Status of the SHIFT project

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On behalf of the SHIFT collaboration

November 22, 2020

Uppsala University

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- Collaboration between theorists and experimentalists from Uppsala, Stockholm, and Chalmers

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- Three approaches/tracks:
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    2. Composite Higgs Models (CHMS)
    3. Indirect approach (Effective Field Theory and di-Higgs)
- Collaboration between theorists and experimentalists from Uppsala, Stockholm, and Chalmers
- This talk is not exhaustive. A complete list of publications can be found here.

People involved

- **Stockholm**: Nabila Ahlgren, Stefio Yosse Andrean, Filip Backman, Laura Barranco Navarro, Christophe Clement, Karl Gellerstedt, Tom Ingebretsen Carlson, Xuanhong Lou, David Milstead, Patrawan Pasuwan, Laura Pereira Sanchez, Joergen Sjolin, Sara Strandberg, Antonia Strubig, Ellen Riefel
- **Chalmer's**: Avik Banerjee, Diogo Buarque Franzosi, Gabriele Ferretti
- **Uppsala**: Elin Bergeaas Kuutmann, Christina Dimitriadi, Rikard Enberg, Arnaud Ferrari, Max Isacson, Simon Johansson Nyberg, Thomas Mathisen, Luca Panizzi, Jakub Salko, Venugopal Ellajosyula
- **International collaborators**: Rachid Benbrik, Yao-Bei Liu, Tanumoy Mandal, Stefano Moretti

Higgs fine-tuning problem

- Higgs mechanism responsible for generating masses of SM particles
- Mass of the Higgs boson itself destabilized by quantum effects $\rightarrow$ Higgs fine-tuning problem

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

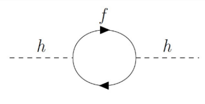
$$\mu^2 = m_{bare}^2 - \frac{|\lambda_f|^2}{8\pi^2}\left(\Lambda_{UV}^2 + ...\right) + ...$$

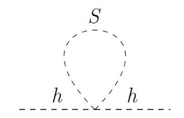
- Largest corrections from top quarks
- This leading correction can be controlled if there exist new particles with properties similar to those of the top quark
- Two main classes of solutions studied in the SHIFT project:
    - Supersymmetry
    - Composite Higgs Models (CHM)

Supersymmetry track

Solving the Higgs Fine-Tuning problem (SHIFT)
Supersymmetry

- Every SM particle has a 'super'partner with similar properties but a spin that differs by half a unit





$$\mu^2 = m^2_{bare} - \frac{|\lambda_f|^2}{8\pi^2}\left(\Lambda^2_{UV} + ...\right) + \frac{\lambda_S}{16\pi^2}\left(\Lambda^2_{UV} + ...\right) + ...$$

- Cancellation if $\lambda_S = |\lambda_f|^2$
- Higgs boson mass protected by chiral symmetry
- Dominant sources of fine-tuning are removed by scalar top squarks or stops

Next-to-minimal Supersymmetric Standard Model with Gauge-mediated SUSY breaking

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	gauge eigenstates	mass eigenstates
Higgs bosons	h_d, h_u, h_s, a, a_s	H_1, H_2, H_3, H_4, H_5 $(H_1, H_2, H_3, A_1, A_2)$
	H_d^-, H_u^+	$H^\pm$
neutralinos	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0, \tilde{S}, \tilde{\eta}_1, \tilde{\eta}_2, \tilde{\eta}_3$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0, \tilde{\chi}_6^0, \tilde{\chi}_7^0, \tilde{\chi}_8^0$
charginos	$\tilde{W}^\pm, \tilde{H}_d^-, \tilde{H}_u^+$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

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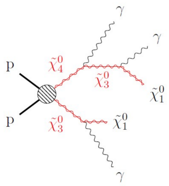

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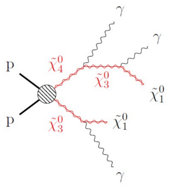
- Identified model with large $\sigma \times$BR larger than about 1 fb to $3\gamma + E_T^{miss}$ final state, with low background.



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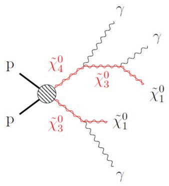
- **On-going analysis looks promising at generator level.** Limited by MC statistics for the background.



