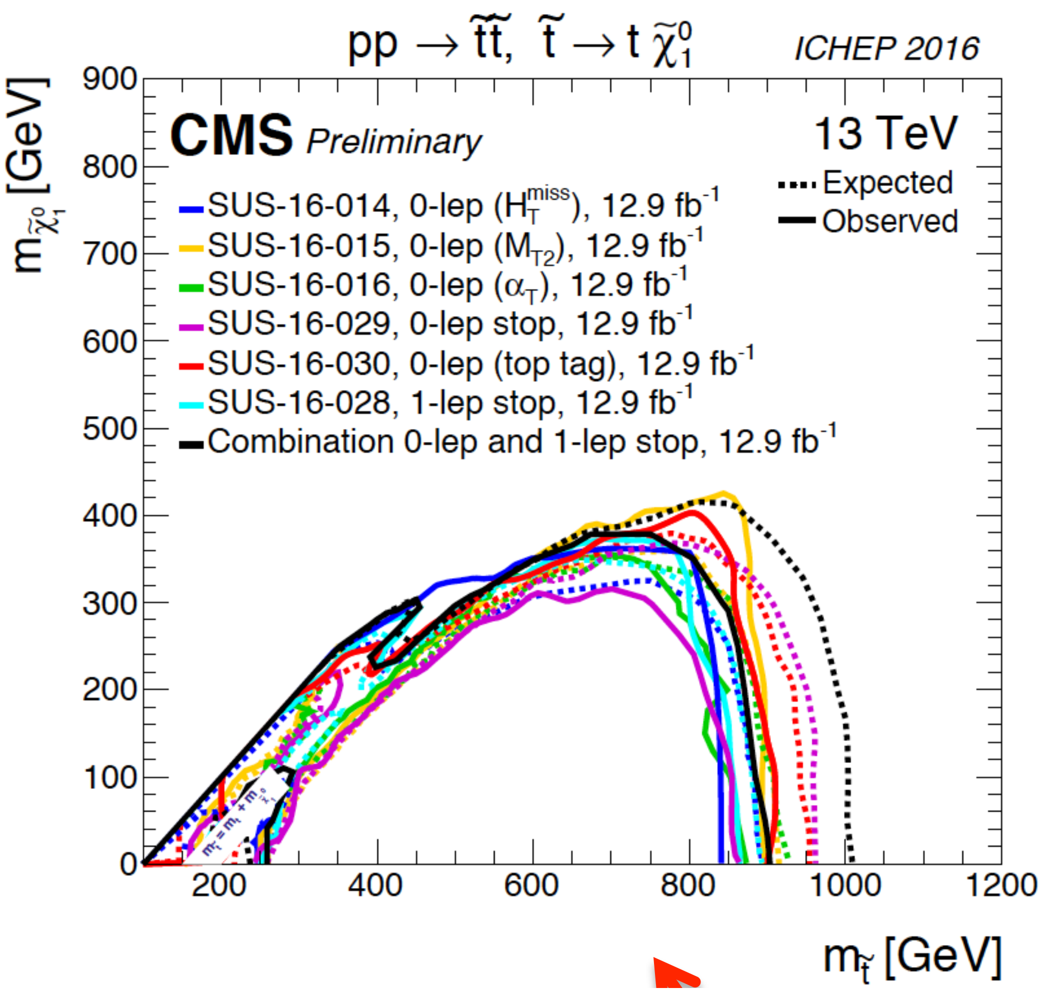
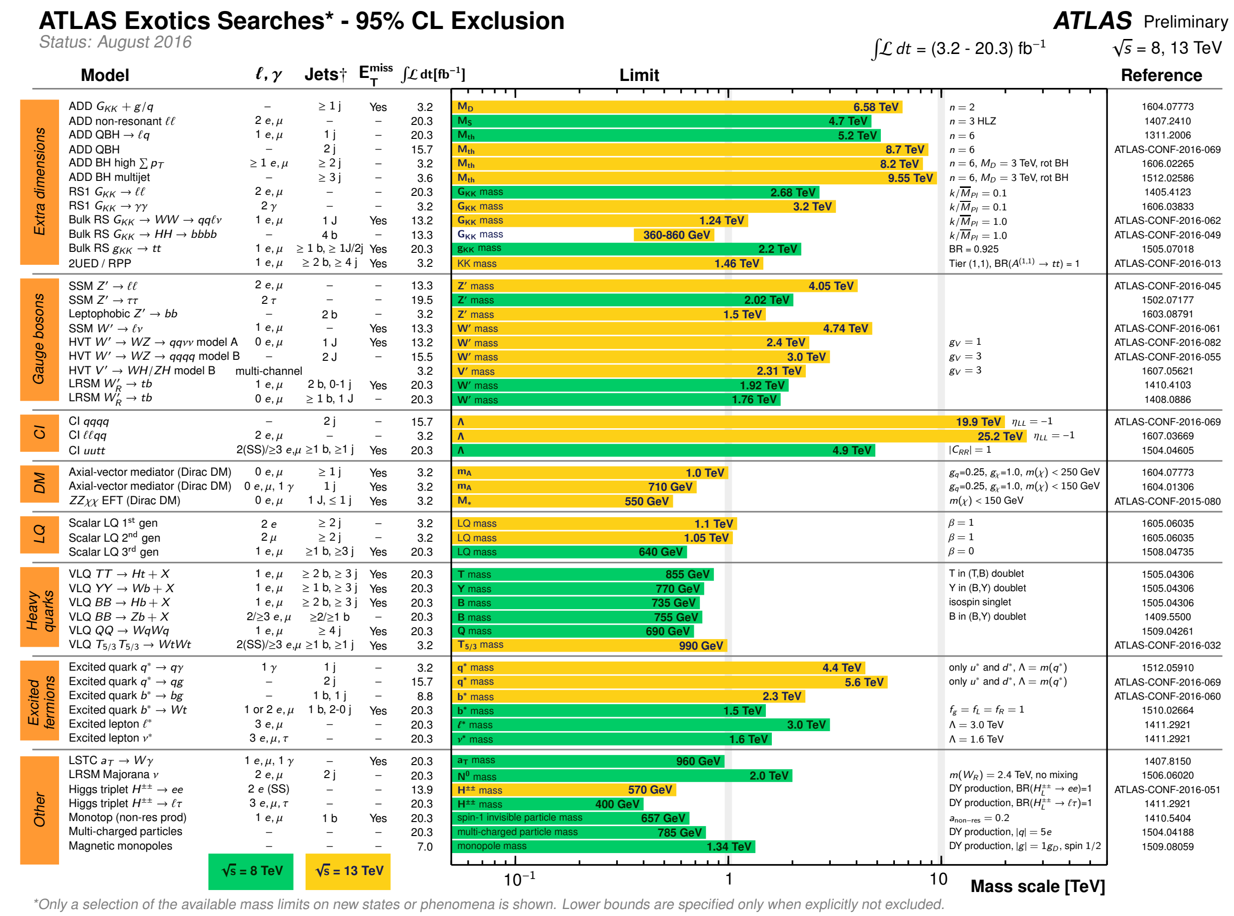
Prospect of LHC searches

LianTao Wang
University of Chicago

CLHCP, Dec 19, 2016

Present



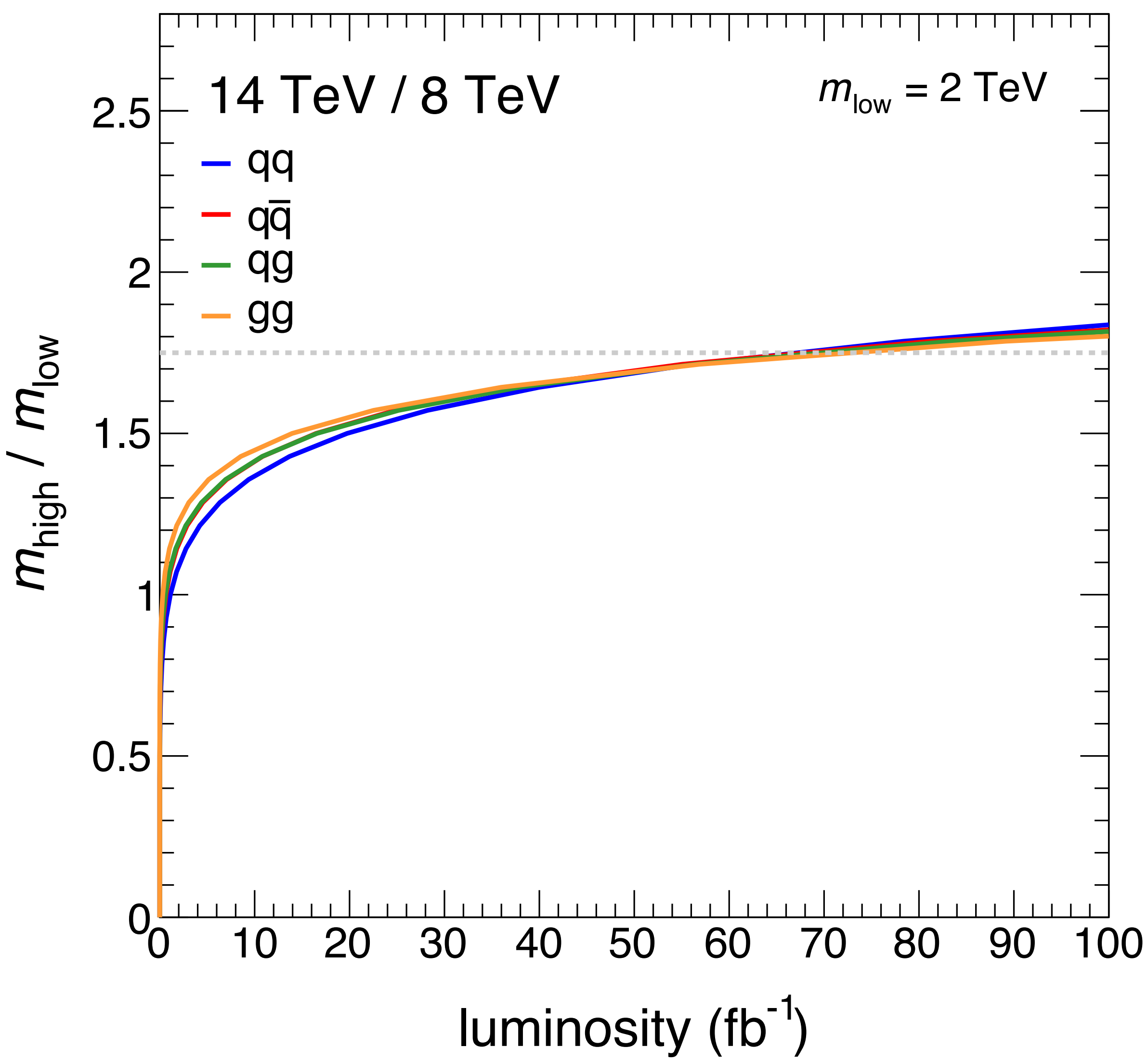


– No "early" discovery.

– Disappointed? Yes. Surprised? Not much.

As data accumulates

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



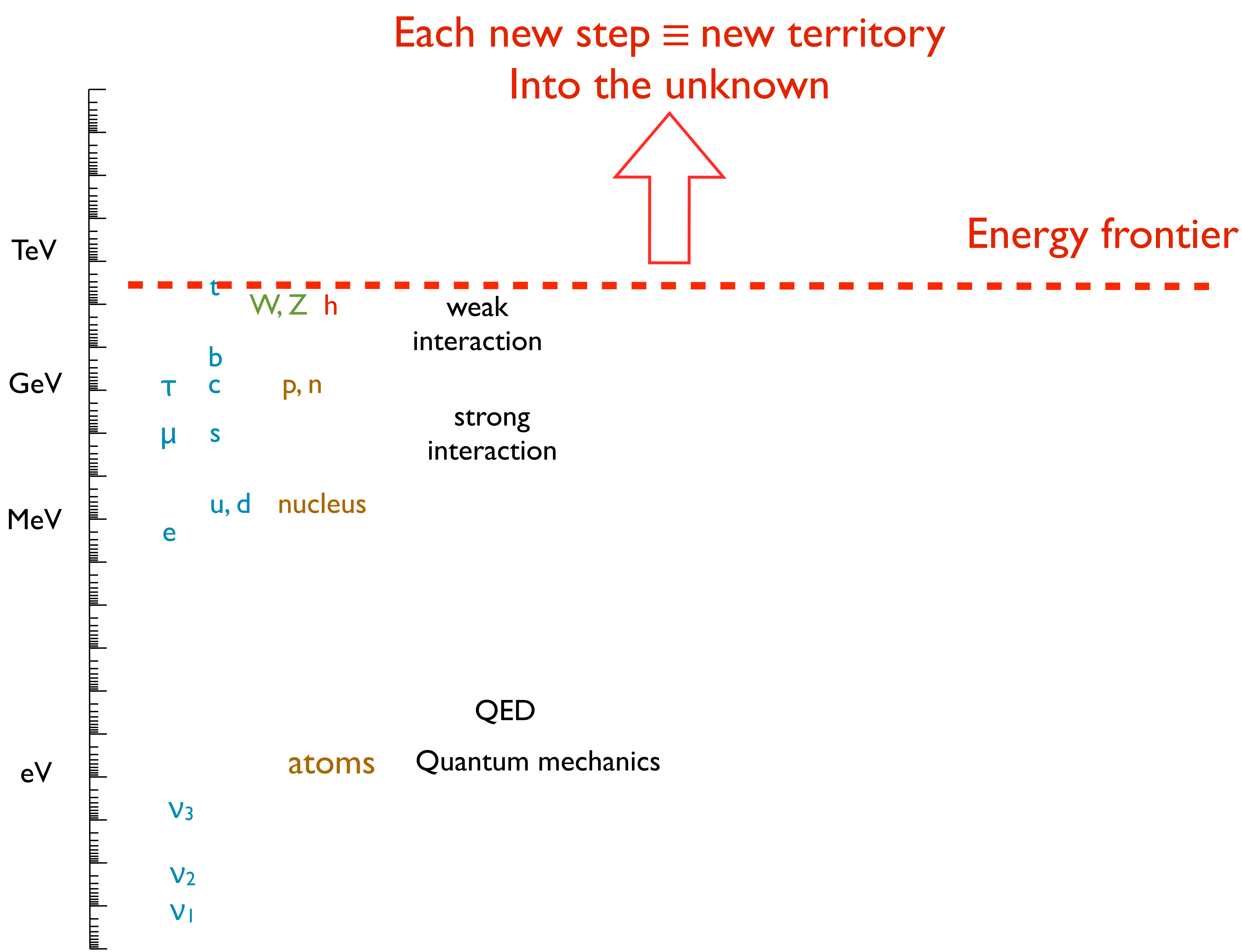
Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

Reaching the "slow" phase after Moriond 2017

Road ahead:

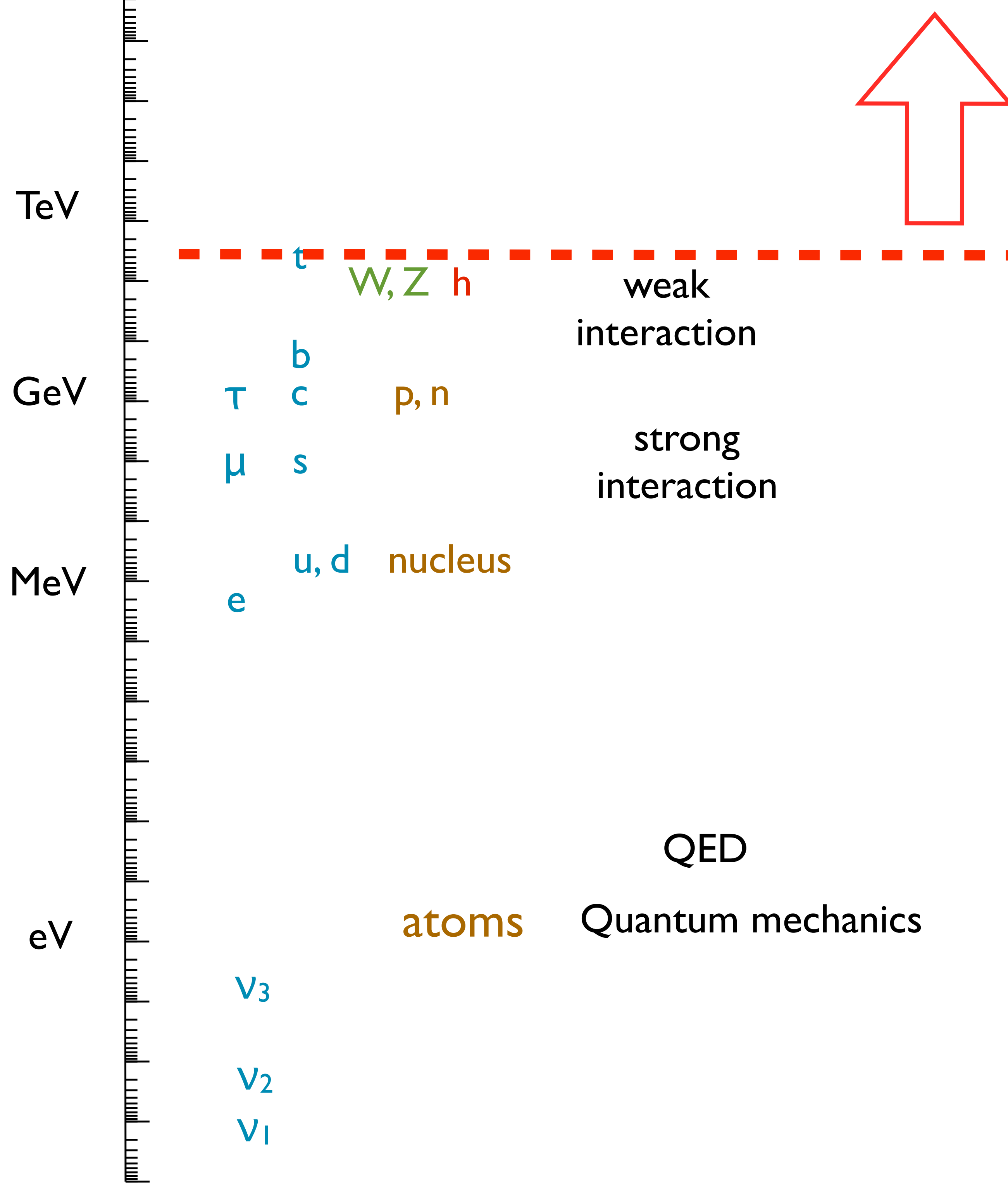
Difficult? Yes.

