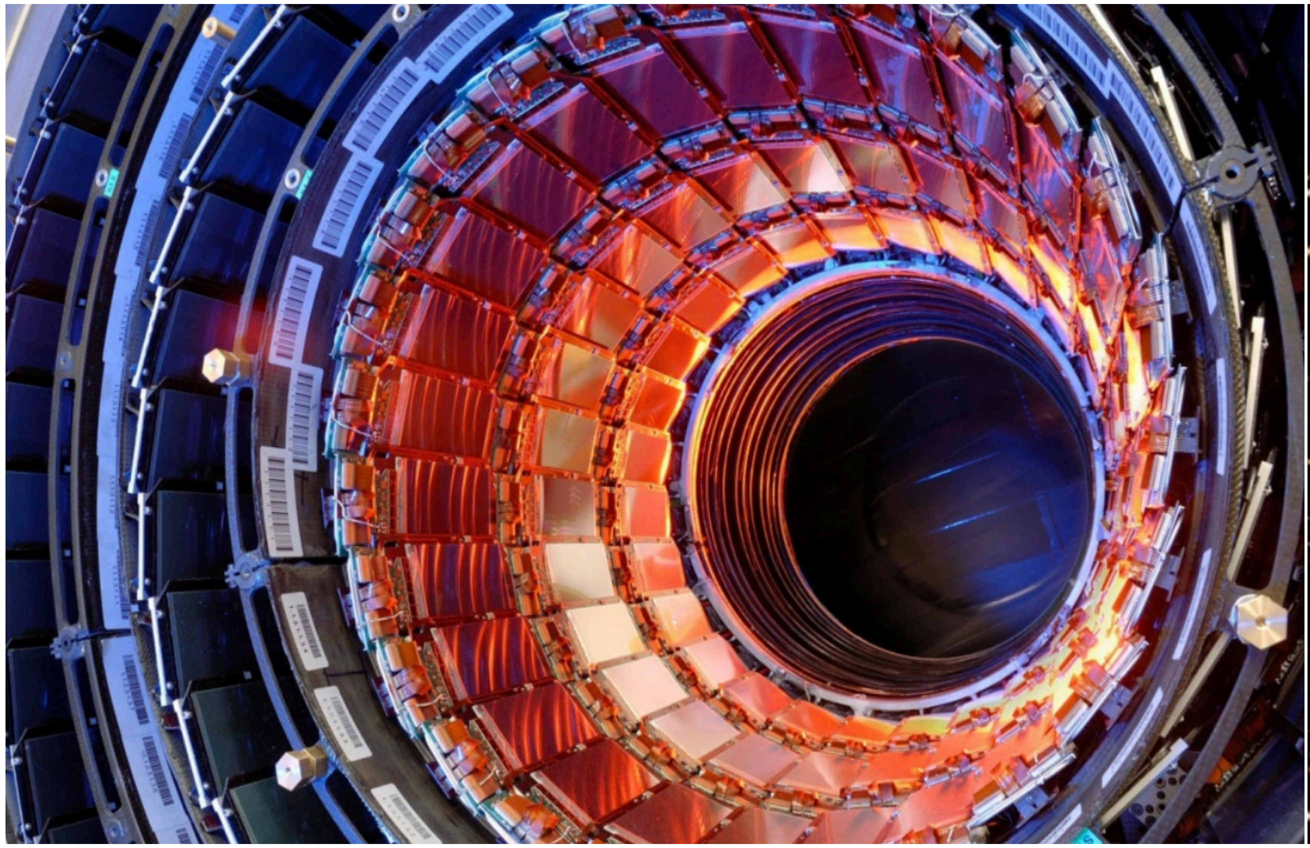


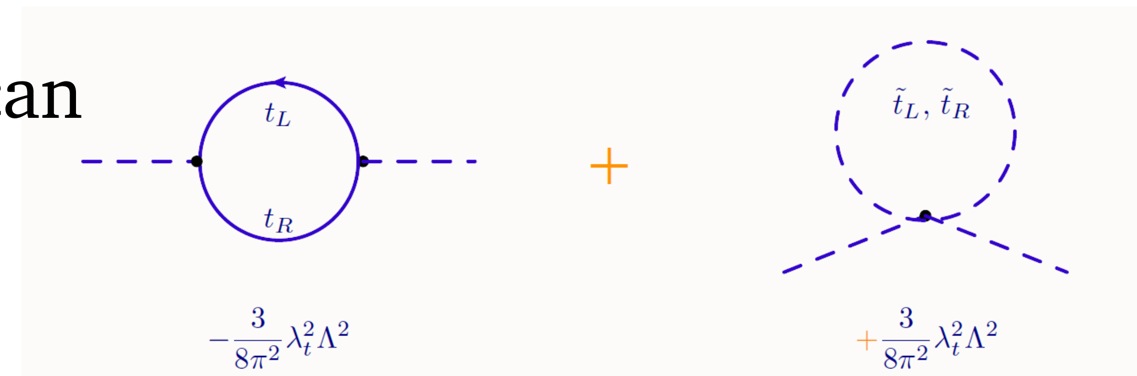
Supersymmetry at LHC:
experimental overview and future trigger challenges

Cristina Botta, University of Zurich

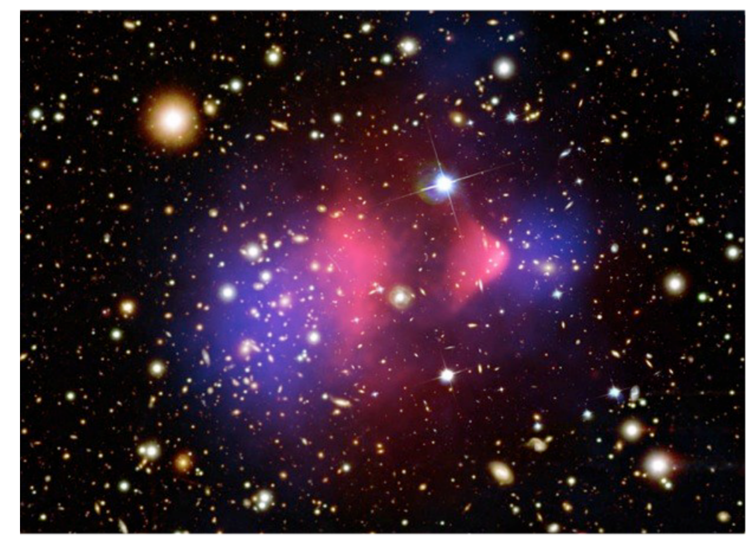
LTP/PSI Thursday Colloquia

Supersymmetry and its needs

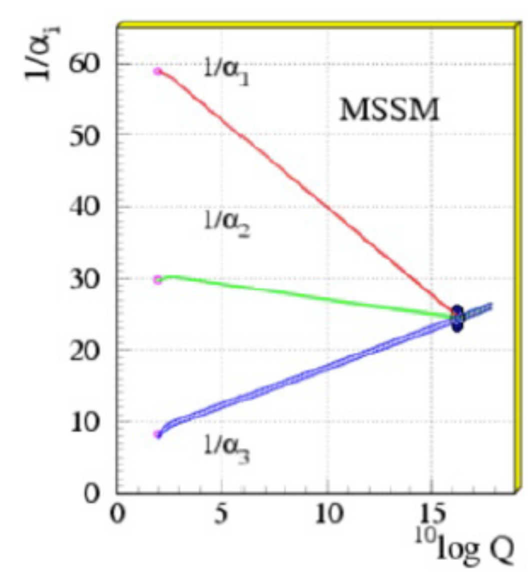
- **Still the most attractive theory model that could potentially solve most of the shortcomings of the Standard Model**



- **very compelling theory:** symmetry that can rotate boson into fermions and viceversa
  - needs **partners for all SM particles**, spin different by 1/2, charged under SM charges

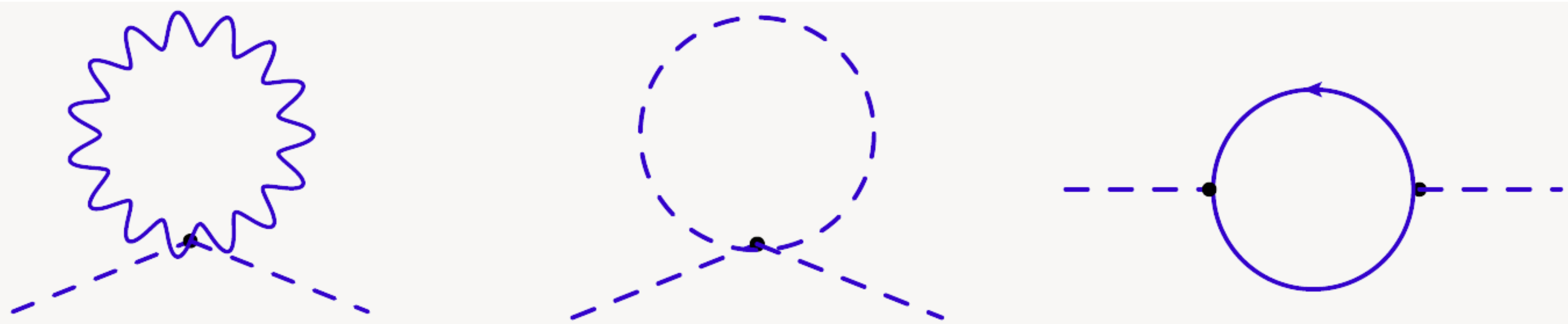


- can solve **the Hierarchy problem**, and make the theory natural
  - if the most important states to solve the problem are at the weak scale: **Higgsinos <~300 GeV, top squarks <~1TeV, gluinos <~2 TeV**
- can provide a **Dark Matter candidate**
  - **if R-parity is conserved:** stable LSP
  - neutral candidate of the extended EWK sector perfect WIMP: **lightest neutralino**
- can predict the **SM forces unification**
  - at the high scale, just below the Planck scale



The hierarchy problem

- **The discovery of the Higgs boson has led to an unprecedented situation: first "fundamental" scalar particle to be observed**
  - the **quantum correction to the input value of the Higgs mass parameter** from higher order Feynman diagrams **have quadratic divergence in Λ^2**



$\frac{9}{64\pi^2}g^2\Lambda^2$ $\qquad$ $\frac{1}{16\pi^2}\lambda^2\Lambda^2$ $\qquad$ $-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$

From interaction with massive gauge bosons

From self interaction

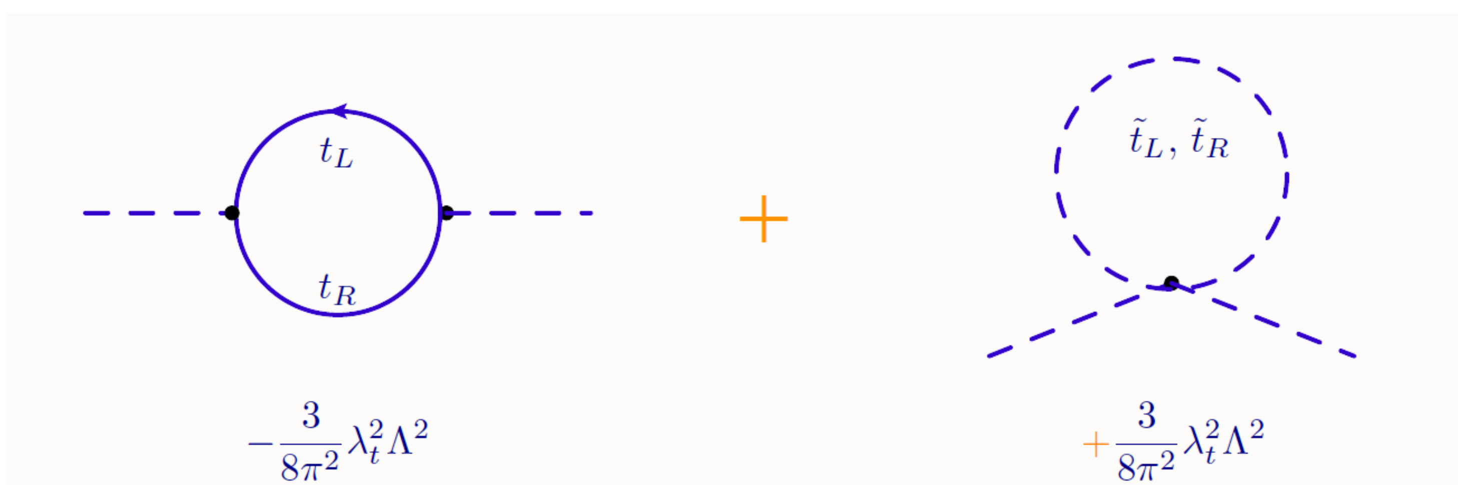
From interaction with fermions: dominated by top Yukawa coupling

- **The problem: $\Lambda = M_{Pl} \sim 10^{19}$ GeV** (limit of validity of theory)
  - **getting m_H = 125 GeV requires an extremely delicate cancellation** between value at Λ and the **contribution from all intermediate scales**: **theory is fine-tuned (i.e. not natural)?**

Solutions to the hierarchy problem

- **What if Λ (scale up to which the SM is valid) ~ TeV ?**
  - **m_H** is a **message:** scale of new physics

- **New physics has to be special: cancel the quadratic divergences**
  - theory above this scale must be free of quadratic divergences
  - to have exact cancellation need **a lot of new states and a symmetry to relate couplings of NP to those of the SM**



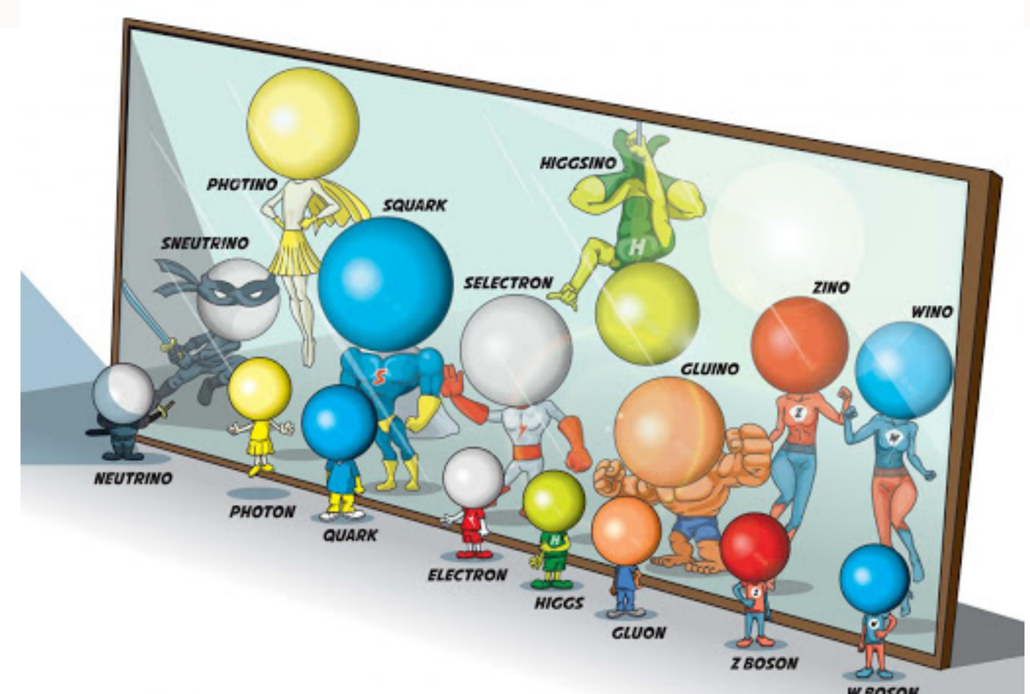
- **How massive should new physics be? Subjective**
  - **is 1 TeV ok? 10 TeV? 100 TeV?** depends how much fine tuning is accepted

Paramount example: Supersymmetry

- **Introduce in SM Lagrangian Symmetry that can rotate boson into fermions and viceversa**
  - Extremely predictive
  - **More than double the particle of SM**
    - two Higgs doublets (5 Higgses, a light and a heavy cp-even, a cp-odd one, and two charged ones: h,H,A,H$^{\pm}$)
  - Fewer parameters
- **But of course we know that Supersymmetry is broken in nature…**
  - we are made out of electrons and not selectrons!
  - given they have different masses divergences cancel up to some extent
  - SUSY-breaking Lagrangian: a lot of new free parameters (100!) and contains terms that violate B and/or L numbers

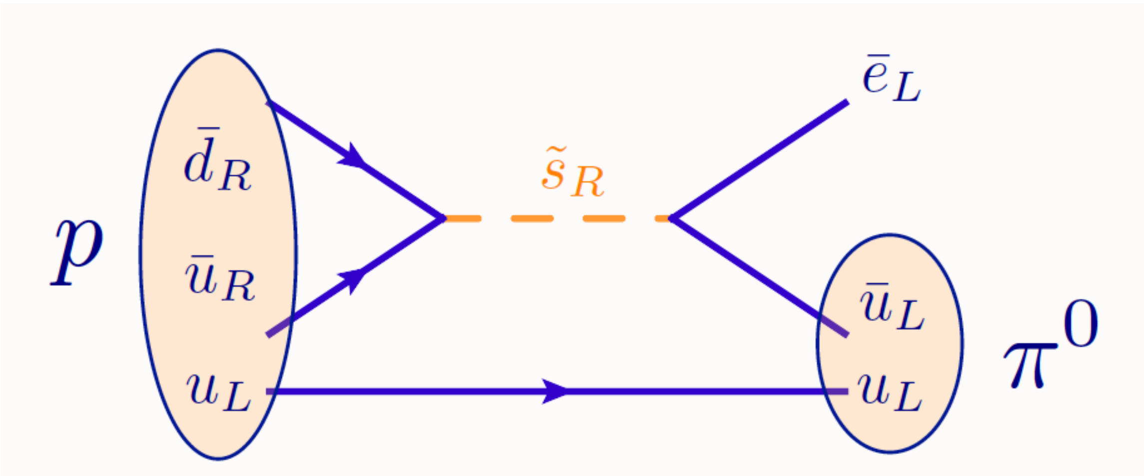
MSSM particle content

particles	sparticles
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$ $\tilde{u}_R$ $\tilde{d}_R$
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R ν_R	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$ $\tilde{e}_R$ $\tilde{\nu}_R$
H_u H_d	$\tilde{H}_u$ $\tilde{H}_d$
g^a_μ W^a_μ B_μ	$\tilde{g}^a$ $\tilde{W}^a$ $\tilde{B}$



Supersymmetry also for Dark Matter

- those could cause catastrophic proton decay



$$\Gamma \sim \frac{|\lambda''_{112}\lambda'_{112}|^2 m_p^5}{m_{\tilde{s}}^4} < 10^{34} \text{ years}$$

  - to avoid that is the **product of B, L violating Yukawa couplings that has to be extremely small**

- **Easy solution: impose a new global symmetry, R-parity**
  - that forbids these terms and it is respected by gauge interactions

