

Experimental Physics at Hadron Colliders CERN Summer Students Lectures, July 24-26, 2024 - Lecture 4/4

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Work Plans

Lecture 1: Introduction, fundamentals, cross sections

Lecture 2: Standard model measurements

Lecture 3: Higgs physics

Lecture 4: Searches for new physics

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Standard Model (recap)

Our best theory to describe the most basic building block of the universe

- Relativistic Quantum Field Theory
- Data: symmetries SU(2)xU(1)xSU(3) and fields



describes the gauge interactions of the quarks and leptons

parametrized by 3 gauge couplings **g**₁, **g**₂, **g**₃

breaks electro-weak symmetry and gives mass to the W^{\pm} and Z bosons

Higgs sector

 $+ |\mathcal{D}_{\mathcal{P}}|^{2} - \vee (\phi)$

2 free parameters Higgs mass Higgs vev

flavor sector



leads to masses and mixings of the quarks and leptons

22 free parameters to describe the masses and mixings of the quarks and leptons

Ordinary matter consists only of three types of matter particles: the up and down quark and electrons







Phenomena not explained

- Gravity
- Dark Matter
- Dark Energy
- Neutrino Masses
- Matter-antimatter asymmetry

Theory problems







Experimental results not explained

- No experimental result is accepted as definitively contradicting the SM
- At any given moment several experimental results differ significantly from SM predictions.
- Some examples include
 - Anomalous magnetic dipole moment of muon
 - Flavor anomalies
 - W mass measurements
- Are these statistical fluctuations, systematic biases, or first evidence for BSM?







What makes a BSM candidates and good or attractive BSM theory?









- What makes a BSM candidates and good or attractive BSM theory?
 - Containment as low-energy approximation
 - Predictive power it explains new phenomena
 - Simplicity it has a simpler structure
 - Deductibility it has fewer ad hoc assumptions and free parameter
 - Completeness inherent reasons for nonexistence of otherwise possible effects









Effective Field Theory Approach

Motivation for ETFs

Energy scale of new physics (Λ) might be out of reach for direct searches



deviations from the SM requiring high precision measurements



Not insensitive to its effects, but the pattern in our data may be more subtle, i.e. we find small



Effective Field Theory Approach



- a four-fermion interaction of strength GF
 - Full theory replaced by a Taylor expansion in terms of E/m_W
 - Accurate predictions up to a scale $\Lambda \sim m_W$



Not a new idea. Long history in particle physics - e.g. Fermi theory of decay

In low energy regime, we can "integrate out" the W boson and replace it with

No knowledge of the SM required. Follows from know fields (fermions) and symmetries (QED)

Effective Field Theory Approach

- Expanding w/o explicit new physics model
 - Provides a renormalisable quantum field theory
 - Results are universal and can be propagate to other experiments
 - Minimal non-redundant set of operators is called bases.
 - It gets complicated quickly. "Warsaw" basis includes 2499 distinct operators

$$L_{\text{EFT}} = L_{\text{SM}} + \sum_{i} \frac{C_{i}^{(5)}}{\Lambda} \mathcal{O}_{i}^{(5)} + \sum_{i} \frac{C_{i}^{(0)}}{\Lambda} \mathcal{O}_{i}^{(5)} + \sum_{i} \frac{C_$$

Lepton-number violating





 \mathcal{O}_i : operators = interaction terms at a given expansion order C_i : operators = Wilson coefficients, free parameters

Effective Field Theory Approach Example Higgs Physics









Dark Matter Searches





Seek evidence for DM particle interactions with

- Nucleons, nuclei, electrons, photons ...
- May prove DM but not identify particle

• May identify particle but cannot prove DM



Pingo

What is dark matter?

- 1) WIMP
- 2) Axion
- 3) MACHOs (Massive Compact Halo Objects)
- 4) Sterile Neutrinos
- 5) Primordial black whole
- 6) None of the above
- 7) I don't have an opinion









Dark Matter Searches at Colliders

- DM particle do not leave visible signatures in collider experiments
- DM inferred using missing energy, missing mass, or **missing transverse** momentum

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Dark Matter Searches









Dark Matter Searches

Mono-jet analysis





Impressive event with ~1.7 TeV jet and ~1.7 TeV missing transverse energy

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- Generalization of the spacetime symmetries of QFT that transforms bosons and fermions and vice versa
- Provides a framework to answer many questions and puzzles in particle physics
- If SUSY were an exact symmetry of nature, particles and superpartners would differ in spin by 1/2 and degenerate in mass. Superpartners have not been observed!













- General strategy and typical SUSY signatures
 - High-pT jets from heavy squark and gluinos
 - Missing momentum from two LSPs produced at the end of a decay chain
 - Electroweakino decays with leptons
- Selection variables
 - H_T, E_T^{miss}, m_{eff}, …
 - Long-lived particles



. . .











