Beyond the Standard Model

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EXCELENCIA
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A body of knowledge

Empirical evidence of BSM
(Neutrino, Dark Universe, Asymmetry)

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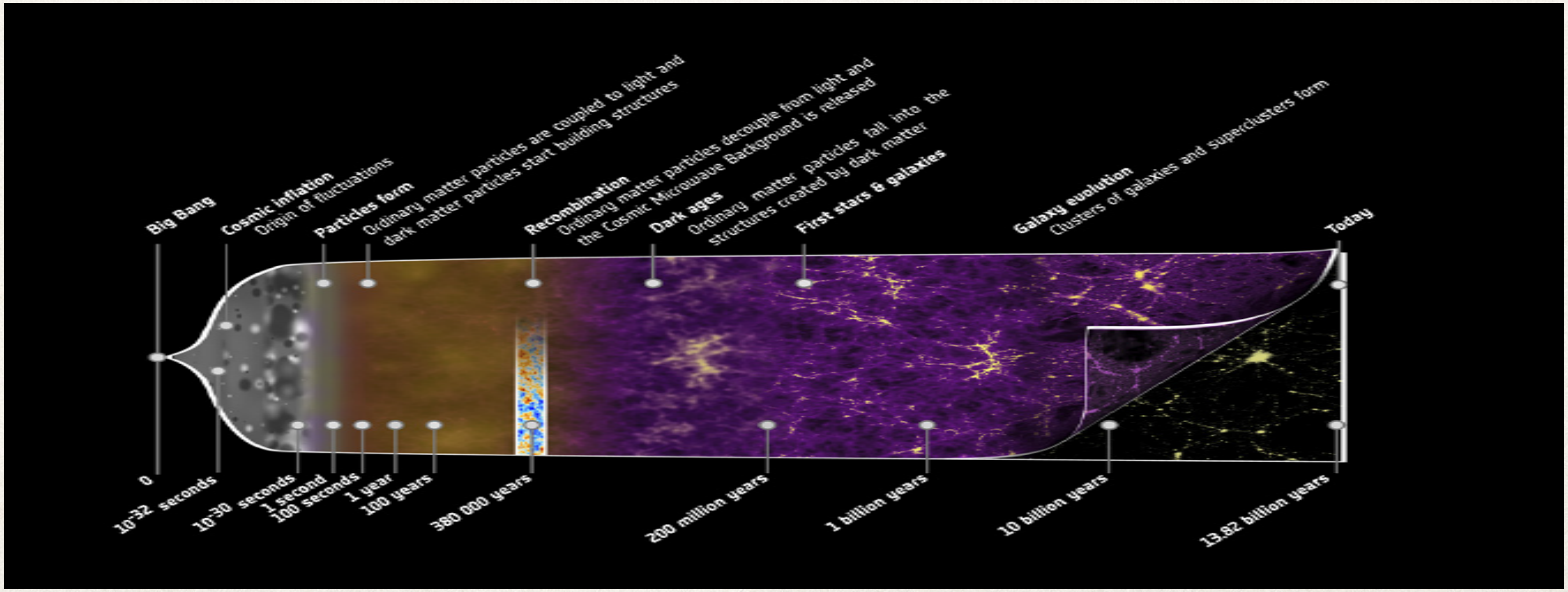
None of these discoveries
possible within Particle Physics
need **Cosmology, Astrophysics and Nuclear Physics**
to understand
Expanding Universe, Solar model,
Astrophysical production and propagation etc



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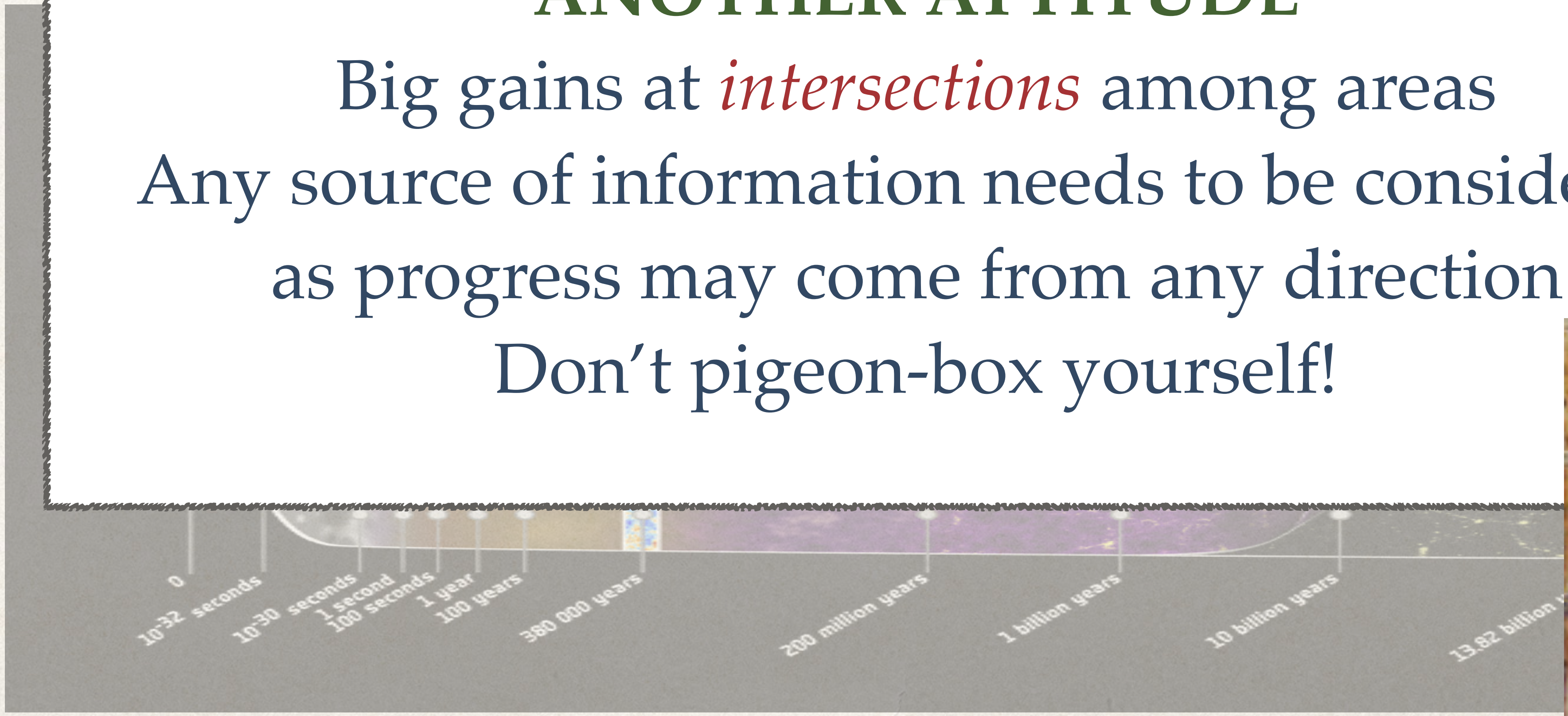


ONE ATTITUDE

Particle Physics, Earth-based experiments

Truly fundamental, true probes of Nature

whereas others

quantitative, modelling, uncontrollable sources

ANOTHER ATTITUDE

Big gains at *intersections* among areas

Any source of information needs to be considered as progress may come from any direction

Don't pigeon-box yourself!

In these lectures

Phenomenology probes

1. Evidence
(DM, Neutrinos, Baryogenesis & Inflation)
2. Rationale
(Example of Naturalness)
3. Models for the Higgs and beyond
(Supersymmetry & Composite Higgs)
4. Looking ahead

Evidence

Hard-core BSM evidence:

Let's start with Dark Matter

Dark Matter in a nutshell

- ~ 1/4 of the current Universe
- *likely* a particle
- dark: no coupling to EM
- massive (cold, > 10 KeV)
- no color interactions
- stable

(caveats are possible)

Dark Matter

Strong evidence of some form of gravitational source consistent with the existence of a new sector BSM

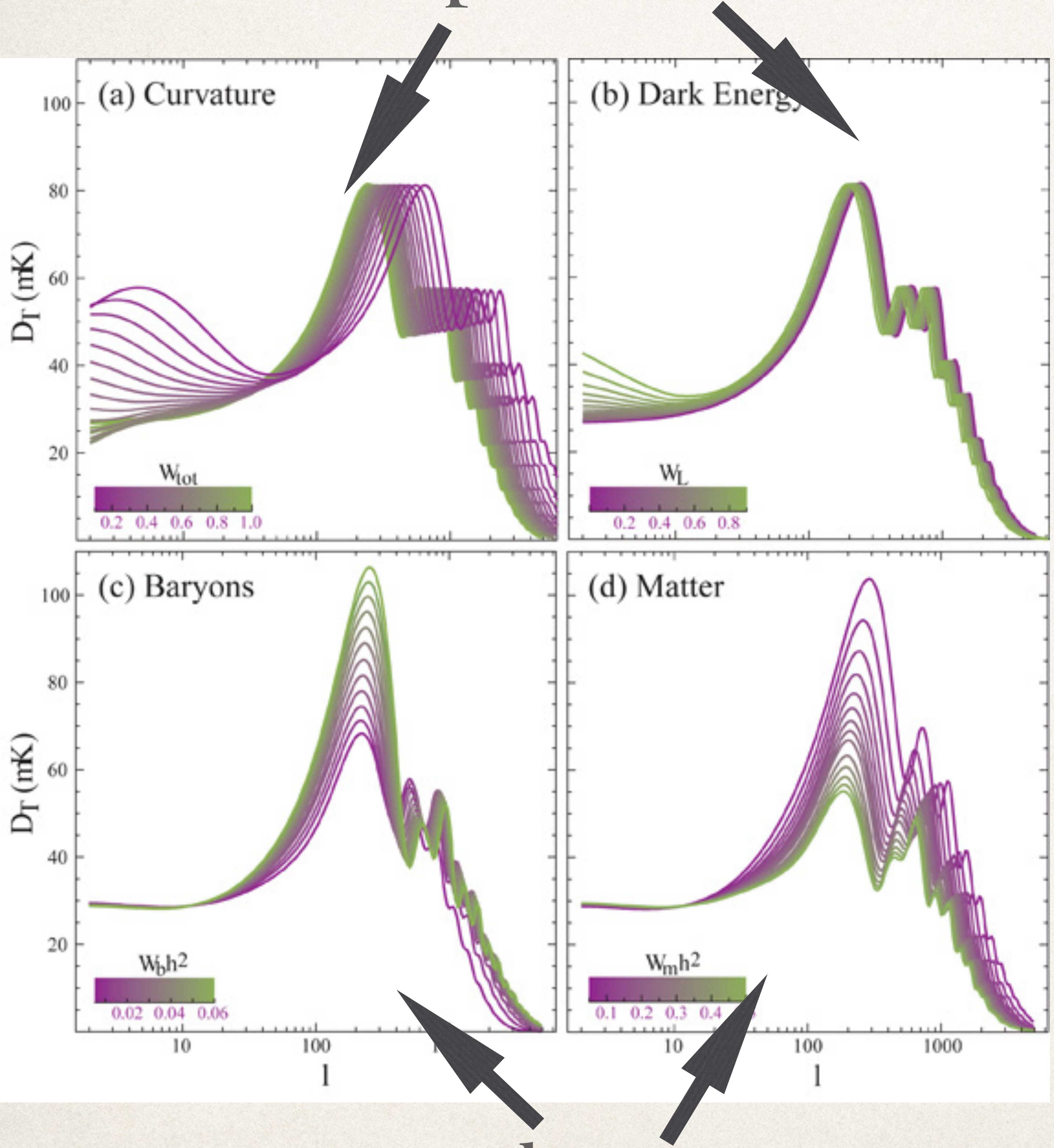
Astrophysical/cosmological
rotation curves
structure formation (e.g. simulations)
dynamical events, e.g. galaxy mergers
CMB (Planck) …

No evidence so far of other interactions

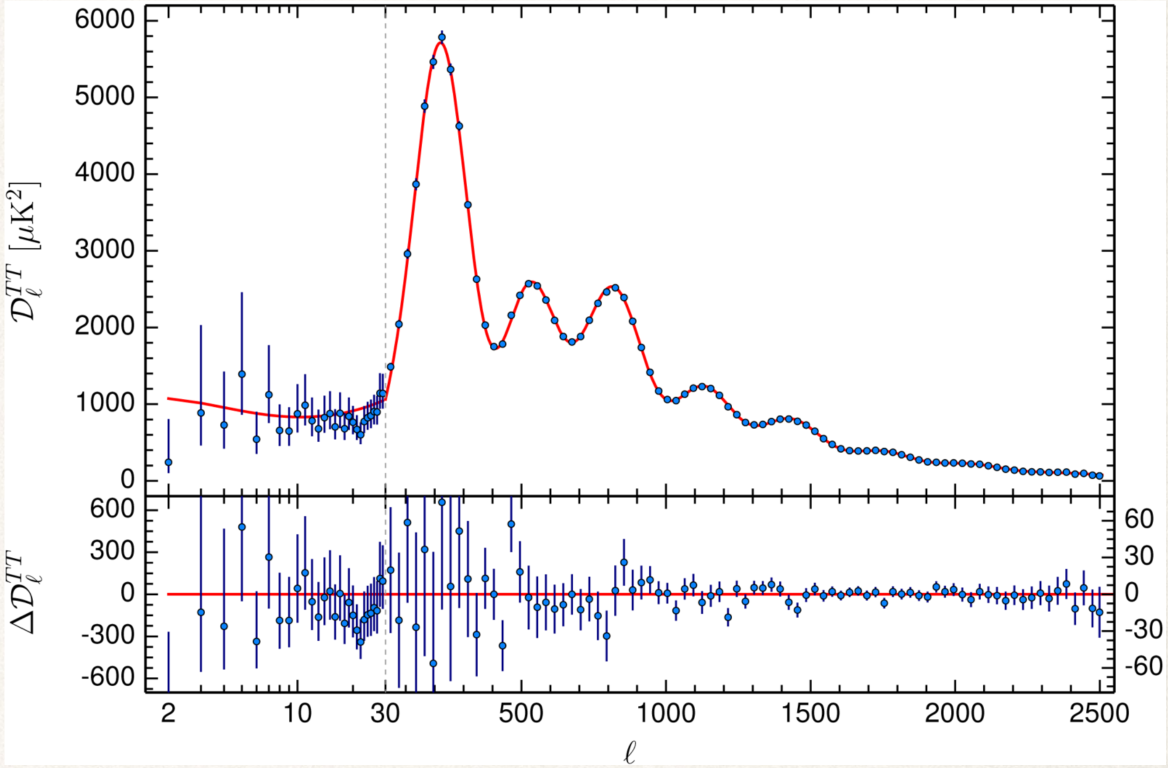
Direct detection experiments
Indirect detection via production of SM particles

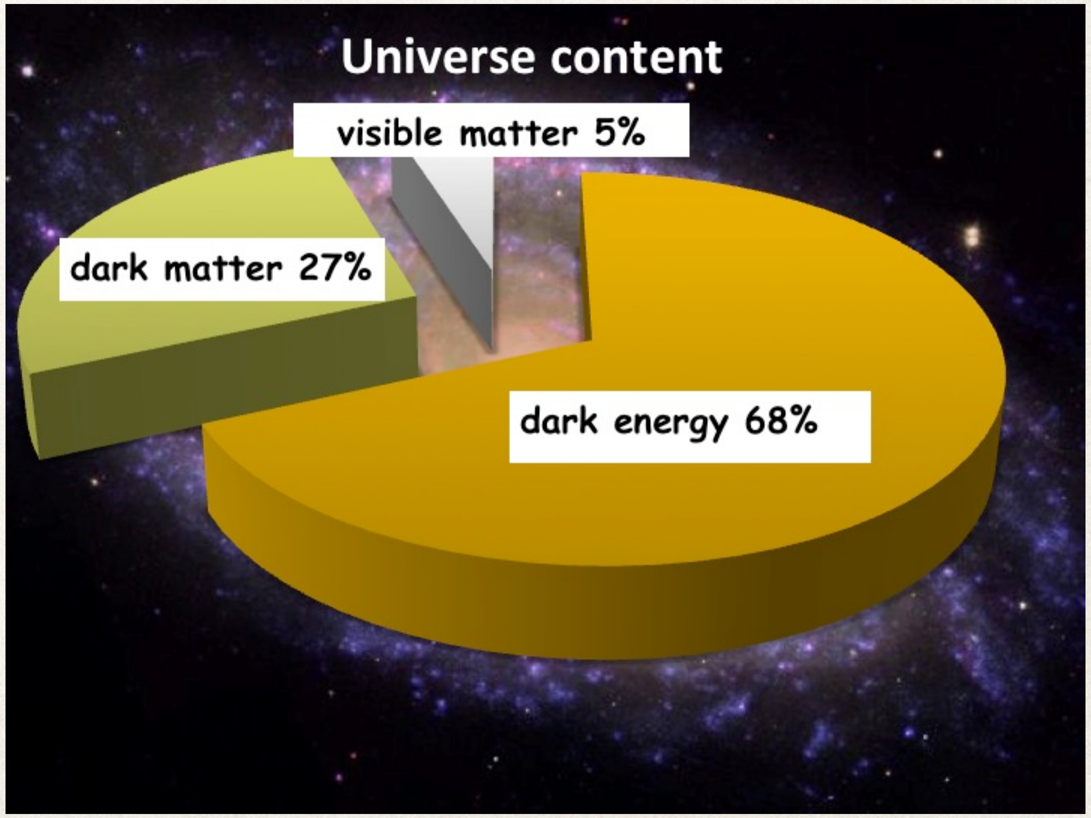
Dark Matter: CMB evidence

position

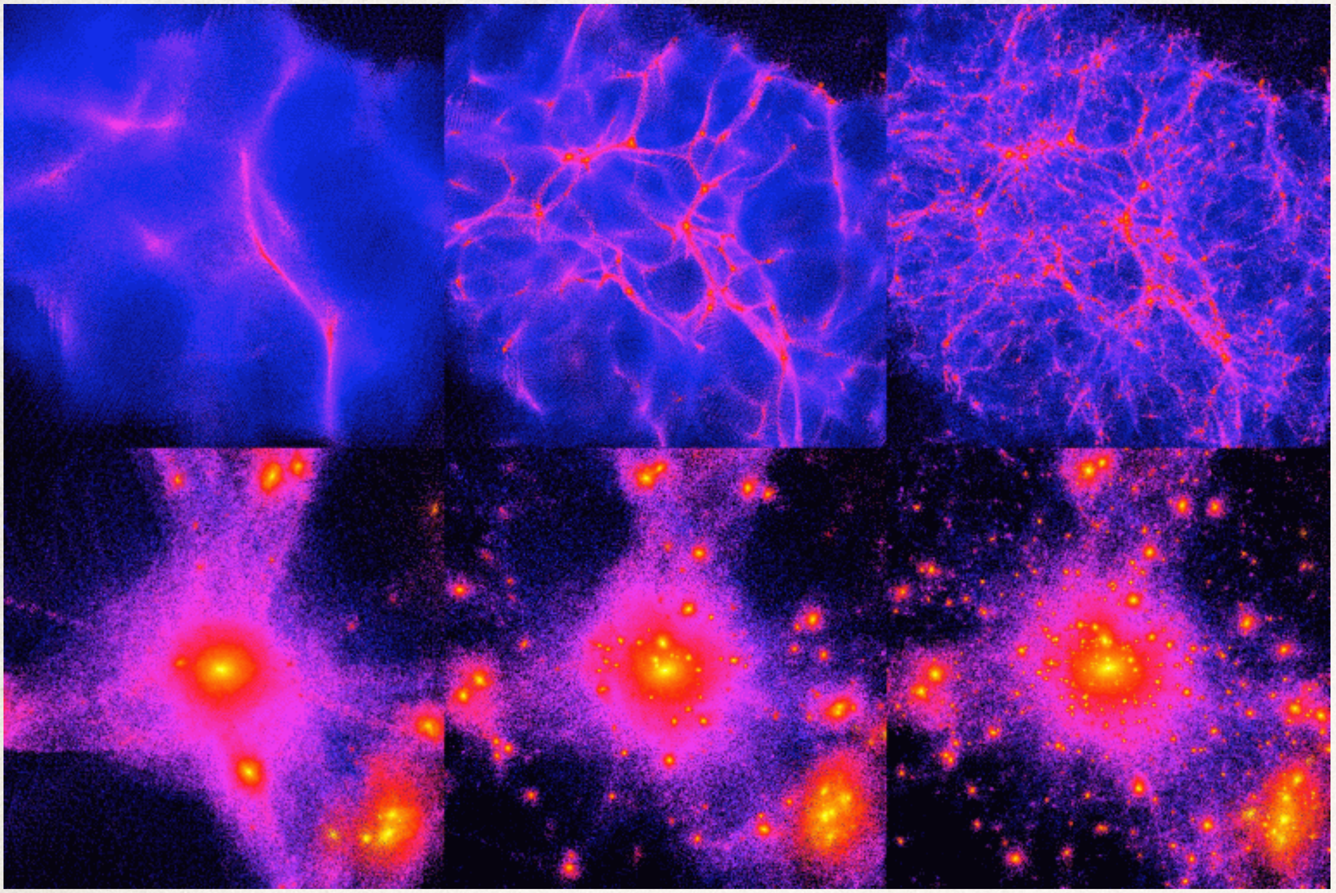


shapes





Dark Matter: simulations, mergers

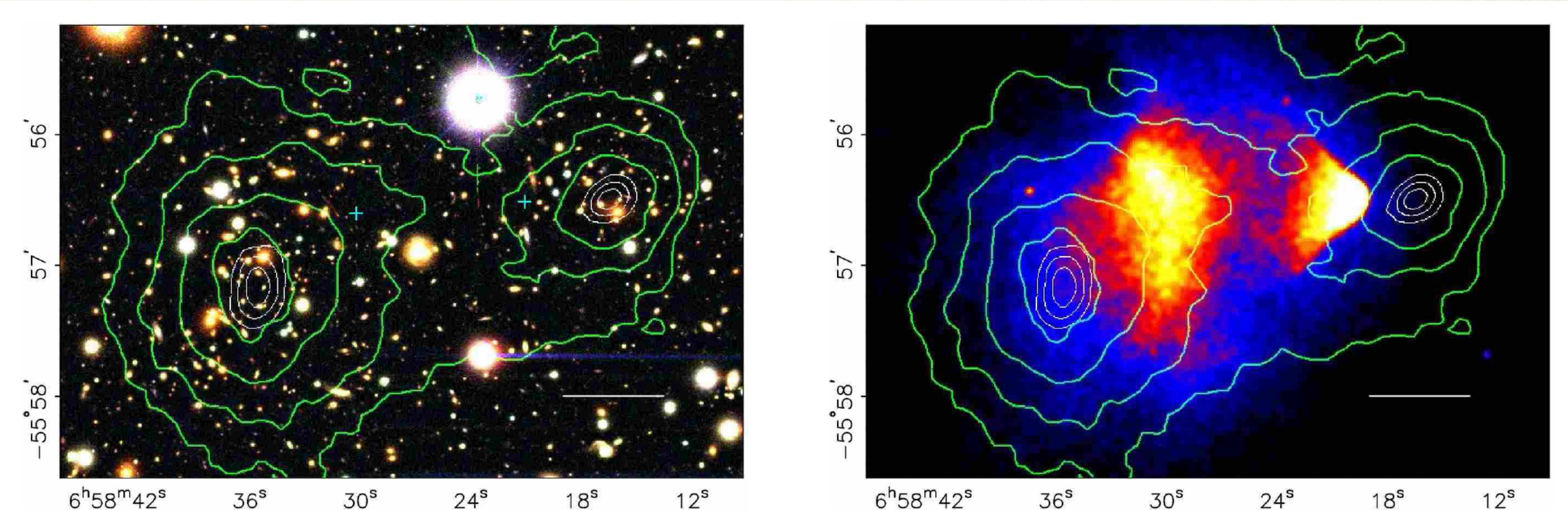


(hot, warm, cold)

hotter DM dissolves *small* structures, only big survive and they collapse slowly not what we observe

warm (KeV) and/or cold (GeV)

dynamical processes maps of DM, strong tests of MOND vs CDM info on self-interactions



gravitational lensing

X-ray

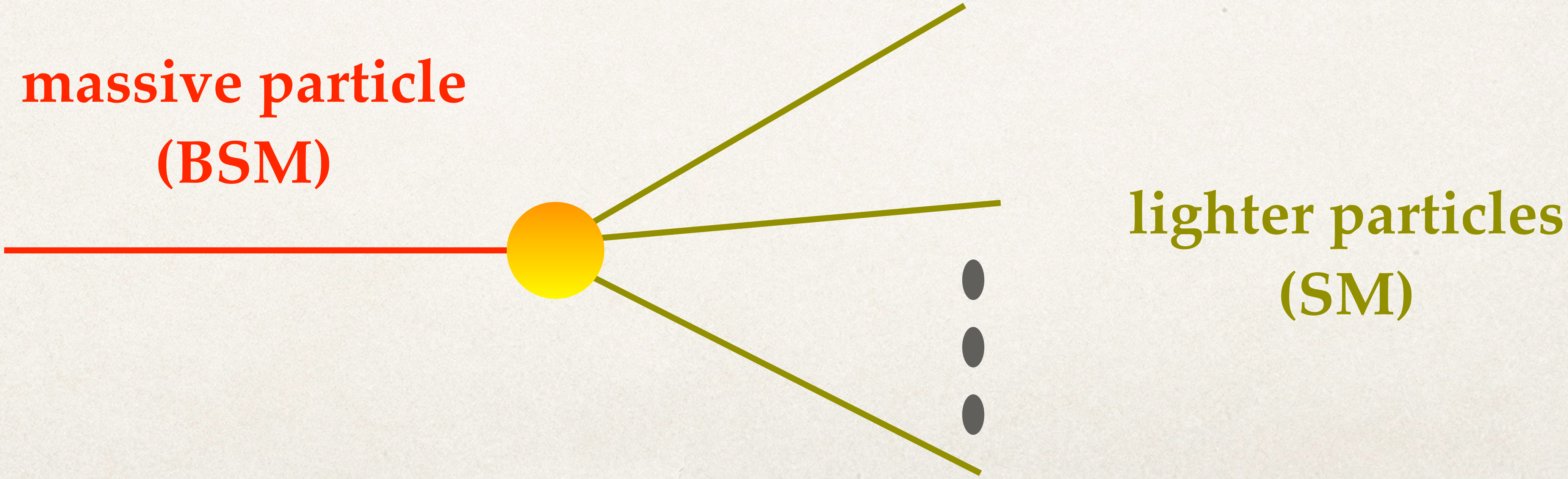
Archetypical Dark Matter

E.g. SUSY Neutralino

(we will learn more on SUSY in the next lecture)

Massive: mass comes from SUSY breaking
Weak state: SUSY partner of neutral Z or Higgs
Stable: Consequence of a remnant symmetry
(Symmetries for DM: typically parities (R-parity))

STABILITY



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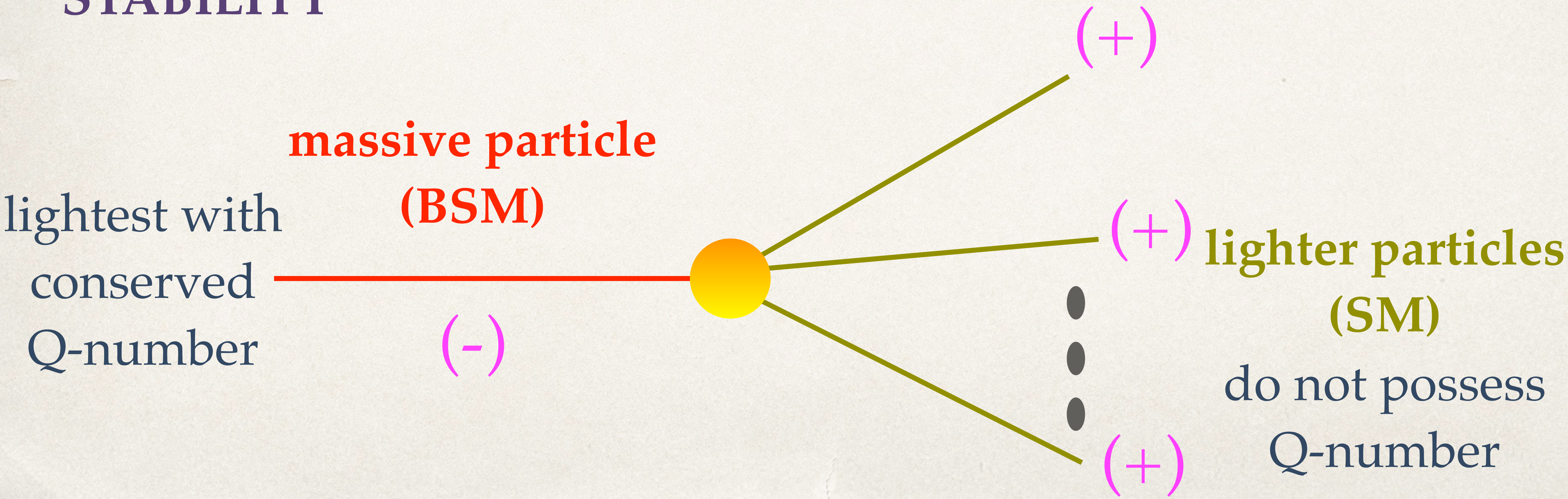

lightest with conserved Q-number

massive particle (BSM)

(-)

(+)

(+)

(+)

lighter particles (SM)

do not possess Q-number

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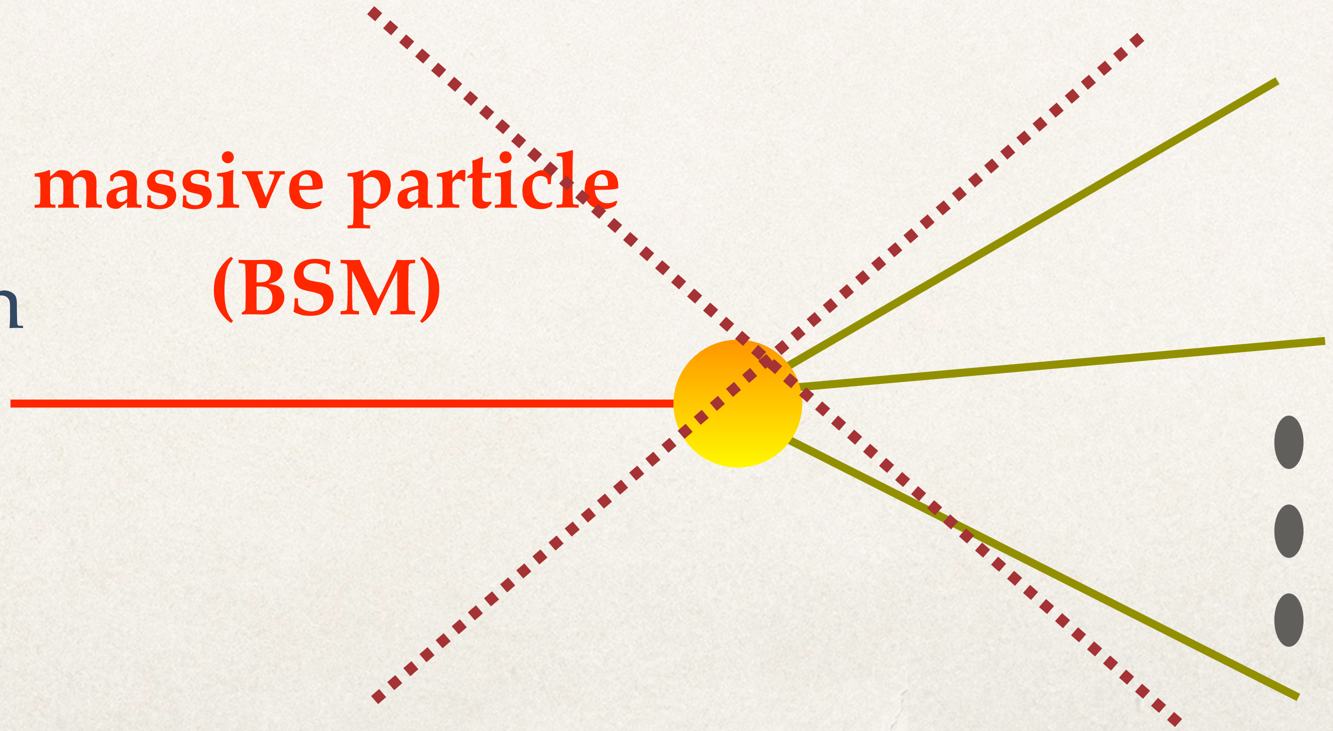

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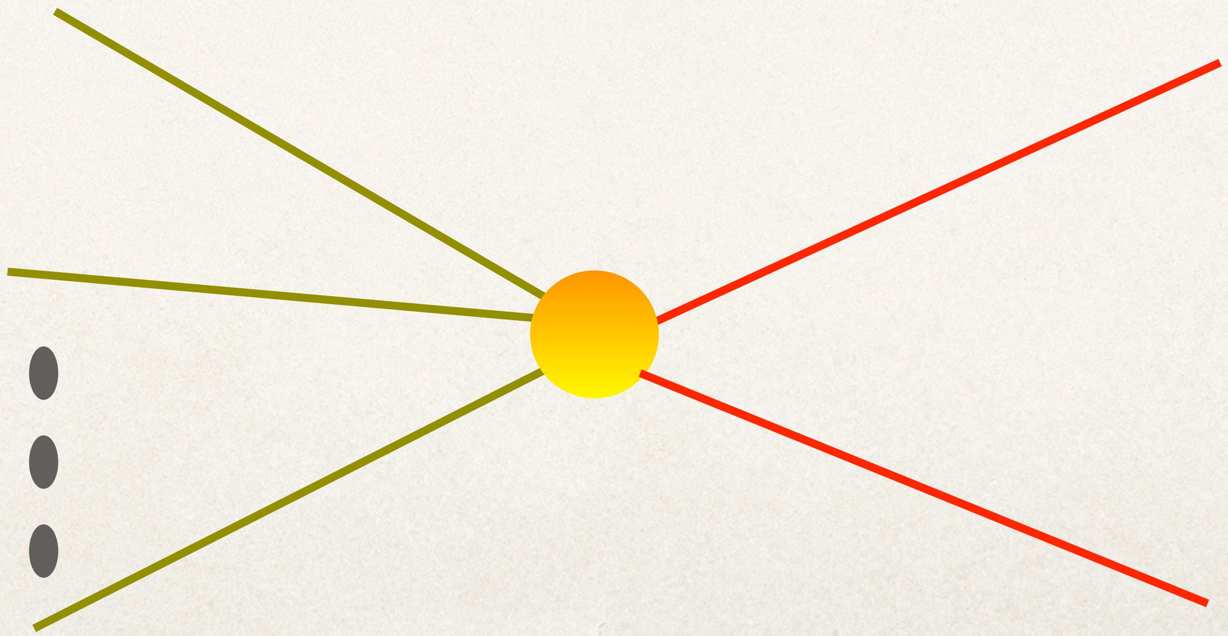
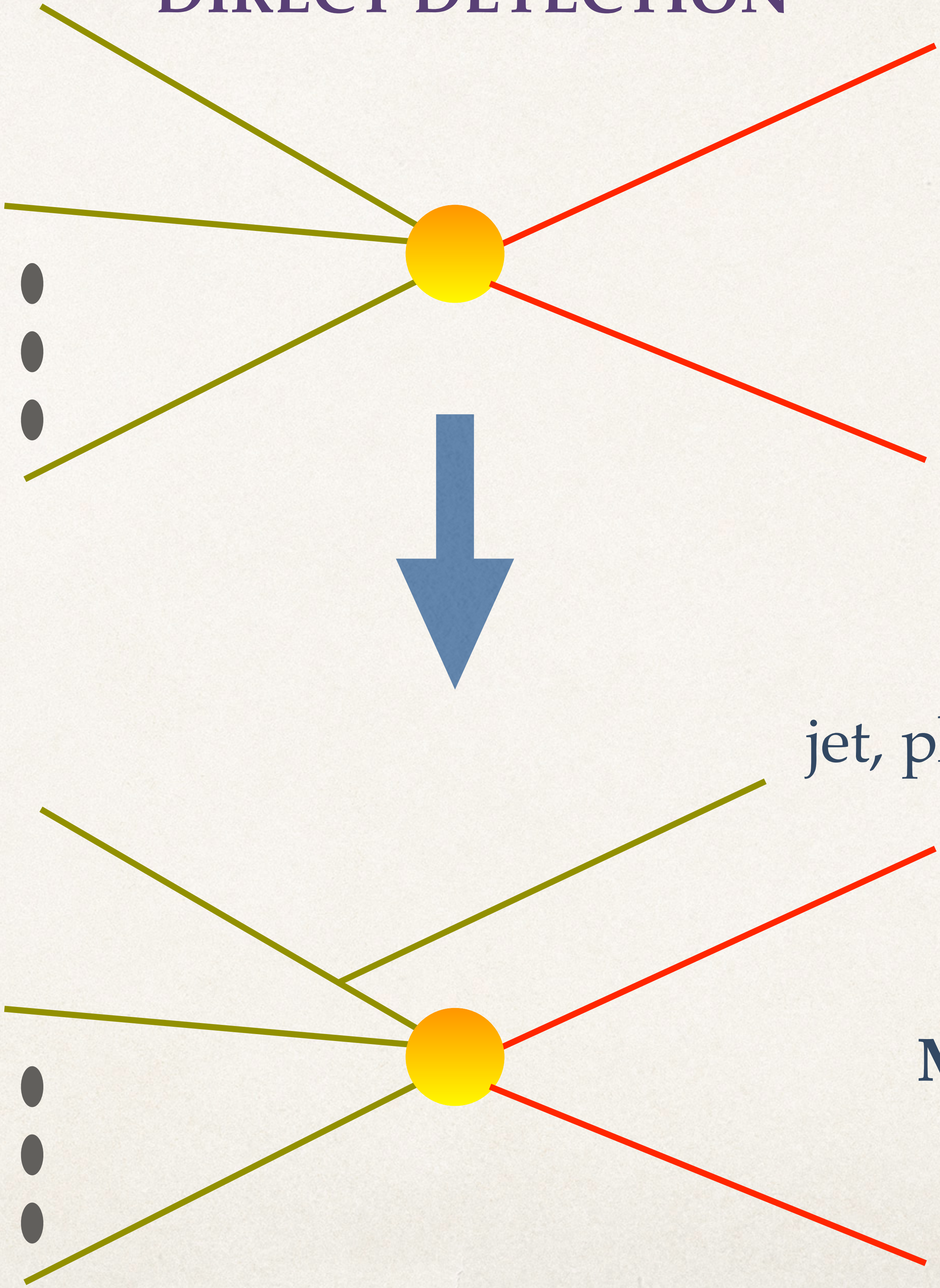


