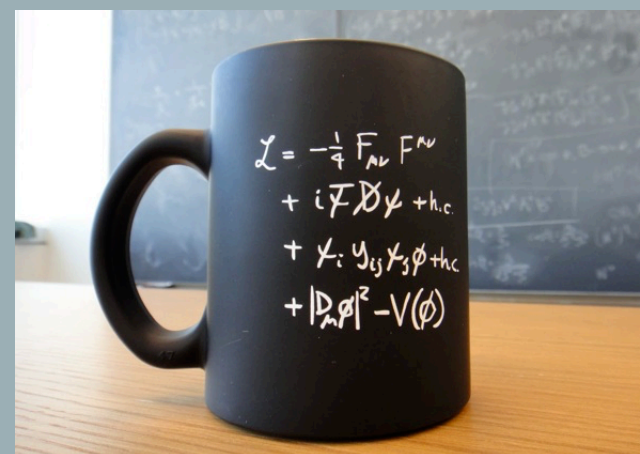


# THE SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL



S. Dawson, BNL

DIS, 2021



# PREDICTIONS.....

## Physics in 2006

S. Dawson

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**Abstract.** Any consideration of future physics facilities must be made in the context of the Tevatron and the LHC. I discuss some examples of physics results which could emerge from these machines and the resulting questions which would remain for a high energy  $e^+e^-$  collider. Particular attention is paid to the electroweak symmetry breaking sector. If a light Higgs boson exists, it will be observed at the LHC and the role of any later accelerator will be to map out the Higgs boson mass and couplings and then determine the space of possible models. If there is no light Higgs boson then some effects of a strongly interacting electroweak symmetry breaking sector will be observed at the LHC and I discuss the role of a high energy linear collider in exploring this scenario.

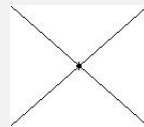
The future is unclear....

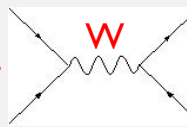
\*In 2006 I thought we were going to measure everything possible about the Higgs or observe strongly interacting WW scattering

# HISTORY: PREDICTING THE SCALE OF NEW PHYSICS

- Fermi theory becomes non-perturbative at  $E \sim 600 \text{ GeV}$

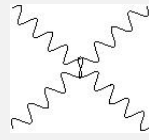
- W boson saves the day**

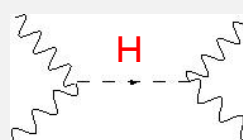


$$G_F E^2 \rightarrow G_F M_W^2$$


- WW scattering grows with energy and violates unitarity at  $E \sim 3 \text{ TeV}$

- Higgs boson  $< 800 \text{ GeV}$  restores unitarity**



$$E^2/v^2 \rightarrow O(1)$$


**NO LOSE THEOREMS**

## THE NEW PARADIGM

- **Past:** Guaranteed discoveries ensured by **no-lose theorems**
  - Beyond the Fermi theory (**the W**)
  - Beyond the bottom quark (**the top**)
  - Beyond the electroweak theory (**the Higgs**)
    - Scattering amplitudes grow with energy without W, top, Higgs....
    - Knew the scale of new physics

**Future : No guarantees, need to examine many possibilities**

Look for new physics in many places

# CURRENT LIMITS IN THE 1-10 TEV RANGE

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

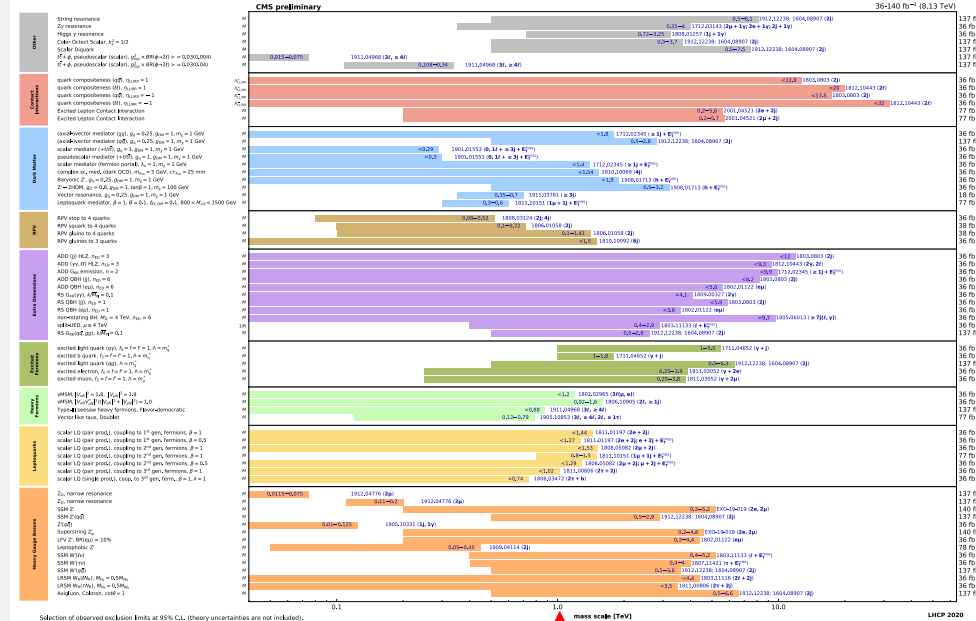
$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1} \quad \sqrt{s} = 8, 13 \text{ TeV}$$