- Simplified models
- Historically, searches were performed on full SUSY models
 - In Run 1, simplified models became the standard
 - Focus on a specific process X decay chain
 - Interpret the analysis in this context
- Avoid tailored analysis for specific benchmarks
- More robust analysis strategies









Direct Searches for Supersymmetry Gluino Searches







ATLAS SUSY Searches* - 95% CL Lower Limits

00	Model	Si	ignatur	e	∫£ dt [fb [−]	1]	Ма	ass limit
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0$	0 ε, μ	2-6 jets	E_T^{miss}	139	ą	[1x, 8x Degen.]	
arches		mono-jet	1-3 jets	E_T^{miss}	36.1	ą ~	[8x Degen.]	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \chi_1$	0 ε,μ	2-0 jets	E_T	139	ig ig		
Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_{1}^{0}$	1 e, µ	2-6 jets		139	ĝ		
ive	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_{1}^{0}$	ее, µµ	2 jets	E_T^{miss}	36.1	ĝ		
clus	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{X}_{1}^{\prime}$	0 e, μ SS e, μ	7-11 jets 6 jets	$E_T^{\rm mass}$	139 139	ē ē		
lnc	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$	0-1 <i>e</i> ,μ SS <i>e</i> ,μ	3 <i>b</i> 6 jets	$E_T^{ m miss}$	79.8 139	ĩg ĩg		
	$ ilde{b}_1 ilde{b}_1$	0 e, µ	2 b	$E_T^{ m miss}$	139	${ar b_1\ ar b_1}$		
arks tion	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} b \tilde{\chi}_2^0 {\rightarrow} b h \tilde{\chi}_1^0$	0 e, μ 2 τ	6 b 2 b	E_T^{miss} E_T^{miss}	139 139	${ar b_1\ ar b_1}$	Forbidden	
and	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e, µ	≥ 1 jet	E_T^{miss}	139	\tilde{t}_1		
pro	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$	1 e, µ	3 jets/1 b	E_T^{miss}	139	Ĩ ₁		Forbidde
ect	$t_1t_1, t_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau G$	1-2 T	2 jets/1 b	Emiss Emiss	139	t_1 \bar{c}		
3" Gii	$I_1I_1, I_1 \rightarrow c X_1 / c c, c \rightarrow c X_1$	0 e, μ	mono-jet	E_T^{miss}	139	\tilde{t}_1		
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0$	1-2 e, µ	1-4 b	E_T^{miss}	139	\tilde{t}_1		
	$l_2 l_2, l_2 \rightarrow l_1 + Z$	3 e, µ	1.6	Enuss	139	<i>t</i> ₂	-	Forbidde
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets ee, μμ	≥ 1 jet	E_T^{miss} E_T^{miss}	139 139	$\frac{\tilde{\chi}_1^{\pm}}{\tilde{\chi}_1^{\pm}}$	$\frac{\tilde{\chi}_{1}^{0}}{\tilde{\chi}_{2}^{0}}$ 0.205	
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via WW	2 e, µ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$		0.42
	$\chi_1^+\chi_2^\circ$ via Wh $\tilde{v}^\pm \tilde{v}^\mp$ via \tilde{e}_{\pm} (2)	Multiple <i>t</i> /jets	5	Emiss Emiss	139	$\chi_1^{-}/$	X ₂ Forbidden	
N: N	$\chi_1\chi_1 \text{via } \ell_L/\nu$ $\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}^0$	2 ε, μ 2 τ		E_T E_T^{miss}	139	$\frac{\lambda_1}{\tilde{\tau}}$	[TL, TR.L] 0.16-0.3	0.12-0.39
шë	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, µ	0 jets	E ^{miss}	139	ĩ	0.056	
	ĤĤ Ĥ→hĈ/ZĈ	0 e. µ	≥ 1 jet > 3 h	E_T Emiss	36.1	ĩ	0.13-0.23	
	111,11-10,20	4 e,μ	0 jets	$E_{T_{int}}^{T}$	139	Ĥ	0.10-0.20	
		0 <i>e</i> ,µ ≧	≥ 2 large jet	$s E_T^{mas}$	139	Ĥ		
ъ.,	$\operatorname{Direct} \tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{ m miss}$	139	$\frac{\tilde{\chi}_{1}^{\pm}}{\tilde{\chi}_{1}^{\pm}}$	0.21	
live	Stable g R-hadron		Multiple		36.1	ē	0.2.1	
ng-	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple		36.1	ĝ	[τ(ĝ) =10 ns, 0.2 ns]	
P g	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell \tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	ē, μ̃		24
						T		
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e,μ	0 into	remiss	139	$\tilde{\chi}_1^{\pm}/$	$\tilde{\chi}_1^{\theta}$ [BR($Z\tau$)=1, BR(Ze)=1]	
	$\chi_1 \chi_1 / \chi_2 \rightarrow W W / Z \ell \ell \ell \ell \nu \nu$ $\tilde{a} \tilde{a} \rightarrow a a \tilde{\nu}^0 \tilde{\nu}^0 \rightarrow a a a$	4 e, µ	Ujets I-5 large iet	E _T	36.1	\tilde{x}_1 / \tilde{a}	$X_2 = [A_{i33} \neq 0, A_{12k} \neq 0]$ $Im(\tilde{X}^0) = 200 \text{ GeV} = 1100 \text{ GeV}$	
~	$\widetilde{gg}, \widetilde{g} \rightarrow qq \alpha_1, \alpha_1 \rightarrow qq q$ $\widetilde{t}, \widetilde{t} \rightarrow t\widetilde{X}^0, \widetilde{X}^0, \rightarrow ths$		Multiple	•	36.1	ь ĩ	[λ''_{112} =2e-4, 1e-2]	
J.	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{1}^{\pm} \rightarrow bbs$		$\geq 4b$		139	ĩ	- 323	Forbidd
Ľ.	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b		36.7	\tilde{t}_1	[qq, bs]	0.42
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, µ 1 µ	2 b		36.1	\tilde{t}_1	[1e-10< X' <1e-8, 3e-10< X'	<3e-91
	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}/\tilde{\chi}_{1}^{0}, \tilde{\chi}_{2}^{0} \rightarrow tbs, \tilde{\chi}_{1}^{+} \rightarrow bbs$	1-2 е. ц	≥6 iets		139	\tilde{X}^0_{-}	0.2-0.3	2
		, p	,510			~1	012-010	_
*Only a	a selection of the available ma	ass limits on r	new state	s or	1	0-1		

phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Preliminary

Reference

 $\sqrt{s} = 13 \text{ TeV}$

1.85 m(𝔅10)≤400 GeV 2010.14293 0.9 $m(\tilde{q})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 2102.10874 2.3 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 2010.14293 1.15-1.95 Forbidden m($\tilde{\chi}_1^0$)=1000 GeV 2010.14293 2.2 m($\tilde{\chi}_{1}^{0}$)<600 GeV 2101.01629 1.2 m(g)-m($\tilde{\chi}_{1}^{0}$)=50 GeV 1805.11381 m($\bar{\chi}_{1}^{0}$) <600 GeV 1.97 2008.06032 1.15 1909.08457 $m(\tilde{g})-m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$ 2.25 m($\tilde{\chi}_{1}^{0}$)<200 GeV ATLAS-CONF-2018-041 1.25 1909.08457 $m(\tilde{g})-m(\tilde{\chi}_1^0)=300 \text{ GeV}$ 1.255 m(X⁰₁)<400 GeV 2101.12527 0.68 2101.12527 10 GeV<Δm(b̃₁, X̃⁰₁)<20 GeV 0.23-1.35 $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ 1908.03122 0.13-0.85 $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ ATLAS-CONF-2020-031 1.25 $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 2004.14060,2012.03799 Forbidden 0.65 $m(\tilde{\chi}_1^0)=500 \text{ GeV}$ 2012.03799 Forbidden 1.4 m(71)=800 GeV ATLAS-CONF-2021-008 0.85 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1805.01649 0.55 $m(\tilde{t}_1, \tilde{c})-m(\tilde{\ell}_1^0)=5 \text{ GeV}$ 2102.10874 0.067-1.18 m(X20)=500 GeV 2006.05880 0.86 $m(\tilde{\chi}_{1}^{0})=360 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=40 \text{ GeV}$ 2006.05880 Forbidden 0.96 $m(\tilde{\chi}_1^0)=0$, wino-bino 2106.01676, ATLAS-CONF-2021-022 $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^{0})=5$ GeV, wino-bino 1911.12606 0.42 $m(\tilde{\chi}_1^0)=0$, wino-bino 1908.08215 m(X10)=70 GeV, wino-bino 2004.10894, ATLAS-CONF-2021-022 1.06 1.0 $m(\tilde{\ell}, \tilde{v})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1908.08215 2-0.39 1911.06660 $m(\tilde{\chi}_{1}^{0})=0$ 0.7 $m(\tilde{\chi}_{1}^{0})=0$ 1908.08215 1911.12606 $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$ 0.29-0.88 $BR(\tilde{\chi}_{1}^{0} \rightarrow h\bar{G})=1$ 1806.04030 $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$ 0.55 2103.11684 0.45-0.93 ATLAS-CONF-2021-022 0.66 Pure Wino ATLAS-CONF-2021-015 Pure higgsino ATLAS-CONF-2021-015 2.0 1902.01636,1808.04095 2.05 2.4 1710.04901,1808.04095 m($\tilde{\chi}_{1}^{0}$)=100 GeV 0.7 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ 2011.07812 $\tau(\tilde{l}) = 0.1 \text{ ns}$ 2011.07812 0.625 1.05 Pure Wino 2011.10543 0.95 1.55 m($\tilde{\chi}_1^0$)=200 GeV 2103.11684 Large $\lambda_{112}^{\prime\prime}$ 1.3 1.9 1804.03568 1.05 ATLAS-CONF-2018-003 0.55 m(X10)=200 GeV, bino-like 0.95 Forbidden m($\tilde{\chi}_{1}^{\pm}$)=500 GeV 2010.01015 0.42 0.61 1710.07171 $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ 0.4-1.45 1710.05544 BR($\tilde{t}_1 \rightarrow q\mu$)=100%, cos θ_i =1 1.6 2003.11956 1.0 Pure higgsino ATLAS-CONF-2021-007

Mass scale [TeV]

