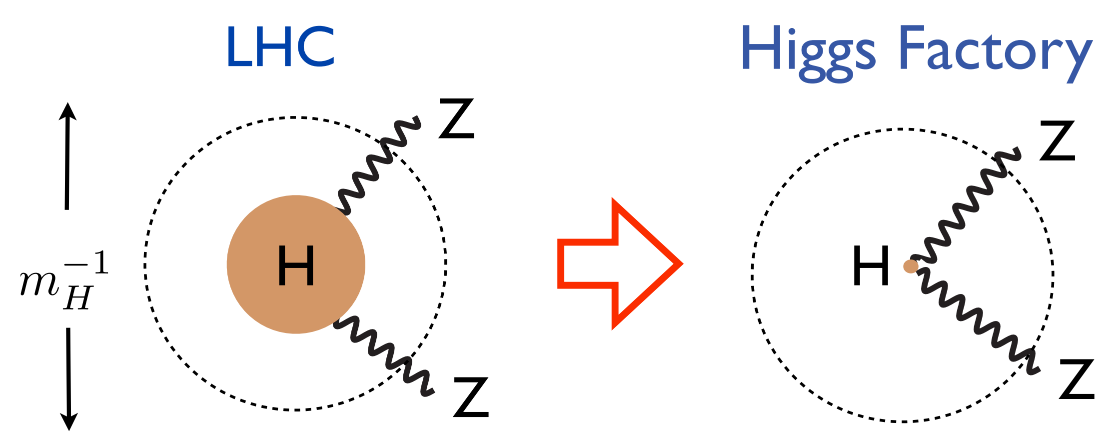


4-5% on Higgs coupling, reach TeV new physics

Higgs coupling: a "no-lose"

- Any attempt to address the Higgs mass problem has to introduce something couples to the Higgs.
  - Will generally induce shifts in Higgs coupling.

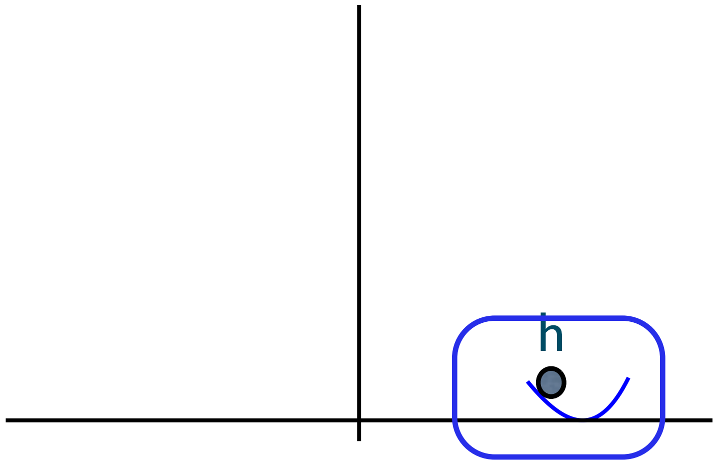




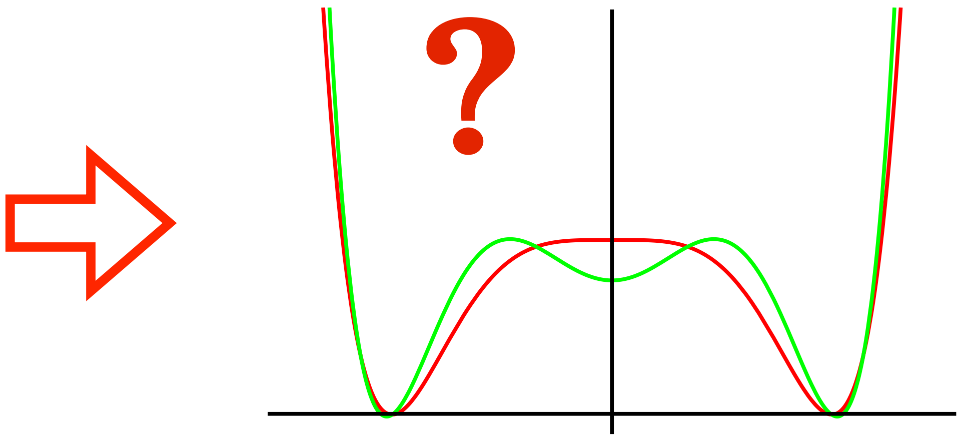
$$\kappa_Z = \frac{g_{hZ}(\text{Measured})}{g_{hZ}(\text{SM})}$$

Higgs factory has what it takes!

Nature of EW phase transition



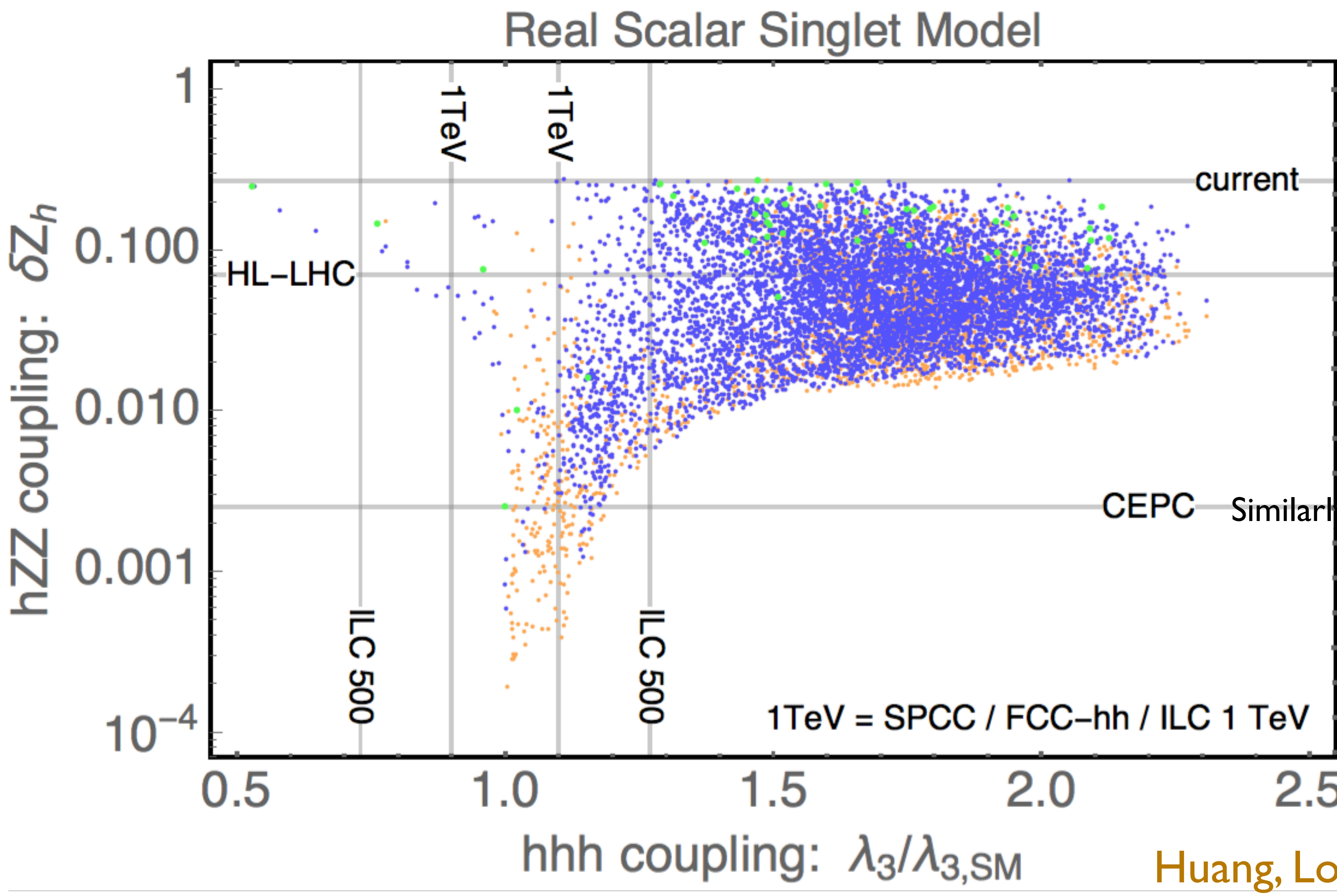
What we know from LHC
LHC upgrades won't go much further



"wiggles" in Higgs potential

Big difference in triple Higgs coupling

Probing nature of EW phase transition



Similarly FCC-ee and ILC 250

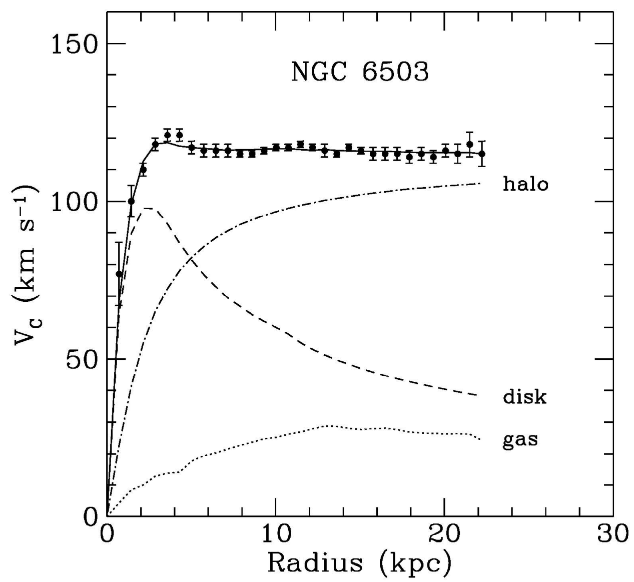
Huang, Long, LTW, 1608.06619

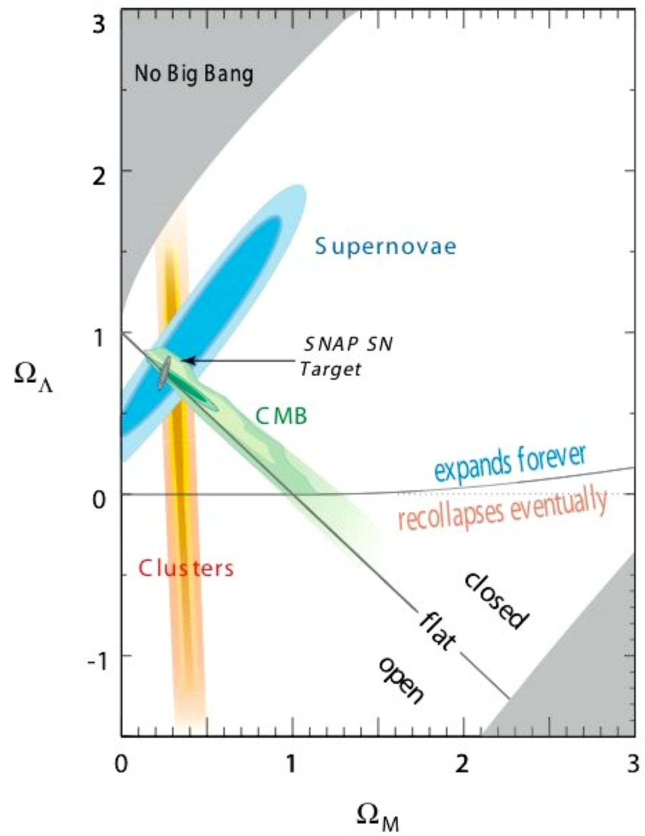
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = “strongly” first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Dark matter