Prepare to stop? Absolutely not!



Each new step ≡ new territory
Into the unknown
Energy frontier
TeV
GeV
MeV
eV
t
W, Z
h
weak
interaction
b
τ
c
p, n
μ
s
strong
interaction
u, d
nucleus
e
QED
atoms
Quantum mechanics
ν3
ν2
ν1

Each new step ≡ new territory
Into the unknown



Energy frontier

SM “complete”.

We don’t know what’s ahead.

Confusion is normal and expected

Essential to make the next step!

SM has big mysteries.

- Mechanism of electroweak symmetry breaking.
- Dark matter.
- Matter anti-matter asymmetry in the universe
- Flavor....
- We must keep looking!
    - At the LHC and beyond.

What are we looking for?

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- We want to search for clues to solve the big mysteries of the SM. None has been answered yet.

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- Our wish list has not changed much from 10 years ago.
  - All the papers we have written before 2009 (except technicolor). Keep looking for them!

What are we looking for?

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- Our wish list has not changed much from 10 years ago.
  - All the papers we have written before 2009 (except technicolor). Keep looking for them!
- At the same time, new physics may show up in unexpected places.

Where is new physics

Where is new physics

- We often ask (for the last 20 years): is X dead (X≈SUSY)?

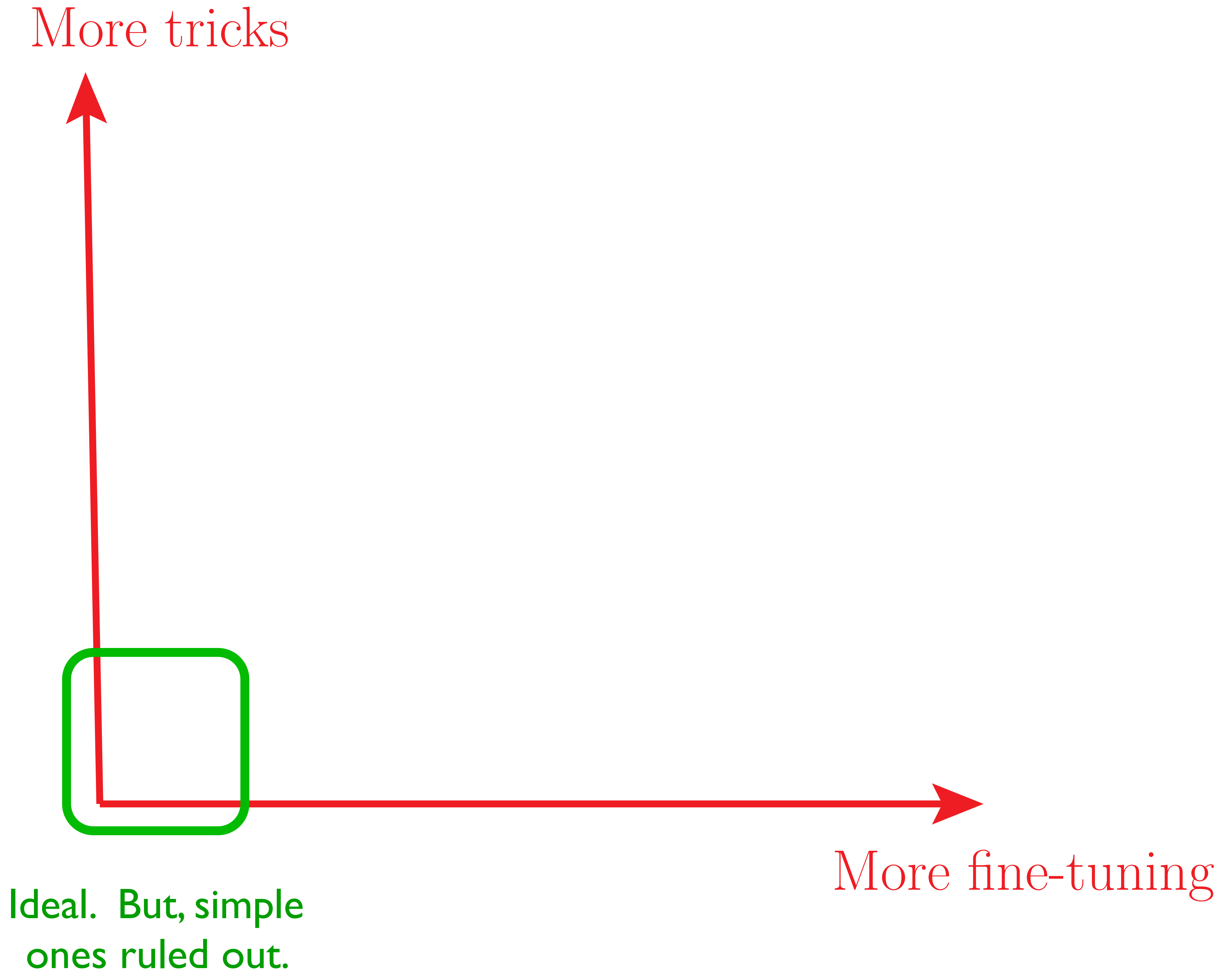
Where is new physics

- We often ask (for the last 20 years): is X dead ($X \approx$SUSY)?

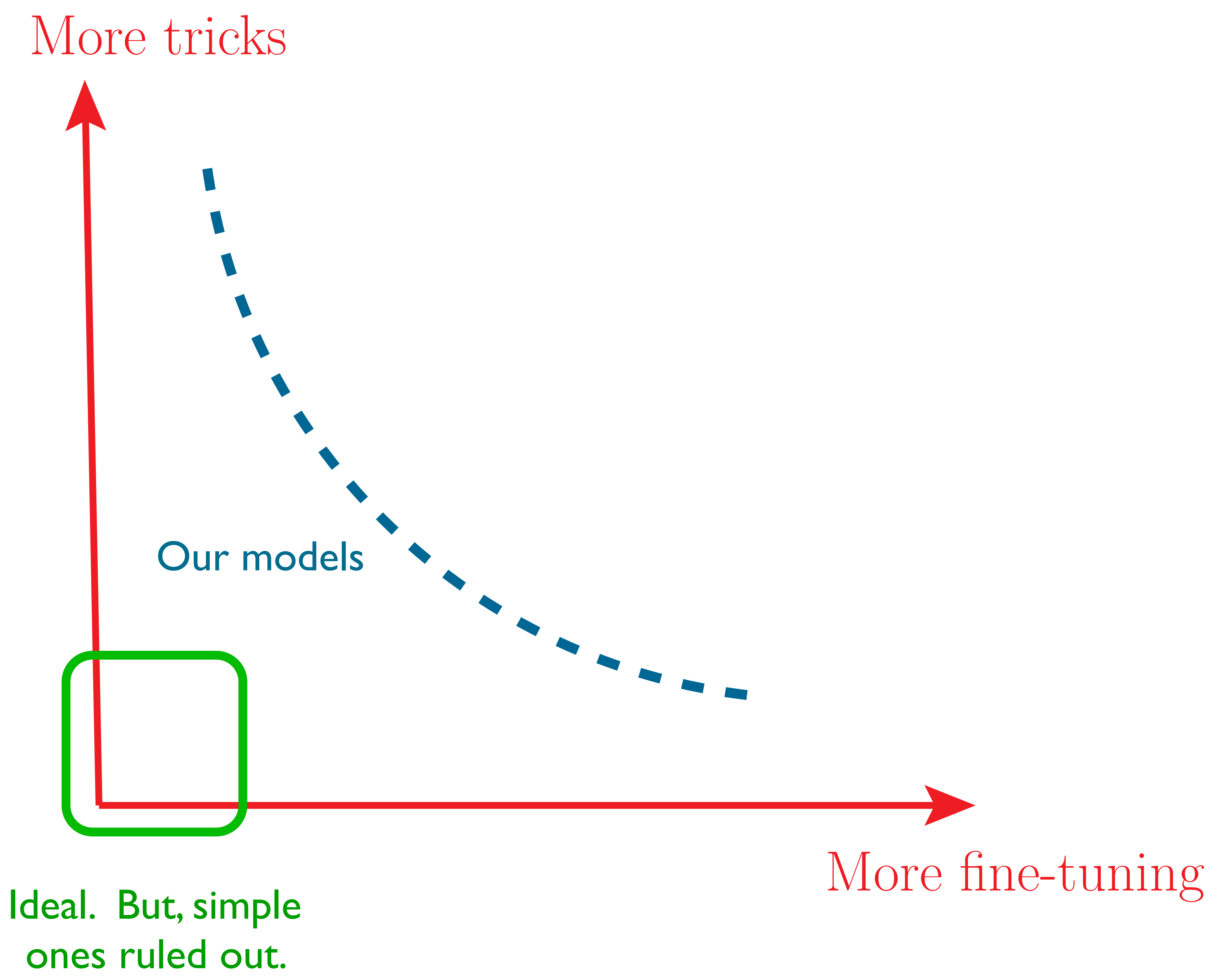
- The answer is of course: no.

  New physics will never die, they just get heavier.

Where we are in theory space



Where we are in theory space



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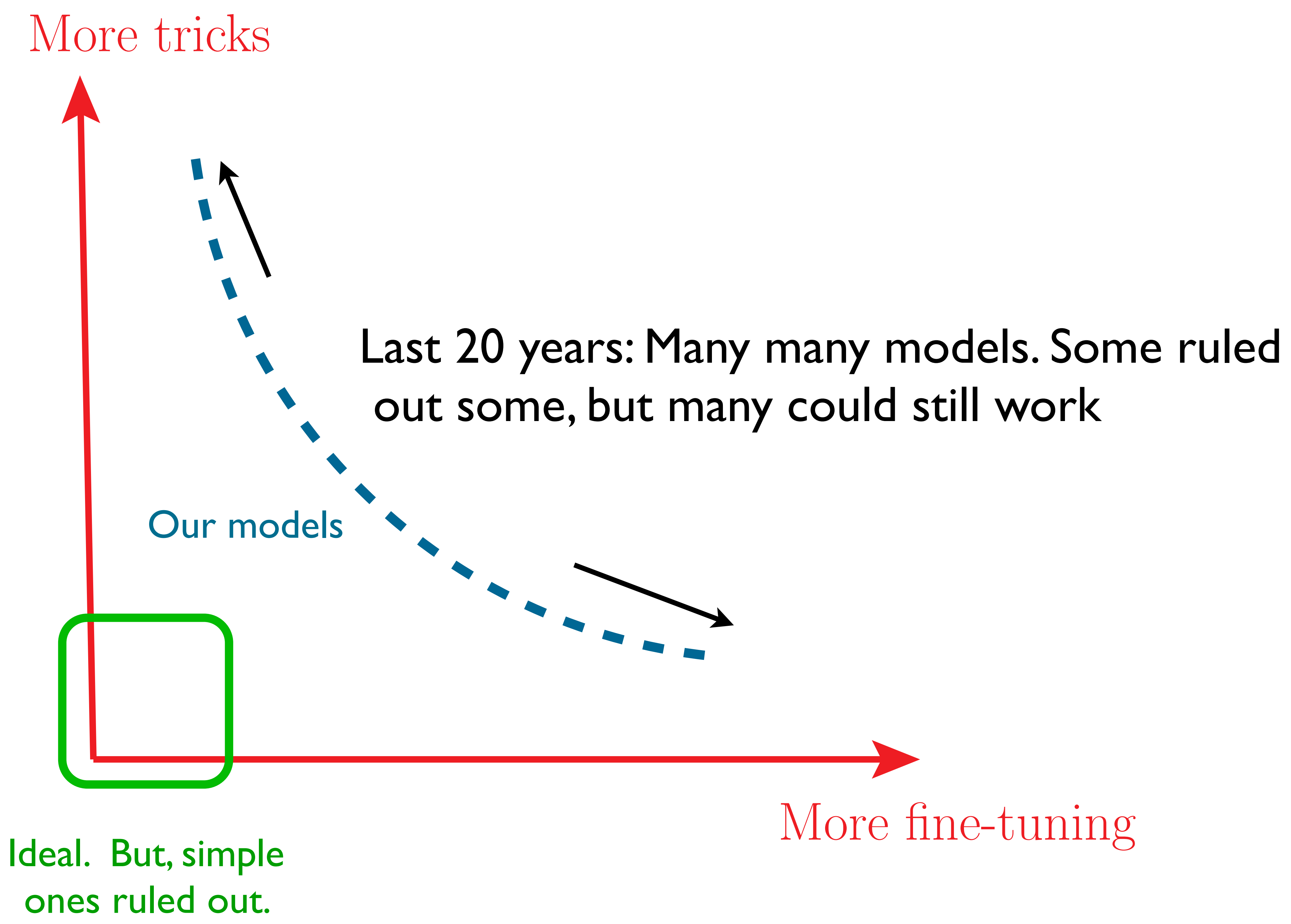
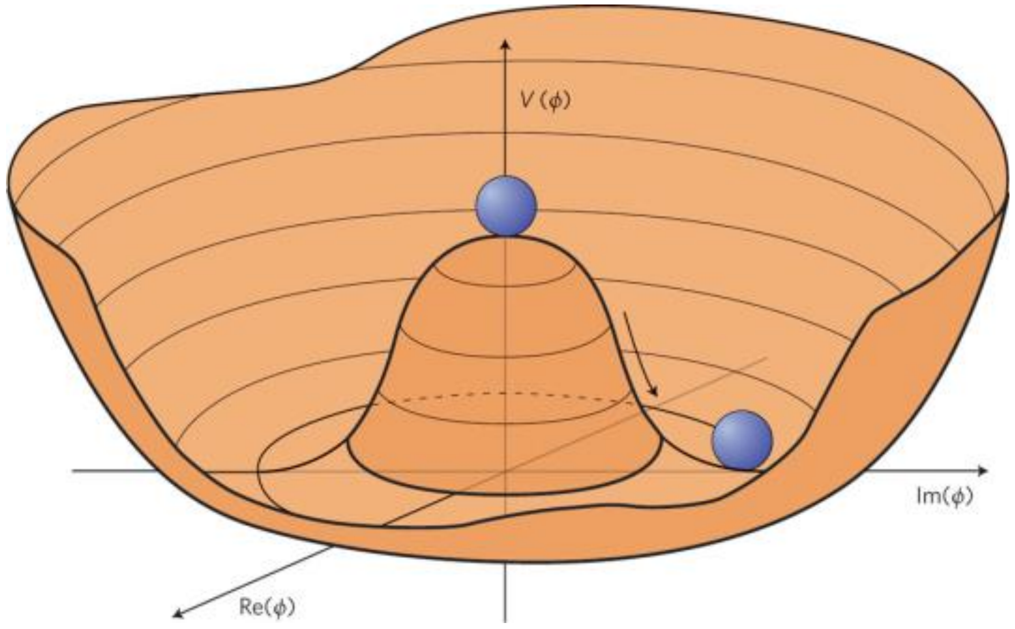


