Searches for Supersymmetry with the ATLAS Detector at the Large Hadron Collider in Final States with Tau Leptons

Alexander Mann

mann@cern.ch

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

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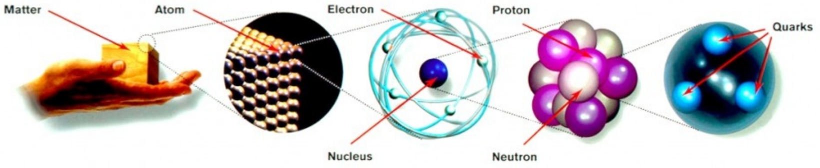
Searches for **Supersymmetry**
with the **ATLAS Detector** at the **Large Hadron Collider**
in Final States with **Tau Leptons**

1. Standard Model of Particle Physics
2. Supersymmetry
3. LHC & ATLAS
4. Tau Leptons
5. Searches
6. Summary & Conclusions

INTRODUCTION

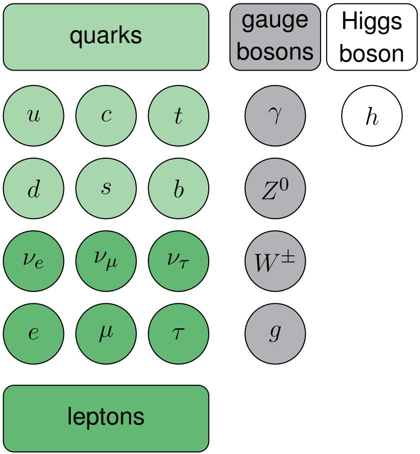
Elementary particles = smallest known building blocks of matter



The Standard Model of Particle Physics

Building Blocks

Standard Model: describes known (elementary) particles and their interactions



- Fermions (spin $^1/_2$):
  6 quarks (3 up-type, 3 down-type)
  + 6 leptons (3 charged, 3 neutral)
  - arranged in 3 generations
  - differ by mass (and stability / lifetime)
  - plus their antiparticles
- Bosons (integer spin):
  - γ: electromagnetic interactions
  - Z^0, $W^\pm$: weak interactions
  - g: strong interactions
- Higgs mechanism explains mass of elementary particles
  - Higgs boson as excitation of Higgs field
  - only known scalar elementary particle
  - discovered 2012 at the LHC

The Standard Model of Particle Physics

Open questions

- Standard Model: predictive theory, testable, successful
- But: important open questions remain

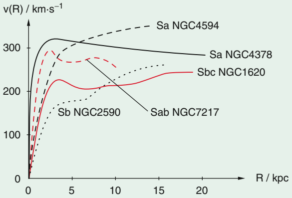
- Nature of Dark Matter?
- Hierarchy problem $\rightarrow$ fine-tuning of the Higgs mass?
- Matter–antimatter asymmetry in the Universe?
- Unification of forces at high energies (Grand Unified Theory)?
- Neutrino oscillations $\rightarrow$ non-zero neutrino masses?
- ...
- Discrepancies of values predicted by SM theory with experimental observations?

- Will likely require answers outside current Standard Model

$\Rightarrow$ "New Physics" or "Beyond-Standard-Model (BSM) Physics"

Dark Matter (DM)

- Existence inferred from
  - observation of rotation curves of spiral galaxies
  - bullet cluster
  - large-scale structure formation
  - ...
- From spectrum of Cosmic Microwave Background:
  - Baryonic ("ordinary") matter: $\sim 5\,\%$
  - Dark Matter: $\sim 26\,\%$
  - Dark Energy: $\sim 69\,\%$
- Among SM particles no candidate for Cold DM

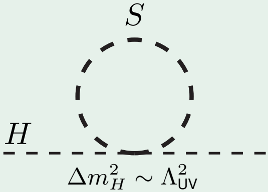


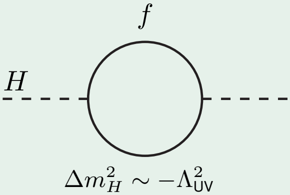
Rotation curves of spiral galaxies

Bullet Cluster

Hierarchy problem of the Higgs mass

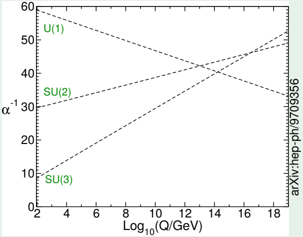
- Higgs: (elementary) scalar particle
- Higgs mass receives large loop corrections
- Cut-off scale $\Lambda_{\text{UV}} \sim$ Planck scale $(10^{19}\,\text{GeV})$
- Requires fine-tuning of parameters to arrive at observed value for $m_H = 125\,\text{GeV}$





Gauge Coupling Unification

- Grand Unified Theory: unification of forces,
  electromagnetic, weak and strong
- Extrapolation of running coupling constants
  - expect intersection at GUT scale $(10^{16}\ \mathrm{GeV})$



→ look beyond the SM: Supersymmetry →

Extending the Standard Model: Supersymmetry

Basic idea of Supersymmetry (SUSY)

- Postulate additional symmetry:

$$\text{fermion} \quad \xleftrightarrow{\Delta s = 1/2} \quad \text{boson}$$

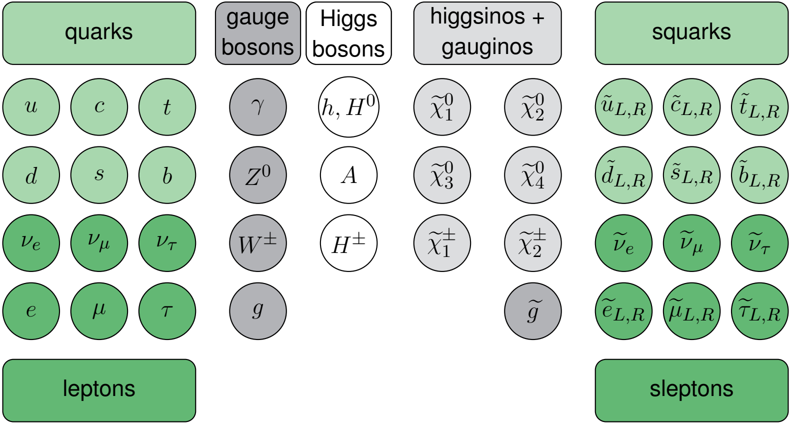
- Particles form "supermultiplets"
  - match fermionic and bosonic degrees of freedom
  - i. e. "for every fermion there's a boson and vice-versa"

