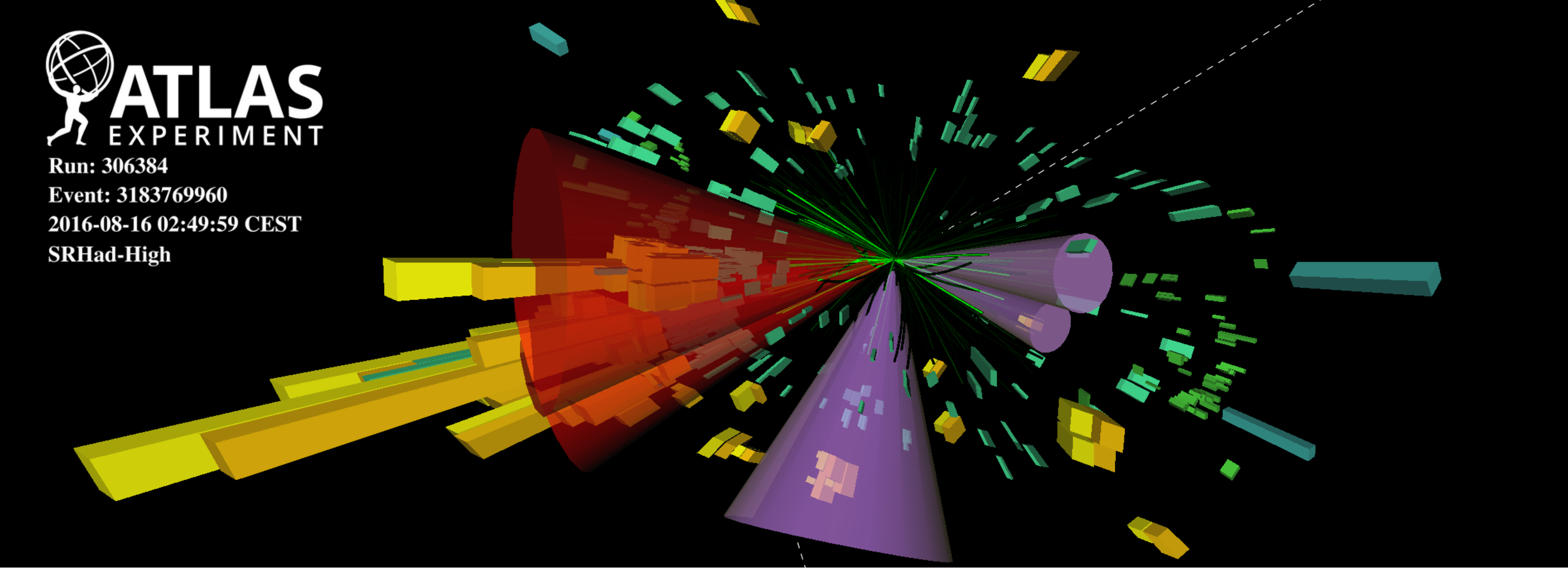
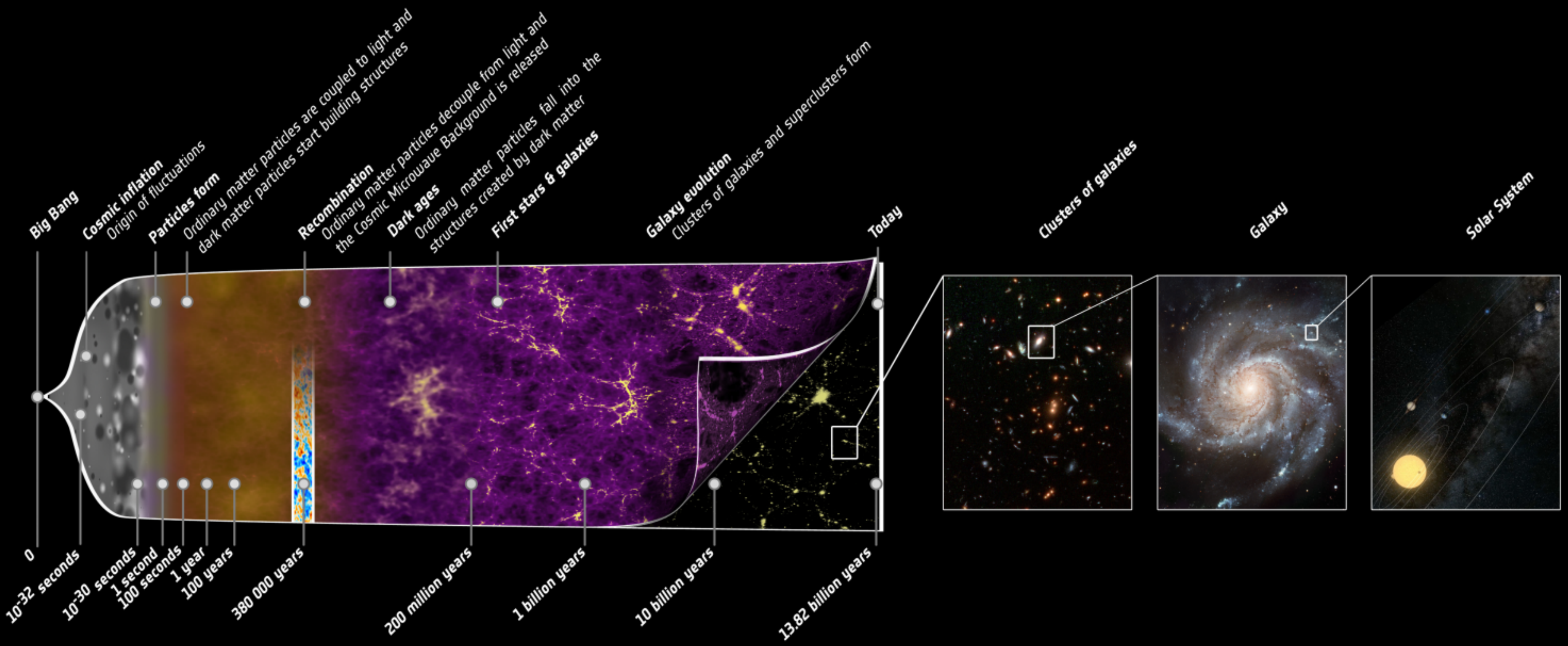


Search for new physics in association with Higgs bosons

Jeanette Lorenz (LMU München)

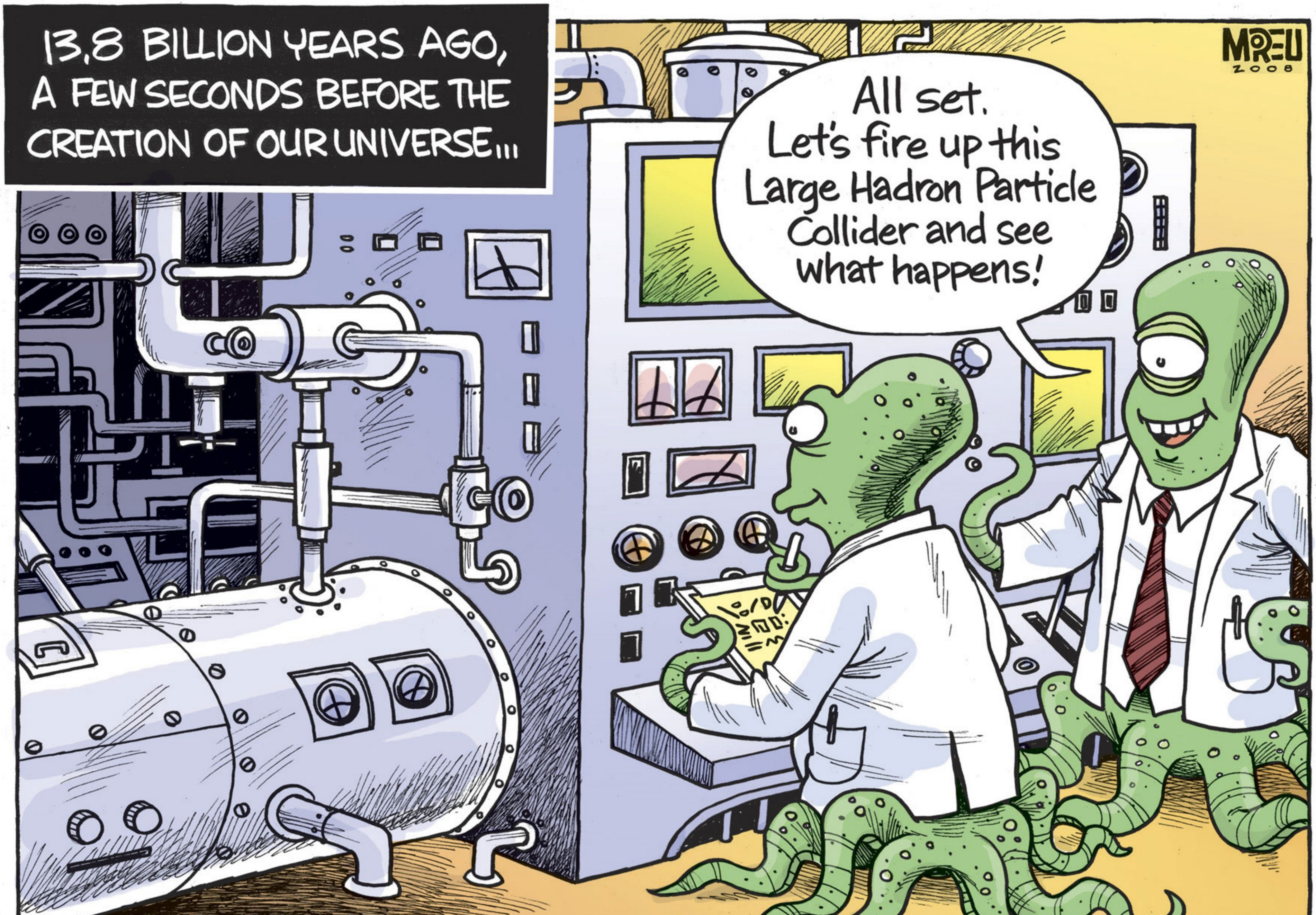
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

LMU, 17.06.2020



[https://www.nasa.gov/mission_pages/planck/multimedia/pia16876b.html]

[CERN theory common room]



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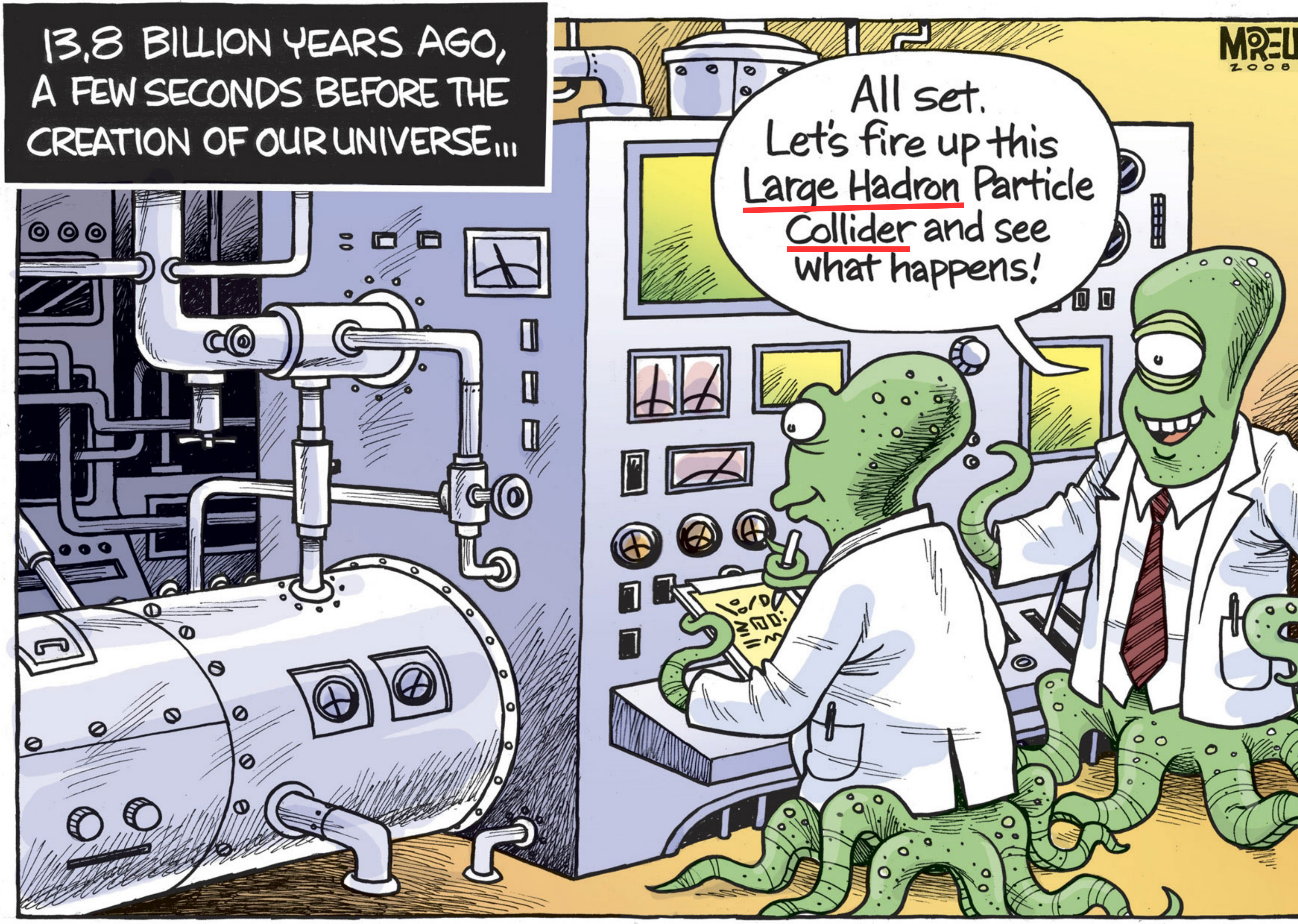
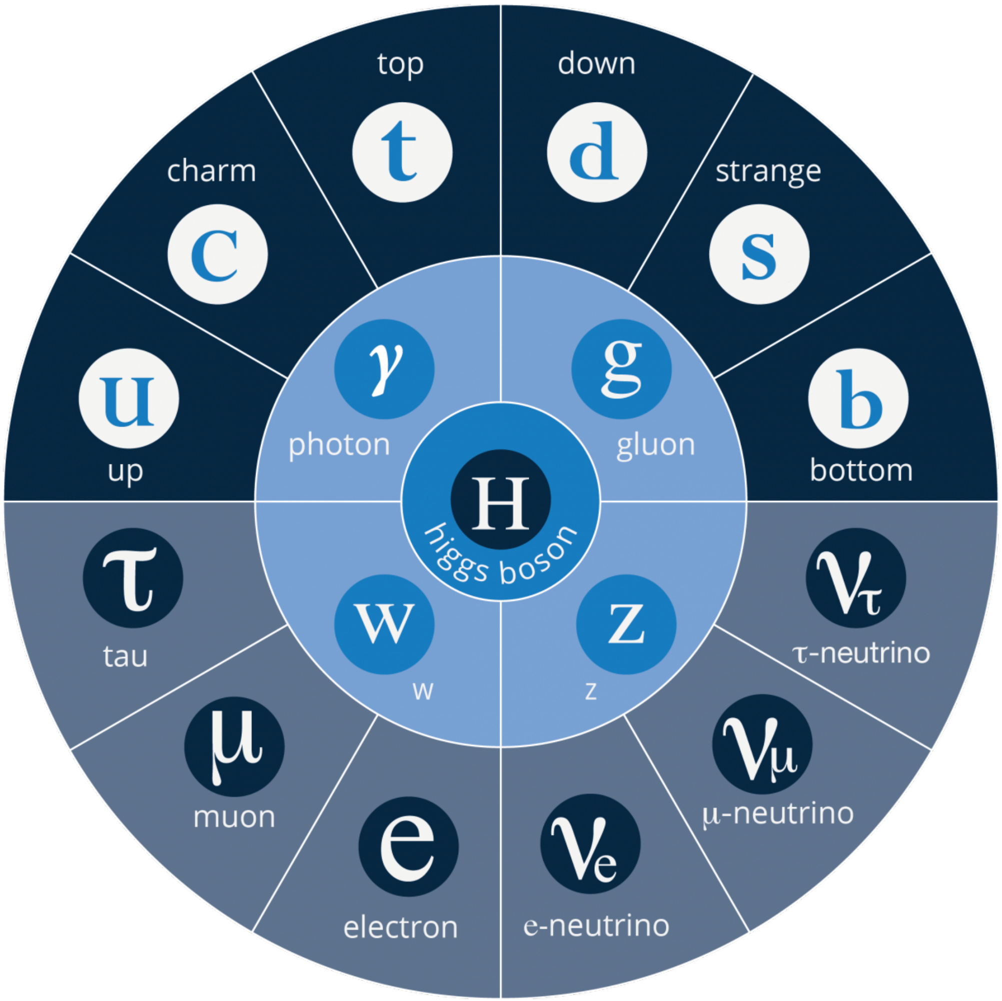


The Standard Model of Particle Physics



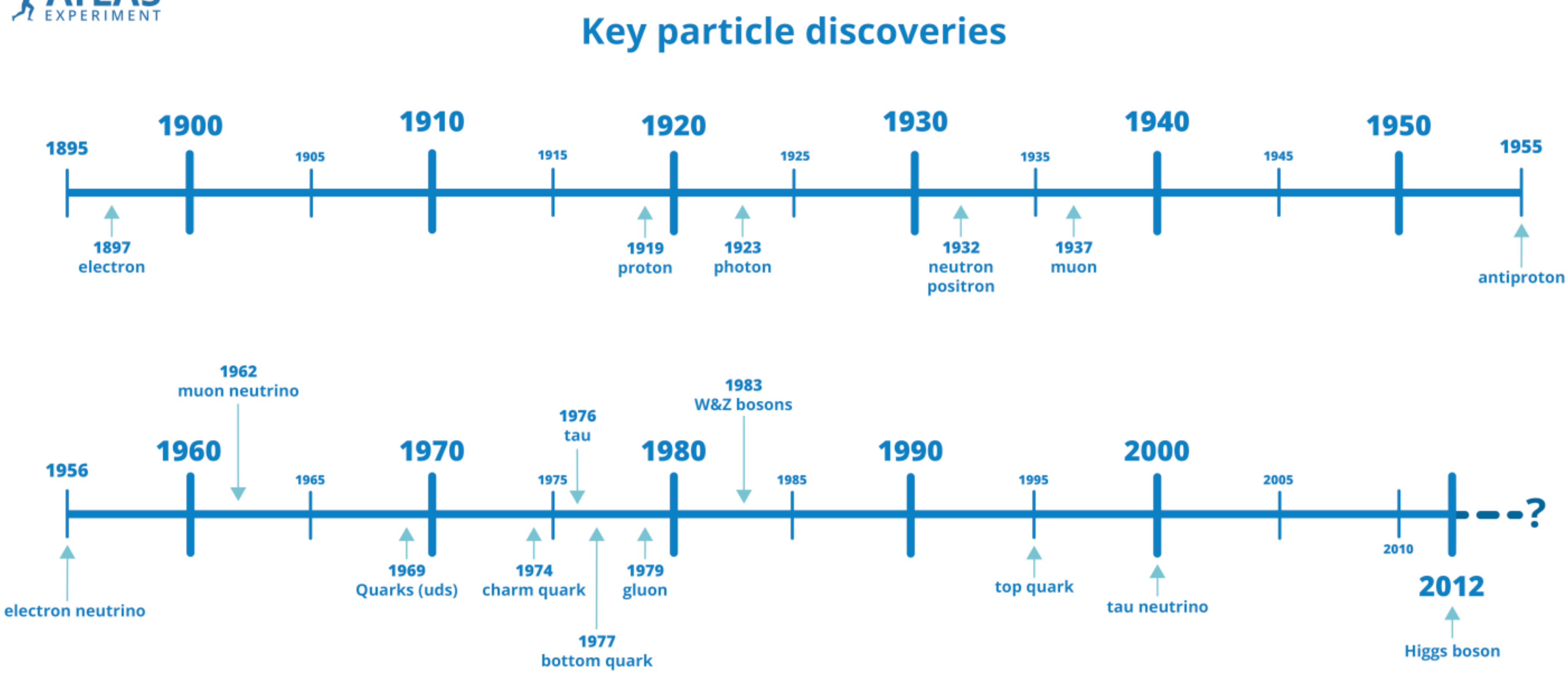
Fermions (spin 1/2):
- 6 **leptons** (plus anti-particles)
- 6 **quarks** (plus anti-particles)
- Ordered in 3 generations with increasing mass

Bosons (spin 1):
- **Photon** → electromagnetic interaction
- **W^{+-},Z** → weak interaction
- **Gluon** → strong interaction

Boson (spin 0):
- **Higgs** boson → excitation of Higgs field

Experimental discovery

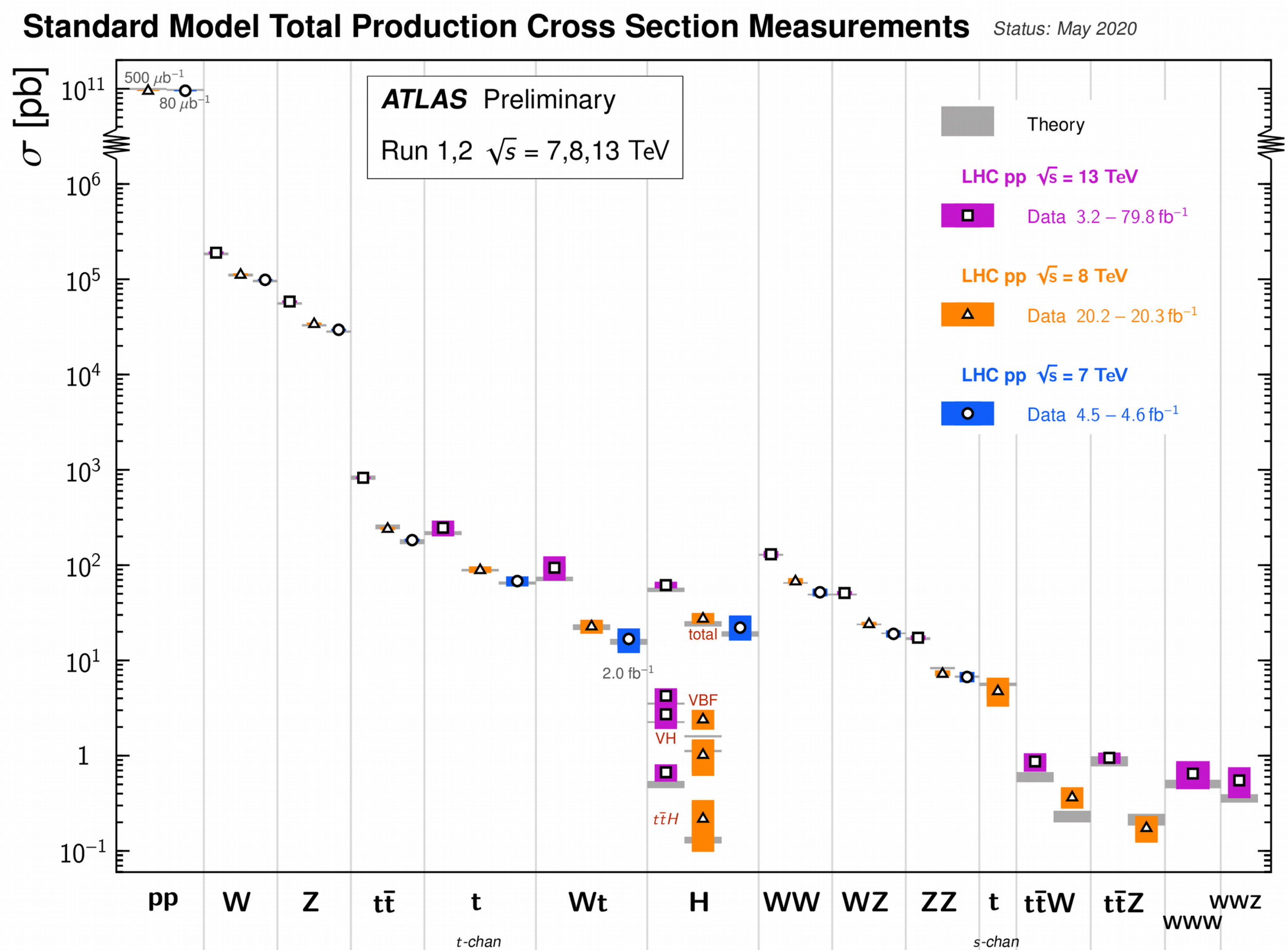
[ATLAS-PHOTO-2019-009]



Higgs boson discovered in 2012, completing the Standard Model.

Precision measurements of the Standard Model

[ATL-PHYS-PUB-2020-010]



Open questions remain!

- The Standard Model (SM) is a very successful theory and correctly describes electroweak and strong interactions.

  → *e.g. correctly predicting anomalous magnetic moment of electron to a relative precision of 10^{-10}, in agreement with experiment.*
- On the other hand also **general gravity tested very precisely**, but not both theories work at very small scales/very high energies → **Planck scale**.

Questions:

- Neutrino masses? Are neutrinos Majorana particles? Sterile neutrinos?
- What is the origin of fermion generations, masses, mixing, CP violation?
- Why does matter dominate over antimatter in the universe?
- Primordial expansion of the universe in inflation – what is the role of the Higgs field in it?
- What is Dark Matter in Universe composed of?
- Higgs boson as only scalar 0 particle very special in SM – further scalar particles? Hierarchy problem?

Open questions remain!

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The Higgs (sector)

Higgs boson as scalar particle special in SM

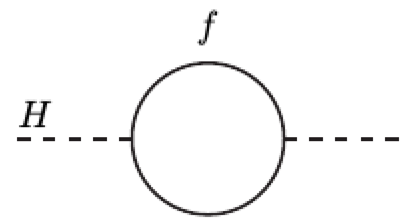
→ *Elementary particle?*

→ *Are there other scalar particles? - Many extensions of the SM predict additional Higgs bosons.*

→ *Precise shape of Higgs potential?*

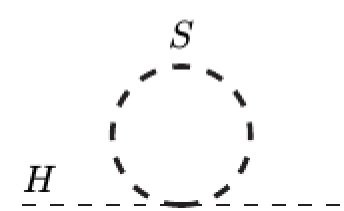
→ ***Hierarchy problem:***

- Mass of Higgs boson might receive large loop corrections.
- Corrections depend on the cut-off scale of the theory → possibly as high as Planck scale at 10^{19} GeV



$$\Delta m_H \sim -\Lambda_{UV}^2$$

Measured value of Higgs mass at 125.1 GeV



$$\Delta m_H \sim \Lambda_{UV}^2$$

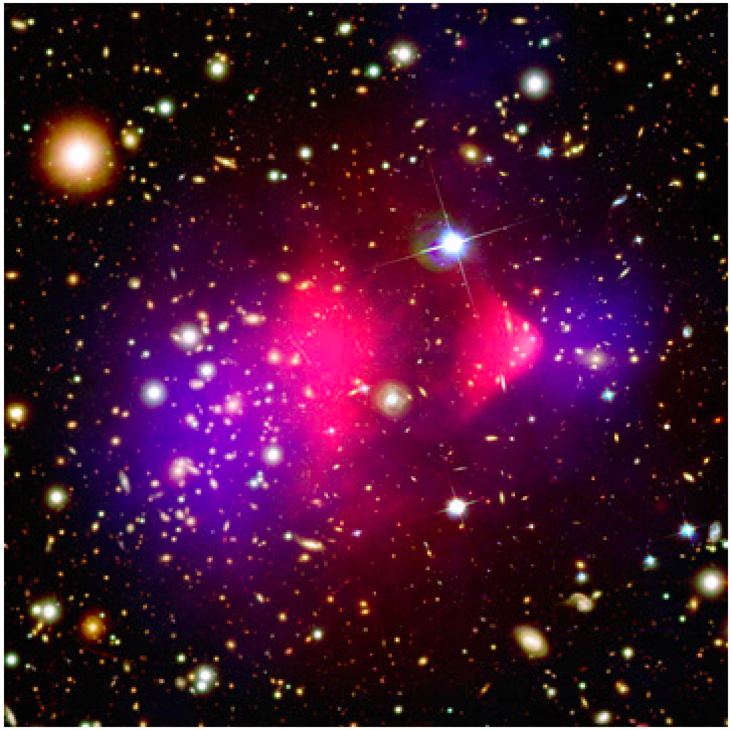
The Higgs boson might serve as window to phenomena beyond the SM!

