BSM in 2017: expecting the unexpected!

Luca Vecchi

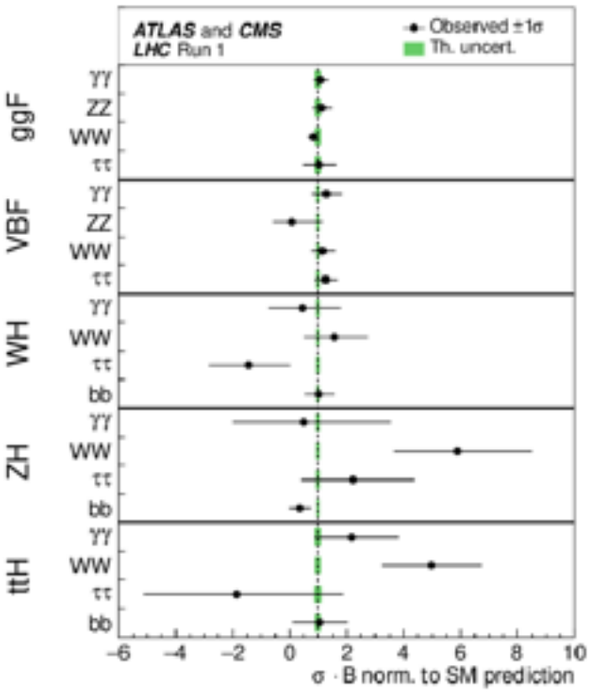
IFAE (20/04/2017)

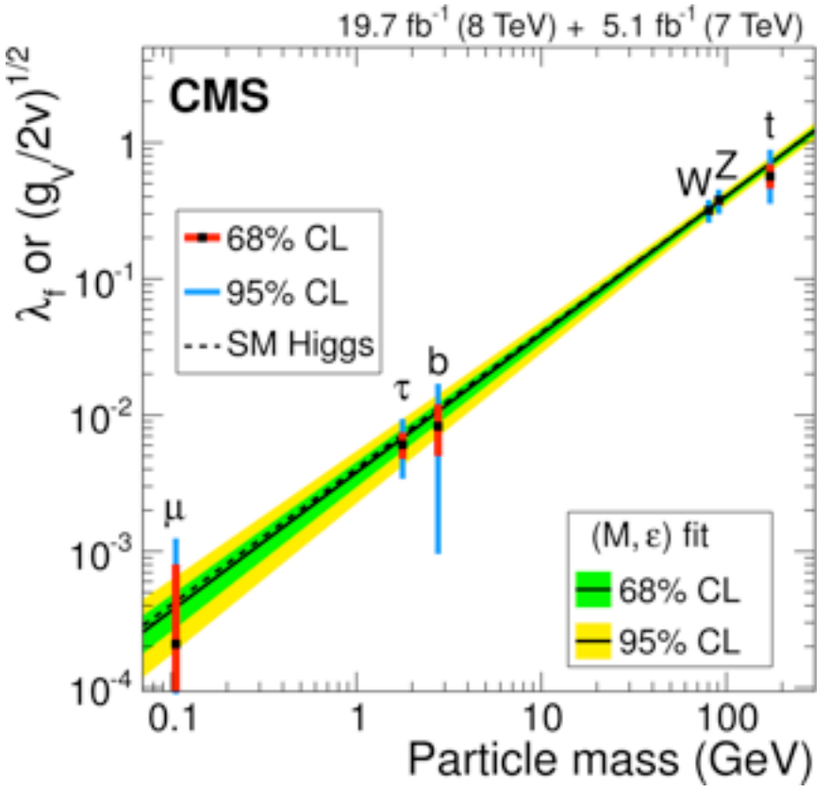
Outline

- **The TeV scale in 2017**
  - most minimal picture=SM+decoupling physics
  - sociology: 2 options for the TeV physics

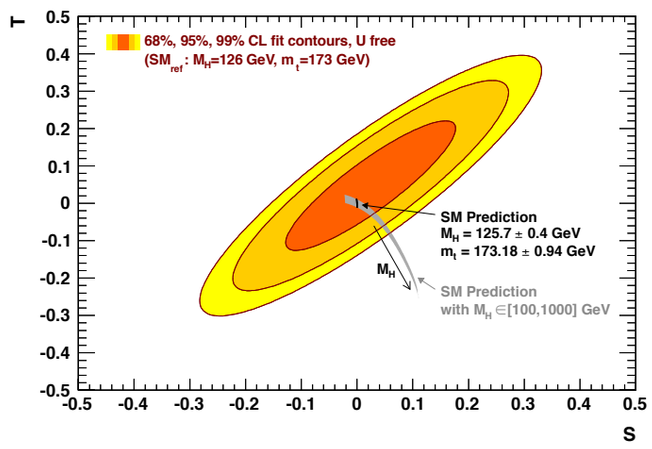
- **Two complementary approaches**
  - EFT & Simplified Models
  - in Dark Matter searches & SM tests

Higgs couplings: signal strengths + indirect

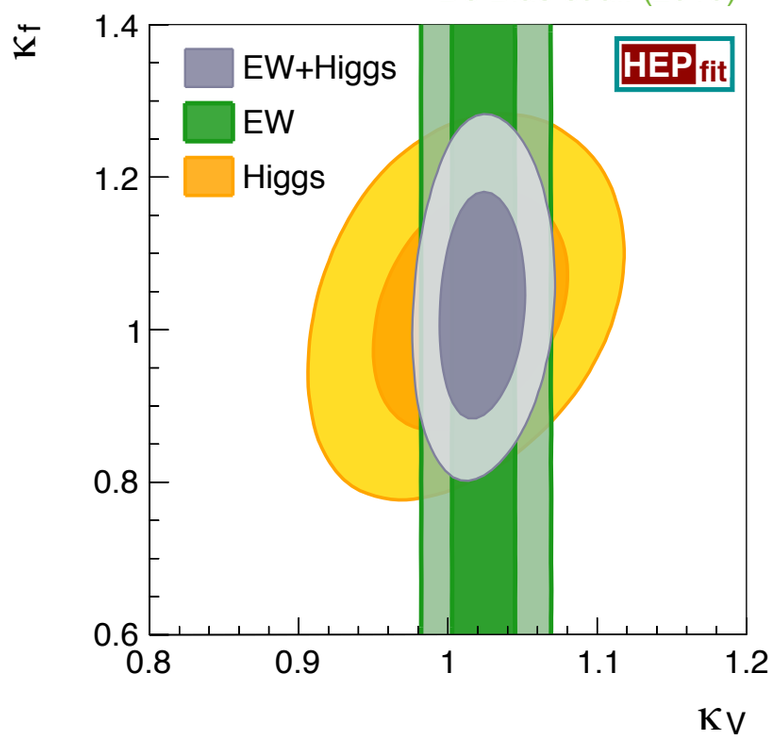




Baak et al. (2012)



De Blas et al. (2016)



Simplest explanation:

EW symmetry broken by one Higgs

Particle physics' EFT:
SM + decoupling sectors + Dark Matter

$$\mathcal{L}_{\text{eft}} = -\frac{1}{4}F^2 + q^\dagger i D q + |DH|^2 - yqqH - \lambda|H|^4 + m_h^2|H|^2 + \Lambda_{\text{CC}}^4 + \mathcal{L}_{\text{DM}} + \sum c_n \frac{O_n}{\Lambda_{\text{UV}}^n}$$

neutrino masses
(or RH neutrino)
SUSY? CH?

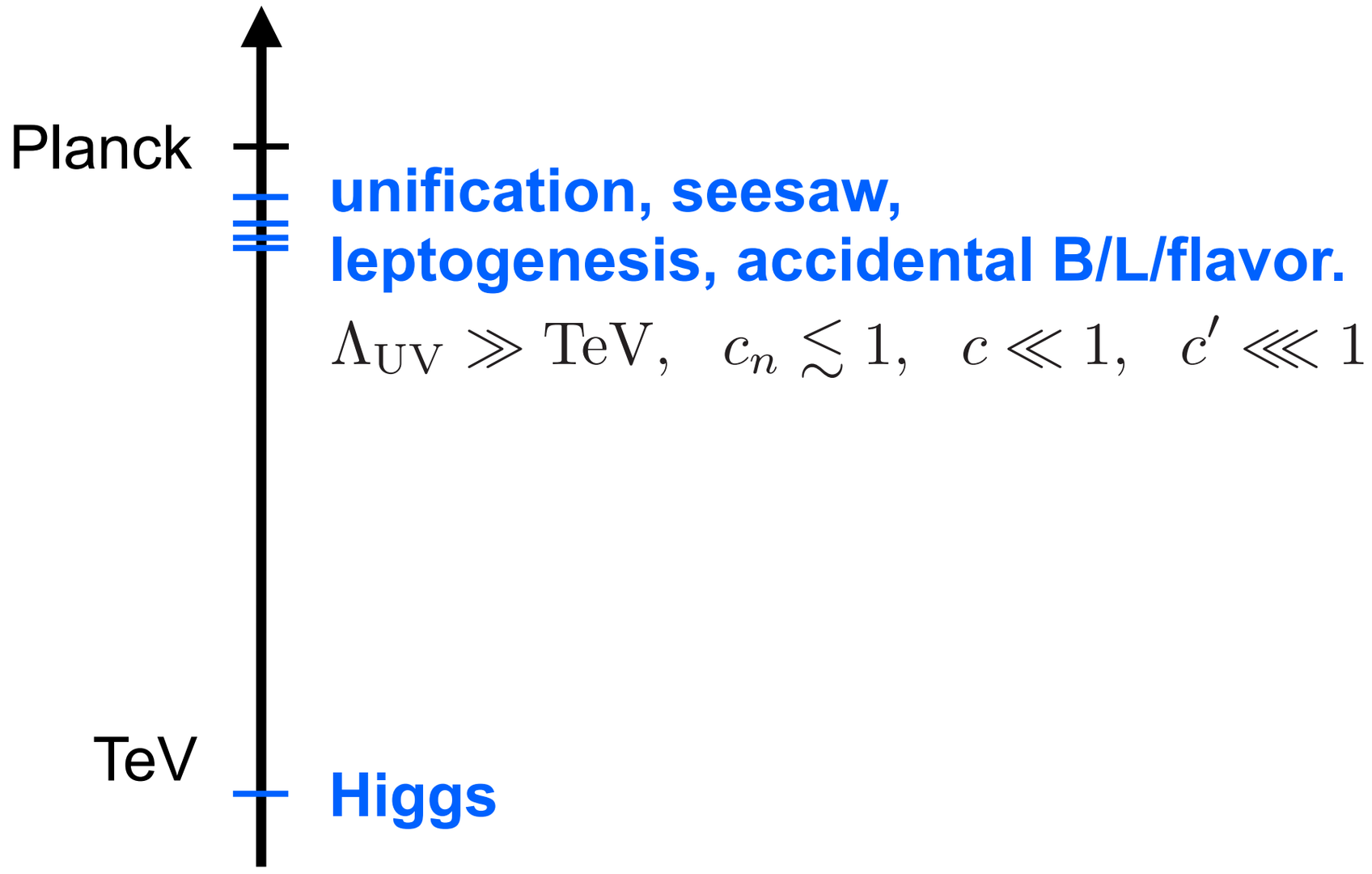
Particle physics' EFT:
SM + decoupling sectors + Dark Matter

