The Future of Particle Physics---A Theorist's Perspective

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14 September 2019

Has the idea of naturalness run its course?

run *its* course

to develop and finish naturally:

The doctor's advice is to let the fever run its course.

I had to accept that the relationship had run its course.

– Thesaurus: synonyms and related words

Based on an image from the BackReaction Blog of [Sabine Hossenfelder]

1939: Scalar fields portend an energy scale associated with new phenomena that are close at hand.

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On the Self-Energy and the Electromagnetic Field of the Electron

V. F. WEISSKOPF
University of Rochester, Rochester, New York

(Received April 12, 1939)

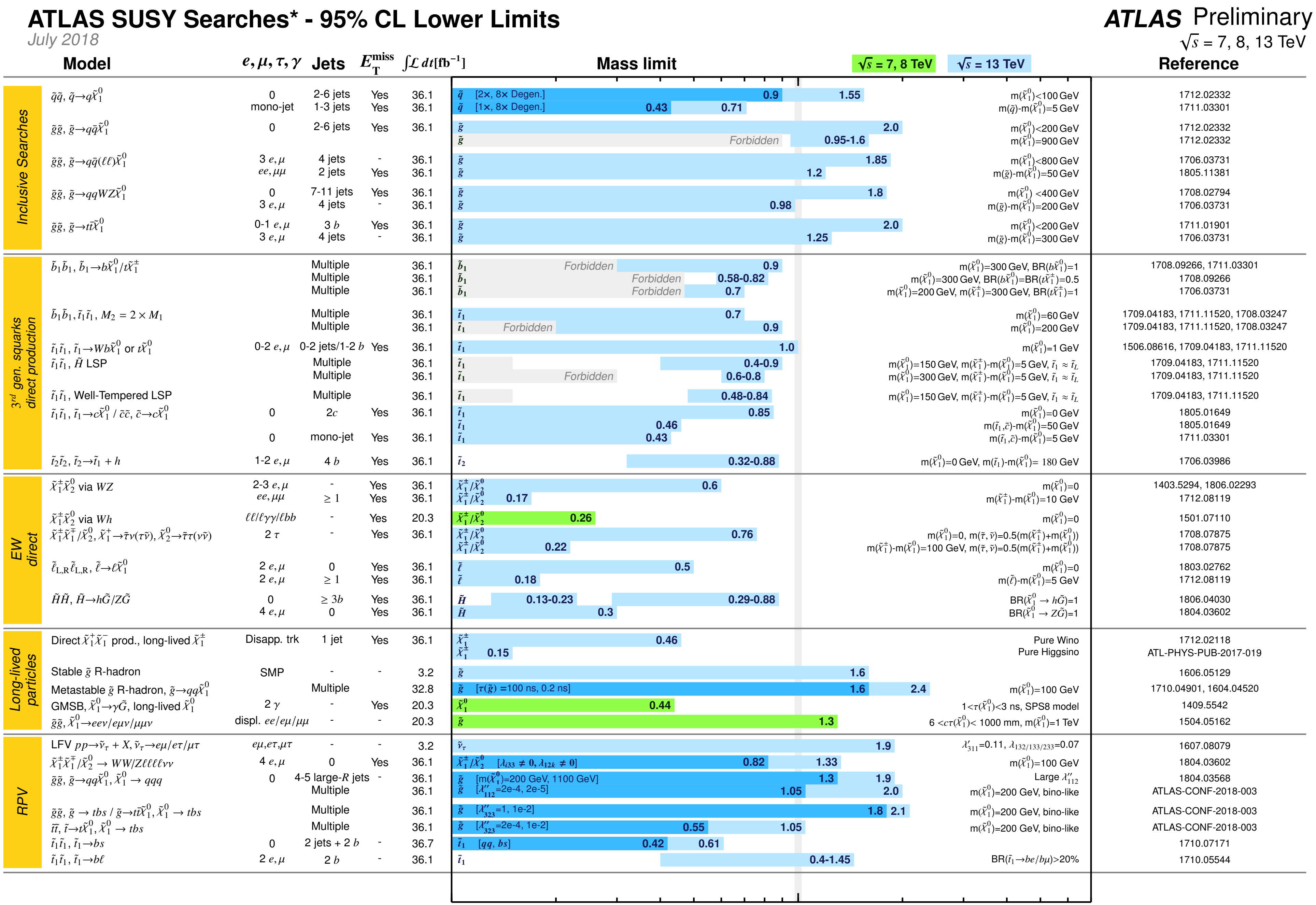
The charge distribution, the electromagnetic field and the self-energy of an electron are investigated. It is found that, as a result of Dirac's positron theory, the charge and the magnetic dipole of the electron are extended over a finite region; the contributions of the spin and of the fluctuations of the radiation field to the self-energy are analyzed, and the reasons that the self-energy is only logarithmically infinite in positron theory are given. It is proved that the latter result holds to every approximation in an expansion of the self-energy in powers of e^2/hc. The self-energy of charged particles obeying Bose statistics is found to be quadratically divergent. Some evidence is given that the "critical length" of positron theory is as small as $h/(mc)\cdot\exp(-hc/e^2)$.