|                                                | Model                                                            | $\ell, \gamma$                              | Jets†                     | $E_{\text{miss}}^T$         | $\int \mathcal{L} dt [\text{fb}^{-1}]$ | Limit                                                   | Reference                                                     |                                                   |
|------------------------------------------------|------------------------------------------------------------------|---------------------------------------------|---------------------------|-----------------------------|----------------------------------------|---------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------|
| Extra dimensions                               | ADD $G_{\text{UV}} + g/q$                                        | $0, e, \mu$                                 | 1-4j                      | Yes                         | 36.1                                   | $M_{\text{Pl}} = 7.7 \text{ TeV}$                       | 1711.03201                                                    |                                                   |
|                                                | ADD non-resonant $\gamma\gamma$                                  | $2\gamma$                                   | -                         | -                           | 36.7                                   | $M_{\text{Pl}} = 8.6 \text{ TeV}$                       | 1707.04147                                                    |                                                   |
|                                                | ADD QBR                                                          | $2\gamma$                                   | 2j                        | -                           | 37.0                                   | $M_{\text{Pl}} = 8.9 \text{ TeV}$                       | 1703.09127                                                    |                                                   |
|                                                | ADD BH high $\Sigma p_T$                                         | $\geq 1, e, \mu$                            | $\geq 2j$                 | -                           | 3.2                                    | $M_{\text{Pl}} = 8.2 \text{ TeV}$                       | 1606.02265                                                    |                                                   |
|                                                | ADD BH multiplet                                                 | $\geq 1, e, \mu$                            | $\geq 3j$                 | -                           | 3.6                                    | $M_{\text{Pl}} = 9.5 \text{ TeV}$                       | 1512.02586                                                    |                                                   |
|                                                | RS1 $G_{\text{UV}} \rightarrow \gamma\gamma$                     | $2\gamma$                                   | -                         | -                           | 36.7                                   | $G_{\text{UV}} \text{ mass} = 4.1 \text{ TeV}$          | 1707.04147                                                    |                                                   |
|                                                | Bulk RS $G_{\text{UV}} \rightarrow WW/ZZ$                        | multi-channel                               | -                         | -                           | 36.1                                   | $G_{\text{UV}} \text{ mass} = 2.3 \text{ TeV}$          | 1608.02380                                                    |                                                   |
|                                                | Bulk RS $G_{\text{UV}} \rightarrow WV \rightarrow \nu\bar{\nu}q$ | $1, e, \mu$                                 | 2j/1j                     | Yes                         | 139                                    | $G_{\text{UV}} \text{ mass} = 2.0 \text{ TeV}$          | 2004.14636                                                    |                                                   |
|                                                | Bulk RS $G_{\text{UV}} \rightarrow tt$                           | $1, e, \mu$                                 | $\geq 1b, \geq 1j$        | Yes                         | 36.1                                   | $G_{\text{UV}} \text{ mass} = 3.8 \text{ TeV}$          | 1804.10823                                                    |                                                   |
|                                                | SUED/RSPP                                                        | $1, e, \mu$                                 | $\geq 1b, \geq 3j$        | Yes                         | 36.1                                   | $G_{\text{UV}} \text{ mass} = 1.8 \text{ TeV}$          | 1803.09678                                                    |                                                   |
|                                                | SSM $Z' \rightarrow \ell\ell$                                    | $2, e, \mu$                                 | -                         | -                           | 139                                    | $Z' \text{ mass} = 5.1 \text{ TeV}$                     | 1603.06248                                                    |                                                   |
|                                                | SSM $Z' \rightarrow \tau\tau$                                    | $2\tau$                                     | -                         | -                           | 36.1                                   | $Z' \text{ mass} = 2.42 \text{ TeV}$                    | 1709.07242                                                    |                                                   |
|                                                | Leptophobic $Z' \rightarrow b\bar{b}$                            | $0, e, \mu$                                 | $\geq 2b$                 | -                           | 36.1                                   | $Z' \text{ mass} = 2.1 \text{ TeV}$                     | 1605.09299                                                    |                                                   |
|                                                | Leptophobic $Z' \rightarrow tt$                                  | $0, e, \mu$                                 | $\geq 1b, \geq 2j$        | Yes                         | 139                                    | $Z' \text{ mass} = 4.1 \text{ TeV}$                     | 2005.05138                                                    |                                                   |
| Gauge bosons                                   | SSM $W' \rightarrow \ell\nu$                                     | $1, e, \mu$                                 | -                         | -                           | 139                                    | $W' \text{ mass} = 6.0 \text{ TeV}$                     | 1606.05609                                                    |                                                   |
|                                                | SSM $W' \rightarrow \tau\nu$                                     | $1\tau$                                     | -                         | -                           | 36.1                                   | $W' \text{ mass} = 3.7 \text{ TeV}$                     | 1601.05992                                                    |                                                   |
|                                                | HVT $W' \rightarrow WZ \rightarrow \nu\bar{\nu}q$ model B        | $1, e, \mu$                                 | 2j/1j                     | Yes                         | 139                                    | $W' \text{ mass} = 4.3 \text{ TeV}$                     | 2004.14636                                                    |                                                   |
|                                                | HVT $V' \rightarrow WV \rightarrow q\bar{q}q$ model B            | $0, e, \mu$                                 | 2j                        | -                           | 139                                    | $V' \text{ mass} = 3.8 \text{ TeV}$                     | 1905.08589                                                    |                                                   |
|                                                | HVT $V' \rightarrow WW/ZZ$ model B                               | $0, e, \mu$                                 | $\geq 1b, \geq 2j$        | Yes                         | 36.1                                   | $V' \text{ mass} = 2.53 \text{ TeV}$                    | 1712.05118                                                    |                                                   |
|                                                | HVT $W' \rightarrow WH$ model B                                  | $0, e, \mu$                                 | $\geq 1b, \geq 2j$        | Yes                         | 139                                    | $W' \text{ mass} = 3.2 \text{ TeV}$                     | CERN-EP-2020-073                                              |                                                   |
|                                                | LRSM $W_2 \rightarrow tb$                                        | multi-channel                               | -                         | -                           | 36.1                                   | $W_2 \text{ mass} = 3.25 \text{ TeV}$                   | 1807.10473                                                    |                                                   |
|                                                | LRSM $W_2 \rightarrow \mu\mu$                                    | $2\mu$                                      | 1j                        | -                           | 60                                     | $W_2 \text{ mass} = 6.0 \text{ TeV}$                    | 1904.12679                                                    |                                                   |
|                                                | CI                                                               | CI $q\bar{q}q\bar{q}$                       | -                         | 2j                          | -                                      | 37.0                                                    | $A = 21.8 \text{ TeV}$                                        | 1703.09127                                        |
|                                                |                                                                  | CI $\ell\ell q\bar{q}$                      | $2, e, \mu$               | -                           | -                                      | 139                                                     | $A = 35.8 \text{ TeV}$                                        | CERN-EP-2020-066                                  |