More specifically: WIMP DM

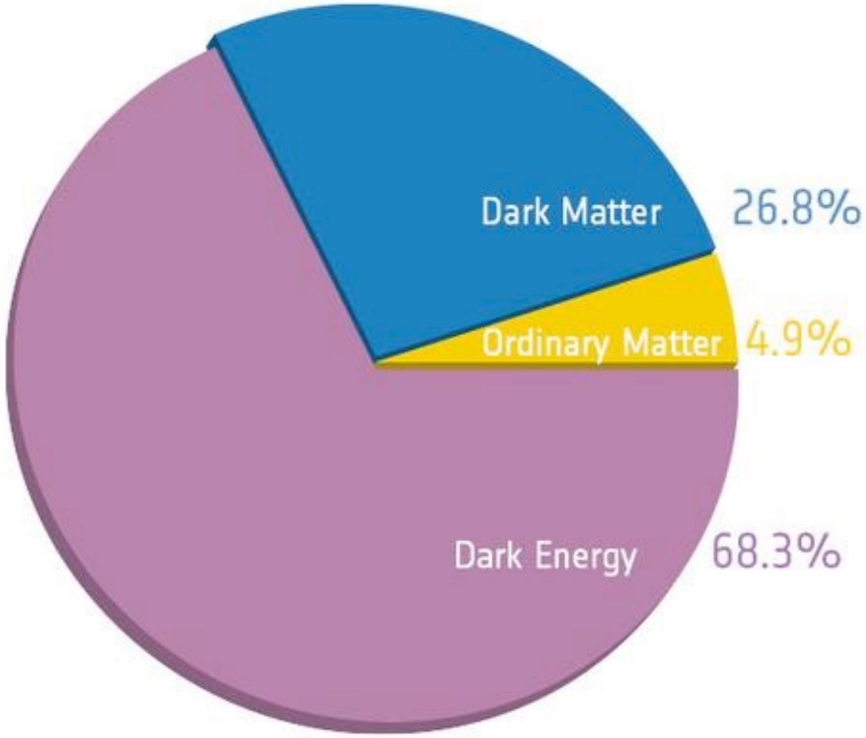
Dark matter



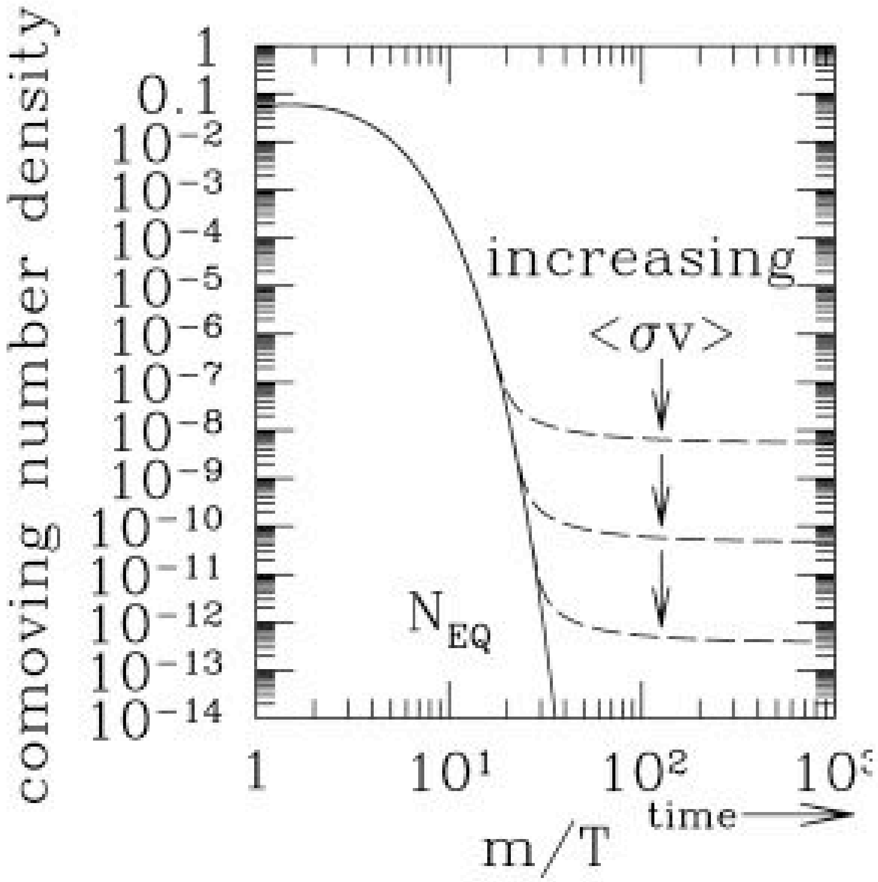


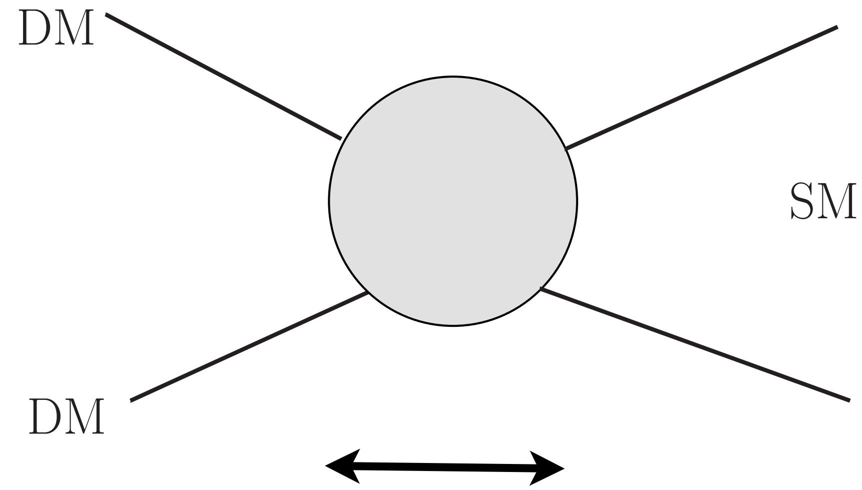
It is there. Not a theorist's imagination.

Only seen its gravitational interaction.
We have to understand them better.
Collider search is a key approach.



WIMP miracle

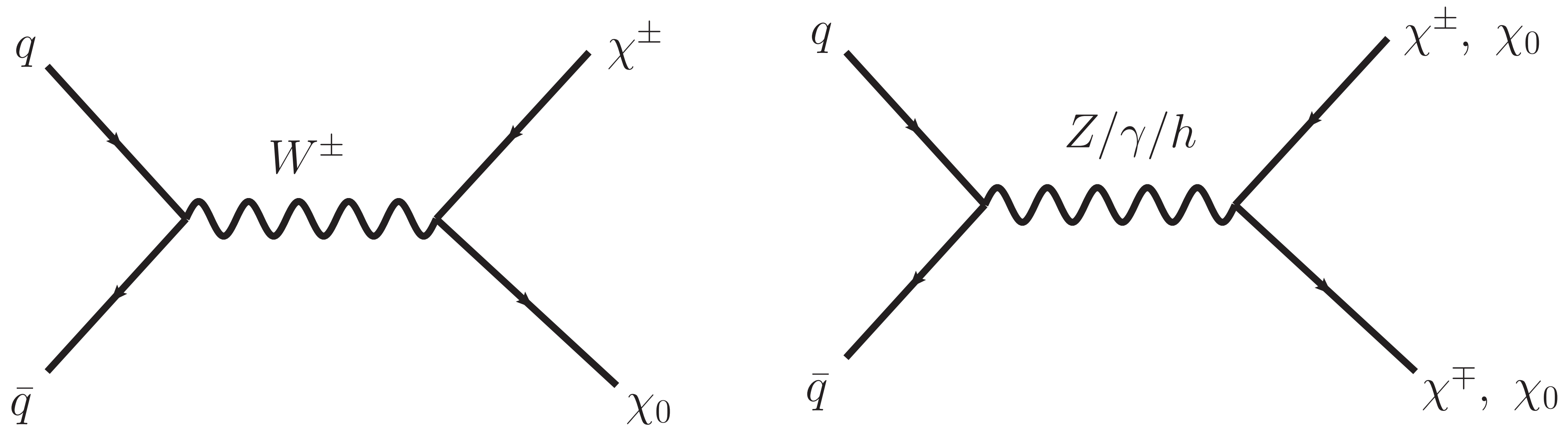




$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

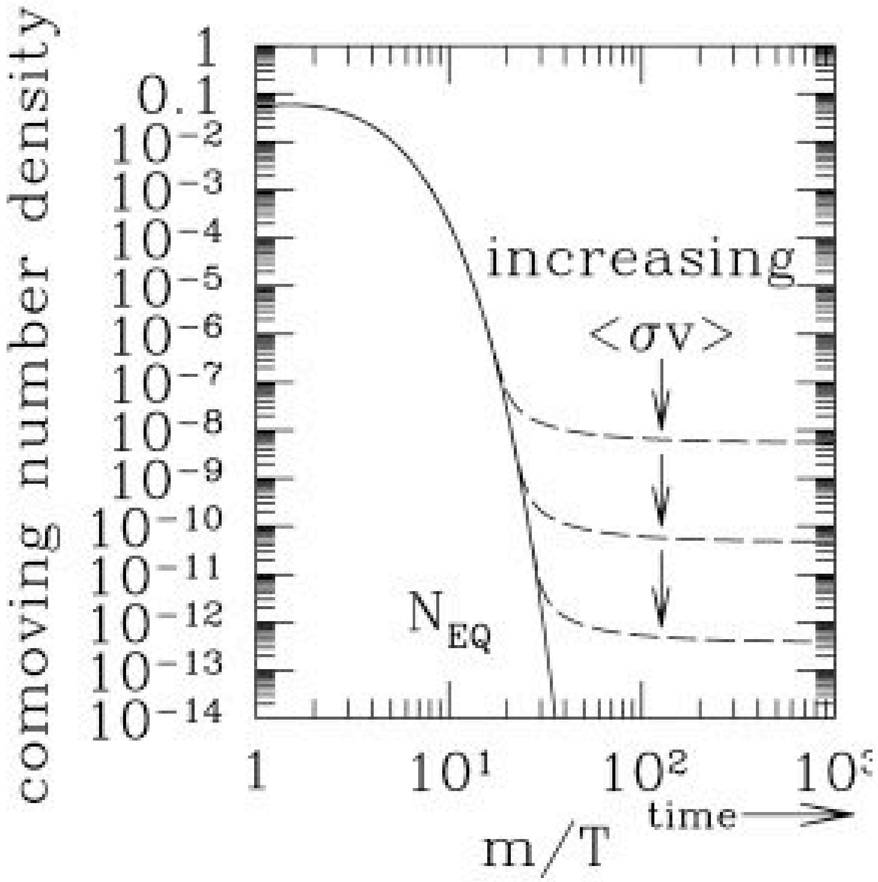
- Thermal equilibrium in the early universe.
- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Major hint for weak scale new physics!

