LHC and beyond

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The Higgs Boson Discovery at LHC

ATLAS & CMS Observation



First observations of a new particle in the search for the Standard Model Higgs boson at the LHC







www.elsevier.com/locate/physletb

Predicted in 1964, discovered in 2012! 48 year hunting!

2013 Nobel Prize

An effort by thousands of scientists and engineers from all over the world

François Englert and Peter Higgs

Huge impact to humanity

Technology Cultural **International Collaboration**



How did we get there anc what are we doing now?



Large Hadron Collider proton-proton collisions Center of mass energy: 7-8-14 TeV

CMS

General Purpose

ALICE

Heavy ion physics

Lake Geneva

LHC ring: km circumference





CERN

General Purpose



The LHC accelerator complex



Depth ~ 50-175 m

LHC Experiments: General Purpose Detectors



LHC Experiments: Specialized Detectors



Other even more specialized experiments













Look into the pp collisions...





Parton Distribution Functions (PDF)

- PDFs are not calculable, but measured in experiments



In a proton, quarks heavier than u,v are only available in the sea





PDFs give the probability to find a parton with a momentum fraction of x

PDFs Sum rules

Momentum sum rule

$$\sum_{i} \int_0^1 dx \ x f_i(x, Q^2) = 1$$

Flavour conservation sum rules

$$\int_{0}^{1} (f_u(x, Q^2) - f_{\overline{u}}(x, Q^2)) dx = 2$$
$$\int_{0}^{1} (f_d(x, Q^2) - f_{\overline{d}}(x, Q^2)) dx = 1$$
$$\int_{0}^{1} (f_s(x, Q^2) - f_{\overline{s}}(x, Q^2)) dx = 0$$



Truth-level event

$$a(q_i q_j \to X) = a_0 \times (1 + \alpha_S a_1 + \alpha_s^2 a_2 + \alpha_s^3 a_3 + \cdots)$$
$$\alpha_S \sim 0.1$$



Hard scattering

Perturbative regime (with a generations) $a_0 \times (1 + \alpha_S a_1 + \alpha_s^2 a_2 + \alpha_s^3 a_3 + \cdots)$ - NLO (now mostly automated) $\alpha_S \sim 0.1$ - NNLO (state-of-the-art that has become standard)

- N3LO possible (with large impact on Higgs results)

 $\alpha_{\rm s}$ - strong coupling







Hard scattering Perturbative regime (with large QC) corrections): $dx_i dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) d\hat{\sigma}(q_i q_j \rightarrow X, \hat{s}, Q^2)$ - NLO (now mostly automated) - NNLO (state-of-the-art that has become standard) - N3LO possible (with large impact on Higgs results)

Parton Distribution Functions



Truth-level event



Hard scattering

Perturbative regime (with large QCD corrections): - NLO (now mostly automated)

- NNLO (state-of-the-art that has become standard)

- N3LO possible (with large impact on Higgs results)

Parton shower

QCD radiation showers not calculable exactly - Approximated in the soft and collinear regime — Pythia/Herwig MC

Parton Distribution Functions



Truth-level event

Hard scattering

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Parton shower

QCD radiation showers not calculable exactly - Approximated in the soft and collinear regime — Pythia/Herwig MC

Parton Distribution Functions

Multiple parton interactions

Additional interactions between partons of the same protons



Truth-level event

Hard scattering

Perturbative regime (with large QCD corrections): - NLO (now mostly automated)

- NNLO (state-of-the-art that has become standard) 🛹
- N3LO possible (with large impact on Higgs results)



Hadronization Pythia, Herwig, Sherpa MC

Parton shower

QCD radiation showers not calculable exactly - Approximated in the soft and collinear regime — Pythia/Herwig MC

Parton Distribution Functions

Multiple parton interactions

Additional interactions between partons of the same protons

Picture by Frank Krauss



Truth-level event

Next

- Hadron decays
- Additional collisions from other protons (pile-up)



Reconstruction

Hard scattering

Perturbative regime (with large QCD corrections): - NLO (now mostly automated)

- NNLO (state-of-the-art that has become standard) 🛹
- N3LO possible (with large impact on Higgs results)



Hadronization Pythia, Herwig, Sherpa MC

Parton shower

QCD radiation showers not calculable exactly - Approximated in the soft and collinear regime — Pythia/Herwig MC

Parton Distribution Functions

Multiple parton interactions

Additional interactions between partons of the same protons

Picture by Frank Krauss



Luminosity

Number of protons per bunch **1.2 × 10**¹¹



Number of collisions that can be produced in a detector per cm² and per second



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High-Luminosity LHC Plan



Design for "ultimate" performance 7.5x10³⁴ cm⁻²s⁻¹ and 4000 fb⁻¹

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Hadron collisions - Luminosity





 $\frac{N_p^2 f k_b \gamma}{4\pi \beta^* \varepsilon_N}$

Luminosity for several bunches kb in trains

Beam size expressed in beam parameters, dependence in beam energy!

Parameter	2010	2011	2012	2016	2017	2018	Nominal	HL-LHC
CoM Energy	7 TeV	7 TeV	8 TeV	13 TeV	13 TeV	13 TeV	14 TeV	14 TeV
Np	1.1 10 ¹¹	1.4 10 ¹¹	1.6 10 ¹¹	1.2 10 ¹¹	1.2 10 ¹¹	1.2 10 ¹¹	1.15 10 ¹¹	2.2 10 ¹¹
Bunches k	368	1380	1380	2300	2450	2500	2808	2760
Spacing	150 ns	50 ns	50 ns	25 ns	25 ns	25 ns	25 ns	25ns
ε (mm rad)	2.4-4	1.9-2.3	2.5	2.6	2.3	2.6	3.75	2.5
β* (m)	3.5	1.5-1	0.6	0.4	0.3-0.4	0.4	0.55	0.15
L (cm ⁻² s ⁻¹)	2x10 ³²	3.3x10 ³³	~7x10³³	1.5x10 ³³	2.0x10 ³⁴	2x10 ³⁴	1034	8x10 ³⁴
PU	~2	~10	~30	~30	~50	~50	~25	~130





angle)



Luminosity grows with energy!