BSM Searches Beyond SUSY

High mass resonances

BSM Searches Beyond SUSY

			CMS preliminary	
	String resonance	м		
	Zy resonance	м		
	Wy resonance	м		
	Higgs y resonance	м		
륲	Color Octect Scalar, k ² _s = 1/2	м		
	Scalar Diquark $t\bar{t} + \phi$, pseudoscalar (scalar), $\sigma^2 = x BR(\phi \rightarrow 2t) > = 0.03(0.004)$	N		0.0
	$t\bar{t} + \phi$, pseudoscalar (scalar), $g_{aa}^2 \times BR(\phi \rightarrow 2I) > = 0.03(0.04)$, M		0.0
	$pp + Z/\gamma + X$	M		
	quark compositeness (11), $\eta_{LL,nit} = 1$	$\Lambda^+_{tL,m}$		
at a ctie	quark compositeness (II), $\eta_{LL,NK} = -1$	AL.m		
aş	Excited Lepton Contact Interaction	M		
	Enclose Explore conduct metaclore	~		
	vector mediator (qq), $g_q = 0.25$, $g_{cre} = 1$, $m_\chi = 1$ GeV	м		
	vector mediator ($t\tilde{t}$), $g_q = 0.1$, $g_{cm} = 1$, $g_t = 0.01$, $m_x > 1$ TeV	м		
	(axial-)vector mediator (qq), $g_q = 0.25$, $g_{OM} = 1$, $m_x = 1$ GeV	м		
	(axial-)vector mediator ($\chi\chi$), $g_{ij} = 0.25$, $g_{cm} = 1$, $m_{\chi} = 1$ GeV	м		
	(axial)-vector mediator (rt), $g_q = 0.1$, $g_{QM} = 1$, $g_l = 0.1$, $m_g \ge m_{med}/2$ scalar mediator (+t/ θ), $a_l = 1$, $a_{med} = 1$ GeV	M		
	scalar mediator ($t\bar{t}$), $q_{r} = 1$, $g_{rm} = 1$, $m_r = 1$ GeV			
	scalar mediator (fermion portal), $\lambda_u = 1$, $m_x = 1$ GeV	м		
2	pseudoscalar mediator (+j/V), $g_q = 1$, $g_{cM} = 1$, $m_\chi = 1$ GeV	м		
Matt	pseudoscalar mediator (+ $t\bar{t}\bar{t}$), $g_q = 1$, $g_{cre} = 1$, $m_x = 1$ GeV	м		
1 a	pseudoscalar mediator (tt), $g_q = 1$, $g_{DN} = 1$, $m_g = 1$ GeV complex so med (dark OCD) m = 5 GeV cr = 25 mm	м		
•	Barvonic Z', $a_i = 0.25$, $a_{int} = 1$, $m_e = 1$ GeV			
	Z' mediator (dark QCD), $m_{dark} = 20$ GeV, $r_{mu} = 0.3$, $\alpha_{dark} = \alpha_{dark}^{mak}$			
	$Z' - 2HDM$, $g_{Z'} = 0.8$, $g_{CM} = 1$, $tan\beta = 1$, $m_x = 100 \text{ GeV}$	м		
	Leptoquark mediator, $\beta = 1$, $B = 0.1$, $\Delta_{r, crv} = 0.1$, $800 < M_{LQ} < 1500$ GeV	м		
	axion-like particle, f ⁻¹ = 1.2 TeV ⁻¹	м		
	inelastic dark matter model, $y = 10^{-7}$, $a_0 = 0.1$	м		
	dark Higgs model, $g_n = 0.25$, $g_{cm} = 1$, $\theta = 0.01$, $m_x = 200$ GeV, $m_{z'} = 700$ GeV	, M		
	RPV stop to 4 quarks	м		
2	RPV squark to 4 quarks	м		
e	RPV gluino to 4 quarks	M		
	nev gianos to 5 quarks	~		
	ADD (jj) HLZ, neo = 3	м		
	ADD $(\gamma\gamma, \ell\ell)$ HLZ, $n_{\rm ED} = 3$	м		
	ADD G_{00} emission, $n_{00} = 2$	м		
	ADD QBH (μ), $h_{00} = 0$ ADD QBH (μ), $h_{00} = 4$	M		
	ADD QBH (e_T), $n_{e_D} = 4$. M		
ie	ADD QBH ($\mu\tau$), $n_{ED} = 4$	м		
1 and 1	ADD QBH (yj), $n_{\rm HD} = 6$	м		
ä	RS $G_{KK}(U)$, $k/\overline{M}_{H} = 0.1$	м		
붋	$RS G_{KK}(\gamma\gamma), K/M_{H} = 0.1$ $RS G_{V}(\alpha^{2}, \alpha \alpha), K/M_{V} = 0.1$	M		
	R5 OBH (ii), $n_{\rm m} = 1$			
	RS QBH (yj), n _{ep} = 1	м		
	non-rotating BH, $M_{\odot} = 4$ TeV, $n_{CO} = 6$	м		
	3-brane WED $g_{ex}(\phi + g \rightarrow ggg)$, $g_{grav} = 6$, $g_{drav} = 3$, $\epsilon = 0.5$, $m(\phi)/m(g_{ex}) = 0.1$	$m(g_{ex})$		
	split-UED, µ ≥ 2 TeV	1R		
	excited light quark (qq), $\Lambda = m_a^2$	м		
- 2	excited light quark (qq), $f_3 = f - f' = 1$, $\Lambda = m_q^*$	м		
le ce	excited b quark, $f_s = f = f' = 1$, $\Lambda = m_q^*$	м		
	excited electron, $f_2 = f = f' = 1$, $\Lambda = m_0^2$ excited muon, $f_2 = f = f' = 1$, $\Lambda = m^2$	M		
	µ	~		
	$vM5M$, $ V_{aV} ^2 = 1.0$, $ V_{\mu V} ^2 = 1.0$	м		
	$vMSM$, $ V_{\mu\nu} ^2 = 1.0$, $ V_{\mu\nu} ^2 = 1.0$	м		
nion	VMSM, $ V_{all}V_{\mu N} ^2/(V_{all} ^2 + V_{\mu N} ^2) = 1.0$ Turn III seesaw beaus fermions. Flavor democratic	м		
₹.	Vector like taus. Doublet			
	Vector like taus, Singlet	м		
	Z ₀ , narrow resonance, ε ² = 8 × 10 ⁻⁶ (90% C.L.)	м		0.01
	Z ₀ , narrow resonance, $r^{2} = 7 \times 10^{-7} (90\% \text{ C.L.})$	M	0.0011_0.0025 TeV (MS-PAS-EX0.21.005 (2u)	
	Z_0 , narrow resonance, $\epsilon^2 = 3 \times 10^{-6}$ (90% C.L.)		0.0042-0.0079 TeV CM	S-PAS-EXO-21-005 (2µ)
	55M Z'(II)	м		
	55M Z'(qq)	м		
2	Z(qq)	м		
000	superstring \mathcal{L}_{φ} LEV \mathcal{I}'_{φ} BB(μ_{φ}) = 10%	M		
ge	LFV Z, BR(e_T) = 10%	M		
Gau	LFV Z', BR(µt) = 10%	M		
le la	55M W'(tv)	M		
Ŧ	Leptophobic Z'	м		
	SSM W(qq) LRSM W ₁ (M_1) M ₂ = 0.5M ₂	M		
	55M W(TV)	M		
	LRSM $W_n(eN_n)$, $M_{N_n} = 0.5M_{W_n}$	M		
	LRSM $W_R(\tau N_R)$, $M_{\tau N_R} = 0.5M_{\pi N_R}$	м		
	Axigiuon, Coloron, cate = 1	м		
		0.0	001 0.0	10