|                                                |                                                                  | CI $\ell\ell\tau\bar{\tau}$                 | $2\tau, e, \mu$           | $\geq 1b, \geq 1j$          | Yes                                    | 36.1                                                    | $A = 2.57 \text{ TeV}$                                        | 1811.02395                                        |
|                                                | DM                                                               | Adial-vector mediator (Dirac DM)            | $0, e, \mu$               | 1-4j                        | Yes                                    | 36.1                                                    | $m_{\text{DM}} = 1.55 \text{ TeV}$                            | 1711.03201                                        |
|                                                |                                                                  | Colored scalar mediator (Dirac DM)          | $0, e, \mu$               | 1-4j                        | Yes                                    | 36.1                                                    | $m_{\text{DM}} = 1.67 \text{ TeV}$                            | 1711.03201                                        |
|                                                |                                                                  | VV <sub>UV</sub> EFT (Dirac DM)             | $0, e, \mu$               | $1j, \geq 1j$               | Yes                                    | 36.1                                                    | $m_{\text{DM}} = 700 \text{ GeV}$                             | 1608.02372                                        |
| LQ                                             | Scalar reson. $s \rightarrow t\bar{t}$ (Dirac DM)                | $0, 1, e, \mu$                              | $1b, 0, 1j$               | Yes                         | 36.1                                   | $m_{\text{DM}} = 3.4 \text{ TeV}$                       | 1612.07443                                                    |                                                   |
|                                                | Scalar LQ 1 <sup>st</sup> gen                                    | $1, 2, e$                                   | $\geq 2j$                 | Yes                         | 36.1                                   | $LQ \text{ mass} = 1.4 \text{ TeV}$                     | $p = 1$<br>1902.02377                                         |                                                   |
|                                                |                                                                  | Scalar LQ 2 <sup>nd</sup> gen               | $1, 2, e$                 | $\geq 2j$                   | Yes                                    | 36.1                                                    | $LQ \text{ mass} = 1.56 \text{ TeV}$                          | $p = 1$<br>1902.02377                             |
|                                                |                                                                  | Scalar LQ 3 <sup>rd</sup> gen               | $2\tau$                   | 2b                          | -                                      | 36.1                                                    | $LQ \text{ mass} = 1.03 \text{ TeV}$                          | $R[LQ \rightarrow b\tau] = 0$<br>1902.08103       |
|                                                |                                                                  | Scalar LQ 2 <sup>nd</sup> gen               | $0, 1, e, \mu$            | 2b                          | Yes                                    | 36.1                                                    | $LQ \text{ mass} = 970 \text{ GeV}$                           | $R[LQ \rightarrow \tau b] = 0$<br>1902.08103      |
|                                                | Heavy quarks                                                     | VLO $TT \rightarrow H\gamma/Z/\bar{W}b + X$ | multi-channel             | -                           | -                                      | 36.1                                                    | $T \text{ mass} = 1.37 \text{ TeV}$                           | SUGRA-stable<br>1808.02343                        |
|                                                |                                                                  | VLO $BB \rightarrow W\gamma/Zb + X$         | multi-channel             | -                           | -                                      | 36.1                                                    | $B \text{ mass} = 1.34 \text{ TeV}$                           | SUGRA-stable<br>1808.02343                        |
|                                                |                                                                  | VLO $T_{13}T_{13} \rightarrow Wt + X$       | $2(S/S) \geq 1b, \geq 1j$ | Yes                         | 36.1                                   | $T \text{ mass} = 1.64 \text{ TeV}$                     | $\langle T_{13} \rangle = 1$<br>1807.18883                    |                                                   |
|                                                |                                                                  | VLO $V \rightarrow Wb + X$                  | $1, e, \mu$               | $\geq 1b, \geq 1j$          | Yes                                    | 36.1                                                    | $V \text{ mass} = 1.65 \text{ TeV}$                           | $\langle V \rangle = 1$<br>1812.07443             |
|                                                |                                                                  | VLO $B \rightarrow Hb + X$                  | $0, e, \mu$               | $2\gamma, \geq 1b, \geq 1j$ | Yes                                    | 79.8                                                    | $B \text{ mass} = 1.21 \text{ TeV}$                           | $\kappa = 0.5$<br>ATLAS-CONF-2018-024             |
|                                                |                                                                  | VLO $QQ \rightarrow W\gamma Wq$             | $1, e, \mu$               | $\geq 4j$                   | Yes                                    | 20.3                                                    | $Q \text{ mass} = 890 \text{ GeV}$                            | 1509.04261                                        |
|                                                | Excited fermions                                                 | Excited quark $q^* \rightarrow q\gamma$     | -                         | 2j                          | -                                      | 139                                                     | $q^* \text{ mass} = 5.3 \text{ TeV}$                          | only $u^*$ and $d^*$ , $A = m(q^*)$<br>1910.08447 |
|                                                |                                                                  | Excited quark $q^* \rightarrow q\gamma$     | $1\gamma$                 | 1j                          | -                                      | 36.7                                                    | $q^* \text{ mass} = 2.6 \text{ TeV}$                          | $A = m(q^*)$<br>1708.05460                        |
|                                                |                                                                  | Excited quark $q^* \rightarrow q\gamma$     | $3, e, \mu$               | $\geq 1b, 1j$               | -                                      | 36.1                                                    | $q^* \text{ mass} = 3.8 \text{ TeV}$                          | 1805.09299                                        |
| Excited lepton $\ell^* \rightarrow \ell\gamma$ |                                                                  | $3, e, \mu$                                 | -                         | -                           | 20.3                                   | $\ell^* \text{ mass} = 1.6 \text{ TeV}$                 | 1411.2921                                                     |                                                   |
| Excited lepton $\ell^* \rightarrow \ell\gamma$ |                                                                  | $3, e, \mu, \tau$                           | -                         | -                           | 20.3                                   | $\ell^* \text{ mass} = 1.6 \text{ TeV}$                 | 1411.2921                                                     |                                                   |
| Other                                          | Type III Seesaw                                                  | $1, e, \mu$                                 | $\geq 2j$                 | Yes                         | 79.8                                   | $N \text{ mass} = 560 \text{ GeV}$                      | ATLAS-CONF-2018-020                                           |                                                   |
|                                                | LRSM Majorana $\nu$                                              | $2\mu$                                      | 2j                        | -                           | 36.1                                   | $N \text{ mass} = 870 \text{ GeV}$                      | $m(W_2) = 4.1 \text{ TeV}, g = g_F$<br>1809.11105             |                                                   |
|                                                | Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$                  | $2, 3, 4, e, \mu$ (BS)                      | -                         | -                           | 20.3                                   | $H^{\pm\pm} \text{ mass} = 400 \text{ GeV}$             | DV production, $\langle H^{\pm\pm} \rangle = 1$<br>1710.07348 |                                                   |
|                                                | Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$                  | $3, e, \mu, \tau$                           | -                         | -                           | 20.3                                   | $H^{\pm\pm} \text{ mass} = 400 \text{ GeV}$             | DV production, $\langle H^{\pm\pm} \rangle = 1$<br>1411.2921  |                                                   |
|                                                | Multi-charged particles                                          | -                                           | -                         | -                           | 36.1                                   | $\text{multi-charged particle mass} = 1.22 \text{ TeV}$ | DV production, $\langle H^{\pm\pm} \rangle = 1$<br>1812.0873  |                                                   |
|                                                | Magnetic monopoles                                               | -                                           | -                         | -                           | 36.1                                   | $\text{magnetic mass} = 2.37 \text{ TeV}$               | DV production, $\langle H^{\pm\pm} \rangle = 1$<br>1905.10130 |                                                   |