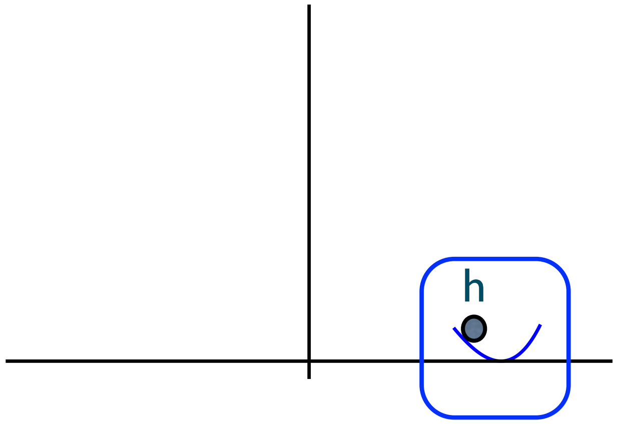
Main targets

1. Higgs and Naturalness

Mysteries of the Higgs boson



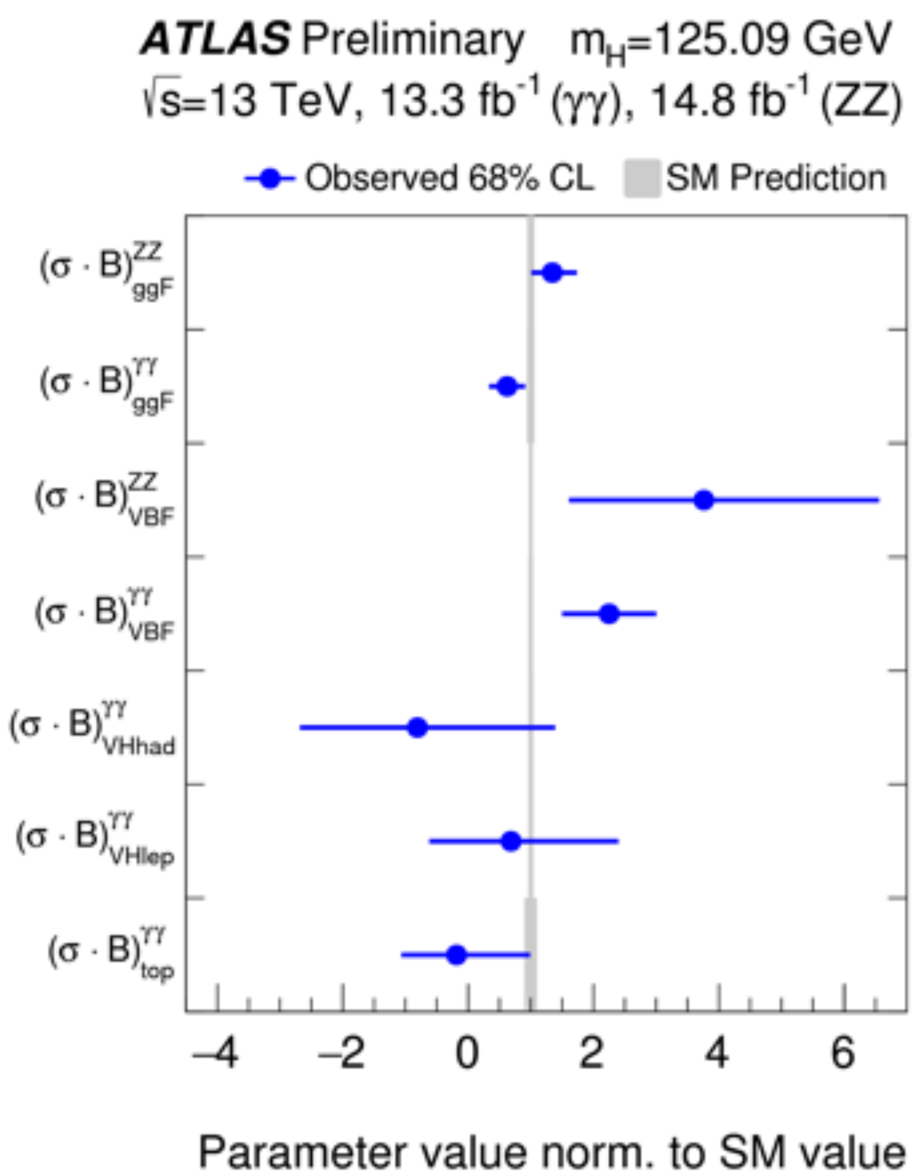
Mysteries of the Higgs boson

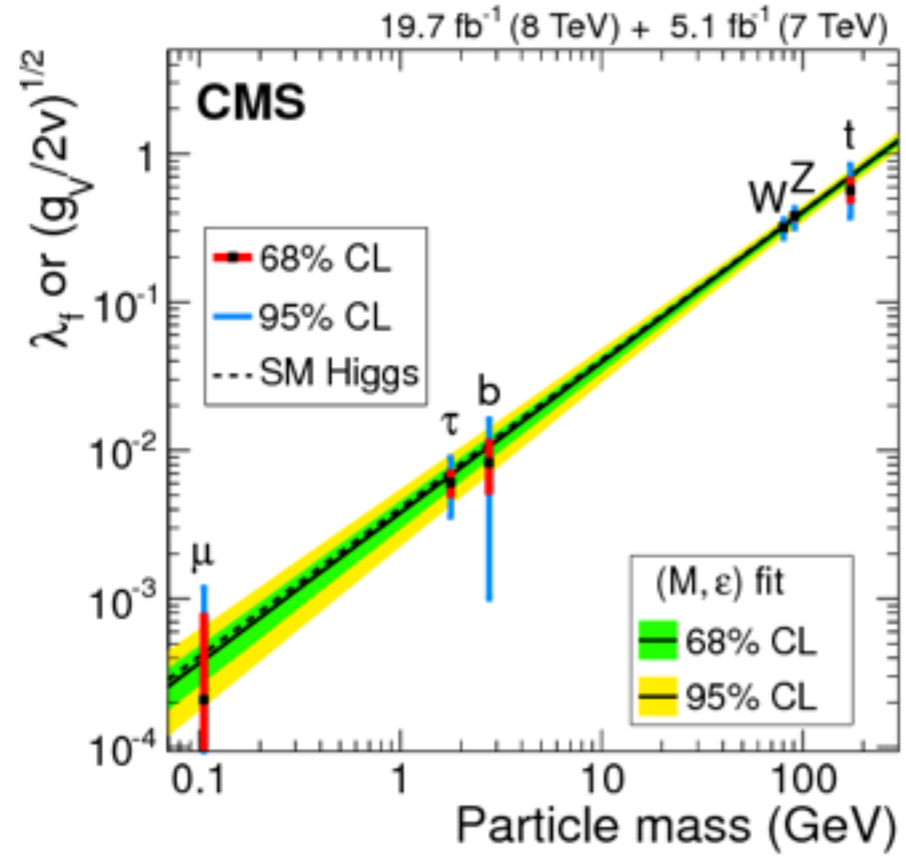


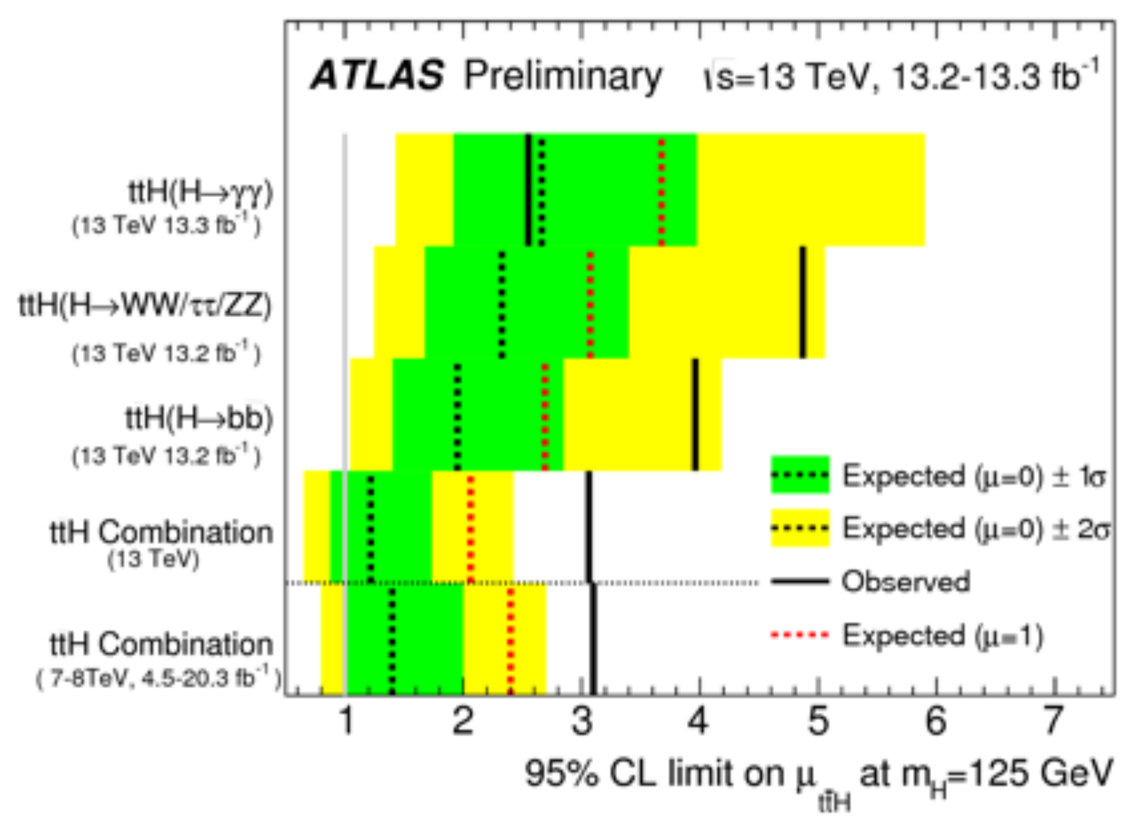
What we know now

- How to predict/calculate Higgs mass?
- What does the rest of the Higgs potential look like?
- Is it connected to the matter anti-matter asymmetry?

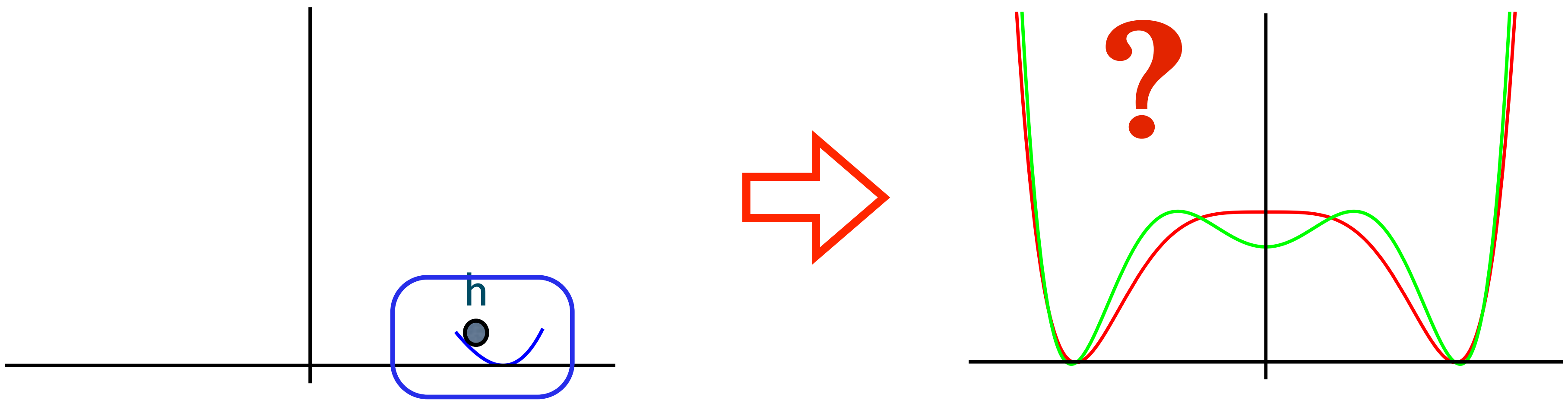
Understanding the Higgs better







Nature of EW phase transition



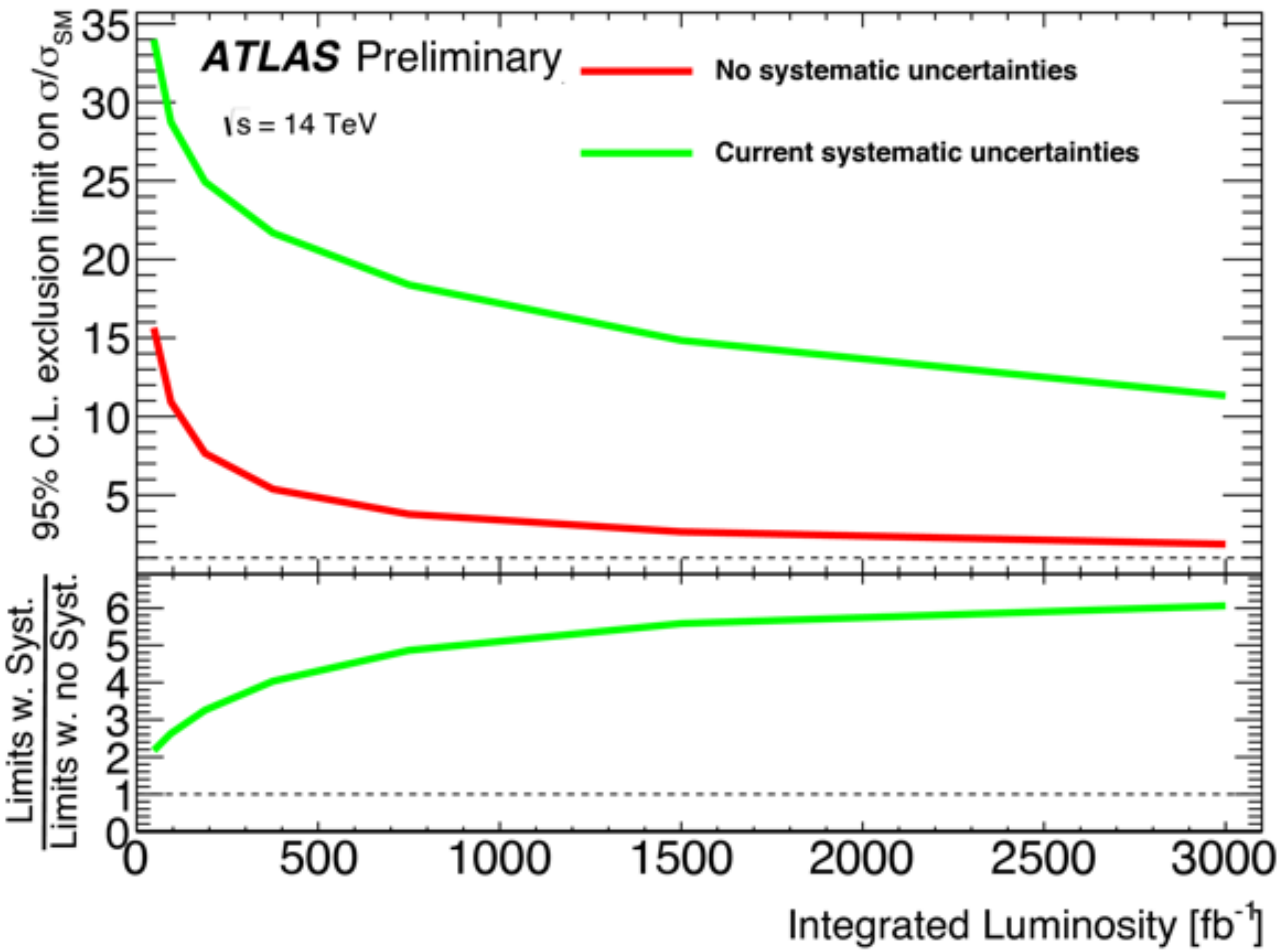
What we know from

Related to the question of matter anti-matter asymmetry in the universe

- Generic predictions of non-minimal electroweak phase transition.

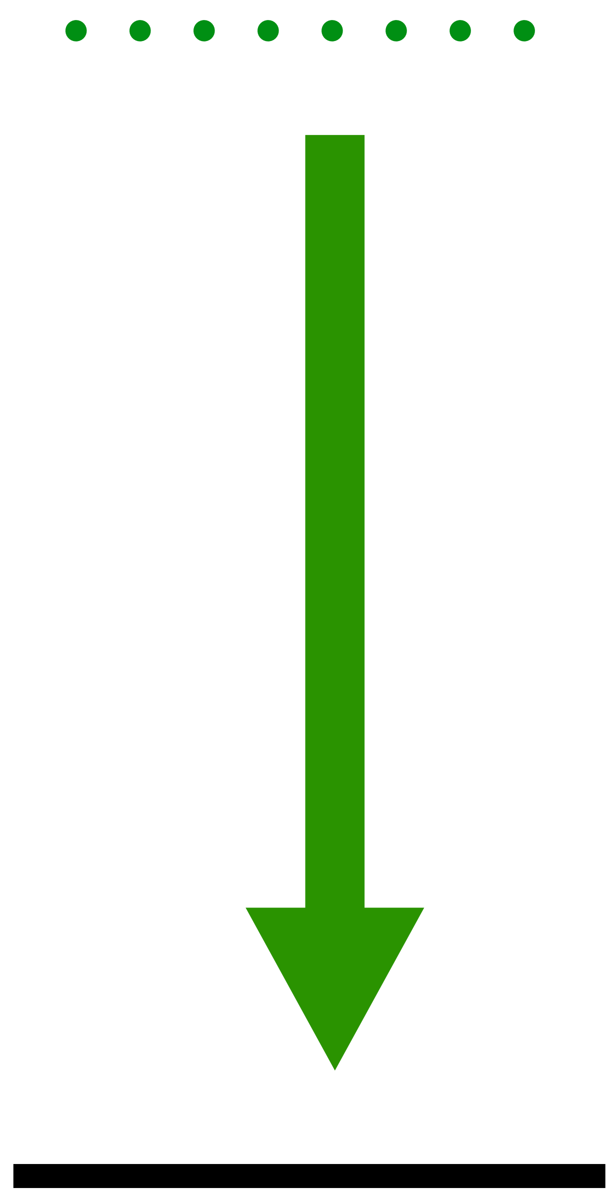
Order 1 deviation in triple Higgs

Probing self coupling with di-Higgs



Difficult. But we need to try harder.
Could give us surprises

Explaining EWSB: naturalness

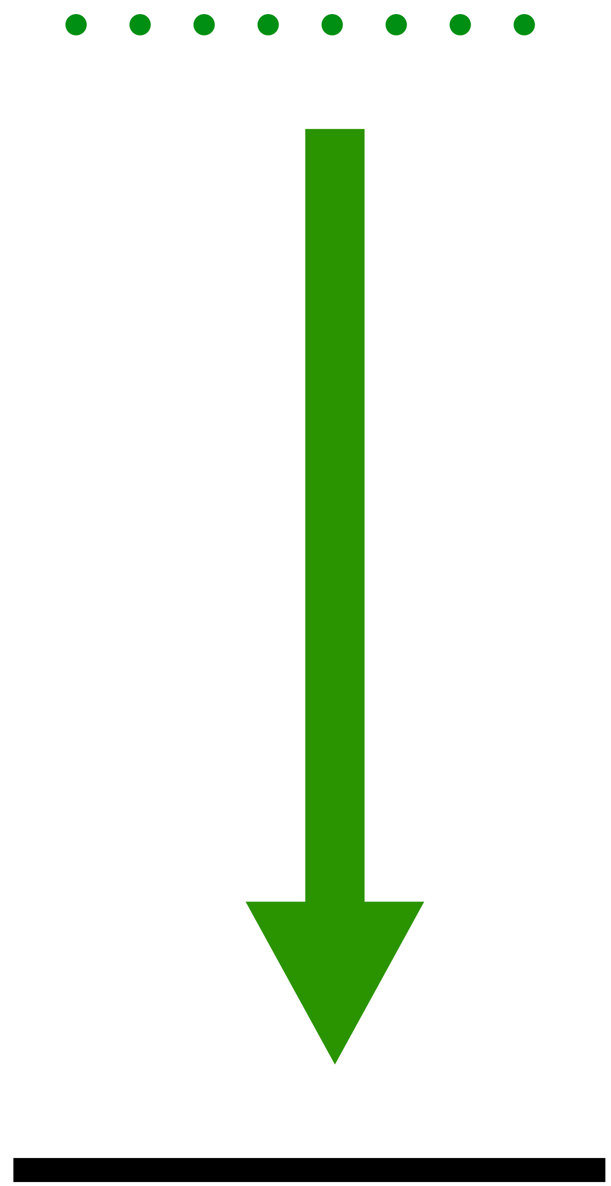


The energy scale of new physics responsible for EWSB

Electroweak scale, 100 GeV.

m_h , m_W …

Explaining EWSB: naturalness



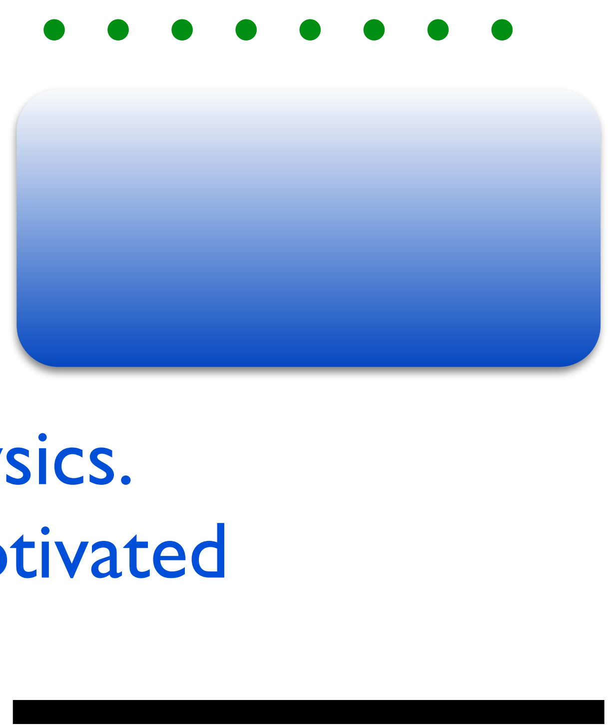
The energy scale of new physics responsible for EWSB

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

If so, why is so different from 100 GeV?