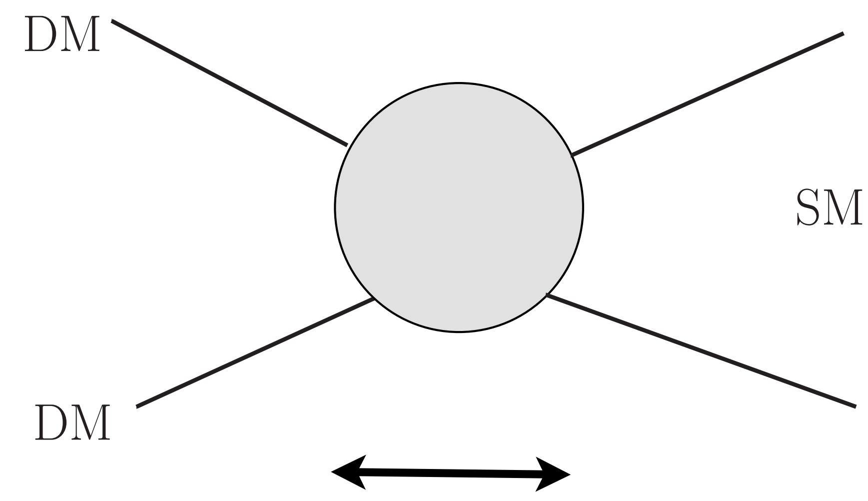
Simplest WIMP: part of weak multiplet



- Mediated by W/Z/h.
- Predictive, no unkown particle as mediator.
- The original WIMP proposal.

WIMP mass





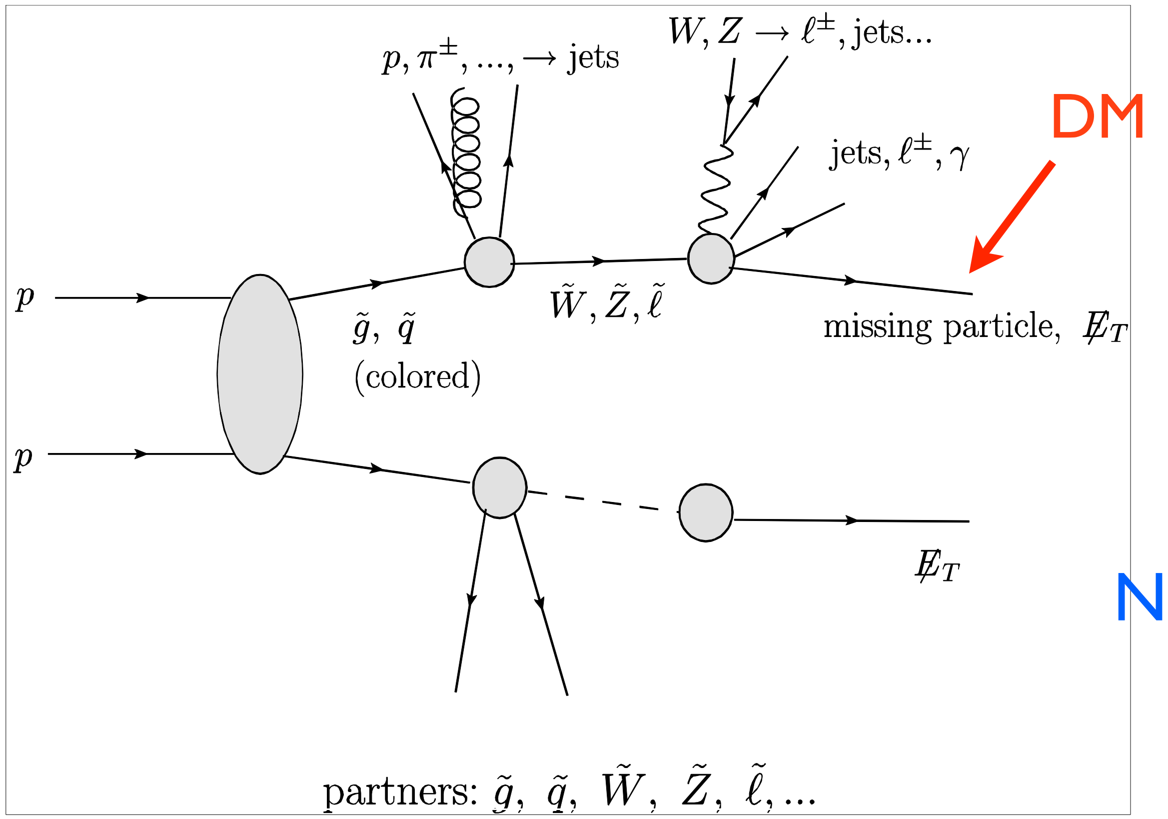
$$\langle \sigma v \rangle \sim \frac{g_{\mathrm{D}}^4}{m_{\mathrm{DM}}^2}$$

– More precisely, to get the correct relic abundance

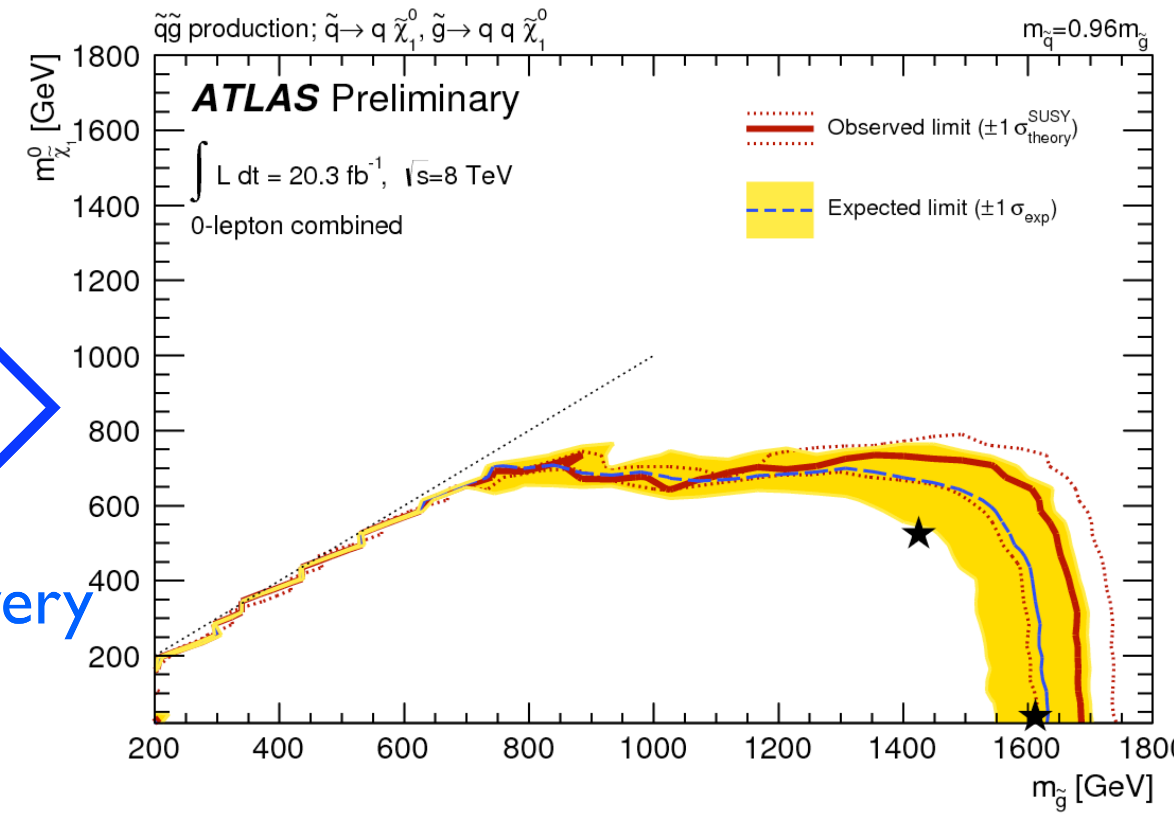
$$M_{\mathrm{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

TeV-ish in simplest models

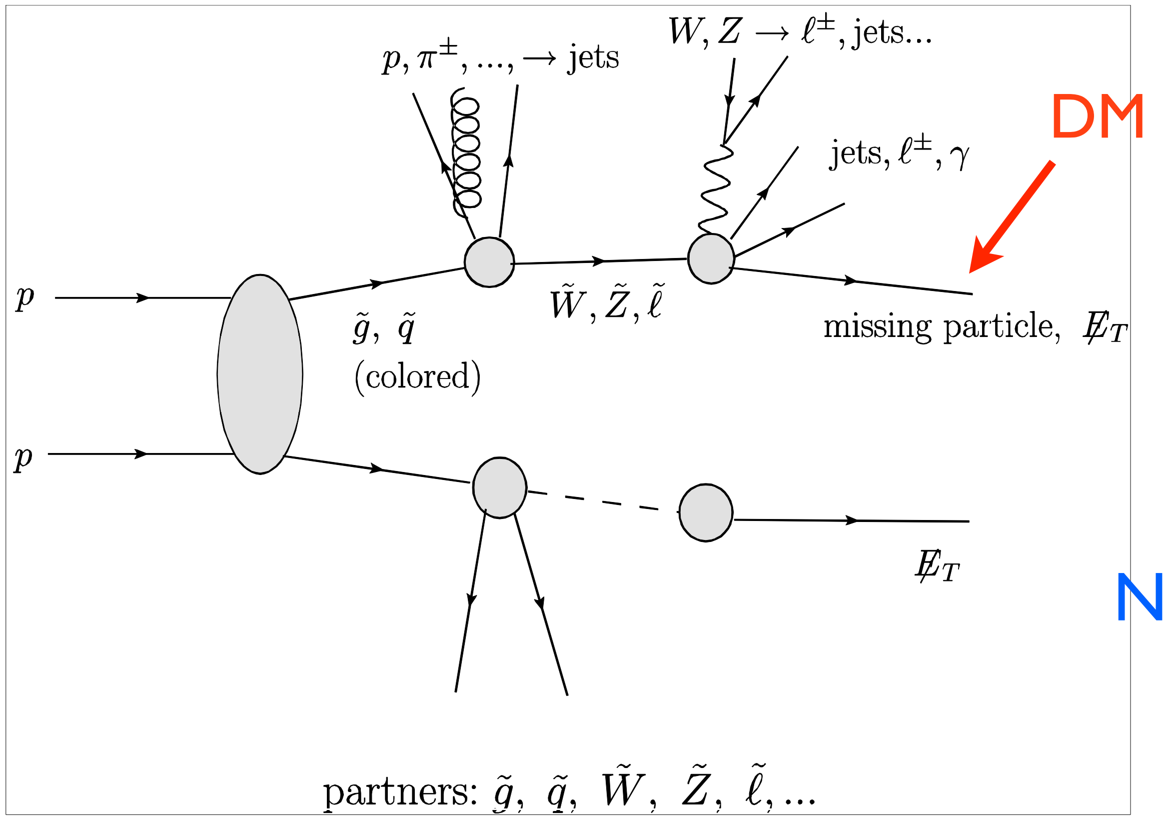
“standard” story.



