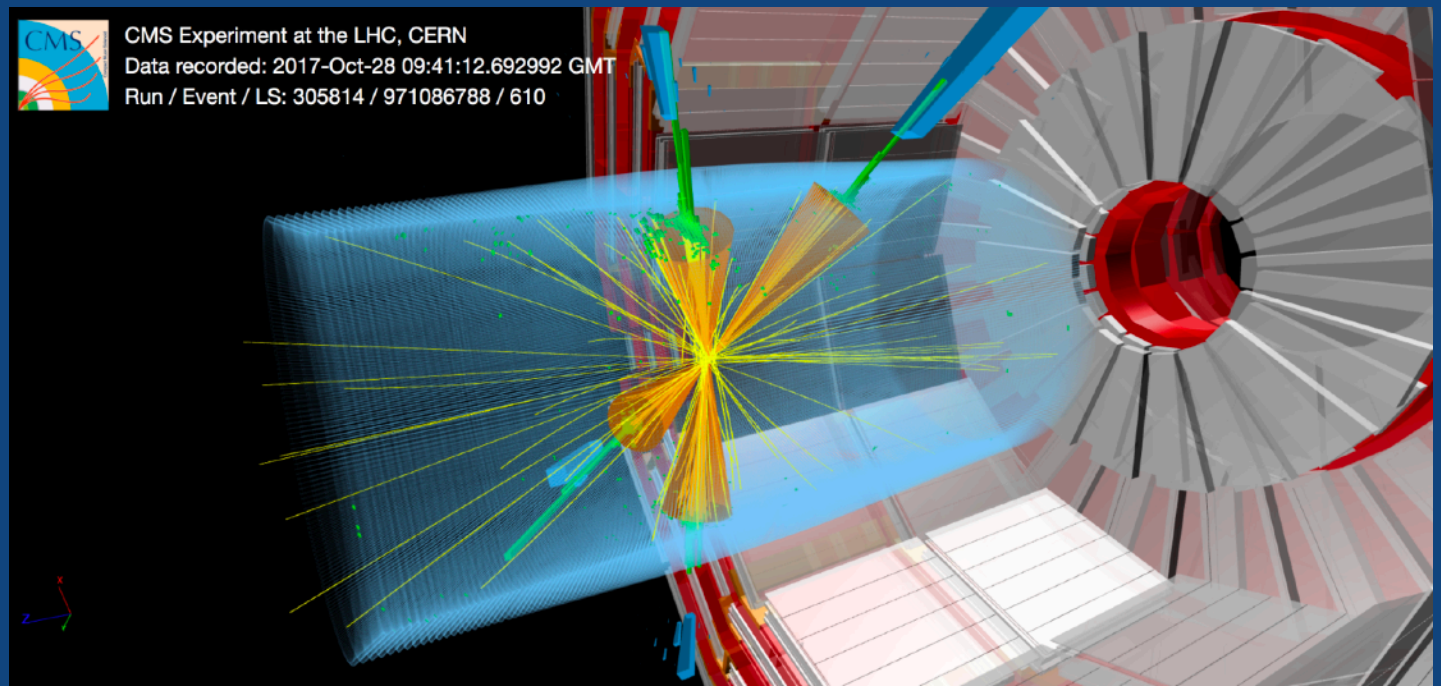
402-0703-00L

Phenomenology of Physics Beyond the Standard Model

Exp Lecture 2: Sparticles search

Annapaola de Cosa adecosa@phys.ethz.ch



Objectives

Objectives for today and next classes

- Discuss (in general terms) search strategy for direct (and indirect) detection of BSM particles at collider experiments
- Interpret results from a variety of searches probing different BSM models
- Evaluate the experimental feasibility of newly proposed BSM searches at colliders.
- Know where to find more detailed informations

In this lecture

- (Brief) Recap from previous episodes
- SUSY particles production @ LHC
  - how do we expect SUSY to be produced at hadron colliders
- Tracking back SUSY
  - SUSY experimental signatures and particle reconstruction at LHC experiments
- Strategies for hunting SUSY
  - General approach for BSM searches
  - Probing different SUSY scenarios: R-Parity Conserved, Violated and Exotic SUSY
  - Focus on some signal selection and background estimation strategies
  - Interpretation of results

Not in this lecture

- A complete and exhaustive review of SUSY searches
- A detailed explanation of all the experimental techniques used to hunt SUSY
    - Focus on some of them
    - We'll see more in the next lectures as these **techniques are common** to many BSM searches

But…you can dive into the most up-to-date SUSY searches browsing the following links:

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Going beyond the SM

Quest for Supersymmetry particles



- Not a precise idea of what the destination is →
  - R-parity conserving SUSY
  - R-parity violating
  - Exotic SUSY signatures
- Not a ~solitary expedition, but multiple crews →
  - Unknown is not just Higgs boson mass, but up to >100 new parameters
- The implications may be well beyond what initially contemplated →
  - Searches targeting SUSY are sensitive to many other BSM models too!

New SUSY particles

Supersymmetry relates bosons and fermions:
Q|fermion>=|boson>, Q|boson>=|fermion>

For each SM particle a SUSY partner is introduced, with the same quantum numbers and couplings as the SM particle, except for the spin



The MSSM particles zoo

The Minimal Supersymmetric Standard Model (MSSM) is the minimal extension of the SM incorporating SUSY

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	(same) (same) $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	-1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	-1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 3/2	-1 -1	$\tilde{G}$	(same) (same)

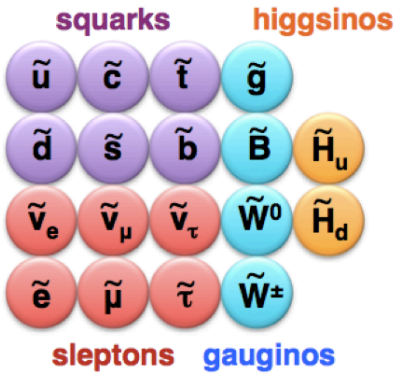
In general, gauge eigenstates ≠ mass eigenstates

Mixing

- 3rd generation
- 4 higgsinos mix with winos and bino to give 4+4 massive charginos and neutralinos

It introduces:

- 9 scalar leptons (3 generations)
- 12 scalar quarks (3 generations)
- 1 gluino
- 1 bino, 3 winos
- 4 higgses (H_u^+, H_u^0), (H_d^0, H_d^-) Higgs sector must assume two higgs doublets (anomaly cancellation)
- 4 higgsinos $(\tilde{H}_u^+, \tilde{H}_u^0)$, $(\tilde{H}_d^0, \tilde{H}_d^-)$
- 1 gravitino in GMSB



From full Models to Simplified Models

Problem for the experimentalist

Huge number of parameters, impossible to scan the full parameter space

choice of parameters ⇒ mass hierarchy and branching ratios

⇒ decay chains ⇒ experimental signatures

From full Models to Simplified Models

Problem for the experimentalist

Huge number of parameters, impossible to scan the full parameter space

choice of parameters ⇒ mass hierarchy and branching ratios

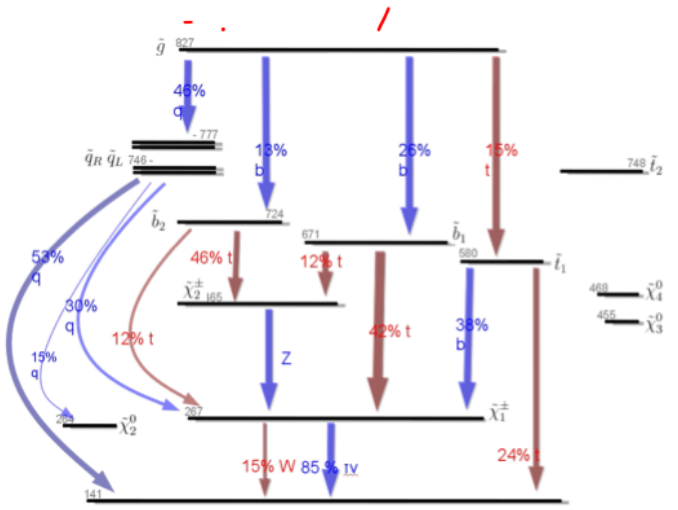
⇒ decay chains ⇒ experimental signatures

Solution 1

Choose a specific SUSY breaking mechanism and reduce the number of parameters. E.g. MSUGRA, universality of sparticle masses at GUT scale assumed, from 105 to 5 free parameters

Pro: a realistic SUSY model

Con: very constrained,
risk to miss signatures



From full Models to Simplified Models

Problem for the experimentalist

Huge number of parameters, impossible to scan the full parameter space

choice of parameters ⇒ mass hierarchy and branching ratios

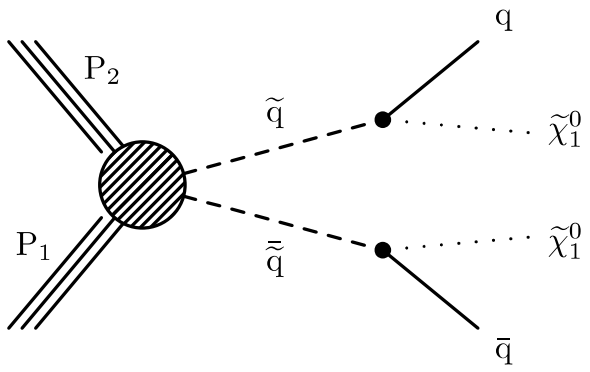
⇒ decay chains ⇒ experimental signatures

Solution 2

Simplified models attempt to capture the behaviour of a small number of kinematically accessible sparticles, assuming all others play no role (decoupled). E.g. one SUSY production process with a fixed decay chain.

Pro: allows to make experimental constraints on individual sparticles and decay modes

Con: by no means complete models, fail to capture effects coming from competing production and decay processes



From full Models to Simplified Models

Problem for the experimentalist

Huge number of parameters, impossible to scan the full parameter space

choice of parameters ⇒ mass hierarchy and branching ratios

⇒ decay chains ⇒ experimental signatures

Solution 3

Phenomenological MSSM (pMSSM): start from MSSM and apply a series of assumptions motivated by either experimental constraints (e.g. consistency with DM relic abundance, no new CP violation, …) or general features of possible SUSY breaking mechanisms

⇒ Reduce to 19 free parameters

Pro: still a realistic SUSY model

Con: it's still 19 free parameters !

From full Models to Simplified Models

Problem for the experimentalist

Huge number of parameters, impossible to scan the full parameter space

choice of parameters ⇒ mass hierarchy and branching ratios

⇒ decay chains ⇒ experimental signatures

➔ **In practice a mixture of these three approaches**

- simplified models and some benchmark full models for individual searches
- at the end of the Run, combine results of all searches to constrain pMSSM

Going beyond the SM

Quest for Supersymmetric particles

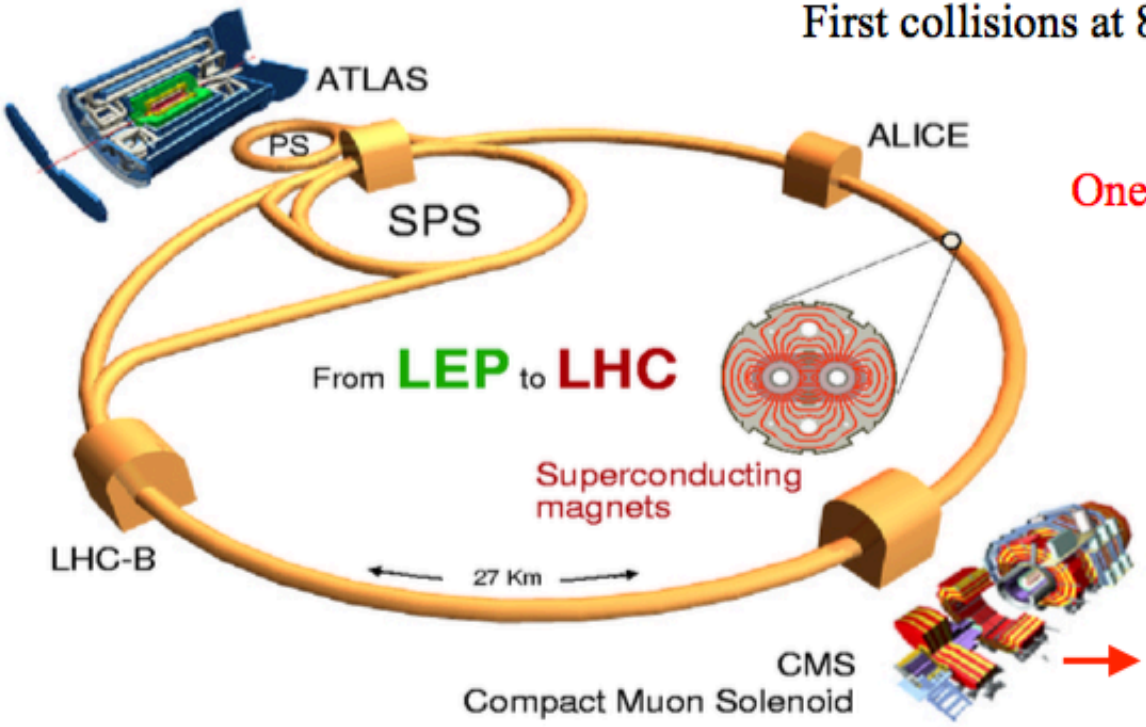


- Not a precise idea of what the destination is

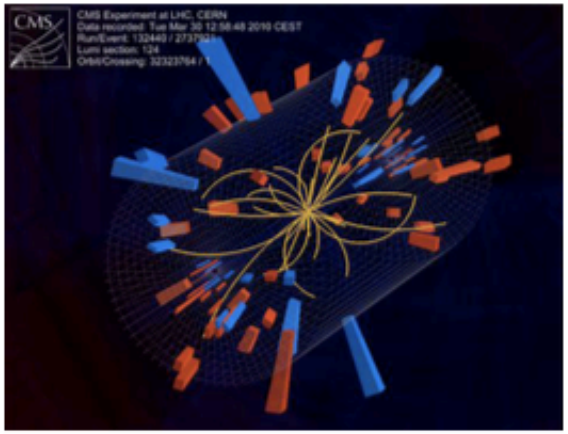
- R-parity conserving SUSY
- R-parity violating SUSY
- Exotic SUSY signatures

Searches at the LHC

First collisions at 900 GeV : 23 November 2009
First collisions at 7 TeV : 30 March 2010
First collisions at 8 TeV: 5 April 2012



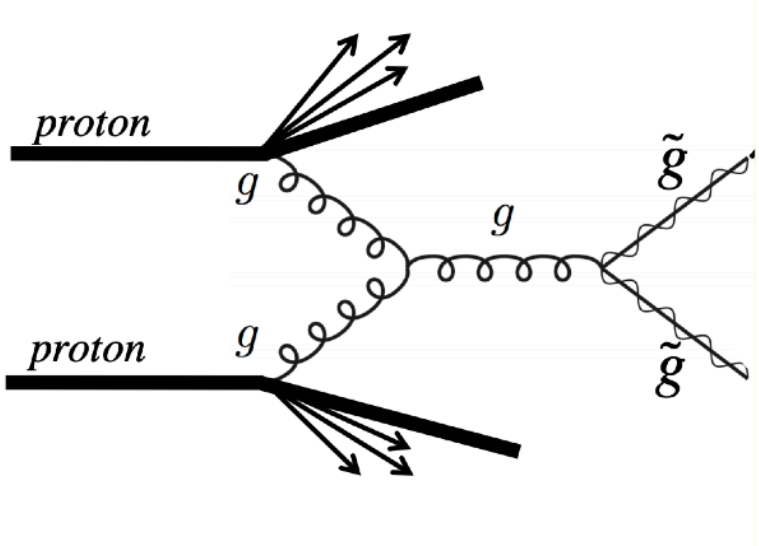
One of the first LHC collisions:

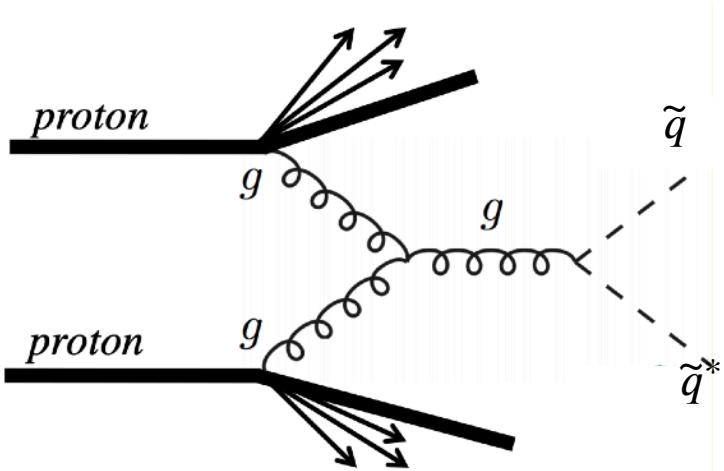


Run-1 @ 7-8TeV: ~30 fb^{-1}
Run-2 @ 13TeV: ~150 fb^{-1}
Run-3 @ 13.6TeV: ~200 fb^{-1} up to 2024