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness of electroweak symmetry breaking

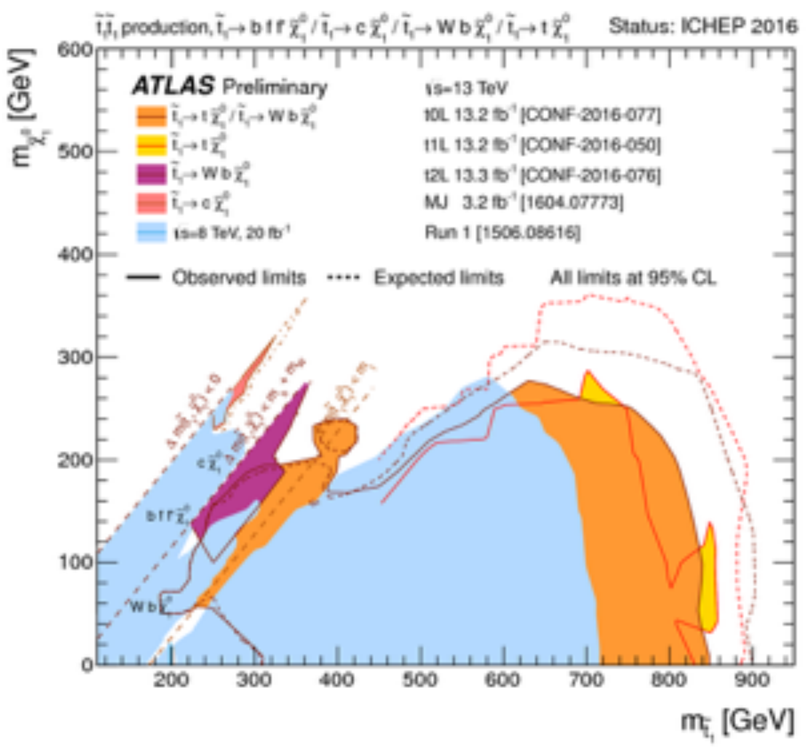


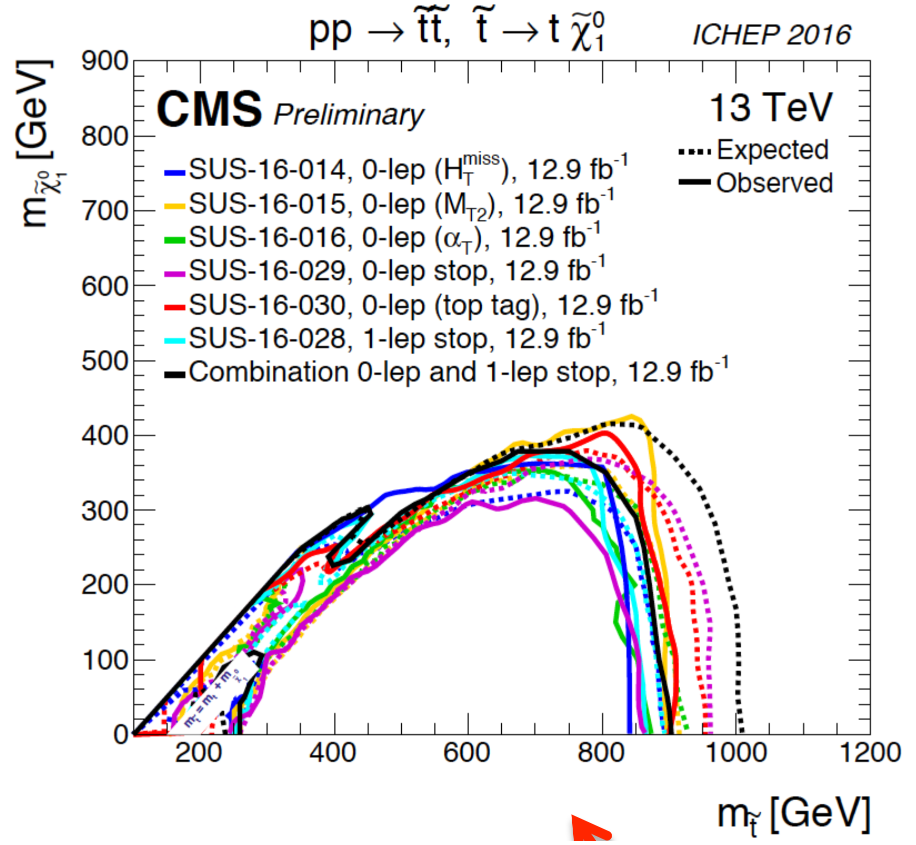
The energy scale of new physics
responsible for EWSB

TeV new physics.
Naturalness motivated

Electroweak scale, 100 GeV.
m_h , m_W …

For example: top partner (SUSY)

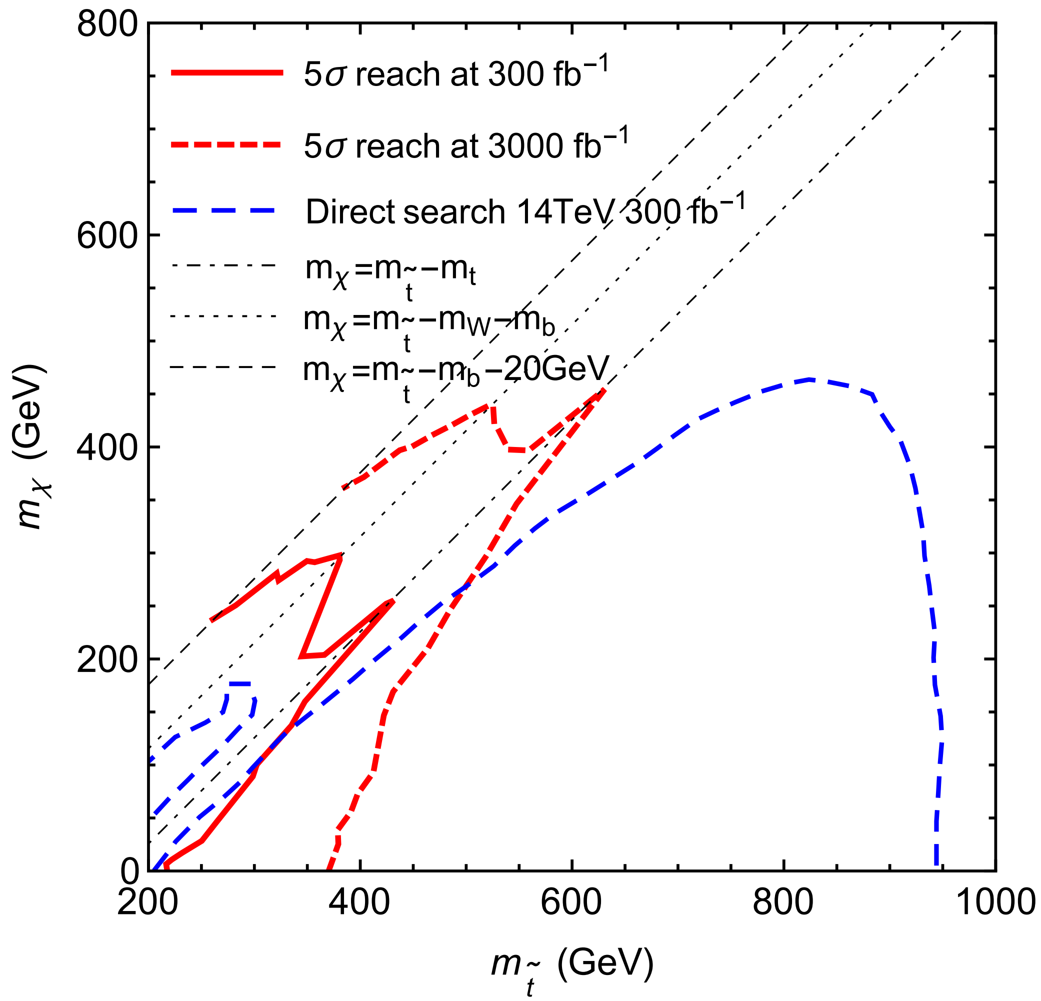


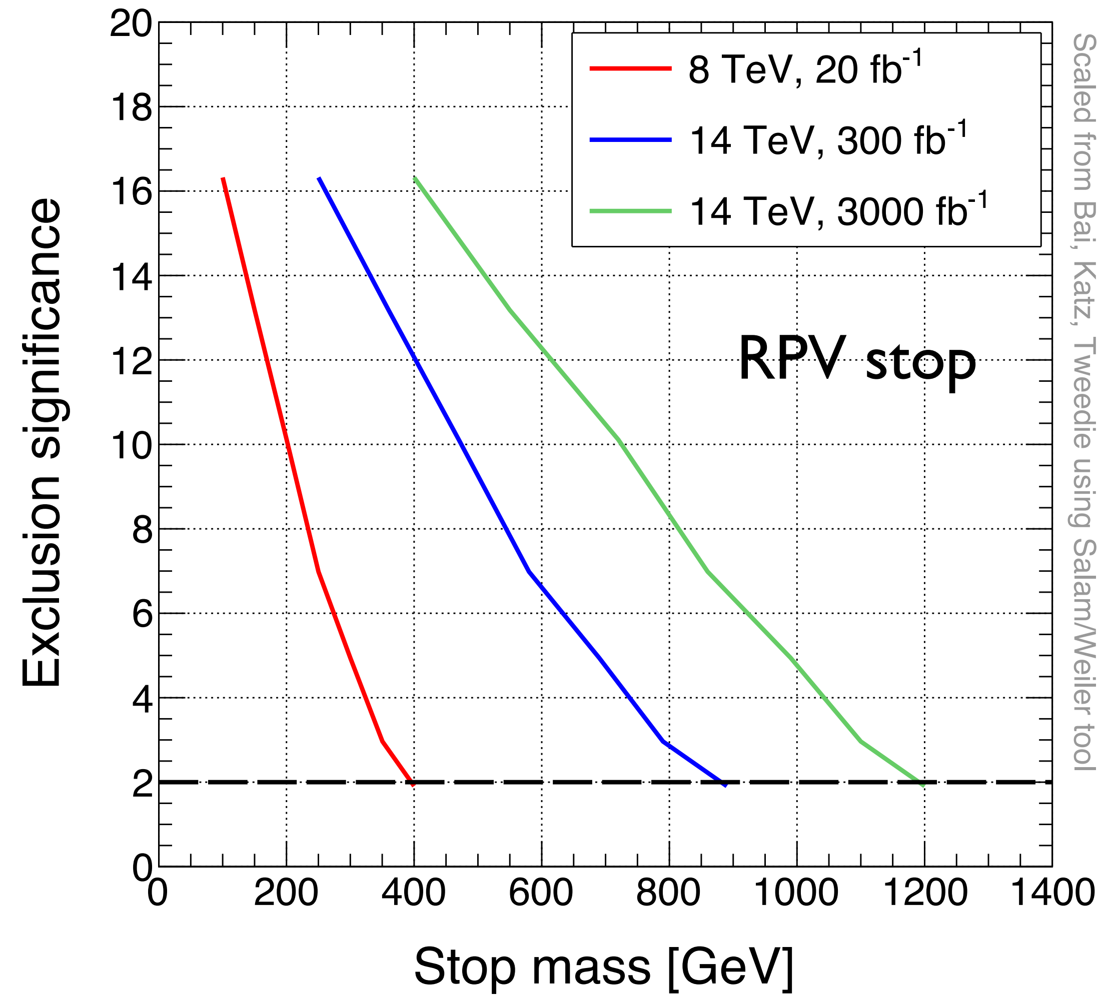


- Naturalness $\propto m_{stop}^2$
- LHC will teach us a lot about naturalness!

Cover gaps, look for alternatives

An and LTW, 1506.00653

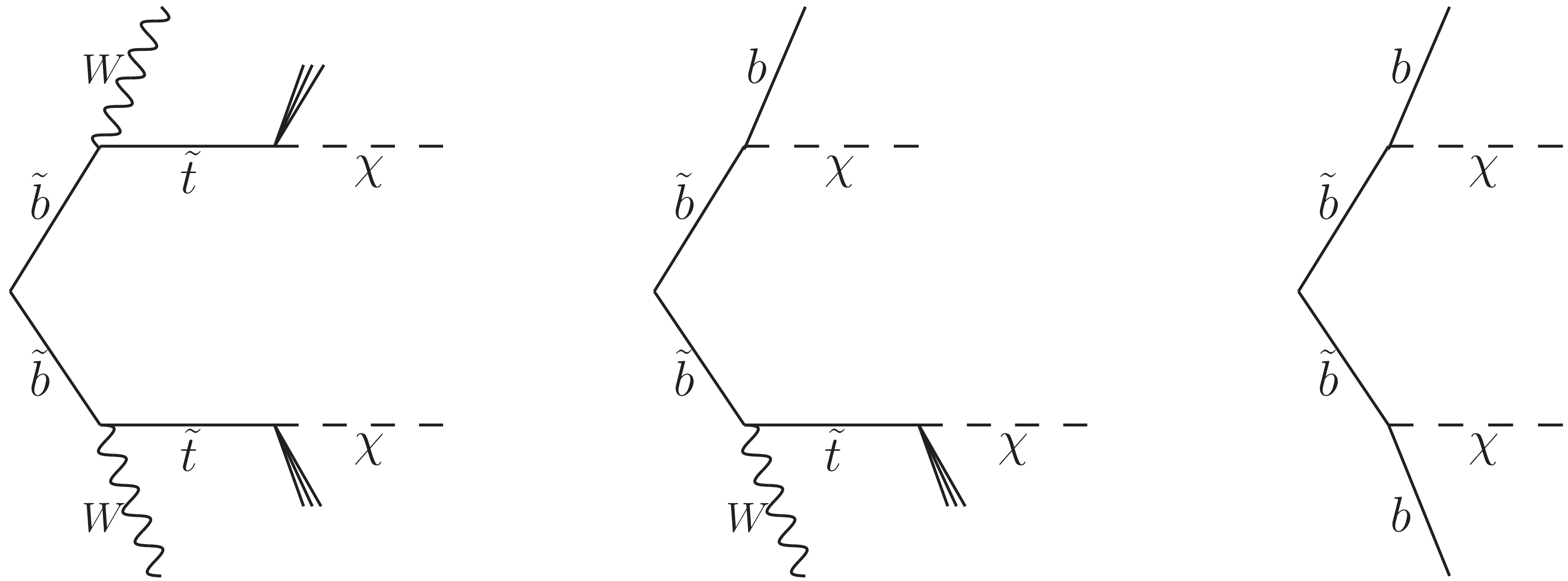


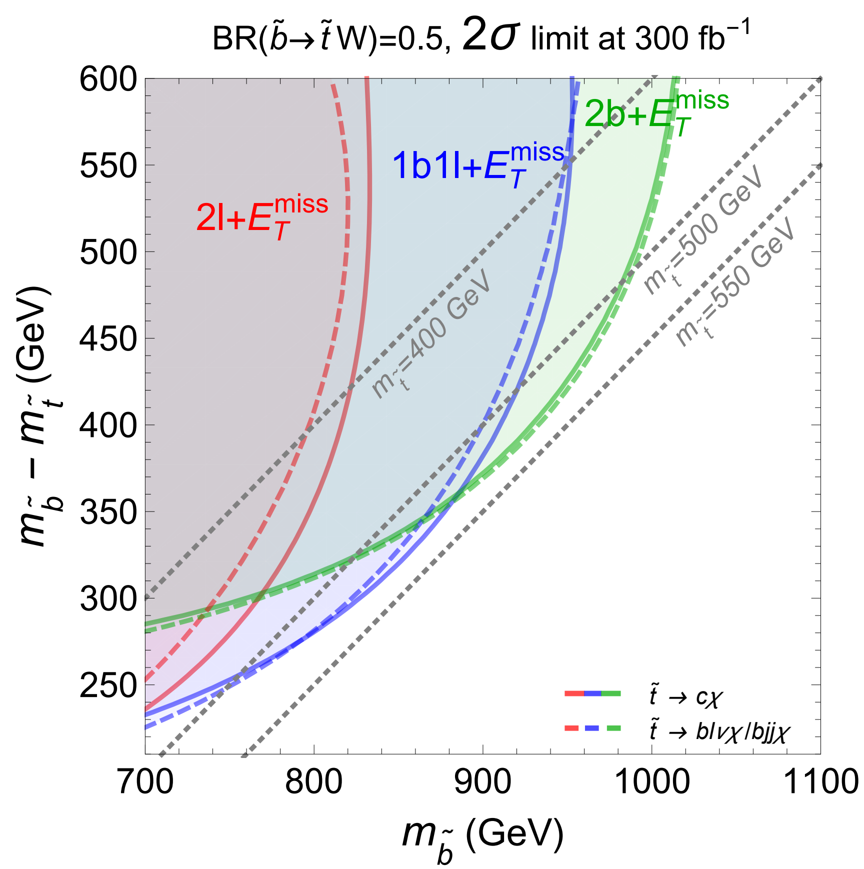


- Compressed, stealth, RPV...
- Run 2 will leave no stone unturned.