Consequences

- Solves problems!
- Predicts new particles
  - cannot match known SM particles in supermultiplets
  - basically doubling of particle content
  - something we can search for at colliders
- Theoretically appealing: physics in general builds on symmetries
  - Supersymmetry = only non-trivial extension of Poincaré symmetry group (Haag-Łopuszański-Sohnius-Theorem)

Going Beyond the Standard Model: Supersymmetry

Particle content of the **M**inimal **S**upersymmetric **S**tandard **M**odel (MSSM)



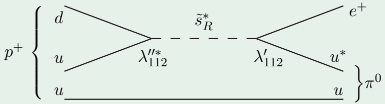
- “For every fermion there is a boson”
- Exception: Higgs sector — need two complex Higgs doublets ($2\times$SM) $\Rightarrow$ 5 Higgs bosons
- “electroweakinos” and higgsinos mix to neutralinos $\widetilde{\chi}^0_{1,2,3,4}$ and charginos $\widetilde{\chi}^\pm_{1,2}$

Where *are* all these particles?

- Standard Model and SUSY particles: same quantum numbers (except spin)
- No SUSY particles experimentally observed yet ⇒ contradiction?
- Solution: SUSY particles heavier
  ⇒ i. e. SUSY is a *broken* symmetry
  ⇒ SUSY particles can have *any* mass

R-parity and its phenomenology

- SUSY allows proton to decay:



$$p^+ \to e^+ \, \pi^0$$

- contradiction?

- Remedy: introduction of R-parity
  - SM particles: $R = +1$,
  - SUSY particles: $R = -1$
  - multiplicative quantum number
- Here: assume R-parity conservation
  - no proton decay
  - pair production of SUSY particles
  - lightest SUSY particle (LSP) stable, often $\widetilde{\chi}^0_1$
    ⇒ detector signature: “missing energy”
    (imbalance in total momentum)

Dark Matter (DM)

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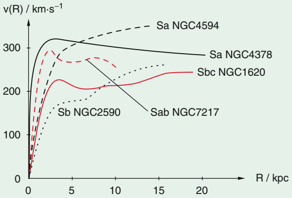
  - Dark Matter: $\sim 26\,\%$
  - Dark Energy: $\sim 69\,\%$
- Among SM particles no candidate for Cold DM
- lightest SUSY particle:
  stable, massive, and weakly-interacting:
  perfect **candidate for Cold Dark Matter** ✓



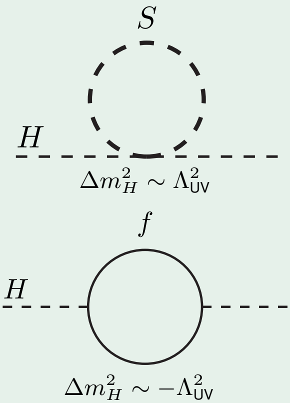
Rotation curves of spiral galaxies

Bullet Cluster

Open Questions

Hierarchy problem of the Higgs mass

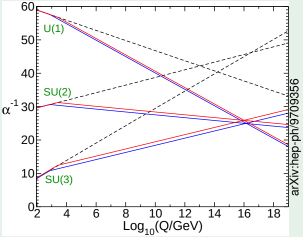
- Higgs: (elementary) scalar particle
- Higgs mass receives large loop corrections
- Cut-off scale $\Lambda_{\text{UV}} \sim$ Planck scale $(10^{19}\,\text{GeV})$
- Requires fine-tuning of parameters to arrive at observed value for $m_H = 125\,\text{GeV}$
- loop corrections from bosons S and fermions f cancel exactly in (unbroken) SUSY
  $\Rightarrow$ **stabilization of Higgs mass** at EWK scale ✓



Open Questions

Gauge Coupling Unification

- Grand Unified Theory: unification of forces,
  electromagnetic, weak and strong
- Extrapolation of running coupling constants
  - expect intersection at GUT scale (10^{16} GeV)
  - find **intersection of extrapolated running couplings** if including SUSY ✓



→ look beyond the SM: Supersymmetry →

General Idea for What Follows

- SUSY works — let's set out to look for it
- How? $\rightarrow$ produce heavy new particles predicted by SUSY
- How? $\rightarrow$ smash some known particles into each other and study collision products, e. g.

$$p + p \longrightarrow X, \quad \text{SUSY} \in X?$$

- How? $\rightarrow$ with particle collider machines and collision detectors

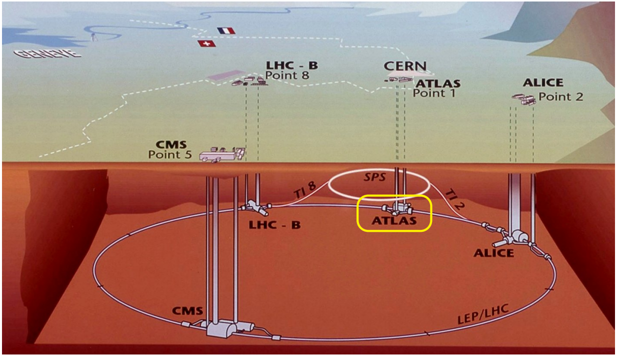
- The more energy in collisions, the better
- Need large machines and large detectors

LHC AND ATLAS

Where Do We Get Our Data From?