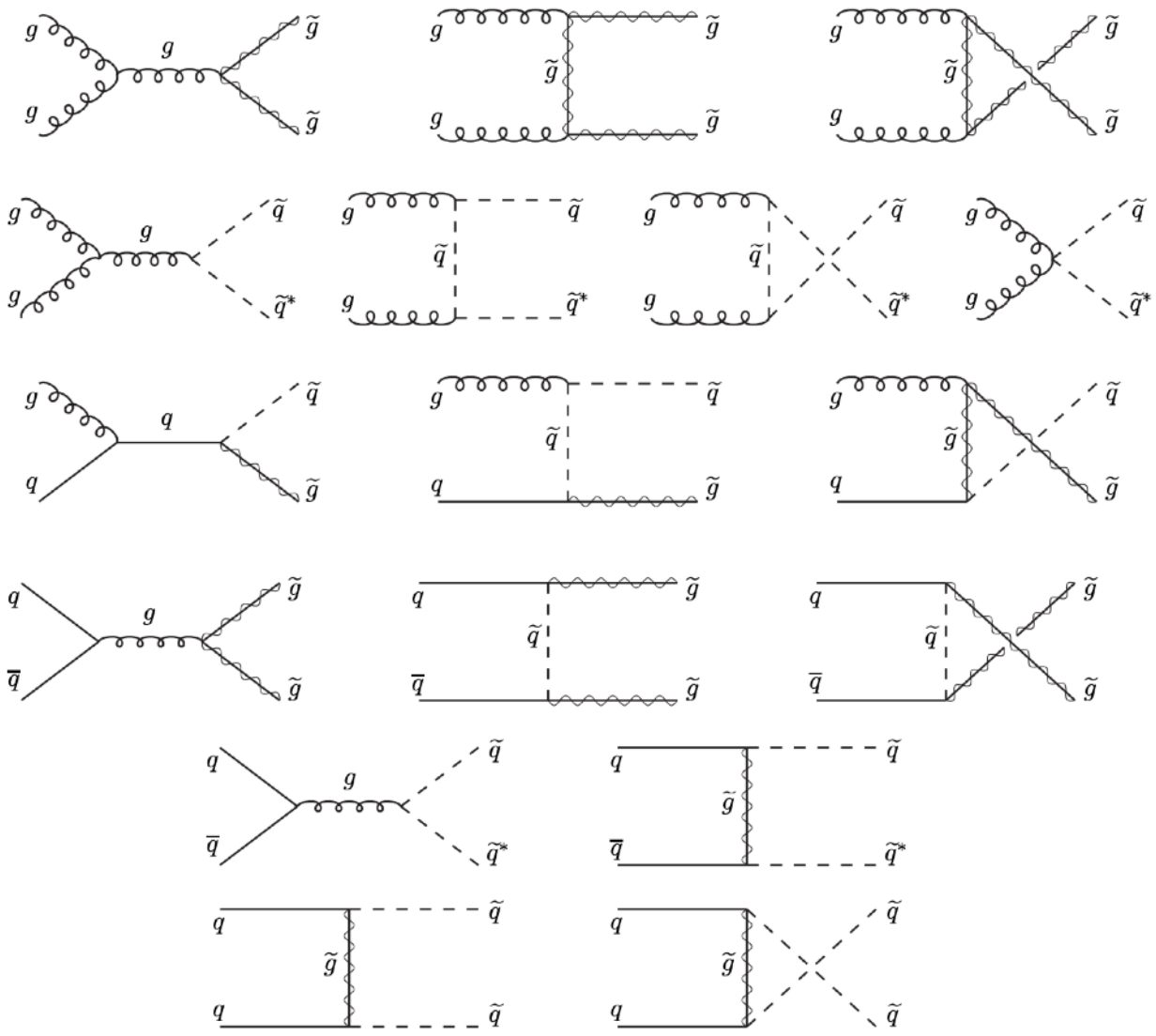
SUSY particles production at the LHC

From hard scattering in a pp-collision, gluinos or squarks can be pair-produced as follows

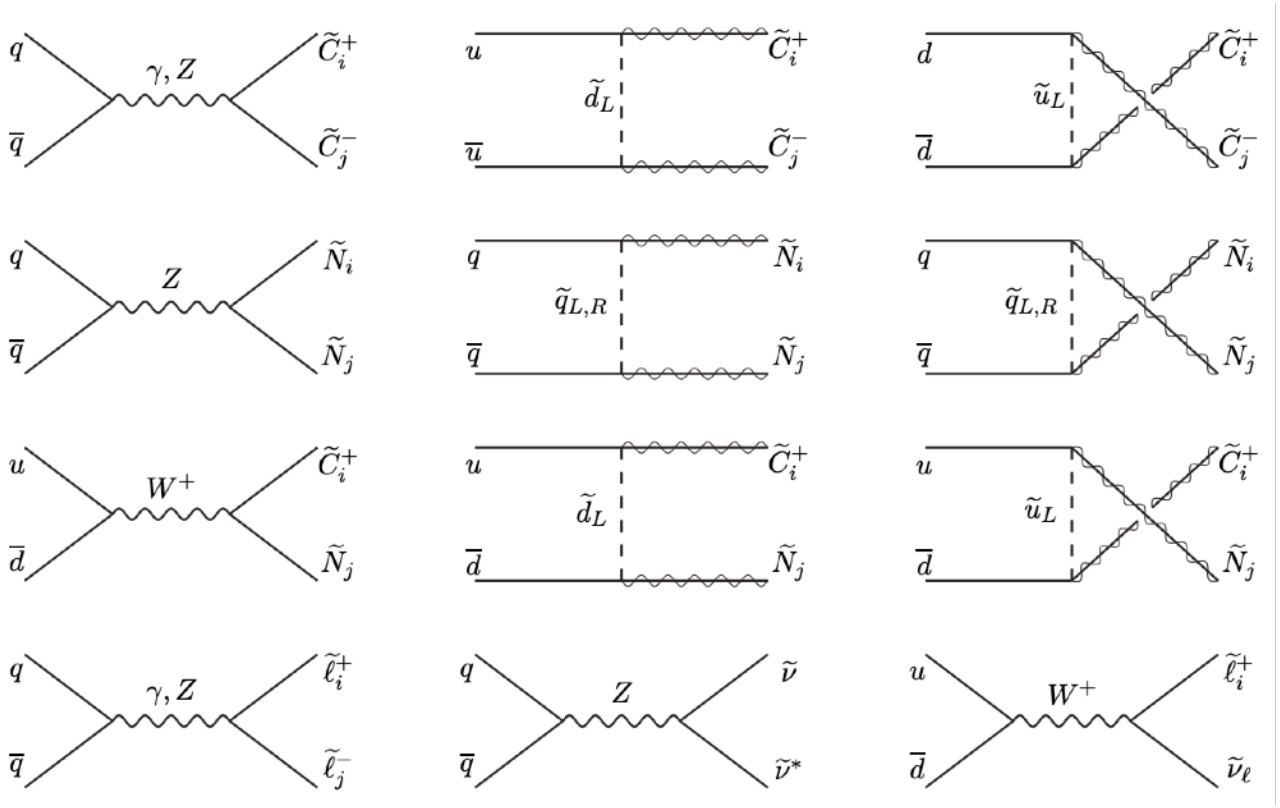




Strong production



Electroweak production



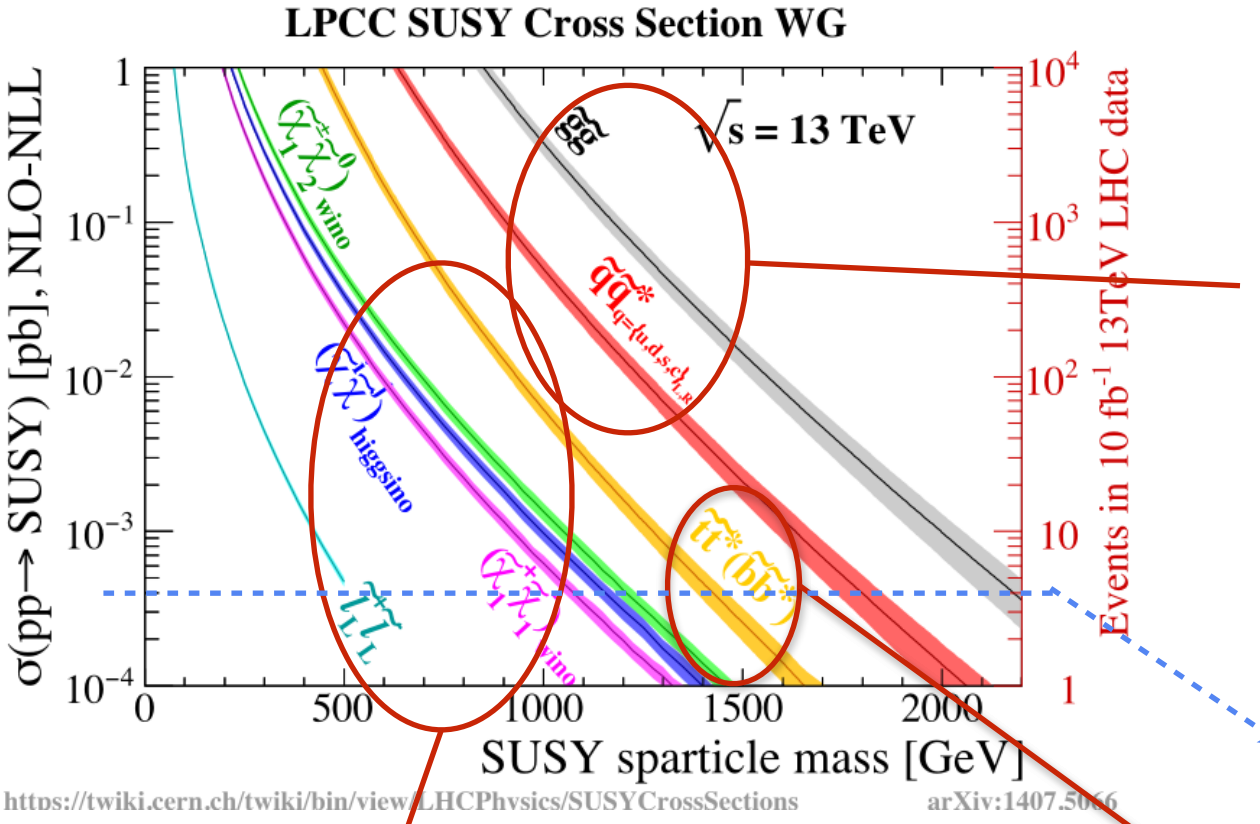
Chargino pair

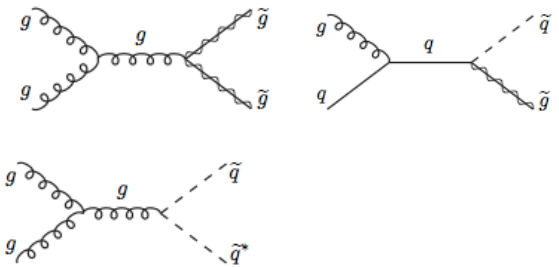
Neutralino pair

Chargino neutralino

Slepton pair
Sneutrino pair
Sneutrino – slepton

SUSY particle production at the LHC

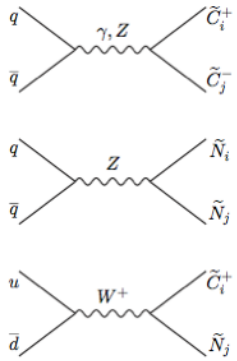




Gluinos and 1st,2nd generation squarks:
produced through strong interaction at the LHC
"high" cross-section for masses up to 2TeV

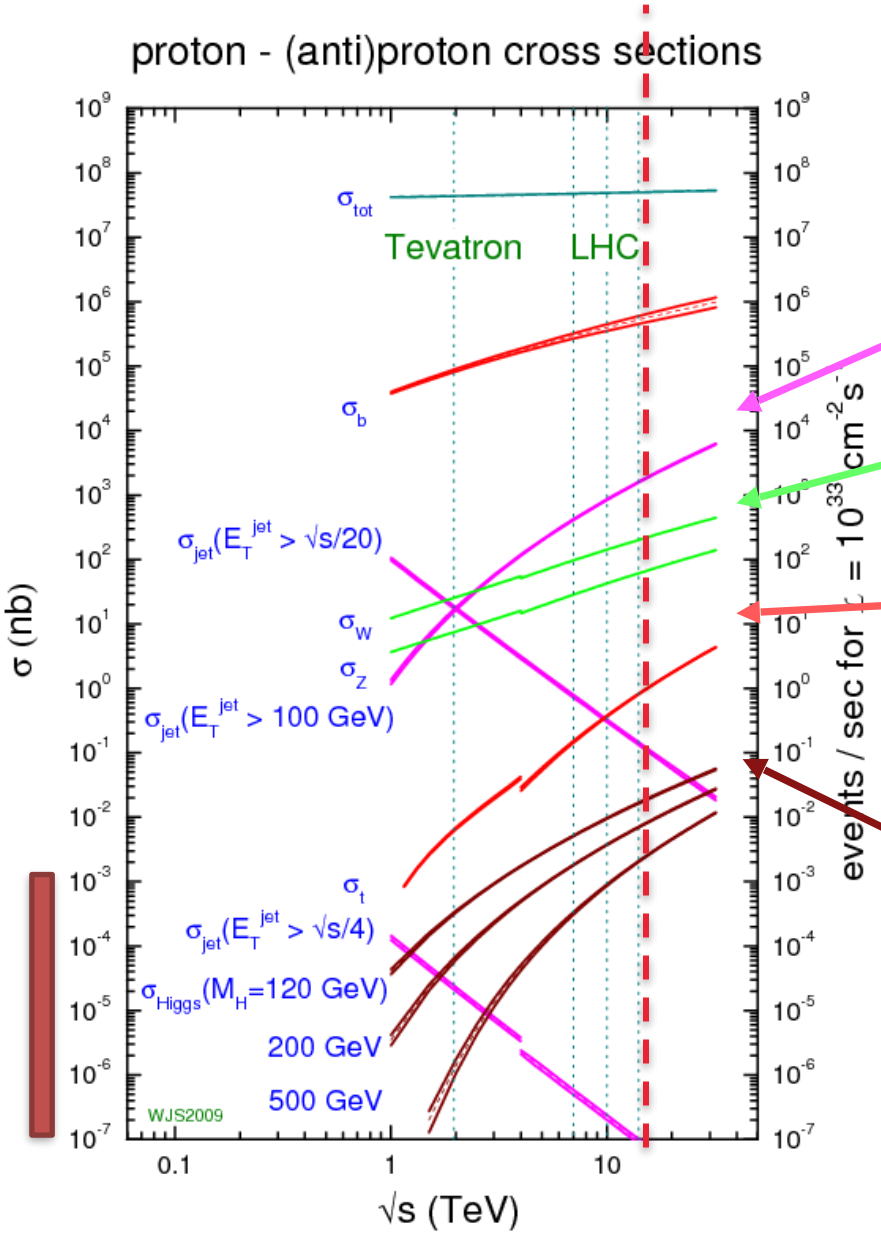
expected 3 events for 10 fb^{-1} of collision data

3rd generation squarks:
"moderate" cross-section for masses up to 1.5 TeV



Charginos, neutralinos, sleptons:
produced through weak interaction.
"smaller" cross-section, but still detectable for light mass values

SM processes at the LHC



High p_T QCD jets

W / Z + jets

top

Higgs @ 120 GeV

Interval of plot in previous page

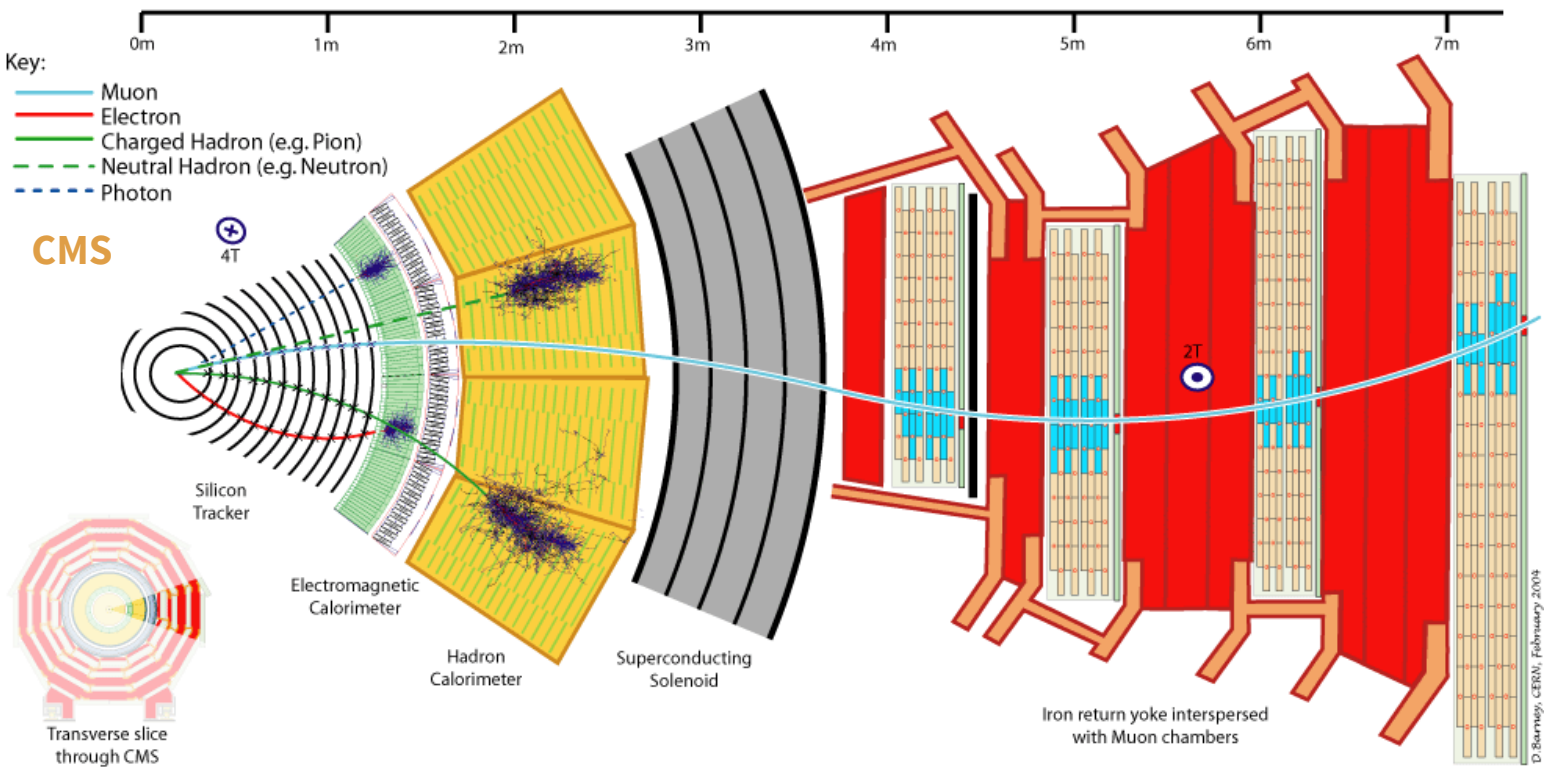
Particle Reconstruction

High p_T e,ɣ

High p_T jets

High p_T μ

Global quantities
Total and Missing Transverse Energy



Visible particles are reconstructed from tracks and energy deposits in the detector by an algorithm that