\*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter J (J).

## Overview of CMS EXO results



Selection of observed exclusion limits at 95% CL, (theory uncertainties are not included).

mass scale [TeV]

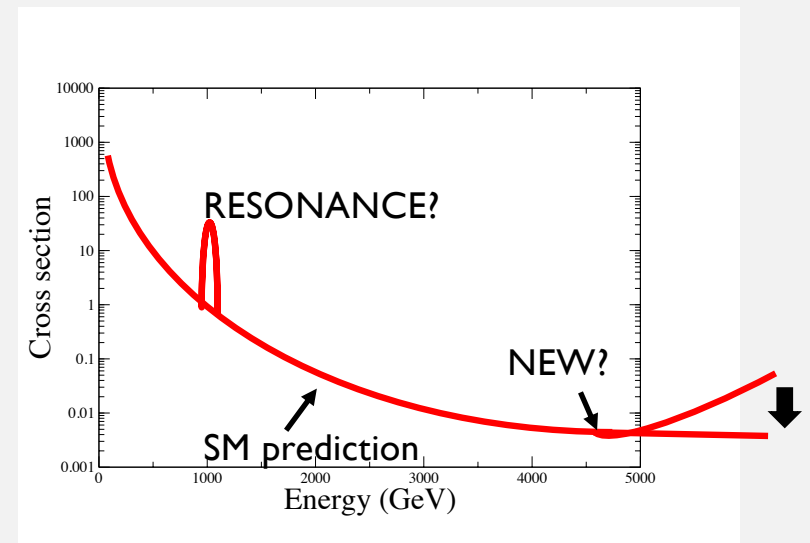
LHC2020

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\*\*\*\*But we don't really have a target mass\*\*\*\*

## NO SIGN OF ANY NEW PARTICLES

- No shortage of models predicting more particles
  - But no evidence yet....
- Look for new physics in tails of distributions
  - Requires precision calculations of SM predictions for comparison
  - This is much harder than looking for resonances



## NEW PHYSICS AT HIGH SCALES: NO NO LOSE THEOREM

Use effective field theory: precision calculations

NO?

Can we determine source of new physics from EFT?

Is there a light (weak scale) resonance?

YES?

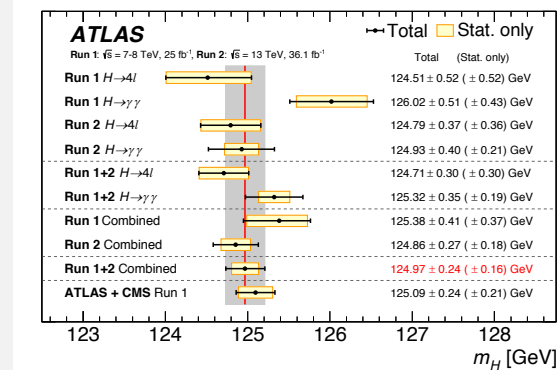
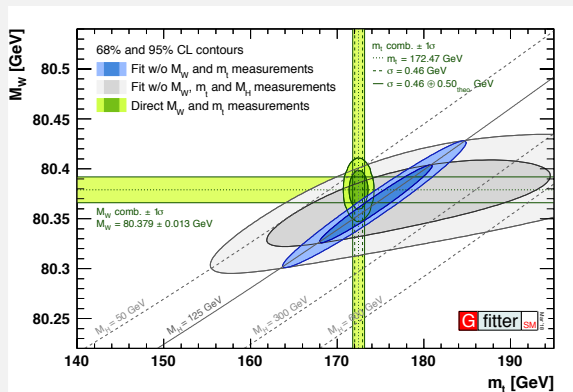
Current limits will be strengthened at HL-LHC

Find resonance!

At high scales this is a  
well defined program

# PRECISION CONSTRAINS NEW PHYSICS

- Use precision measurements to constrain BSM physics (long history starting with LEP and SLD)
- Higgs mass is precision observable

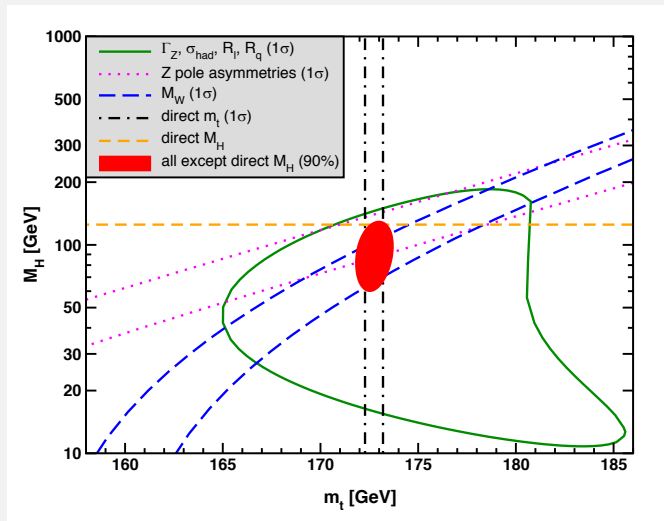


*SM predicts relationship between  $M_t$ ,  $M_W$ , and  $M_H$*

↑  
At the loop level



# $M_H$ FROM INDIRECT MEASUREMENTS

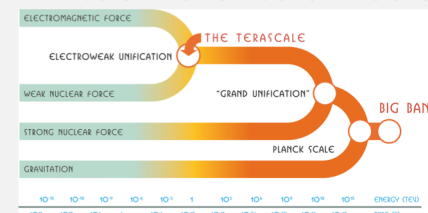


Consistent picture, but  
room for new physics

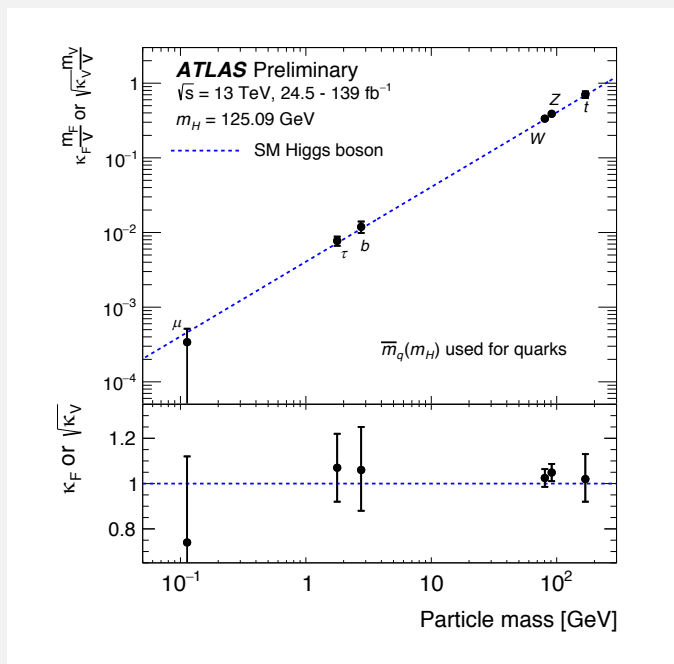
[1908.07327](#)

# WHY MIGHT NEW PHYSICS HIDE IN HIGGS SECTOR?

- Many *unanswered questions*: dark matter, the pattern of fermion masses (including neutrinos), baryogenesis, strong CP violation, EW hierarchy....
- Why does the SM only have one Higgs doublet?
  - No good answer to this question
- Higgs can be portal to dark matter
  - Motivates models with extra Higgs gauge singlet
- Higgs models can be constructed to have flavor violation such as  $H \rightarrow \mu e$ 
  - Motivates 2HDM type models