Sbottom helps stop search

Haipeng An, Jayin Gu and LTW





Promising reach
for stop nearly
degenerate with LSP

My favorite channel.

Effective, Mini-split, spread, zprime-mediation, ...

Heavy squarks $\tilde{u},\ \tilde{d},\ \ldots$ / $\tilde{t},\ \tilde{b}$

$m_{\tilde{t},\tilde{b}} < m_{\tilde{u},\tilde{d}}$

10s - 100s TeV

$\tilde{g}$

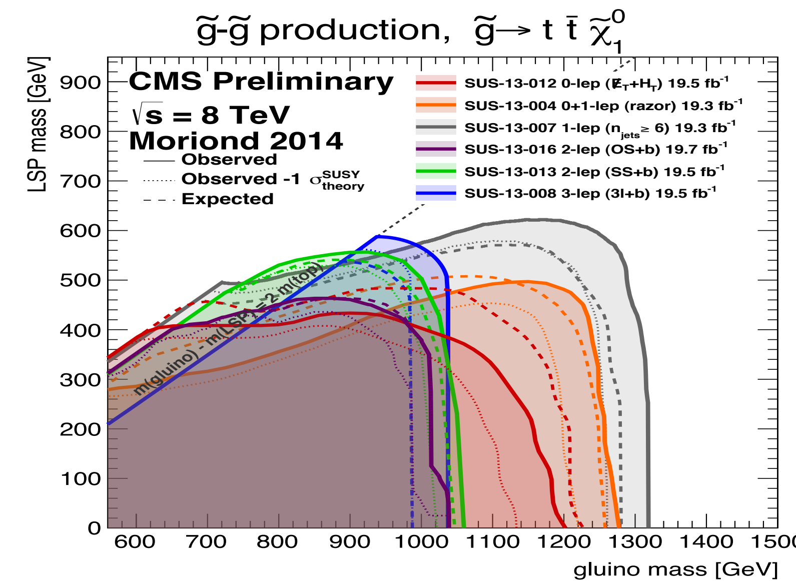
TeV-ish

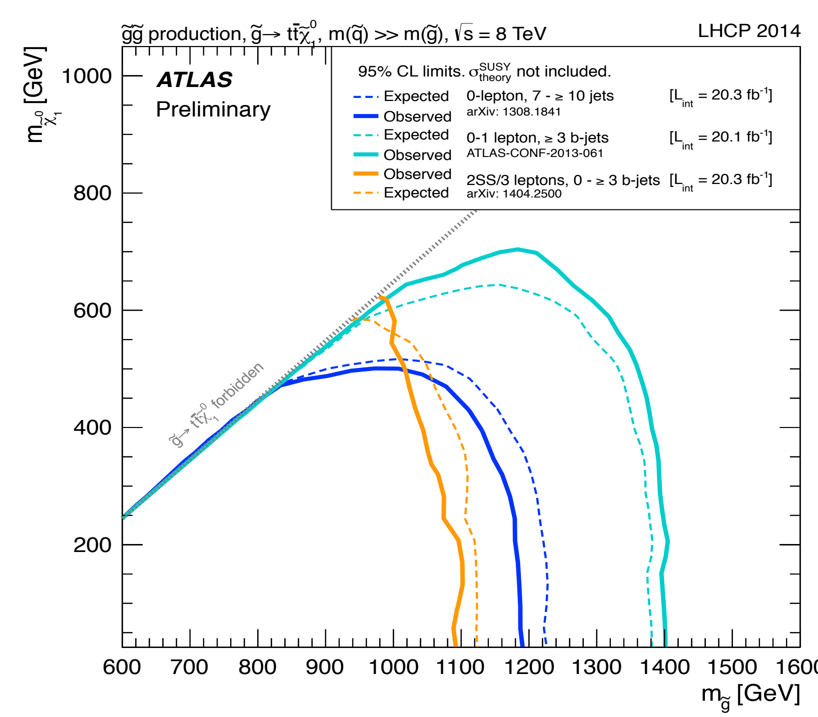
Light gaugino $\tilde{N}\ \tilde{C}^{\pm}$

Fermionic partners still tend to be light.

LHC signal

$$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t},\ t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots$$

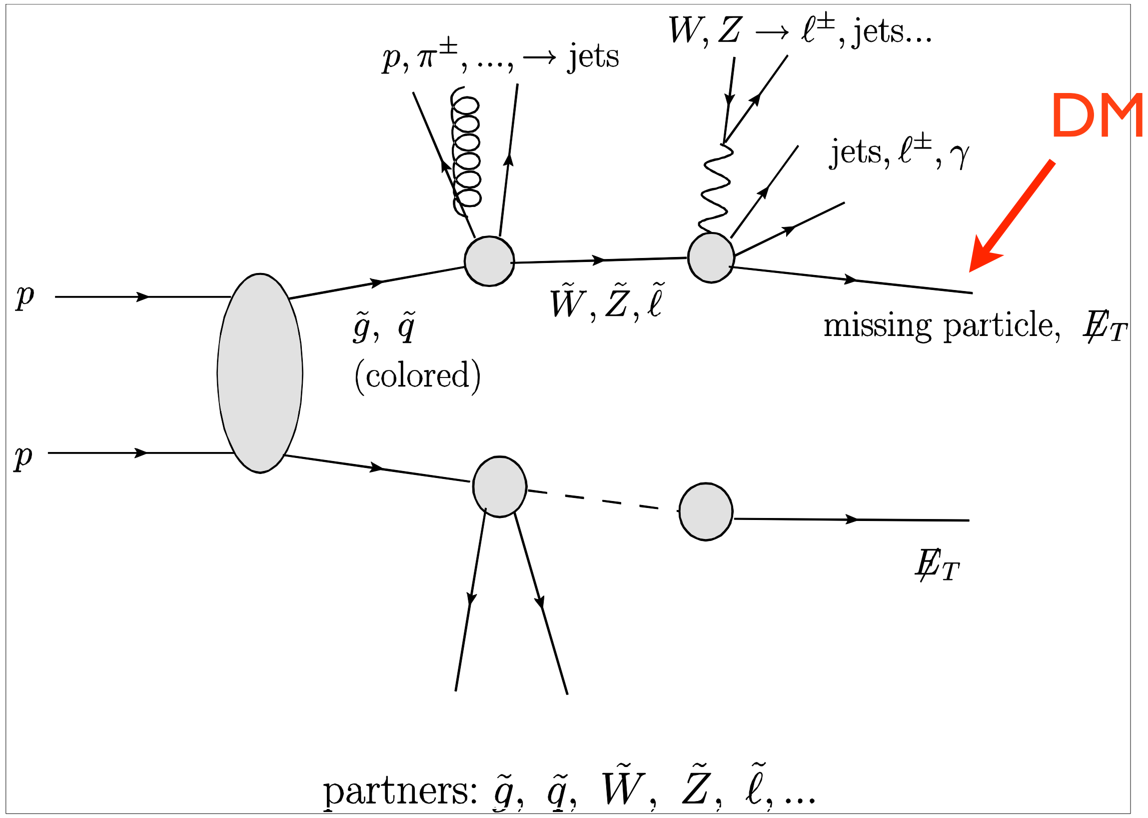




Main targets

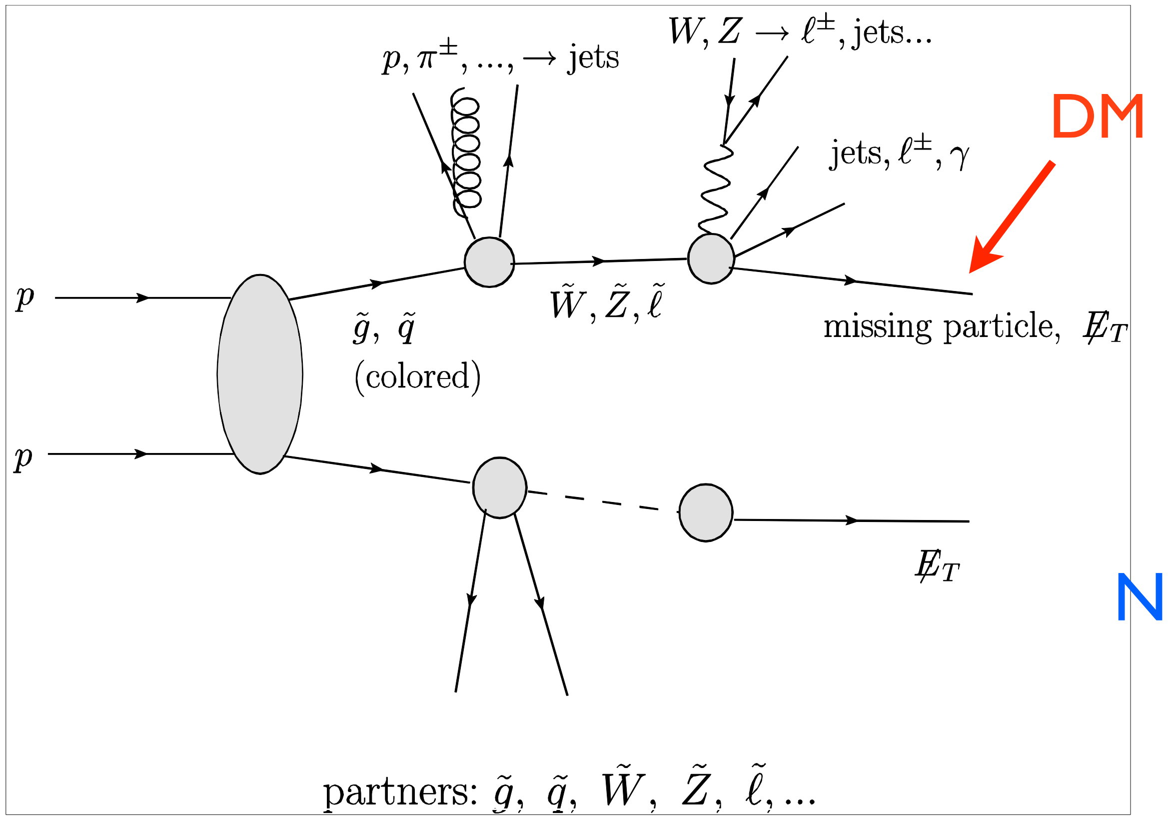
2. dark matter

“standard” story.

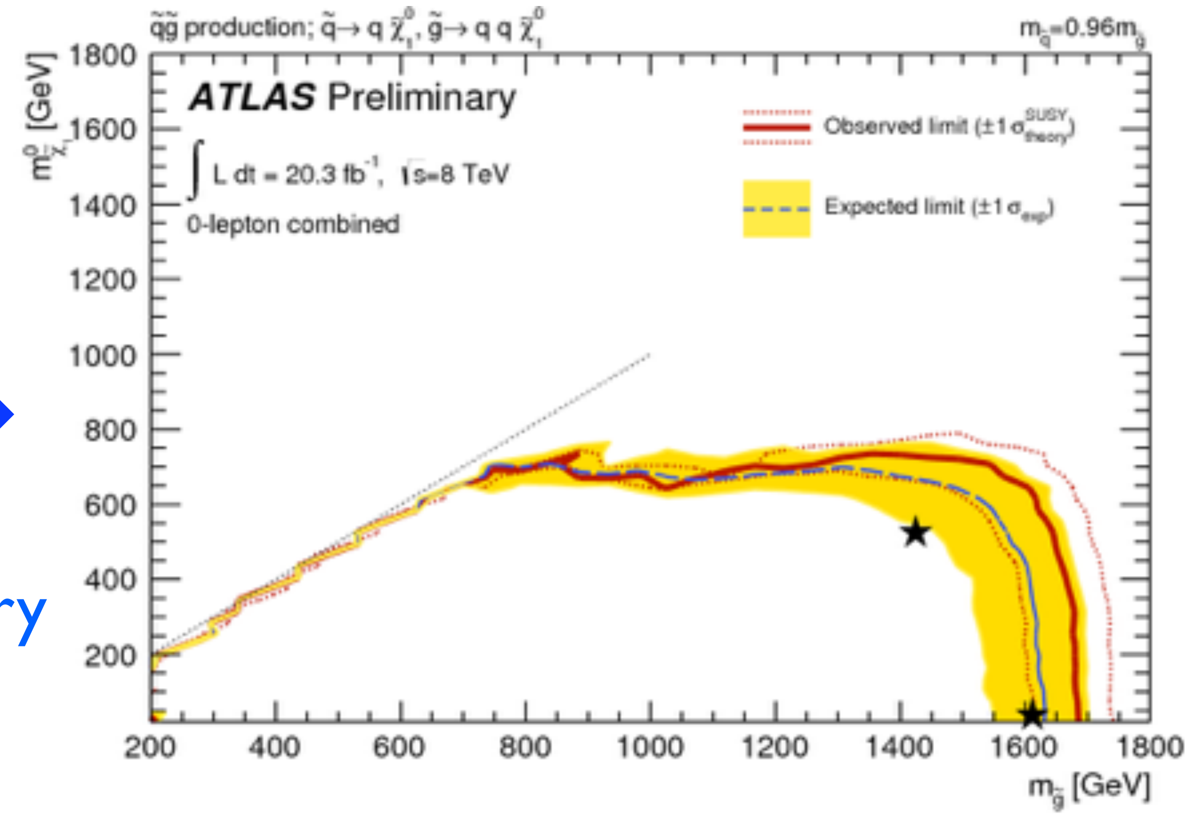


- WIMP is part of a complete model at weak scale.
- It’s produced as part of the NP signal, shows up as missing energy.

“standard” story.