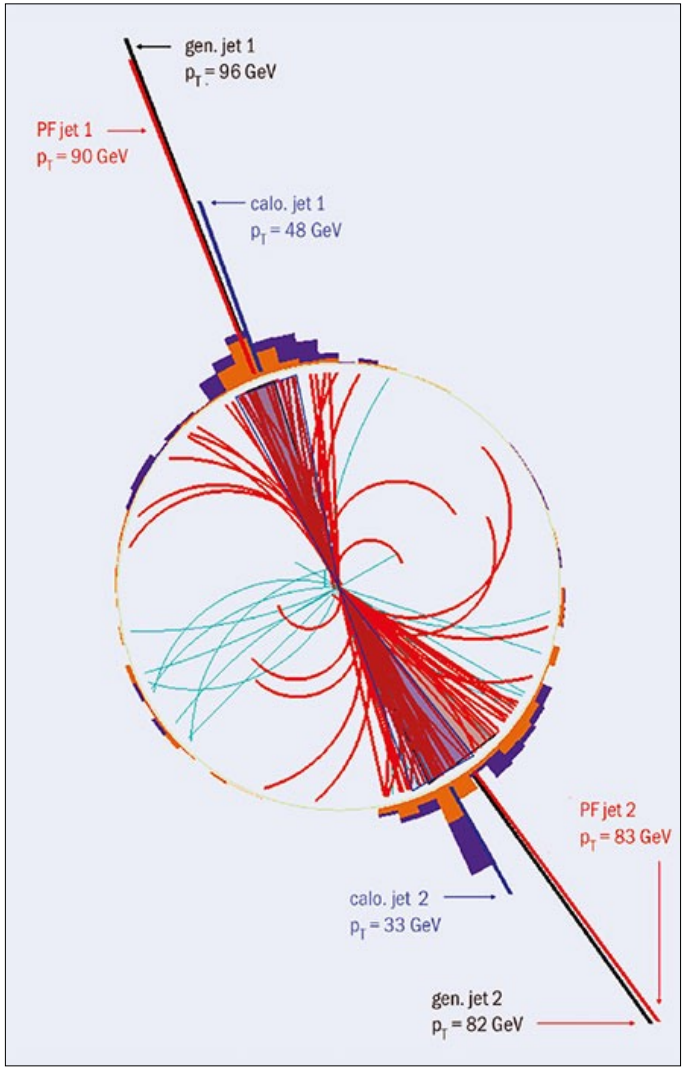
- combines information from all subdetectors
- creates a consistent set of reconstructed particles for each collision event (electrons, photons, muons, charged hadrons, neutral hadrons)

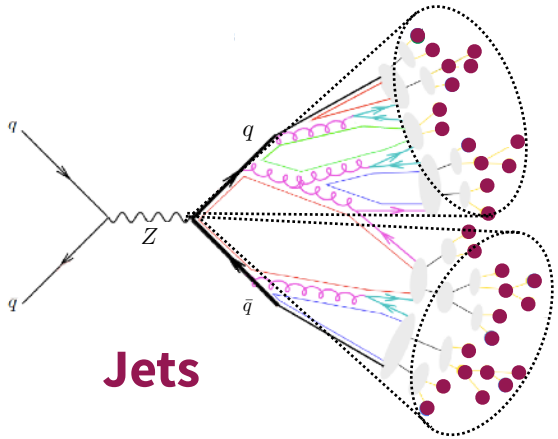
JET reconstruction

Quarks are confined by strong interaction, they hadronize producing charged and neutral hadrons giving rise to an hadronic shower

These particles appeared close to each others and grouped together forming ***jets*** of particles

Identified particles are clustered together based on their distance with the anti-kT 0.5 algorithm (infrared safe)



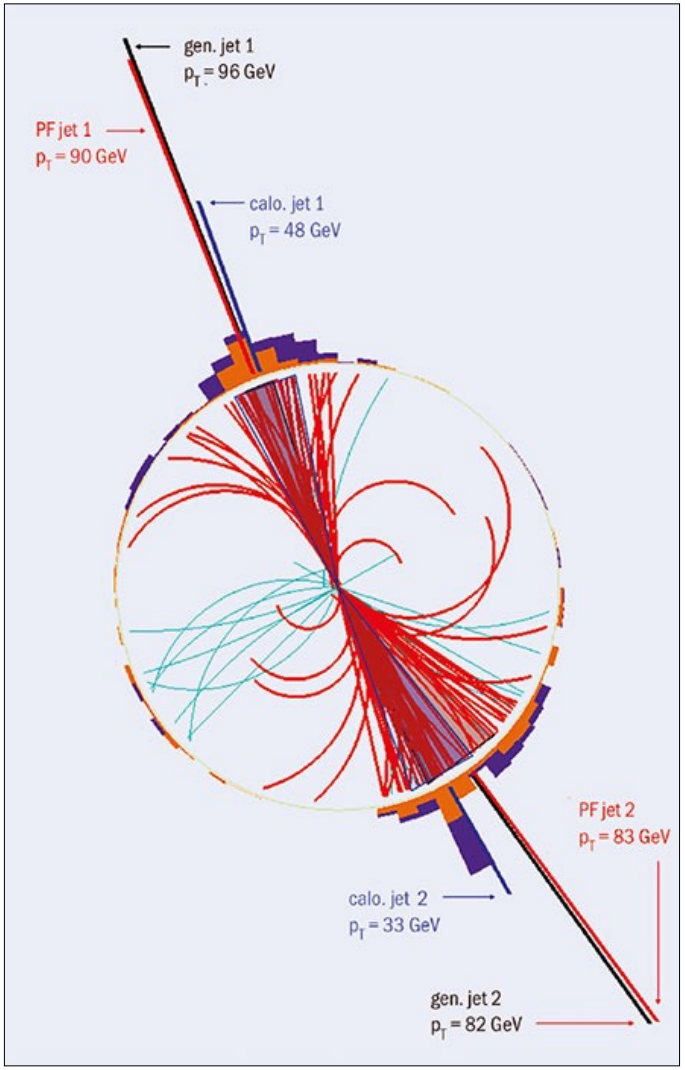


JET reconstruction

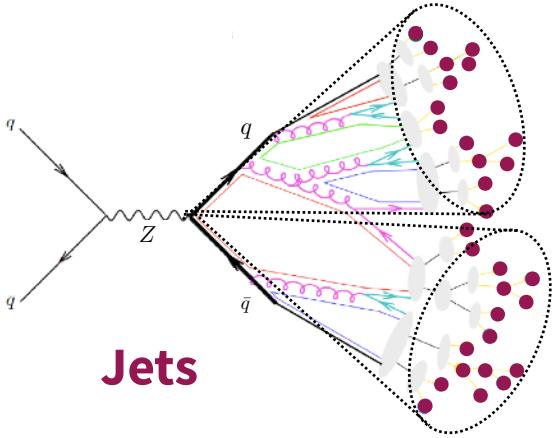
Quarks are confined by strong interaction, they hadronize producing charged and neutral hadrons giving rise to an hadronic shower

These particles appeared close to each others and grouped together forming ***jets*** of particles

Identified particles are clustered together based on their distance with the anti-kT 0.5 algorithm (infrared safe)



Typical energy resolutions of calibrated jets are about **6-7% at 200-300 GeV**

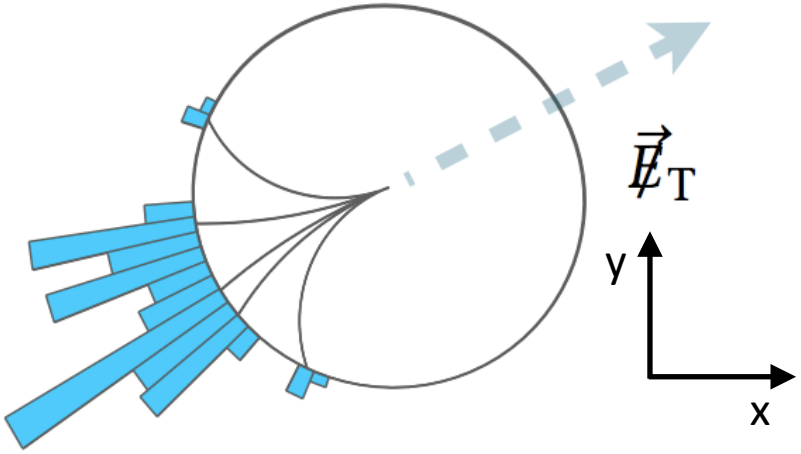


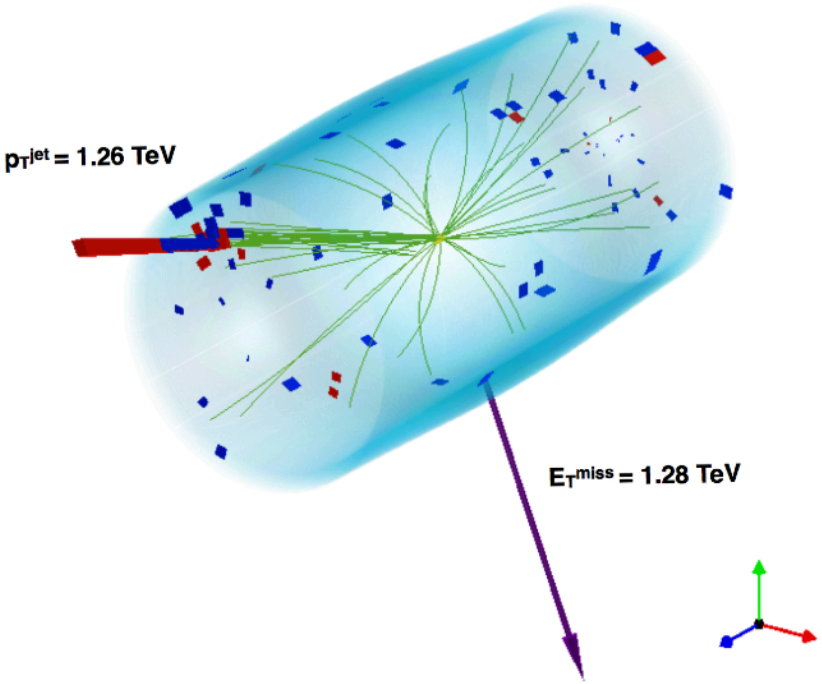
Jets

Missing momentum

Particles such as neutrinos are invisible to detectors

- Their signature is actually a ***missing signature***, identified by an energy imbalance in the plane transverse to the beams



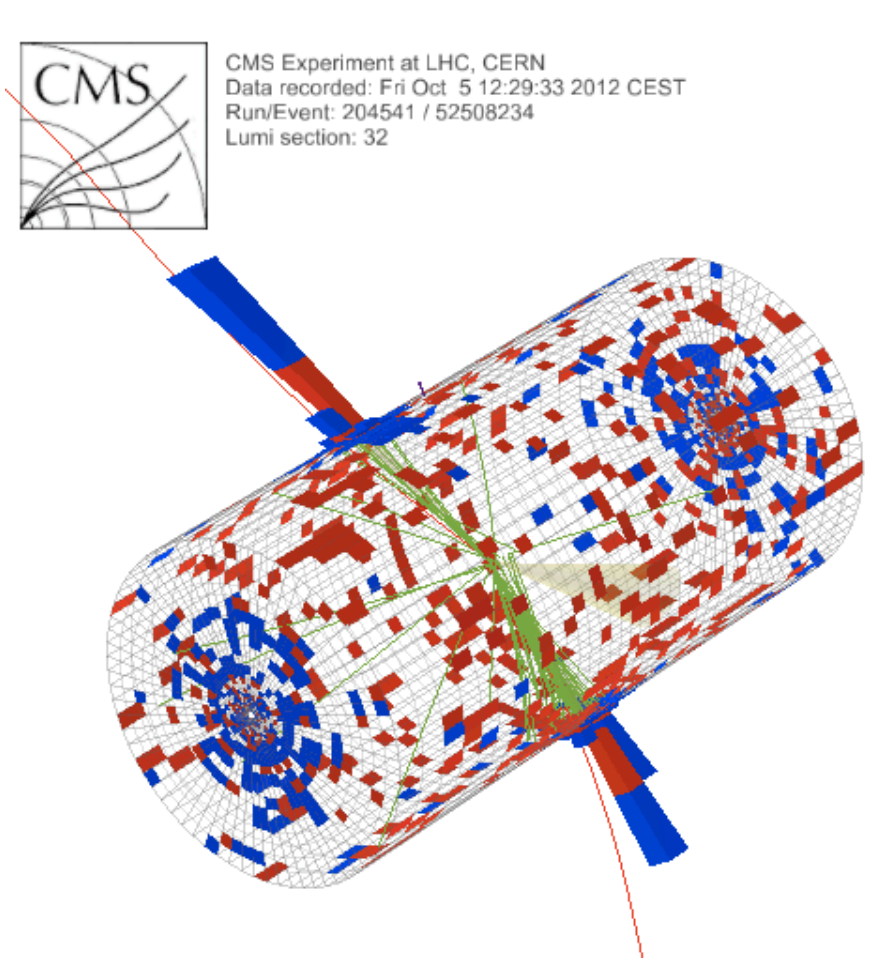


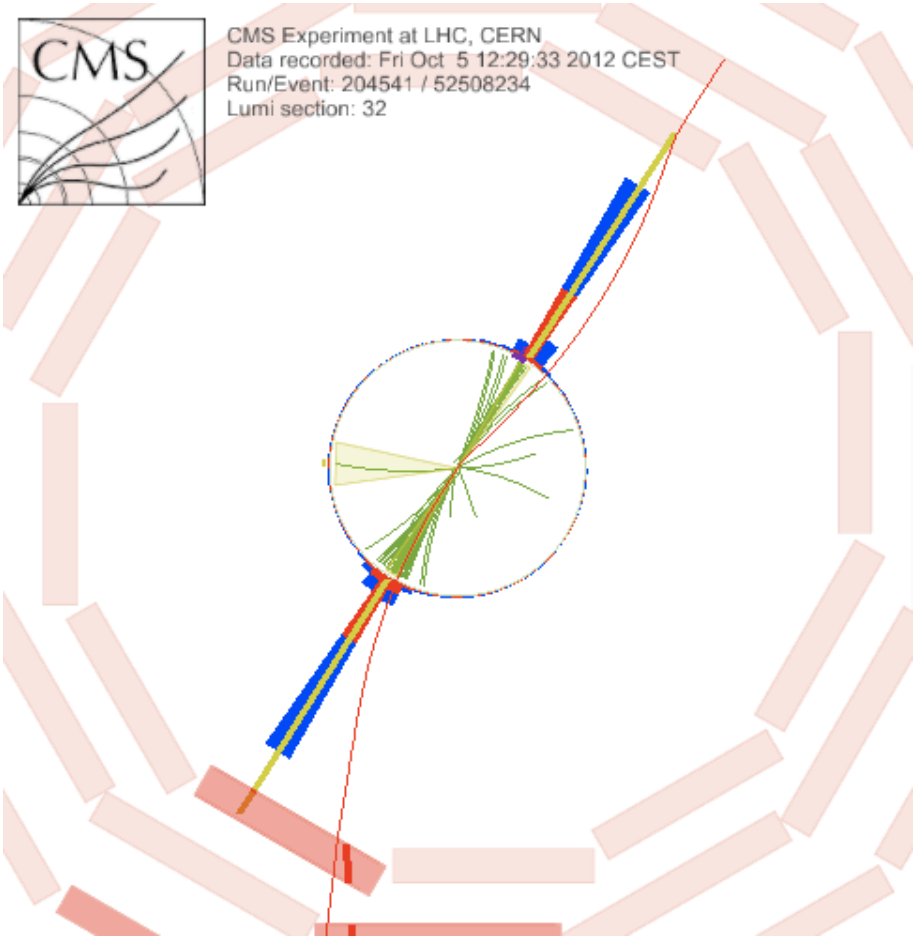
- **Missing transverse momentum, MET,** (E_T^{miss}) is defined as ***the negative sum of the transverse momenta of all reconstructed particles***

$$\mathrm{E_T^{miss}} = -\sum_i \mathrm{p_T}^i$$

Event reconstruction

Dijet event





Different search strategies

Different strategies for different signal hypotheses:

- Searches for RP-Conserving SUSY
- Searches for RP-Violating SUSY
- Searches of non-prompt decays or stable particles (exotic signatures)

Matter parity and R-parity

Matter parity: $$P_M = (-1)^{3(B-L)}$$

All components of matter super-multiplets have P_M = -1

Higgs and gauge super-multiplets have P_M = +1

R-parity: $$P_R = (-1)^{3(B-L)+2s}$$

Since angular momentum is conserved, conservation of P_R and P_M are equivalent.