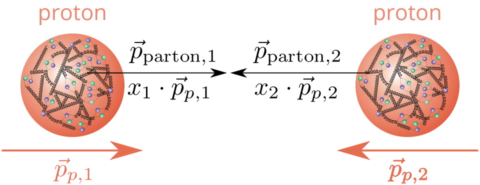
Large Hadron Collider

- Circular (synchrotron) hadron collider with $26.7\,\mathrm{km}$ circumference, successor of LEP
- Proton–proton collisions at centre-of-mass energy $E_{\text{CoM}} = \sqrt{s} = 13\,\mathrm{TeV}$ (Run 2)
  (2010 – 2011: 7 TeV, 2012: 8 TeV; design value: $14\,\mathrm{TeV}$)
- 4 interaction points with beam crossings, 4 big detectors: ATLAS, CMS, ALICE, LHCb



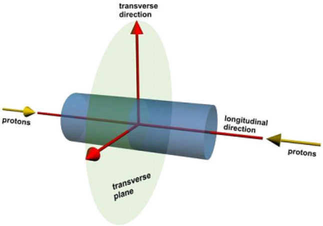
What's inside a proton?

- LHC = proton–proton collider: $|\vec{p}_{p,1}| = |\vec{p}_{p,2}| = 6.5\,\text{TeV} = E^{pp}_{\text{CoM}}/2$
- Hard-scatter process involves partons (quarks and gluons)
- Initial momentum along beam axis (z-axis) unknown



Transverse quantities

- Need to use transverse quantities
  - e. g. $p_{\text{T}} = \sqrt{p_x^2 + p_y^2}$ (invariant under boost along z)
- Similar for "invisible" (weakly interacting) particles:
  "missing transverse momentum" ($|\vec{p}_{\text{T}}^{\,\text{miss}}| = E_{\text{T}}^{\text{miss}}$)



Luminosity

- Number of collision events:

$$N = \sigma \cdot L$$

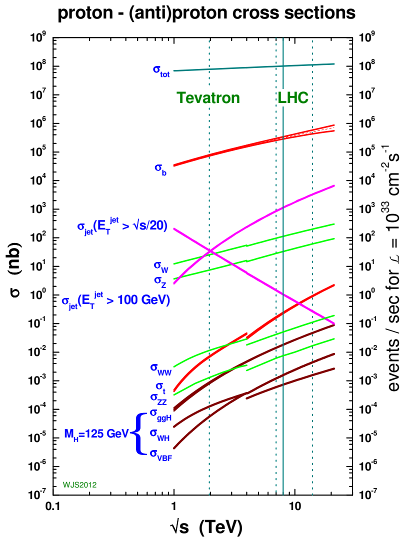
  - σ: cross section (unit: barn, $1\,\mathrm{b} = 10^{-24}\,\mathrm{cm}^2$)
  - L: integrated luminosity

$$L = \int \mathcal{L}\,\mathrm{d}t$$

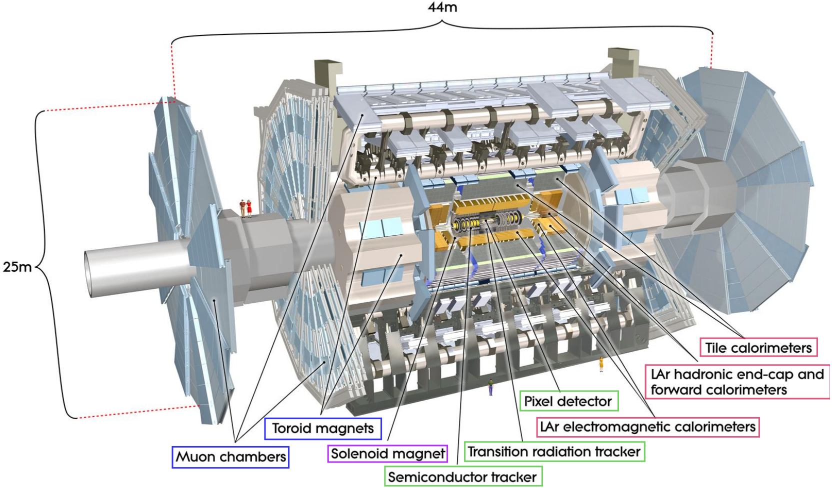
- Instantaneous luminosity:
  - computed from beam parameters

$$\mathcal{L} = \frac{f N_{\text{bunches}} N_1 N_2}{4\pi s_x s_y}$$

- "New Physics" = small cross section
  - typically $\sigma_{\text{SUSY}} \lesssim \mathcal{O}(1\,\mathrm{pb})$
  - $\Rightarrow$ 1 SUSY event per hour
  - swamped with background events...