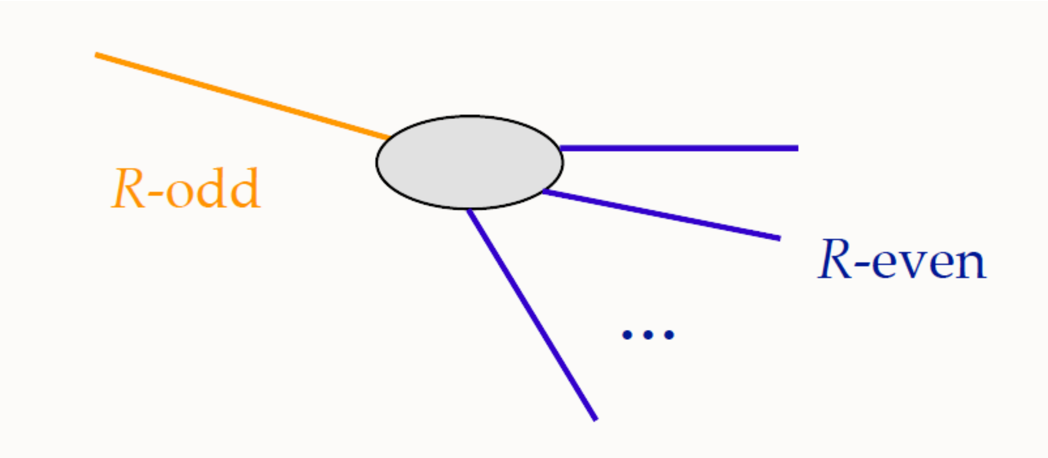
$$P_R = (-1)^{3(B-L)+2s}$$

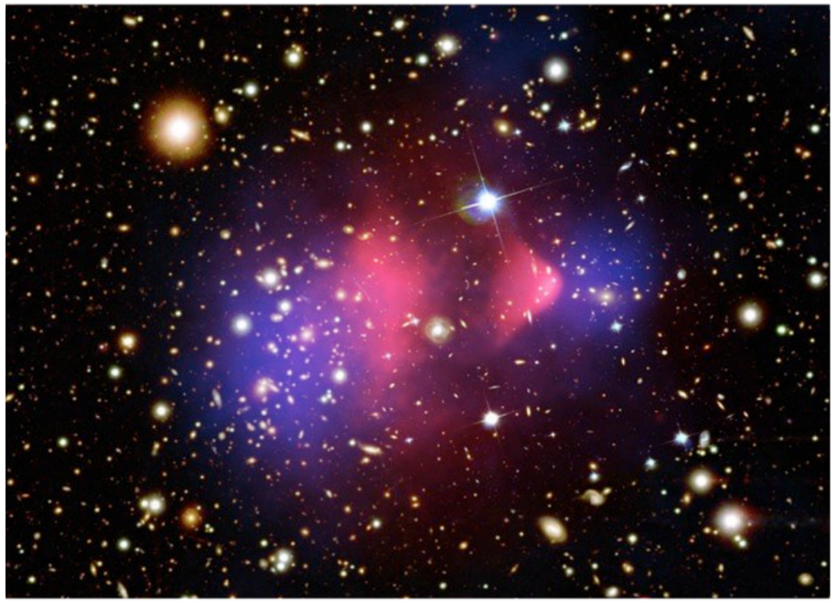
[Trust that it works!]

even	odd
f (spin 1/2)	$\tilde{f}$ (spin 0)
V (spin 1)	$\tilde{V}$ (spin 1/2)
H (spin 0)	$\tilde{H}$ (spin 1/2)

Supersymmetry also for Dark Matter

- **Consequence: Lightest Supersymmetric Particle (LSP) is stable**
  - something that is odd under R-parity can't decay in any number of even R-parity states





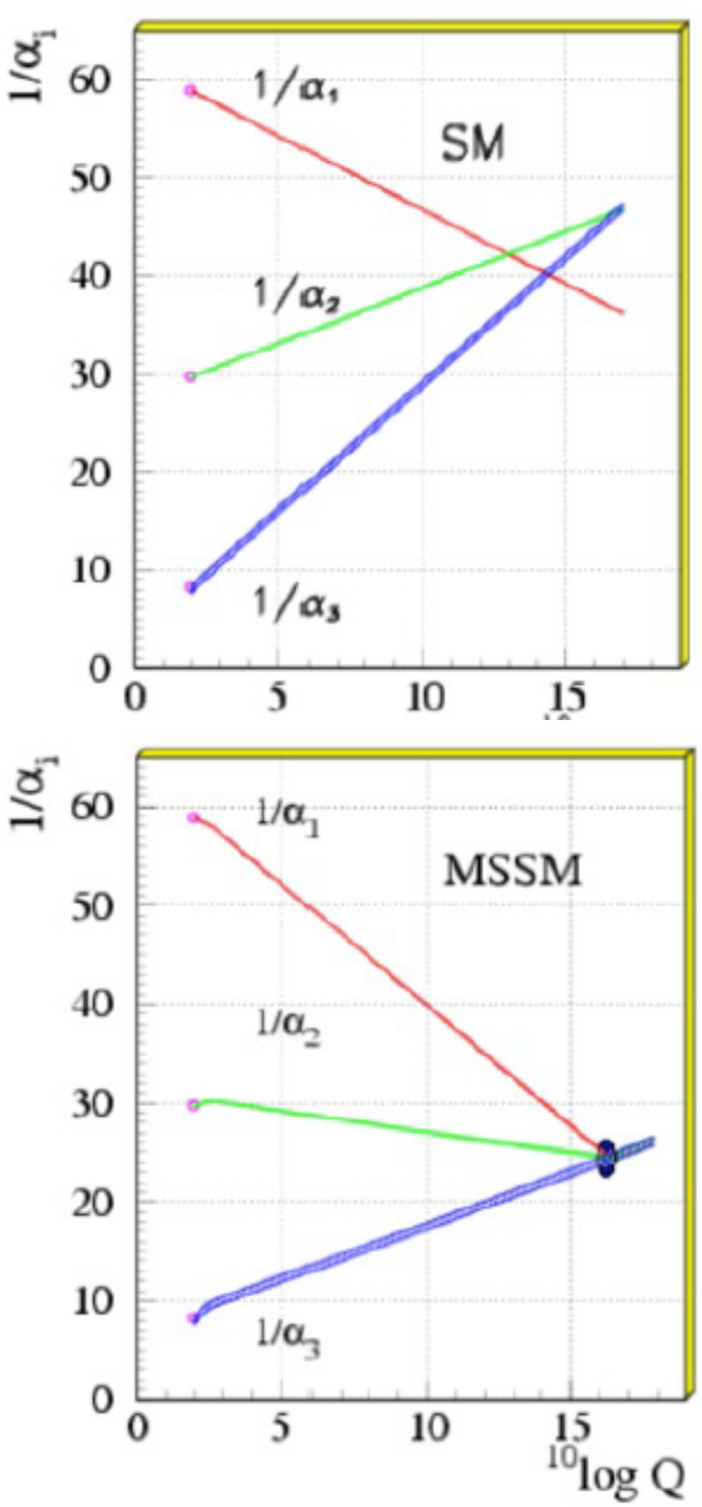
- **LSP must be neutral and not over-close the universe: an attractive WIMP (Weakly Interactive Massive Particle) DM candidate**
  - if we require LSP to be **charged only under EWK interactions,** and have **EWK scale mass**
  - **lightest neutralino (most of the models)**
    - the superpartners of the SM EWK bosons: mix to form mass eigenstates: $\tilde{B},\ \tilde{W}^3,\ \tilde{h}_u,\ \tilde{h}_d$

      neutralinos: $\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$

      charginos: $\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$

Supersymmetry also for Unification

- **Evolution of SM gauge couplings suggests a common origin at a high scale: $M_{GUT} \sim 10^{15}, 10^{16}$ GeV**



- **Common origin** of SM gauge interactions in single interaction?

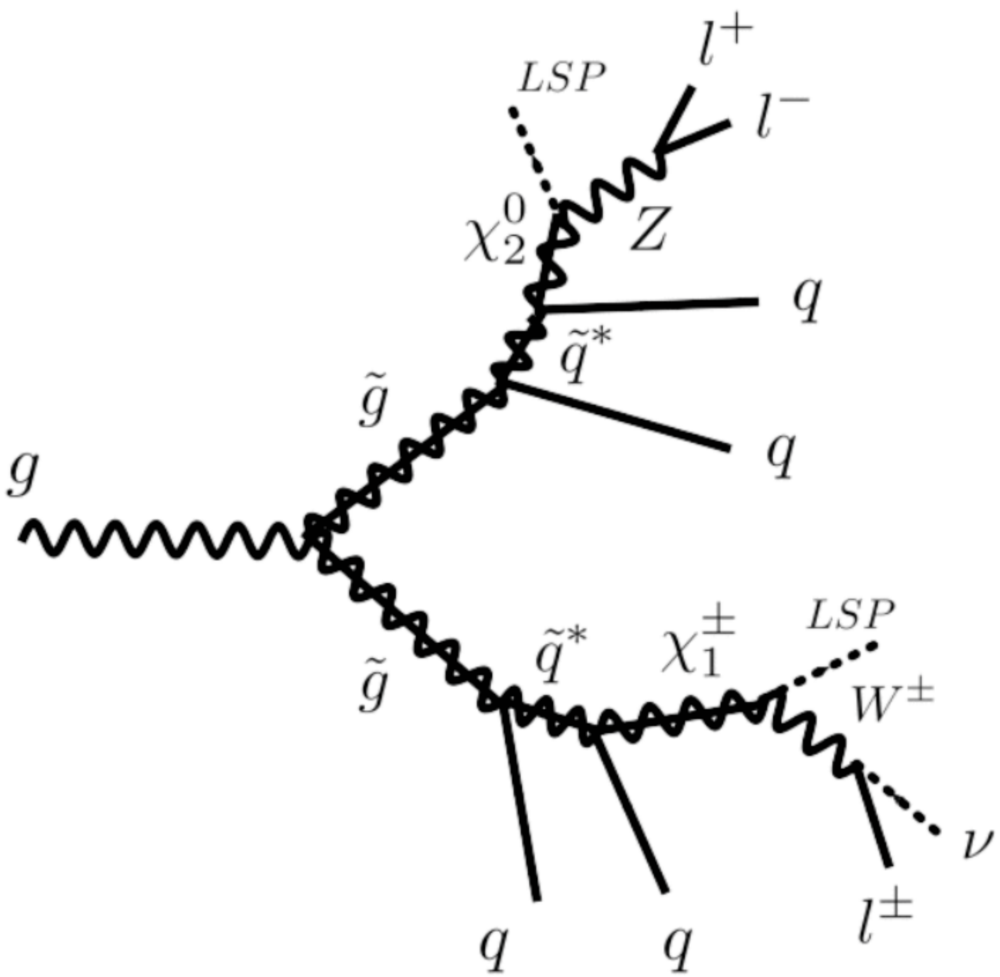
$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SO(10)$$

- **Precision unification** requires new charged states between SM and M_{GUT}
- **New SM charged matter** in MSSM makes numerical unification work significantly better!
- **Unification** is insensitive to exact value of this scale, but it can't be too heavy

The original ATLAS and CMS mandate

- **Probe in full the EWK scale, O(100-1000) GeV, directly:**
  - **Establish mechanism of EWK Symmetry Breaking**
    - **Discover the Higgs (LEP >115 GeV, SM theory <1 TeV)**
  - **If Higgs found, then directly search for the new particles that can explain m_H**
    - **Of course SUSY: explain m_H, DM candidate, Unification**
    - But also exhaustive search for **all other new physics models:**
      - Extra dimensions, Little Higgs theories, compositeness, non-SUSY WIMP DM candidates, heavy neutrinos, Leptoquarks, black holes as signed of low scale quantum gravity…
  - **ATLAS and CMS were design to do this**
    - **Seven years of LHC at 7/8/13 TeV: ATLAS & CMS found no new physics**
    - **Many BSM models excluded** in their simplest realisations: **what about SUSY?**

SUSY Signatures

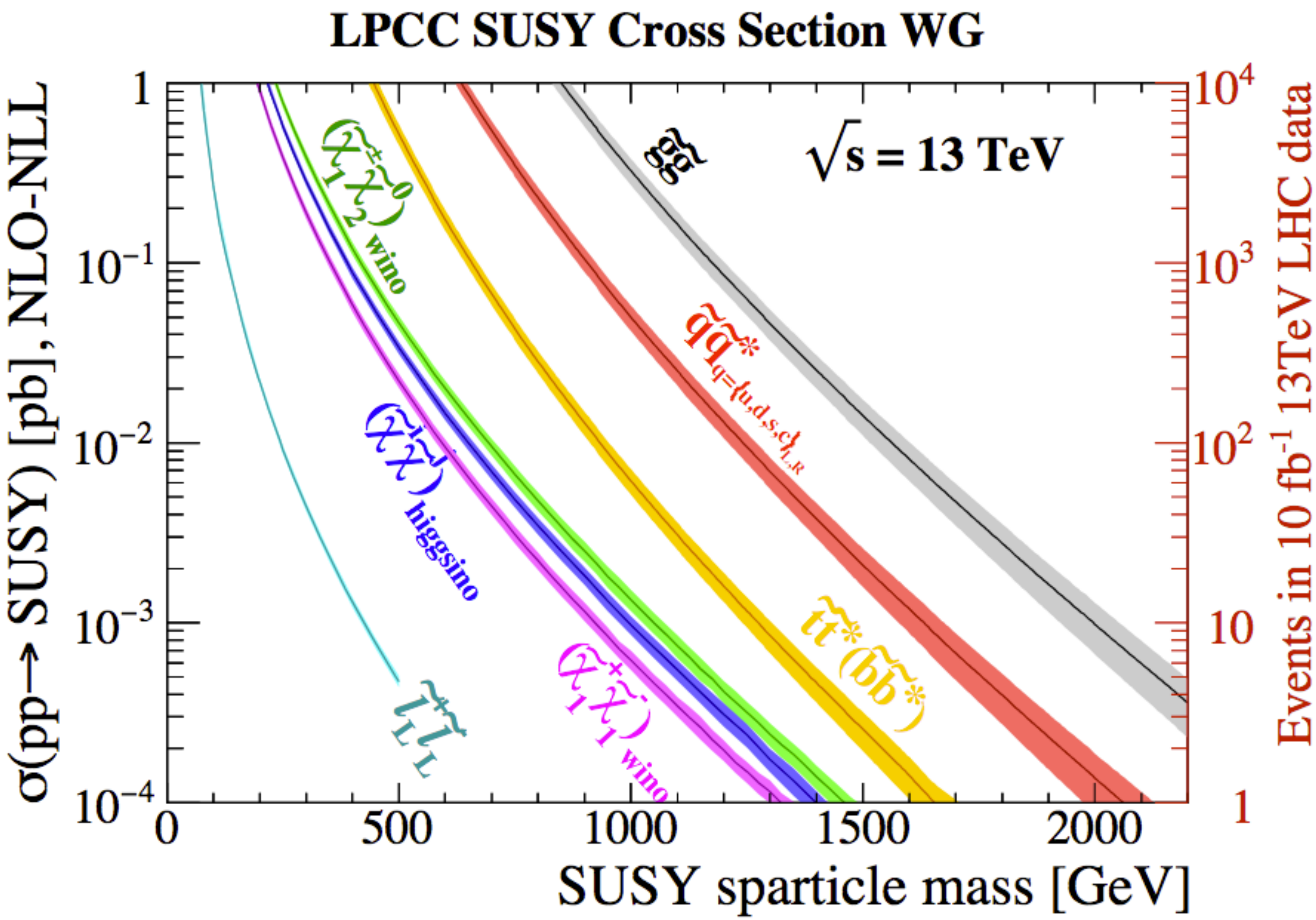


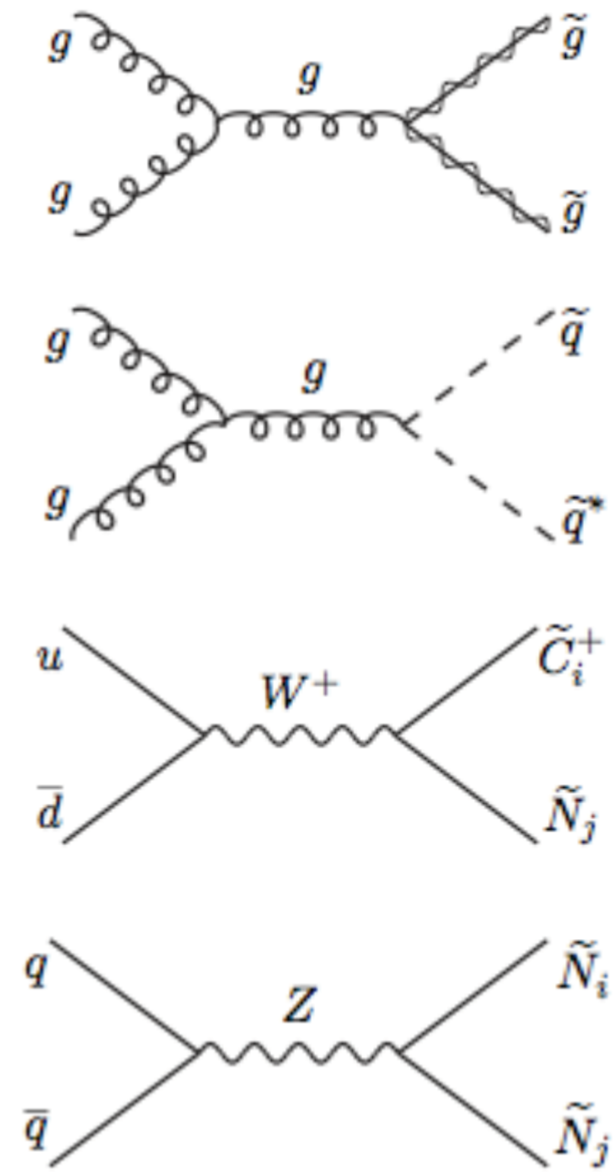
[gluino pair production]

- **R-parity: produce superparticles in pairs**
  - we start from an even R-parity state
  - superpartners are R-parity odd
- **We can produce superparticles which carry SM charges through their SM gauge interactions**
  - gluinos can be pair produced thanks to their color charge
- **Superparticles then cascade down until they hit the LSP**
  - the lightest state that carries R-parity and therefore it can't decay

- **Generic signature is then:**
  - **missing energy (E_T^{miss} at pp collisions)**
  - **non-resonant signals**
  - **quite some visible and energetic SM particles in the final states**

