New ideas for TeV-scale model building

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### Standard Model Total Production Cross Section Measurements

**Status:** March 2021

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<th>Process</th>
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**σ [pb]**

- 10^{-8} to 10^{11}

**Reference**

- ATLAS Preliminary
- LHC pp $\sqrt{s} = 13$ TeV
- Data stat @ syst
- 0.081
- EPJC 79 (2019) 760
- 4.6
- EPJC 77 (2017) 367
- JHEP 02 (2017) 117
- 20.2
- JHEP 02 (2017) 117
- 4.6
- JHEP 02 (2017) 117
- 36.1
- EPJC 80 (2020) 528
- 20.2
- EPJC 74 (2014) 3109
- 4.6
- EPJC 74 (2014) 3109
- 5.0 × 10^{-9}
- 0.081
- EPJC 79 (2019) 760
- 20.2
- EPJC 77 (2017) 367
- 3.2
- JHEP 02 (2017) 117
- 20.2
- JHEP 02 (2017) 117
- 4.6
- JHEP 02 (2017) 117
- 36.1
- EPJC 79 (2019) 884
- 20.3
- EPJC 75 (2016) 78
- 4.6
- EPJC 73 (2014) 3109
- 139
- ATLAS-CONF-2019-032
- 20.3
- EPJC 75 (2016) 78
- 4.5
- EPJC 75 (2016) 78
- 3.2
- JHEP 01 (2018) 63
- 20.3
- JHEP 01 (2016) 64
- 2.0
- PLB 716, 142-159 (2012)
- 36.1
- EPJC 79 (2019) 535
- 20.3
- PRD 93, 092004 (2016)
- 4.6
- EPJC 72 (2012) 2173
- 36.1
- PRD 97 (2018) 032005
- 20.3
- JHEP 01, 098 (2017)
- 4.6
- JHEP 93, 128 (2013)
- 20.3
- PLB 735 (2014) 311
- 20.3
- PLB 756, 229-246 (2016)
- 36.1
- PRD 99, 072009 (2019)
- 20.3
- 36.1
- PRD 99, 072009 (2019)
- 20.3
- 79.8
- PLB 798 (2019) 134913
- 36.1
- PLB 798 (2019) 134913
- 79.8
- PLB 798 (2019) 134913
- 139
- EPJC 80 (2020) 1085
Testing the Standard Model

The LHC tests the Standard Model to a very high precision, many of these measurements have percent precision and some even permille [error of 19 MeV on the W mass].
Those are impressive achievements a single theory, developed long time ago based on rather simple building blocks can predict Nature’s behaviour in a huge range of energies with unparalleled precision in many kinematic situations involving numerous different particles

So why aren’t we just happy?
Because that can’t be it

DARK UNIVERSE

LIGHT QUANTUM SCALAR

CPV@QCD axions

FERMION HIERARCHIES

MATTER/ANTIMATTER

QUANTUM GRAVITY

Why now?

Why three?
Because that can’t be it

THERE ARE MANY MYSTERIES TO SOLVE
MANY DISCOVERIES TO BE MADE
the LHC’s future is ensured through HL
exploit its potential for discovery
GAME ISN’T OVER
So here we are finding our path through SYMMETRIES & DYNAMICS aiming for a UNIFIED FRAMEWORK
Discoveries = Resonances?
And resonances have been searched for, indeed!
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PROMPT, DISPLACED, DISAPPEARING...

+ excellent agreement in SM observables

no stone unturned
Angst, anyone?

War absolutely sucks but good example of group’s ability for mobilising people and resources driven by a big idea (preservation).

Thanks to the LHC, we have witnessed a large-scale mobilisation of talent behind the idea of understanding Nature a selfless, intellectual drive.

It is a remarkable success and its continuation requires re-focusing as we learn more about Nature.

Scenarios for new physics at the TeV-scale are evolving.
Then what?
Connecting ideas with experiments
A cosmological Higgs

- Dark Matter
  - Higgs portal
  - Higgs DM mediator

- Inflation
  - Higgs inflation
  - Inflaton vs Higgs

- Phase transitions
  - Baryogenesis
  - Gravitational waves

- Fate of the Universe
  - Stability

- UV sensitivity
  - Naturalness
  - Heavy new physics
  - Relaxation

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**
Many faces of Dark Matter

**THEORY**
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…

**COLLIDERS**

**DIRECT DETECTION**

**CMB: relic, tilt**

**INDIRECT DETECTION**

**SIMULATIONS**
New opportunities at the LHC
Run3 and beyond

The LHC is a hadron machine, a **discovery** machine, yet it had to re-invent itself to become a **precision** machine.