No discovery yet



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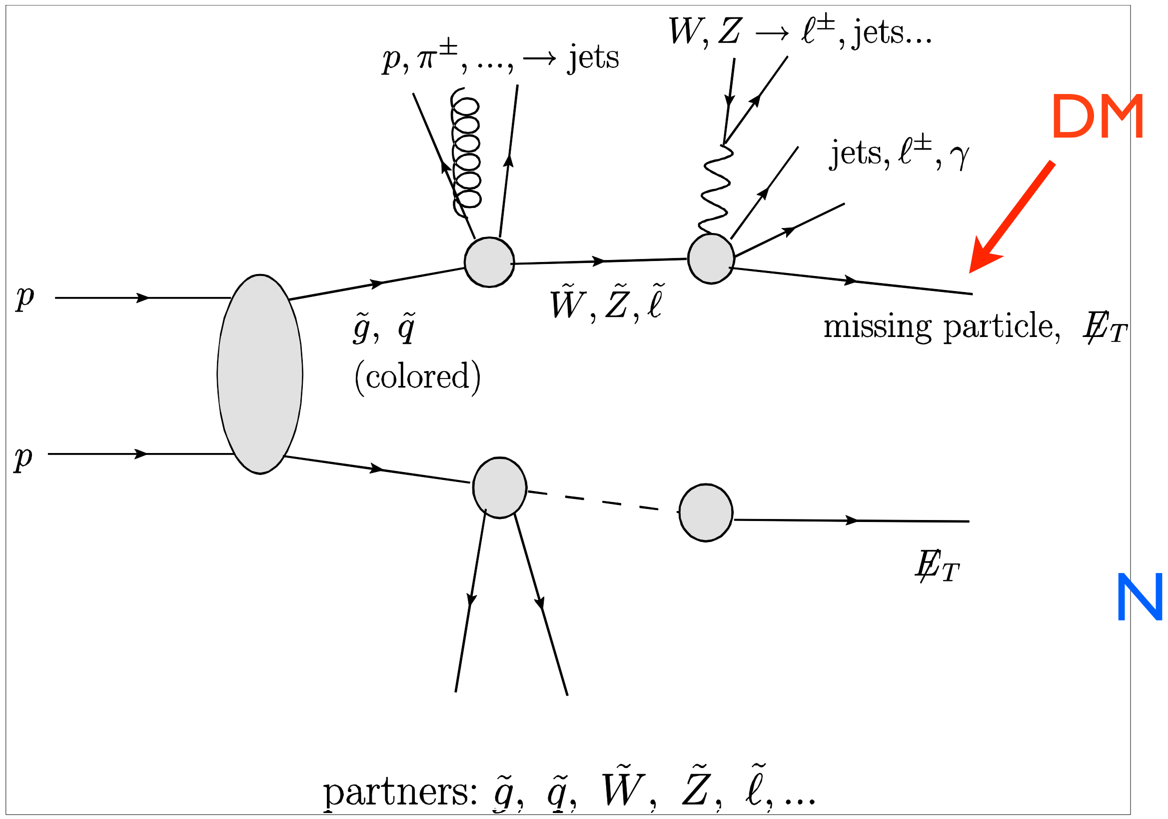

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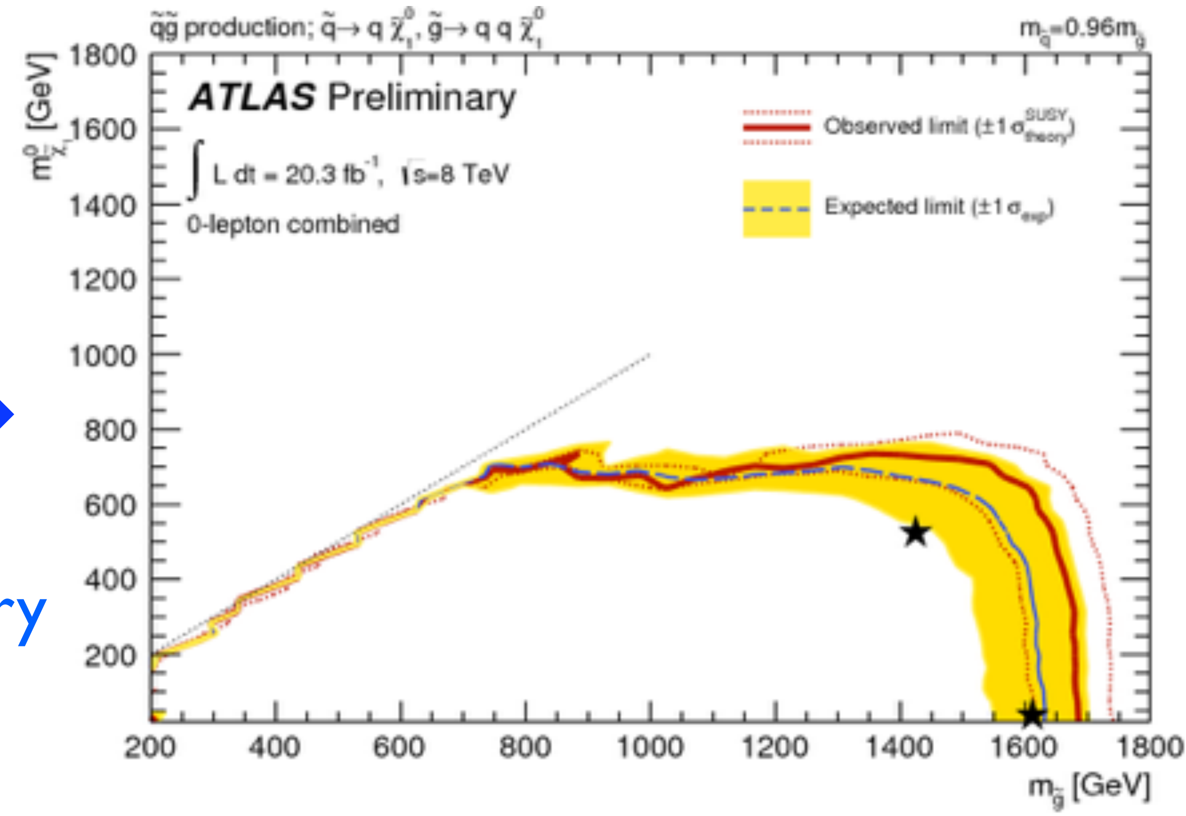
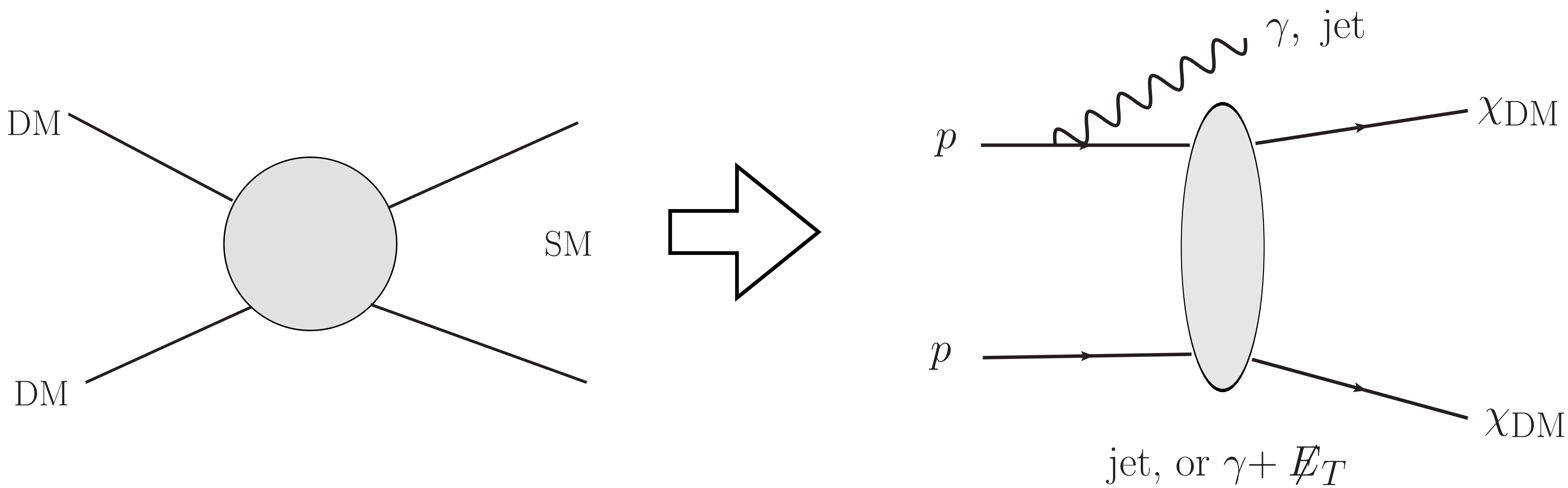


Of course, most WIMP parameter space not covered yet.
Still plausible at the LHC, will keep looking.

Focus more on basic channel

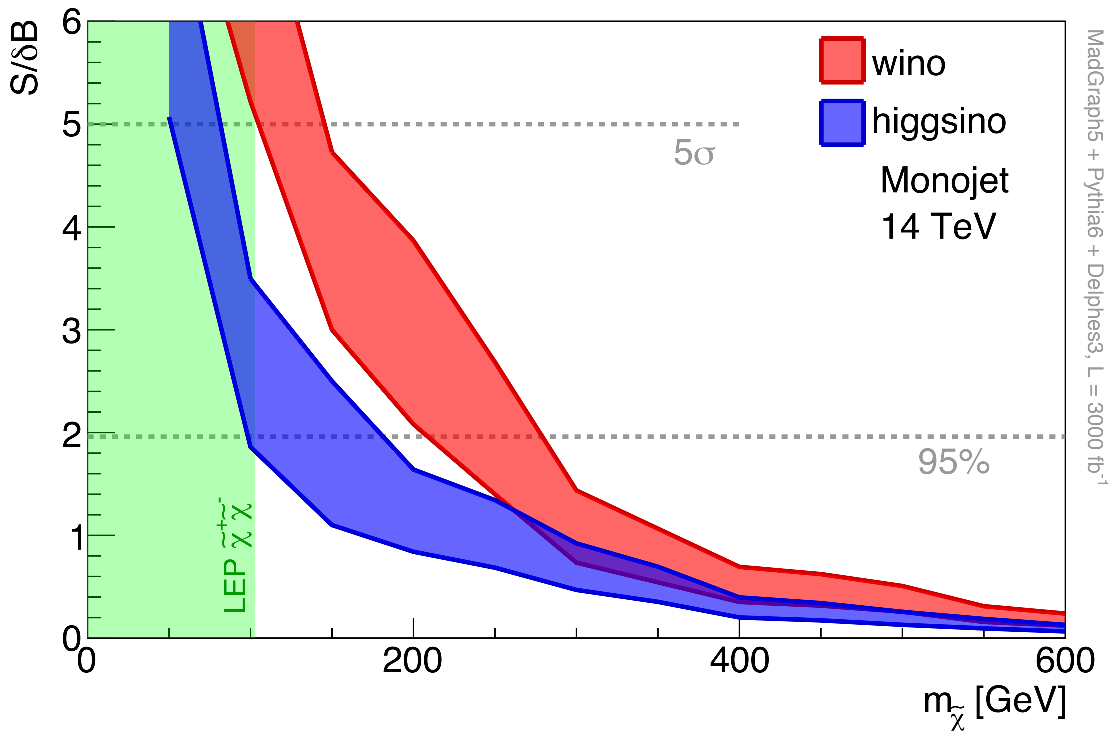
- pair production + additional radiation.

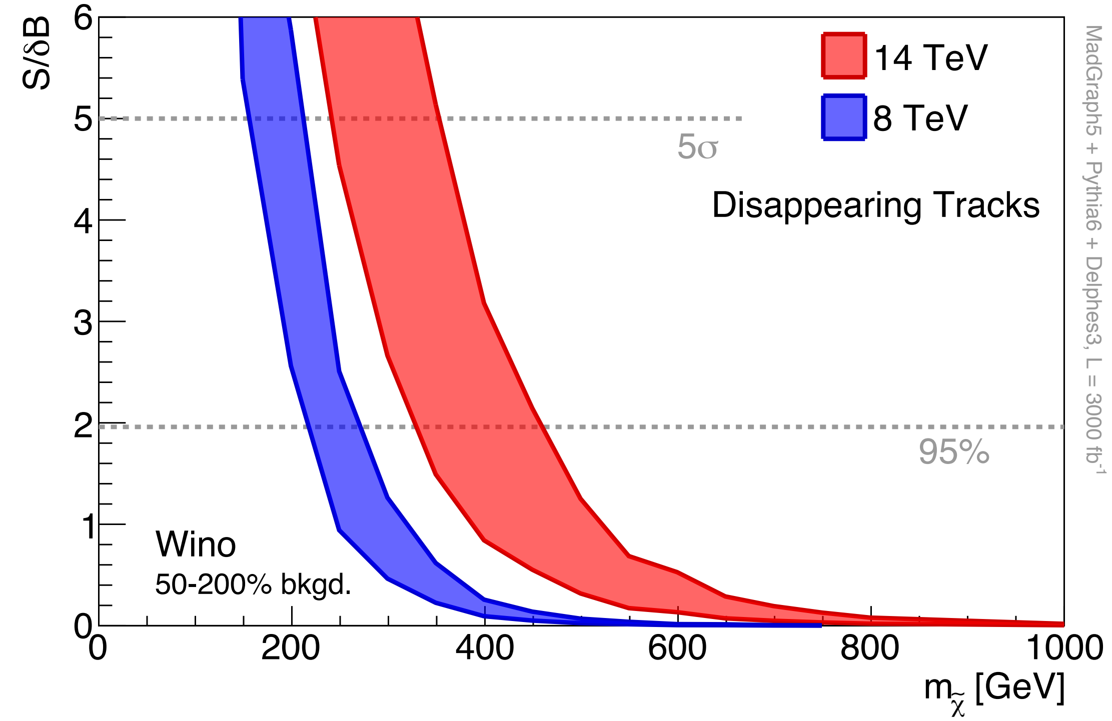


- Mono-jet, mono-photon, mono-Higgs...
- Have become "Standard" LHC searches.

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

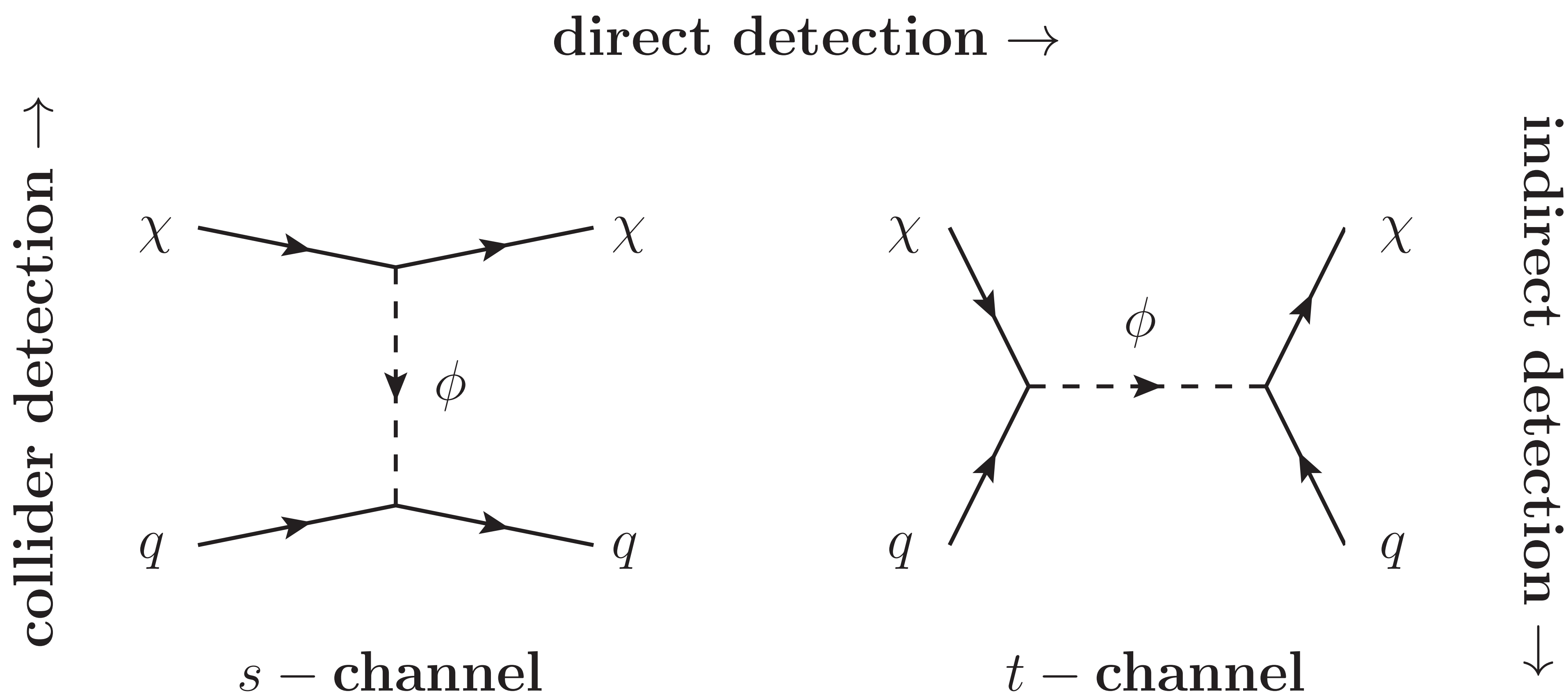
Focusing on more basic channel





- Very challenging. Systematics dominated
  - Weak discovery reach at 14 TeV, 3 ab^{-1} .
- Disappearing track promising!

Consider new mediators



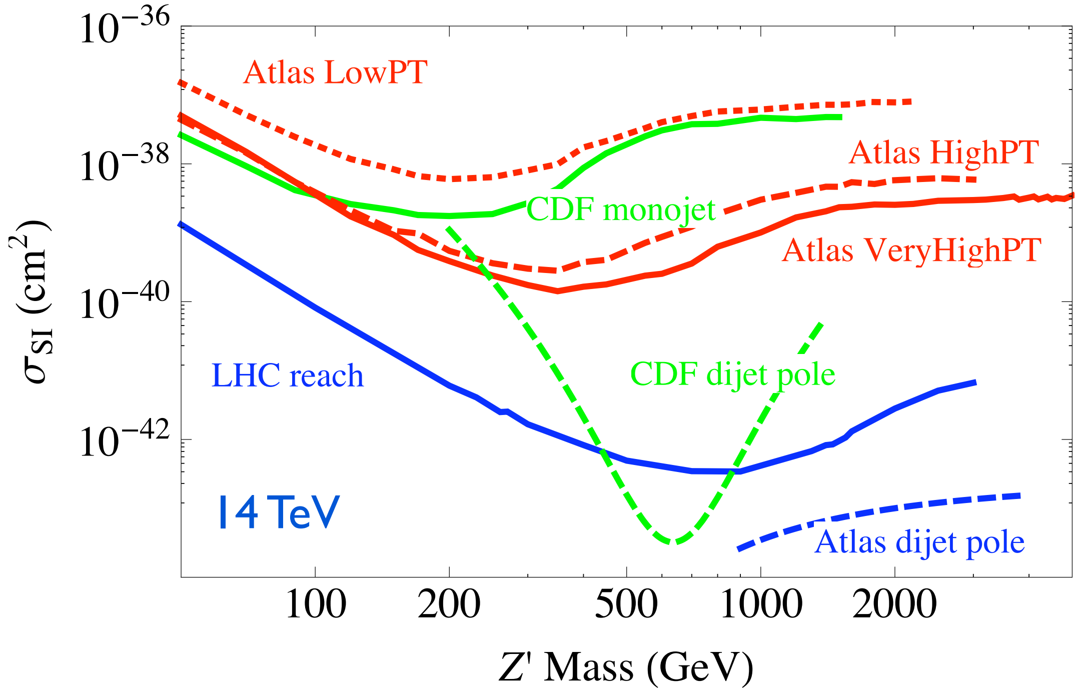
ϕ can be scalar or Z'

