Particle Phenomenology at NBI

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Current:



EFT phenomenology group

Graduated:



THE VELUX FOUNDATIONS







Our ability to learn from the vacuum - empty space, is profound

People noticed a while ago when you smash things together

very interesting things happen.Source interesting things happen.Crockcroft and Walton in 1930–1932 used a large potential
difference to smash a proton into lithiumpp</t

Cool 1930 tech !

People/Things born in 1930:

Increasing coolness.



Buffett



Eastwood



Connery



Particle Physics (arguably)

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Why is the vacuum so exciting?

4.5 inch, 80 000 eV



Around the same time Lawrence/Livingston cyclotron was developed

grad student who did the work

COOLER 1931 tech !

"Dr Livingston has asked me to advise you that he has obtained 1,100,000 volt protons. He also suggested that I add 'Whoopee'!"

> —Telegram to Lawrence, 3 August 1931

The mission to put more and more energy in small spaced is motivated out of the fact that if you do that - you can make profoundly new particles



11 inch, 1 MeV



What is the big picture?



Livingston chart: 1985

Livingston chart: 2014

Images: http://www.hep.ucl.ac.uk/iop2010/talks/14.pdf

The ultimate atom smasher

So many decades later the ultimate large energy in a small space machine is the LHC



The ultimate atom smasher

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The ultimate atom smasher

Leading up to LHC we had discovered all but the final box below at other atom smashers. Theoretical consistency implied that there should be something more.



S/B Weighted Data

Bkg Fit Component

S+B Fit

±1σ

±2 σ

140

m_{yy} (GeV)

A beast has emerged from the vacuum like no other





CERN at the time of the discovery.

The Nobel Prize in Physics 2013



Photo: A. Mahmoud Francois Englert



Photo: A. Mahmoud Peter W. Higgs

Was a bit hard to dig out, these gentleman supplied the theory that told us fundamentally its nature so we knew how to look for it in this mess.

So now what is the big picture?



Images: http://www.hep.ucl.ac.uk/iop2010/talks/14.pdf



Michael Trott, Niels Bohr Institute



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Big picture: SM a very good approx.



The measurement precision and accuracy is generically not at the % level

How the heck is this holding up at all??



Its a basic field theory fact (mostly) - decoupling.