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

Overview of CMS EXO results

		_
	0.5-7.9 TeV 1911.03 947 (2j)	13
	0.35-4 TeV 1712.03143 (2µ + 1y; 2e + 1y; 2j + 1y)	36
	1.5-8 TeV 2106.10509 (1j + 1y)	13
	072-3.25 TeV 1808.01257 (1j + 1y)	36
	0.5-3.7 TeV 1911.03947 (2)	13
	0.5-7.5 TeV 1911.03947 (2j)	13
015-0.075 TeV 1911.049	$(3t, \ge 4t)$	13
	$0.108 - 0.34 \text{ TeV}$ 1911.04968 (3 <i>I</i> , \geq 4 <i>I</i>)	13
	0.6-1.6 TeV CMS-PAS-EXO-19-009 (pp + 11, pp + y)	37
	<24 TeV 2103.02708 (27)	714
	<36 TeV 2103.02708 (21)	14
	0.2-5.6 TeV 2001.04521 (2e+2j)	77
	0.2-5.7 TeV 2001.04521 (2µ + 2j)	77
		۲.,
	0.35-0.7 TeV 1911.03701 (23)	18
	0.2-1.92 (ev 2103.027/06/26, zm	14
	0.3-2.8 (eV 1911.0394/12)/ <105.34(10.1021.0311/~311.0394/12)/	110
		110
	0.2 4.04 (ev 2105.02 /06 (20, 24)	14
	$\frac{1}{2} \left[\frac{1}{2} \left$	130
	215 TeV 2107 13021 (>114 m ^{2/2})	10
	<0.47 TeV 2107 13021 (>114 m ²¹)	10
	$= 0.3 \text{ TeV} [1001 01553 (0, 1) + = 2i + n^{0.01}]$	36
	$0.05 - 0.42$ Toy 2107 10.892 (0, $14 + 23 + 0^{110}$)	13
	<1.54 TeV 1810 10069 (41)	16
	<1.6 TeV 1908.01713 (h + n ^{-tran})	36
	15-51 TeV 2112 11125 (2i + p ²⁽ⁱⁿ⁾)	13
	0.5 - 3.1 TeV 1908.01713 (h + p ^{-(**)})	36
	$0.3 - 0.6$ TeV 1811.10151 (1 μ + 1 i + p_{μ}^{max})	77
	0.5-2 TeV CMS-PAS-EXO-21-007 (pp + yy)	110
0.003-0.08 TeV. CMS-PA	-EXO-20-010 (2 displaced μ + p ^{minn})	13
0.02-0.08 TeV CMS-PA	-EXO-20-010 (2 displaced μ + p ^{minn})	13
	0.16=0.352 TeV (MS-PAS-EXO-21-012 ($1t + 2j + p_{T}^{mins}, 2t + p_{T}^{mins})$	13
		-
	0.08-0.52 TeV 1808.03124 (2); 4j)	36
	0 1 - 1 4 TeV 1806 01 058 (21)	38
	<1.5 TeV 1810.10 092 (Gj)	36
		-
	<12 TeV 1803.08 030 (2j)	36
	<9.1 TeV 1812 10443 (2y, 2t)	36
	<9.1 TeV 1812.10443 (2 y , 2 <i>t</i>) <10.8 TeV 2107.13021 (≥ 1 j + p _T ^(t))	36
	<9.1 TeV 1812.10443 (2y, 2t) <10.8 TeV (2107.13021 (>1j + p _T ^{min}) <8.2 TeV 1803.08030 (2j)	36 10 36
	<9.1 TeV [1812.10443 (2γ, 2ℓ) <10.8 TeV [2107.13021 (≥ 1j + p _T ^(tm)) <8.2 TeV [1803.08030 (2j) <5.6 TeV [2205.06709 (eµ) <5.2 TeV [2205.06709 (eµ)]	36 10 36 13
	<9.1 TeV [1812.10443 (2γ, 2ℓ) <10.8 TeV [2107.13021 (≥ 1j + p _T ^(tm)) <8.2 TeV [1803.08030 (2j) <5.6 TeV [2205.06709 (eµ) <5.2 TeV [2205.06709 (er)] <5.2 TeV [2205.06709 (er)]	36 10 36 13 13
	<9.1 TeV 1812.10443 (2y, 2t) <10.8 TeV [2107.13021 (= 1j + p _T ^(tm)) <8.2 TeV [803.08030 (2j) <5.6 TeV [2205.06709 (eµ) <5.2 TeV [2205.06709 (er) <5 TeV [2205.06709 (µT)] <5 TeV [2205.06709 (µT)] 2.7.5 TeV [205.PA5-EXO-20-012 (y + j)]	36 10 36 13 13 13
	<9.1 TeV 1812.10443 (2y, 2t) <10.8 TeV [2107.13.021 (≥ 1j + p _T ^(Tm)) <8.2 TeV [803.08.030 (2j) <5.6 TeV [2205.06709 (eµ) <5.2 TeV [2205.06709 (er) <5 TeV [2205.06709 (µT) <5 TeV [2205.06709 (µT) <2.7.5 TeV [2205.06709 (µT) <2.7.5 TeV [2205.0620 (y + j)] <4.78 TeV [2103.02.208 (2t)]	36 10 36 13 13 13 13 13
	<9.1 TeV 1812.10443 (2y, 2t) <10.8 TeV 2107.13021 (≥ 1j + p _T ⁽¹⁰⁾) <8.2 TeV 1803.08030 (2j) <8.2 TeV 1803.08030 (2j) <5.5 6 TeV 2205.06709 (eµ) <5.2 TeV 2205.06709 (er) <5 TeV 2205.06709 (µr) 2-7.5 TeV (205.96709 (µr) 2-7.5 TeV (205.96709 (µr)) <4.78 TeV 2103.02 708 (2t) <4.1 TeV 1809.00327 (2y)	36 10 36 13 13 13 13 13 14 36