$$\mathcal{L}_{\text{eft}} = -\frac{1}{4}F^2 + q^\dagger iDq + |DH|^2 - yqqH - \lambda|H|^4$$
$$+m_h^2|H|^2 + \Lambda_{\rm CC}^4 + \mathcal{L}_{\rm DM} + \sum c_n \frac{O_n}{\Lambda_{\rm UV}^n}$$

Naturalness= dimensional analysis works

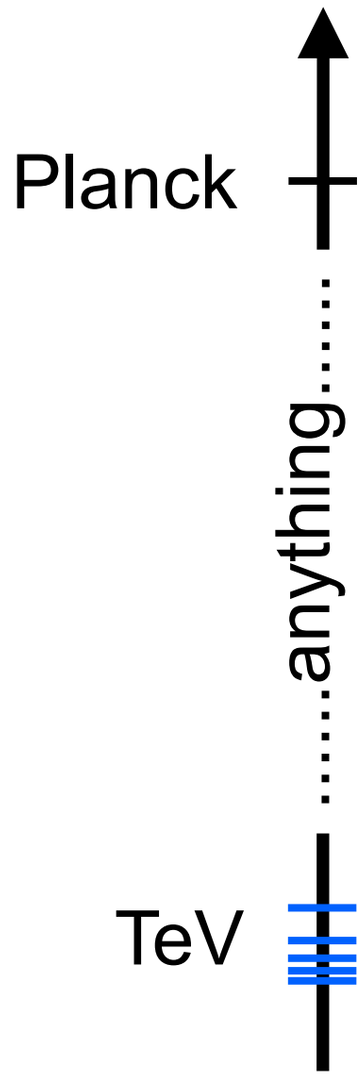
$$\begin{cases} \Lambda_{\rm CC}^4 = c' \Lambda_{\rm UV}^4 \\ m_h^2 = c\Lambda_{\rm UV}^2 \end{cases}$$

Fine-tuning: **the “nightmare option”**



Fine-tuning with a purpose:
-- Tuning of Cosmological Constant Weinberg (1987)
-- Tuning EW ~ QCD scales Agrawal et al. (1998)

Naturalness: **the “attractive option”**



SUSY and/or Composite Higgs

$$\Lambda_{\rm UV} \sim {\rm TeV}, \quad c_n \ll 1, \quad c \sim 1, \quad c' \lll 1$$

-- Can still have GUT, seesaw, etc
-- c_n<<1 protected by “symmetries”
-- Cosmological Constant?
-- Why is EW ~ QCD?

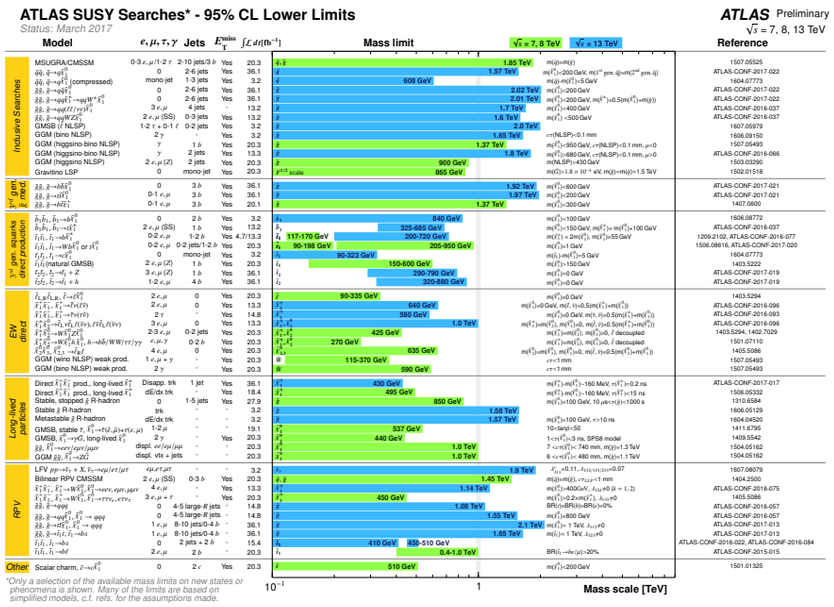
BSM theorists

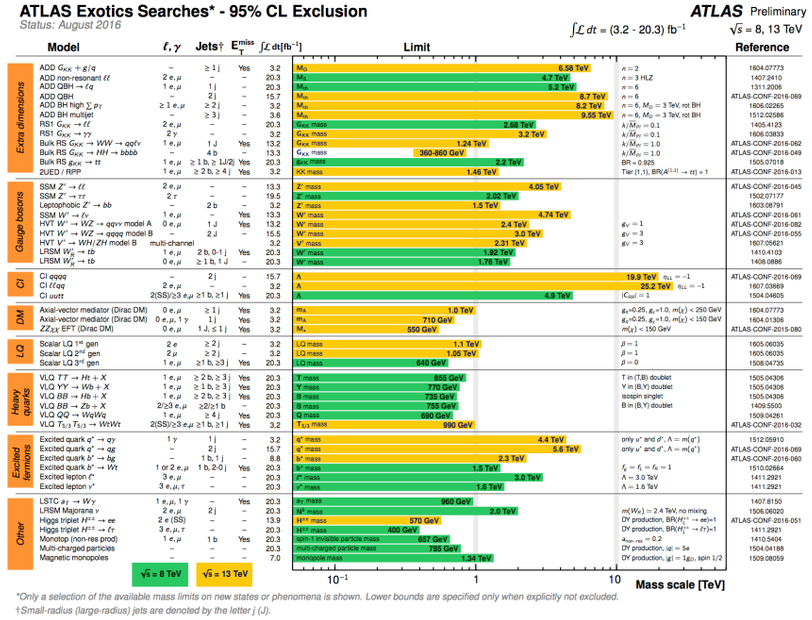
Modified Higgs couplings?
TeV resonances?

Planck

.....anything.....

TeV





LHC+Tevatron+LEP ???

A bit of sociology: **what is “less un-natural”?**

un-naturalness
in theory space

complicated model →

Ugly

Empty

UV cutoff →

un-naturalness
in Higgs mass

No Favored Scenario!!!