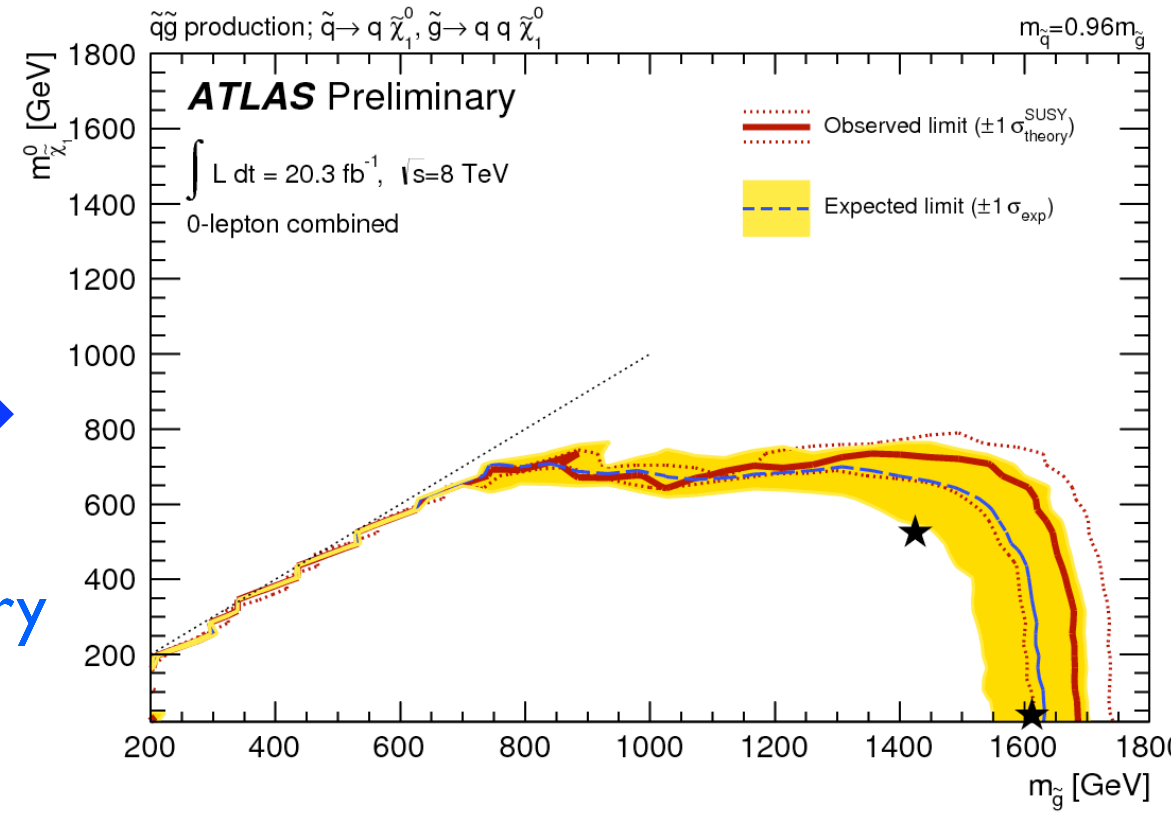
No discovery yet



“standard” story.



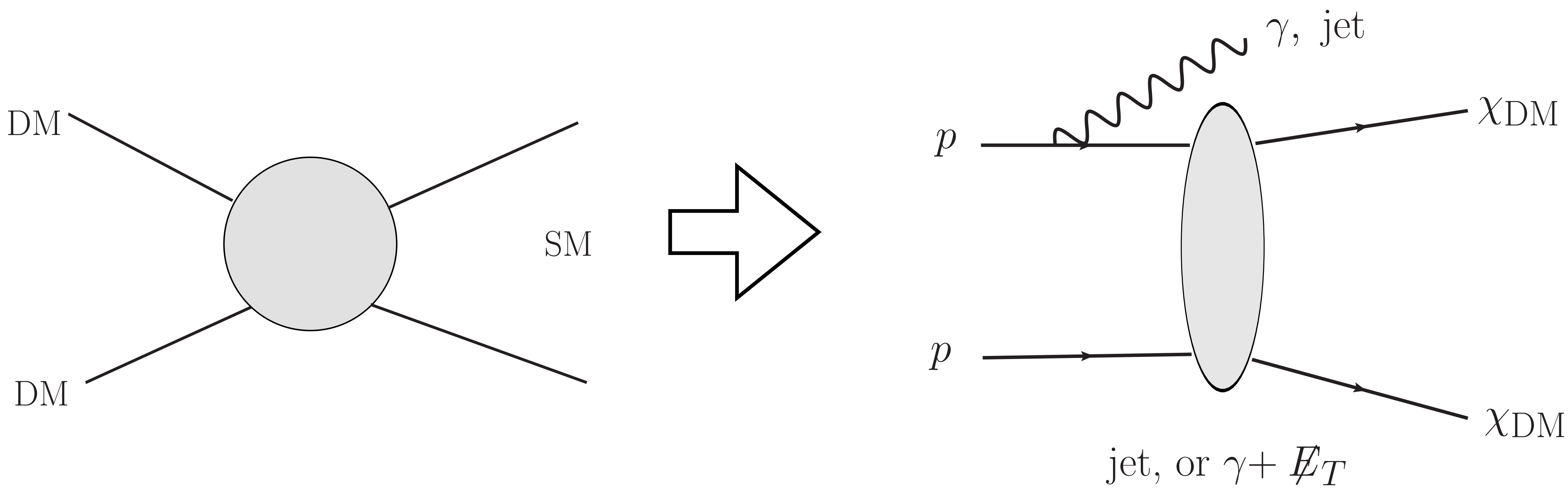
No discovery yet



Of course, most WIMP parameter space not covered yet.
Still plausible at the LHC, will keep looking.

Focus more on basic channel

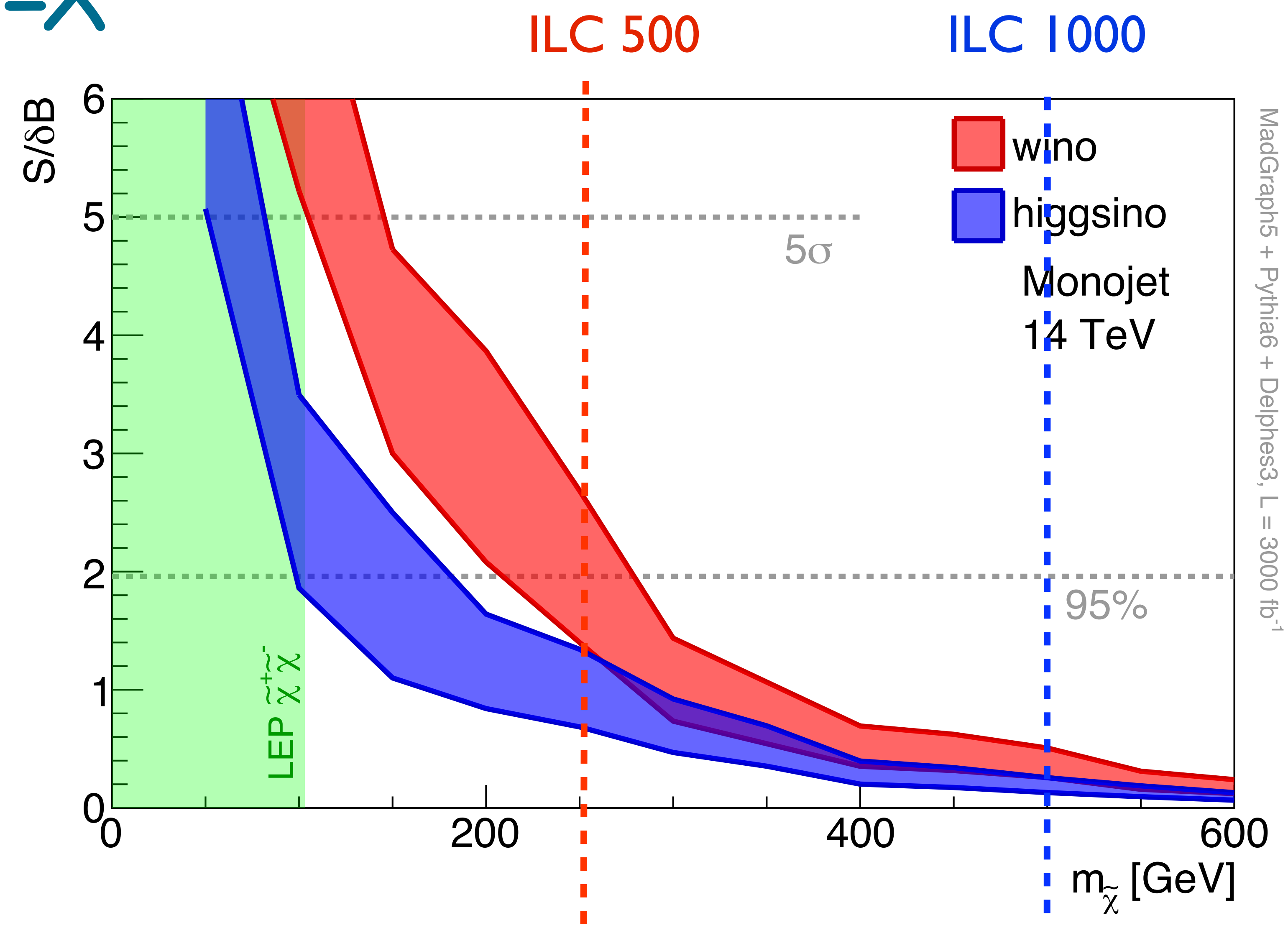
- pair production + additional radiation.