		36 10 36 13 13 13 13 14 36 13
	<9.1 TeV	36 10 36 13 13 13 13 14 36 13 36
	<9.1 TeV	36 10 36 13 13 13 13 14 36 13 36 13
	<9.1 TeV	36 10 36 13 13 13 13 13 14 36 13 36 13 36
	<	36 10 36 13 13 13 13 14 36 13 36 13 36 13 36 13
	<9.1 TeV	36 10 36 13 13 13 14 36 13 36 13 36 13 13
	<9 1 TeV	36 10 36 13 13 13 14 36 13 36 13 36 13 36 13 36 13 13
	<0.1 TeV	36 10 36 13 13 13 14 36 13 36 13 36 13 13 13 13
	<	36 10 36 13 13 13 14 36 13 36 13 36 13 36 13 13 13 13 13 13 13
	<9.1 TeV, 1812.10.443 (2y, 2t)	36 10 36 13 13 13 13 13 13 13 13 36 13 36 13 13 13 13 36 23 36
	+01 TeV [181210443 (2y, 2t) <10.8 TeV [2107.13.021 (± 1j + p ⁽ⁱⁿ⁾) <82 TeV [2005.06.003 (2j)	36 10 36 13 13 13 13 14 36 13 36 13 36 13 36 13 36 13 36 36 13 36 36 36 36
	(*9.1 %/ 1812-10443 (2y, 2/) <0.8 TeV [1803 08030 (2j)	36 10 36 13 13 13 14 36 13 36 13 13 13 13 13 36 36 36 36 36 36
		36 10 36 13 13 13 14 36 13 36 13 36 13 13 13 13 36 36 36 36 36 36 36 36 36 36 36 36
	x x	36 10 36 13 13 13 13 14 36 13 36 13 36 13 13 13 36 36 36 36 36 36 36 36 36 36 36 36 36
	••0 1 №V 1812.10.43 (2v, 2t) •0.0.8 TeV [207.13021 (≥ 1j + pt ⁻⁺⁺) •0.8 TeV [203.06036 (2j) ••5.6 TeV [202.05 0709 (ep) ••5.6 TeV [202.05 0709 (ep) ••5.7 TeV [052.05 0708 (2p) ••5.7 TeV [052.05 0708 (2p) ••5.7 TeV [052.05 0708 (2p) ••5.7 TeV [103.050.0002 (2p) ••5.7 TeV [103.050.0002 (2p) ••5.7 TeV [105.0002 (2p) ••5.7 TeV [105.0002 (2p) ••5.7 TeV [105.0002 (2p) ••5.7 TeV [105.0002 (2p + 2p) ••5.9 TEV [105.0002 (2p + 2p) ••5.9 TEV [105.0005 (3p); ≥ 1] + 2e) ••5.9 TEV [105.0005 (3p); ≥ 1] + 2e) ••5.9 TEV [105.0005 (3p); ≥ 1] + 2e) ••5.9 TEV [202.00505; 1805.10005 (3p; ≥ 1] + 2e) ••5.9 TEV [105.0005 (3p); ≥ 1] + 2e) ••5.9 TEV [105.000505 (3p; ≥	36 10 36 13 13 13 13 14 36 13 36 13 36 13 36 13 36 13 36 36 36 36 36 36 36 36 36 36 36 36 36
	$ \begin{array}{c} + 0.1 \mbox{ INV} 112121043 (2y, 2t) \\ + 10.8 \mbox{ IVV} 1207.13021 (= 1j + pt^{-m}) \\ + 3.2 \mbox{ IVV} 1203.08 \mbo$	36 10 36 13 13 13 13 14 36 13 36 13 36 13 36 13 36 13 36 36 36 36 36 36 36 36 36 36 36 36 36
0.125	<9.1 W/ 1812-104.43 (2y, 2/)	36 10 36 13 13 13 14 36 13 36 13 36 13 36 13 36 36 36 36 36 36 36 36 36 36 36 36 36
0.125-	••0.1 TeV 1812.10.443 (2γ, 2/) ••0.0 TeV 10.13 02.1 (± 1j + p;"*) ••0.0 TeV 1003.00.00030 (2j) ••0.1 TeV 1003.00.00030 (2j) ••0.1 TeV 1003.00.000 (pt) ••0.1 TeV 1000.0000 (pt) (pt) (pt) ••0.1 TeV 1000.000000 (pt) (pt) (pt)	36 10 36 13 13 13 14 36 13 36 13 13 13 13 36 36 36 36 36 36 36 36 36 36 36 36 36
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0.125 150.075 TeV 1912.04 7		36 10 36 13 13 13 13 14 36 13 36 13 36 13 36 13 36 36 36 36 36 36 36 36 36 36 36 36 36
0.125 15-0.075 TeV 1912.04 7 0.01-0.125		36 10 36 13 13 13 13 14 36 13 36 13 36 13 36 13 36 13 36 36 36 36 36 36 36 36 36 36 36 36 36
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0.125-4 15-0.075 TeV 1912.04 7 0.01-0.125	1001041 (2y, 20 1001041 (2y, 2	36 10 36 13 13 13 14 36 13 36 36 13 36 36 13 36 36 36 13 13 36 36 13 13 36 36 13 13 36 36 13 13 13 13 13 13 13 13 13 13