If you calculate:

- SM particles have P_R = +1
- SUSY particles have P_R = -1

R-parity conservation (RPC) and DM

If R-parity is conserved:

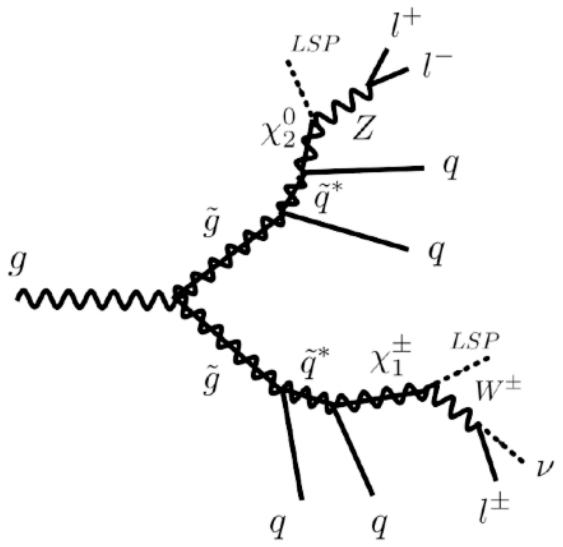
- SUSY particles can only be pair produced, e.g. gg → gluino gluino
- Decay of a SUSY particle into SM particles + odd number of SUSY particles
  - Lightest SUSY particle (LSP) is stable

- All SUSY particles will eventually decay into LSP
  - In vast majority of models, LSP is neutralino
  - Weakly interacting massive particle ("WIMP")
  - Candidate for cold dark matter in the Universe



Generic SUSY RPC signatures

Specific SUSY symmetry breaking mechanism and particle mass spectrum determine SUSY phenomenology



However, some general considerations are possible:

- If R-parity is conserved, each sparticle decay-chain contains a (neutral) LSP
- If sparticles are as heavy as thought, LSP and all other decay products receive a significant boost.

n lep + m jets + MET

large undetected transverse momentum (MET) from LSP
+
hard hadronic/leptonic activity

Generic SUSY RPC signatures

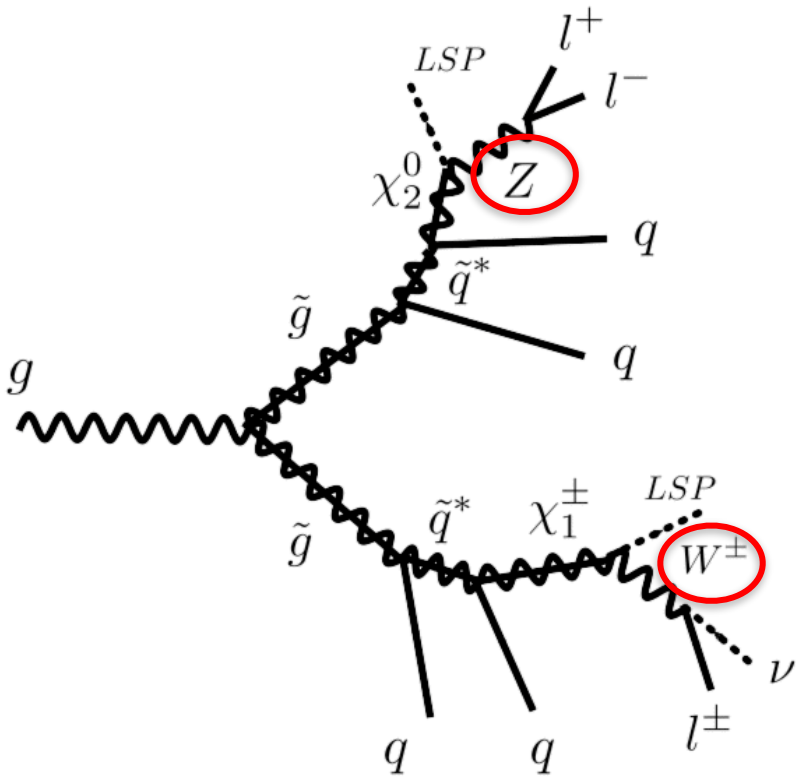
n lep + m jets + MET

	0 lep + m jets + MET	1 lep + m jets + MET	2 lep(OS) + m jets + MET	2 lep(SS) + m jets + MET	>= 3 lep + m jets + MET
Signal signature					
Main backgrounds	QCD TTbar, W+jets Z(→νν) + jets	TTbar W+jets	TTbar Z→ ll	WZ, ttW, ttZ, ttH, 1L process + "fake lepton"	WZ, ZZ ttW, ttZ, ttH, 2L process + "fake lepton"
	10^3-10^9 pb	10^3-10^4pb	10^2-10^3 pb	~0.1 pb	<0.1 pb

decreasing background

increasing signal acceptance

Generic SUSY RPC signatures



W to leptons: 32.6%
W to hadrons: 67.4%

Z to l^+l^-: 10.1%
Z to hadrons: 69.9%

Larger signal acceptance
in “all-hadronic” final states

More data from hadronic decays
More “clean” signature in leptonic decays

Search in a nutshell

Definition of the Signal Region(s) (SR)

e.g. all events with at least one hard jet with pT > 100 GeV and missing transverse energy > 150 GeV and 0 leptons

Search in a nutshell

Definition of the Signal Region(s) (SR)

Estimation of expected number of signal events from SUSY hypothesis

Search in a nutshell

Definition of the Signal Region(s) (SR)

Estimation of expected number of signal events from SUSY hypothesis

Estimation of expected contribution of SM background data in SR, using MC simulations and/or control selections in data (CRs)

Search in a nutshell

Definition of the Signal Region(s) (SR)

Estimation of expected number of signal events from SUSY hypothesis

Estimation of expected contribution of SM background data in SR, using MC simulations and/or control selections in data (CRs)

Assess uncertainty on the signal and background estimation

- limited statistics of the control regions
- experimental: jet energy scale, lepton reco. efficiency, …
- theoretical: pdfs, factorization and renormalization scales, …
- modelling: pile-up, underlying event, parton showering model, …

Search in a nutshell

Definition of the Signal Region(s) (SR)

Estimation of expected number of signal events from SUSY hypothesis

Estimation of expected contribution of SM background data in SR, using MC simulations and/or control selections in data (CRs)

Assess uncertainty on the signal and background estimation

Evaluate statistical compatibility of number of events in data with SM background prediction

Search in a nutshell



Definition of the Signal Region(s) (SR)

Estimation of expected number of signal events from SUSY hypothesis

Estimation of expected contribution of SM background data in SR, using MC simulations and/or control selections in data (CRs)

Assess uncertainty on the signal and background estimation

Evaluate statistical compatibility of number of events in data with SM background prediction

Interpretation: in case of a statistically significant excess of events in data over SM prediction, can it be attributed to a new physics signal

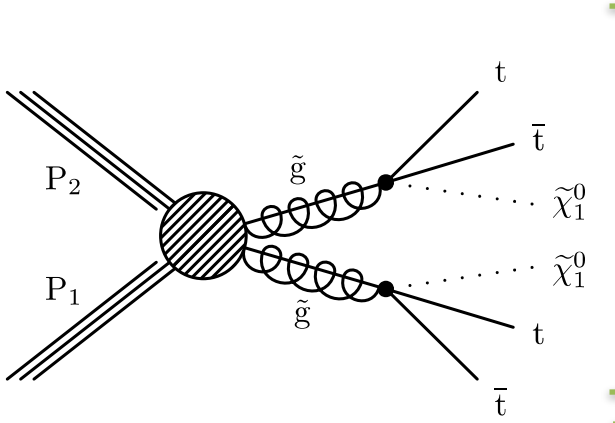
0 - lepton + MET + jets searches

n lep + m jets + MET

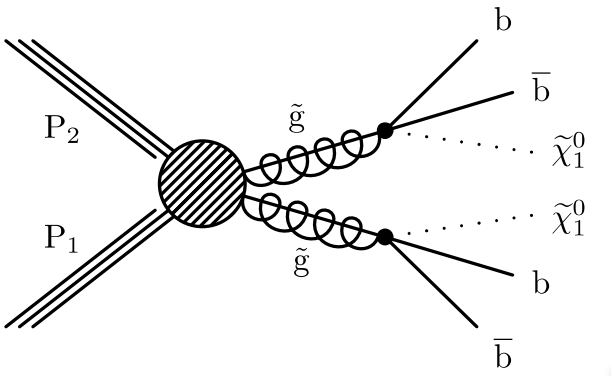
	0 lep + m jets + MET	1 lep + m jets + MET	2 lep(OS) + m jets + MET	2 lep(SS) + m jets + MET	>= 3 lep + m jets + MET
Signal signature					
Main backgrounds	QCD TTbar, W+jets $Z \rightarrow \nu\nu$	TTbar W+jets	TTbar $Z \rightarrow ll$	WZ, ttW, ttZ, ttH, 1L process + "fake lepton"	WZ, ZZ ttW, ttZ, ttH, 2L process + "fake lepton"
	10^3-10^9 pb	10^3-10^4pb	10^2-10^3 pb	~0.1 pb	<0.1 pb

Signal Regions definition

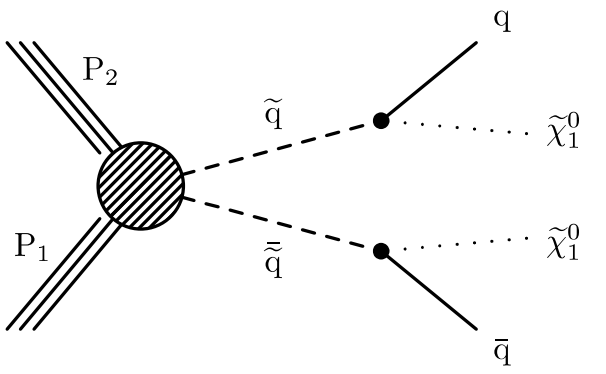
Definition of the Signal Region(s) (SR)



- 12 jets in final state
- 4 of them from b-quark hadronization



- 4 jets
- all of them are from b-quark

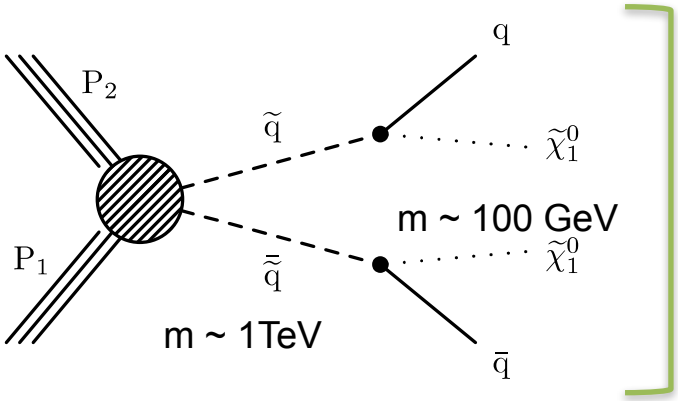


- 2 jets
- none of them are from b-quark

Different jet and b-jet multiplicities

Signal Regions definition

Definition of the Signal Region(s) (SR)

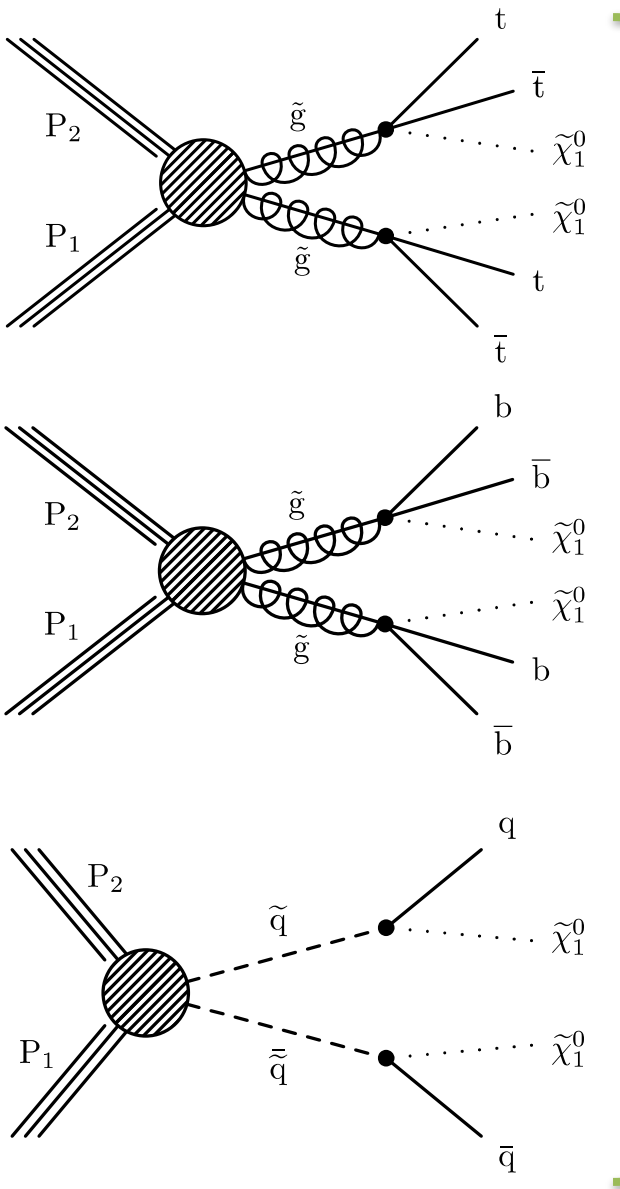


Assuming m_{squark} ~ 1 TeV and m_{LSP} ~ 100 GeV

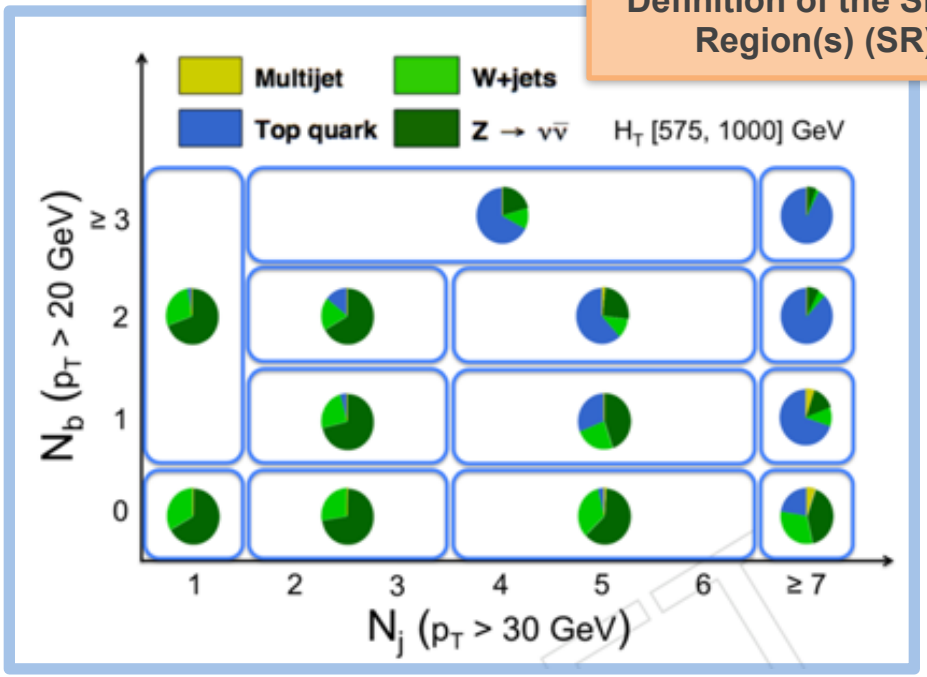
1000-100 GeV = 900 GeV of phase space available to boost the invisible LSP (and the quark)

Order of magnitude of expected MET for this signal

Signal Regions definition



Definition of the Signal Region(s) (SR)



To capture different signals, **use different selection criteria**, based on:

- n-jets and n-b-jets
- event activity (H_T), and ME_T

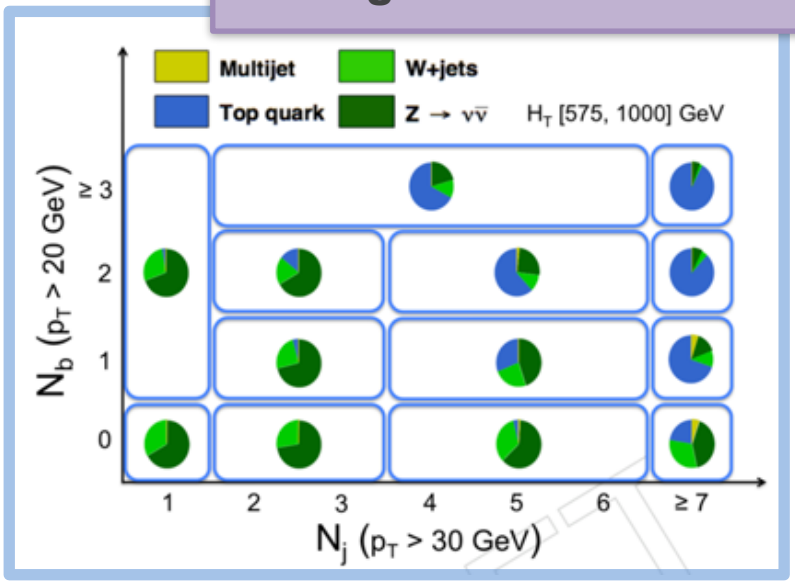
⇒ Bin the phase space (pre-selection) in all these variables and define ~300 signal regions

"Inclusive search"

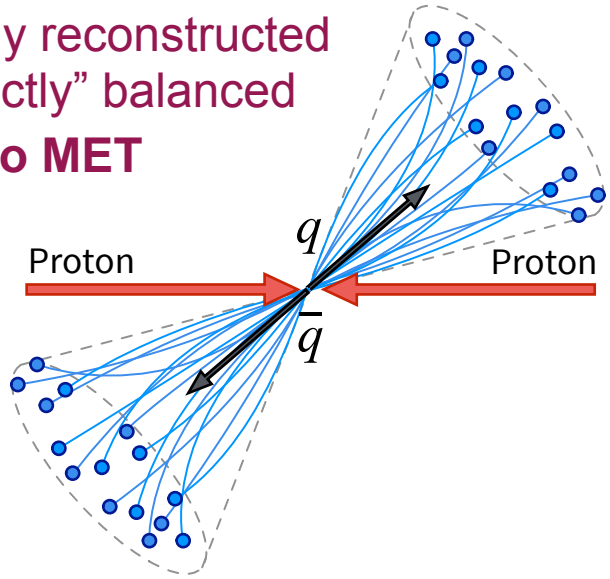
SM backgrounds

- Lost-lepton: semi-leptonic TTbar events and leptonic W+jets events where leptons are not reconstructed or are outside detector acceptance
- Neutrinos: Z+jets events where the Z decays into a pair of neutrinos
- Artificial MET: dijet and multi-jet events where MET is not caused by non-interacting particles but is due to jet mis-reconstruction.

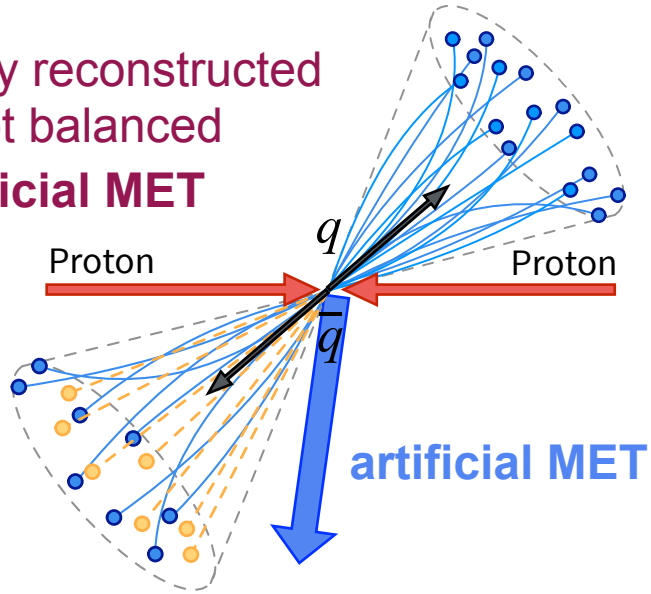
Background estimation



jet correctly reconstructed
p_T "perfectly" balanced
no MET



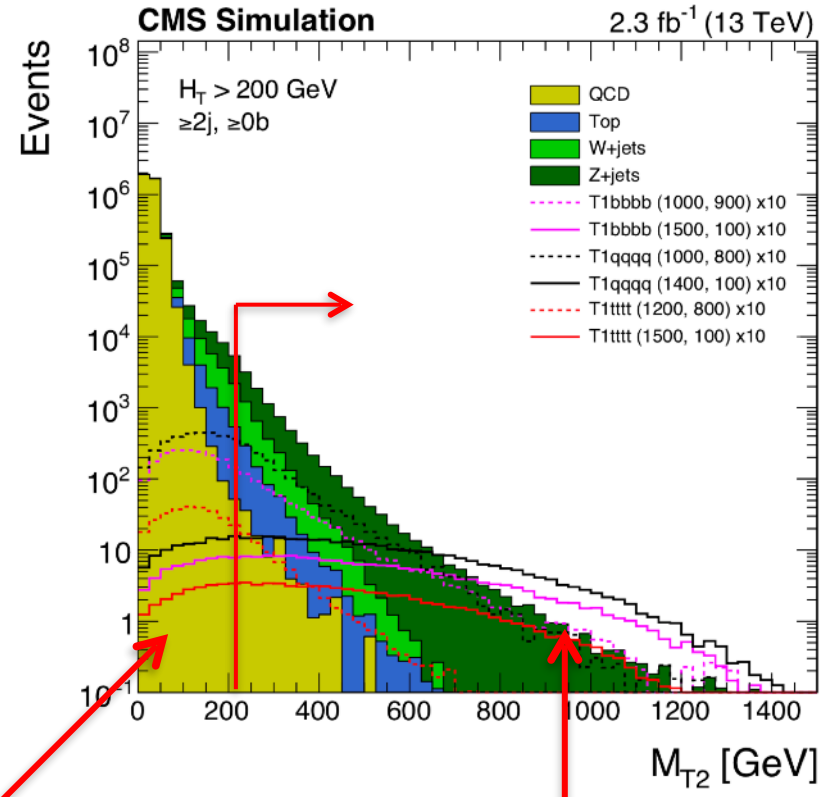
jet not fully reconstructed
p_T not balanced
artificial MET



SM backgrounds, kinematics

Background estimation

- Let's look at data distribution after preselection
- For our purpose we can consider M_{T2} ~ equivalent to the MET



multi-jets events only in the left-tail of distribution

signal is expected in the right tails

Background estimation

Definition of the Signal Region(s) (SR)

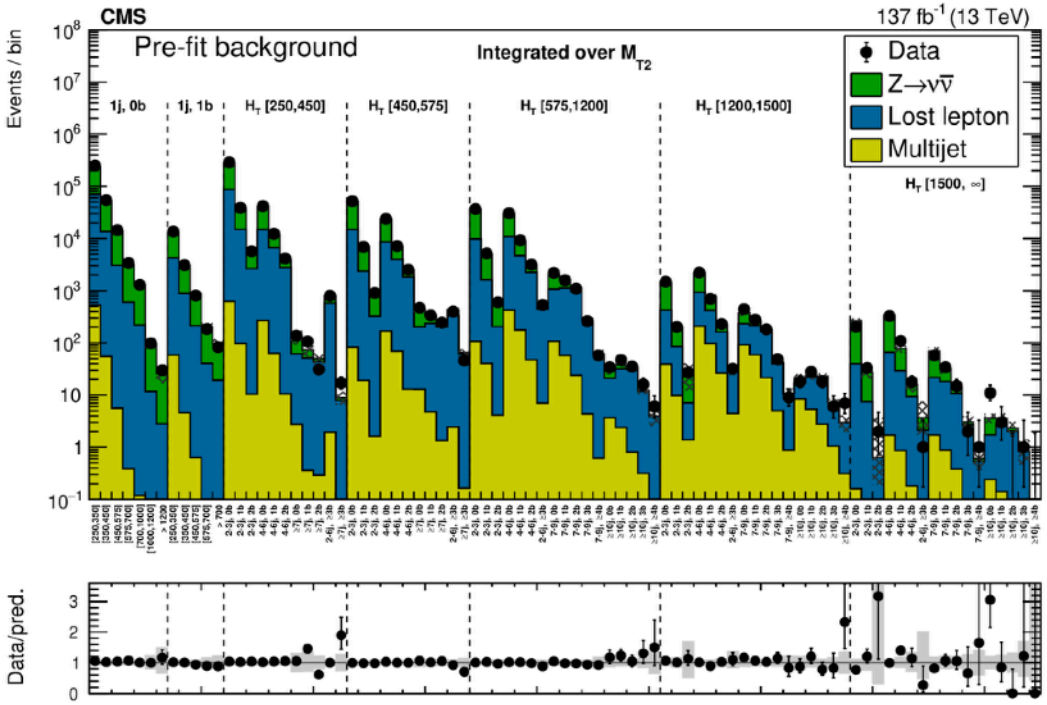
Estimation of expected number of signal events from SUSY hypothesis

Estimation of expected contribution of SM background data in SR, using MC simulations and/or control selections in data (CRs)

Examples of bkg estimation methods presented in next lectures

Unblinding!

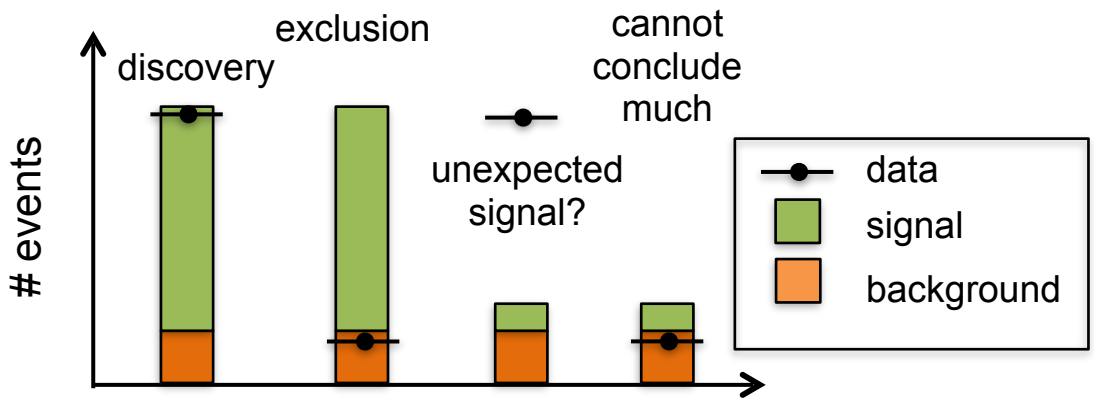
Statistical analysis



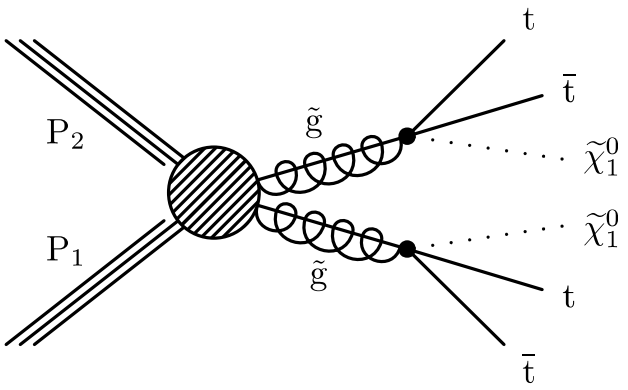
Data in SR are kept blind until the analysis strategy is consolidated and reviewed (to avoid experimentalist bias)

After unblinding data in all SRs is compared to the total bkg prediction.

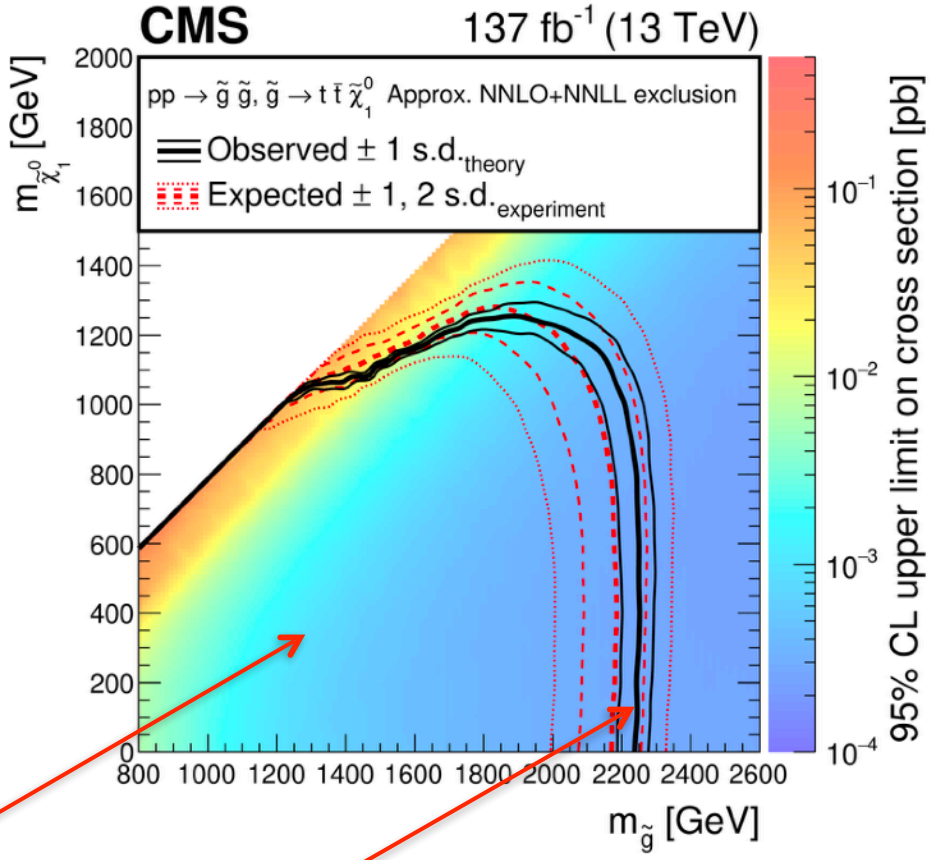
Is observation compatible with the background-only hypothesis?



Interpretation



Reminder: simplified model
- each model an independent hypothesis
- only few sparticles play a role (LSP and parent), all others decoupled



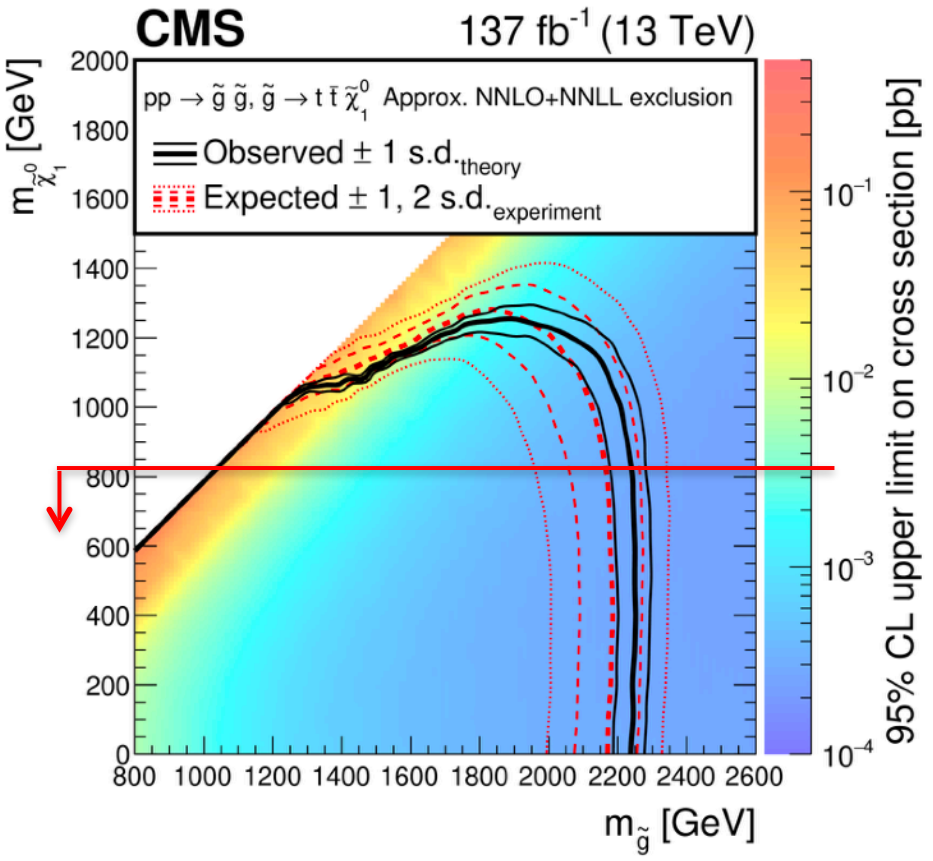
colour indicates the measured cross-section upper limit

lines indicate the region of the plane which is excluded by the data

CMS-SUS-19-005

Interpretation

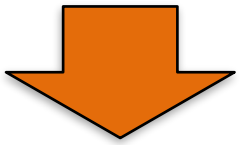
for light/medium light LSP, gluino excluded up to very large (~2TeV) masses