- Mono-jet, mono-photon, mono-Higgs...
- Have become "Standard" LHC searches.

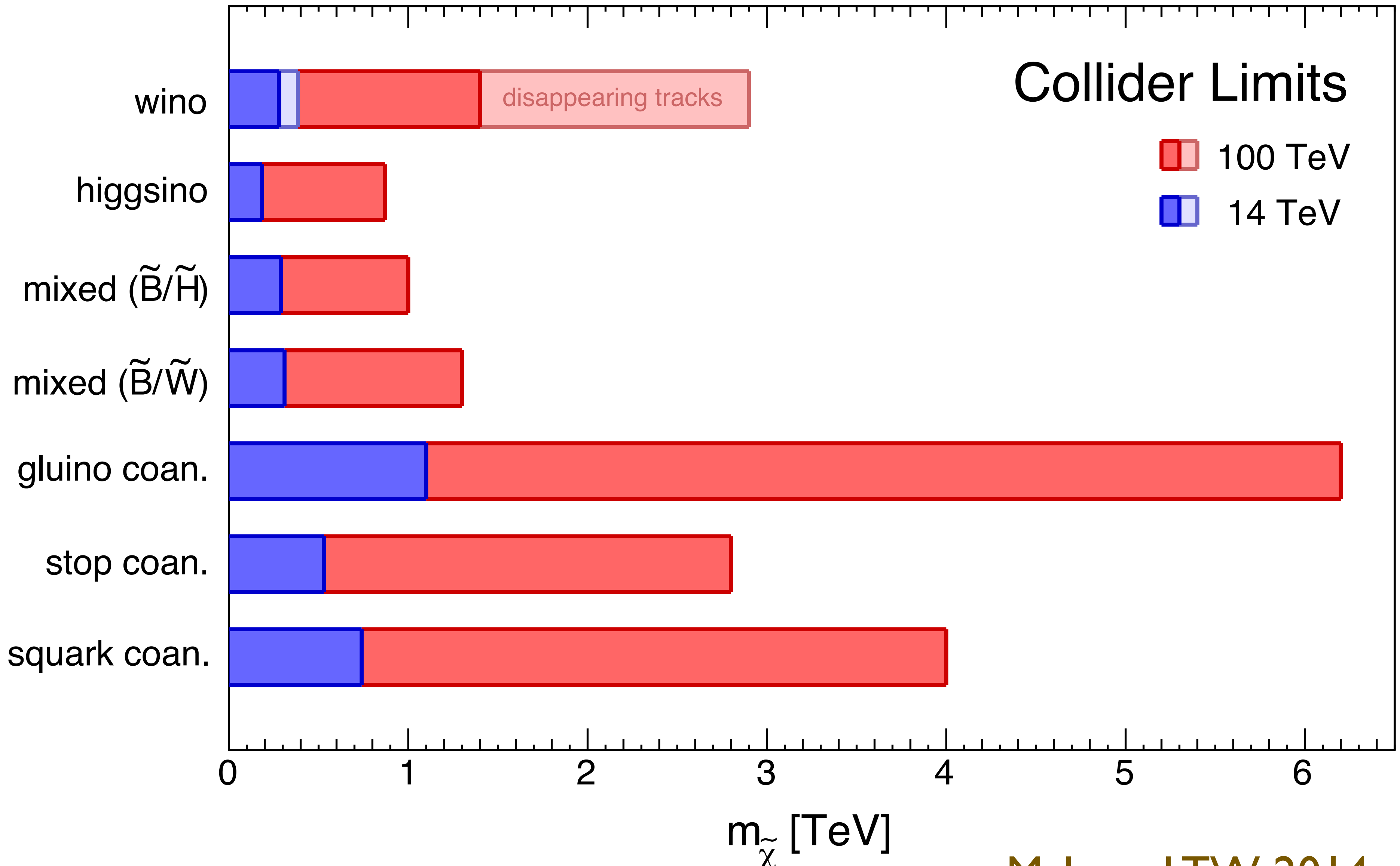
Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
Bai, Fox, Harnik, 1005.3797

Mono-X



- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Very weak discovery reach at 14 TeV, 3 ab^{-1} .
- Reach at lepton collider, about 1/2 E_{CM}.

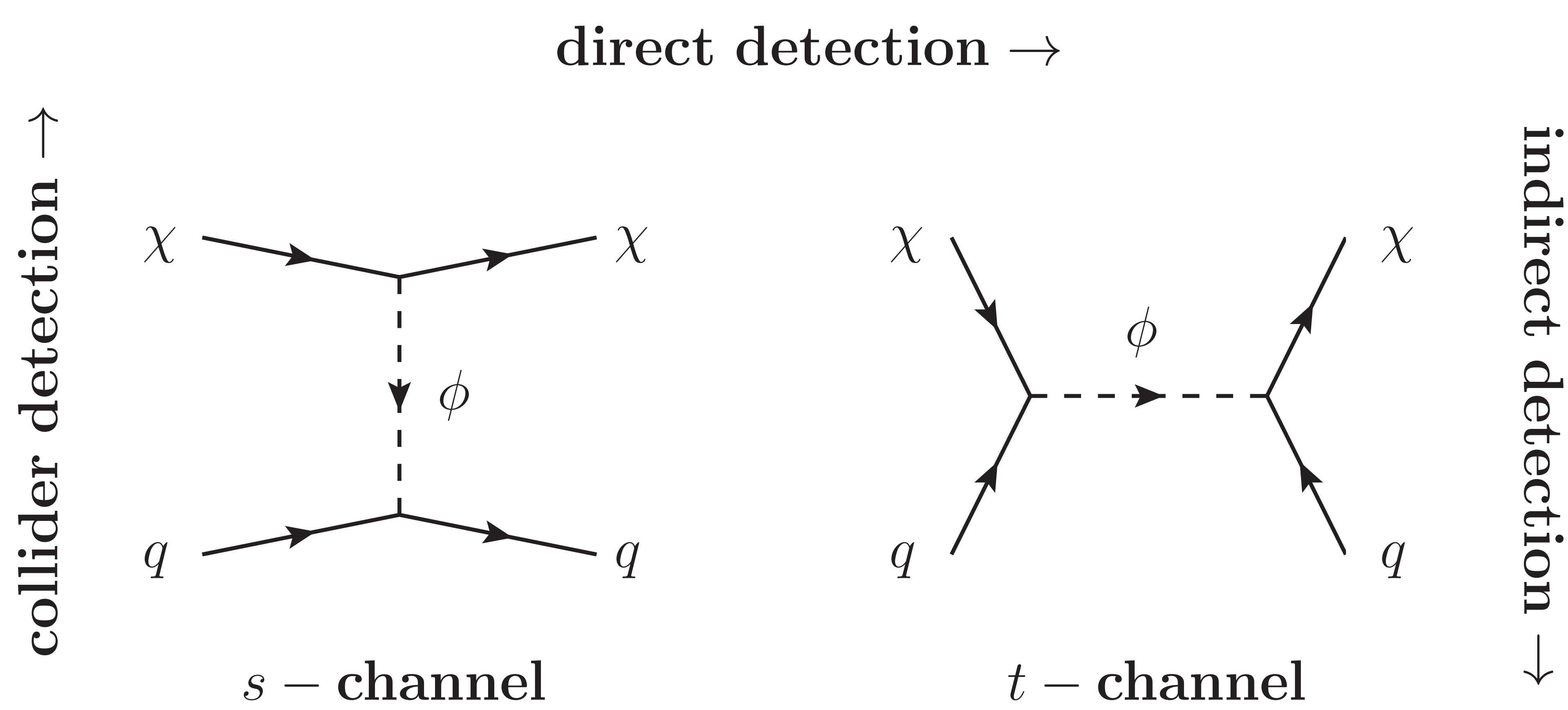
At 100 TeV pp collider



M. Low, LTW 2014

$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

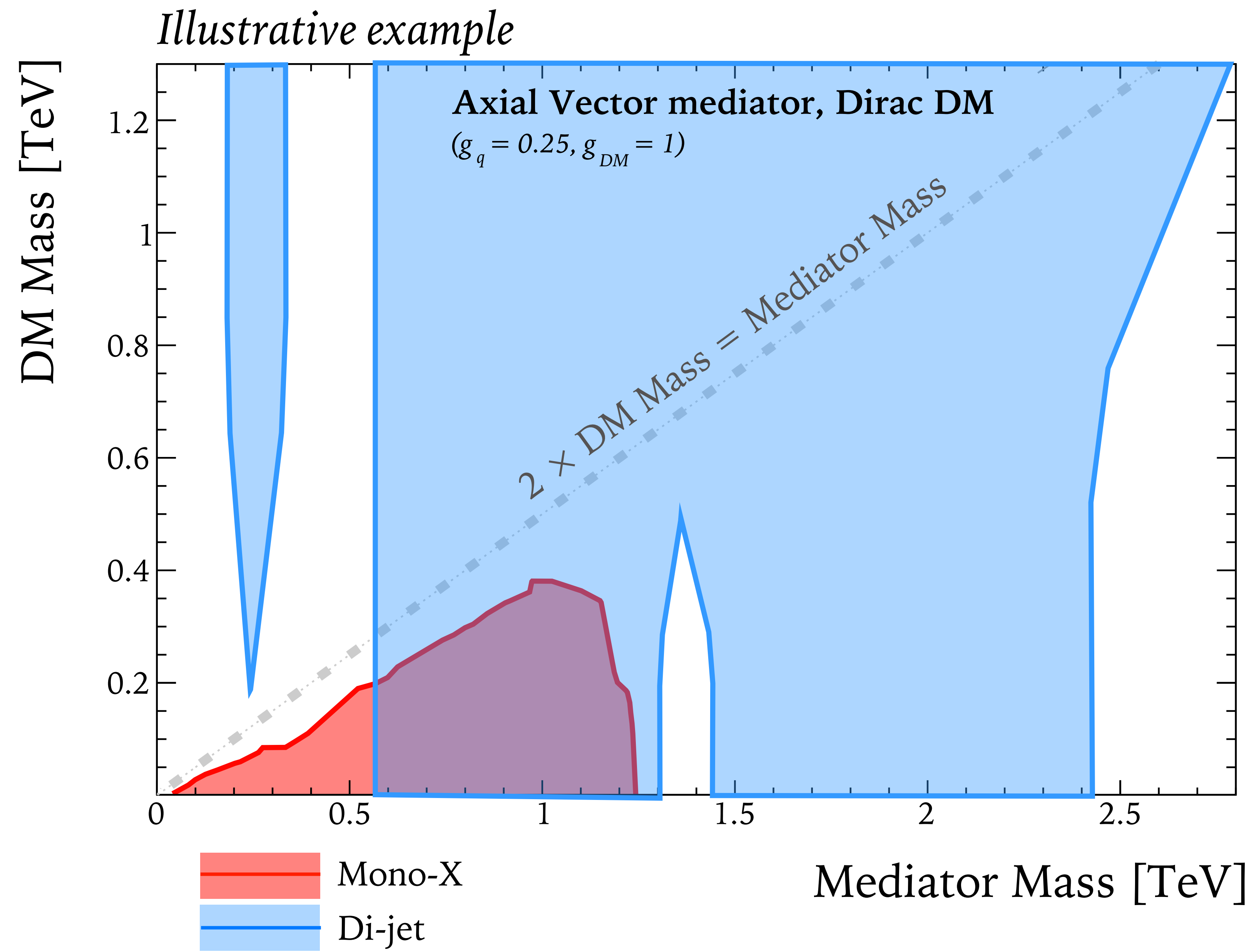
Consider new interactions of DM



scalar or Z'