SUSY production at LHC 13 TeV

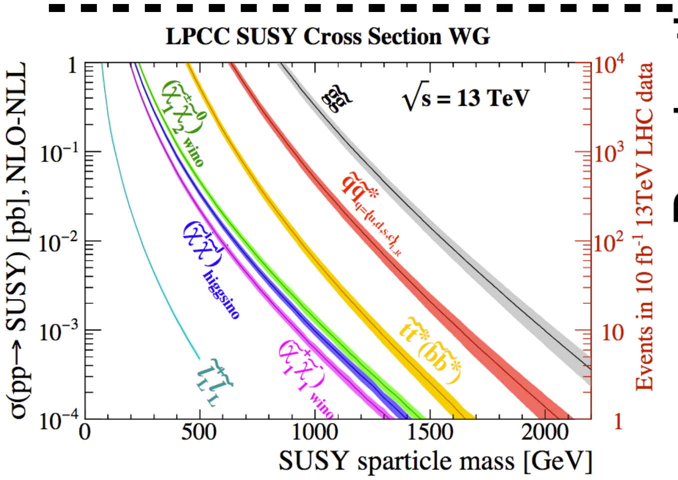


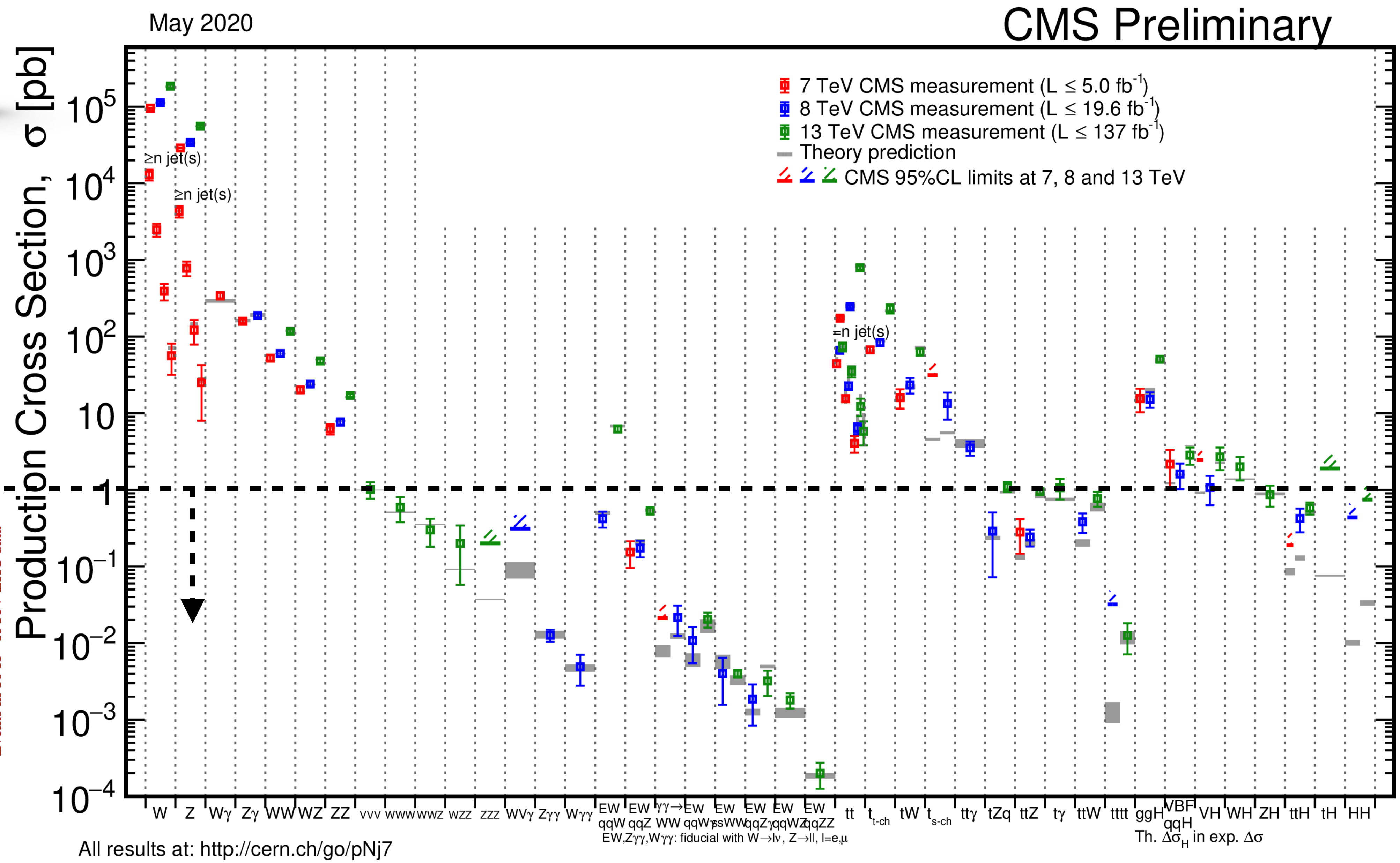


- Cross section falls as a rock with the sparticle mass
- Strong sector: largest cross sections, gluon induced
- EWK sector: much lower cross sections, quark induced

Search tools: ATLAS and CMS

CMS SM Summary results

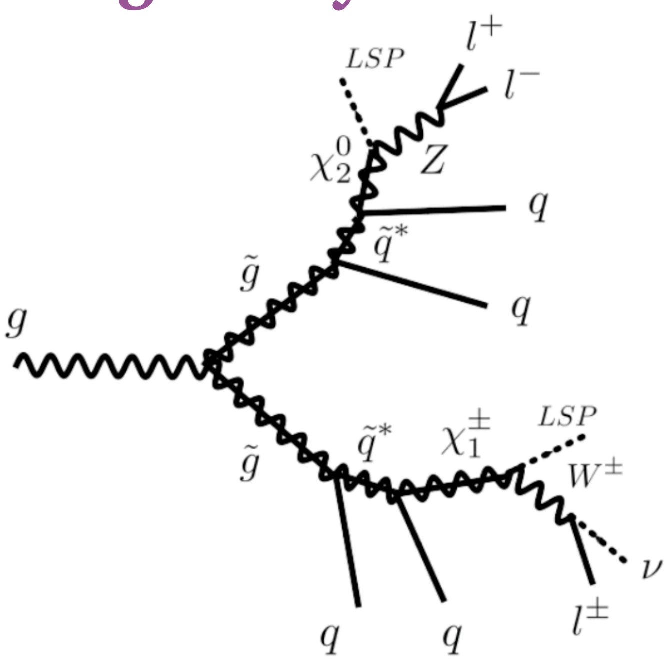


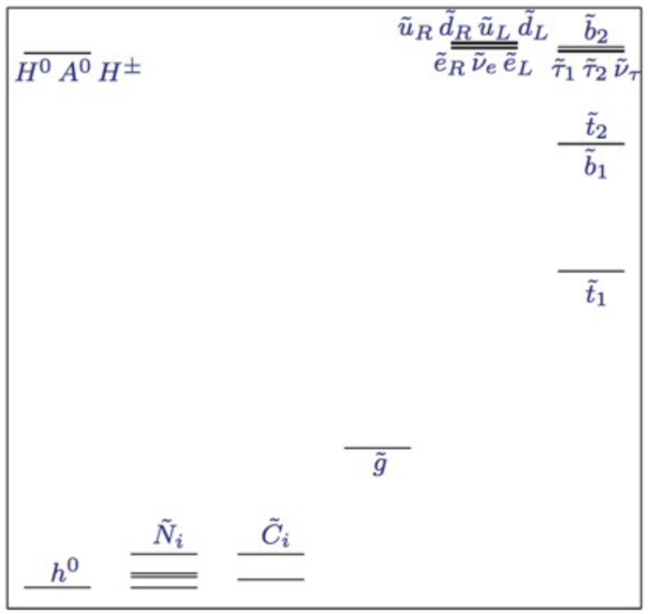


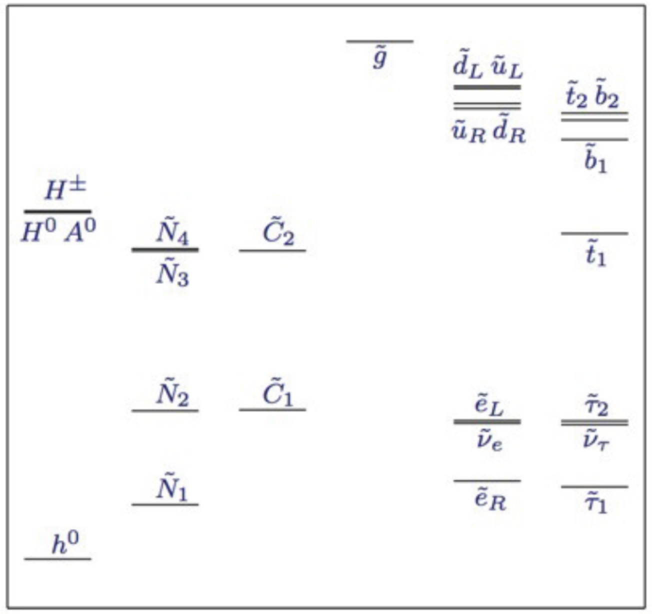
- **We have learnt how to calibrate well our detectors:**
  - agreement between measurements and predictions for **many SM processes**
- **Demonstrate sensitivity to rare SM processes with same NP cross section**
  - advanced bkg reduction techniques
  - large dataset: LHC Run2 2015-18 **~140 fb⁻¹ @ 13 TeV**

SUSY simplified models

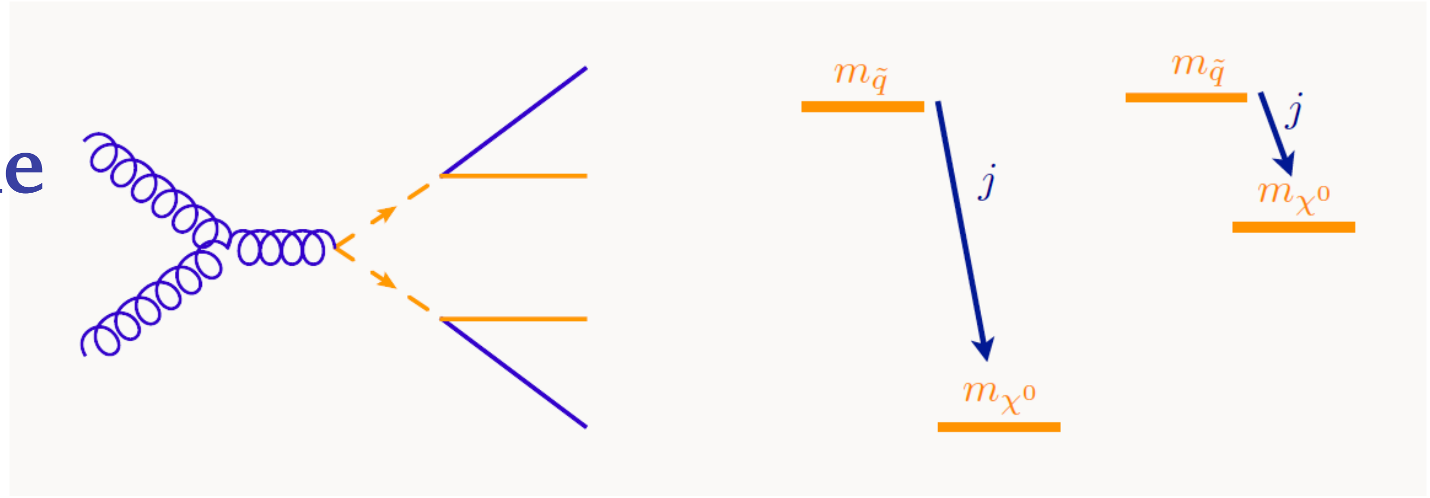
- **So many possible mass spectra (different SUSY models, different tuning of the parameters): a potential mess**
  - sparticles decay into lower masses sparticles down to SM particles and the LSP: **long decay chain**





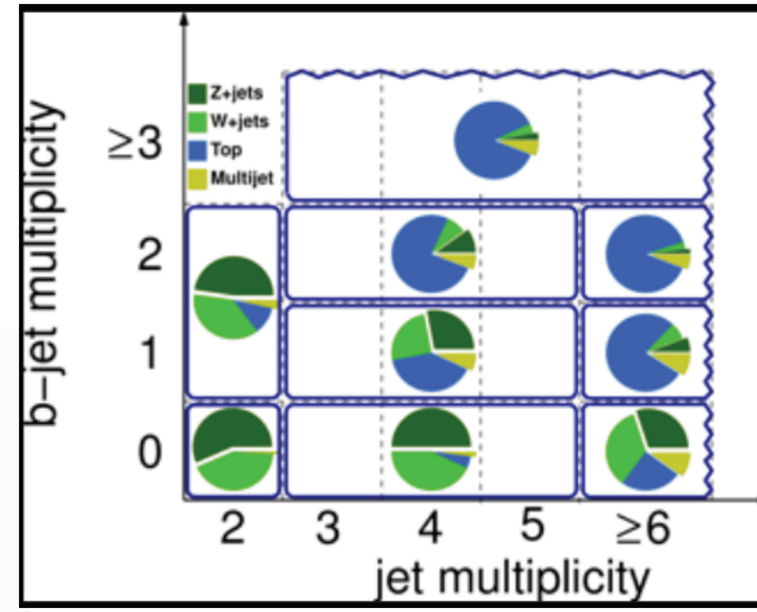


- **Simplified Models approach: focus on a few particles at a time**
  - ex. concentrate on direct light squark production and **the only open decay mode if light squarks are NLSP** (all other particles not in the reach)

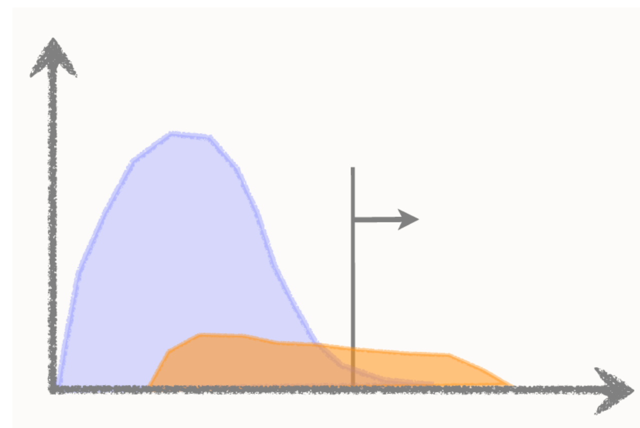


squarks as NLSP, final state: jets + E_T^{miss}

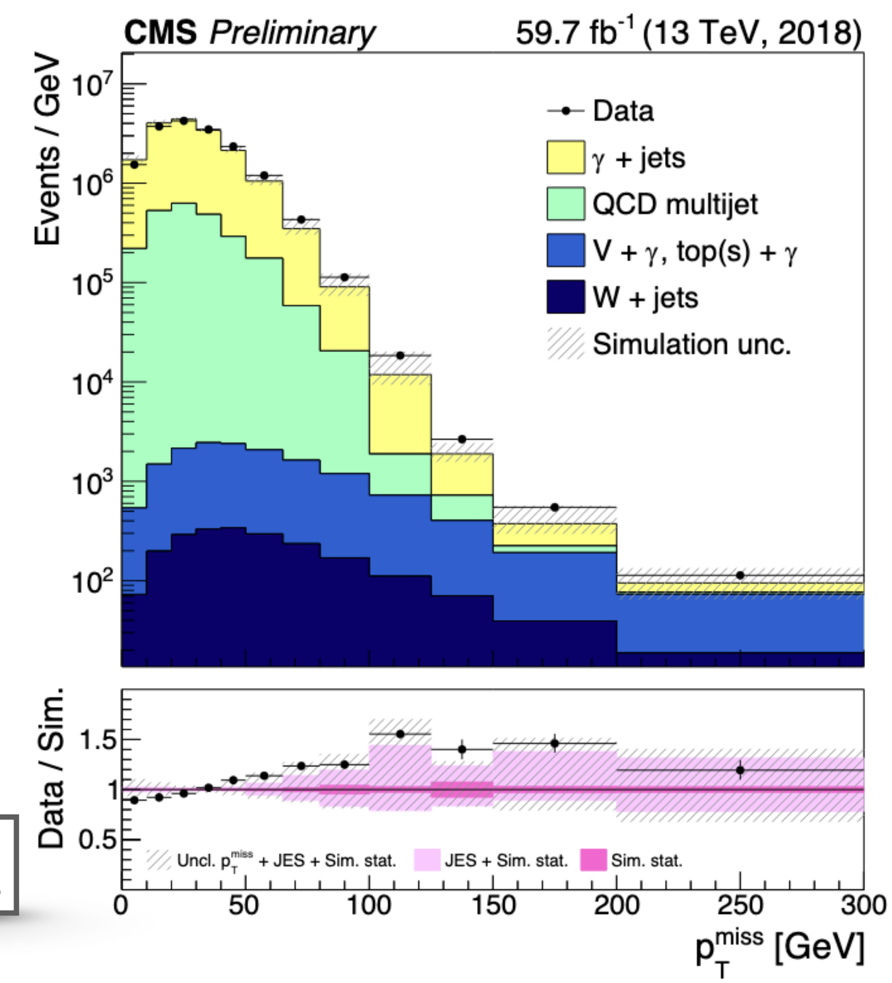
Search strategies at ATLAS and CMS



- **Standard discovery strategy:**
  - demand multiple energetic objects: jets, b-jets, leptons
  - determine suitable kinematic variables (E_T^{miss}, M_T, M_{T2}, H_T…) and count events in the tails
  - in SM bkg any kinematic variable with dimension of mass falls more rapidly



- **Experimental challenges**
  - hard to understand tails due to detector effects and bkg modelling in extreme regions of the phase-space
  - regions where the predictions from MC are subject to sizeable uncertainties



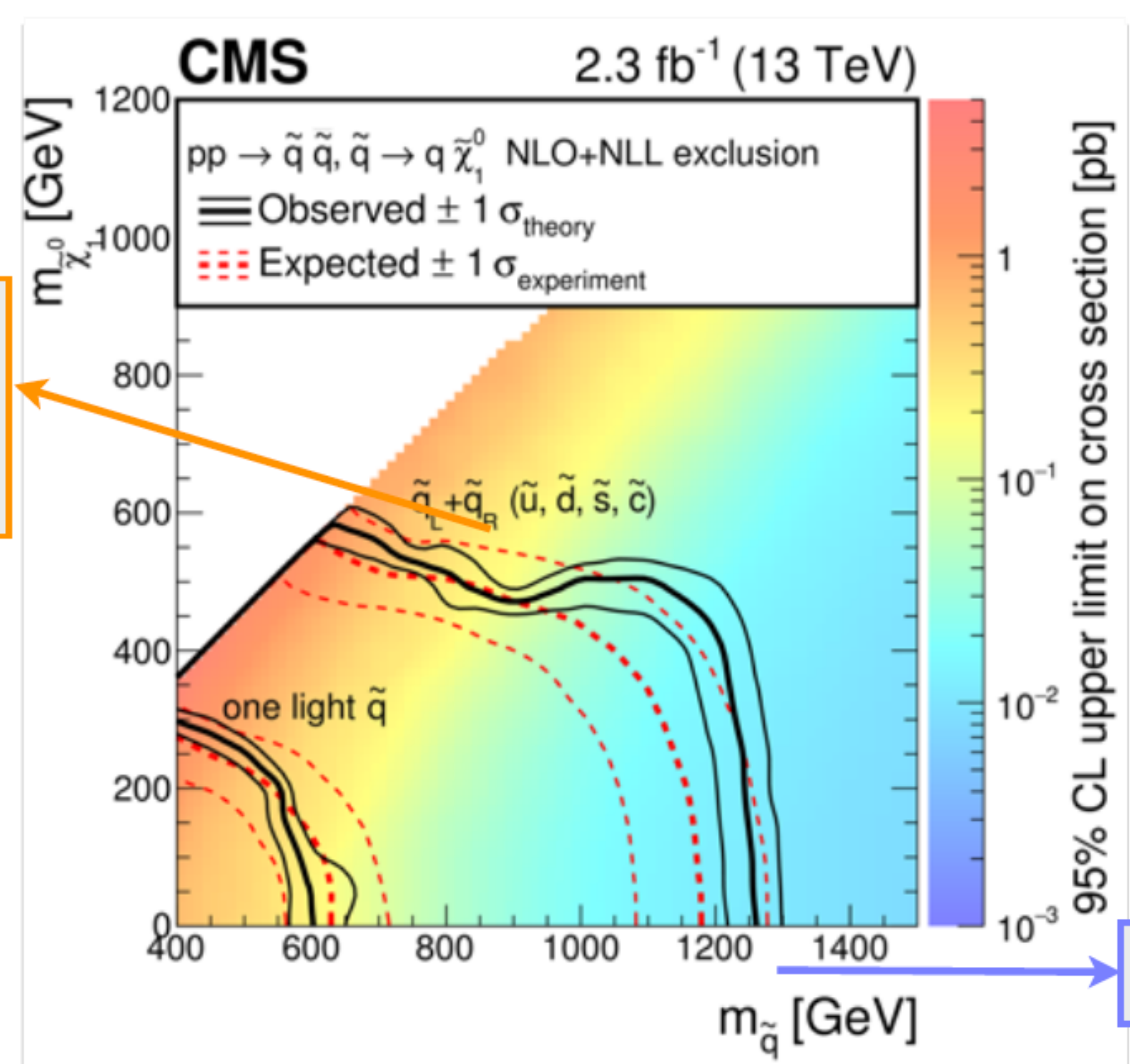
- **Rely as much as possible on data**
  - define "control-regions (CR)" kinematically closed to the "signal-regions (SR)" enriched in a specific background to normalise the predictions