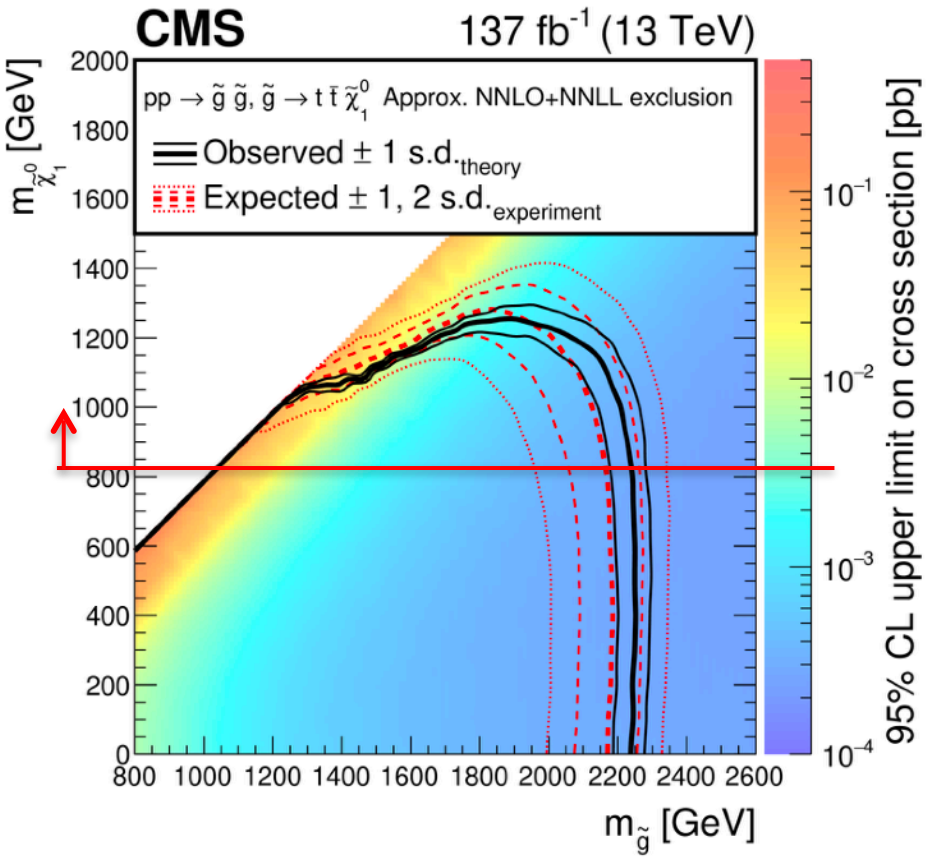


Interpretation

Heavy LSP → gluino excluded only for given range of (large) masses







Can use different **handles** to compensate for the smaller MET produced by signals ... and continue our voyage?

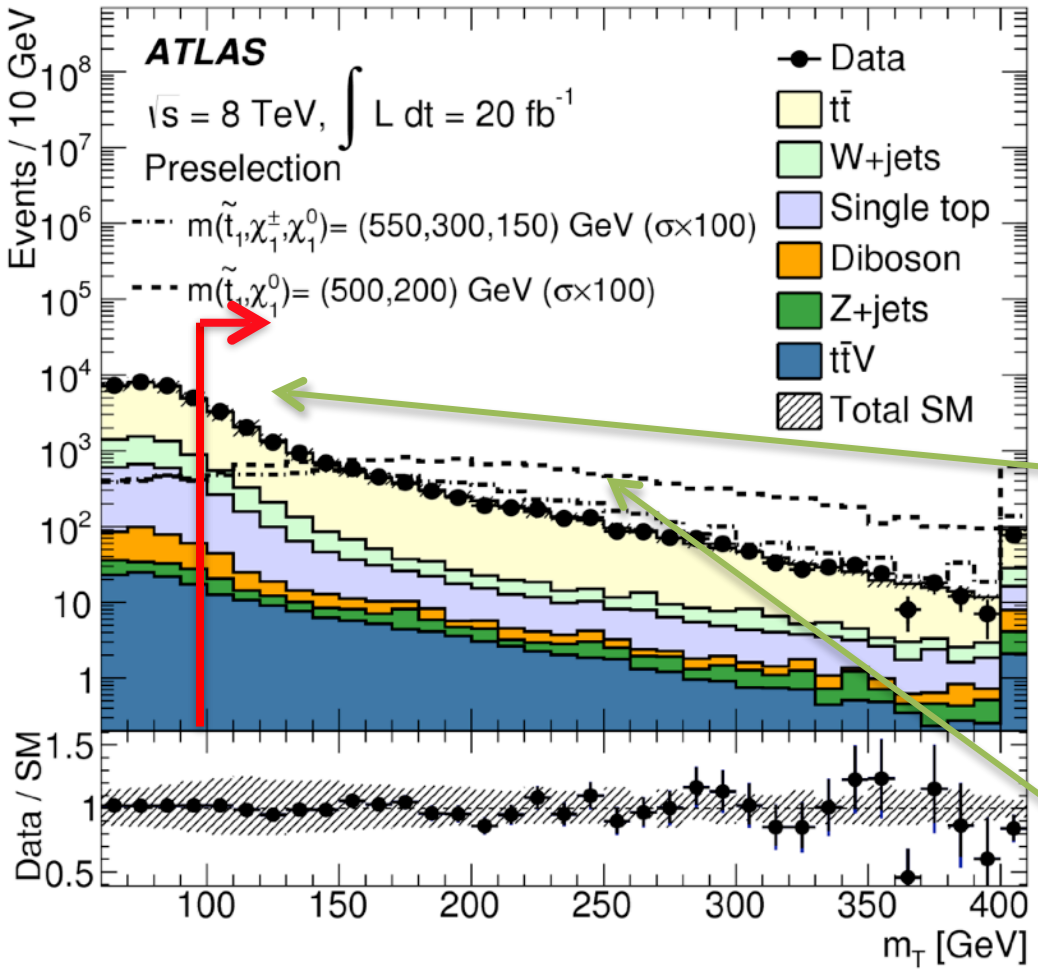
1 - lepton + MET + jets searches

n lep + m jets + MET

	0 lep + m jets + MET	1 lep + m jets + MET	2 lep(OS) + m jets + MET	2 lep(SS) + m jets + MET	>= 3 lep + m jets + MET
Signal signature					
Main backgrounds	QCD TTbar, W+jets $Z \rightarrow \nu\nu$	TTbar W+jets	TTbar $Z \rightarrow ll$	WZ, ttW, ttZ, ttH, 1L process + "fake lepton"	WZ, ZZ ttW, ttZ, ttH, 2L process + "fake lepton"
	10^3-10^9 pb	10^3-10^4pb	10^2-10^3 pb	~0.1 pb	<0.1 pb

Reduced signal acceptance is more than compensated by suppression of backgrounds (in particular QCD and $Z \rightarrow \nu\nu$)

1-lepton + MET searches



Transverse mass:

$$m_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos \Delta\phi(\vec{\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right)}$$

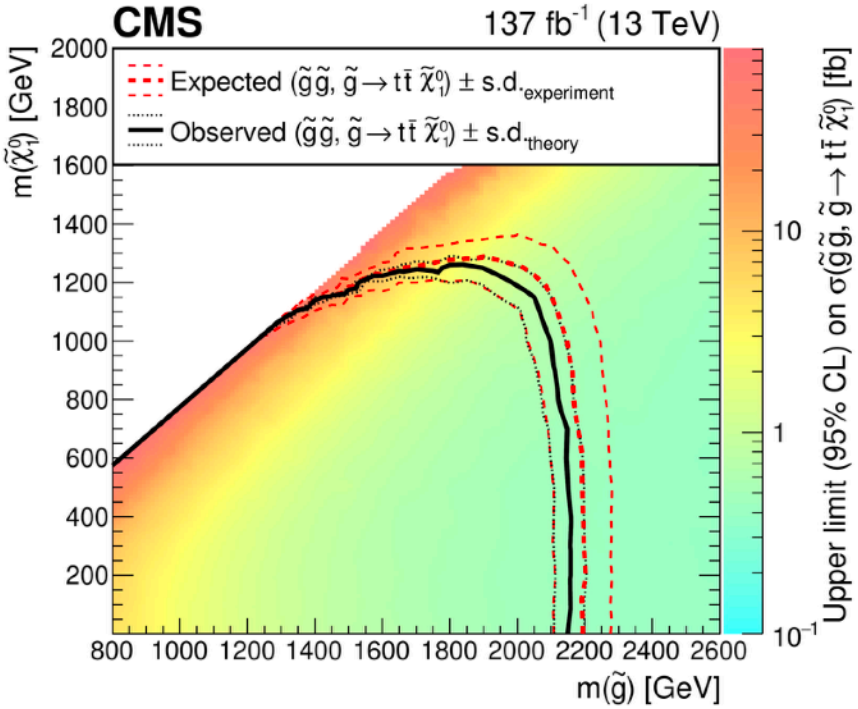
For a lepton from W →l nu decay, m_T < mass(W)

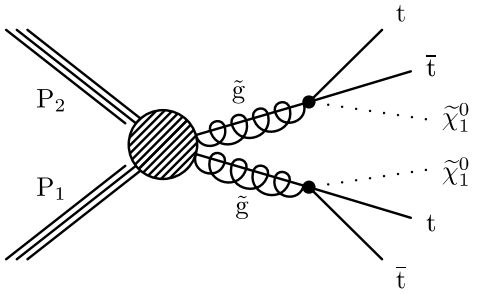
Distribution endpoint smeared by MET resolution tails

For signal, MET is from sum of neutrinos and pair of LSP in the event: m_T doesn't have endpoint at mass(W) value

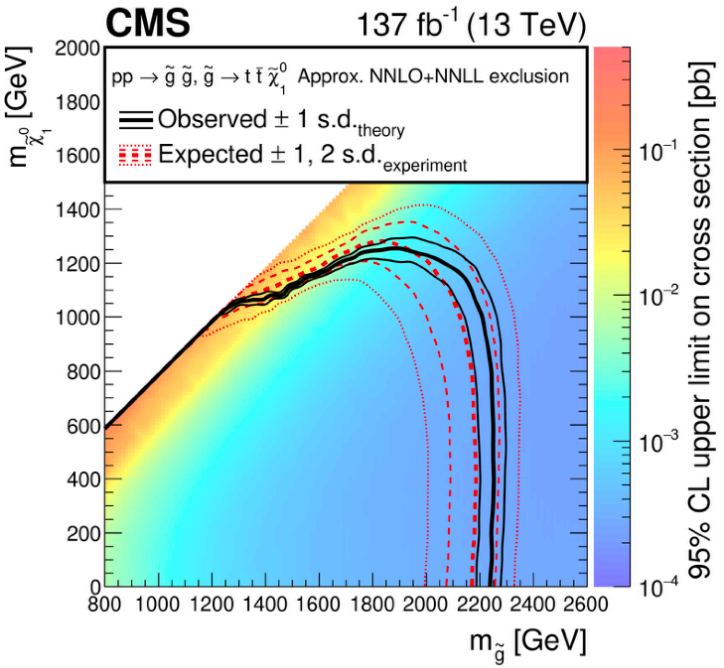
1-lepton searches: gluino production

1 lep - gluino production

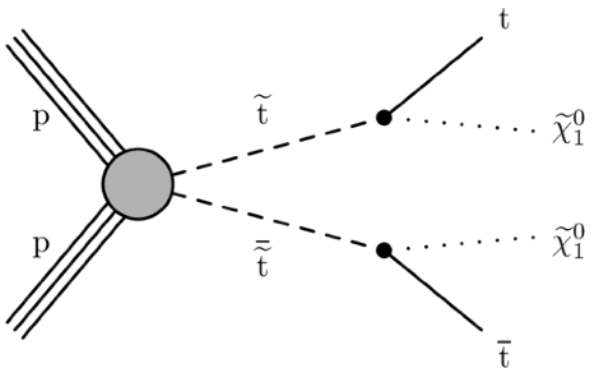




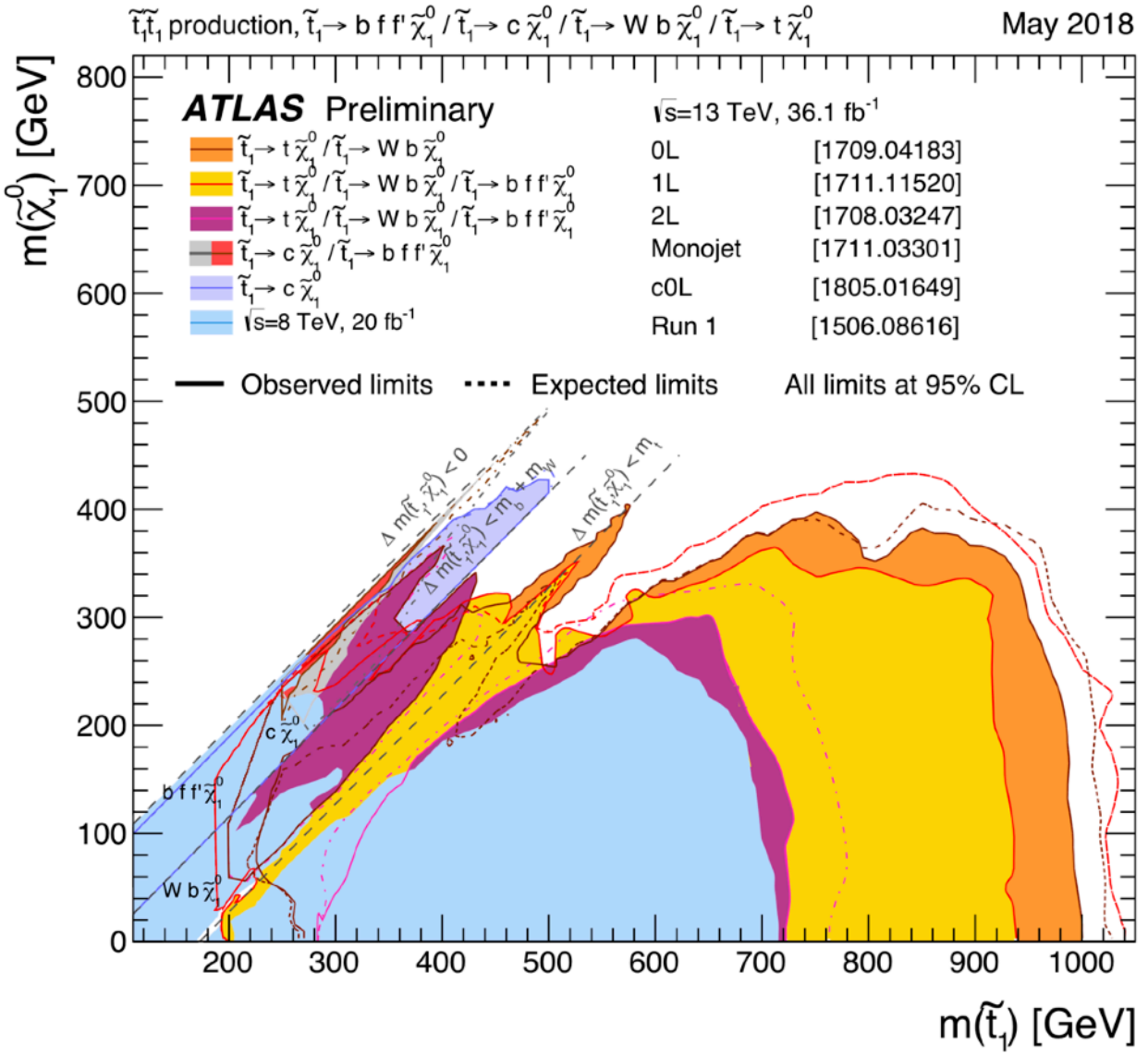
0 lep - gluino production



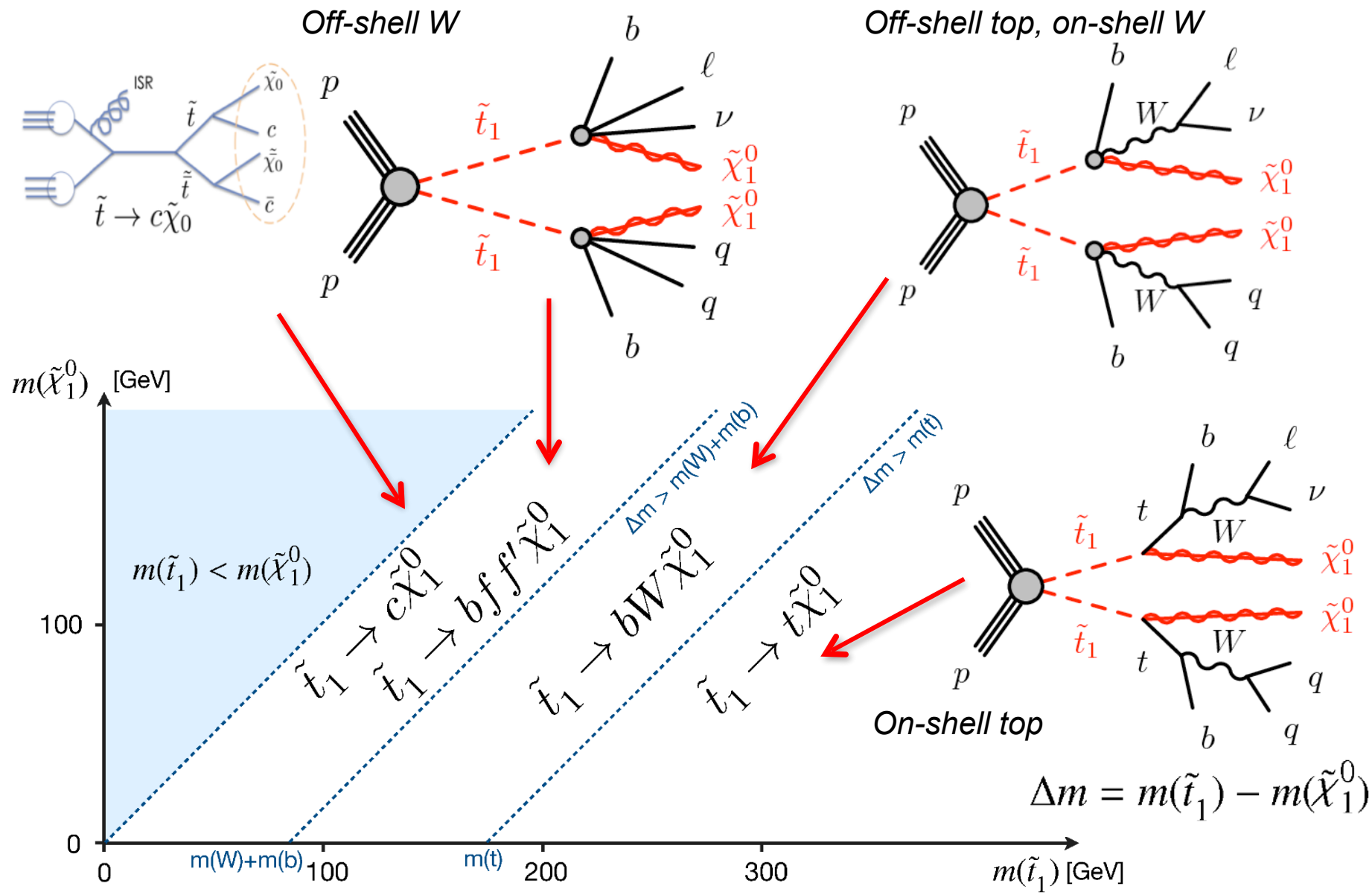
1-lepton searches: direct stop production