- **Exotic states at the TeV may be there**:
  - gauginos in SUSY, Nambu Goldstone Bosons in CH, mirror world in Twin Higgs, etc.
  - may contribute to the Higgs potential, baryon asymmetry, mediate couplings to DM, etc

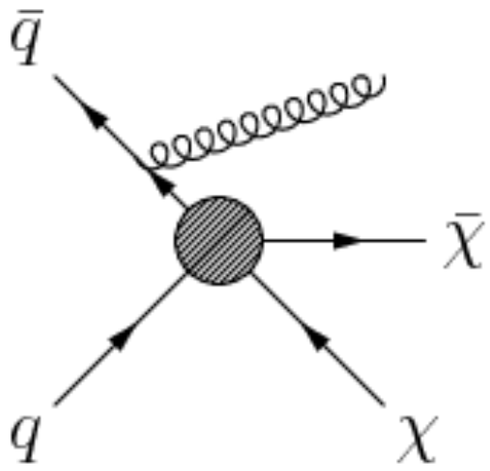
- How to proceed? **EFT and Simplified Models**

EFT approach to BSM

PROS: quite general and systematically improvable
CONS: best suited for fixed energy, high precision experiments

Ex: **Dark Matter EFT**

$$\frac{\overline{q}\gamma^\mu q\ \overline{\chi}\gamma_\mu\chi}{\Lambda^2_{\rm UV}}$$



$$\mathcal{A} = \mathcal{A}_{\rm SM}\left[1 + c_{\rm int}\frac{q^2}{\Lambda^2_{\rm UV}} + \mathcal{O}\left(\frac{q^4}{\Lambda^4_{\rm UV}}\right)\right]$$

grows with energy, but it is an expansion in momentum transfer...

$$\left.\begin{aligned}\Lambda_{\rm UV} &\sim 500\ {\rm GeV}\\ \frac{1}{\Lambda^2_{\rm UV}} &= \frac{g_*^2}{m_*^2}\end{aligned}\right\} \quad m_* \sim g_* \times 500\ {\rm GeV}$$

Directly accessible if weakly-coupled

Friedland, Graesser, Shoemaker, LV (2011)
Shoemaker, LV (2011)

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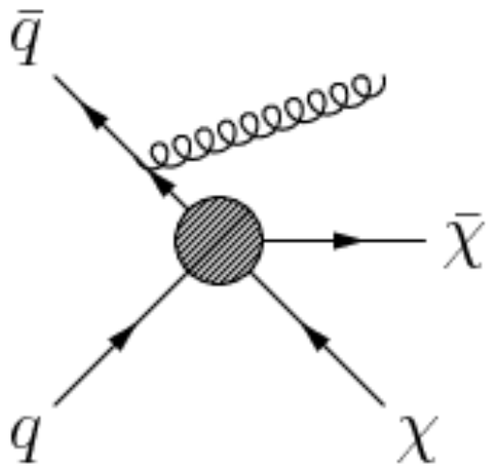

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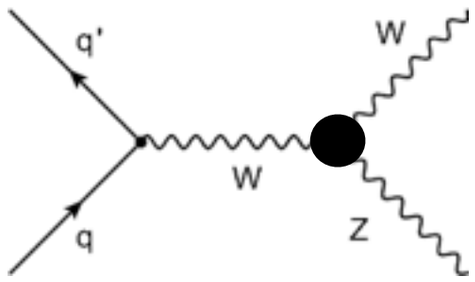
valid for a certain class!!!

Friedland, Graesser, Shoemaker (2011)
Shoemaker, LV (2011)

Ex: **Standard Model EFT**

$$\frac{1}{\Lambda_{\rm UV}^2}\,{\rm tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right]$$



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Butter et al (2016)

$$\left.\begin{aligned}\Lambda_{\rm UV} &\sim 700\ {\rm GeV}\\ \frac{1}{\Lambda_{\rm UV}^2} &= \frac{g^2}{16\pi^2}\frac{g}{m_*^2}\end{aligned}\right\} \quad m_* \sim 50\ {\rm GeV}$$

Directly accessible

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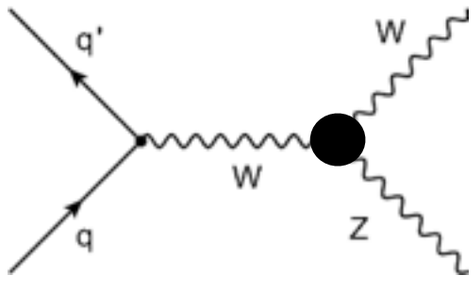

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Directly accessible

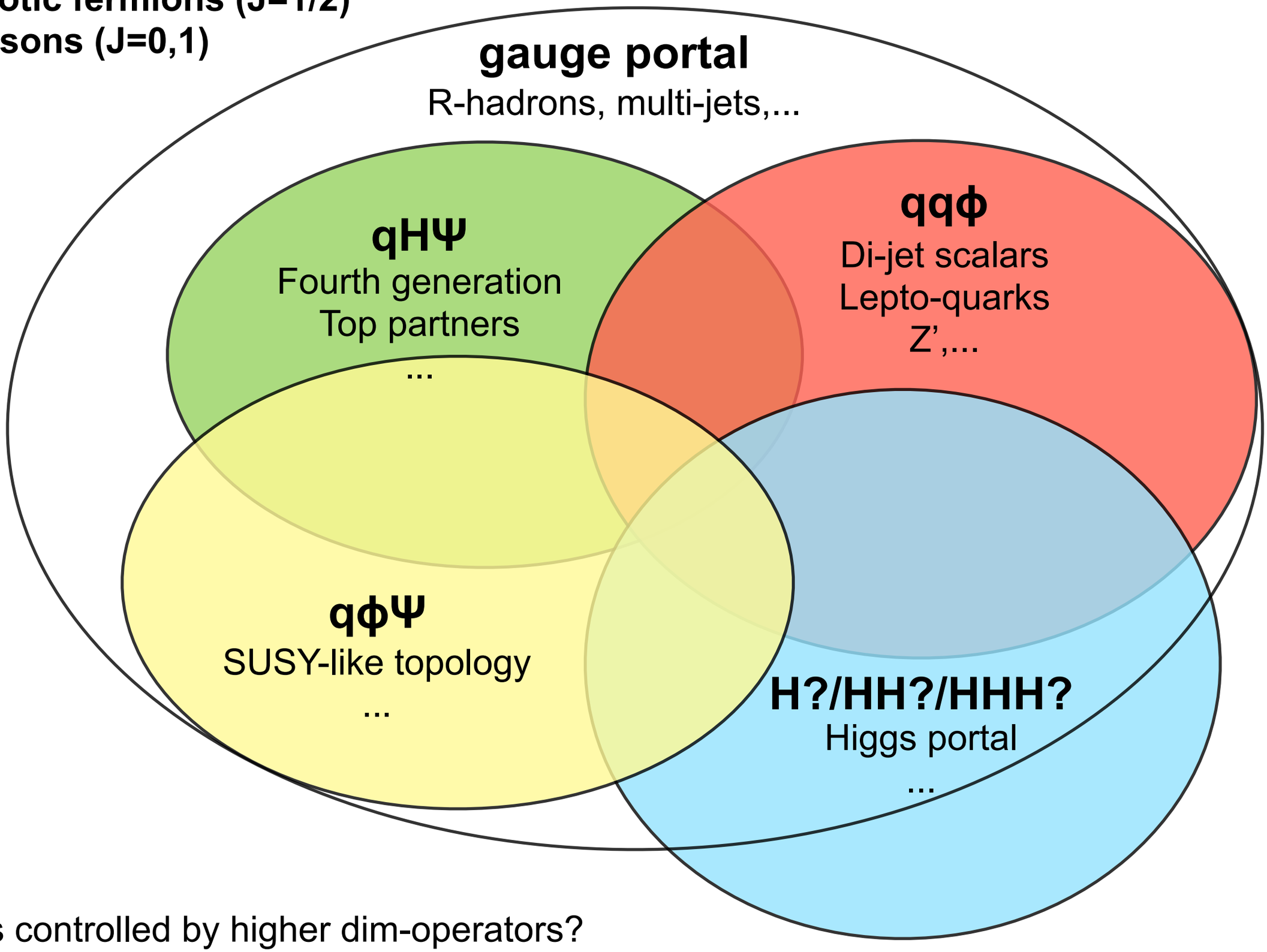
valid for a certain class and some caveat!!!

Liu et al (2016)
Contino et al (2016)

Simplified models

PROS: direct connection with new (weakly-coupled) particles
CONS: a lot of freedom

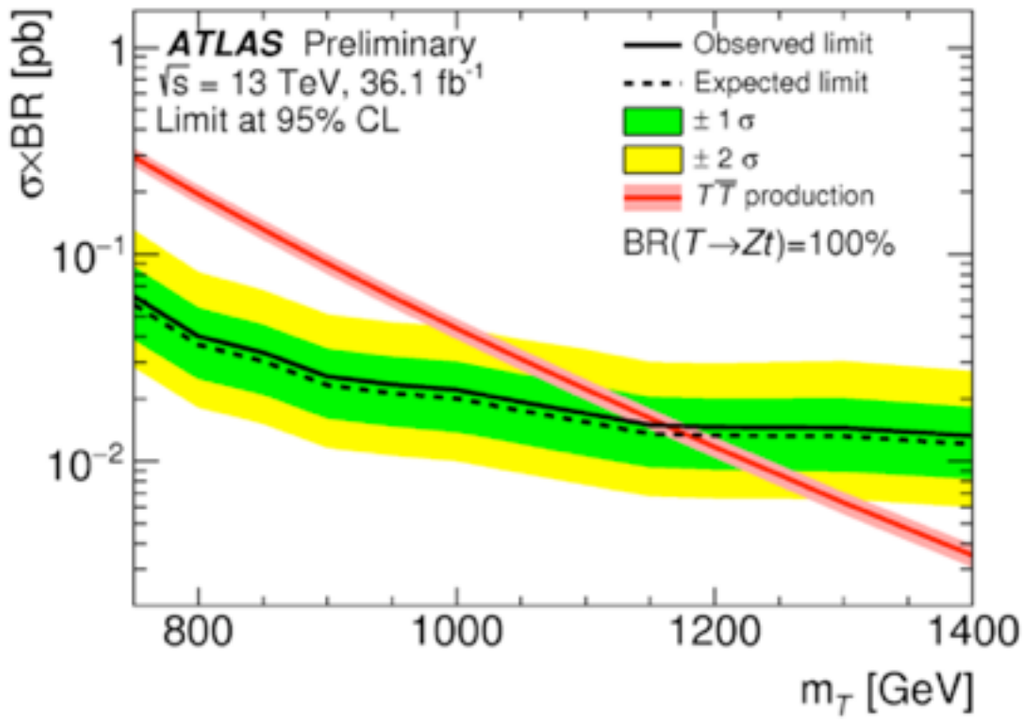
q = SM fermion
H = Higgs
Ψ = exotic fermions (J=1/2)
ϕ = bosons (J=0,1)