Dark Matter (DM)

Existence of Dark Matter established by many cosmological and astrophysical observations, e.g.:

- Rotation curves of galaxies,
- Gravitational lensing,
- Measurements of anisotropy of cosmic microwave background.

Ordinary (baryonic) matter: ~5 %
Dark matter: ~26 %
Dark energy: ~69%

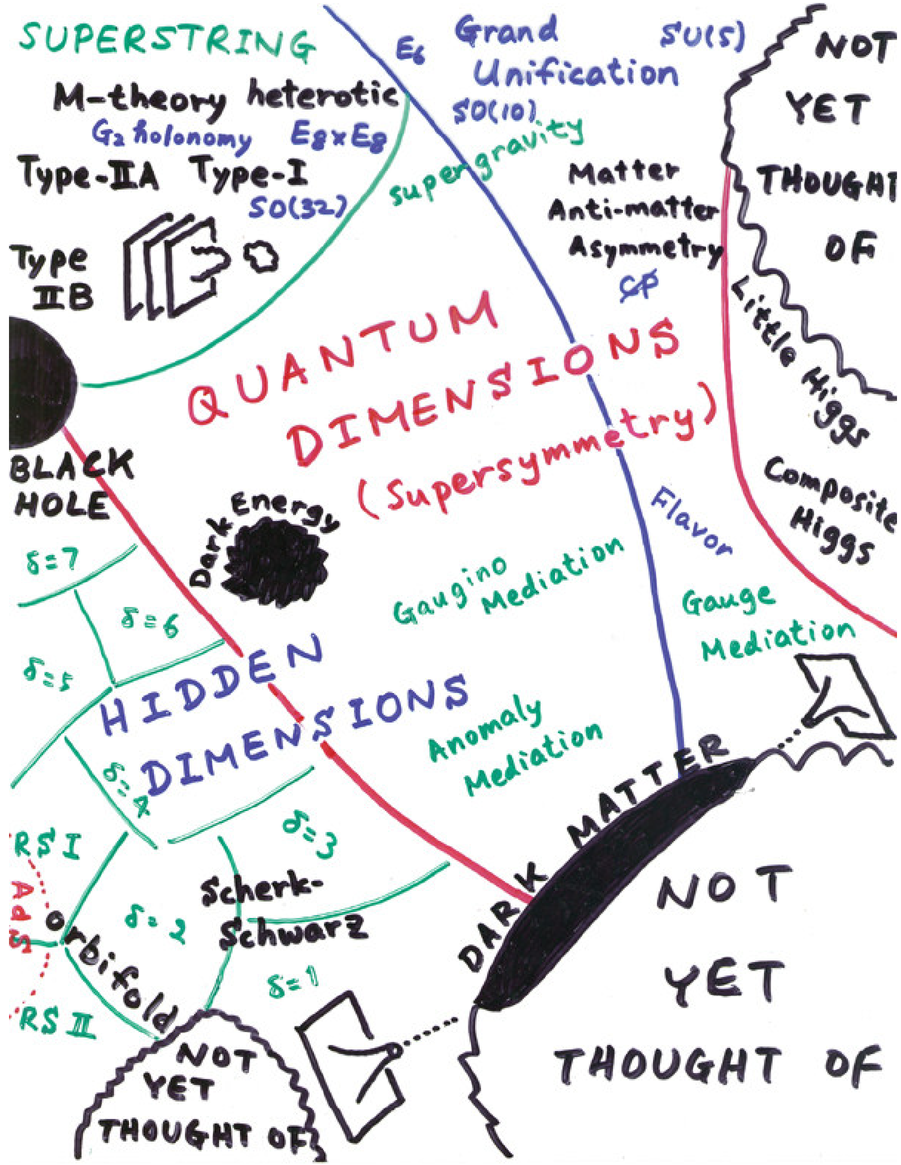


[D. Clowe et al., Astrophys. J. 648, L109 (2006)]

No candidate for (cold) Dark Matter in the SM.

Possible solutions?

Vast amount of theories and ideas proposed to address these open questions.



[Illustration by Hitoshi Murayama]

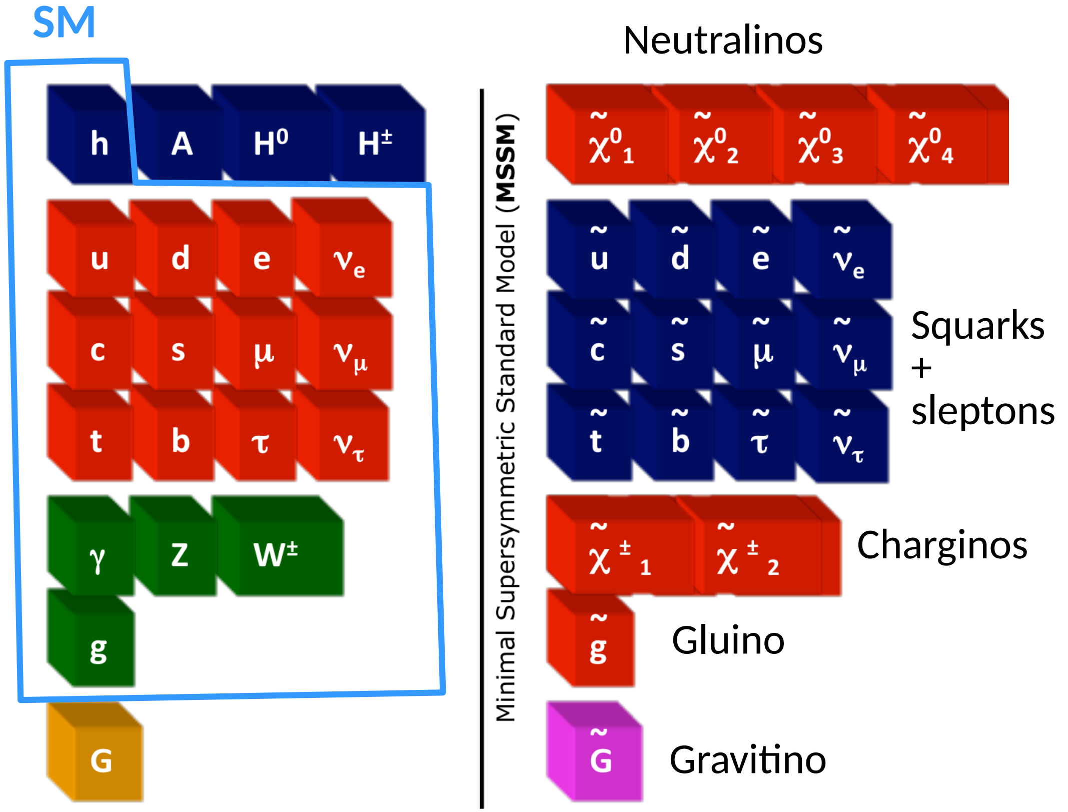
One popular solution: Supersymmetry (SUSY)

- Symmetry between fermions and bosons.
- Supersymmetric partner particles to every Standard Model particle.

→ Roughly doubling of number of particles wrt Standard Model in the **M**inimal **S**upersymmetric **S**tandard **M**odel.

Extended Higgs sector necessary.

Supersymmetric partners of W, Z and Higgs bosons mix to charginos and neutralinos.



Properties of SUSY particles

- SM and SUSY particles ordered in supermultiplets.
  → *SM particles and their SUSY partners have the same quantum numbers* ***except the spin (differs by +- ½)***

- No SUSY particles seen yet.
  → *SUSY* ***cannot be exact, but needs to be (softly) broken***
  (such as not to introduce new quadratic corrections to the Higgs mass).
  → *Certain SUSY particles expected to be relatively light.*

- SUSY theories in general allow the decay of the proton
  → *Not observed (strong limits ~ $10^{31\text{-}33}$ years)*
  → *Introduce (ad hoc) multiplicative, conserved, quantum number:* ***R-parity***

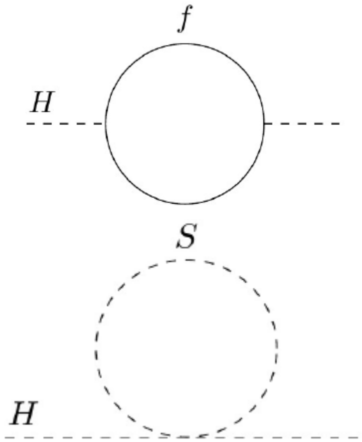
$$R = (-1)^{3(B-L) + 2s} = \begin{cases} +1 & \text{SM particles} \\ -1 & \text{SUSY particles} \end{cases}$$

Lightest SUSY particle (LSP) stable

SUSY solves some of the open questions!

Lightest SUSY particle might be a Dark Matter candidate

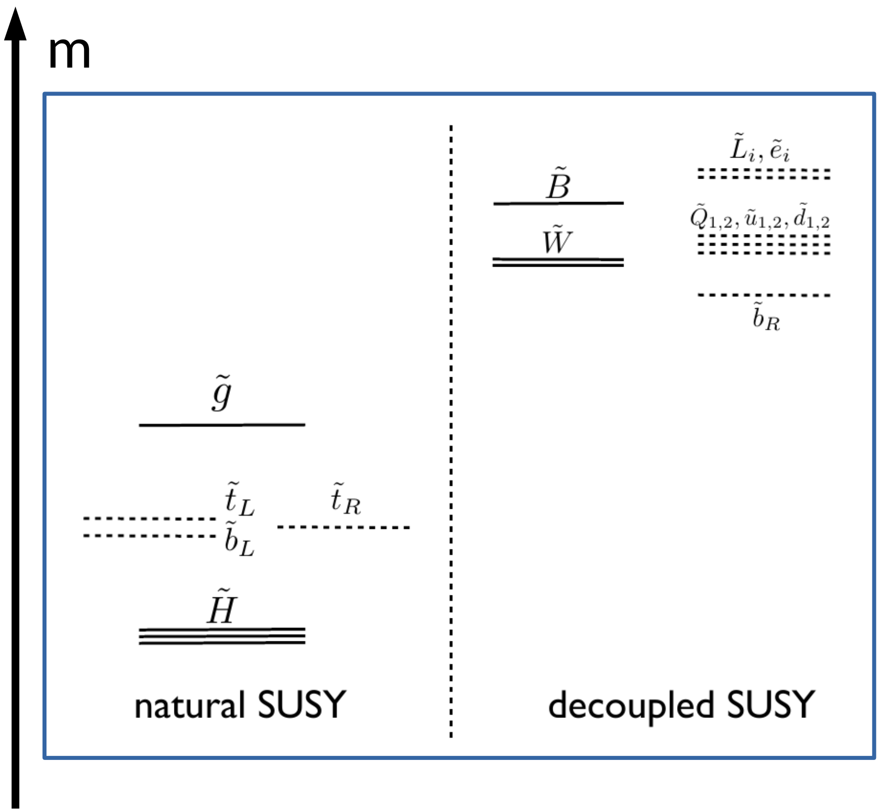
...if R-Parity conserved...



Higgs mass might get stabilized

...as new loop corrections with opposite sign
→ possibly **solution of the hierarchy problem**, if SUSY particles not too heavy.

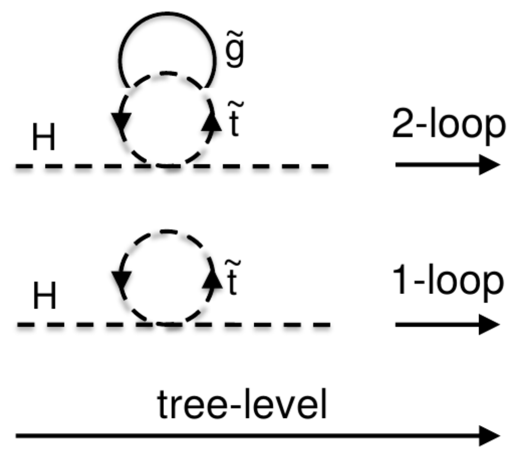
Natural SUSY



[JHEP 1209 (2012) 035]

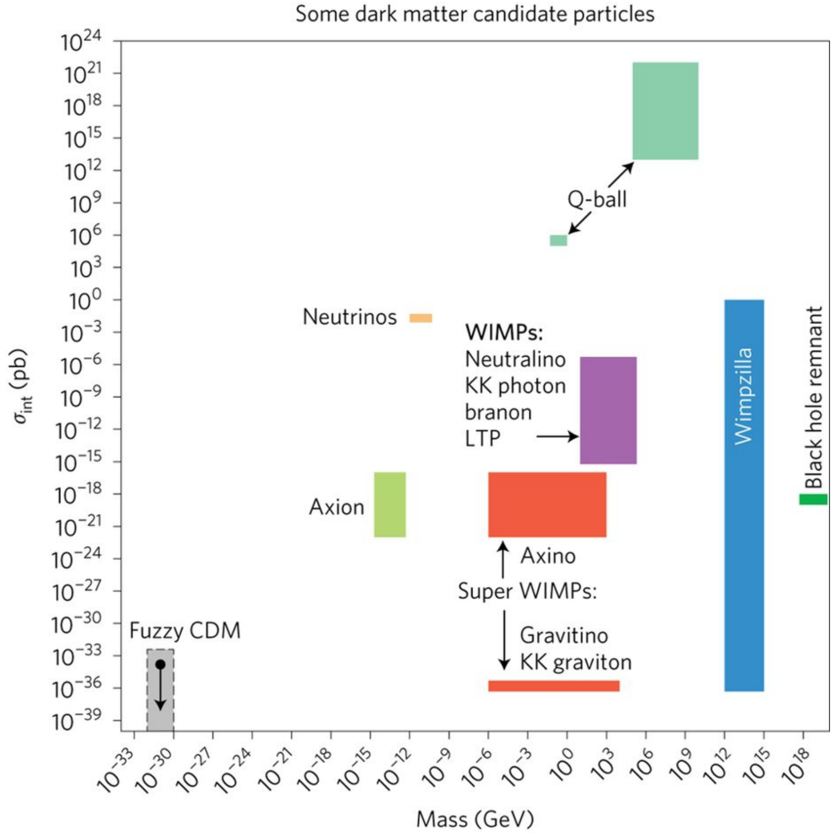
In MSSM **stop masses enter at one-loop** level into Higgs mass matrix, **gluino masses at two-loop level** and the **higgsino mass parameter μ at tree level**.

→ *Natural* SUSY models feature relatively light stops, gluinos and higgsinos.



LSP not the only candidate for Dark Matter

[https://www.nature.com/articles/nphys4049/figures/1 from Nature Physics volume 13, pages 224–231 (2017)]

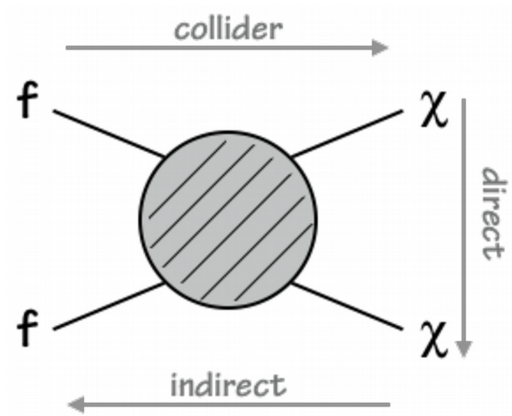


Many extensions beyond the SM provide DM candidates, not only SUSY.

→ Comprehensive search program by different experiments, and using different methods necessary.

LHC …

[ATLAS-CONF-2018-051]



XENON1T, LUX, Panda-X, Picasso…

Fermi-LAT, MAGIC, Planck, H.E.S.S. …

Open questions considered in this talk

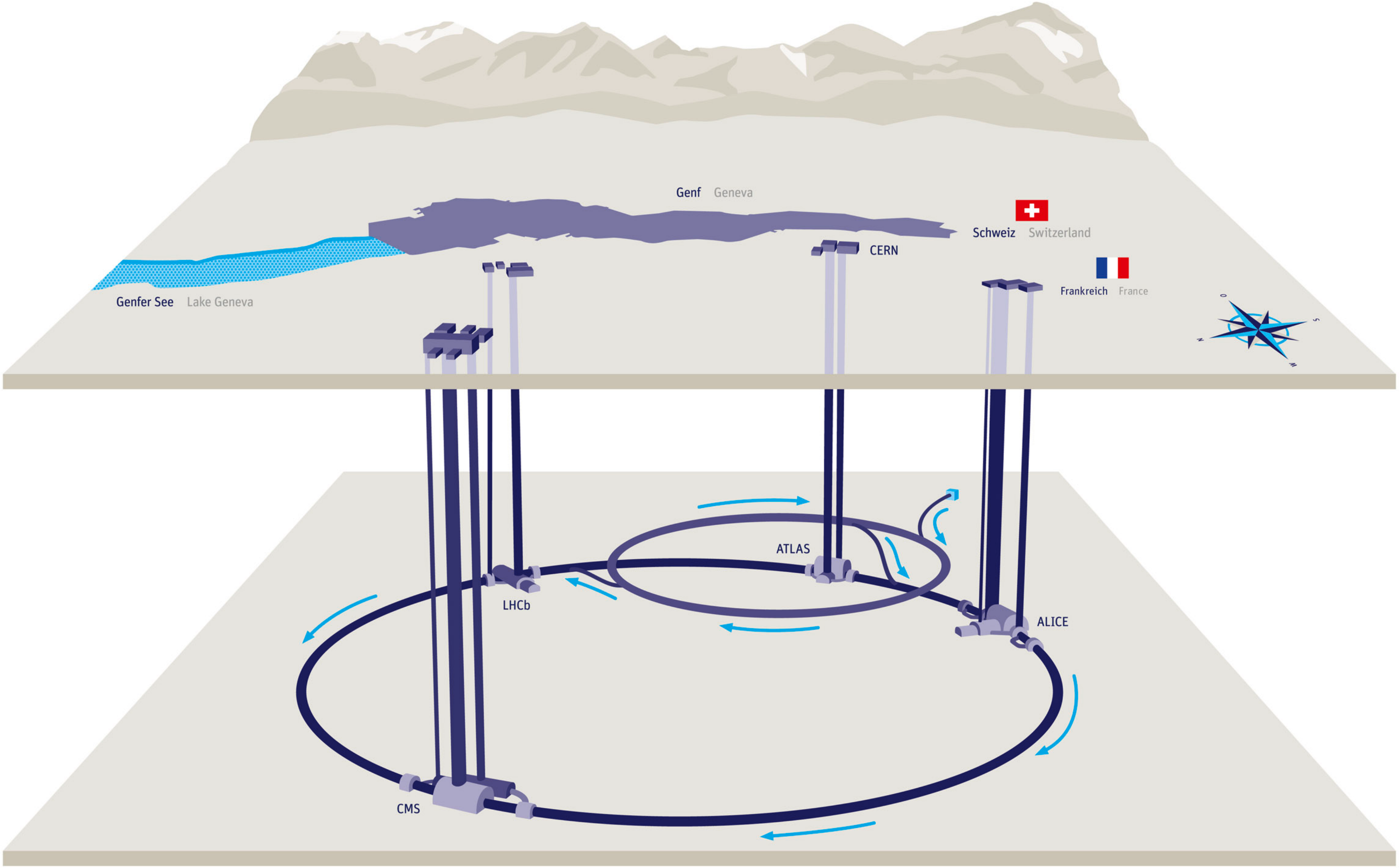
- SUSY as solution for the hierarchy problem arising from the scalar nature of the Higgs boson?
  → *Searches for SUSY particles and specifically for SUSY particles coupling to Higgs boson.*

- Coupling of Dark Matter and Higgs sector?
  → *Search for Dark Matter in association with a Higgs boson.*

- Are there additional Higgs bosons?
  → *Direct searches for further Higgs bosons.*
  → *Reinterpretation of precision measurements of the Higgs boson in extensions of the Standard Model.*

Large Hadron Collider (LHC)

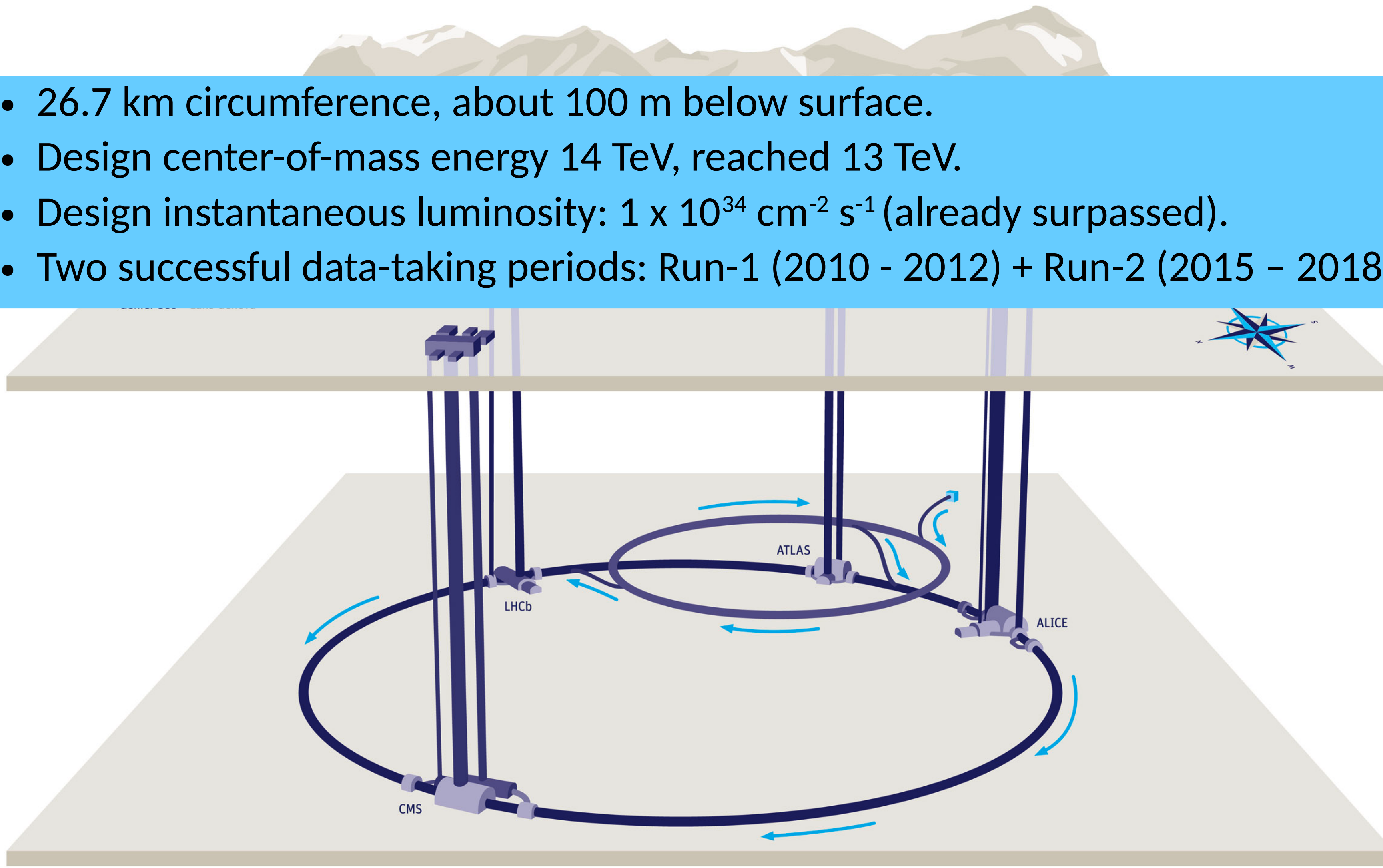
[Link]



Large Hadron Collider (LHC)

[Link]

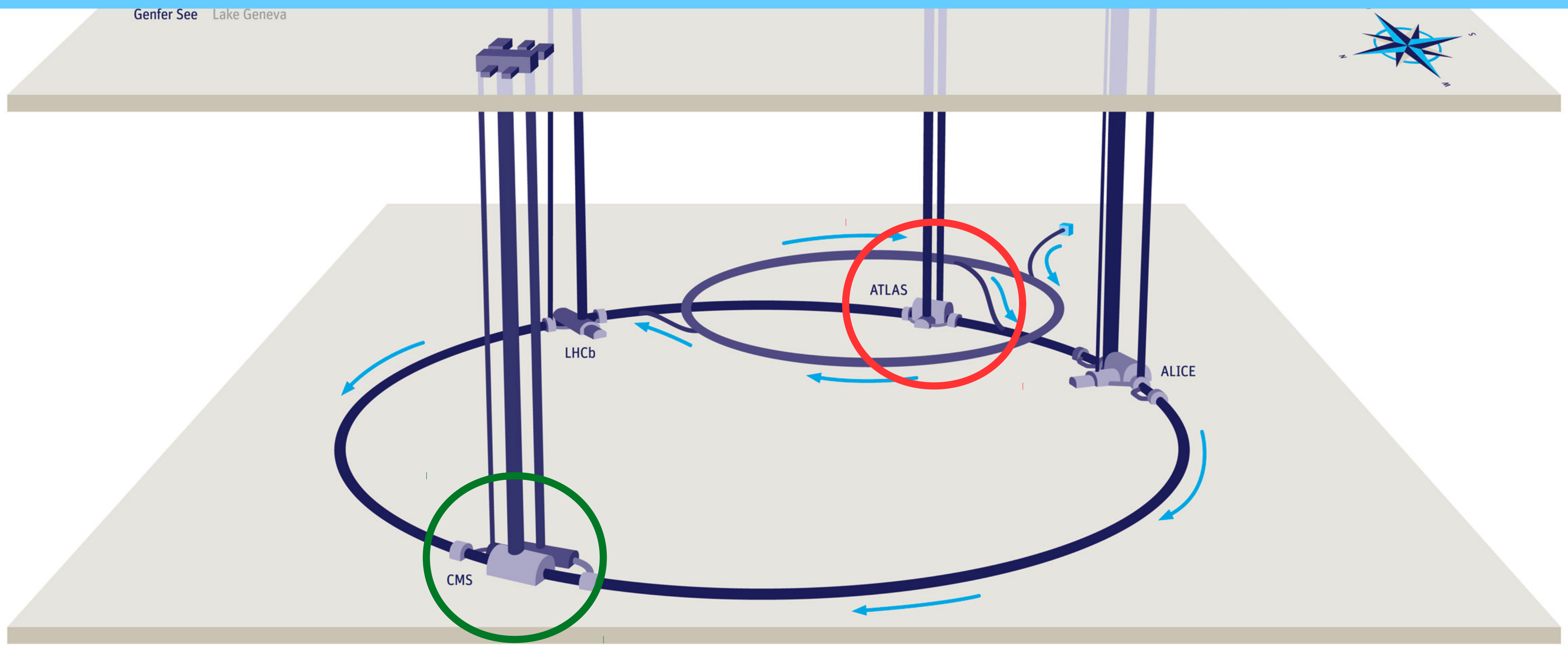
- 26.7 km circumference, about 100 m below surface.
- Design center-of-mass energy 14 TeV, reached 13 TeV.
- Design instantaneous luminosity: 1×10^{34} cm^{-2} s^{-1} (already surpassed).
- Two successful data-taking periods: Run-1 (2010 - 2012) + Run-2 (2015 – 2018).