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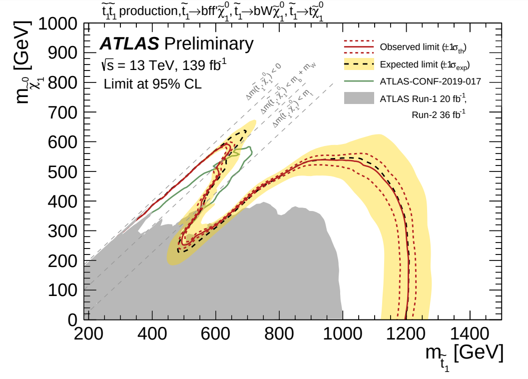
R-parity conserving SUSY

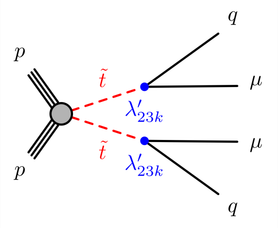
- Stop decays to top quark pairs in final states with one isolated e/μ, multiple jets, and E_T^{miss}
- Decay mode depends on SUSY mass spectrum.
- Updated result on full Run 2 dataset released as CONF note in February: ATLAS-CONF-2020-003
- Paper is coming soon.
- Plan to continue involvement also in the future

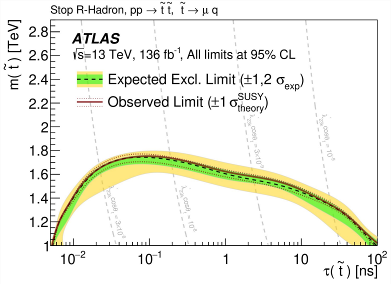


R-parity violating SUSY

Allow stop to decay to SM particles via RPV couplings.

- Stop long-lived due to small coupling.
- Displaced vertex (DV) + muon
- Published in August 2020: Phys. Rev. D 102, 032006
- DV + jets in progress





Compositeness track

Solving the Higgs Fine-Tuning problem (SHIFT)
Composite Higgs models

- The Higgs boson is a composite pseudo-Nambu-Goldstone boson (pNGB) from spontaneous breaking of a global symmetry in a new strongly coupled sector
  $\rightarrow$ This protects the Higgs mass.
- All models of composite Higgs predict **new scalars** in the form of pNGBs (with the notable exception of the MCHM)
- Models with partial compositeness predict **new vector-like fermions**.
- **pNGBs**
  - **Neutral**: Light but with weak couplings
  - **Electrically charged**: Heavier, possibly $\mathcal{O}(1\text{ TeV})$
  - **Coloured**: even heavier, above $\mathcal{O}(1\text{ TeV})$
- **Vector-like fermions**
  - **Quarks**: $\mathcal{O}(\text{TeV})$
  - **Leptons**: $\mathcal{O}(\text{TeV})$

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- Mesonic ($\langle\psi\psi\rangle$ and $\langle\chi\chi\rangle$) and baryonic condensates ($\langle\psi\psi\chi\rangle$ or $\langle\psi\chi\chi\rangle$) are formed.

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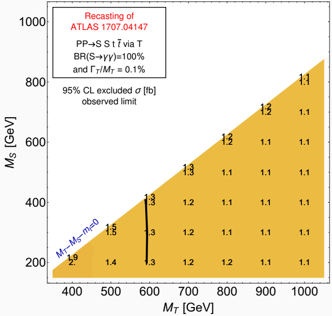
- Types of condensates depend on the gauge group and the coset being considered.

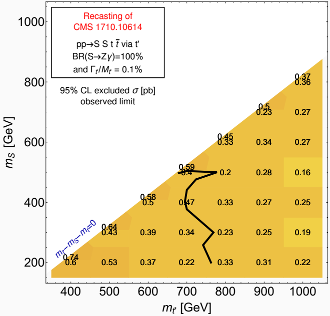
Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)			5/12		M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)			5/3		M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	√
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	√
	SO(10)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	5/12		M7	
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	Sp(4)	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	1/3	$\psi\psi\chi$	M8	√
	SO(11)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	8/3		M9	
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	SO(10)	$4 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M10	
	SU(4)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	2/3		M11	√
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	SU(5)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	4/9	$\psi\psi\chi$	M12	

arxiv:1902.06890

Exotic decays of vector-like top partners

- ATLAS and CMS have searched for vector-like top-partners decaying to SM particles ($T \to Ht, Zt, Wb$) $\Rightarrow$ Bounds around 1.3 TeV
- These searches assume 100% branching to SM particles $\to$ **Constraints relax if this is not true.** arxiv:1907.05929
- Many models predict non-standard decays of VLT
- Example: $T \to St$, where S can be a scalar or a pseudo-scalar
- Branching ratios of these exotic states depend on their properties.