Decays controlled by higher dim-operators?

qHΨ pair-production + decay (higher dim-operators subdominant)

ATLAS-CONF-2017-015



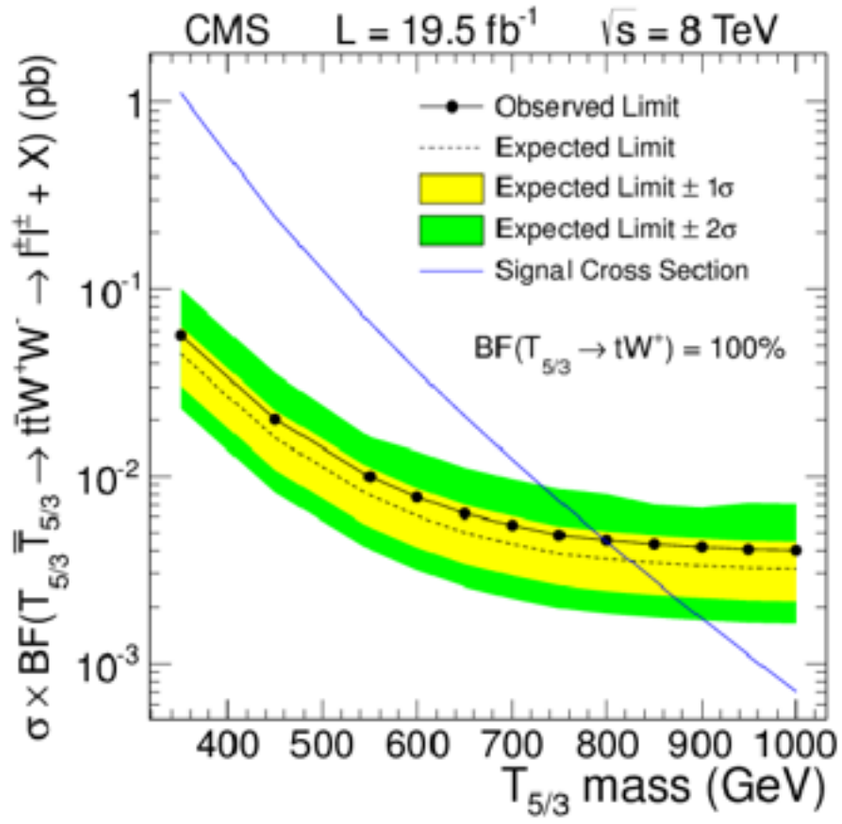
$$X_{2/3} \to tH, tZ, bW^+$$

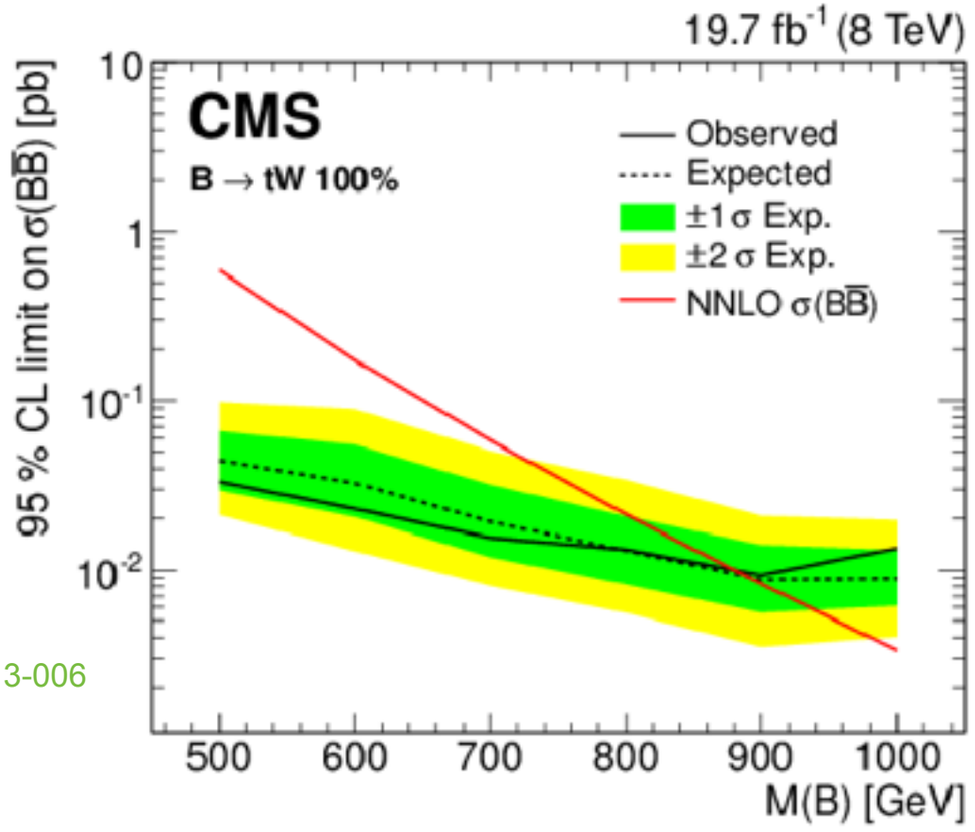
$$X_{-1/3} \to bH, bZ, tW^-$$

$$X_{5/3} \to tW^+$$

$$X_{-4/3} \to bW^-$$

CMS-B2G-12-012





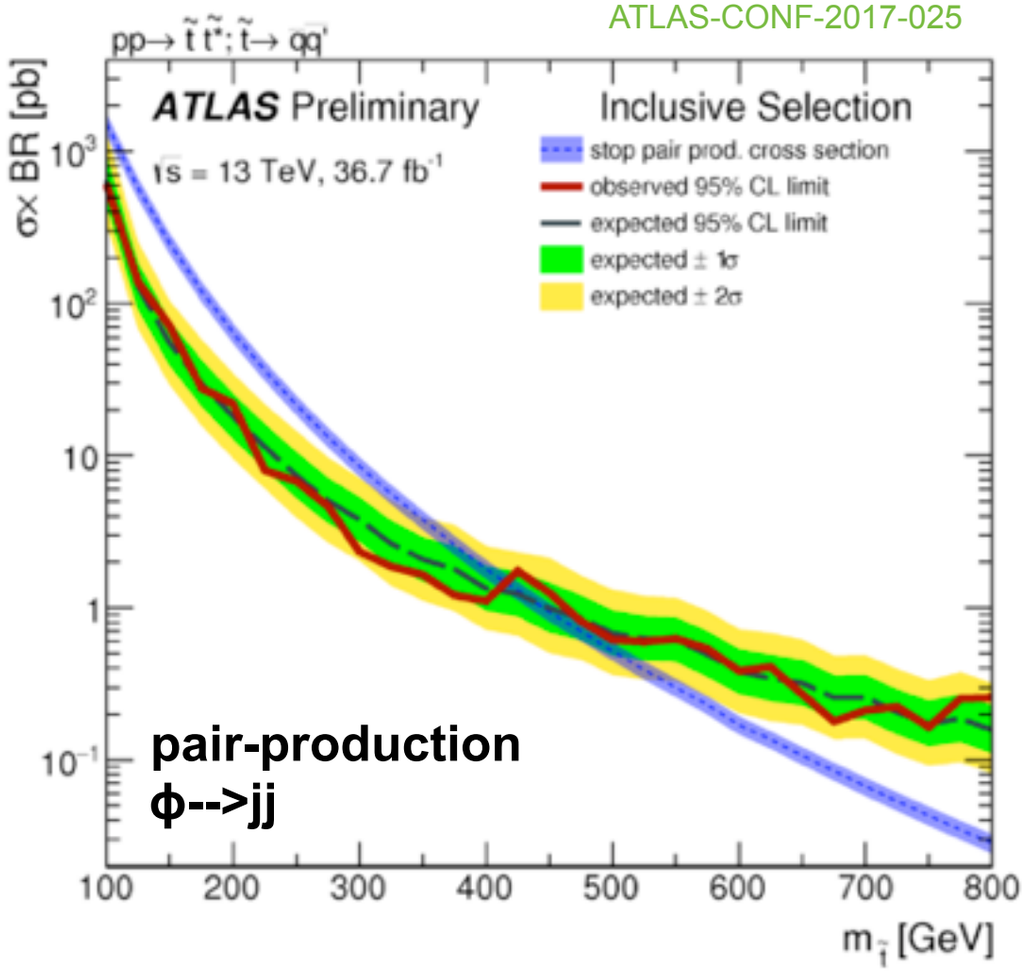
CMS-B2G-13-006

qqϕ single or pair-production + decay (higher dim-operators subdominant)