BSM Searches with Exotic Signatures

- Signatures depend on charge and lifetime
 - Muon-like particles with large mass (large dE/dx)
 - Track segments
 - Displaced particles (tracks, leptons, jets)

For very long lifetimes, particles can be trapped in calorimeters and decay after months

BSM Searches with Exotic Signatures

Overview of CMS long-lived particle searches

JDD, <i>q̃→tbs, m_ã</i> = 2500 GeV	ã	
JDD, $\tilde{q} \rightarrow tbs$, $m_{\tilde{a}} = 2500 \text{ GeV}$	ã	
JDD. $\tilde{t} \rightarrow \overline{dd}$. $m_{\tilde{t}} = 1600 \text{ GeV}$	ĩ	
JDD, $\tilde{t} \rightarrow \overline{dd}$, $m_{\tilde{t}} = 1600 \text{ GeV}$	ĩ	
$_{\rm QD}, \tilde{t} \rightarrow bl, m_{\tilde{t}} = 600 {\rm GeV}$	ĩ	1808
QD, $\tilde{t} \rightarrow bl$, $m_{\tilde{t}} = 460 \text{ GeV}$	ĩ	
QD, $\tilde{t} \rightarrow bl$, $m_{\tilde{t}} = 1600 \text{ GeV}$	ĩ	
GMSB, <i>ĝ→gĜ</i> , m _ĝ = 2450 GeV	ĝ	
GMSB, <i>g̃→gĜ</i> , m _{g̃} = 2100 GeV	ĝ	
Split SUSY, $\tilde{g} \rightarrow q \bar{q} \chi_1^0$, $m_{\tilde{g}} = 2500 \text{ GeV}$	ĝ	
Split SUSY, $ ilde{g} ightarrow q ar{q} \chi_1^0$, $m_{ ilde{g}} = 1300~{ m GeV}$	ĝ	1802
Split SUSY (HSCP), $f_{\tilde{g}g} = 0.1$, $m_{\tilde{g}} = 1600$ GeV	ĝ	
mGMSB (HSCP) $ aneta=10,\mu>0$, $m_{ ilde{ au}}=247$ GeV	τ	
Stopped $\tilde{t}, \tilde{t} \rightarrow t \chi_1^0, m_{\tilde{t}} = 700 \text{ GeV}$	ĩ	
Stopped $\tilde{g}, \tilde{g} \rightarrow q \bar{q} \chi_1^0, f_{\tilde{g}g} = 0.1, m_{\tilde{g}} = 1300 \mathrm{GeV}$	ĝ	
Stopped $\tilde{g}, \tilde{g} \rightarrow q \bar{q} \chi_2^0(\mu \mu \chi_1^0), f_{\tilde{g}g} = 0.1, m_{\tilde{g}} = 940 \mathrm{GeV}$	ĝ	
AMSB, $\chi^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$, $m_{\chi^{\pm}} = 700 \text{ GeV}$	χ^{\pm}	
$\tilde{g} \rightarrow q \bar{q} \chi_1^0$ or $q_{_{u/d}} \bar{q}_{_{d/u}} \chi_1^{\pm}, \chi_1^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$, $m_{\tilde{g}} = 1600 \text{GeV}, m_{\chi_1^0} = 1575 \text{GeV}$	χ_1^{\pm}	
$\tilde{q} \rightarrow q \chi_1^0$ or $q' \chi_1^{\pm}$, $\chi_1^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$, $m_{\tilde{q}} = 2000$ GeV, $m_{\chi_1^0} = 1000$ GeV	χ_1^{\pm}	
$\rightarrow t\chi_1^0 \text{ or } b\chi_1^{\pm}, \chi_1^{\pm} \rightarrow \chi_1^0 \pi^{\pm}, m_{\tilde{t}} = 1100 \text{ GeV}, m_{\chi_1^0} = 1000 \text{ GeV}$	χ_1^{\pm}	
GMSB, $\chi_1^0 \rightarrow H\tilde{G}(50\%)/Z\tilde{G}(50\%)$, $m_{\chi_1^0} = 600 \text{ GeV}$	χ_1^0	
GMSB, $\chi_1^0 \rightarrow H\tilde{G}(50\%)/Z\tilde{G}(50\%)$, $m_{\chi_1^0} = 300 \text{ GeV}$	χ_1^0	
GMSB SPS8, $\chi_1^0 \rightarrow \gamma \tilde{G}$, $m_{\chi_1^0} = 400 \text{ GeV}$	χ_1^0	
GMSB, co-NLSP, Ĩ→/Ĝ, mĩ = 270 GeV	Ĩ	
$f \to Z_D Z_D (0.1\%), Z_D \to \mu \mu, m_H = 125 \text{ GeV}, m_X = 20 \text{ GeV}$	X	2112.12
$H \to Z_D Z_D (0.1\%), Z_D \to \mu \mu (15.7\%), m_H = 125 \text{ GeV}, m_X = 5 \text{ GeV}$	X	2112.13
$4 \rightarrow XX(10\%), X \rightarrow ee, m_H = 125 \text{ GeV}, m_X = 20 \text{ GeV}$	X	
$4 \rightarrow XX(0.03\%), X \rightarrow II, m_H = 125 \text{ GeV}, m_X = 30 \text{ GeV}$	X	
$H \to XX(10\%), X \to bb, m_H = 125 \text{ GeV}, m_X = 40 \text{ GeV}$	X	
$H \to XX(10\%), X \to bb, m_H = 125 \text{ GeV}, m_X = 40 \text{ GeV}$	X	
$H \to XX(10\%), X \to bb, m_H = 125 \text{ GeV}, m_X = 40 \text{ GeV}$	X	
$T \rightarrow XX(10\%), X \rightarrow TT, m_H = 125 \text{ GeV}, m_X = 7 \text{ GeV}$	X	
dark QCD, $m_{\pi_{DK}} = 5$ GeV, $m_{X_{DK}} = 1200$ GeV	X _{DK}	