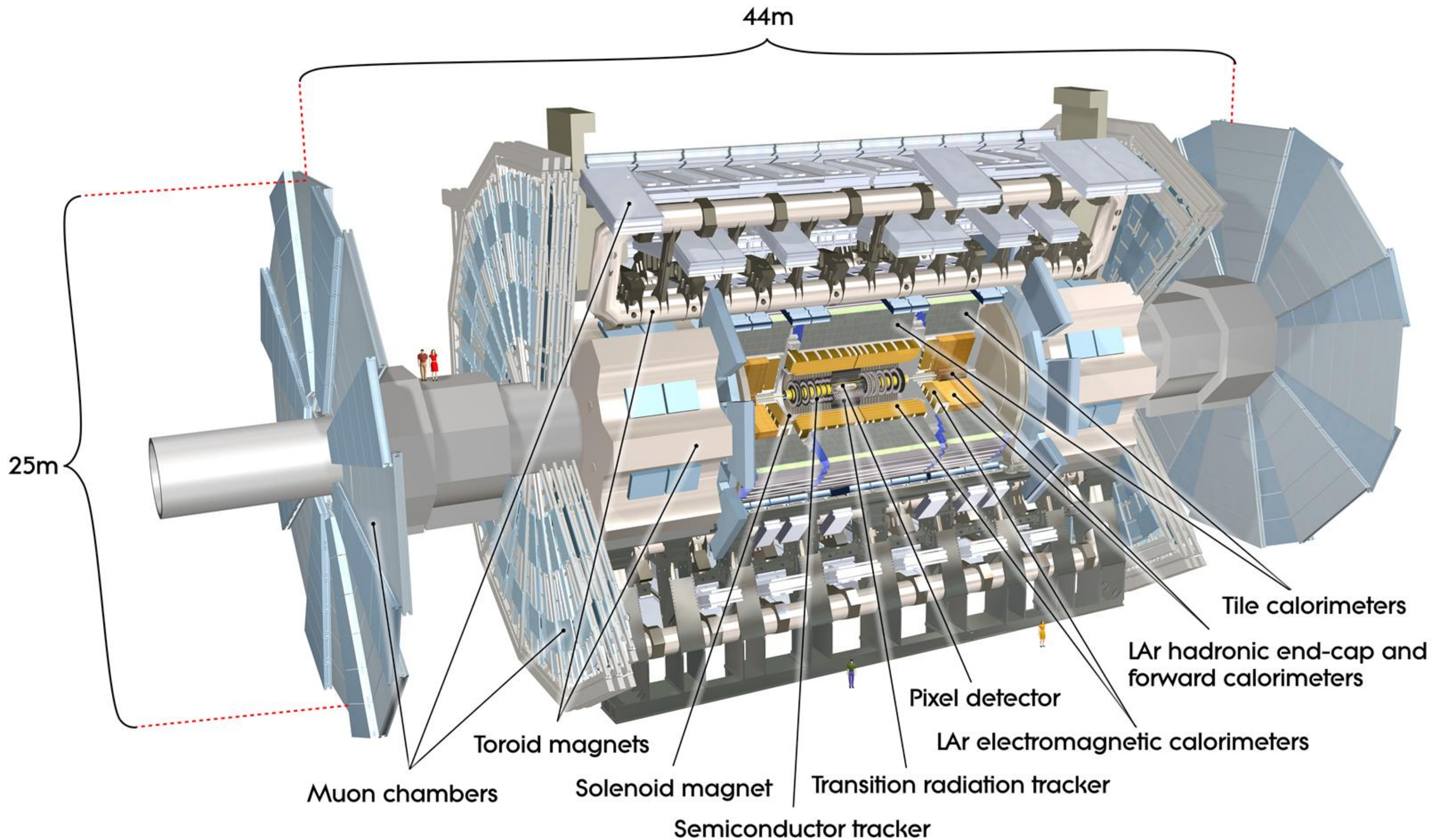
Large Hadron Collider (LHC)

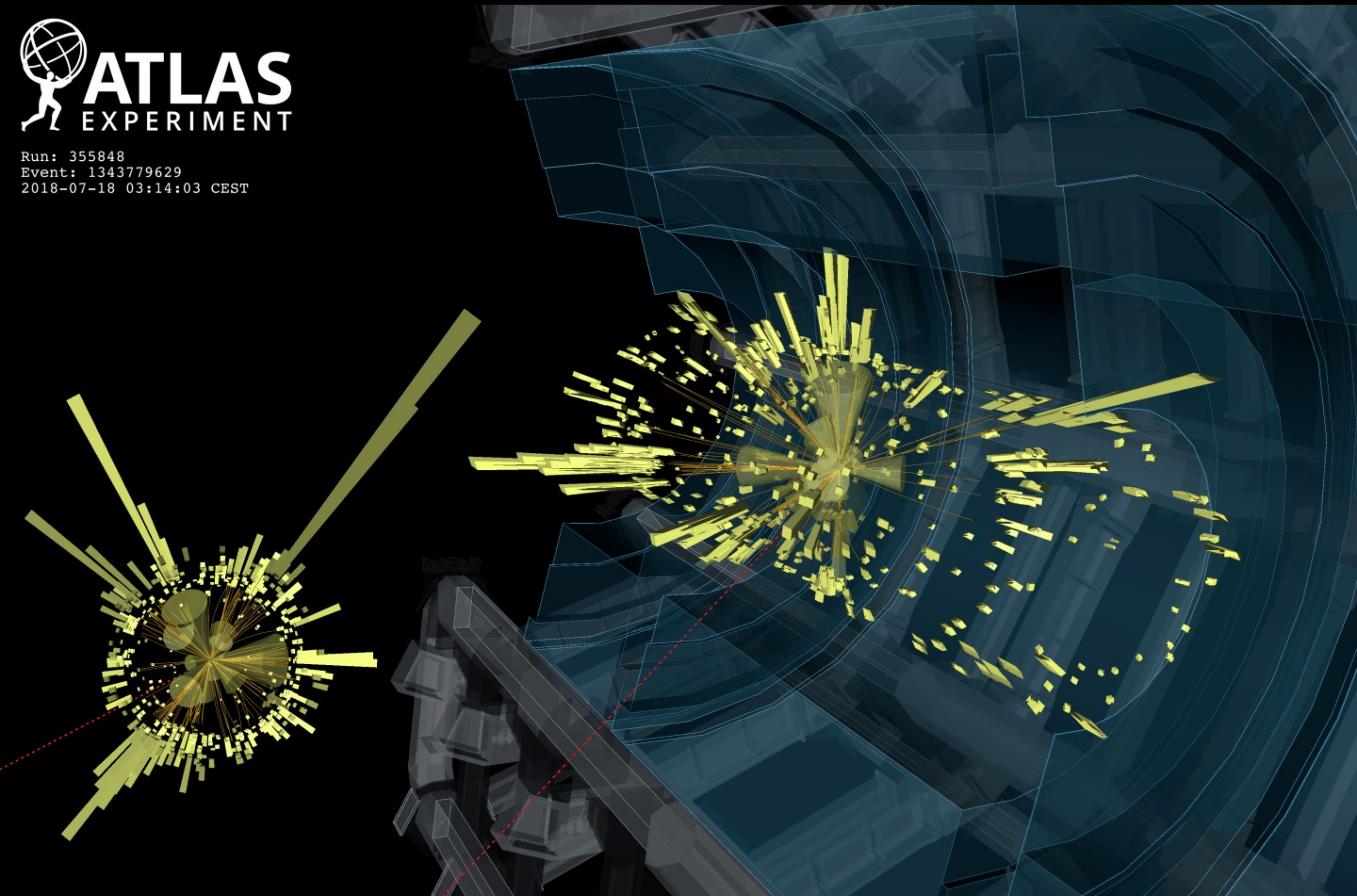
[Link]

- Various experiments at four interaction points.
- Two general purpose experiments: **CMS** and **ATLAS**.
  → *Doubling of dataset & cross-check of findings.*
- Available data for analysis from Run-2 (ATLAS): 139 fb^{-1}



ATLAS detector

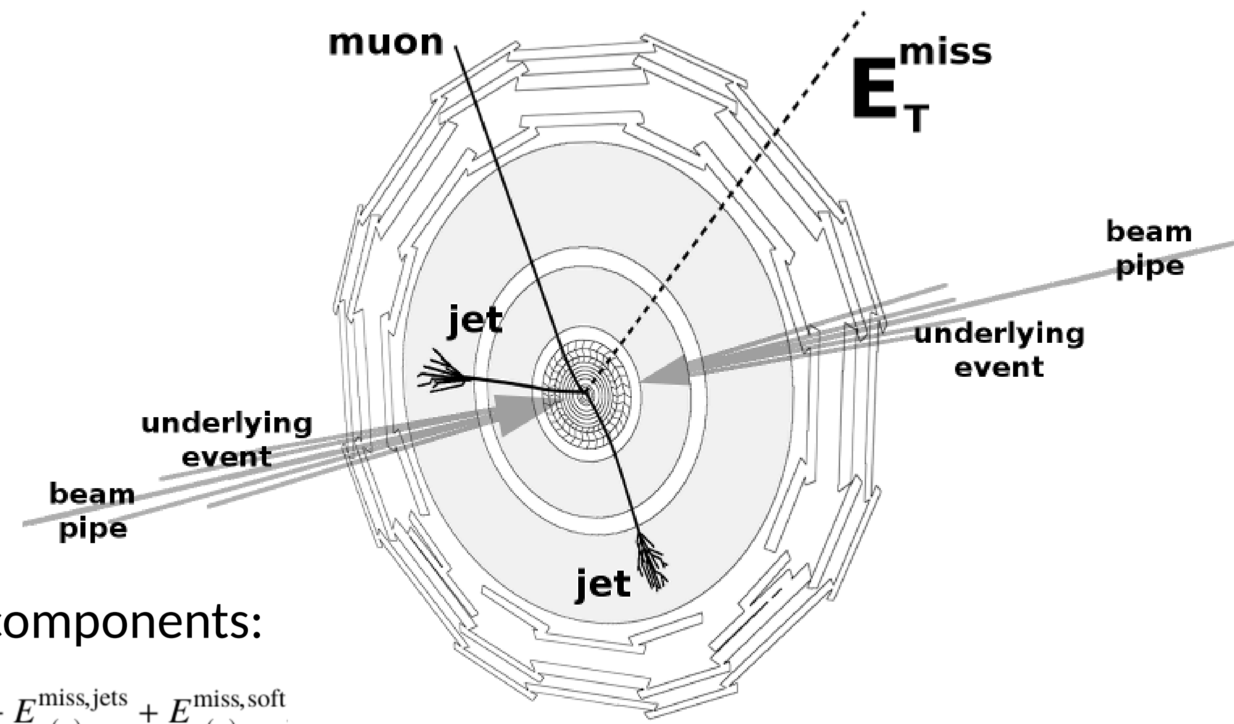



ATLAS
EXPERIMENT
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST

Missing transverse momentum: E_T^{miss}

[Jet Goodson]

Invisible particles to the detector (like neutrinos or dark matter particles) result in a momentum imbalance in the perpendicular plane to the proton-proton collision
=> **missing transverse momentum** (E_T^{miss})



Calculated using the x- and y-components:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},\mu} + E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,soft}}$$

The **soft term** is composed of all tracks or energy deposits not associated to a reconstructed particle.

E_T^{miss} can also arise from mis-measurements
→ Important to minimize!

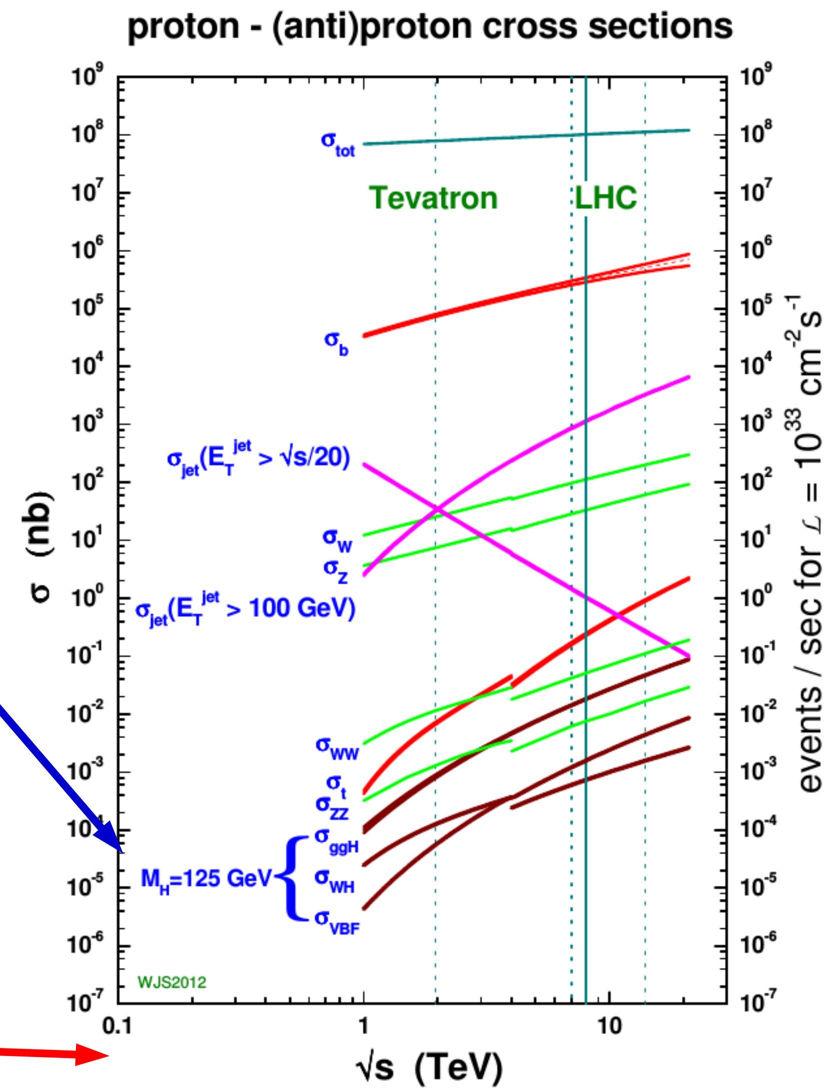
What can we measure at the LHC?

- Predictions for processes of the Standard Model
  (cross section is measure on how frequent a process occurs)

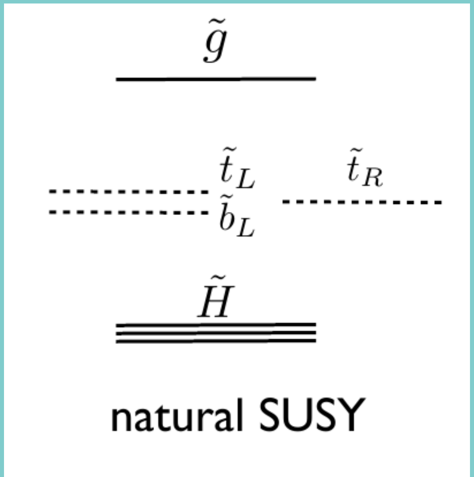
- Higgs boson productions:
  1 Higgs bosons in about 10^{10} collisions
  (e.g. in 2017: about 3 million collisions per second)

- Need to run complex algorithms during data-taking to filter processes we are really interested in….
  → *Trigger*

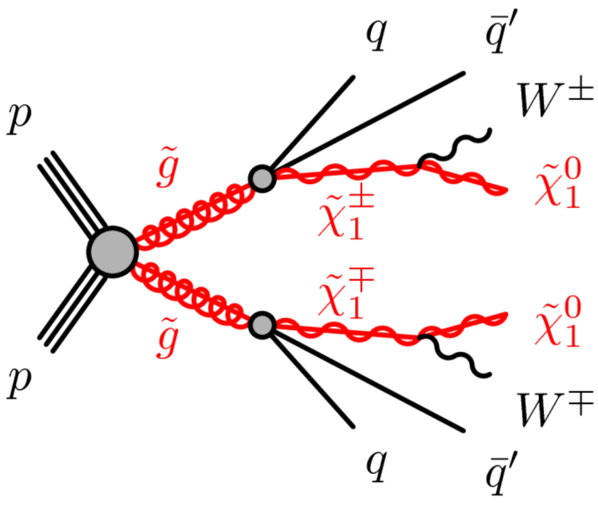
Maybe unknown physics down there?



[http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html]



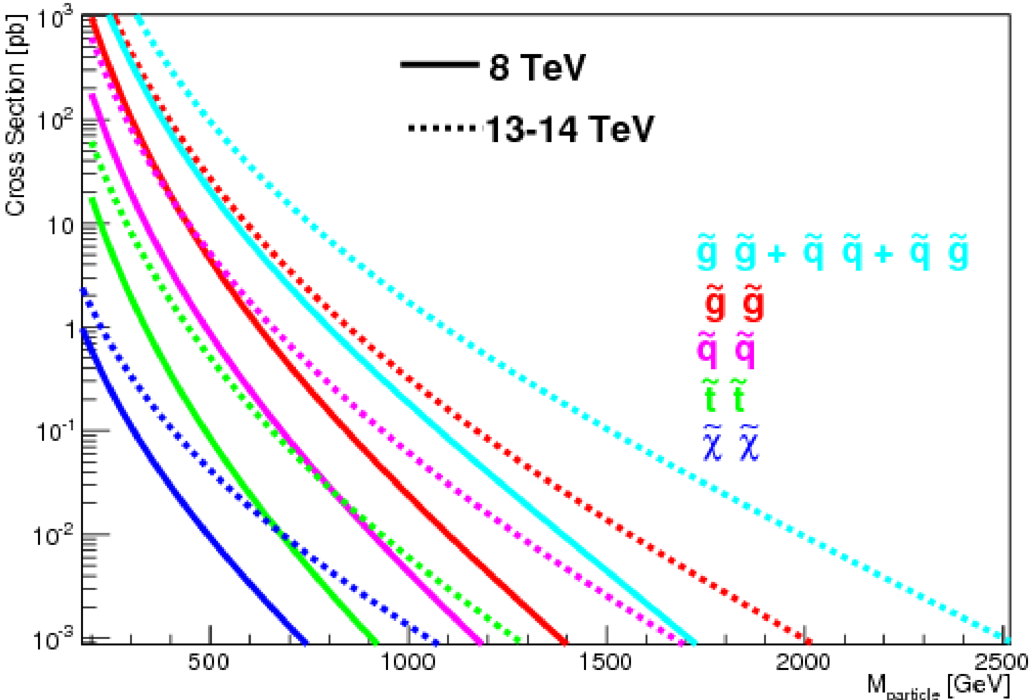
Searches for supersymmetric particles



Searches for supersymmetric particles

Higher cross sections for (strong) production of gluinos and squarks than for (electroweak) production of charginos/neutralinos

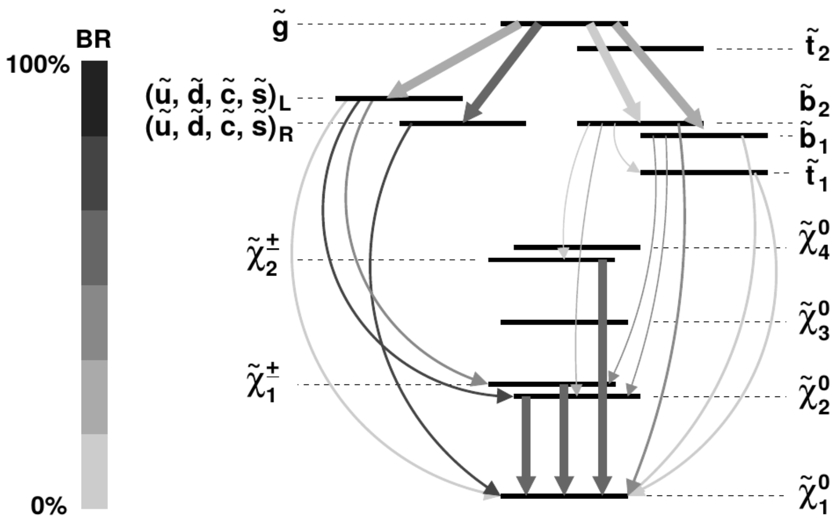
- *Mass dependent.*



[http://inspirehep.net/record/1326406]

Searches for gluinos/squarks were more accessible in first Run-2 data, while searches for charginos/neutralinos profit from the full available dataset.

Supersymmetric models

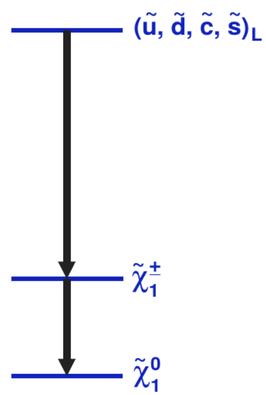


In case of MSSM 124 free parameters!

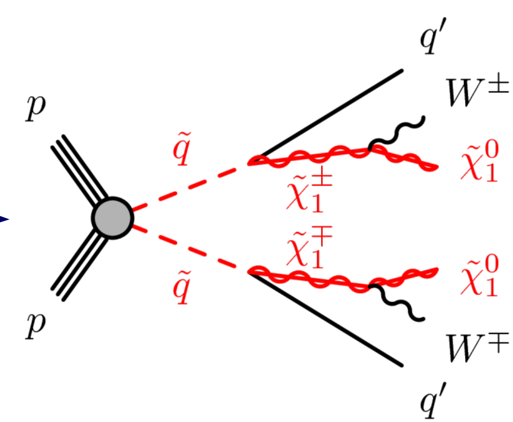
We cannot deal with that many free parameters!*

but sometimes we at least look at certain reductions, like the pMSSM with 19 parameters

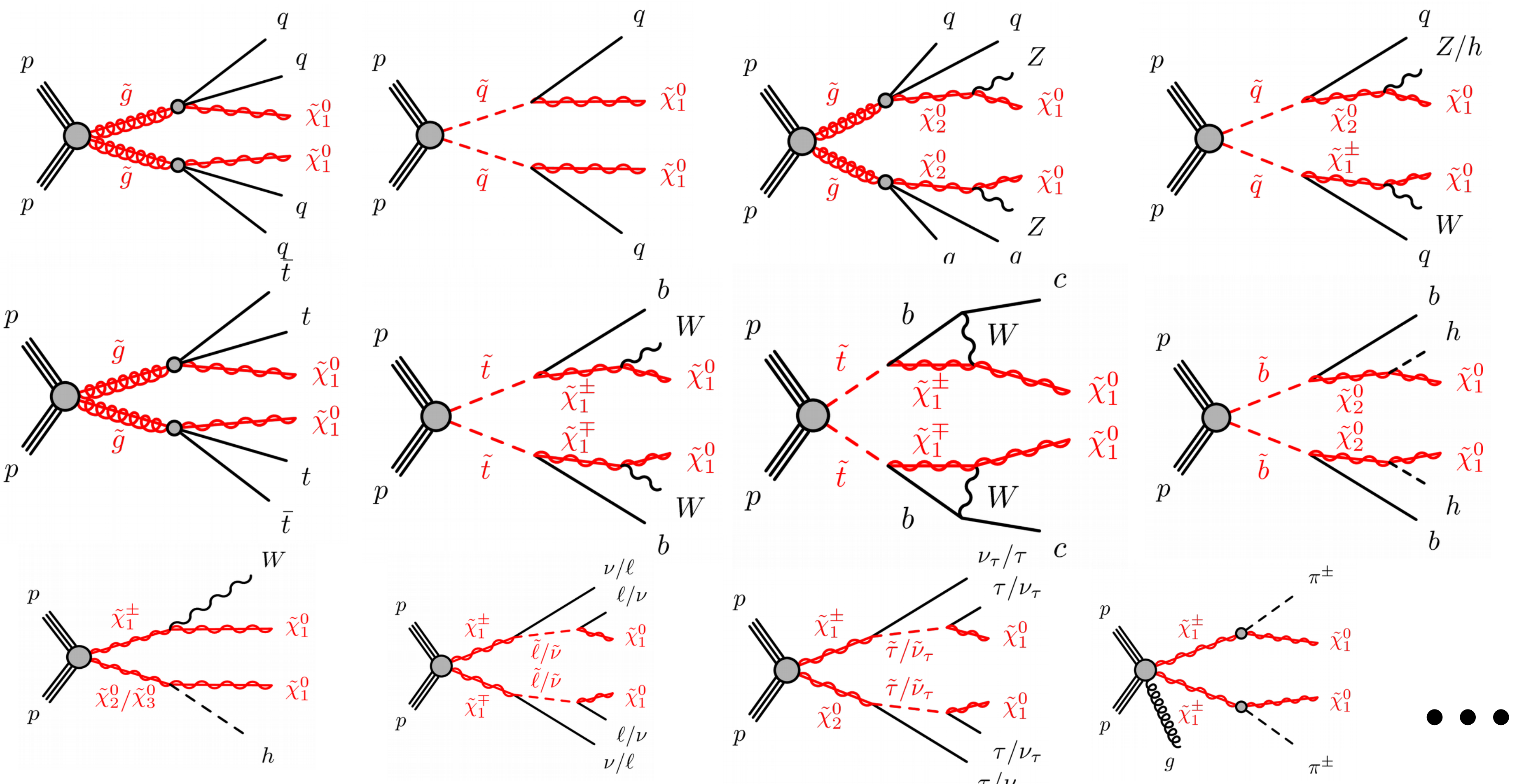
Usually only look at a specific decay chain



Simplified model



Many different simplified models

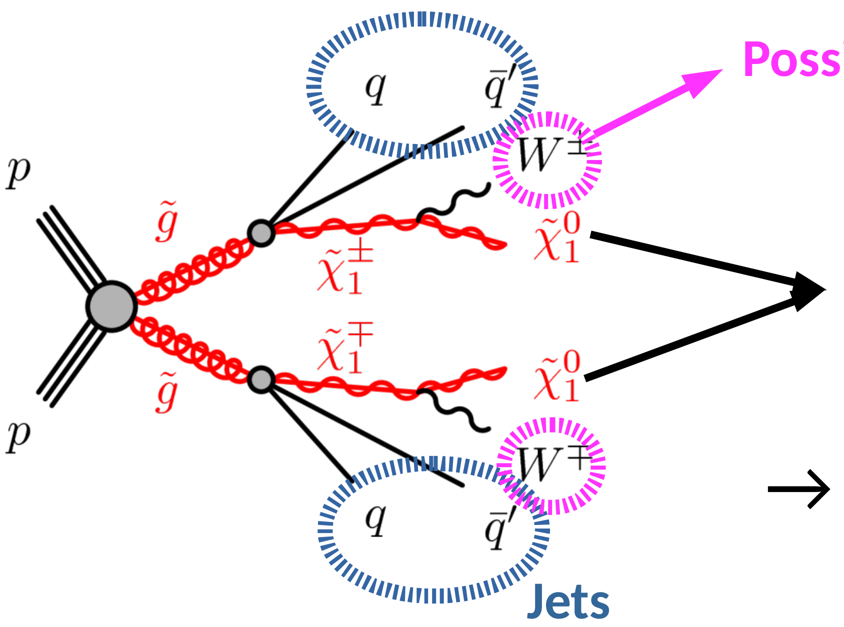


=> Very different experimental signatures to look for!*

* *We can get back to complete SUSY model by combining different simplified models/signatures.*

Example signature

E. g. strong production of gluinos:



Lightest supersymmetric particle (LSP): stable in R-parity conserving theories → **missing transverse momentum**

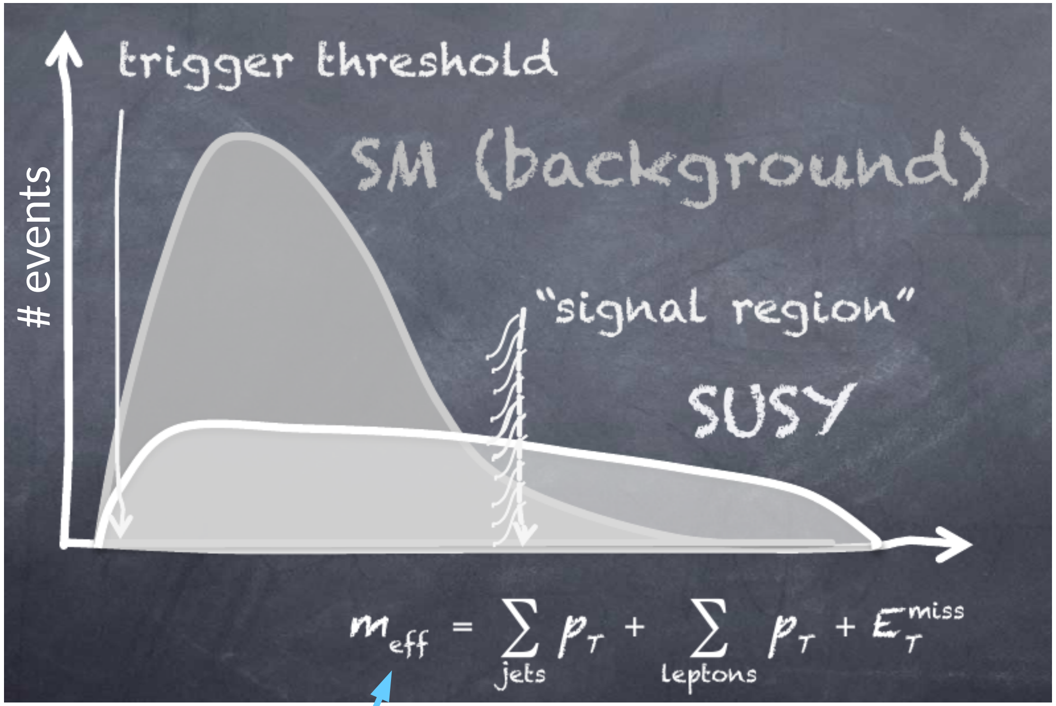
→ Jets + leptons + E_T^{miss}

Distinguish signal from background

Use kinematic variables to separate signal from background
(→ signal/search region).