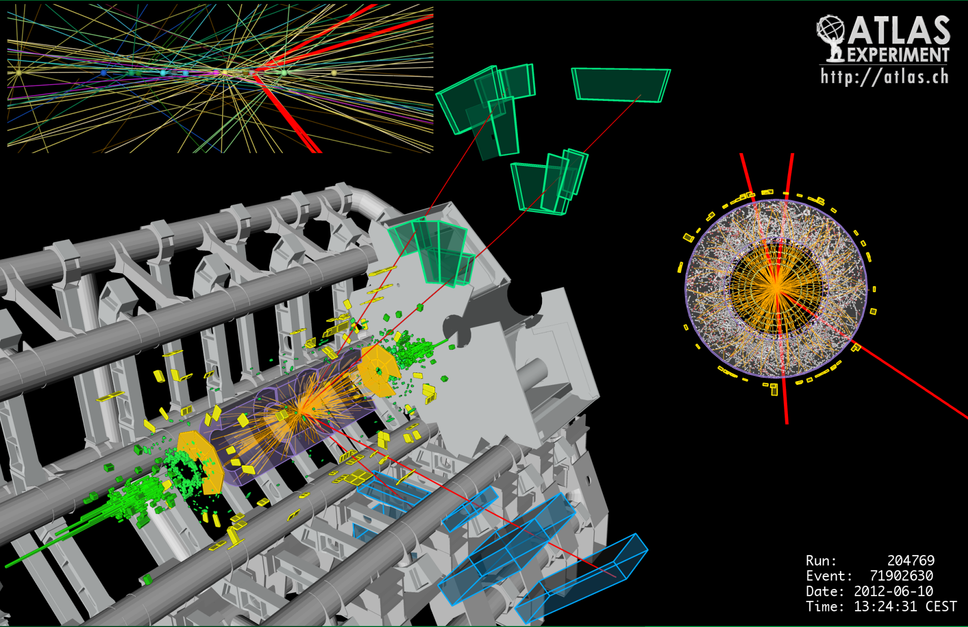
The ATLAS Detector



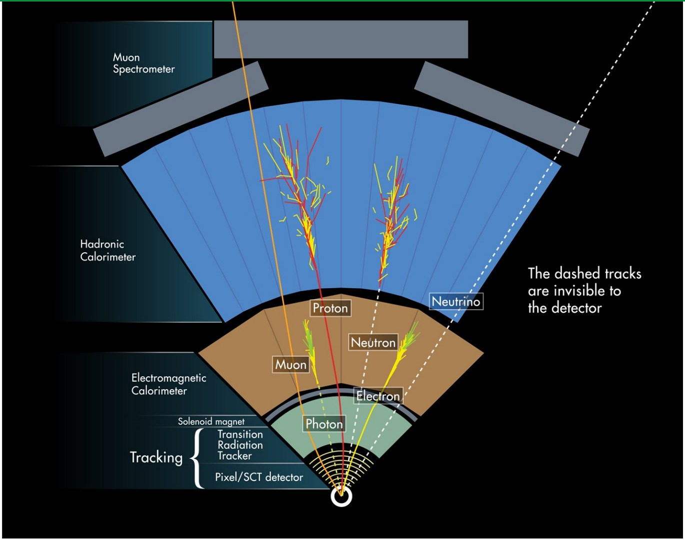
- 44 m $\times$ 25 m $\times$ 25 m, 7000 tonnes
- Subdetectors = concentrical cylinders surrounding nominal IP
- Tracking detectors — solenoid magnet — calorimeters — muon spectrometer

An ATLAS Collision Event

This is (to some extent) what it looks like before reconstruction



Reconstruction of Physics Objects from the Data

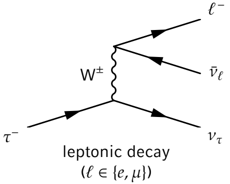


- Register and identify all “visible” particles
- Infer physical processes in the collision event

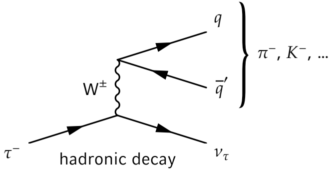
Tau Leptons

What's special about them?

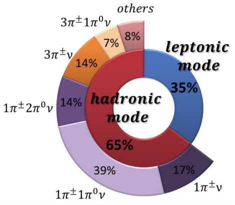
- Tau lepton: heaviest known lepton, $m(\tau) = 1777\,\mathrm{MeV}$
  - heavier than lightest mesons (π^0 (135.0 MeV), $\pi^\pm$ (139.6 MeV), $K^\pm, \ldots$)
  - can decay both to leptons or to hadrons
- Tau lepton: short lifetime, $c\tau = 0.087\,\mathrm{mm}$
  - decay before reaching active detector regions



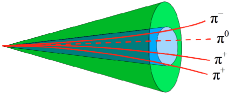
$\mathrm{BR}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau) \sim \frac{1}{6}$



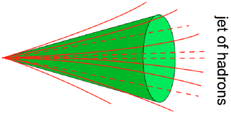
$\mathrm{BR}(\tau^- \to \text{hadrons}\ \nu_\tau) \sim \frac{4}{6}$



- leptonic decays: leptons (e, μ) from tau decay register as “prompt” light leptons
- hadronic decays: can be reconstructed from detector signature of decay



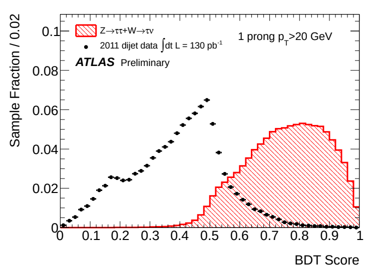
schematic signature
of a hadronically decaying tau lepton



schematic signature
of a jet arising from a quark

Identification

- Detector signature of a tau lepton:
  - a few tracks, pointing to a secondary vertex
  - clustered energy deposit in the calorimeters, collimated jet
- Very similar to that of a jet
  - jet production very large cross section at LHC
- Need sophisticated analysis techniques to discriminate real tau leptons from jets mimicking a tau leptons ("fakes")

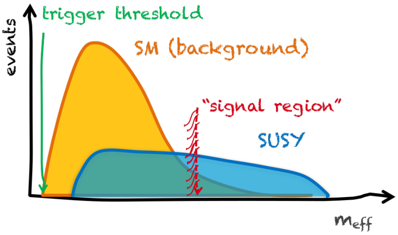


HOW TO SEARCH FOR SUSY

How Do We Search for Supersymmetry at the LHC?

Looking for a tiny excess. . .

- Additional (SUSY) particles
  $\Rightarrow$ additional possible reaction channels
  $\Rightarrow$ additional event counts compared to Standard Model
- General assumption in many searches for BSM physics



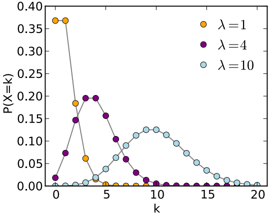
Recipe

1. Define signal-enriched event selection ("signal region" — usually "tails")
2. Do a counting experiment
3. Compare event yields expected from SM and SUSY with event yields observed in data

Proper Interpretation of Search Results

Goals

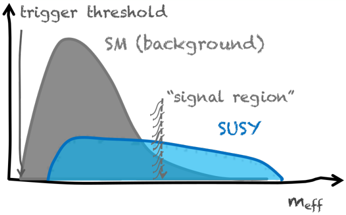
1. Find SUSY if it's there.
2. And do not find it if it's not there.