CMS DP-2020/031

Exclusion limits

- **Typical ATLAS and CMS results for specific simplified event topology:**
  - exclusion limit contours, in the phase space defined by the free parameters of the model (e.g. squark and LSP masses in this case)
    - **solid, black curves:** observed 95% CL exclusion limits assuming the NLO+NLL SUSY cross sections (thick line), or their $\pm 1\sigma$ variations (thin lines).
    - **dashed, red curves:** expected 95% CL exclusion limits and corresponding $\pm 1\sigma$ experimental uncertainties

Not enough visible momentum

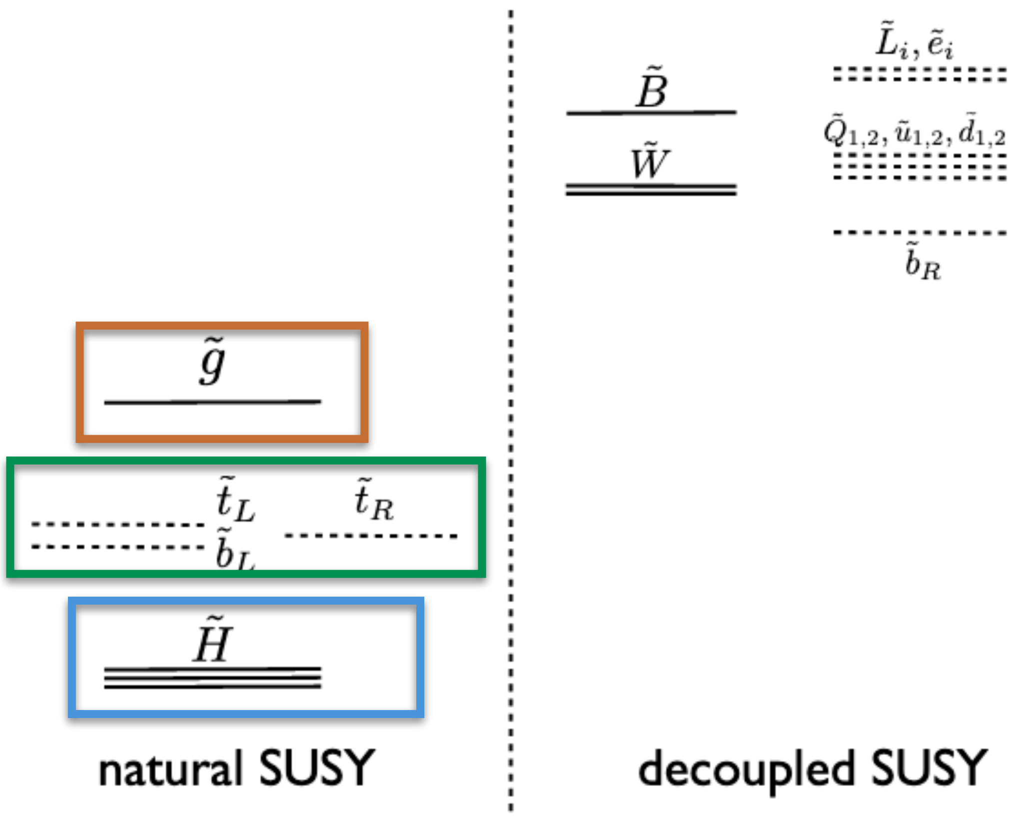


Big difference: 8 squarks vs 1 squark

Not enough signal events

SUSY searches at LHC in 2021

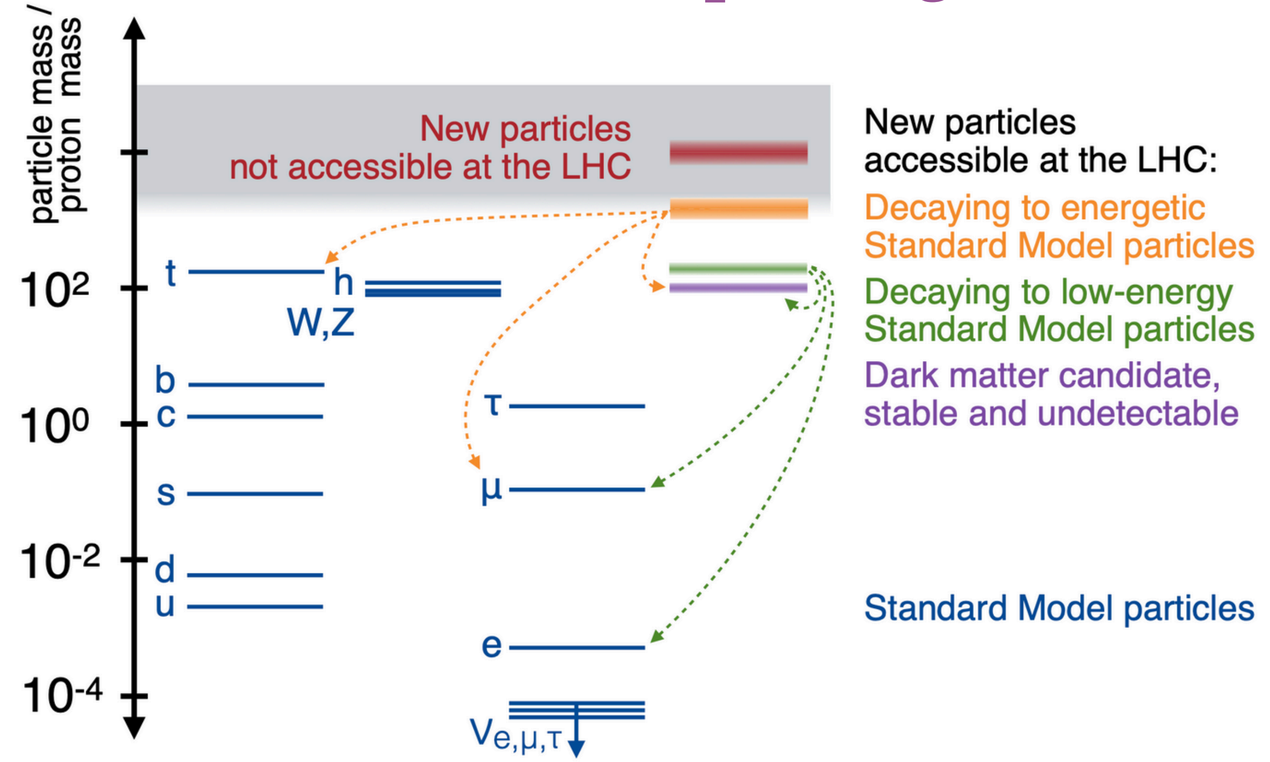
- **Update standard searches to full dataset: Run2 legacy results**
  - **exclude most of the region of the parameter space** where SUSY can give us naturalness **and** DM **and** unification
    - i.e. the superparticle masses **are light enough such that the fine tuning due to m_H is drastically reduced**
    - it's not needed to have the whole zoo of MSSM states near the weak scale, but just the states most important for addressing the hierarchy problem:



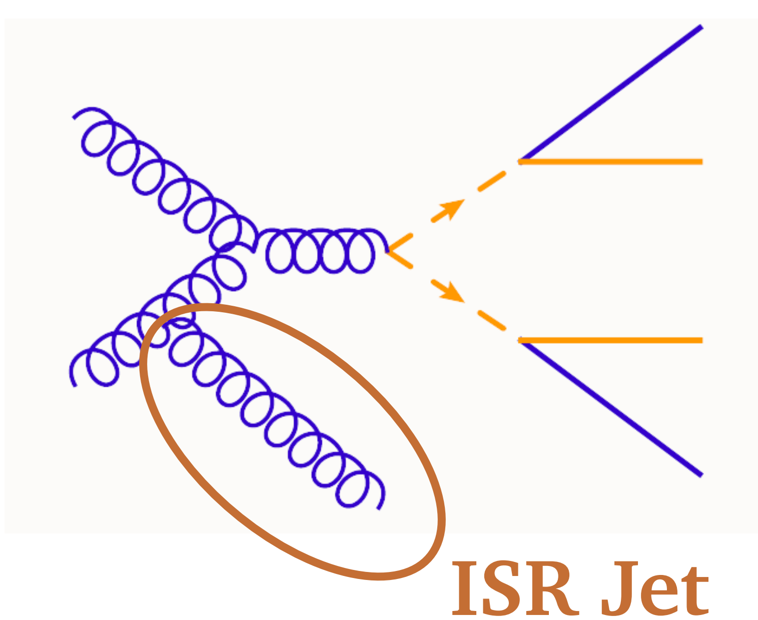
- **gluinos** - stops have their own hierarchy problem without 'light' gluinos **<~2 TeV**
- **stops** - most important quantum correction come from top **<~1 TeV**
- **higgsinos** - mass related to m_H at tree level **<~300 GeV**

SUSY searches at LHC in 2021

- **Before relaxing assumptions: designed new analysis strategies to target remaining corners, experimentally challenging**
  - **Compressed mass spectra: scenarios with small mass splitting between the NLSP and the LSP**
    - **visible energy and E_T^{miss} are relatively low, low-momentum/ displaced objects**
    - signal events do not even pass standard trigger requirements, let alone strict kinematic cuts to separate signal from bkg
    - standard searches **are not so sensitive to these scenarios**

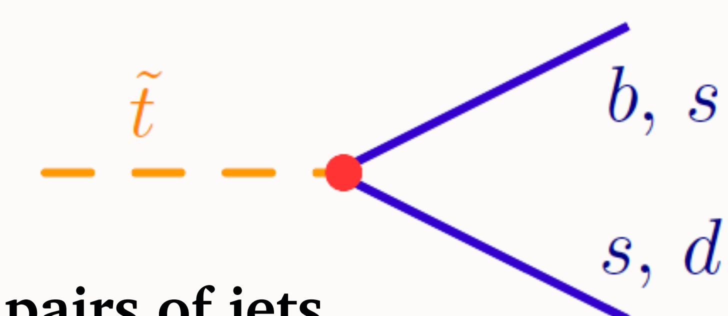


- **General approach to search for compressed SUSY: ISR Jet to boost the superparticles pair system and induce E_T^{miss}**
  - **penalty: reduces rate by $O(\alpha_s) \sim 0.1$**
  - LSP is haviest, carries most of the boost, other decay products remain soft

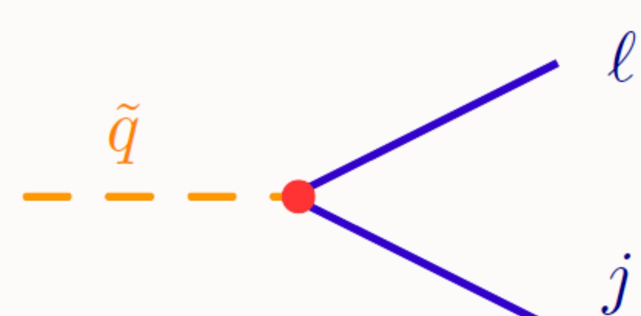


SUSY searches at LHC in 2021

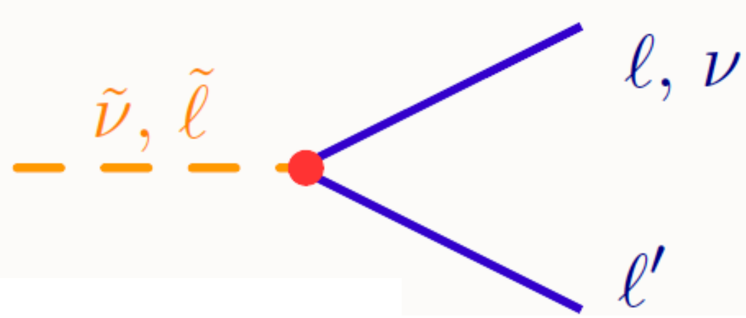
- **Giving up on DM: R-Parity violating SUSY (RPV)**
  - eliminate **E_T^{miss}** by allowing RPV couplings: **LSP doesn't have to be stable**
  - give up on SUSY to provide dark matter candidate to keep open the possibility of having **SUSY at the weakscale** and provide a solution to the hierarchy problem
  - **But what about proton decay?:** can be controlled by switching on **only B-violating or only L-violating** couplings
  - **Signature: no E_T^{miss},** multiple (resonant) SM objects, possibly **displaced vertices** (depending on coupling decays can be very slow)



stops into a pairs of jets



squarks into a lepton and a jet (same signatures as LQ!)

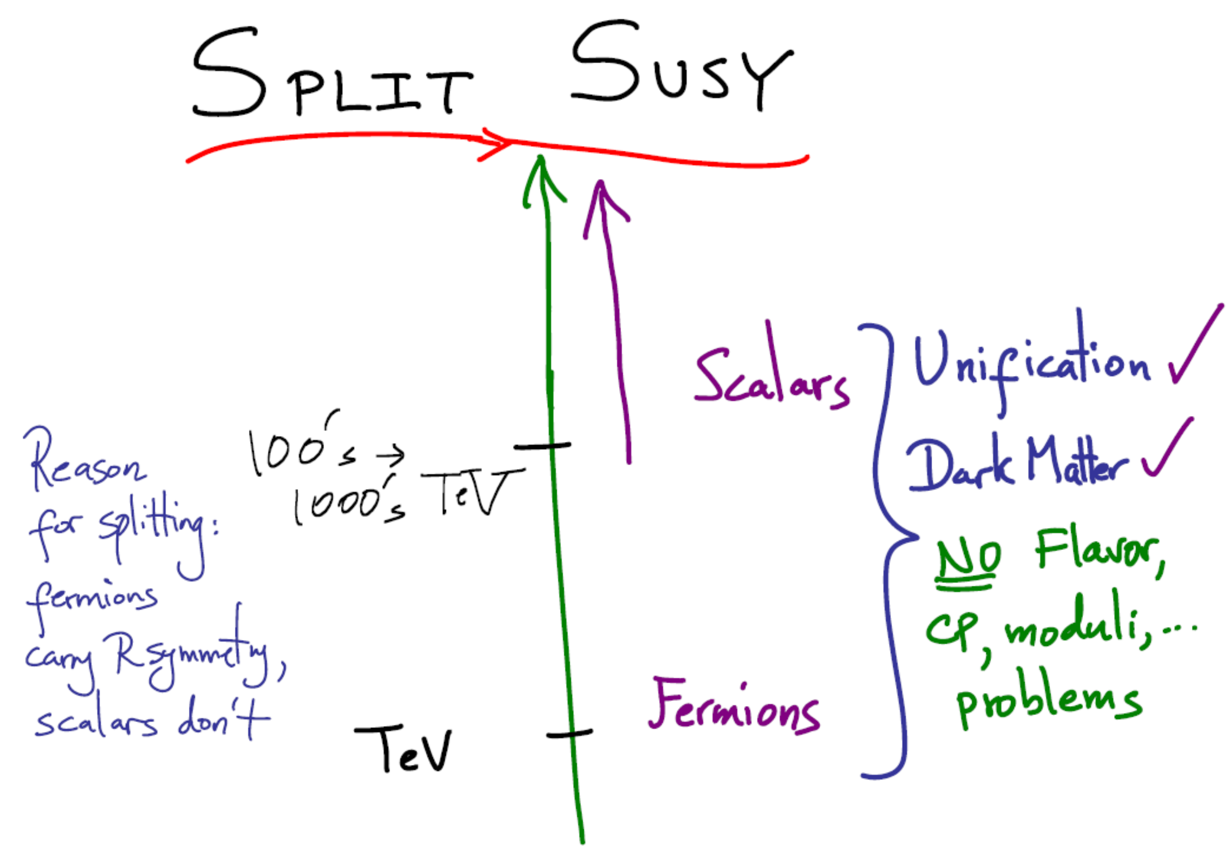


sleptons into flavour non conserving pair of leptons (eμ resonances!)

also, RPV for B-physics anomalies?

SUSY searches at LHC in 2021

- **Giving up on Naturalness: mini-split SUSY**
  - maybe much of the spectrum is simply out of reach: **accept fine tuning**, no elegant solution to the hierarchy problem
  - theory built in the past years: **sfermions up to ~100 TeV, keep -inos near(ish) the weak scale**
    - **compatible with current observations, provide a viable DM candidate and Unification**
  - **can predict displaced decays** in searches for accessible -inos that decay through heavy sfermions



From Arkani-Hamed's talk

[Arvanitaki, Craig, Dimopoulos, Villadoro; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski]

A non-comprehensive selection of results

- Provide an overview of current status of searches focusing on few particular examples either from ATLAS or CMS

Squarks and Gluinos in full hadronic final states: CMS, 137 fb^{-1}, 1908.04722, 1909.03460

Squarks and Gluinos in final states with one isolated lepton: ATLAS, 139 fb^{-1}, 2101.01629

Stops quarks in full hadronic, semileptonic, and dileptonic final states: ATLAS 139 fb^{-1}, 2004.14060, 2012.03799, 2102.01444, CMS 137 fb^{-1} 2107.10892

Electroweakinos in multilepton final states: CMS 137 fb^{-1}, 2106.14246, PAS-SUS-18-004, PAS-SUS-21-002, 2012.08600, ATLAS 139 fb^{-1} 2106.01676

Sleptons: ATLAS 139 fb^{-1} 1911.12606, 1908.08215, 1911.06660, CMS 137 fb^{-1} PAS-SUS-21-001

Searches for R-parity violating decays: CMS 132 fb^{-1} 2012.01581, CMS 137 fb^{-1} 2102.06976, ATLAS 139 fb^{-1} 2106.09609, ATLAS 139 fb^{-1} 2103.11684

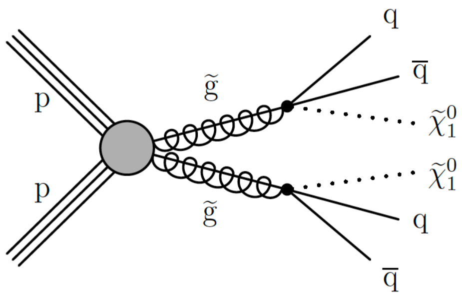
Searches in final states with displaced objects: CMS 101 fb^{-1} 2004.05153, CMS 132 fb^{-1} 2012.01581, ATLAS 136 fb^{-1} ATLAS-CONF-2021-015

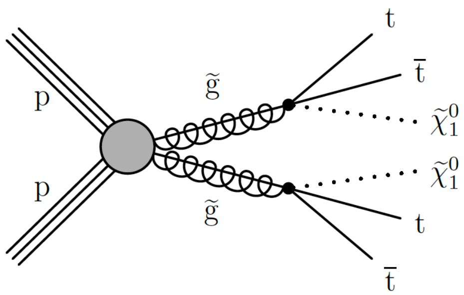
Many many other results in ATLAS SUSY Public Results, CMS SUSY Public Results