EW SM states

pair production BSM

Archetypical Dark Matter



DIRECT DETECTION

EW SM states

pair production
BSM

Neutral particle
Escapes detection

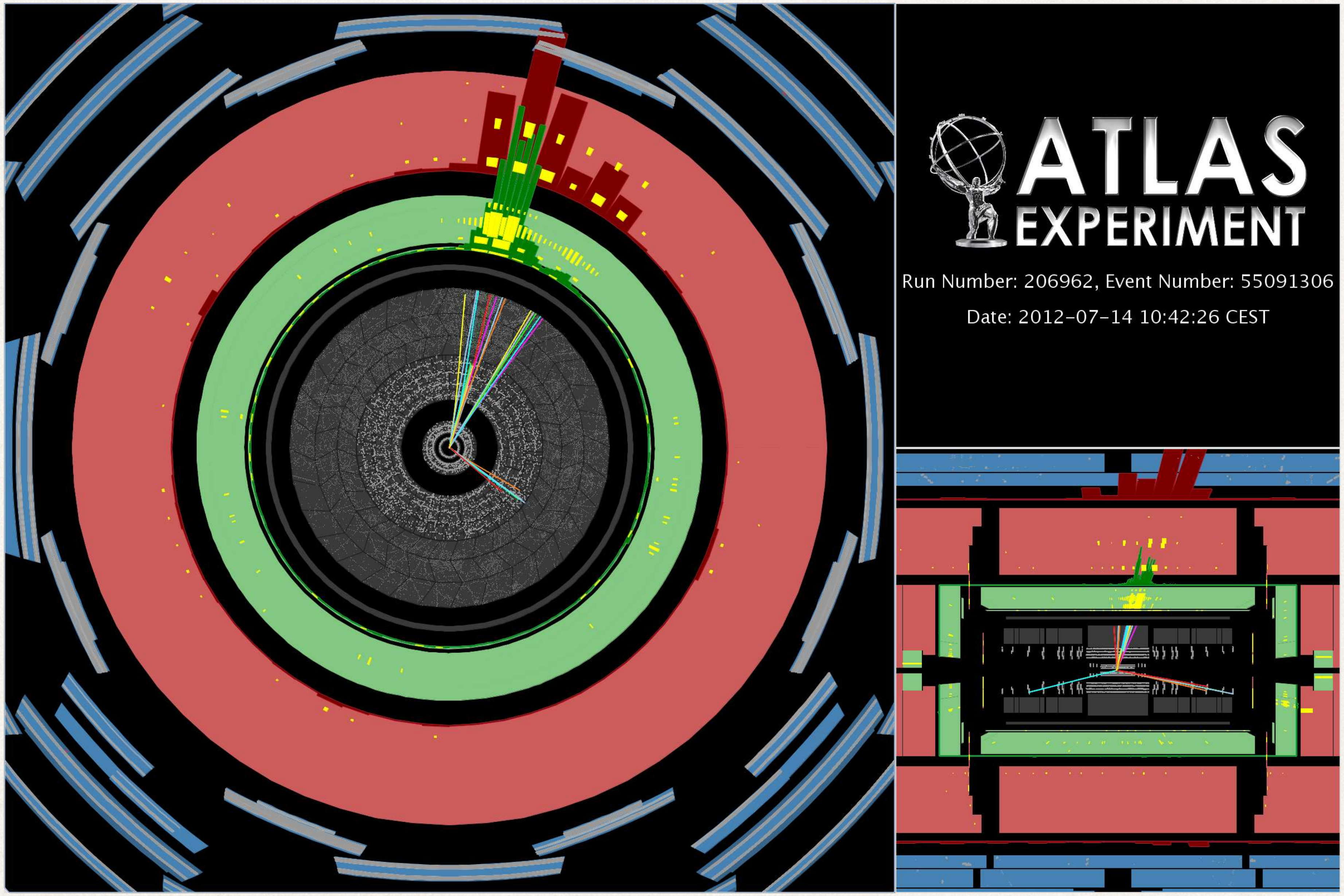
jet, photon, W, h, Z, top…

EW SM states

Mono-X signatures

Archetypical Dark Matter

DIRECT DETECTION

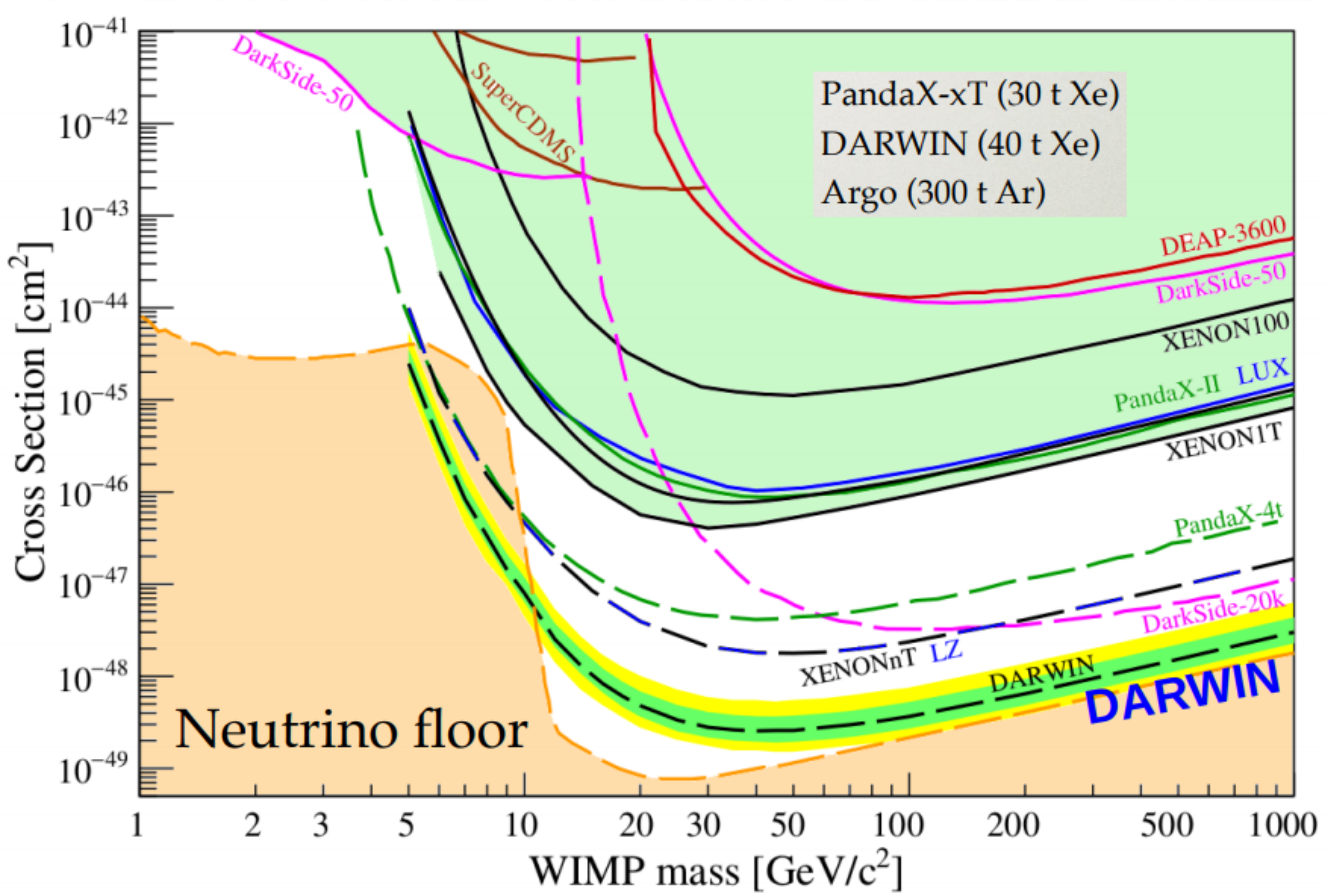


Archetypical Dark Matter

DIRECT DETECTION

Recoil instead of production

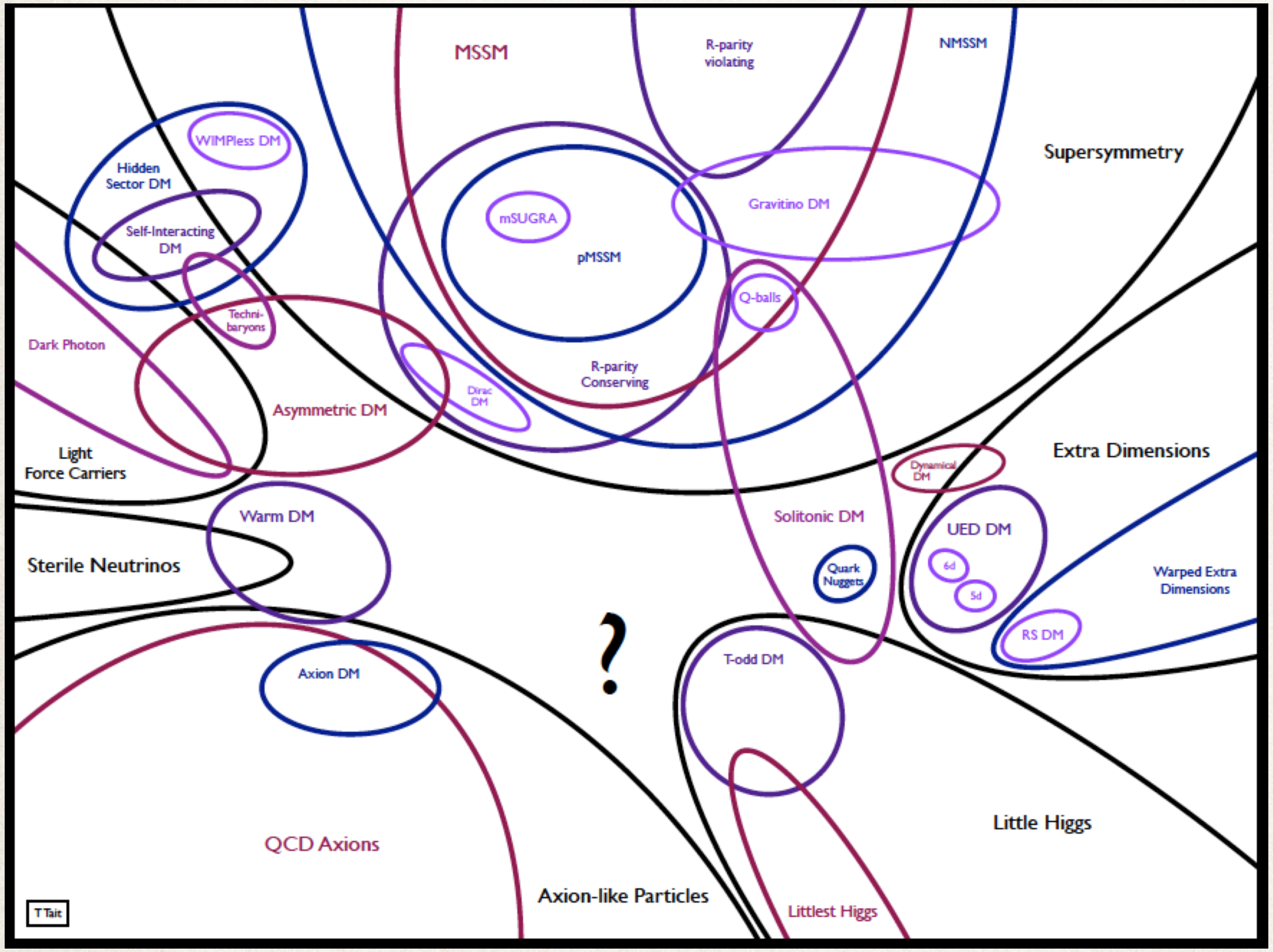
interactions
with nucleons



mass

Many theory possibilities for Dark Matter

For a long time, DM as a thermal WIMP was a *paradigm*
Model building: WIMPs in all kinds of scenarios
(SUSY, extra-dimensions, gauge extensions of SM…)
but we are becoming much more open (axion-like, very light/heavy)



A snapshot of models for
Dark Matter

Popular models =
linked to solutions to other
problems in the SM

Discovery to characterization
of Dark Matter
leading to new discoveries

Thanks to Tim Tait

DM: a poster-child for complementarity

THEORY

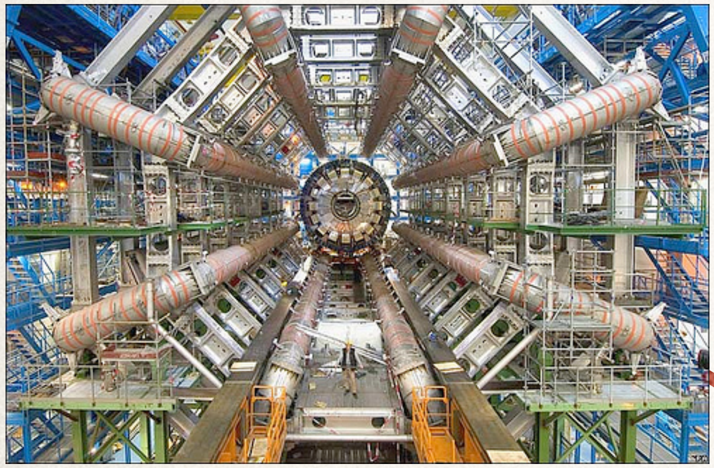
Discrete symmetries

Dynamical stability

self-interactions

Link to Higgs…

COLLIDERS



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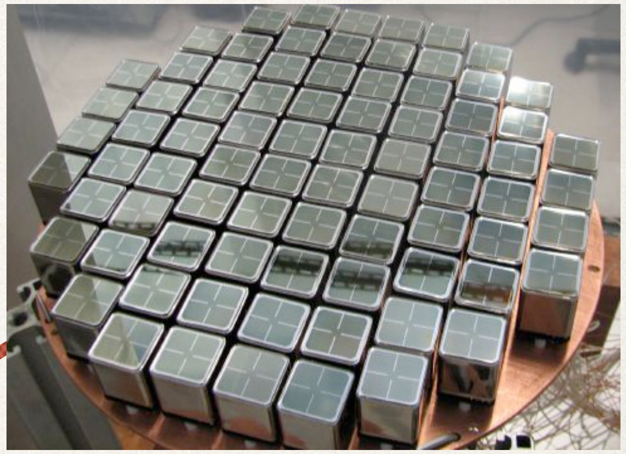
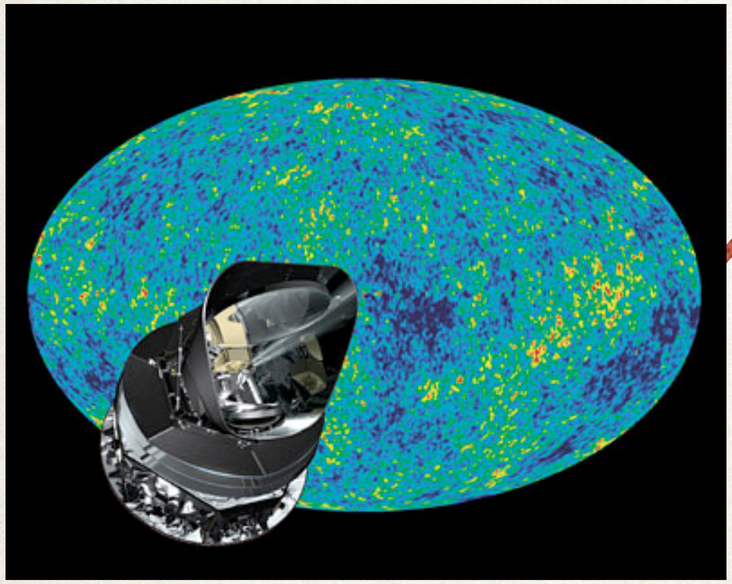
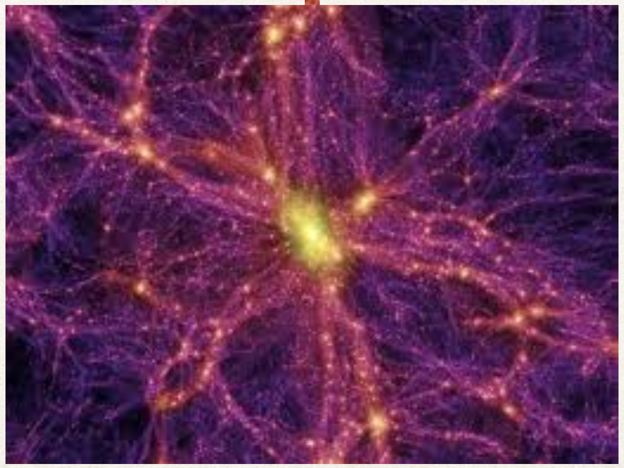


DARK MATTER

CMB: relic, tilt



INDIRECT DETECTION



SIMULATIONS

Dark Matter overview

DM is exciting because a discovery in one form of detection can be then be correlated to other handles for searches, hence characterization of the discovery is possible

Whereas there is plenty of evidence for DM,
nothing ensures DM has non-gravitational interactions, incl self-interactions

Dark Matter overview

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Often DM models are linked to solutions to other issues of the SM, and this implies some form of coupling to the SM

Writing down motivated models which explain the relic abundance is not hard, but hiding them from colliders/DD/ID can be quite problematic: Vanilla models like axions, SUSY WIMPS, etc are very much in trouble

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Null results from searches may be discouraging, but the BSM field had been dominated by a handful of proposals (SUSY and the likes)

There are lots of new ideas out there, waiting to be explored

Neutrino masses

(see exercise at the end)
See Gabriela's lectures

Neutrino masses usually generated via **see-saw**
new heavy state (**sterile** neutrino), mixes with **active** neutrinos

Example: light (<TeV) sterile neutrinos
type I see-saw mechanism

Yukawa interaction

$$Y_{\alpha a}\overline{L}_L^{\alpha} H \Psi_{Ra} + h.c.$$

active sterile

EWSB mass mixing

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

$$m_{light} \sim m_D^2/m_N$$
$$m_{heavy} \sim m_N$$

if mN is not too large: heavy neutrinos modify Higgs/massive gauge boson properties at LHC

Neutrino overview

Neutrino masses, via the see-saw, may open a window to heavy new physics

Neutrino experiment is an active area, and surprises could come from it e.g. measurement of CP violation, violation of fundamental symmetries

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Sterile neutrinos could be DM (KeV) and be the origin of the baryon asymmetry of the Universe via decays (leptogenesis)

Unfortunately at low energies we can measure only few reduced parameters, and cosmological/astrophysical constraints on the origin of this new sector are very model dependent, if any. The see-saw mechanism may not be falsifiable

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The window to heavy neutrino DM may be closed in the near future with experiments like SHIP

Focus should be on models which can be probed in other ways than oscillations

Baryogenesis

Matter/antimatter asymmetry of the Universe cannot be accommodated in the SM, evidence for BSM

Sakharov's conditions: we need models which provide new sources of CP violation and produce a **strong first order phase transition** or heavy particles which decay in a baryon/lepton-violating way

Most interesting scenarios are falsifiable (enough measurements can be done) and are related to other issues of the SM. An archetypical example is EW baryogenesis, which may be ruled out using various measurements (LHC, EDMs…)
Strong 1st order PT: Link to **detection of Gravitational Waves**

Inflation

Large scale structure of the Universe homogeneous and flat

Period of rapid expansion of the Universe

Example: Inflation driven by a scalar particle (inflaton)

three parameters:

1. height of the potential: usually means trans-planckian field excursions
2. spectral index: very close to 1, but not quite
3. scalar to tensor ratio: constrained to be small

In the usual paradigm

$$n_s = 1 + 2\eta - 6\epsilon$$

$$r = 16\epsilon$$

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \qquad \eta = M_p^2 \frac{V''(\phi)}{V(\phi)}$$

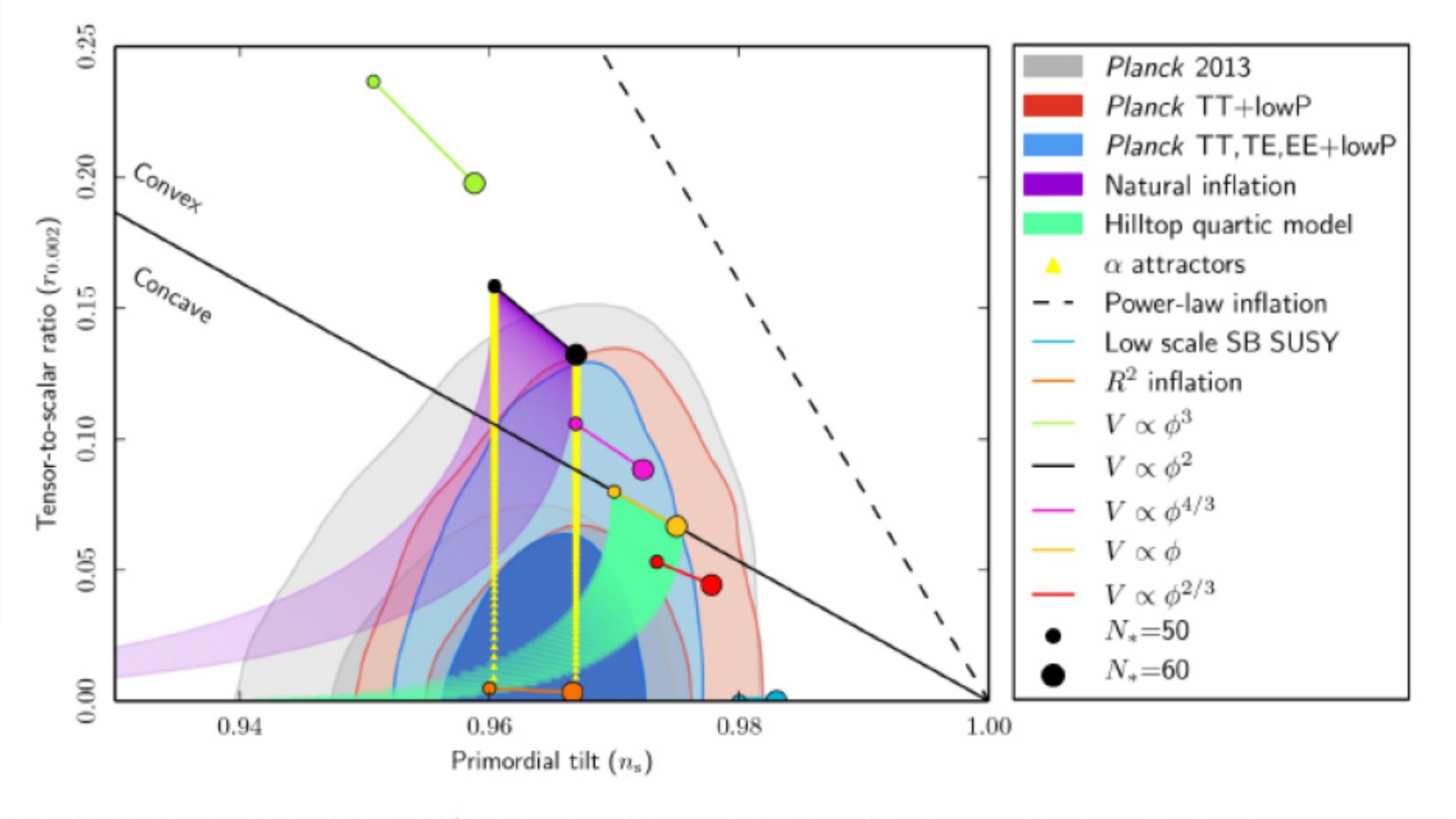

Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

Inflation overview

Seems like a simple, elegant solution to the flatness problem but

Specific realizations require a set of tunings/unnatural features:
initial conditions, or when to start rolling
introduces a hierarchy problem (height to width of the potential)
trans-planckian field excursions may need quantum gravity
period of reheating/preheating is an obscure aspect (introduced by hand, not predictive)

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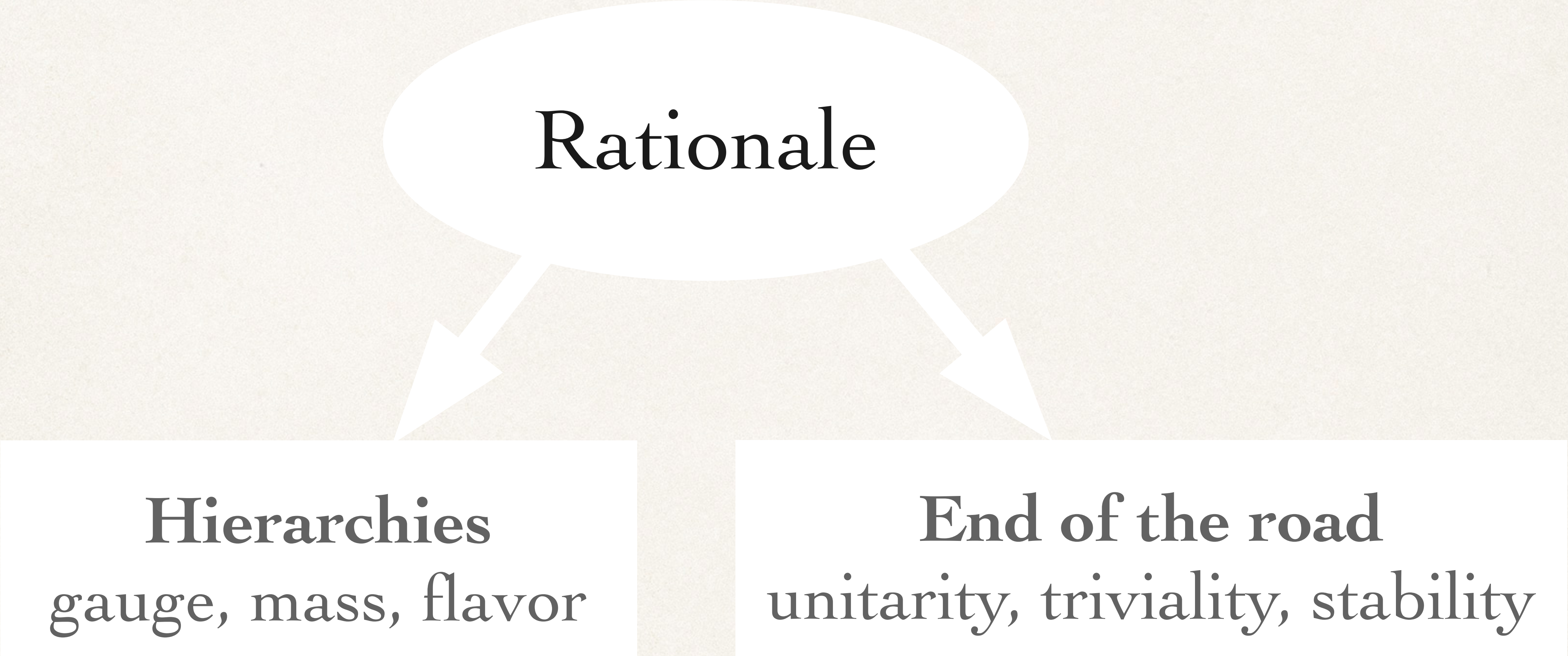
Other not-so-good features
no big deviations from almost-gaussian have been observed so
after tuning of the height, spectrum is essentially two parameters
and we may not sensitive to models with small tensor-to-scalar ratio (i.e. would never see primordial gravitational waves)

In the field of Cosmology, the Inflationary paradigm seems like SUSY in Particle Physics back in the 90's

Rationale

Rationale for New Physics

Even if we had no evidence for BSM, there would be a rationale for new physics



Rationale

Hierarchies
gauge, mass, flavor

End of the road
unitarity, triviality, stability

Symmetries and/or dynamics
New states

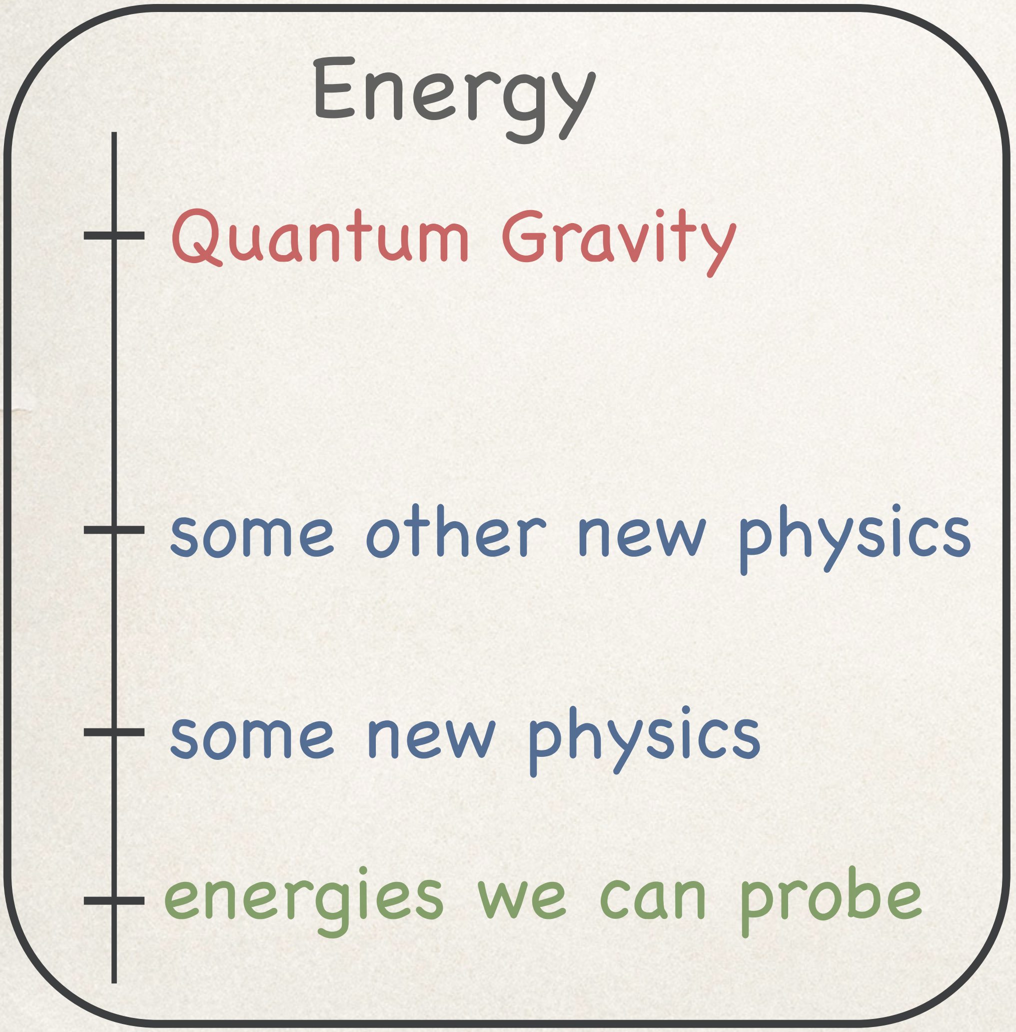
Rationale for New Physics

Example: Naturalness

Predictive theory: quantum mechanical. In QFT, physical quantities *run*

mass term in a Lagrangian, quantum corrections

$$\mathcal{L}_m = -m_\Psi \bar{\Psi}\Psi - m_\phi^2 \phi^2$$


Energy

Quantum Gravity

some other new physics

some new physics

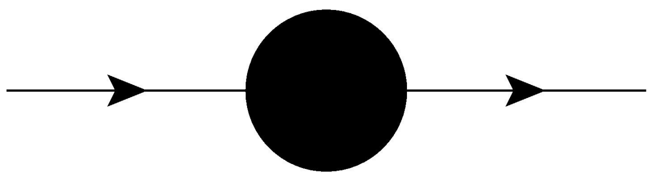
energies we can probe

Fermions

Massless fermion, additional symmetry

$$\Psi \to e^{-i\gamma_5\theta}\Psi$$

if this chiral symmetry is preserved QM



$$\delta m_\Psi \propto m_\Psi \log(\mu_1/\mu_2)$$

chiral symmetry protects fermions masses from large UV corrections

Light fermions are technically natural

Rationale for New Physics

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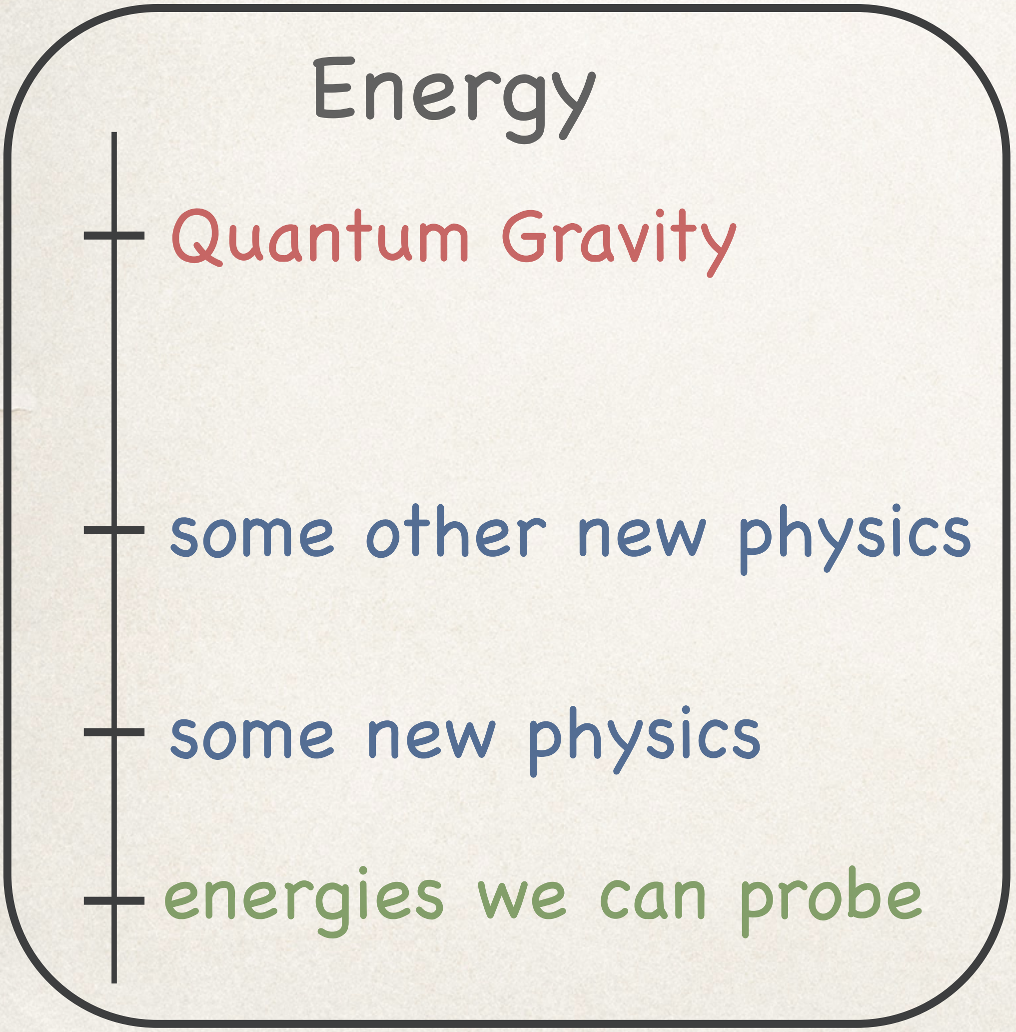

