Experimental Physics at Hadron Collider



Lecture 4

Searches for New Physics Conclusions and Outlook

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CERN Summer Students Lectures

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CMS diphoton event







Lecture 1: Basic concepts, cross sections and QCD results

- Preamble
- Context and mission of the LHC -
- Fundamentals of hadron collisions -
- Luminosity and total cross section -
- Cross sections measurements -
- Jet production measurements -
- Measurement of the strong coupling constant -

Lecture 2: SM Measurements

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

Outline

Lecture 3: Higgs physics

- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

Lecture 4: Searching for new physics BSM and future Hadron Colliders

- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Searches for unconventional signatures
- EFT and high energy observables
- Outlook on future colliders
- Conclusions



Direct Searches for New Physics

From Lectures 2 and 3:



In lectures 2 and 3 we have discussed how important it is to probe new physics through precision measurements of Standard Model parameters.

Within the current precision all measurements are consistent with the Standard Model

To further probe the Standard Model it is also extremely important to search directly for new phenomena which would yield different predictions than the Standard Model.

Global fit of the Standard Model: fully consistent!



With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

The Standard Model still raises a large number of open questions and there are important unexplained phenomena that are very important guidelines to search directly for new physics scenarios.



The <u>Unsatisfactory</u> Standard Model

Z = - 4 Fm FMV + ご ダダ + h.c. + Y: Y: 4:0+ h.c. + $D_{\mu}\phi l^2 - V(\phi)$

More fundamental questions (not explained by the SM):

- Description of gravity at small distant scales?
- Why is the mu parameter in the Higgs potential negative?
- Why is the charge quantised and the charge of the electron equal that of the proton (grand unification)?
- ... and many more!

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

 $\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$

From neutron electric dipole moment measurements

The strong CP problem

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries
- Gauge Hierarchy (and Naturalness) -
- Flavour hierarchy (includes neutrino masses)

Experimental observations (not explained by the SM):

- Anomalous magnetic moment of the muon (experiment currently taking data at FERMILAB (muon g-2, results coming soon) over 3σ discrepancy with expectation.
- B Lepton Flavor anomalies (see secures by Mark)
- and of course...

4

Unexplained Observed Phenomena



- The nature of Dark Energy?



Why is the Hierarchy an Issue? Naturalness

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:

Solutions:

- Weakly coupled: introduce fields in the theory that can cancel the quadratic divergence and alleviate the fine tuning (e.g. SUSY)
- **Strongly coupled** (Composite): in this case the above does not apply. The Higgs could be either a generic bound state or a pseudo goldstone boson (similarly to the pion in Chiral perturbation theory).



Warped extra **dimensions**: Difference between scales generated by warping.

Anthropic principle: fine tuning is acceptable since it is a condition for existence of the universe as it is.



Nutshell description:

- For all fermions degree of freedom SUSY adds a boson degree of freedom
- To all bosons degree of freedom, SUSY adds a fermions

What SUSY addresses:

- It resolves the gauge hierarchy (naturalness problem)
- It allows unification of gauge couplings
- Local SUSY requires gravitino and therefore via SUSY naturally brings the graviton and is an essential ingredient in string theory
- It provides a natural candidate for dark matter

The only few (non negligible) issues:

- It has not been found! If it exists it has to be broken
- If the super-partners are too heavy fine tuning reemerges and one of the main issues (naturalness) reappears).
- With a much larger number of fields come a much larger number of parameters!

Supersymmetry

An elegant, simple and complete solution...



The main predictions of SUSY

- Superpartners that should be at a reachable scale!
- A candidate dark matter particle: the neutralino (typically).
- An extended Higgs sector. Its minimal realisation is the MSSM (2 Higgs doublets so 5 Higgs bosons, 3 neutral and 2 charged).



The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



Reaching SUSY from an extended Higgs sector

SUSY could modify the couplings of the Higgs

From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

μ -jets channel

Intricate search for a non trivial interference pattern in ttbar mass.



Search for Higgs to top pair

Searches for Natural and Strongly Produced SUSY



Searches for Natural and Strongly Produced SUSY



More intricate scenarios

Weak production of charginos, neutralinos and sleptons

Weak production in compressed scenarios





1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

R-Parity violating SUSY



Resulting in topologies without LSP in the final state and therefore no MET.

 $\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$

RPV components of superpotential



Searches for Charginos and Neutralinos (Examples)

Weak production of charginos and neutralinos



Example of boosting to find small mass differences.

SUSY in highly compressed scenarios

 $p'' \tilde{\chi}_{1}^{\pm}$ χ_{1} π^{\pm} Disappearing tracks topologies (Uses MET Trigger - requires ISR jet) ATLAS-PHYS-PUB-2018-031

p



Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).





Very Large Number of SUSY Searches (in large variety of topologies and models)