The situation is, however, entirely different for a particle with Bose statistics. Even the Coulombian part of the self-energy diverges to a first approximation as $W_{st} \sim e^2 h/(mca^2)$ and requires a much larger critical length that is $a = (hc/e^2)^{-\frac{1}{2}} \cdot h/(mc)$, to keep it of the order of magnitude of mc^2. This may indicate that a theory of particles obeying Bose statistics must involve new features at this critical length, or at energies corresponding to this length; whereas a theory of particles obeying the exclusion principle is probably consistent down to much smaller lengths or up to much higher energies.

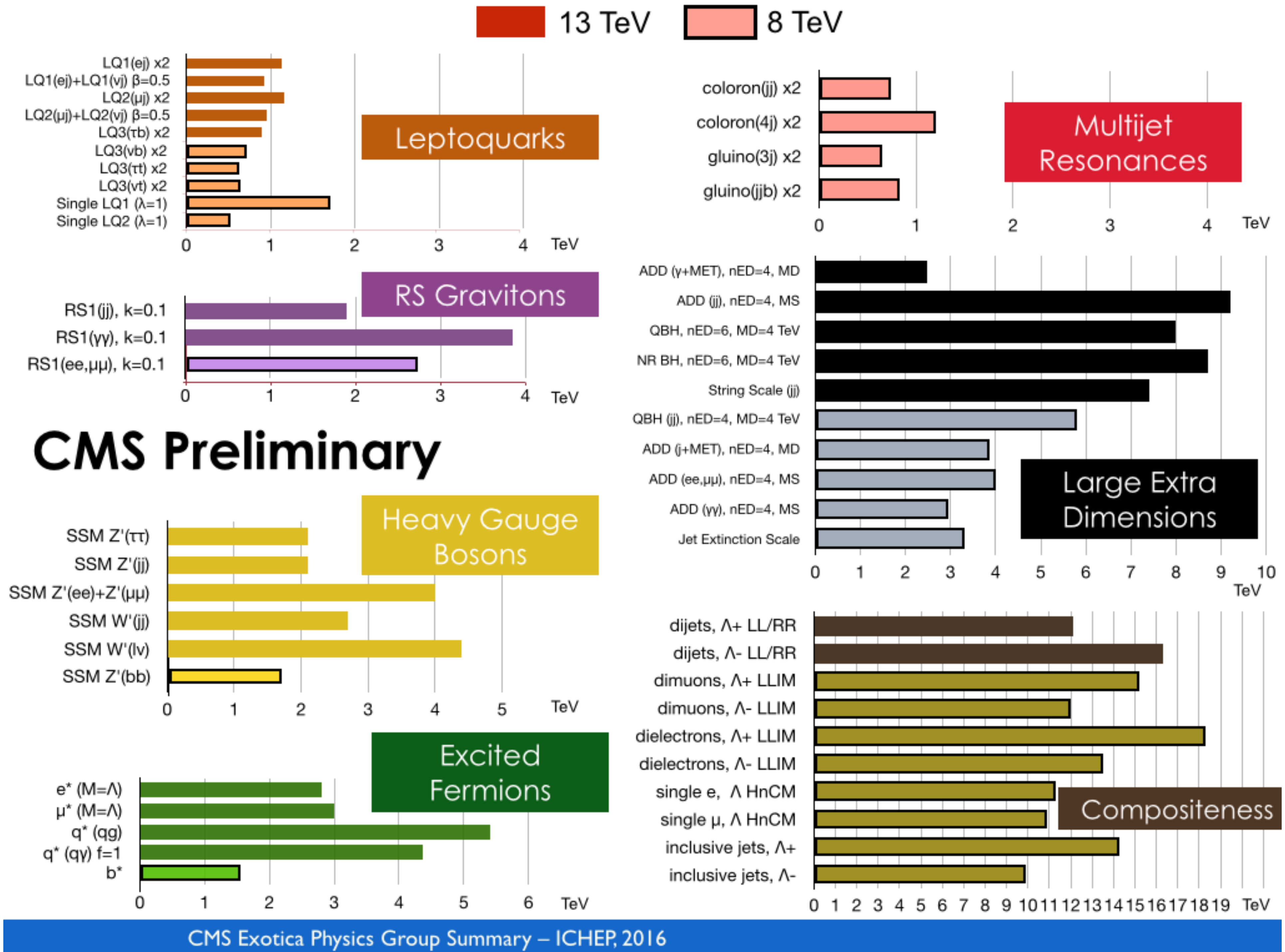
Weisskopf’s arguments imply that there should be new physics at the scale of $m_H/g \sim 1$ TeV. But where is the new TeV-scale physics?