squark like

MonoX vs direct search for mediator

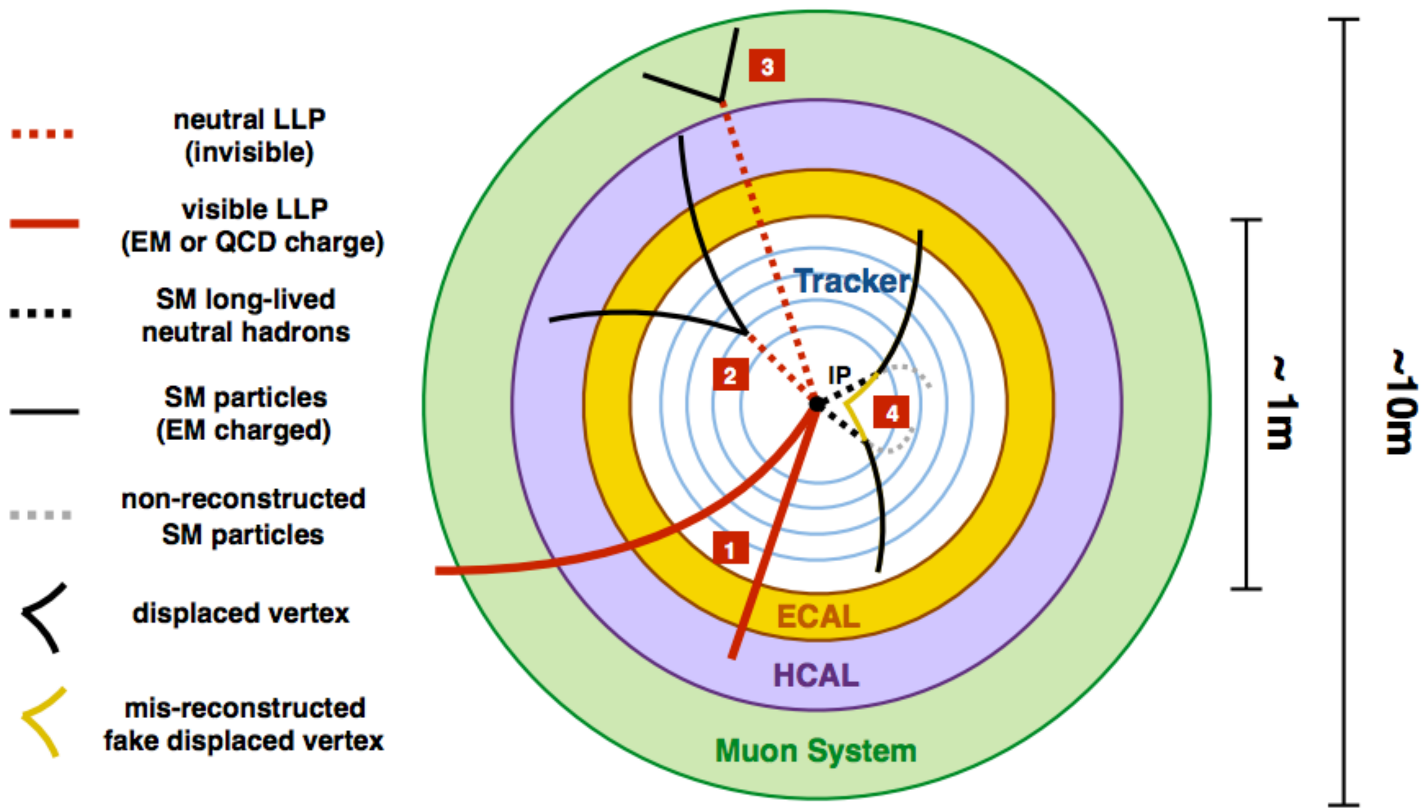


Good coverage at the LHC.

For a “to-do-list”, see dark matter forum publication: 1507.00966

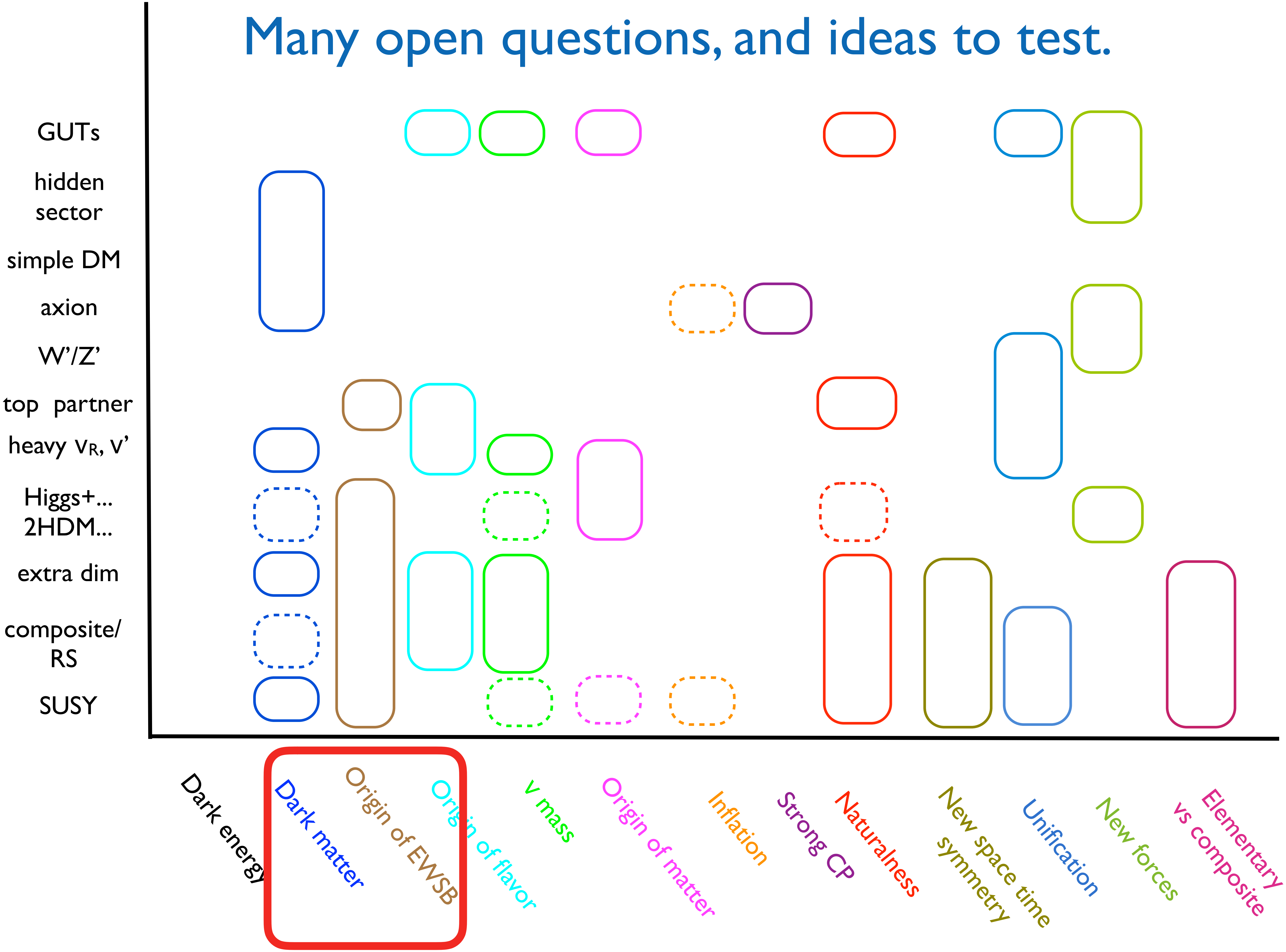
More dark-stuff searches

- Looking for dark sector. Very weakly coupled to the SM.
  - Connection with dark matter, neutrino, etc.
  - Many have not been searched for yet.
- Can come from Higgs portal, but could be more general.
- Displaced-Long lived, soft, kink, ...



Curtin and Sundrum

Many open questions, and ideas to test.