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Scalars

Massless scalar, scale invariance

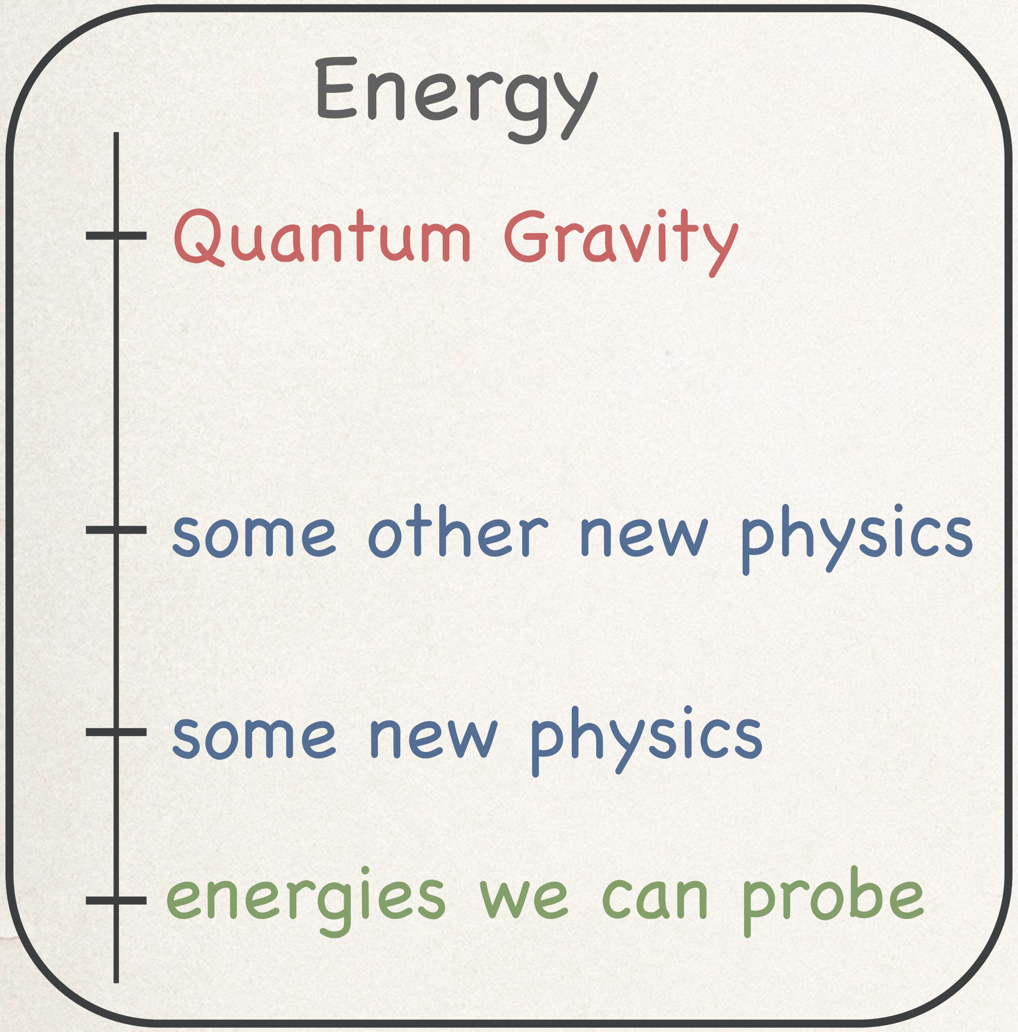
This classical symmetry is not preserved QM (is anomalous)

scalars are not protected by a symmetry, are UV sensitive, natural value for the mass is the highest scale it couples to

Light scalars are **unnatural**

Rationale for New Physics

Example: Naturalness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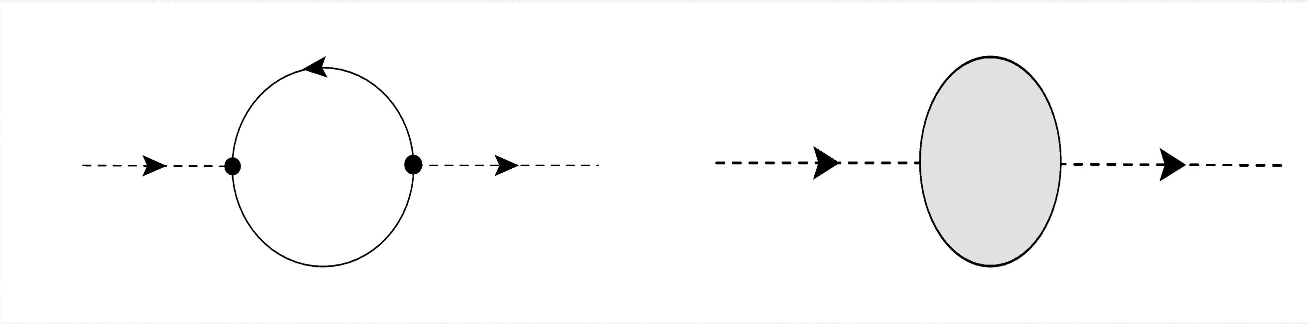
Quantum corrections to scalars



threshold corrections

QGrav

$$\delta m_{\phi}^{2} \propto c_{1}\,\Lambda_{NP}^{2} + c_{2}\,M_{Pl}^{2}$$

(Physical mass)^2 = (bare mass)^2 + (unsuppressed Qcorrections)^2

light scalar = enormous fine-tuning

The Higgs is a scalar, and there is no sight of new physics so far
Should we just live with it?

Is a tuning all there is?

Example: Naturalness

At the beginning of the EW theory, people were trying to figure out how to make sense of a gauge theory with massive W,Z

mass terms spoil renormalizability (predictivity) of the gauge theory

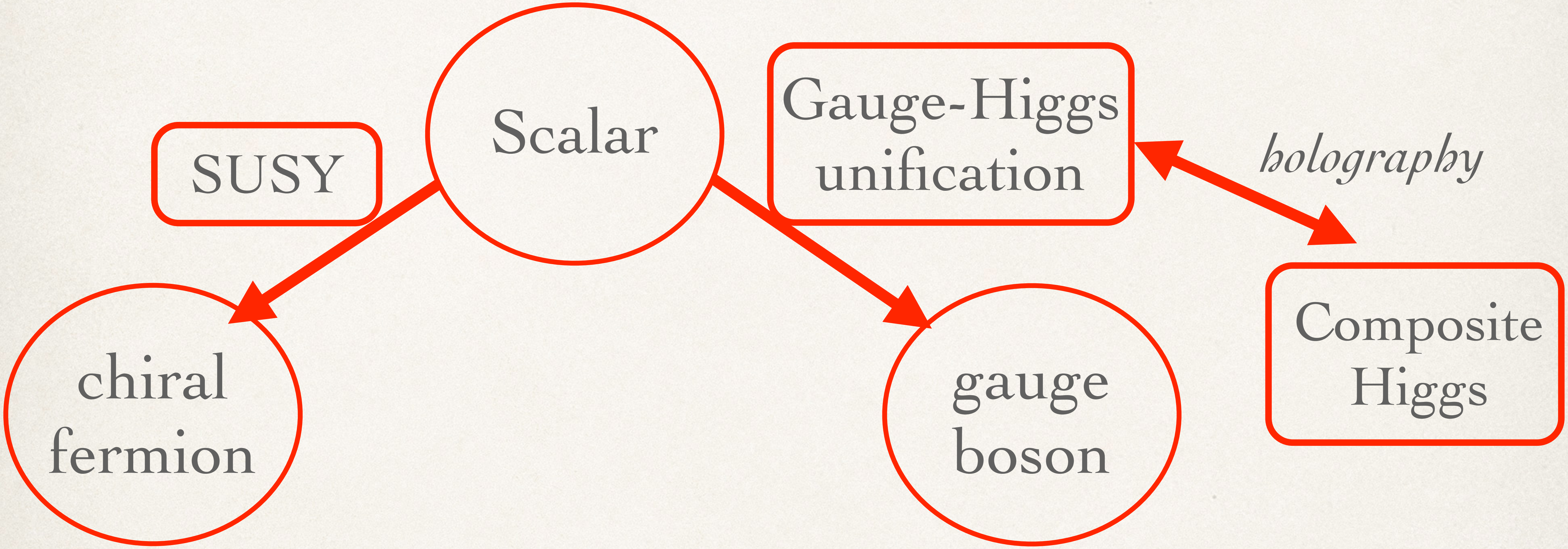
Feinberg (1958) proposed divergences were cancelled if a precise set of cancellations would happen (invoked fine-tuning)

At the end the story was more subtle
The concept of Spontaneous Symmetry Breaking
secret renormalizability

I view fine-tunings as calls for
new principles to be discovered

Light scalars

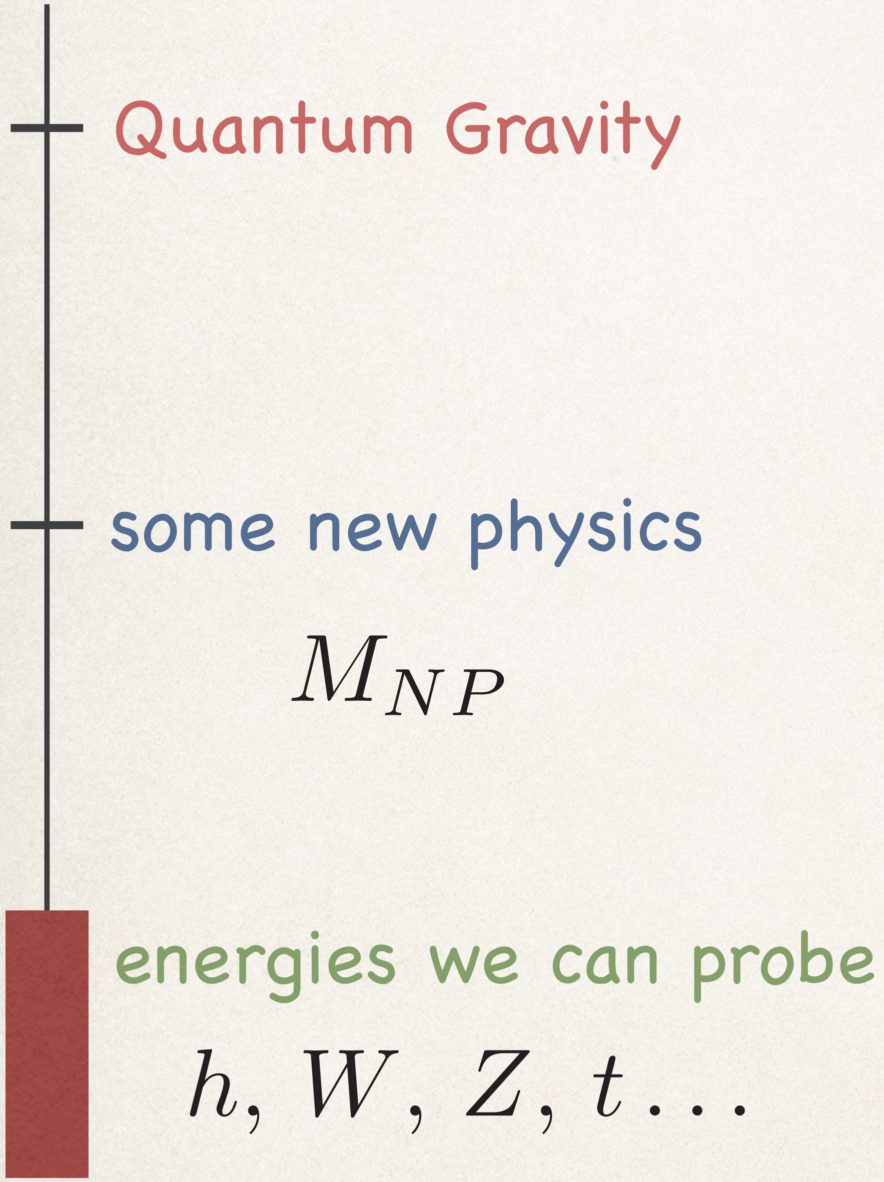
The light Higgs is a reality
symmetry/duality arguments to explain its nature



Many, many possible realizations (phenomenology)
Predict new states, to be discovered
(SUSY partners, techni-baryons and mesons, spin-two…)
AND induce deviations in the Higgs behaviour

Back to the Higgs

The Higgs is a very special creature in the SM:
a fundamental and light scalar



Quantum Gravity

some new physics

M_{NP}

energies we can probe

$h, W, Z, t\dots$

$$\boxed{\delta m_h^2 \sim M_{NP}^2 \Rightarrow m_h^{phys} \sim M_{NP}}$$

unless

1. There’s *nothing* (DESERT)

2. Something *special* happens

2i.) fine-tuning (small=huge-huge)

$$m^2_{h,phys} \simeq m^2_{h,bare} + \delta m_h^2$$

2ii.) new symmetries

$$\delta m_h^2 \propto \text{ parameter breaks the symm}$$

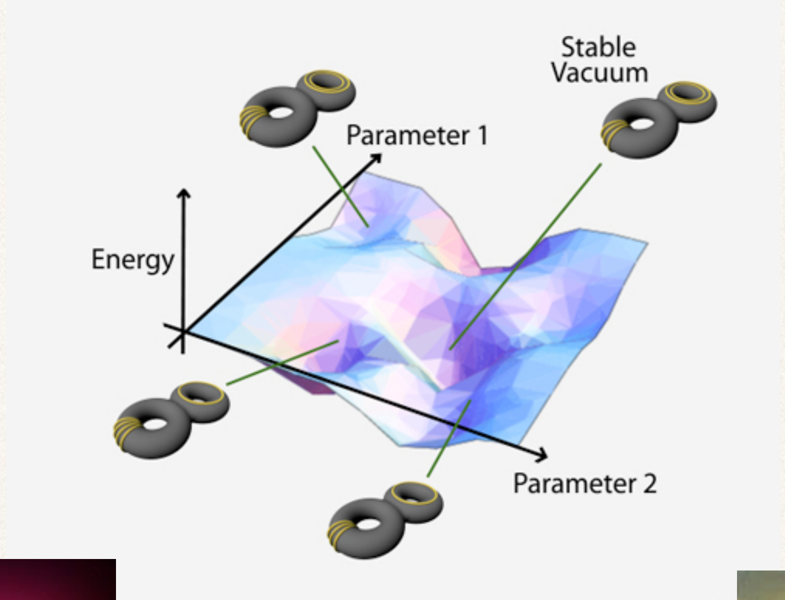
2iii.) dynamics

scalar=bound state of fermions or gauge fields

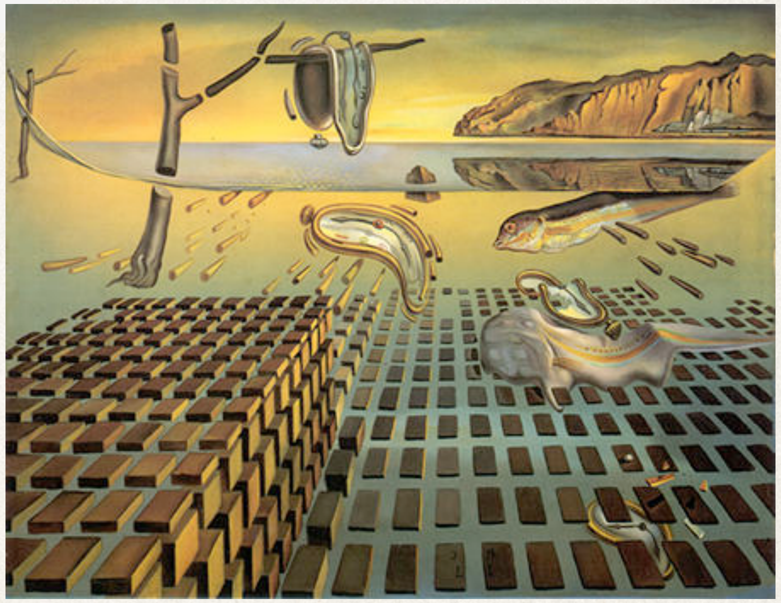
Back to the Higgs

What fundamental principle could be behind this behaviour?

Landscape of String Theory?



Something like Superconductivity?



New dimensions? Supersymmetry?

Supersymmetry

Symmetries

We build field theories imposing symmetries on the action

Example s=0, 1/2, 1, 2

Klein-Gordon, Dirac, Yang-Mills, Fierz-Pauli

great ref: Landau-Lifshitz ClassFT

What is possible or not depends on whether a symmetry can be written for it

Coleman-Mandula **no-go theorem** [1962]:

Lie Algebra = Poincare $\otimes$ Internal

symmetries of S-matrix

(space-time, internal)

=> internal and external (s-t) symmetries do not talk to each other

Supersymmetry (SUSY)

Supersymmetry is a way around that
abandons the Lie group framework
internal generators = > fermionic **Q**
super-Poincare algebra

SUSY has important consequences

Q | B > = | F >
Q | F > = | B > *

Fermions and bosons are no longer two separate worlds

Normal field B or F -> SUSY field is both

e.g. Higgs -> SUSY Higgs $(H, \tilde{H})$ Higgs (s=0)+Higgssino (s=1/2)

All fields in superfield are *degenerate*

=> Higgs should come with a 125 GeV fermion

**being sloppy with daggers*

SUSY breaking

=> Higgs should come with a 125 GeV fermion

=> electron should come with a 0.511 GeV charged scalar

=> there should be a massless fermion (photino) force mediator

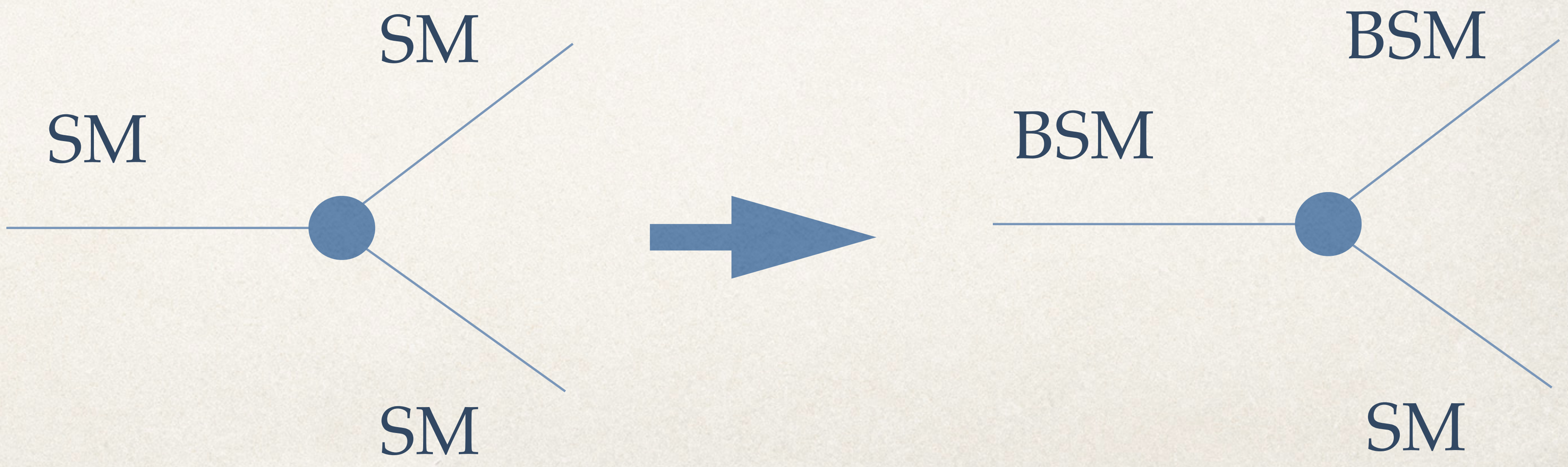
etc, etc

All that is wrong!

Then SUSY must be *broken*=> splitting between partners in the superfield of order the SUSY breaking scale

if SUSY is broken, does any symmetry survive?

yes, R-parity



SUSY breaking

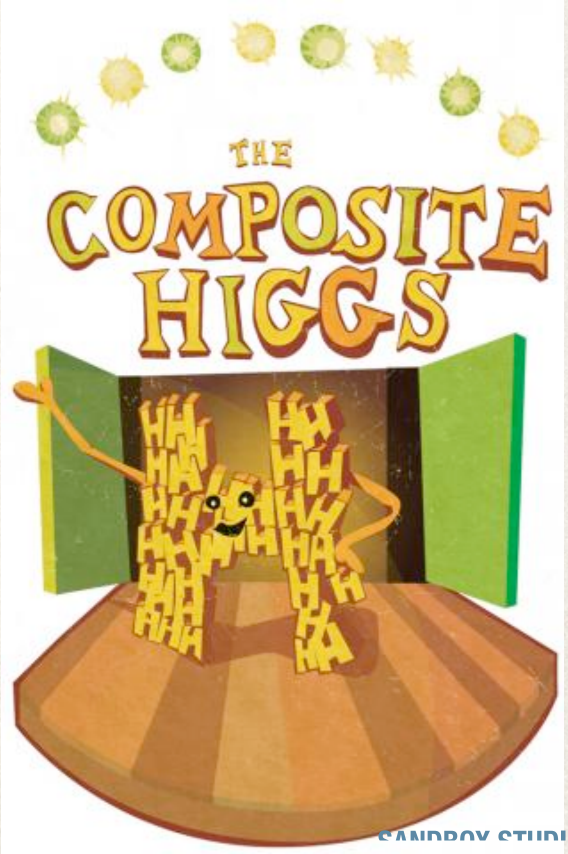
if SUSY is broken, does any symmetry survive?

yes, SUSY is still a good symmetry above SUSY breaking scale
Higgsino : chiral fermion -> protected by chiral symmetry
Higgs -> protected by chiral symmetry at high-energies

$$\delta m_h^2 \propto \text{ parameter breaks the symm } \sim m_{soft}^2 \sim (TeV)^2$$

Higgs is *naturally light* in SUSY
as long as the SUSY particles are not too far from the EW scale
Naturalness in SUSY => light SUSY particles

Compositeness



SANDBOX STUDIO

Composite Higgs in a nutshell

$4\pi f$

UV completion

m_ρ

f

confinement
SSB global
resonances

v

explicit
breaking
pGB scale
EWSB

As pions in QCD:
light Higgs as a pseudo-GB from
spontaneous breaking of a global symmetry

Contrary to pions in QCD:
the Higgs has

1. CP-even properties
2. its potential needs to trigger EWSB
3. it should couple as mass

Contrary to the SM Higgs:
EWSB can be non-linearly realized,
Higgs could be a singlet (not doublet)

Composite Higgs: Quantum numbers

$\mathcal{G} \to \mathcal{H}$

pGBs from SSB

$$\Sigma(x) = \exp(i\sqrt{2}h^a(x)X^a/f)\Sigma_0$$

The CP properties of the resulting pGBs depend on the CP properties of the strong sector

A. **Coupling to gauge**

part of the global sym H is weakly gauged

depends on the embedding

$$\Pi_1(p^2)\Sigma^T A_\mu A_\nu \Sigma$$

B. **Coupling to fermions**

many options for fermion rep

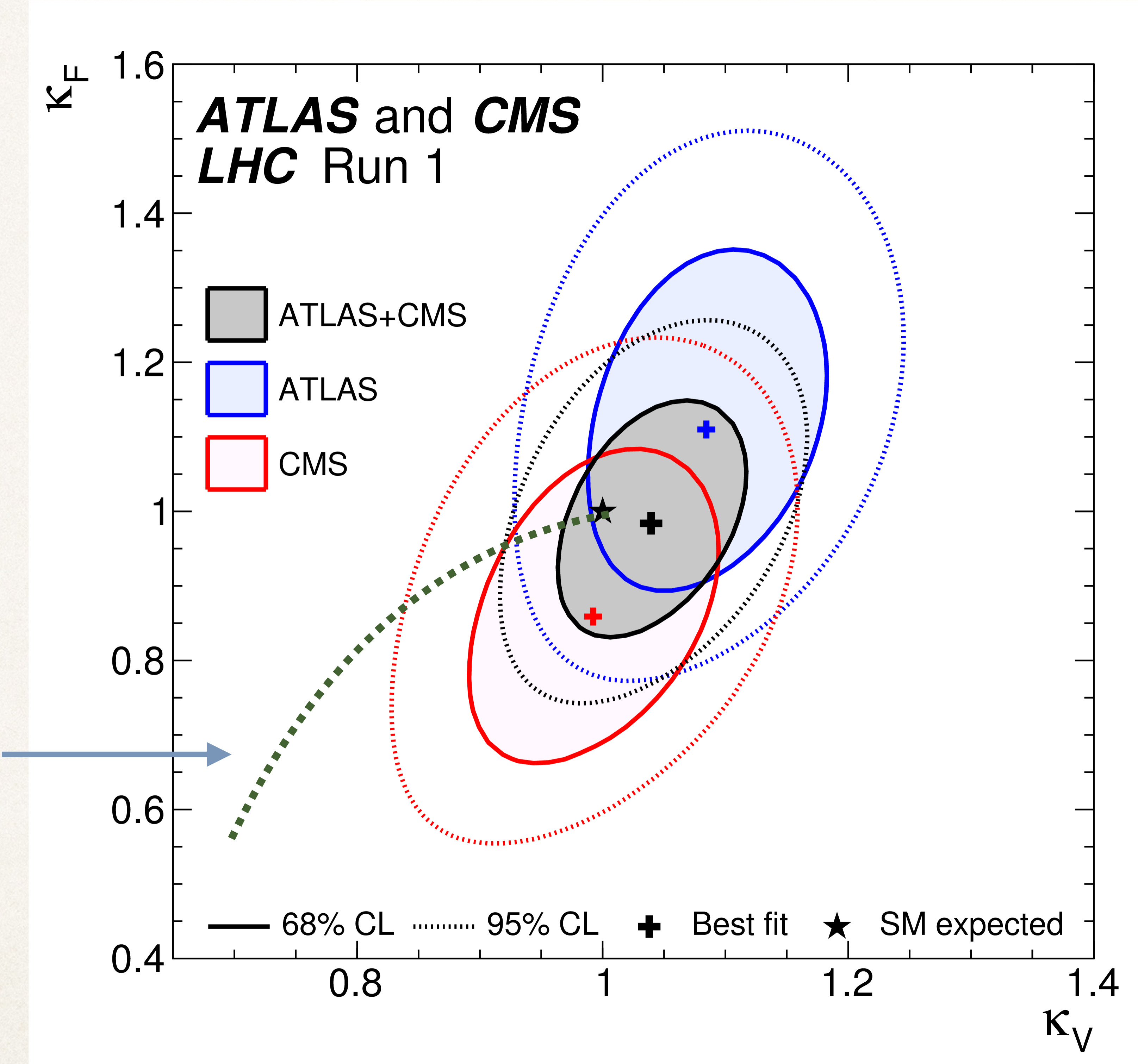
$$\overline{\Psi}\Gamma^i\Sigma_i\Psi$$

choice of global breaking and embedding: **CP-even scalar doublet**

pheno: Non-linear realization, Higgs couplings deviations

Composite Higgs: Quantum numbers

coupling to fermions



coupling to vectors

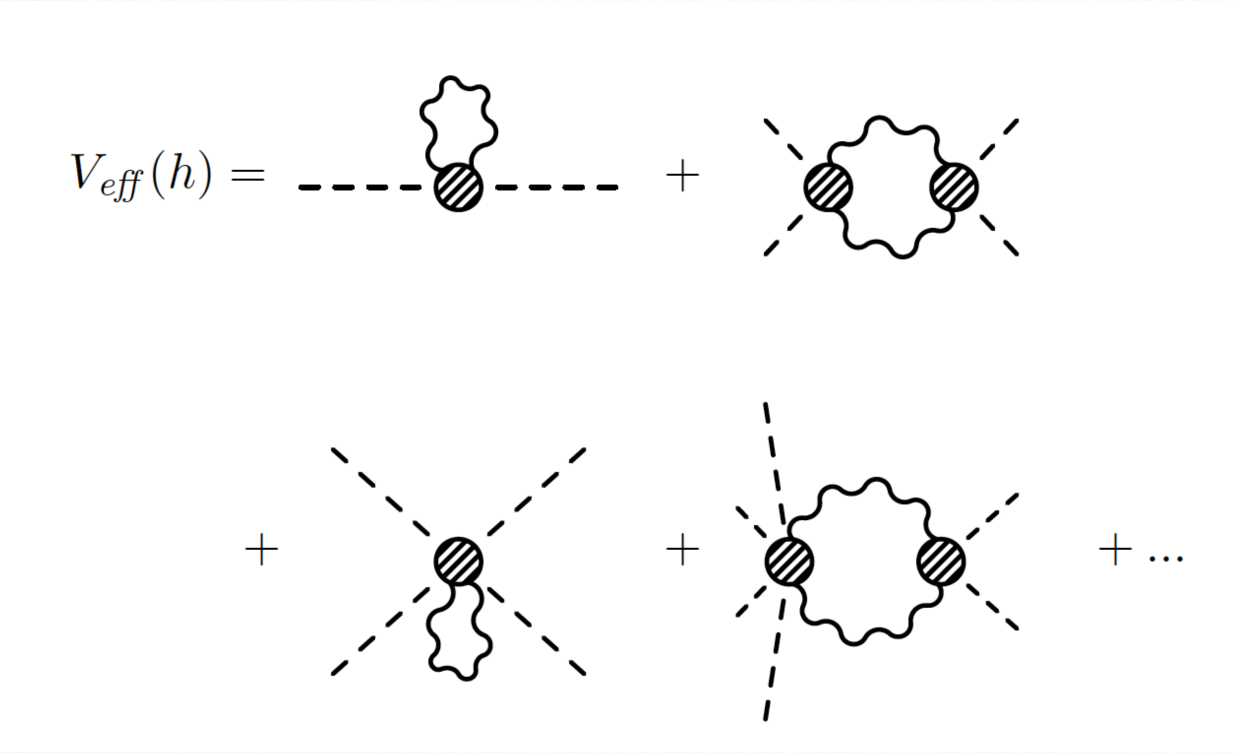
different CHMs
correspond to different lines
the effect decreases as

$$\xi = v^2/f^2$$

Composite Higgs: Potential and EWSB

Usual paradigm:
potential generated via **Coleman-Weinberg** contributions

e.g. GAUGE



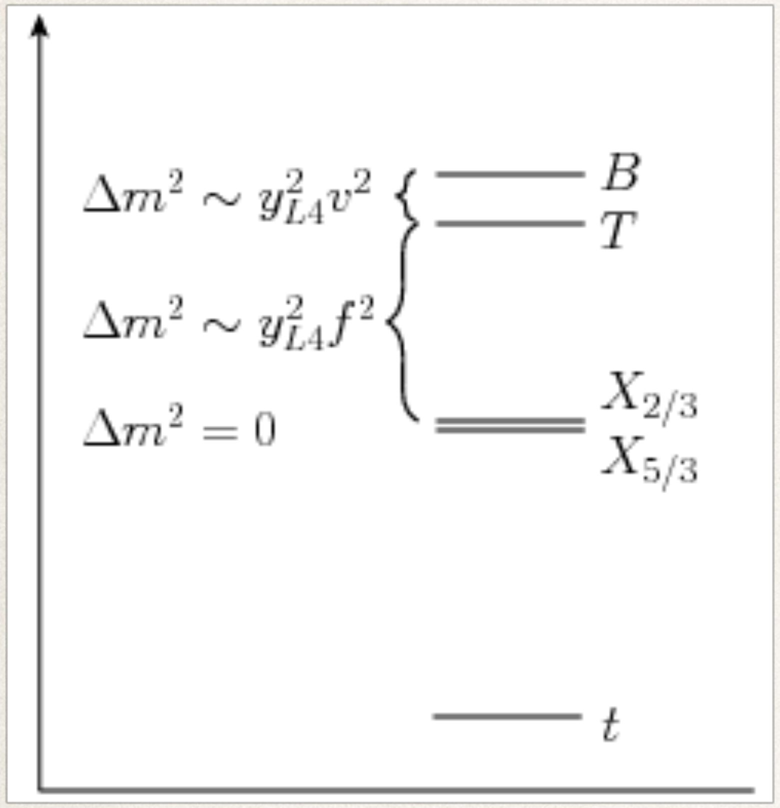
Georgi-Kaplan (80's)
gauge-top *does not* trigger EWSB
need new fermionic resonances
TOP-PARTNERS

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2}\,\frac{v^2}{f^2}\,m_T^2$$

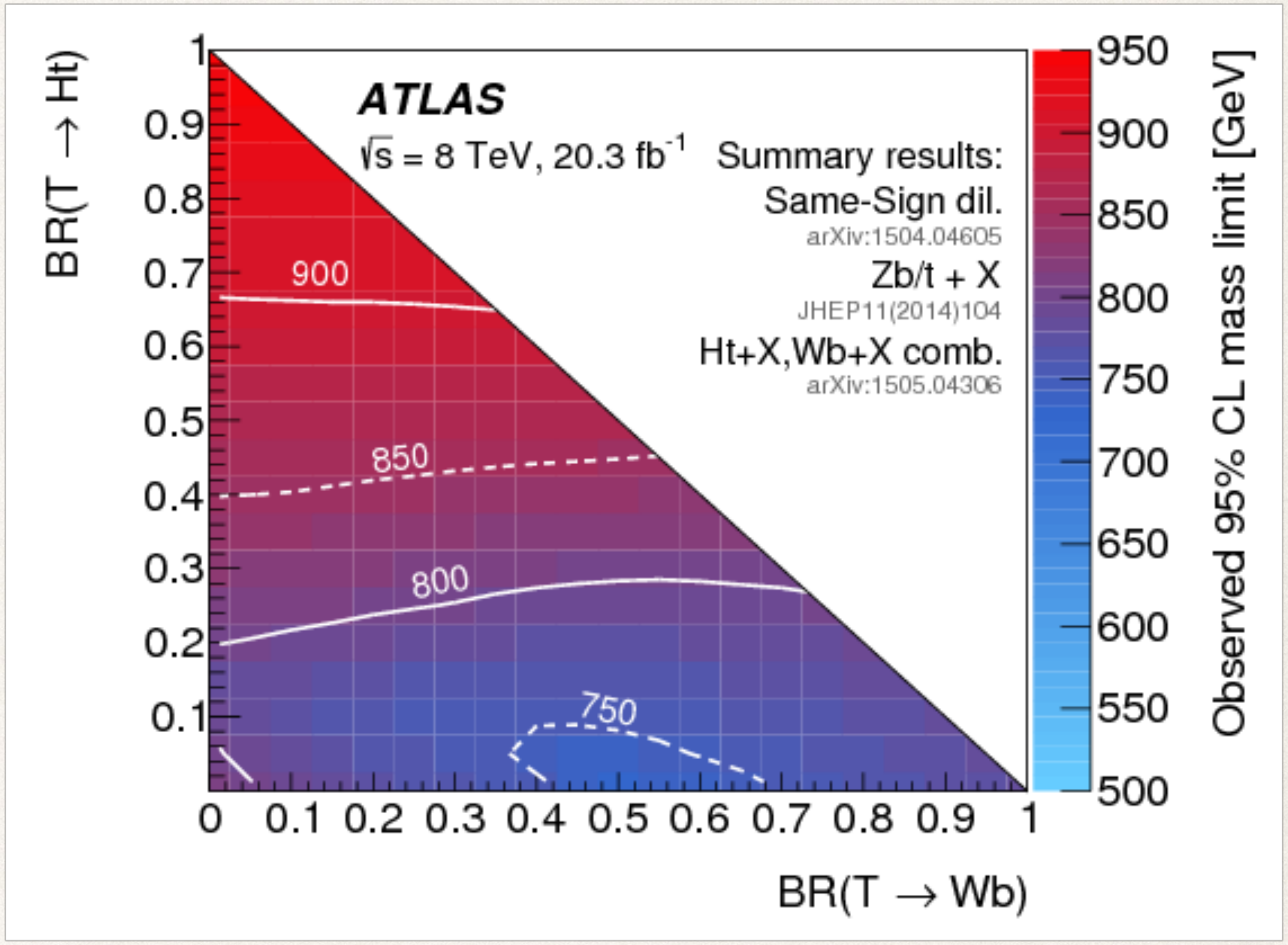
pheno: New, light (below TeV) techni-baryons
should couple to the Higgs, W, Z