$$\phi \to tt, tb, bb, tj, bj, jj$$

$$\phi_\mu \to \bar{t}t, \bar{b}b, \bar{j}j$$

ATLAS-CONF-2017-025



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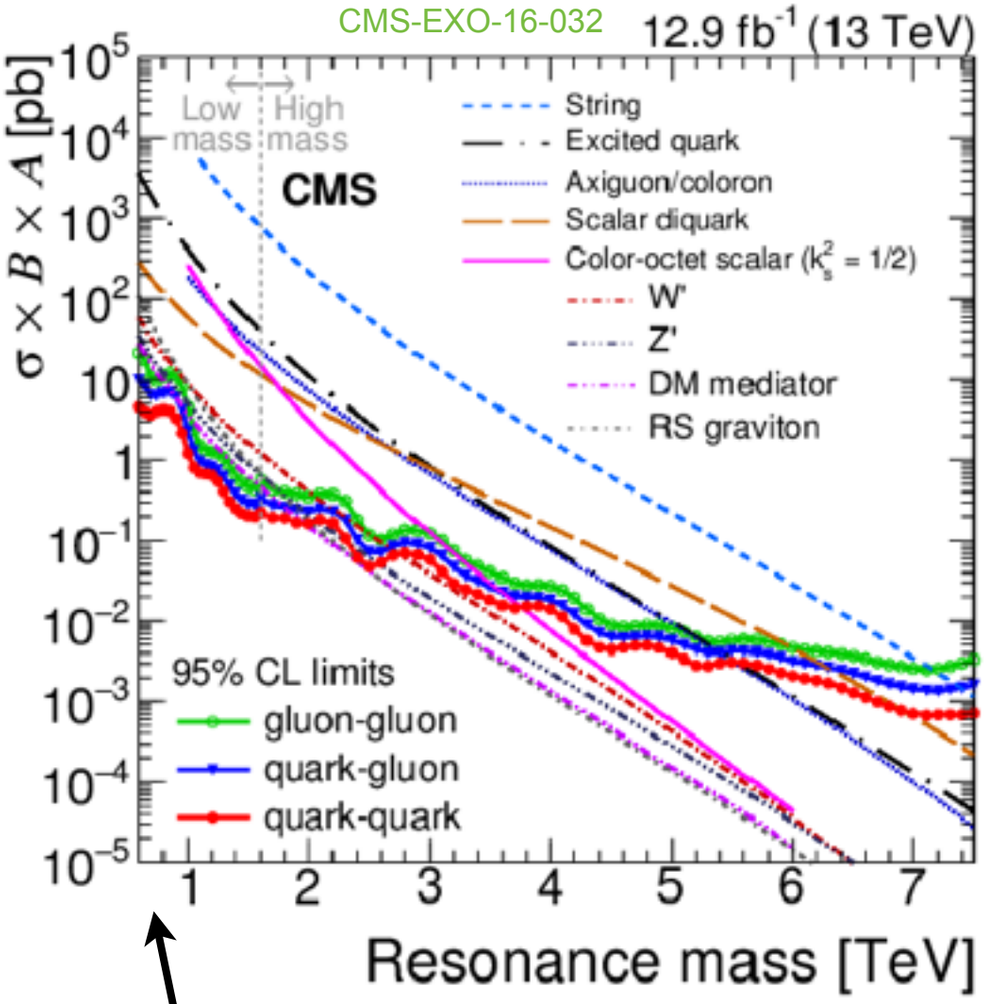
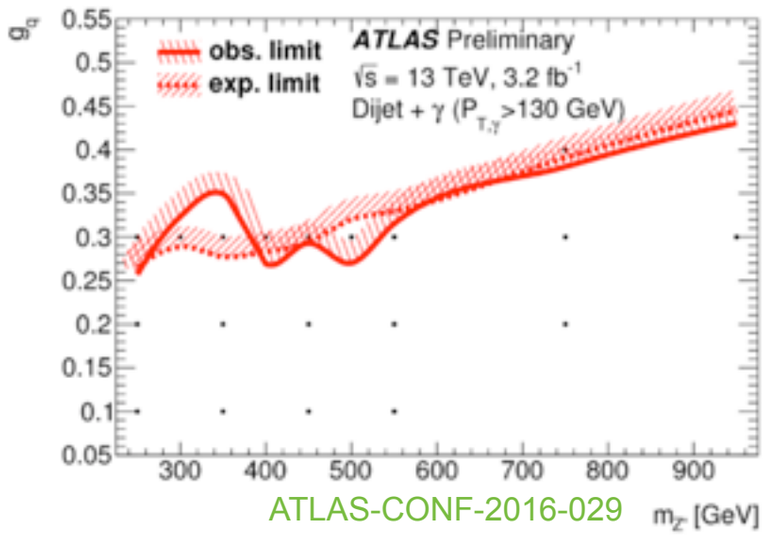




ATLAS-CONF-2016-029

Bound state decay into $\gamma\gamma$, VV, etc.

Strassler, Katz (2012)

A lot of freedom with 2 or more exotic particles, e.g. qϕΨ!

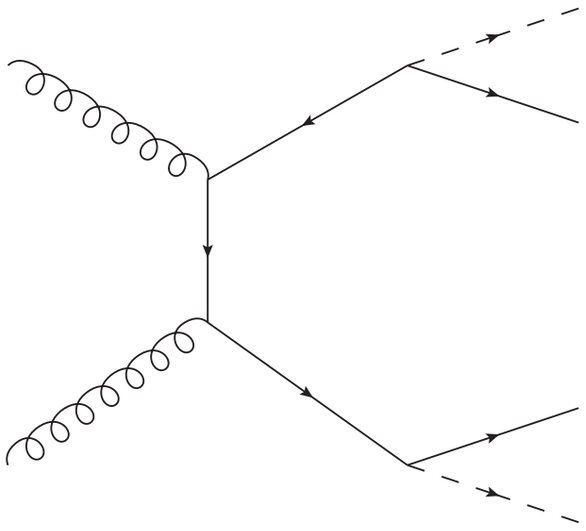
-- non-SUSY signatures (one or both colored)

-- may be combined with small decay rates (from qHΨ or higher dim-operators)

Ex: $\Psi \sim (\mathbf{3}, \mathbf{R})_{\mathbf{Y}}$

$\Phi \sim (\mathbf{1}, \overline{\mathbf{R}})_{\mathbf{2/3-Y}}$

$$\delta\mathcal{L} = \underbrace{\lambda u^c \Phi \Psi}_{\lambda \lesssim 0.1} + \underbrace{\mathrm{HDO}}_{\Phi \to \mathrm{SM}}$$

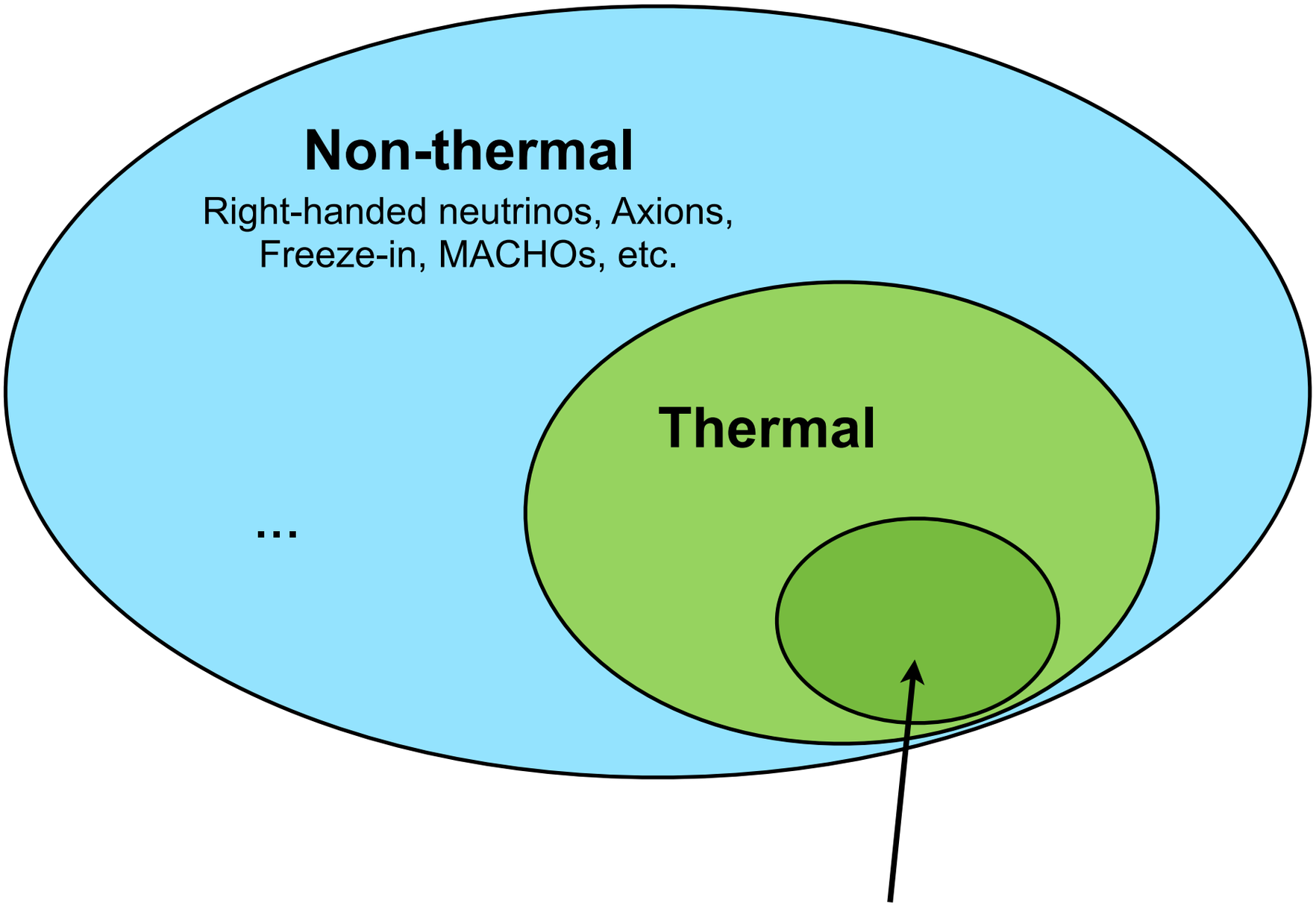


$$pp \to jj + \mathrm{SM} + \mathrm{SM}$$

if SM=jj: colored particles hiding at 500 GeV?!