ATLAS SUSY Searches* - 95% CL Lower Limits March 2019						ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}$ HL/HE-LHC SUSY Sea		Search	HL-LHC , $\int \mathcal{L} dt = 3ab^{-1}$: 5σ discovery (95% CL exclusion) HE-LHC, $\int \mathcal{L} dt = 15ab^{-1}$: 5σ discovery (95% CL exclusion)		Simulatio					
	Model	Signat	ture ∫	<i>L dt</i> [fb ⁻¹	Mass limit		i i i i i i i i i i i i i i i i i i i	Reference		Model	e,μ,τ,γ	Jets	Masslimit			Section
	$ ilde{q} ilde{q}, ilde{q} ightarrow q ilde{\chi}_1^0$	0 <i>e</i> , μ 2-6 je	ets E_T^{miss}	36.1	<i>q̃</i> [2x, 8x Degen.] 0.9	1.55	$m(\tilde{\chi}_1^0) \leq 100 \text{GeV}$	1712.02332		$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_{1}^{0}$	0	4 jets	ž.	2.9 (3.2) TeV	$m(\tilde{\chi}_1^0)=0$	2.1.1
hes	$\tilde{a}\tilde{a}$ $\tilde{a} \rightarrow a \bar{a} \tilde{\chi}_{1}^{0}$	mono-jet 1-3 je $0 e, \mu$ 2-6 je	ets E_T^{miss} ets E_T^{miss}	36.1 36.1	<i>q</i> [1×, 8× Degen.] 0.43 0.71	2.0	$m(\tilde{q})-m(\chi_1^0)=5 \text{ GeV}$ $m(\tilde{\chi}_1^0)<200 \text{ GeV}$	1711.03301 1712.02332	0	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	4 jets	8	5.2 (5.7) TeV	$m(\tilde{x}_1^0)=0$	2.1.1
earc	-0	., .,			ğ Forbidden	0.95-1.6	$m(\tilde{\chi}_1^0)=900 \text{ GeV}$	1712.02332	luin	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_1^0$	0	Multiple	Γ. B.	2.3 (2.5) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.3
/e S($\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^\circ$	$3 e, \mu$ 4 jet $ee, \mu\mu$ 2 jet	ts $E_T^{ m miss}$	36.1 36.1	τος τος	1.85 1.2	m(𝔅˜1)<800 GeV m(ĝ)-m(𝔅˜1)=50 GeV	1706.03731 1805.11381	G	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{c} \tilde{\chi}_{1}^{0}$	0	Multiple	Ξ.	2.4 (2.6) TeV	m($\tilde{\chi}_{1}^{0}$)=500 GeV	2.1.3
clusiv	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 <i>e</i> , μ 7-11 je 3 <i>e</i> , μ 4 jet	iets E_T^{miss} ts	36.1 36.1	$ ilde{ ilde{g}} ilde{ ilde{$	1.8	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0)=200 \text{ GeV}$	1708.02794 1706.03731		NUHM2, $\tilde{g} \rightarrow t\tilde{t}$	0	Multiple/2b	ž.	5.5 (5.9) TeV		2.4.2
Inc	$\tilde{g}\tilde{g},\tilde{g}{\rightarrow}t\bar{t}\tilde{\chi}^0_1$	$0-1 e, \mu$ $3 b$	E_T^{miss}	79.8	õ oo e	2	1.15 $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	ATLAS-CONF-2018-041		$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0	Multiple/2b	Ĩ,	1.4 (1.7) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.2, 2.1
	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	5 e,μ 4 jet		36.1	2	1.25	$\mathbf{m}(\tilde{g}) \cdot \mathbf{m}(\mathcal{X}_1) = 300 \text{ GeV}$	1706.03731	top	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0	Multiple/2b	Ĩ,	0.6 (0.85) TeV	$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$	2.1.2
	$b_1 b_1, b_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^x$	Multir Multir Multir	ple ple ple	36.1 36.1 36.1	b_1 Forbidden 0.9 b_1 Forbidden 0.58-0.82 b_1 Forbidden 0.7	m(Â	$\begin{array}{c} m(\tilde{\chi}_{1}^{0}) = 300 \ \mathrm{GeV}, \ BR(b\tilde{\chi}_{1}^{0}) = 1\\ m(\tilde{\chi}_{1}^{0}) = 300 \ \mathrm{GeV}, \ BR(b\tilde{\chi}_{1}^{0}) = BR(t\tilde{\chi}_{1}^{+}) = 0.5\\ \tilde{\chi}_{1}^{0}) = 200 \ \mathrm{GeV}, \ m(\tilde{\chi}_{1}^{+}) = 300 \ \mathrm{GeV}, \ BR(t\tilde{\chi}_{1}^{+}) = 1\end{array}$	1708.09266, 1711.03301 1708.09266 1706.03731	ŝ	$\tilde{\imath}_1\tilde{\imath}_1,\tilde{\imath}_1{\rightarrow}b\tilde{\chi}^*/\iota\tilde{\chi}^0_1,\tilde{\chi}^0_2$	0	Multiple/2b	7	3.16 (3.65) TeV		2.4.2
rks	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 <i>e</i> ,μ 6 <i>b</i>	E_T^{miss}	139	<i>b</i> ₁ Forbidden	0.23-1.35	$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$	SUSY-2018-31		$\tilde{\mathcal{X}}_{1}^{+}\tilde{\mathcal{X}}_{1}^{-}, \tilde{\mathcal{X}}_{1}^{\pm} \rightarrow W^{\pm}\tilde{\mathcal{X}}_{1}^{0}$	2 e,µ	0-1 jets	\tilde{X}_{i}^{\pm}	0.66 (0.84) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.1
squa	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$	0-2 <i>e</i> , <i>µ</i> 0-2 jets/	$/1-2 b E_T^{\text{miss}}$	36.1	\tilde{t}_1 0.23-0.48 \tilde{t}_1 1.0		$\Delta m(\chi_2, \chi_1) = 130 \text{ GeV}, m(\chi_1) = 0 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	5051-2018-31 1506.08616, 1709.04183, 1711.11520	lino.	$\tilde{\chi}_1^* \tilde{\chi}_2^0$ via WZ	3 e, µ	0-1 jets	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.92 (1.15) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.2