Runll and beyond: Resonance limits to local operators

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

		miss	1	$\int \mathcal{L} dt = (3)$	5.2 – 79.8) ID ⁻¹	$\sqrt{s} = \delta$, 13 lev
Model	ℓ, γ Jets† E	$T \int \mathcal{L} dt [fb]$	⁻¹] Limit			Reference
ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{ccccc} 0 \ e, \mu & 1-4 \ j \\ 2 \ \gamma & - & \\ & - & 2 \ j \\ \geq 1 \ e, \mu & \geq 2 \ j \\ & - & \geq 3 \ j \\ 2 \ \gamma & - & \\ \\ \mbox{multi-channel} \\ 1 \ e, \mu & \geq 1 \ b, \geq 1 \ J/2 \ j \\ 1 \ e, \mu & \geq 2 \ b, \geq 3 \ j \end{array}$	Yes 36.1 - 36.7 - 37.0 - 3.2 - 3.6 - 36.7 36.1 Yes 36.1 Yes 36.1	M _D I Ms I Mth I Mth I G _{KK} mass I GKK mass I KK mass I.8	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 2.3 TeV 3.8 TeV TeV	$\begin{split} n &= 2 \\ n &= 3 \text{ HLZ NLO} \\ n &= 6 \\ m &= 6, M_D = 3 \text{ TeV, rot BH} \\ n &= 6, M_D = 3 \text{ TeV, rot BH} \\ k/\overline{M}_{Pl} &= 0.1 \\ k/\overline{M}_{Pl} &= 1.0 \\ \Gamma/m &= 15\% \\ \text{Tier (1,1), } \mathcal{B}(A^{(1,1)} \rightarrow tt) = 1 \end{split}$	1711.03301 1707.04147 1703.09217 1606.02265 1512.02586 1707.04147 CERN-EP-2018-179 1804.10823 1803.09678
$\begin{array}{c} \text{SSM } Z' \rightarrow \ell\ell \\ \text{SSM } Z' \rightarrow \tau\tau \\ \text{Leptophobic } Z' \rightarrow bb \\ \text{Leptophobic } Z' \rightarrow tt \\ \text{SSM } W' \rightarrow \ell\nu \\ \text{SSM } W' \rightarrow \tau\nu \\ \text{HVT } V' \rightarrow WV \rightarrow qqqq \ \text{mode} \\ \text{HVT } V' \rightarrow WH/ZH \ \text{model B} \\ \text{LRSM } W'_R \rightarrow tb \end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	- 36.1 - 36.1 - 36.1 Yes 36.1 Yes 36.1 Yes 36.1 - 79.8 36.1 36.1	Z' mass Z' mass Z' mass Z' mass W' mass Z' mass W' mass Z' mass W' mass Z' mass W' mass Z' mass	4.5 TeV 2.42 TeV 2.1 TeV 3.0 TeV 5.6 TeV 3.7 TeV 4.15 TeV 2.93 TeV 3.25 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	1707.02424 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.06992 ATLAS-CONF-2018-016 1712.06518 CERN-EP-2018-142
CI qqqq CI llqq CI tttt	$\begin{array}{ccc} - & 2 j \\ 2 e, \mu & - \\ \ge 1 e, \mu & \ge 1 b, \ge 1 j \end{array}$	- 37.0 - 36.1 Yes 36.1	Λ Λ Λ	2.57 TeV	$\begin{array}{c c} \textbf{21.8 TeV} & \eta_{LL} \\ \hline & \textbf{40.0 TeV} \\ C_{4t} = 4\pi \end{array} & \eta_{LL} \end{array}$	1703.09217 1707.02424 CERN-EP-2018-174
Axial-vector mediator (Dirac DI Colored scalar mediator (Dirac $VV_{\chi\chi}$ EFT (Dirac DM)	$\begin{array}{llllllllllllllllllllllllllllllllllll$	Yes 36.1 Yes 36.1 Yes 3.2	m _{med} 1.55 Te m _{med} 1.67 T M, 700 GeV	IV FeV	$\begin{split} g_q = &0.25, g_\chi = &1.0, m(\chi) = 1 \text{ GeV} \\ g = &1.0, m(\chi) = 1 \text{ GeV} \\ m(\chi) < &150 \text{ GeV} \end{split}$	1711.03301 1711.03301 1608.02372
Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	$\begin{array}{ll} 2 \ e & \geq 2 \ j \\ 2 \ \mu & \geq 2 \ j \\ 1 \ e, \mu & \geq 1 \ b, \geq 3 \ j \end{array}$	- 3.2 - 3.2 Yes 20.3	LQ mass 1.1 TeV LQ mass 1.05 TeV LQ mass 640 GeV		$\begin{split} \beta &= 1\\ \beta &= 1\\ \beta &= 0 \end{split}$	1605.06035 1605.06035 1508.04735
$\label{eq:states} \begin{array}{l} \mbox{VLQ } TT \rightarrow Ht/Zt/Wb + X \\ \mbox{VLQ } BB \rightarrow Wt/Zb + X \\ \mbox{VLQ } T_{5/3} T_{5/3} \rightarrow Wt + X \\ \mbox{VLQ } Y \rightarrow Wb + X \\ \mbox{VLQ } B \rightarrow Hb + X \\ \mbox{VLQ } QQ \rightarrow WqWq \end{array}$	$ \begin{array}{l} \mbox{multi-channel} \\ \mbox{multi-channel} \\ \mbox{C} 2(SS)/\geq 3 \ e,\mu \geq 1 \ b,\geq 1 \ j \\ 1 \ e,\mu \qquad \geq 1 \ b,\geq 1 \ j \\ 0 \ e,\mu,2 \ \gamma \qquad \geq 1 \ b,\geq 1 \ j \\ 1 \ e,\mu \qquad \geq 4 \ j \end{array} $	36.1 36.1 Yes 36.1 Yes 3.2 Yes 79.8 Yes 20.3	T mass 1.37 TeV B mass 1.34 TeV T _{5/3} mass 1.64 TeV Y mass 1.44 TeV B mass 1.21 TeV Q mass 690 GeV	eV f	$\begin{array}{l} & \text{SU(2) doublet} \\ & \text{SU(2) doublet} \\ & \mathcal{B}\big(T_{5/3} \rightarrow Wt\big) = 1, \ c\big(T_{5/3} Wt\big) = 1 \\ & \mathcal{B}\big(Y \rightarrow Wb\big) = 1, \ c\big(YWb\big) = 1/\sqrt{2} \\ & \kappa_B = 0.5 \end{array}$	ATLAS-CONF-2018-XXX ATLAS-CONF-2018-XXX CERN-EP-2018-171 ATLAS-CONF-2016-072 ATLAS-CONF-2018-XXX 1509.04261
Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $p^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton γ^*	$ \begin{array}{cccc} - & 2j \\ 1\gamma & 1j \\ - & 1b, 1j \\ 3e, \mu & - \\ 3e, \mu, \tau & - \end{array} $	- 37.0 - 36.7 - 36.1 - 20.3 - 20.3	q' mass q' mass b' mass /' mass y' mass 1.6 Te	6.0 TeV 5.3 TeV 2.6 TeV 3.0 TeV eV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0$ TeV $\Lambda = 1.6$ TeV	1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
Type III Seesaw LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Yes 79.8 - 20.3 - 36.1 - 20.3 Yes 20.3 - 20.3 - 7.0	Nº mass 560 GeV 2 Nº mass 870 GeV 2 H ^{±±} mass 870 GeV 2 H ^{±±} mass 400 GeV 2 spin-1 invisible particle mass 657 GeV 2 multi-charged particle mass 785 GeV 2 monopole mass 1.34 TeV 2	.0 TeV	$m(W_R) = 2.4$ TeV, no mixing DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ $a_{non-res} = 0.2$ DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2	ATLAS-CONF-2018-020 1506.06020 1710.09748 1411.2921 1410.5404 1504.04188 1509.08059
	$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ T}$	ſeV	10 ⁻¹ 1	10	Mass scale [TeV]	