# FROM DISCOVERY TO PRECISION MEASUREMENTS



- Higgs couplings to fermions and gauge bosons *fixed in SM*
- What if we allowed couplings to deviate by constant rescaling?
- SM is excellent approximation of Higgs sector

# FIRST STEP TO HIGGS COUPLINGS: $\kappa$ APPROACH

- $\kappa_i = (\text{Higgs coupling to particle } i) / (\text{SM Higgs coupling to particle } i)$ 
  - Simple rescaling; no momentum dependence
  - Gauge invariance of SM requires  $\kappa = 1$
- Assuming loops resolved and no BSM:

|          | CMS                   | ATLAS                |
|----------|-----------------------|----------------------|
| $k_Z$    | $.99^{+.11}_{-.12}$   | $1.10^{+.08}_{-.08}$ |
| $k_W$    | $1.10^{+.12}_{-.17}$  | $1.05^{+.08}_{-.08}$ |
| $k_t$    | $1.11^{+.12}_{-.10}$  | $1.02^{+.11}_{-.10}$ |
| $k_b$    | $-1.10^{+.33}_{-.23}$ | $1.06^{+.19}_{-.18}$ |
| $k_\tau$ | $1.01^{+.16}_{-.20}$  | $1.07^{+.15}_{-.15}$ |
| $k_\mu$  | $.79^{+.58}_{-.79}$   | $<1.51$ at 95% cl    |

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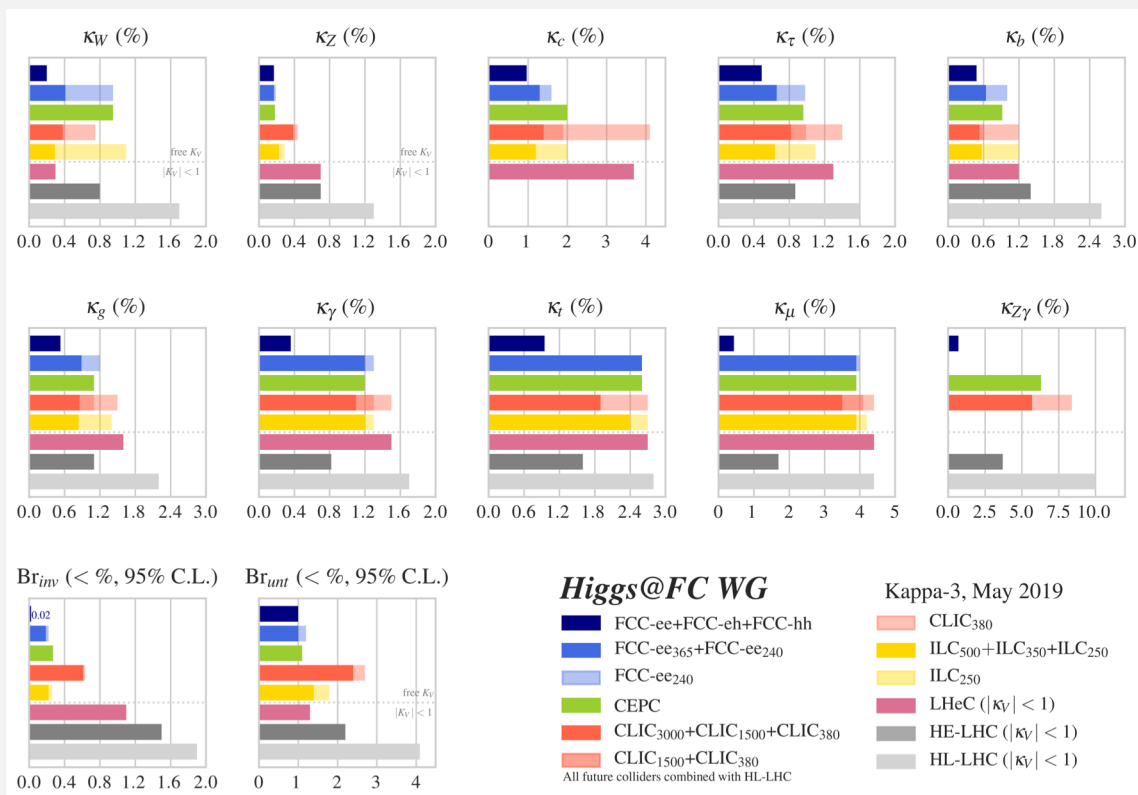
- Couplings to gauge bosons at 8-12%
- Couplings to 3<sup>rd</sup> generation fermions at 15-20%

We are just getting to the interesting regime: Generically expect deviations

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 6\% \left( \frac{1000 \text{ TeV}}{\Lambda} \right)^2$$

CMS, [arXiv:1809.10733](https://arxiv.org/abs/1809.10733)  
 ATLAS, [ATLAS-CONF-2019-005](https://arxiv.org/abs/ATLAS-CONF-2019-005)

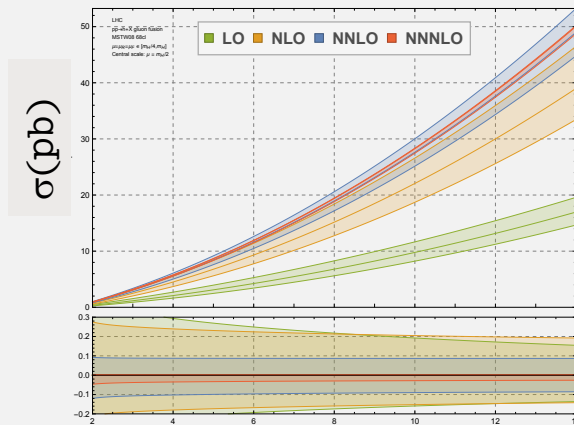
# PROJECTIONS



Possibilities for couplings at the % level

# CAN WE CALCULATE LHC HIGGS PROCESSES TO ~5% ACCURACY?

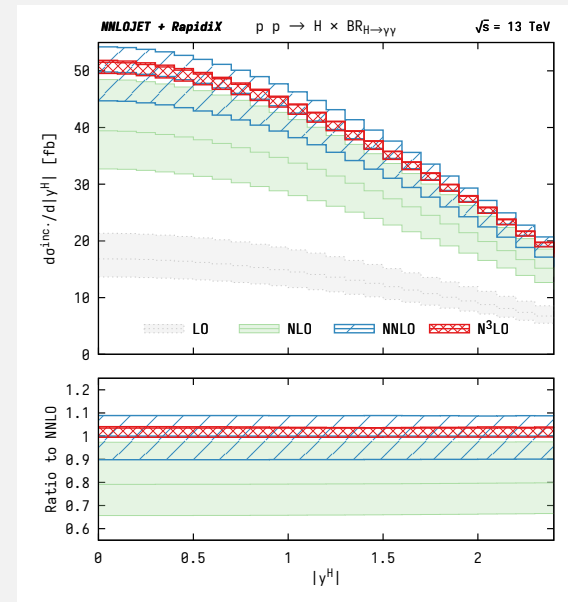
- Dominant Higgs production mechanism is gluon fusion
- Higgs production from gluon fusion known at N<sup>3</sup>LO