gen. a ct pro	$\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP	Multip	ple	36.1	<i>ī</i> ₁ 0.48-0.84	m($\tilde{\chi}_1^{\pm}$)=150 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^{0}$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520	harg eutre	$\tilde{\chi}_1^*\tilde{\chi}_2^0$ via Wh, Wh $\!$	1 e, µ	2-3 jets/2b	$\tilde{X}_1^{\pm}/\tilde{X}_2^0$	1.08 (1.28) TeV	m(X ⁰ ₁)=0	2.2.3
3 rd g	$ \begin{aligned} t_1 t_1, t_1 \to \tau_1 b \nu, \tau_1 \to \tau G \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \to c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \to c \tilde{\chi}_1^0 \end{aligned} $	$0 e, \mu$ 2 c	$E_T^{\text{miss}} = E_T^{\text{miss}}$	36.1 36.1	<i>c</i> 0.85	1.10	$m(\tilde{\tau}_1) = 800 \text{ GeV}$	1805.01649	U e	$\tilde{\chi}_2^* \tilde{\chi}_4^0 {\rightarrow} W^* \tilde{\chi}_1^0 W^* \tilde{\chi}_1^*$	2 e,µ	-	$\tilde{\chi}_2^* / \tilde{\chi}_4^0$	0.9 TeV	$m(\tilde{\chi}_{1}^{0})=150, 250 \text{ GeV}$	2.2.4
		$0 e, \mu$ mono-	-jet E_T^{miss}	36.1			$\begin{array}{c} m(\tilde{t}_1,\tilde{c})\text{-}m(\tilde{\chi}_1^0){=}50\mathrm{GeV} \\ m(\tilde{t}_1,\tilde{c})\text{-}m(\tilde{\chi}_1^0){=}5\mathrm{GeV} \end{array}$	1805.01649 1711.03301	~	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} + \tilde{\chi}_{3}^{0}\tilde{\chi}_{1}^{0}, \tilde{\chi}_{2}^{0} \rightarrow Z\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{\pm} \rightarrow W\tilde{\chi}_{1}^{0}$	2 e,µ	1 jet	$\tilde{\chi}^{\pm}_{\pm}/\tilde{\chi}^{0}_{2}$	0.25 (0.36) TeV	m(x10)=15 GeV	2.2.5.1
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 <i>e</i> ,μ 4 <i>b</i>	E_T^{miss}	36.1	<i>ĩ</i> ₂ 0.32-0.88		m($\tilde{\chi}_1^0$)=0 GeV, m(\tilde{t}_1)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986	sinc	$\tilde{X}_1^{\pm} \tilde{X}_2^0 + \tilde{X}_2^0 \tilde{X}_1^0, \tilde{X}_2^0 \rightarrow Z \tilde{X}_1^0, \tilde{X}_1^{\pm} \rightarrow W \tilde{X}_1^0$	2 e, µ	1 jet	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.42 (0.55) TeV	m(X10)=15 GeV	2.2.5.1
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	$\begin{array}{c} \textbf{2-3} \ e, \mu \\ ee, \mu \mu \end{array} \ge 1$	$E_T^{\text{miss}} \\ E_T^{\text{miss}} \\ .$	36.1 36.1	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = 0.6 $ $ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = 0.17 $		$\begin{array}{c} m(\tilde{\chi}_1^0) {=} 0 \\ m(\tilde{\chi}_1^\pm) {-} m(\tilde{\chi}_1^0) {=} 10 \ GeV \end{array}$	1403.5294, 1806.02293 1712.08119	Higg	$\tilde{\boldsymbol{\chi}}_{2}^{0} \tilde{\boldsymbol{\chi}}_{1}^{*}, \tilde{\boldsymbol{\chi}}_{1}^{*} \tilde{\boldsymbol{\chi}}_{1}^{\mp}, \tilde{\boldsymbol{\chi}}_{1}^{*} \tilde{\boldsymbol{\chi}}_{1}^{0}$	2μ	1 jet	\tilde{X}_{2}^{0}	0.21 (0.35) TeV	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0){=}5{\rm GeV}$	2.2.5.2
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\pm}$ via WW $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^{0}$ via Wh	2 e, μ 0-1 e,μ 2 b	E_T^{miss} E_T^{miss}	139 36.1			$ m(\tilde{\chi}_1^0) = 0 $ $ m(\tilde{\chi}_1^0) = 0 $	ATLAS-CONF-2019-008 1812.09432	Vino	$\tilde{\chi}_{2}^{*}\tilde{\chi}_{4}^{0}$ via same-sign WW	2 e,µ	0	Wino	0.86 (1.08) TeV		2.4.2
N 9Ct	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L / \tilde{\nu}$	2 <i>e</i> , µ	E_T^{miss}	139	$\tilde{\chi}_{1}^{\pm}$ 1.0		$m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$	ATLAS-CONF-2019-008	2	$\tilde{\tau}_{i} = \tilde{\tau}_{i} = , \tilde{\tau} \rightarrow \tau \tilde{\chi}_{i}^{0}$	2 7	-	+	0.53 (0.73) TeV	$m(\tilde{\chi}_{+}^{0})=0$	2.3.1
dire	$\chi_1^-\chi_1^-/\chi_2^-, \chi_1^- \rightarrow \tilde{\tau}_1 \nu(\tau \tilde{\nu}), \chi_2^- \rightarrow \tilde{\tau}_1 \tau(\nu \tilde{\nu})$	2τ	E_T	36.1	$\begin{array}{cccc} \chi_1/\chi_2 & & 0.76 \\ \chi_1^{+}/\chi_2^{0} & & 0.22 \end{array}$	$m(\! ilde{\mathcal{X}}_1^{\pm}) ext{-}m$		1708.07875	ac .	77	2τ. τ(e, μ)		-	0.47 (0.65) TeV	$m(\tilde{x}_{i}^{0})=0$ $m(\tilde{x}_{i})=m(\tilde{x}_{0})$	2.32