ATLAS SUSY Summary results

CMS SUSY Summary results

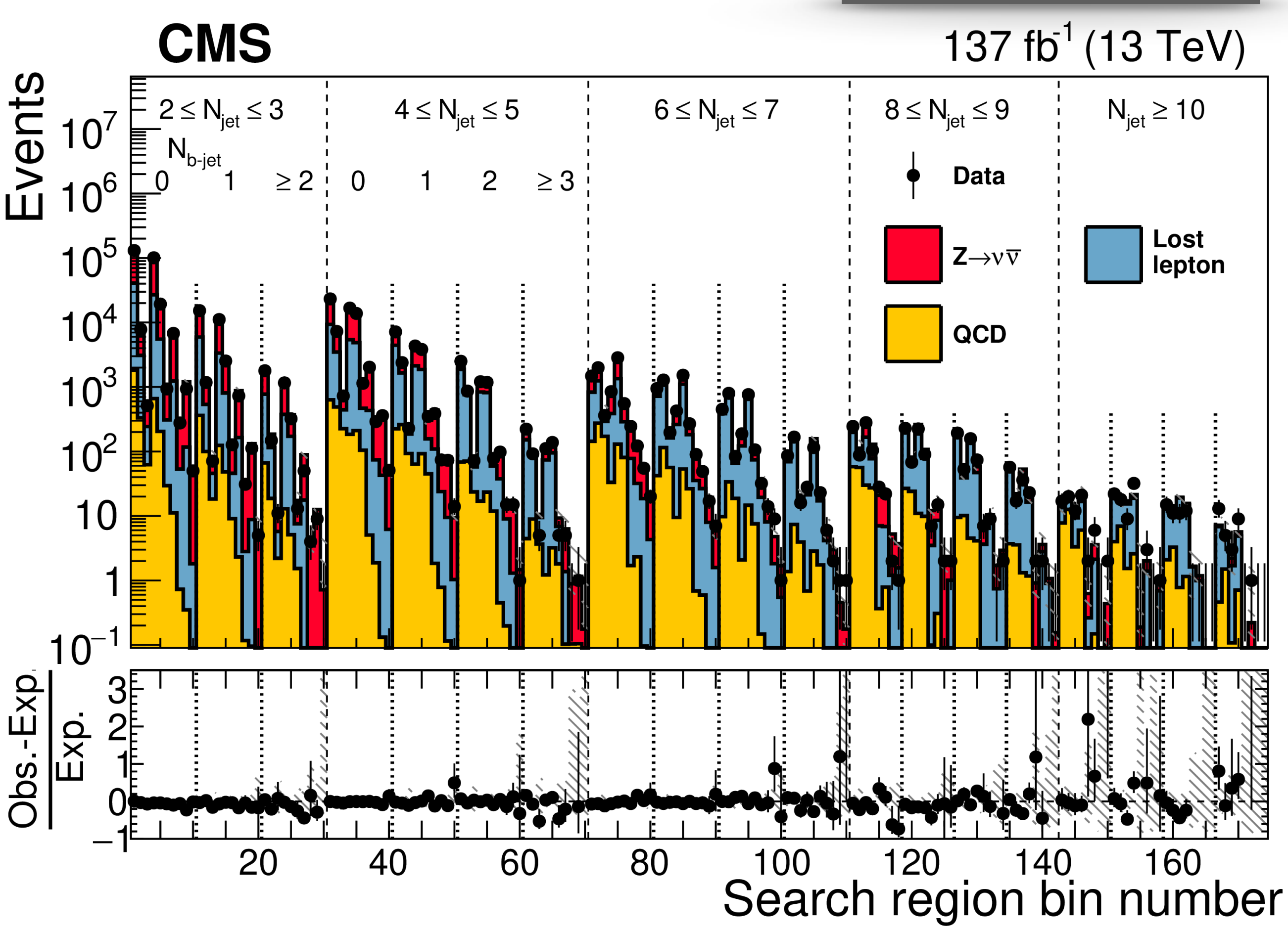
Gluinos: a full hadronic search

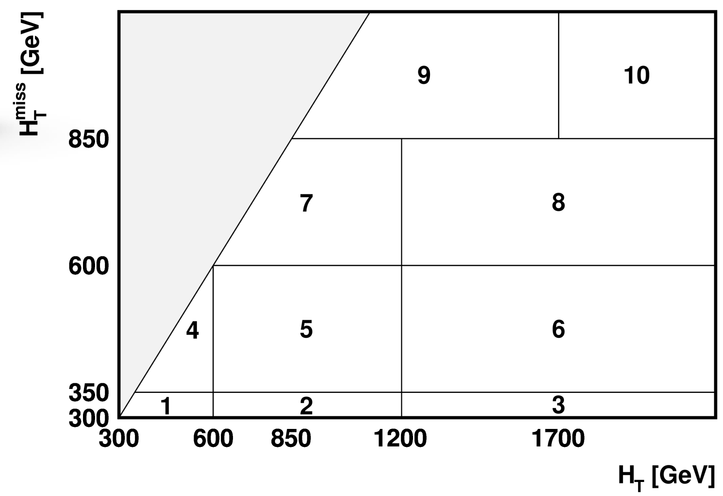


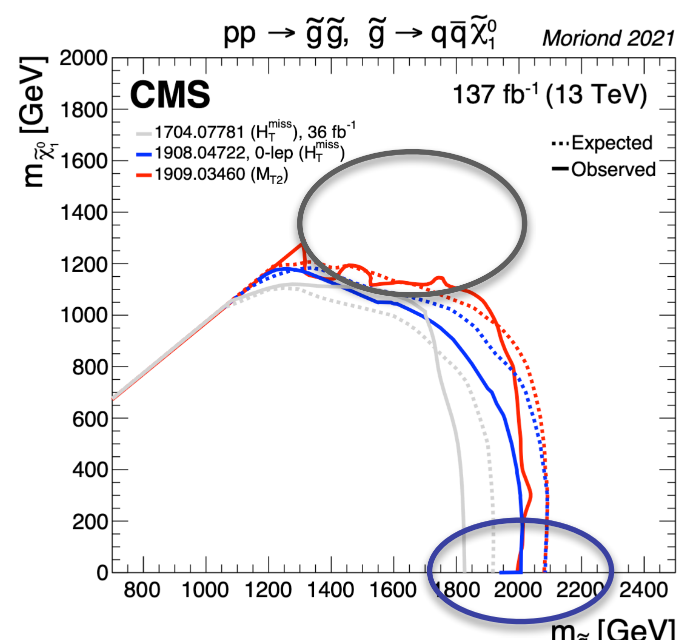


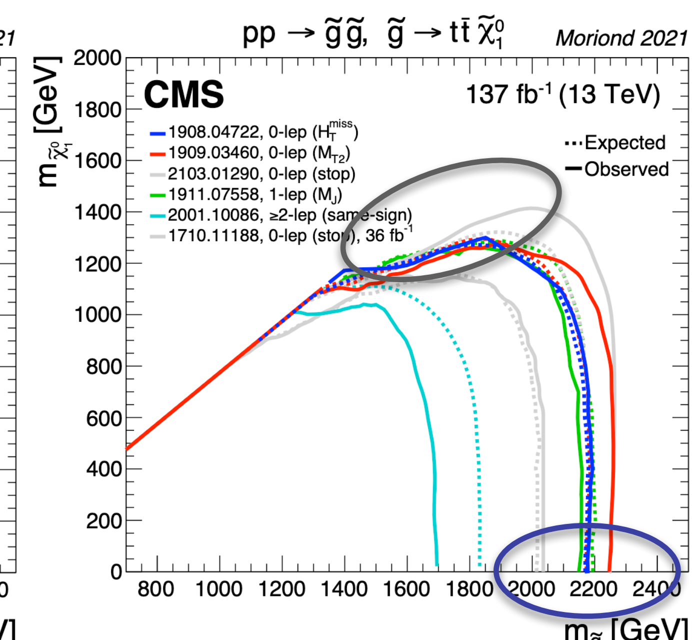
- **Typical simplified model: gluinos NLSP, decay through virtual squarks, if top squarks more naturalness-friendly**
  - inclusive full hadronic searches: **multiple jets and large E_T^{miss}**
  - many SRs to target different sparticle mass spectra, and bkg composition: **N_{jets}, $N_{b\text{-}jets}$, E_T^{miss}, H_T, H_T^{miss}, M_{T2}**

CMS:1908.04722



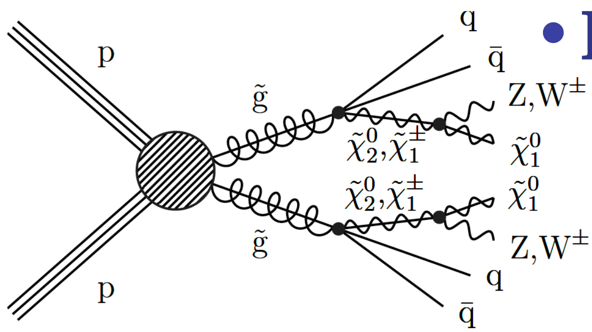






CMS SUSY Summary results

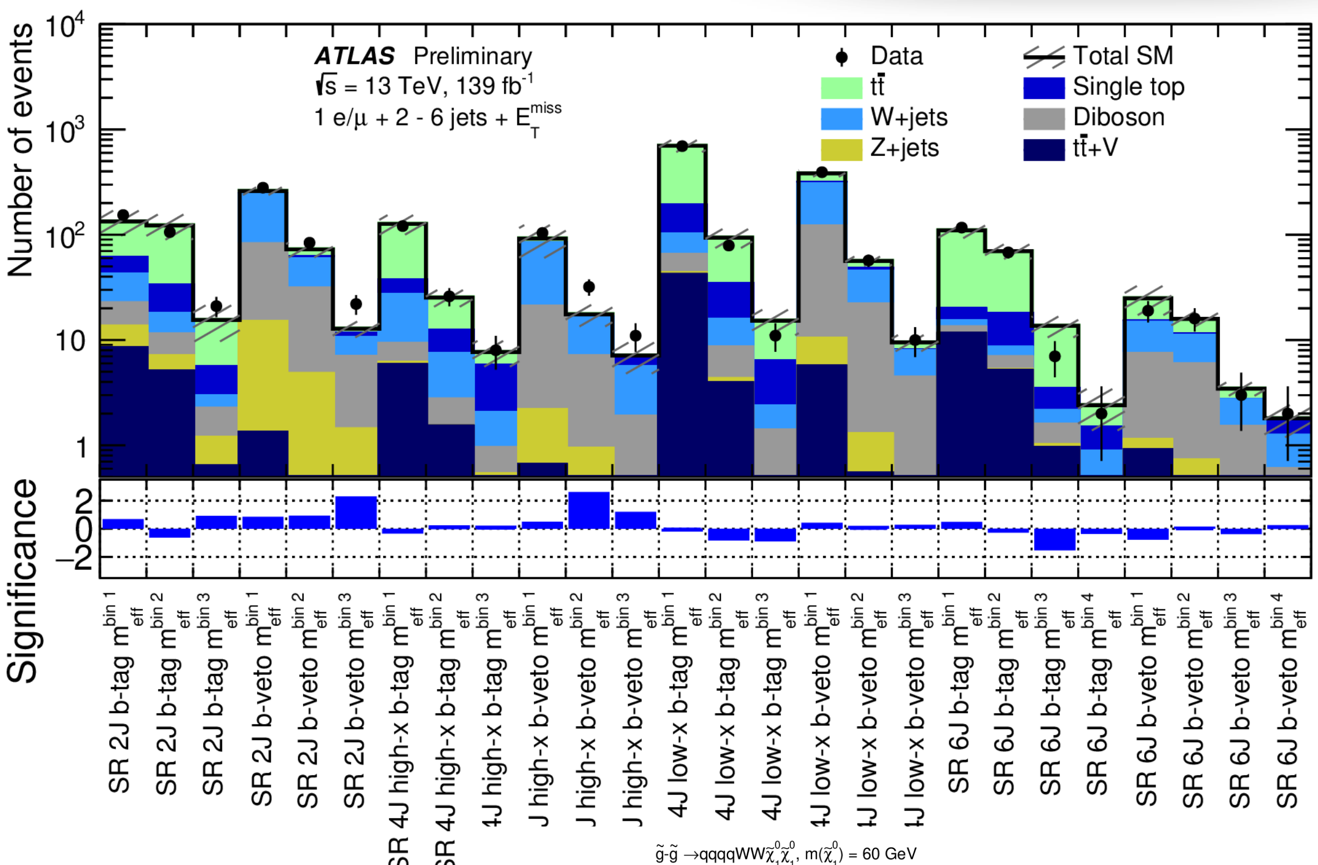
Gluinos: when charginos are available

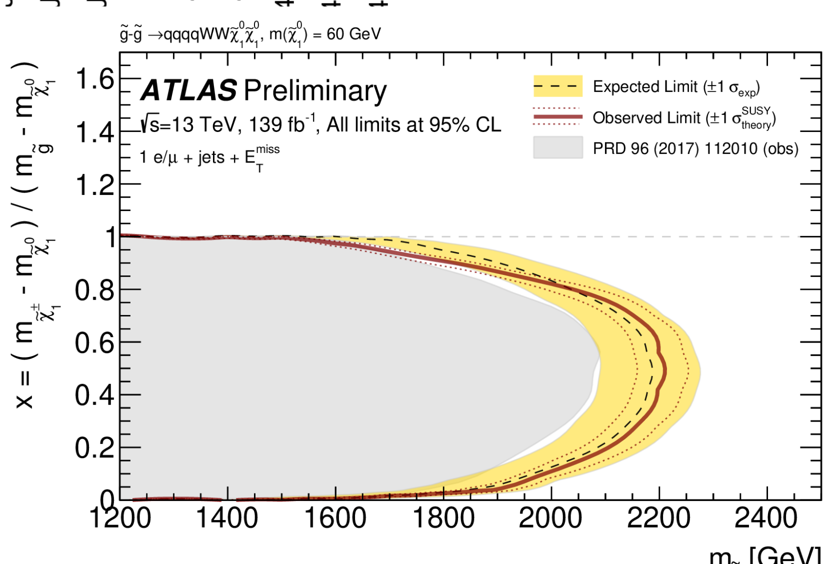


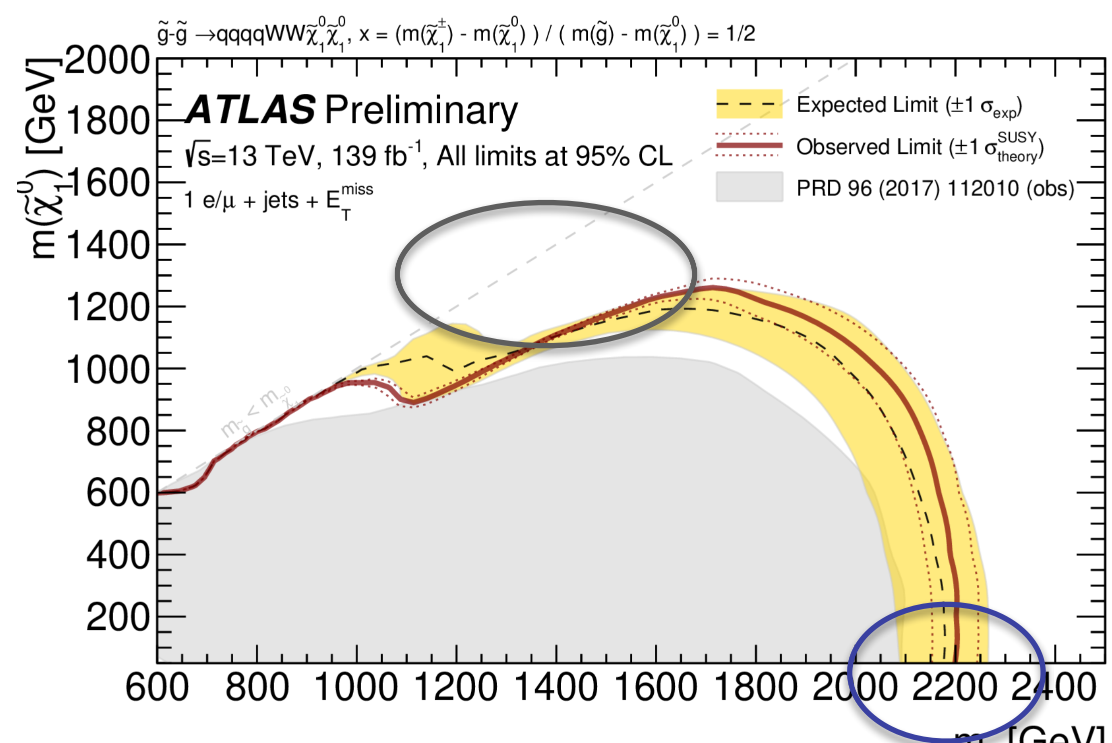
- **Model "next door" gluinos NNLSP, Wino NLSP or Higgsinos LSP**
  - single lepton searches exploiting one W→$\ell\upsilon$, or tagging Z→qq/$\ell\ell$

ATLAS: 2101.01629

- **Several signal regions with one lepton (e,μ), jets, and E_T^{miss}**
  - target different **gluino, chargino and LSP masses** and bkg composition
  - binned with: $M_T(\ell,E_T^{miss})$, N_{bjets}, m_{eff} (scalar sum: E_T^{miss}, ℓ, jets p_T)
  - ℓp_T down to 6/7 GeV to target Δm(chargino-LSP) of few tens of GeV (Higgsino LSP)

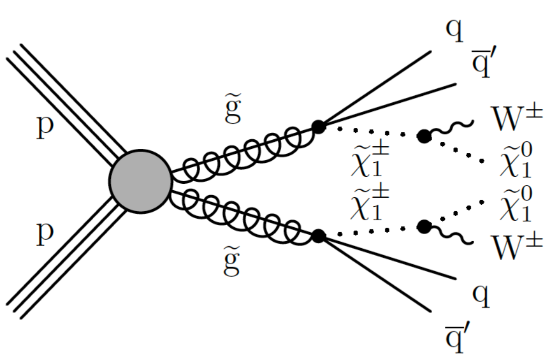




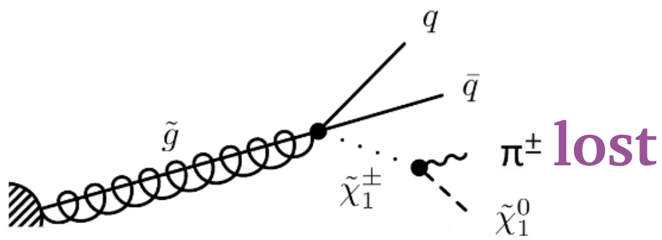


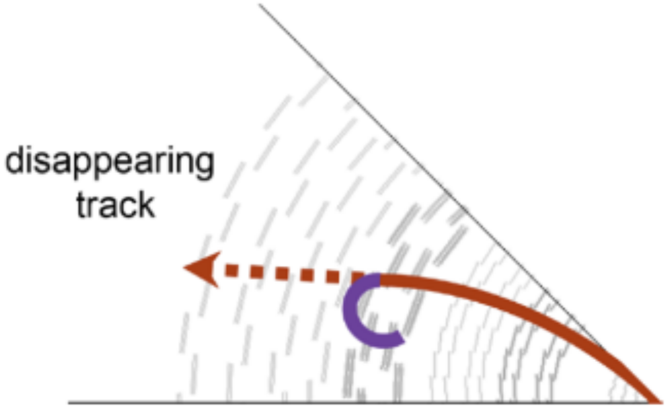
Gluinos: compressed regions?