Important complementarity of different searches addressing different decay channels

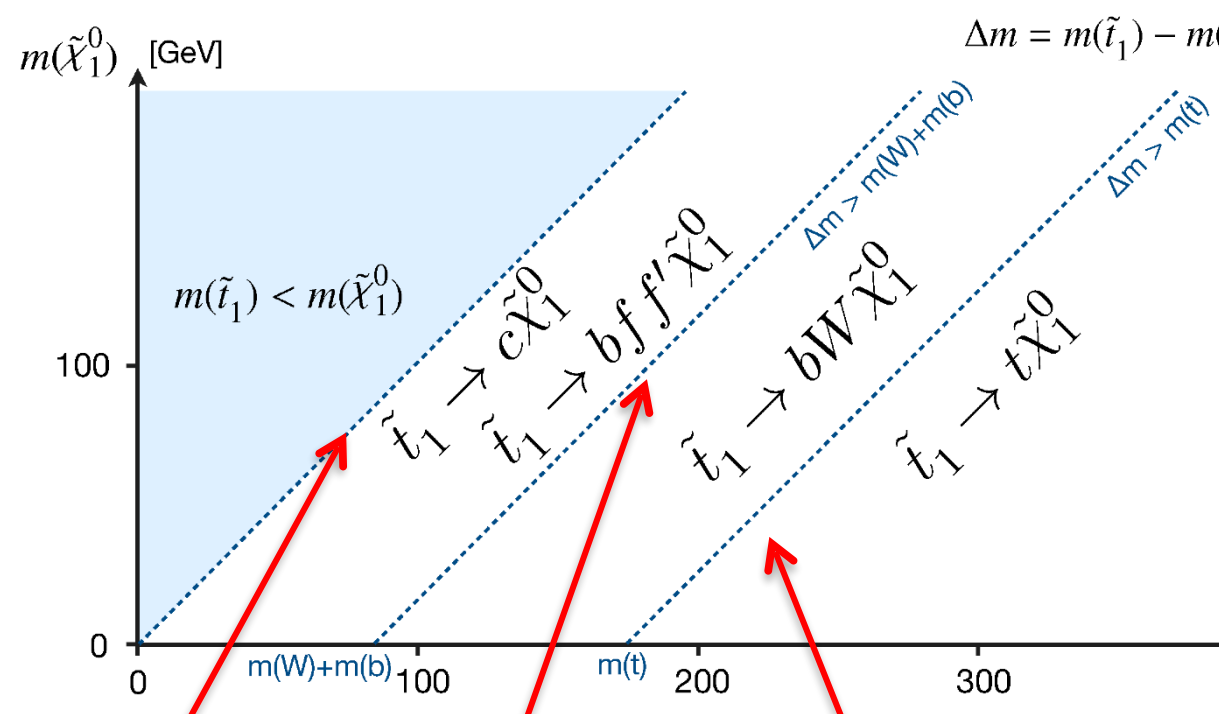


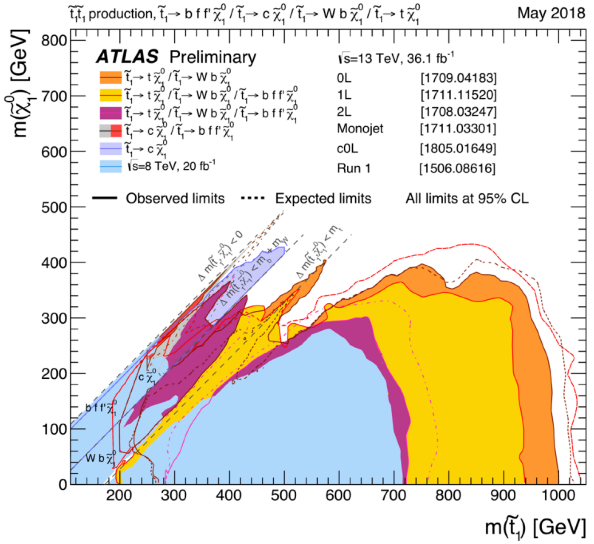
Direct stop production



Direct stop production

These "**compressed spectra**" are addressed with dedicated searches
In the end the **coverage** is practically **without gaps**





b-quark produced at rest

c-quark and LSP produced ~at rest

LSP produced at rest. Signal looks like SM TTbar production: "stealth stop" region

2L + MET search

n lep + m jets + MET

	0 lep + m jets + MET	1 lep + m jets + MET	2 lep(OS) + m jets + MET	2 lep(SS) + m jets + MET	>= 3 lep + m jets + MET
Signal signature					
Main backgrounds	QCD TTbar, W+jets $Z \rightarrow \nu\nu$	TTbar W+jets	TTbar $Z \rightarrow ll$	WZ, ttW, ttZ, ttH, 1L process + "fake lepton"	WZ, ZZ ttW, ttZ, ttH, 2L process + "fake lepton"
	10^3-10^9 pb	10^3-10^4pb	10^2-10^3 pb	~0.1 pb	<0.1 pb

Many more RPC searches exist, targeting different signals, also including photons in the final state

But the rationale is the same as we discussed so far

More options?

Different strategies for different signal hypotheses:

- Searches for RP-Conserving SUSY
- Searches for RP-Violating SUSY
- Searches of non-prompt decays or stable particles (exotic signatures)

R-parity violation (RPV)

- R-parity conservation (RPC) → stable LSP→ large MET
- SUSY Lagrangian also allows R-parity violating (RPV) terms

"leptonic RPV" "semi-leptonic RPV" "hadronic RPV"

$$W_{\not R} = \lambda_{ijk}\tilde{L}_i\tilde{L}_j\tilde{E}^c_k + \lambda'_{ijk}\tilde{L}_i\tilde{Q}_j\tilde{D}^c_k + \lambda''_{ijk}\tilde{U}^c_i\tilde{D}^c_j\tilde{D}^c_k$$

LSP can decay to lqq'

LSP can decay to l+l-v

LSP can decay to q q'qbar'

Lepton number violating terms

expected signature:
$pp \rightarrow$ SUSY $\rightarrow$ many leptons + X

Baryon number violating term

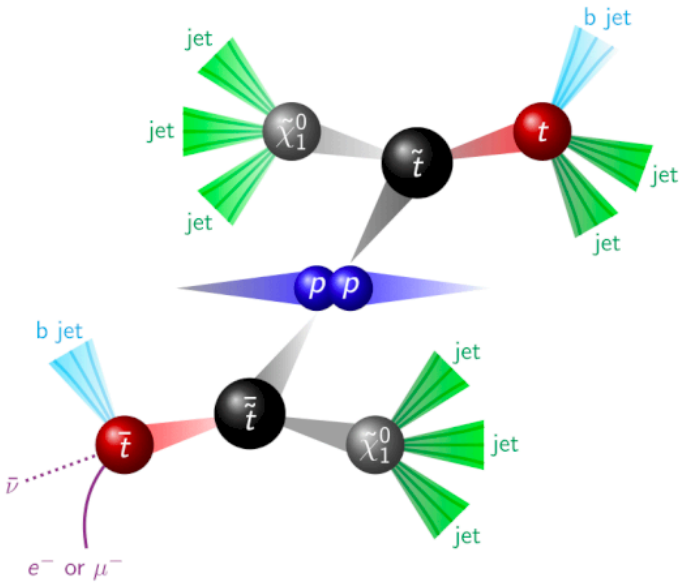
expected signature:
$pp \rightarrow$ SUSY $\rightarrow$ hadrons

R-parity violation (RPV)

- Either lepton or baryon number violation
- Pair-produced SUSY particles have the same production cross sections as in RPC case
- SUSY particles can be single produced
- SUSY particles can decay exclusively into SM particles (LSP is no more stable!)
    - invariant mass peak to access the sparticle mass
    - low (or no) MET in the final state
    - often high-multiplicity events

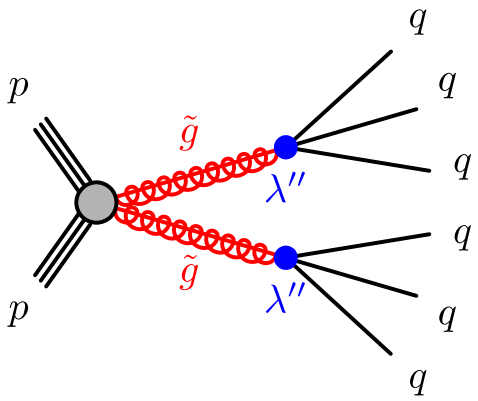
Different signature, different search strategies compared to RPC SUSY

Few examples in the following slides



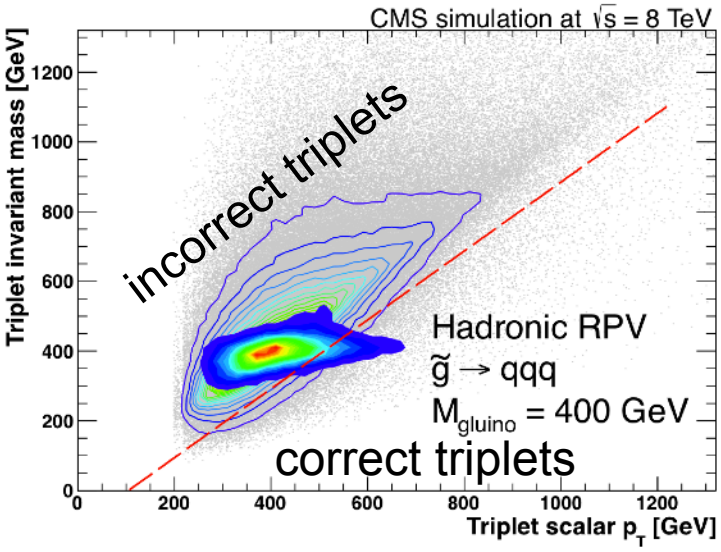
RPV gluino search

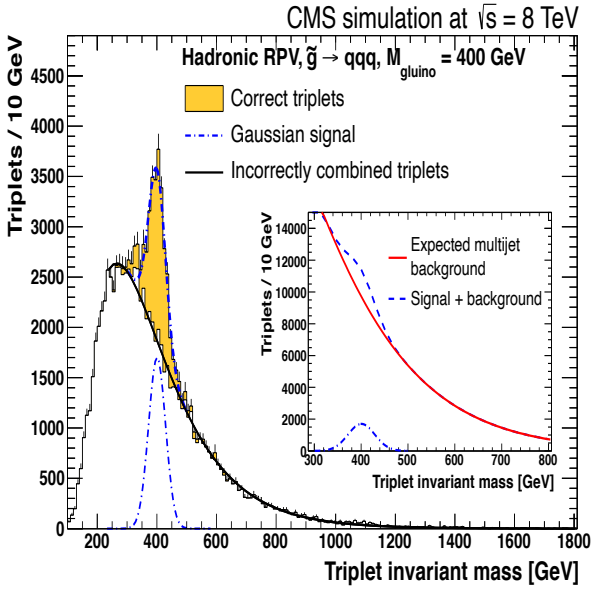
We can reconstruct a mass peak



- Need to solve a combinatorial problem
  - combine 6 highest p_T jets into all possible unique triplets
  - require each triplet to pass

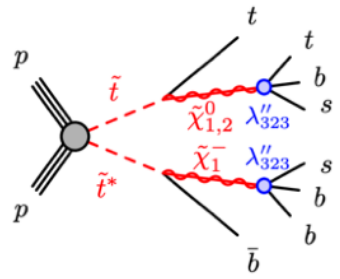
    $M_{jjj} < \Sigma_{jjj}|p_{TJet}| - \Delta$ (diagonal offset)
- remaining combinatorial background has a smoothly falling distribution; absorbed in the estimation of the QCD background
- a "bump hunt" of a Gaussian signal over an optimized functional form for the background