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}_{1}^{0}$	$\begin{array}{ccc} 2 \ e, \mu & & 0 \ \text{jet} \\ 2 \ e, \mu & & \geq 1 \end{array}$	ts E_T^{miss} I E_T^{miss}	139 36.1	${ ilde\ell}{ ilde\ell} { ildel}{ ildel} 0.7$		$ \begin{array}{c} m(\tilde{\chi}_1^0) = 0 \\ m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV} \end{array} $	ATLAS-CONF-2019-008 1712.08119	St	77	2τ, τ(e, μ)	-	Ŧ	0.81 (1.15) TeV	$m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\tau}_{L})=m(\tilde{\tau}_{R})$	2.3.4
	$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	$0 \ e, \mu \ge 3$	$b E_T^{\text{miss}}$	36.1	<i>H</i> 0.13-0.23 0.29-0.88		$BR(\tilde{\chi}_1^0 \to h\tilde{G}) = 1$	1806.04030	_	carz caci	Discos tele	4 - 1		0.0407-14		
J		$+e,\mu$ 0 jet	E_T	30.1			$BR(\mathcal{X}_1 \to ZG) = 1$	1710 00110		$\chi_1^*\chi_1^*, \chi_1^*\chi_1^*$, long-lived χ_1^* $\tilde{\chi}^{\pm}\tilde{\chi}^{\pm}$, $\tilde{\chi}^{\pm}\tilde{\chi}^0$ long-lived $\tilde{\chi}^{\pm}$	Disapp. trk.	1 jet 1 iet	$\chi_1^{\pm} = [\tau(\chi_1^{\pm})=\ln s]$ $\tilde{\chi}^{\pm} = [\tau(\tilde{\chi}^{\pm})=\ln s]$	0.8 (1.1) TeV	Wino-Like X ₁	4.1.1
-live icles	Direct $x_1 x_1$ prod., long-lived x_1	Disapp. lik i je		30.1			Pure Wind Pure Higgsino	ATL-PHYS-PUB-2017-019		MCCM Fighterwood DM	Disapp. trk	1 jot	N ₁ [(N ₁)-maj	0.99 (0.9) ToV	Wee Rep DM	4.1.1
-ong part	Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron $\tilde{g} \rightarrow a a \tilde{Y}^0$	Multir Multir	ple ple	36.1 36.1	\tilde{g} $\tilde{v} = [\tau(\tilde{v}) = 10 \text{ ns. } 0.2 \text{ ns}]$	2.0	$\mu(\tilde{\chi}^0) = 100 \text{ GeV}$	1902.01636,1808.04095 1710.04901.1808.04095		MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	2.0 (2.1) TeV	Wino-like DM	4.1.3
	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	<i></i> <i></i>		3.2	$\tilde{\gamma}_{\tau}$	1.9	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$	1607.08079	lived les	MSSM Electroweak DM	Disapp. trk.	1 jet	DM mass	0.28 (0.3) TeV	Higgsing-like DM	413
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 <i>e</i> , <i>µ</i> 0 jet	ts E_T^{miss}	36.1	$\dot{\chi}_{1}^{\pm} / \ddot{\chi}_{2}^{0} [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] $ 0.82	1.33	$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1804.03602	artic	MSSM, Electroweak DM	Disapp. trk	1 jet	DM mass	0.55 (0.6) TeV	Higgsino-like DM	4.1.3
>	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\chi_1^{\circ}, \chi_1^{\circ} \rightarrow qqq$	4-5 large Multip	<i>-R</i> jets ple	36.1 36.1	$ \begin{array}{l} \tilde{g} & [m(\mathcal{X}_1) = 200 \text{ GeV}, 1100 \text{ GeV}] \\ \tilde{g} & [\lambda_{112}'' = 2e^{-4}, 2e^{-5}] \end{array} $	1.3 1.9 5 2.0	$\mathbf{Large} \ \mathcal{X}_{112}^{0}$ $\mathbf{m}(\tilde{\chi}_{1}^{0})=200 \text{ GeV, bino-like}$	1804.03568 ATLAS-CONF-2018-003	2 0	noom, Lieutoweak Din	2.0400.000	. jet		0.00 (0.0) 101	(¹) (0) (1)	4.1.5
R	$\widetilde{t}\widetilde{t}, \ \widetilde{t} \to t\widetilde{\chi}_1^0, \ \widetilde{\chi}_1^0 \to tbs$	Multip 2 jets -	ple ⊾2 h	36.1	$\tilde{g} = [\lambda_{323}'' = 2e-4, 1e-2]$ 0.55 1.0	5	$m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003		\tilde{g} R-hadron, $\tilde{g} \rightarrow qq \chi_1^0$ $\tilde{g} = B_{-}hadron, \tilde{g} \rightarrow qa \tilde{\chi}^0$	0	Multiple	g = [T(g) = 0.1 - 3 ns] $\tilde{g} = [T(\tilde{g}) = 0.1 - 10 \text{ ns}]$	3.4 TeV	m(X ₁)=100 GeV	4.2.1
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 jets + $2 e, \mu$ $2 b$)	36.1	$\tilde{t}_1 = [qq, v_3]$ 0.42 0.01 $\tilde{t}_1 = 10 + V_{} + 10 + 0 + 10 + V_{} = 0$	0.4-1.45	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$	1710.05544		CMCD 5	dias!	monpre	5	2.0 100		4.2.1
		1 μ DV	/	136	$t_1 [1e-10 < \lambda_{23k}^* < 1e-8, 3e-10 < \lambda_{23k}^* < 3e-9] $ 1.0	1.6	$BR(t_1 \to q\mu) = 100\%, \cos\theta_t = 1$	ATLAS-CONF-2019-006		GMSB µ→µG	aispi. µ	-	μ	0.2 TeV	cr =1000 mm	4.2.2
						1	• • • • • • •									arXi
*Only	a selection of the available mas	s limits on new st mits are based or	tates or n	1(D^{-1}	1	Mass scale [TeV]					1	0 ⁻¹ 1 Mass so	cale [TeV]		
sim	olified models, c.f. refs. for the as	sumptions made).													