How can you be certain?

- Main result from search:
  - expected and observed yields in signal regions
- Counting experiment $\Rightarrow$ counts follow Poisson distribution $\Rightarrow$ fluctuations
- Statistical evaluation of yields and their uncertainties
  - quantifies probability at which signal hypothesis can be ruled out
  - proper treatment of uncertainties crucial

How We Model SUSY



Problem: vast SUSY parameter space

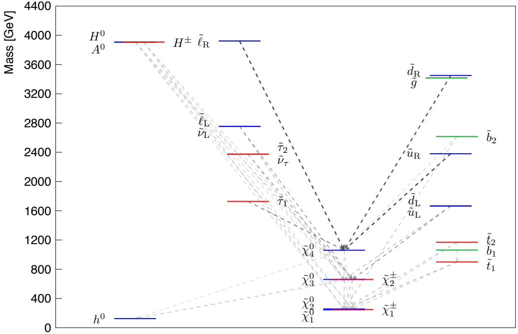
- Don't know SUSY breaking mechanism, don't know SUSY particle masses
- $\Rightarrow$ MSSM has 105 (additional) parameters
  - masses, phases and mixing angles of the MSSM Lagrangian

Approaches

- Assumptions on parameters being zero (based on experimental findings)
  - pMSSM (phenomenological MSSM), 19 parameters
- Assumptions on SUSY-breaking mechanism
  - gravity-mediated SUSY breaking (mSUGRA / CMSSM)
  - gauge-mediate SUSY breaking (GMSB)
- Simplified models
  - now widely used in LHC SUSY searches

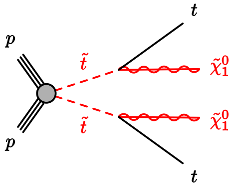
Complete Model

- Includes all SUSY particles → many possible decays with varying branching ratios
- Large number of parameters, many different final states
- Often small number of decay channels dominant → idea: use *simplified model*



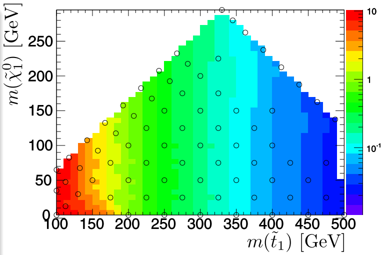
Simplified Models

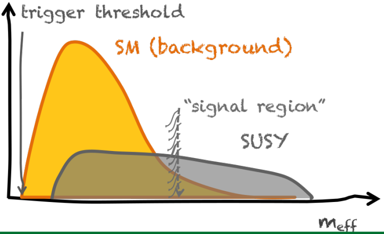
- Pick specific production mode
- Fix decay and branching ratios (e. g. 100 %)
- Assume other SUSY particles decoupled



Advantages

- Well-defined final state
  - easier to optimize for
- Minimal set of parameters
  - allows 2-D scan of signal models
- Another important motivation:
  search results easy to reinterpret for theorists
  - decouple experimental signatures
    from details of SUSY model





Using simulation

- For well-known Standard-Model processes

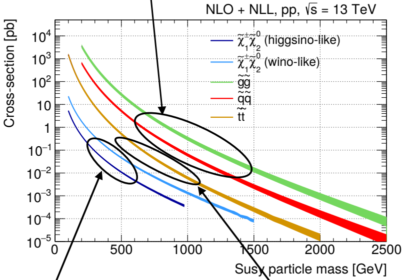
Using data

- For processes which are difficult to simulate, e. g. due to misidentified objects ("fakes")
- Rely on data-driven estimation techniques as much as possible
  - ABCD method
  - Jet smearing
  - Matrix method
  - Fake-factor method
  - Charge-sign method
  - ...

SUSY SEARCHES WITH TAU LEPTONS

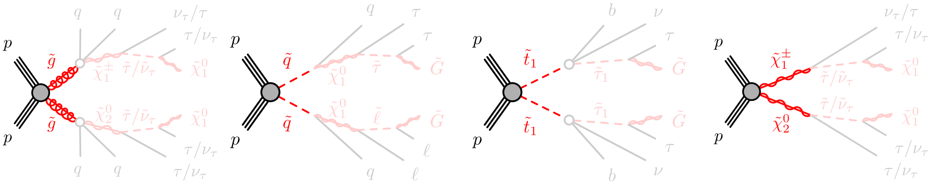
Different Production Modes of SUSY Particles

Strong production
highest production x-sections, inclusive final states

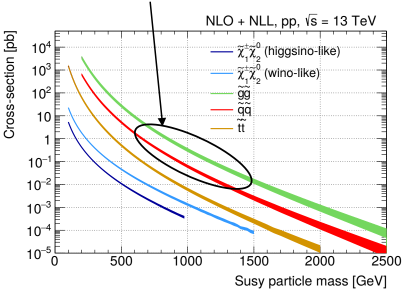


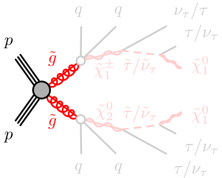
Electroweak production,
leptons and no jets

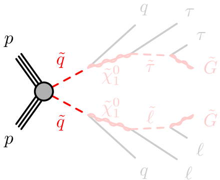
3rd generation,
final states with b-jets



Strong production
highest production x-sections, inclusive final states







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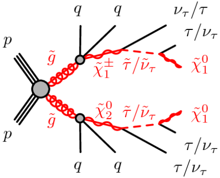
- Search for production of squarks and gluinos, $3.2\,\mathrm{fb}^{-1}$, $\sqrt{s} = 13\,\mathrm{TeV}$ (2015 dataset)
- Targets final states with jets (strong production), $\geq 1\tau_{\mathrm{had}}$, and $E_{\mathrm{T}}^{\mathrm{miss}}$



simplified model

- Two mutually exclusive channels: $= 1\,\tau_{\mathrm{had}}$ & $\geq 2\,\tau_{\mathrm{had}}$

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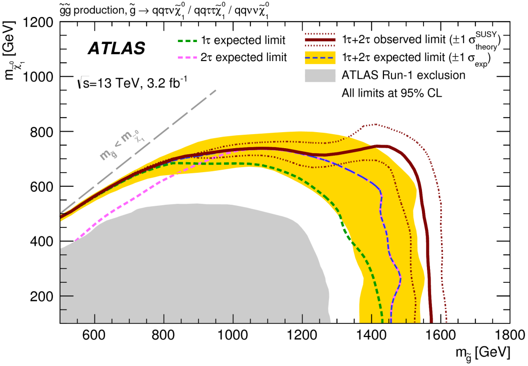
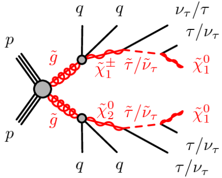
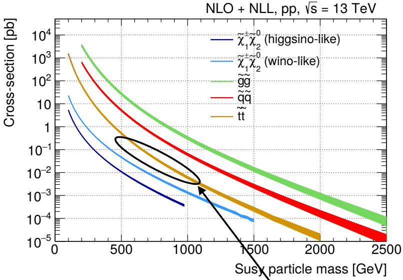


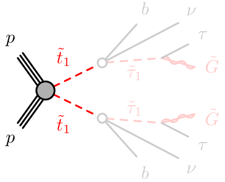


- No excess observed in any signal selection → set exclusion limits
- . . . in our simplified model
  - excluding gluino masses up to 1.6 TeV for LSP masses up to 750 GeV
- Example how $3.2\,\text{fb}^{-1}$ of Run-2 data beat $20.3\,\text{fb}^{-1}$ from Run 1 (grey areas)

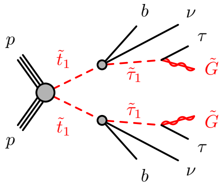
Top-Squark Production

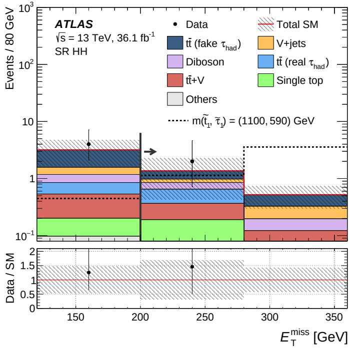


3rd generation,
final states with b-jets



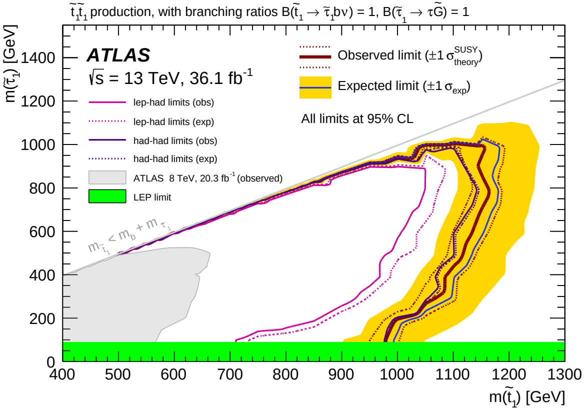
- Model assumes these three SUSY particles within reach:
  $\tilde{t}$ $\tilde{\tau}$ $\sim$ massless $\tilde{G}$
- Interesting model with intriguing detector signature:
  b-jets, tau leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$



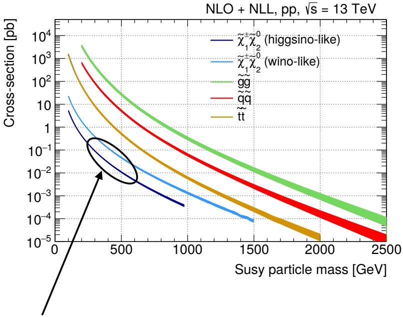


- Analysis selections:
  "lep-had" and "had-had" channels
- Dominant background:
  top-quark pair production ($t\bar{t}$)

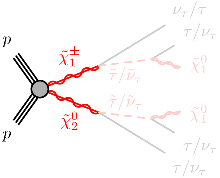
- Agreement between expectation and observed event yields in signal selections
  - no excess attributable to a signal from BSM physics
- Combine lep-had and had-had channel statistically for highest possible sensitivity
- Exclusion of top-squark masses up to 1.16 TeV at 95 % confidence level



	SR LH	SR HH
Observed events	3	2
Total background	2.2 ± 0.6	1.9 ± 1.0
Fake τ_{had} + e/μ	1.4 ± 0.5	—
$t\bar{t}$ (fake τ_{had})	—	$0.6 \pm^{0.7}_{0.6}$
$t\bar{t}$ (real τ_{had})	0.22 ± 0.12	$0.28 \pm^{0.30}_{0.28}$
$t\bar{t} + V$	0.25 ± 0.14	0.26 ± 0.12
Diboson	0.15 ± 0.11	0.28 ± 0.13
Single-top	$0.10 \pm^{0.24}_{0.10}$	0.13 ± 0.11
V + jets	0.032 ± 0.014	0.26 ± 0.09
Others	0.082 ± 0.022	0.09 ± 0.04
Signal ($m(\tilde{t}_1)$ = 1100 GeV, $m(\tilde{\tau}_1)$ = 590 GeV)	3.3 ± 0.7	4.7 ± 1.2



Electroweak production,
leptons and no jets



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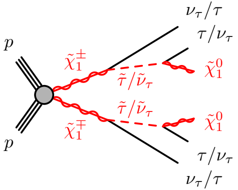
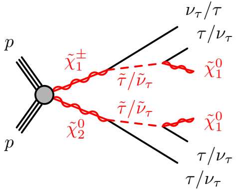
- Search for electroweak production of neutralino $\widetilde{\chi}_2^0$ and chargino $\widetilde{\chi}_1^\pm$
- Analysis selects events with two hadronically decaying tau leptons and $E_\mathrm{T}^\mathrm{miss}$

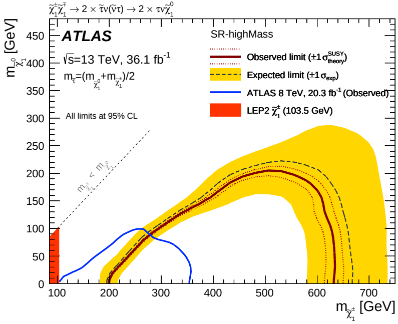


$\widetilde{\chi}_1^\pm \widetilde{\chi}_1^\mp$ production, 2 τ

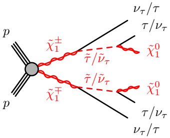


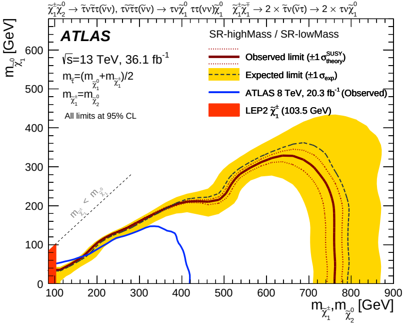
$\widetilde{\chi}_1^\pm \widetilde{\chi}_2^0$ production, 1 – 3 τ

- No significant excess observed

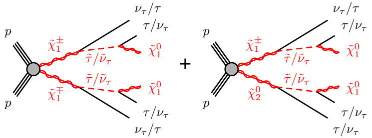


$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production





$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production

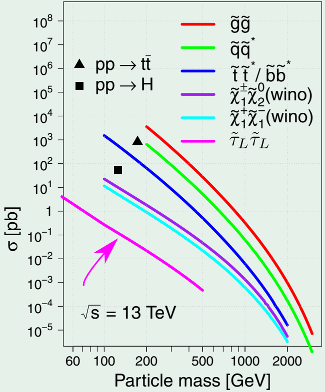


→

Direct Stau Production: Motivation & LEP Result

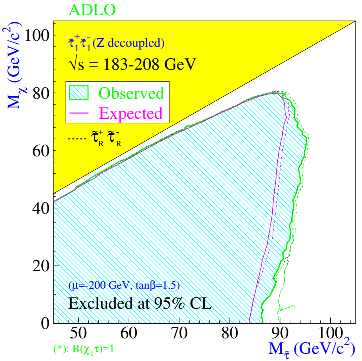
Direct production of tau slepton pairs

- Very small cross section

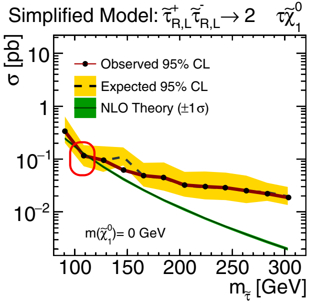


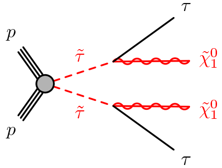
Combined LEP Result (from 2004)

- Searches for $\tilde{\tau} \to \tau\tilde{\chi}_1^0$ decays
- BR($\tilde{\tau} \to \tau\tilde{\chi}_1^0$) of 100 % and massless $\tilde{\chi}_1^0$, lower limit on $m(\tilde{\tau})$: around 90 GeV
- Exclusion extends almost to diagonal



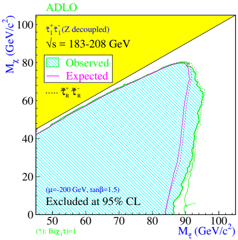
LEP results for $\tilde{\tau} \to \tau\tilde{\chi}_1^0$



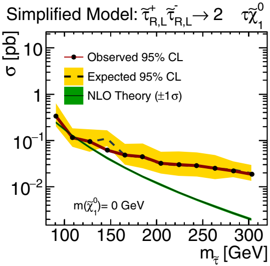


- ATLAS Run-1 analysis (MVA)
  - BDT trained on 12 input variables ($E_{\mathrm{T}}^{\mathrm{miss}}, m_{\mathrm{eff}}, m_{\mathrm{T2}}, m_{\tau\tau}, \ldots$)
- (Only) one scenario excluded with $m(\tilde{\tau}) \approx 110\,\mathrm{GeV}$ and massless LSP
  - cross sections above 0.115 pb excluded, theoretical cross-section at NLO 0.128 pb

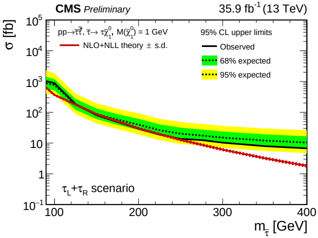
Direct Stau Production: Status Quo



LEP, 2004



ATLAS, 2015

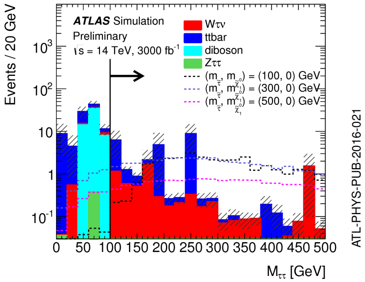


CMS, 2017

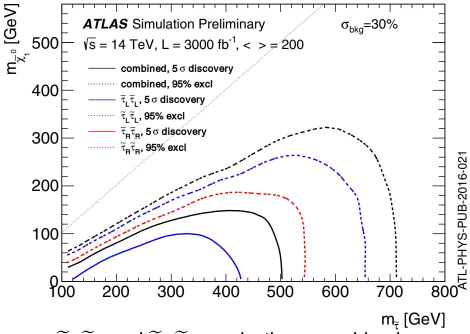
- LEP result from 2004 still standing as only collider result
- No sensitivity at a hadron collider yet
  - LEP limits actually quite impressive: assume only $\tilde{\tau}_R$ xsec + good coverage → hard to beat
  - race between ATLAS and CMS for first expected sensitivity?
  - no results published with 2015 – 2017 dataset yet
- For now: take a look into the future. . .

Performance Study for HL-LHC

- High luminosity (HL): $\mathcal{L} = 3000\,\text{fb}^{-1}$ at $\sqrt{s} = 14\,\text{TeV}$ (HL-LHC)
- Parametrized simulation of performance of upgraded ATLAS detector
  - includes resolution effects, reconstruction efficiencies and misidentification rates



Signal selection



$\tilde{\tau}_L\tilde{\tau}_L$ and $\tilde{\tau}_R\tilde{\tau}_R$ production + combined

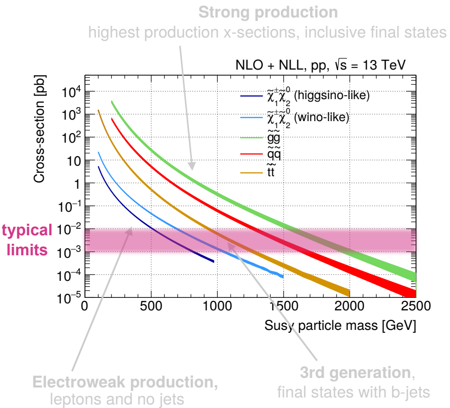
CURRENT SUSY STATUS

Current SUSY Status

Exclusion limits on SUSY masses

ATLAS lower limits on SUSY masses (from simplified models):

- Gluinos: 1.6 – 2 TeV
- Squarks (1st / 2nd generation): 1.2 – 1.8 TeV
- Third-generation squarks: 0.9 – 1 TeV
- Gauginos: start to exceed 1 TeV (but strongly dependent on decay)
- Sleptons (1st / 2nd generation): approach 500 GeV

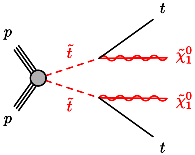


Upper limits on visible cross section

- Upper limits on visible cross section $\langle A\,\epsilon\,\sigma\rangle^{95}_{\mathrm{obs}} \sim 0.2\,\mathrm{fb}$
  - A: acceptance (of analysis selection), ϵ reconstruction efficiency (detector effects)
  - or equivalently on number of additional BSM events in the signal selection
- Typical upper limits $1 - 10\,\mathrm{fb}$ (assuming $A \cdot \epsilon \sim 2 - 20\,\%$)

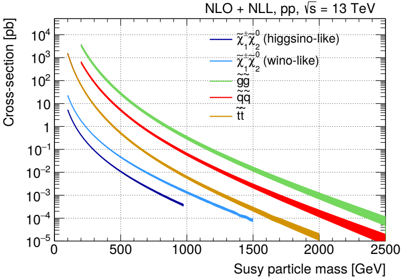
Simplified Models

- SUSY mass limits above derived in model-dependent way
- Come with important simplifying assumptions
- Often chosen to maximise acceptance of selection



e. g. branching ratio

- Example:
  assume $\mathcal{B} = 10\,\%$ rather than $100\,\%$



Limitations of Limits

Impact of intermediate masses

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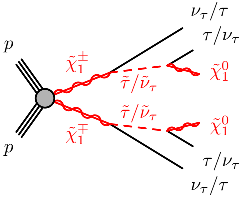

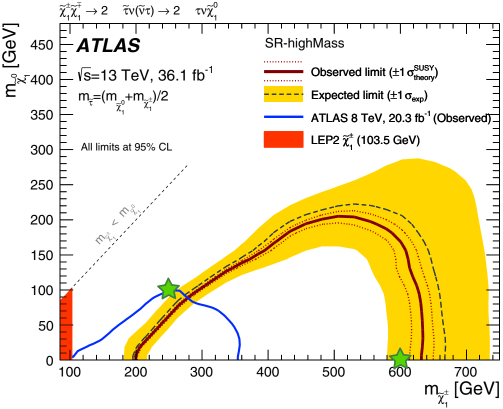

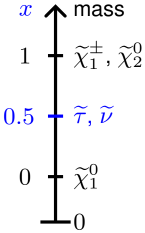

$$m(\tilde{\tau}, \tilde{\nu}_\tau) = ??$$

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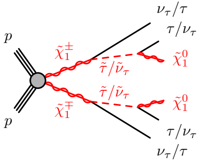

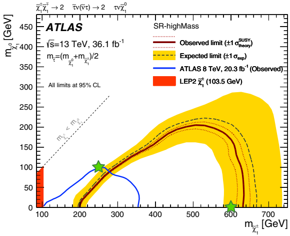

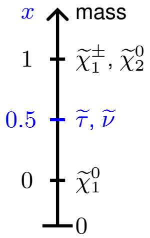

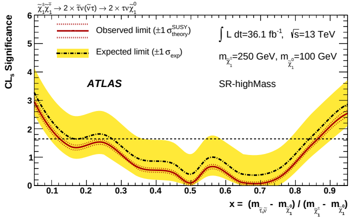

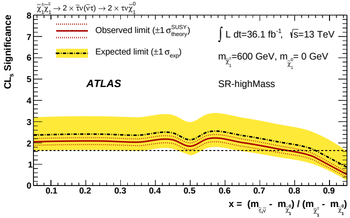

- CL_s as function of x — exclusion at 95 % confidence level: $\text{CL}_s > 1.64$
- $(250, 100)$, extreme x: m_{T2} requirement more efficient (large mass splitting)
  $(600, 0)$, large x: $\rightarrow p_{\text{T}}(\tau)$ too soft

Summary & Outlook

Supersymmetry

- Appealing (hypothetical) extension of the Standard Model
- Provides answers to open questions of the SM
- Signatures provide guidelines for searches for BSM physics

Searches with Tau Leptons

- Final states with tau leptons important part of search program at ATLAS, covering all relevant production modes
- So far null results: no sign for SUSY (or any BSM physics) at "LHC energies"

What now?

- LHC still taking data in 2018
- Final results from Run-2 dataset will come in 2019 / 2020
  - improved understanding of the data, detector, and improved reconstruction performance
  - more comprehensive coverage of signatures, in particular "compressed" spectra
  - follow-ups on potential excesses (2 – 3 σ)