Composite Higgs: Potential and EWSB

typical distribution of top-partners



Panico et al. 2016

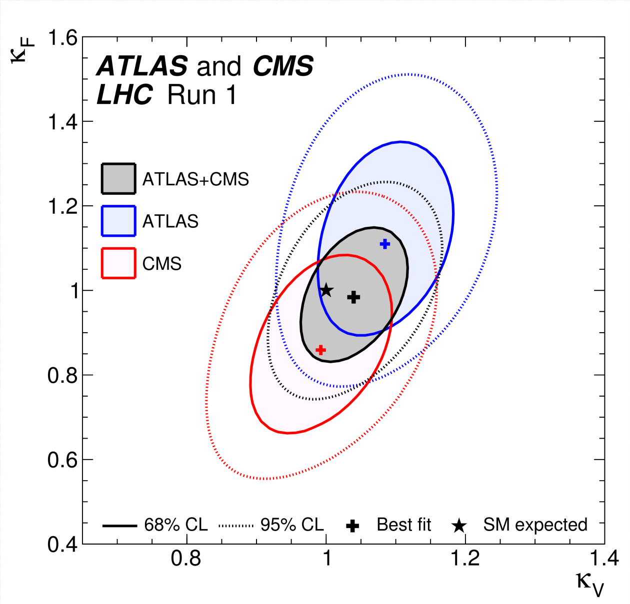


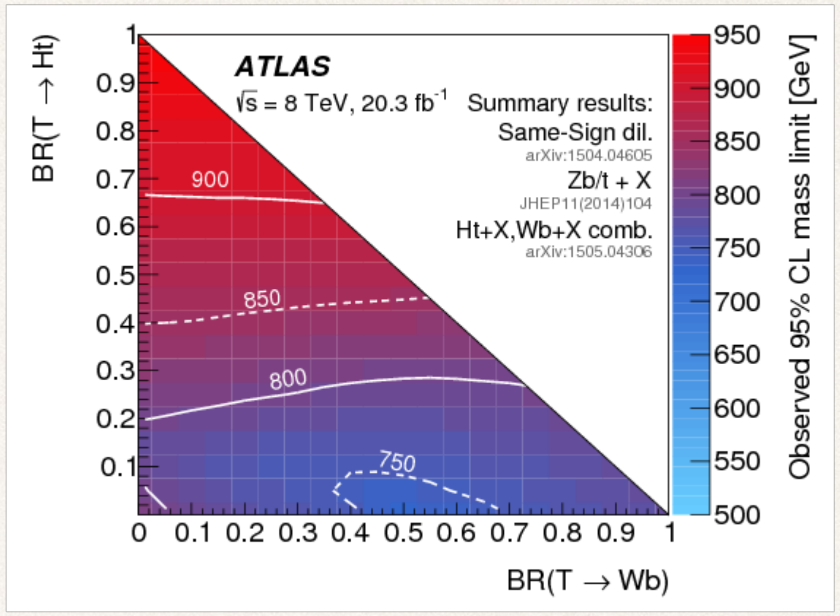
resonances below ~ 800 GeV are excluded

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

tuning in the Higgs potential severe

Status in model-building





Given the experimental constraints,
lack of deviations in the Higgs behaviour and
absence for new composite fermions
interest in more natural (non-minimal) models

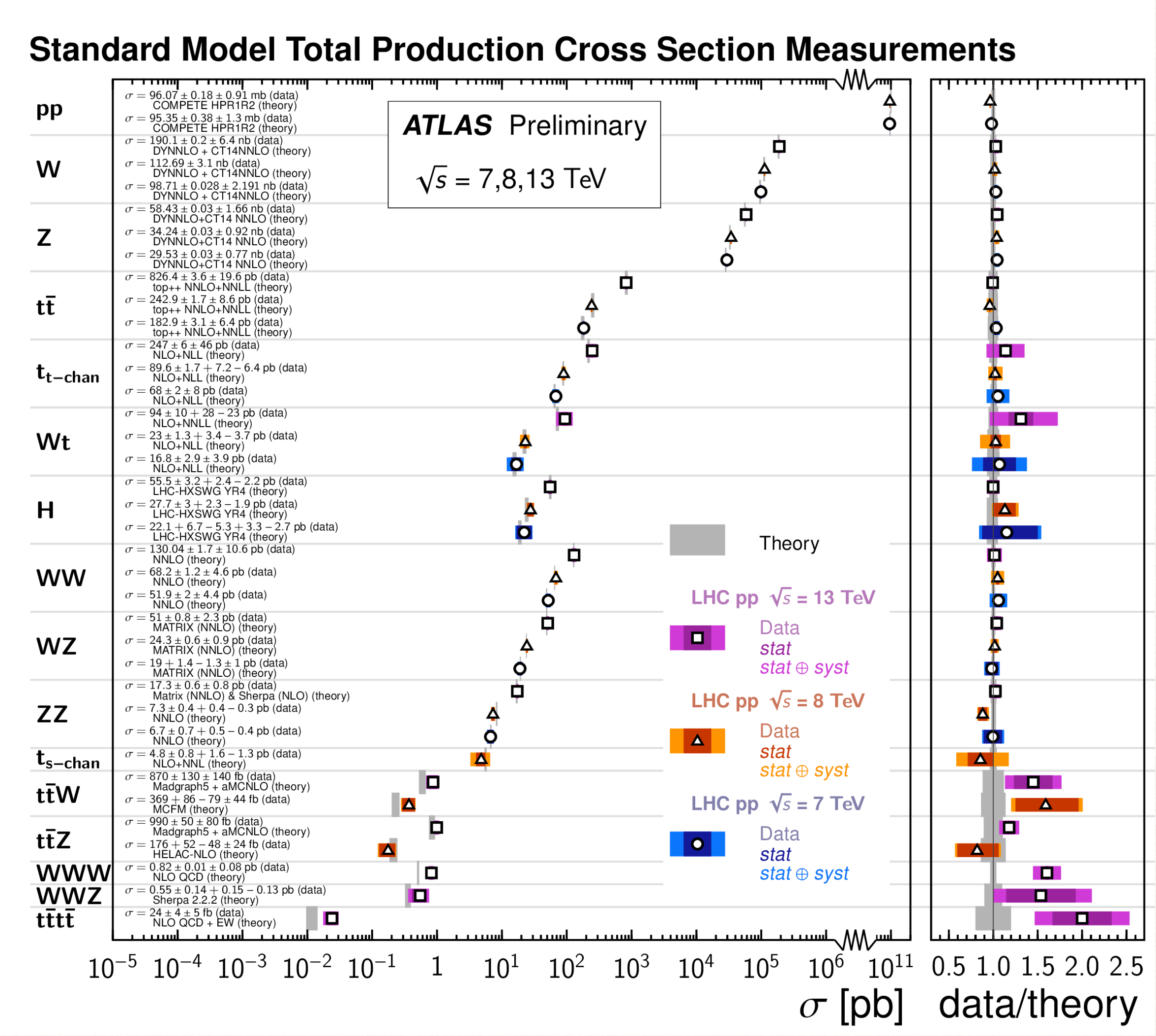
e.g. new ways to trigger EWSB and fermion mass generation, measure of tuning of the theory, un-coloured fermion resonances…

Looking ahead

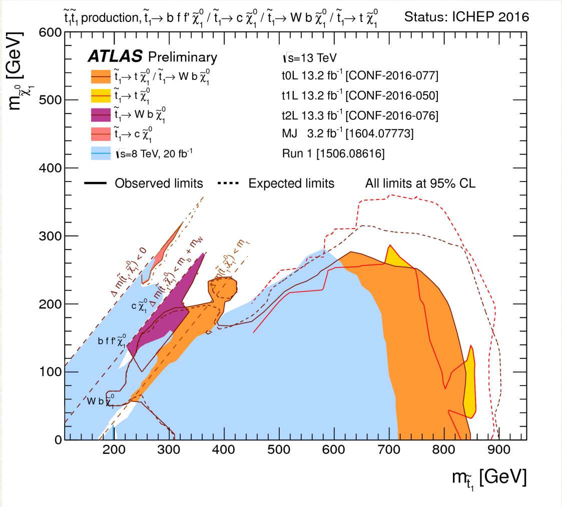
Let's start with the LHC

The LHC is in a mature stage, already providing precision tests for the SM in most channels (excl the Higgs)

Precise tests of the full structure of the SM, based on QFT, symmetries (global/gauge) and consistent ways to break them non-trivial tests of perturb.->non-perturb. QCD



Absence of excesses: interpreted as new physics exclusions



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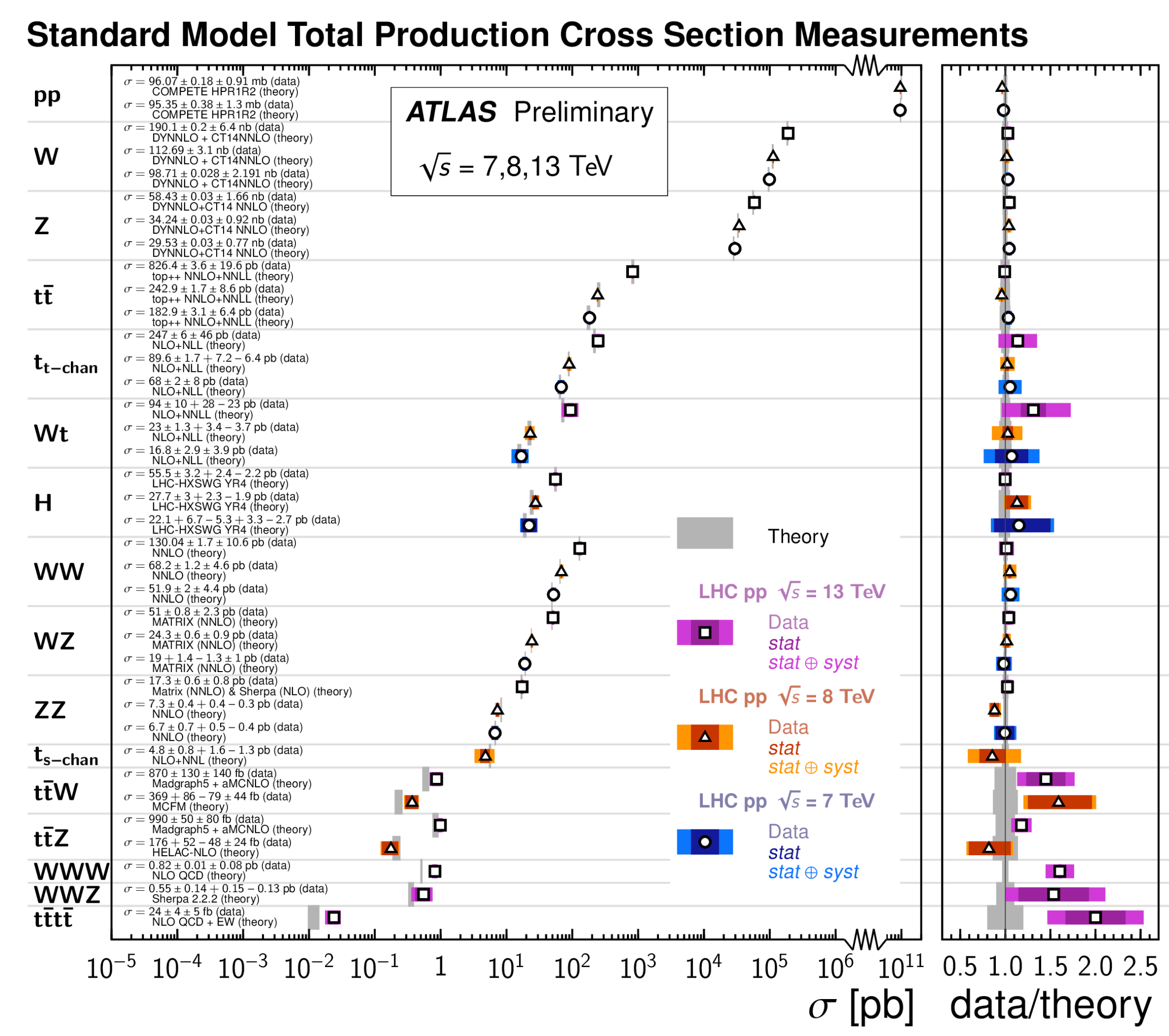

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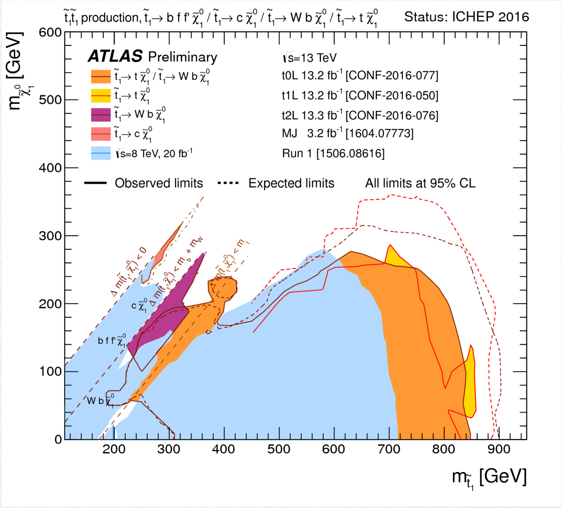


exclusions: rather impressive, many at the TeV
searches: outstanding coverage of possible topologies
any hints: (like in flavor) extremely tempting

So here we are

Neutrinos

Light Higgs

Inflation

Unification

Matter/Antimatter

CP QCD

Dark Matter

Dark Energy

Quantum Gravity

finding our path through **SYMMETRIES & DYNAMICS**

aiming for a **UNIFIED FRAMEWORK**

SM+GR

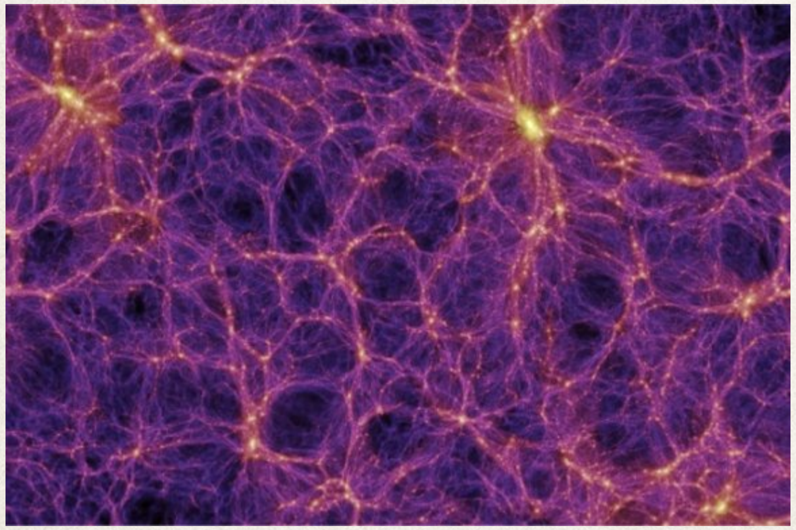
What we would hope for

Special relativity
+
equivalence principle

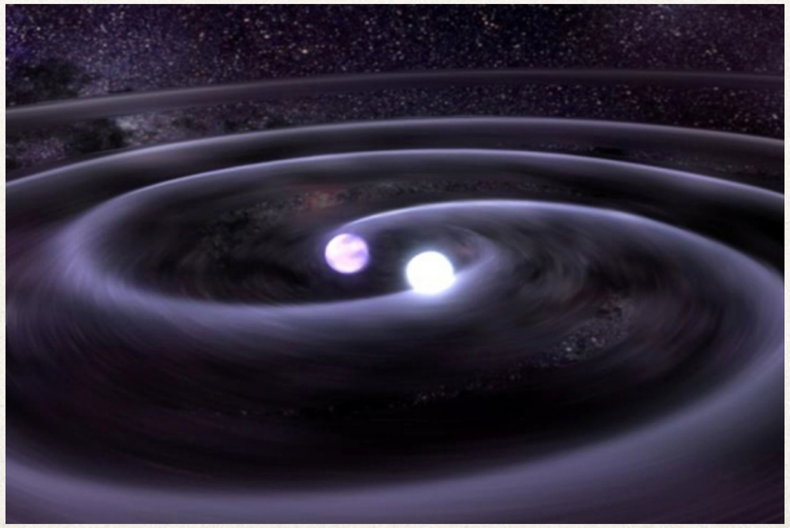
development of new, sophisticated mathematical framework

General relativity

Universe's evolution



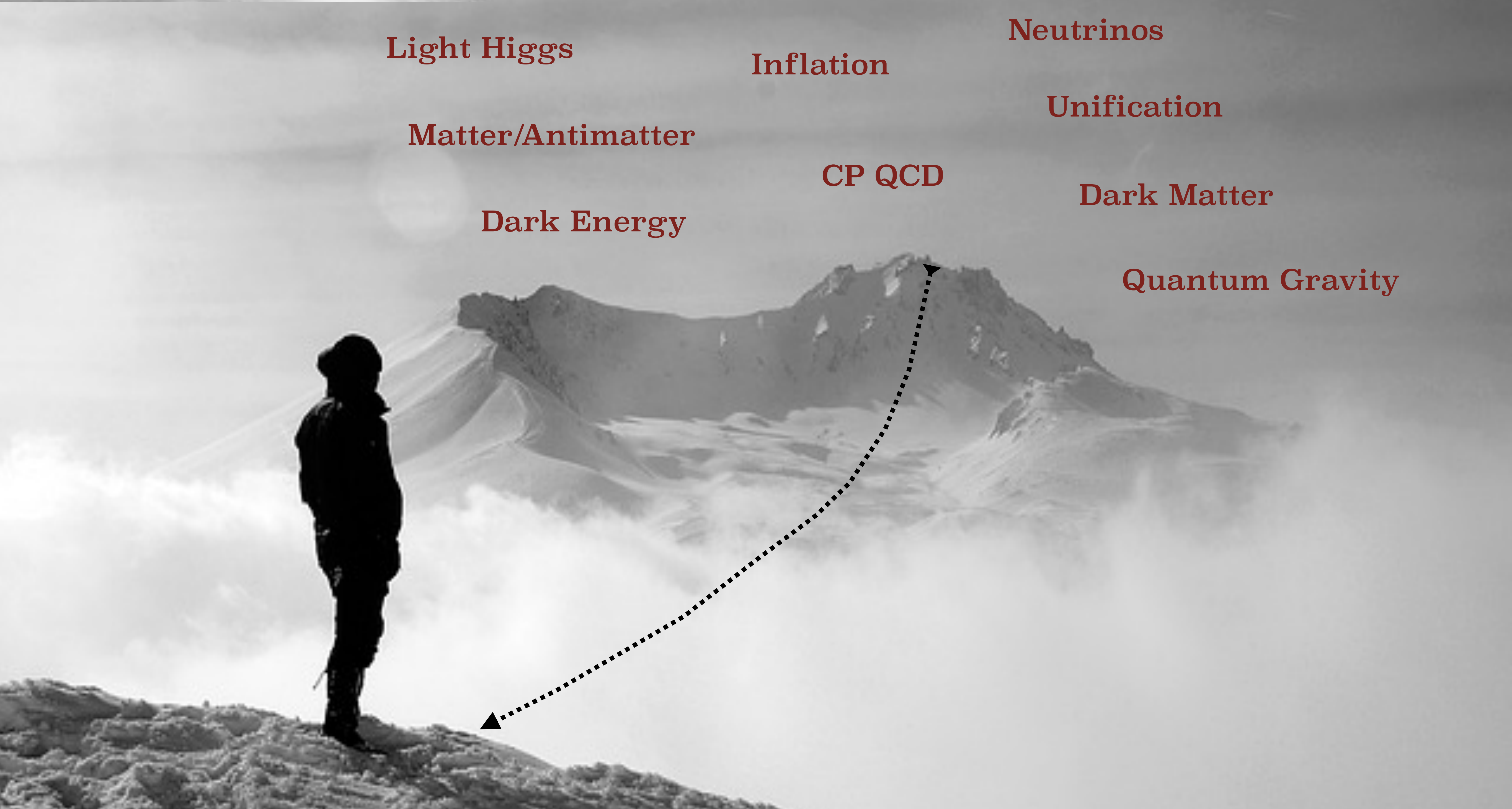
gravitational waves



black holes

Some years ago

String theory, *the* final theory
Mathematical consistency (anomalies, SUSY)
+guiding principles (QGrav, unification,3 families)
trickle down to the SM, a boundary condition



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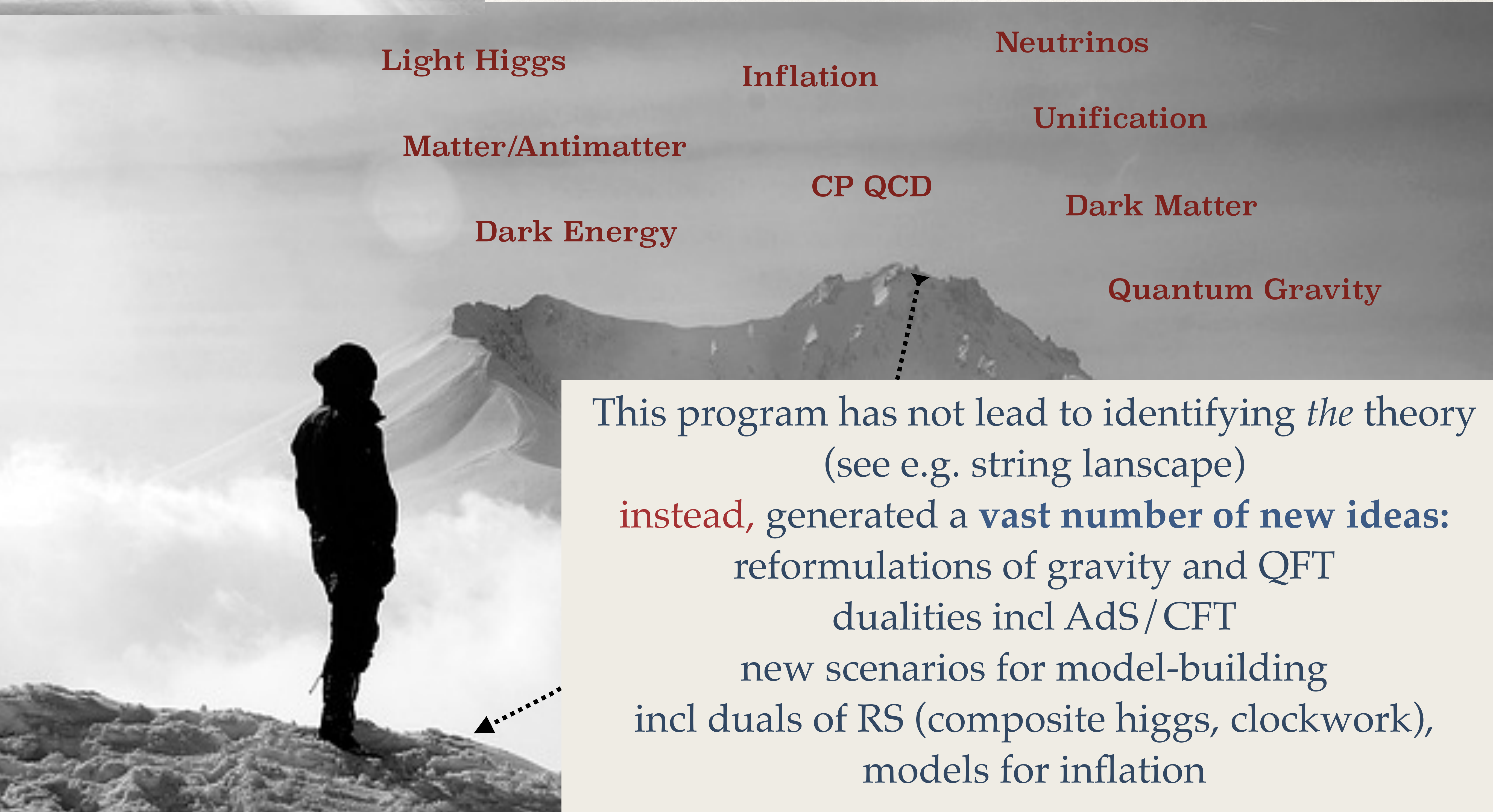

Light Higgs

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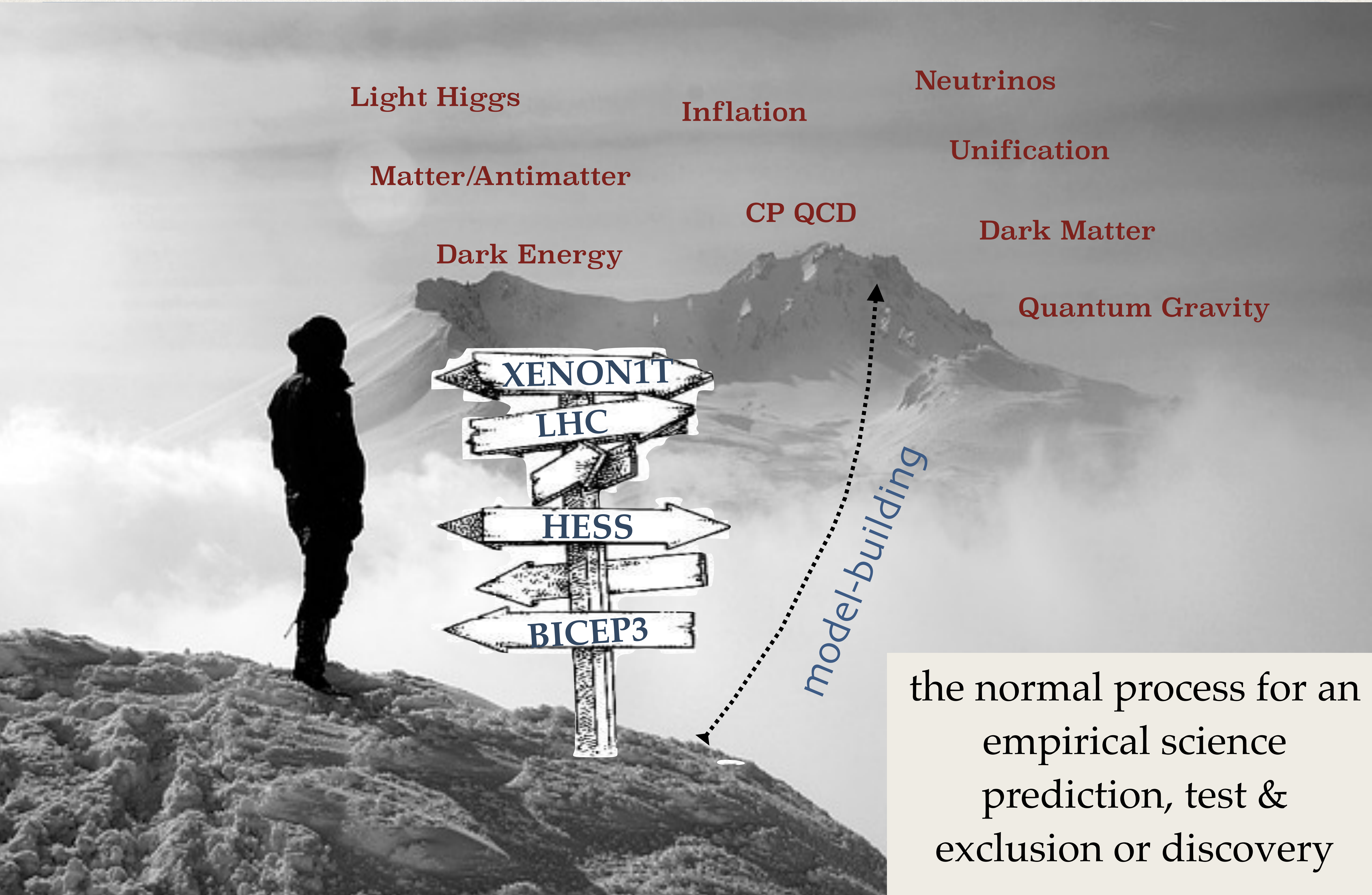
Quantum Gravity

This program has not lead to identifying *the* theory
(see e.g. string lanscape)
instead, generated a **vast number of new ideas:**
reformulations of gravity and QFT
dualities incl AdS/CFT
new scenarios for model-building
incl duals of RS (composite higgs, clockwork),
models for inflation

So here we are again, post-LHC Run2



Light Higgs

Inflation

Neutrinos

Unification

Matter/Antimatter

CP QCD

Dark Matter

Dark Energy

Quantum Gravity

the normal process for an empirical science prediction, test & exclusion or discovery

One way forward:
Connecting ideas/experiments

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

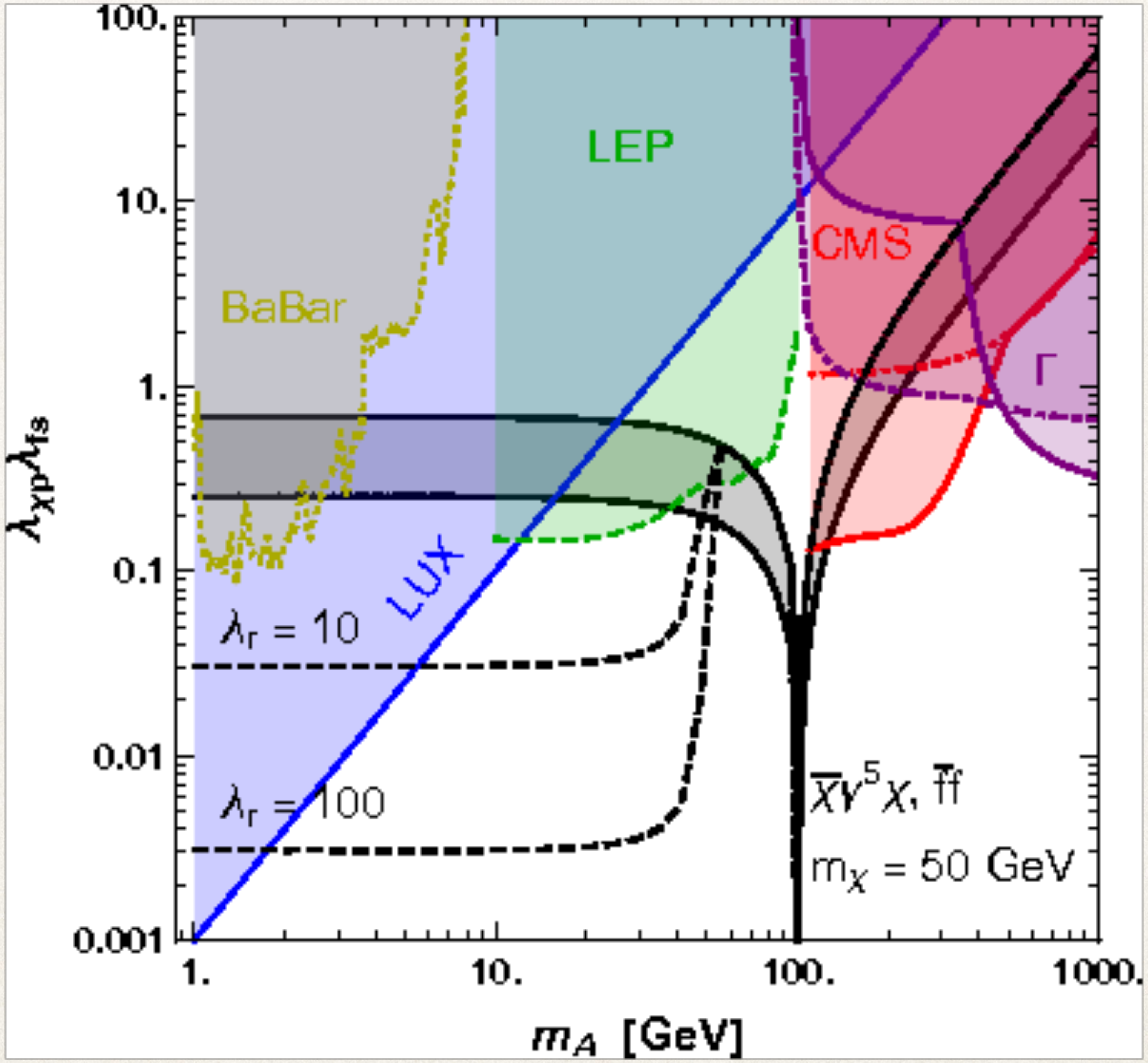
Fate of the Universe
Stability

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

Complementarity

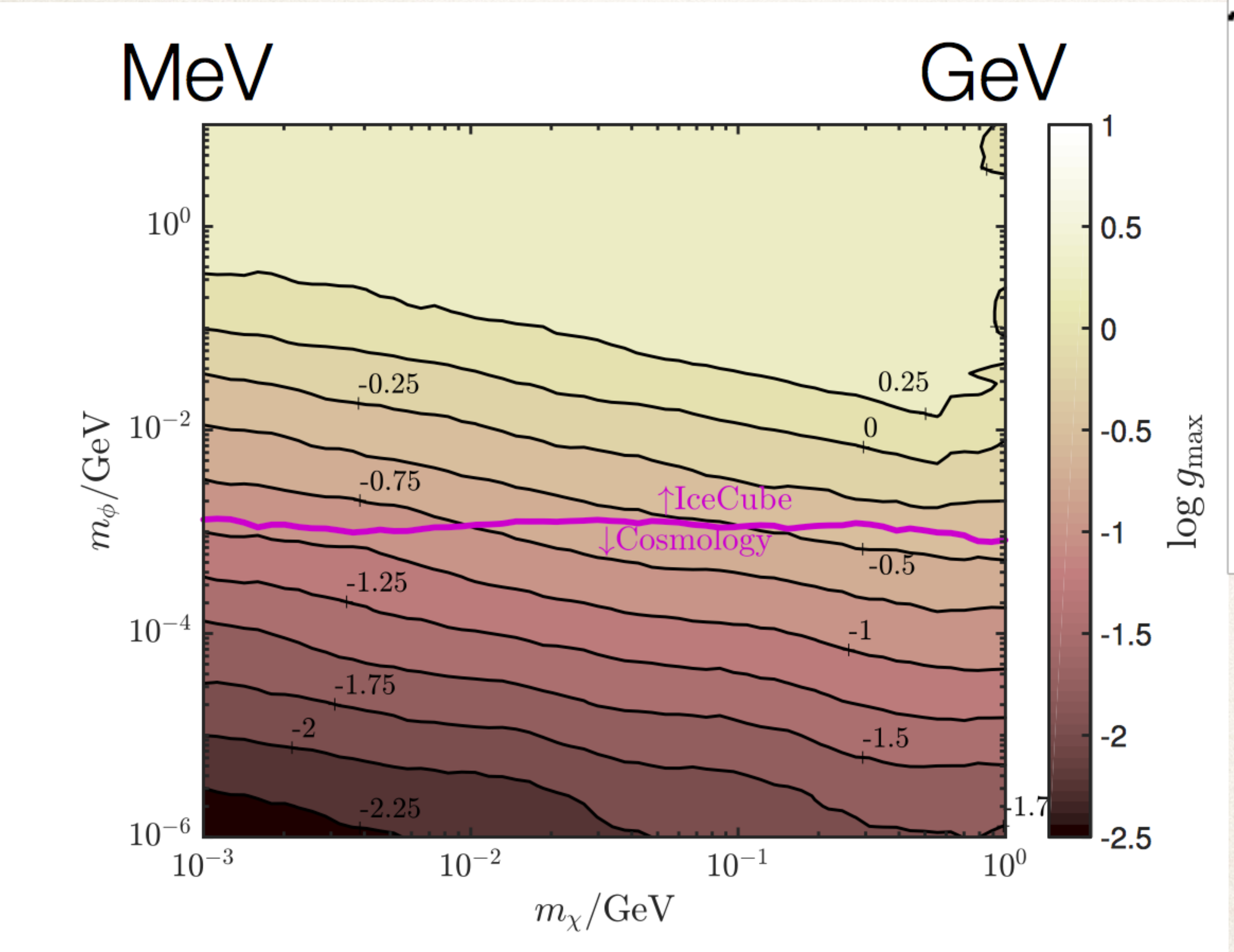
example: propose a solution to an astrophysical excess with a PP model