Now that these bounds have been pushed away from v

USE that

ATLAS Preliminary

v/M < 1

to simplify/for more powerful conclusions

- bound many models at once
- bound multiple resonances at same time

*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).

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

Deviations then "look like" local contact operator effects in EFT

General "BSM is heavy" approach is EFT



Probing an S-matrix below a particle threshold



- The observable is a function of the external Lorentz invariants: f(s,t,u)
- The observable is an analytic function of these invariants except in special regions of phase space where an internal state goes on-shell. This is the "Landau Principle".



- IF the collision probe can never reach the $\sim m_{heavy}^2$ THEN the observable's dependence on that scale is DRAMATICALLY, practically, (wonderfully!) simplified
- No non-analytic behavior due to that state, and you can Taylor expand in LOCAL functions

$$\langle \rangle \sim O_{SM}^0 + \frac{f_1(s, t, u)}{M_{heavy}^2} + \frac{f_2(s, t, u)}{M_{heavy}^4} + \cdots$$

The locality is due to the uncertainty principle
 See the review for the basics (1706.08945 Brivio,MT)

The research program

Now that we have found a Higgs:

• We must calculate in a theory that takes into account that the Standard Model should be extended



- All interactions modified to most general ones allowed by symmetry and experimental bounds.
- Interaction pattern in the minimal theory can be broken.
 The Higgs is now a microscope for new physics.

Not a trivial exercise

Quantum mechanical corrections required. Such as



Each dot can be 59 types of :

What are we doing in the EFT pheno group?





If the elephant is too heavy to make directly, look for its shadow

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{SMEFT}$$

we work on interpreting the shadow of even newer beasts in the LHC data.

What are we doing in the EFT pheno group?



What do students do?

Ward Identities for the Standard Model Effective Field Theory

Tyler Corbett,* Andreas Helset,† and Michael Trott‡

Consistent constraints on the Standard Model Effective Field Theory

Equations of motion, symmetry currents and EFT below the electroweak scale

Andreas Helset and Michael Trott



Higgs Decay to Two Photons at One Loop in the Standard Model Effective Field Theory.

e Berthier and Michael Trott

On one-loop corrections in the Standard Model Effective Field Theory; the $\Gamma(h \rightarrow \gamma \gamma)$ case.

Christine Hartmann and Michael Trott,

Gauge fixing the Standard Model Effective Field Theory

Andreas Helset^{*a*}, * Michael Paraskevas^{*b*}, † and Michael Trott^{*a*‡}

Effective interpretations of a diphoton excess

Laure Berthier,^a James M. Cline,^{a,b} William Shepherd,^a Michael Trott^a

The Z decay width in the SMEFT: y_t and λ corrections at one loop.

Christine Hartmann^a, William Shepherd^{a,b} and Michael Trott^a

Interpreting W mass measurements in the SMEFT.

Mikkel Bjørn and Michael Trott,

Towards consistent Electroweak Precision Data constraints in the SMEFT

Laure Berthier and Michael Trott

On interference and non-interference in the SMEFT

Andreas Helset and Michael Trott

Incorporating doubly resonant W^{\pm} data in a global fit of SMEFT parameters to lift flat directions.

Laure Berthier, Mikkel Bjørn and Michael Trott

Equations of Motion for the Standard Model Effective Field Theory: Theory and Applications.

Abdurrahman Barzinji, Michael Trott and Anagha Vasudevan,

On expansions in neutrino effective field theory

Gitte Elgaard-Clausen and Michael Trott

Recent Phd school slides with info: yumpu.com/en/document/view/62870587/marialaach The research of this group is defining the LHC physics legacy: <u>https://indico.cern.ch/event/826136/contributions/3603139/</u> <u>attachments/1928348/3195116/MethodologyEF_STXS.pdf</u>