- **Gluinos excluded up to 2 TeV for massless LSP, expected limits weaken down to 1.2 TeV in compressed region**
  - smaller $\Delta m(\tilde{g}\text{-LSP})$, signal is more SM bkg like

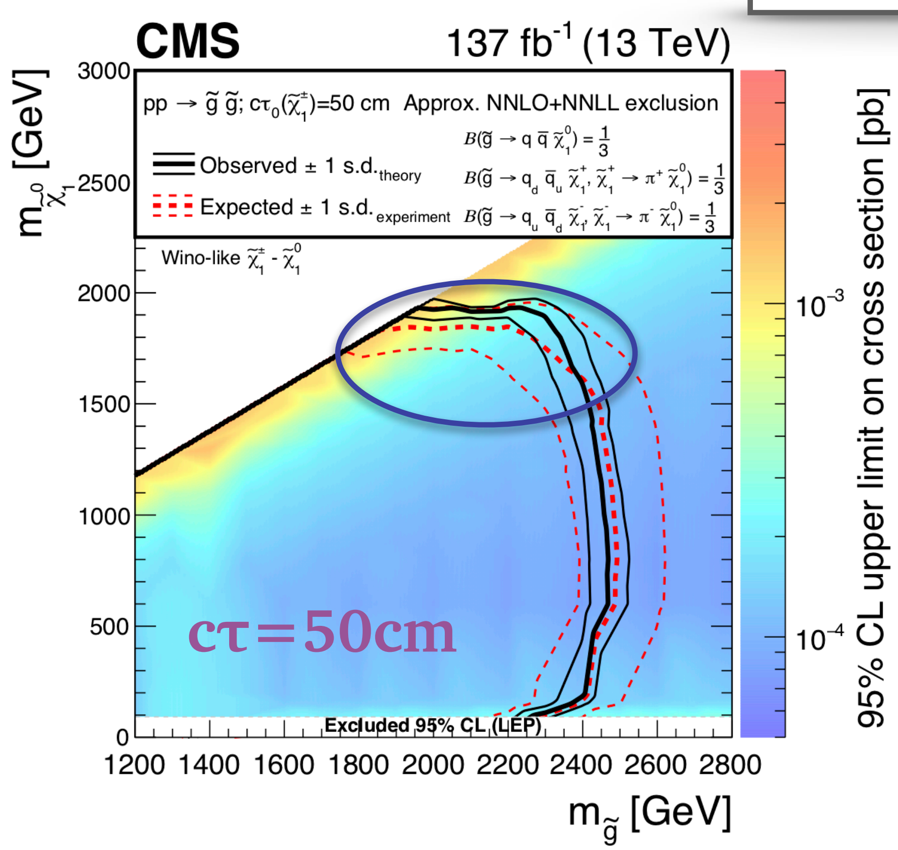


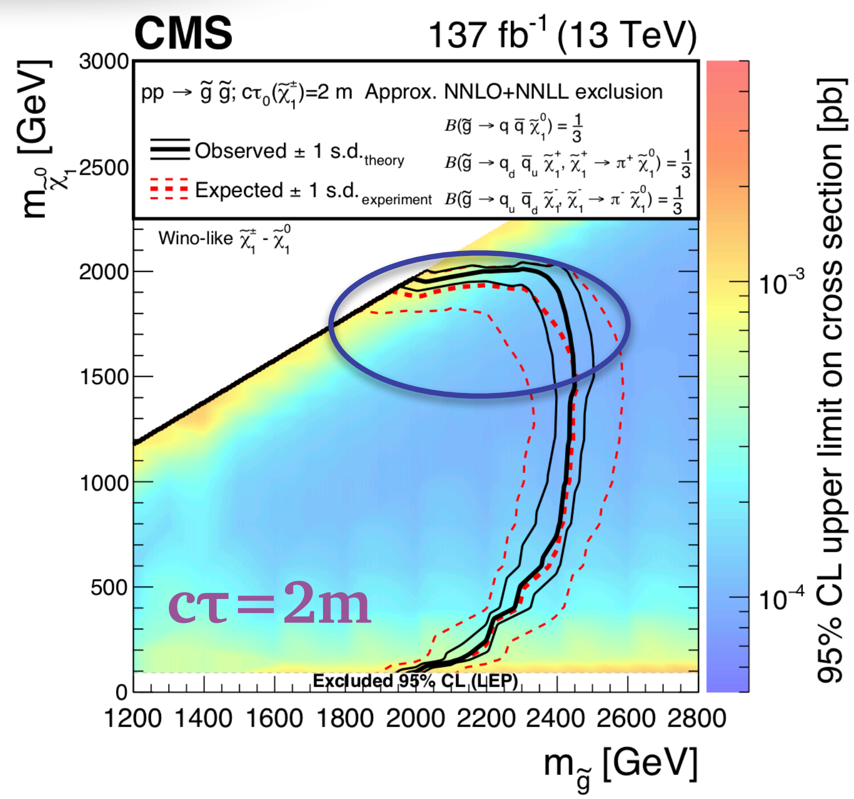
- **In peculiar topologies this region is accessible:**
  - assuming Wino LSP Δm(chargino, neutralino)~O(100)MeV
  - chargino is long lived (cτ of ~10s cm), and decays into a soft pion and neutralino
  - identification of disappearing tracks inside the tracker volume (<1m) reduce bkg as much as 10000x





CMS:1908.04722

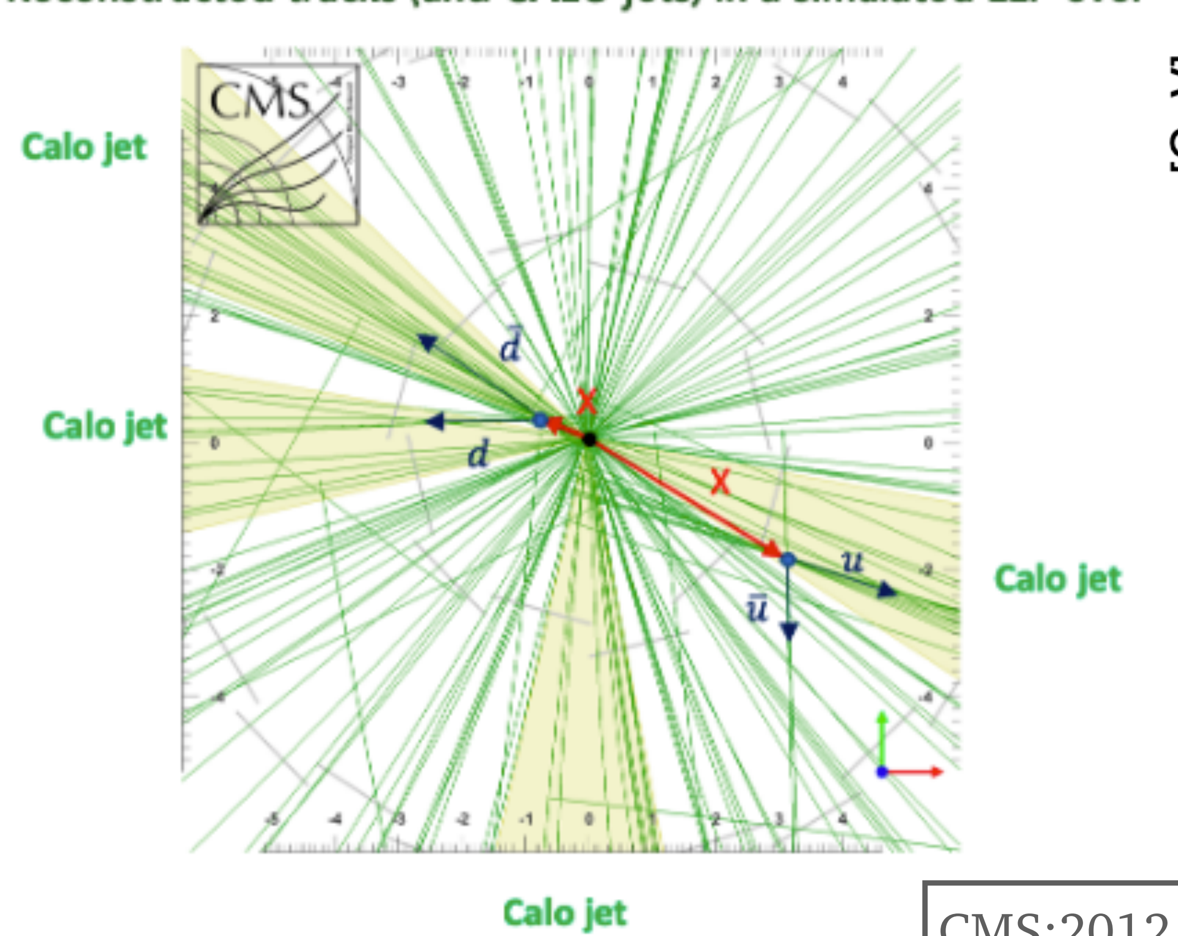


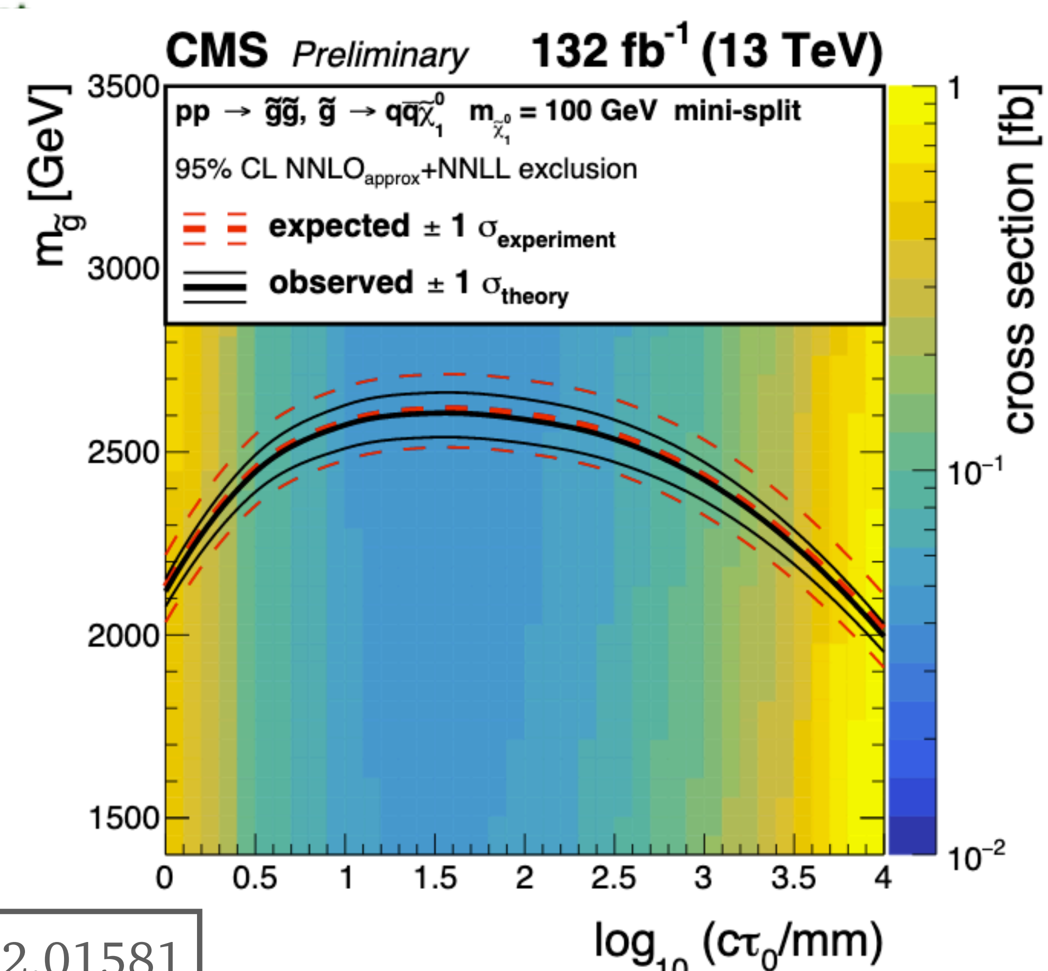


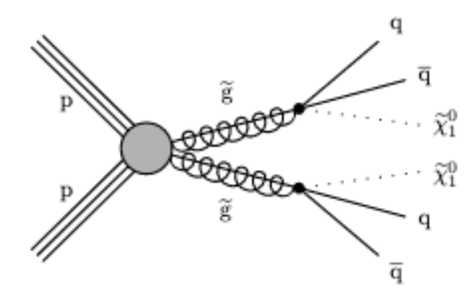
Gluinos: very off-shell decays?

- **Long-lived particles can arise not only from small phase-space but also from off-shell decays**
  - in Split SUSY models squarks are predicted to be very heavy, **and gluinos decay into SM quarks can features displaced jets**
  - dedicated triggers based on "Calo-Jets" to target **decays of gluinos within the tracker volume**
  - Calo-Jets associated to tracks, examine all possible pairs of jets and attempt to reconstruct a SV for each jet pair

Reconstructed tracks (and CALO jets) in a simulated LLP event



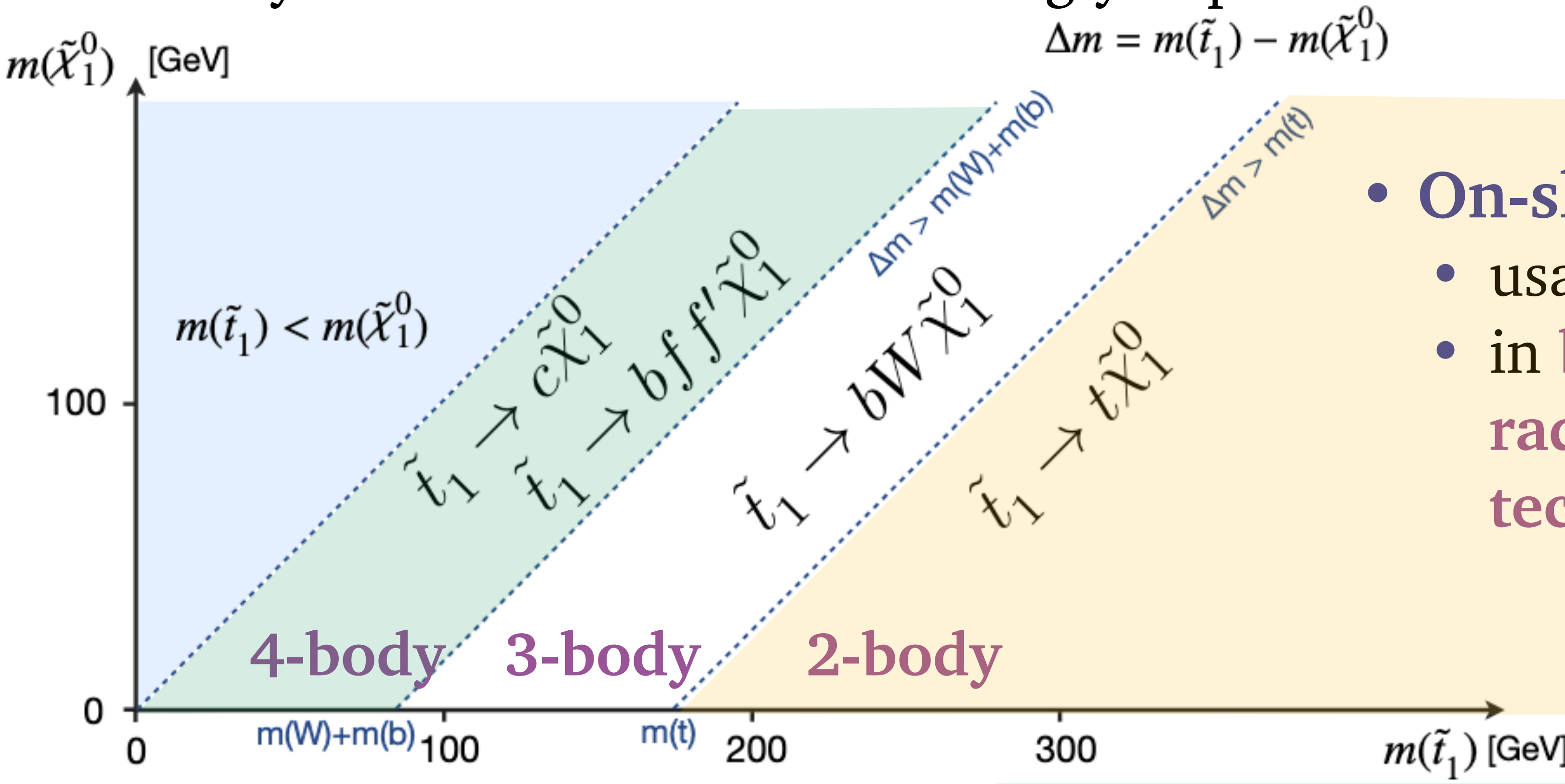




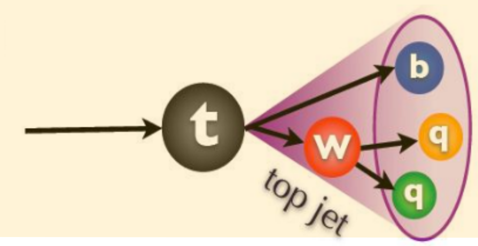
CMS:2012.01581

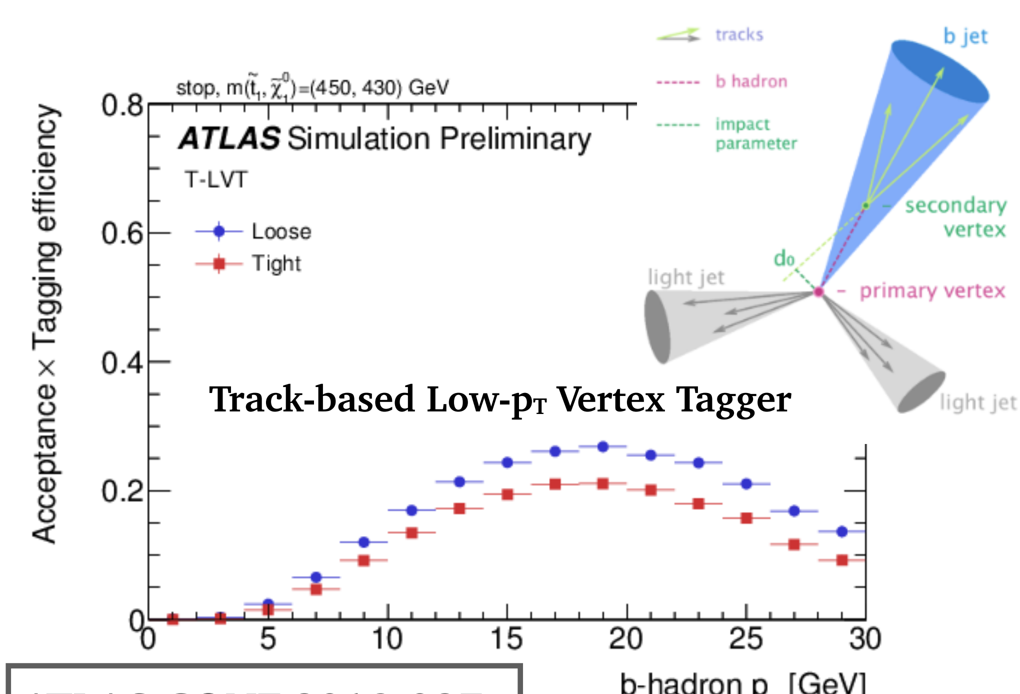
Top squarks: can they still be light?