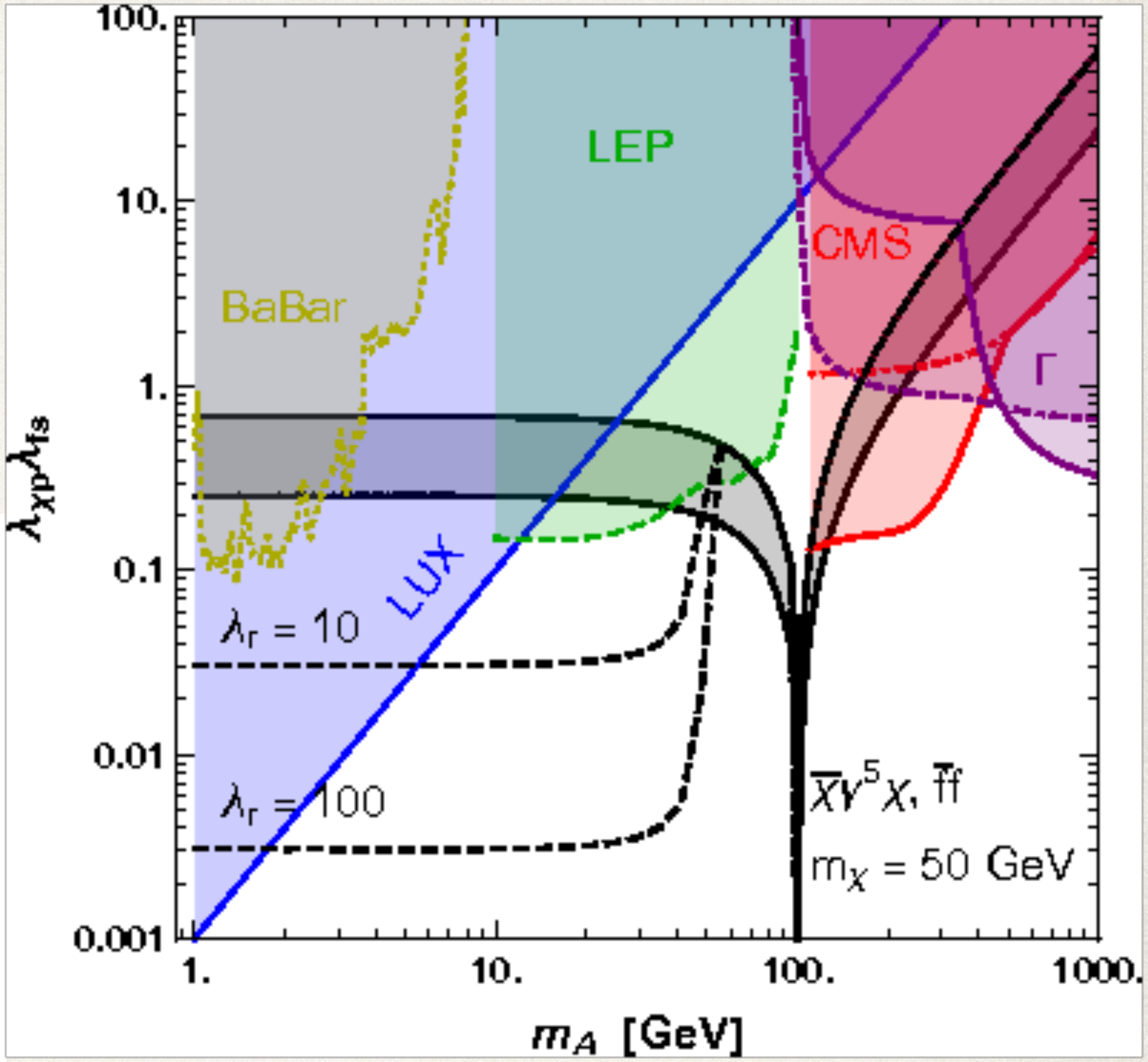
Escudero, Hooper, Witte. 1612.06462

Astrophysics/others

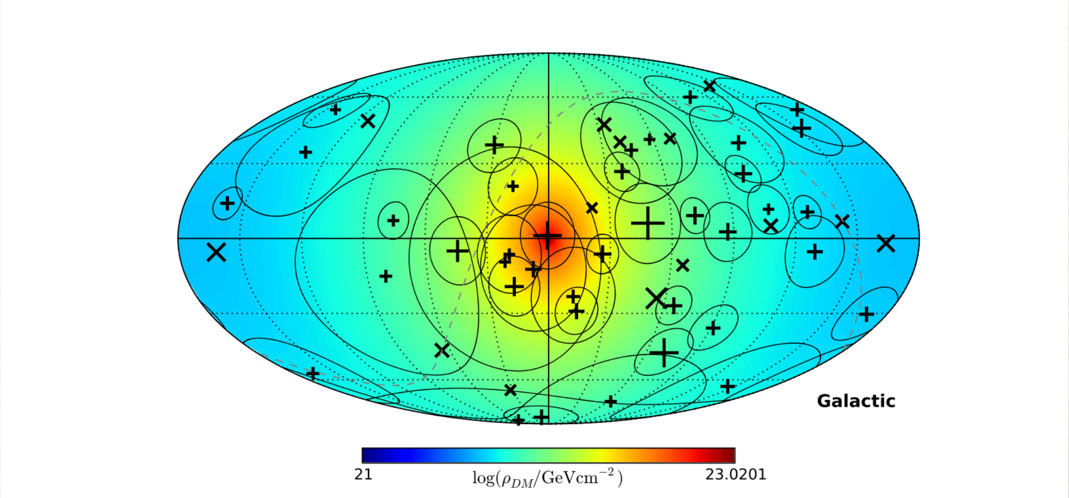
example: propose a solution to an astrophysical excess with a PP model, explore whether it is related to a coupling with neutrinos



Arguelles, Keirandish,Vincent. 1703.00451



Escudero, Hooper, Witte. 1612.06462

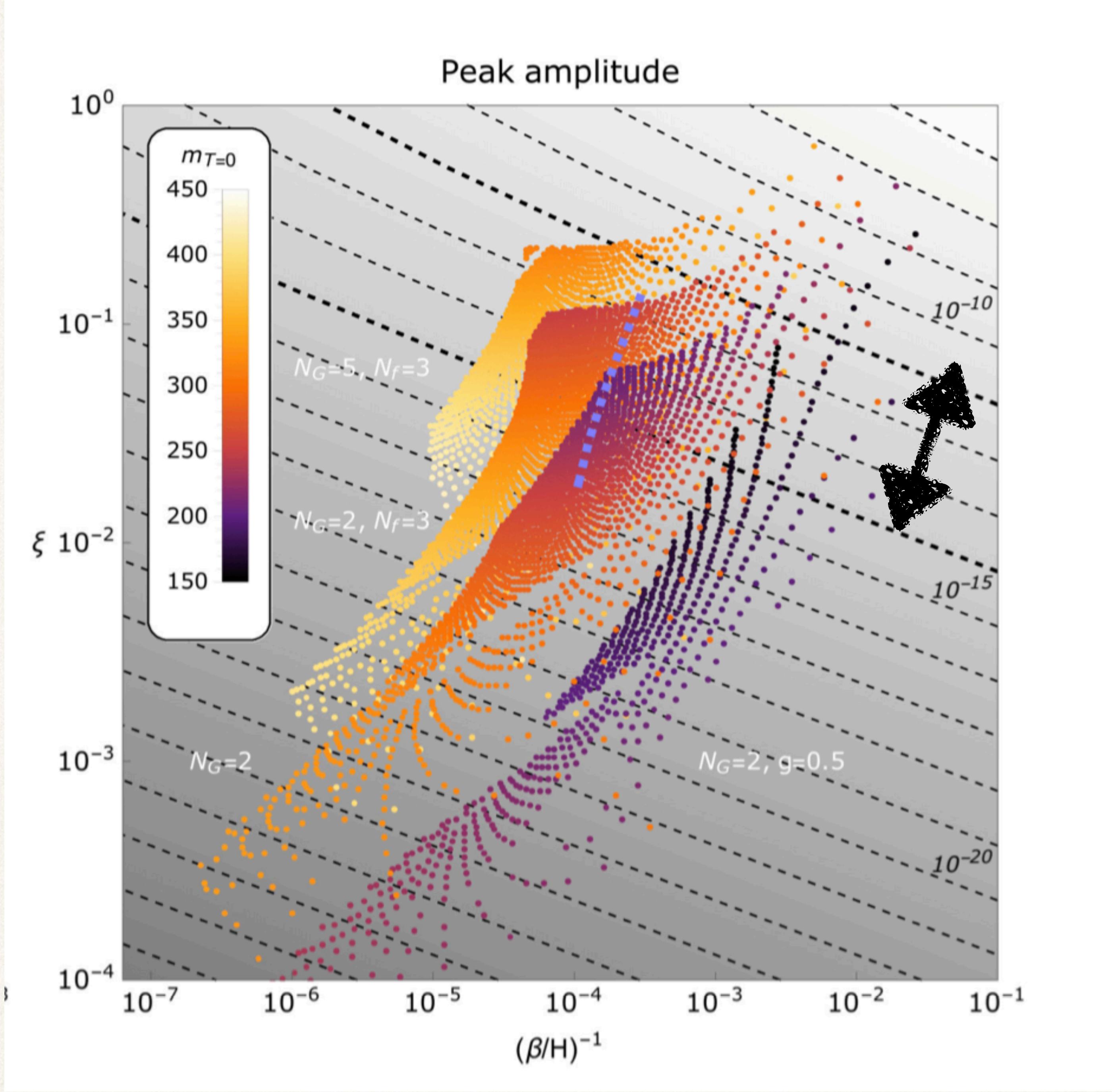


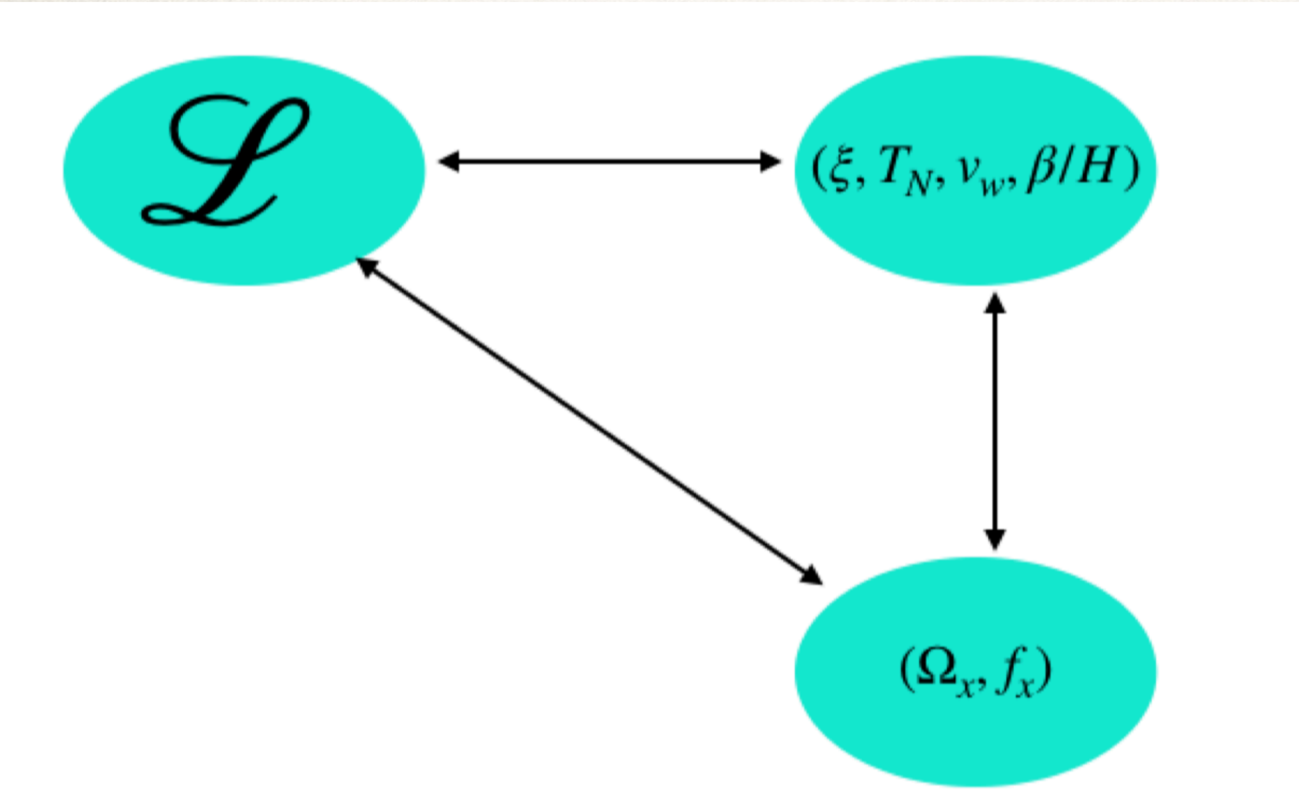
Gravitational waves/others

another example:

CROON, VS, WHITE. 1806.02332

Dark sectors and GWs. Classify sectors with 1st order PT and compute their GW signatures. Map onto DM models.

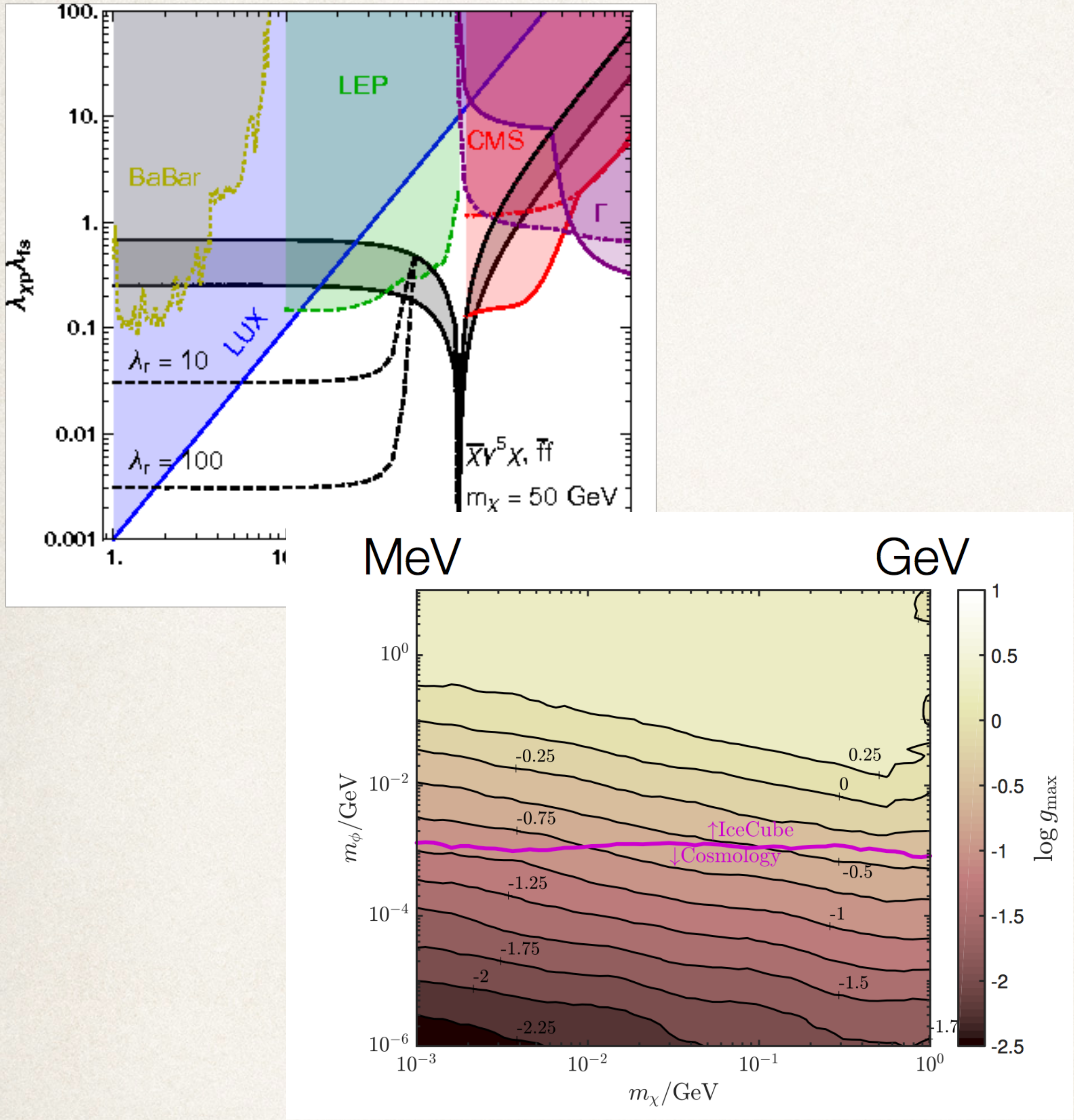




Regions: different dark sectors

Arrow: ~ region LISA (1yr)

These days we think a lot more about **complementarity**



1. New experiments, ways they present results, access to data

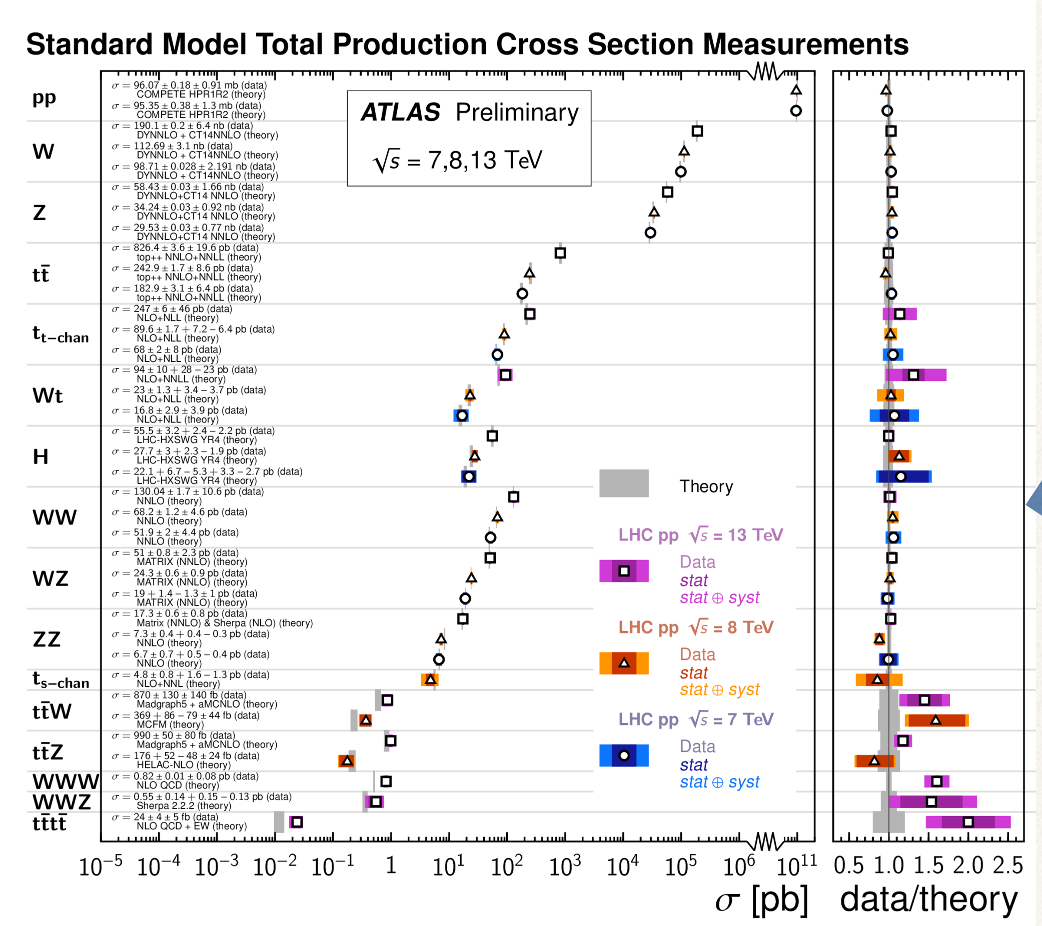
2. Simple straw-man models

3. Development of public tools, or recasting, so we can tackle complex processes and focus on the fundamental ideas

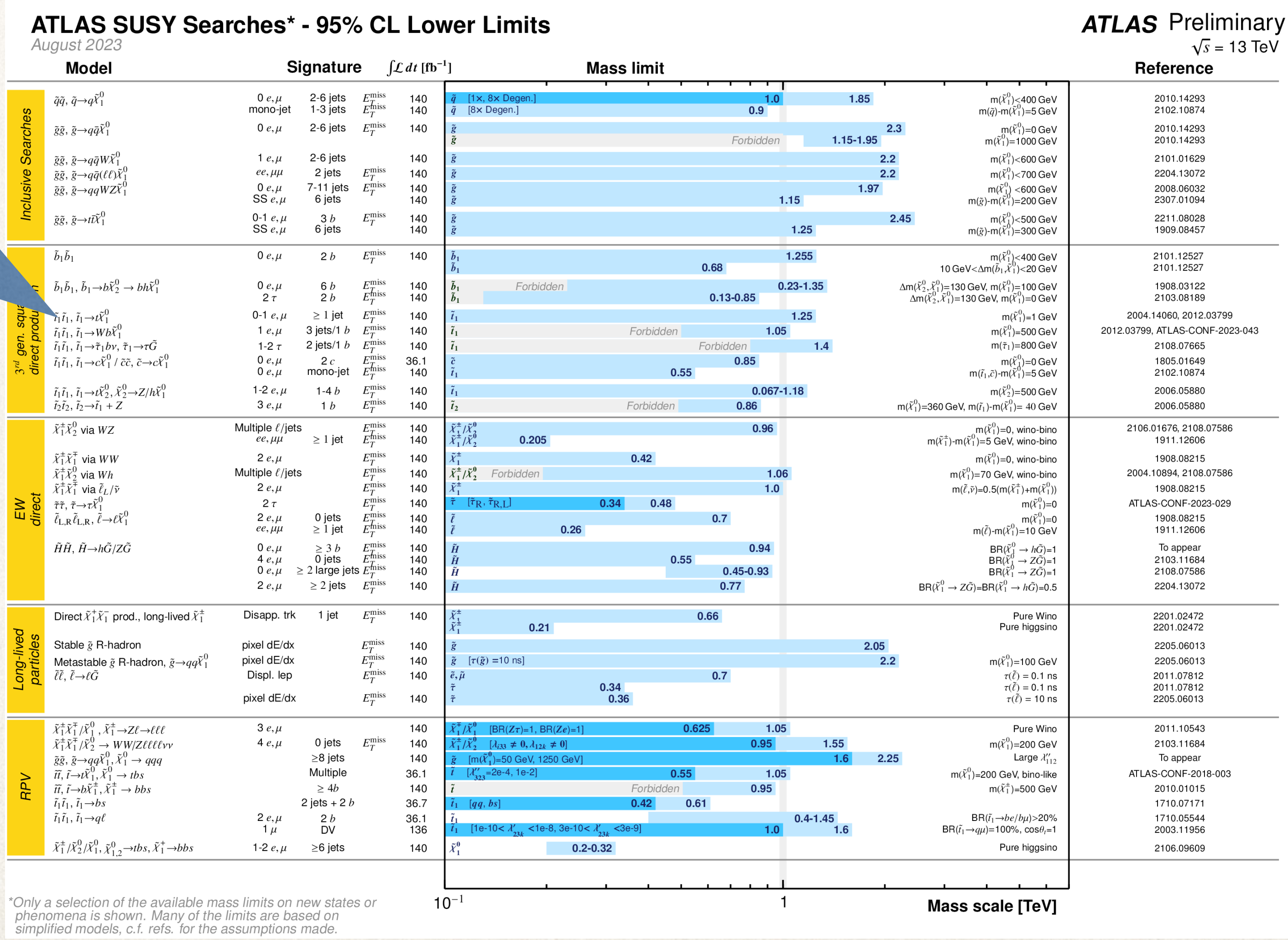
Back to the LHC:
Direct versus indirect searches

Direct searches for new phenomena

consistency of data vs
SM predictions



Interpretation in models:
exclusion regions



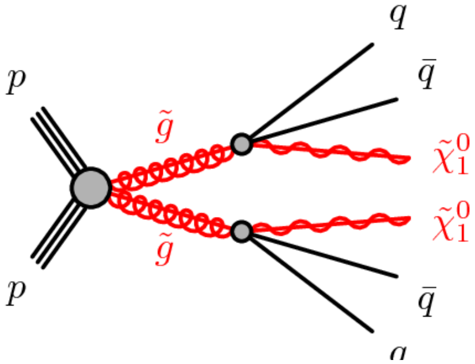
Coloured states to the very exotic

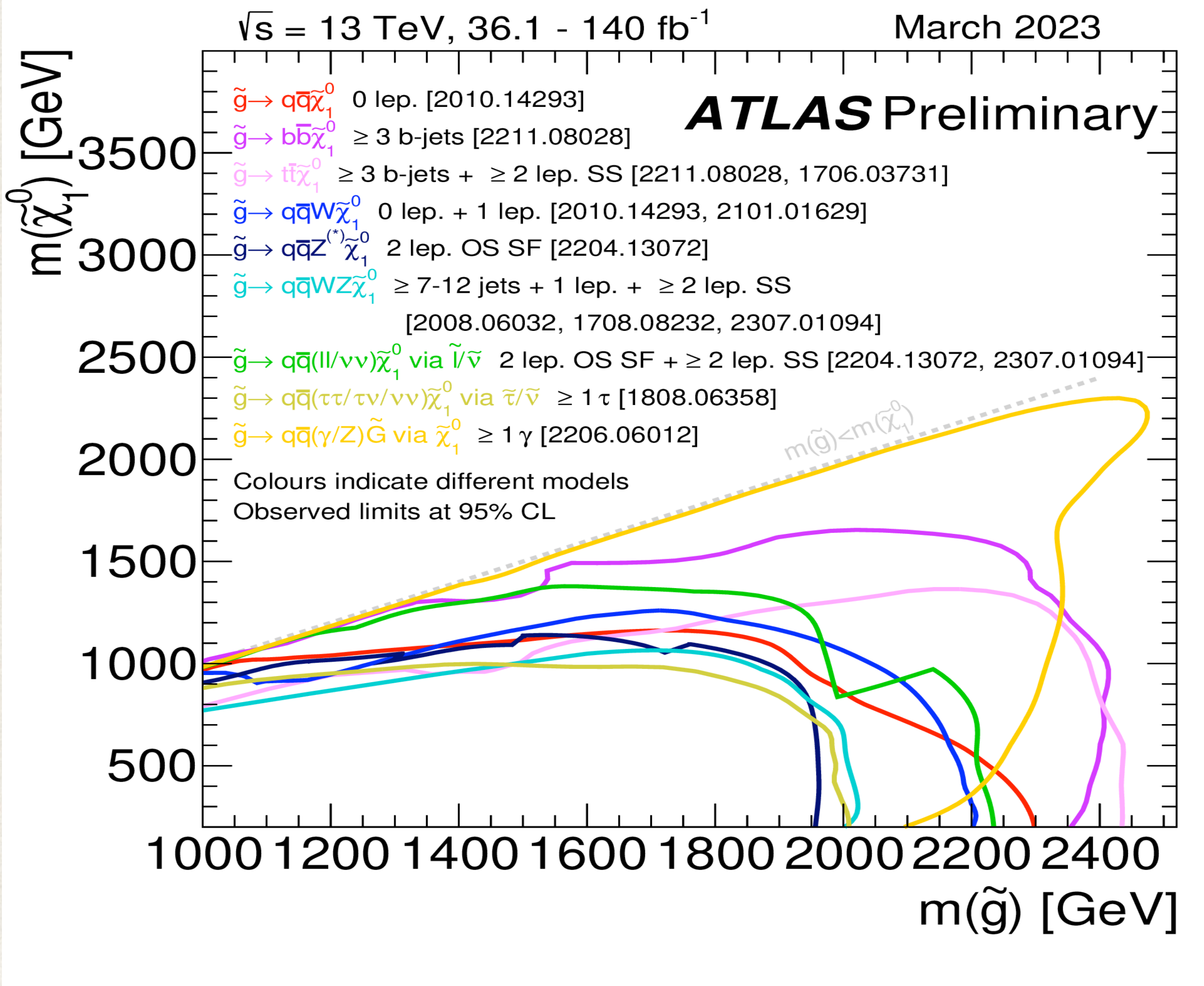
SUSY Benchmark

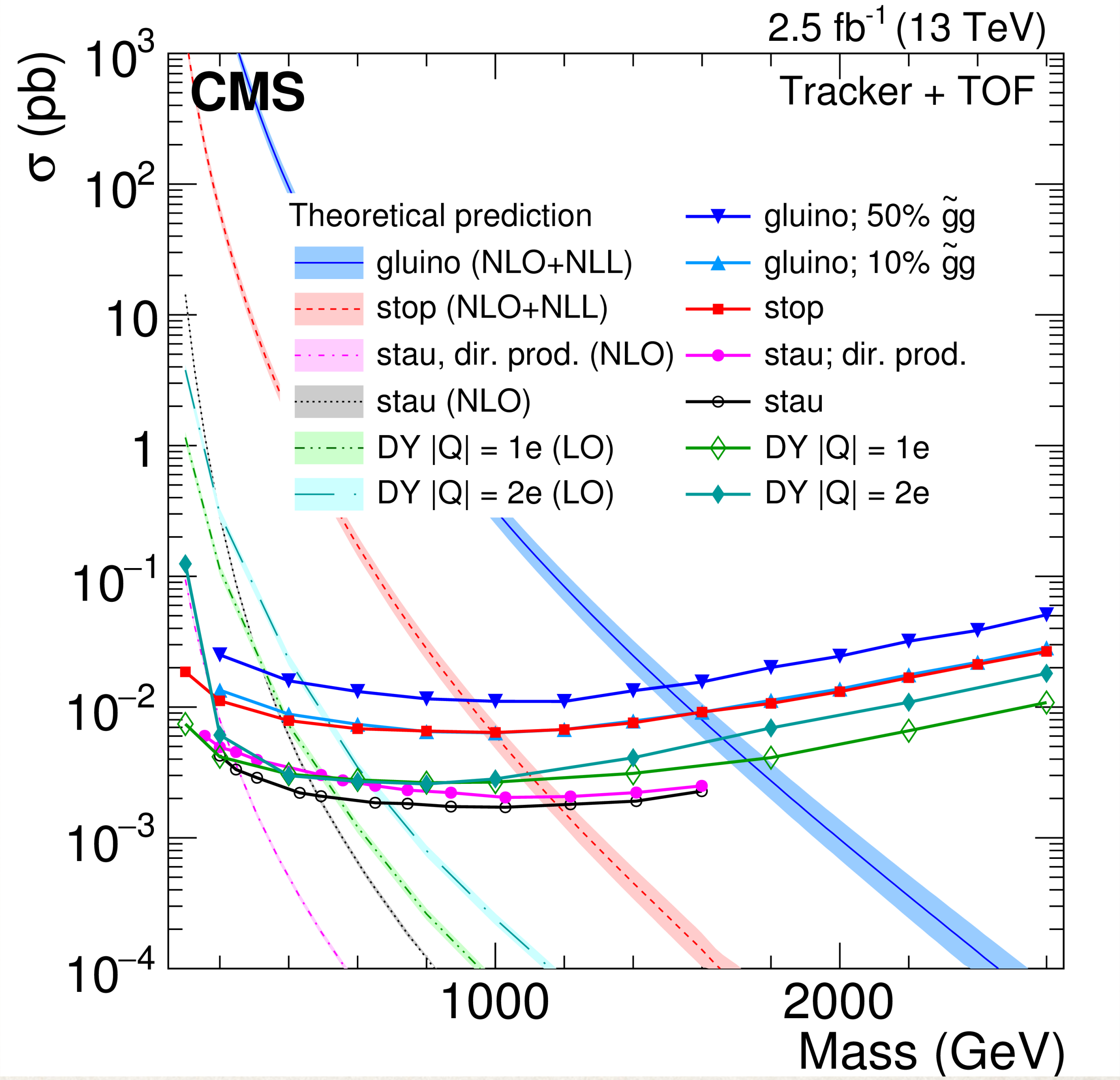
Jets+MET

some-SUSY

HSCPs





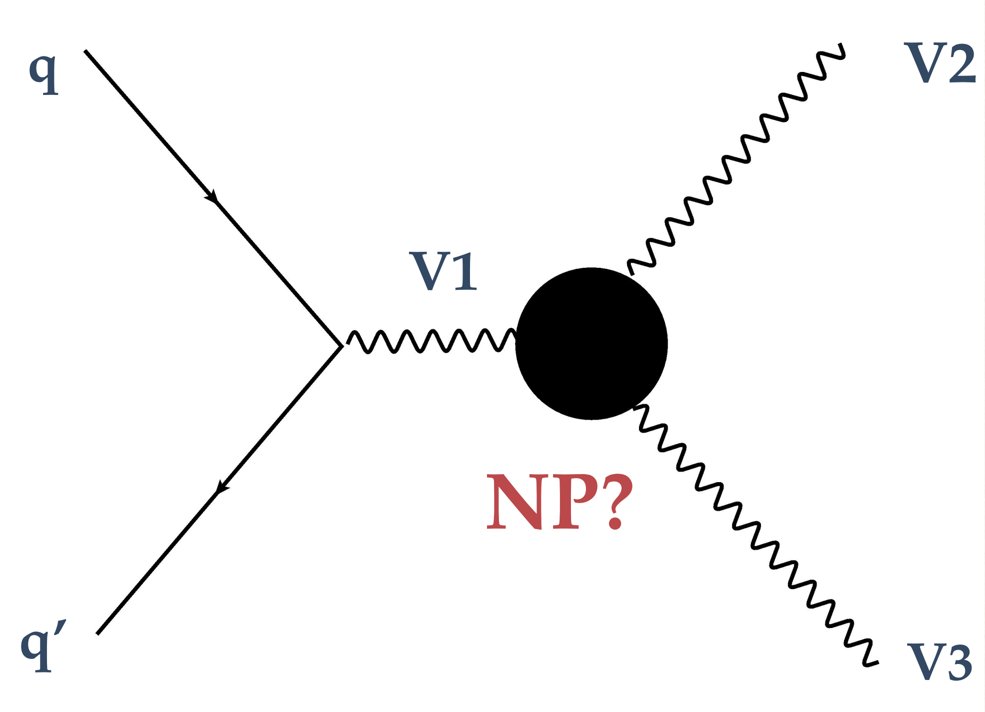


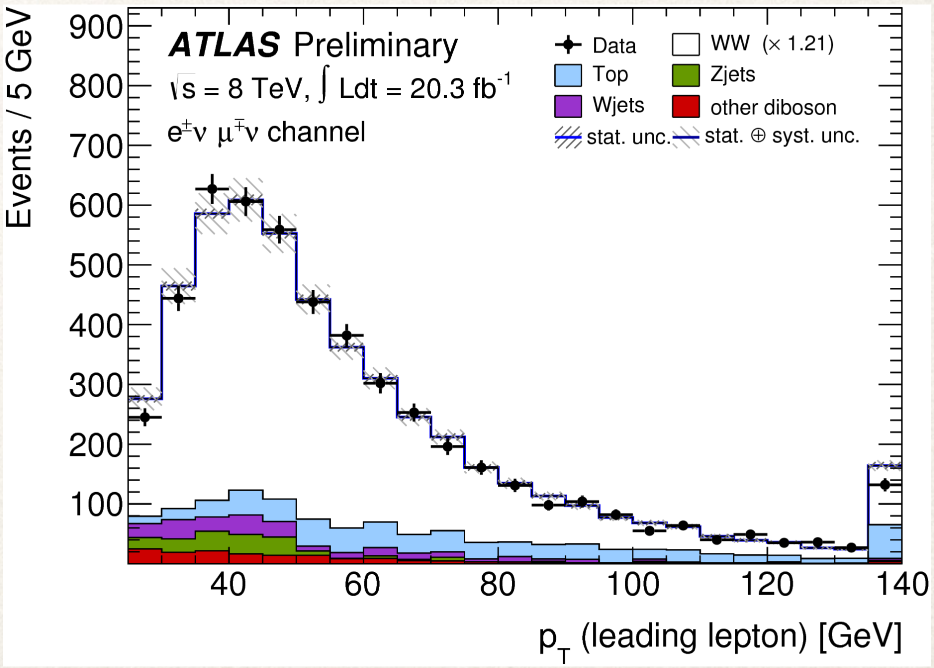
Indirect searches

Focus on SM particles' behaviour
precise determination of couplings and kinematics
comparison with SM,
search for deviations