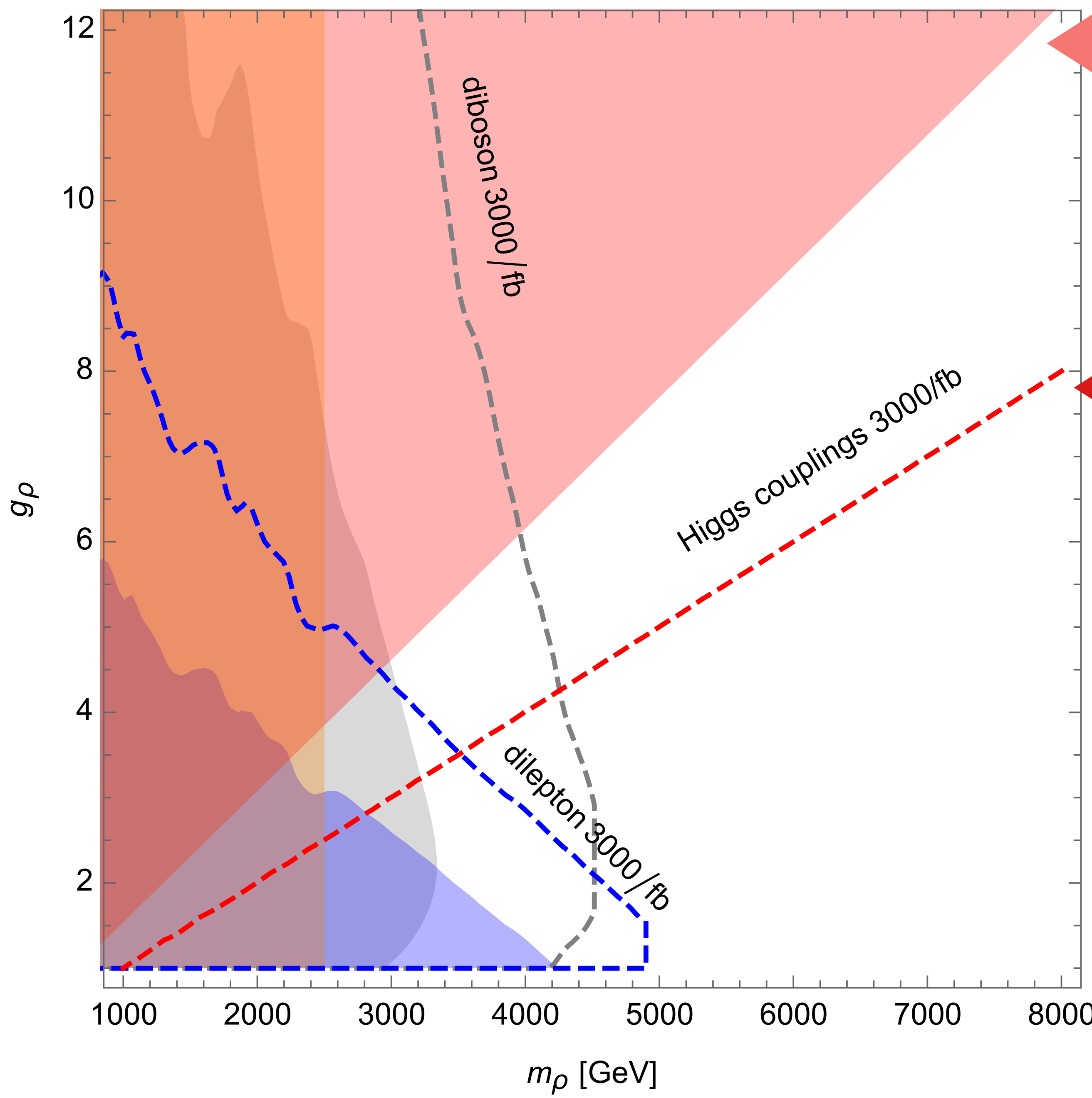


Looking towards the future.

- Uncertain for sure.
- But, we are not completely in the dark.
  - We have challenges. We have interesting questions
  - Electroweak symmetry breaking, dark matter, and much more.
- LHC and beyond, we will keep searching for answers.

A lot to look forward to!

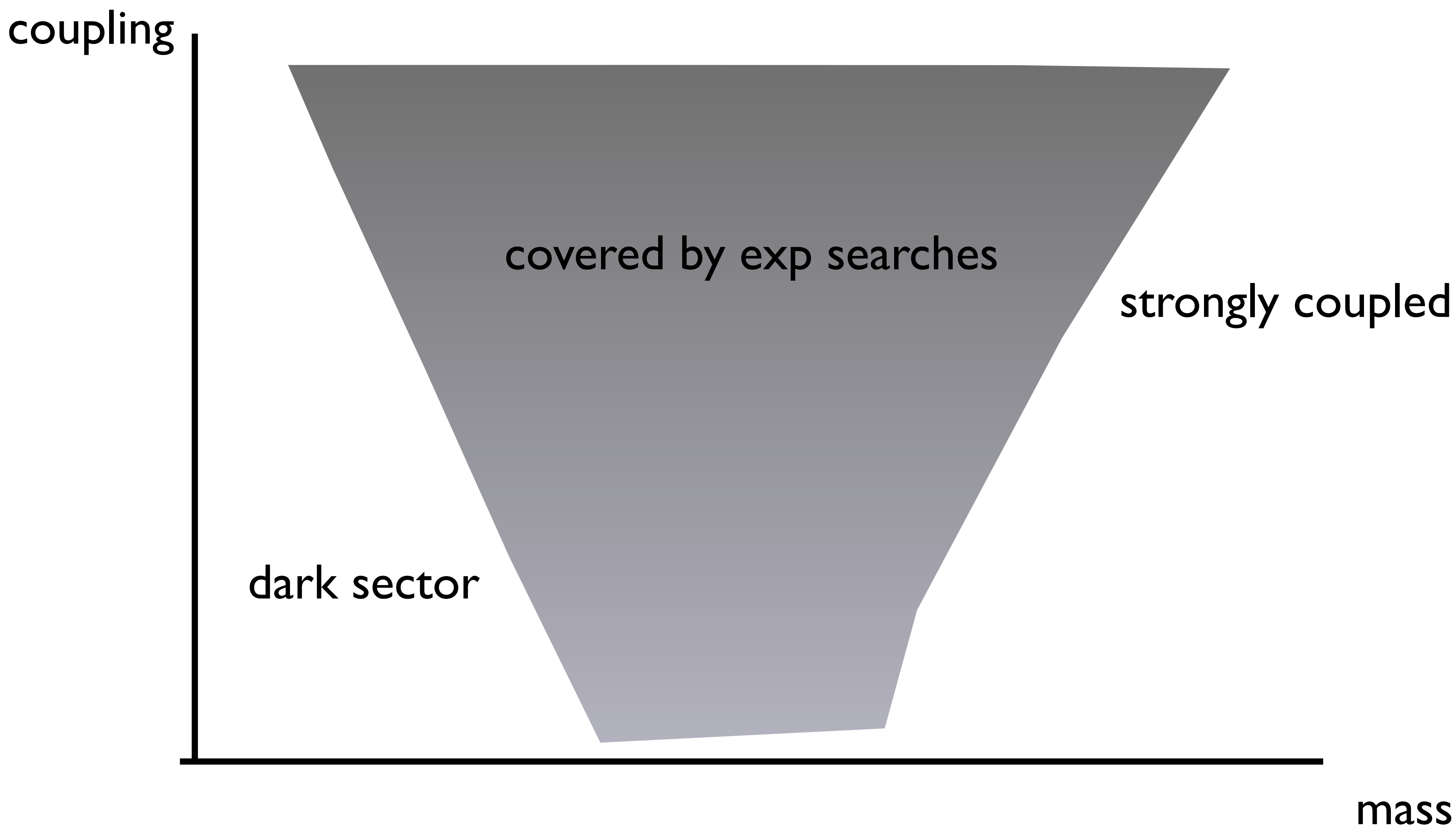
Higgs coupling vs direct search



Excluded by current Higgs Coupling measurements

Reach of HL-LHC

Generic searches, pushing boundary

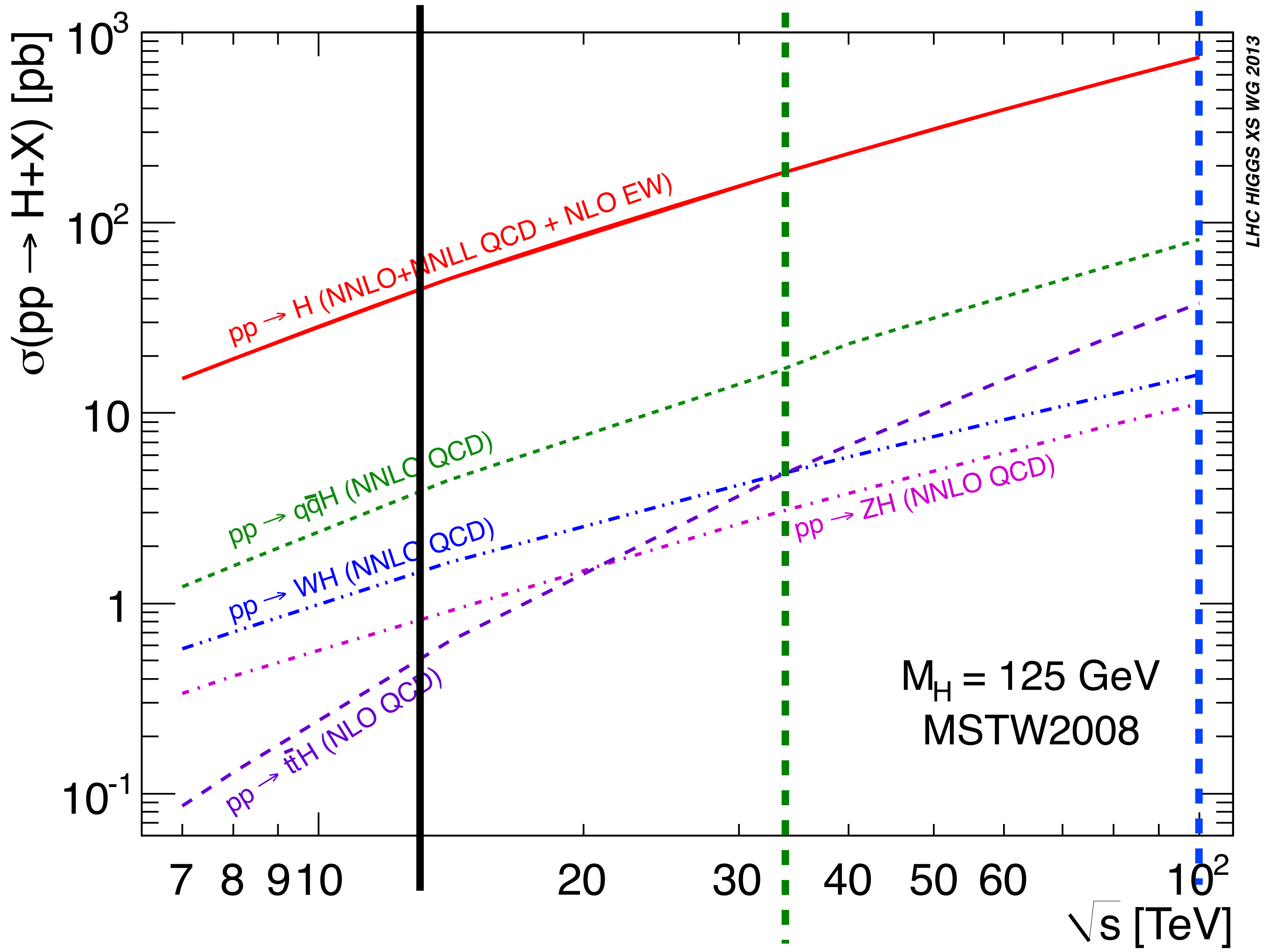


A lot of models motivating these searches may look like solutions waiting for a problem.

But, we should cast a wide net for unexpected.