-- some work to be done...

-- but cannot hide...



WIMPs with sizable couplings to the SM:

complementary { Direct-detection
Indirect-detection
Colliders

q = SM fermion
H = Higgs
Ψ = exotic fermions (J=1/2)
ϕ = bosons (J=0,1)

Dark matter
(SM-neutral)

gauge portal
R-hadrons, multi-jets,...

qHΨ
Fourth generation
Top partners
...

qqϕ
Di-jet scalars
Lepto-quarks
Z',...

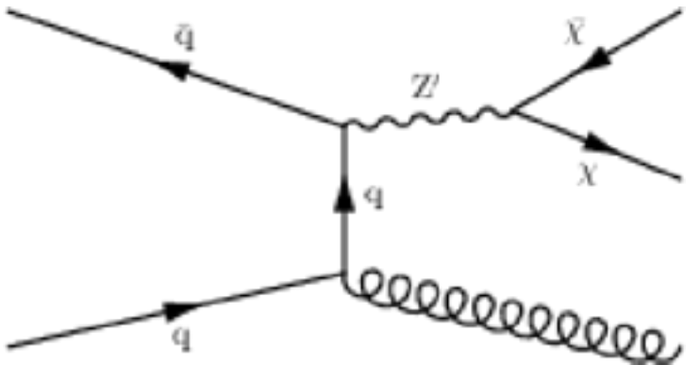
qϕΨ
SUSY-like topology
...

H?/HH?/HHH?
Higgs portal
...

Mediators already
constrained by non-MET searches:
we are ADDING signatures!!!

Ex: **Mono-jets+MET with Z' mediator**

Only useful if weakly-coupled!!!



$$m_X, m_{Z'}, g_X, g_q, \Gamma_{Z'}$$

on-shell mediator

$$\begin{cases} g_q^2 \mathrm{BR}(Z' \to X X) \\ m_{Z'} \end{cases}$$

off-shell mediator

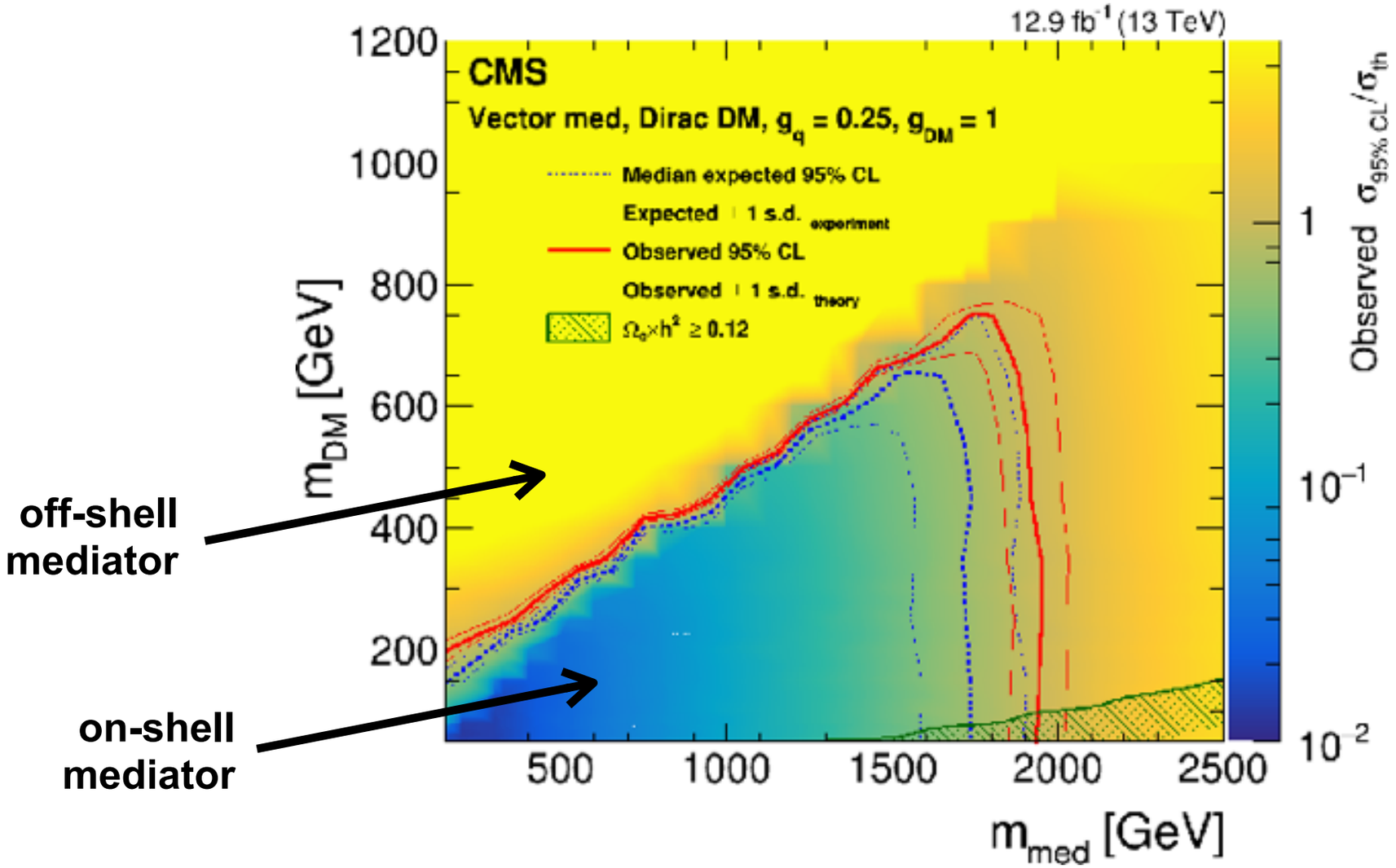
$$\begin{cases} m_X \\ g_q^2 g_X^2 \end{cases}$$

Friedland, Graesser, Shoemaker, LV (2011)
Shoemaker, LV (2011)

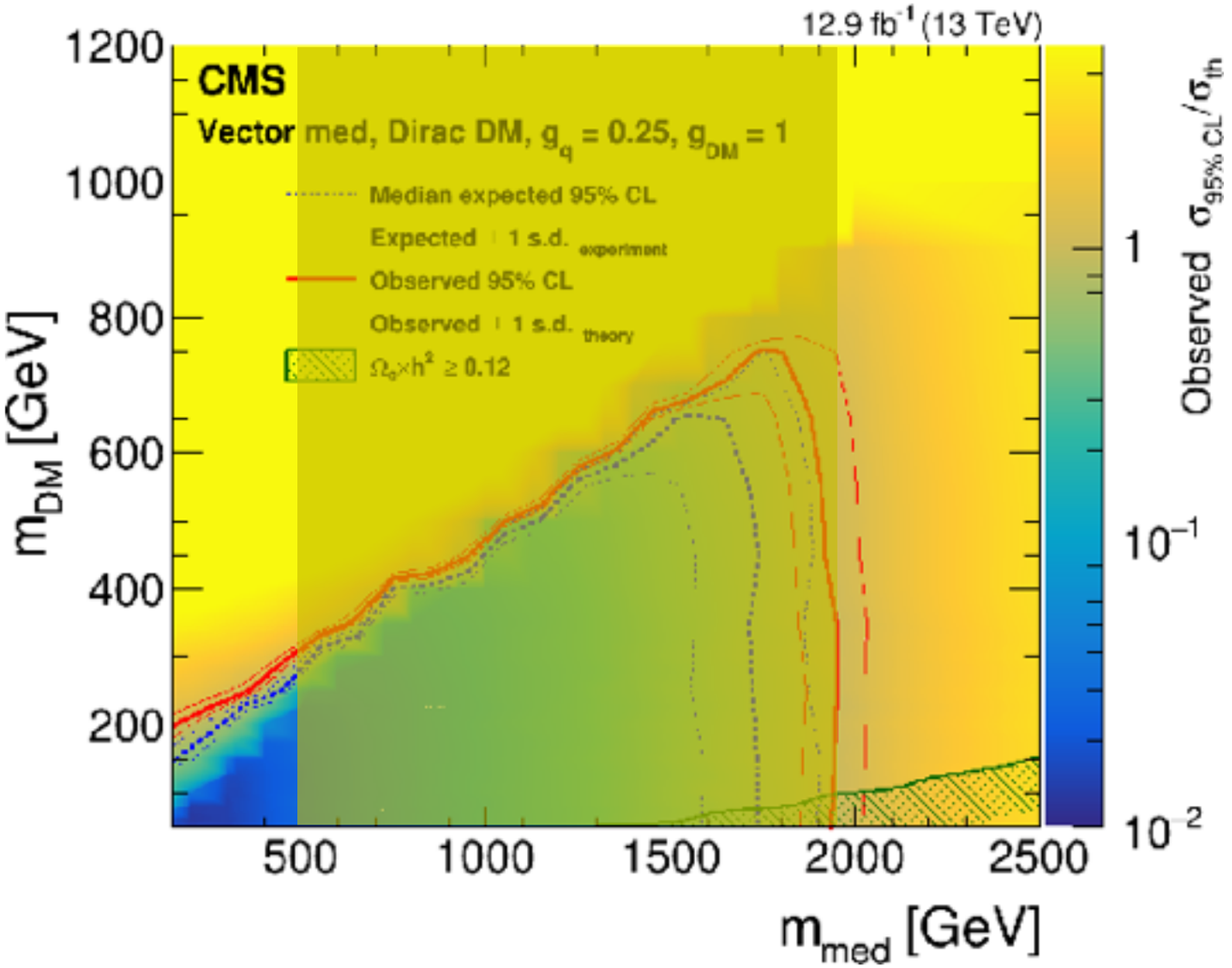
Suggestion by DM Working Group:

-- we must **assume** a width...