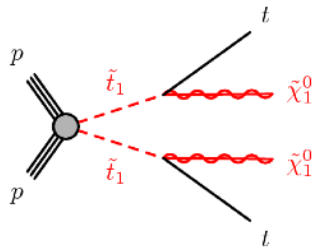


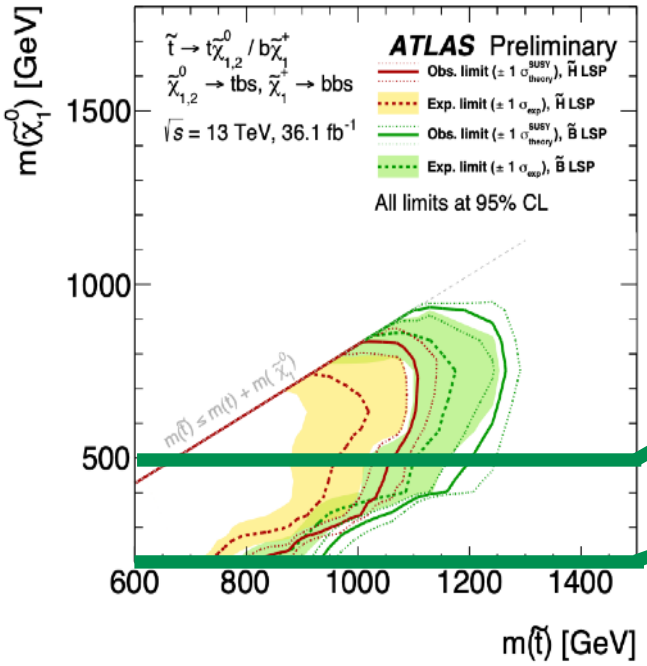
RPV top squark search

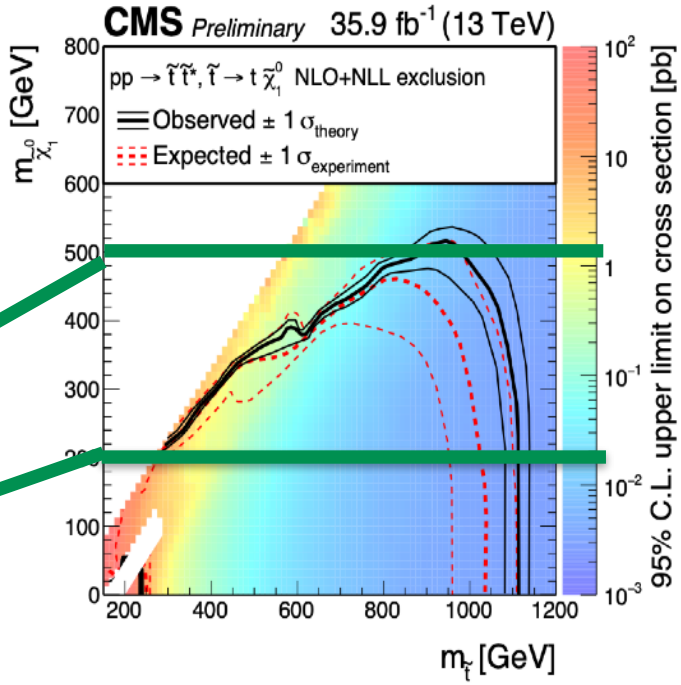
RPV



RPC



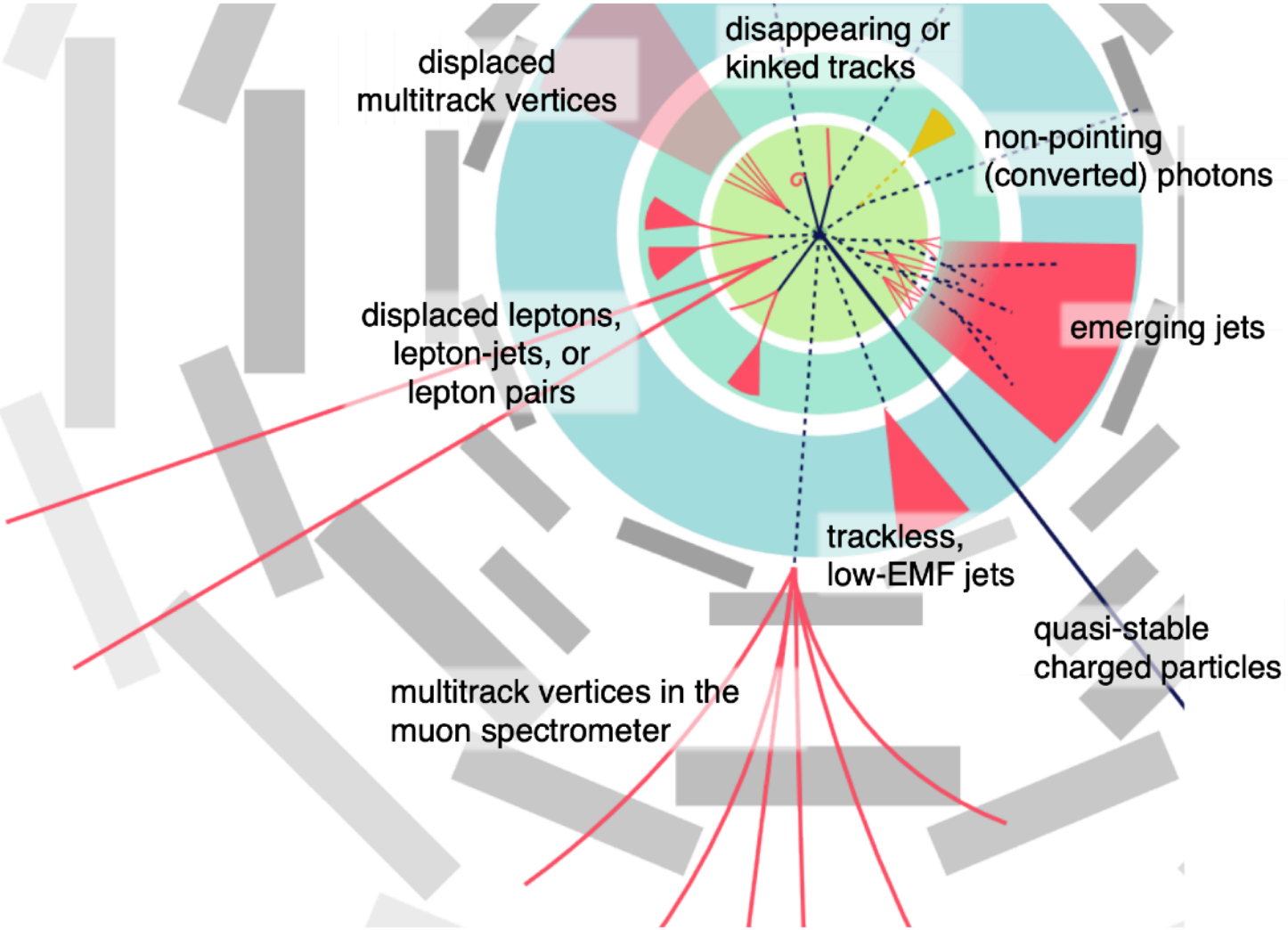




Similar final state as the RPC analysis:1L and many jets, but mostly without MET

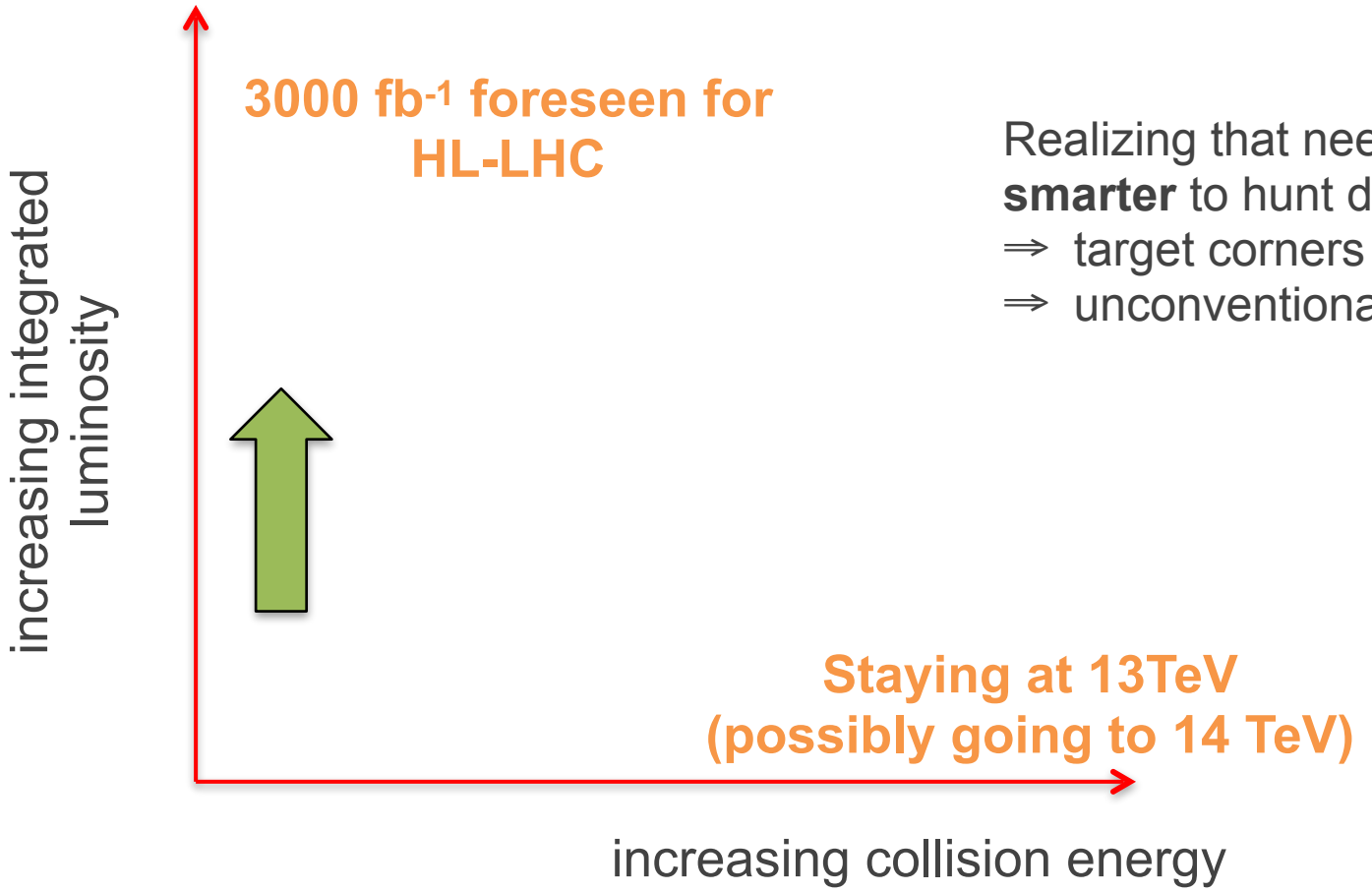
Very different limits depending on the considered model (RPV or RPC)

Exotic signatures



https://arxiv.org/pdf/1903.04497.pdf

What is next?



Realizing that need to **get smarter** to hunt down SUSY!

⇒ target corners

⇒ unconventional signatures

Summary

- SUSY is quite complex (and very fascinating): lots of SUSY hypotheses and lots of searches underway at particle colliders
    - RPC: MET driven searches; look for excess of events in the tails of MET-related distributions
    - RPV: Mass peak reconstruction; bump hunt search
    - Exotic SUSY scenarios: Unconventional signatures; demand ad hoc strategies (reconstruction) —> will this later in the course
- A comprehensive inclusive strategy is critical to probe SUSY (and other BSM scenarios)
    - Explore different final states
- Stringent constraints to some regions of the parameter space
    - Need more statistics, different strategies to rule out SUSY in the corners

References

ATLAS & CMS SUSY Summary plots:

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Recent review articles:

- PDG review, “Supersymmetry, Part II (Experiment)” rpp2018
- “Supersymmetry after the Higgs Discovery”, 2014, Springer
    - Chapter “Lessons for SUSY from the LHC after the first run”
- (Theory) S.Martin, “A Supersymmetry Primer”, 2011, hep-ph/9709356

Additional material

Course Program

What's the objective of this course? To introduce you to the quest for new physics beyond the standard model (BSM), presenting a selection of theoretical models predicting the existence of new particles and interactions, along with a presentation of experimental methods deployed at particle colliders to probe such models.

- 24. Feb : **Introduction** Part 1 by A. de Cosa and Part 2 by M. Spira
- 03. Mar: **Standard Model** by M. Spira
- 10. Mar: **GUT** by M. Spira
- 17. Mar: **Supersymmetry** Part 1 by M. Spira
- 24. Mar: **Supersymmetry** Part 2 by M. Spira
- 31. Mar: **SUSY Standard Model** by M. Spira
- 14. Apr: **SUSY-GUT** by M. Spira
- 21. Apr : **SUSY and SUSY Higgs Phenomenology** by M. Spira
- 28. Apr : **Sparticle Search and R-Parity Violation** by A. de Cosa
- 05. May: **MSSM Higgs Bosons Search** by A. de Cosa
- 12. May: **Supersymmetric Dark Matter** by M. Spira
- 19. May: **Dark Matter Searches** by A. de Cosa
- 26. May: **Hidden Valley Theory** by M. Spira and Search by A. de Cosa
- 02. Jun: **Experimental Strategies for BSM Searches** by A. de Cosa

2L OS + MET search

All hadronic (or lepton veto) + MET	1-lepton + MET	2-lepton opposite-sign + MET	2-lepton same-sign + MET	>= 3 leptons + MET
QCD TTbar, W+jets Z→ nunu	TTbar W+jets	TTbar Z→ ll	WZ, ttW, ttZ, ttH 1L process + "fake lepton"	WZ, ZZ ttW, ttZ, ttH 2L process + "fake lepton"

- Background from fully-leptonic TTbar decays and Z→ ll events is not negligible compared to expected signal
- However, background can be nicely and precisely estimated from data

2L OS + MET search

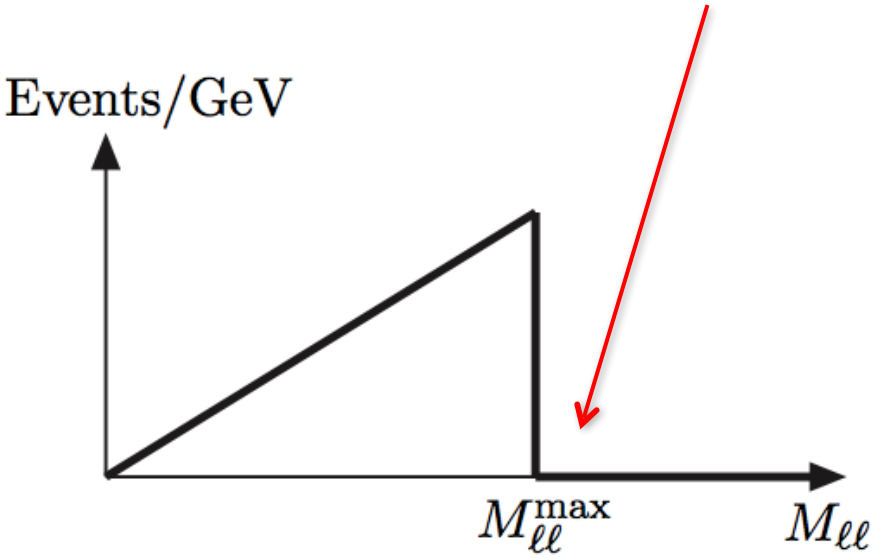
$$\tilde{\chi}_2^0 \rightarrow \ell\tilde{\ell} \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$

$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$

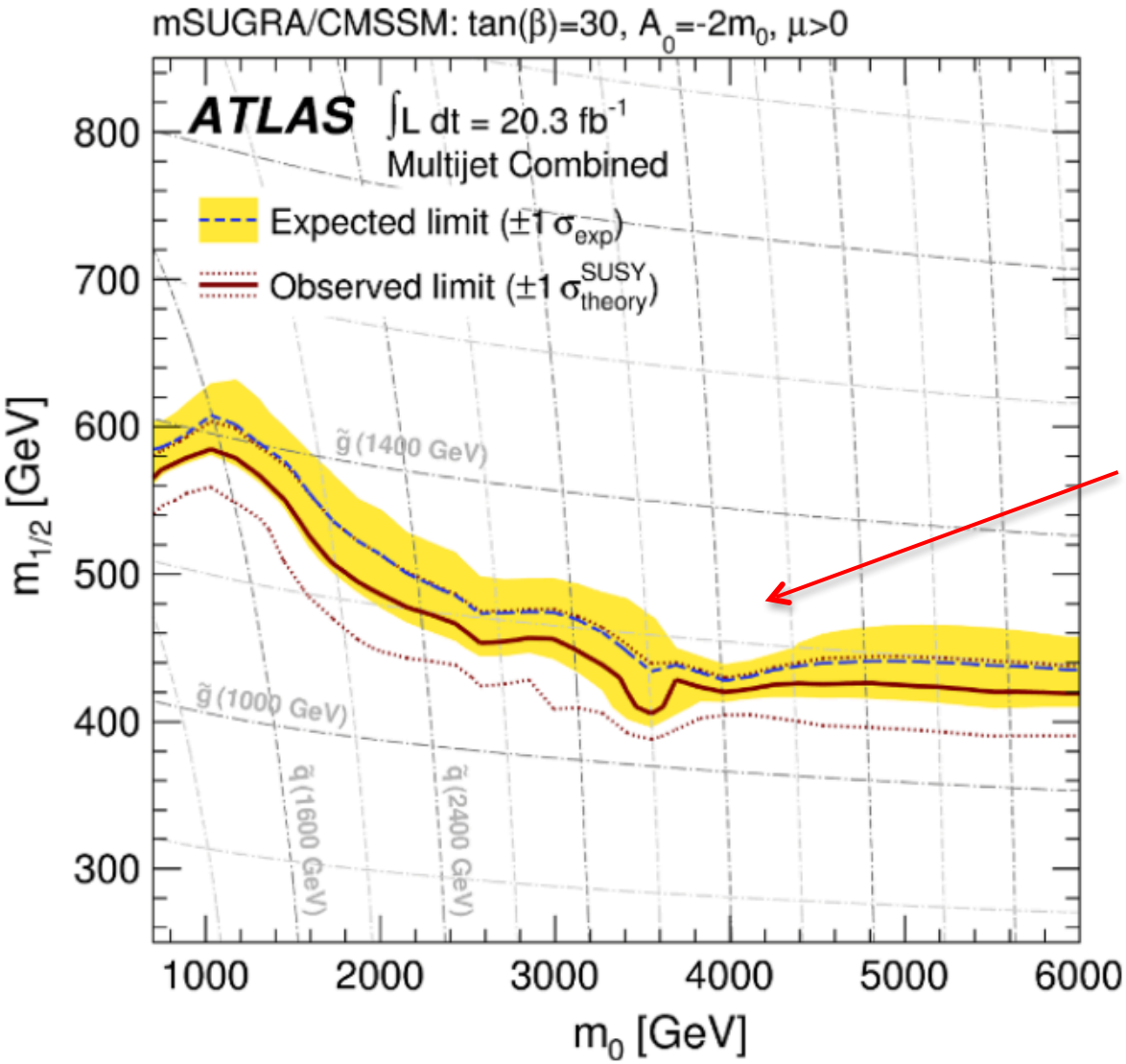
edge position depends on the difference in mass between the two neutralinos

Dominant and LARGE background:
fully leptonic ttbar events

Peculiarity of this channel:
"edge" in the M(ll) distribution



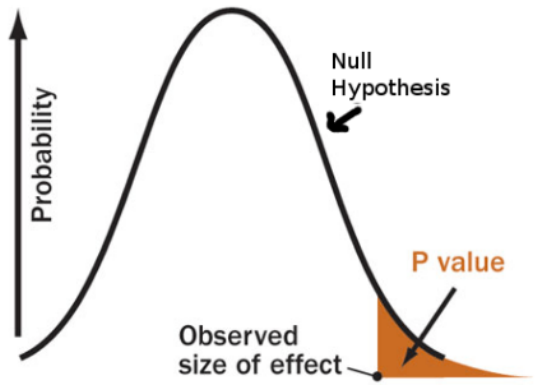
0 - lepton + MET results: full model



E.g. : mSUGRA model

lines indicate the region of the “parameters plane” which is excluded by the data

P-value



- **P-value:**
  probability of finding as outcome of the experiment a number of events that is more incompatible or equally incompatible with the bkg-only hypothesis (null hypothesis)

  p-value = 0.0000003 <=> 5 σ significance
  => discovery of a new particle

Non prompt decays in RPV SUSY

Lifetime of neutralino from few picoseconds to nanoseconds depending on how weak the coupling λ is