ATLAS SUSY Searches* - 95% CL Lower Limits

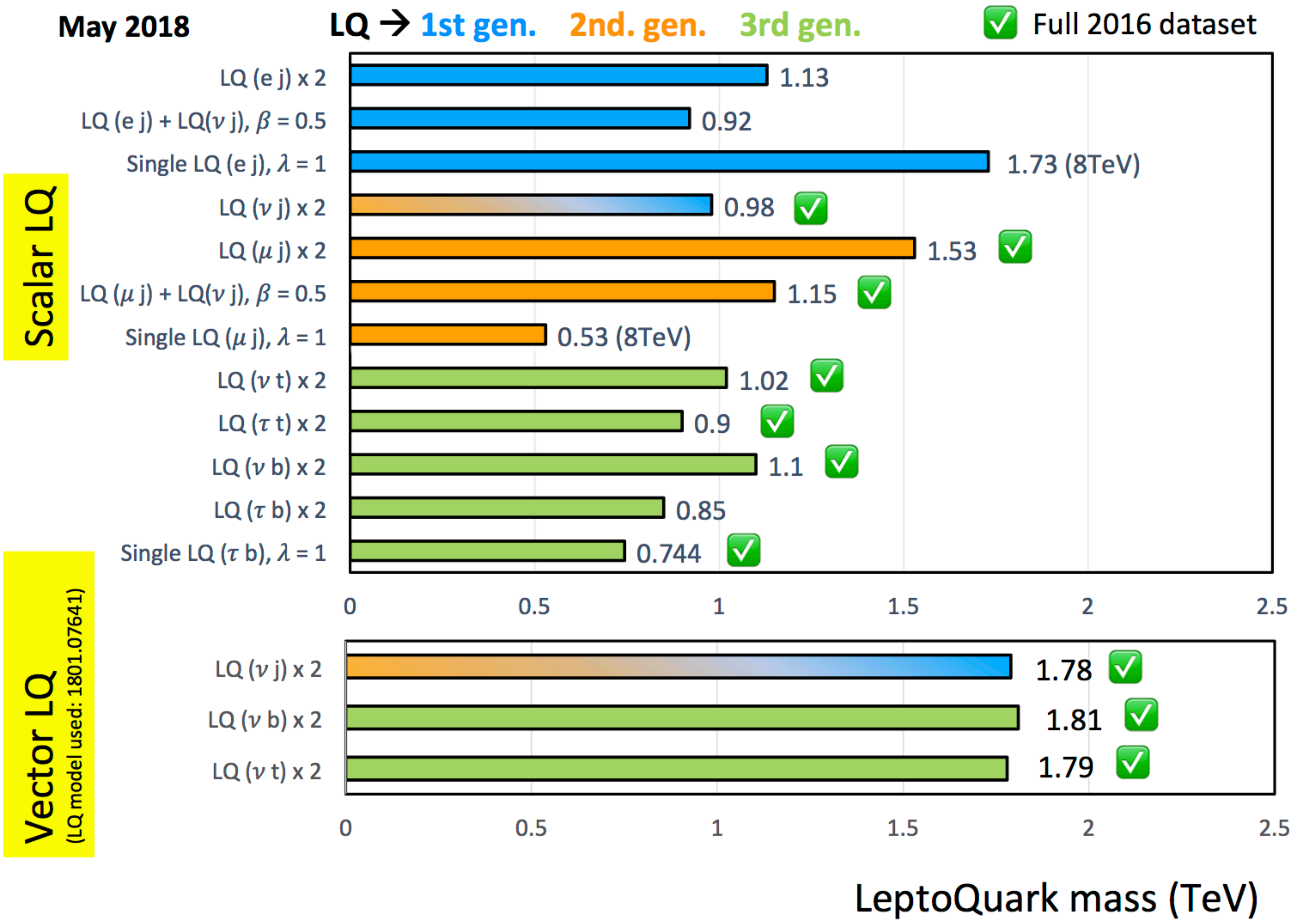
July 2018



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



13 TeV
8 TeV
Leptoquarks
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)
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
0 1 2 3 4 TeV
CMS Preliminary
Large Extra Dimensions
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
0 1 2 3 4 5 6 7 8 9 10 TeV
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
0 1 2 3 4 5 TeV
Compositeness
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-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
0 1 2 3 4 5 6 TeV
CMS Exotica Physics Group Summary – ICHEP, 2016



May 2018
LQ → 1st gen. 2nd. gen. 3rd gen.
Full 2016 dataset
Scalar LQ
LQ (e j) x 2
1.13
LQ (e j) + LQ(ν j), β = 0.5
0.92
Single LQ (e j), λ = 1
1.73 (8TeV)
LQ (ν j) x 2
0.98
LQ (μ j) x 2
1.53
LQ (μ j) + LQ(ν j), β = 0.5
1.15
Single LQ (μ j), λ = 1
0.53 (8TeV)
LQ (ν t) x 2
1.02
LQ (τ t) x 2
0.9
LQ (ν b) x 2
1.1
LQ (τ b) x 2
0.85
Single LQ (τ b), λ = 1
0.744
0
0.5
1
1.5
2
2.5
Vector LQ
(LQ model used: 1801.07641)
LQ (ν j) x 2
1.78
LQ (ν b) x 2
1.81
LQ (ν t) x 2
1.79
0
0.5
1
1.5
2
2.5
LeptoQuark mass (TeV)

At what point do you lose interest in extending the new physics searches?

- Keep in mind that after Run 2, you will only have collected 5% of the total luminosity expected during the LHC lifetime.