Some analyses just use simple combination of cuts on kinematic variables
→ 'cut-and-count',

Others do shape analyses or use e.g. machine learning techniques.



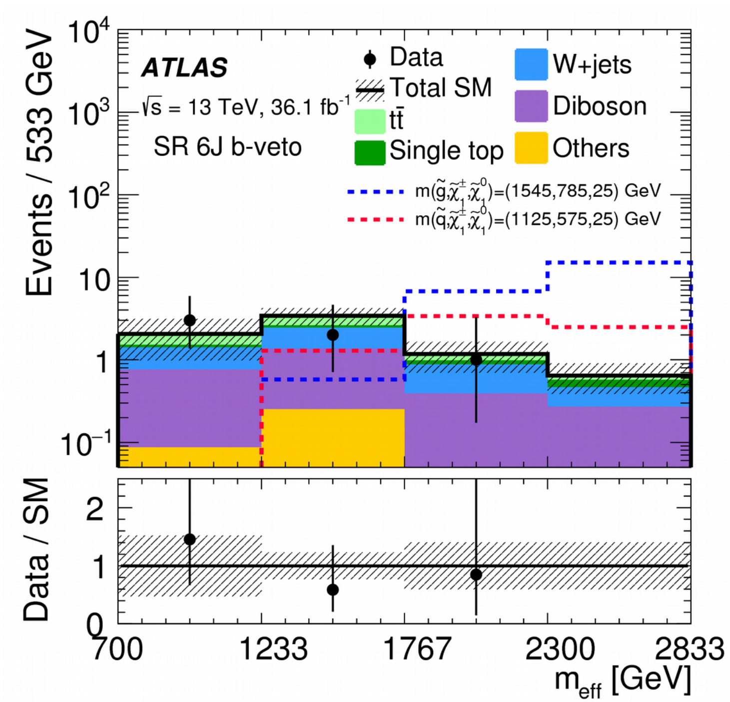
m_{eff} particularly important in searches for gluinos and squarks

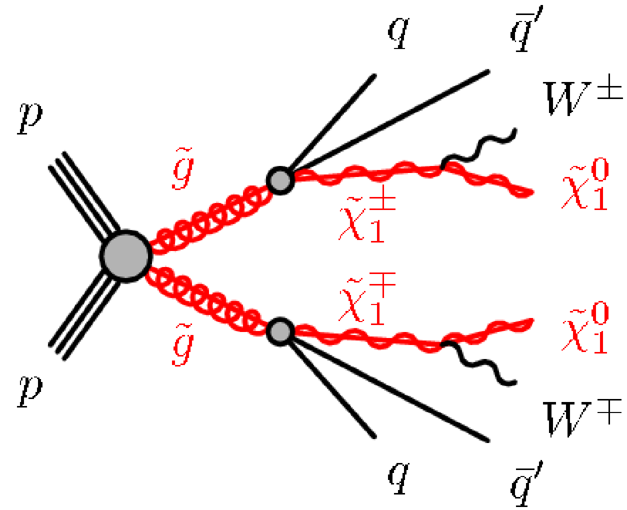
Search for gluinos/squarks in final states with a lepton

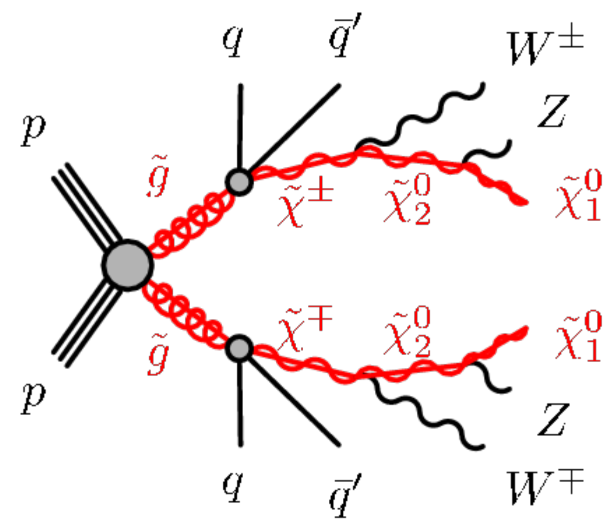
[Phys. Rev. D 96 (2017) 112010]

Requiring an isolated electron or muon helps to suppress the large multijet background at hadron colliders

→ *Generic sensitivity to supersymmetric model with leptons in the decay products.*

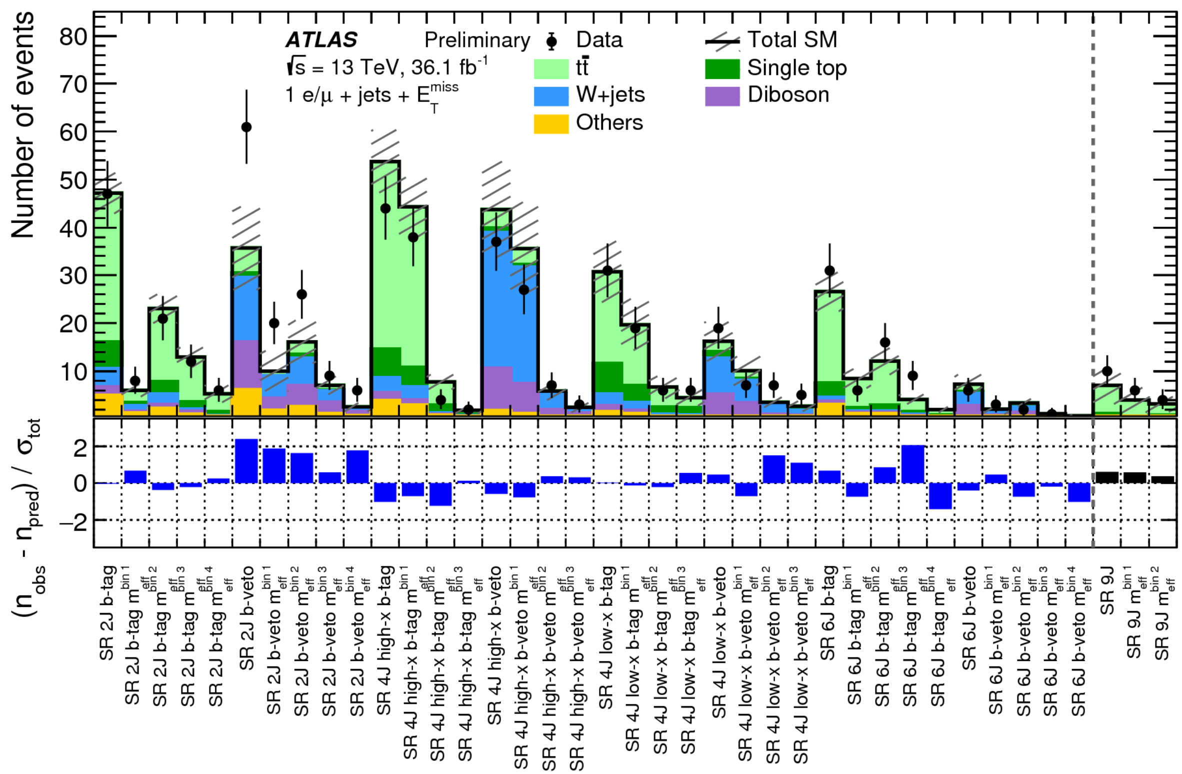






Search for gluinos/squarks in final states with a lepton

[Phys. Rev. D 96 (2017) 112010]

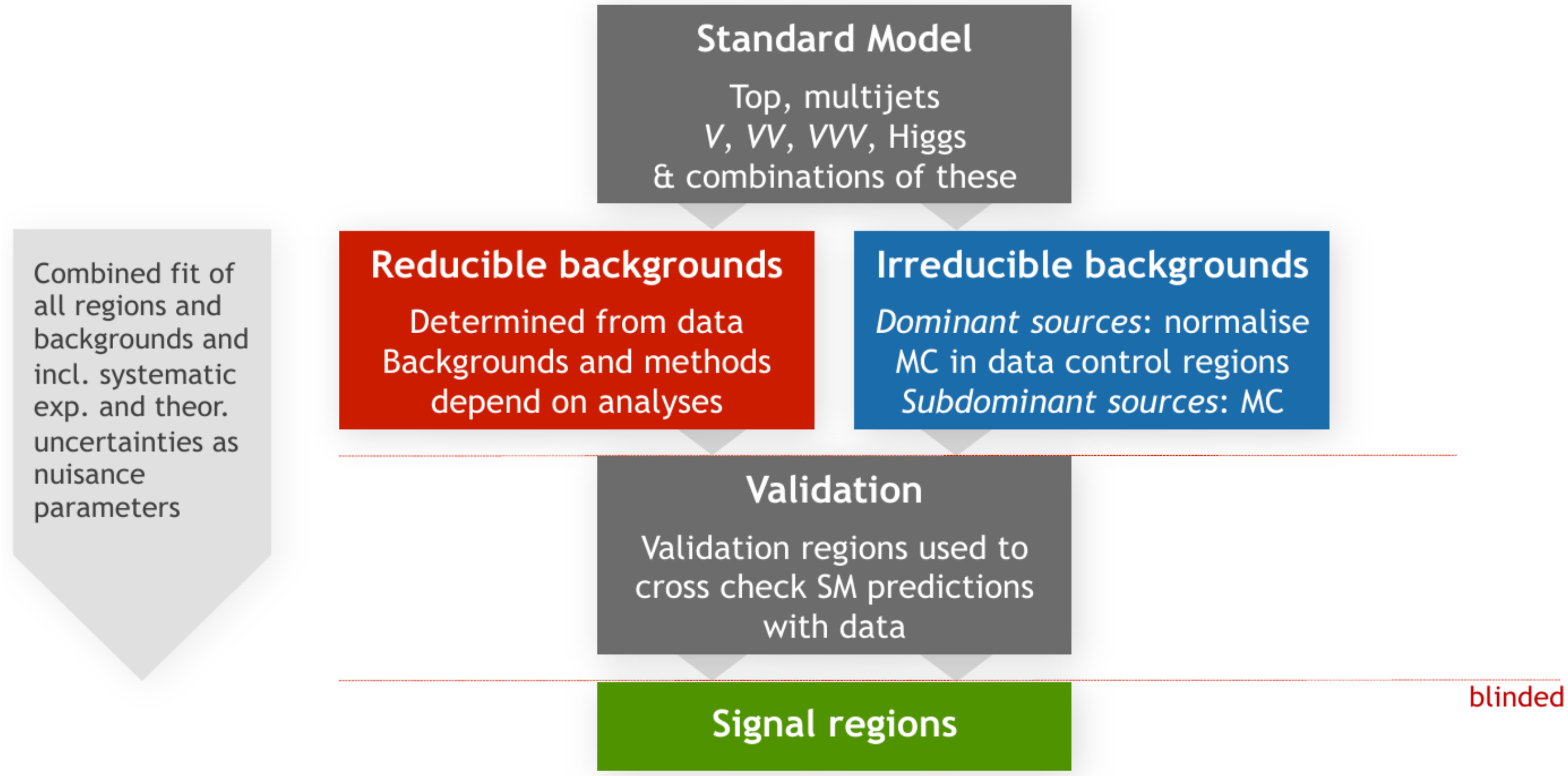


30 different search regions with requirements on different kinematic variables (jets or b-tagged jets, m_{eff} and $m_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos([\Delta\varphi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})]))}$).

Simultaneous fit of search regions allows to search for shape differences between background and signal.

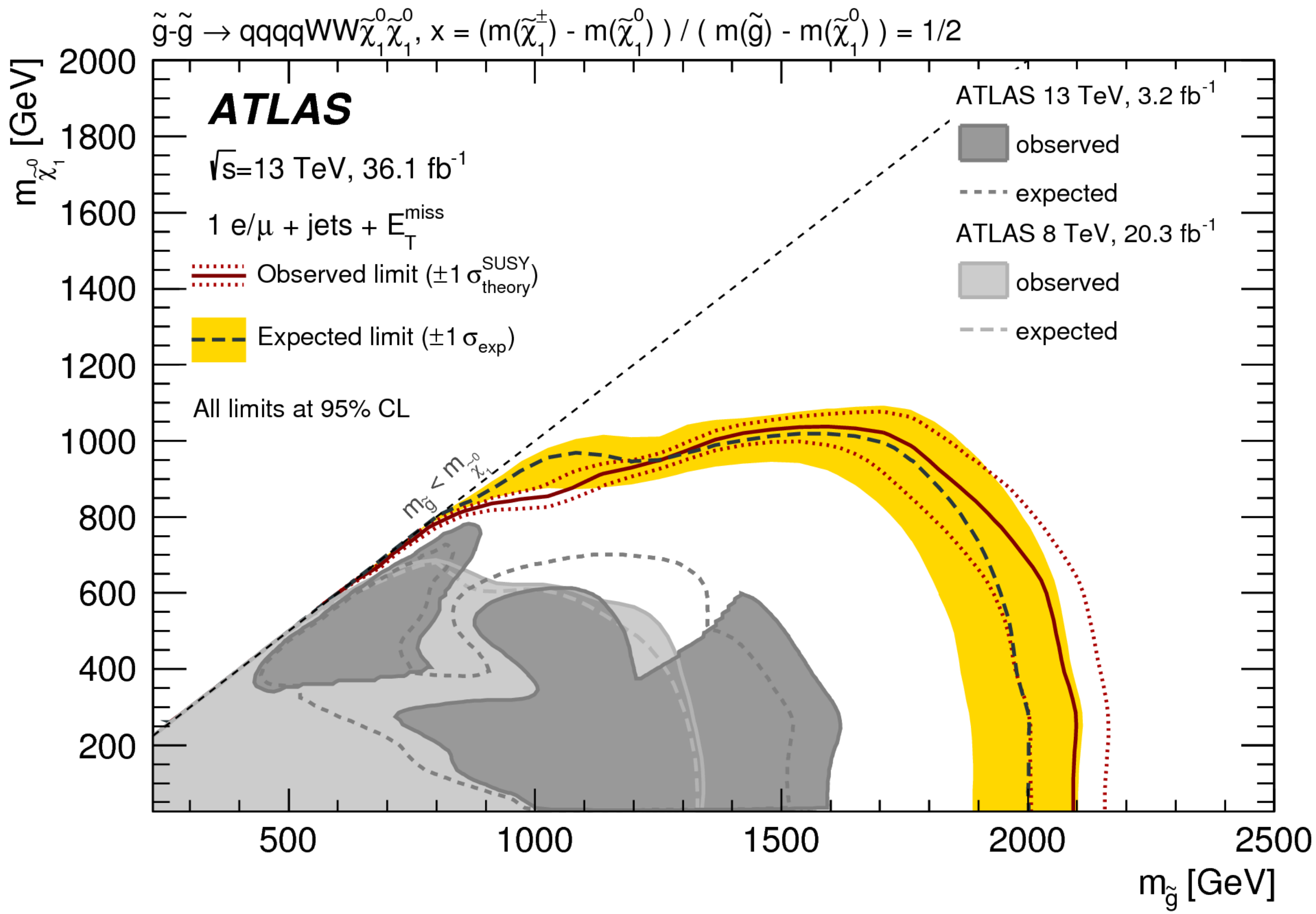
Essential to estimate the backgrounds

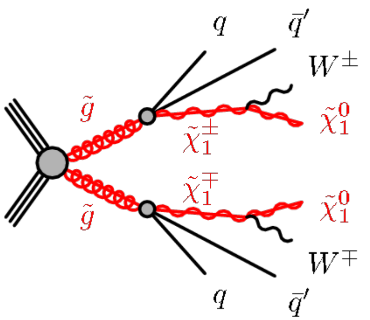
- **Reducible backgrounds:** backgrounds with another final state in comparison to the signal.
- **Irreducible backgrounds:** backgrounds show the same final state as the signal.



Search for gluinos/squarks in final states with a lepton

[Phys. Rev. D 96 (2017) 112010]

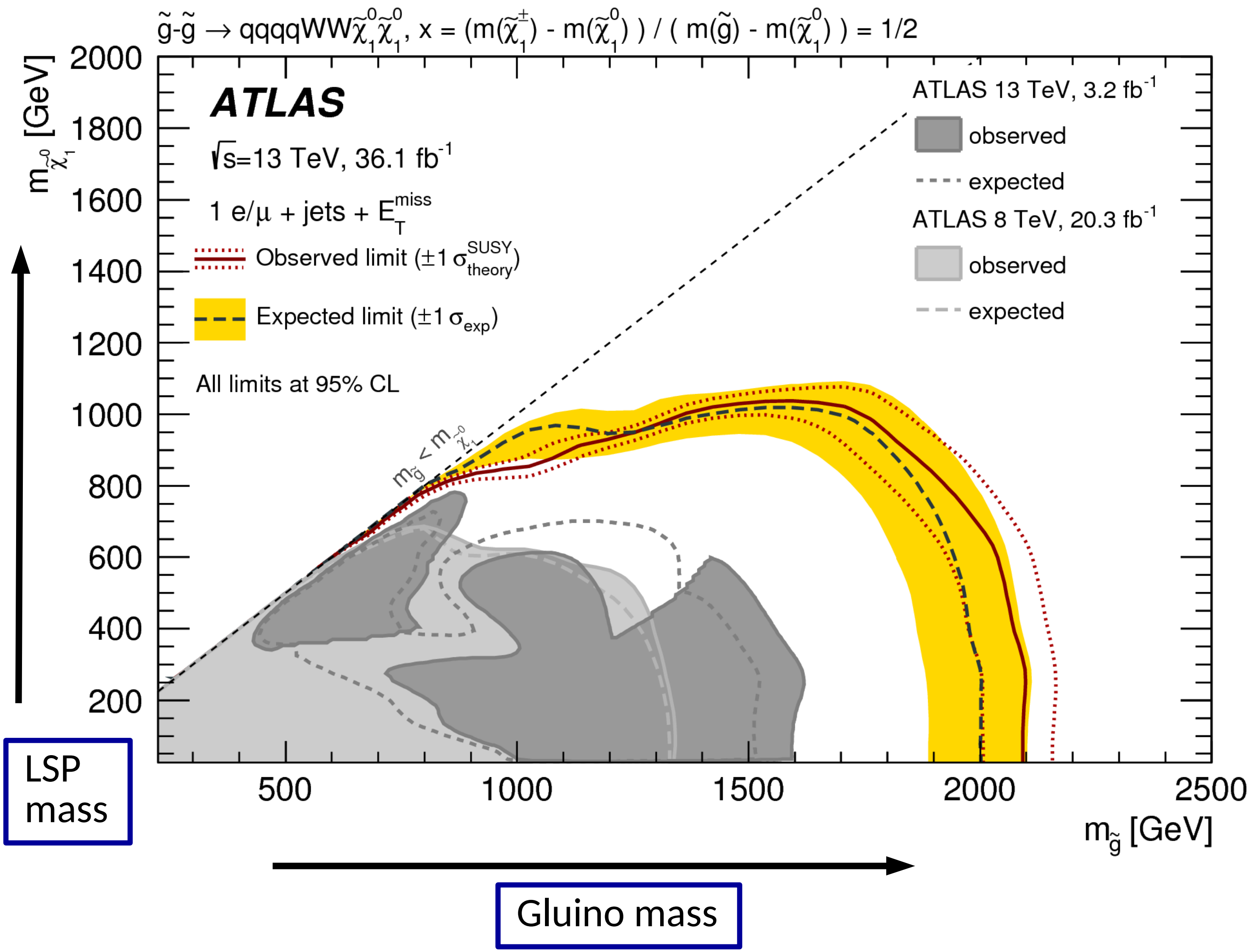


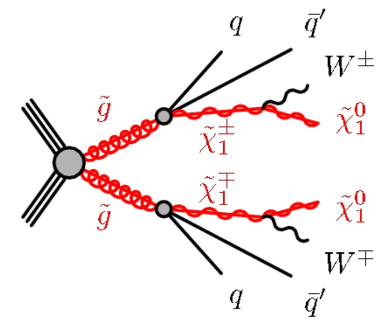


Exclusion limits up to 2.1 TeV on the gluino mass

Search for gluinos/squarks in final states with a lepton

[Phys. Rev. D 96 (2017) 112010]





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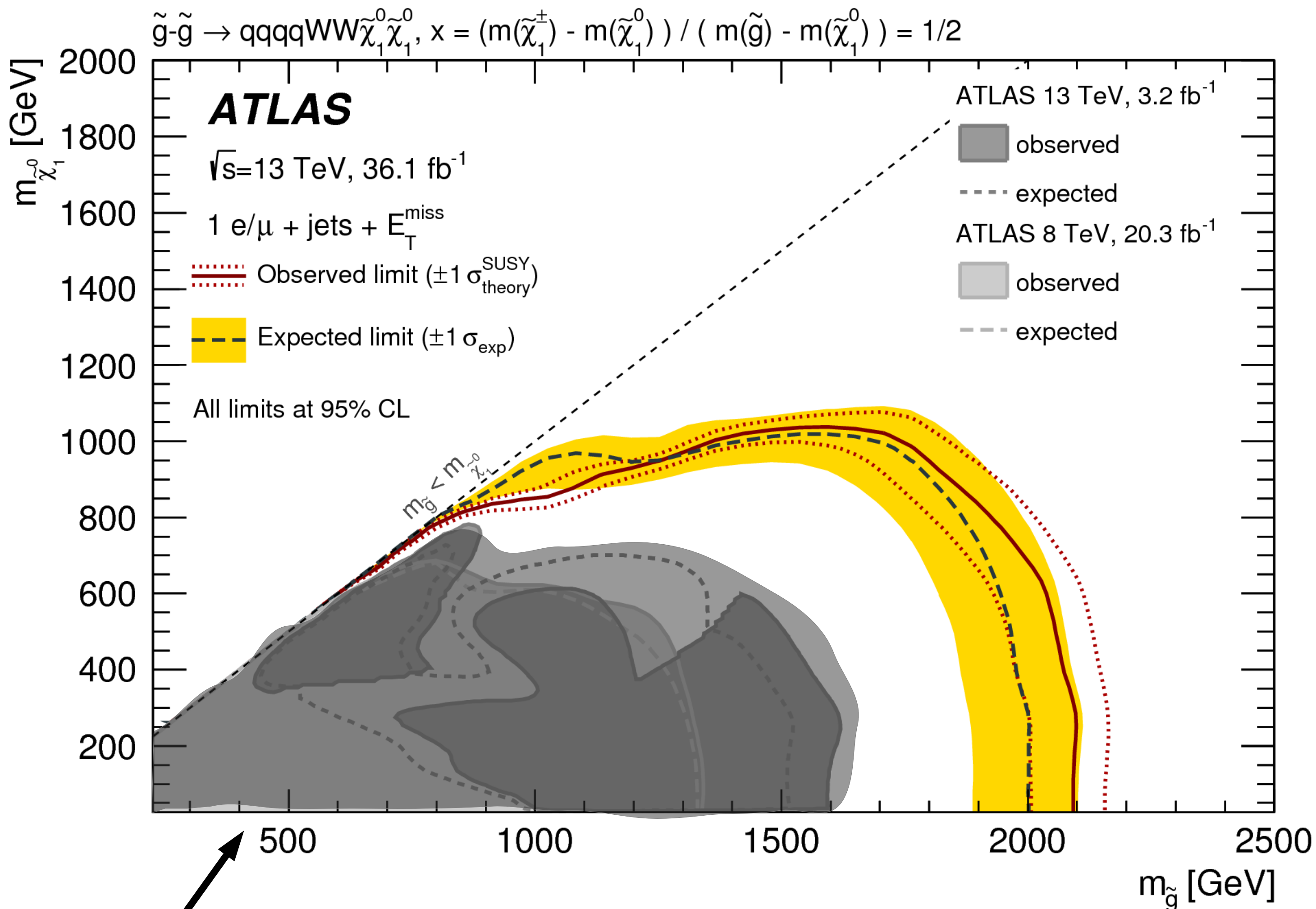
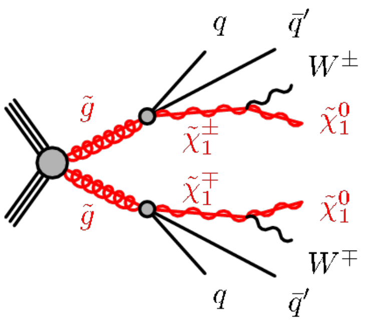


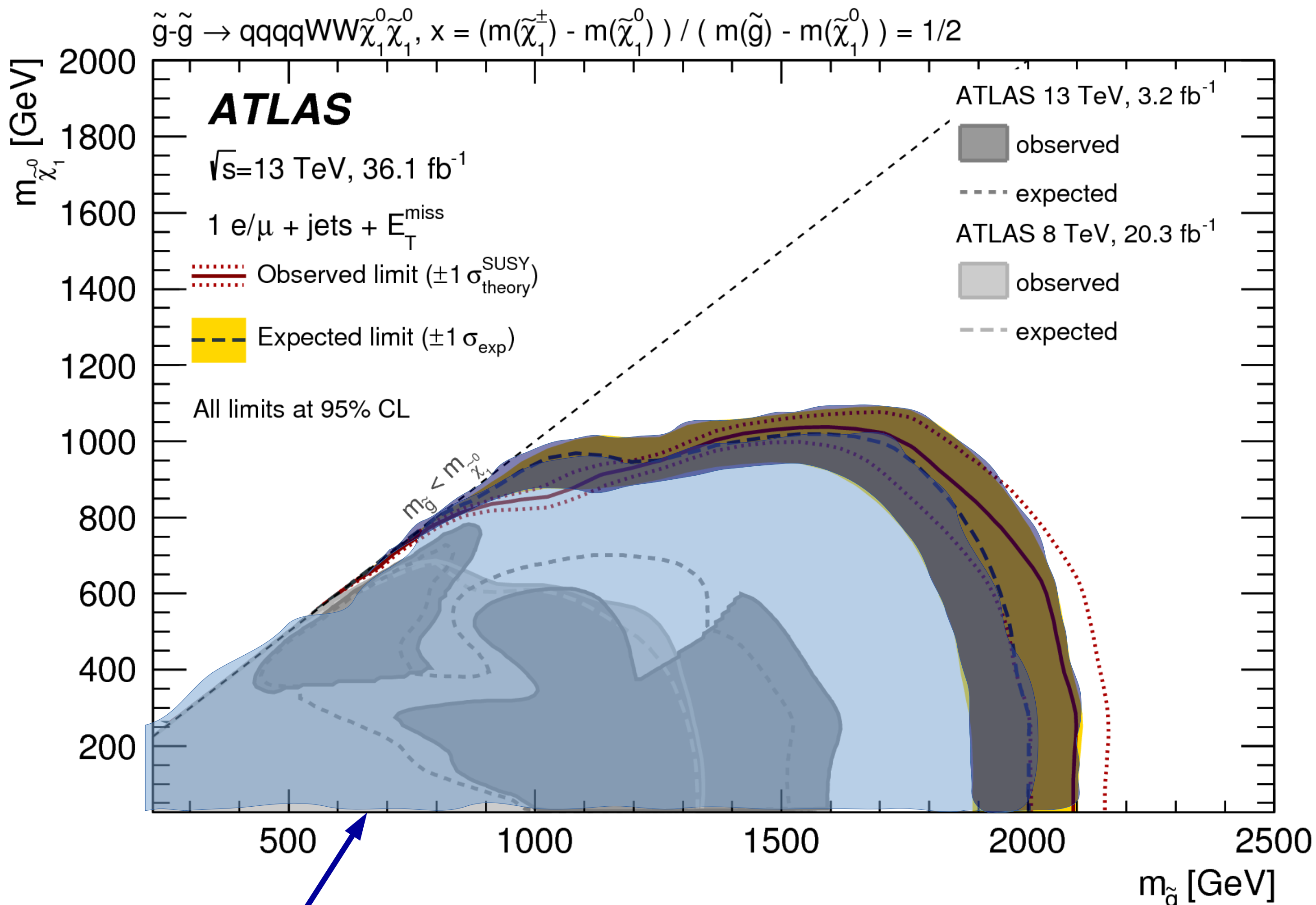


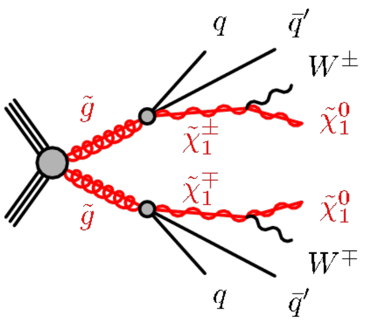
Exclusion limits up to 2.1 TeV on the gluino mass

Parameter space excluded by previous analyses.