Indirect searches using the Higgs
since 2012, relatively new
Higgs as a window to NP
expect deviations in its behaviour
Run2 data and beyond
precision Higgs Physics

e.g. Anomalous trilinear gauge couplings, aka **TGCs**

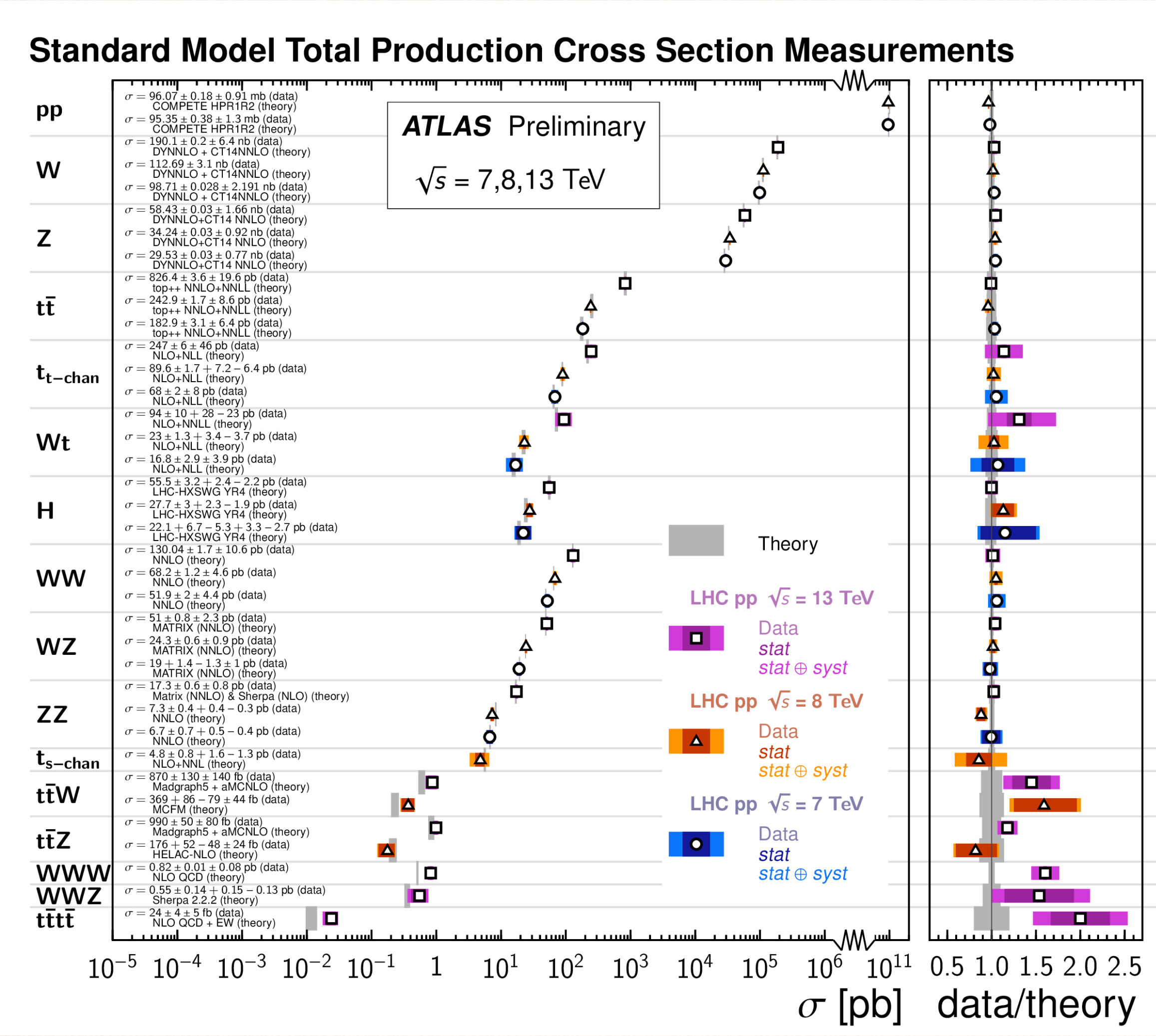


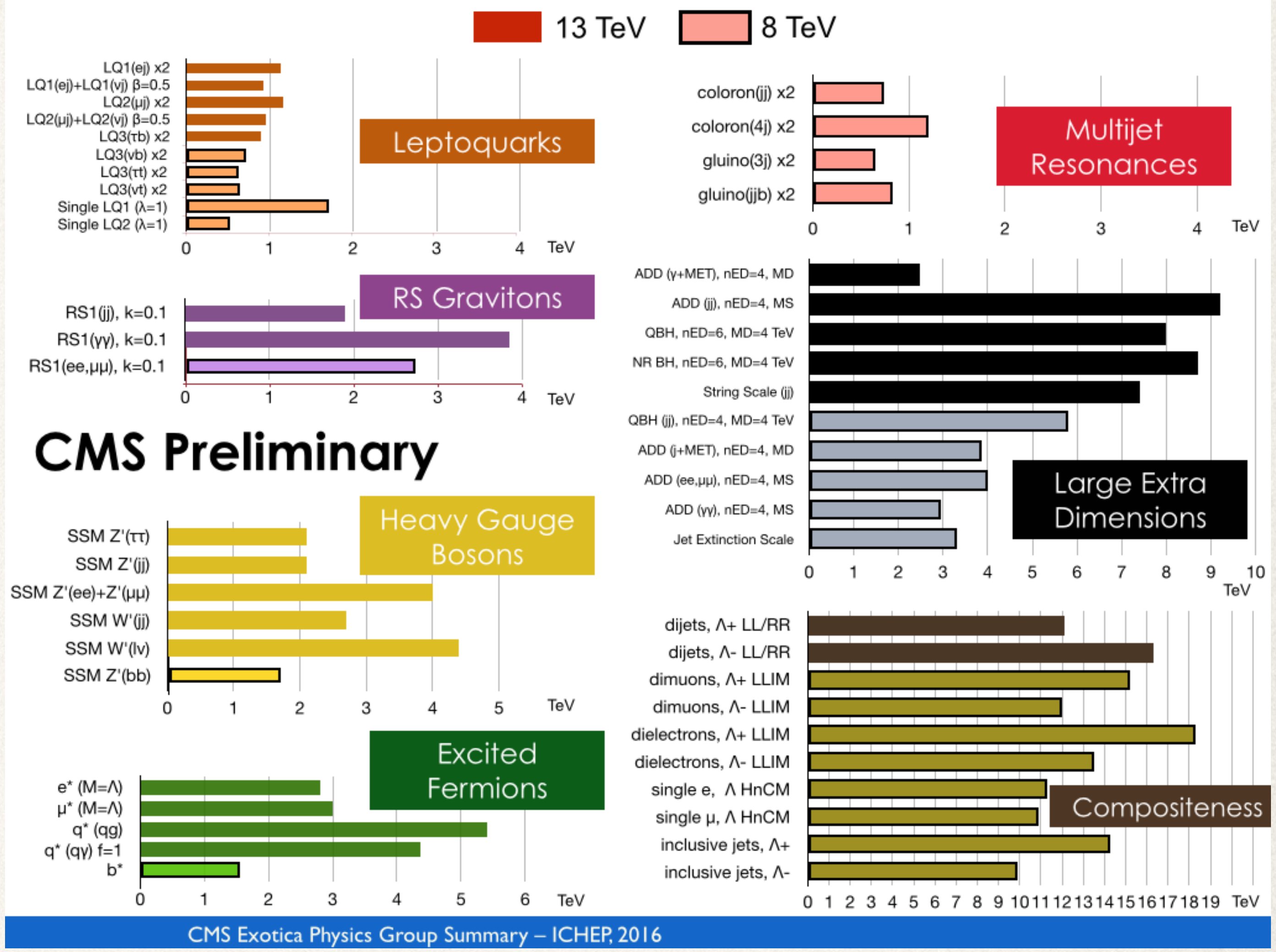


LEP, Tevatron, LHC

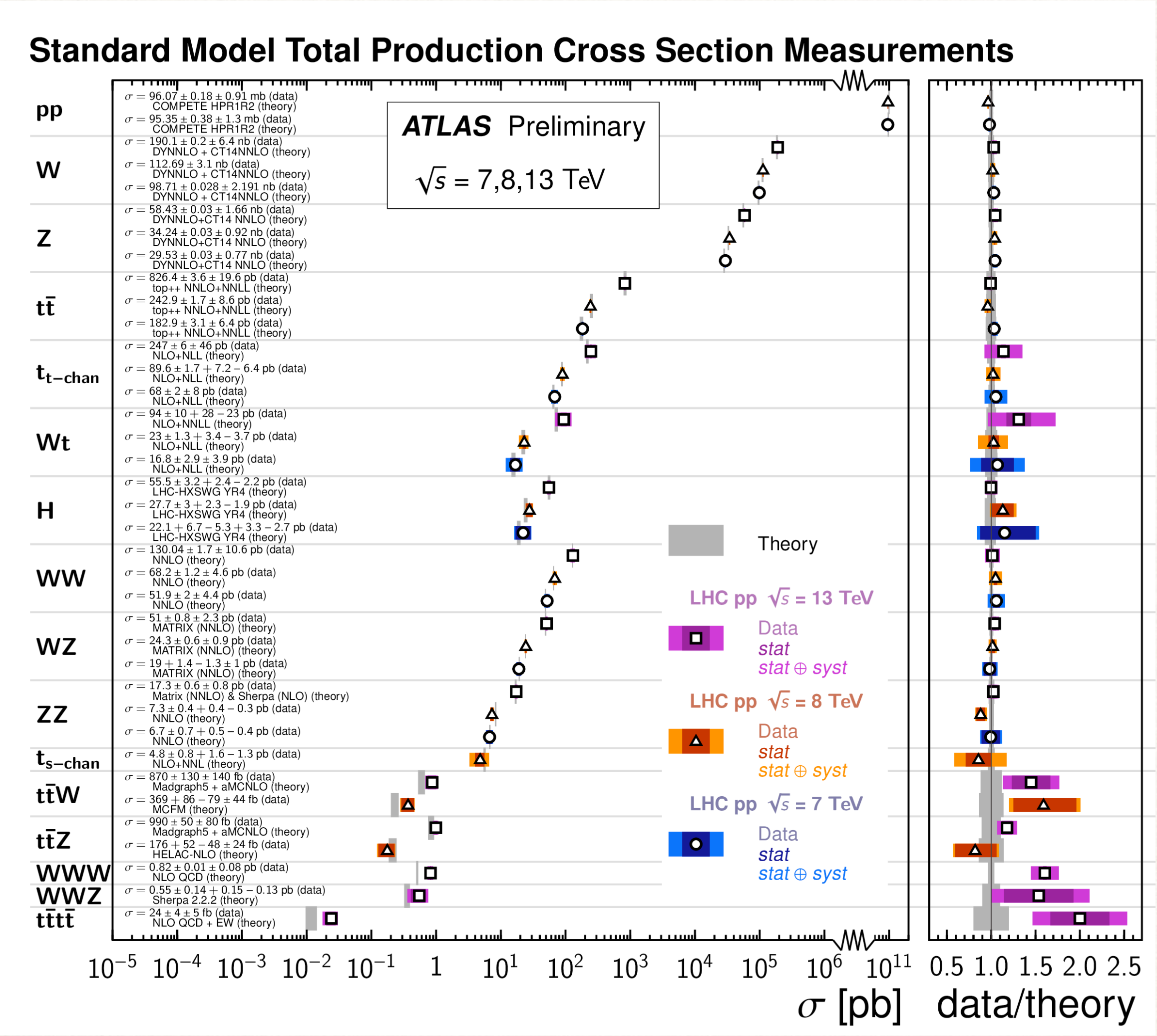
Casting a wide net: the *new* SM

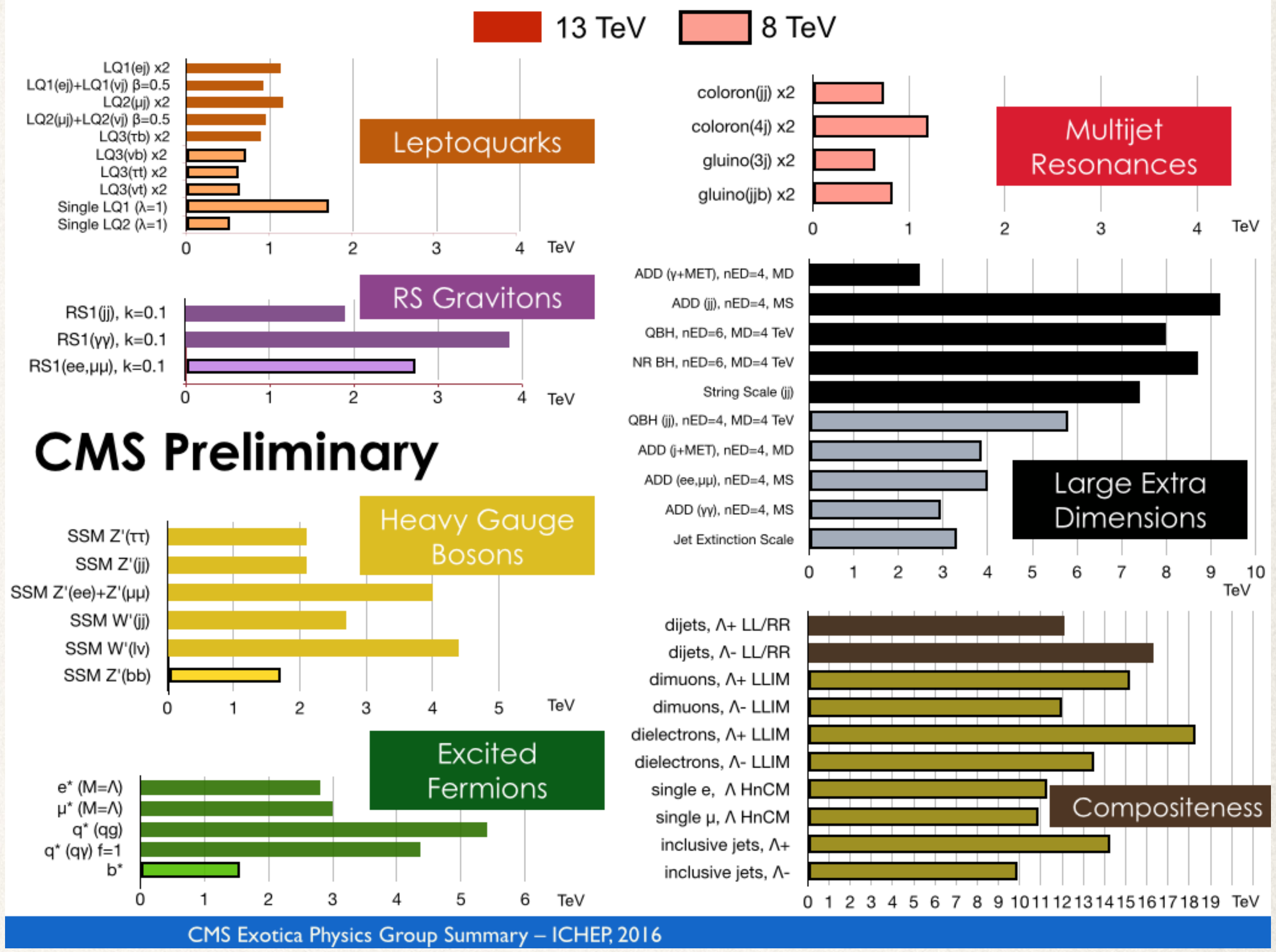
Why EFT?


Standard Model Total Production Cross Section Measurements
ATLAS Preliminary
$\sqrt{s}$ = 7,8,13 TeV
pp
W
Z
$t\bar{t}$
$t_{t-\mathrm{chan}}$
Wt
H
WW
WZ
ZZ
$t_{s-\mathrm{chan}}$
$t\bar{t}W$
$t\bar{t}Z$
WWW
WWZ
$t\bar{t}t\bar{t}$
Theory
LHC pp $\sqrt{s}$ = 13 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 8 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 7 TeV
Data
stat
stat ⊕ syst
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{11}
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory


13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
0 1 2 3 4 TeV
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS Gravitons
0 1 2 3 4 TeV
CMS Preliminary
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Heavy Gauge Bosons
0 1 2 3 4 5 TeV
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Excited Fermions
0 1 2 3 4 5 6 TeV
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
0 1 2 3 4 TeV
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
0 1 2 3 4 5 6 7 8 9 10 TeV
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
CMS Exotica Physics Group Summary – ICHEP, 2016

Why EFT?





The SM is a good description of Nature at the LHC

==> new resonances/phenomena may be **heavy**

==> Our hopes for simple/natural models are not realised

==> We should adopt a more **model-independent** strategy when interpreting data

EFT approach

Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

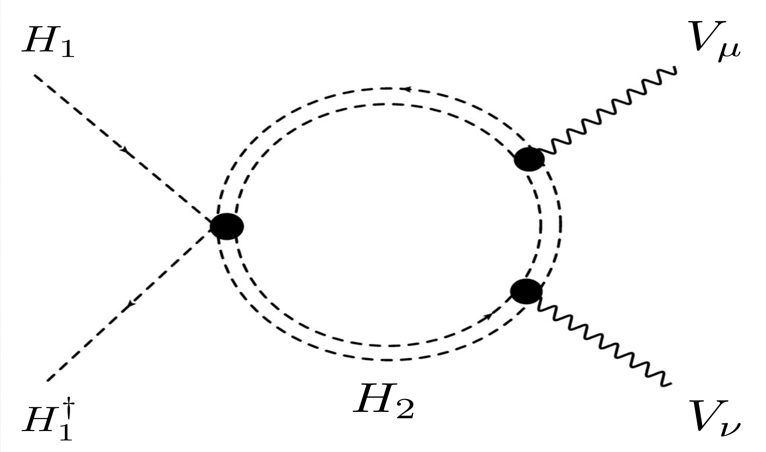
dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\,\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\,\mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

example:

2HDM

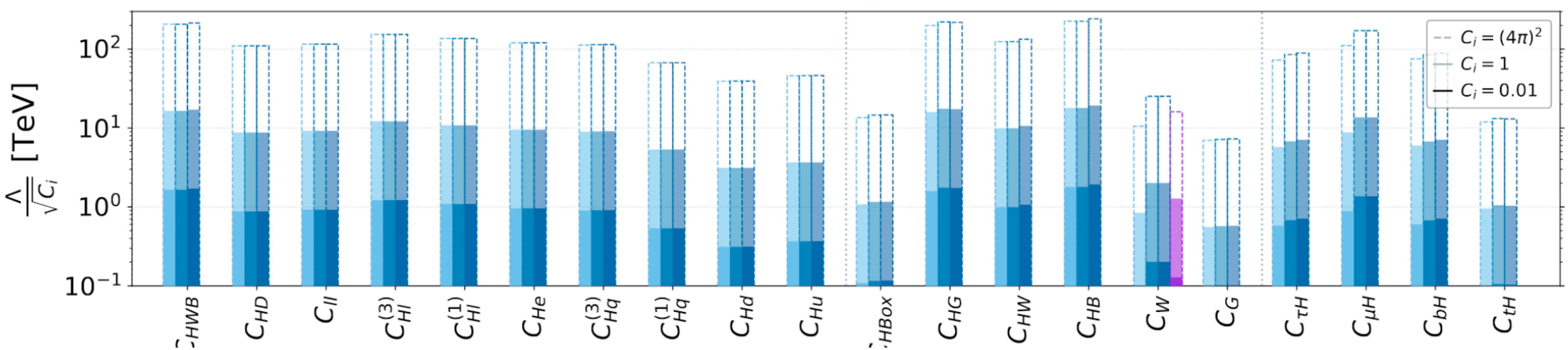


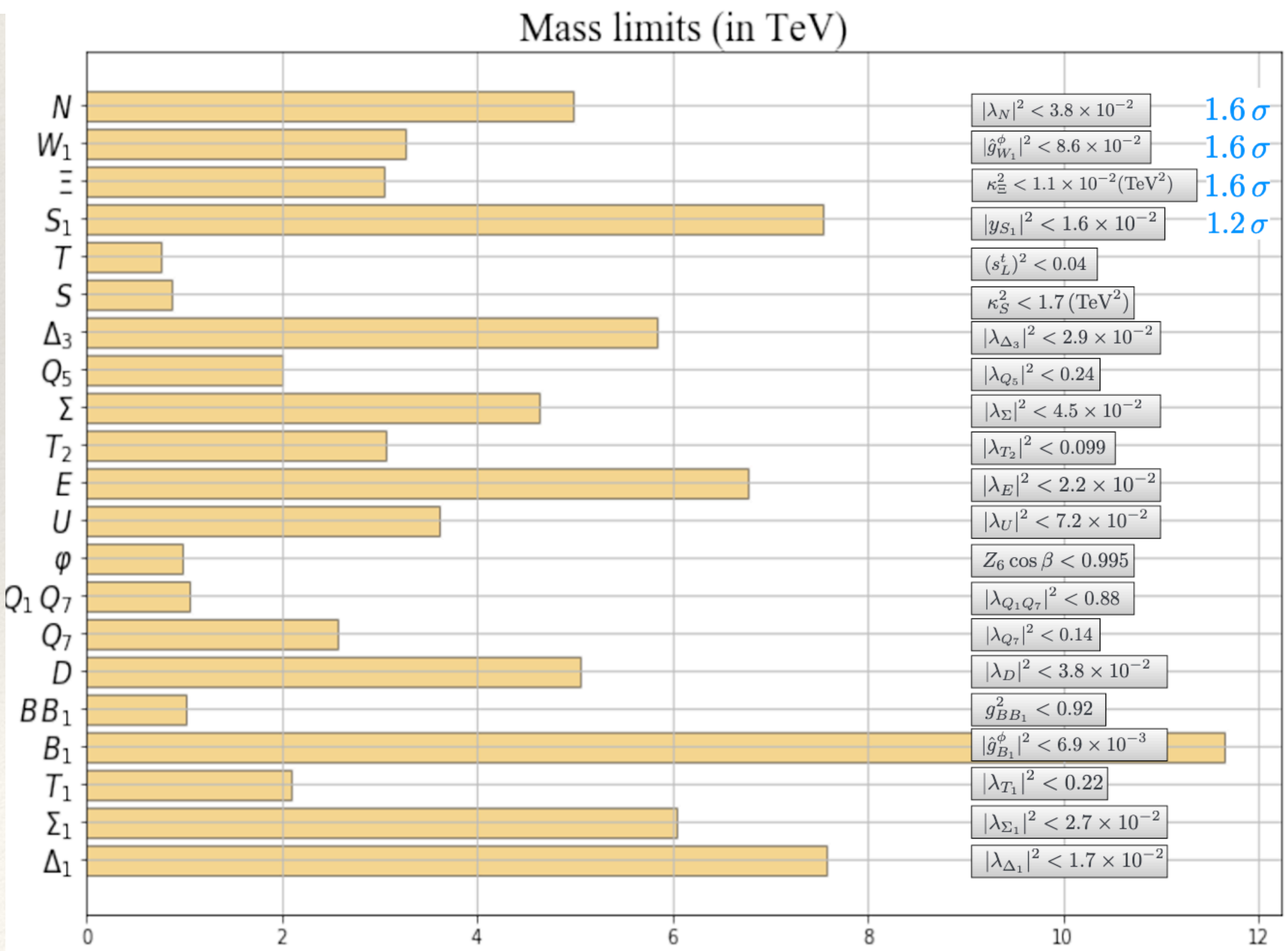
$$\boxed{\frac{ig}{2m_W^2}\,\bar{c}_W}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$

where $\bar{c}_W = \dfrac{m_W^2\,(2\,\tilde{\lambda}_3+\tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$

Current SMEFT constraints reach the TeV for most of t he param space

Ellis, Madigan, Mimasu, VS, You
2012.02779, JHEP





And when translated into vanilla extensions of the SM, the mass limits are also probing the TeV scale

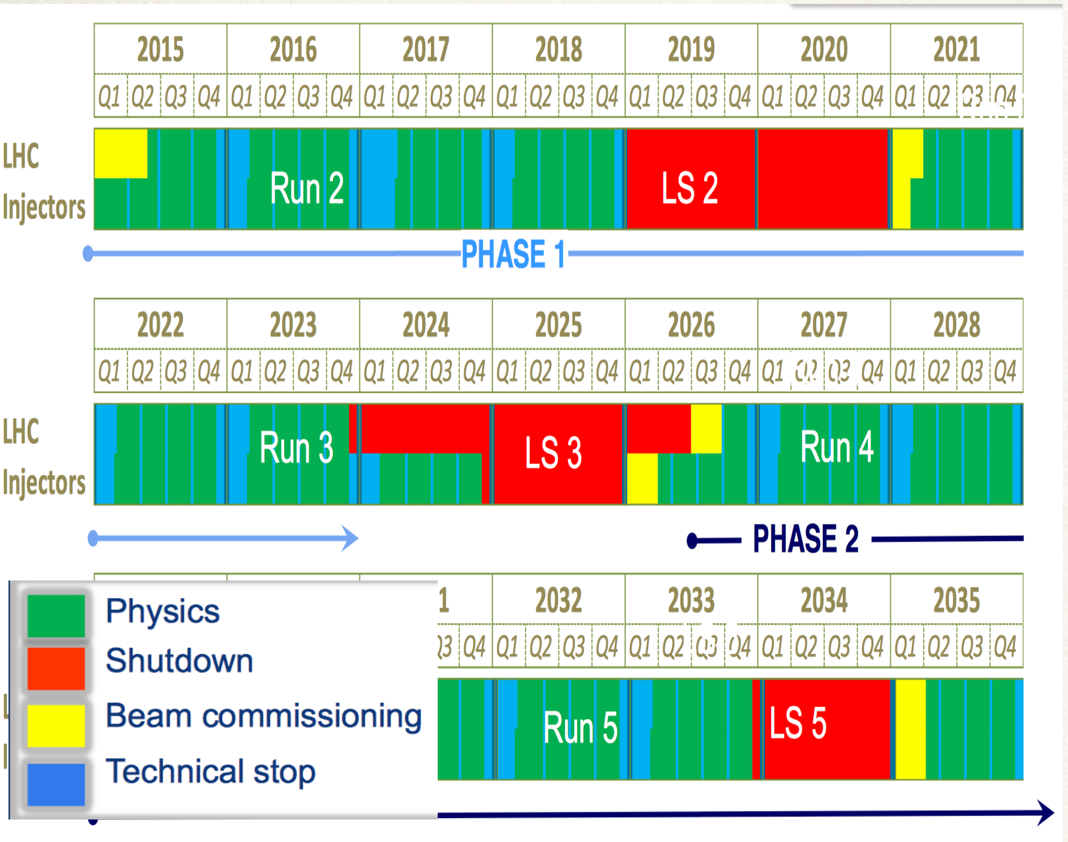
Lots of work needed to advance this area: higher-order calculations, optimisation of strategies, better exp understanding of correlations…

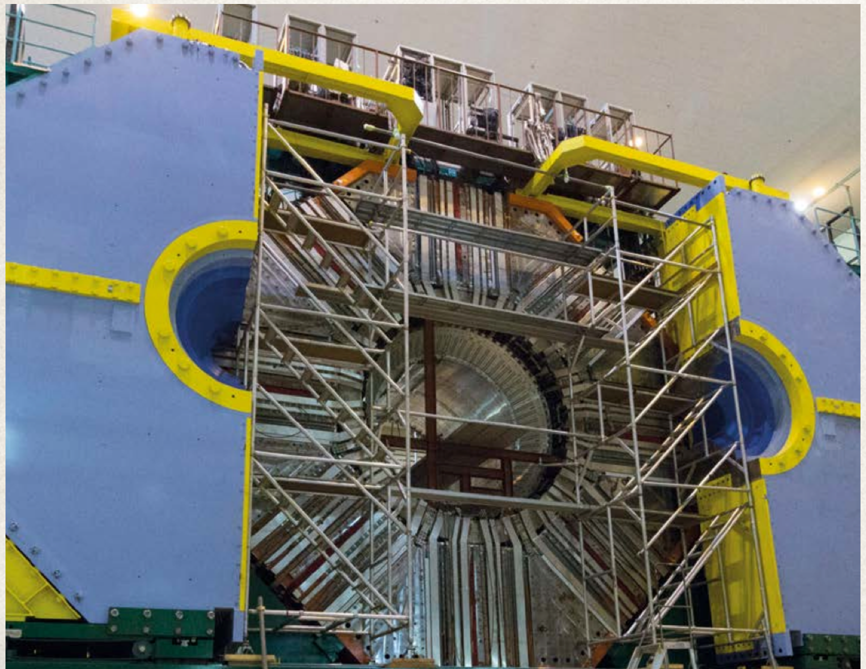
Final words

We haven't figured out what is beyond the Standard Model BUT…

For the LHC, this is just the beginning

HL-LHC (High-Luminosity) LHC approved, to deliver 3000 inverse fb of data.
Funding ensured until ~2040





LHC hopefuls

gains from more data and better understanding of the environment

Testing non-standard kinematic features
Reaching high-precision in Higgs physics
Searches for invisible particles (monoX)
Blind spots (DV, disap. tracks, quirks)

and, of course, FLAVOUR
with Belle-II, NA62 complementing LHCb

Smaller experiments may be key

Narrower focus

BUT

cheaper, shorter time-scale

develop creative experimental techniques

often enlarge the initial physics focus

And what about the cool/crazy stuff?

Dark Energy and its interaction with us

Alternatives to space-time symmetries (e.g. emergent gravity)

Very light dark matter (new exp techniques)

Dark moments in the Universe's history, pre-BBN

Connections between IR and UV physics, e.g. BHs

…

We need to *challenge* the well-stablished paradigms,
may be quickly ruled out
but one **always** learn something new from these explorations
And, remember that falsifying ideas is part of our job description

Thank you for listening

Questions?

Conclusions

- Here we are, looking for a way to advance our understanding of nature, to reach discovery

- Scaling back from an ambitious program to find *the* theory of everything. Facing the challenges/opportunities that more data brings

- Use of simplified models to organize/interpret searches, less model biased, and suitable to complementarity studies. Yet theoretical advances require more than simplified models, asking difficult questions from model building

- Keeping at the edge of the interpretation of data: bringing many towards precision (akin to SM) and to Artificial Intelligence techniques (NNs and the likes), but we should not lose track of our core mission:

Understanding Nature

(and having fun on the way!)

Additional material (Exercises)

In tutorial 3 we saw that for the Standard Model, at one-loop order,

$$\beta_1 = \frac{41}{6} \qquad \beta_2 = -\frac{19}{6} \qquad \beta_3 = -7\ ,$$

whereas for the MSSM

$$\beta_1 = 11 \qquad \beta_2 = 1 \qquad \beta_3 = -3\ . \tag{4}$$

a) Defining $\alpha_i(\mu) \equiv \frac{g_i^2(\mu)}{4\pi}$, solve the RG equation (1) to find a relationship between $\alpha_i(M_Z)$ and $\alpha_i(\mu_0)$ for a general scale μ_0.
Hint: Equation (1) takes the simplest form when written in terms of α^{-1}.

b) Grand Unified Theories predict that at some scale $\mu_0 = M_{GUT}$,

$$\frac{5}{3}\alpha_1(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_3(M_{GUT}). \tag{5}$$

Assuming this, derive

$$\alpha_3(M_Z)^{-1} = \alpha_2(M_Z)^{-1} + \frac{\beta_3 - \beta_2}{3\beta_1/5 - \beta_2}\left[\frac{3}{5}\alpha_1^{-1}(M_Z) - \alpha_2^{-1}(M_Z)\right]. \tag{6}$$

c) Taking the (rough) experimental values $g_1(M_Z) = 0.357$ and $g_2(M_Z) = 0.652$, and assuming all the Standard Model couplings unify at M_{GUT}, what value of $g_3(M_Z)$ do we predict from equation (6)? Does the MSSM do any better, if we assume that SUSY is broken just above the electroweak scale?

d) Show that if we introduce the fine-structure constant $\alpha = \frac{e^2}{4\pi}$, with $e = g_2 \sin\theta_W$ and $\tan\theta_W = \frac{g_1}{g_2}$, then equation (6) can be recast as

$$\alpha_3(M_Z)^{-1} = \alpha^{-1}\left[\sin^2\theta_W + \frac{3 - 8\sin^2\theta_W}{5}\,\frac{b_3 - b_2}{b_1 - b_2}\right]\ , \tag{7}$$

where $b_3 = \beta_3$, $b_2 = \beta_2$ and $b_1 = \frac{3}{5}\beta_1$. Furthermore, show that the unification scale is given by

$$\log\left(\frac{M_{GUT}}{M_Z}\right) = \frac{2\pi\,(3 - 8\sin^2\theta_W)}{5\alpha\,(b_1 - b_2)}\ , \tag{8}$$

and that at the unification scale, the value of the coupling is

$$\alpha_{GUT} = \frac{5\alpha\,(b_1 - b_2)}{5\sin^2\theta_W\, b_1 - 3\cos^2\theta_W\, b_2}\ . \tag{9}$$

e) What is the Unification scale and value of the coupling at M_{GUT} predicted by:

(i) the Standard Model?

(ii) the MSSM?

Dirac, Weyl and Majorana Fermions

Recall the Dirac equation for a four-component (Dirac) fermion:

$$(\not{p} - m)\Psi = 0 \qquad \text{where} \qquad \not{p} = p_\mu \gamma^\mu \ . \tag{1}$$

Further recall (from Standard Model tutorial 1) that the action of charge congugation can be represented as a matrix acting on Ψ:

$$\Psi^c = C\,\overline{\Psi}^T \qquad\qquad C = -i\,\gamma^2\gamma^0 \tag{2}$$

If we define

$$\Psi \equiv \begin{pmatrix} \xi \\ \overline{\eta} \end{pmatrix} \equiv \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \ , \tag{3}$$

then ξ and η are left- and right-handed[1] two-component (Weyl) spinors respectively, and the equation of motion (1) becomes two coupled differential equations:

$$(\overline{\sigma}_\mu p^\mu)\,\xi = m\,\overline{\eta} \tag{5a}$$

$$(\sigma_\mu p^\mu)\,\overline{\eta} = m\,\xi \tag{5b}$$

Remember that in the chiral basis,

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \overline{\sigma}^\mu & 0 \end{pmatrix} \qquad \text{where} \qquad \sigma^\mu = (\mathbb{1}_2,\, \vec{\sigma}) \ , \quad \overline{\sigma}^\mu = (\mathbb{1}_2,\, -\vec{\sigma}) \ . \tag{6}$$

Note that the two equations (5) decouple when $m = 0$.