-- we must **assume** the couplings...



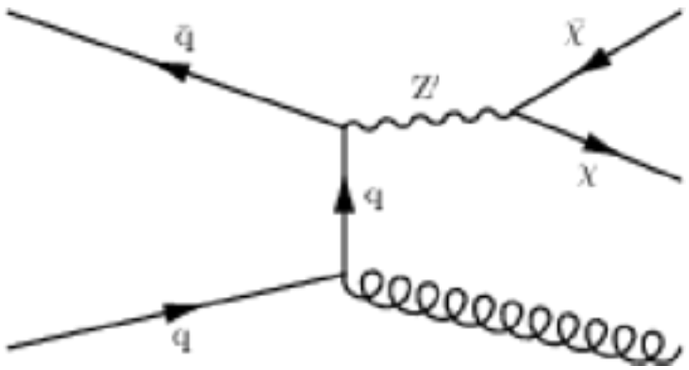
Comparison with **di-jet** bounds???



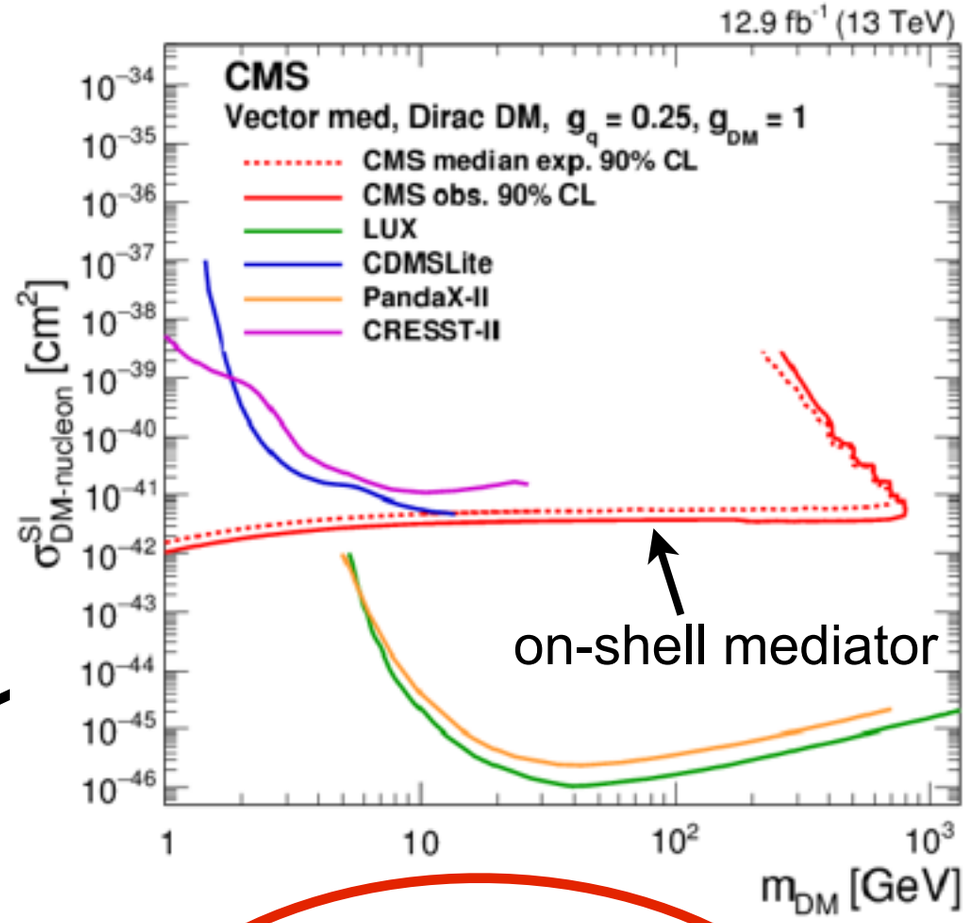
Almost entirely excluded!!!

low mass constrained in,
e.g. ATLAS-CONF-2016-029

Comparison with **Direct Detection**???



$$m_X, m_{Z'}, g_X, g_q, \Gamma_{Z'}$$



off-shell mediator

$$\begin{cases} m_X \\ g_q^2 g_X^2 \end{cases}$$

DD often better!

very different momentum transfers...

Complementary,
NOT competitors!!!

Summary

- **Main objectives for Particle Physics**:
  - uncovering nature of the Higgs potential (future)
  - probing the TeV scale (now)

- **No guaranteed signatures at LHC**:
  - mostly indirect (EW data, flavor violation, neutron and electron EDM, proton decay, etc.)
  - best hope: TeV relics of “naturalizing physics” (Higgs potential, baryogenesis, dark-matter, etc.)
  - no favored BSM model, but very strict rules for the game...

- **Keep looking (th. and exp.)**:
  - 2 complementary probes: EFT & Simplified Models
  - no obvious blind spots at LHC
  - still, many non-standard (non-SUSY) searches may be optimized: colored stuff hiding?!
  - dark matter searches complementary to mediator searches (no sharp distinction)
  - dark matter searches at colliders are complementary to DD and ID

Recall the 750 GeV anomaly:
new physics may first show up in unconventional channels...

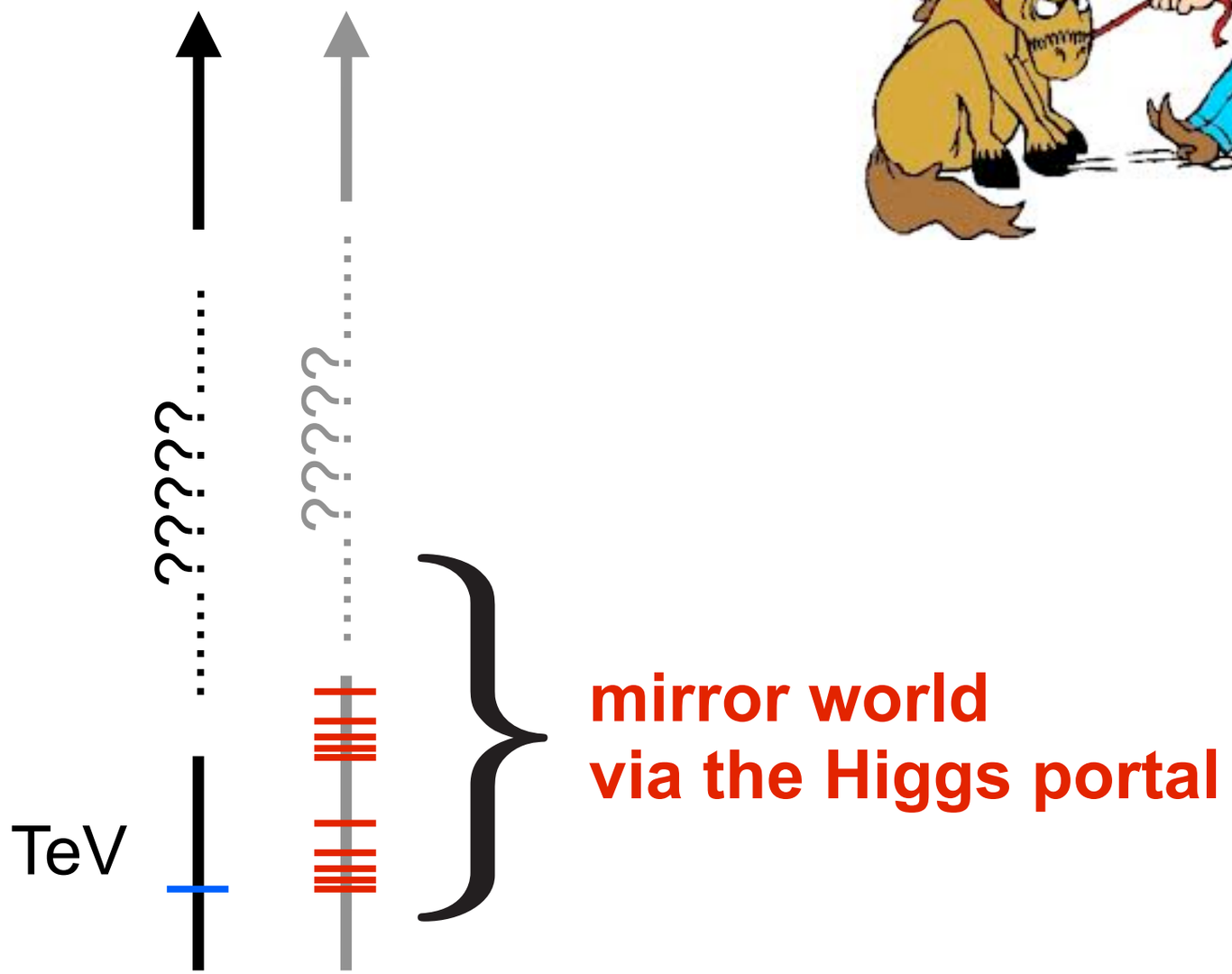
Expect the unexpected!