- **Assume stop NLSP: direct top squark pair production**
  - decay modes and kinematic strongly depends on **Δm(t̃-LSP)**



- **On-shell tops: $\Delta m > m_t$**
  - usage of hadronic **top taggers**
  - in **boosted regime** exploit **large radius jets and jet substructure techniques**





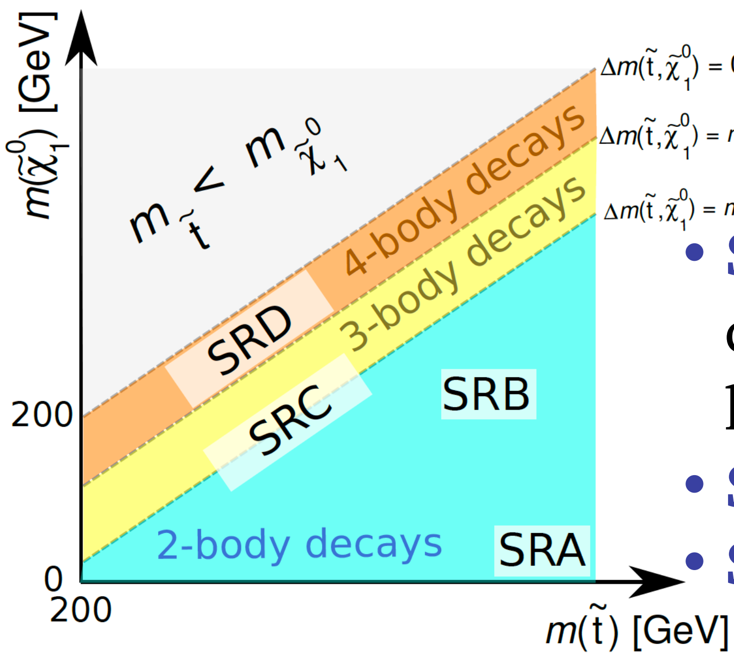
Track-based Low-p_T Vertex Tagger

ATLAS_CONF-2019-027

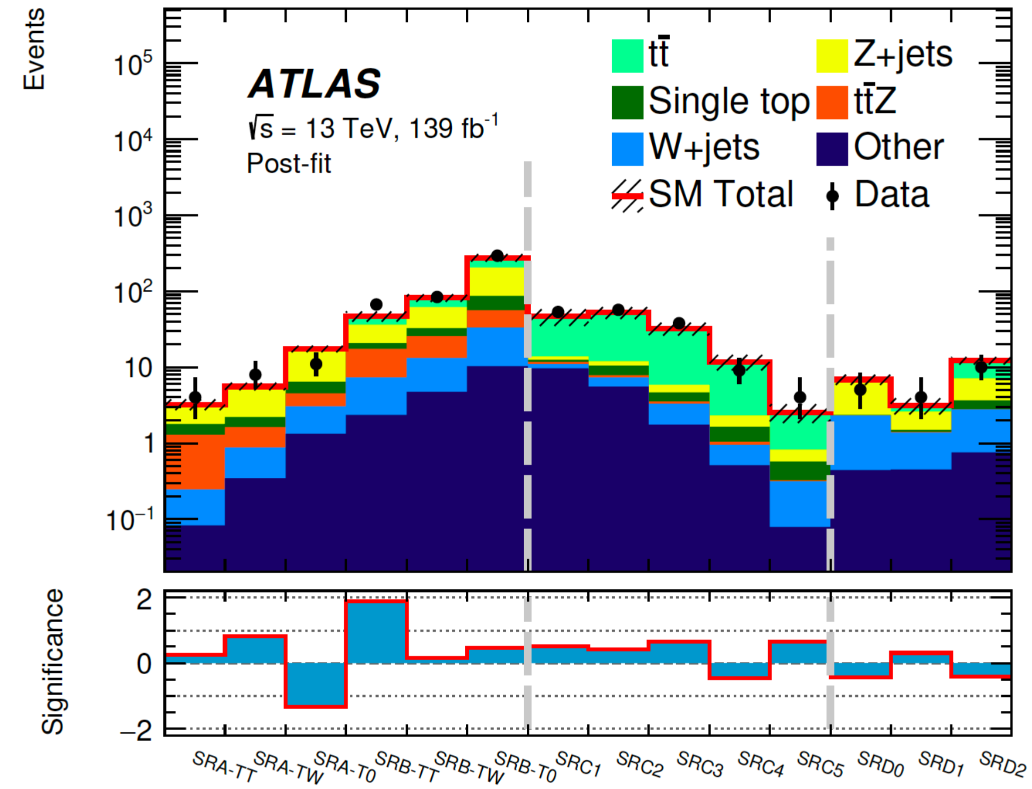
- **Compressed region ($\Delta m < m_W$): off-shell t and W**
  - challenging: very soft decay products
  - **LSP reproduce the correct DM abundance** (cohannihilation stops and LSP)
  - **high-p_T ISR jet** to boost sparticle pair and reduce overwhelming bkg with:
    - **soft b-tagging with track-jets/ secondary vertices (5 GeV)**
    - **soft leptons (down to 3.5/4 GeV)**

Top squarks: 0 leptons search

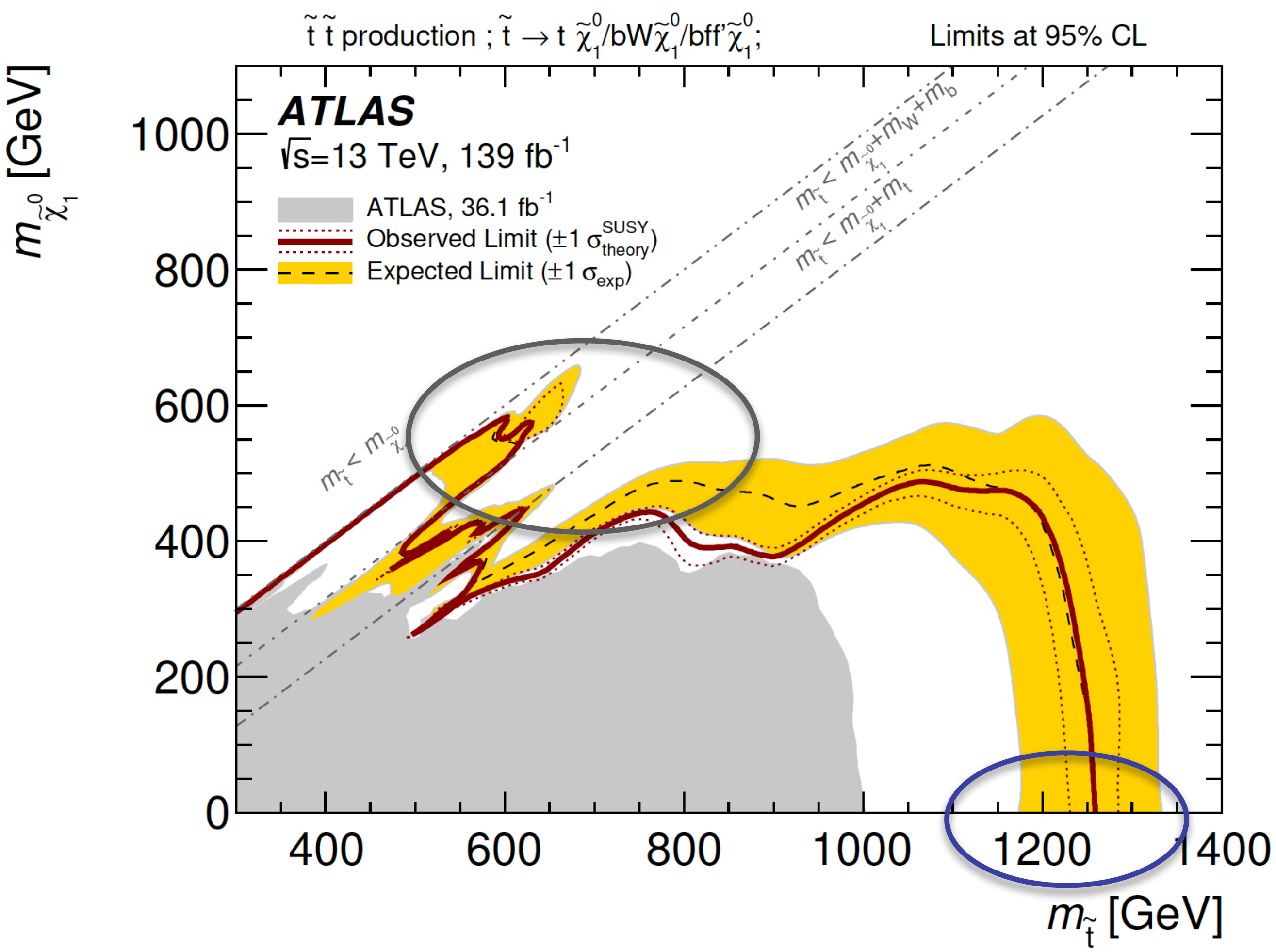
- **Full hadronic search: veto e/μ, E_T^{miss}>250 GeV**

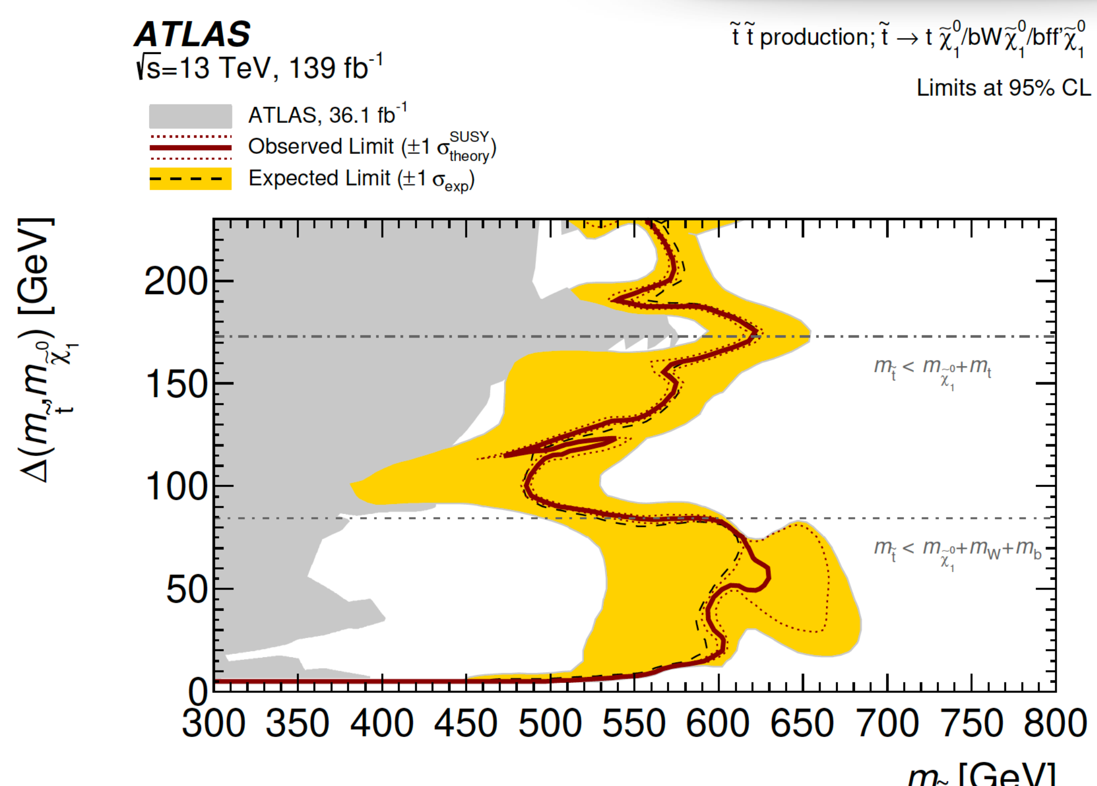


- **SRA-C:** $N_{jets} \geq 4$ GeV, $N_{bjets} \geq 2$, count numbers of reconstructed hadronic top/hadronic W
- **SRC-D:** use a high-p_T jet from ISR
- **SRD:** track-jets with p_T>5 GeV



ATLAS 2004.14060





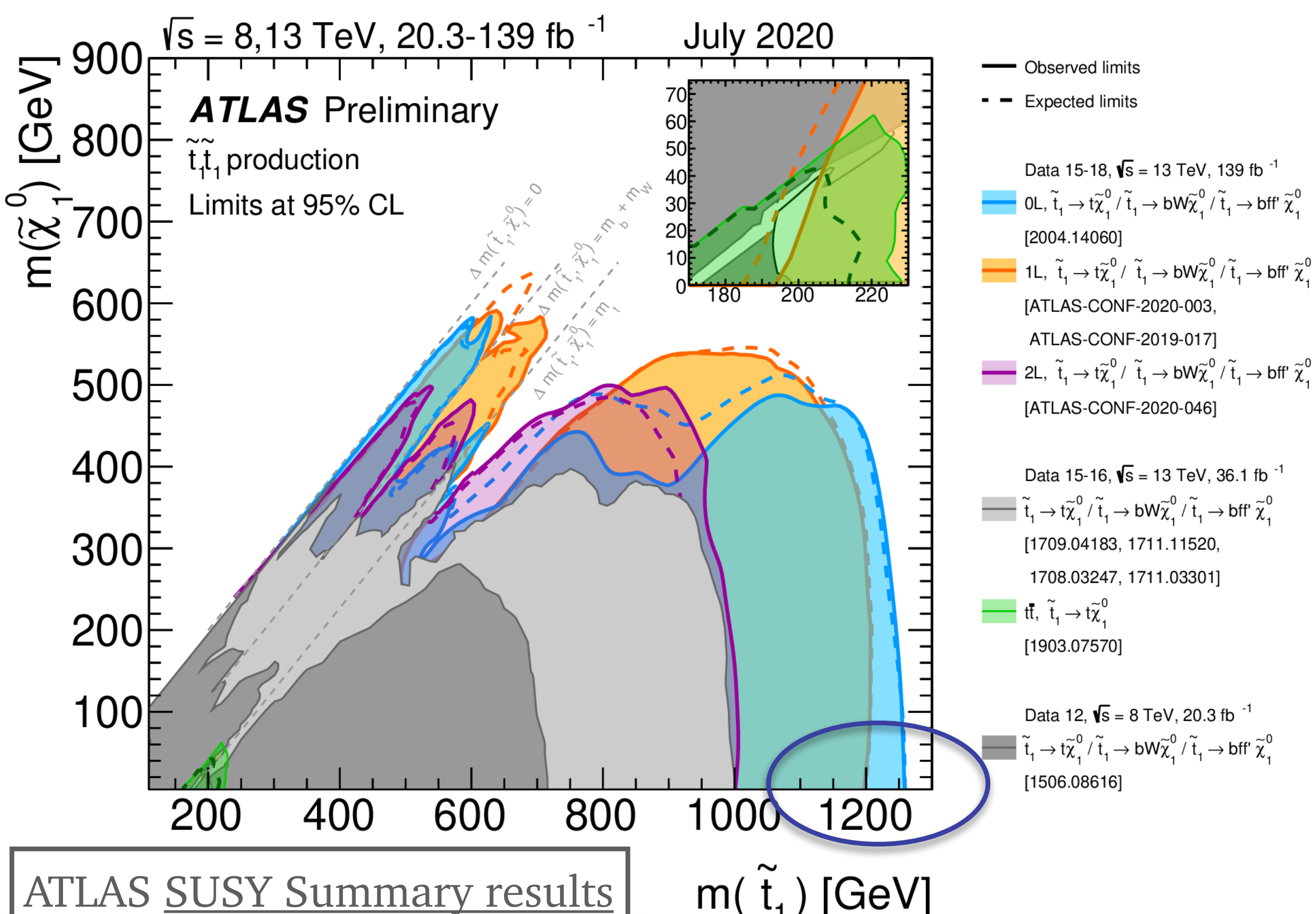
Top squarks: 1 or 2 leptons searches

ATLAS 2012.03799

- **Single lepton search: one e/μ, E_T^{miss}>250 GeV**
  - SR for compressed region: **ISR jet, soft b-tagging and soft leptons**: e(μ)[4.5(4)-25] GeV
  - SR with on-shell tops: use **hadronic top tagging, and 'topness' variable** to estimate compatibility with di-lepton ttbar with lost lepton (main bkg)

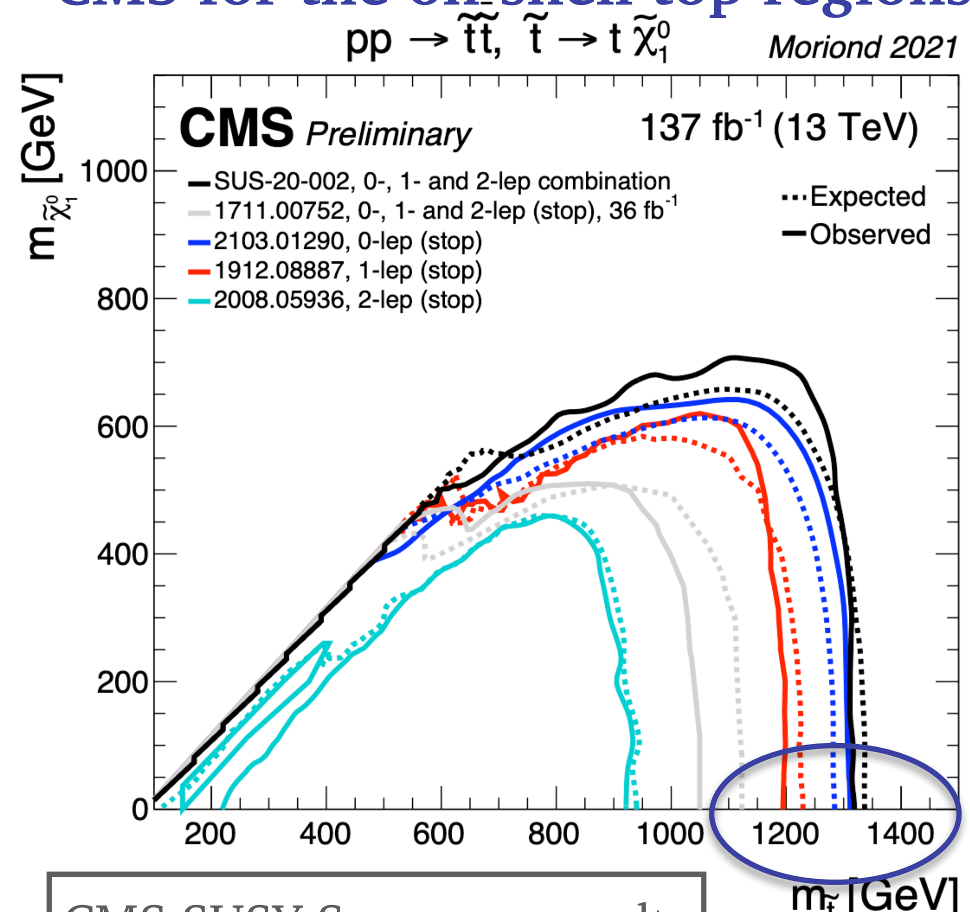
ATLAS 2102.01444

- **Dilepton search: two OS e/μ, E_T^{miss}>250 GeV**
  - SR for compressed region: **ISR jet and soft leptons:** e [4.5-25] GeV, μ [4-25] GeV
  - SR with on-shell tops: use of **lepton-based stransverse mass m_T^{ll}**



ATLAS SUSY Summary results

- **DNN hadronic top taggers used by CMS for the on-shell top regions**

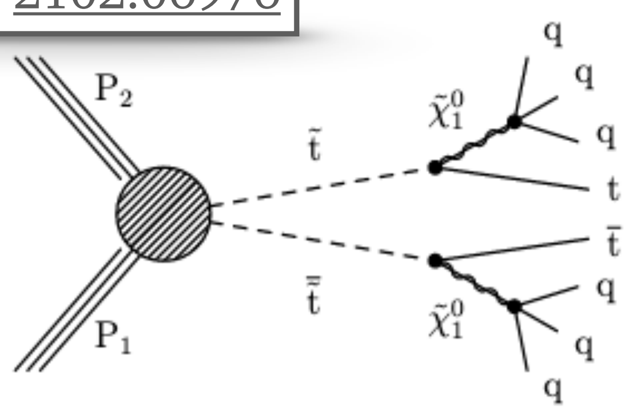


CMS SUSY Summary results

Top squarks in RPV models

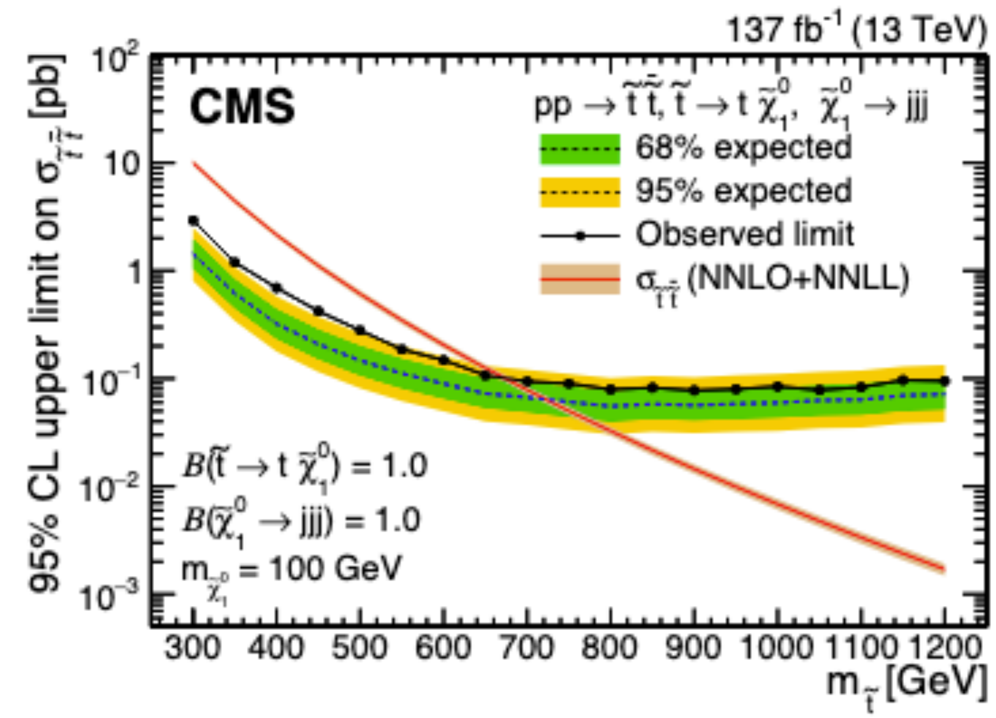
- **In RPV models LSP is not stable: no E_T^{miss}**
  - **full hadronic final states are much harder,** but high multiplicity and resonant structure can offer handles