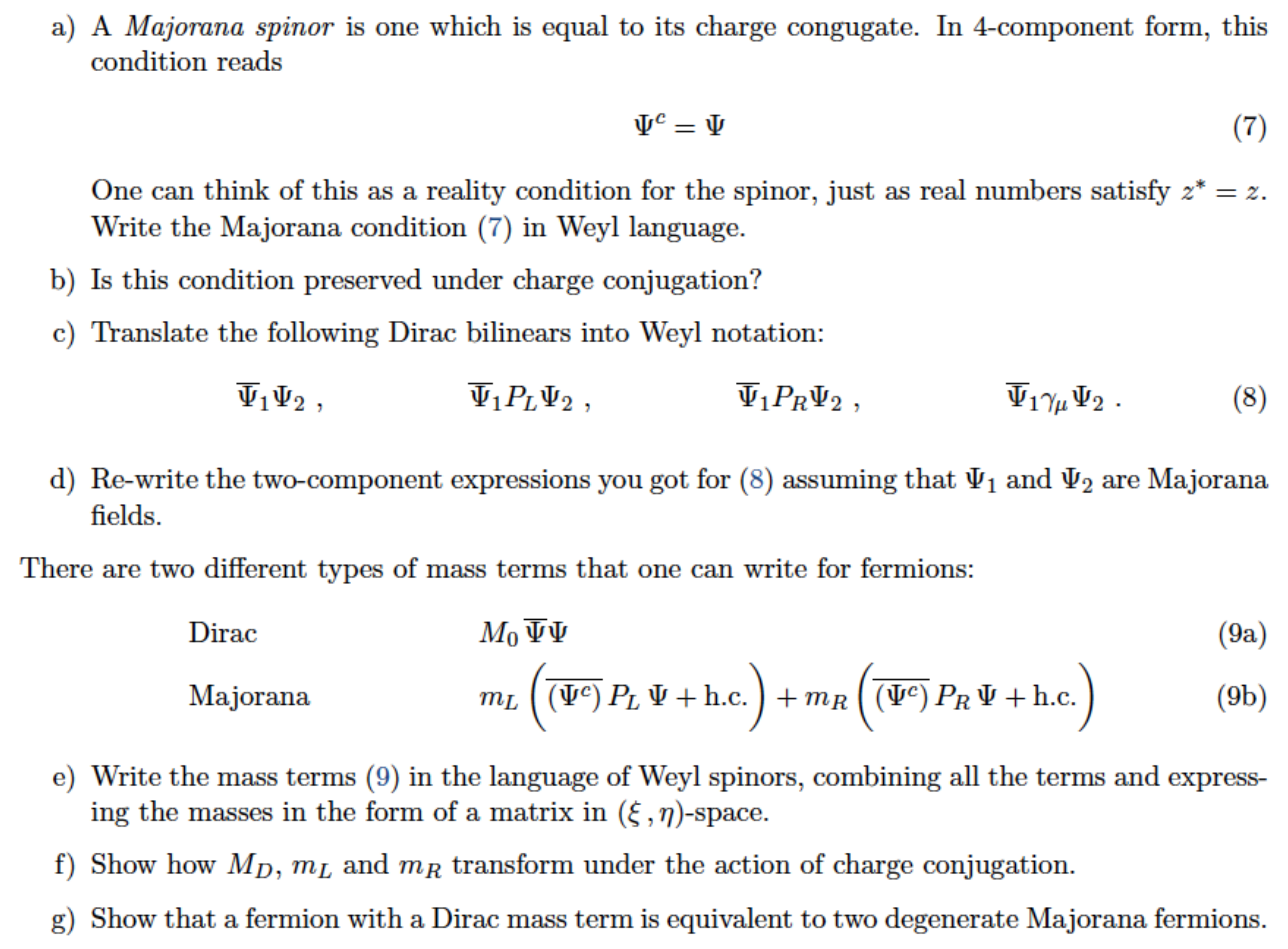
---

[1] We can project onto the left- and right-handed components with

$$P_L = \frac{1}{2}(\mathbb{1} - \gamma^5) \qquad\qquad P_R = \frac{1}{2}(\mathbb{1} + \gamma^5) \ . \tag{4}$$

Note: $P_R + P_L = \mathbb{1}$ and $P_R P_L = P_L P_R = 0$.

Dirac, Weyl and Majorana Fermions



a) A *Majorana spinor* is one which is equal to its charge congugate. In 4-component form, this condition reads

$$\Psi^c = \Psi \tag{7}$$

One can think of this as a reality condition for the spinor, just as real numbers satisfy $z^* = z$. Write the Majorana condition (7) in Weyl language.

b) Is this condition preserved under charge conjugation?

c) Translate the following Dirac bilinears into Weyl notation:

$$\overline{\Psi}_1 \Psi_2 \,, \qquad \overline{\Psi}_1 P_L \Psi_2 \,, \qquad \overline{\Psi}_1 P_R \Psi_2 \,, \qquad \overline{\Psi}_1 \gamma_\mu \Psi_2 \,. \tag{8}$$

d) Re-write the two-component expressions you got for (8) assuming that Ψ_1 and Ψ_2 are Majorana fields.

There are two different types of mass terms that one can write for fermions:

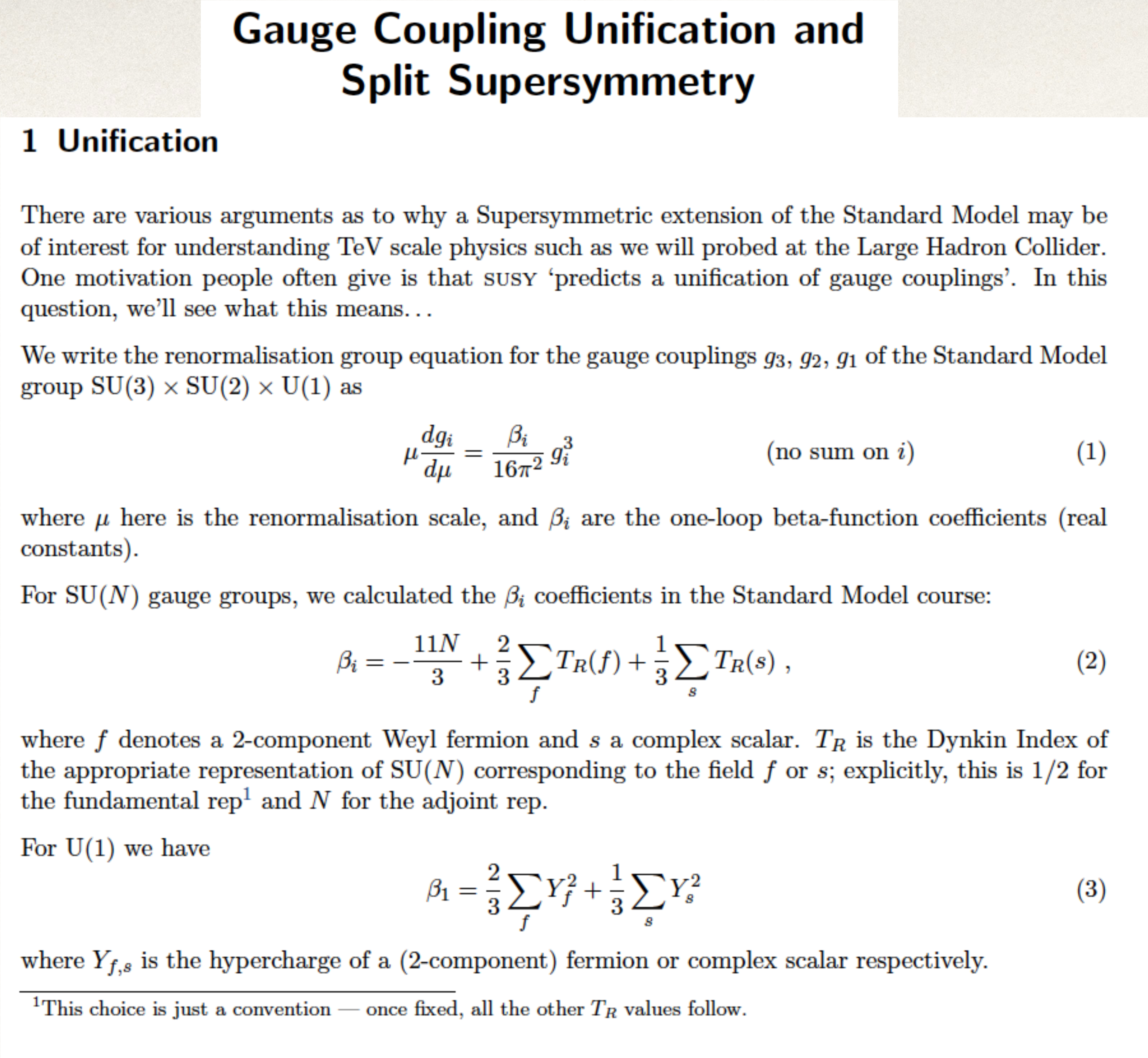
$$\text{Dirac} \qquad M_0\, \overline{\Psi}\Psi \tag{9a}$$

$$\text{Majorana} \qquad m_L \left(\overline{(\Psi^c)}\, P_L\, \Psi + \text{h.c.} \right) + m_R \left(\overline{(\Psi^c)}\, P_R\, \Psi + \text{h.c.} \right) \tag{9b}$$

e) Write the mass terms (9) in the language of Weyl spinors, combining all the terms and expressing the masses in the form of a matrix in $(\xi\,, \eta)$-space.

f) Show how M_D, m_L and m_R transform under the action of charge conjugation.

g) Show that a fermion with a Dirac mass term is equivalent to two degenerate Majorana fermions.



Gauge Coupling Unification and Split Supersymmetry

1 Unification

There are various arguments as to why a Supersymmetric extension of the Standard Model may be of interest for understanding TeV scale physics such as we will probed at the Large Hadron Collider. One motivation people often give is that SUSY 'predicts a unification of gauge couplings'. In this question, we'll see what this means...

We write the renormalisation group equation for the gauge couplings g_3, g_2, g_1 of the Standard Model group $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ as

$$\mu \frac{dg_i}{d\mu} = \frac{\beta_i}{16\pi^2}\, g_i^3 \qquad \text{(no sum on } i\text{)} \tag{1}$$

where μ here is the renormalisation scale, and β_i are the one-loop beta-function coefficients (real constants).

For $\mathrm{SU}(N)$ gauge groups, we calculated the β_i coefficients in the Standard Model course:

$$\beta_i = -\frac{11N}{3} + \frac{2}{3}\sum_f T_R(f) + \frac{1}{3}\sum_s T_R(s)\ , \tag{2}$$

where f denotes a 2-component Weyl fermion and s a complex scalar. T_R is the Dynkin Index of the appropriate representation of $\mathrm{SU}(N)$ corresponding to the field f or s; explicitly, this is $1/2$ for the fundamental rep[1] and N for the adjoint rep.

For U(1) we have

$$\beta_1 = \frac{2}{3}\sum_f Y_f^2 + \frac{1}{3}\sum_s Y_s^2 \tag{3}$$

where $Y_{f,s}$ is the hypercharge of a (2-component) fermion or complex scalar respectively.

---

[1] This choice is just a convention — once fixed, all the other T_R values follow.

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[1] This choice is just a convention — once fixed, all the other T_R values follow.

In tutorial 3 we saw that for the Standard Model, at one-loop order,

$$\beta_1 = \frac{41}{6} \qquad \beta_2 = -\frac{19}{6} \qquad \beta_3 = -7\ ,$$

whereas for the MSSM

$$\beta_1 = 11 \qquad \beta_2 = 1 \qquad \beta_3 = -3\ . \tag{4}$$

a) Defining $\alpha_i(\mu) \equiv \frac{g_i^2(\mu)}{4\pi}$, solve the RG equation (1) to find a relationship between $\alpha_i(M_Z)$ and $\alpha_i(\mu_0)$ for a general scale μ_0.
Hint: Equation (1) takes the simplest form when written in terms of α^{-1}.

b) Grand Unified Theories predict that at some scale $\mu_0 = M_{GUT}$,

$$\frac{5}{3}\alpha_1(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_3(M_{GUT}). \tag{5}$$

Assuming this, derive

$$\alpha_3(M_Z)^{-1} = \alpha_2(M_Z)^{-1} + \frac{\beta_3 - \beta_2}{3\beta_1/5 - \beta_2}\left[\frac{3}{5}\alpha_1^{-1}(M_Z) - \alpha_2^{-1}(M_Z)\right]. \tag{6}$$

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e) What is the Unification scale and value of the coupling at M_{GUT} predicted by:

(i) the Standard Model?

(ii) the MSSM?

2 Split Supersymmetry

The idea of Split Supersymmetry is to forget using SUSY as a solution to the hierarchy problem, but to still require that it leads the unification of gauge couplings and provides a dark matter candidate. We'll look at this idea, following reference [1]; their starting point was to note that the beta-function coefficients, b_i, can be written as

$$b_3 = \frac{1}{3}\left(4N_g - 33 + N_3\right) \tag{10a}$$

$$b_2 = \frac{1}{3}\left(4N_g - 22 + \frac{n_H}{2} + N_2\right) \tag{10b}$$

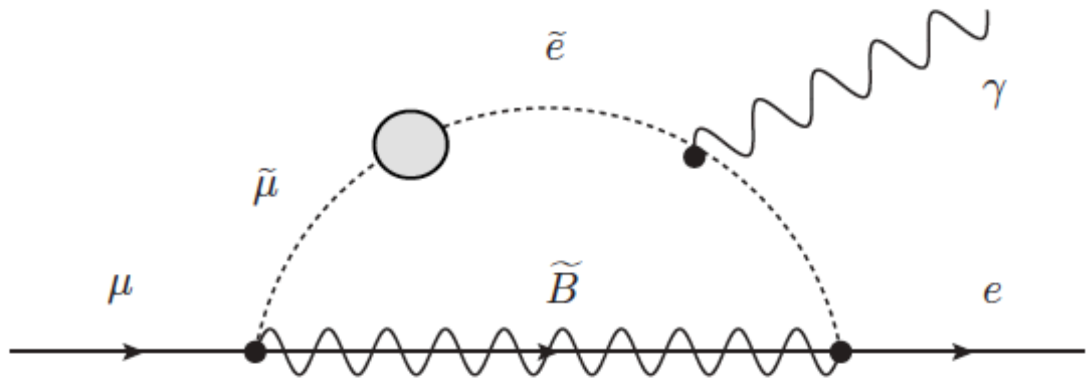
$$b_1 = \frac{1}{3}\left(4N_g + \frac{3n_H}{10} + N_1\right) \tag{10c}$$

where N_g counts the contribution to the β-functions from complete SU(5) irreps, and it is normalized such that the 3 families of SM quarks and leptons give $N_g = 3$.[2] For the MSƧM one can easily show that $N_g = \frac{9}{2}$. The number of Higgs doublets is n_H, and N_i $(i = 1, 2, 3)$ give the contributions from matter in incomplete GUT multiplets (for example, in the MSƧM, this includes contributions from the gauginos and higgsinos).

The important observation is that N_g actually cancels out in the equations (7) and (8), and so doesn't enter into the predictions for α_s or M_{GUT}. Split SUSY makes use of this fact: All *scalars* in the MSƧM can be very heavy, except one Higgs, and unification can still take place.[3] We still need the gauginos ($\widetilde{g}$, $\widetilde{W}$ and $\widetilde{B}$) and Higgsinos $\widetilde{h}_{u,d}$ to have masses of order the TeV scale in order to retain the nice features of unification, and to also have interesting dark matter candidates.

a) If we send the scale of ~~SUSY~~ to the GUT scale, what are the natural values for the squark and slepton masses? What about the fermionic superpartners (gauginos and higgsinos)?

b) Another interesting feature of split SUSY is that pushing the scalar masses to high scales alleviates the most pressing bounds from flavor-changing neutral currents (FCNCs), CP violation, proton decay and so on. The reason is that all those dangerous bounds are based on calculating a diagram that is suppressed by a factor of the scalar masses. For example, let's look at the M_{scalar} dependence of the $\mu \to e\gamma$ bound: the SUSY particles typically contribute to this process through a diagram of the type:



where the mass insertion (grey blob) comes from a flavor-violating, soft SUSY-breaking term of the form $-m^2_{\widetilde{e}\widetilde{\mu}}\,\widetilde{e}\,\widetilde{\mu}$. One can use naïve dimensional analysis (NDA) to estimate the size of this contribution to the branching ratio to be

$$\mathrm{BR}(\mu \to e\,\gamma) \approx \frac{g'^2\,e^2}{16\pi^2}\left(\frac{m^2_{\widetilde{e}\widetilde{\mu}}}{m^2_{\widetilde{\ell}}}\right)^2 \frac{v^2}{m^2_{\widetilde{\ell}}}\,\frac{v^2}{m^2_{\widetilde{B}}} \tag{11}$$

where $m_{\widetilde{\ell}}$ is the slepton mass, and we have used the fact that μ decays are dominated by $\mu \to e\,\nu_\mu \overline{\nu}_e$, which goes as G_F^2. Is this formula dimensionally correct?

c) Assume $m^2_{\widetilde{e}\widetilde{\mu}} \approx m^2_{\widetilde{\ell}}$ (no flavor hierarchy) and $m_{\widetilde{B}} \approx v$. Find the experimental constraint on the $\mathrm{BR}(\mu \to e\,\gamma)$ and use it to derive a lower bound on $m_{\widetilde{\ell}}$.

d) In split SUSY, gluinos (gluini?!) are lighter than squarks, so it is interesting to think about how gluinos decay. Use NDA to estimate the decay width $\Gamma_{\widetilde{g}}$, and hence the decay length, $c\tau$, of the gluino as a function of $m_{\widetilde{g}}$ and $m_{\widetilde{q}}$ (assuming that $m_{\widetilde{g}} \gg m_{\mathrm{LSP}}$, so there *are* SUSY particles for $\widetilde{g}$ to decay into).

Long lived gluinos are a 'smoking gun' feature of split SUSY. The LHC is looking for them by keeping the detectors on when there are no collisions; as gluinos carry color charge, if they hang around long enough they end up getting bound up into R-hadrons (hadrons with non-trivial charge under R-parity) that can potentially be brought to rest by all the material in the detector. If the beams are colliding, the detector is too busy detecting other things to notice the intermittent decays of these R-hadrons, but when there are no collisions, one would only expect to register cosmic rays, and *possibly* the decay of interesting stuff trapped in the detector.

References

[1] G. F. Giudice and A. Romanino, "Split supersymmetry," Nucl. Phys. B **699** (2004) 65 [Erratum-ibid. B **706** (2005) 65] [arXiv:hep-ph/0406088].

1 Goldstone Bosons

According to Goldstone's theorem, whenever a global symmetry group G is spontaneously broken down to a smaller one H, it gives rise to $\dim(G) - \dim(H)$ massless bosons known as *Goldstone bosons.*

Today we're going to look at what happens when we spontaneously break a global symmetry:

$$\mathrm{SU}(N) \longrightarrow \mathrm{SU}(N-1)\ . \tag{1}$$

a) How many Goldstone bosons (GBs) are generated by this breaking?

There are many ways to parameterise the GB fields, but we will try to be smart and choose a representation which clearly shows how all the fields transform under $\mathrm{SU}(N)$ and $\mathrm{SU}(N-1)$.

b) Explain how the $N \times N$ matrix

$$U_{N-1} \equiv \begin{pmatrix} \hat{U}_{N-1} & 0 \\ 0 & 1 \end{pmatrix} \qquad \text{with} \quad \hat{U}_{N-1} \ \text{an} \ (N-1)\times(N-1) \ \text{matrix} \tag{2}$$

provides a represention of the unbroken symmetry transformations.

Let's represent the GBs by introducing an $N \times N$ matrix Π in the following way

$$\phi(x) = e^{i\Pi(x)/f}\,\phi_0(x) \tag{3}$$

where

$$\Pi(x) = \begin{pmatrix} 0_{(N-1)\times(N-1)} & \vec{\pi}(x) \\ \vec{\pi}^\dagger(x) & 0 \end{pmatrix} \qquad \vec{\pi}(x) = \begin{pmatrix} \pi_1(x) \\ \vdots \\ \pi_{N-1}(x) \end{pmatrix} \in \mathbb{C}^{N-1} \tag{4}$$

$$\phi_0(x) = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \vdots \\ 0 \\ \pi_0(x) \end{pmatrix} \qquad \pi_0(x) \in \mathbb{R} \tag{5}$$

c) How does ϕ transform under the unbroken symmetries?

d) Does ϕ contain the right number of degrees of freedom?

e) We would like to see how ϕ transforms under the *broken* symmetries. We will first represent the broken symmetries by the transformation:

$$U_{\text{broken}} = \exp\left\{ i \begin{pmatrix} 0 & \vec{\alpha} \\ \vec{\alpha}^\dagger & 0 \end{pmatrix} \right\} \qquad\qquad \vec{\alpha} \in \mathbb{C}^{N-1} \tag{6}$$

Show that ϕ transforms as

$$\phi \to U_{\text{broken}}\, e^{i\Pi/f}\phi_0 = e^{i\Pi'/f}\phi_0 \tag{7}$$

to first order in $\vec{\alpha}$, where

(i) The $\vec{\pi}$ field shifts linearly:

$$\vec{\pi}' = \vec{\pi} + f\,\vec{\alpha}. \tag{8}$$

(ii) The field ϕ_0 is invariant under SU$(N-1)$ transformations.

f) Although one says that the SU(N) symmetry has been spontaneously broken down to SU$(N-1)$ what really happens is that the broken part of the symmetry is realized in a way that is different from the unbroken parts. To see this more clearly compare how the fields transform under a broken symmetry vs. how they transform under the unbroken ones. For the broken generators one says that the symmetries are "non-linearly" realized. Thus for infinitesimal tranformations involving the broken generators one requires that the shifts in (8) are symmetries. Show that this statement is consistent with the statement of Goldstone's theorem that the GBs are massless.

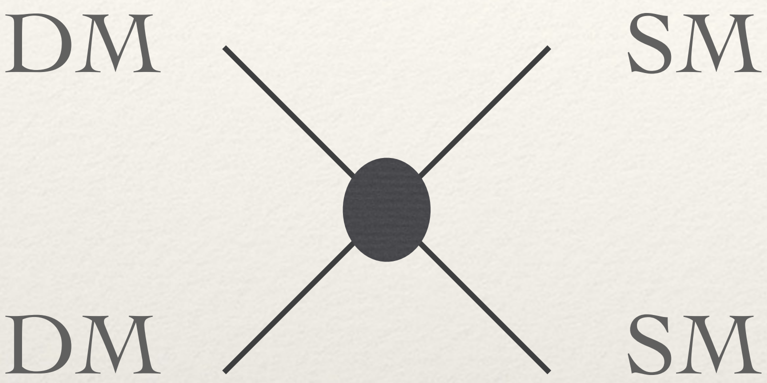
g) This shift symmetry also implies that no potential is generated (no quartic coupling, no term made up of powers of the field) and only derivative interactions are allowed. To see this explicitly, expand the GB kinetic term

$$\partial_\mu \phi^\dagger\, \partial^\mu \phi \tag{9}$$

up to quartic order in the fields.

Example of DM calculation

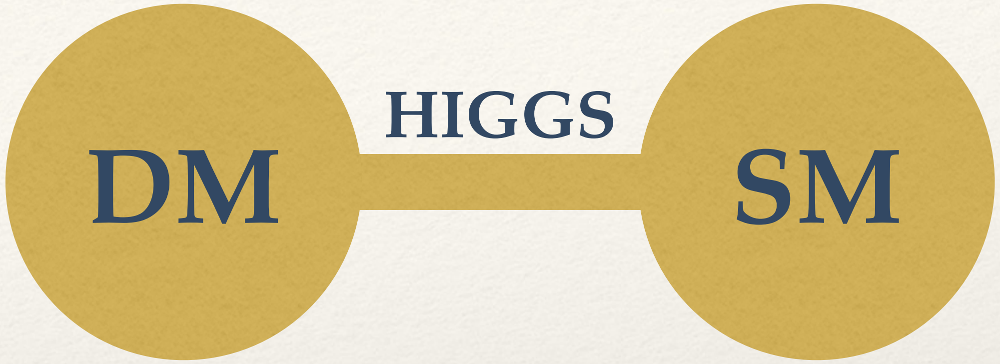
thermal production
cold (massive) DM



@ T >> mass ⇄
@ T ~ mass →
@ T << mass *freeze-out*

compute relic abundance after freeze-out (xF=m/TF) and compare with Planck's value

example: Higgs portal



e.g. Scalar DM

$$\mathcal{L} \supset -\frac{\lambda_S}{2} S^2 \, \Phi^\dagger \Phi$$

new parameters:
mass and coupling

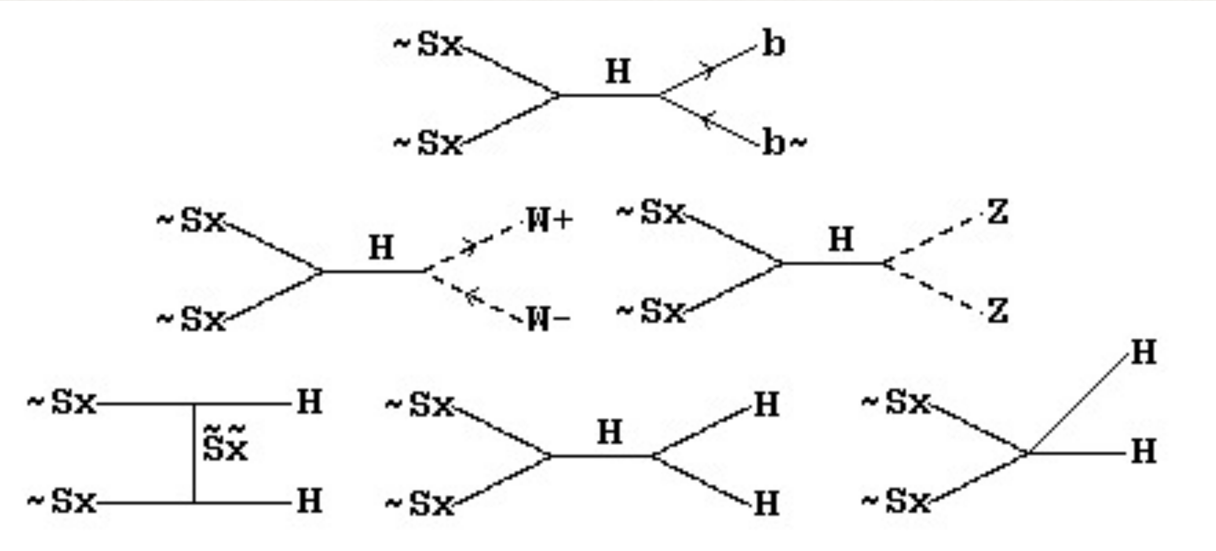
one could use numerical tools, *micromegas, madDM, SARAH..*
here, analytical expressions

Example of DM calculation

A step-by-step guide
relic abundance calculation

1. Introduce the model in Feynrules and output in CompHep format

2. In CompHep, compute scattering amplitudes



and output to Mathematica

3. In Mathematica, simplify expression and expand

$$\lim_{v \ll c} \sigma_{ann} v = \underbrace{a}_{\text{s-wave}} + \underbrace{b v^2}_{\text{p-wave}} + \ldots$$

thermal average is simply

$$\langle \sigma_{ann} v \rangle = a + 3b/x_F$$

4. Compute the relic abundance

e.g. for s-wave (unsuppressed)

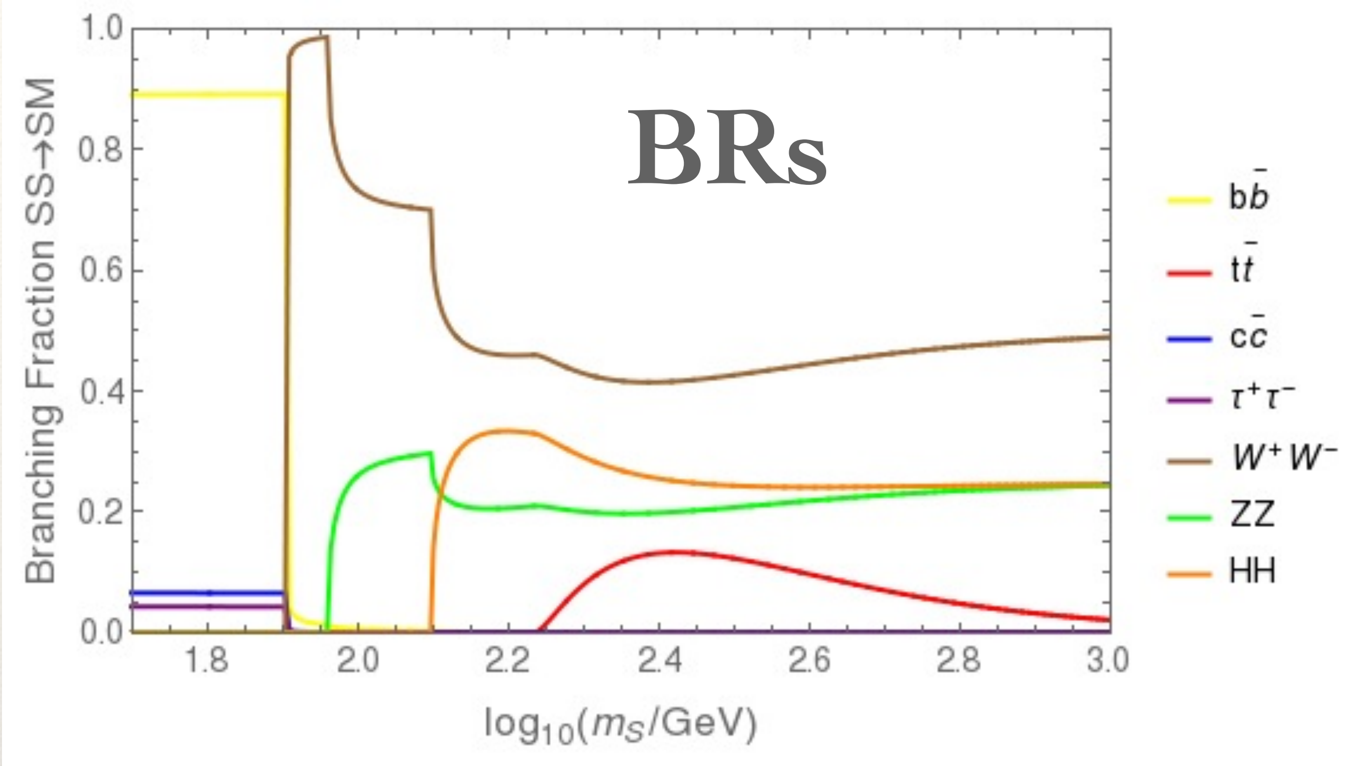
$$\Omega_{DM} h^2 = 1.69 \times \frac{x_f}{20} \sqrt{\frac{100}{g_*}} \left(\frac{10^{-10}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle_0} \right)$$

compare with Planck

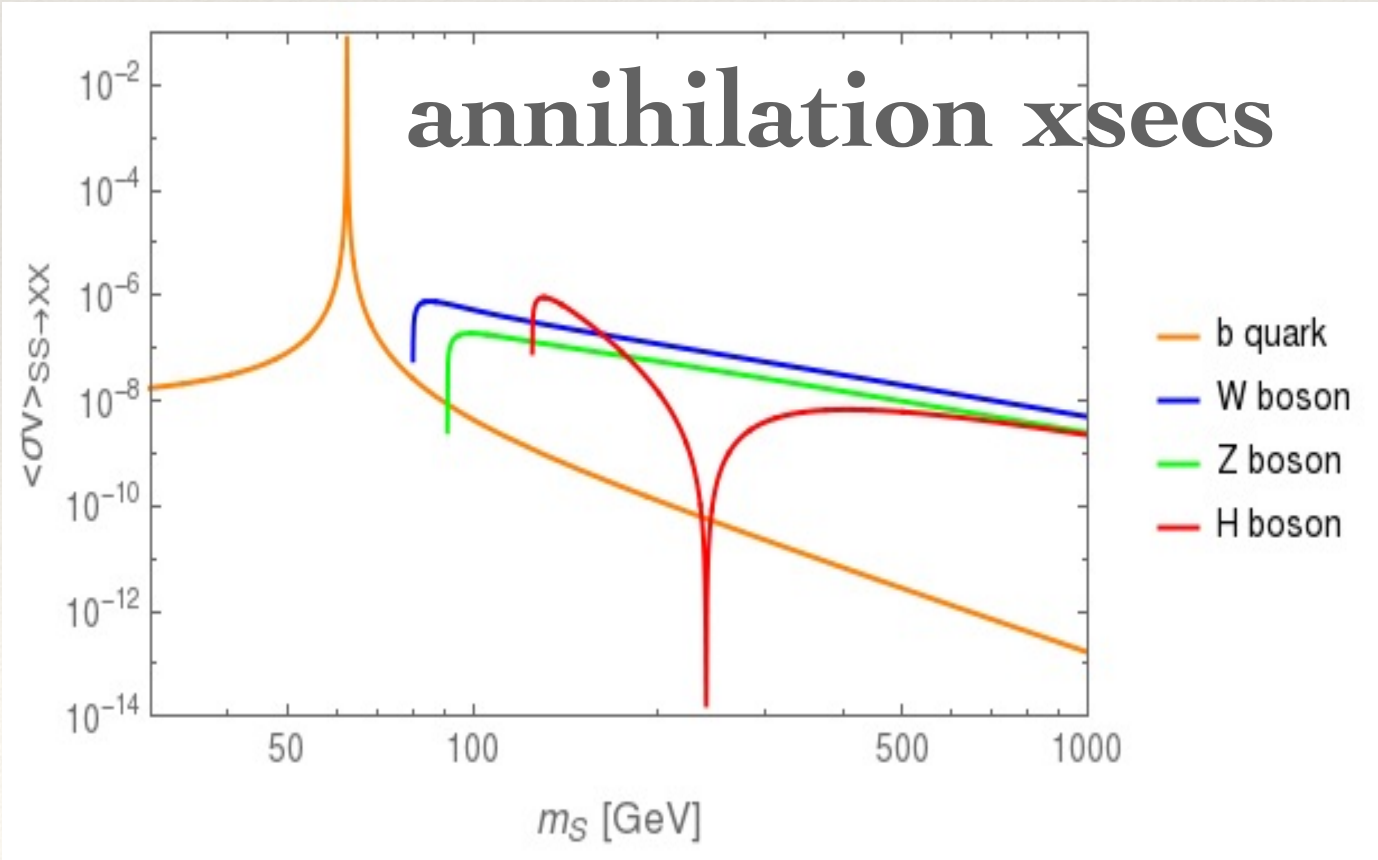
$$\Omega_{DM} h^2 = 0.1188 \pm 0.0010$$

Example of DM calculation

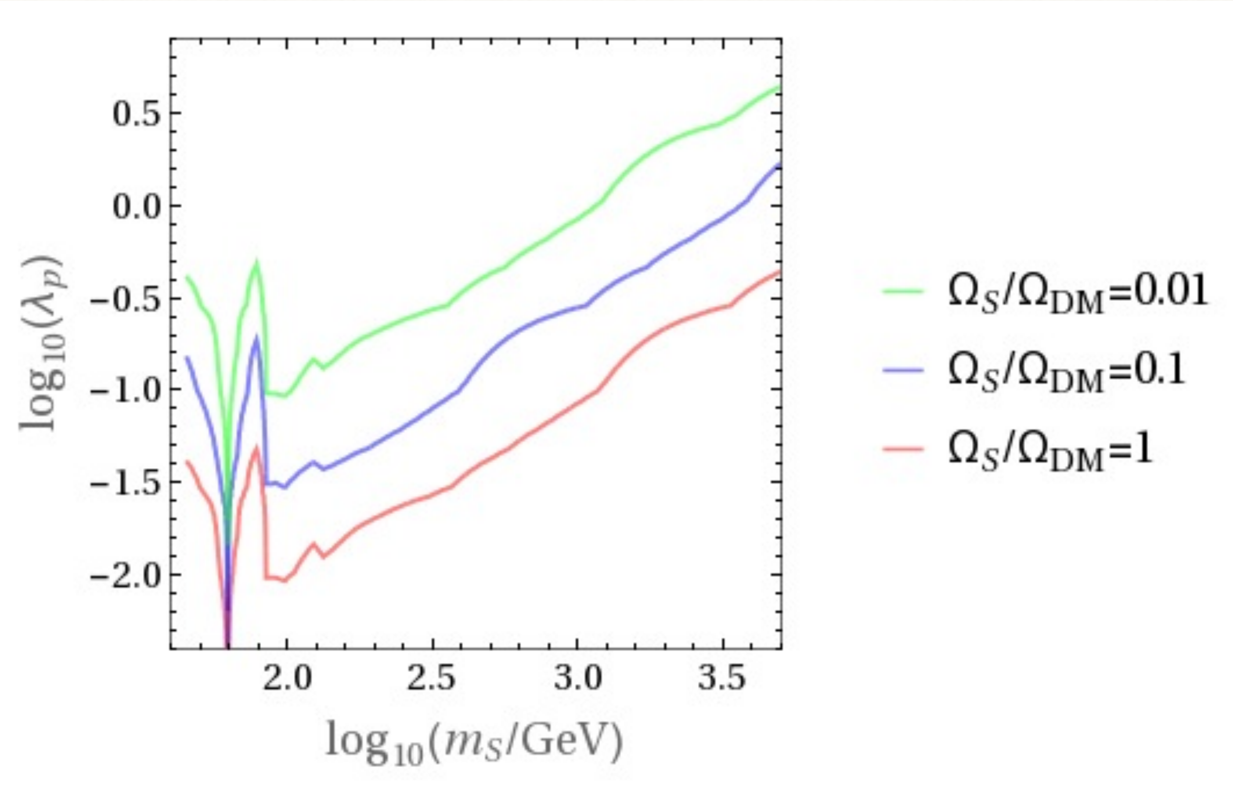
BRs



annihilation xsecs



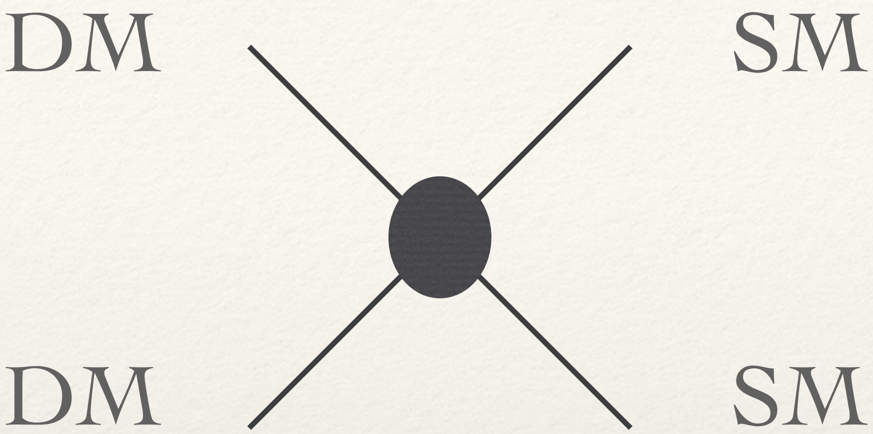
Planck constraints



Example of DM calculation

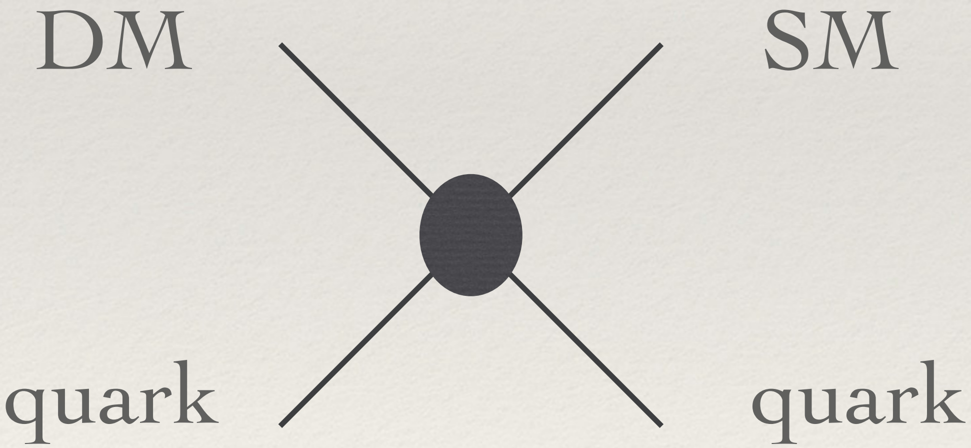
similar calculation for **direct and indirect detection**