Emittance (fixed at injection)

Beta* Focussing





Fiducial volume and acceptance

Fiducial volume: phase space in which a given final state is measured (can include other than geometrical cuts)

Fiducial cross section

Total cross section

$$\sigma_{\rm fid} = \frac{N - B}{C_{W/Z} \cdot L_{\rm int}}$$



passing selection

No theoretical uncertainty from extrapolation outside experimental acceptance

 $\sigma_{\rm tot} = \sigma_{W/Z} \times BR(W/Z \to \ell \nu / \ell \ell) = \frac{\sigma_{\rm fid}}{A_{W/Z}}$



The total cross section at hadron collider



Total cross section: 100 mb

Nominal LHC Luminosity $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



Number of events produced: $\sigma \times L =$ $100 \times 10^{-27} (cm^2) \times 2 \times 10^{34} cm^{-2} s^{-1}$ $\sim 2 \times 10^9$ events/sec



Production rates at Hadron Colliders



LHC timeline

W: May 2010 Z: Jun 2010

Top: Jul 2010

WW: Dec 2010 WZ: Mar 2011 ZZ: Jul 2011

H: July 4, 2012



Total cross sections at LHC





Vector boson production (often referred to as Drell Yan).

LEP ~4 M Z per experiment LHC ~100 M (leptonic) / exp. (for 100 fb⁻¹)



Single top production $tq \sim 200 \,\mathrm{pb}$



Top pair production

 $t\bar{t} \sim 1\,\mathrm{nb}$



Diboson production $WW \sim 100 \,\mathrm{pb}$ $ZZ \sim 20 \,\mathrm{pb}$



Fiducial cross sections at LHC

Standard Model Production Cross Section Measurements





Status: February 2022

Very large number of fiducial cross section measurement made at the LHC

Down to processes as rare as three boson production

Now measured VBS diboson production (VVjj)





Jet cross sections





Differential jet production cross sections

Example: Double differential jet cross section measurement



Count number of events in reconstructed bins of $(\Delta p_T, \Delta y)$

Unfold to truth particle jet quantities taking into account reconstruction and trigger efficiencies and unfolding resolution matrix

 $\frac{d^2\sigma}{dp_T dy} = \frac{1}{\varepsilon \mathcal{L}} \frac{N_j}{\Delta p_T \Delta y}$



Ratios of differential jet production cross sections



Measurement of the ratio of cross sections

- **R3/2** is the ratio of inclusive 3-jet to inclusive 2-jet cross sections as a function of the average pT of the two leading jets:



Using ratios can improve precision by cancelling systematic uncertainties.

- Again interesting dependence in strong coupling constant.
- Main experimental uncertainty partly canceled but still dominant.
- With the transverse momenta of all the jets can infer the energy scale of the process.



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Measurement of the Strong Coupling Constant α_s

Crucial dependence of the strong coupling constant with the energy scale predicted (1973):



Asymptotic freedom: QCD is perturbative at high energies



From the measurements of jet cross sections and their ratios, the strong coupling constant can be measured at the highest energy scales!



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The di-lepton mass spectrum at LHC





The challenge of the W Mass Measurement



Cannot measure **W mass** directly from its decay particles because the **neutrino** is not measured directly in the detector

Measure W recoil precisely

Strategy: fit two kinematic distributions in several categories



PI_T: Clean energy measurement, but more sensitive to the modelling of the W transverse momentum

M_T: Less sensitive to modelling but more difficult to reconstruct because of the missing transverse energy

 $m_T = \sqrt{2 p_T^l p_T^{miss} (1 - \cos \Delta \varphi)}$





The challenge of the W Mass Measurement



Cannot measure **W mass** directly from its decay particles because the neutrino is not measured directly in the detector

> Measure W recoil precisely

Strategy: fit two kinematic distributions in several categories

ALEPH
DELPH
L3
OPAL CDF
D0 ATLAS
ATLAS
ATLAS

 $m_W = 80369.5 \pm 18.5 MeV$ (large component from modeling)

$$m_T = \sqrt{2 p_T^l p_T^{miss} (1 - \cos \Delta \varphi)}$$





The challenge of the W Mass Measurement



Strategy: fit two kinematic distributions in several categories

Cannot measure W mass directly from its decay particles because the neutrino is not measured directly in the detector

> Measure W recoil precisely

$$m_T = \sqrt{2 p_T^l p_T^{miss} (1 - \cos \Delta \varphi)}$$

For further improvements: Special precision-data runs with low pile-up events







Final states: WW WZ ZZ Wγ Ζγ

Anomalous **Triple Gauge Couplings**







Di- (and Tri-) boson measurements at the LHC

Large number of processes measured and used to constrain anomalous gauge couplings