Search for gluinos/squarks in final states with a lepton

[Phys. Rev. D 96 (2017) 112010]



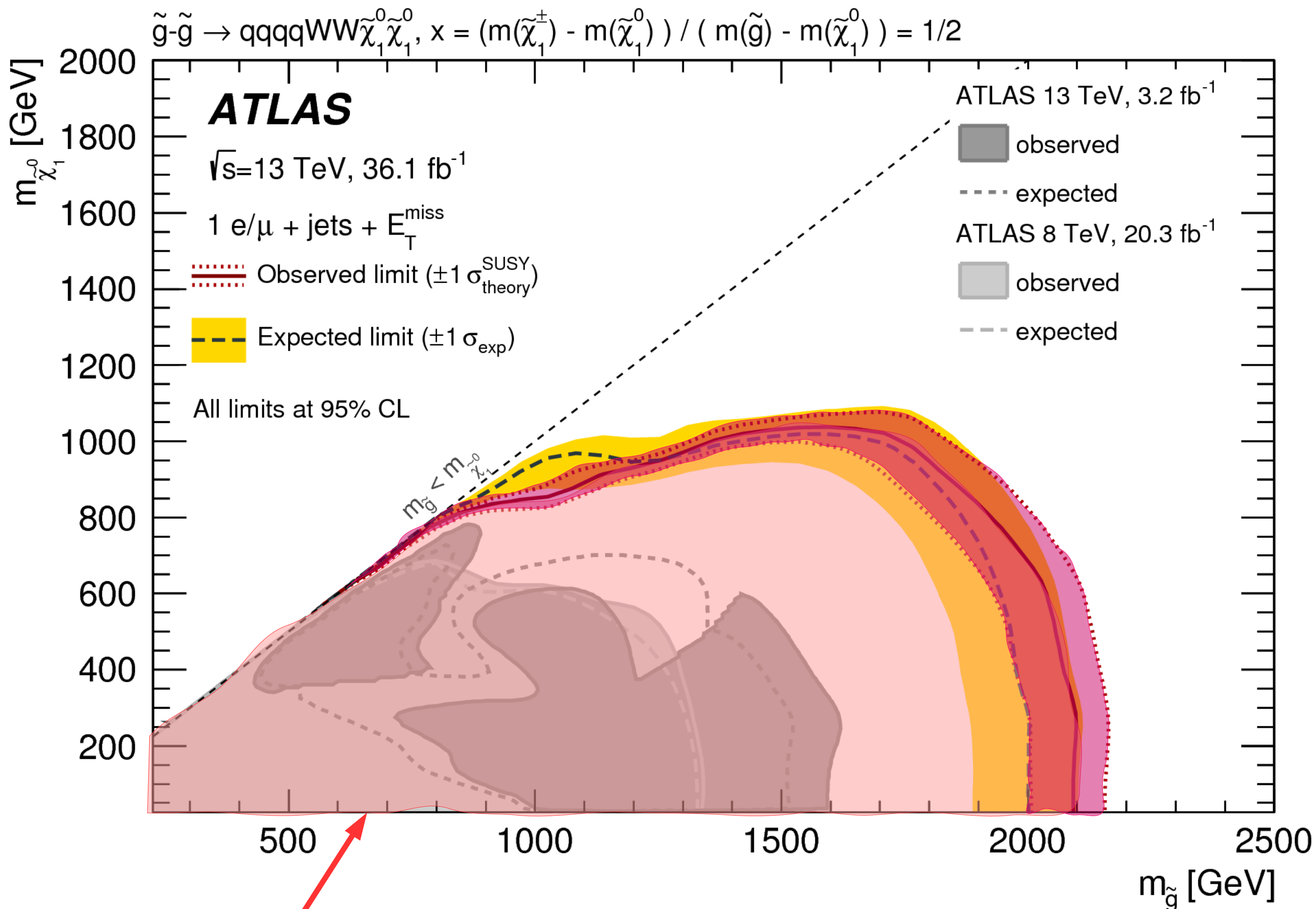


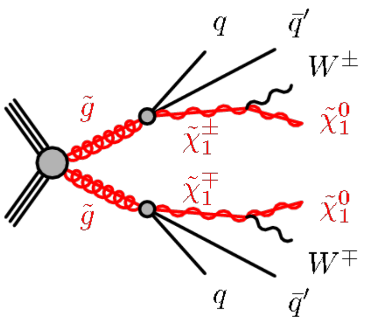
Exclusion limits up to 2.1 TeV on the gluino mass

Expected exclusion (plus uncertainties) of parameter space if SM realized.

Search for gluinos/squarks in final states with a lepton

[Phys. Rev. D 96 (2017) 112010]

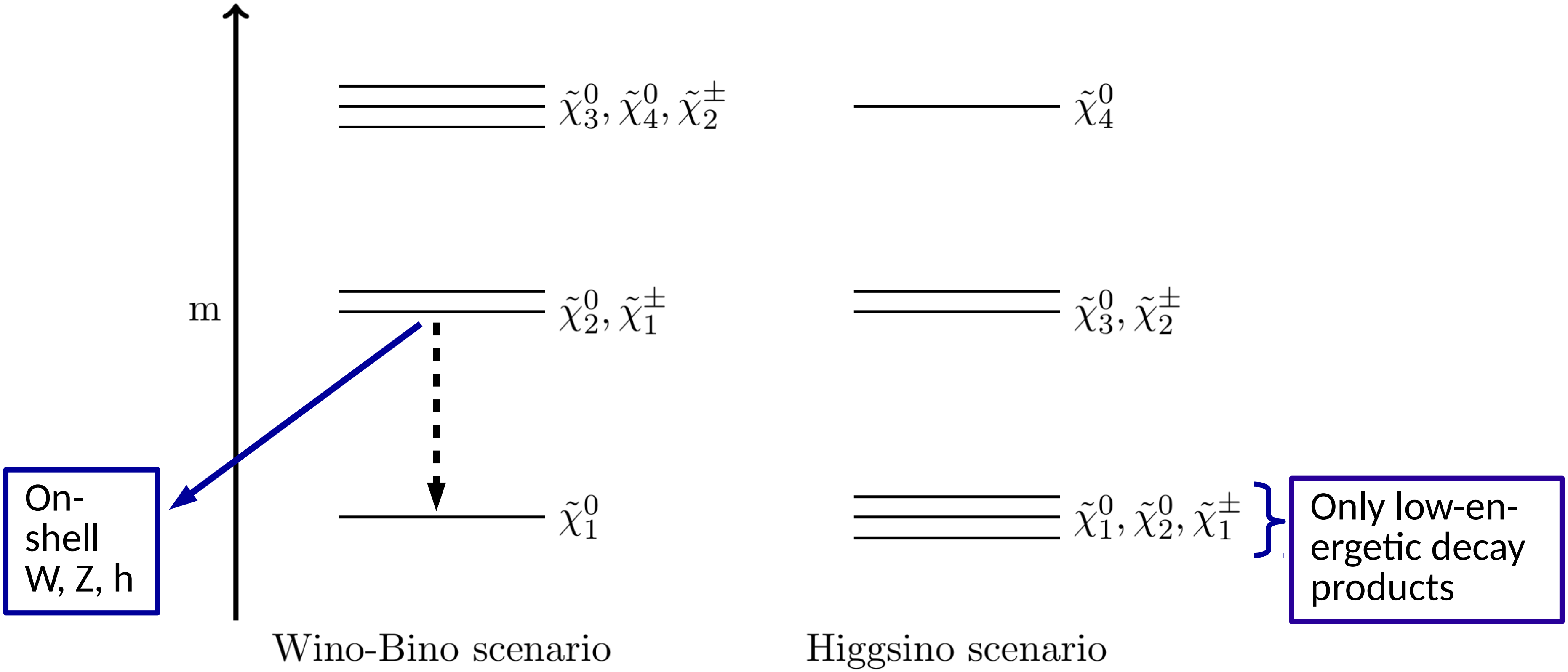




Exclusion limits up to 2.1 TeV on the gluino mass

Observed exclusion (plus uncertainties) of parameter space given the data.

Searches for charginos and neutralinos



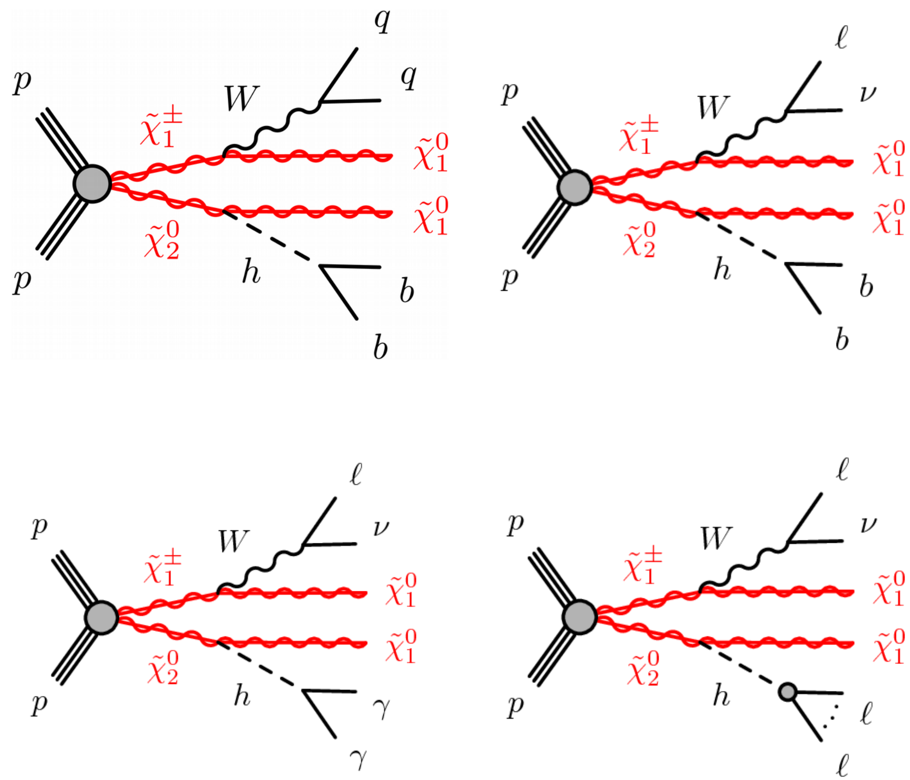
Depending on parameters in the SUSY model, mass difference between LSP and lightest charginos/next-to-lightest neutralinos sizeable (so that on-shell emission of W, Z, h possible), or very compressed mass spectrum.

Searches for neutralinos/charginos with decays to a Higgs

[Phys. Rev. D 100 (2019) 012006]

Often a Higgs boson is created in decays of neutralinos.

Discovering corresponding signatures would explicitly link Higgs bosons with supersymmetric particles.
Necessary for SUSY solving hierarchy problem!



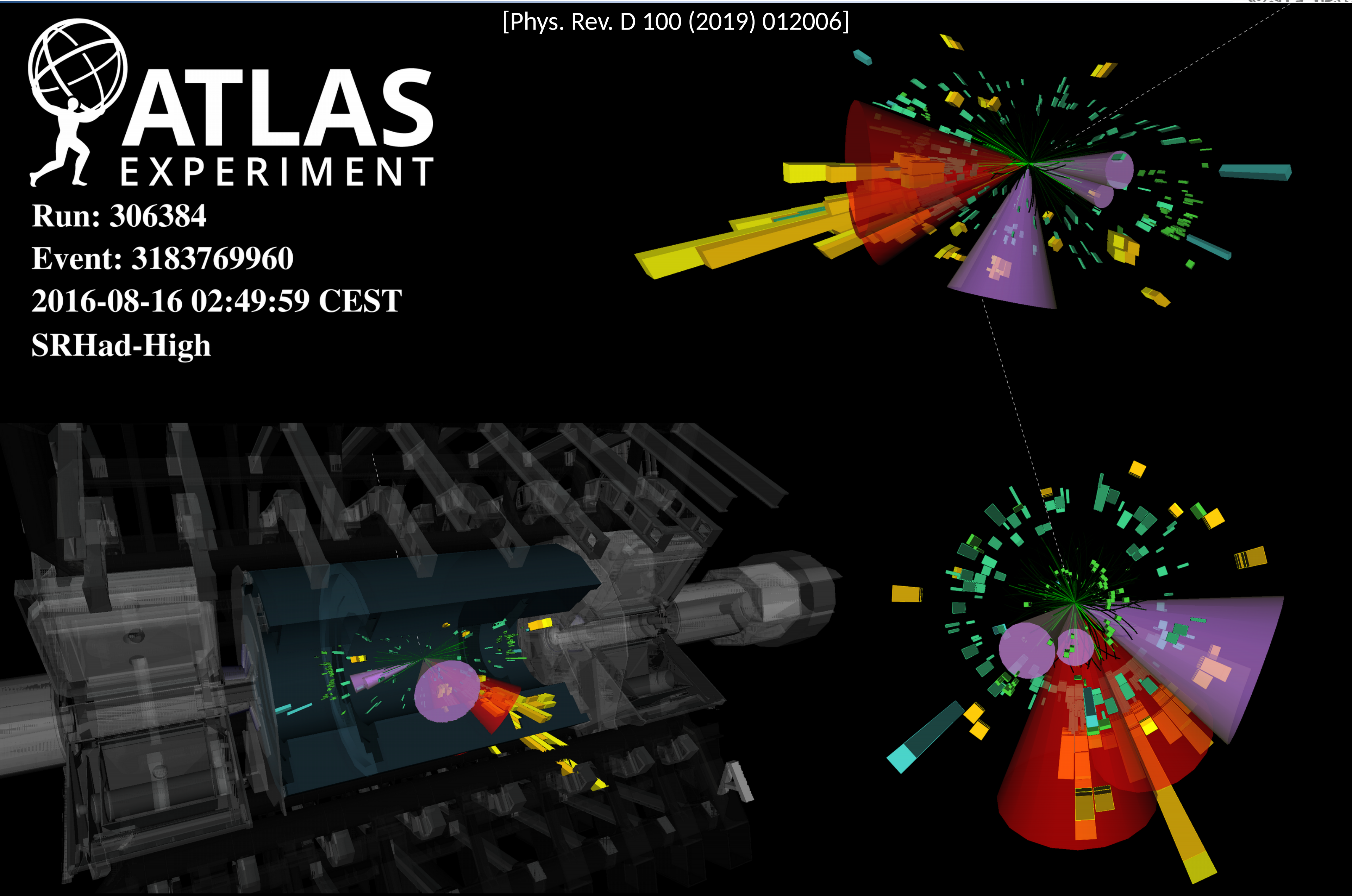
Different signatures depending on decay of Higgs:

- Hadronic (with $b\bar{b}$),
- 1 e/μ + $b\bar{b}$,
- Two same-sign leptons,
- 3 leptons,
- 1 e/μ + γγ

→ *different searches*

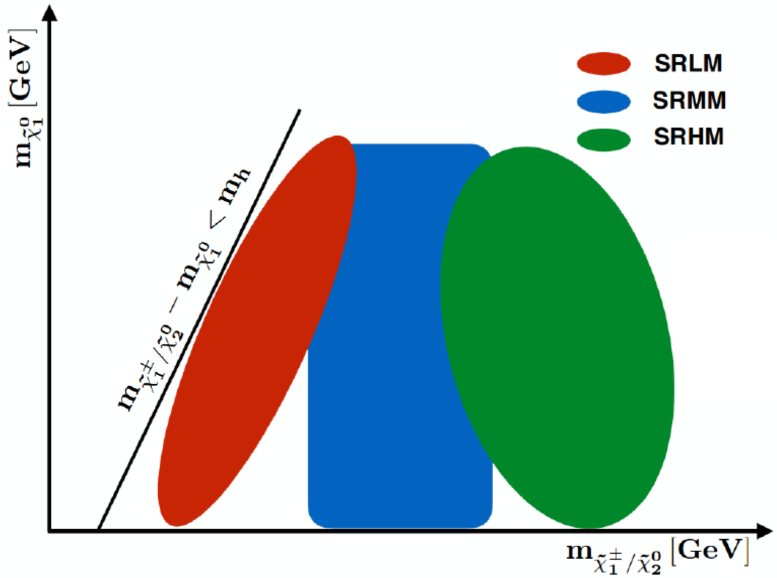
Event in a signal region of the fully hadronic search

[Phys. Rev. D 100 (2019) 012006]



1 lepton + 2 b-jets (139 fb^{-1})

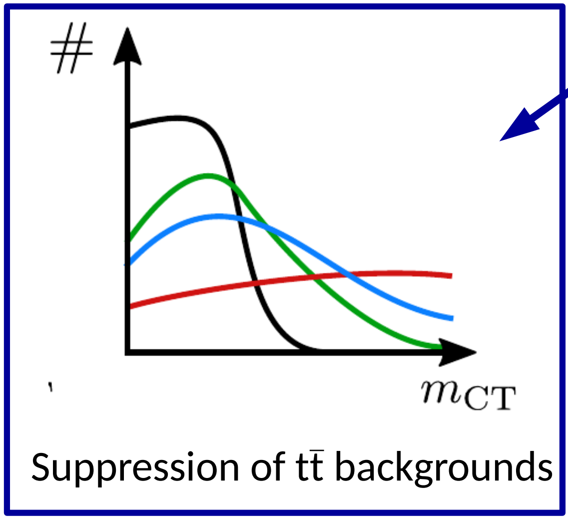
[arXiv:1909.09226, accepted by EPJ C]

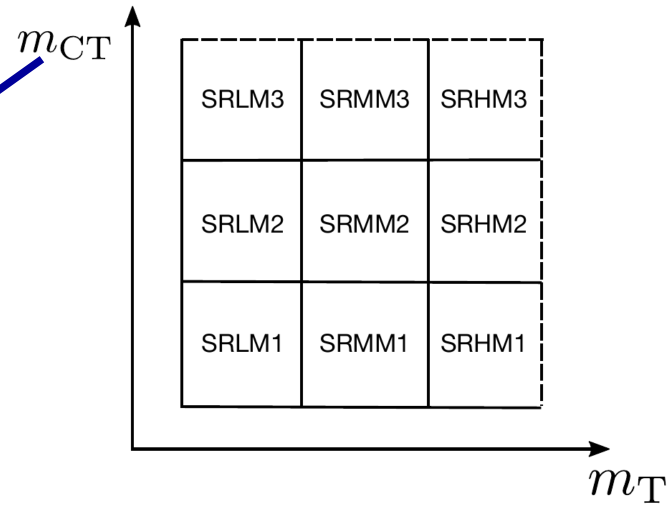


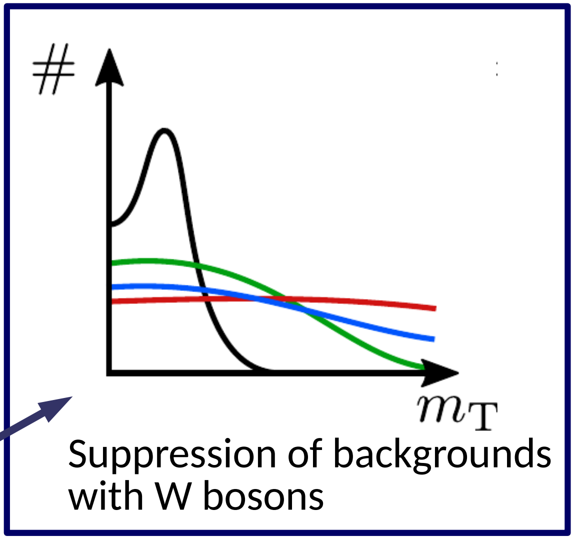
Define nine regions in the phase space with different kinematics due to different mass differences between charginos/next-to-lightest neutralino and LSP

→ *low mass*, *medium mass*, *high mass*

- Require invariant mass of two b-tagged jets to be close to Higgs mass.







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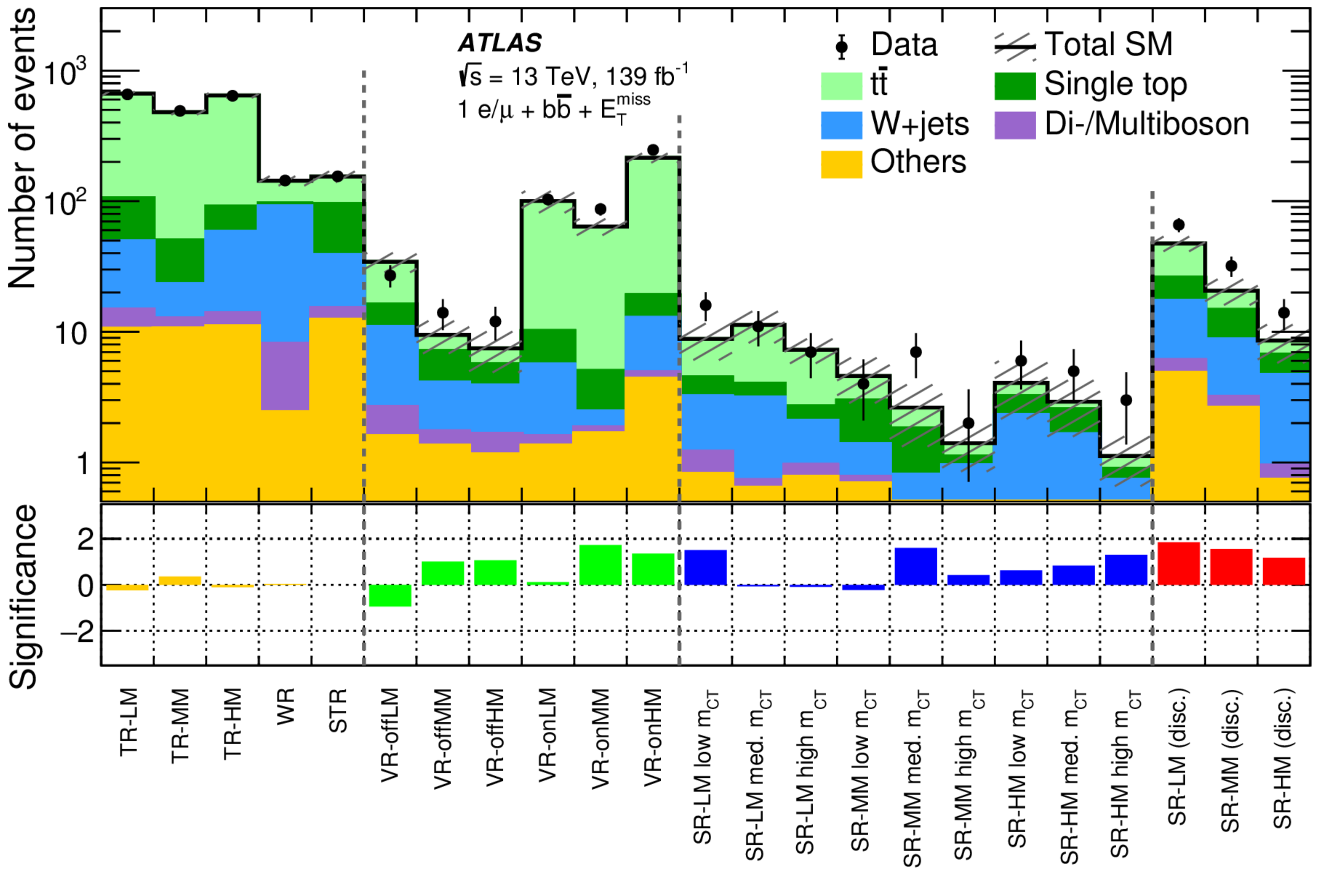
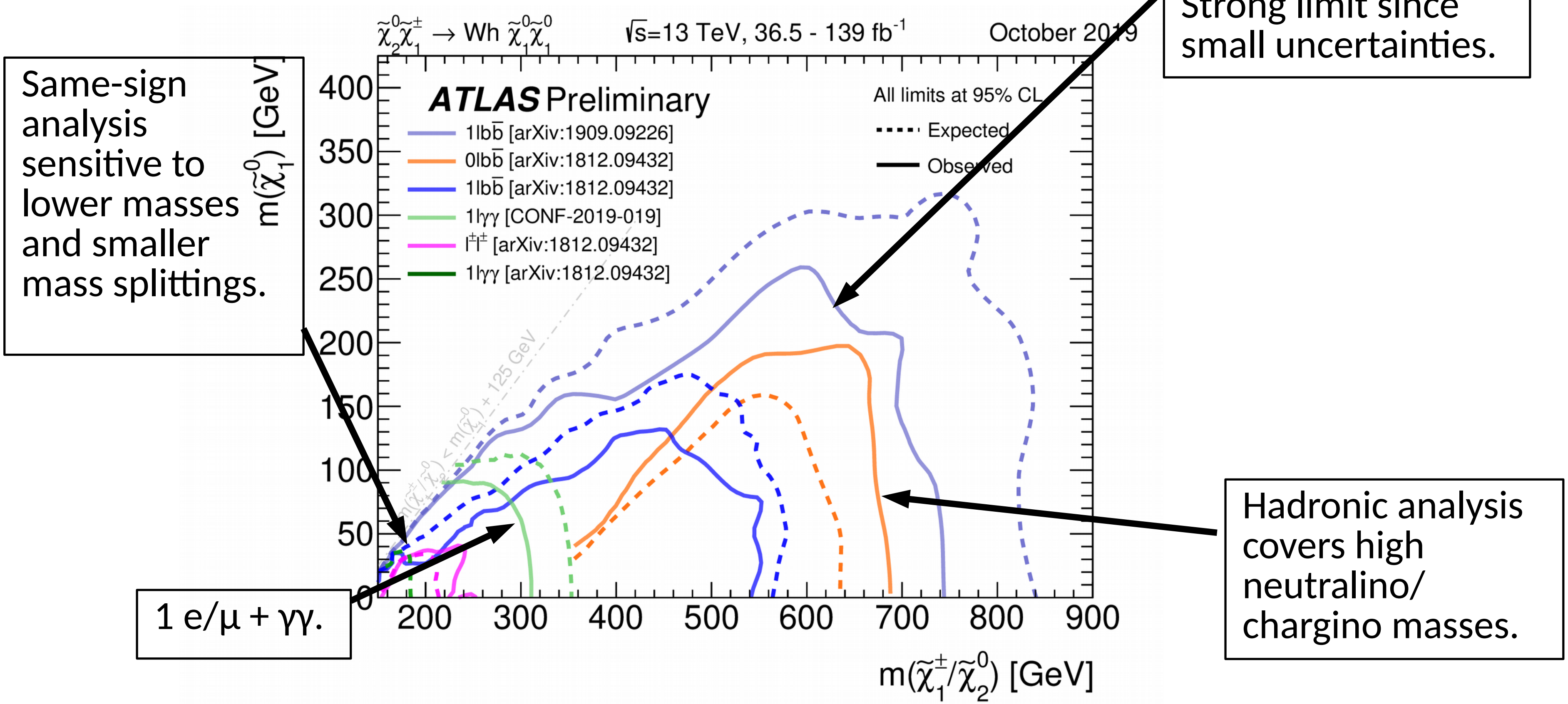


Slight overshoot in data, but consistent with background expectations.