relic abundance



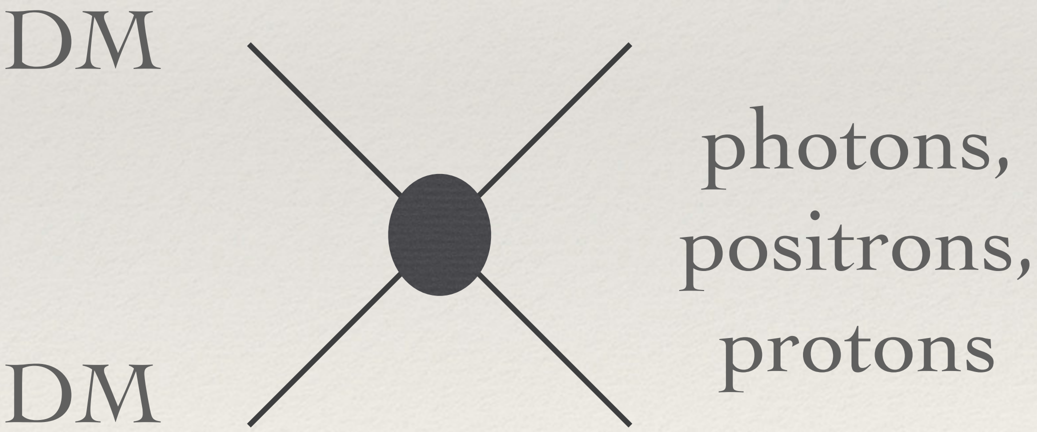
@freeze-out

direct detection



today, local DM density

indirect detection



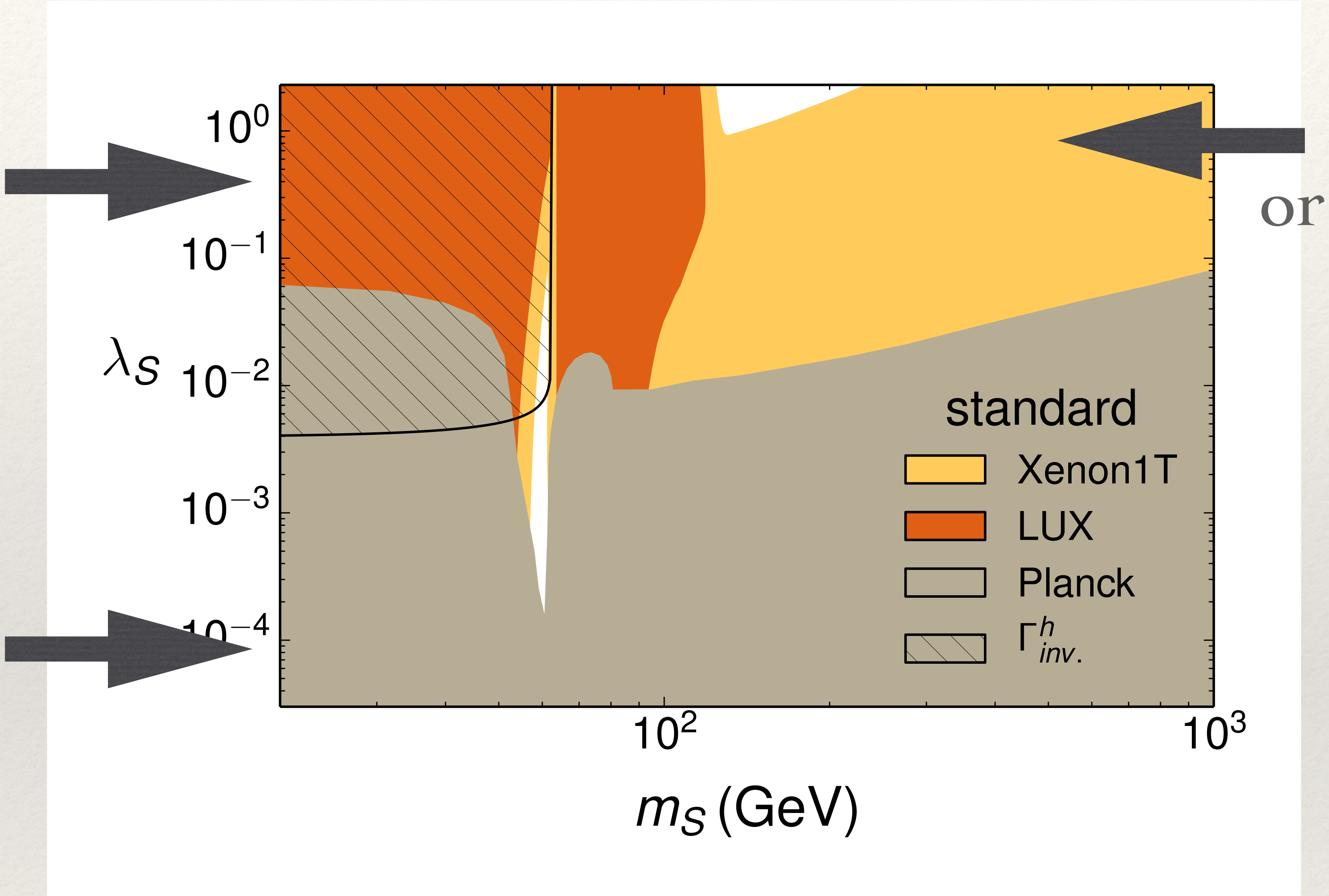
today, DM density at source
CMB tilt

Example of DM calculation

Summary for Higgs portal

constrained by DD, relic abundance and Higgs invisible width

EXCLUDED
by DD



will be
EXCLUDED
or discovered soon

EXCLUDED
by Planck

whereas indirect detection not relevant,
only secondary photons from b's and W's

Challenges

1. Theory biases

Is the EFT framework really *model-independent?*
Not completely
e.g. In non-linear realisations of EWSB
the Higgs could be a **SINGLET**
as opposed to the doublet case

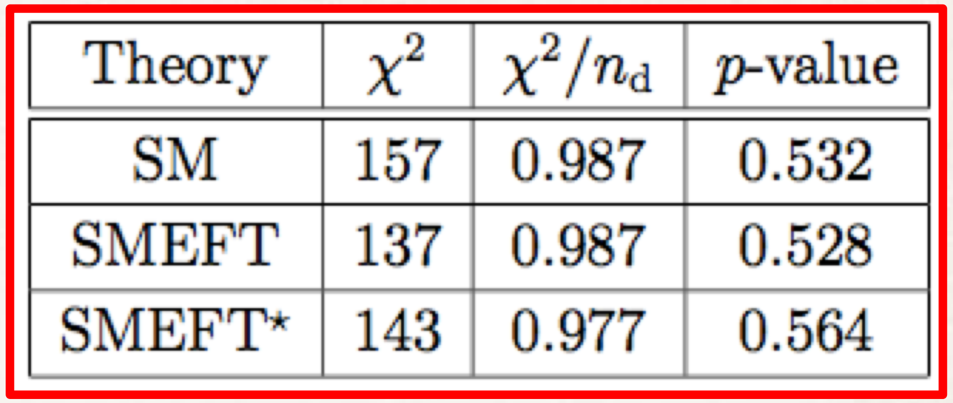
Higgs = (vev + higgs particle + W/Z dofs)

CONSEQUENCES
*de-correlation of Higgs and VV
*EFT expansion changes

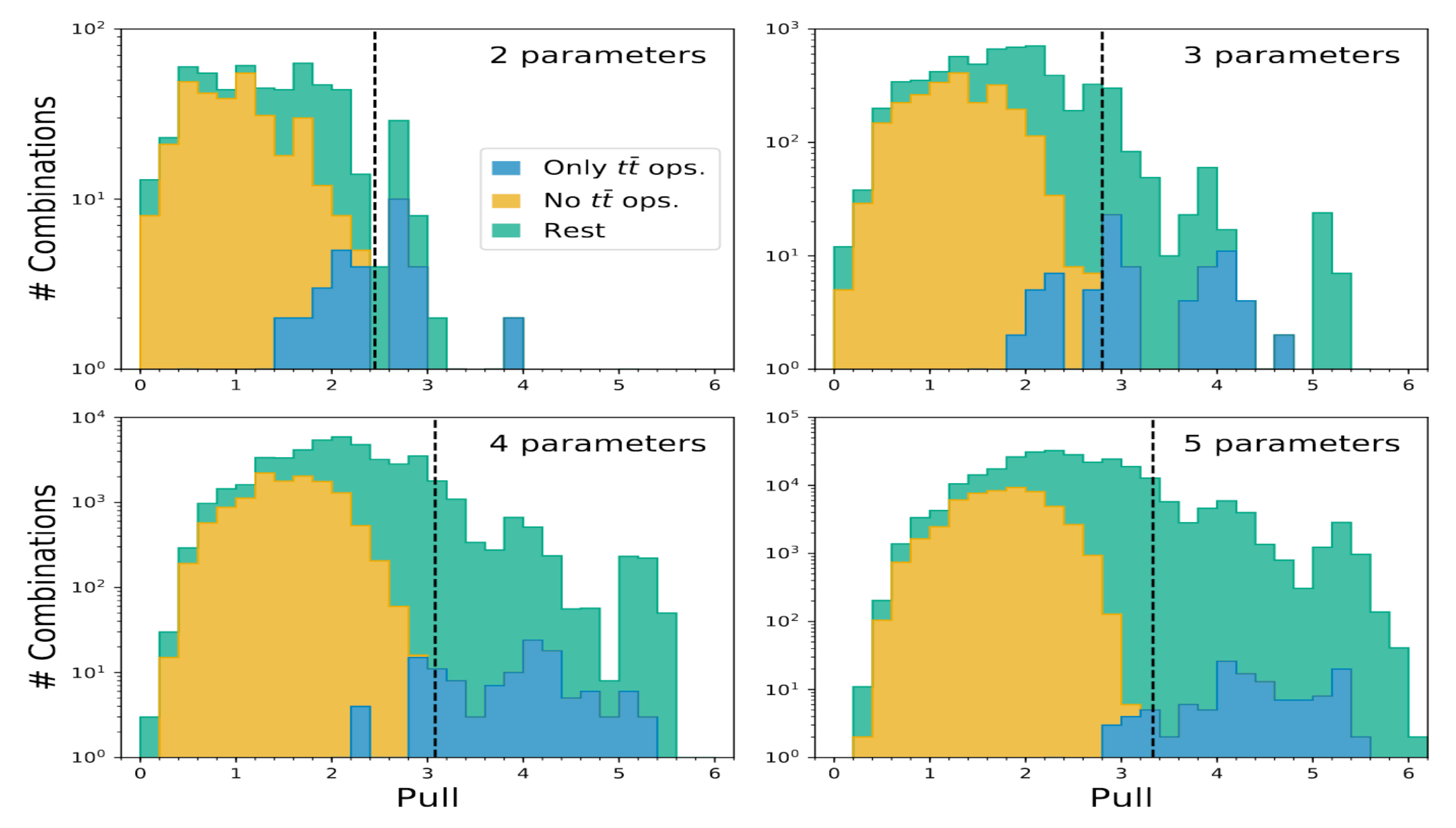
EFT provides a *large enough* set of deformations from the SM serves the purpose of guiding searches and interpretation in terms of UV models

2. Parameter complexity

BUT EFT's extra parameters constrained by current measurements
Data can't favour SM yet

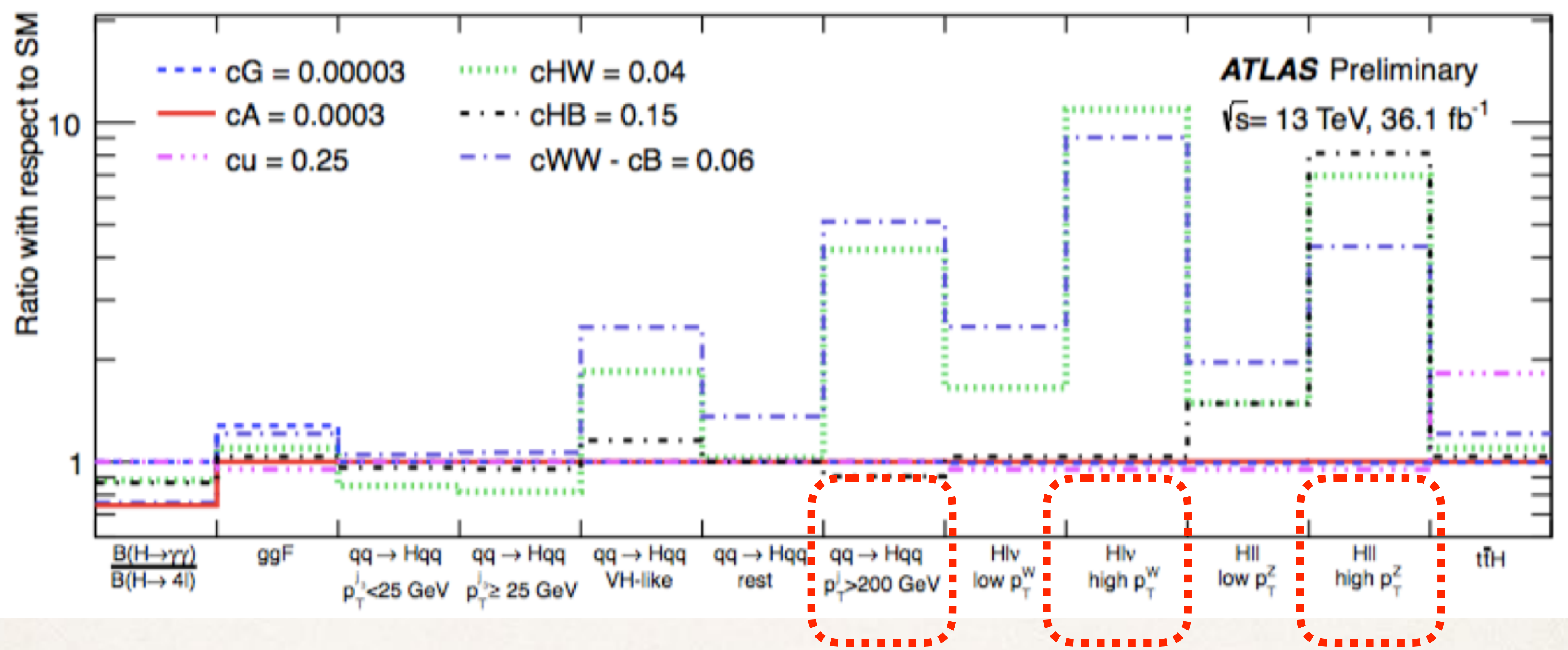


Theory	χ^2	χ^2/n_{d}	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564



Combination of many channels is key—> GLOBAL FITS

3. *Extreme* kinematics



In these regions our theoretical/experimental understanding is weaker

e.g. WW at high-pT (large EW corrections)

e.g. Higgs+jet at high-pTH

and the **EFT validity** needs to be taken into account

This problem can be addressed by working harder

Many of us developing MC tools EFT@NLO and dim-8 effects

EFT approach

THEORY

Model-independent parametrization deformations respect to the SM

Well-defined theory
can be improved order by order in momentum expansion
consistent addition of higher-order QCD and EW corrections

Connection to models is straightforward

EXPERIMENT

Beyond kappa-formalism: Allows for a richer and generic set of kinematic features

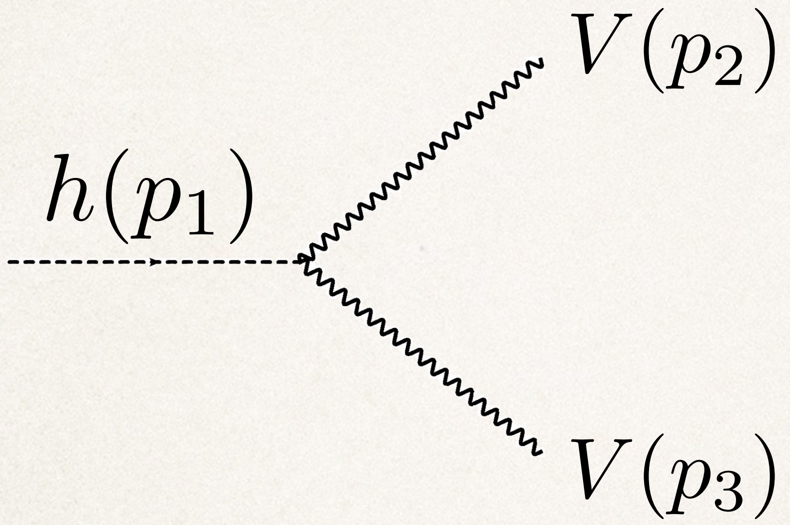
Higher-order precision in QCD/EW

Can treat EFT effects on backgrounds and signal consistently

The way to combine all Higgs channels and EW production

EFT and differential information

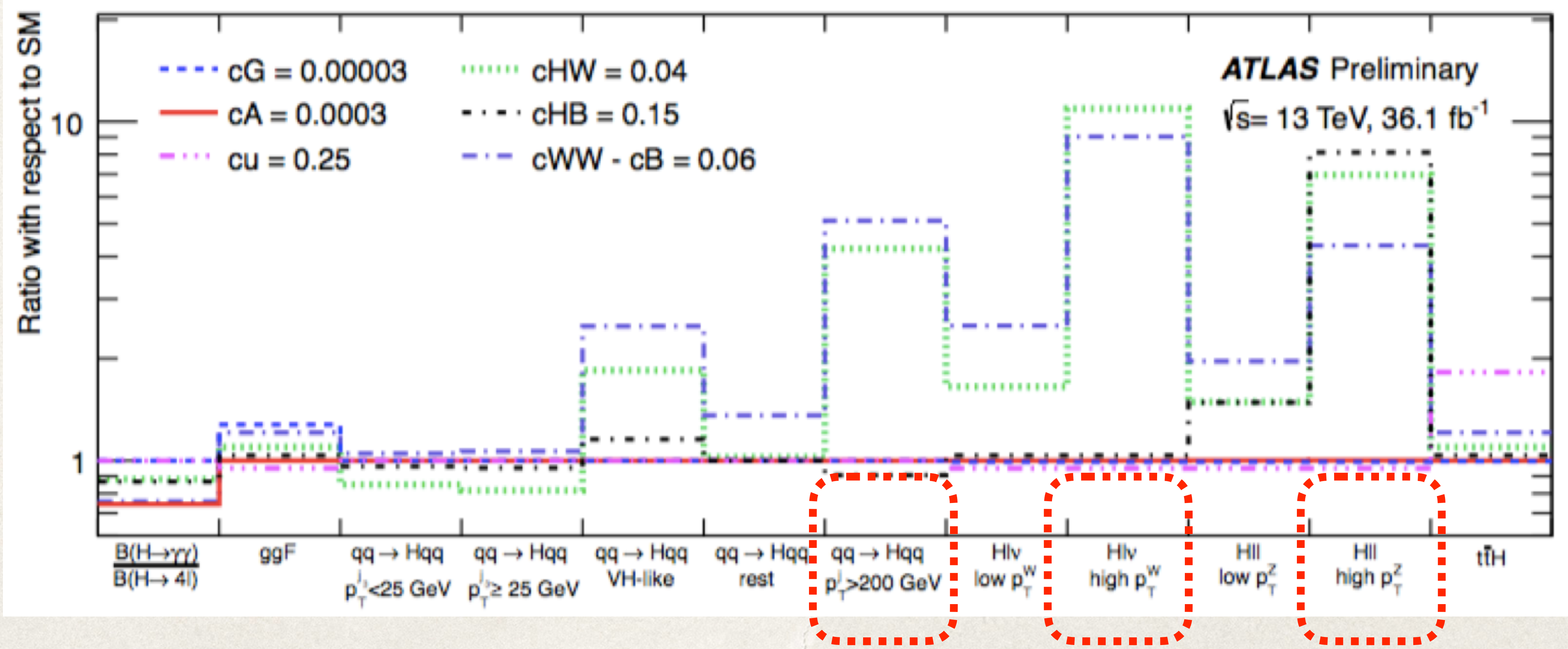
$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_\nu \partial_\mu V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$



$$i\eta_{\mu\nu}\left(g^{(1)}_{hVV}\left(\frac{\hat{s}}{2}-m_V^2\right)+2g^{(2)}_{hVV}m_V^2\right)$$

$$-ig^{(1)}_{hVV}p_3^\mu p_2^\nu \quad -i\tilde{g}_{hVV}\epsilon^{\mu\nu\alpha\beta}p_{2,\alpha}p_{3,\beta}$$

+ *off-shell pieces*



Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

$$\bar c_H = -\left[-4\tilde\lambda_3\tilde\lambda_4 + \tilde\lambda_4^2 + \tilde\lambda_5^2 - 4\tilde\lambda_3^2\right]\frac{v^2}{192\,\pi^2\,\tilde\mu_2^2}$$

$$\bar c_6 = -\left(\tilde\lambda_4^2 + \tilde\lambda_5^2\right)\frac{v^2}{192\,\pi^2\,\tilde\mu_2^2}$$

$$\bar c_T = (\tilde\lambda_4^2 - \tilde\lambda_5^2)\,\frac{v^2}{192\,\pi^2\,\tilde\mu_2^2}$$

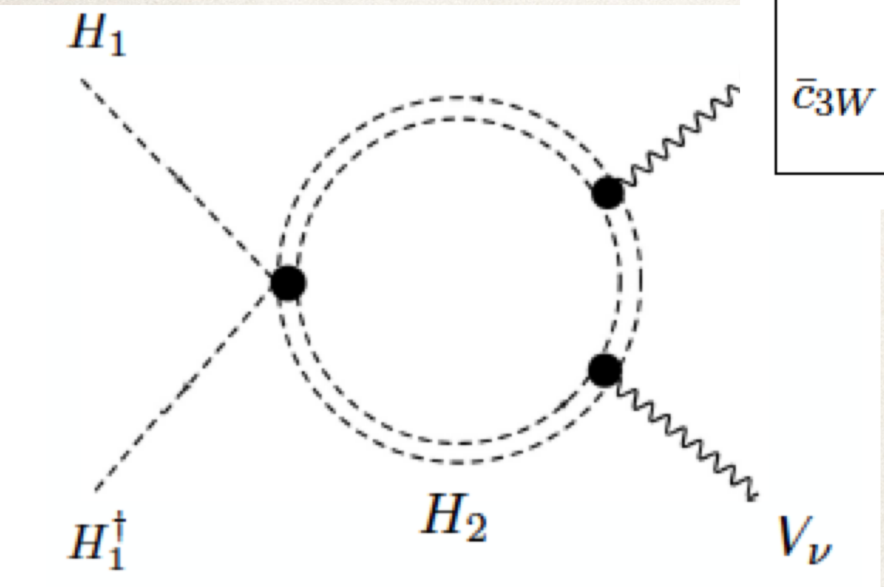
$$\bar c_\gamma = \frac{m_W^2\,\tilde\lambda_3}{256\,\pi^2\,\tilde\mu_2^2}$$

$$\bar c_W = -\bar c_{HW} = \frac{m_W^2\,(2\,\tilde\lambda_3 + \tilde\lambda_4)}{192\,\pi^2\,\tilde\mu_2^2} = \frac{8}{3}\,\bar c_\gamma + \frac{m_W^2\,\tilde\lambda_4}{192\,\pi^2\,\tilde\mu_2^2}$$

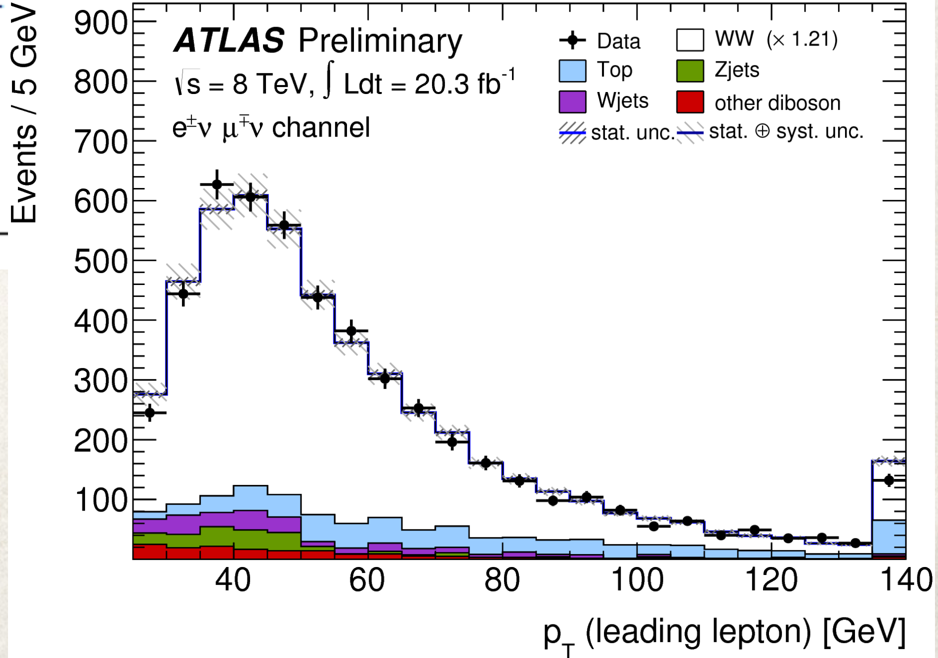
$$\bar c_B = -\bar c_{HB} = \frac{m_W^2\,(-2\,\tilde\lambda_3 + \tilde\lambda_4)}{192\,\pi^2\,\tilde\mu_2^2} = -\frac{8}{3}\,\bar c_\gamma + \; m_W^2\,\tilde\lambda_4$$

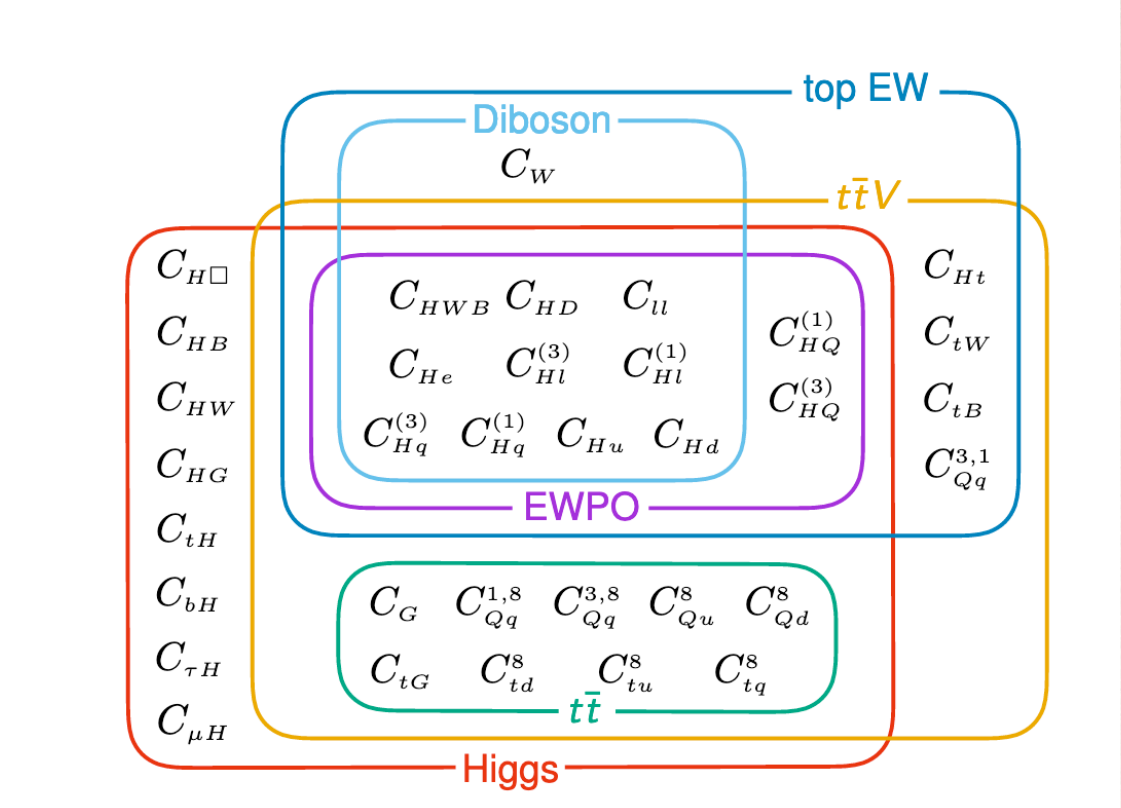
$$\bar c_{3W} = \frac{\bar c_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde\mu_2^2}$$

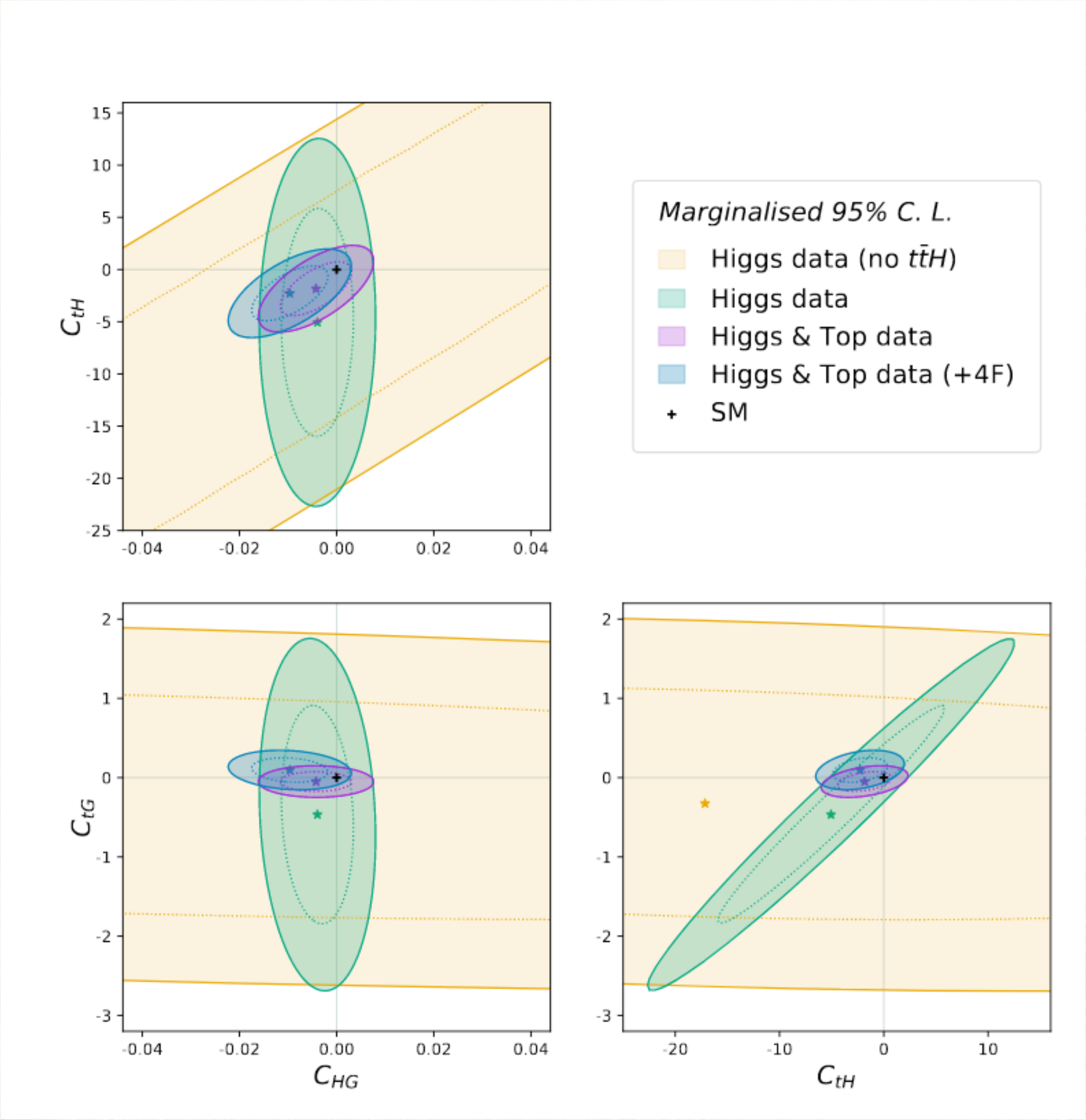
MODELS



DATA







Ellis, Madigan, Mimasu, VS, You
2012.02779, JHEP

A truly global EFT analysis is possible with Run2 data (+LEP)

We performed the most complete global fit with Higgs+Diboson+Top+4F data (341 observables) against 20 (MFV)/34 (top-specific) operators

This is an example of the interplay between Higgs (green) and Higgs+Top (pink) information

These *combinations*
and *public* frameworks to do fits
(like our ***Fitmaker***)
are going to become state-of-the-art