Diboson Cross Se	ection Measurements	Status: July 2017
γγ	$\sigma = 16.82 \pm 0.07 + 0.75 - 0.78 \text{ pb (data)}$ 2 γ NNLO + CT10 (theory) $\sigma = 44 + 3.2 - 4.2 \text{ pb (data)}$	
$W_{\alpha} \rightarrow \ell_{\nu\alpha}$	$\sigma = 2.77 \pm 0.03 \pm 0.36 \text{ pb (data)}$	ΔΤΙ ΔS Preliminary
$-[n_{int}=0]$	NNLO (theory) $\sigma = 1.76 \pm 0.03 \pm 0.22 \text{ pb (data)}$	
$Z\gamma \rightarrow \ell \ell \gamma$	$\sigma = 1.507 \pm 0.01 + 0.083 - 0.078 \text{ pb (data)}$ NNLO (theory) $\sigma = 1.31 \pm 0.02 \pm 0.12 \text{ pb (data)}$ NNLO (theory)	Run 1,2 $\sqrt{s} = 7,8,13$ TeV
$-[n_{jet}=0]$	$\sigma = 1.189 \pm 0.009 + 0.073 - 0.067 \text{ pb (data)}$ NNLO (theory) $\sigma = 1.05 \pm 0.02 \pm 0.11 \text{ pb (data)}$ NNLO (theory)	
$- Z\gamma \rightarrow \nu \nu \gamma$	$\sigma = 68 \pm 4 + 33 - 32 \text{ fb (data)}$ NNLO (theory) $\sigma = 0.133 \pm 0.013 \pm 0.021 \text{ pb (data)}$ MCFM NLO (theory)	
WV→ℓvjj	$\sigma = 209 \pm 28 \pm 45 \text{ fb (data)}$ MC@NLO (theory) $\sigma = 1.37 \pm 0.14 \pm 0.37 \text{ pb (data)}$ MC@NLO (theory)	
– WV→ℓvJ	$\sigma = 30 \pm 11 \pm 22 \text{ fb (data)}$ MC@NLO (theory)	
ww	$\sigma = 142 \pm 5 \pm 13 \text{ pb (data)}$ NNLO (theory) $\sigma = 68.2 \pm 1.2 \pm 4.6 \text{ pb (data)}$ NNLO (theory) $\sigma = 51.9 \pm 2 \pm 4.4 \text{ pb (data)}$ NNLO (theory) $\sigma = 51.9 \pm 2 \pm 4.4 \text{ pb (data)}$	
$-WW \rightarrow e\mu$, [n _{jet} = 0]	$\sigma = 529 \pm 20 \pm 52 \text{ fb (data)}$ NNLO (theory) $\sigma = 374 \pm 7 + 26 - 24 \text{ fb (data)}$ approx. NNLO (theory) $\sigma = 262.3 \pm 12.3 \pm 23.1 \text{ fb (data)}$ MCEM (theory)	
$-WW \rightarrow e\mu, [n_{jet} \ge 0]$	$\sigma = 563 \pm 28 + 79 - 85 \text{ fb (data)}$ MCFM (theory)	
$-$ VVV \rightarrow e μ , [n _{jet} = 1]	$\sigma = 136 \pm 6 \pm 14.3 \text{ fb} (data)$ NLO (theory) $\sigma = 50.6 \pm 2.5 \text{ pb} (data)$	
WZ	$\sigma = 30.0 \pm 2.0 \pm 2.5 \text{ pb (data)}$ MATRIX (NNLO) (theory) $\sigma = 24.3 \pm 0.6 \pm 0.9 \text{ pb (data)}$ MATRIX (NNLO) (theory) $\sigma = 19 + 1.4 - 1.3 \pm 1 \text{ pb (data)}$	LHC pp $\sqrt{s} = 7$ Te
– WZ→ℓvℓℓ	$\sigma = 252.8 \pm 13.2 \pm 12 \text{ fb (data)}$ MATRIX (NNLO) (theory) $\sigma = 140.4 \pm 3.8 \pm 4.6 \text{ fb (data)}$ MCFM NLO (theory)	Stat Stat ⊕ syst
ZZ	$\sigma = 17.2 \pm 0.6 \pm 0.7 \text{ pb (data)}$ Matrix (NNLO) & Sherpa (NLO) (theory) $\sigma = 7.3 \pm 0.4 + 0.4 - 0.3 \text{ pb (data)}$ NNLO (theory)	LHC pp √s = 8 TeN
	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ NNLO (theory) $\sigma = 46.4 \pm 1.5 + 1.8 - 1.7 \text{ fb (data)}$ Matrix (NNLO) & Sherpa (NLO) (theory)	Data stat stat ⊕ syst
– ZZ→4ℓ	$\sigma = 25.2 + 2.4 - 2.3 + 1.4 - 1.2 \text{ (b)} (\text{data})$ PowhegBox & gg2ZZ (theory) $\sigma = 25.4 + 3.3 - 3 + 1.6 - 1.4 \text{ (b)} (\text{data})$ PowhegBox & gg2ZZ (theory)	LHC pp √s = 13 Te
– ZZ→ℓℓvv	$\sigma = 9.7 + 1.5 - 1.4 + 1 - 0.8 \text{ fb (data)}$ PowhegBox & gg2ZZ (theory) $\sigma = 12.7 + 3.1 - 2.9 \pm 1.8 \text{ fb (data)}$ PowhegBox & gg2ZZ (theory)	Data stat
– ZZ*→4ℓ	$\sigma = 73 \pm 4 \pm 5 \text{ fb (data)}$ PowhegBox norm. to NNLO & gg2ZZ (theory) $\sigma = 29.8 + 3.8 - 3.5 + 2.1 - 1.9 \text{ fb (data)}$ PowhegBox & gg2ZZ (theory)	stat⊕ syst

0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4

ratio to best theory



Even more rare processes...



Exposing the need for NNLO QCD calculations



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Higgs






Higgs Decay Branching Fractions (m_H = 125 GeV)



Possible to test Higgs sector with many decay modes



Discovery channel: 2 photons



sidebands

Diphoton candidate event



ineorem

Sensitive to new physics

High mass resolution O(1%) allowing data driven estimate of background in the

180 $\int L dt = 4.5 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$ ATLAS $\int L dt = 20.3 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}$ - Data 160 · S/B weighted sum — Signal+background Signal strength categories 140 \mathbf{N} Background 120 — Signal $m_{\mu} = 125.4 \text{ GeV}$ 100 · soccales 10000000 god/ 20 bkg σ 110 140 150 ATLAS Preliminary Data 50000F $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ — Fit ----- Background 40000 30000 Full Run 2 20000 10000 $H \rightarrow \gamma \gamma$, $m_H = 125.09 \text{ GeV}$ 1500 Data-Backgr 500 120 140 150 130 110

Observation implies that the bump does not originate from spin 1 particle: Landau-Yang





Discovery channel: 4 leptons







Very high S/B ratio

Backgrounds can be estimated from MC

Polarization can be reconstructed





Discovery channel: WW





Large event rate

Large background from SM WW and top quark production

Mass resolution spoiled by the presence of neutrinos





Higgs boson mass



0.11% uncertainty

Measurement done exclusively in the di-photon and 4-leptons channels





Precision measurements and predictions



The knowledge of the Higgs mass has large impact on the precision of indirect measurements!



Higgs observation in tau channel



background from Z production plus 2 jets

VBF process



with two forward jets





Higgs observation with b-quark decays



W/Z associate process



Run: 209787 Event: 144100666 Date: 2012-09-05 Time: 03:57:49 UTC



Z decays into b-quarks



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Overview of the Higgs Boson exploration





Higgs Boson Coupling Precision at LHC and HL-LHC

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2
κγ	13%	1.04 ± 0.06	1.10 ± 0.08
κ_W	/ 11%	1.05 ± 0.06	1.02 ± 0.08
κ _Z	11%	0.99 ± 0.06	1.04 ± 0.07
Kg	14%	0.95 ± 0.07	0.92 ± 0.08
$\tilde{\kappa_t}$	30%	0.94 ± 0.11	1.01 ± 0.11
к	26%	0.89 ± 0.11	0.99 ± 0.16
$\kappa_{ au}$	15%	0.93 ± 0.07	0.92 ± 0.08
κμ	_	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21
ĸz	γ -	$1.38_{-0.36}^{0.31}$	1.65 ± 0.34
B_{i}	inv	< 11 %	< 16 %

Nature 607, 52-59 (2022)

Nature 607, 60-68 (2022)



What we know about the Higgs

- Gives mass to the W and Z bosons
- Gives mass to 3rd generation fermions via Yukawa interaction
- Evidence it couples to the 2nd generation fermions as expected
- Has spin 0
- Not composite (down to 10⁻¹⁹ m)







Di-Higgs Production and Higgs Self Coupling

Higgs pair production through gluon fusion and VBF







Cross section ~1000× smaller than Higgs production Expect ~100k events produced at HL-LHC

maximize sensitivity: bb, $\gamma\gamma$, $\tau\tau$, WW



Di-Higgs Production and Higgs Self Coupling

Higgs pair production through gluon fusion and VBF







Cross section ~1000× smaller than Higgs production still Expect ~100k events produced at HL-LHC Multiple channels being investigated to maximize sensitivity: bb, $\gamma\gamma$, $\tau\tau$, WW

Prospects for HL-LHC



Possible observation of HH signal at 5σ constraint on the Higgs self coupling of $0.5 < k_{\lambda} < 1.5$



Searches



SUPERSYMMETRY (SUSY)

• A favorite, ideal, long-time candidate to explain most of questions raised

- unification of forces, no fine-tuning required for Higgs mass
- Unfortunately, no evidence for SUSY found yet

Strong SUSY production

Large cross section



Symmetry between bosons and fermions, provides dark matter candidate, provides

Mass gluino > 2 TeV (depending on models)





Searches for Natural and Strongly Produced SUSY



Searches for Weakly Coupled and Complex 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).