Higgs rare decay at hadron collider

- The "ultimate" Higgs factories



# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

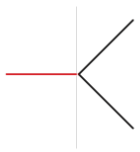
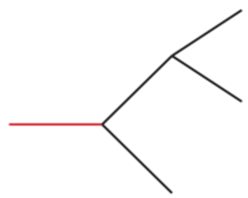
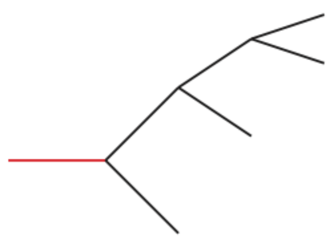
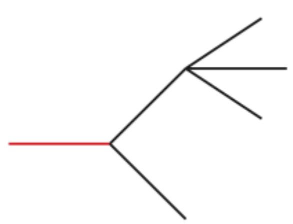
33 TeV > 500 million

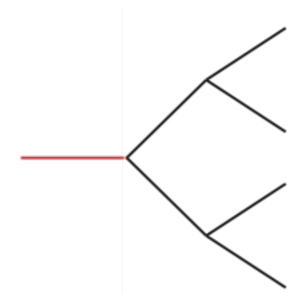
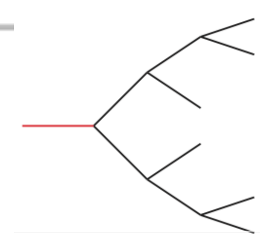
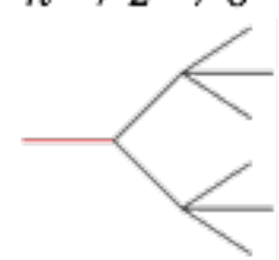
14 TeV > 150 million

In comparison, O(million) Higgs at ee Higgs factories

Hadron collider good for rare but clean signal

Some possible channels

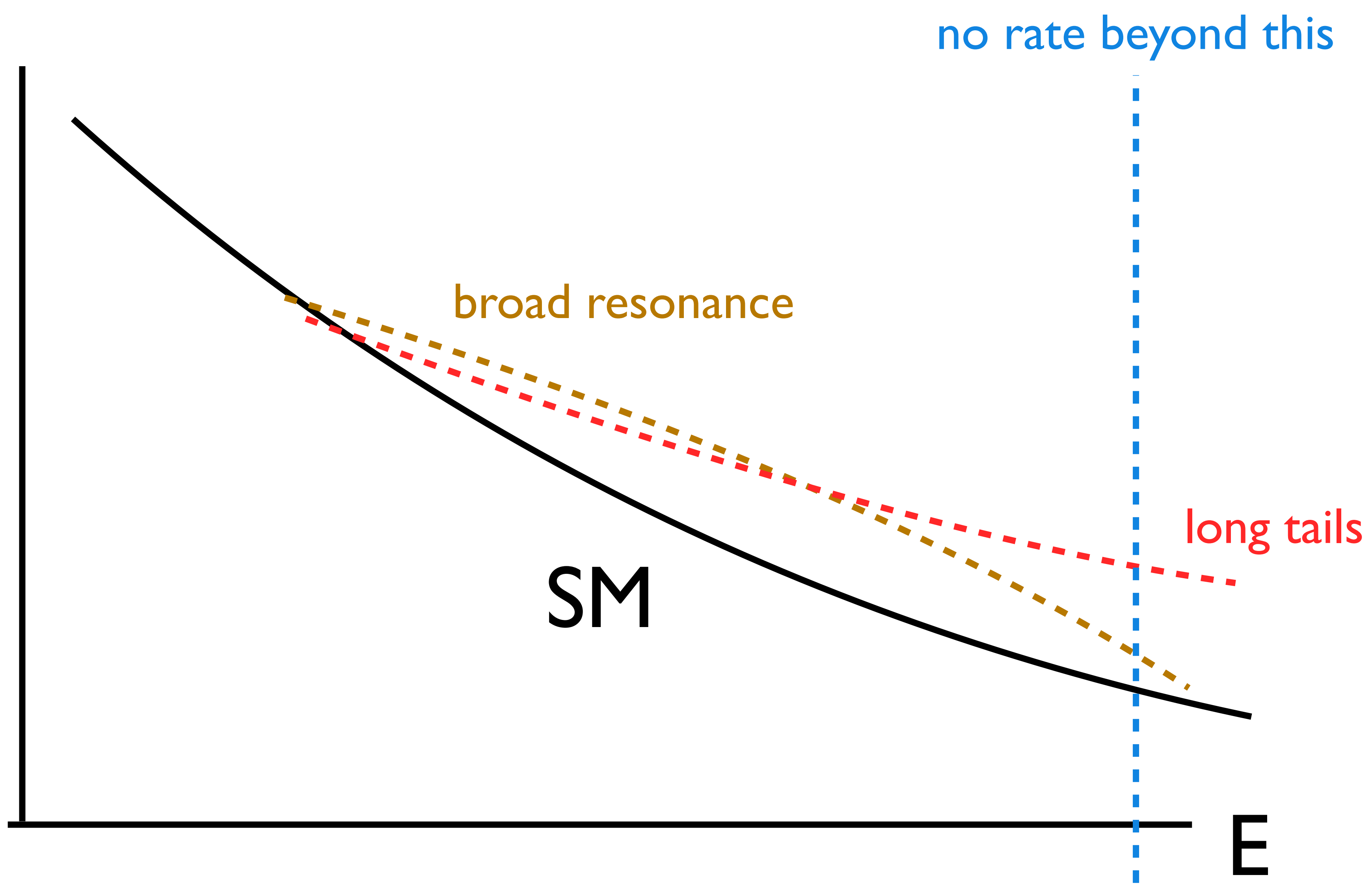
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_{\mathrm{T}}$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_{\mathrm{T}}$
	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
	$h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$
	$h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
	$h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$
	$h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
	$h \to (\mu^+\mu^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_{\mathrm{T}}$
	$h \to jj + \not{E}_{\mathrm{T}}$
	$h \to \tau^+\tau^- + \not{E}_{\mathrm{T}}$
	$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
	$h \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
$h \to 2 \to 4 \to 6$ 	$\boxed{h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\mathrm{T}}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}} + X$
$h \to 2 \to 6$ 	$\boxed{h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\mathrm{T}}}$
	$h \to \ell^+\ell^- + \not{E}_{\mathrm{T}} + X$

adapted from slides of Zhen Liu

Good sensitivity from the LHC

Examples



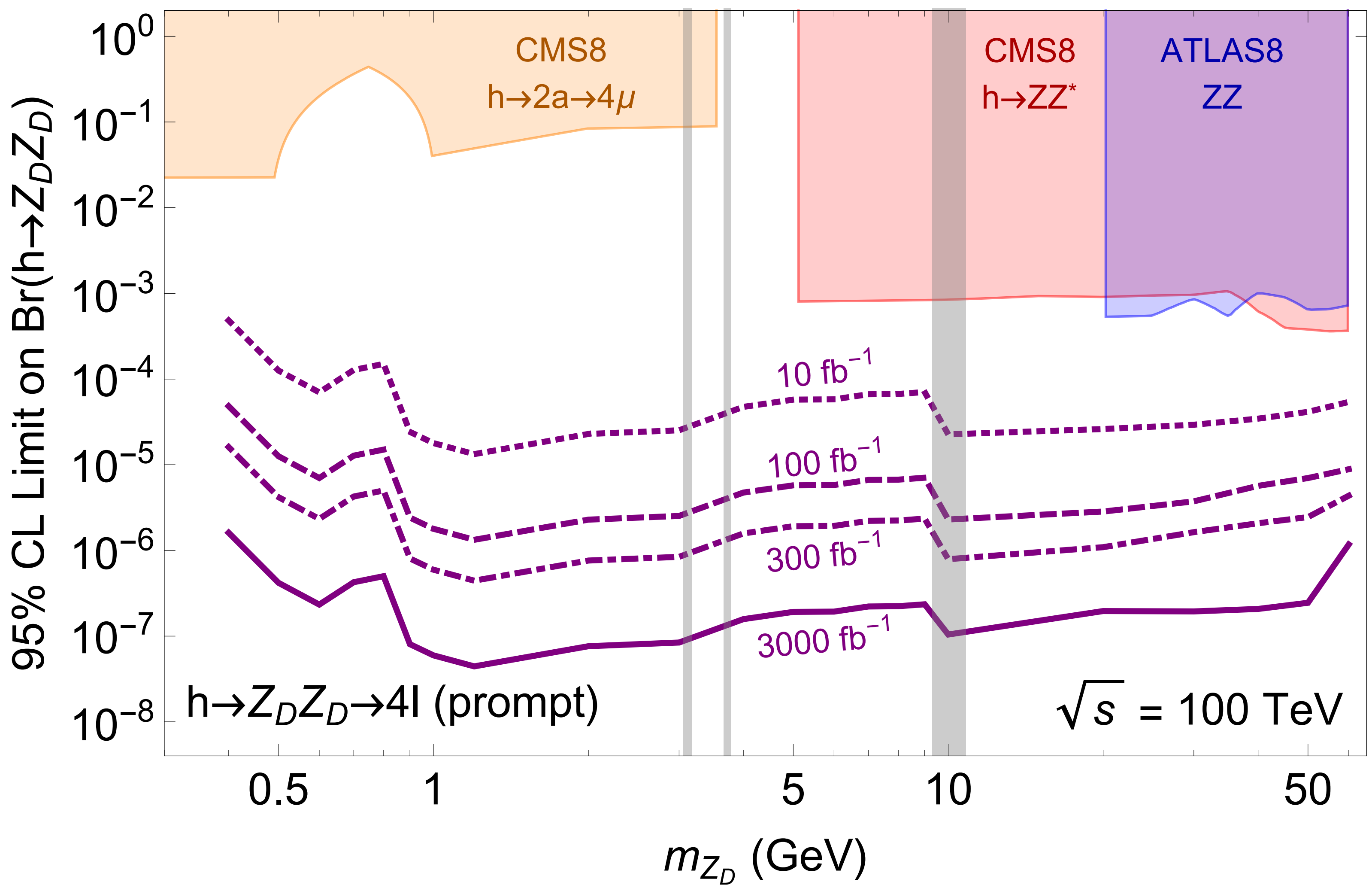
- Final states can be di-boson, ttbar, etc.
- Can be closely related to electroweak symmetry breaking

In addition to high energy colliders

- High intensity beams
- Observation of early universe
- Table top experiments
- ...
- Should think of even more possible probes.
- Here, I will focus on colliders and the questions they can directly address.

New physics Higgs rare decays

dark photon



Curtin, Gori, Shelton

More examples. Such as possible connection with naturalness mentioned earlier

Understanding the Higgs better