**Precision LHC-> new opportunity**

Traditional resonant searches have been so far unfruitful.

On the other hand, more statistics and better understanding of the experiment allows diving into extreme kinematic regions.

Let’s embrace this state-of-affairs to perform different searches for new phenomena, beyond resonances.
Change in paradigm: 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
EFT is the new black

I assume you roughly know what is SMEFT and also know this is a word increasingly present in LHC analyses.

There are good theoretical reasons to adopt (NOW) an EFT interpretation of the LHC data:
no light NP, nice/tractable framework…

And experiments, after lots of tensioning and some reticence, are also adopting it as a default option to re-interpret SM measurements.
Current SMEFT constraints reach the TeV for most of the parameter space. When translated into vanilla extensions of the SM, the mass limits are also probing the TeV scale.

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Lots of work needed to advance this area: higher-order calculations, optimisation of strategies, better experimental understanding of correlations...
Many scenarios beyond EFT

Many scenarios for new physics do not predict resonances at LHC but could be discovered in this machine using its non-resonant behaviour.
The light case: pseudo-Goldstone

What if your new sector was very light?
Imagine, for example, you are looking for a particle which decays into photons with mass $\ll$ GeV

Resonant searches would be impossible
Triggers remove very soft stuff
indistinguishable from QCD backgrounds

This particle can’t be searched for a high-energy collider like the LHC

BUT

what if your new particle was a pseudo-Goldstone boson?
its couplings to SM particle would grow with energy
we may not see the particle as a resonance but feel its effect in high-energy tails
The light case: pseudo-Goldstone

Gavela, No, VS, Troconiz. 1905.12953, PRL

A lot more to explore for LHC probes of TeV-scale pGB: more channels, controlling high-pT, combination, interplay with other probes (low-E, GWs...)
The broad case

Non-resonant phenomena: close-by resonances overlap and form a quasi-continuum
How weird is this? what is the theoretical interpretation?

Remember that in QCD at large-Nc expect a tower of resonances
example: s=1 rho, rho’… and a whole tower until LambdaQCD
width ~ 1/Nc^2
but Nc=3 not a large number, so rho and rho’ are relatively narrow
but after that we got a continuum of the “rho-tower”
mesonic QCD in the intermediate region is non-resonant

In many scenarios for BSM physics there is a well-motivated region
of non-resonant behaviour which has been largely unexplored
(focus on low-hanging fruit)
The broad case

There are plenty of examples of BSM models which predict towers or resonances with the same quantum numbers

**EXTRA-DIMENSIONS**

**Example:** Warped Extra-Dimensions

\[ ds^2 = e^{-2k|x|y} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 dy^2 \]

Fields propagating in the xdim behave as a tower of 4D fields with the same quantum numbers but increasing mass

Kaluza-Klein tower

**Unavoidable:** KK-gravitons coupled to SM particles via the stress-tensor mass and 1/coupling \( \sim \) TeV

This tower’s resonances could be close-by and produce a continuum would **evade resonant searches**

KK-gravitons could be much lighter than typical limits ( \( >\sim \) TeV) and only discovered by analysis of tails
The broad case

AND there are plenty of other scenarios with the same rough characteristics related to Extra-Dimensions via **dualities**

Unparticles
Black-Holes w/hair
quantum critical Higgs
*a new quasi-conformal sector*

**Giudice et al.**
1711.08437, JHEP

This is a rather unexplored area
*more work needed on modelling, and reinterpretation from EFTs*
LHC quo vadis? or how do we make the best use of what is coming next? (~ E, more lumi)
Summary

LHC quo vadis? or how do we make the best use of what is coming next? (~ E, more lumi)

*Direct* searches will continue testing broader sets of models

*Indirect* searches for NP have gained a lot of traction at the LHC

but advancement requires more intense thy/exp communication
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New opportunities in the precision era for the LHC are there any blind spots in experimental searches? model-building exploration could inspire them e.g., Reece’s talk today on SUSY leftovers
the LHC can probe TeV scale new physics via non-resonant searches, they cover a wide range of models, more theoretical effort needed here