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$\sqrt{s}$  (TeV)

[1503.06056](#)



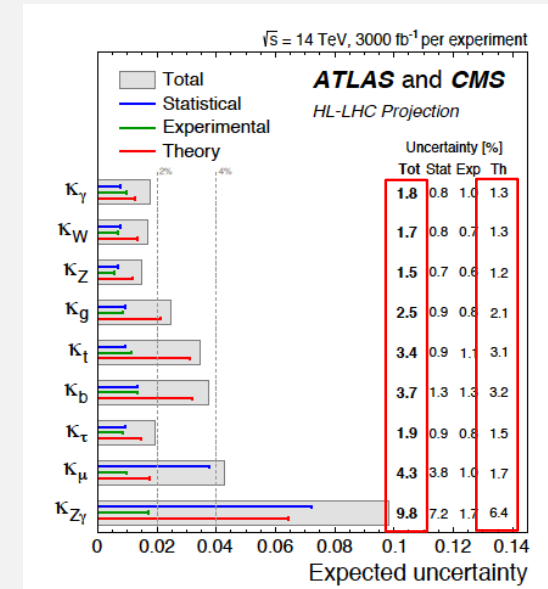
[2102.07607](#)

# THEORY ERRORS DOMINATE EXPERIMENTAL EXTRACTIONS OF HIGGS PARAMETERS

## ATLAS, Global Higgs signal strength

| Uncertainty source                          | $\Delta\mu/\mu$ [%] |
|---------------------------------------------|---------------------|
| Statistical uncertainty                     | 4.4                 |
| Systematic uncertainties                    | 6.2                 |
| Theory uncertainties                        | 4.8                 |
| Signal                                      | 4.2                 |
| Background                                  | 2.6                 |
| Experimental uncertainties (excl. MC stat.) | 4.1                 |
| Luminosity                                  | 2.0                 |
| Background modeling                         | 1.6                 |
| Jets, $E_T^{\text{miss}}$                   | 1.4                 |
| Flavour tagging                             | 1.1                 |
| Electrons, photons                          | 2.2                 |
| Muons                                       | 0.2                 |
| $\tau$ -lepton                              | 0.4                 |
| Other                                       | 1.6                 |
| MC statistical uncertainty                  | 1.7                 |
| Total uncertainty                           | 7.6                 |

## FUTURE

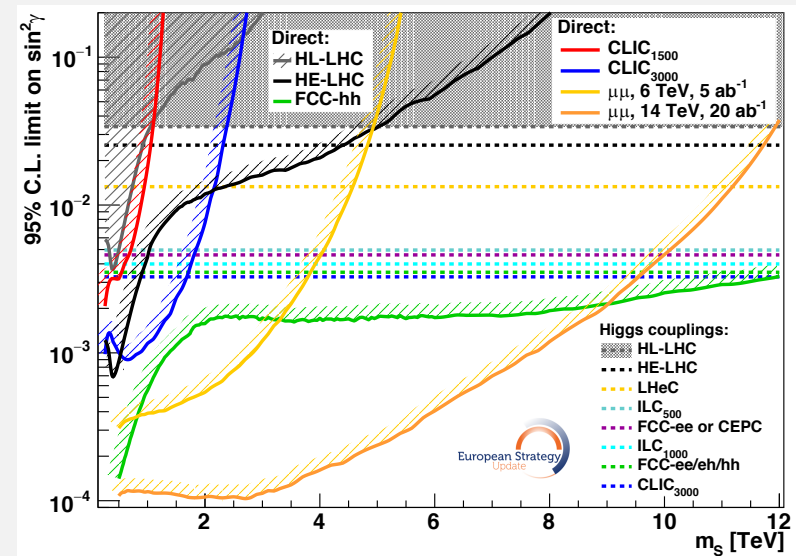


# HOW HIGH IN SCALE CAN WE GO?

- No evidence for any TeV scale resonance
- Theorists are being increasingly clever at devising scenarios that evade limits
- Precision calculations ever more precise
- Strategy: Look for new physics in precision Higgs measurements: **COMPLEMENTARITY OF APPROACHES**

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Model with heavy scalar singlet



European Strategy Report



## HIGGS SELF COUPLINGS COMPLETELY UNKNOWN

- We know that the Higgs couples to fermions and gauge bosons at the **10-20% accuracy level**
- We **postulate** that the Higgs interactions come from a scalar potential:

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- The potential could just as easily be an effective theory:

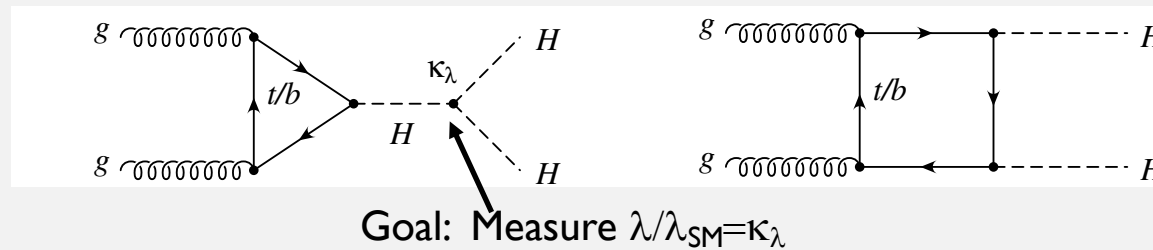
$$V \rightarrow -\frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