Example from ATLAS (same for CMS)

2 TeV

HL-LHC YR 1812.07831

3 TeV





Very Large Number of SUSY Searches (in large variety of topologies and models)

ATLAS SUSY S	earches* - 95% CL Lower Limi	ts		ATLAS Preliminary	HL/HE-LH	IC SUSY	Searches	HL-LHC, $\int \mathcal{L} dt = 3ab^{-1}$; 5σ d HE-LHC, $\int \mathcal{L} dt = 15ab^{-1}$; 5σ d	scovery (95% CLexclusion)	Si	mulat	
Model	Signature $\int \mathcal{L} dt [\mathbf{fb}^{-1}]$	Mass limit	1	$\sqrt{s} = 13$ lev Reference	Model	e, μ, τ, γ	Jets	Mass limit			Sectio	
$\tilde{q}\tilde{q},\tilde{q}\! ightarrow\!q ilde{\chi}_1^0$	$0 e, \mu$ 2-6 jets E_T^{miss} 36.1 \tilde{q} [2x, 8x Degen	0.9 1.55	$m(\tilde{\chi}_1^0) < 100 \text{ GeV}$	1712.02332	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_{1}^{0}$	0	4 jets 🖁		2.9 (3.2) TeV	$m(\bar{\chi}_{1}^{0})=0$	2.1.	
$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$0 \ e, \mu$ 2-6 jets E_T 36.1 \tilde{g}	2.	$m(q)-m(x_1)=5 \text{ GeV}$ $m(\tilde{\chi}_1^0)<200 \text{ GeV}$	1712.02332	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_{1}^{n}$	0	4 jets g		5.2 (5.7) TeV	$m(\chi_1^0)=0$	2.1.1	
$\overset{\text{Gorden}}{\overset{\text{Gorden}}}{\overset{\text{Gorden}}}{\overset{{Gorden}}{\overset{Gorden}}}}}}}}}}}}}}}}}}$	$3 e, \mu$ 4 jets 36.1 \tilde{g}	1.85	$m(\tilde{\chi}_1) = 900 \text{ GeV}$ $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$	1712.02332	$\tilde{g}_{\tilde{g}}, \tilde{g} \rightarrow t \tilde{\chi}_{1}^{0}$	0	Multiple 2		2.3 (2.5) TeV 2.4 (2.6) TeV	$m(\chi_1)=0$ $m(\chi_1^0)=500 \text{ GeV}$	2.1.	
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	$e_{e,\mu\mu}$ 2 jets E_T^{min} 36.1 g 0 e,μ 7-11 jets E_T^{miss} 36.1 g	1.2	$m(\hat{g})-m(\chi_1)=50 \text{ GeV}$	1805.11381		-			5.5 (5.9) TeV		2.4.	
$\widetilde{g}\widetilde{g}, \ \widetilde{g} \to t \widetilde{t} \widetilde{X}_1^0$	$3 e, \mu$ 4 jets 36.1 g $0-1 e, \mu$ $3 b E_T^{miss}$ 79.8 g $2 e, \mu$ 4 jets 26.1 g								1.4 (1.7) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.2, 2	
$\tilde{h}_{t}\tilde{h}_{t}\tilde{h}_{t}\sim b\tilde{v}^{0}/t\tilde{v}^{\pm}$	$3 e, \mu$ 4 jets 36.1 g	Forbidden							0.6 (0.85) TeV	$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$	2.1.	
$v_1v_1, v_1 \rightarrow v_{\Lambda} 1/\Lambda 1$	Multiple 36.1 \tilde{b}_1 Multiple 36.1 \tilde{b}_1	Take ho	ne mess	ages for Hl	LHC:				3.16 (3.65) TeV		2.4.	
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$0 e, \mu$ $6 b$ E_T^{miss} 139 \tilde{b}_1 For \tilde{b}_1	bidden		0.66 (0.84) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.						
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$	0-2 e, μ 0-2 jets/1-2 $b E_T^{\text{miss}}$ 36.1 \tilde{t}_1			0.92 (1.15) TeV	$m(\tilde{\chi}_1^0)=0$	2.2.2						
$\begin{array}{c} \mathbf{i}_{11}, \text{ weil-tempered LSP} \\ \mathbf{i}_{10}, \mathbf{i}_{1} \rightarrow \tilde{\tau}_{1} bv, \tilde{\tau}_{1} \rightarrow \tau \tilde{G} \\ \mathbf{i}_{10}, \mathbf{i}_{1} \rightarrow \tilde{\tau}_{10} v, \tilde{\tau}_{10} \rightarrow \tau \tilde{G} \\ \mathbf{i}_{10}, \mathbf{i}_{10} \rightarrow \tilde{\tau}_{10} v, \tilde{\tau}_{10} \rightarrow \tau \tilde{G} \end{array}$	$\prod_{i \to \tau \tilde{G}} \frac{1\tau + 1e_{\mu}\tau 2 \text{ jets}/1b}{0 e^{\mu}} = \sum_{i \to \tau} \frac{50.1}{2} \prod_{i \to \tau} \frac{r_{1}}{1}$									$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=150,250 \text{ GeV}$	2.2.	
$c_1 c_1 t_1, t_1 \rightarrow c x_1 / c c, c \rightarrow c x_1$	USCOVERY POTENTIAL OT GIUINOS UP TO $U(2-3 IeV)$											
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ 4 b E_T^{miss} 36.1 $\tilde{\iota}_2$								0.42 (0.55) TeV	$m(\tilde{x}_{1}^{0})=15 \text{ GeV}$	2.2.5	
$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	$\begin{array}{cccc} 2\text{-}3 \ e,\mu & E_T^{\text{miss}} & 36.1 \\ ee,\mu\mu & \geq 1 & E_T^{\text{miss}} & 36.1 \\ \end{array} \begin{array}{c} \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \\ \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 & 0.17 \end{array}$	$\mathbf{D}_{\mathbf{i}}$									2.2.5	
$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via WW $ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via Wh	$\frac{2e,\mu}{0.1e,\mu} = \frac{E_T^{\text{miss}}}{2b} = \frac{139}{E_T^{\text{miss}}} = \frac{\chi_1^2}{36.1} \qquad \qquad$											
$\sum_{\substack{\lambda = 1 \\ \lambda_1 \neq \lambda_1}} \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\pm} \forall ia \tilde{\ell}_L / \tilde{\nu}$	$ \begin{array}{cccc} & & & & & & & & & & & & & & & & & $										2.3.1	
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0}$	$2 e, \mu$ 0 jets E_T^{miss} 139 $\tilde{\ell}$			- + + ' - - f [0.47 (0.65) TeV	$m(\tilde{\chi}_1^0)=0, m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.2	
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	$\begin{array}{cccc} 2 \ e, \mu & \geq 1 \\ 0 \ e, \mu & \geq 3 \ b \end{array} \begin{array}{c} E_T^{\text{miss}} & 36.1 \\ \tilde{\ell} & 0.18 \\ \tilde{H} & 0.1 \end{array}$	3-0.23 DIS	covery p	otential of E	EVV SUSY	up to	O(1 Iev)		0.81 (1.15) TeV	$m(\tilde{\chi}_1')=0, m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.4	
7	$4 e, \mu$ 0 jets E_T^{miss} 36.1 \tilde{H}	0.3				•	X	,	0.8 (1.1) TeV	Wino-like $\tilde{\chi}_1^a$	4.1.	
Direct $\chi_1 \chi_1$ prod., long-lived $\lambda_1 = \frac{1}{2}$	χ_1^- Disapp. trk 1 jet E_T^{mass} 36.1 $\chi_1^ \tilde{\chi}_1^\pm$ 0.15								0.88 (0.9) TeV	Wino-like DM	4.1.	
Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq$	Multiple 36.1 \tilde{g} $\tilde{\chi}_1^0$ Multiple 36.1 \tilde{g} $[\tau(\tilde{g}) = 10 \text{ ns}, 0]$.2 ns]	m(X1)=100 GeV	1710.04301,1000.04033	b "moom, Electroweak DM	וואספוע ווא.	i jei Dimina	55	2.0 (2.1) TeV	Wino-like DM	4.1.	
$LFV \ pp \to \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \to e\mu/e\tau/\mu^{2}$ $\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{2}^{0} \to WW/Z\ell\ell\ell\ell_{YY}$	$\tau \qquad e\mu, e\tau, \mu\tau \qquad 3.2 \qquad \tilde{\nu}_{\tau} \\ 4 e, \mu \qquad 0 \text{ jets} \qquad E_{\tau}^{\text{miss}} \qquad 36.1 \qquad \tilde{\chi}_{\tau}^{*} / \tilde{\chi}_{0}^{0} \qquad [d_{i33} \neq 0].$	1.9	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$ m $(\tilde{\chi}^0)=100$ GeV	1607.08079 1804.03602	ອຊີອີ ສີ່ງວີ ຫຼື MSSM, Electroweak DM	Disapp. trk.	1 jet DM ma	SS	0.28 (0.3) TeV	Higgsino-like DM	4.1.3	
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$	4-5 large- <i>R</i> jets 36.1 $\tilde{g} [m(\tilde{\chi}^0_1)=200 \text{ Ge}]$ Multiple 36.1 $\tilde{g} [\tilde{\chi}^0_{112}=2e-4, 2e-4]$	V, 1100 GeV] 1.3 1.9 5] 1.05 2.	Large λ_{112}'' $m(\tilde{\chi}_1^0)=200$ GeV, bino-like	1804.03568 ATLAS-CONF-2018-003	ິງ ຕິ MSSM, Electroweak DM	M Disapp. trk.	1 jet DM ma	S5	0.55 (0.6) TeV	Higgsino-like DM	4.1.3	
$\underbrace{\widetilde{tt}, \widetilde{t} \to t \widetilde{\chi}_1^0, \widetilde{\chi}_1^0 \to tbs}_{\widetilde{t}_1 \widetilde{t}_1, \widetilde{t}_1 \to bs}$	Multiple 36.1 $\tilde{g} [\lambda''_{323}=2e-4, 1e-2]$ 2 jets + 2 b 36.7 $\tilde{t} [aa, bs]$	^{2]} 0.55 1.05 0.42 0.61	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003 1710.07171	\tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^n$ \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^n$	0	Multiple g [r(3.4 TeV 2.8 TeV	m(x1)=100 GeV	4.2.	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	داد-8, 3e-10< λ' _{23k} <3e-9]	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1$	1710.05544 ATLAS-CONF-2019-006	GMSB $\tilde{\mu} \rightarrow \mu \tilde{G}$	displ. µ	- μ <u>μ</u>		0.2 TeV	cr =1000 mm	4.2.	
*Only a selection of the availabl	le mass limits on new states or 10 ⁻¹	<u> </u>	Mass scale [TeV]				10 ⁻¹	1	IVaTI ele se aseM		ar	
phenomena is shown. Many o simplified models, c.f. refs. for	f the limits are based on the assumptions made.											
									$2 T_{\rm e}$			
			2 Iev						JIEV	HL	LH	
										18	312.0	
	Example from	TI AILAS (same to	or UNIS)									