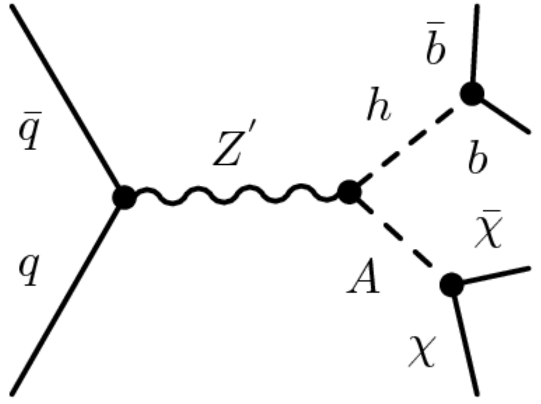
Searches for neutralinos with decays to a Higgs

[ATL-PHYS-PUB-2019-044]

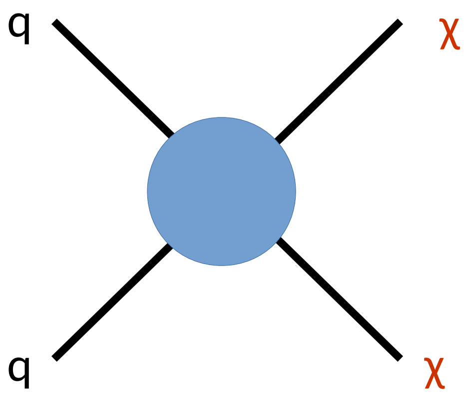
Nice complementarity of the different searches:



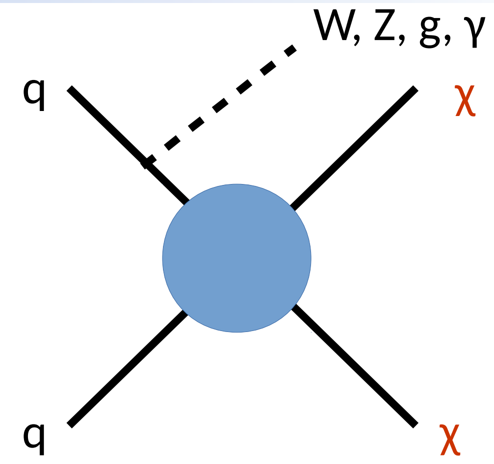
Search for Dark Matter in Association with a Higgs boson



Dark matter models at colliders



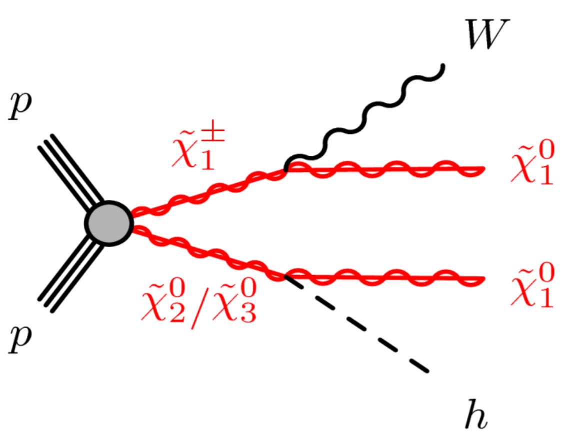
Dark matter particles invisible to LHC detectors → this signature cannot directly be detected



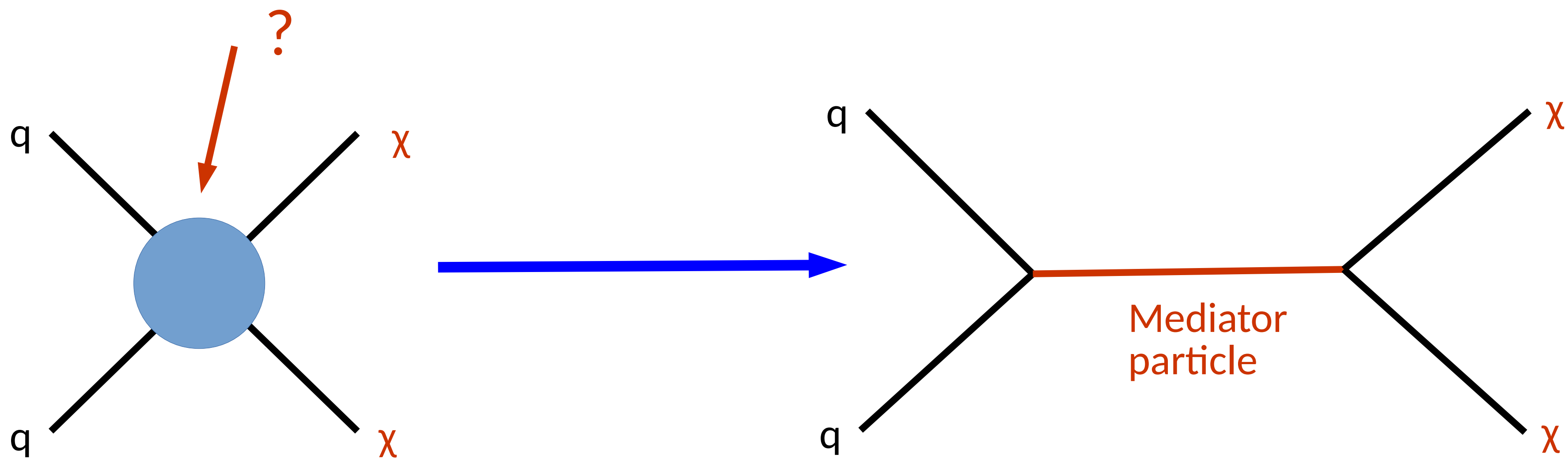
Initial state emission → recoils against dark matter particles.

Generic model good for sizable cross-sections, a priori no assumptions on specific model.

Or detect dark matter particles in decay of other new particles → specific models/extensions of the SM (like SUSY).

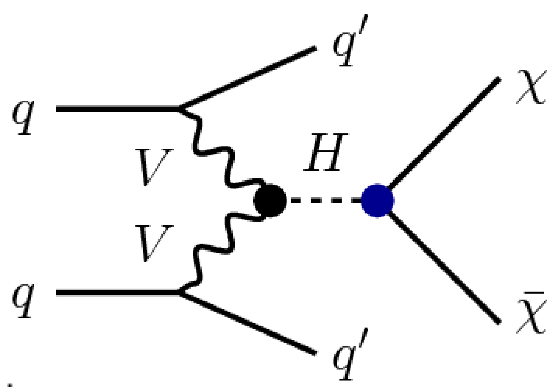


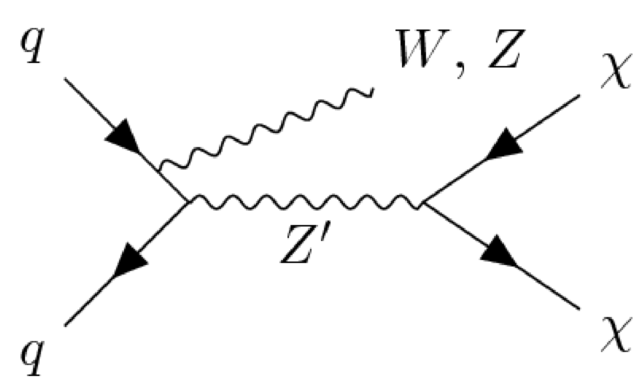
Dark matter models with mediators



Mediator particle can be SM particle (Z or H)

or a new particle – e.g. spin 1 or 0



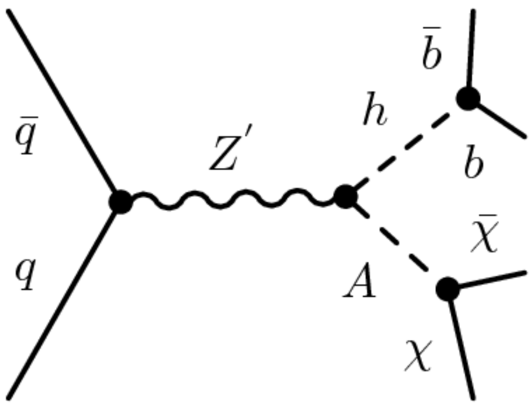


Search for a Higgs boson in association with Dark Matter

[ATLAS-CONF-2018-039]

Emission of a Higgs boson from the colliding partons Yukawa suppressed

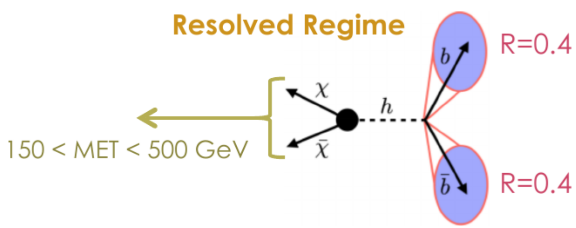
→ Detection of DM in association with Higgs boson in final state would directly probe coupling of DM sector with Higgs sector

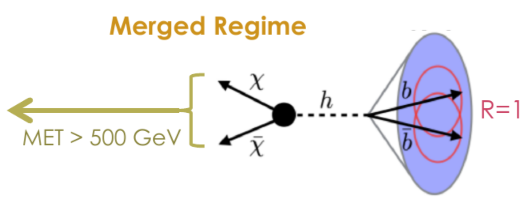


→ Search for Higgs boson decaying to $b\bar{b} + E_T^{miss}$ in a final state without leptons.

Two cases:

- Good separation between b-tagged jets, so that they can be resolved.
- b-tagged jets merge into a large jet → mass of large jet corresponds to Higgs boson mass, the two b-tagged jets are identified from tracks composing the large jet.

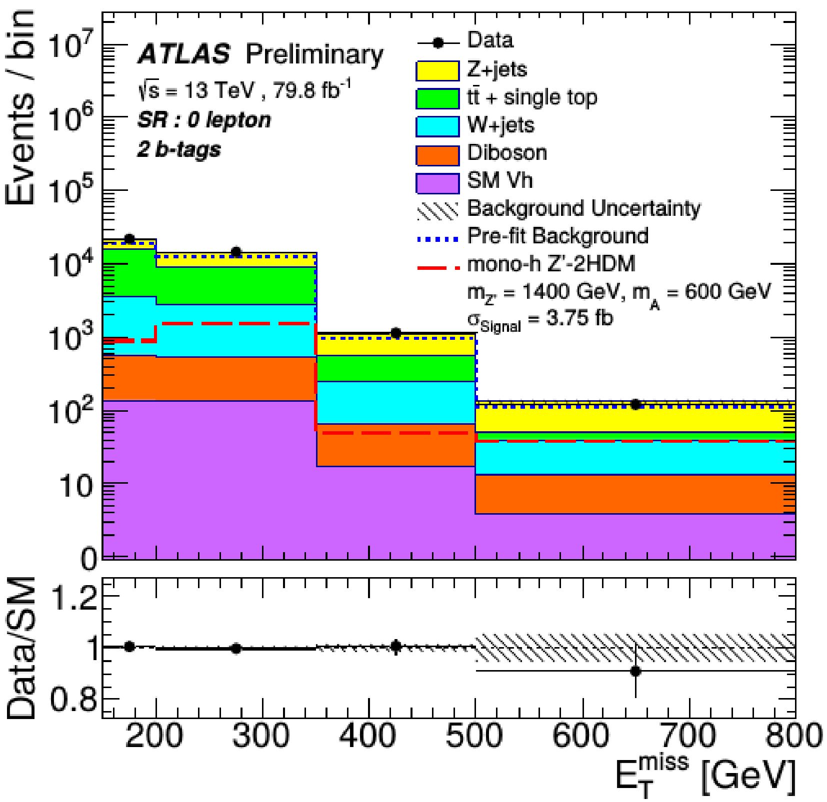


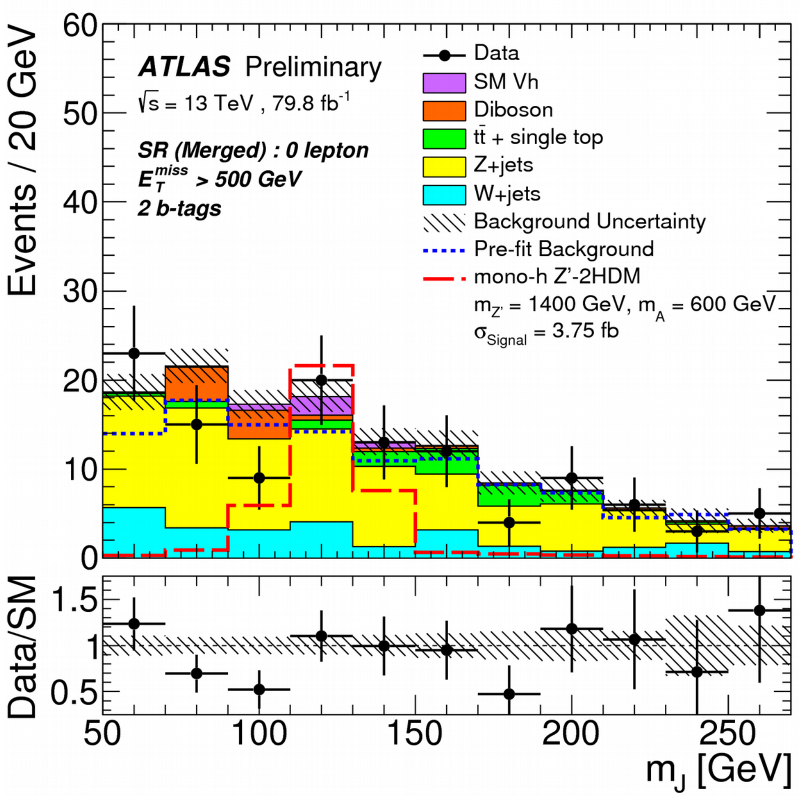


Search for a Higgs boson in association with Dark Matter

[ATLAS-CONF-2018-039]

Exploiting E_T^{miss} distribution and invariant mass of the two b-tagged jets.

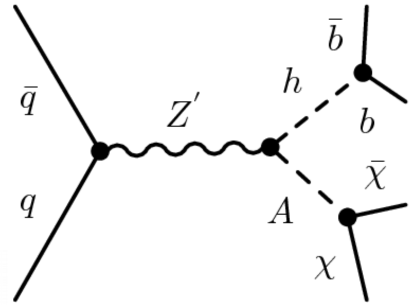


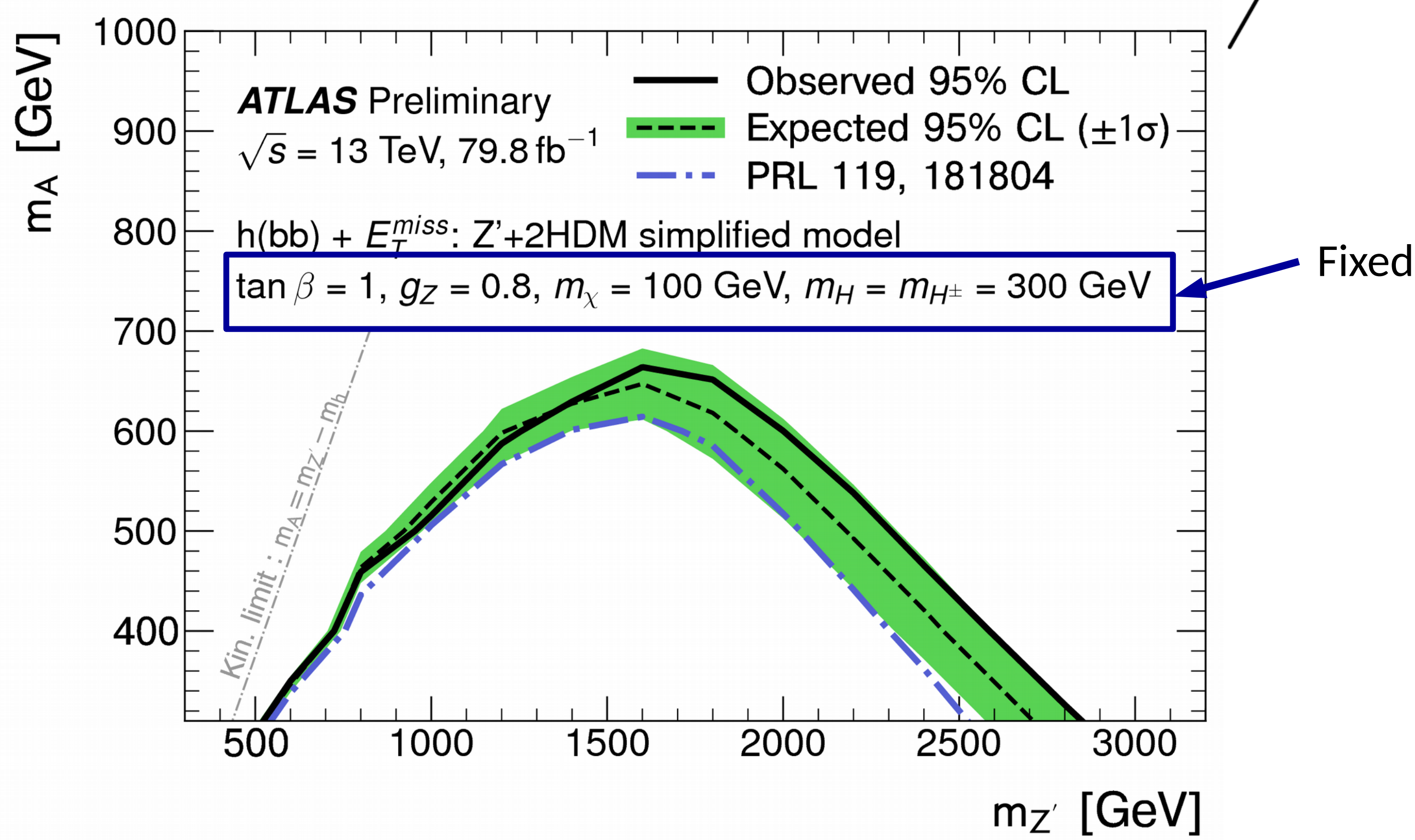


Search for a Higgs boson in association with Dark Matter

[ATLAS-CONF-2018-039]

Limits set on mass of mediator (Z') and Higgs boson A. Dark matter mass fixed, as well as coupling strength and mass of other Higgs bosons.



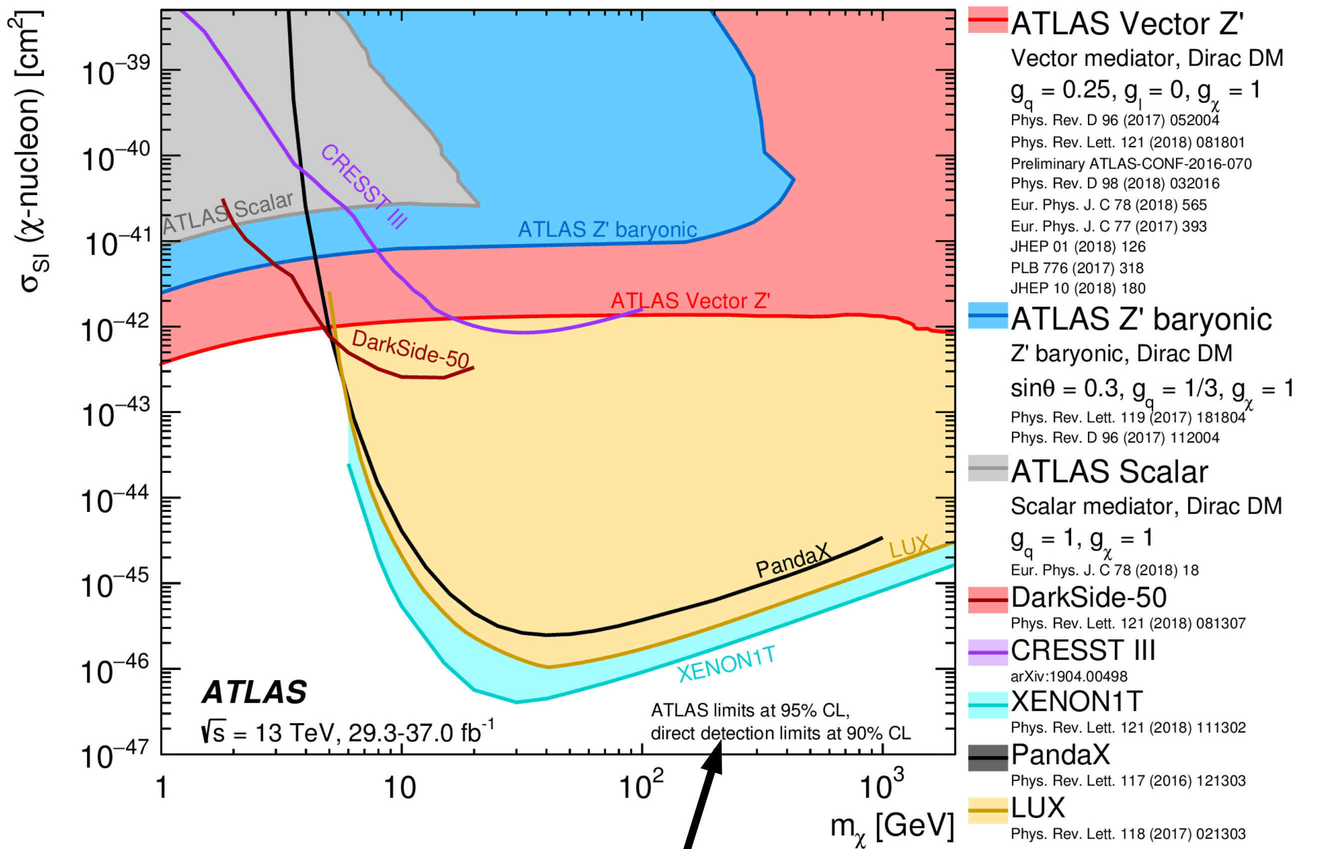


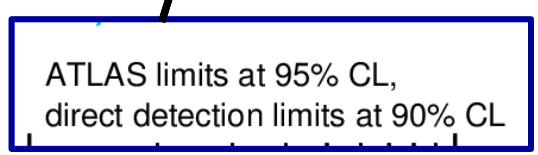
Comparison to non-collider dark matter searches

[JHEP 05 (2019) 142]

For specific models and parameter assumptions comparison between collider and direct detection experiments possible

→ *Collider experiments cover dark matter masses down to 1 GeV in these models*





Comparison only valid for a very specific model with specific parameters!

Comparison to non-collider dark matter searches

[JHEP 05 (2019) 142]

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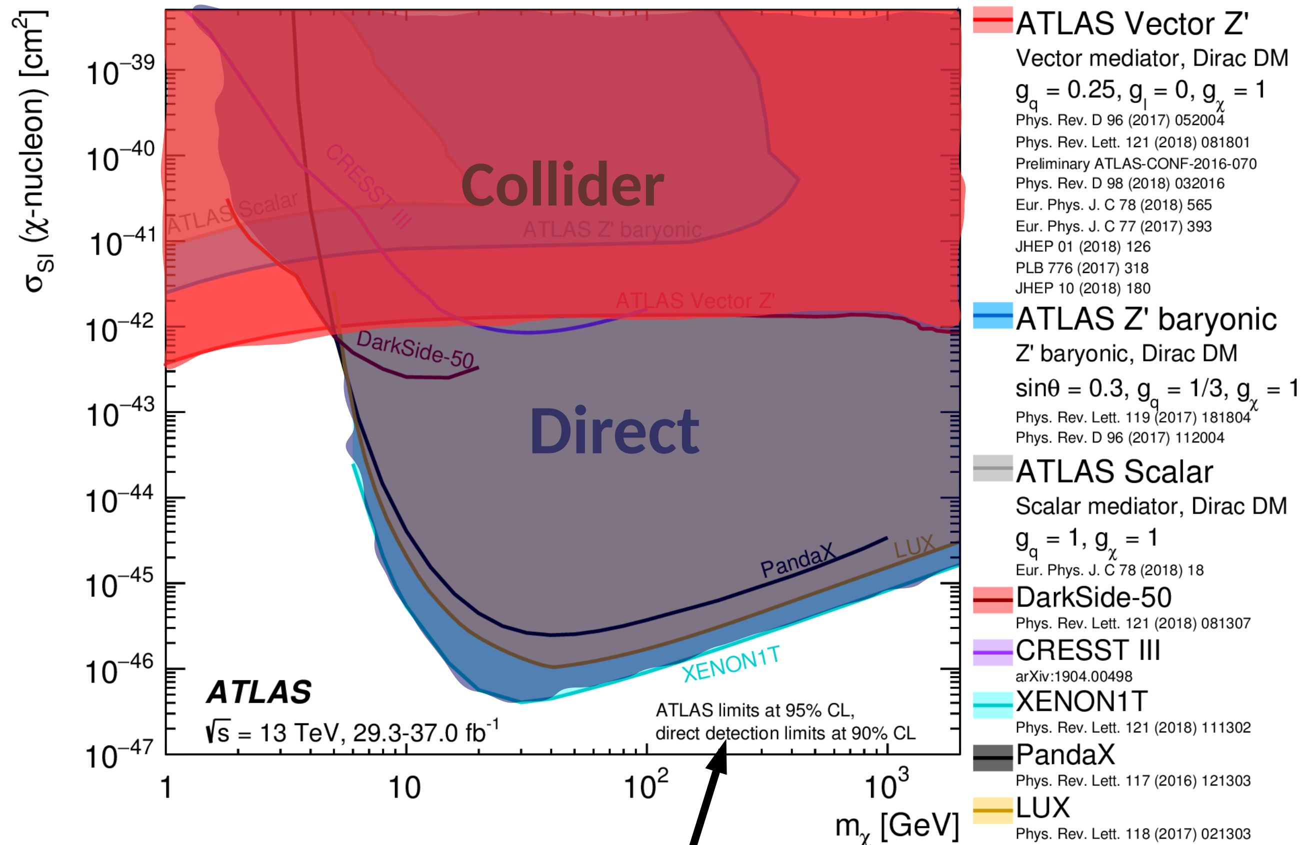

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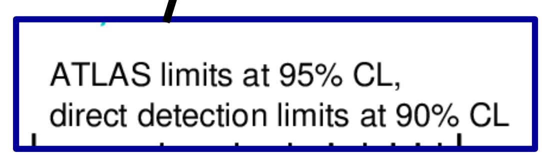


Searches for further Higgs bosons

More Higgs bosons?

Many extensions of the Standard Model predict more than one Higgs boson:

- E.g. Two-Higgs-Doublet models (2HDM) predict 5 Higgs bosons: two neutral CP even (h, H), one CP odd (A) and two charged Higgs bosons (H^{+-}).

  → *SUSY is an example for a 2HDM.*

Search possibilities?

- Reinterpret precision measurements of the Higgs boson.
- Direct searches for additional Higgs bosons.