CMS Preli	minary	
	2104.13474 (J	ets with displaced vertices)
		2012.01581 (Displ
1	2104.13474 (Jets	with displaced vertices)
		2012.01581 (Displace
1808.05082 (2μ + 2 jets)	
		2110.04809 (
		2012.01581 (Di
		2012.01581 (
		2012.01581
1802.02110 (Jets + MET)	
		1909.03460 (Di
		1909.034
		1909.034
		2212.0
		2212
		2110.04809 (Displ
		2205 00502 (D ian)
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2112.13703 (D.		1411 6977 (I
		2110.04809 (Displaced lepton
		2012.01581 (Displaced iet
		2110.13218 (Displace
		21(
		2107.0483
		1810.10069 (Emerging j
0 ⁻⁷	10) ⁻⁵
-	10	

SUSY RPV

SUSY RPC

Higgs+Other

Let the machine search ...

- Unsupervised machine learning with autoencoder for anomaly detection
- Mass spectrum analysed using bumb hunter with two different width assumption

It's not all limits ...

Example: di-photon excess at 95 GeV

arXiv:2303.12018 arXiv:2306.03889

Towards the HL-LHC

- Run 2: 140/fb
- Run 3: ~450/fb
- HL-LHC: ~3000/fb (~20 x today's dataset)

Towards the HL-LHC

ATLAS and CMS upgrades entering production

L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

- Full optical readout
- 7.5 kHz HLT output

Calorimeter Endcap

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≈ 3.8

29 Markus Klute

DAQ & High-Level Trigger

https://cds.cern.ch/record/2759072 Heterogenous architecture

- 60 TB/s event network

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL single crystal granularity at L1 trigger
- with precise timing for e/γ at 30 GeV ECAL and HCAL new Back-End boards

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ~ 3

TECHNICAL DESIGN REPOR

MIP Timing Detector

https://cds.cern.ch/record/2667167

- Precision timing with: • Barrel layer: Crystals + SiPMs • Endcap layer:
 - Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- · Neutron and mixed-field radiation monitors

Quiz

- Why do you think the Standard Model is incomplete? How should a "good" extension of the Standard
- Model look like?
- How can we search for DM at the LHC?
- How can we study energy scales beyond the reach of the LHC?
- What is the most exciting opportunity at CERN for you?

Conclusion

- the discovery of the Higgs Boson
- There are many open fundamental questions in particle physics
- New tools are available to address these questions
- The (physics) program of the LHC is filled with exciting opportunities for you!
- Outlook:

We have seen a broad physics program from ATLAS and CMS highlighted by

References and further reading

Textbooks

- Modern Particle Physics by Mark Thomson
- QCD at Colliders by Ellis, Stirling, and Weber
- Pictures
 - CERN Document Server
 - Wikipedia
 - Or reference on page
- References
 - Previous CERN Summer Lectures https://indico.cern.ch/category/97/
 - MIT's OCW 8.701 and 8.811
 - KIT's Particle Physics master courses (you can contact me)
 - Public results from ATLAS, CMS, and LHC combination groups
 - Or reference on page
- Markus Klute 32