ϕ squark like

MonoX vs direct search for mediator

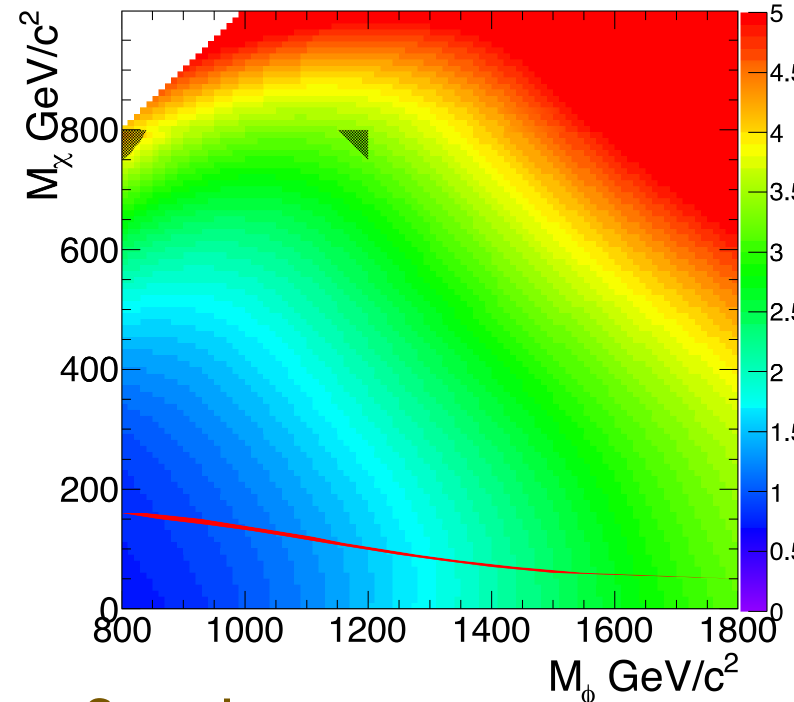
An, Ji, LTW, 1202.2894

s-channel



Haipeng An, Hao Zhang, LTW, 1308.0592

t-channel



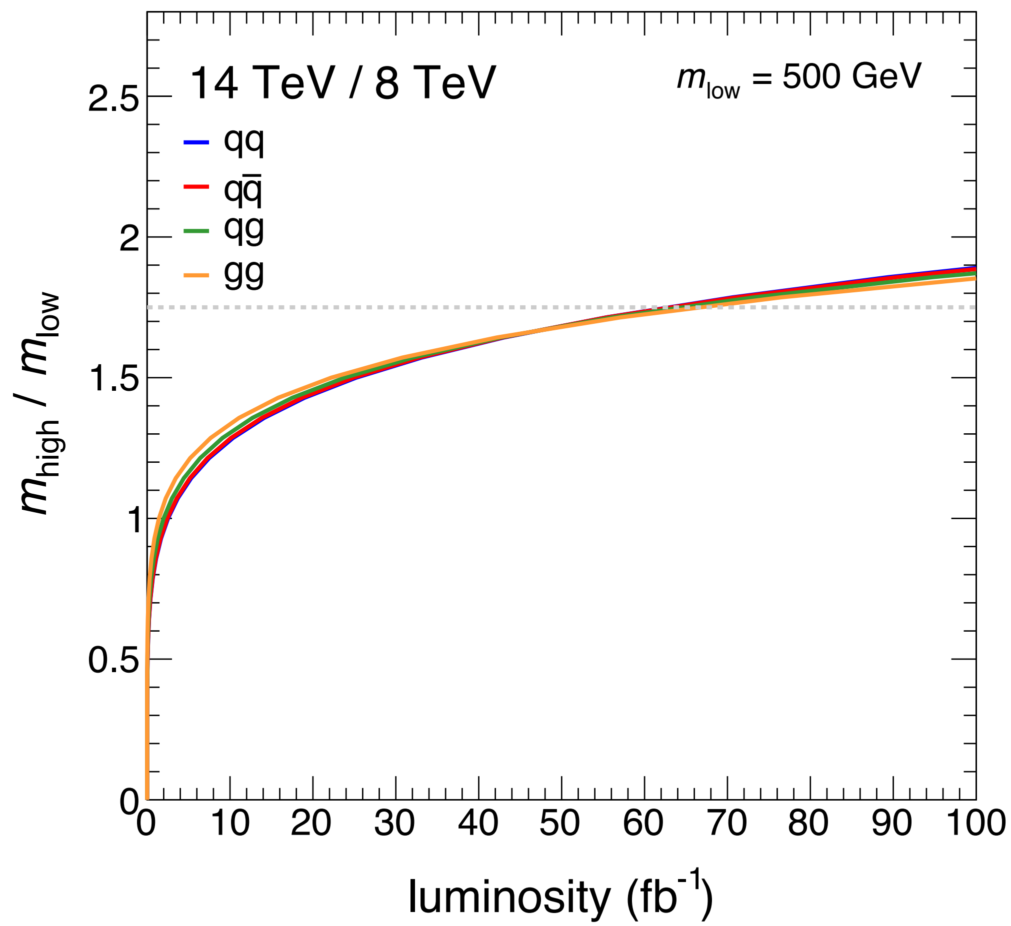
See also
Busoni, De Simone, Jacques, Morgante, Riotto, 1405.3101

See also:
Chang, Edezhath, Hutchinson, Luty, 1307.8120
Bai, Berger, 1308.0612
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679
Papucci, Vichi, Zurek, 1402.2285

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

Channel with most "growth" potential

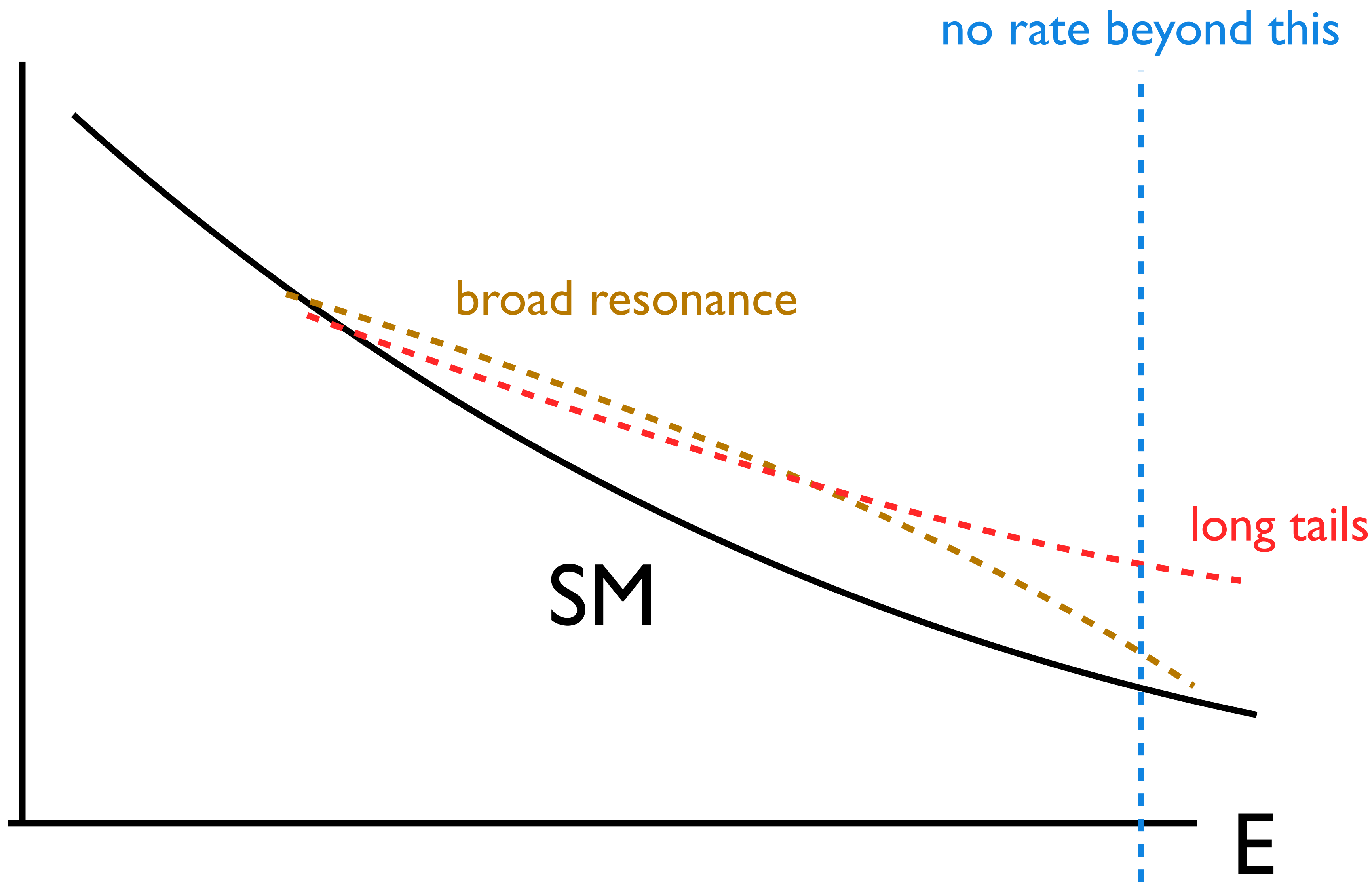
500 GeV, e.g. pair of 250 GeV electroweak-ino



Weakly coupled, back ground limited (small S/B)

Examples: electroweak-ino pair production
dark matter. Weak boson fusion, etc.

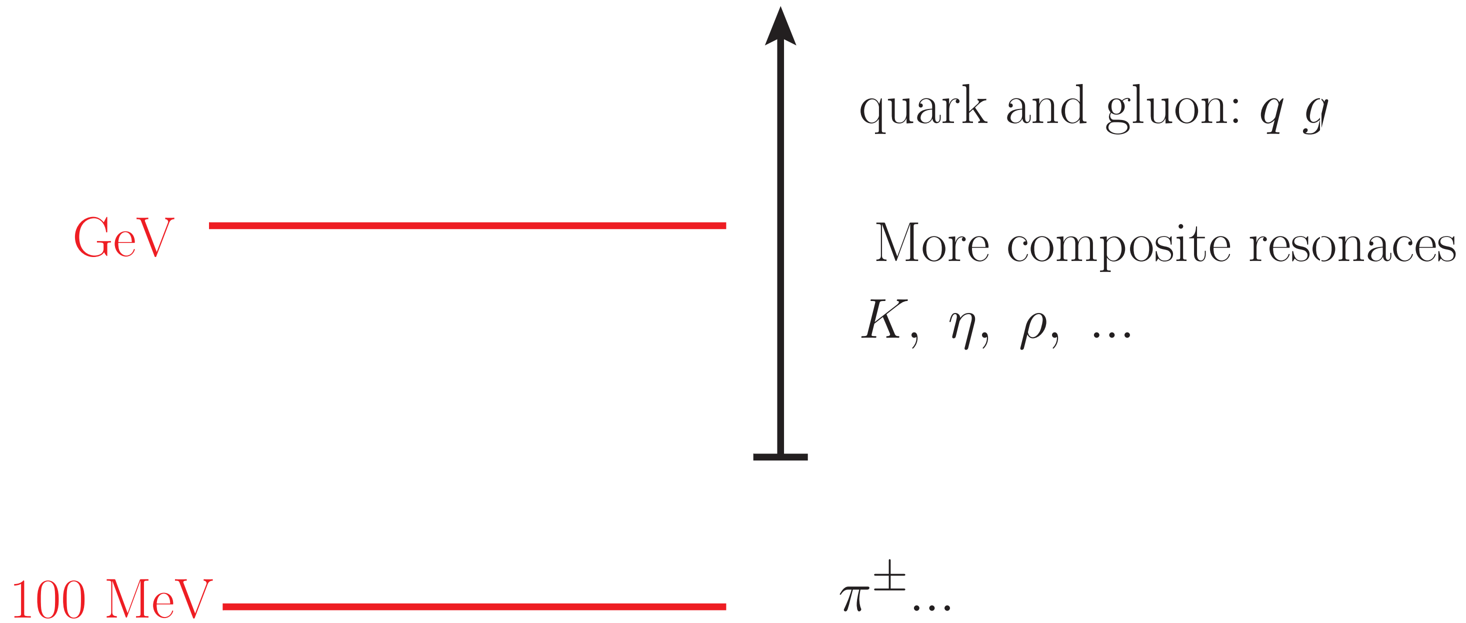
Example



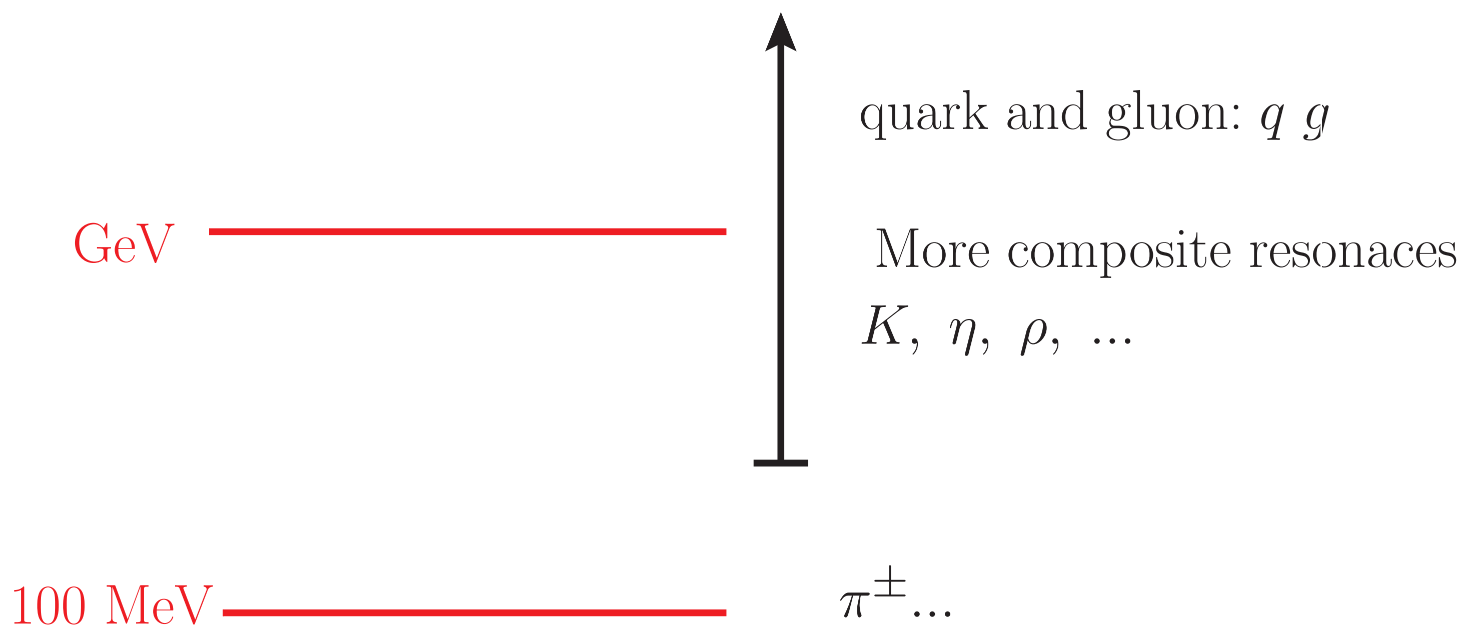
- Motivation? Strongly coupled heavy new physics

e.g. Greco, Liu, Pomarol, Rattazzi

“Learning” from QCD



“Learning” from QCD

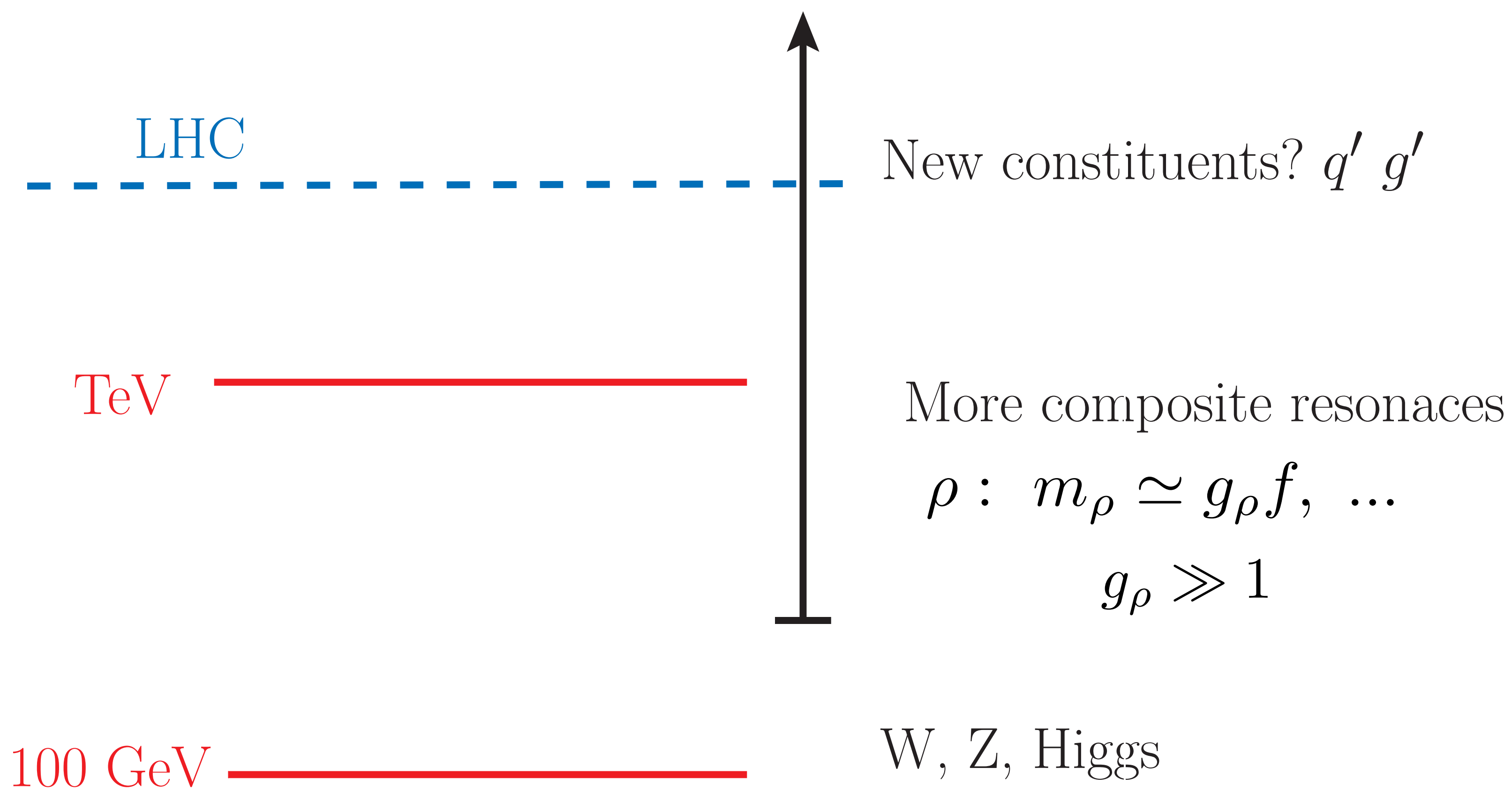


$\Rightarrow$ new strong dynamics, symmetry breaking

$\Rightarrow$ SM Higgs

- Construct a new strong dynamics in which the low lying states will be the SM Higgs.
- Composite Higgs models. Still a natural theory.
- Nature may be more interesting, but it could also just repeat itself.