Measurements of Higgs couplings & reinterpretation

[Phys. Rev. D 101, 012002 (2020)]

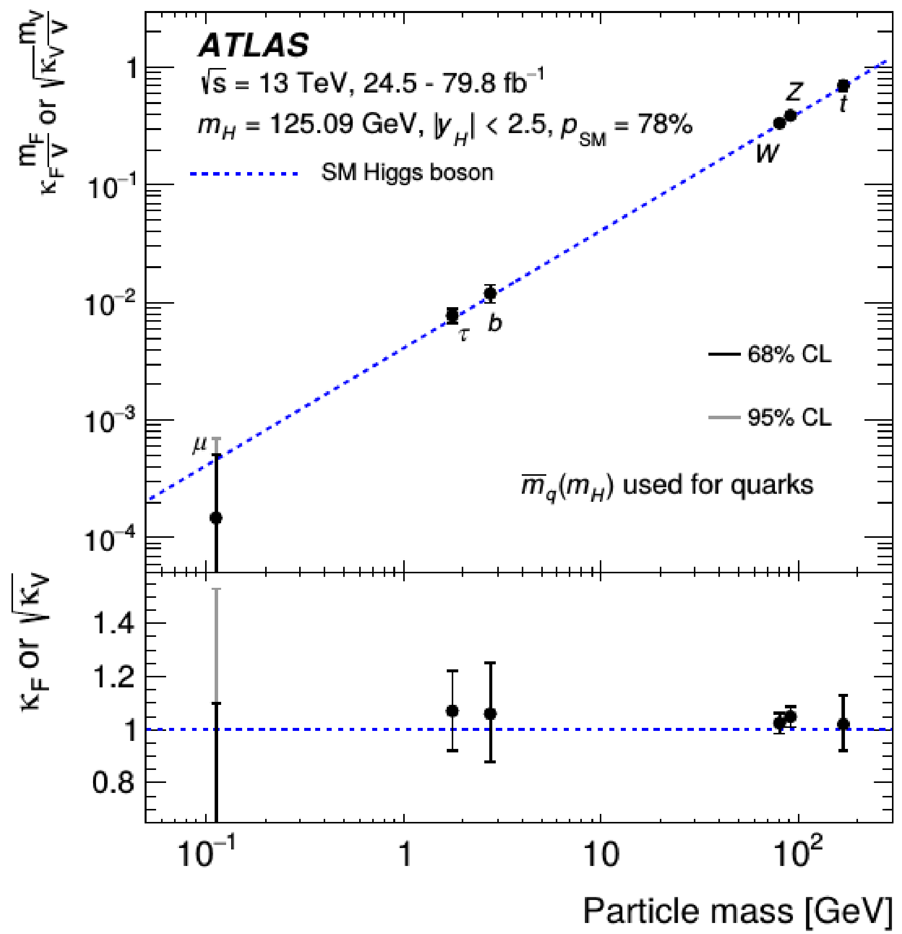
Since discovery of Higgs bosons precise measurements of cross sections, decay widths,…

→ *Possible to search for discrepancies between theoretical predictions for the SM and measurements.*

Deviations in cross sections and decay widths can be parametrized in the κ-framework

$$(\sigma \cdot \mathrm{BR})(i \to h \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_h^{SM} \kappa_h^2}$$

→ κ's at 1 if at SM value



Measurements of Higgs couplings & reinterpretation

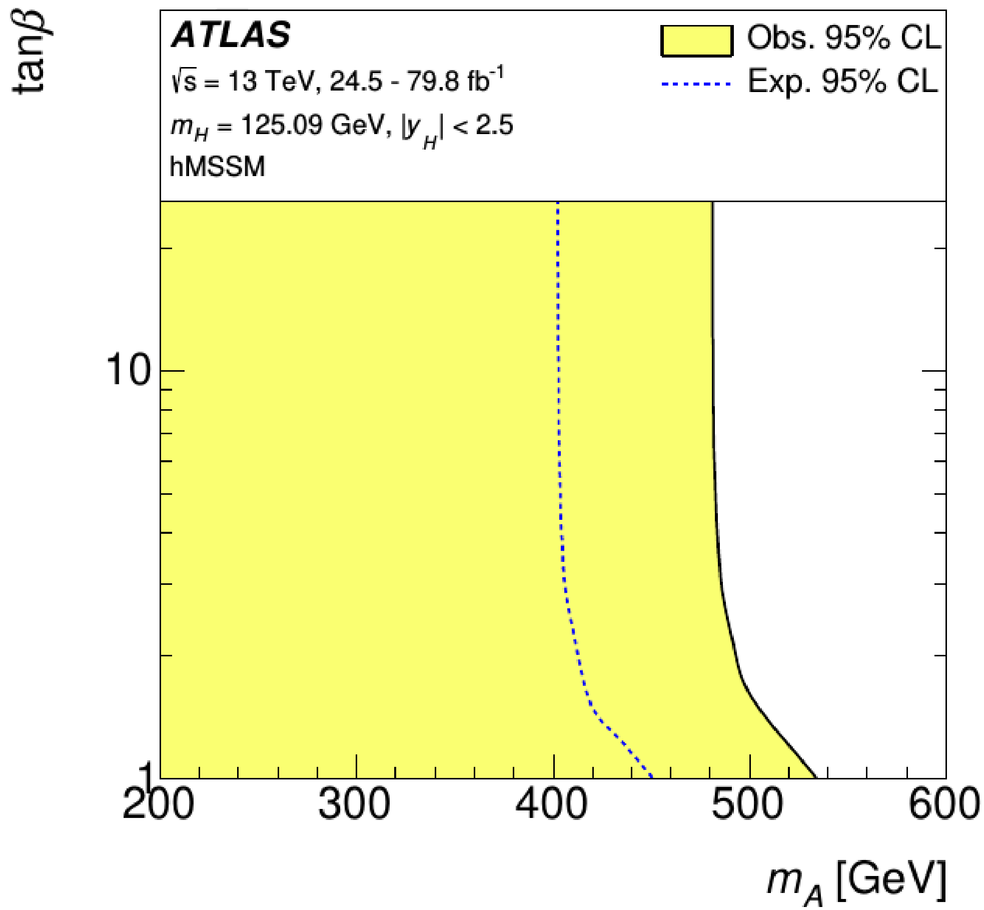
[Phys. Rev. D 101, 012002 (2020)]

Parameters in the κ-framework can be re-parametrized assuming an extension of the SM.

→ *E.g. hMSSM, which is a simplification of the MSSM, where only the Higgs sector is relevant, all other parameters are assumed to decouple kinematically.*

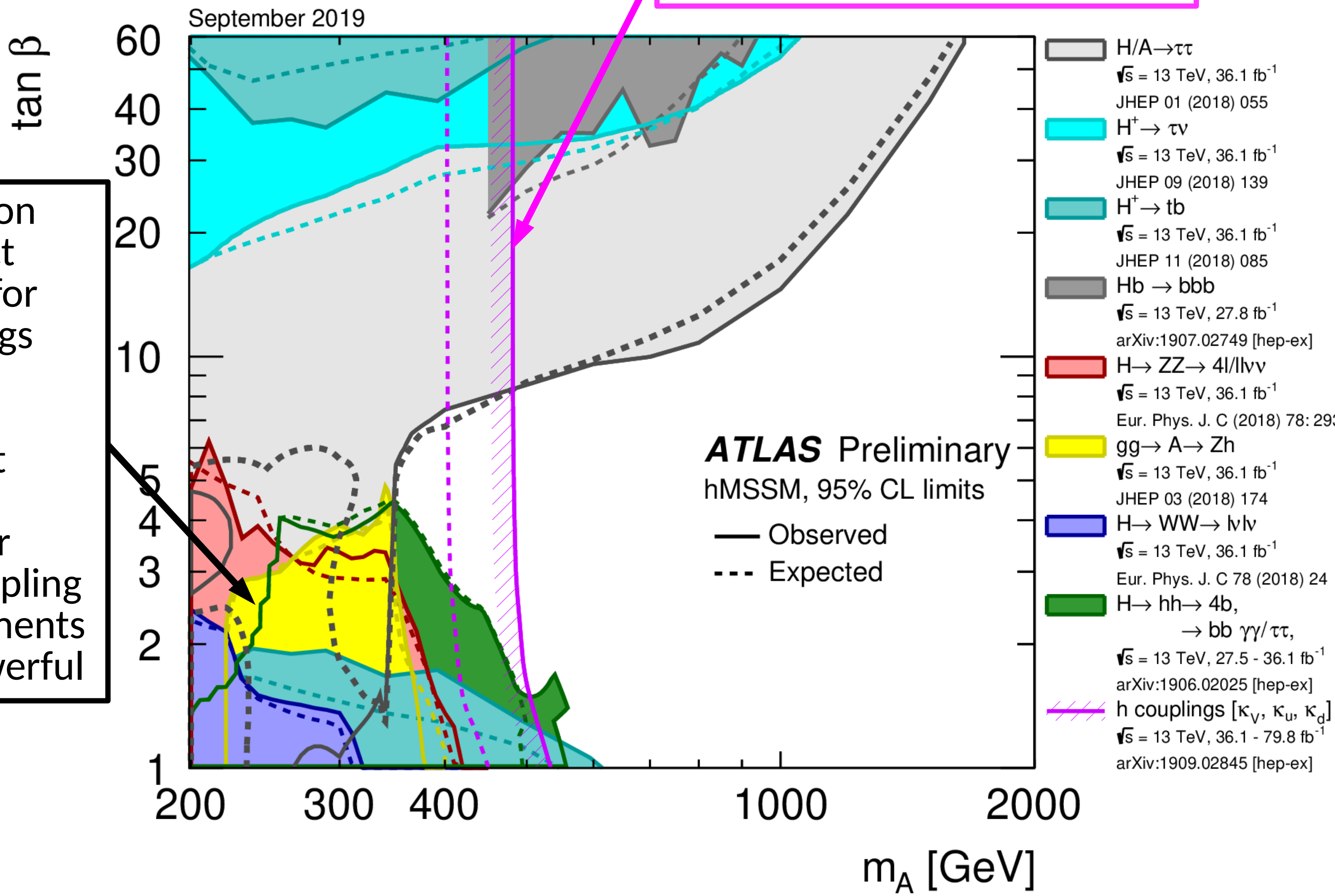
→ *Relevant parameters at tree level m_A and tanβ*

→ *Precision measurements translated into constraints on the hMSSM.*



Constraints in hMSSM

Reinterpretation of coupling measurements



Comparison with direct searches for heavy Higgs bosons

→ in most parts of parameter space coupling measurements more powerful

[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-034/fig_01.png]

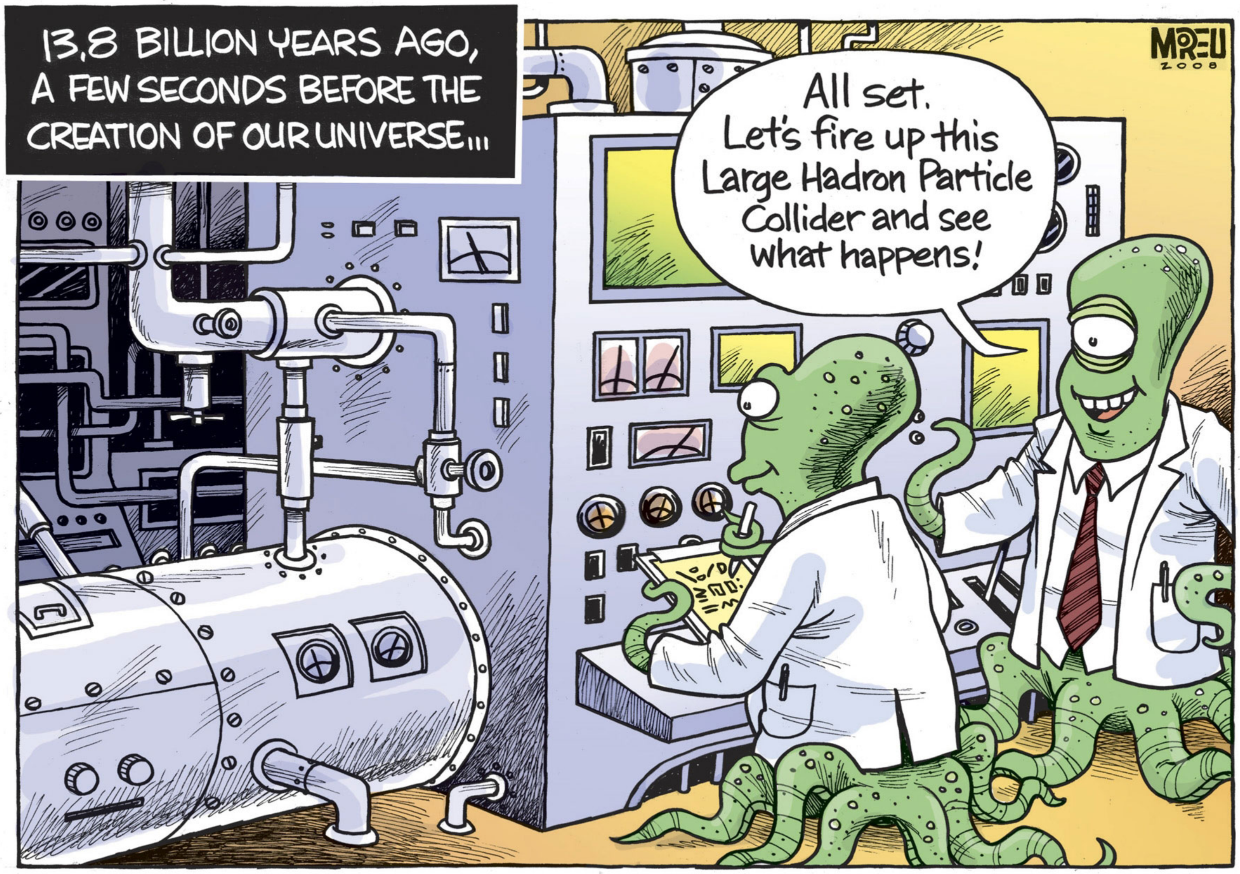
Summary

Many open questions in the Standard Model directly or indirectly linked with the Higgs boson:

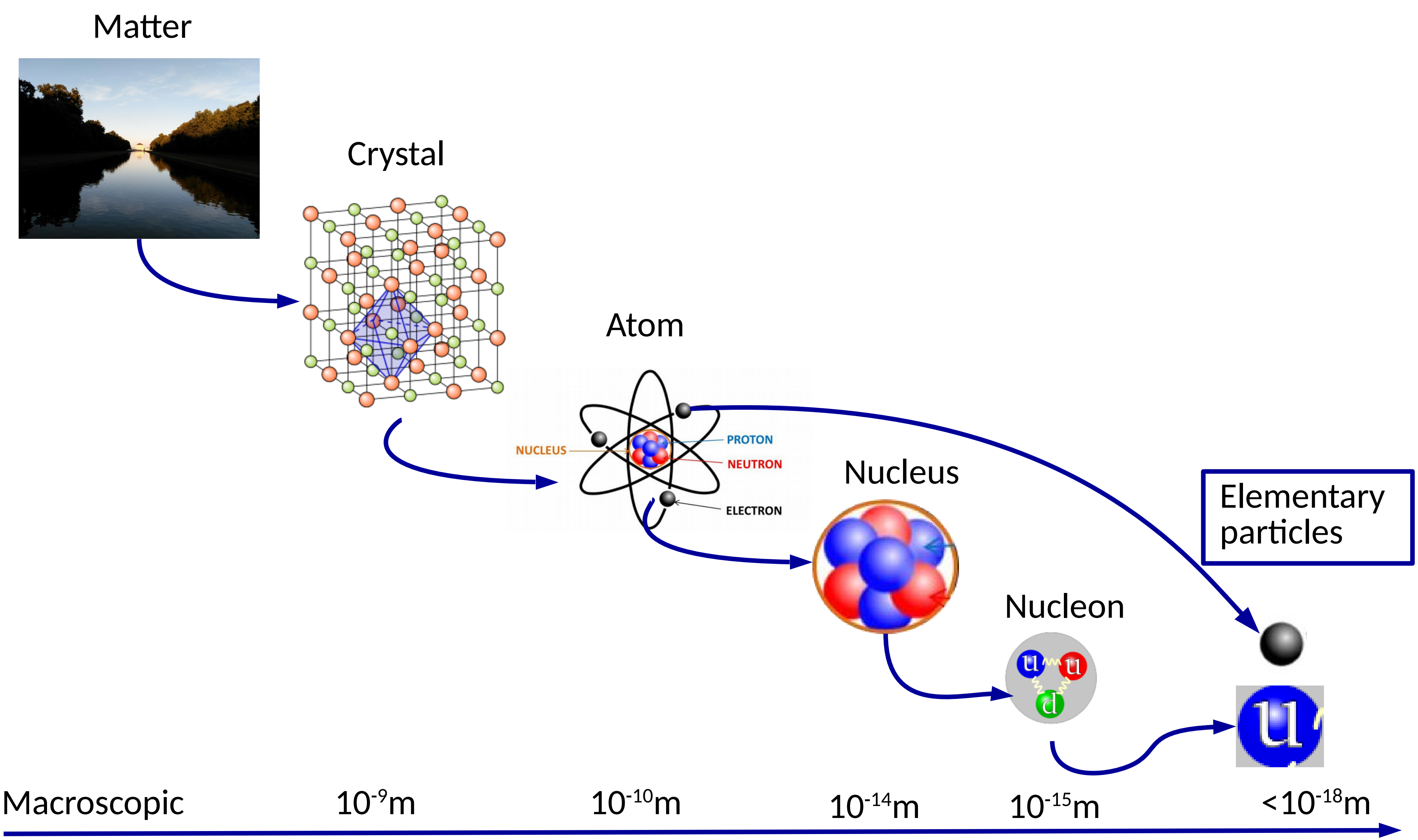
- Why is the mass of the Higgs at the value it is?
- Is there a link between Dark Matter and the Higgs boson?
- Are there more scalar particles?

Comprehensive search program at the LHC
→ Supersymmetric particles, Dark Matter particles, other extensions of the SM.
→ Nothing found yet, but promising avenue for the future (colliders)!

Backup


13,8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
MORELI 2008
All set. Let's fire up this Large Hadron Particle Collider and see what happens!

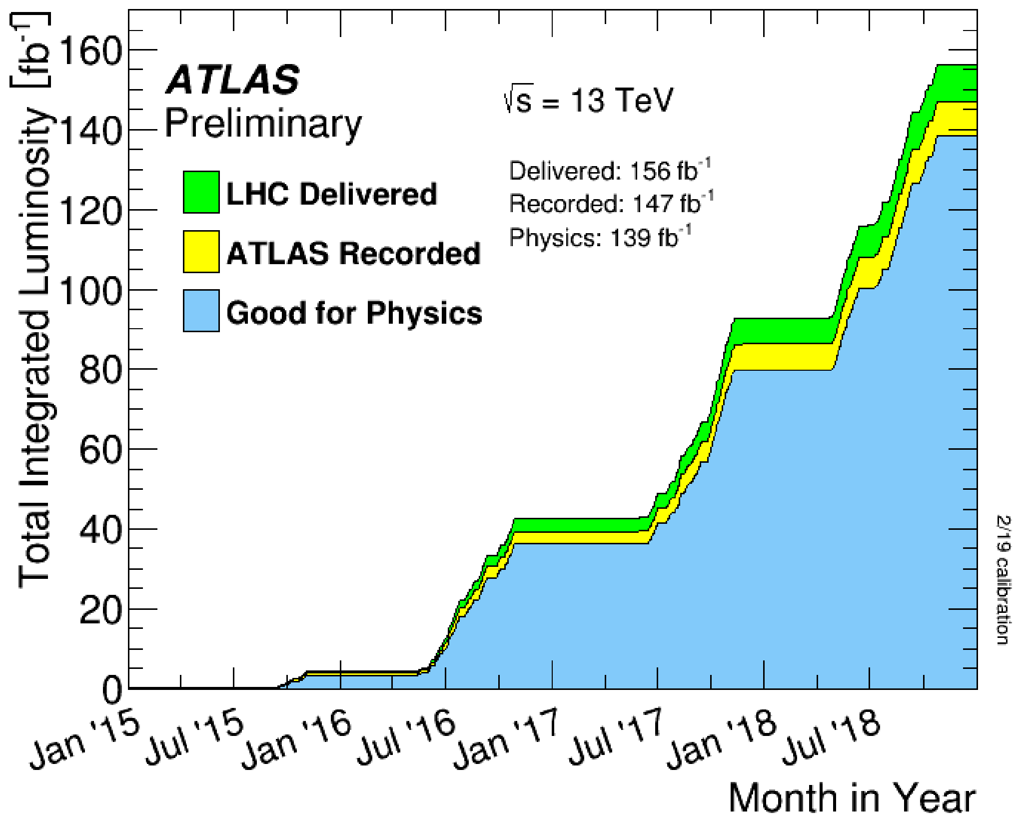
Scales


Matter
Crystal
Atom
NUCLEUS
PROTON
NEUTRON
ELECTRON
Nucleus
Nucleon
u
u
d
Elementary particles
u
Macroscopic
10^-9m
10^-10m
10^-14m
10^-15m
<10^-18m

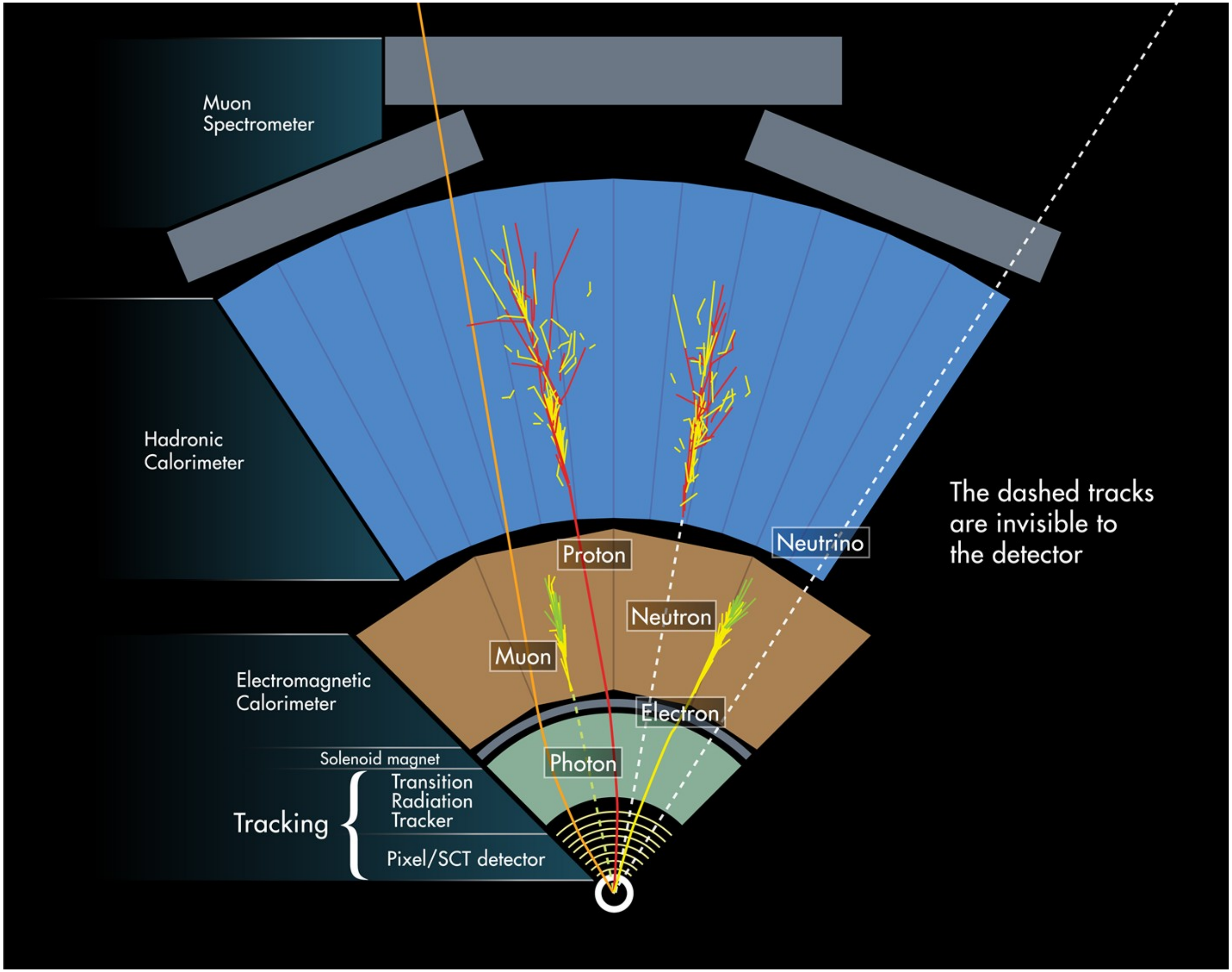
Excellent performance of LHC and detectors

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2]

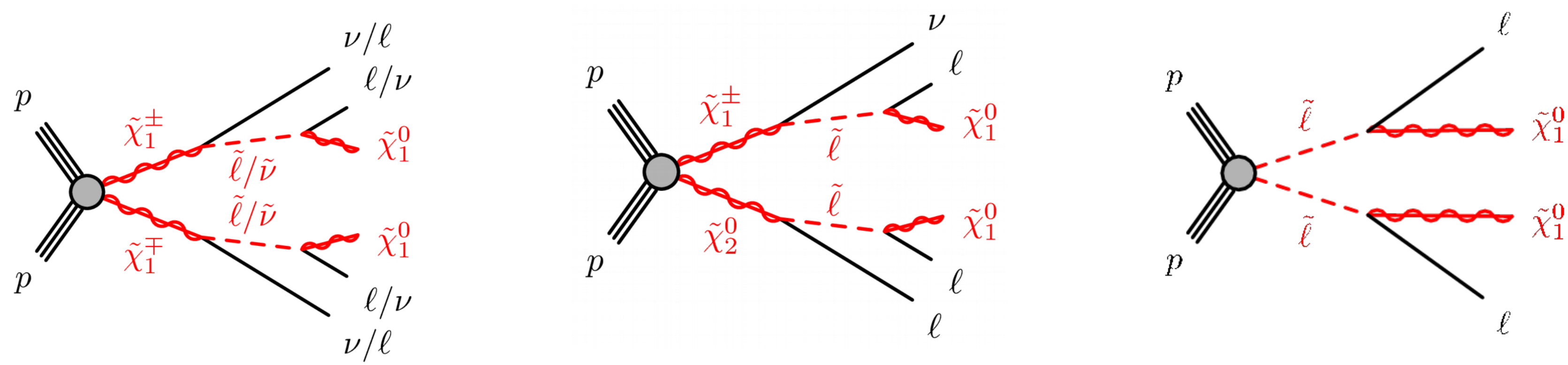
- 156 fb^{-1} proton-proton data delivered by the LHC in Run-2 (2015 -2018).
- Because of inefficiencies 147 fb^{-1} recorded.
- Need to require **extremely high quality** of data - about 139 fb^{-1} available for analyses.



Particle identification



Focus on chargino/neutralino production - possible decay modes



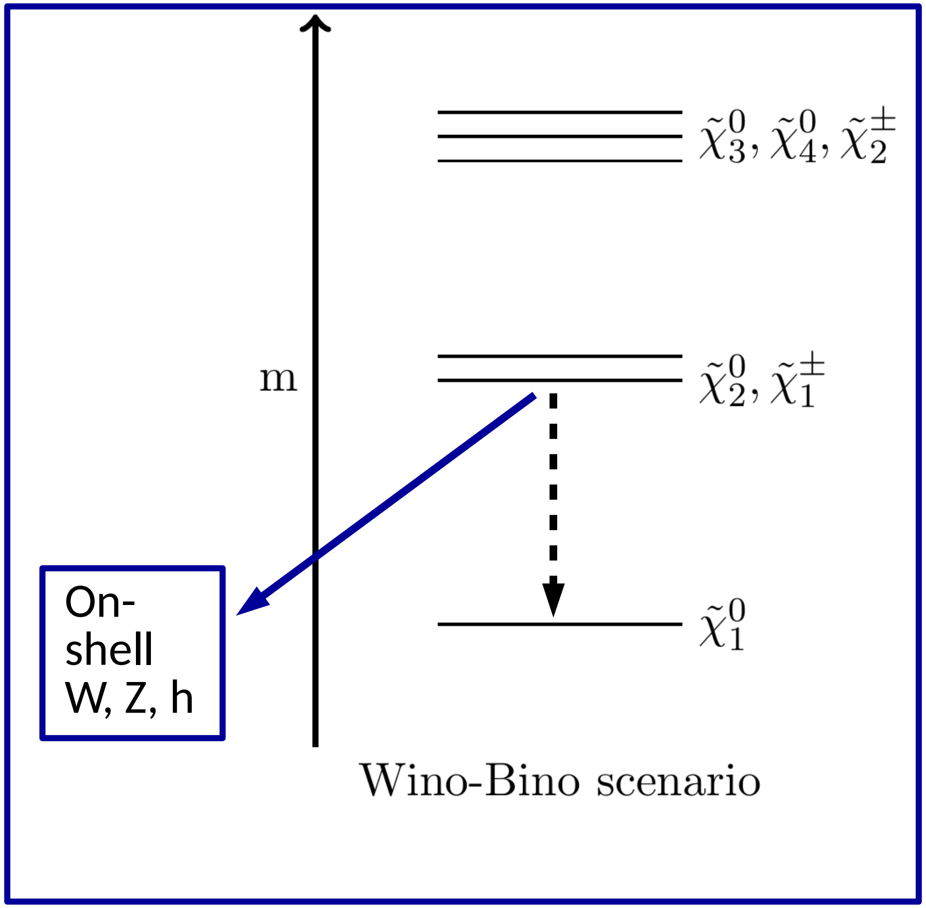
Decays of charginos/neutralinos/sleptons **often** studied in multi-lepton signatures + E_T^{miss}:

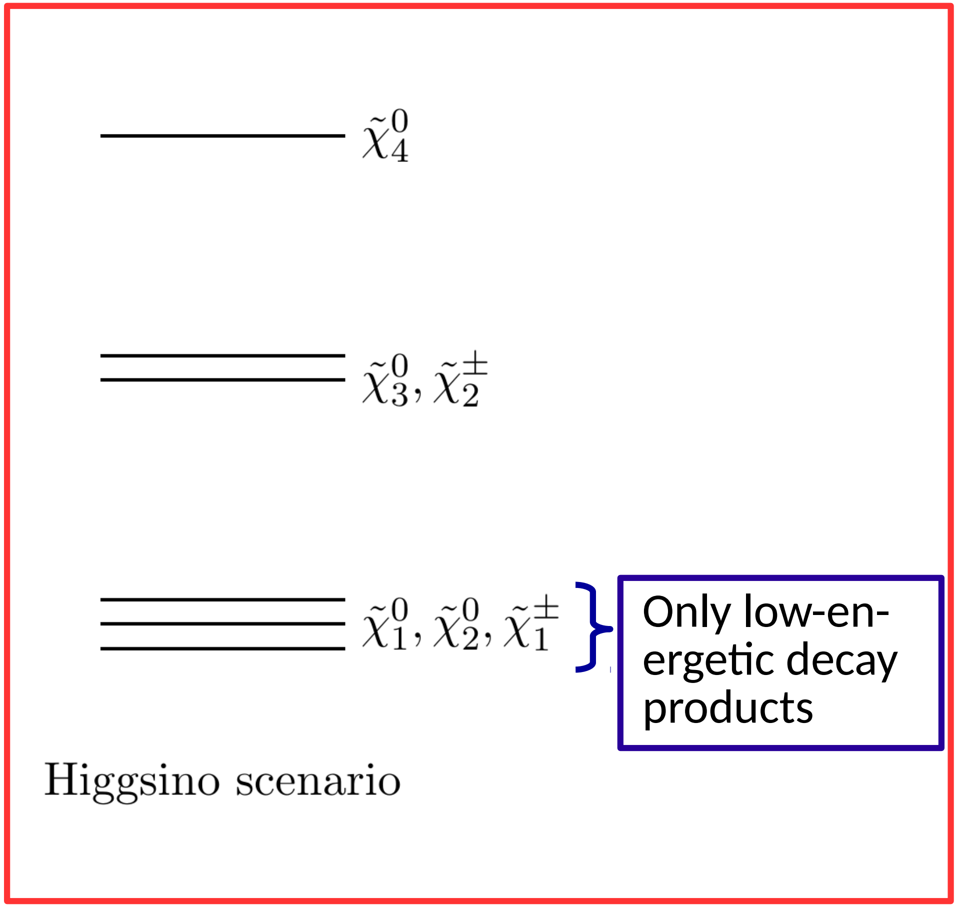
→ *2,3 or 4 leptons*
→ *rather clean signatures*

But not only!