We have few handles on measuring  $\lambda_4$

Must measure  $\lambda_3 = \frac{M_H^2}{2v} = .13v$

# HH PRODUCTION

- HH first occurs at one-loop

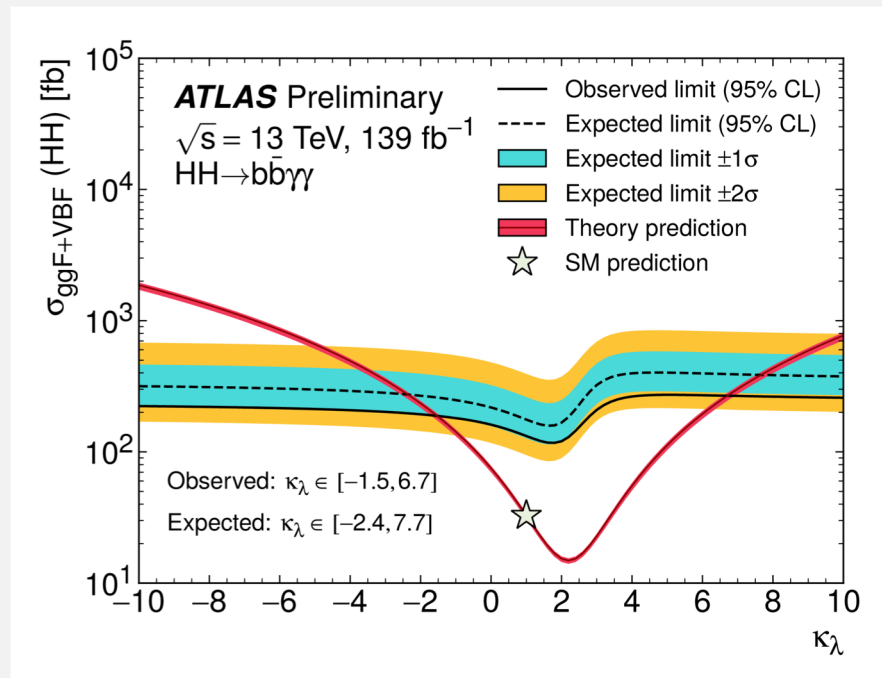


- Large cancellation between diagrams
- Very small rate at LHC

**Measurement of Higgs tri-linear coupling  
necessary to confirm structure of Higgs potential**

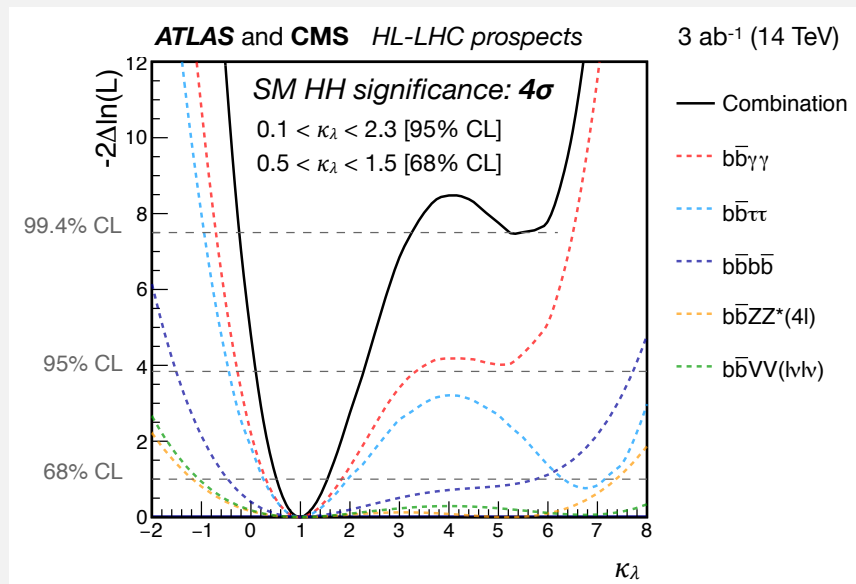
*The next big thing.....*

## CURRENT STATUS OF HH SEARCHES: RESULTS WITH 137 FB<sup>-1</sup>



- This search is sensitive to models with heavy neutral scalars and is a sensitive probe of new physics

# HIGGS TRI-LINEAR COUPLING IN THE FUTURE



| Collider   | Accuracy on $\kappa_\lambda$ | Running Years |
|------------|------------------------------|---------------|
| HL-LHC     | 50%                          | 12            |
| HE-LHC     | 10-20%                       | 20            |
| ILC(500)   | 27%                          | 21            |
| CLIC(1500) | 36%                          | 15            |
| CLIC(3000) | +11%,<br>-7%                 | 23            |
| FCC(hh)    | 5%                           | 13            |

**Difficult measurement at all colliders!**

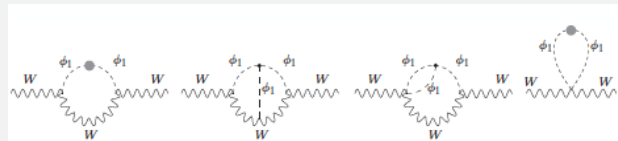
[arxiv:1902.00134.pdf](https://arxiv.org/abs/1902.00134), [arxiv:1905.03764](https://arxiv.org/abs/1905.03764)

# COMPLEMENTARITY WITH PRECISION MEASUREMENTS

- Indirect constraints on HHH coupling from Higgs coupling measurements



- Indirect constraints from precision observables such as  $M_W$



- Combining HH searches with indirect constraints gives limit

$$-1.8 < \lambda/\lambda_{SM} < 9.2$$

[2102.07651](#)

S. Dawson, BNL

\*This before new  $b\bar{b}\gamma\gamma$  limit

NO RESONANCES?  
ASSUME A HIERARCHY OF SCALES

$\Lambda \gg M_W$  where complete theory exists

- Any new particles or symmetries are at this scale
- Expect effects of heavy particles at low scales to be suppressed

$M_W$  Only SM particles in theory at low scales

## SCALES

- High scale,  $\Lambda$ : Complete model with unknown heavy states
  - Integrate out heavy particles to get non-renormalizable effective Lagrangian
  - Renormalization group evolve to low scales



This is sad scenario where there is no intermediate scale physics

- Weak Scale,  $M_W$ : Standard Model + remnants of high scale model
  - Described by effective field theory

## MODEL INDEPENDENT PARAMETERIZATION OF NEW PHYSICS: SMEFT

- Useful to have a model independent formulation of new physics
  - SM works at the EW scale with SM-like Higgs
  - Treat  $SU(3) \times SU(2) \times U(1)$  as good symmetry with doublet Higgs,  $\phi$

$$L = L_{SM} + \sum_{n=1}^{\infty} \sum_k \frac{c_{n,k}}{\Lambda^n} O_{n,k}$$

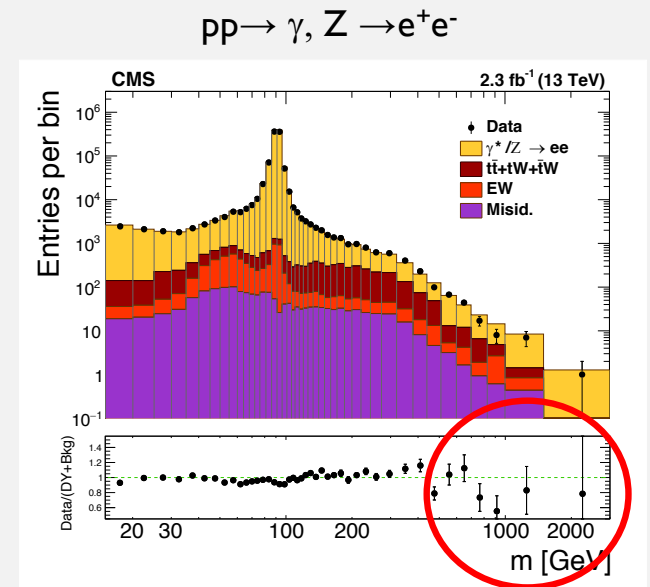
- $O_{n,k}$ : Gauge invariant  $4+n$  dimensional operators constructed from SM fields
- All BSM effects in coefficients,  $c_{n,k}$
- Allows for a systematic parameterization of deviations from SM predictions without affecting agreement with low energy measurements