- If you discover new physics consistent with explanations of the gauge hierarchy problem (why is $m_W/M_{PL} \sim 10^{-17}$?), the little hierarchy problem becomes much less pressing.

Final thoughts on naturalness

- The announcement of the death of naturalness may be premature.
- There is still room for theoretical innovations.
- However, in evaluating new approaches to naturalness, it is important to consider how one could test these ideas experimentally (i.e. what observable phenomenon would convince you that Nature has employed a natural theory for the dynamics of electroweak symmetry breaking?).

The current status of particle physics

- With the discovery of the Higgs boson, we have entered a new era of particle physics

  - There is no longer a no-lose theorem to guarantee future discoveries
  - We are in a data-driven era—i.e., we depend on new data to guide future directions in BSM physics
  - The principle of naturalness, although not dead, is under tension.
  - So how do we motivate the next generation of colliders?

Do we really know the particle content of the TeV-scale effective theory?

- The scalar sector of the SM has a single Higgs boson. Why not multiple families of Higgs scalars?
- What about vector-like quarks and leptons?
- Flavor anomalies have revived interest in leptoquarks.
- Are there new gauge bosons lurking in the region of 1—10 TeV?
- Dark matter may be the tip of the iceberg. The structure of the dark sector could be highly non-minimal. Future colliders may provide opportunities to access the dark sector (e.g., via the Higgs portal).

So, where do we go from here?

- Explore the Higgs sector as thoroughly as possible (since, you have never seen anything like it before).
    - Experimental studies at present and future colliders
    - Implications for early universe cosmology

- Precision, precision, precision.

- Exploit the LHC to its maximum. Search for BSM physics in regions with significant SM backgrounds.

- Provide a roadmap for future energy-frontier facilities.

ilc

FCC
hh ee he

clic

MUON COLLIDER

CEPC

The 5 P’s (thanks to Marie-Helene Genest)

<table>
<tr><th></th><th>ILC (250)</th><th>CLICino</th><th>FCC-ee</th><th>CEPC</th><th>FCC-hh</th><th>SppC</th></tr>
<tr><td rowspan="3">Physics case</td><td colspan="4">Precision exploration of Higgs
Can probe BSM indirectly -> point to a scale?</td><td colspan="2" rowspan="3">Triple-Higgs coupling at 5%...
Possible direct access to BSM
No no-lose theorem, but broader exploration</td></tr>
<tr><td></td><td colspan="3">Top threshold</td></tr>
<tr><td colspan="2"></td><td colspan="2">Beam E measurement -> better precision Z program</td></tr>
<tr><td rowspan="2">Progress needed</td><td rowspan="2">shovel ready ?</td><td rowspan="2">Design report coming soon?</td><td>No CDR yet</td><td>No TDR yet</td><td colspan="2">Magnet development needed</td></tr>
<tr><td colspan="2">detector needs > ILC</td><td>HE-LHC as a first step?</td><td></td></tr>
<tr><td>Price</td><td>40% cost reduction => descoped 1st energy goal</td><td>~FCC-ee</td><td>Tunnel = cost of HE-LHC</td><td>Smaller need of international funding?</td><td colspan="2">x 2-3 FCC-ee/CEPC [1]?</td></tr>
<tr><td rowspan="2">Politics</td><td>Needs Japanese ok as soon as possible</td><td colspan="2">CERN: existing center / maintain</td><td>Multiple international centers</td><td></td><td></td></tr>
<tr><td colspan="4">e^+e^- easier to ‘sell’ ? / stepping stone while waiting for magnet development?</td><td colspan="2"></td></tr>
<tr><td>Possibilities for the future</td><td>Increase to 500 GeV; or new acceleration techniques?</td><td>-> 1.5 TeV
-> 3 TeV</td><td colspan="2">Stepping stone for future hadronic collider</td><td colspan="2">Far future...</td></tr>
</table>

[1] https://arxiv.org/abs/1509.08369 by the director of APC Fermilab