- **Main backgrounds:**
  - Irreducible: mainly diboson production, sometimes $t\bar{t}$ (+ X)
    → *estimation using control and validation regions*
  - Reducible: fakes → data-driven background estimation
- Often suppression of top backgrounds by (b-tagged) jet veto

Searches for charginos and neutralinos





Depending on parameters in the SUSY model, mass difference between LSP and lightest charginos/next-to-lightest neutralinos sizeable (so that on-shell emission of W, Z, h possible), or very compressed mass spectrum.

Search for SUSY particles in final states with 4 leptons

[Phys. Rev. D 98 (2018) 032009]

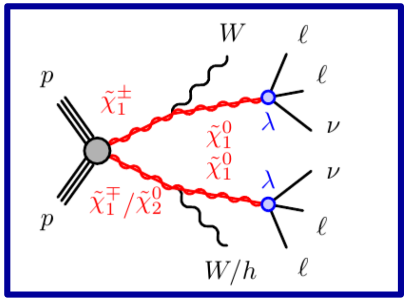
- SUSY models may contain long cascade decay chains → possibly very lepton-rich final state.

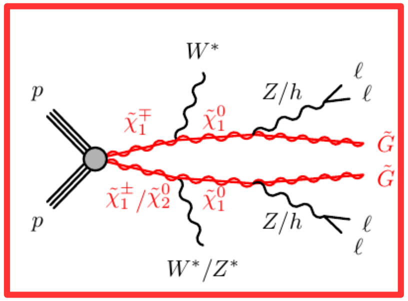
- Or: Scenarios with R-parity violation lead to decays of the LSPs with a potentially lepton-rich signature.

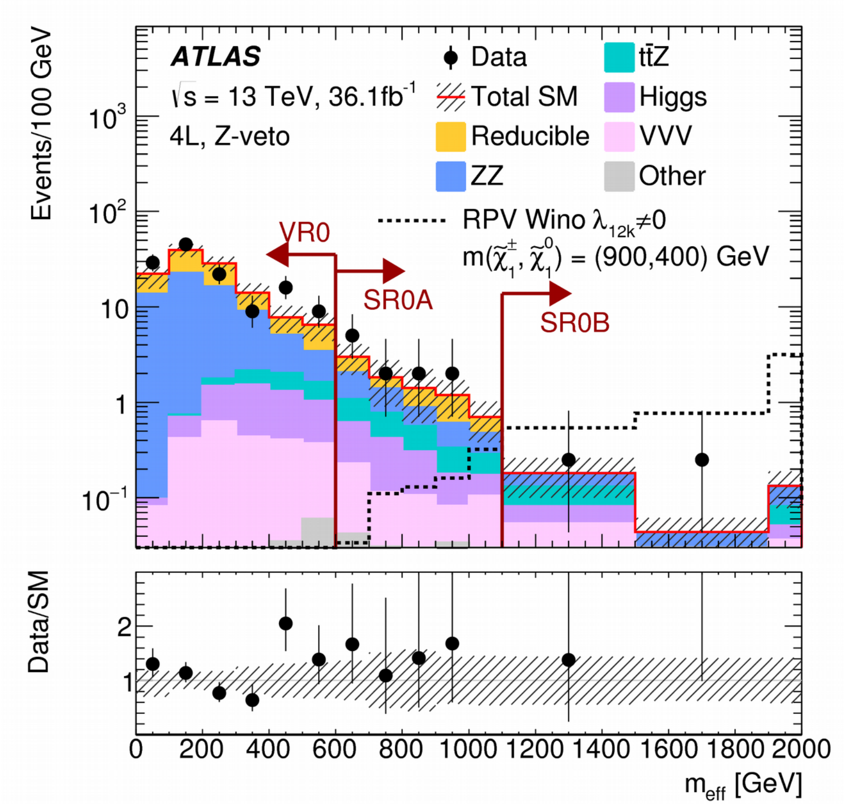
↔ only low SM background.

→ **Search requiring at least four isolated leptons**. Only few further kinematic criteria necessary to enhance potential signal over background
→ m_{eff} or E_T^{miss}

Sensitive to a wide range of different models!





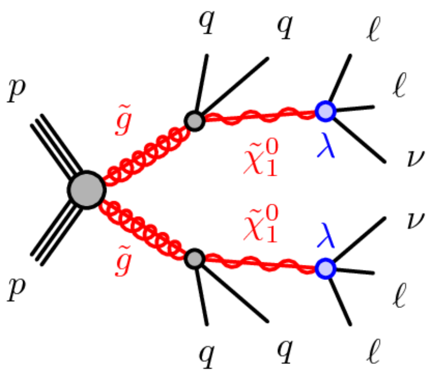


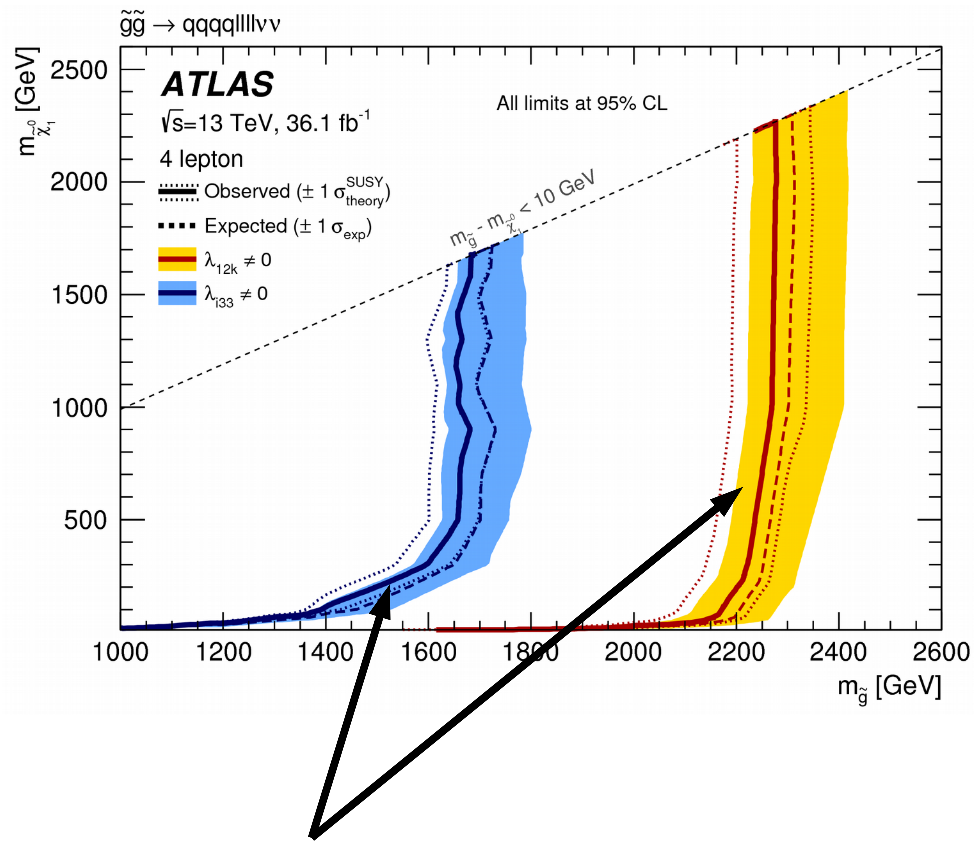
Constraints on gluino pair-production

[Phys. Rev. D 98 (2018) 032009]

The analysis is sensitive on gluino decays in RPV-violating scenarios.

Parameter λ controls if LSPs decay preferentially into tau-rich or light-lepton-rich final states.





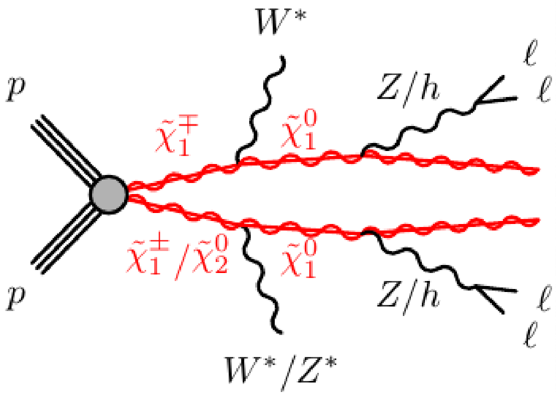
Limits depending on the RPV coupling

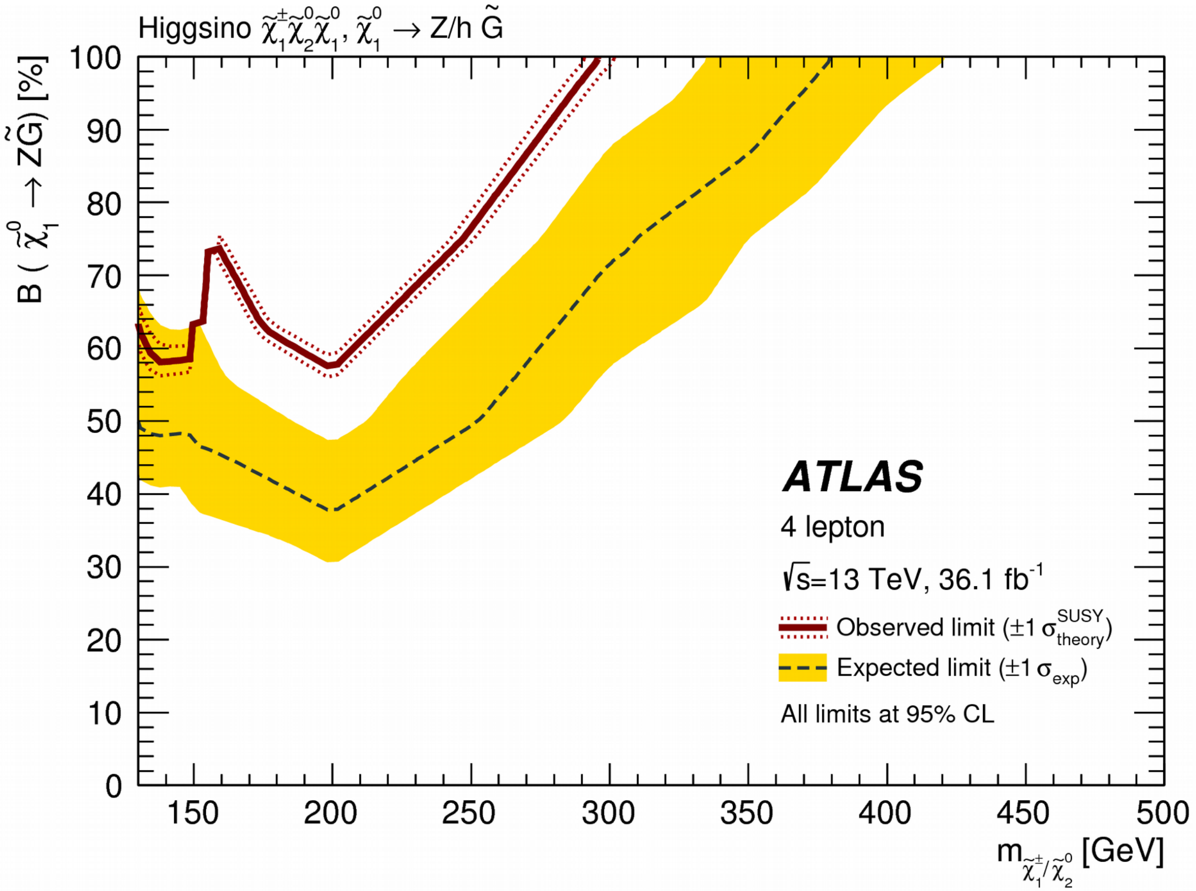
Constraints on Higgsino models

[Phys. Rev. D 98 (2018) 032009]

General gauge mediated:

- Compressed Higgsino states.
- 4 leptons from $\tilde{\chi}^0_1$ to gravitino.





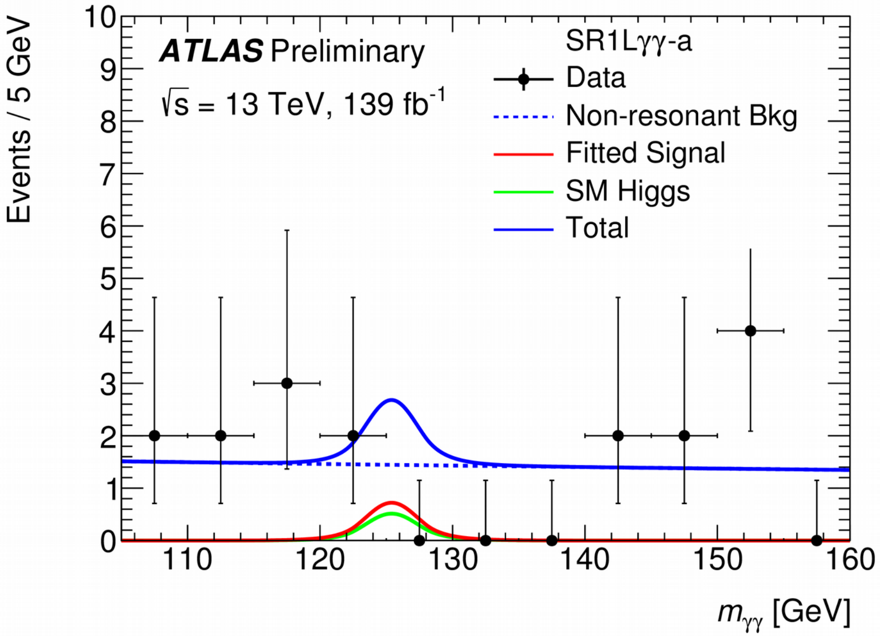
Improved 1 lepton + 2 photons analysis for 139 fb^{-1}

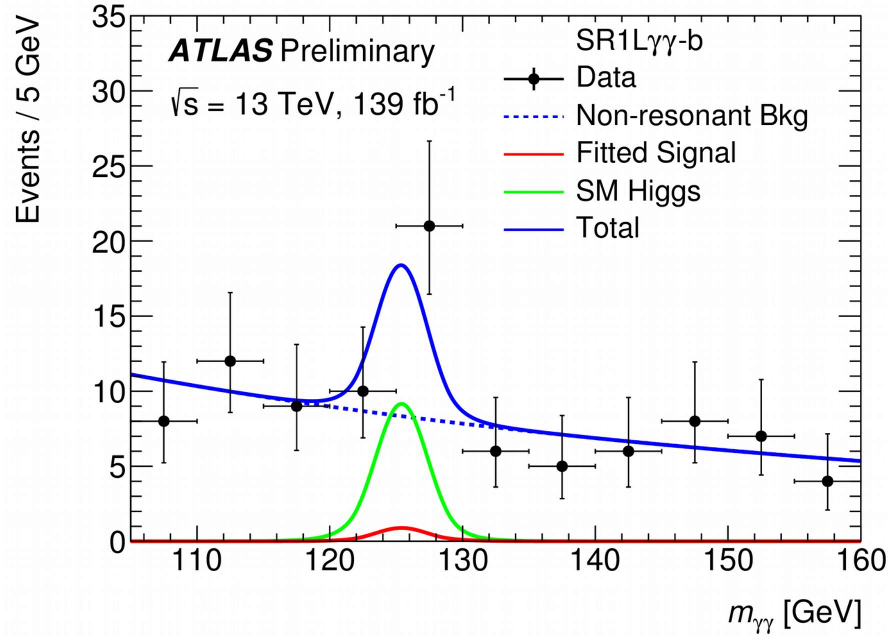
[ATLAS-CONF-2019-019]

- Re-look at signal regions with excesses in 139 fb^{-1}.

- Improved background and signal model:
  - Peaking background and signal described by double-sided Crystal Ball functions
  - Non-peaking backgrounds (side-band) by fitting $f_{k;d}(x;b,\{a_k\}) = (1-x^d)^b x^{\sum_{j=0}^{k} a_j \log(x)^j}$

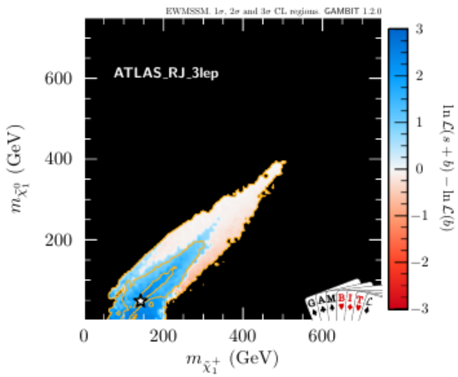
- Data consistent with background estimates.

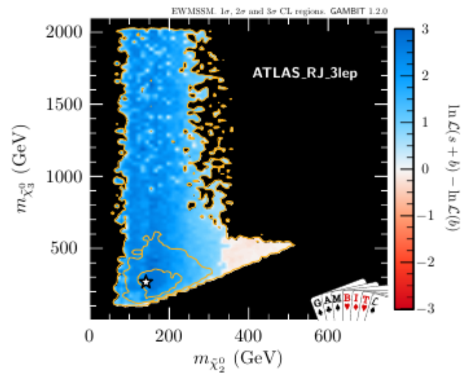




Loopholes? Analysis of electroweak searches by Gambit

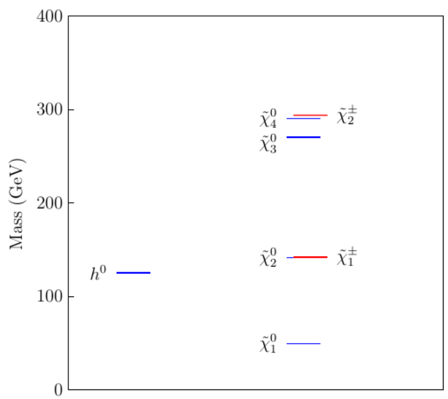
[arXiv:1809.02097]

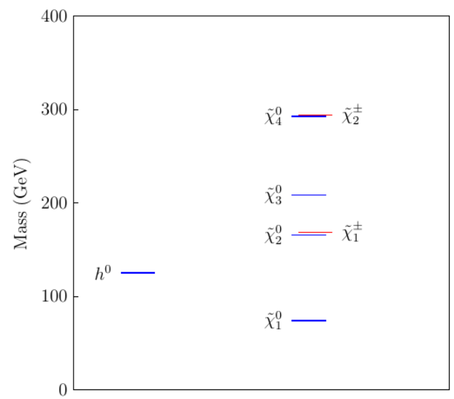




Likelihood combination of various LEP, ATLAS and CMS searches for electroweakinos:

→ *using best possible signal region in case of the multi-bin signal regions in cases where no information on correlations provided, else approximation of full likelihood of search.*





- $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0,\ \tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^\mp$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_1^0,\ \tilde{\chi}_3^0 \to Z + \tilde{\chi}_2^0 \to Z + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0,$
  $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0,\ \tilde{\chi}_4^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to h + \tilde{\chi}_1^\pm \to h + W^\pm + \tilde{\chi}_1^0,\ \tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_1^\pm \to W^\pm + \tilde{\chi}_1^0,\ \tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^+ + W^- + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to Z + \tilde{\chi}_1^\pm \to Z + W^\pm + \tilde{\chi}_1^0,$
  $\tilde{\chi}_4^0 \to h + \tilde{\chi}_2^0 \to h + Z + \tilde{\chi}_1^0$

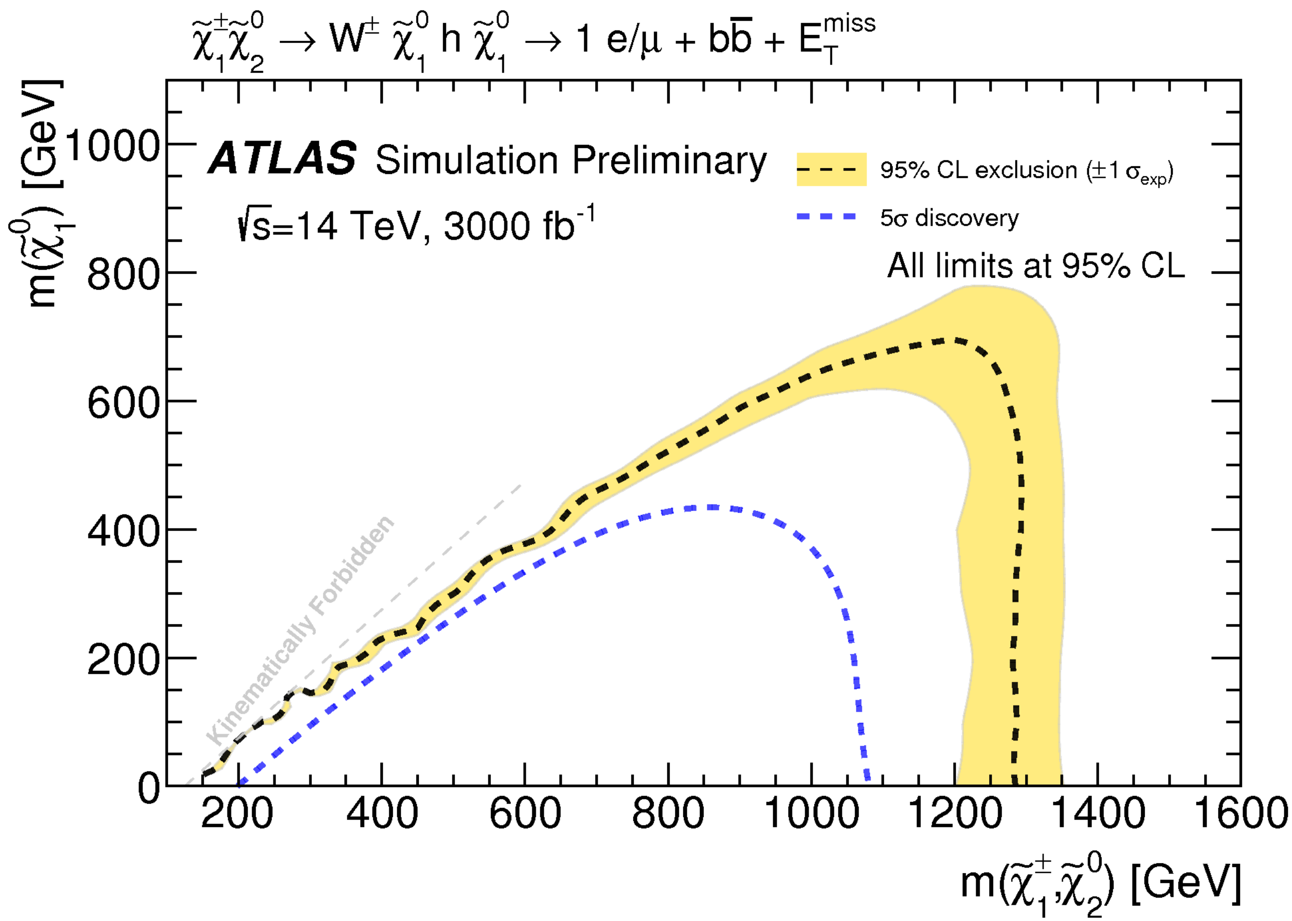
Due to little excesses at different places two interpretations:

- *Potential model that could result in the excesses,*
- *Shortcomings of current searches.*

Conclusion is that current searches are not sensitive to longer decay chains.

Where we might go to with HL-LHC

[ATL-PHYS-PUB-2018-048]



Expected to reach limits up to ~1200 GeV for specific chargino/neutralino decays for HL-LHC

…and what we could do at future colliders

[CERN-ESU-004]

Constraints from relic density:

- Pure Wino: 3 TeV
- Pure Higgsino: 1.1 TeV

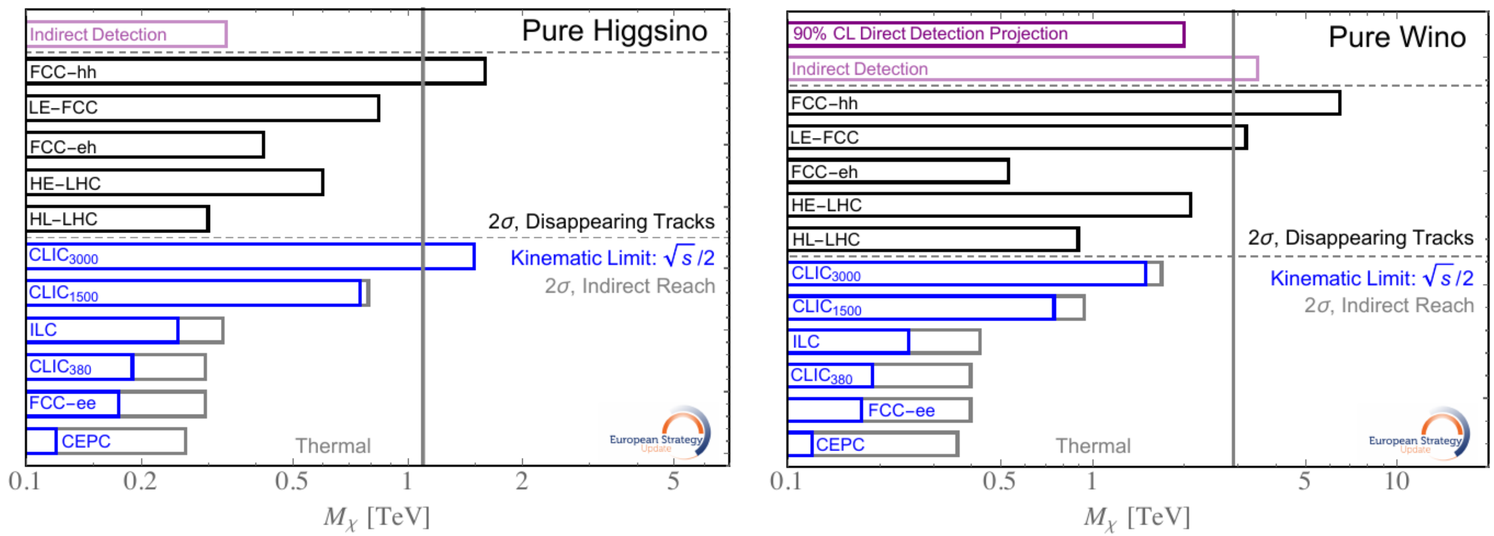


Fig. 8.14: Summary of 2σ sensitivity reach to pure Higgsinos and Winos at future colliders. Current indirect DM detection constraints (which suffer from unknown halo-modelling uncertainties) and projections for future direct DM detection (which suffer from uncertainties on the Wino-nucleon cross section) are also indicated. The vertical line shows the mass corresponding to DM thermal relic.