# DRELL-YAN

- Extremely precisely known in SM (NNLO QCD+...)
- Large number of events: potential sensitivity to SMEFT operators that contribute effects  $O(p_T^2/\Lambda^2)$
- In SMEFT, tree level 4-fermion contributions (extensive literature)
- Can also be 1-loop corrections from new SMEFT operators

Look in tails of distributions

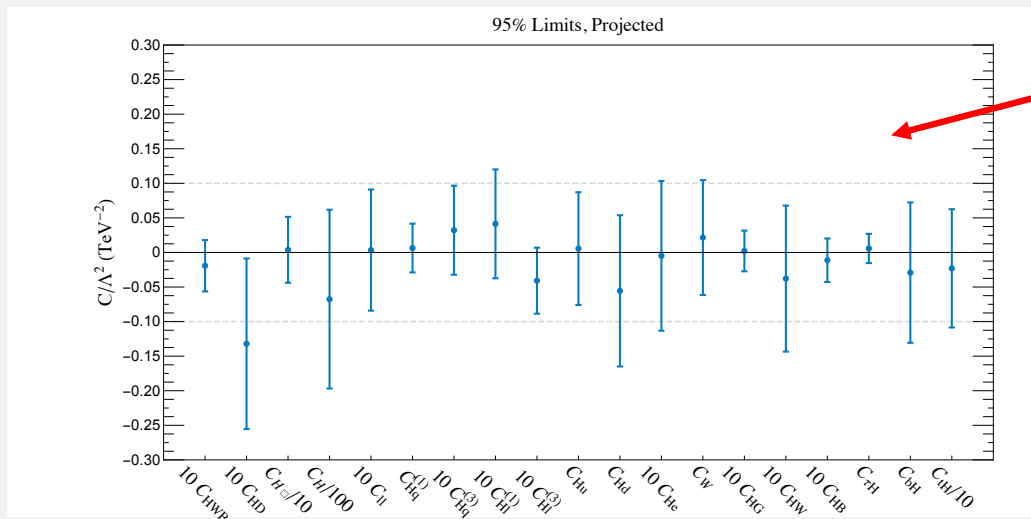


Room for new physics?

PDFs extracted from tails

# LEARNING FROM SMEFT

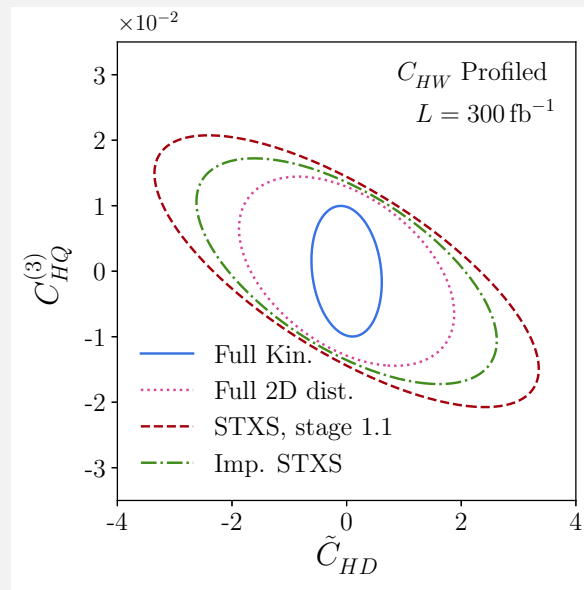
- Global fits include **LEP precision data, VV production, Higgs production....**
- Effective field theory connects different processes with large correlations
- **Precision requires a complete set of operators, not just one at a time**



- Includes subset of higher order corrections in fit
- No indication of new physics from this type of approach
- **MANY!** Independent global fits

## NEW TECHNIQUES

- Machine learning to extract possible deviations from SM



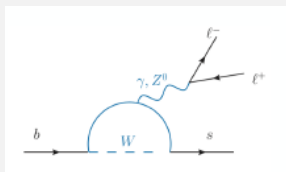
- Much more precise results from full kinematics (machine learning) than from looking at distributions (STXS)
- MADMINER: automated tool

# SEARCH IN NEW PLACES

- Maybe the new physics is not apparent at high energy scales

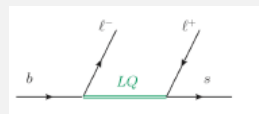
$$R_K = \frac{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{dq^2} dq^2}$$

= 1 + (radiative corrections) in SM

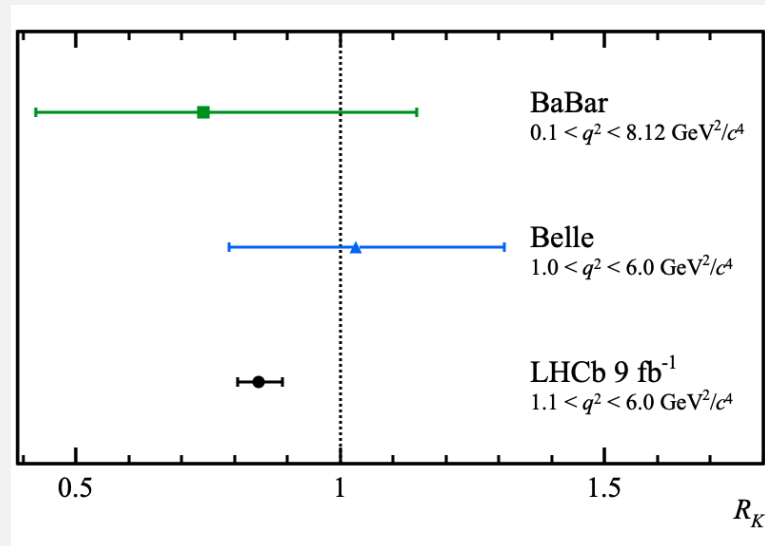


Small CKM angles

S. Dawson, BNL



Leptoquark?



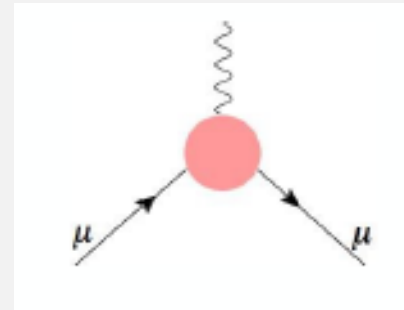
Lepton flavor violation at  $3.1\sigma$ ?

↑  
SM

LHCb, [2103.11769](https://arxiv.org/abs/2103.11769)

## SEARCH IN NEW PLACES

- $(g-2)_\mu$  is now  $4.2\sigma$  from SM (up from  $3.7\sigma$ )
- Has inspired immense theory effort
- Can be explained with new particle contributions
- Many possibilities, many models



## CONCLUSIONS

- No evidence so far for new physics at the LHC
- Need to look for new heavy resonances and tease out small effects from precision measurements
- Very hard!

Case for the existence of new physics remains strong: we just don't know where it will be!