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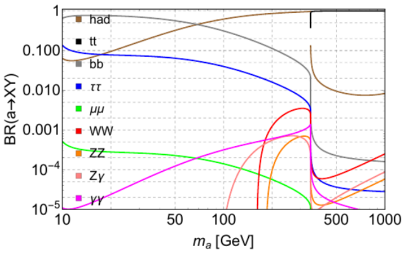
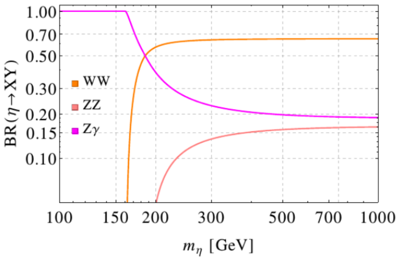
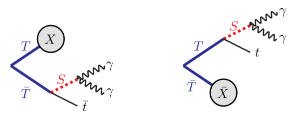
- Example: $T \rightarrow St$, where S can be a scalar or a pseudo-scalar
- **Branching ratios of these exotic states depend on their properties.** arxiv:1803.00021

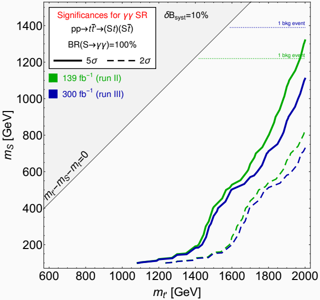


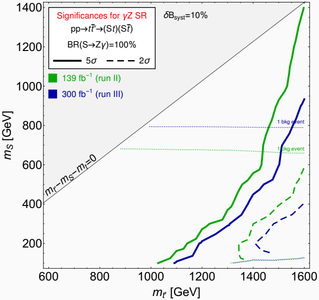


Possible final states of interest

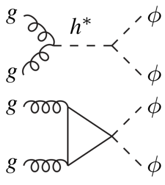


- Model independent search for VLT with decays to non-SM particles decays to exotic scalar + t/b
- Signal: $pp \to T\bar{T} \to tS(\to Z\gamma/\gamma\gamma) + X$
- Optimistic reach in Run 2 and Run 3 evaluated in arxiv:1907.05929
- Analysis in ATLAS progessing well.



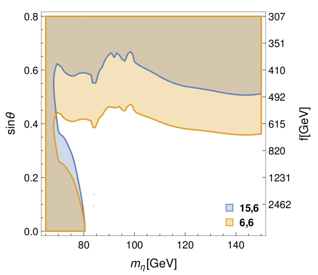


pNGBs in composite Higgs models



$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{2}\sqrt{1-\frac{v^2}{f_\phi^2}}\,\frac{m_h^2}{v}h\phi^2$$

$$\mathcal{L}_{\text{eff}} \supset \frac{m_t}{2f_\phi^2}\phi^2\bar{t}t$$



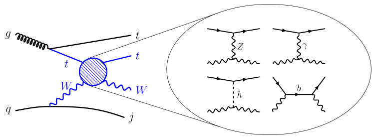
- Non-QCD production of pNGBs considered.
- The production cross-section is a function of m_ϕ and f_ϕ
- The BRs will define benchmarks characterized by coupling values.
- Bounds in the $\{m_\phi, \sin\theta\}$ plane (where $\sin\theta = \frac{\langle v \rangle}{f_\phi}$) for each decay channel and for benchmark choices of the couplings.

arxiv:2005.13578

Indirect track

Probing the EW $ttWj$ production

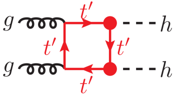
- Experimental constraints demanding custodial symmetry leaves the top-Z couplings unprotected.
- Constraints still very weak and they can be mapped to the top sector EFT operators.
- Wt scattering has enhanced energy sensitivity compared to ttZ.



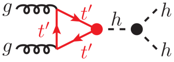
- However, signal very challenging to simulate and fake lepton background requires fitting tricks to avoid signal bias.
- Measurement on-going in ATLAS.

Di-Higgs production with jets

- Goal is to understand **if jets can provide additional information in di-higgs production** for probing new scalar or vector like top partners in the loops or for improved EFT sensitivity.
- Studies the borderland between resonant and non-resonant production.
- Very educational for general understanding of the emergence and validity of EFTs.
- One model is based on signal decomposition based on coupling factorisation allowing for flexible access to the full parameter space for each mass point. For example:



$\mathcal{A}_i \propto \kappa^2_{ht't'}$



$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{ht't'}$

$$\sigma_S^{t'}(m_t') = \kappa^2_{ht't'}\ \hat{\sigma}_5(m_t') + \kappa^2_{hhh}\kappa^2_{ht't'}\ \hat{\sigma}_6(m_t') + \kappa^4_{ht't'}\ \hat{\sigma}_7(m_t') + (\kappa^{ht't}_{L,R})^4\ \hat{\sigma}_8(m_t') + \kappa_{hht't'}\ \hat{\sigma}_9(m_t')$$

Summary

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  - On-going pheno study on NMSSM+GMSB models showed promise at the generator level.
  - Full Run 2 analyses in R-parity conserving and violation MSSM are public.
    (ATLAS-CONF-2020-003 and Phys. Rev. D 102, 032006)
  - New final states being added to the above analyses.

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- **General news**: 2020 Nordita program that was canceled because of COVID-19 is rescheduled for 11-30 April 2021, likely in a hybrid mode.