Nature vs. BSM

Andreas Weiler
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20th annual RDMS CMS Collaboration Conference
Tashkent
13/9/2018

“Is nature natural?”

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Shouldn’t we believe that the Standard Model is exactly correct?

The ability to fit data is not everything. The SM fails to explain many of the most important features of particle physics.

The SM is incapable of explaining the phase transition to an ordered state that breaks $SU(2)_L \times U(1)_Y$.

1. The most general renormalizable potential for the Higgs field is

$$V = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

2. For some reason, $\mu^2 < 0$.

The value of μ^2 receives large quantum corrections with both signs of order of the fundamental scale $\Lambda \gg \mu$.

Sophisticated people call this the “gauge hierarchy problem”. We have no clue as where μ^2 comes from.

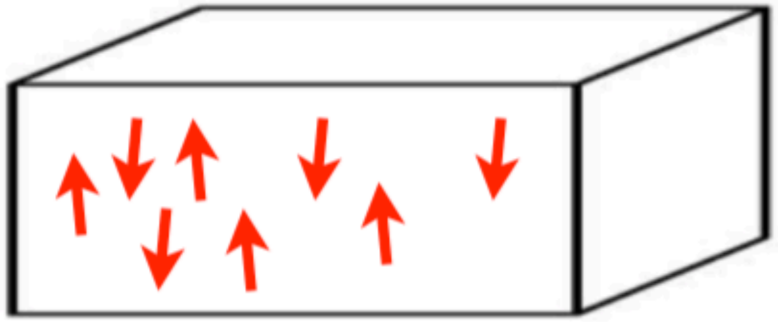
We have experimentally performed the tuning

$$\mu \ll \Lambda$$

many times…

Landau, Ginzburg

For generic T, a ferromagnet is not at critical point T_C



$$\Lambda^{-1} \longleftrightarrow a$$ atomic spacing

$$\mu^{-1} \longleftrightarrow \xi$$ coherence length

$$\Lambda \gg m \quad \longleftrightarrow \quad \xi \gg a$$ critical point

Landau, Ginzburg

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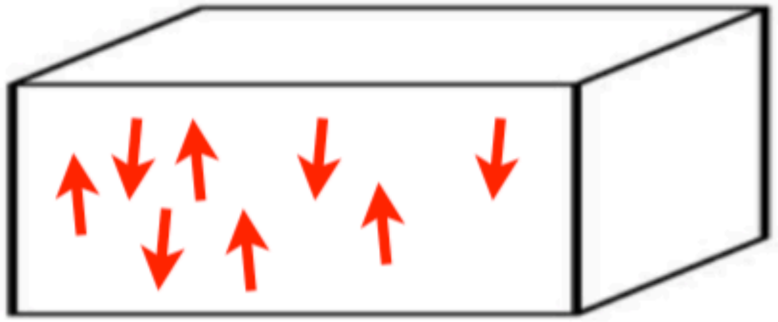

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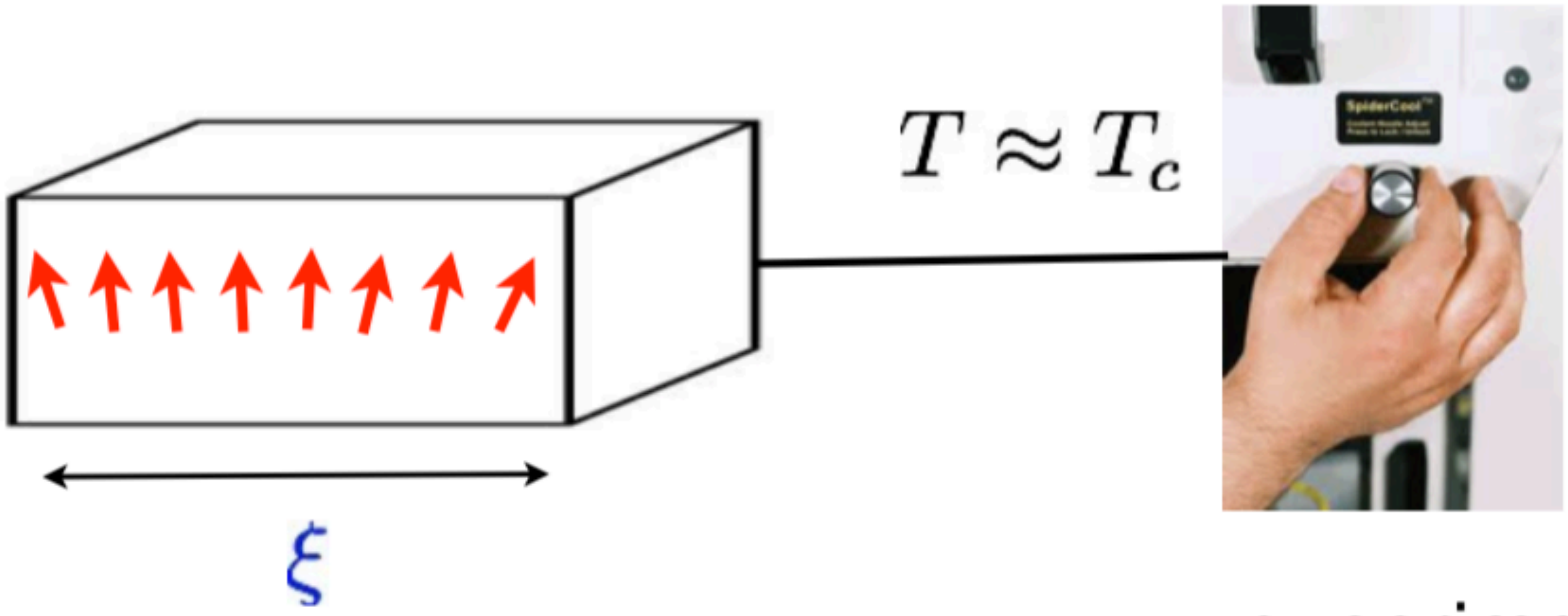

experimenter

Landau, Ginzburg

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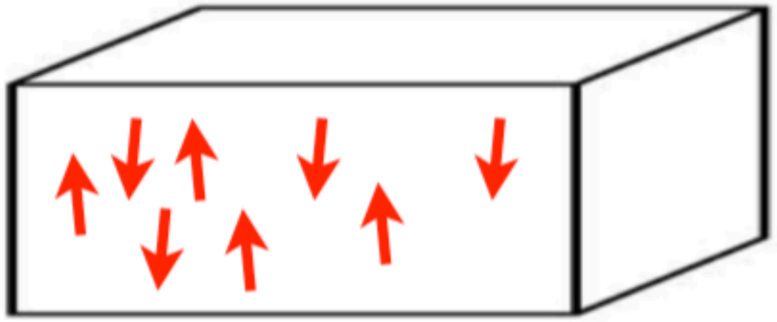

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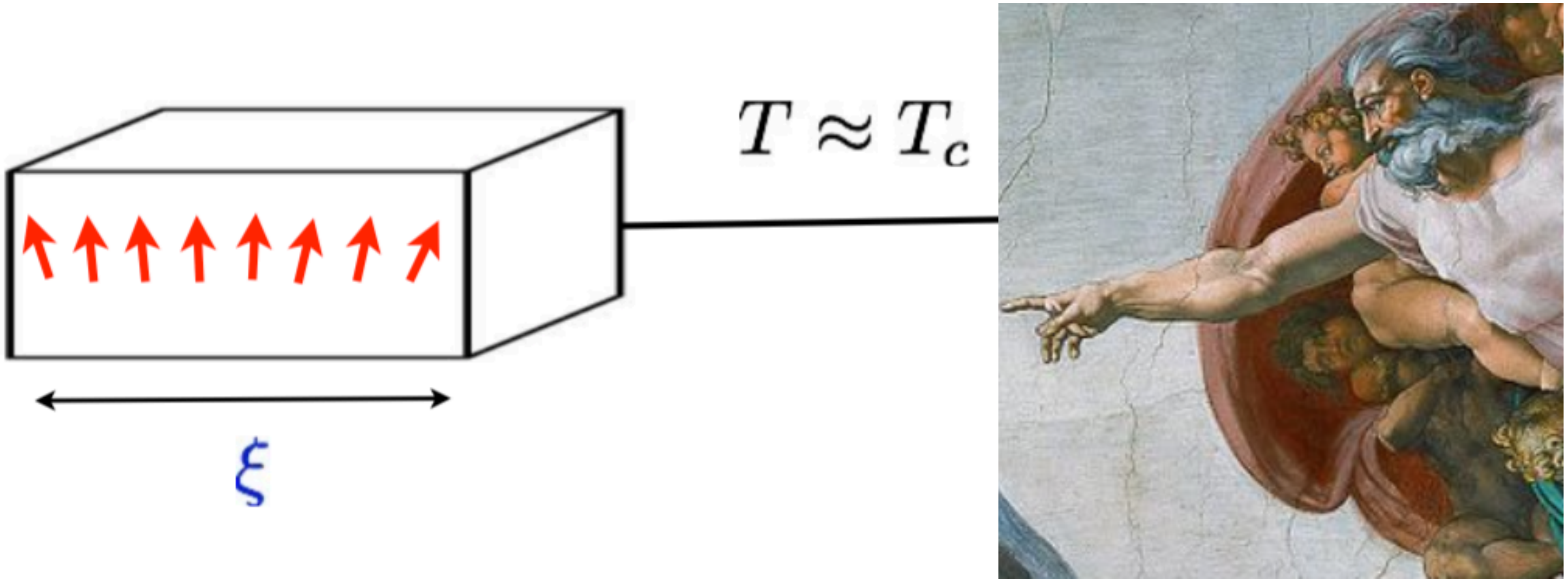

Landau, Ginzburg

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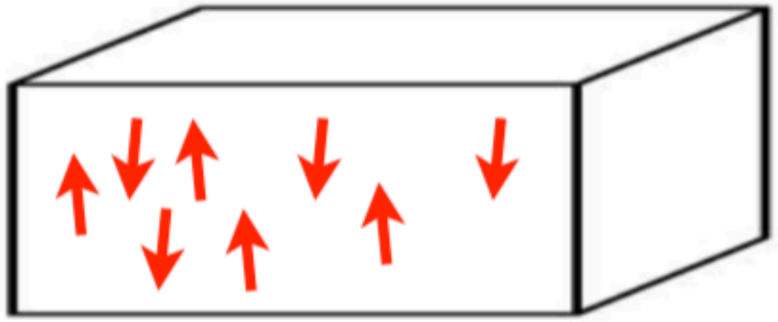

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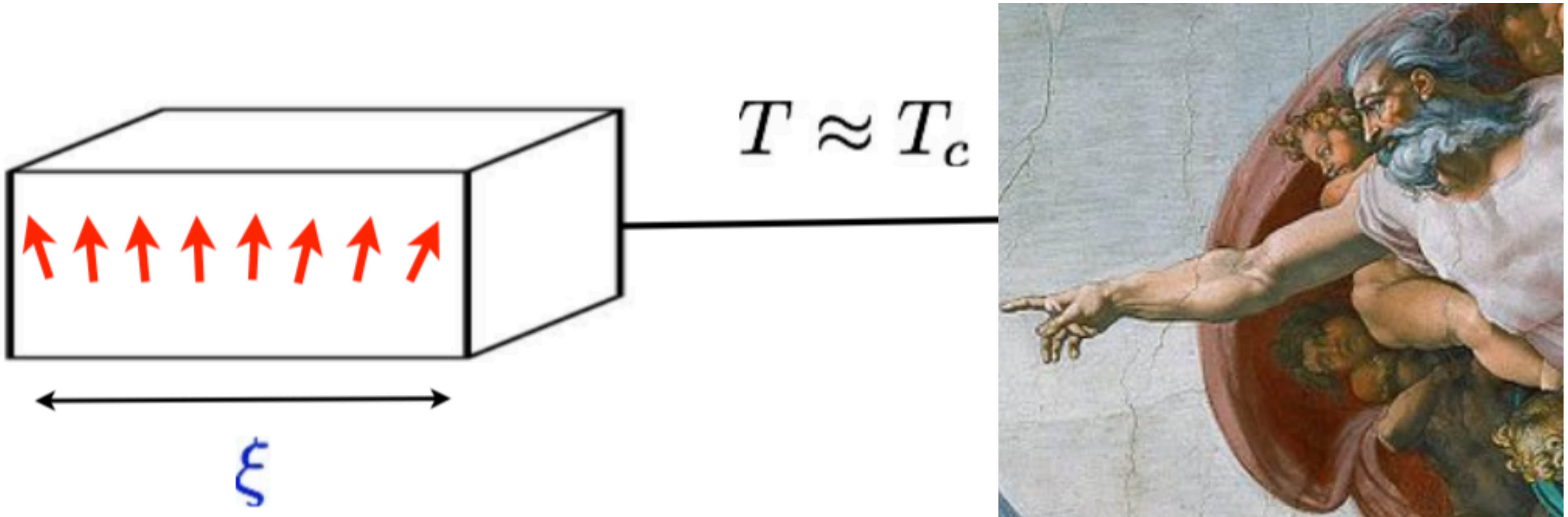


There is a strong analogy here to the theory of superconductivity.

$$F = F_0 + \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \dots$$

(Landau-Ginzburg free energy)

In 1950, Landau and Ginzburg proposed a phenomenological theory that explained many properties: the thermodynamics of the phase transition, the critical magnetic field, the presence of Type I and Type II, etc.

However, Landau Ginzburg gave no fundamental understanding of superconductivity. That was found only in 1957, by Bardeen, Cooper, and Schrieffer.

For the electroweak phase transition, we are still in the Landau-Ginzburg era.

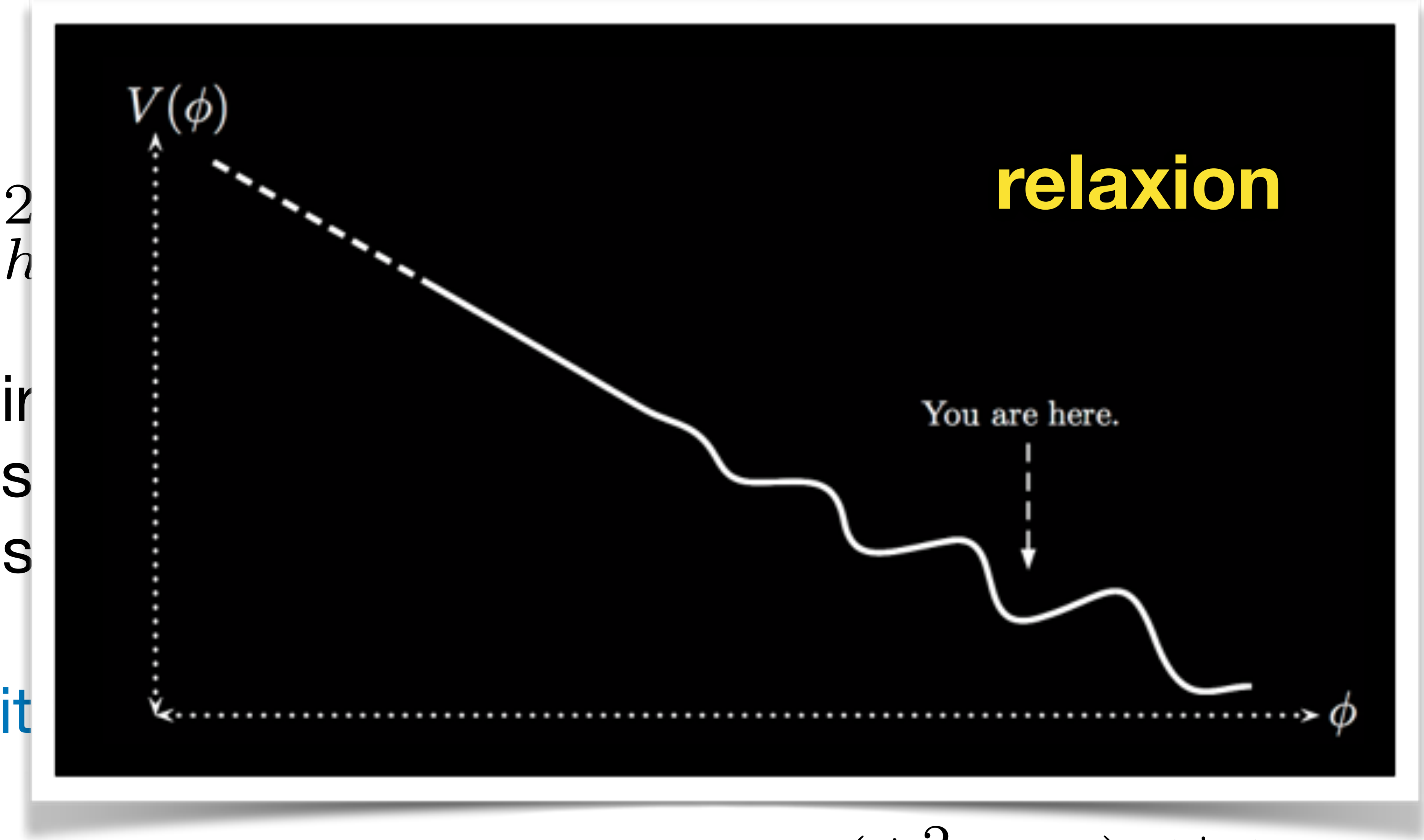
What are the options?

Solutions

- Protect $m_h^2\,\phi^*\phi$ by some symmetry
  - Susy: chiral symmetry. Super-multiplet (higgs,higgsino). Exact susy guarantees equal mass of fermion and higgs boson (also at quantum level).
  - Composite pGB Higgs: shift symmetry $\phi \to \phi + \alpha$
- Make Higgs mass dynamical and select $(\Lambda^2 - \varphi)\,\phi^*\phi$ vacuum with cosmological dynamics (Relaxion)