Generic Search for Dark Matter

Generic Searches for Dark Matter



Complementarity of searches at colliders, direct and indirect searches!

Searches for Dark Matter at the LHC

- Invisible Higgs searches (Lecture 3).

- In order to be observed invisible final states need additional objects to be associated with. Mono-anything searches: Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top.



Generic Searches for Dark Matter



A jet with pT of 1707 GeV. The ETmiss of 1735 GeV is shown as the white dashed line. No additional jets with pT above 30 GeV is found.

Mono jet search prospects

Reach close to TeV range at HL-LHC



Generic Searches for Dark Matter

Searches for the dark matter mediator

in e.g. in dijet events extending at low masses



Numerous strategies to also cover lower masses e.g.:

- boosting (ISR photon/jet) -
- Trigger level analyses _

Dijet Trigger level analysis





Searches for new Physics Beyond the Standard Model in non SUSY theories

Panorama of Searches for Conventional Signatures

Searches for Vector Like Quarks

Simple additional chiral fermions are essentially ruled out by Higgs data.

Fermions that are not Chiral

- The L and R components transform the same way under SM symmetries.
- Interact with SM through mixing with SM quarks. —
- Present in models where the Higgs is a pseudo Goldstone _ boson (e.g. in Composite Higgs and little Higgs models).
- Present in Warped Extra dimension models. -

Large variety of possible states and complex channels

- Heavy quark partners with charges -1/3, 2/3, 4/3 and 5/3. -
- Complex channels looking for T(2/3), B(1/3): Ht+X, Wt+X, Wb+X, Zb+X, Zt+X (Performed at Run 2) so far and T(5/3) 4tops final state.

And still many more !!

Searches for W'and Z'

High mass states motivated in many theories e.g. Grand Unified and additional gauge symmetries.

- electrons, muons, taus, jets, b-jets and tops.
- di-bosons including vector bosons and Higgs bosons

Searches for high mass states of spin 0 and 2

Motivated in Randall Sundrum models (Graviton and radion)

Searches in various channels dijet, diphoton and di-leptons

Any many more

- Quark compositness
- **Leptoquarks:** predicted in grand unified theories and interest raised by lepton flavor universality anomalies
- Heavy neutrinos: produced in theories for neutrino masses (e.g. Seesaw)
- High mass and high activity events: strong gravity (from extra dimension theories), mini black holes, quantum black holes...
- Searches for low mass states.





Searches for High Mass Resonances





ATLAS Dijet search

ATLAS-CONF-2019-007

Limits on excited quarks at 6.7 TeV



Highest mass (central) dijet event ~8 TeV







Transverse mass (in lepton-MET search)



Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

Electron pT = 1.1 TeVMET = 1.16 TeV



Improving Reconstruction Techniques

Jet substructure reconstruction improvements reconstructing a vector boson, a Higgs boson or a top quark.



Search for intermediate mass resonance as a single jet investigating its substructure.