Thank You

Subtle Naturalness:

neutral Naturalness, Twin Higgs, Folded SUSY

Chacko et al. (2005)
Craig et al. (2015)
...



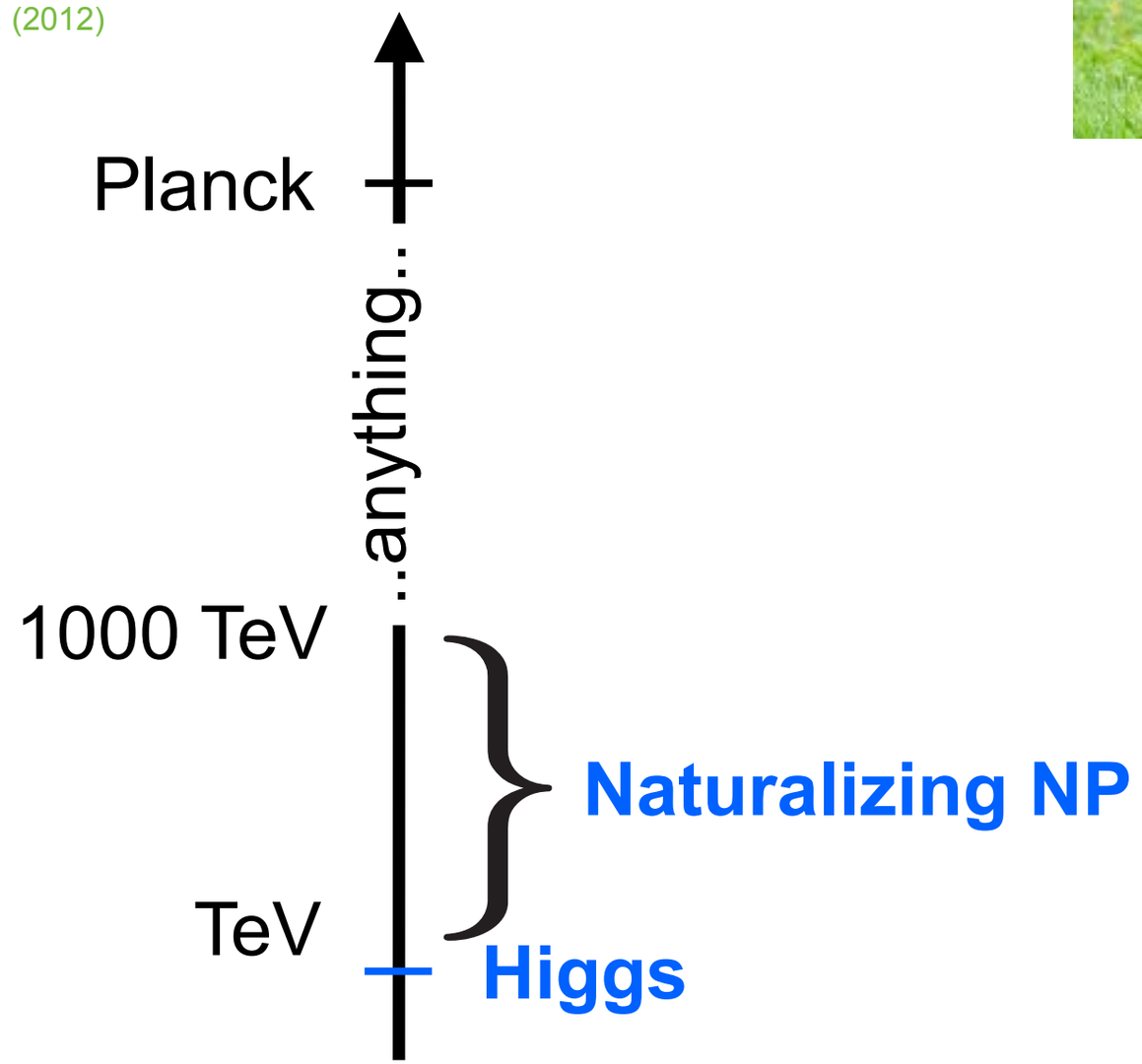
PROS
-- small tuning (at least 10%, however...)
-- signatures via Higgs portal

CONS
-- very involved (tuning in theory space?)
-- unknown UV completion

Relaxed Naturalness

meso-tuning: we are close... (again?!)

Wells (2004)
Dimopoulos et al. (2012), Arkani-Hamed et al. (2012)
LV (2013)
Gherghetta et al. (2015)



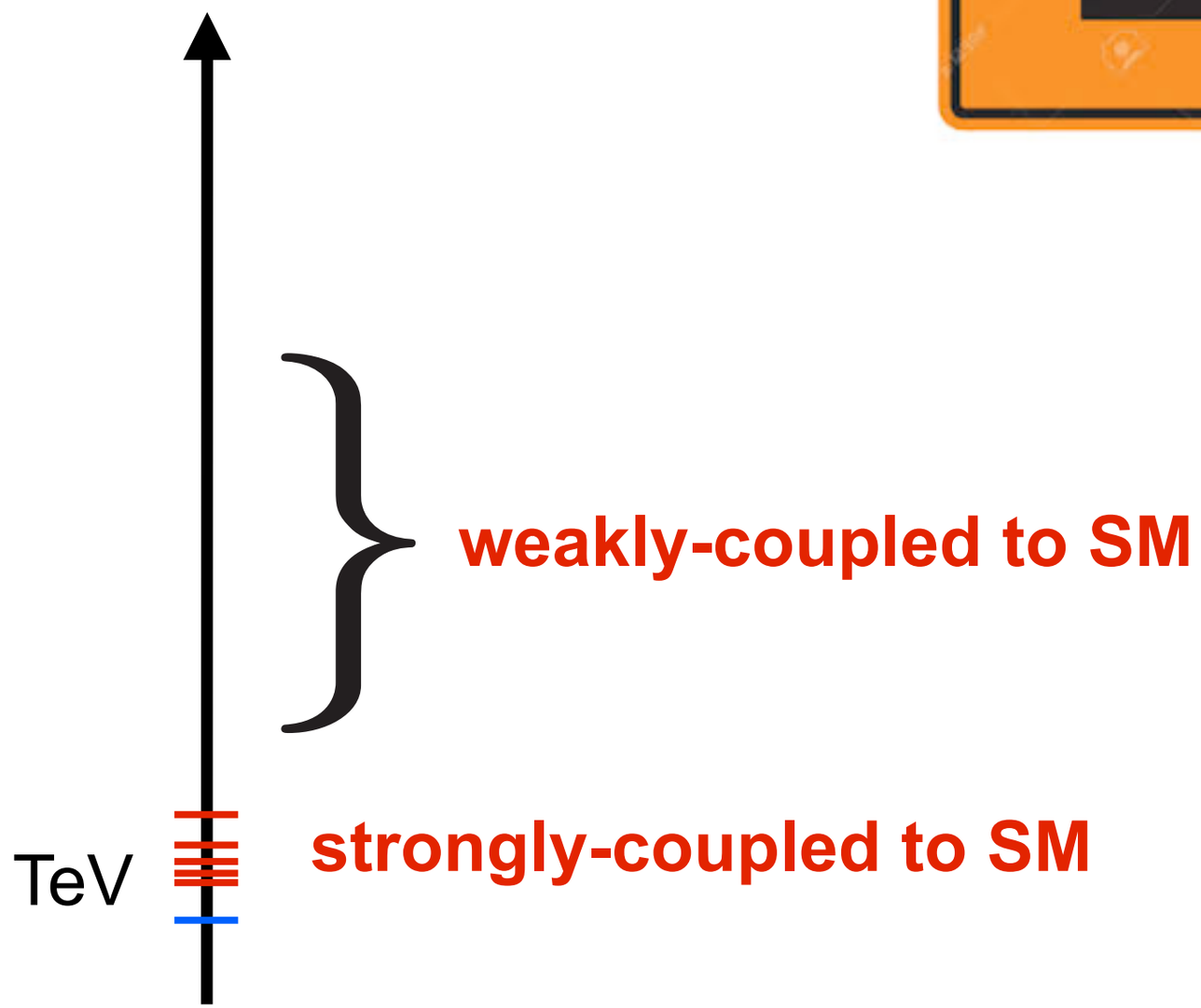
PROS
-- simplicity (natural in theory space!). **SUSY=theory of Higgs mass and GUT, CH=theory of flavor**
-- UV insensitive (can have GUT, etc.)

CONS
-- little Hierarchy (most of the weak-Planck hierarchy is stabilized)
-- only indirect signatures guaranteed: flavor violation, dipole moments (dark matter?)

Alternative Naturalness:

conformality, finite naturalness, natural tuning, ...

Bardeen (1995)
Shaposhnikov et al. (2008)
Strumia et al. (2013)
Dubovsky et al. (2013)
...



PROS
-- in agreement with data
-- predictions: new states to generate baryon asymmetry, neutrino masses, etc.

CONS
-- Is it viable?! Landau pole of hyper-charge introduces a threshold...
-- GUT?