Solutions

- Protect m_h^2



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    Exact sus
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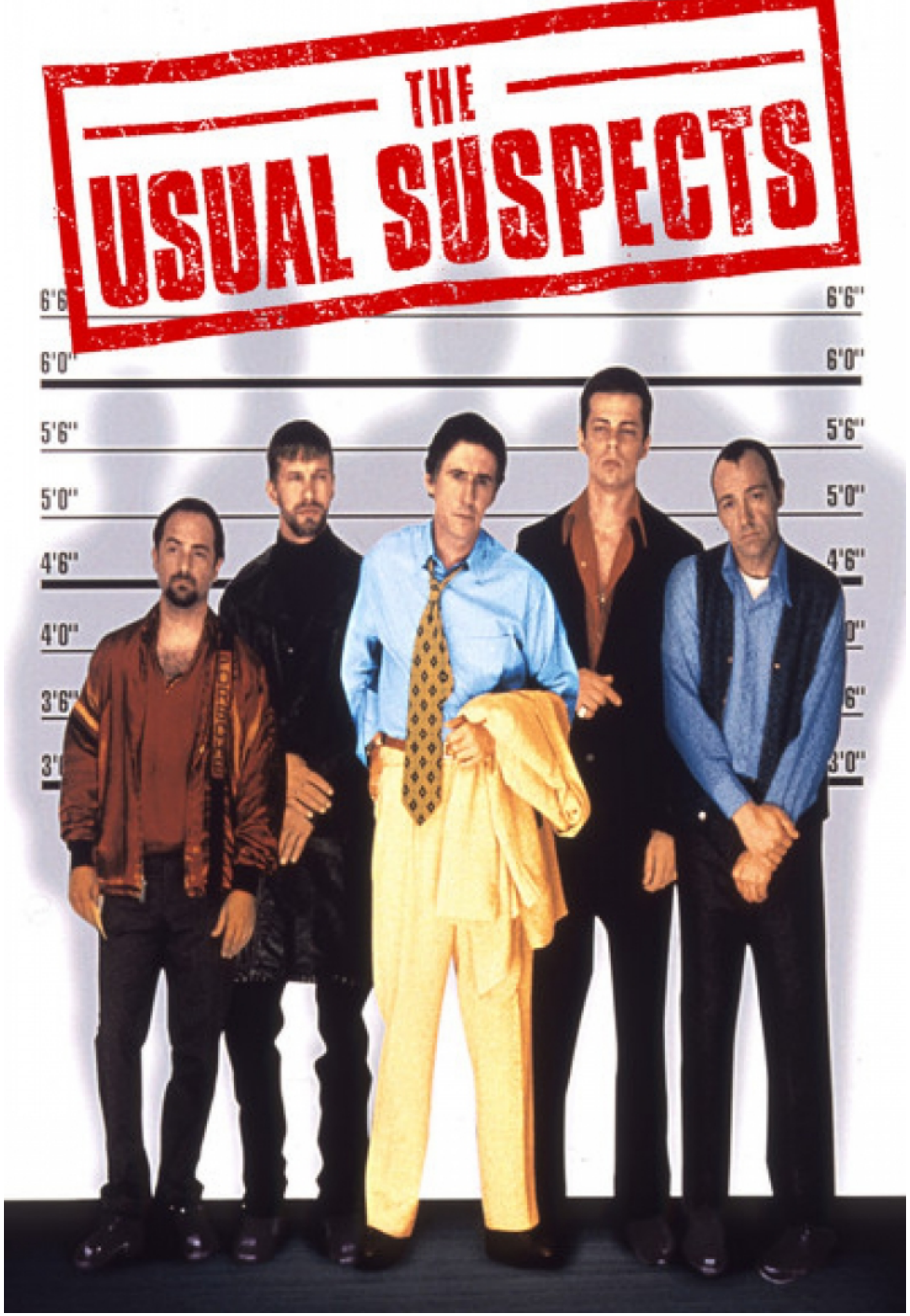


xMSSM

scalar top partners

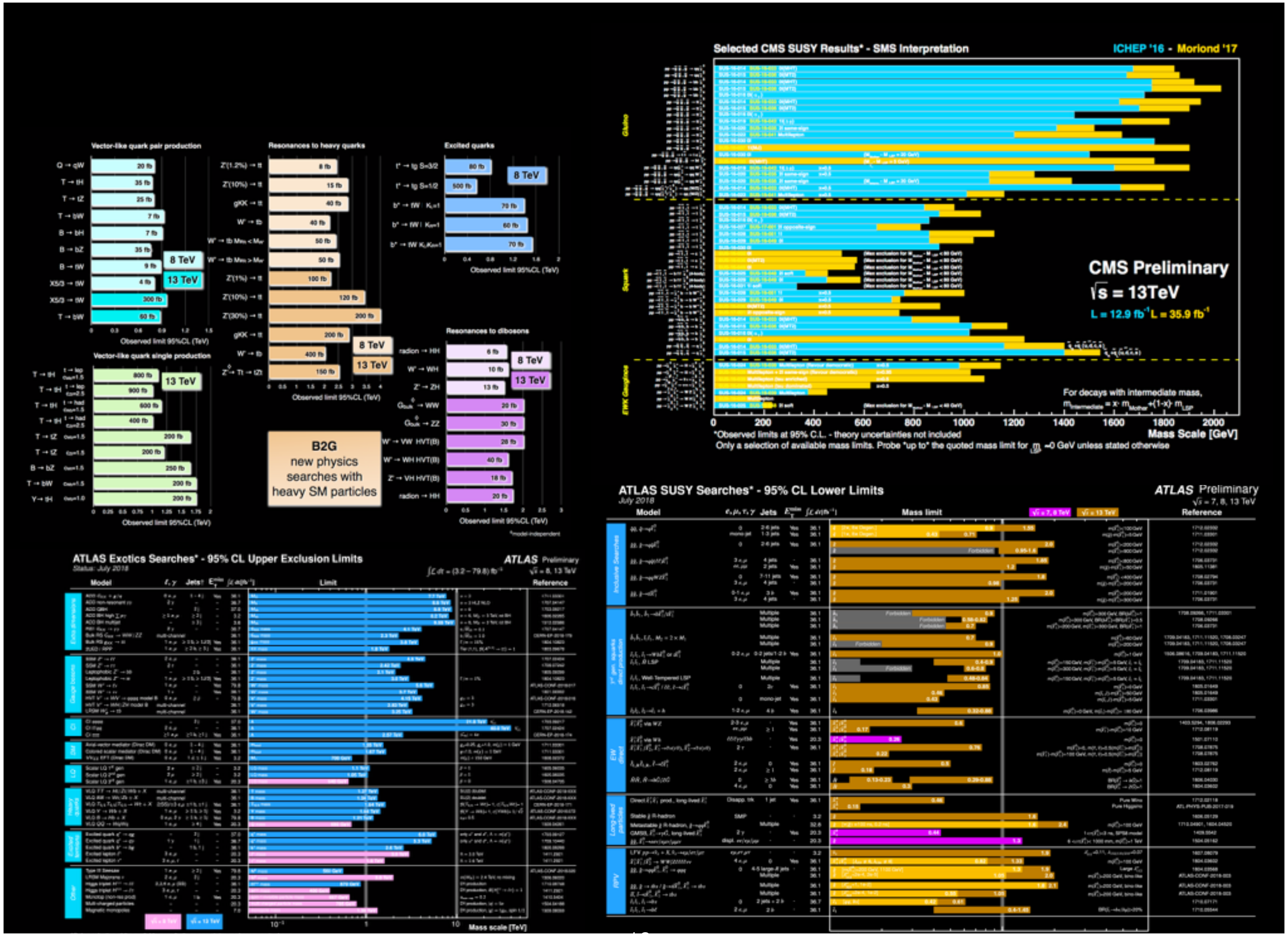
DM ✓

composite pGB Higgs

fermionic top partners

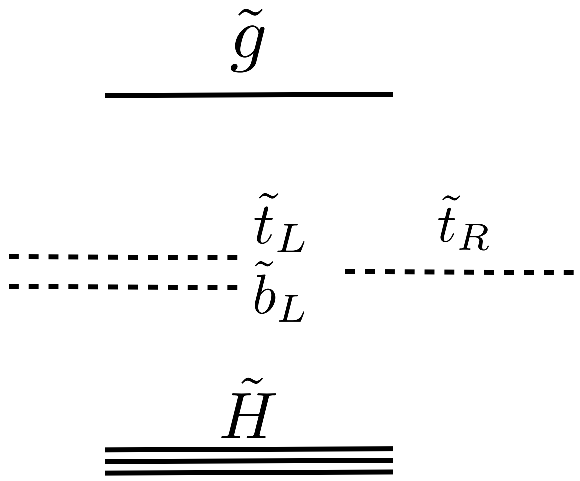
DM ?

Thus far…


Vector-like quark pair production
Resonances to heavy quarks
Excited quarks
8 TeV
13 TeV
Observed limit 95%CL (TeV)
Vector-like quark single production
Resonances to dibosons
B2G
new physics
searches with
heavy SM particles
Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP = 0 GeV unless stated otherwise
ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018
ATLAS Preliminary
√s = 8, 13 TeV
Model
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
Mass scale [TeV]

Minimally natural susy

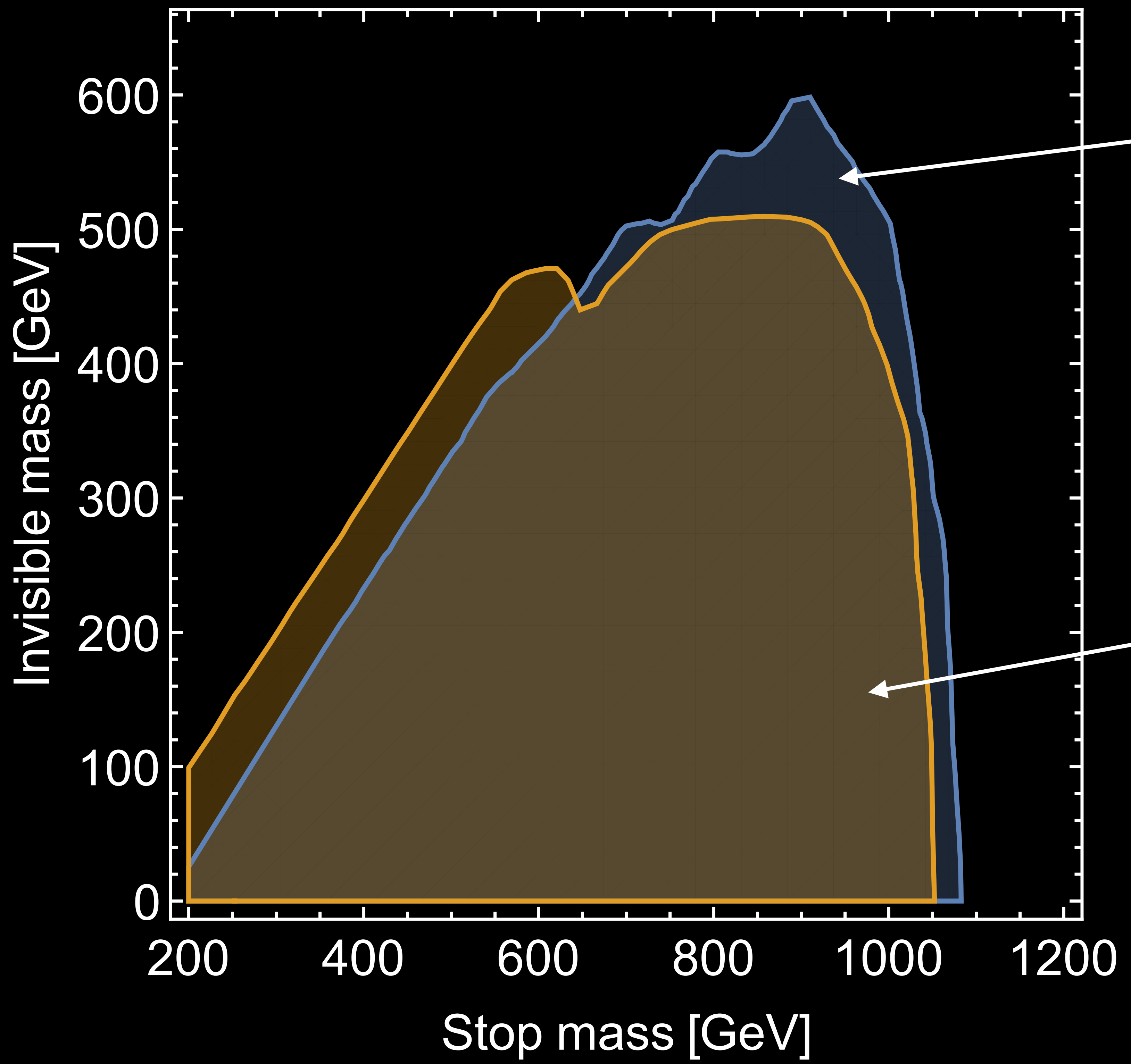
sparticle masses	δm_H^2 <<	vs current limits (13 TeV, 36 fb^{-1})
$\approx 1000\,\mathrm{GeV}$	2loop	**2020 GeV**
$\approx 500\,\mathrm{GeV}$	1loop	**1050 GeV**
$\approx 250\,\mathrm{GeV}$	tree	**145 GeV**



natural SUSY

O(1) departure from natural expectation!

Not for lack of trying

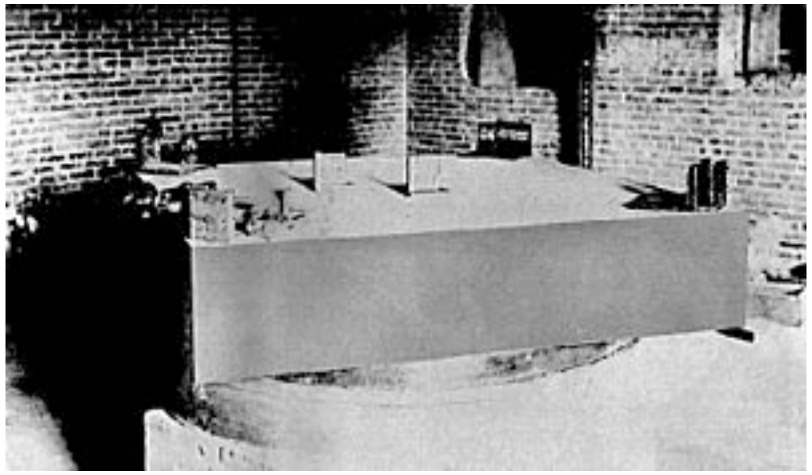


Projected reach
(c. 2012)
full LHC run
@ 14 TeV

CMS (e.g.)
exclusion w/
1/100 of full
LHC data set


ALICE
CMS
ATLAS
LHCb

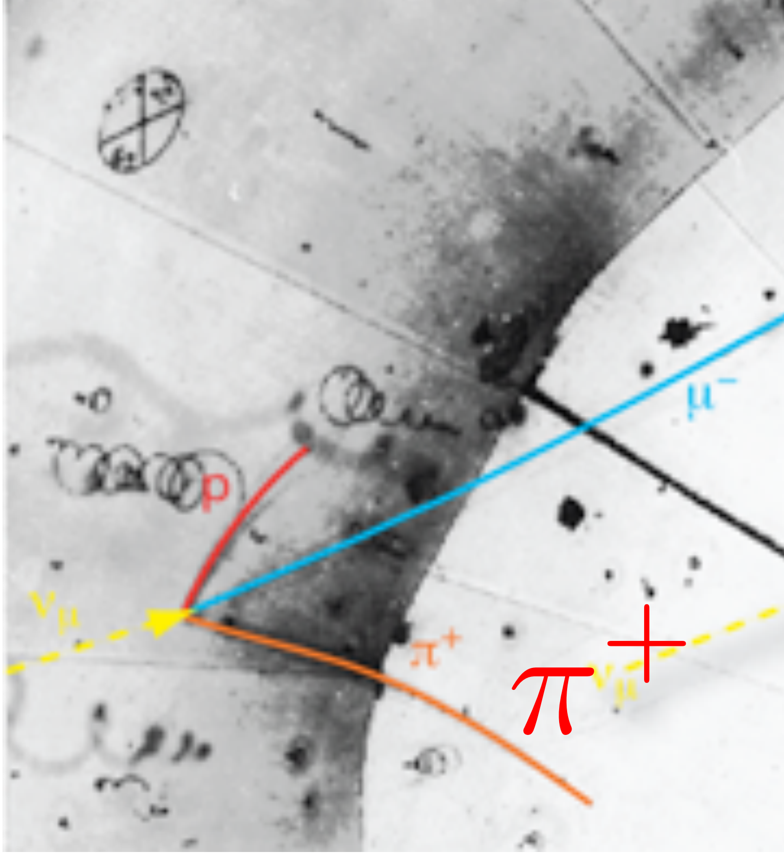
?
=



Recent development:
DM vs. composite Higgs

Composite Higgs & composite DM

Balkin, Ruhdorfer, Salvioni, **AW**



$$U = e^{i\pi/f}\langle\phi\rangle \quad \mathcal{L}_{\rm eff} = \frac{f^2}{4}\,{\rm tr}(\partial_\mu U^\dagger \partial^\mu U) + \ldots$$

- Higgs and DM are pseudo Goldstone bosons
- Same symmetry that protects Higgs mass also stabilises DM

(analog to R parity in SUSY)

Composite Higgs & composite DM

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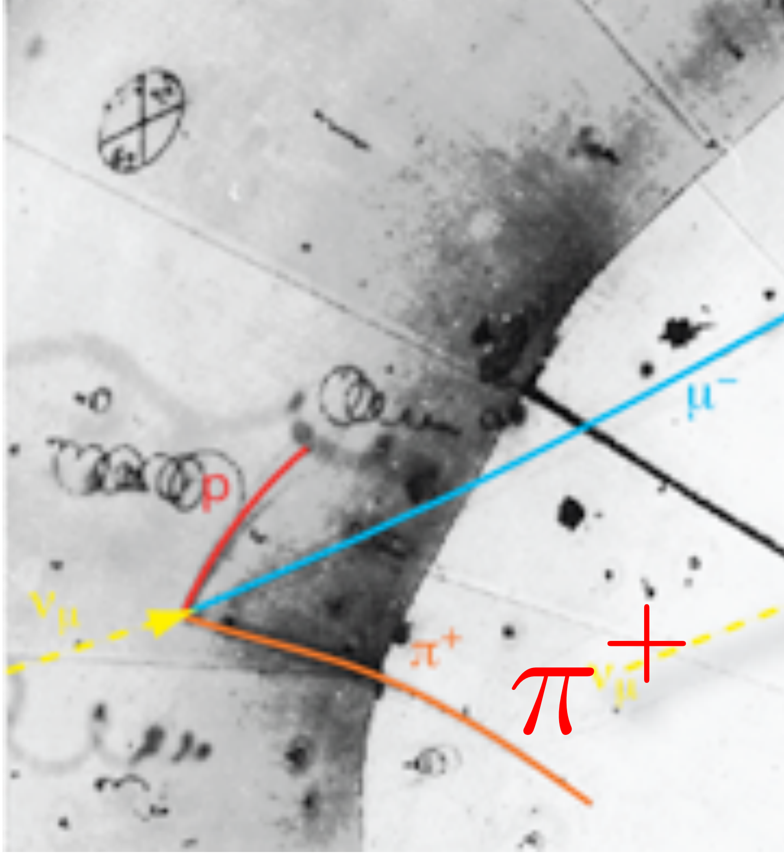

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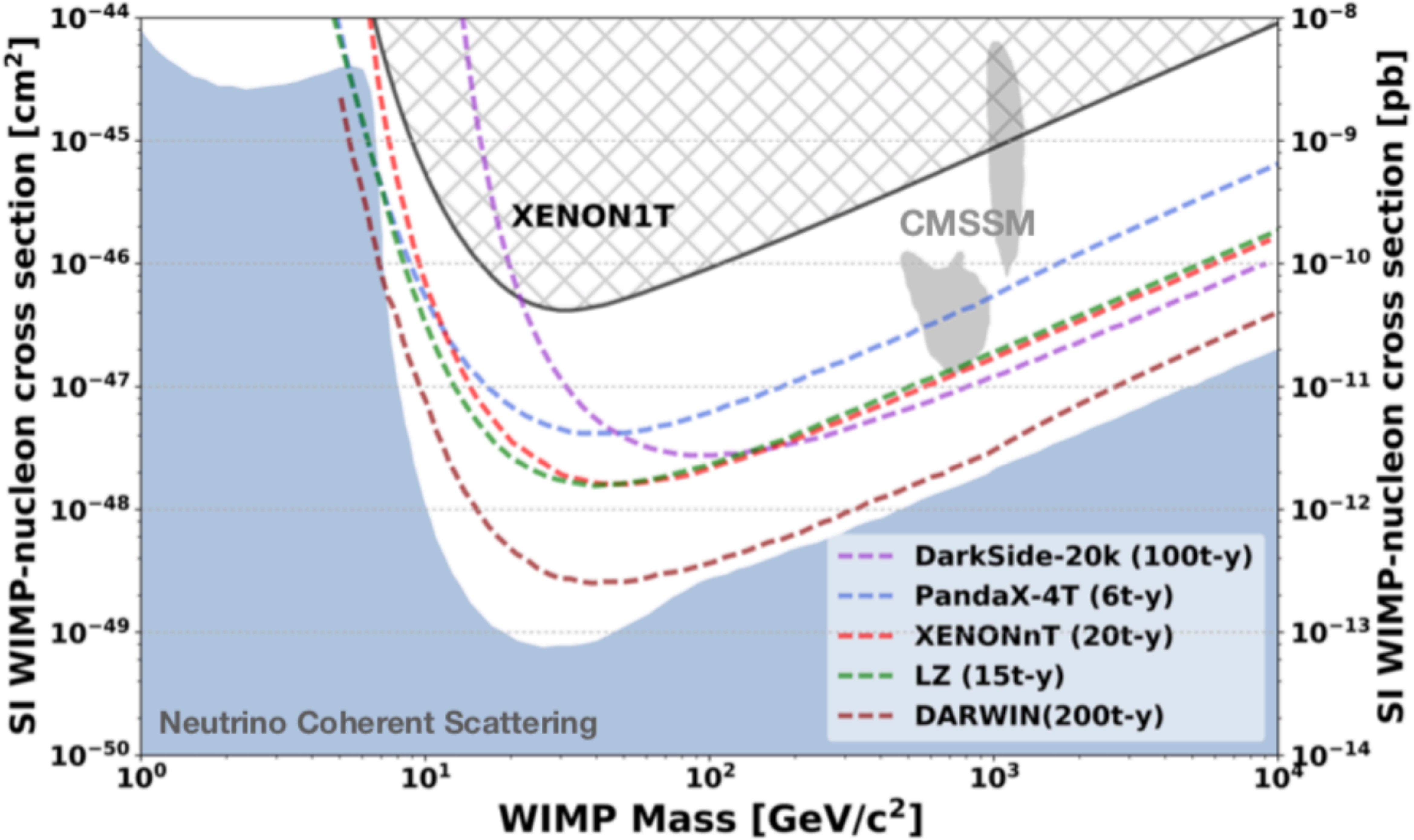
- Higgs and DM are pseudo Goldstone bosons

- Same symmetry that protects Higgs mass also stabilises DM

$$\boxed{\pi \longrightarrow -\pi} \qquad (U \to U^\dagger)$$

(analog to R parity in SUSY)

WIMPs are getting squeezed



Goldstone DM

$$\chi \to \chi + f$$ GB shift symmetry

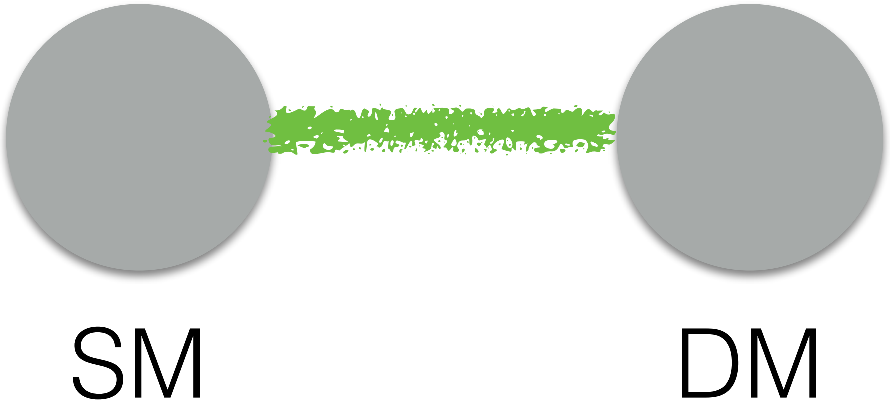
Only sizeable coupling between DM and SM:

$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi) + \dots$$

Neglible direct detection signal:

$$\frac{E^2_{\rm recoil}}{f^2} \sim \frac{(100{\rm MeV})^2}{(1{\rm TeV})^2} \sim 10^{-8}$$

$$\mathcal{L}_{SM}(h) + \mathcal{L}_{DM}(\chi) + \lambda h^2 \chi^* \chi + \underline{\frac{1}{f^2}\partial_\mu (h^2) \partial^\mu (\chi^* \chi)} + \ldots$$



see e.g.1607.02474

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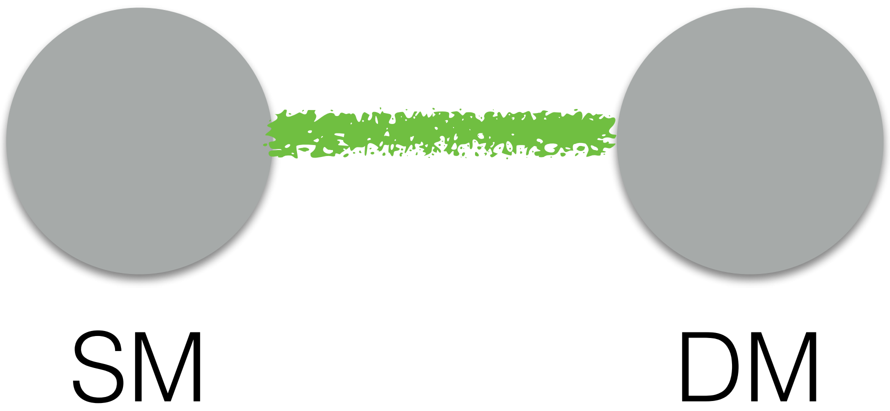

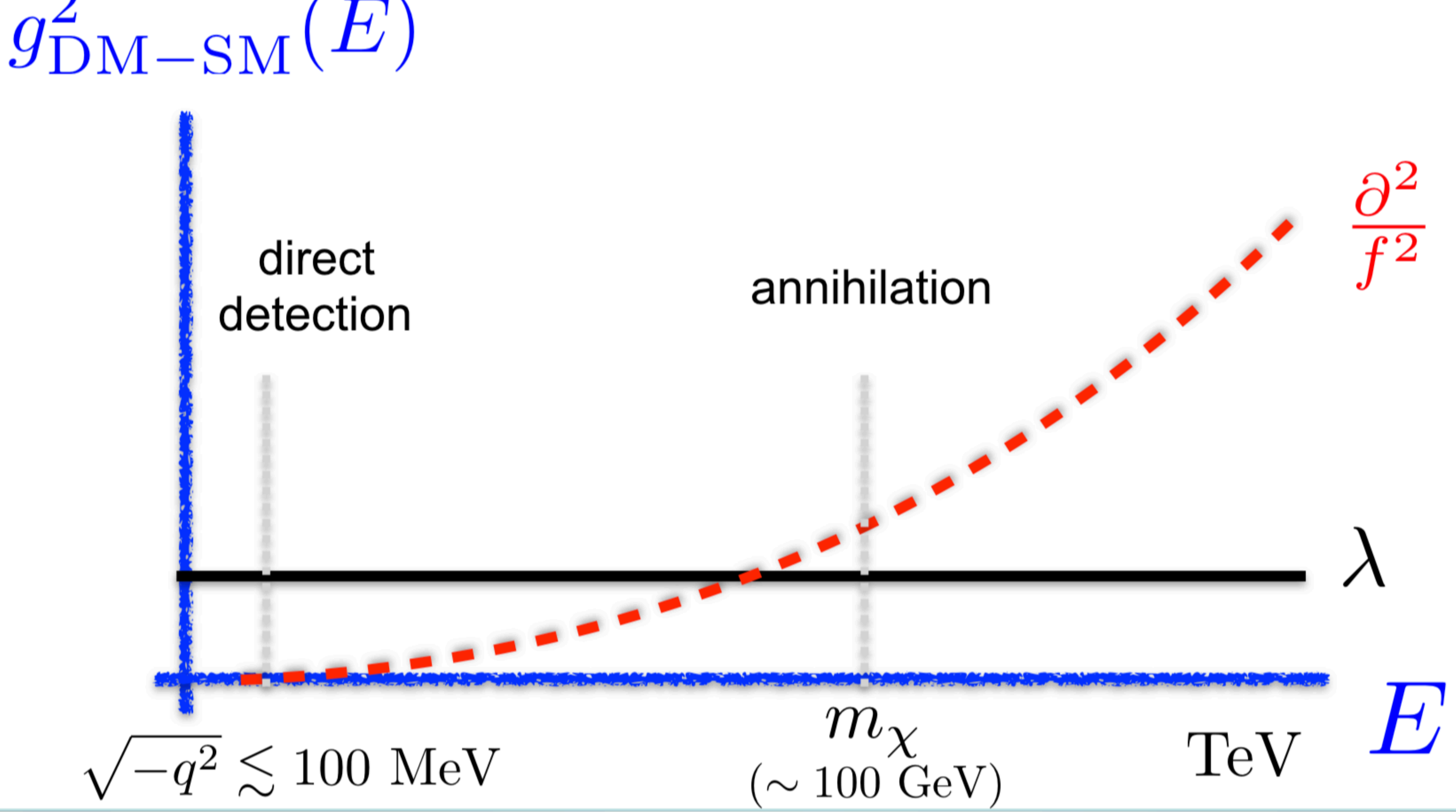

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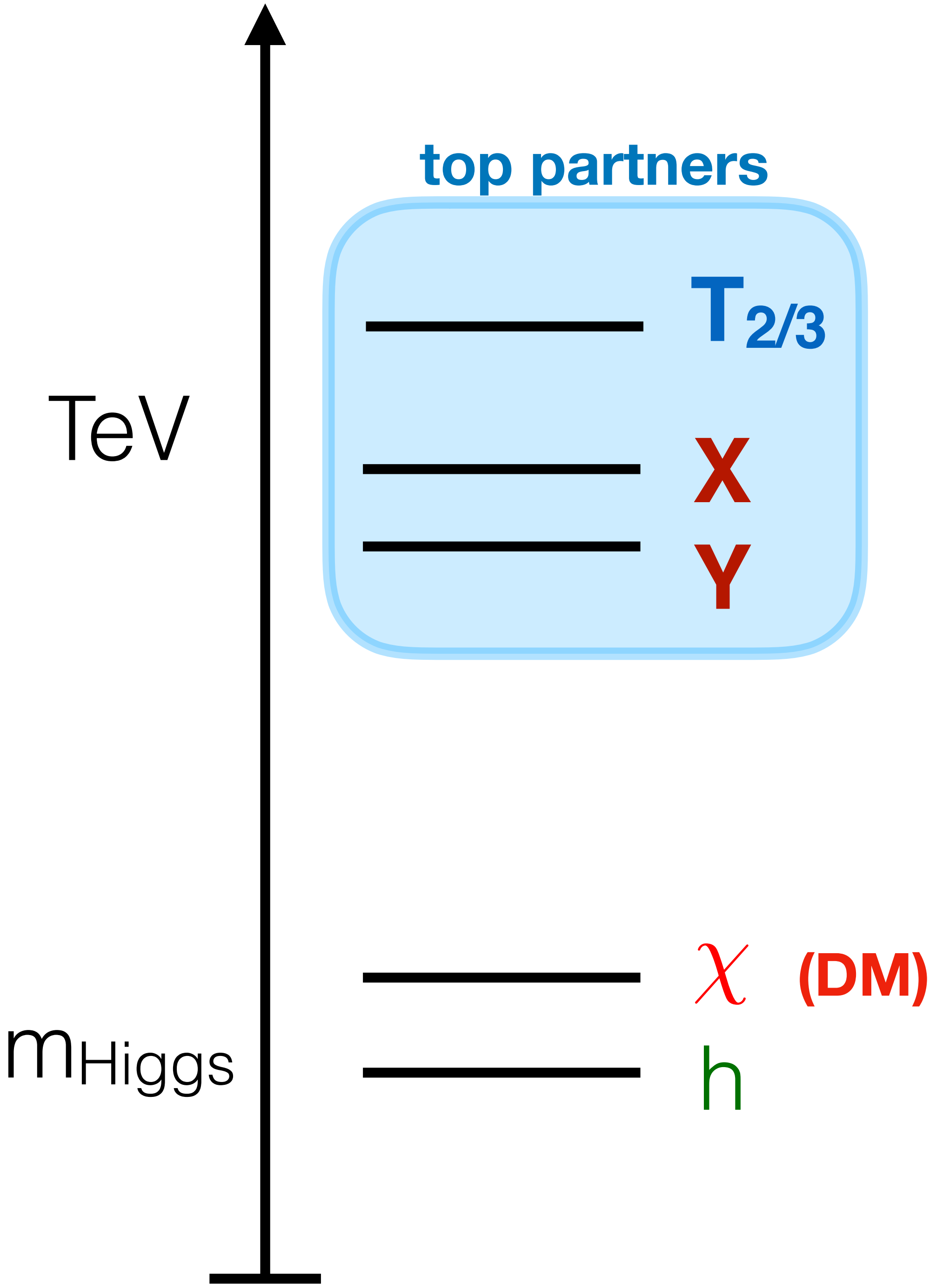
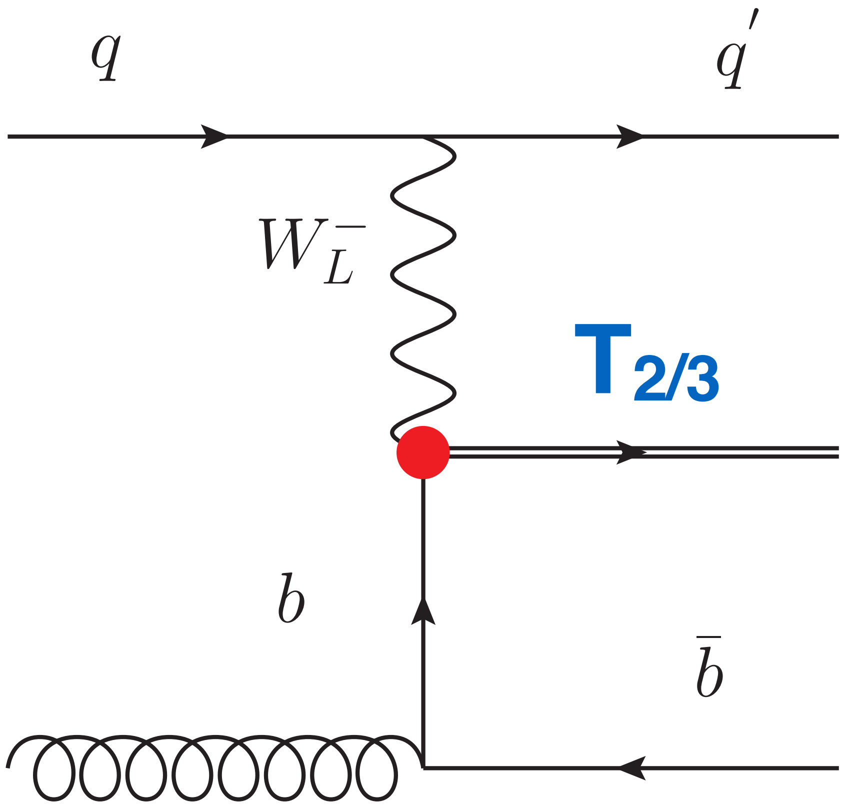
Fermionic top partners+ MET



new signatures (single top +MET)



$$\mathrm{BR}(S \to \chi^* \mathcal{Y}) = \mathrm{BR}(S \to \chi \mathcal{Z}) \simeq \frac{1}{6}\,.$$

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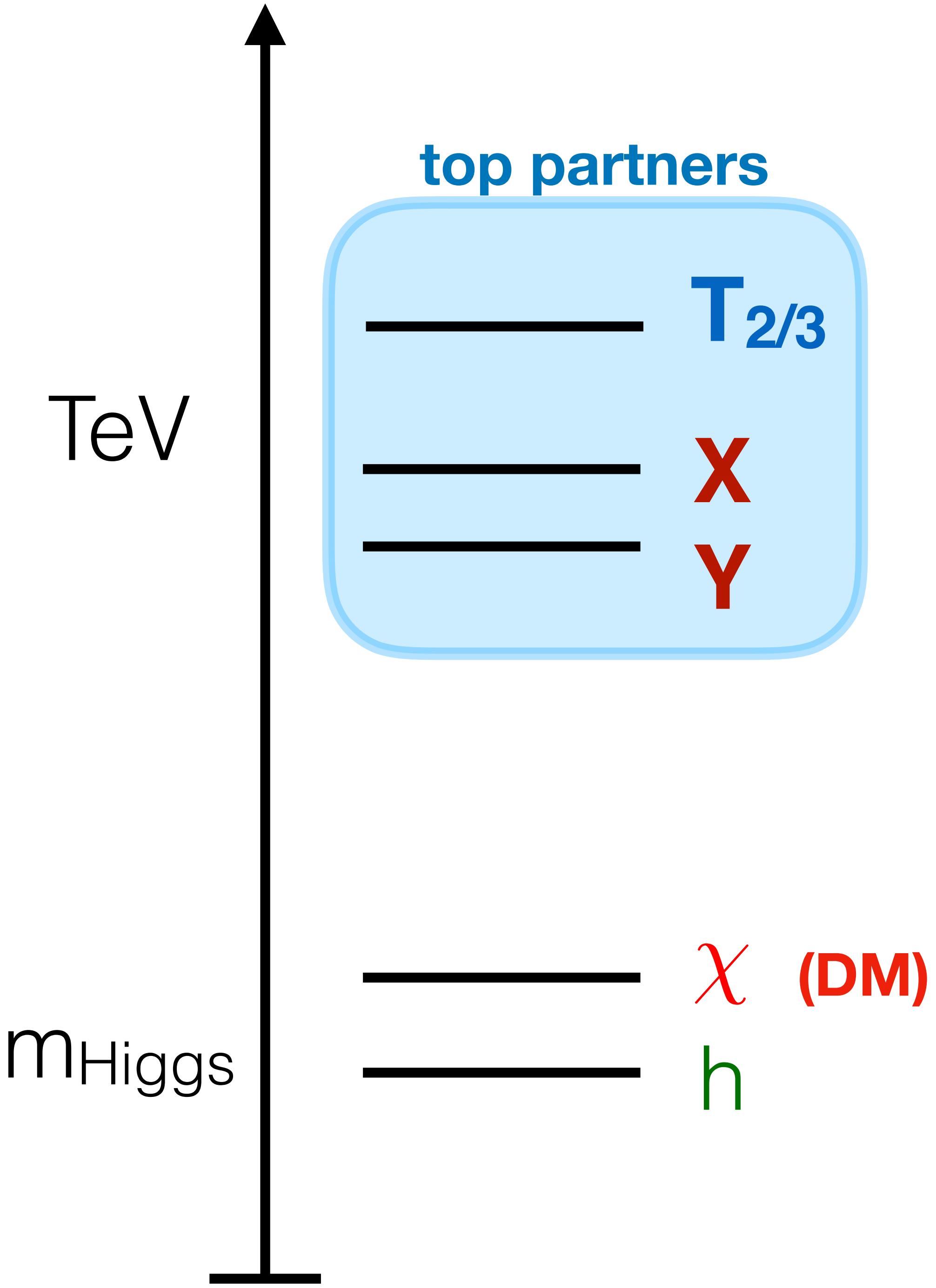

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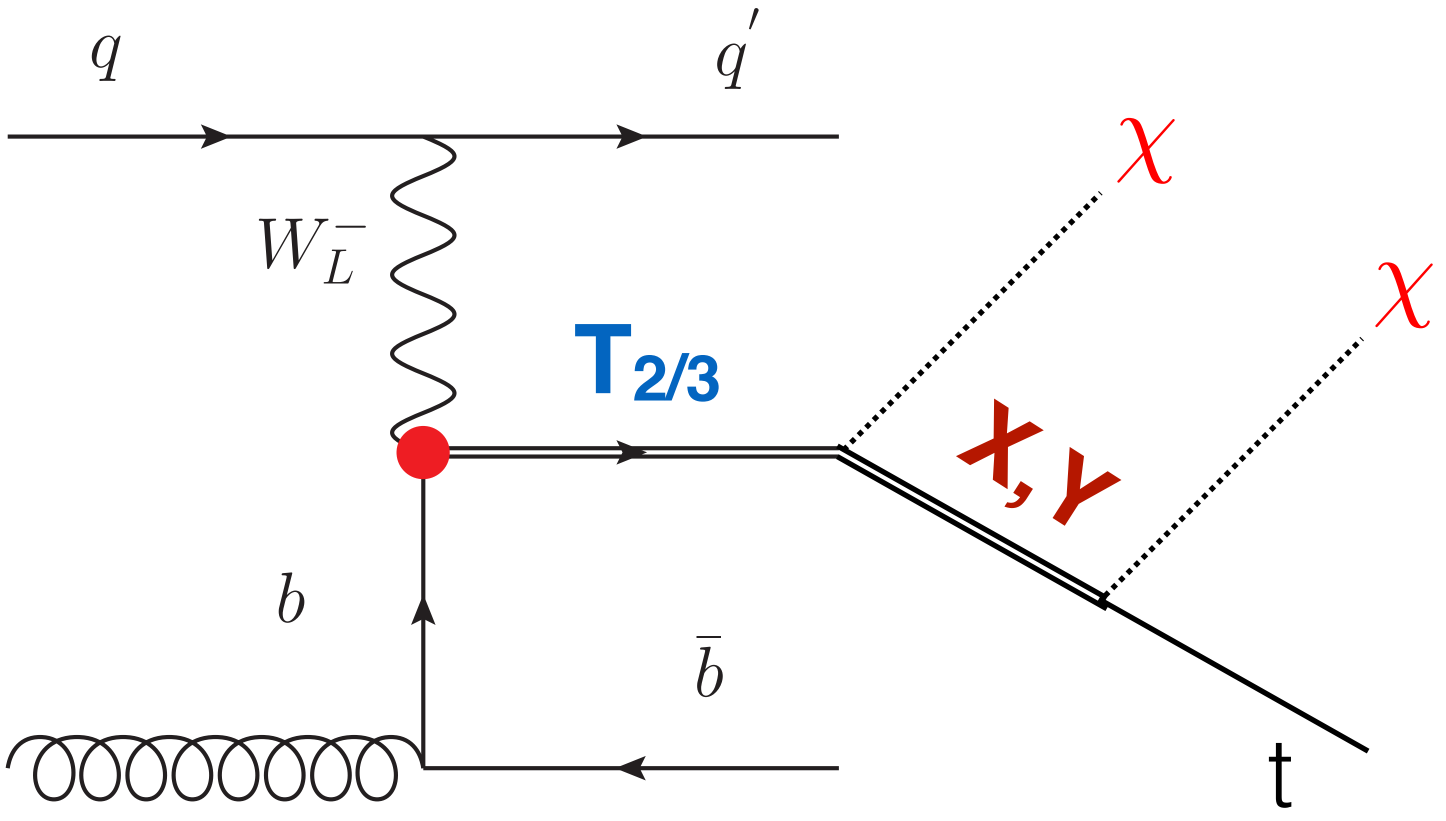

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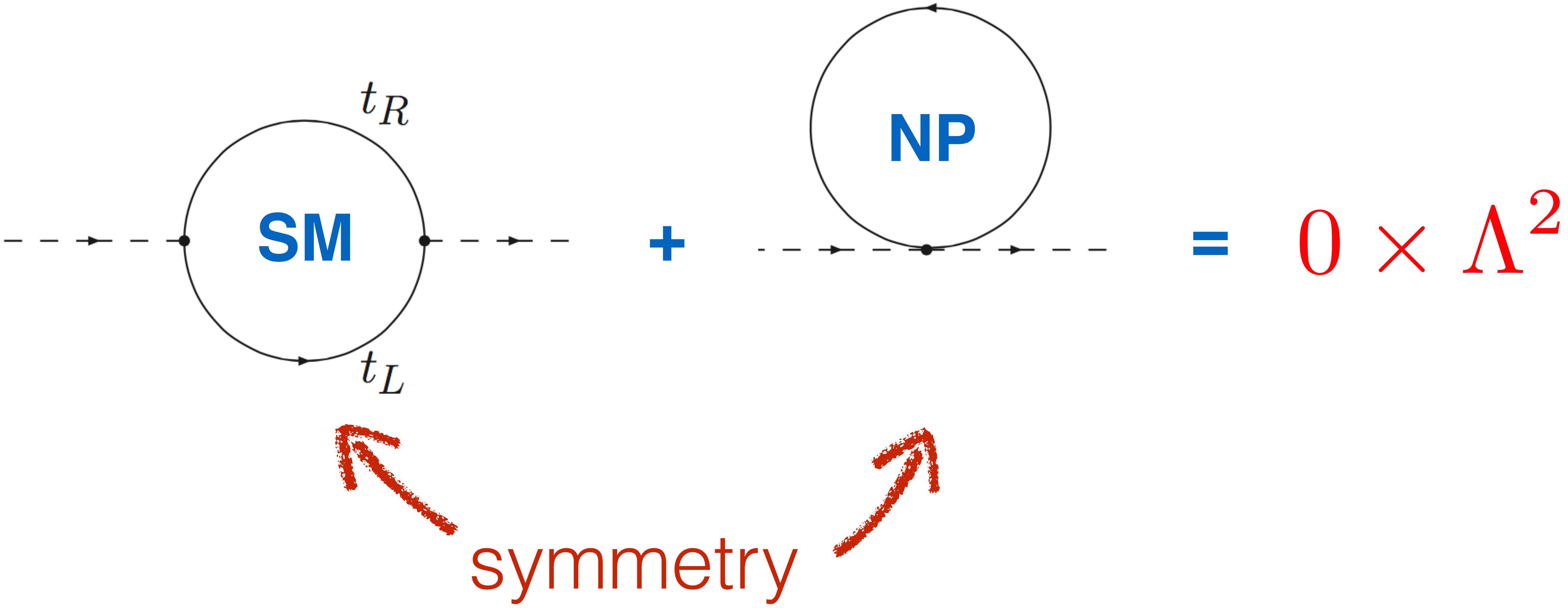
Unusual suspects

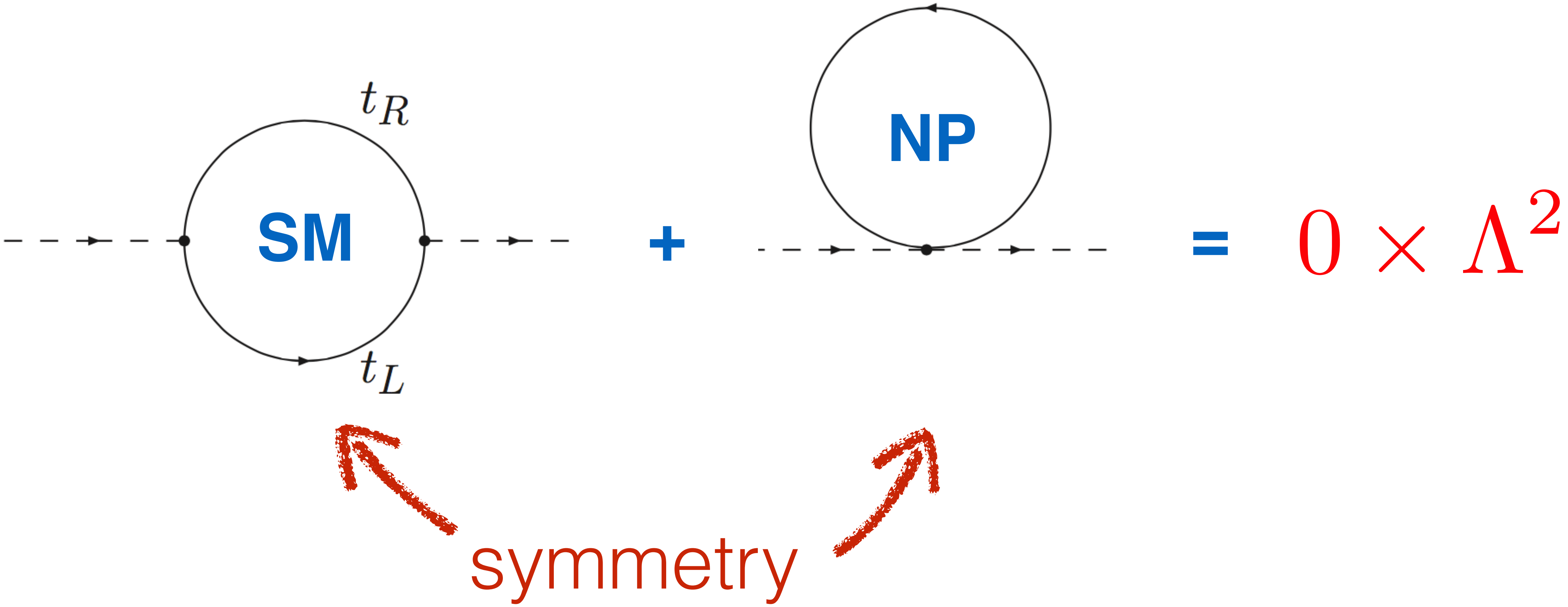
The unusual suspects



SM + NP = $0 \times \Lambda^2$

symmetry

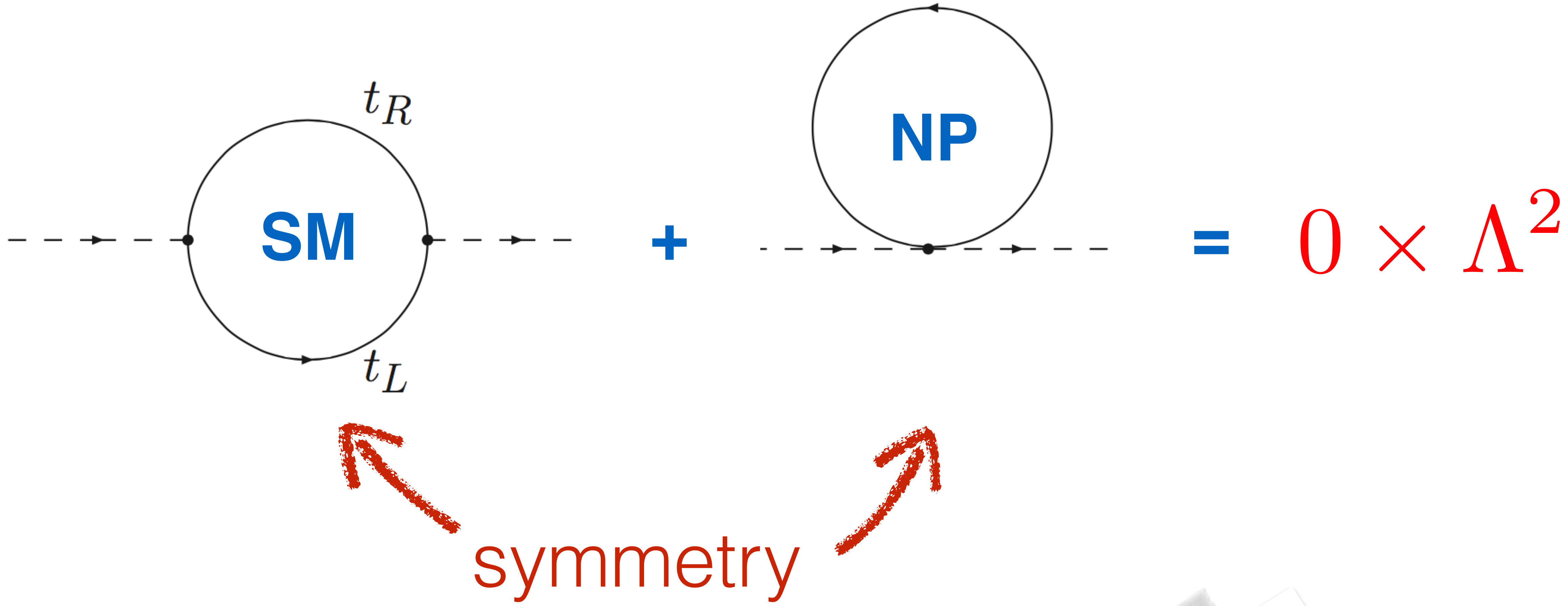
The unusual suspects



NP is related to the top by a symmetry, natural new particle mass around TeV

Symmetry commutes with color: NP will be produced copiously at the LHC!

The unusual suspects



NP is related to the top by a symmetry, natural new particle mass around TeV

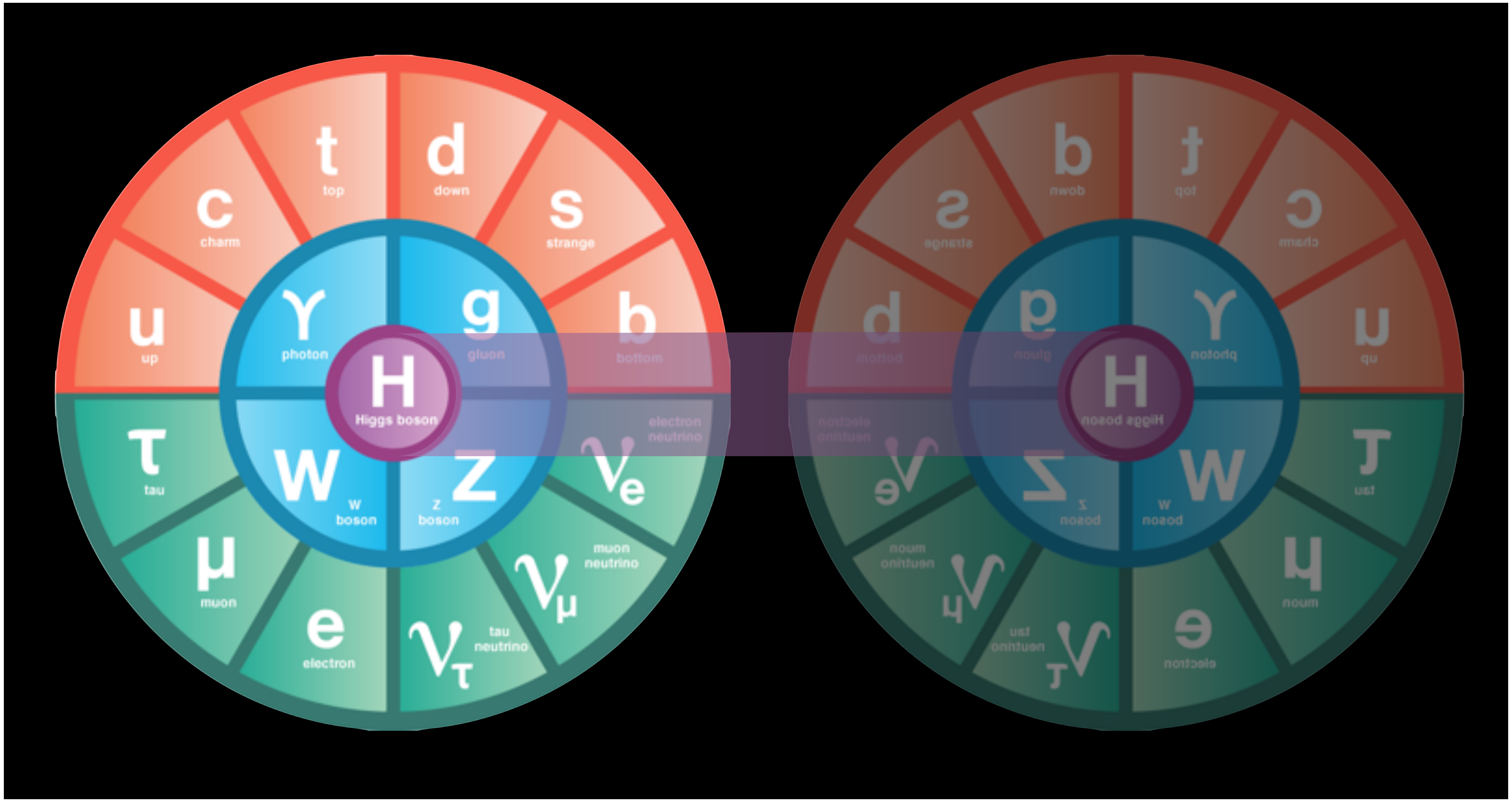
Symmetry s with
color: N produced
copious ne LHC!

Not true!

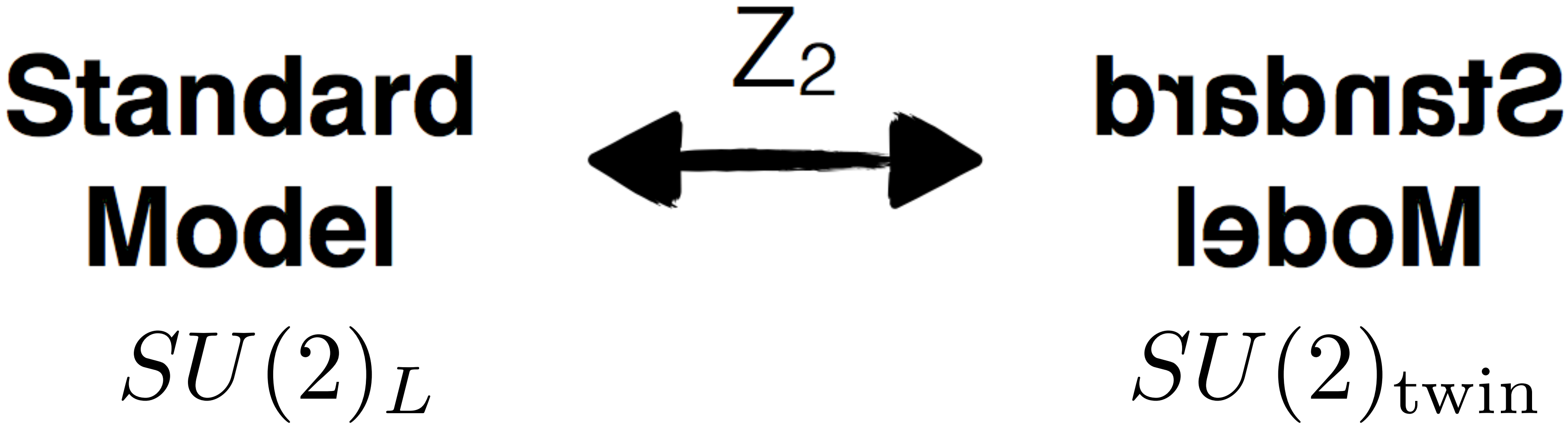
Twin Higgs & co

Chacko, Goh, Harnik ’05

New ingredient: discrete symmetry



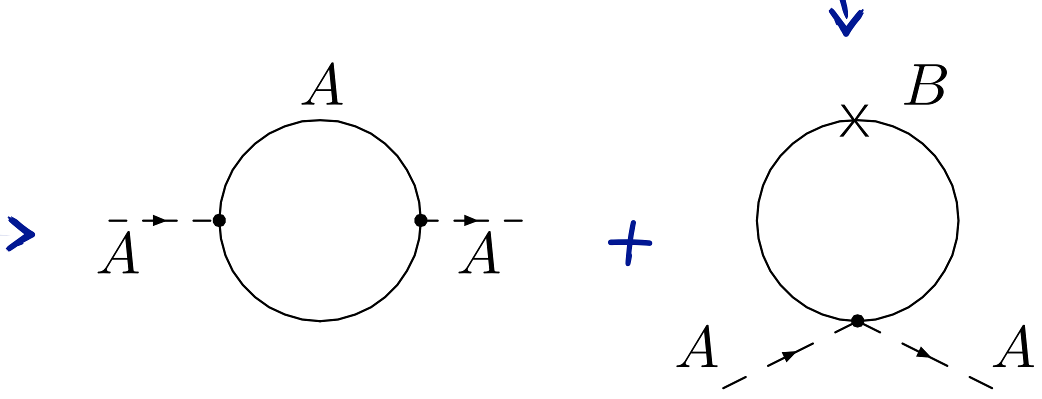
Twin Higgs



Quadratic divergences from SM top quark loops cancelled by loops of “Twin” top quarks.

$$\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$$

$$= y_t h \, \bar{t}_A t_A + y_t \left(f - \frac{|h|^2}{2f} \right) \bar{t}_B t_B + \dots$$



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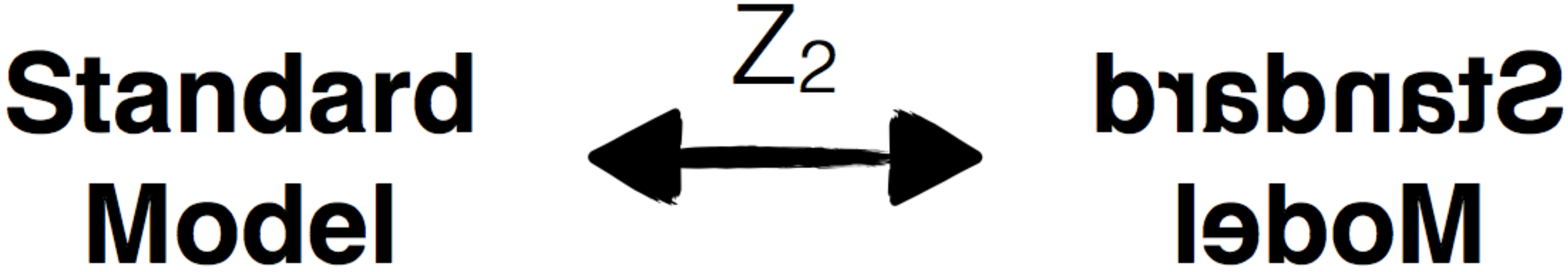

$$SU(2)_L \qquad\qquad SU(2)_{\text{twin}}$$

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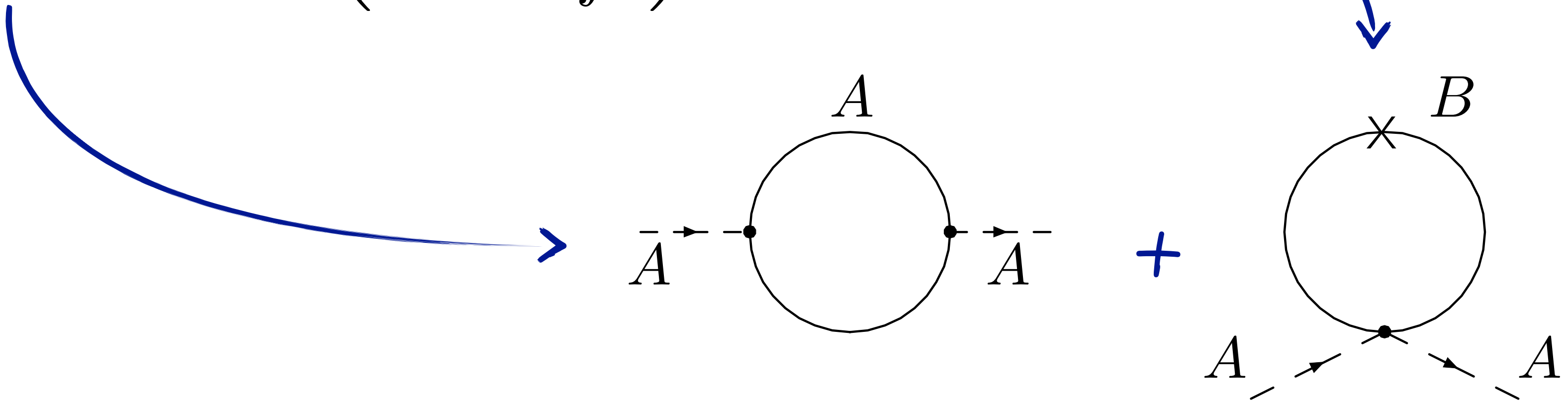
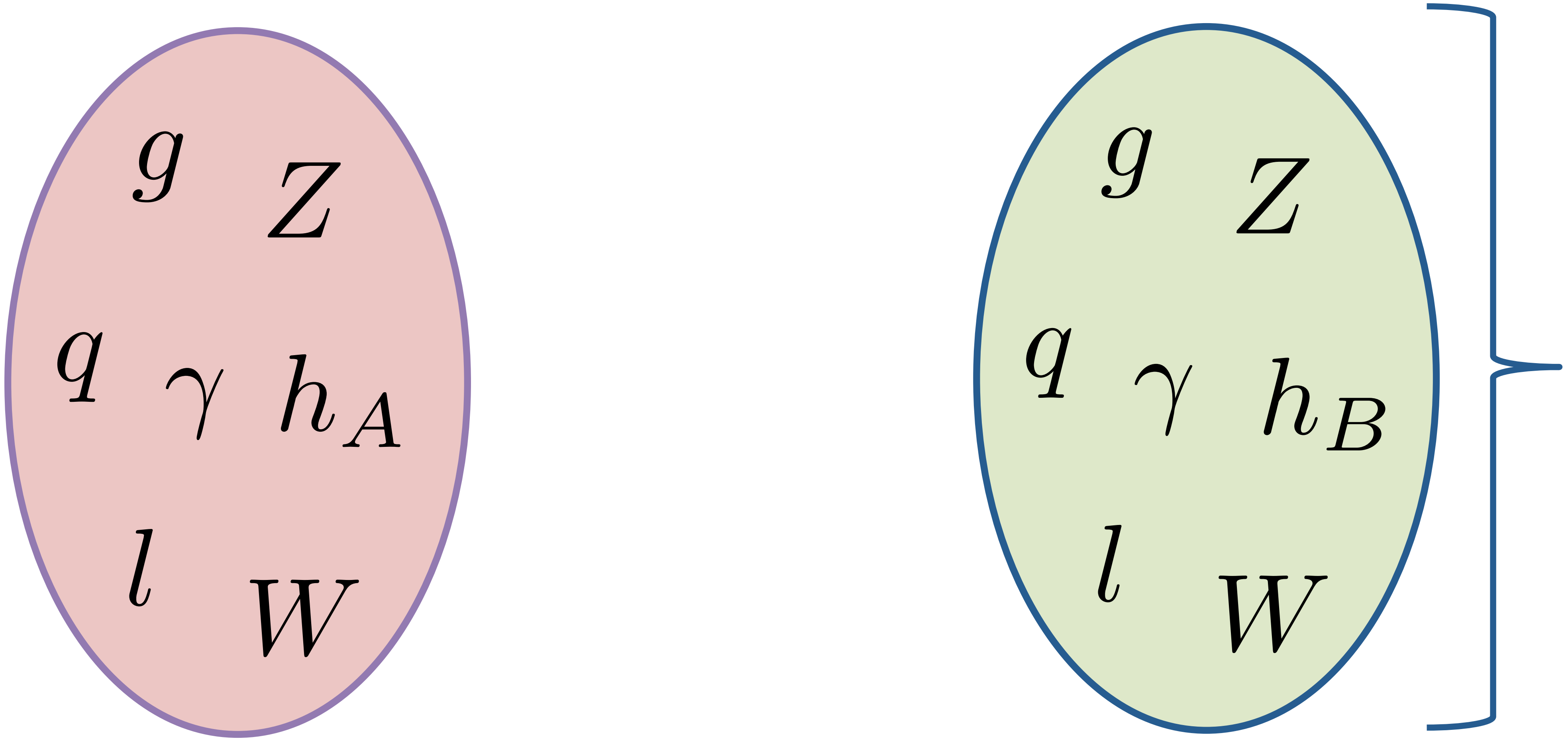


$$= 0 \times \Lambda^2$$

Standard Model

“Twin” Standard Model

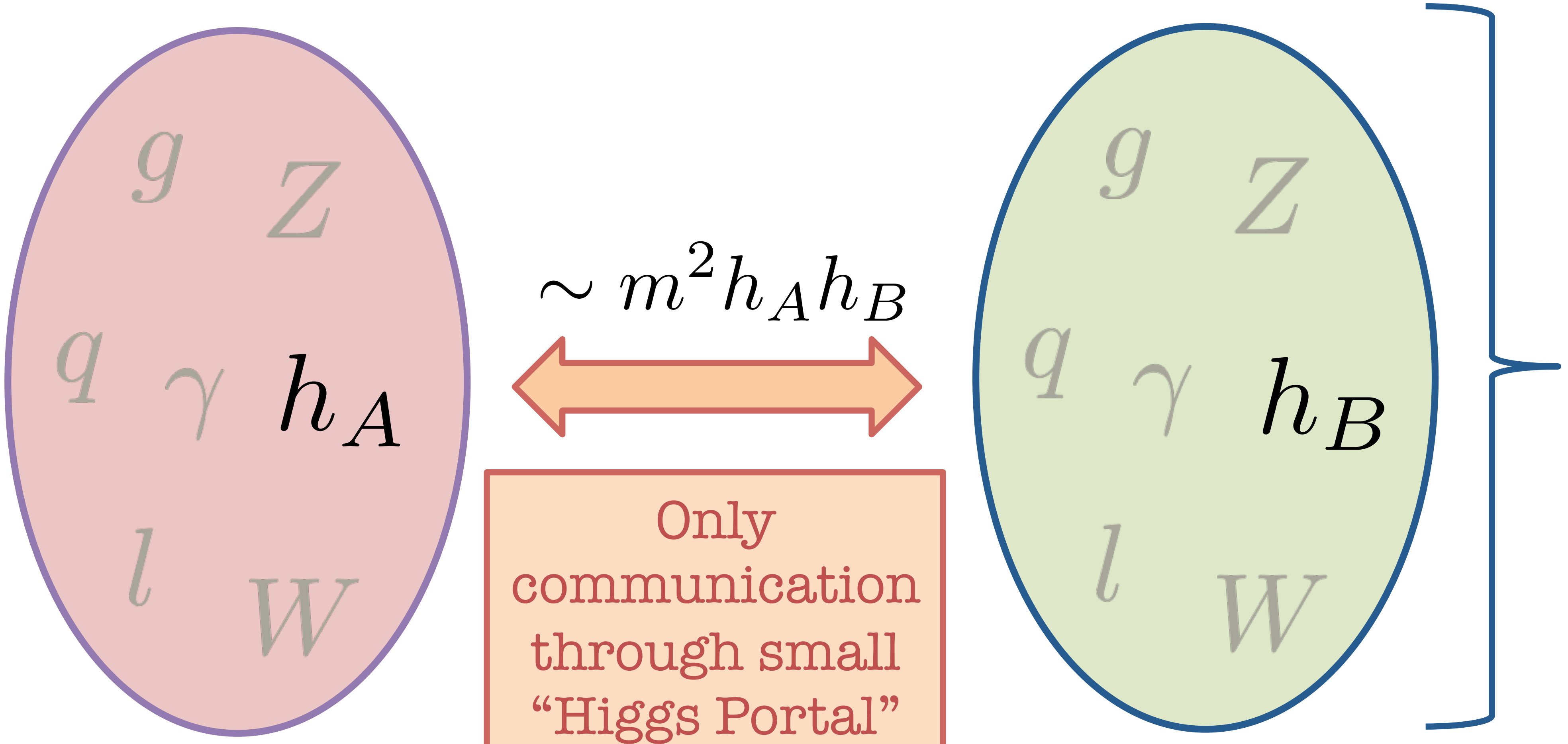


These fields completely neutral: “Neutral Naturalness”

Predictions for Twin sector most robust for the Twins of the SM fields that couple most strongly to Higgs.

Standard Model

“Twin” Standard Model

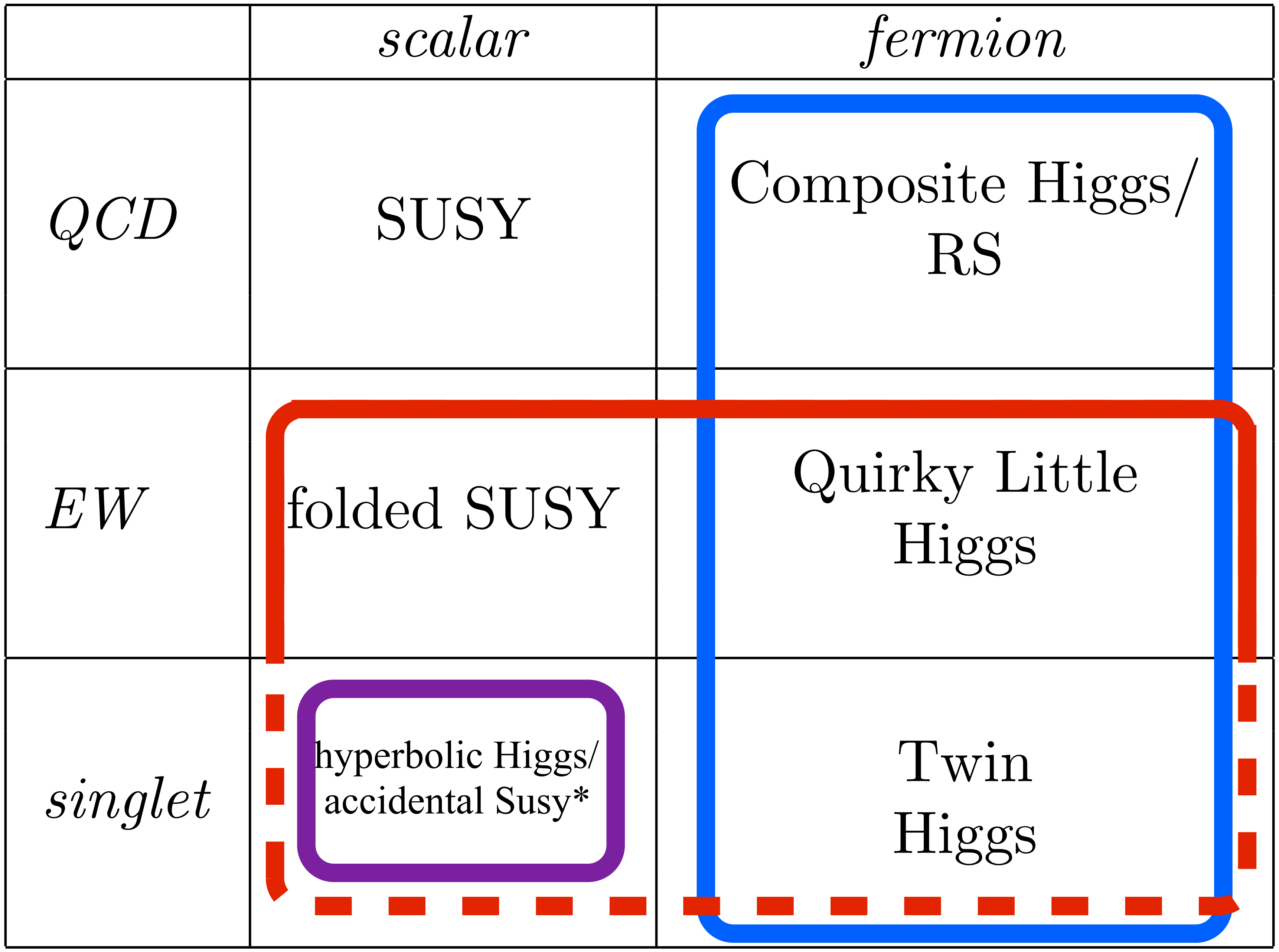


$\sim m^2 h_A h_B$

Only communication through small “Higgs Portal” mixing

These fields completely neutral: “Neutral Naturalness”

LHC production **top partner spin**



		scalar	*fermion*
strong direct production	*QCD*	SUSY	Composite Higgs/ RS
DY direct production	*EW*	folded SUSY	Quirky Little Higgs
Higgs portal direct production	*singlet*	hyperbolic Higgs/ accidental Susy*	Twin Higgs

Mirror Glueballs

Higgs portal observables

Higgs coupling shifts

$\sim$ tuning

* Cohen… '18, Cheng, Li, Salvioni, … '18

Why not?

Higgs portal maintains equilibrium down to T~GeV

$\Delta N_{\mathrm{eff}} >> 1$

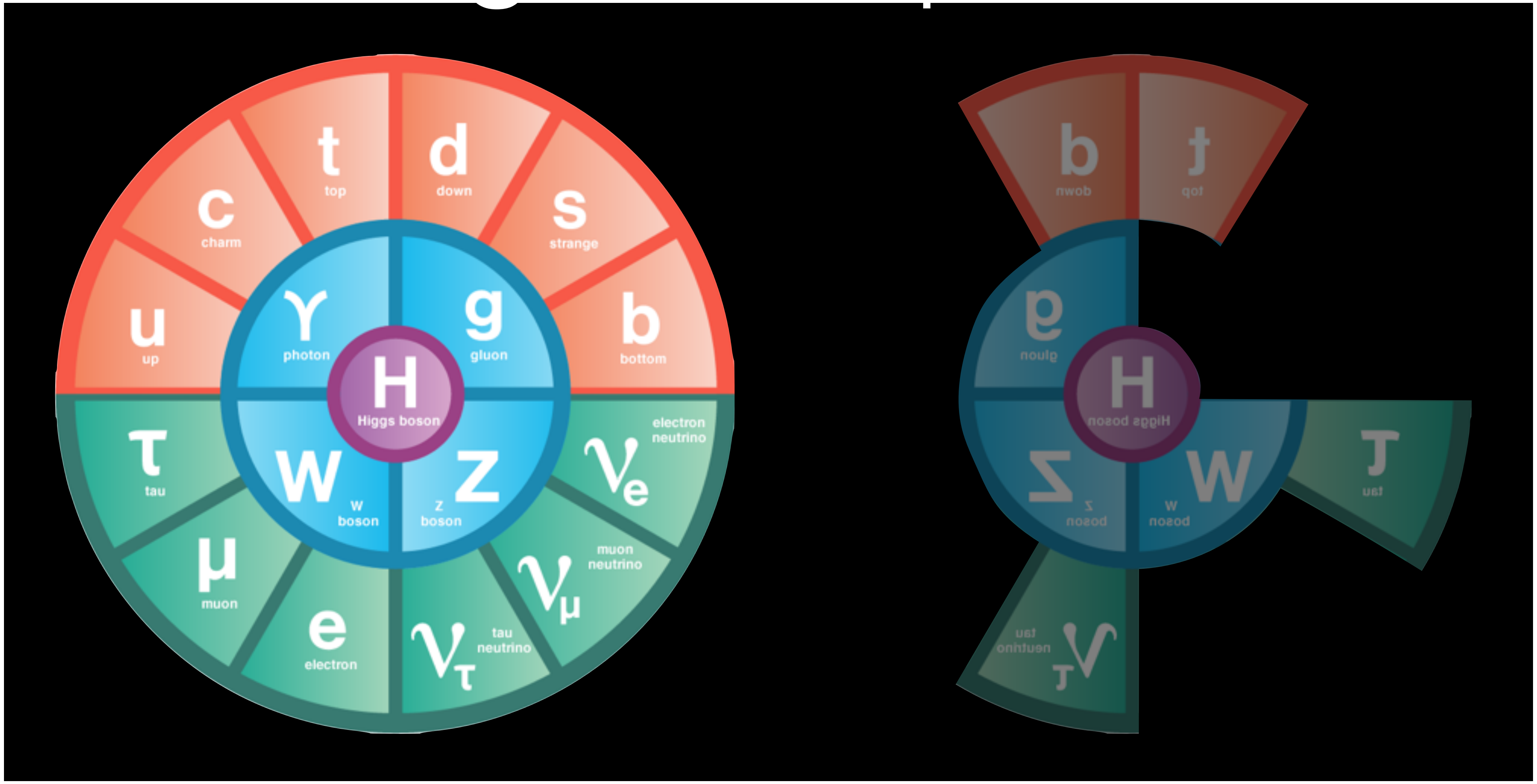
$$\Delta N_{\mathrm{eff}} \lesssim 0.6$$

This is excluded by CMB measurements…

1) change cosmology

2) change spectrum

only 3rd generation twinned



“fraternal twin Higgs”

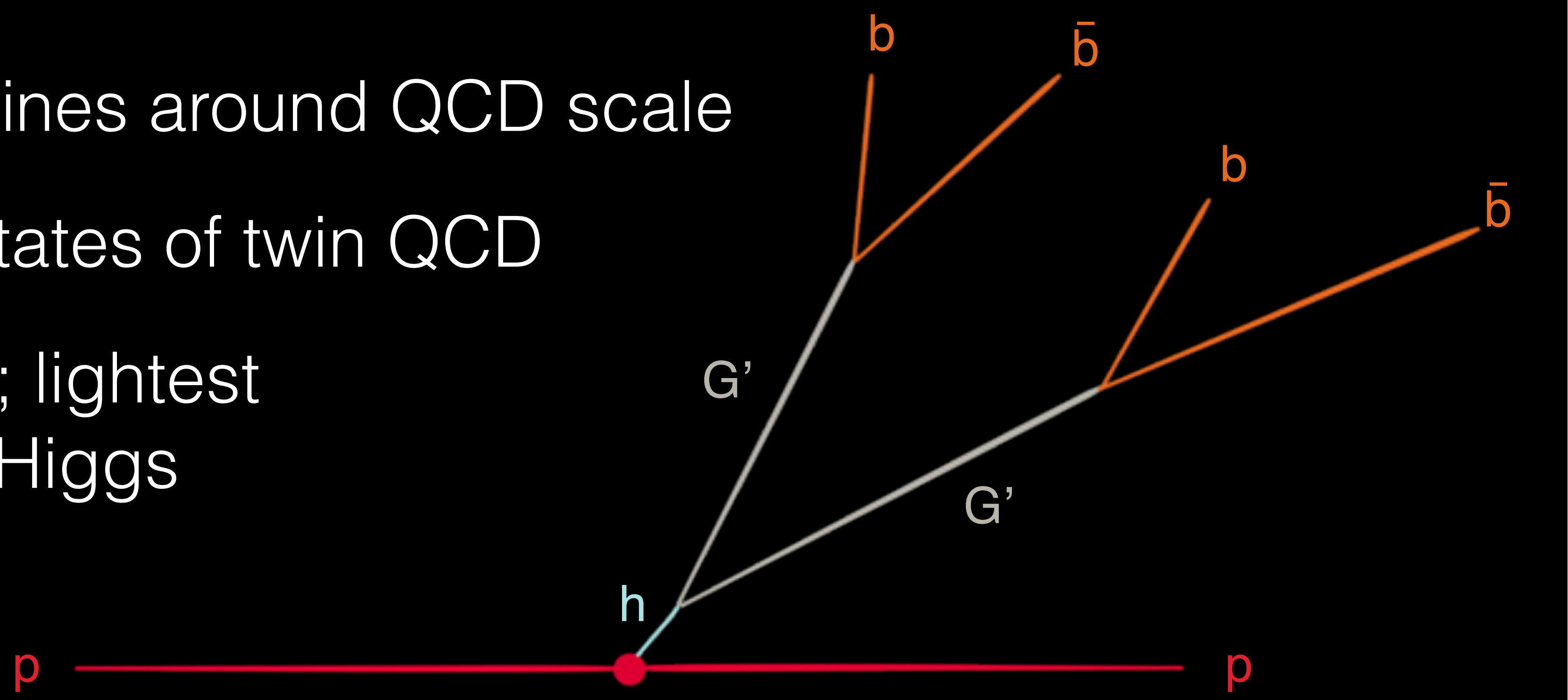
Craig et al ‘18

[Craig,Katz, Strassler, Sundrum ’15; Curtin, Verhaaren ‘15]
[Serra, Stelzl, AW’18]

Exotic Higgs Decays

- Must have twin QCD, confines around QCD scale
- Higgs couples to bound states of twin QCD
- Glueballs most interesting; lightest have same quantum # as Higgs

$$\mathcal{L} \supset \frac{v}{f}\frac{h}{f} G'_{\mu\nu} G'^{\mu\nu}$$



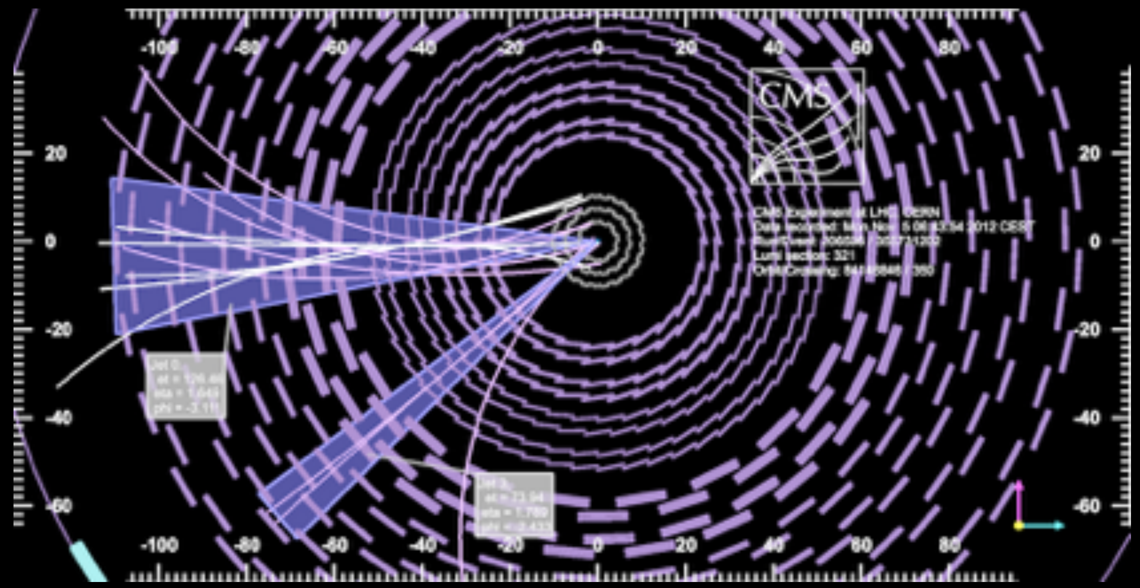
Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, length scale ~ LHC detectors
Hidden Valley signature [Strassler, Zurek ’06]



important signature

[Craig, Katz, Strassler, Sundrum '15; Curtin, Verhaaren '15]
[Serra, Stelzl, AW'18]

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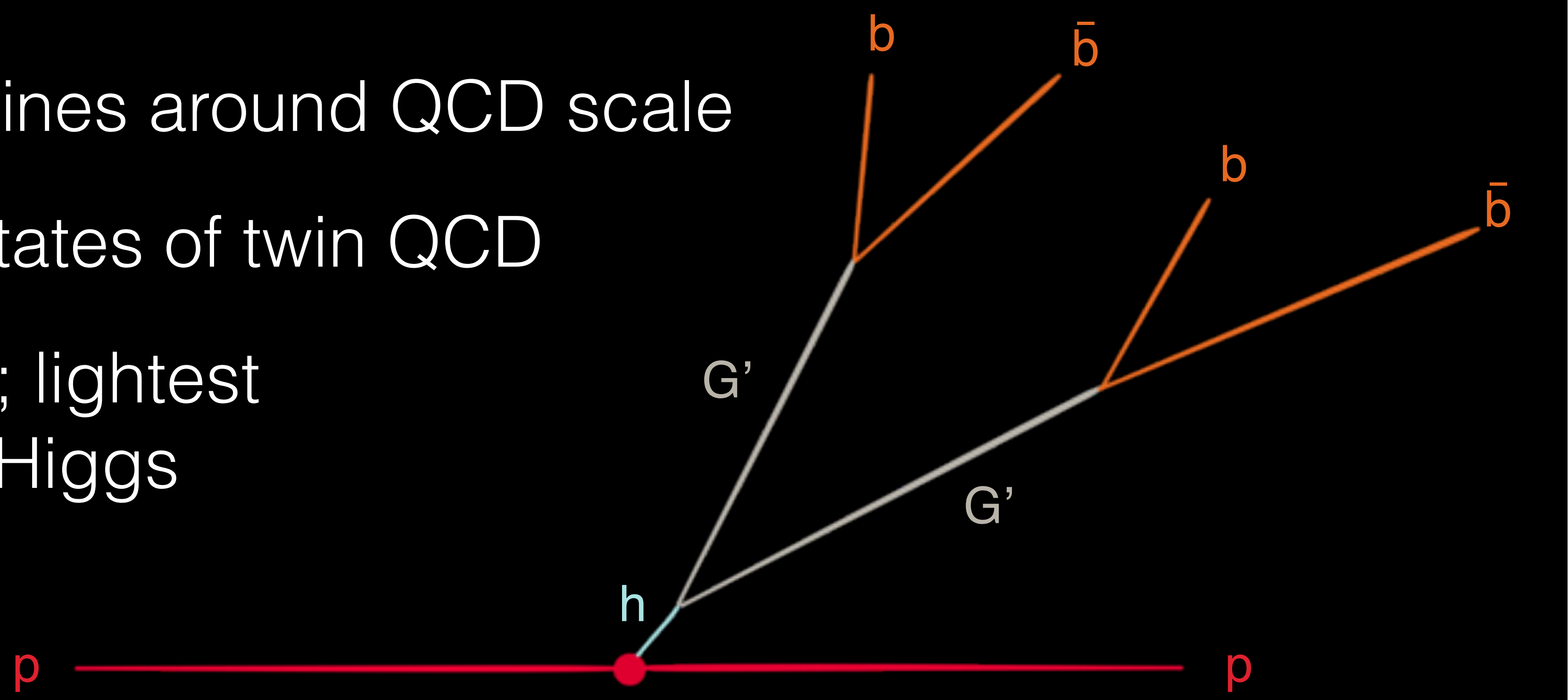

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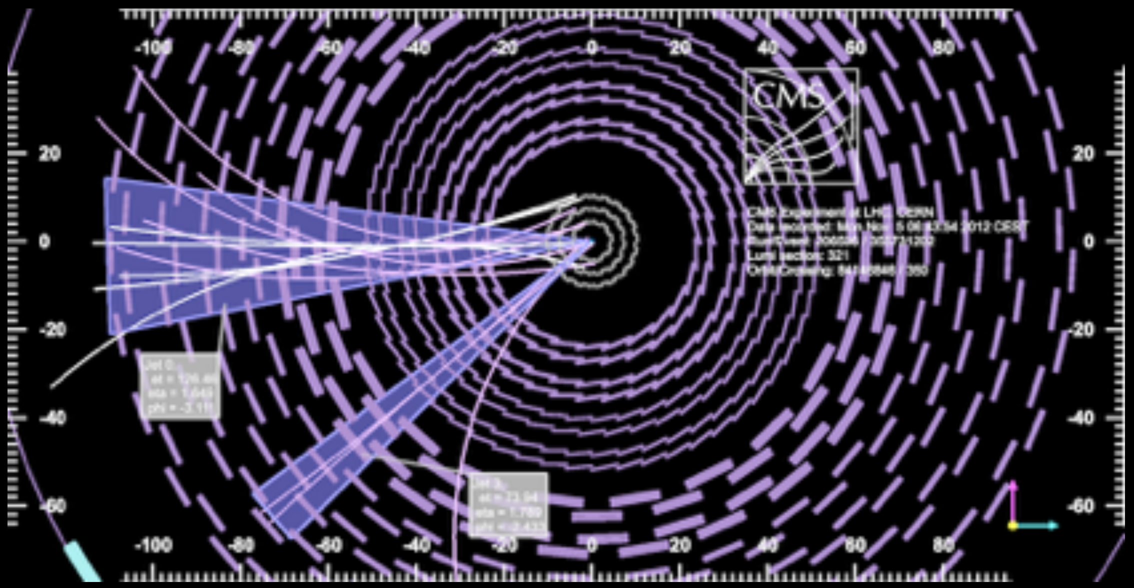


Long-lived, length scale ~ LHC detectors
Hidden Valley signature [Strassler, Zurek '06]

important signature

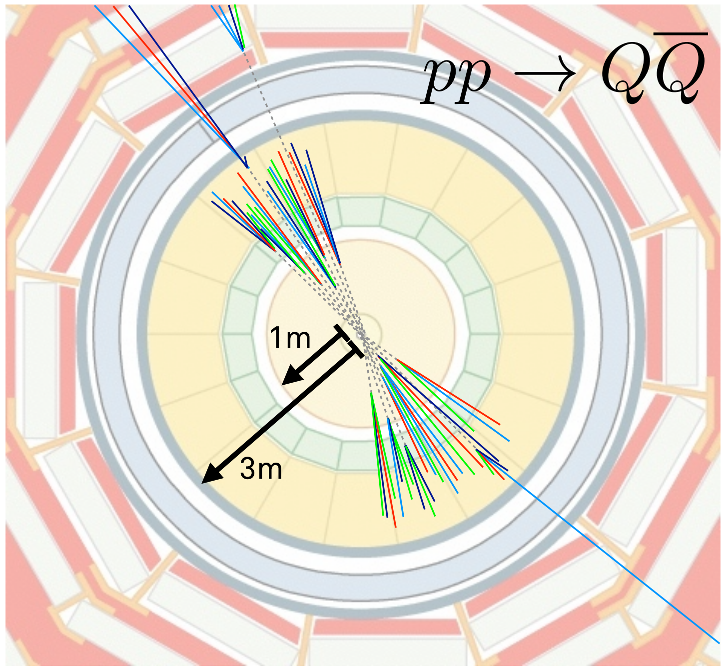
LLPs

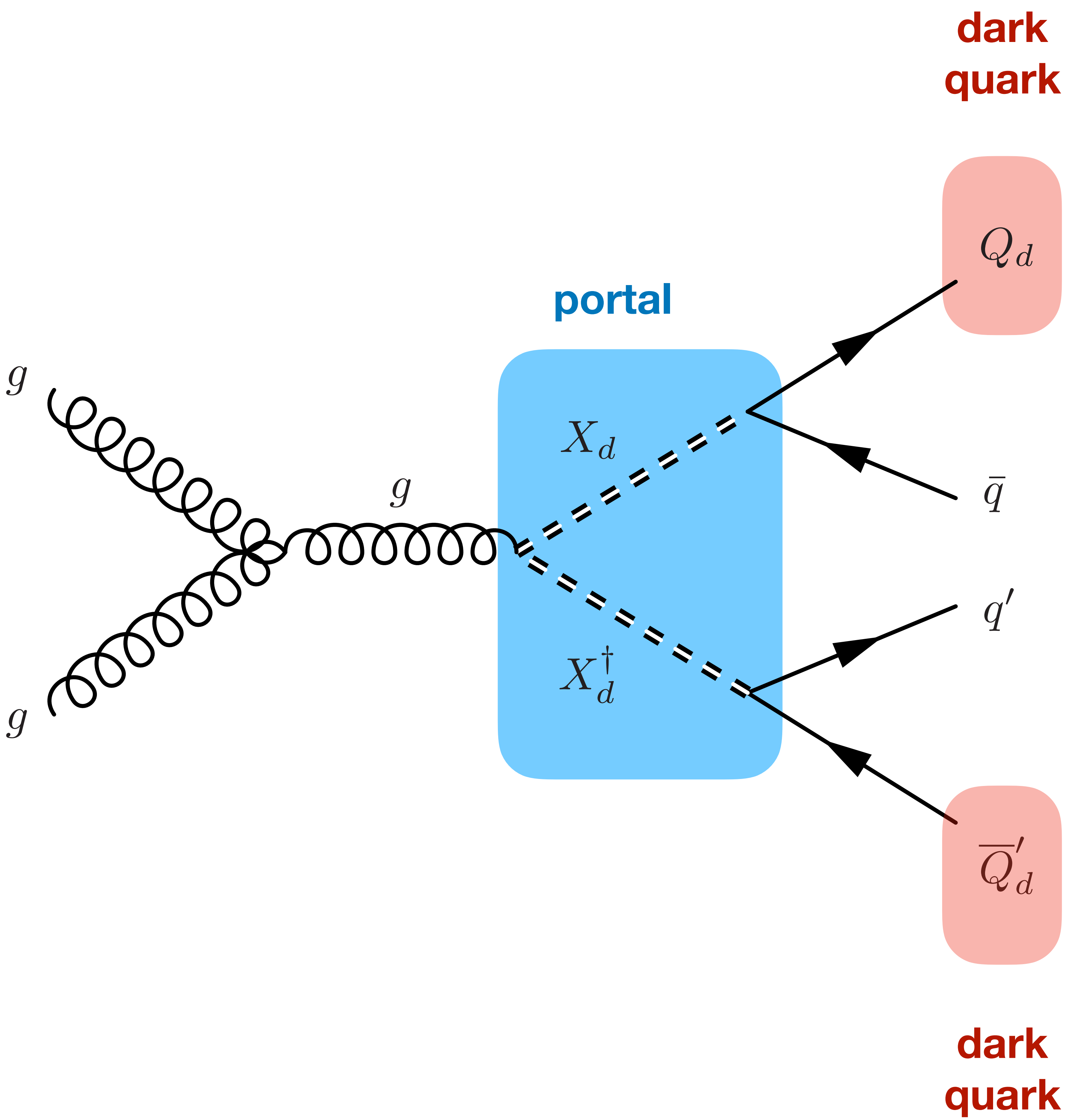
- Long Lived, length scale: LHC detectors
- New confining gauge group
- These ingredients are present in many new BSM extensions, e.g. “emerging jets”
- Emerging jets: motivated by asymmetric DM, cogenesis of baryon asymmetry and DM

Emerging Jets

Schwaller, Stolarski, **AW** ‘15

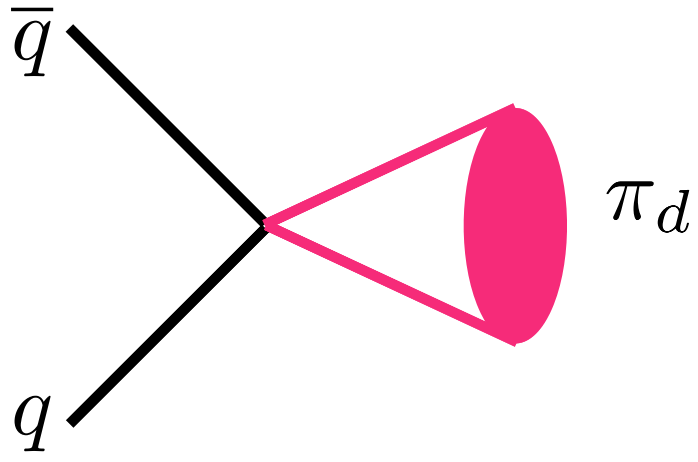
NEW: First search by **CMS PAS EXO-18-001**





dark quark
Q_d
portal
g
X_d
$\bar{q}$
g
q'
$X_d^\dagger$
g
$\overline{Q}'_d$
dark quark

Dark Pion Lifetime

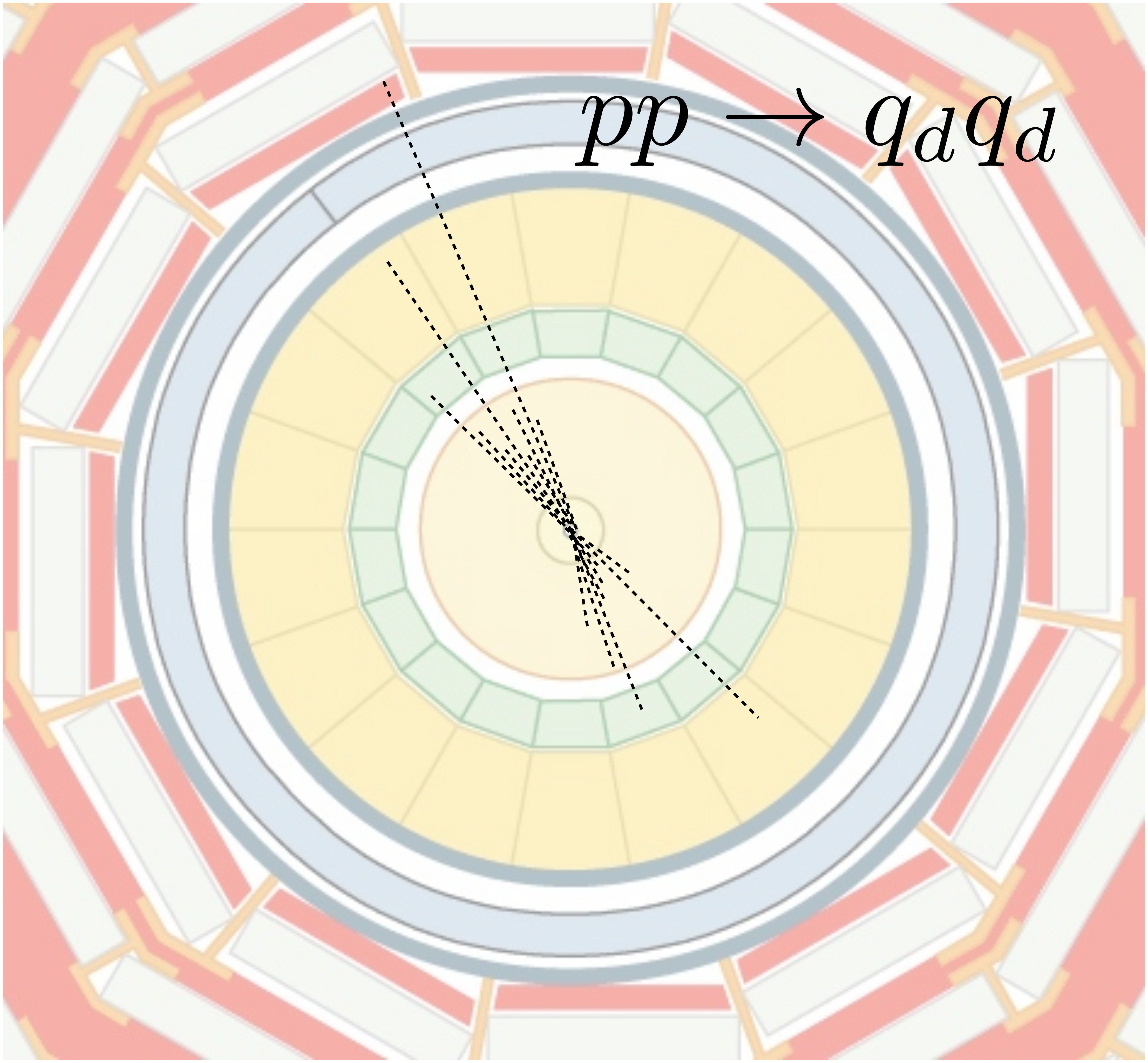


$$\frac{1}{M_X^2}\overline{Q}\gamma_\mu Q\,\bar{d}_R\gamma^\mu d_R$$

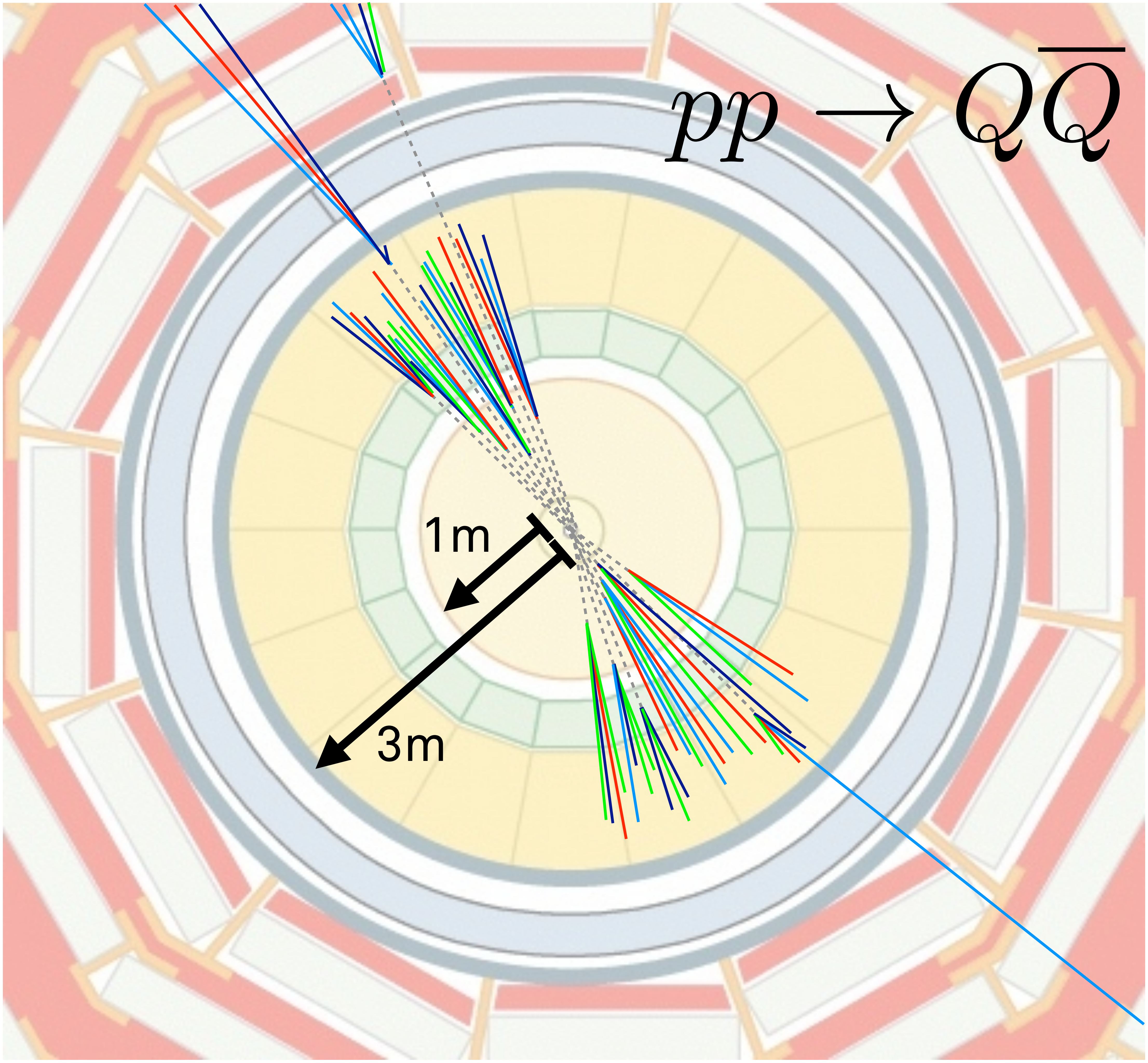
Use chiral Lagrangian to estimate

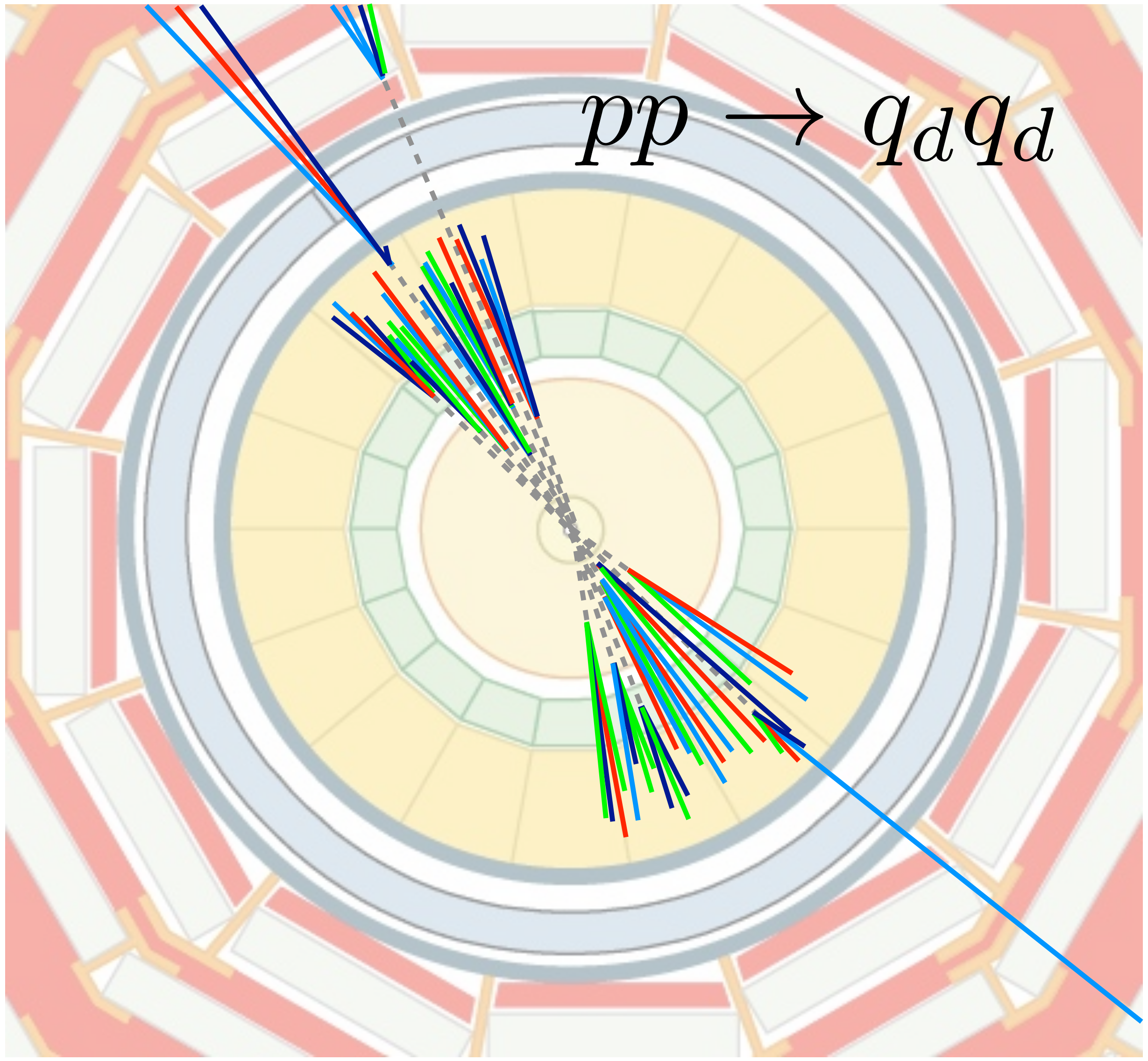
$$\Gamma(\pi_d \to \bar{d}d) \approx \frac{f_{\pi_d}^2 m_{\mathrm{d}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

$$c\tau \approx 5\,\mathrm{cm} \times \left(\frac{1\ \mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\mathrm{d}}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \mathrm{TeV}}\right)^4$$



$$pp \to q_d q_d$$

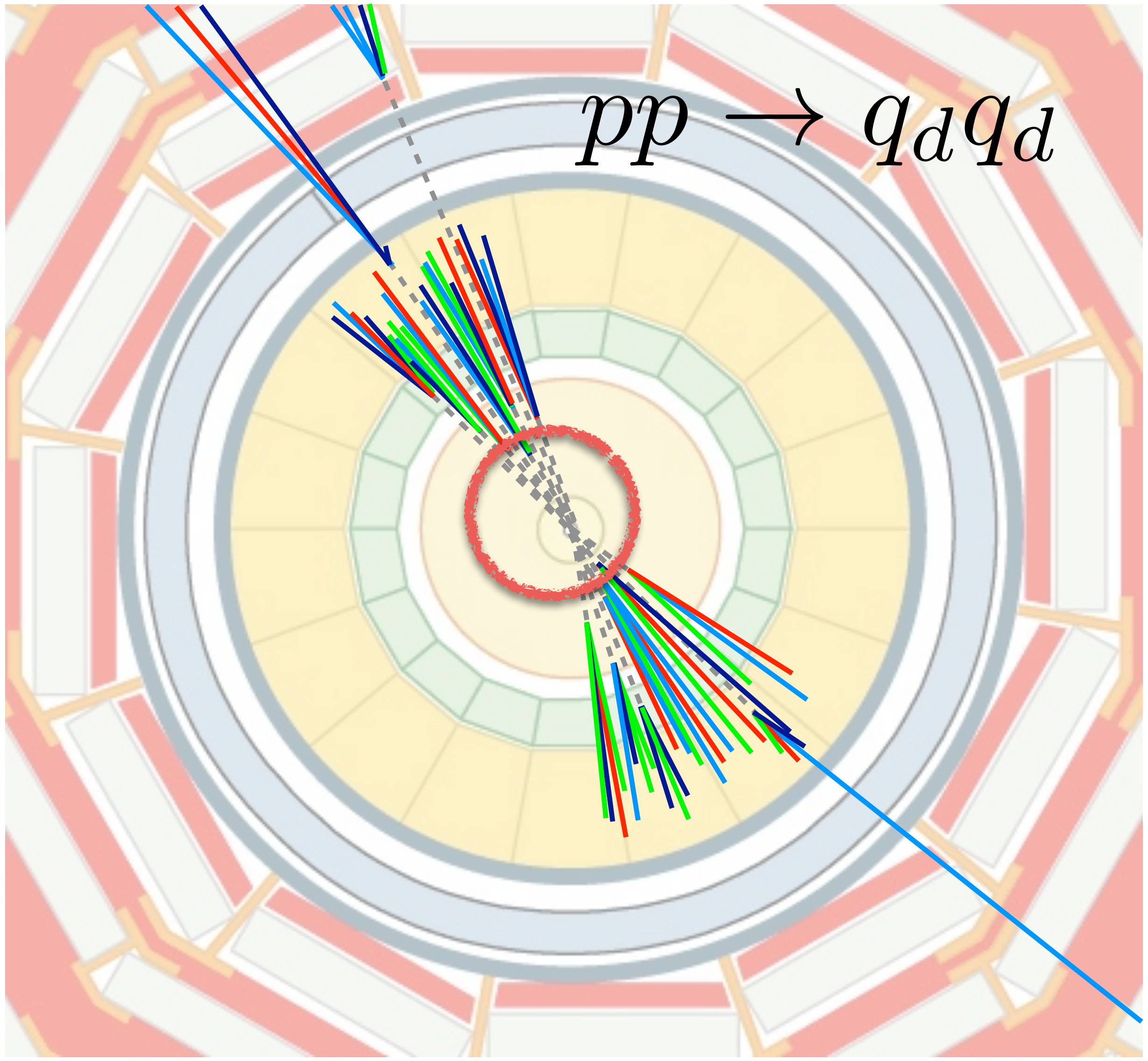

$pp \to Q\overline{Q}$
1m
3m



Decay lifetime of ~ cm

Exponential decay profile: Several displaced vertices inside a jet "cone" (or calo-jet)

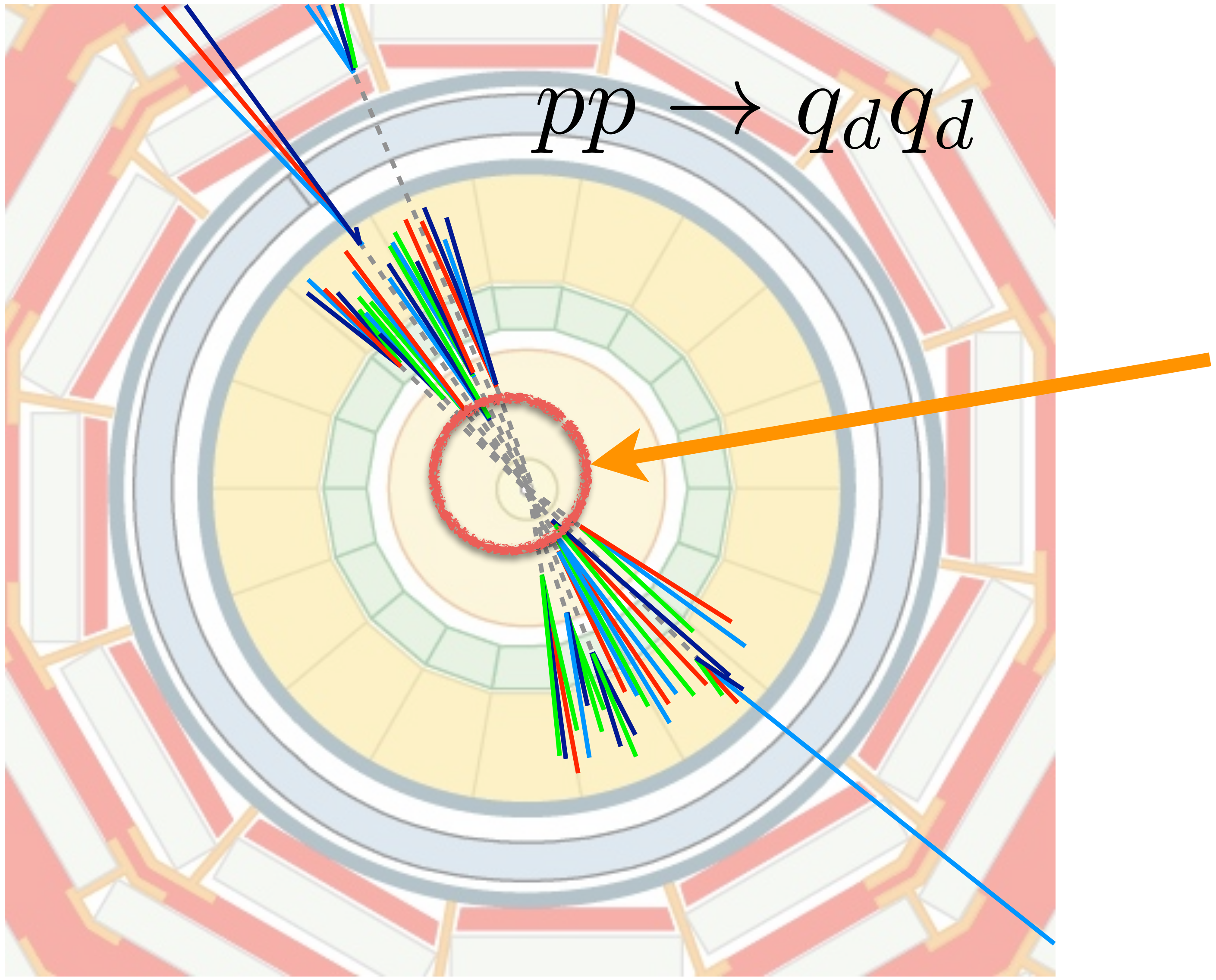
No/few tracks originating from interaction point



Look for Hcal-jets with no/few tracks below distance to interaction point (inside circle)

New ‘track-less’ signature

Universal for a large class of displaced physics



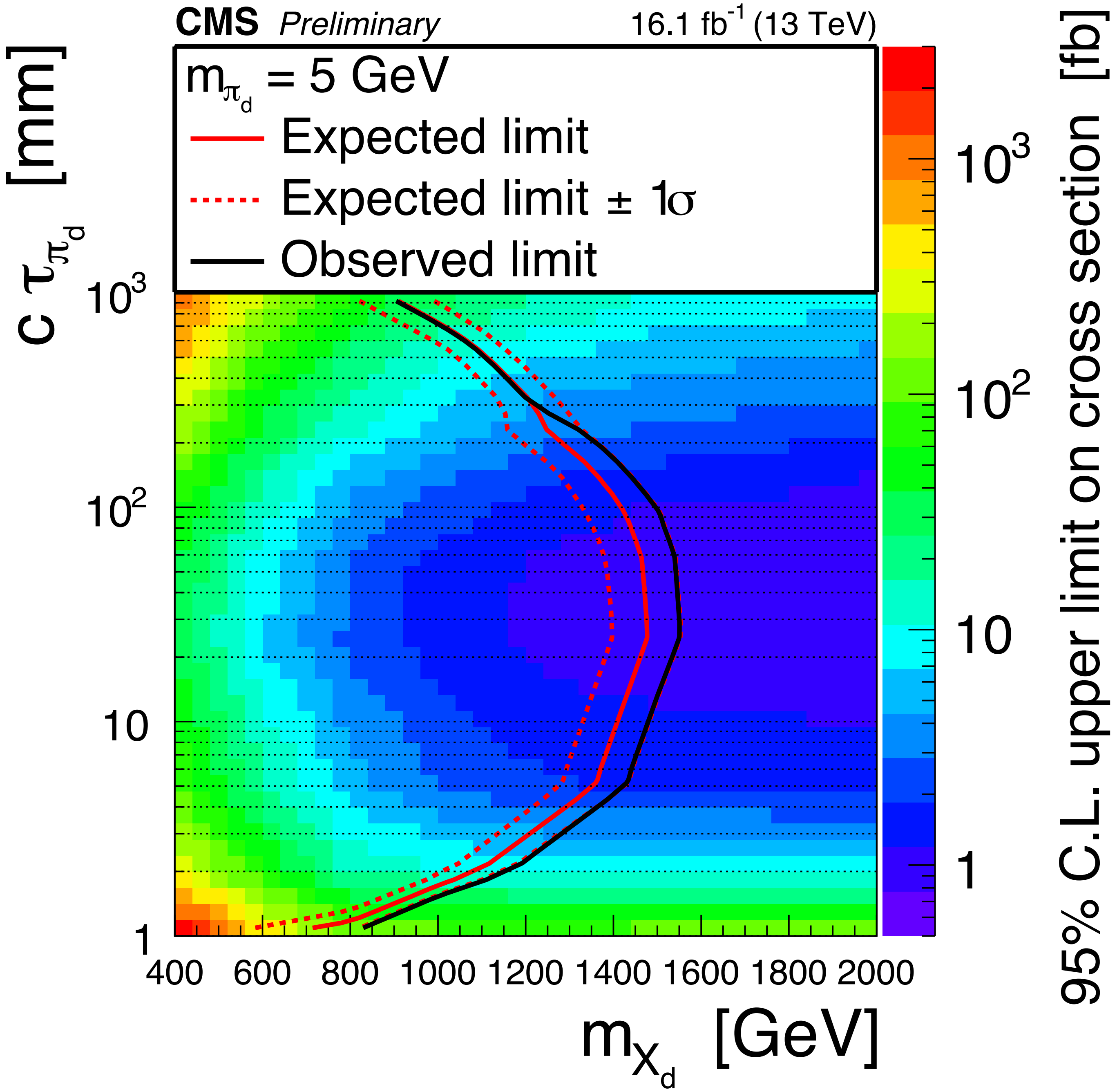
Look for Hcal-jets with no/few tracks below distance to interaction point (inside circle)

New ‘track-less’ signature

Universal for a large class of displaced physics

Emerging jets search

“Mediator particles with masses between 400 and 1250 GeV are excluded for dark hadron decay lengths between 5 and 225 mm.”