Searches for diboson in two boosted jets signatures

Di boson candidate event in a fully hadronic search, each jet has a mass compatible with a vector boson (W or Z).

Direct searches at the cross roads with Standard Model measurements in the high energy domain



Jet cross sections predictions and jet calibration with multi TeV jets

Measurement of di-boson in the high mass regime

Any deviation in the measurements with a special attention to the high energy regime can be the manifestation of new higher energy domain new physics.

Powerfull and consistent framework to interpret the effect of higher energy new physics (above a higher scale): Effective Field Theory.

Very Large Number of Searches (in large variety of topologies and models)

Overview of CMS EXO results

		CMS		
SSM Z'(<i>ll</i>)	М _{7'}	1803.06292 (2 <i>l</i>)		
SSM $Z'(a\bar{a})$	<u>г</u> М _{7'}	1806.00843 (2 j)		2.7
LFV Z', BR($e\mu$) = 10%	M _{7'}	1802.01122 (e µ)		
SSM $W'(\ell v)$	М _W	1803.11133 (<i>l</i> + E ^{miss})		
SSM W'($q\bar{q}$)	M _{W'}	1806.00843 (2 j)		
SSM W'(τv)	M _W	$1807.11421 (\tau + E_{\tau}^{miss})$		
LRSM $W_{\rm R}(\ell N_{\rm R}), M_{\rm N_{\rm P}} = 0.5 M_{\rm W_{\rm P}}$	M _{W-}	1803.11116 (2ℓ + 2j)		
LRSM $W_B(\tau N_B)$, $M_{N_B} = 0.5 M_{W_B}$	M _W	1811.00806 ($2\tau + 2i$)		
Axigluon, Coloron, $cot\theta = 1$	M _C	1806.00843 (2j)		
scalar LQ (pair prod.), coupling to 1 st gen. fermions, $\beta = 1$	MLO	1811.01197 (2e + 2j)	1.44	
scalar LQ (pair prod.), coupling to 1^{st} gen. fermions, $\beta = 0.5$	Min	1811.01197 (2e + 2j; e + 2j + E ^{miss})	1.27	
scalar LQ (pair prod.), coupling to 2^{nd} gen. fermions, $\beta = 1$	Min	1808.05082 (2μ + 2j)	1.53	
scalar LQ (pair prod.), coupling to 2^{nd} gen. fermions, $\beta = 0.5$	Min	1808.05082 ($2\mu + 2j; \mu + 2j + E_{m}^{miss}$)	1.29	
scalar LQ (pair prod.), coupling to 3^{rd} gen. fermions, $\beta = 1$	Min	1811.00806 (2τ + 2j) 1.02		
scalar LQ (single prod.), coup. to 3^{rd} gen. ferm., $\beta = 1, \lambda = 1$	M _{LQ}	1806.03472 (2τ + b) 0.74		
excited light guark ($q\bar{q}$), $\Lambda = m_a^*$	M∝*	1806.00843 (2i)		
excited light quark (qy), $f_S = f = f' = 1$, $\Lambda = m_a^*$	q <i>М</i> _*	$1711.04652 (\mathbf{v} + \mathbf{i})$		
excited b quark, $f_s = f = f' = 1$, $\Lambda = m_s^*$	q M⊾∗	$1711.04652 (\mathbf{v} + \mathbf{i})$	1.8	
excited electron. $f_s = f = f' = 1$. $\Lambda = m_s^*$. т ₀ М., *	1811.03052 (v + 2 e)		
excited muon, $f_S = f = f' = 1$, $\Lambda = m_{ij}^{\mu}$	л.,е М.,.*	$1811.03052 (\mathbf{y} + 2\mathbf{\mu})$		
μ	μ			
quark compositeness ($qar{q}$), $\eta_{ m LL/RR}=1$	$\Lambda^+_{LL/RR}$	1803.08030 (2j)		
quark compositeness ($\ell\ell$), $\eta_{ m LL/RR}=1$	$\Lambda^+_{LL/RR}$	1812.10443 (2 <i>l</i>)		
quark compositeness ($qar{q}$), $\eta_{ ext{LL/RR}}=-1$	$\Lambda_{LL/RR}^{-}$	1803.08030 (2j)		
quark compositeness ($\ell\ell$), $\eta_{ m LL/RR}=-1$	$\Lambda_{LL/RR}^{-}$	1812.10443 (2 <i>l</i>)		
ADD (jj) HLZ, $n_{ED} = 3$	Ms	1803.08030 (2 j)		
ADD ($\gamma\gamma$, $\ell\ell$) HLZ, $n_{ED} = 3$	Ms	1812.10443 (2γ, 2 <i>ℓ</i>)		
ADD G_{KK} emission, $n = 2$	MD	1712.02345 (≥ 1j + E ^{miss})		
ADD QBH (jj), $n_{ED} = 6$	М _{ОВН}	1803.08030 (2j)		
ADD QBH ($e\mu$), $n_{ED} = 6$	M _{QBH}	1802.01122 (e µ)		
RS G _{KK} ($q\bar{q}, gg$), $k/\overline{M}_{Pl} = 0.1$	М _{Gкк}	1806.00843 (2j)	1.8	
RS $G_{KK}(\ell \ell)$, $k/\overline{M}_{Pl} = 0.1$	MGKK	1803.06292 (2 <i>l</i>)		
RS G _{KK} ($\gamma\gamma$), $k/\overline{M}_{Pl} = 0.1$	MGKK	1809.00327 (2γ)		
RS QBH (jj), $n_{ED} = 1$	M _{OBH}	1803.08030 (2j)		
RS QBH ($e\mu$), $n_{ED} = 1$	M _{QBH}	1802.01122 (е µ)		
non-rotating BH, $M_{\rm D}$ = 4 TeV, $n_{\rm ED}$ = 6	M _{BH}	1805.06013 (≥ 7j(ℓ, γ))		
split-UED, $\mu \ge 4$ TeV	1/R	1803.11133 (ℓ + E ^{miss})		2.9
(axial-)vector mediator ($\chi\chi$), $g_a = 0.25$, $g_{DM} = 1$, $m_y = 1$ GeV	Mmed	1712.02345 (≥ 1j + E ^{miss})	1.8	
(axial-)vector mediator $(q\bar{q})$, $q_{\rm c} = 0.25$, $q_{\rm DM} = 1$, $m_{\rm v} = 1$ GeV	Mmod	1806.00843 (2 j)		2.6
scalar mediator $(+t/t\bar{t})$, $q_{q} = 1$, $q_{DM} = 1$, $m_{y} = 1$ GeV	M _{med}	1901.01553 (0 , $1\ell + \ge 3i + E_{miss}^{miss}$) 0.29		
pseudoscalar mediator $(+t/t\bar{t})$, $q_{g} = 1$, $q_{DM} = 1$, $m_{y} = 1$ GeV	M _{med}	1901.01553 (0 , $1\ell + \ge 3i + E_{\pm}^{\text{miss}}$) 0.3		
scalar mediator (fermion portal), $\lambda_{\mu} = 1, m_{\chi} = 1$ GeV	M.⊾	1712.02345 (≥ 1i + E ^{miss})	1.4	
complex sc. med. (dark QCD), $m_{\pi_{DK}} = 5$ GeV, $c\tau_{X_{DK}} = 25$ mm	, , φ _u М _{Хрк}	1810.10069 (4 j)	1.54	
	0.0			
I ype III Seesaw, $B_e = B_\mu = B_\tau$	M _{Sigma}	$1/08.07962 (\geq 3l)$ 0.84		
string resonance	Ms	1806.00843 (2 j)		
		0.1 1	.0	
		n	ass scale	[TeV]