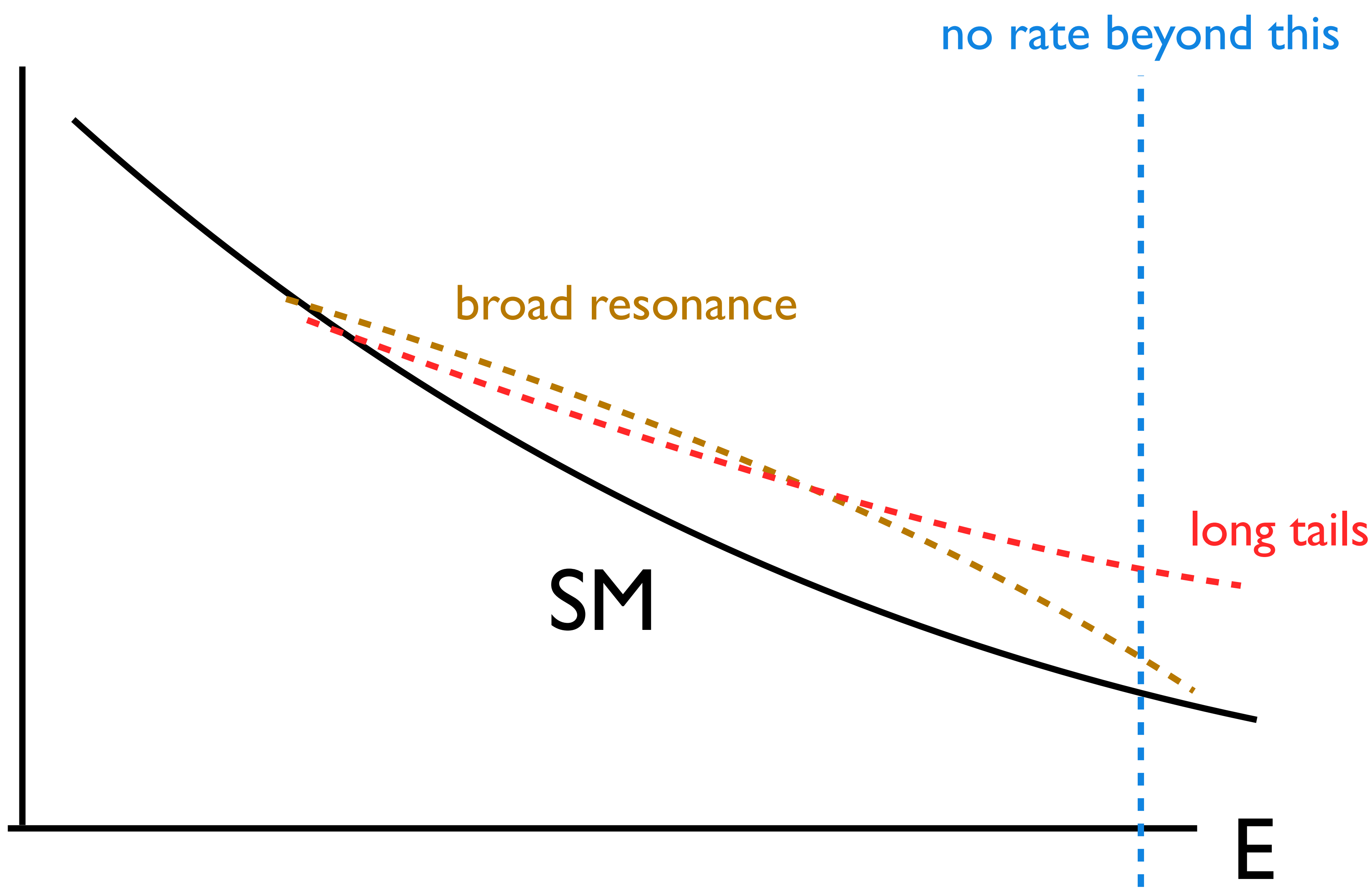
Composite Higgs



- Many models in this class.

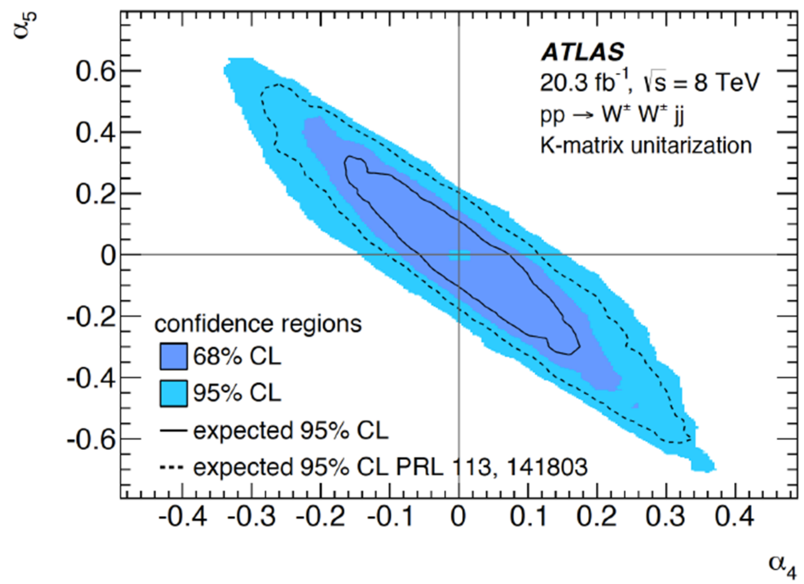
– Similar scenarios: Randall-Sundrum...

Example



- Final states can be di-boson, ttbar, etc.
- Closely related to electroweak symmetry

On-going EFT style searches



$$L_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]$$

$$L_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D_\nu\Phi\right]$$

$$L_{M,0} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$L_{M,1} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$L_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$L_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

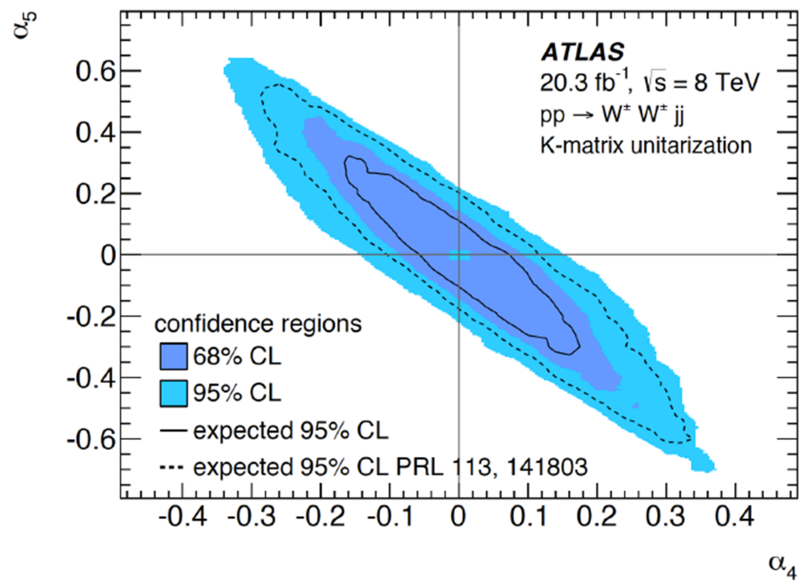
$$L_{T,0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

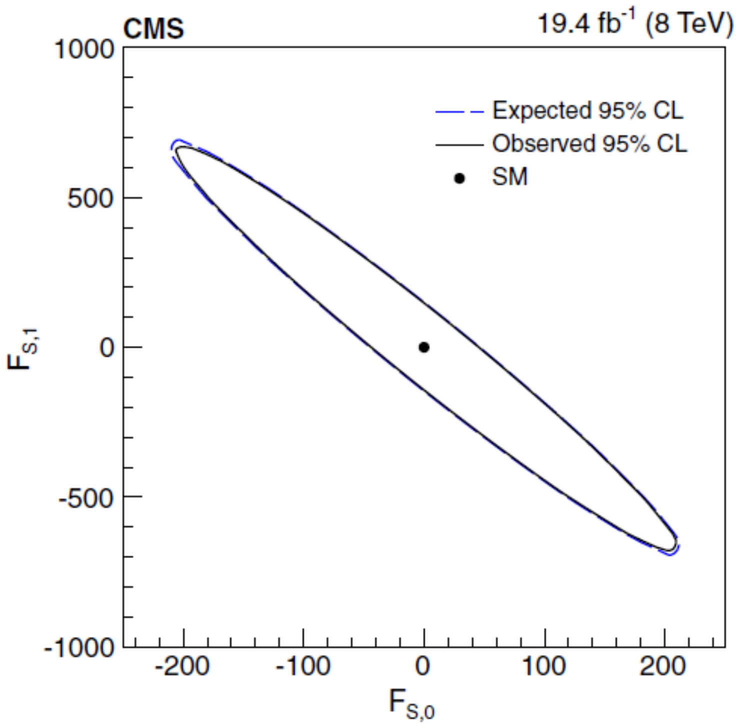
$$L_{T,1} = Tr\left[W_{\alpha\nu}W^{\mu\beta}\right] \times Tr\left[W_{\mu\beta}W^{\alpha\nu}\right]$$

$$L_{T,2} = Tr\left[W_{\alpha\mu}W^{\mu\beta}\right] \times Tr\left[W_{\beta\nu}W^{\nu\alpha}\right]$$

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu] \\
\mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

Comment





- EFT may not model this kind of physics well. Similar to the case of dark matter.
- May need UV complete simplified models, mediators...
- Tagging the polarization of W/Z can be useful.

A word on the future

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- If LHC discover some new physics

  The next step will be clear.

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- If LHC discover some new physics

  The next step will be clear.

- Without LHC discovery.
  - Physics case for a 100 TeV pp collider stronger than HE-LHC at 28 TeV.
  - Cost+technological challenge. Perhaps easier to "sell" only as a second step of a circular Higgs factory in longer term.
  - CEPC is the obvious next step.

Conclusion

- LHC run 2 is pursuing a comprehensive program which covers the ground pretty well.

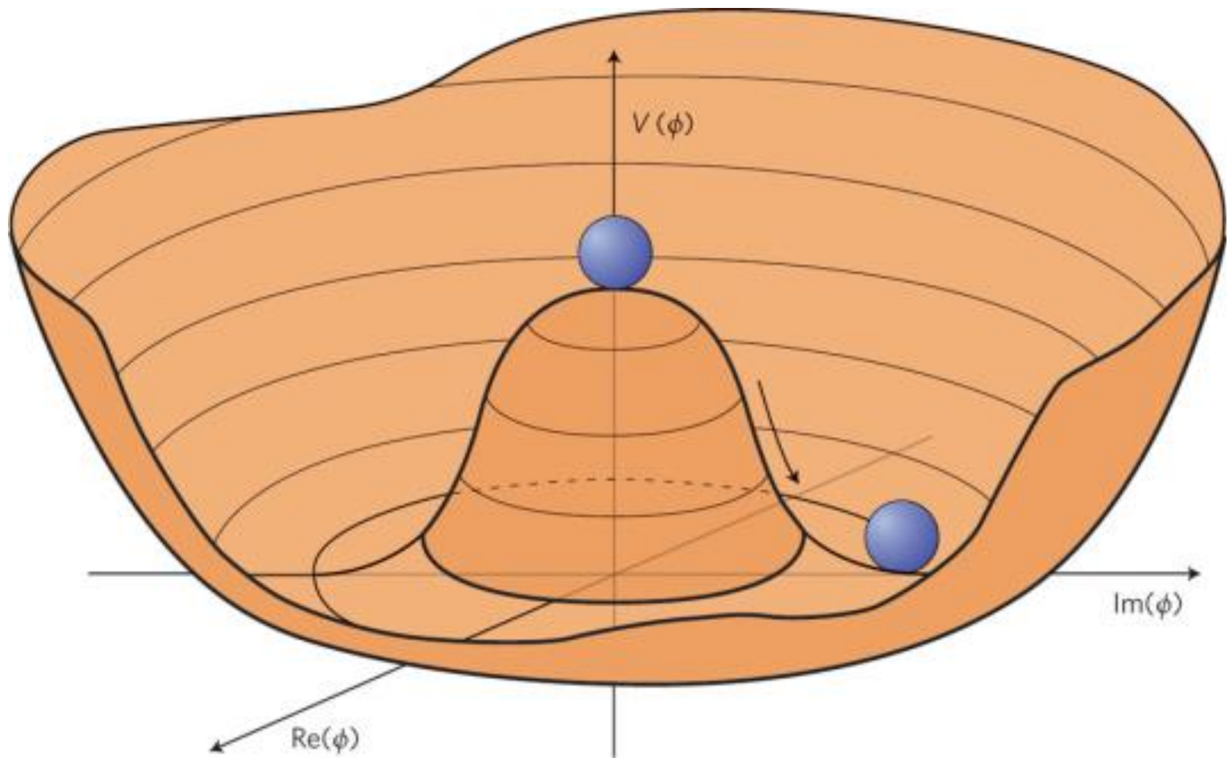
- Moriond 2017 can be an interesting juncture.

  Between early discovery vs slow gain with lumi

- In the longer run, focusing on weakly coupled or broad features. Di-boson, ttbar, etc.

A lot to look forward to!

“Simple” picture: Mexican hat



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

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

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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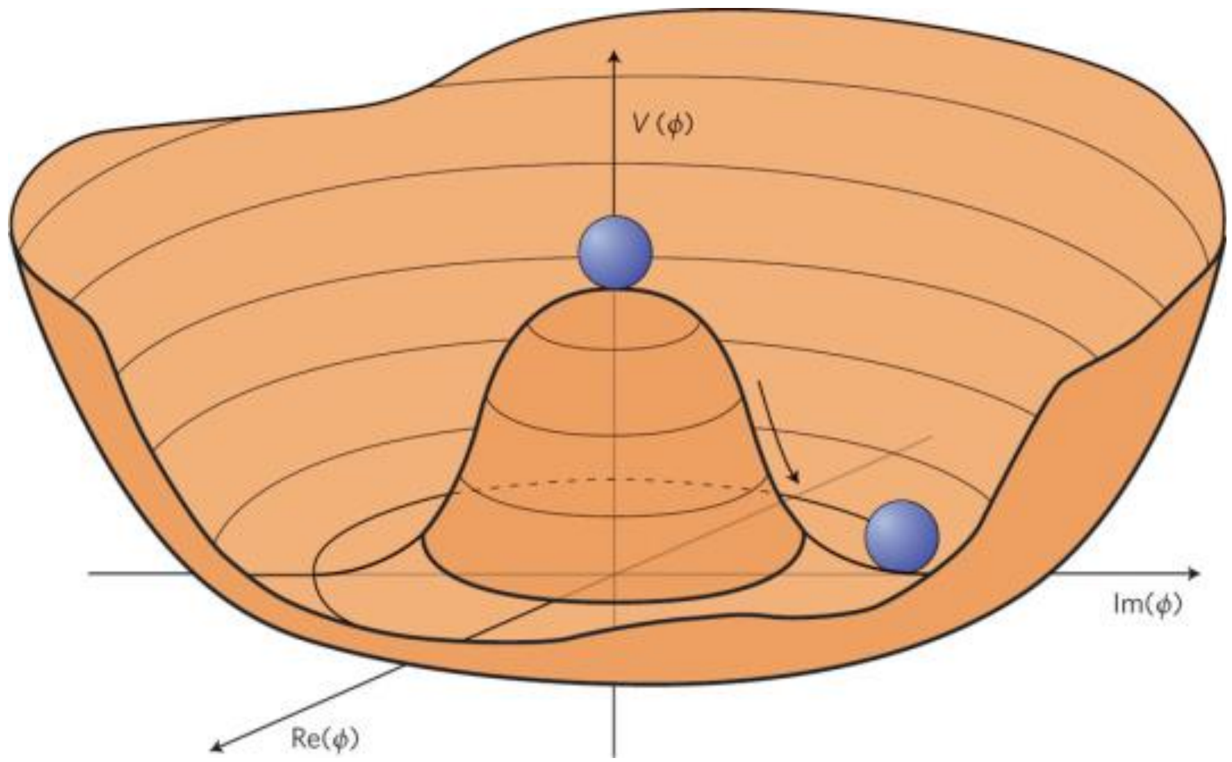

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However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

Higgs is special

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle