BSM: Supersymmetry

Hadron Collider School

HASCO 2018

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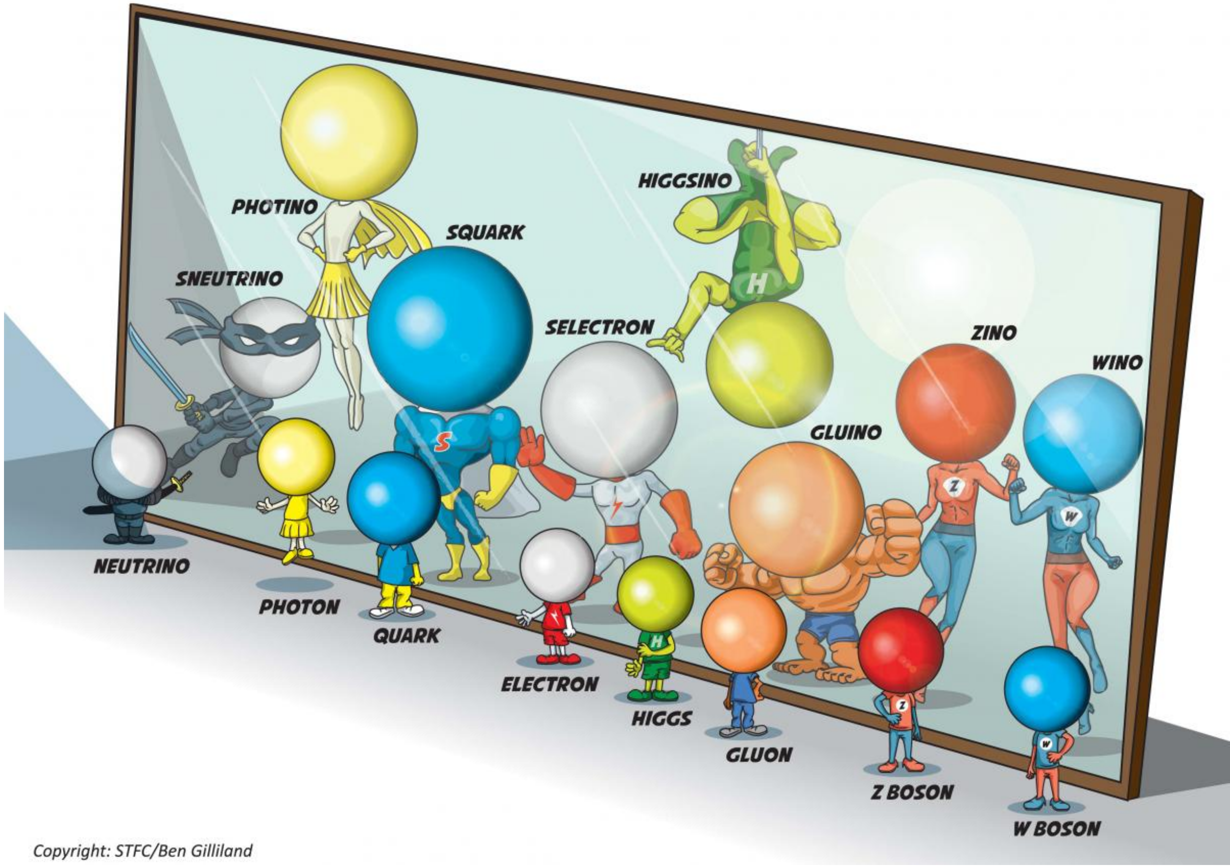

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Introduction

Contents of this lecture

Do we need BSM physics?

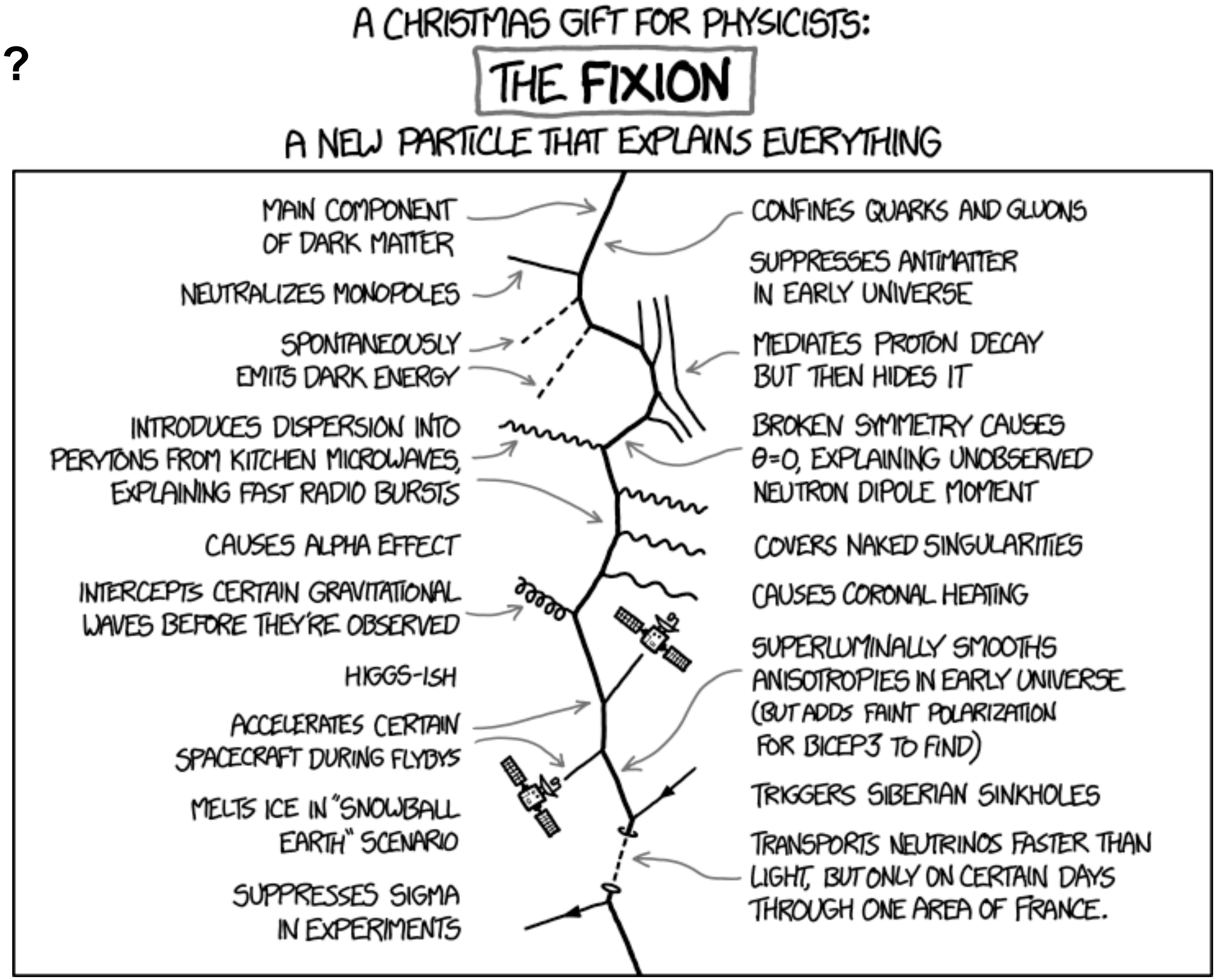
- SM successes
- SM limitations

Supersymmetry

- Basic Concepts
- SUSY spectrum
- SUSY features

Experimental Approach

- Guidance
- How to make a search
- Current status



https://xkcd.com/1621/

The Standard Model

Particle physics, today

The Standard Model is a gauge theory describing

- Elementary particles
  - Fermions
  - Bosons
- Fundamental interactions
  - Strong
  - Electromagnetic
  - Weak

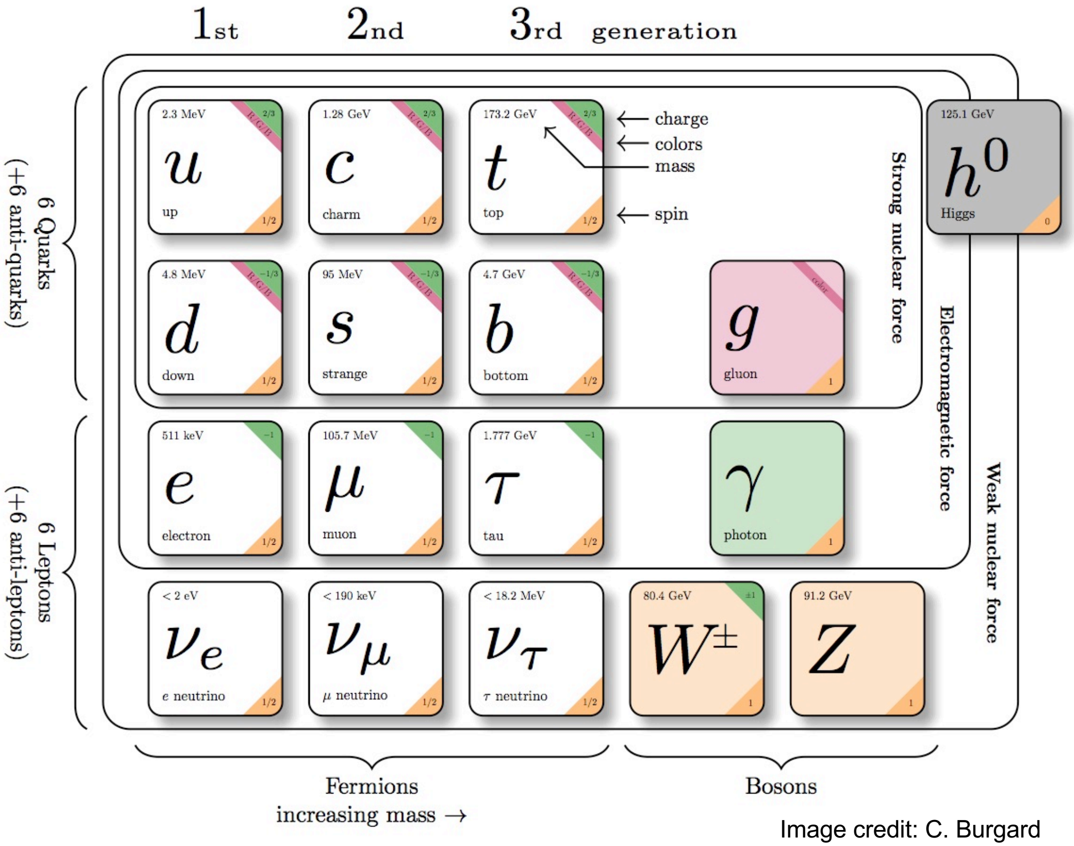
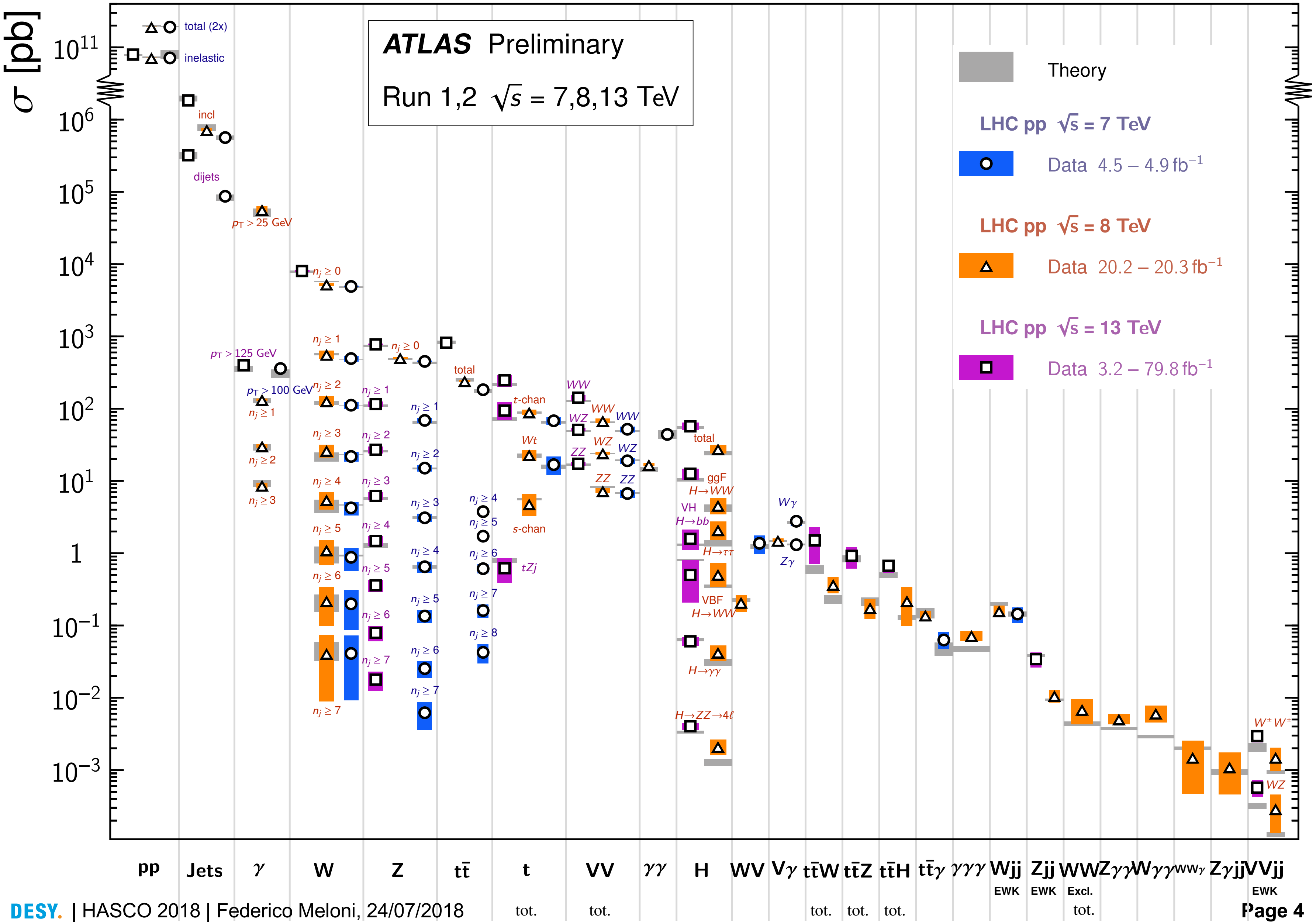


Image credit: C. Burgard

The Standard Model successes



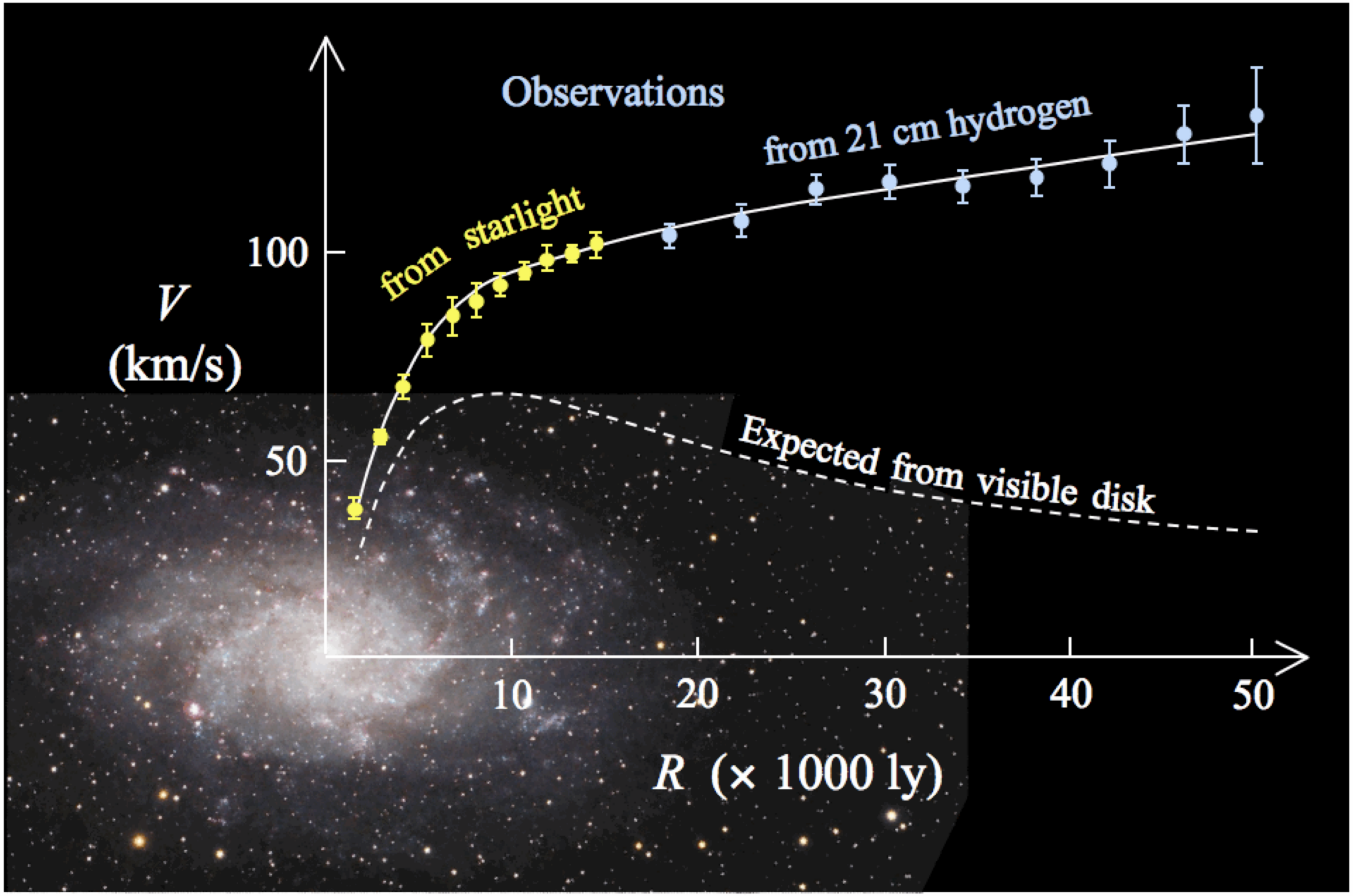
Standard Model shortcomings

Even with such a successful description of Nature, a few, but major, pieces are missing in the puzzle:

- Neutrino masses (and flavour oscillation) not predicted
- Matter-antimatter imbalance
- Unification of forces
- No gravity!
- Missing Dark Matter candidate
- Hierarchy problem

Let's see some in detail…

Dark Matter

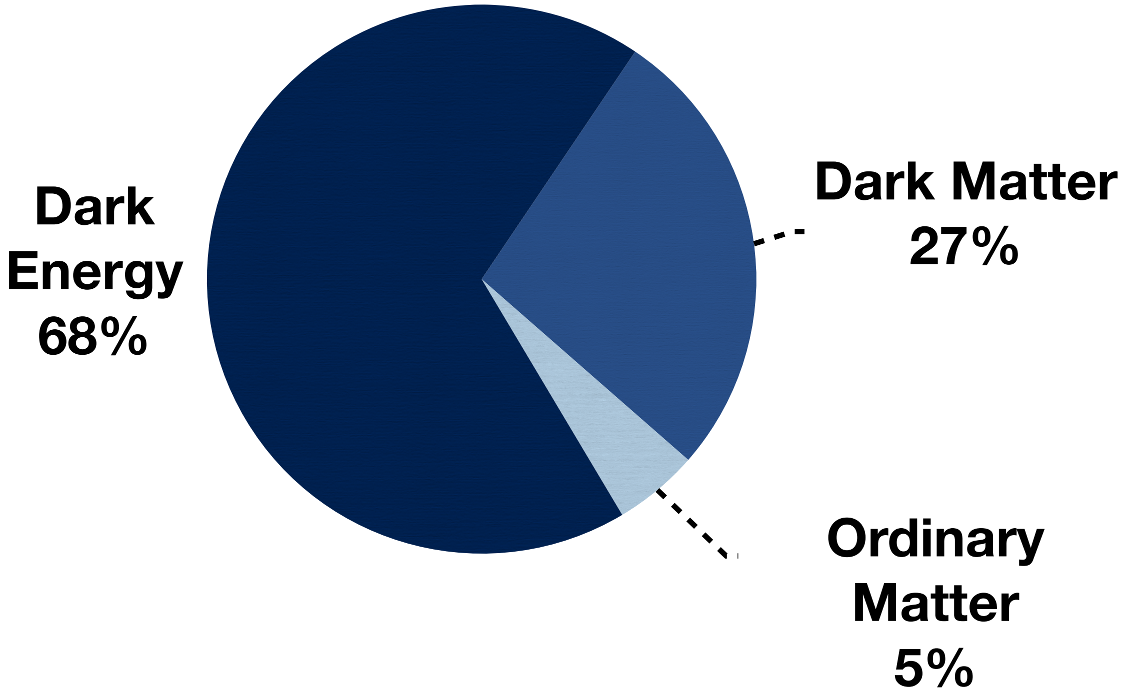

Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

Dark Matter

The Standard Model can account only for a small fraction of the total energy in the Universe.

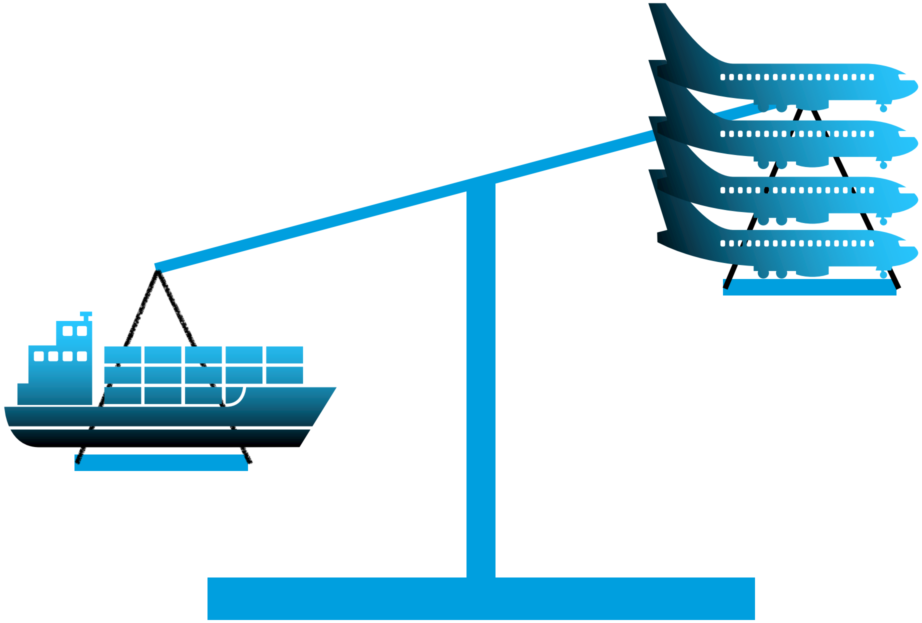
In order to explain Dark Matter, we need a particle that is:

- Stable
- Weakly interacting (we hope)
- Massive



Hierarchy problem

Just a human bias?



Hierarchy problem

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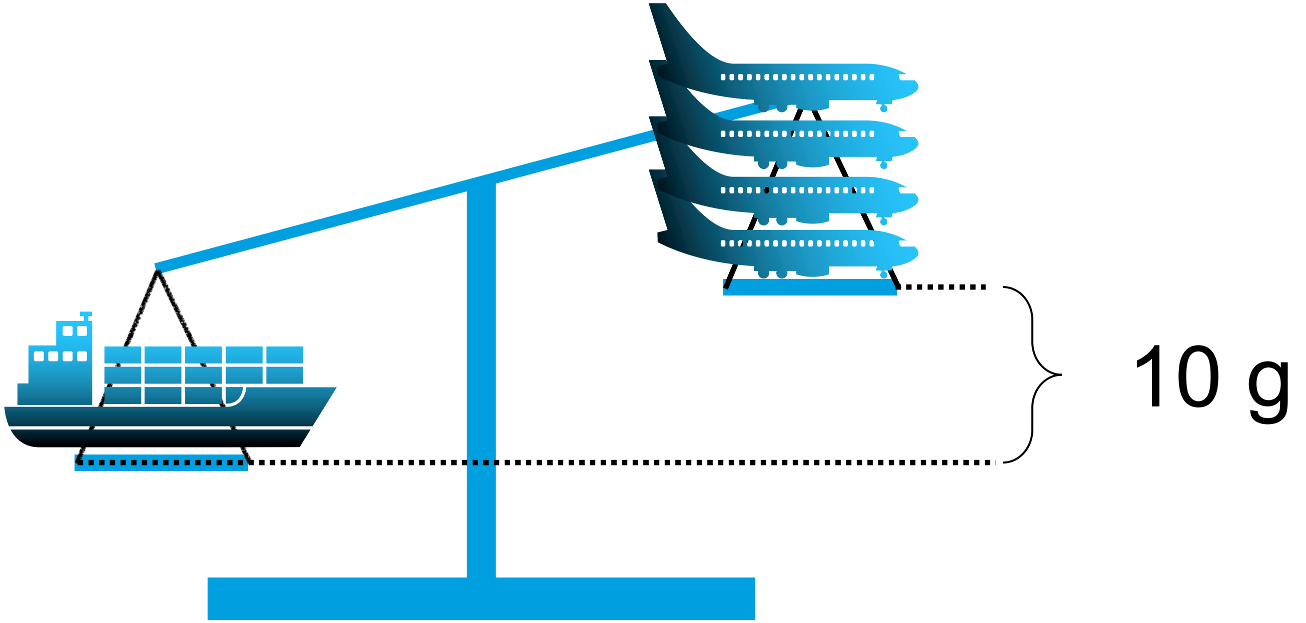
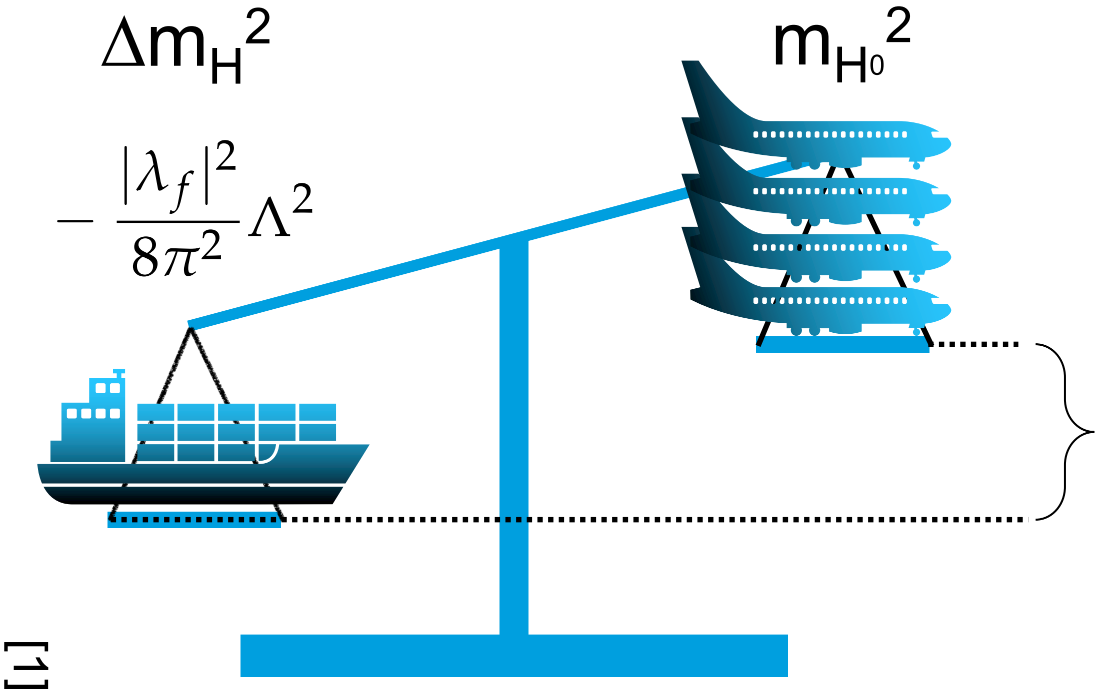


Very hard to believe without some meticulous fine-tuning!

Hierarchy problem

Just a human bias?

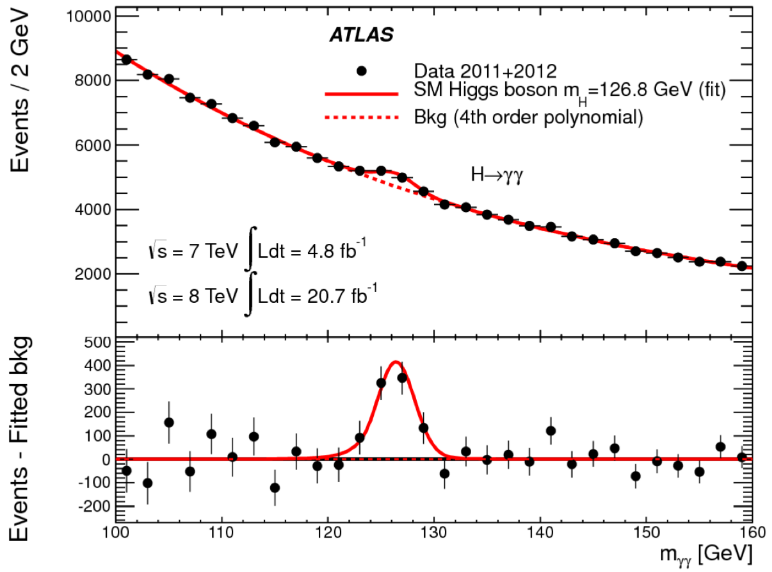


Δm_H^2

$- \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2$

$m_{H_0}^2$

m_H=124.97±0.24 GeV [1]



Similarly hard to believe!

[1] 1806.00242

Beyond Standard Model physics

We are mostly looking for the unknown

- Significantly less hints on where to look with respect to e.g. top quark and Higgs discoveries

You can use two approaches:

- **Top-down** “Come up with a theory and look for a problem [it might solve]”
  - Build your model from first principles
  - Make predictions
  - **Test with data**
- **Bottom-up** “Come up with a problem and look for a theory [that might solve it]”
  - Build your model to explain a specific observation
  - Make other predictions
  - **Test with data**

Symmetries

Group theory description: group elements change the state of the system

- Example: elements of *SO(3)* rotate objects in R^3

Continuous transformations are represented by **Lie groups**

Symmetries for us are symmetries of the Lagrangian

- **Noether's theorem**: to a continuous symmetry corresponds a conserved quantity

Groups can (locally) be described in terms of their **generators**

- Example: for *SO(3)* this is the so(3) Lie algebra $[J_i, J_j]=i\, \varepsilon_{ijk}\, J_k$

The Standard Model's symmetries

External (space-time symmetries):

- Translations
- Rotations & boosts

Poincaré symmetry

Internal:

- Gauge symmetries, i.e. $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Isospin, strangeness, baryon number, lepton number…

The Poincaré algebra

$$
\begin{aligned}
[P_\mu, P_\nu] &= 0 \\
[M_{\mu\nu}, P_\rho] &= -i(g_{\mu\rho}P_\nu - g_{\nu\rho}P_\mu) \\
[M_{\mu\nu}, M_{\rho\sigma}] &= -i(g_{\mu\rho}M_{\nu\sigma} - g_{\mu\sigma}M_{\nu\rho} - g_{\nu\rho}M_{\mu\sigma} + g_{\nu\sigma}M_{\mu\rho})
\end{aligned}
$$

The P operators generate translations, M operators generate rotations and boosts

Can the Poincaré symmetry be extended? Can we unify internal and external symmetries (in a non-trivial way)?

- Not using Lie algebras

[Coleman, Mandula, *Phys. Rev.* D**159** (1967)]

Supersymmetry is the only possible external symmetry of the scattering amplitude beyond Lorentz symmetry, for which the scattering is non trivial.

[Haag, Lopuszanski, Sohnius, *Nucl. Phys.* **B88** (1975)]

Supersymmetry

SUSY is a symmetry that relates fermions and bosons

Q | fermion > = | boson >

Q | boson > = | fermion >

Q is a spinorial generator, i.e. it has spin ½

To construct a supersymmetric Lagrangian, i.e. invariant under

| fermion > ⇔ | boson >

We will need to double the spectrum.

$$\begin{aligned} \text{electron } (\psi_e)_L(s=1/2) &\leftrightarrow \phi_{\tilde{e}_L}(s=0) \\ (\psi_e)_R(s=1/2) &\leftrightarrow \phi_{\tilde{e}_R}(s=0) \end{aligned}$$

Supersymmetry

The MSSM particle content

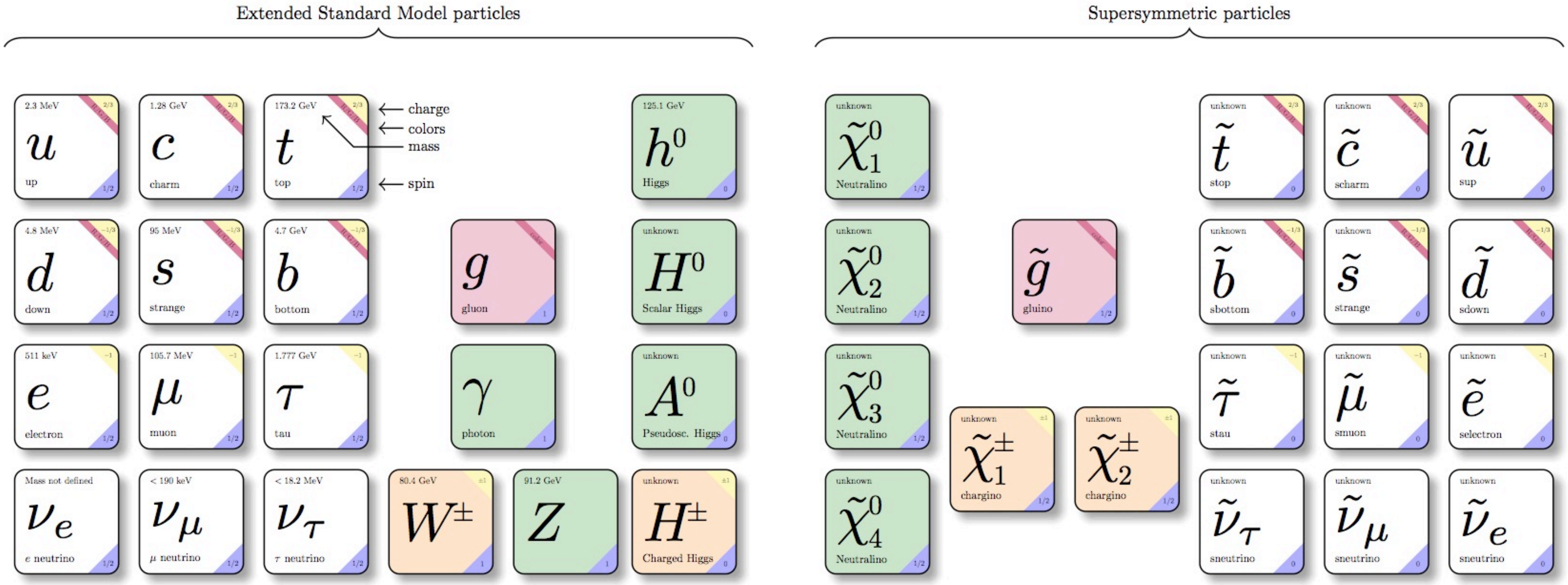


Image credit: M. Rimoldi

- **Scalars have no chirality** (left/right-handed in SUSY particles are just labels)

Supersymmetry breaking

Supersymmetry must be broken

- No scalar 0.511 MeV electrons even though $[P^\mu, Q] = 0$
- Would like to have **spontaneous breaking** using a non-supersymmetric vacuum.

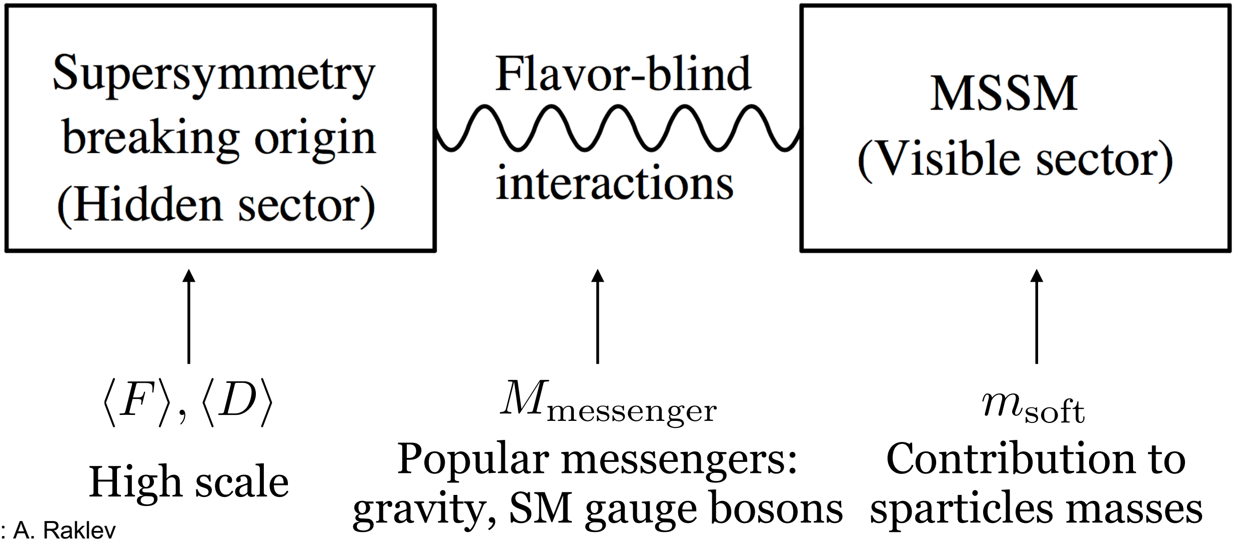
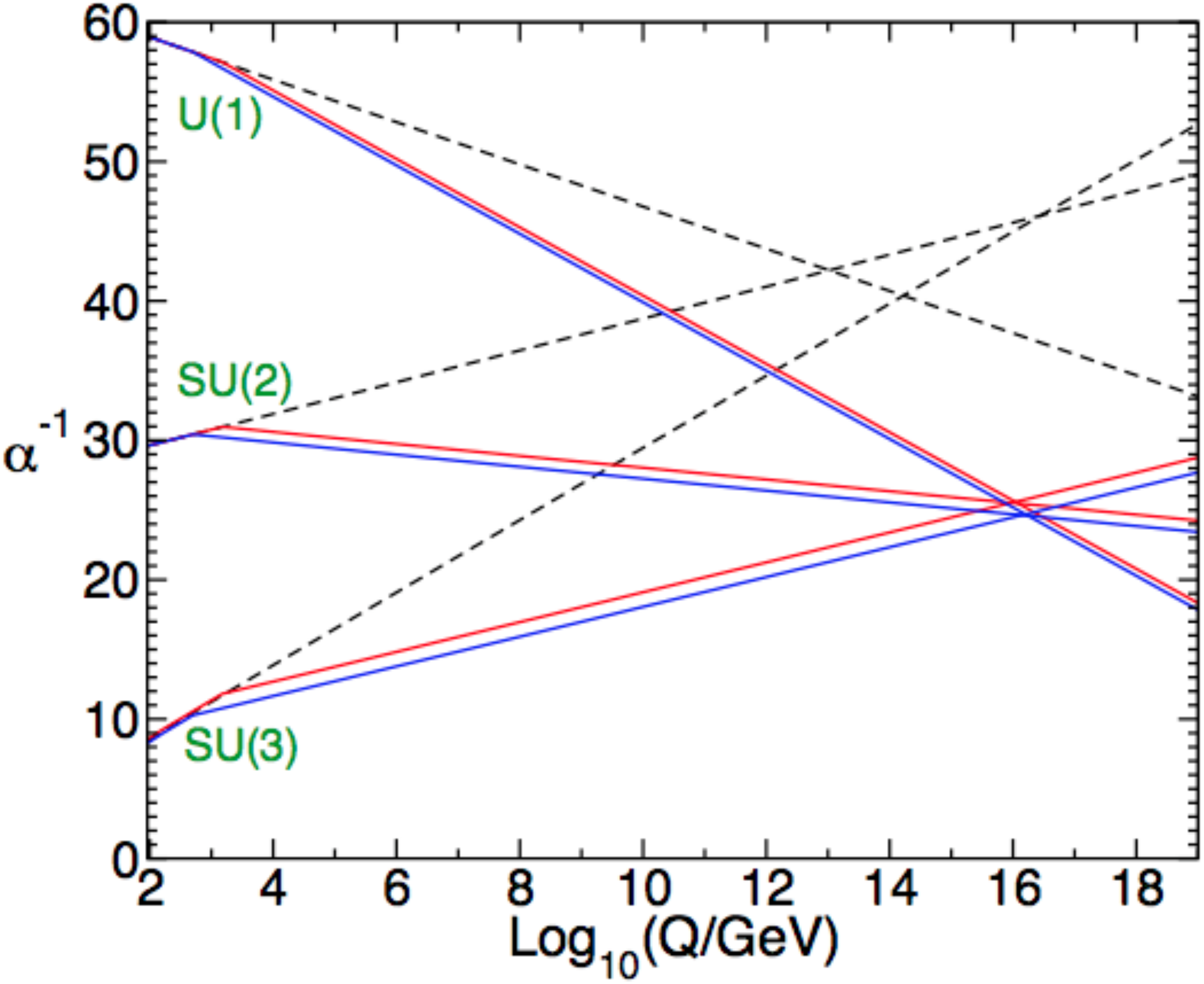


Image credit: A. Raklev

- To parametrize our ignorance of the actual mechanism we introduce explicitly breaking terms. Not *any* terms, only **soft-terms** that do not reintroduce the divergences for scalars.

SM gauge coupling unification



Hierarchy problem

Do you remember those large corrections to the Higgs mass?

The Higgs boson mass has quadratically divergent corrections

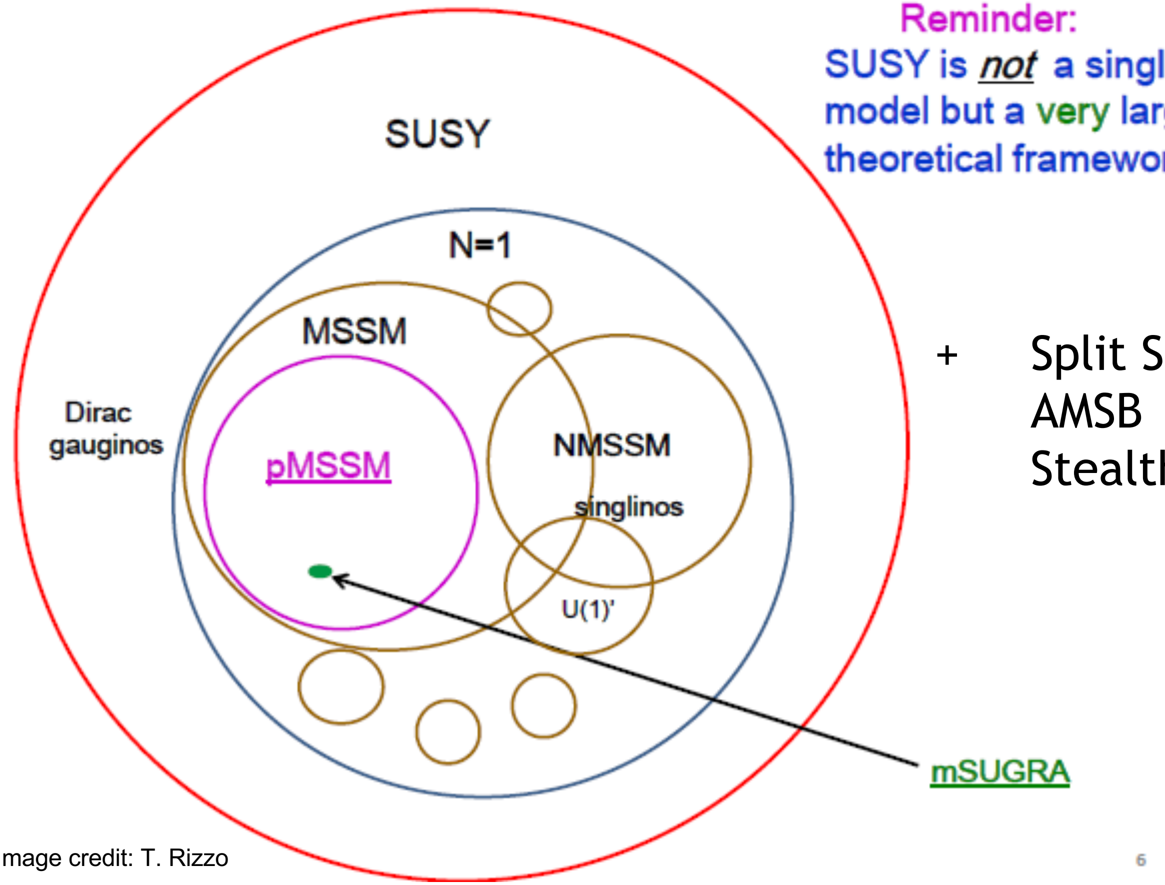
- The additional scalars introduced with SUSY bring additional corrections that help mitigate the divergency

(a) (b)

$$-\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 \qquad \frac{\lambda_s}{16\pi^2}\Lambda^2$$

- $\lambda_s = |\lambda_f|^2$ (particles in the same super-multiplet) and two new scalars for each fermion
- Cancellation depends on SUSY breaking, m_s and m_f are not the same!

The SUSY family



Reminder:
SUSY is *not* a single model but a very large theoretical framework

Image credit: T. Rizzo

\+ Split SUSY
AMSB
Stealth (hidden) SUSY

A lot to consider!

- Various scenarios come with interesting features that can be exploited …

R-parity

A new conserved quantum number

Most general super-potential includes terms Violating Baryon number and Lepton number.

- As a result, the proton is not stable and should decay at a much faster rate than observed
- A new symmetry is introduced to fix this

$$R = (-1)^{3(B-L)+2S}$$

- B is the Barion Number
- L is the Lepton Number
- S is the Spin

R = +1 (particles)

R = -1 sparticles

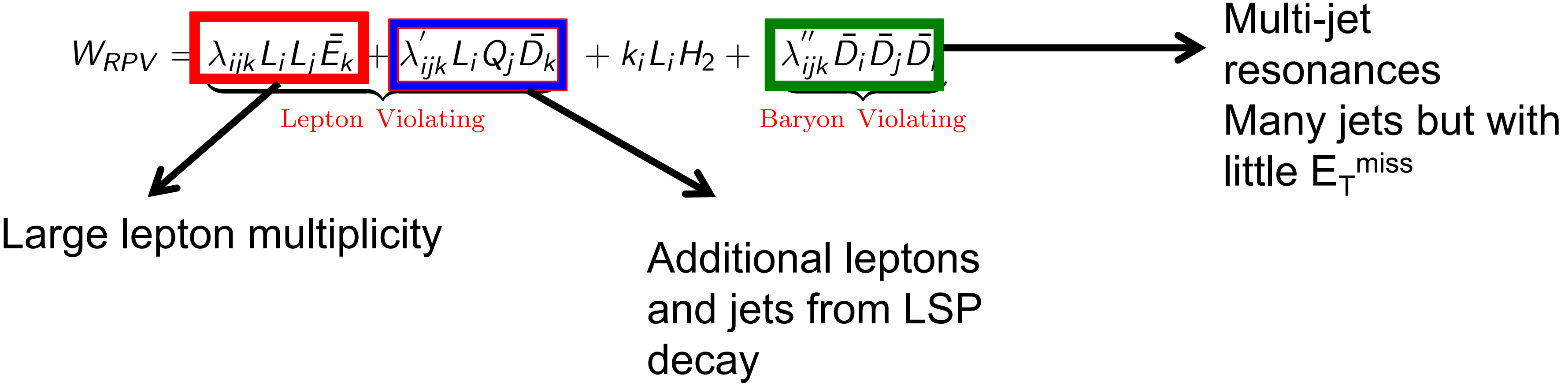
- **SUSY particles are produced in pairs**
- **The Lightest Supersymmetric Particle (LSP) is stable**
- **If the LSP is neutral, it could be DM** (often the neutralino) - E_T^{miss} signature

R-parity violation!

New rules come with new exceptions…

The LSP is not stable

- No Dark Matter candidate
- Less missing momentum, higher particle multiplicity in the final state
- Several possible R-parity violating terms in the Lagrangian, giving many different experimental signatures



$$W_{RPV} = \underbrace{\boxed{\lambda_{ijk} L_i L_j \bar{E}_k} + \boxed{\lambda'_{ijk} L_i Q_j \bar{D}_k}}_{\text{Lepton Violating}} + k_i L_i H_2 + \underbrace{\boxed{\lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}}}_{\text{Baryon Violating}}$$

Large lepton multiplicity

Additional leptons and jets from LSP decay

Multi-jet resonances

Many jets but with little E_T^{miss}

Long lived particle searches

There are many ways SUSY particles could be long lived

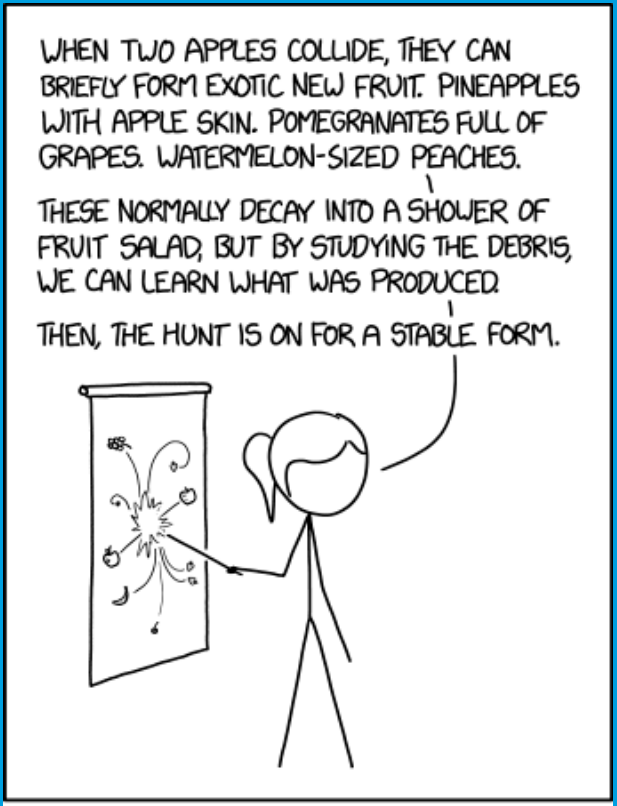
- The lightest SUSY particle is not stable, and decays through a small R-parity violating coupling to SM particles
- The lightest SUSY particle is the gravitino, which has a small coupling – the next-lightest can be long-lived
- Gluinos decaying through very heavy virtual squarks
- Small mass splitting between lightest and next-to-lightest SUSY particle

Even more interesting signatures!

If $c\tau > 1$ mm we can detect decays occurring away from the primary collisions

If $c\tau > 10$ cm we can measure charged long lived particles

Time for a break!



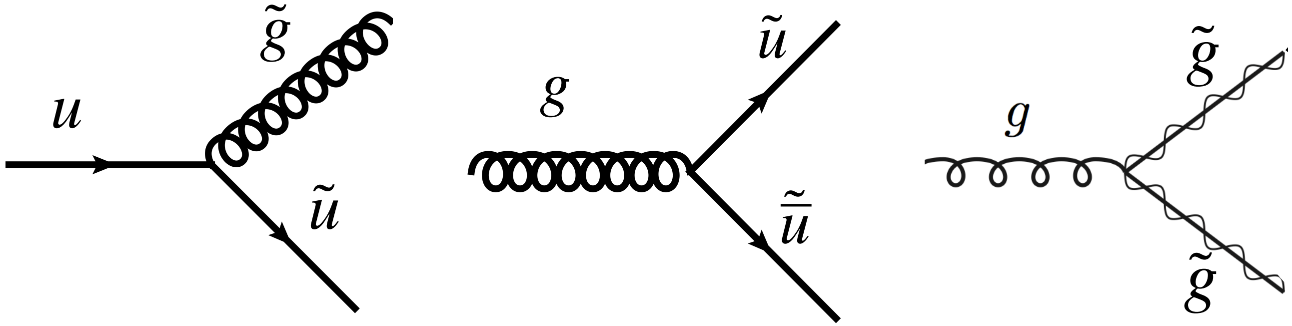
HOW NEW TYPES OF FRUIT ARE DEVELOPED

Production of SUSY particles at the LHC

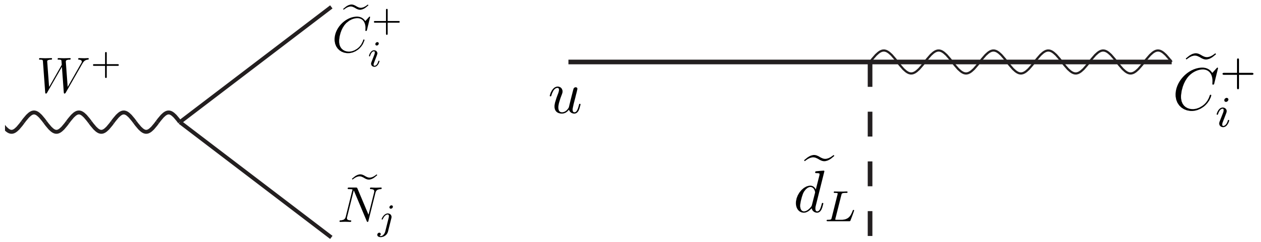
Some examples

We start from gluons and quarks

- SUSY diagrams are obtained from SM ones adding tilde on two of the particles
  - Two for R-parity conserving processes

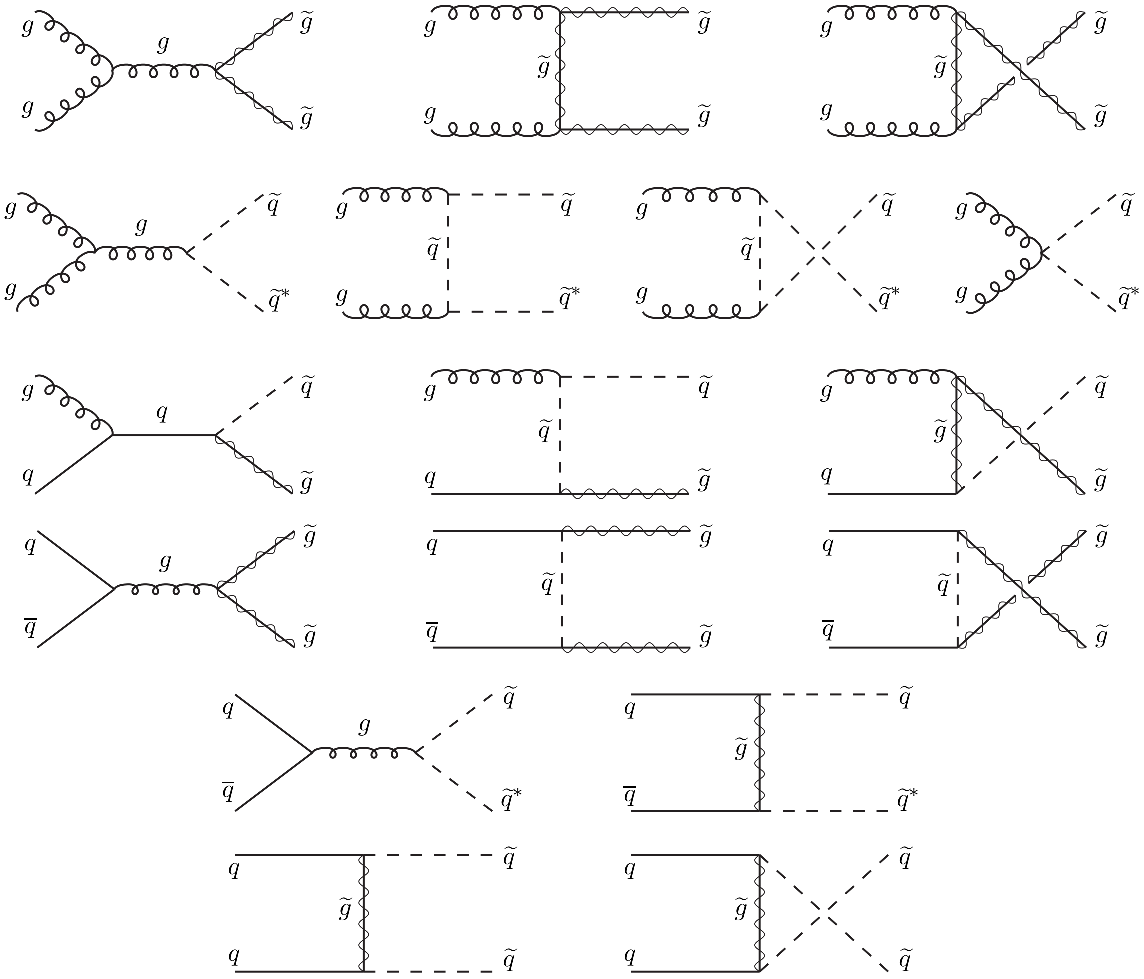


Strong interaction



Weak interaction

Scalar quark and gluino production



gluon-gluon → gluino pair

gluon-gluon → squark antisquark

gluon-quark → squark gluino

quark-antiquark → gluino pair

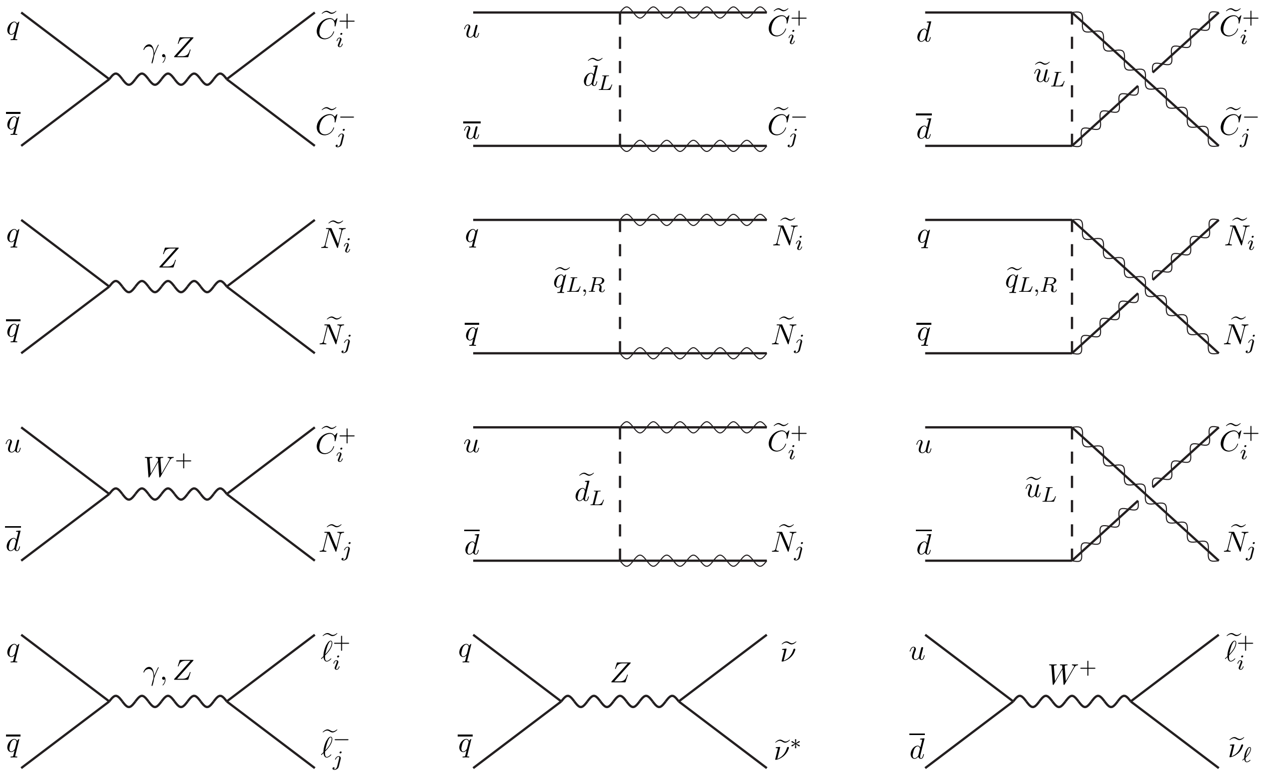
quark-antiquark → squark antisquark

quark-quark → squark pair

There are few bottom and no top quarks in the proton, because of their mass

- Thus, third generation squarks are only produced by boxed diagrams

Electroweak production



Pairs of charginos

Pairs of neutralinos

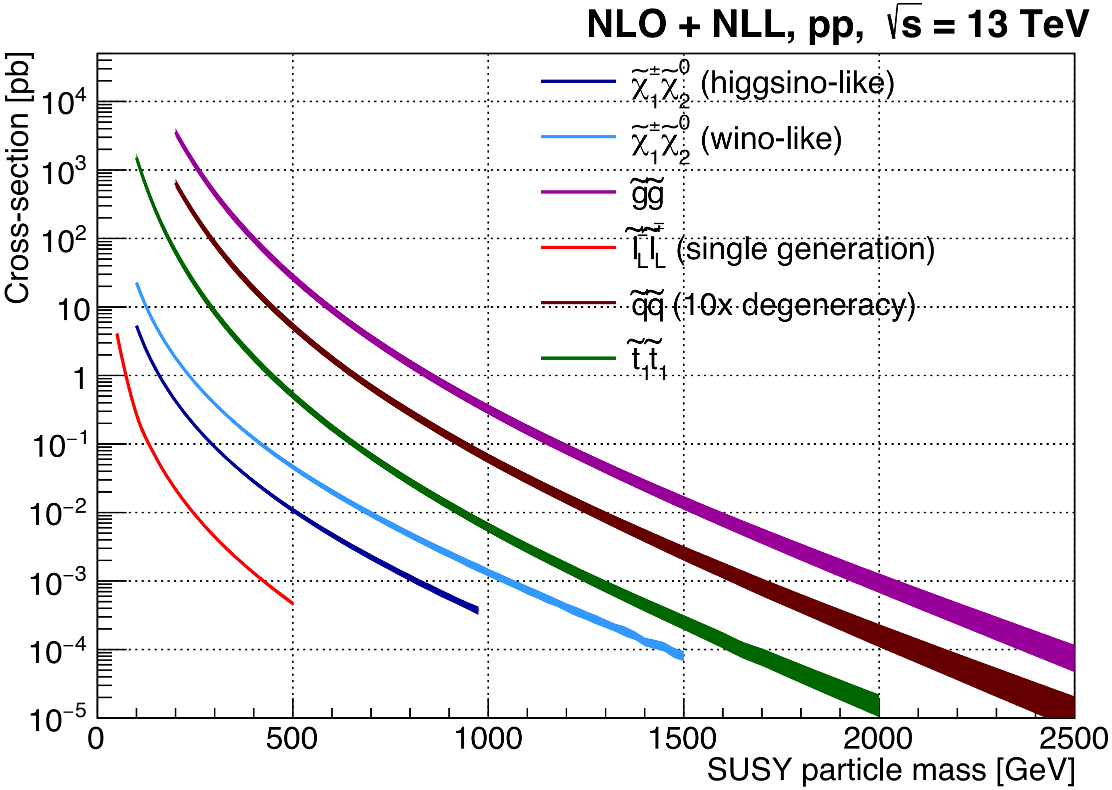
Chargino neutralino

Slepton pairs
Sneutrino pairs
Sneutrino-slepton

Rare processes at the LHC: only quarks in the initial state

- At least two vertices involving the electromagnetic or weak coupling

Cross sections



For the same mass, the cross section is **much larger** for particles produced trough strong interaction (squark and gluinos)

- High cross section means strong existing limits: we are now looking at higher masses

Other cross sections

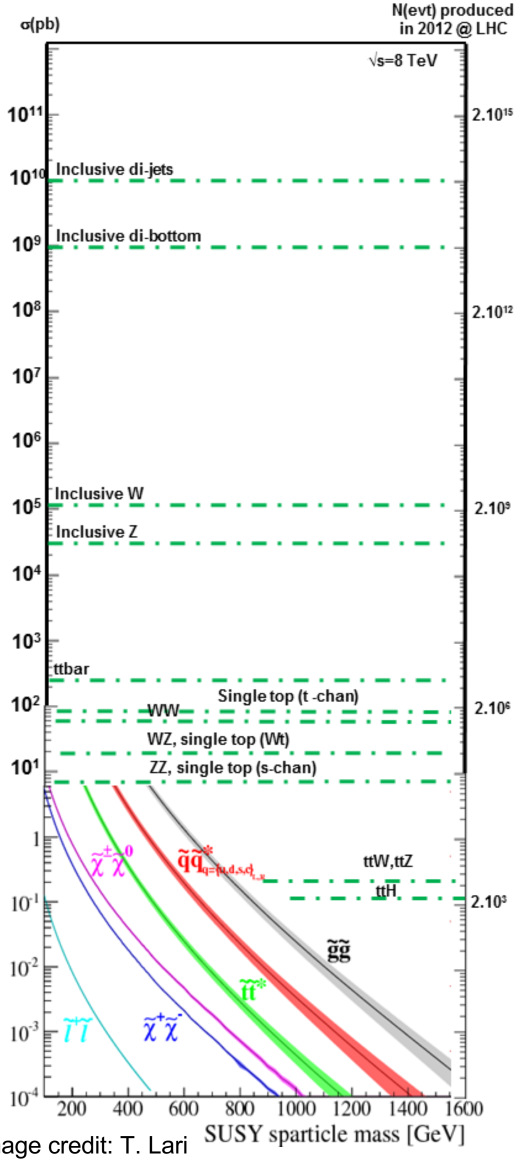


Image credit: T. Lari

Even the SUSY processes with “high” cross-section are a tiny fraction of the total collisions.

- Out of 1 billion collisions per second, *less than one* will produce SUSY particles.

Disk and CPU constraints imply only one collision in 40,000 can be registered

- The first selection of signal candidates is done by the data acquisition software (*trigger)*
- If we are not ready, data will be lost forever

How to search for physics beyond the SM

The simplest SUSY search proceed as follows:

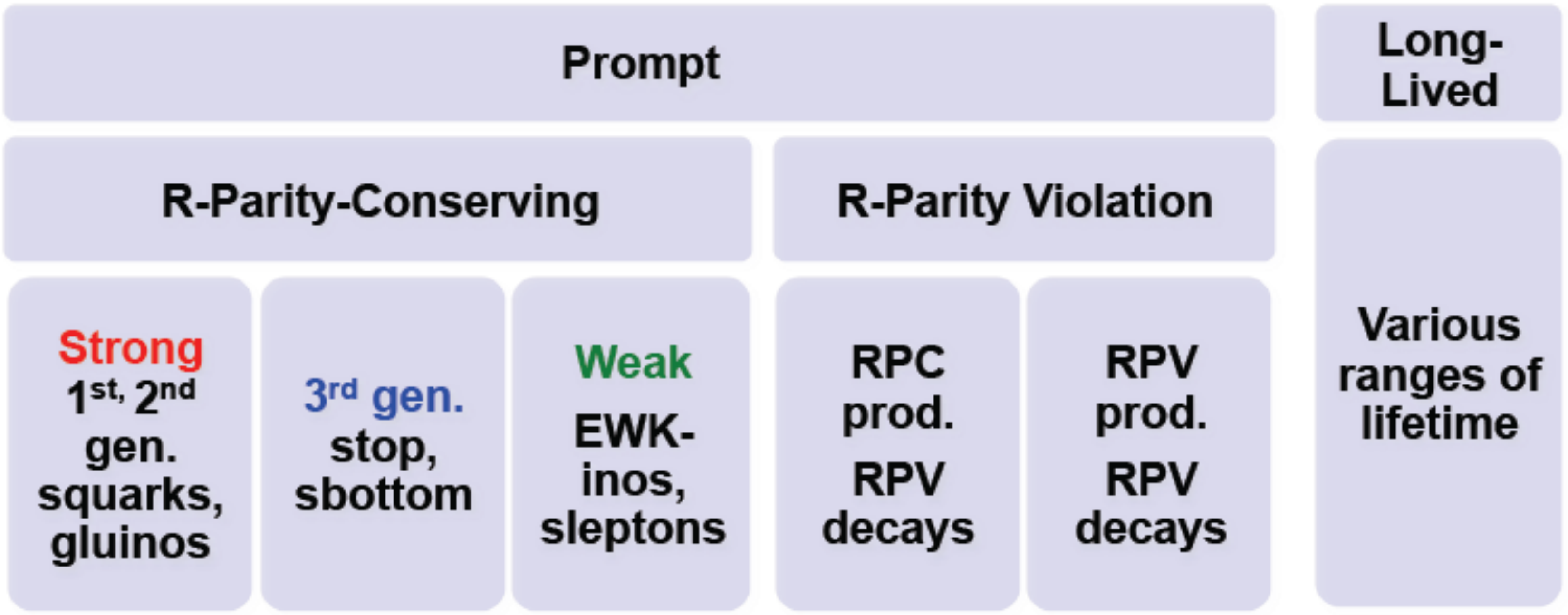
- **Count the number of collisions satisfying a given selection** (say “six jets with p_T > 60 GeV and missing transverse momentum larger than 150 GeV”)
- **Compute the number of background events expected** to pass the selection
- **Compare the observed number of events with the expected background rate**. An excess of the former indicates the presence of a signal.

The key difficulties are:

- How we determine the selection criteria, since we do not know the masses and decays of SUSY particles ?
- How do we compute the expected background rate in such a reliable way that we can attribute an higher observed rate to a non-Standard Model process ?

SUSY search strategy

Search strategy designed to provide coverage for a broad class of SUSY models



Prompt

Long-Lived

R-Parity-Conserving

R-Parity Violation

Strong 1st, 2nd gen. squarks, gluinos

3rd gen. stop, sbottom

Weak EWK-inos, sleptons

RPC prod. RPV decays

RPV prod. RPV decays

Various ranges of lifetime

Image credit: M. D'Onofrio

For each search, a number of signal regions (selections) is optimized based on a variety of models

Models for optimization

“Full” physics models:

- SUSY breaking model @ high scale: non degenerate spectrum at the electroweak scale
- E.g. mSUGRA, GMSB, AMSB etc.

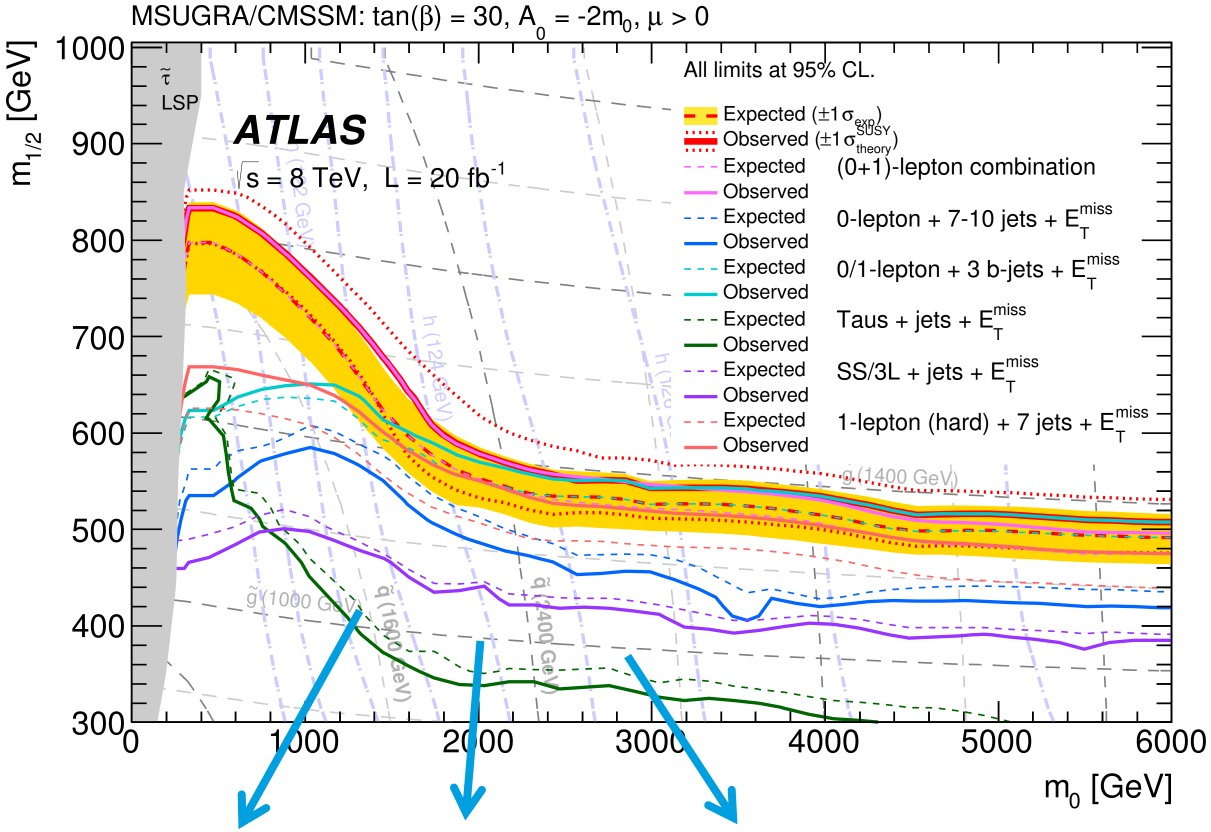
Generalized models:

- Consider only parameters and mass spectrum at the electroweak scale
- E.g. pMSSM, General Gauge Mediated

Simplified models:

- Assume a minimal set of parameters, including the particle masses and the production cross sections
- E.g. sparticle production with 100% BR to a final state of interest

Example: mSUGRA (now ~dead)



m(squarks) m(higgs) m(gluinos)

As a function of m_0 and $m_{1/2}$

- m_0 = mass of the scalar at unification scale (GUT)
- $m_{1/2}$ = mass of the gauginos at GUT
- tan(β) = 30 ratio of the higgs vacuum expectation values
- $A_0 = -2m_0$ trilinear couplings
- μ > 0 sign of Higgs mass term

Various analyses might be sensitive in different regions

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Example: pMSSM

The phenomenological MSSM

Reduces the number of MSSM parameters to a managable level (24 or 19) with experimentally motivated assumptions

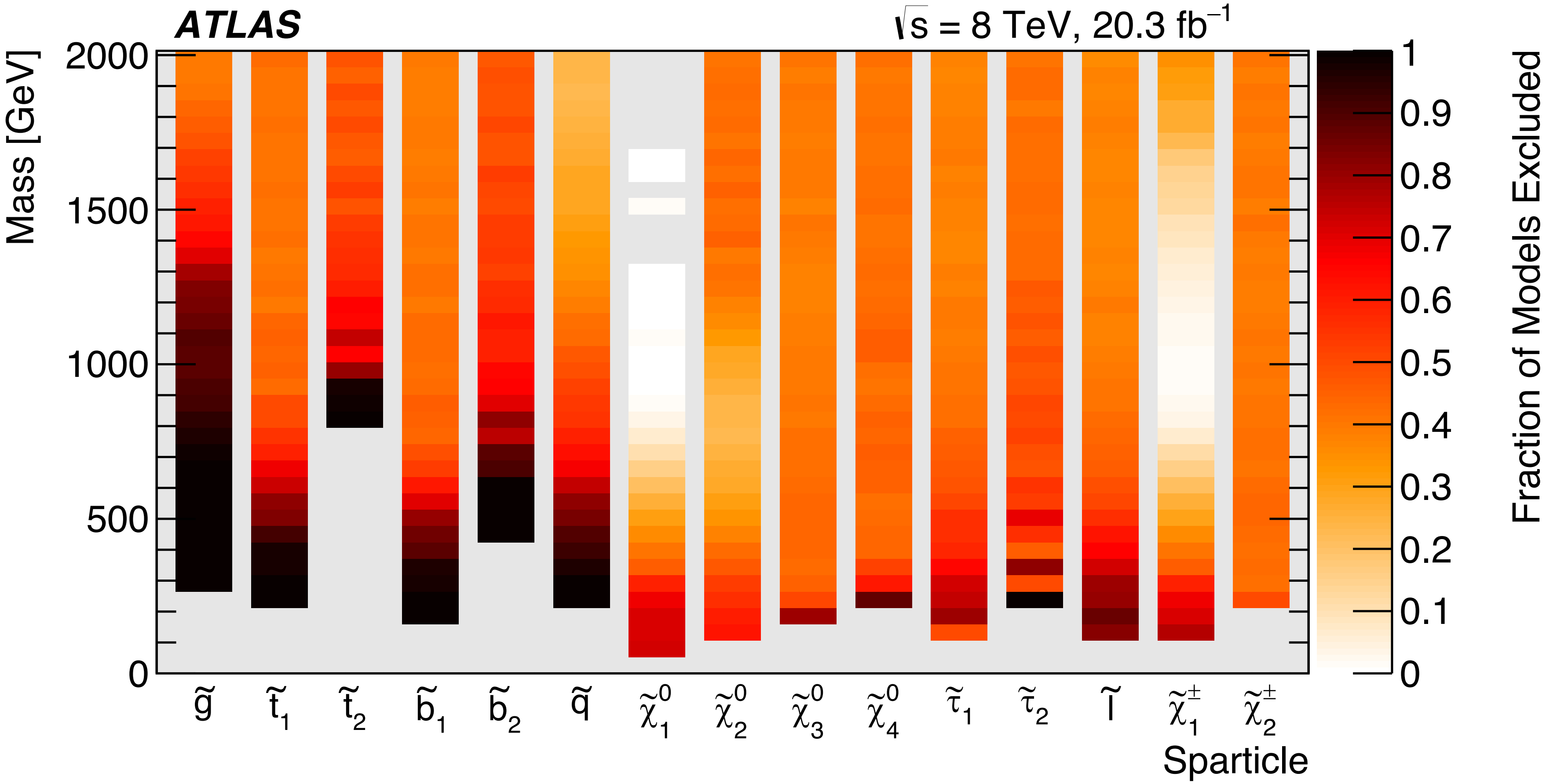
- Is ‘unprejudiced’ with respect to high-scale SUSY
- Can lead to complex spectra & decay patterns
- Allows for correlations, leading to less constrained models

Example: general CP-conserving MSSM with R-parity

- Minimal Flavour Violation at the TeV scale (CKM)
- Lightest neutralino/gravitino is the LSP
- 1st/2nd generation sfermions degenerate
- Ignore 1st/2nd generation Yukawa couplings

Example: pMSSM

Results are not easy to interpret



Models for optimization

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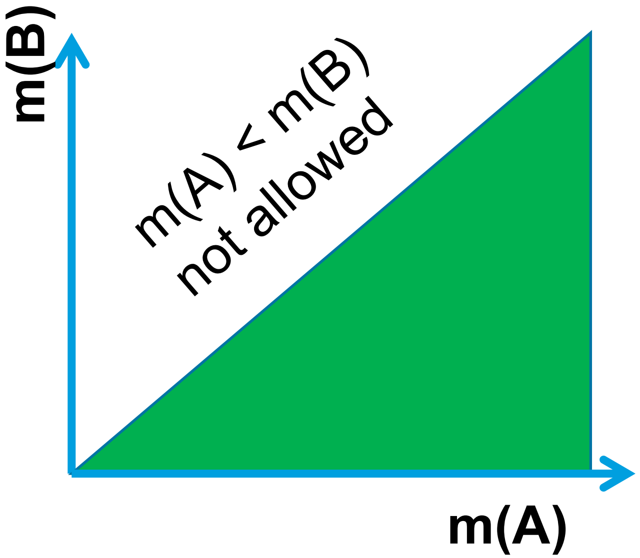
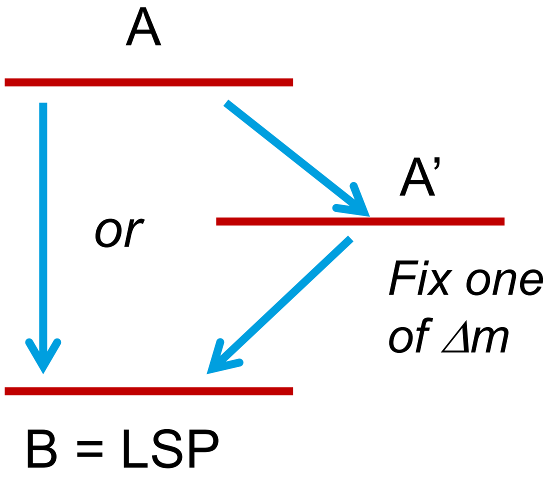
Example: simplified models

From 19 sparticles consider 2 or 3, decouple all others, force a specific decay mode(s) (with fixed Branching Ratio)

- Assumptions on the chirality and nature of particle involved





Very helpful to design analyses

- Well suited to study single production/decay diagrams

Let’s follow an analysis from start to finish

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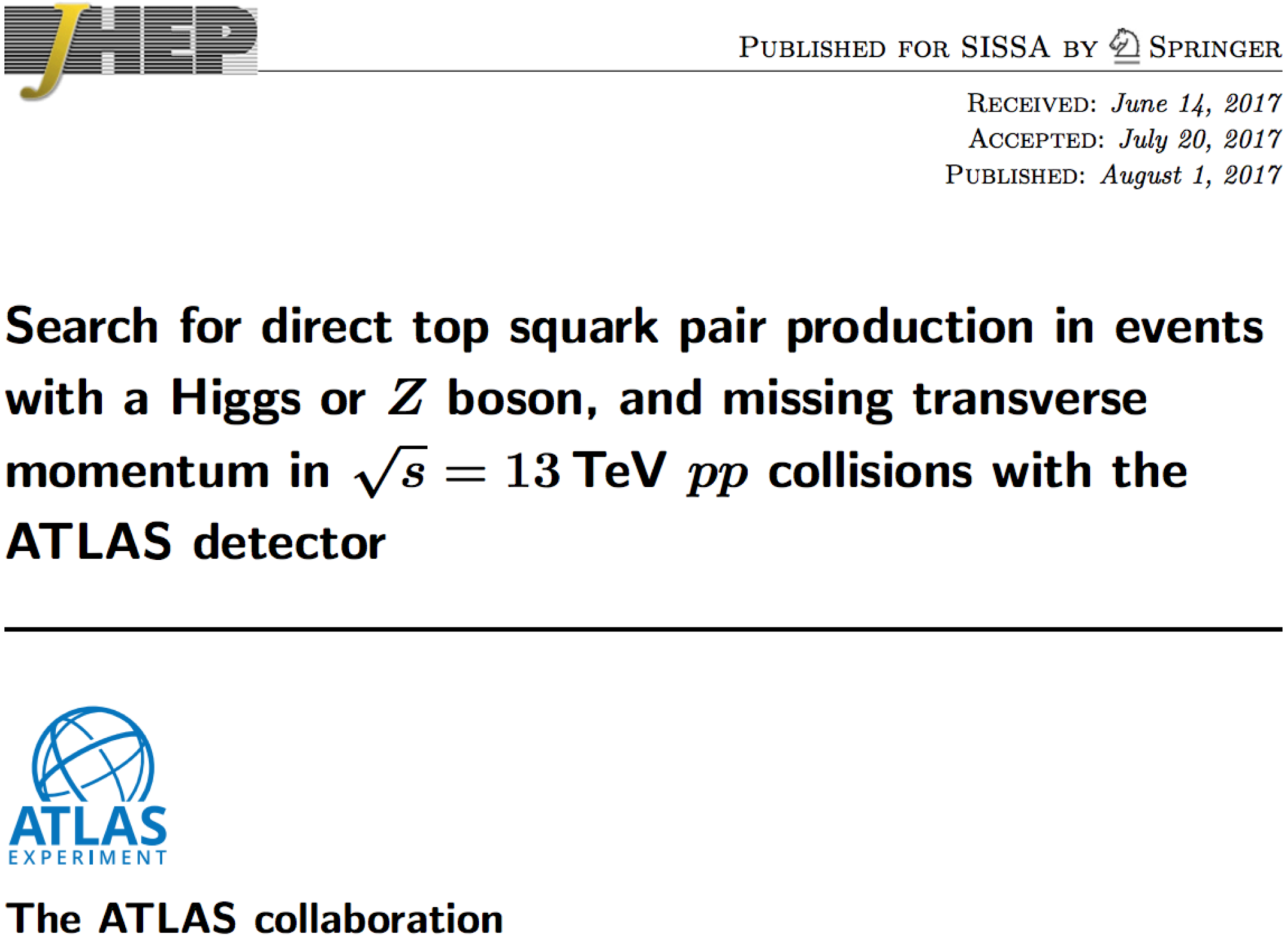

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Search for direct top squark pair production in events with a Higgs or Z boson, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

The ATLAS collaboration

Step 0: pick a model

The top squark is important when considering the Higgs boson mass corrections!

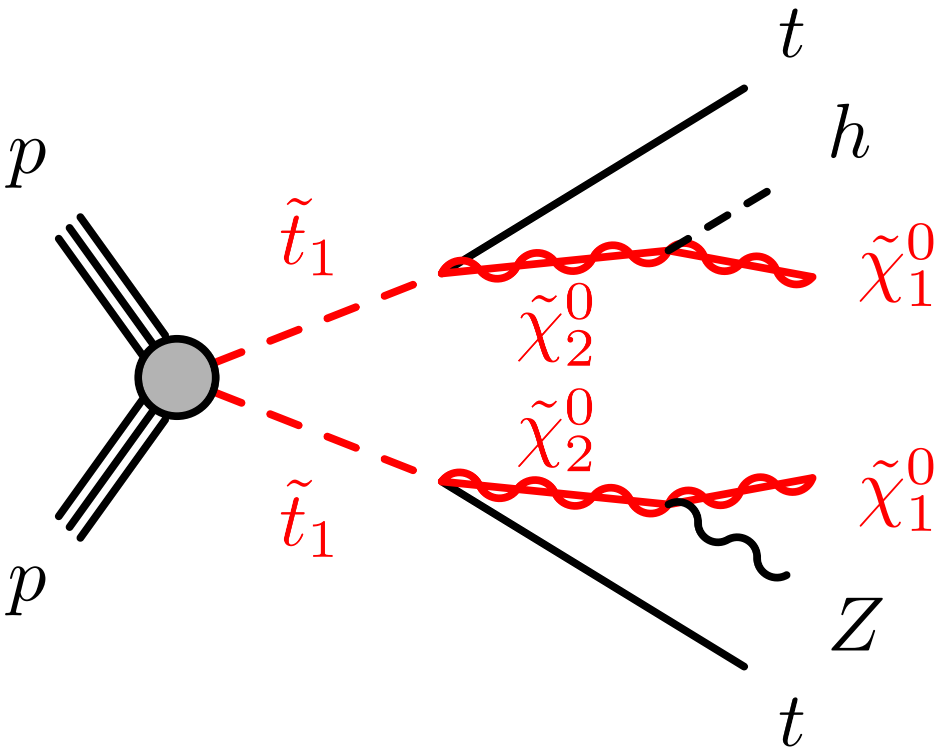
- Partner of the heaviest SM fermion

Long decay chains can escape traditional searches

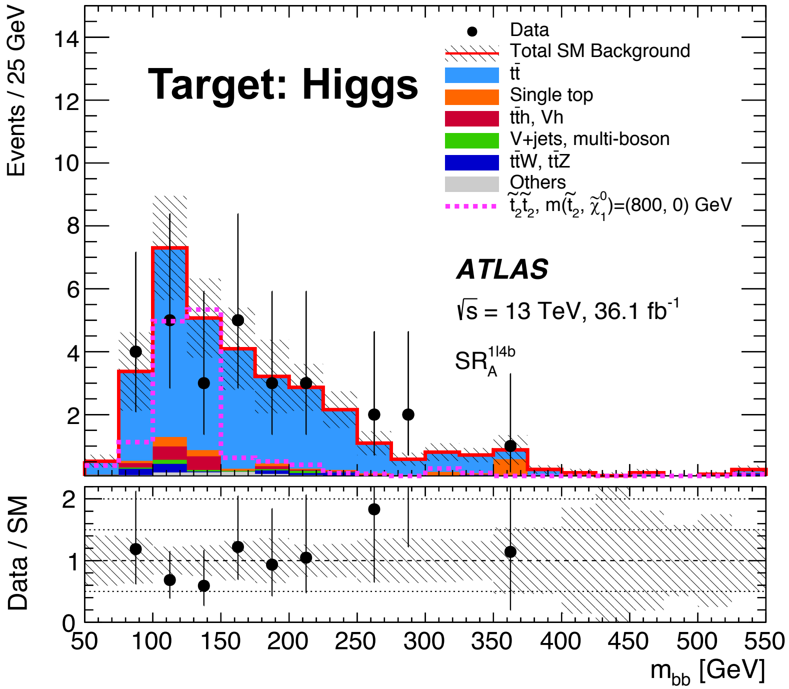
Use simplified models to guide the optimisation

Select events with:

- Many leptons
- Many b-quarks (jets)

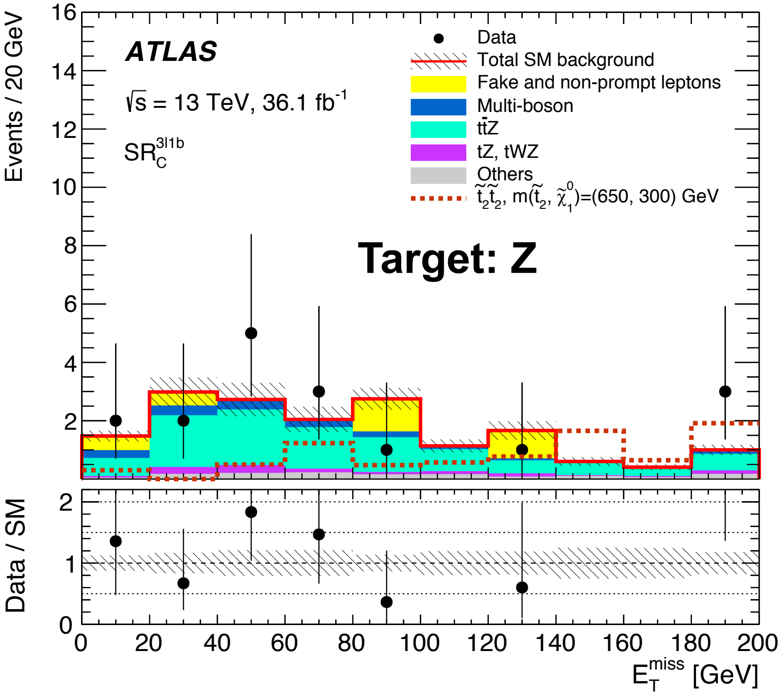


Step 1: define a selection



We are looking for a resonant particle that decays (Higgs -> bb)

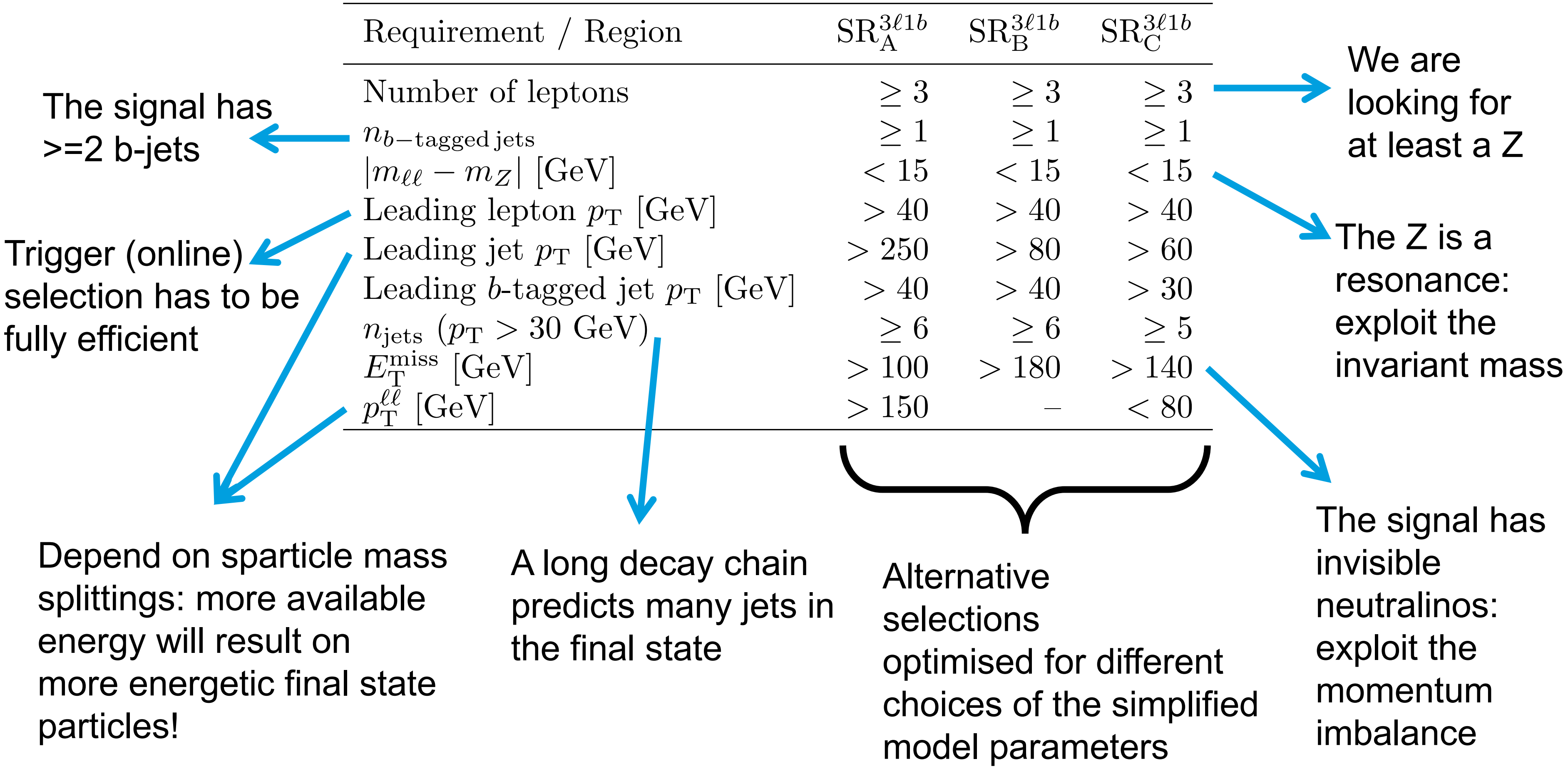
- Use the invariant mass of two b-jets to reduce non resonant backgrounds (top quark pairs)



The signal decays to neutralinos (invisible)

- Exploit E_T^{miss} to reduce the SM processes with fewer invisible particles

Example (Target: Z)



Requirement / Region	$\mathrm{SR}^{3\ell 1b}_{\mathrm{A}}$	$\mathrm{SR}^{3\ell 1b}_{\mathrm{B}}$	$\mathrm{SR}^{3\ell 1b}_{\mathrm{C}}$
Number of leptons	≥ 3	≥ 3	≥ 3
$n_{b-\text{tagged jets}}$	≥ 1	≥ 1	≥ 1
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	< 15	< 15	< 15
Leading lepton p_{T} [GeV]	> 40	> 40	> 40
Leading jet p_{T} [GeV]	> 250	> 80	> 60
Leading b-tagged jet p_{T} [GeV]	> 40	> 40	> 30
n_{jets} ($p_{\mathrm{T}} > 30$ GeV)	≥ 6	≥ 6	≥ 5
$E_{\mathrm{T}}^{\text{miss}}$ [GeV]	> 100	> 180	> 140
$p_{\mathrm{T}}^{\ell\ell}$ [GeV]	> 150	–	< 80

The signal has >=2 b-jets

Trigger (online) selection has to be fully efficient

We are looking for at least a Z

The Z is a resonance: exploit the invariant mass

Depend on sparticle mass splittings: more available energy will result on more energetic final state particles!

A long decay chain predicts many jets in the final state

Alternative selections optimised for different choices of the simplified model parameters

The signal has invisible neutralinos: exploit the momentum imbalance

Example (Target: Higgs)

The signal has >=4 b-jets

Leptonic W decays have an endpoint

Requirement / Region	$\text{SR}^{1\ell 4b}_{\text{A}}$	$\text{SR}^{1\ell 4b}_{\text{B}}$	$\text{SR}^{1\ell 4b}_{\text{C}}$
Number of leptons	1–2	1–2	1–2
$n_{b-\text{tagged jets}}$	≥ 4	≥ 4	≥ 4
m_{T} [GeV]	–	>150	>125
H_{T} [GeV]	> 1000	–	–
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 120	> 150	> 150
Leading b-tagged jet p_{T} [GeV]	–	–	<140
m_{bb} [GeV]	95–155	–	–
p_{T}^{bb} [GeV]	> 300	–	–
n_{jets} (p_{T} ¿60 GeV)	≥ 6	≥ 5	–
n_{jets} (p_{T} ¿30 GeV)	–	–	≥ 7

We are looking for a leptonic top quark pair

The Higgs is a resonance: exploit the invariant mass

The signal has invisible neutralinos: exploit the momentum imbalance

Depend on sparticle mass splittings: more available energy will result on more energetic final state particles!

A long decay chain predicts many jets in the final state

Alternative selections optimised for different choices of the simplified model parameters

Step 2: estimate the backgrounds

Background rates can be estimated using simulation, but is the physics and detector description in the simulation reliable?

- Any excess in data compared to expectation must be confidently attributed to non-Standard Model processes, we need to be sure about our backgrounds!
- Typically, we measure the rate in a set of control selections
  - One control selection for each major background
  - CR (and VR) are designed so that the target signal is negligible there
  - All selections which are difficult to model are common for the CR and the SR

Control selection for background (CR)

Measure the rate in data here

Extrapolate using MC or some scaling law

Validation selection (VR)

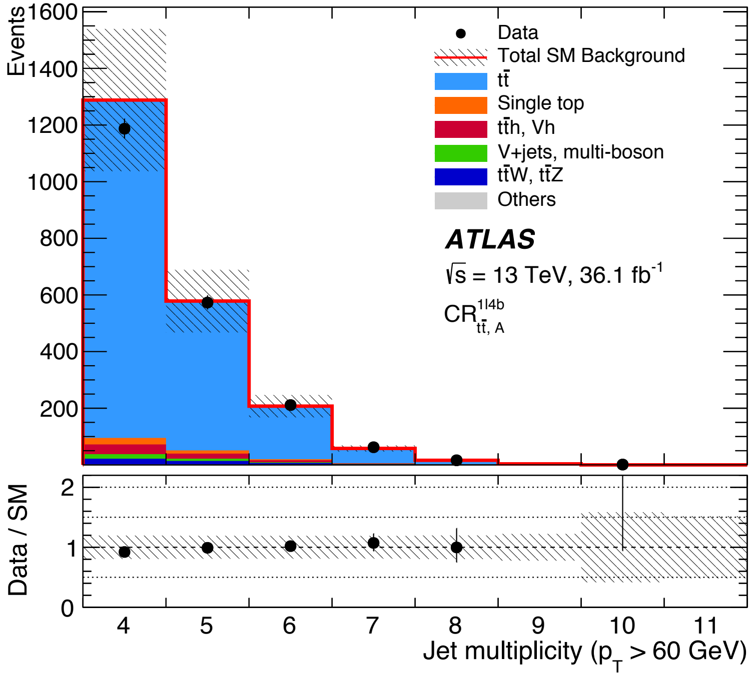
Signal selection (SR)

Example (Target: Higgs)

Find a control selection (CR) for top quark pairs

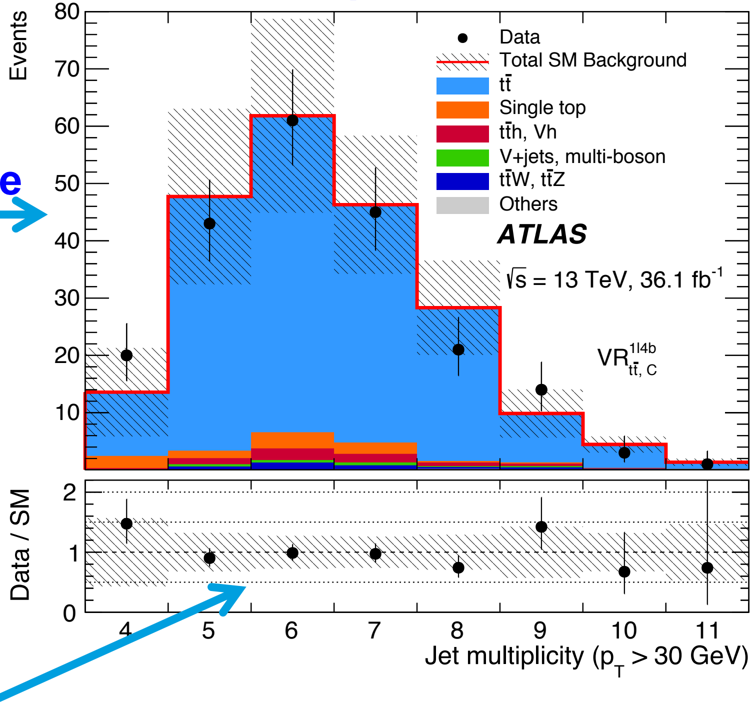
- Top quark pairs are not a resonant process: exploit the m_{bb} sidebands
- Minimise the extrapolation in passing from the CR to the SR
- Check validity in VR closer to SR

Measure the rate in data here



Extrapolate

Test the prediction here



GOOD!

Step 2’: estimate the uncertainties

	$\mathrm{SR}_{\mathrm{A}}^{3\ell 1b}$	$\mathrm{SR}_{\mathrm{B}}^{3\ell 1b}$	$\mathrm{SR}_{\mathrm{C}}^{3\ell 1b}$	$\mathrm{SR}_{\mathrm{A}}^{1\ell 4b}$	$\mathrm{SR}_{\mathrm{B}}^{1\ell 4b}$	$\mathrm{SR}_{\mathrm{C}}^{1\ell 4b}$
Total systematic uncertainty (%)	20	24	15	22	17	30
Diboson theoretical uncertainties (%)	6.7	5.5	2.2	<1	<1	<1
$t\bar{t}Z$ theoretical uncertainties (%)	10	10	4.4	<1	<1	<1
$t\bar{t}$ theoretical uncertainties (%)	–	–	–	17	14	22
Other theoretical uncertainties (%)	9.0	6.8	5.4	1.6	2.4	1.7
MC statistical uncertainties (%)	8.5	18	6	7.3	5.2	13
Diboson fitted normalisation (%)	4.6	3.5	3.8	<1	<1	<1
$t\bar{t}Z$ fitted normalisation (%)	12	11	13	<1	<1	<1
$t\bar{t}$ fitted normalisation (%)	–	–	–	3.4	5.1	3.3
Fake or non-prompt leptons (%)	–	6.5	–	–	–	–
Pile-up (%)	4.7	2.8	0.6	<1	1.4	<1
Jet energy resolution (%)	2.0	2.7	3.0	5.3	<1	13
Jet energy scale (%)	1.0	2.7	3.5	3.2	5.3	6.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution (%)	5.3	2.6	1.6	6.8	6.5	4.0
b-tagging (%)	2.4	1.5	3.0	6.8	2.9	3.5

Total uncertainty on our prediction: **sources can be correlated!**

The background modelling is limited by assumptions made in the programs that we use and our theory knowledge.

Impact of experimental effects on our measurement: resolutions, calibrations…

We only have a finite number of simulated events!

The statistical (Poisson) uncertainty on the number of events in our CRs affect the predictions

Step 3: opening the box

The decision of the selections, the estimation of the background, and all the cross-checks are done with the signal candidates “blinded”, i.e. without having access to them in data

- Once one has the final estimate of expected background and uncertainty, the signal candidates are “unblinded”

	$\mathrm{SR}_{\mathrm{A}}^{1\ell 4b}$	$\mathrm{SR}_{\mathrm{B}}^{1\ell 4b}$	$\mathrm{SR}_{\mathrm{C}}^{1\ell 4b}$
Observed events	10	28	16
Total (post-fit) SM events	13.6 ± 3.0	29 ± 5	10.5 ± 3.2
Fit output, $t\bar{t}$	11.3 ± 2.9	24 ± 5	9.3 ± 3.1
Single top	0.50 ± 0.18	1.7 ± 0.4	0.24 ± 0.07
V+jets, multi-boson	0.20 ± 0.15	0.23 ± 0.10	0.01 ± 0.01
$t\bar{t}h$, Vh	0.89 ± 0.16	1.19 ± 0.35	0.56 ± 0.13
$t\bar{t}W$, $t\bar{t}Z$	0.36 ± 0.21	1.09 ± 0.31	0.10 ± 0.10
Others	0.37 ± 0.20	1.33 ± 0.69	0.34 ± 0.18
Fit input, $t\bar{t}$	7.1	14	6.0
S_{obs}^{95}	7.8	14.6	15.6
S_{exp}^{95}	$9.6^{+4.1}_{-2.3}$	$15.5^{+5.6}_{-4.4}$	$10.4^{+4.2}_{-2.6}$
σ_{vis} [fb]	0.21	0.40	0.43
$p(s = 0)$	0.63	0.82	0.11

Event counts in data

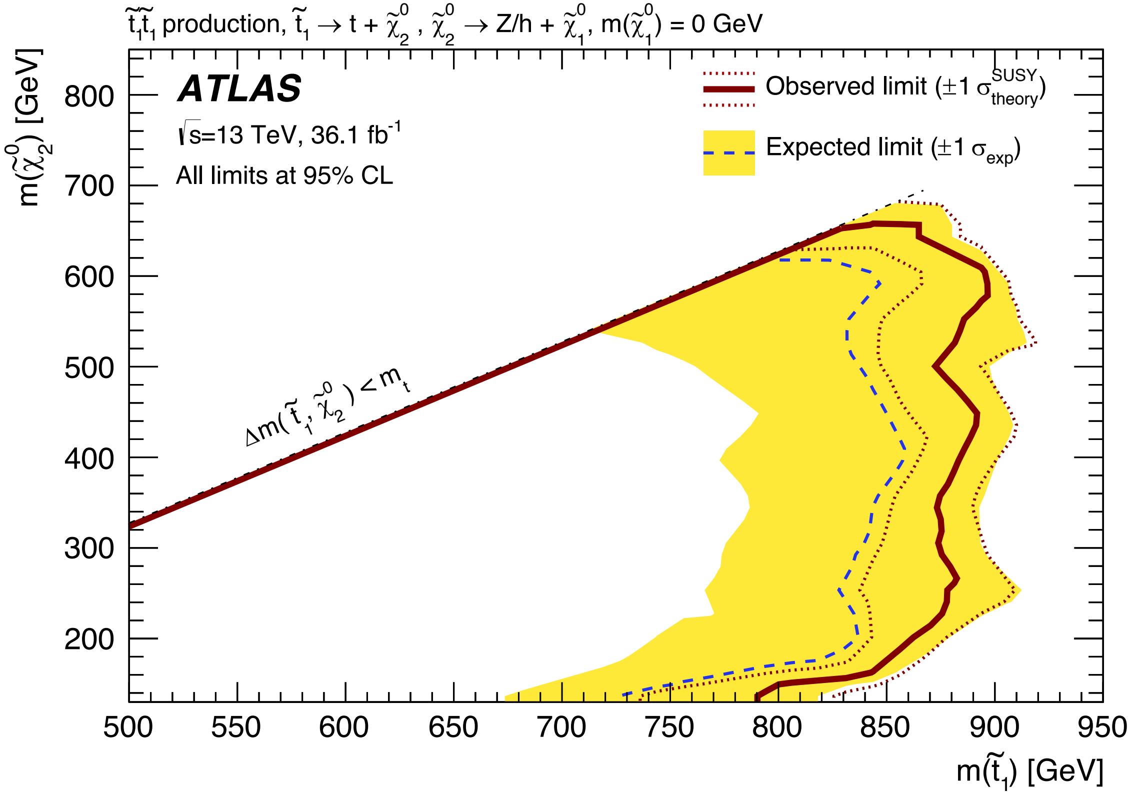
Background expectation

SM background predictions.
For fitted backgrounds, both “before” and “after” yields are provided

Limit on signal rates: the probability of having as few (or fewer) events as observed is < 5%

Limits on SUSY models

Given a negative result, the theory parameter space incompatible with the observation is derived.



Limit on top squark and second lightest neutralino Masses.

Assumptions:

- the LSP is massless
- top squarks decay to a top quark and a second lightest neutralino with 100% branching ratio
- the second lightest neutralino decays to Higgs and Z bosons with 50% branching ratio

Some considerations on LHC results

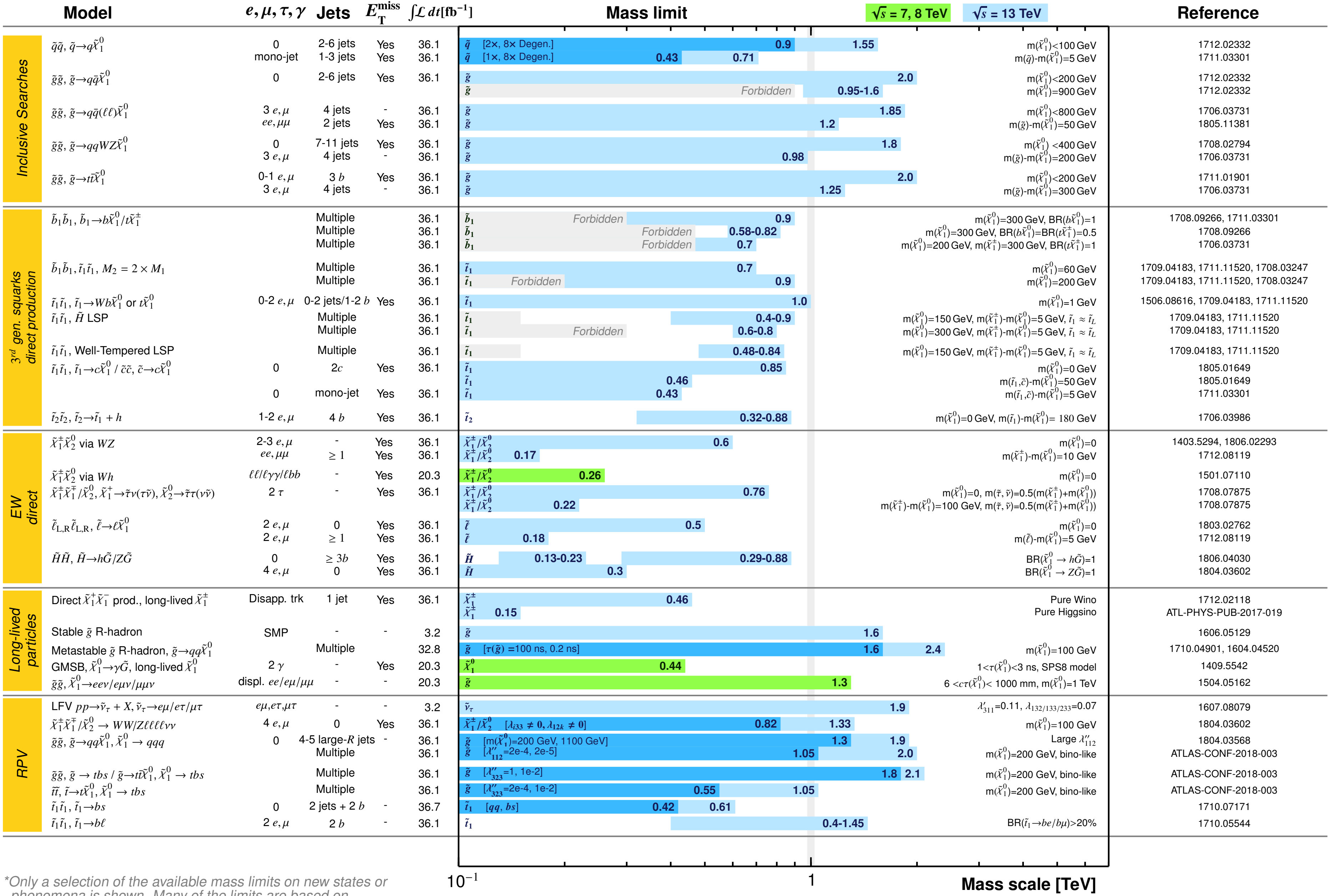
- It’s likely there are multiple competing decay modes for each SUSY particle – the 100% BR limit curve is not the only result, **cross section limits at nominally excluded mass points are also important**.
- Our exclusion plots will never cover all possible diagrams – we provide cutflows, acceptance maps etc. so that **theorists can implement our selections and produce their own limits on other models**.
- **Should we see a signal, we won’t be able to tell whether it’s SUSY or something else for a long time**.

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	$m(\tilde{\chi}^0_1)$<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}^0_1)$<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}^0_1)$=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	$m(\tilde{\chi}^0_1)$<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	$m(\tilde{\chi}^0_1)$ <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}^0_1)$<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	$m(\tilde{\chi}^0_1)$=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	$m(\tilde{\chi}^0_1)$=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	$m(\tilde{\chi}^0_1)$=200 GeV, $m(\tilde{\chi}^\pm_1)$=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	$m(\tilde{\chi}^0_1)$=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	$m(\tilde{\chi}^0_1)$=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	$m(\tilde{\chi}^0_1)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	$m(\tilde{\chi}^0_1)$=150 GeV, $m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	$m(\tilde{\chi}^0_1)$=300 GeV, $m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	$m(\tilde{\chi}^0_1)$=150 GeV, $m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0	$2c$	Yes	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}^0_1)$=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}^0_1)$=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}^0_1)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6	$m(\tilde{\chi}^0_1)$=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.17	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=10 GeV	1712.08119
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.26	$m(\tilde{\chi}^0_1)$=0	1501.07110
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2, \tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.76	$m(\tilde{\chi}^0_1)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1708.07875
						$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.22	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=100 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	$m(\tilde{\chi}^0_1)$=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	$m(\tilde{\ell})$-$m(\tilde{\chi}^0_1)$=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde{\chi}^0_1)$=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 0.44	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}^0_1)$< 1000 mm, $m(\tilde{\chi}^0_1)$=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	$m(\tilde{\chi}^0_1)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [$m(\tilde{\chi}^0_1)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	$m(\tilde{\chi}^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g}\to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde{\chi}^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

*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.

Conclusions

I hope I gave you the feeling that searches for new particles at colliders are interesting

- Supersymmetry has been considered for some decades one of the most promising extensions of the Standard Model (which we know must be extended)

- The negative results from the first two runs of LHC data put new strong constraints on the supersymmetric particle masses

- What we would like is to find some signal
  - It won’t happen if we stop looking for one!