Rare or complex signatures \rightarrow more difficult to observe

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



Summary of SUSY Searches

ATLAS Results (similar for CMS)

ATLAS SUSY Searches* - 95% CL Lower Limits

 $\sqrt{s} = 13$ March 2022 Model Signature $\int \mathcal{L} dt \, [fb^{-1}]$ Mass limit Reference 139 139 E_T^{miss} E_T^{miss} $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ 0 e.µ 2-6 jets 1.85 m(X⁰₁)<400 GeV 2010.14293 0.9 mono-jet 1-3 jets q̃ [8× Degen.] $m(\tilde{q})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 2102.10874 0 e, µ 2-6 jets 139 E_T^{miss} $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ 2010.14293 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}$ 1.15-1.95 m($\tilde{\chi}_{1}^{0}$)=1000 GeV 2010.14293 Forbidden $1 e, \mu$ 2-6 jets 139 2 m(\$\tilde{\chi}_1)<600 GeV 2101.01629 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$ 2 jets E_T^{miss} $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}$ $ee, \mu\mu$ 139 22 m(x10)<700 GeV CERN-EP-2022-014 0 e.µ 7-11 jets 139 1.97 2008.06032 ĝĝ, ĝ→qqWZX E_T^{mi} $m(\tilde{\chi}_{1}^{0}) < 600 \text{ Ge}$ SS e, µ 139 6 jets 1.15 $m(\tilde{g})-m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$ 1909.08457 0-1 e.µ 79.8 139 m($\tilde{\chi}_{1}^{0}$)<200 GeV m(\tilde{g})-m($\tilde{\chi}_{1}^{0}$)=300 GeV 3b E_T^{mi} ATLAS-CONF-2018-041 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ SS e,µ 6 jets 1.25 1909.08457 $\tilde{b}_1 \tilde{b}_1$ 0 e, µ E_T^{miss} 1.255 2b139 $m(\tilde{\chi}_{1}^{0}) < 400 \text{ GeV}$ 2101.12527 0.68 2101.12527 10 GeV<∆m(b₁X⁰)<20 GeV E_T^{miss} E_T^{miss} $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$ 0 e, µ 6b139 139 Forbidden 0.23-1.35 $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ 1908.03122 2 b 0.13-0.85 2103.08189 2τ $\Delta m(\tilde{\mathcal{X}}_{2}^{0}, \tilde{\mathcal{X}}_{1}^{0}) = 130 \text{ GeV. } m(\tilde{\mathcal{X}}_{1}^{0}) = 0 \text{ GeV.}$ 139 0-1 e, µ ≥ 1 jet $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ E_T^{miss} 1.25 $m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ 2004.14060.2012.03799 $1 e, \mu$ 3 jets/1 b E_T^{miss} 139 0.65 2012.03799 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ Forbidden $m(\tilde{\chi}_{1}^{0})=500 \text{ GeV}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b \nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$ 1-2 τ 2 jets/1 b 139 m(T1)=800 GeV 2108.07665 E_T^{miss} Forbidde 36.1 139 0.85 1805.01649 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$ 0 e.µ 2 c E_T^{miss} E_T^{miss} $m(\tilde{\chi}_{\perp}^{0})=0 \text{ GeV}$ 0.55 0 e. µ $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 2102.10874 mono-jet 1-2 e, µ 1-4 b E_T^{miss} 139 0.067-1.18 $m(\tilde{\chi}_2^0)=500 \text{ GeV}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0$ 2006.05880 $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ 3 e,µ 1 b E_T^{miss} 139 Forbidden 0.86 $m(\tilde{\chi}_{1}^{0})=360 \text{ GeV}, m(\tilde{\iota}_{1})-m(\tilde{\chi}_{1}^{0})=40 \text{ GeV}$ 2006.05880 E_T^{miss} E_T^{miss} $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ Multiple ℓ/jets 139 139 0.96 2106.01676, 2108.07586 $m(\tilde{\chi}_{1}^{0})=0$, wino-bind 0.205 ee, μμ ≥ 1 jet $m(\tilde{\mathcal{X}}_{1}^{T})-m(\tilde{\mathcal{X}}_{1}^{T})=5$ GeV, wino-bind 1911.12606 2 e, µ $\begin{array}{c} E_T^{\rm miss} \\ E_T^{\rm miss} \\ E_T^{\rm miss} \end{array}$ $\tilde{\chi}_1^+ \tilde{\chi}_1^{\mp}$ via WW139 0.42 $m(\tilde{\chi}_{1}^{0})=0$, wino-bino 1908.08215 Multiple ℓ/jets 139 $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh $\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ Forbidden 1.06 $m(\tilde{\chi}_1^0)=70$ GeV, wino-bind 2004.10894,2108.0758 139 $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via $\tilde{\ell}_{L}/\tilde{\nu}$ 2 e, µ 1.0 $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1908.08215 E_T^{miss} E_T^{miss} E_T^{miss} 0.16-0.3 0.12-0.39 139 $[\tilde{\tau}_L, \tilde{\tau}_{R,L}]$ 1911.06660 2τ $m(\tilde{\chi}_{1}^{0})=0$ $\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0}$ 0 jets ≥ 1 jet 139 139 2 e,µ $m(\tilde{\chi}_1^0)=0$ 1908.08215 $\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}$ 0.256 $ee, \mu\mu$ $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$ 1911.12606 $0 e, \mu$ $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$ 0.13-0.23 0.29-0.88 1806.04030 36.1 $BR(\tilde{\chi}^0_1 \rightarrow h\tilde{G})=1$ 139 139 0.55 $BR(\tilde{\chi}^0_{\bar{\lambda}} \rightarrow Z\tilde{G})=1$ 2103.11684 0.45-0.93 $BR(\tilde{\chi}_{1}^{0} \rightarrow Z\tilde{G})=1$ 2108.07586 Disapp. trk 0.66 2201.02472 Direct $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}$ prod., long-lived $\tilde{\chi}_{1}^{*}$ 1 jet 139 Pure Wino 0.21 Pure higgsind 2201.02472 Stable 2 R-hadron pixel dE/dx E_T^{miss} 139 2.05 CERN-EP-2022-029 E_T^{miss} E_T^{miss} pixel dE/dx 139 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ $\tilde{g} = [\tau(\tilde{g}) = 10 \text{ ns}]$ CERN-EP-2022-029 $m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ $\tilde{l}\tilde{l}$, $\tilde{l} \rightarrow l\tilde{G}$ Displ. lep 139 0.7 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ 2011.07812 0.34 $\tau(\tilde{\ell}) = 0.1 \, \text{ns}$ 2011.07812 E_T^{miss} pixel dE/dx 139 0.36 CERN-EP-2022-029 $\tau(\tilde{l}) = 10 \text{ ns}$ $\tilde{\chi}_1^+ \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0 \,, \tilde{\chi}_1^+ {\rightarrow} Z\ell {\rightarrow} \ell\ell\ell$ 3 e.µ 1.05 2011.10543 139 0.625 Pure Wino $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow W W / Z \ell \ell \ell \ell \ell \nu \nu$ 0 jets 139 1.55 2103.11684 4 e.µ E_T^{mis} 0.95 m(X⁰₁)=200 GeV 4-5 large jets 1.3 1.9 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$ 36.1 Large $\lambda_{11}^{\prime\prime}$ 1804.03568 Multiple 1.05 ATLAS-CONF-2018-003 $\tilde{u}, \tilde{\iota} \rightarrow \iota \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow \iota bs$ 36.1 0.5 $m(\tilde{\chi}_1^0)=200$ GeV, bino-like $\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{1}^{\pm} \rightarrow bbs$ 139 Forbidden 0.95 $\geq 4b$ m($\tilde{\chi}_{1}^{\pm}$)=500 GeV 2010.01015 2 jets + 2 b $\tilde{l}_1 \tilde{l}_1, \tilde{l}_1 \rightarrow bs$ 36.7 0.42 0.61 1710.07171 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$ 0.4-1.45 $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $2 e, \mu$ 2 b 36.1 1710.05544 1μ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1$ DV 136 2003.11956 $\tilde{\chi}_1^+/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$ 1-2 *e*, µ ≥6 jets 139 0.2-0.32 Pure higgsino 2106.09609

Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made. 10⁻¹

3 TeV HL-LHC YR A large variety of topologies and models ... no discoveries thus far

Prospects for HL-LHC (HE-LHC)

ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}$	F	IL/HE-LHC	SUSY	Search	HL-LHC , $\int \mathcal{L} dt = 3 a d$ HE-LHC, $\int \mathcal{L} dt = 15 a$	h ^{−1} :5or discovery (95% CLexclusion)	Si	mulation
Reference		Model	e, μ, τ, γ	Jets	Mass limit			Section
2010.14293 2102.10874 2010.14293		$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_1^0$	0	4 jets	že –	2.9 (3.2) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.1
2010.14293	9	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\chi_1^{\prime}$	0	4 jets	8	5.2 (5.7) Tev	m(X_1)=0	2.1.1
2101.01629 CERN-EP-2022-014	aluin	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_{1}^{0}$	0	Multiple	8	2.3 (2.5) TeV	m($\hat{\chi}_{1}^{''}$)=0	2.1.3
2008.06032 1909.08457	0	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \vec{c} \tilde{\chi}_{1}^{0}$	0	Multiple	8	2.4 (2.6) TeV	m($\hat{\mathcal{X}}_{1}^{''}$)=500 GeV	2.1.3
ATLAS-CONF-2018-041 1909.08457		NUHM2, $\tilde{g} \rightarrow t\tilde{t}$	0	Multiple/2b	2	5.5 (5.9) TeV	-0	2.4.2
2101.12527		$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow t \tilde{\chi}_1^0$	0	Multiple/2b	71	1.4 (1.7) TeV	$m(\bar{\chi}_{1}^{''})=0$	2.1.2, 2.1.3
2101.12527	Stop	$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow t \chi_1^{\prime \prime}$	0	Multiple/28	<i>t</i> ₁	0.6 (0.85) TeV	$\Delta m(\tilde{r}_1, \chi_1) \sim m(t)$	2.1.2
2103.08189		$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \tilde{\chi}^a / t \tilde{\chi}_1^0, \tilde{\chi}_2^0$	0	Multiple/2b	7	3.16 (3.65) TeV		2.4.2
2004.14060,2012.03799 2012.03799		$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^a \rightarrow W^a \tilde{\chi}_1^0$	2 e,µ	0-1 jets	$\hat{\chi}_{i}^{\pm}$	0.66 (0.84) TeV	$m(\tilde{\chi}_1^0)=0$	2.2.1
2108.07665	ino,	$\tilde{\chi}_1^* \tilde{\chi}_2^0$ 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
2102.10874	harg eutre	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh, Wh $\rightarrow \ell v b \bar{b}$	1 e, µ	2-3 jets/2b	$\tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0$	1.08 (1.28) TeV	$m(\tilde{\chi}_1^0)=0$	2.2.3
2006.05880 2006.05880	0 č	$\tilde{\chi}_2^* \tilde{\chi}_4^0 {\rightarrow} W^* \tilde{\chi}_1^0 W^* \tilde{\chi}_1^*$	2 e,µ	-	$\tilde{\chi}_{2}^{\pm}/\tilde{\chi}_{4}^{0}$	0.9 TeV	$m(\tilde{\chi}_{1}^{0})$ =150, 250 GeV	2.2.4
2106.01676, 2108.07586 1911.12606	0	$\tilde{X}_1^a \tilde{\chi}_2^0 + \tilde{\chi}_2^0 \tilde{\chi}_1^0, \tilde{\chi}_2^0 {\rightarrow} Z \tilde{\chi}_1^0, \tilde{\chi}_1^a {\rightarrow} W \tilde{\chi}_1^0$	2 e,µ	1 jet	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.25 (0.36) TeV	m($\vec{\chi}_{1}^{0}$)=15 GeV	2.2.5.1
1908.08215	gsir	$\tilde{\chi}_1^a \tilde{\chi}_2^0 + \tilde{\chi}_2^0 \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0, \tilde{\chi}_1^a \rightarrow W \tilde{\chi}_1^0$	2 e,µ	1 jet	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.42 (0.55) TeV	m(\$\vec{x}_1^0)=15 GeV	2.2.5.1
2004.10894,2108.07586 1908.08215	Hig	$\tilde{\boldsymbol{X}}_{2}^{0} \tilde{\boldsymbol{X}}_{1}^{*}, \tilde{\boldsymbol{X}}_{1}^{*} \tilde{\boldsymbol{X}}_{1}^{*}, \tilde{\boldsymbol{X}}_{1}^{*} \tilde{\boldsymbol{X}}_{1}^{0}$	2 μ	1 jet	\tilde{X}_{2}^{0}	0.21 (0.35) TeV	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$ =5 GeV	2.2.5.2
1911.06660 1908.08215 1911.12606	Wino	$\tilde{\chi}_{2}^{*}\tilde{\chi}_{4}^{0}$ via same-sign WW	2 e,µ	0	Wino	0.86 (1.08) TeV		2.4.2
1806.04030 2103.11684		$\tilde{\tau}_{LR}\tilde{\tau}_{LR}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	2 τ	-	1	0.53 (0.73) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.3.1
2108.07586	Stau	22	$2\tau, \tau(e, \mu)$	-	Ŧ	0.47 (0.65) TeV	$m(\tilde{\chi}_1^0)=0, m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.2
2201.02472 2201.02472		77	2τ, τ(e, μ)		Ŧ	0.81 (1.15) TeV	$m(\tilde{\chi}_1')=0, m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.4
CERN-EP-2022-029		$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp}, \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{0}$, long-lived $\tilde{\chi}_{1}^{\pm}$	Disapp. trk.	1 jet	$\tilde{\chi}_1^{\pm}$ [$\tau(\tilde{\chi}_1^{\pm})=1ns$]	0.8 (1.1) TeV	Wino-like $\tilde{\chi}_1^a$	4.1.1
CERN-EP-2022-029 2011.07812		$\tilde{\chi}_1^* \tilde{\chi}_1^*, \tilde{\chi}_1^* \tilde{\chi}_1^0$, long-lived $\tilde{\chi}_1^*$	Disapp. trk.	1 jet	$\widehat{\mathcal{X}}_1^* = [\mathbf{r}(\widehat{\mathcal{X}}_1^*) = 1 \text{ns}]$	0.6 (0.75) TeV	Higgsino-like $\tilde{\chi}_1^*$	4.1.1
2011.07812 CERN-EP-2022-029		MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.88 (0.9) TeV	Wino-like DM	4.1.3
2011 10543	ss ed	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	2.0 (2.1) TeV	Wino-like DM	4.1.3
2103.11684	inticl	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.28 (0.3) TeV	Higgsino-like DM	4.1.3
1804.03568 ATLAS-CONF-2018-003	pa	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.55 (0.6) TeV	Higgsino-like DM	4.1.3
2010.01015		\tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$	0	Multipl e	$\tilde{g} = [r(\tilde{g}) = 0.1 - 3 \text{ ns}]$	3.4 TeV	m($\tilde{\chi}_{1}^{0}$)=100 GeV	4.2.1
1710.05544		\tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$	0	Multiple	$\tilde{g} = [\tau(\tilde{g}) = 0.1 - 10 \text{ ns}]$	2.8 TeV		4.2.1
2003.11956 2106.09609		GMSB $\bar{\mu} \rightarrow \mu \bar{G}$	displ. μ	-	μ̈́	0.2 TeV	cr =1000 mm	4.2.2
								arXiv:1
				1	10-' 1	Mass scale [TeV]		



SUSY Searches Outcomes:

Caveats to be aware of:

- Searches typically assume Branching Fractions of 100% into a specific channel
- e.g., squarks of different generation
- model

Limits might be less stringent that they seem to be

Many searches assume mass degeneracy between various SUSY particles,

Interpretation is usually done via simplified model framework, not in the full





DIRECT NEW PHYSICS SEARCHES FROM LHC

Overview of CMS EXO results

Excited

Heavy ermion



		36-140 fb ⁻¹ (13 TeV)
1911.04968 (3ℓ, ≥ 4ℓ)	0.5-8.1 1911.03 0.35-4 1712.03143 (2µ + 1γ; 2e + 1γ; 2 0.72-3.25 1808.01257 (1j + 1γ) 0.5-3.7 1911.03947 (2j) 0.5-7.5 1911.039	3947 (2j) - 1 γ) - ⁷ (2j)	137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹
	0.2-5.6 2001.04521 (2e + 2j) 0.2-5.7 2001.04521 (2μ + 2)	<12.8 1803.0803 (2j) <20 1812.10443 (2 <i>l</i>) <17.5 1803.0803 (2j) <32 1812.10443 (2 <i>l</i>)	36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 77 fb ⁻¹ 77 fb ⁻¹
01.01553 (0 , $1l + ≥ 3j + E_T^{miss}$) 001.01553 (0 , $1l + ≥ 3j + E_T^{miss}$) 0.35–0.7 1911.0376 0.3–0.6 1811.10151 (1 µ	<pre><1.8 1712.02345 (\geq 1j + E^{miss}) 0.5-2.8 1911.03947 (2j)</pre> <1.4 1712.02345 (\geq 1j + E ^{miss}) <1.54 1810.10069 (4j) <1.9 1908.01713 (h + E ^{miss}) 0.5-3.2 1908.01713 (h + E ^{miss}) (\geq 3j) + 1j + E ^{miss})		36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 18 fb ⁻¹ 77 fb ⁻¹
0.08-0.52 1808.03124 (2j; 4j) 0.1-0.72 1806.010	58 (2j) 0.1–1.41 1806.01058 (2j) <1.5 1810.10092 (6j)		36 fb ⁻¹ 38 fb ⁻¹ 38 fb ⁻¹ 36 fb ⁻¹
	<9.3 1 <9.9 <8.2 1803.0 <5.6 1802.01122 (eμ) <4.1 1809.00327 (2γ) <5.9 1803.0803 (2j) <3.6 1802.01122 (eμ) <9.7 0.4-2.9 1803.11133 (ℓ + E ^{miss}) 0.5-2.6 1911.03947 (2j)	<pre><12 1803.0803 (2j) 12.10443 (2γ, 2ℓ) 1712.02345 (≥ 1j + E^{miss}) 803 (2j) 805.06013 (≥ 7j(ℓ, γ))</pre>	36 fb ⁻¹ 36 fb ⁻¹
	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹
<0.88 19 0.12-0.79 1905.	.001-1.431802.02965; 1806.10905 ($3\ell(\mu, e)$; ≥ $1j + 2\ell(\mu, e)$)0.02-1.61806.10905 (≥ $1j + \mu + e$)1.04968 (3ℓ , ≥ 4ℓ)853 (3ℓ , ≥ 4ℓ , ≥ $1\tau + 2\ell$)		36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 77 fb ⁻¹
<1.02 <0.74 1806.03	<1.44		36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 77 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹
ı) 0.45 1909.04114 (2 j)	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 140 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹
1	e as v cale [TeV]	Moriond 20	-)21



Extra Dimensions - an example of bump hunting

- Hierachy problem solved by bringing down Planck scale
 - n extra dimensions, compactified at radius R
 - SM confined to brane in a higher dimensional space
 - Only gravity can access extra dimensions







own Planck scale s R onal space













Dark Matter



Dark Matter Landscape

Dark Sector Candidates, Anomalies, and Search Techniques







Battaglieri et al., arXiv:1707.04591



Dark Matter Landscape









Dark Matter Searches at Colliders

There are three main approaches to detect DM:

- Dark Matter-nucleon scattering (direct detection)
- Annihilation (indirect detection)
- Pair production at colliders

All three processes are just topological permutations of the same Feynman diagram



Leads to complementarity of searches

How to trigger on a pair of DM particles in a collider

Use Initial State Radiation (jet, γ , W, Z, ...)

Mono-anything analyses: mono-jet, mono-photon, mono-top, mono-V, mono-Higgs...

Production at colliders SMDirect detection DMSMDMAnnihilation



Beltran, Hooper, Kolb, Krusberg, and Tait, "Maverick Dark Matter at Colliders" JHEP 09 (2010) 037







1707 GeV \square

Monojet event

," |

MET: 1735 GeV

11

Run: 302393 Event: 738941529 2016-06-20 07:26:47 CEST

//



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Dark Matter Searches at Colliders: Higgs -> invisible



Beltran, Hooper, Kolb, Krusberg, and Tait, "Maverick Dark Matter at Colliders" JHEP 09 (2010) 037



Dark Matter Searches at Colliders



"Maverick Dark Matter at Colliders" JHEP 09 (2010) 037



Dark Matter Searches at Colliders

Complementarity to Direct Detection

Collider experiments competitive w/ direct detection ones



Spin Dependent (axial-vector mediator) up to m_{DM} ~500 GeV



Spin Independent (vector mediator) for very light $m_{DM} < ~5 \text{ GeV}$



Do anomalies exist in the LHC data?



Anomalies do exist... a few examples

Several 3σ local excesses...



Warning: With such large number of searches statical fluctuations are expected and there could be systematic effects!

Local (global) significance at 95 TeV : 3.1σ (2.7σ)

 $\phi \rightarrow \tau^+ \tau^-$

Local (global) significance at 1.2 TeV : 2.8σ **(2.4σ**)





NO NEW PHYSICS OBSERVED → LOOK FURTHER/DEEPER

Explore new tools and techniques





Long-lived particles (LLPs)

Long-lived particles (LLPs) are common in BSM

- Small phase space for decay (e.g. Split SUSY)
- Small couplings to SM particles
 - Suppressed (e.g. Higgs/gauge portal to Dark Sector)
 - Forbidden by symmetry (SUSY R-parity)

Could have escaped observation so far

Challenges:

- Often requires new triggers
- Exotic detector signatures (requiring new tools)
- Non-standard backgrounds





Displaced leptons

Disappearing track

Large pixel dE/dx

Track-less jets

Displaced vertices

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Lifetime limit

.

Status: July 2021

	Model	Signature	∫£ dt [fb	⁻¹]
	RPV ${ ilde t} o \mu q$	displaced vtx + muon	136	ĩ li
	$RPV\chi_1^0 o eev/e\mu v/\mu\mu v$	[,] displaced lepton pair	32.8	χ_1^0
	$\operatorname{GGM} \chi_1^0 \to Z \tilde{G}$	displaced dimuon	32.9	χ_1^0
	GMSB	non-pointing or delayed γ	[/] 20.3	χ_1^0
	GMSB $\tilde{\ell} \to \ell \tilde{G}$	displaced lepton	139	$ ilde{\ell}$ i
X	GMSB $\tilde{\tau} \rightarrow \tau \tilde{G}$	displaced lepton	139	ĩΙ
SUS	AMSB $pp \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^{\pm} \chi_2^0$	$\frac{1}{1}$ disappearing track	136	χ_1^{\pm}
	AMSB $pp \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^{\pm} \chi_2^0$	$\frac{1}{1}$ large pixel dE/dx	18.4	χ_1^{\pm}
	Stealth SUSY	2 MS vertices	36.1	Ŝ١
	Split SUSY	large pixel dE/dx	36.1	ĝ١
	Split SUSY	displaced vtx + E_{T}^{miss}	32.8	ĝ١
	Split SUSY	0 ℓ , 2 – 6 jets + E_{T}^{miss}	36.1	ĝ
	$H \rightarrow s s$	ID/MS vtx, low EMF/trk jet	s 36.1	sl
	VH with $H \rightarrow ss \rightarrow bbb$	$b 2\ell + 2$ displaced vertices	139	s li
10%	FRVZ $H \rightarrow 2\gamma_d + X$	2 $e^{-,\mu-jets}$	20.3	γd
H =	FRVZ $H ightarrow 2\gamma_d + X$	2 μ –jets	36.1	γd
jgs B	FRVZ $H ightarrow 4 \gamma_d + X$	2 μ –jets	36.1	γd
Hiç	$H \rightarrow Z_d Z_d$	displaced dimuon	32.9	Zd
	$H \rightarrow ZZ_d$	2 e, μ + low-EMF trackless	jet 36.1	Zd
	$\Phi(200 \text{ GeV}) \rightarrow s s$	low-EMF trk-less jets, MS v	/tx 36.1	s li
alar	$\Phi(600 \text{ GeV}) \rightarrow s s$	low-EMF trk-less jets, MS v	/tx 36.1	s li
Sc	$\Phi(1 \text{ TeV}) \rightarrow s s$	low-EMF trk-less jets, MS v	/t× 36.1	s li
HNL	$N \to W\ell$	displaced vtx ($\mu\mu$ or μe) +	μ 36.1	N
	$N \to W\ell$	displaced vtx ($\mu\mu$ or μe) +	μ 36.1	Ν
		$\sqrt{s} = 13$ ToV		

*Only a selection of the available lifetime limits is shown.

partial data

full data

/s=8 iev

 $\int \mathcal{L} dt = (18.4 - 139) \, \text{fb}^{-1}$



 $m(\tilde{t}) = 1.4 \text{ TeV}$ 0.003-6.0 m



ATLAS Preliminary $\sqrt{s} = 8, 13 \text{ TeV}$

- Reference
 - 2003.11956
 - 1907.10037
 - 1808.03057
 - 1409.5542
- 2011.07812
- 2011.07812
- ATLAS-CONF-2021-015
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 - 1808.04095
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- ATLAS-CONF-2018-003
 - 1911.12575
 - 2107.06092
 - 1511.05542
 - 1909.01246
 - 1909.01246
 - 1808.03057
 - 1811.02542
 - 1902.03094
 - 1902.03094
 - 1902.03094
 - 1905.09787
 - 1905.09787

NO NEW PHYSICS OBSERVED \rightarrow LOOK FURTHER/DEEPER

Explore new tools and techniques

The highest energy possible

As low backgrounds as possible

The highest luminosity possible



THE LARGE HADRON COLLIDER

LHC and experiments being upgraded

CERN




HL-LHC Upgrade

~1.2 km of accelerator will be upgraded



CLIQ A novel concept of magnet protection, based on fast injection of oscillating currents, will improve the safety of the very large stored energy quadrupoles.

ALICE



CRYOGENICS 2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS will allow cryo-separation between arcs and triplet regions.



BEAM GAS VERTEX Two new novel beam instruments based on beam gas vertex detectors will allow non-invasive accurate measurements of the beam size.



"CRAB" CAVITIES 8 SRF «crab» cavities on each side of ATLAS and CMS experiments to tilt beams at collision.



BEAM SCREEN All new magnets will be equipped with a new special beam screen to intercept collision debris at 60 K temperature and cancel electron-cloud effects.



11 T DIPOLE MAGNET

2 pairs of bending magnets, based on advanced Nb₃Sn superconductor and much stronger than LHC dipoles, to free up space for special collimators in the cold regions



COLLIMATORS

20 novel low impedance collimators for beam stability and further 24 new collimators for improved machine protections

LHC TUNNEL



QUADRUPOLE MAGNETS

24 new quadrupole magnets of 11.4 tesla peak field , based on advanced Nb₂Sn superconductor, to double beam focusing at ATLAS and CMS collision points.

Hi-LUMI Gallery

ya T



CMS



ATLAS

CIVIL ENGINEERING 2 new caverns, 1km underground galleries, two new large shafts; 10 new technical buildings on surface in P1 and P5 (near ATLAS and CMS)

SUPERCONDUCTING LINKS

8 novel electric current superconducting lines, 140 m long and rated for 30-100 kA, based on MgB₂ superconductor operating at a temperature up to 20 K.



Challenging Phase-II Upgrades of ATLAS and CMS

Higher peak luminosity and larger pile-up (from ~ 30 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwith, faster and more granular readout electronics, improved triggers and higher redundancy, to provide similar or better performance than current detectors (including trigger thresholds) in much harsher HL-LHC environment



Event with 78 reconstructed vertices (CMS Run 2 data) Note: ~ 20 expected when detectors were designed



HL-LHC: ~ 140-200 evts/x-ing



New timing detectors with resolution ~ 30 ps in both experiments will allow 4-dimensional identification of primary vertex





Challenging Phase-II Upgrades of ATLAS and CMS

ATLAS tracker (ITk)



$|\eta| < 4$

Low mass, rad hard Barrel: 5 pixel + 4 strip layers End-cap: up to 23 pixel + 6 strip rings Pixel size: 25 x 100 μ m² and 50 x 50 μ m² Strip size (barrel): ~ 75 μ m x 24-42 mm

Total Si area: ~ 180 m² Total # of channels: ~ 5 billion (50 x today)

CMS end-cap calorimeter (HGCAL)



$1.5 < |\eta| < 3$

Unprecedented lat. and long. segmentation (ILC-type) Time resolution ~ 30 ps

EM part (CE-E): Si pads, Cu/CuW/Pb absorber 26 layers, 25 X₀

HAD part (CE-H): Si and scintillator, steel absorber 21 layers, 8.5 λ

~ 600 m² of Si pads (0.5-1 cm²)

10⁶ channels



New High-Energy Collider Projects







e⁺e⁻, √s: 90 - 350 (365) GeV; FCC-hh pp Circumference: 97.75 km





Hadron versus lepton colliders





S/B ~ 10-10

1. Proton are compound objects

- Initial state unknown (particle and momentum)
- Limits achievable precision
- 2. High rates of QCD background
 - Complex triggers
 - High levels of radiation
 - Detector design focus on radiation hardness of many sub-detectors

3. Very high-energy circular colliders feasible



- **1. Electrons are point-like particles**
 - Initial state well-defined (particle, energy, polarization...)
 - High-precision measurements
- 2. Clean experimental environment
 - No (less) need for triggers
 - Lower levels of radiation

3. Very high-energies require linear colliders





After the Higgs boson discovery, no other new physics found Need to also pursue outstanding precision

- PRECISION physics can play a key role -





Top Mass Prediction from Precision Electroweak data



Top discovery at Tevatron

$M_{top} = 175 -> 173 \text{ GeV}$

World average: $m_{top} = 173.1 \pm 0.6 \text{ GeV}$ (0.35%)









July 21-27



Overnight update



Higgs coupling measurement at future colliders





Combination of electroweak measurements



Precision of theory predictions needs to improve to take advantage of this experimental precision for full sensitivity to new physics

Mogens Dam, HK2019





Higgs self-coupling at lepton colliders

Global effective-field-theory analysis can assess Higgs trilinear self-coupling







83

BSM Physics through Exotic Higgs Decays

General search for BSM

e⁺e⁻ collider better than HL-LHC for **MET+hadronic activity final states**





95% C.L. upper limit on selected Higgs Exotic Decay BR

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Z. Liu, H. Zhang, LT Wang, 1612.09284







Final remarks

The standard Model is well established but many questions remain answered

- LHC, including HL-LHC, to provide still 20-30x more data Hence, small discrepancies can still turn into discoveries
- Higgs self coupling measurement at HL-LHC is a major milestone
 - Planning for the next future accelerators has started (see Tatsuya Tanaka's lecture tomorrow for details)
- Expect new exciting sensitivity for BSM physics and potential discoveries Higgs will continue to play an essential role
 - Explore synergies of electron and hadron colliders to maximize physics potential





Constituent Center-of-Mass Energy

Symmetry Magazine, 2009

ATLAS and CMS in more detail

Sub System	ATLAS	CMS							
Design		ter and the second seco							
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside							
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T\sim5 imes10^{-4}p_T\oplus0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 imes 10^{-4} p_T \oplus 0.005$							
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E\sim 3\%/\sqrt{E}\oplus 0.5\%$							
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$							
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\% \text{ (at 50 GeV)}$ $\sim 11\% \text{ (at 1 TeV)}$	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\% \text{ (at 50 GeV)}$ $\sim 10\% \text{ (at 1 TeV)}$							





How bad does it look?