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

Ŭ

4 TeV

10.0

7.7

3.5

6.1

5.5

12.8

8.2

5.9

3.6

Example from CMS (similar for ATLAS)



Very Large Number of Searches (in large variety of topologies and models)

Overview of CMS EXO results



Example from CMS (similar for ATLAS)

Unconventional Signatures

Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.



Image from H. Russel

Difficult signatures requiring specific complex reconstruction and trigger!





Run: 366994 Event: 453765663 2018-11-26 18:32:03 CEST



A Spectacular Heavy Ion Event







Conclusion on Searches

Are there any Anomalies in the Searches done so far?



Local (global) significance at 95.3 GeV : 2.90σ (**1.5σ**)

Upper Limit on



Acceptance ~50% Limit on oxBR~120 fb

Not confirmed (but not conclusively excluded)

Astonishingly small (number of) anomalies given the number of analyses made at the LHC!

ATLAS-CONF-2018-025









Conclusions of Searches

- A vast program of searches has been carried out at the Energy Frontier -
- No stone was left unturned, and any significant deviation has been thoroughly verified (e.g. with _ the Lepton Flavor Universality anomaly in B decays - see M. Williams lectures)



A common effort with the Theory community that has provided fundamental benchmarks to be searched for at the LHC

No significant deviation from the Standard Model has been found so far

Towards HL-LHC and Precision Physics at LHC



http://collider-reach.web.cern.ch/collider-reach/

Towards HL-LHC still a **factor of 20** in luminosity:

- Still room for discoveries!
- Given that the **doubling time of the luminosity** is now counted in **several years**: discoveries will take time, and times for spectacular discoveries (in the sense of immediate) are over.
- Low hanging fruits typically have been (or are being) harvested! Immense amount of work in trying to expand search reach beyond the root-L:
 - With new ideas and developments at all levels. —
 - Improving precision (theoretical and experimental) will be key!





Outlook and Conclusions

The LHC a « Marvel of Technology »

First mention of the LHC in 1977 by sir John Adams (former CERN director) as an option of a superconducting hadron collider to be hosted in the LEP tunnel (requesting that the LEP be made large enough to host a proton collider of at least 3 TeV beam energy). That was a period very busy with extremely important physics results.

- 1984: CERN and ECFA workshop in Lausanne.
- 1992: ATLAS and CMS letters of intent.
- 1994: Approval of the LHC (1993 cancellation of 40 TeV SSC).
- 1995: LHC CDR published.
- 1997-98: ATLAS, CMS, LHCb and ALICE experiments approved.
- 2003-2005: Caverns completed installation started.
- 2008: Experiments installed.
- 2008 September 10: Start of the LHC.
- 2008 September 19: Incident occurs between dipole and quadrupole.
- **2009** November: Beams are back in the LHC!

- 1988: LEP tunnel completed (Europe's largest civil engineering project prior to the channel tunnel).

2007: LHC dipoles installed in LHC (after having been all individually checked at SM18).

Since 2009: 10 years of successful operations and landmark results and 20 years of running ahead!





Glimpse at Future Hadron Colliders

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	
Location	CERN	CERN	CERN	Ch
Circ.	27 km	27 km	100 km	55
COM energy	14 (15?) TeV	27 TeV	100 TeV	70
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	
PU	up to 200	up to 800	up to 1000	
Bunch sp.	25 ns	25 ns	25 ns	
Field	8T	16T	16T	
When?	Until 2037	After 2037?	After 2037	

Much much more in Lecture by R. Corsini

A b at 5 TeV can travel 50cm and a tau 10 cm Decay products of a Z at 10 TeV are separated by $\Delta R = 0.01$

Detector, Trigger DAQ, Reconstruction challenges

Two challenges: higher PU (1000) higher pT

Answer: granularity and resolution

SppC

nina TBD

- 100 km

-140 TeV

TBD

TBS

25 ns

20T

TBS





Conclusions of the Lectures

- the smallest scales.
- results:
 - with the Standard Model Higgs boson.
 - so far revealed no signal of physics beyond the Standard Model.
 - searches, but also a precision measurements machine!
- discoveries and interesting measurements!
- should continue pushed. It will be a common effort with the Theory community.
- Very exciting program ahead with great opportunities for you at LHC and beyond!

Hadron colliders have been extremely successful to unveil many of the secrets of nature at

The first 10 years of the LHC running have been an immense success with major landmark

The discovery of the Higgs boson, and the measurement of its properties all compatible

A vast campaign of searches at the energy frontier leaving no stones unturned, which have

The LHC has proved not to be only a discovery machine with a vast potential in direct

However only 5% of the data has been collected so far, there is therefore still a vast potential for

The level of precision reached in reconstruction and measurements is outstanding, but limits