[CMS PAS EXO-18-001]

Amazing work by UMD CMS team (Belloni, Eno, Jeng, …)

Relaxion paradigm

P.W. Graham, D.E. Kaplan, S.Rajendran ‘15
(earlier work by Abbott 85, G.Dvali,A.Vilenkin 04, G.Dvali 06)

A technically natural solution to the hierarchy problem

Uses dynamics, not symmetries

At the drafting stage, but currently extensive development

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$$m^2|H|^2$$

Higgs mass

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$$= \Lambda^2 - g\phi$$

$$m^2|H|^2 \longrightarrow m^2(\phi)|H|^2$$

Higgs mass

axion-field dependent mass

Relaxion paradigm

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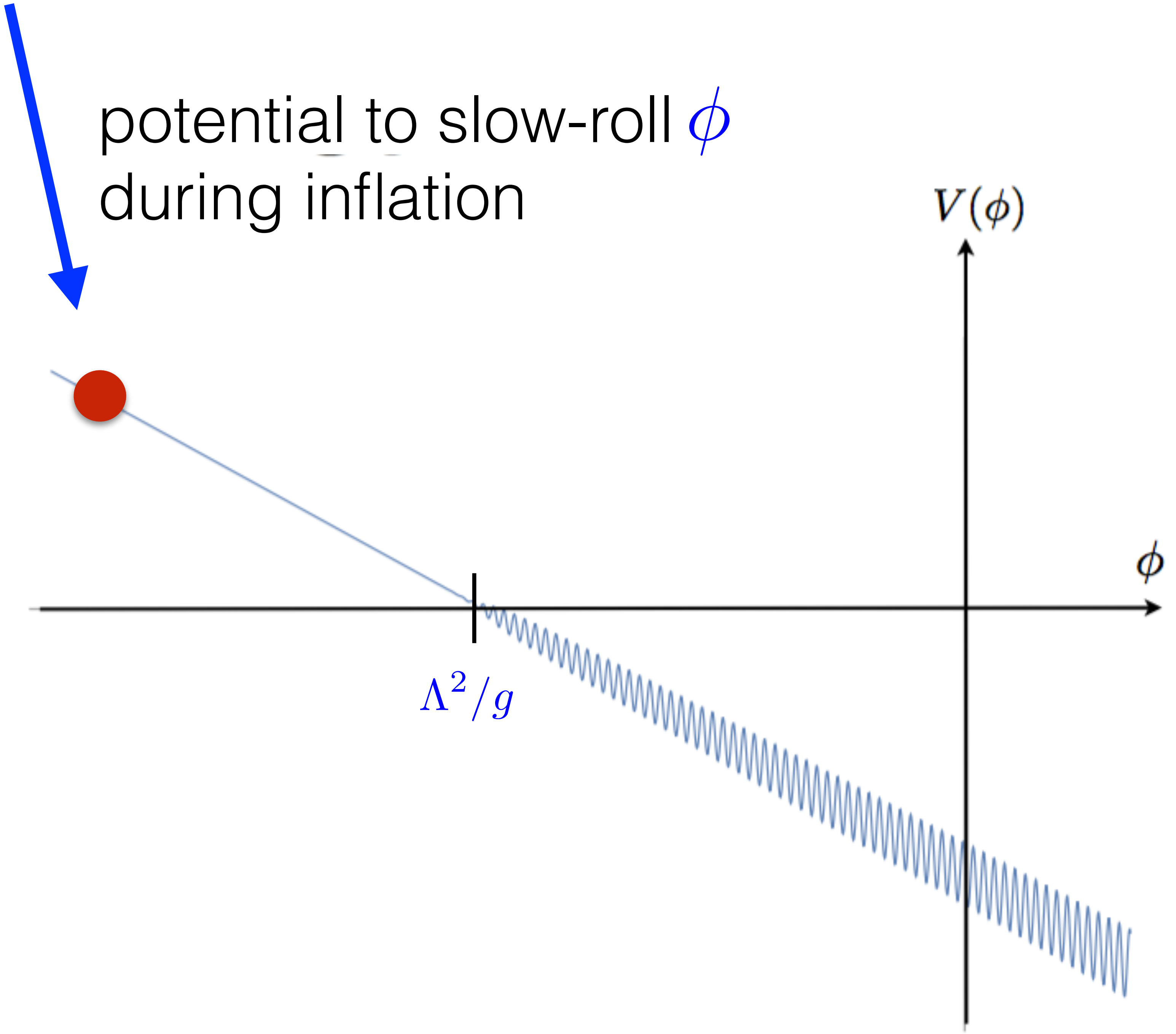
$$= \Lambda^2 - g\phi$$

$$m^2|H|^2 \longrightarrow m^2(\phi)|H|^2$$

Higgs mass   axion-field dependent mass

Clever dynamics stabilizes ϕ at values: $m^2(\phi) \ll \Lambda^2$

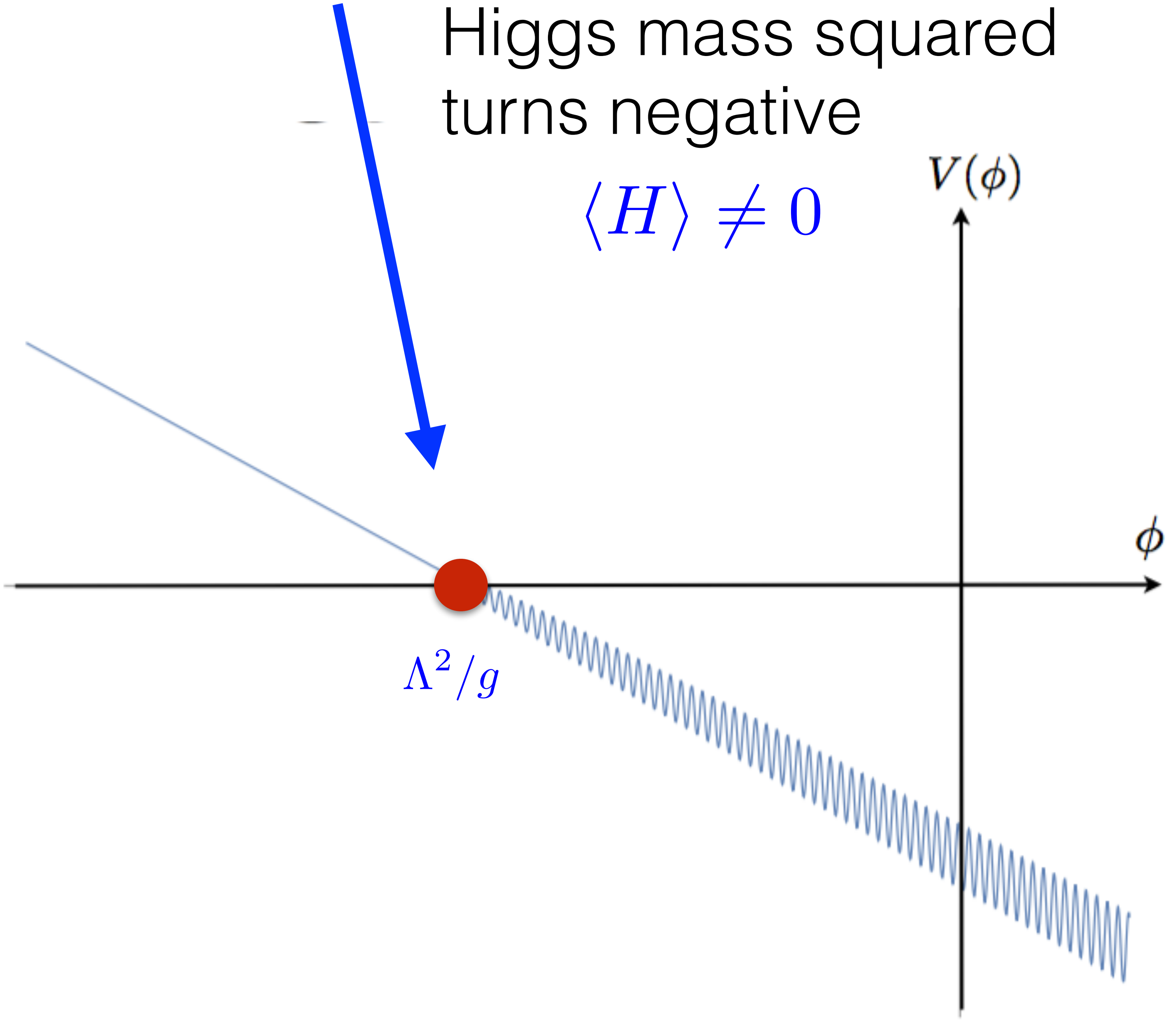
$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h\cos\frac{\phi}{f}$$



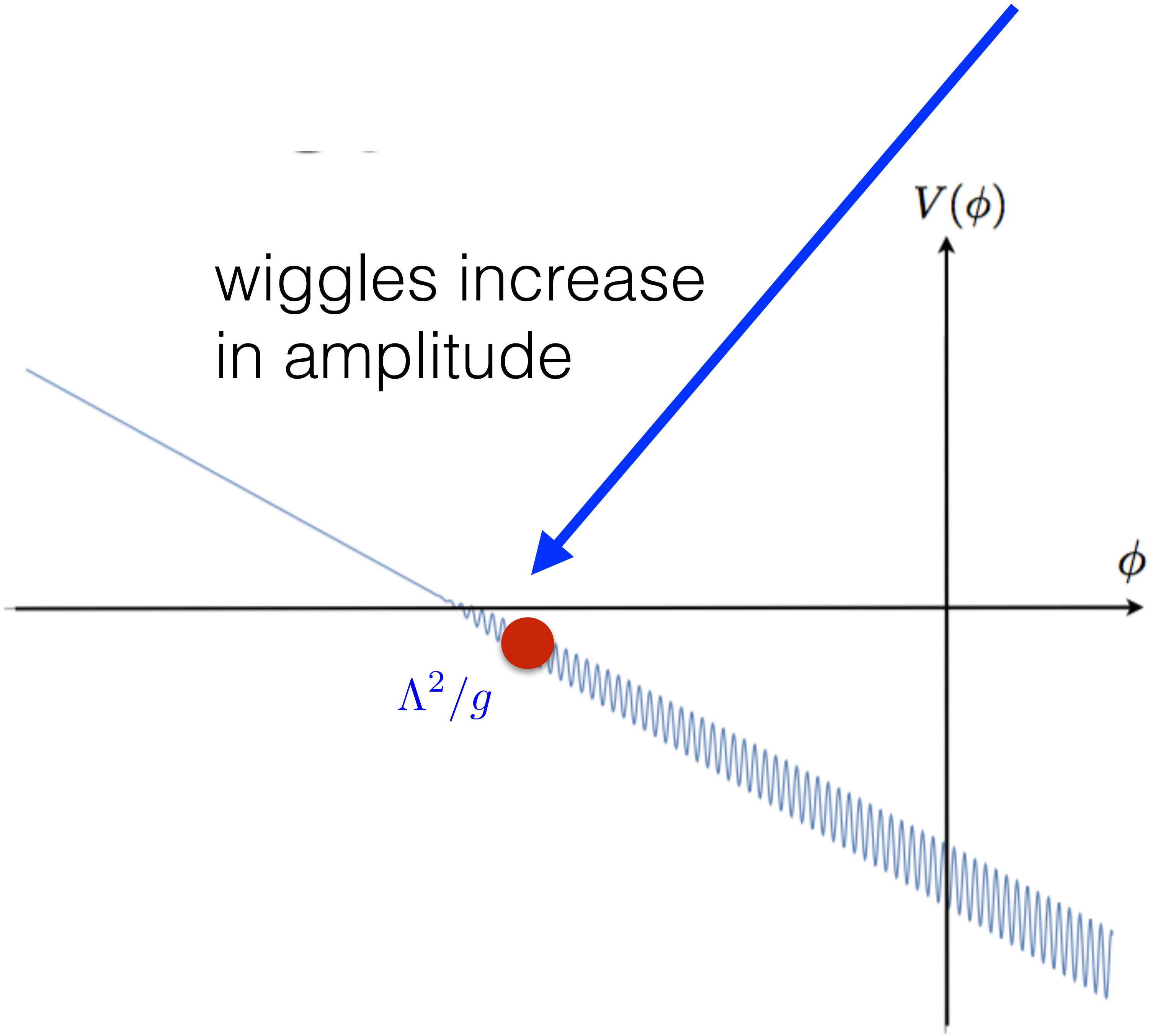
$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

Higgs mass squared
turns negative

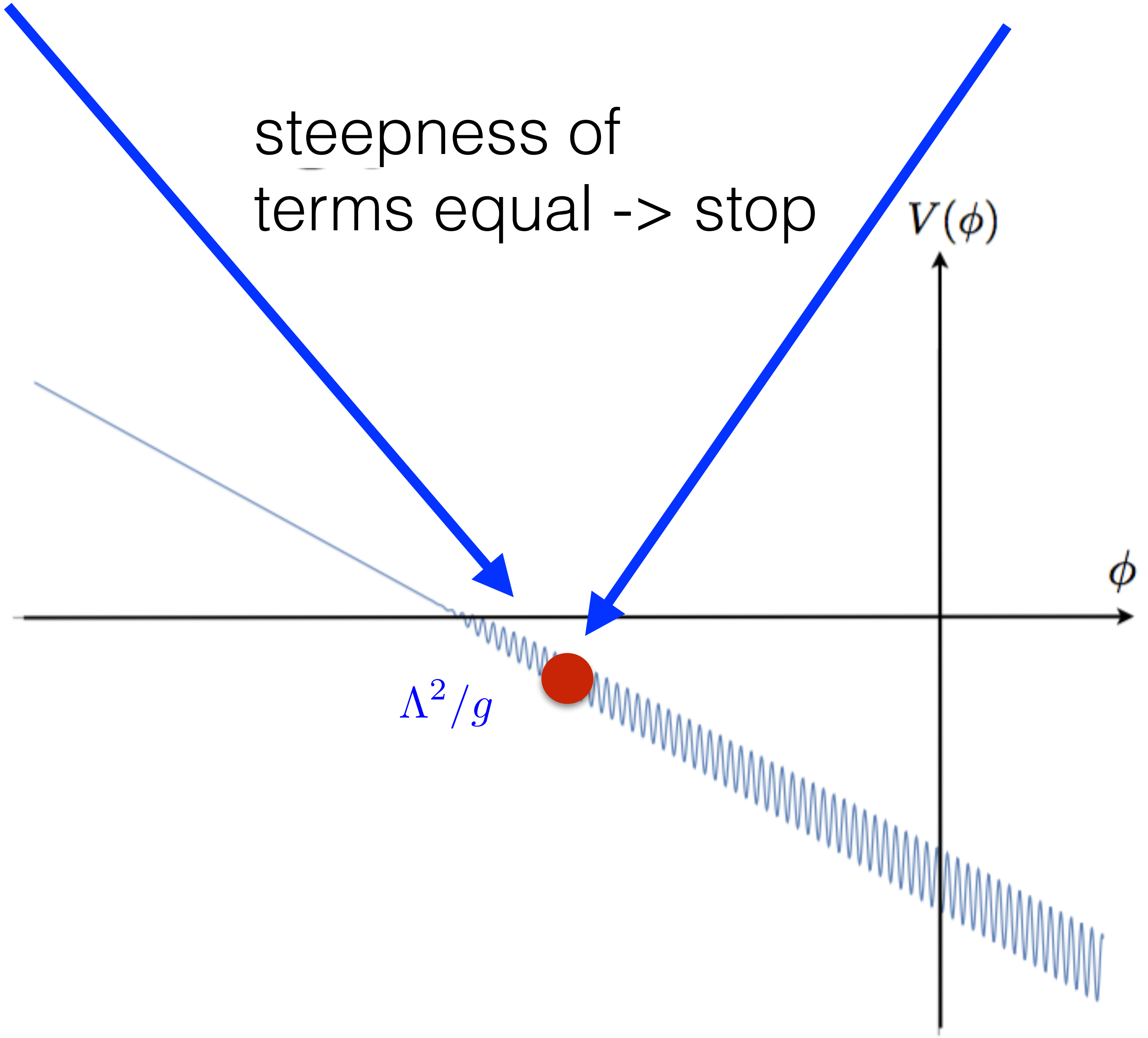
$\langle H \rangle \neq 0$



$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$



$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$



steepness of
terms equal -> stop

$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

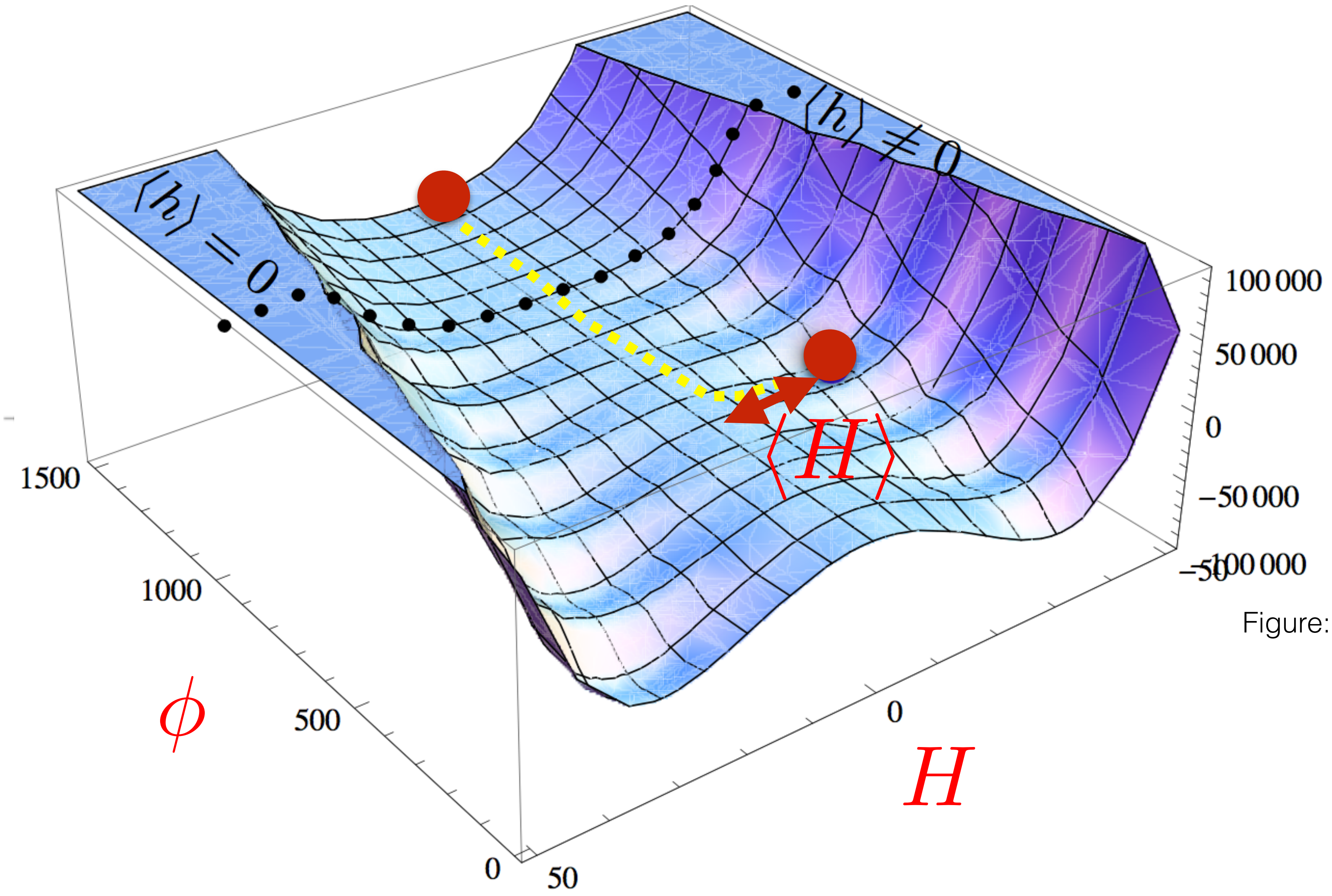


Figure: C. Grojean

- QCD axion doesn't work: $\theta_{QCD} \sim 1$ due to tilt
  - Add new QCD' group => new weak-scale signals!
  - Add additional scanning field => **no** collider signals!

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

More work: Hardy '15; Gupta et al '15; Batell, Giudice, McCullough '15; Choi, Im '15; Kaplan, Rattazzi '15; Di Chiara et al. '15; Ibanez et al. '15; Hook, Marques-Tavares '16; Nelson, Prescod-Weinstein '17; ...]

Some points of concern:

$g \sim 10^{-27}\mathrm{GeV}$ UV completion !?

$N > H^2/g^2 \sim 10^{45}$ inflation !?

$\Delta\Phi \simeq 10^{41}\mathrm{GeV}$ large field excursions

YEP, THAT'S HIM ALL RIGHT... THAT'S THE GUY I MUGGED
7
6
5
4
3
2
1
WHAMOND

Conclusions

- No signs of new physics have appeared so far.

- The Higgs fine-tuning puzzle is as puzzling as ever. Do we simply live in a (mildly?) fine-tuned universe? Or is there a subtle solution?

- Themes of recent years: search for electroweak or neutral new particles at colliders to exhaust possibilities; intriguing possibilities for connections of the weak scale with cosmology.

- Amazing landscape of experiments: LHC, dark matter, EDMs, flavor physics. New physics discovery could come at any time!