CMS 2102.06976

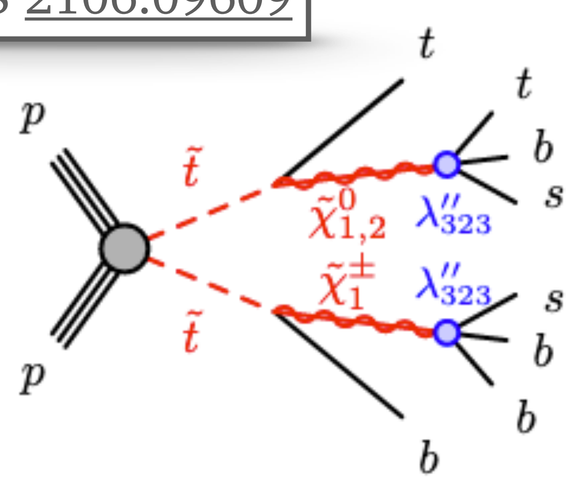


Stop NLSP, Bino LSP

train a neural network (NN) to discriminate signal from irreducible tt + jets background

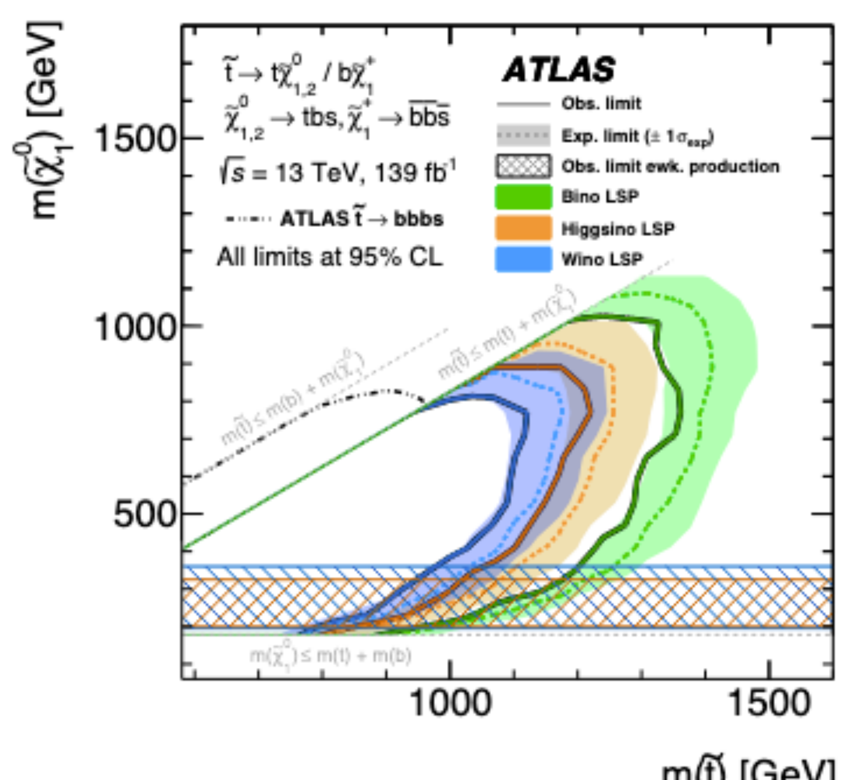


ATLAS 2106.09609



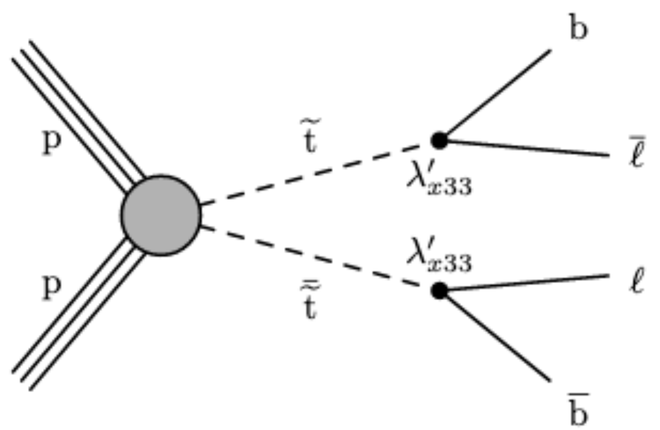
Stop NLSP, Bino/Wino/ Higgsino LSP

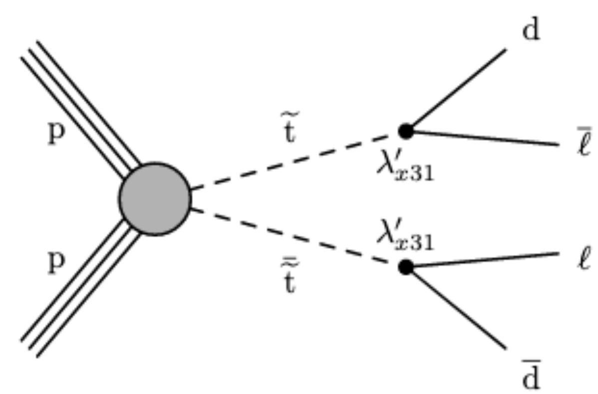
search based on final states with large b-jets multiplicity, lepton + jets final state



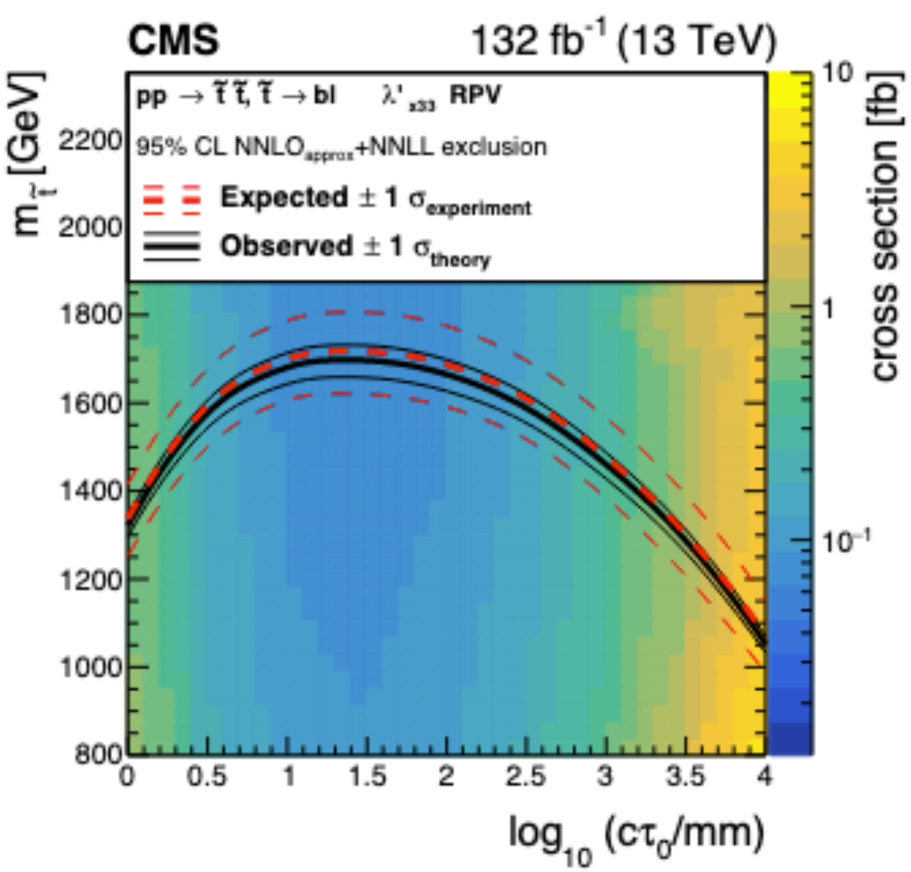
Top squarks in RPV models

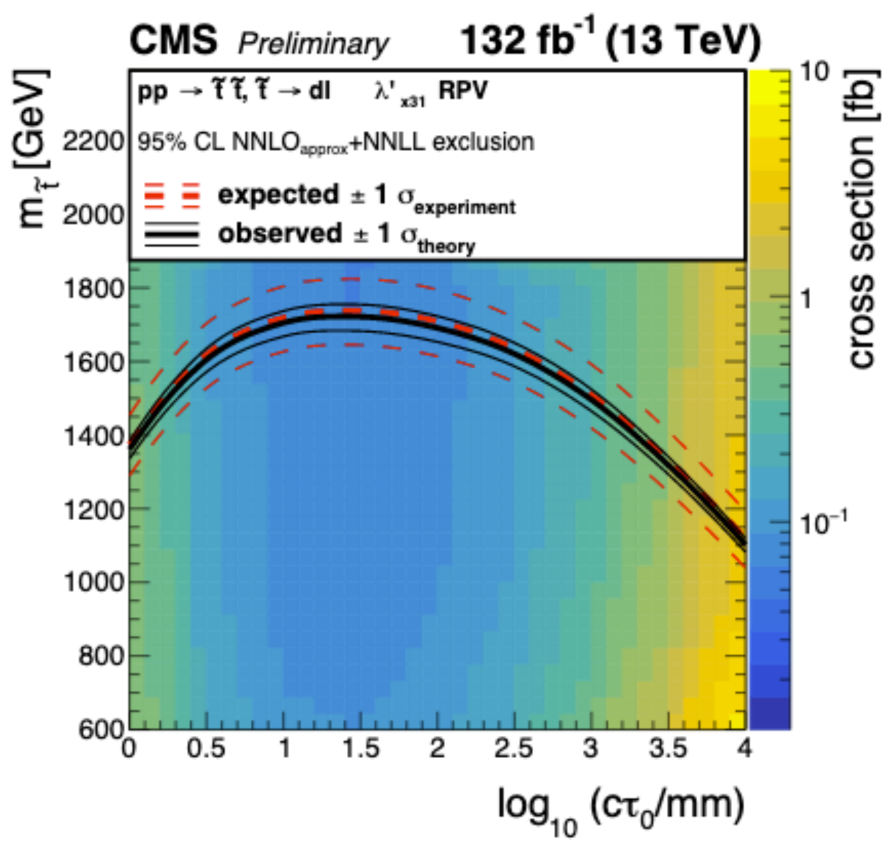
- **Long-lived particles can arise not only from small phase-space but also from small couplings**
  - RPV couplings can be suppressed and, **and LSP can be long-lived**





- signature: pairs of displaced jet and lepton, **originating from a secondary vertex**



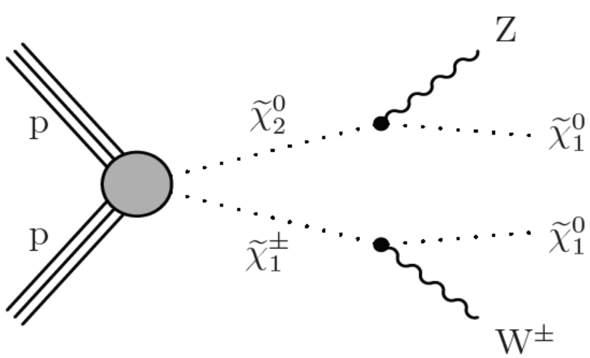


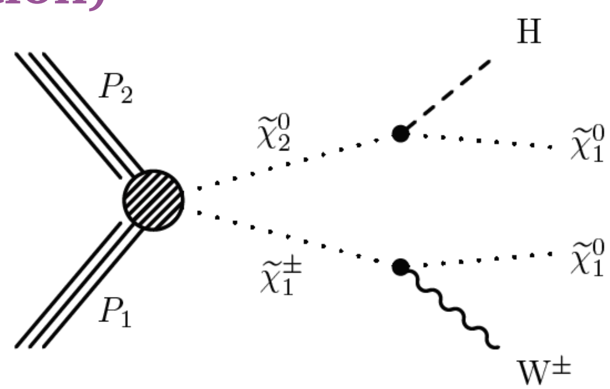
CMS:2012.01581

Electroweakinos: dibosons final states

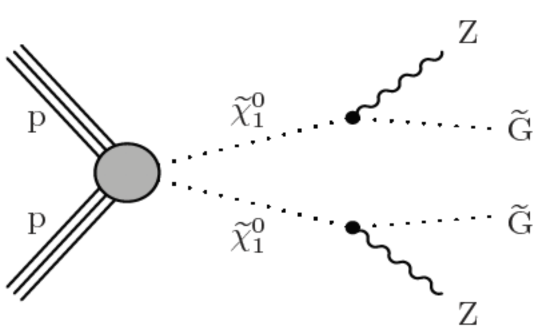
- **EWK sector: much lower cross sections**
  - sensitivity to **lower sparticle masses**
  - final states very much SM like if dealing with W,Z,H hadronic decays, **searches rely on leptonic final states**
  - hadronic final states powerful at higher masses and large Δm

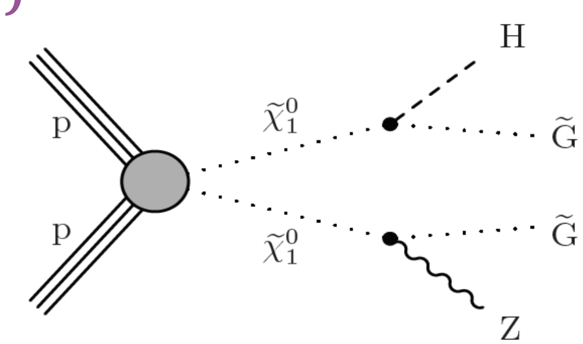
Wino NLSP
(highest cross section)

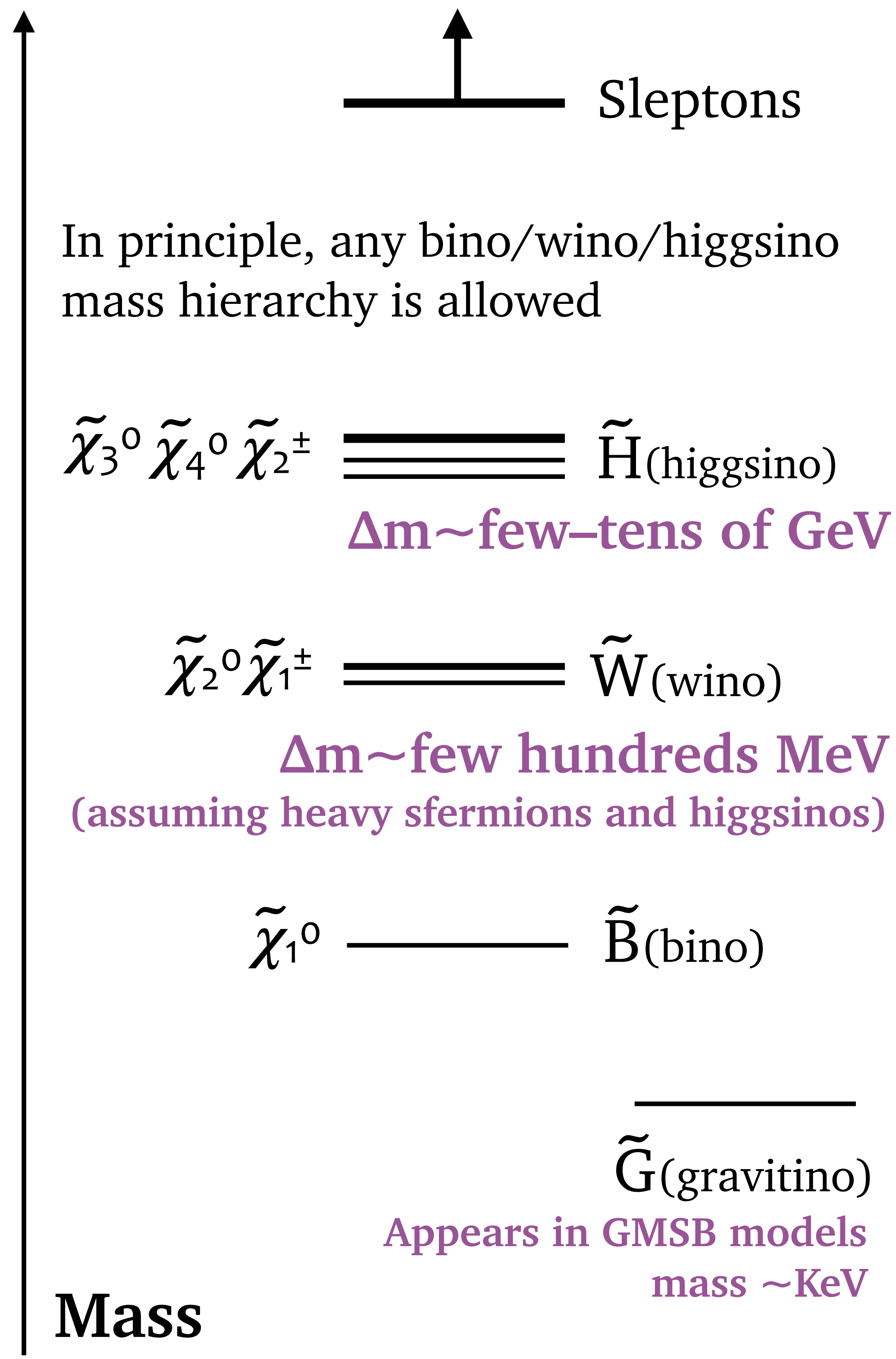




Higgsino NLSP
(masseless LSP)

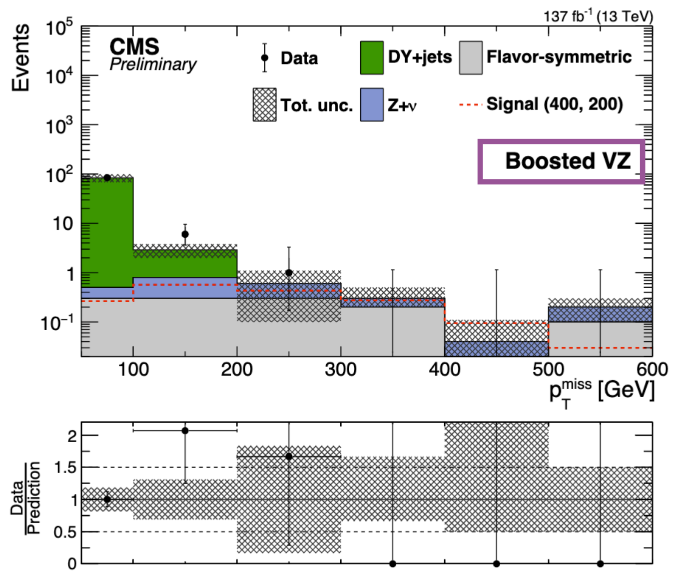


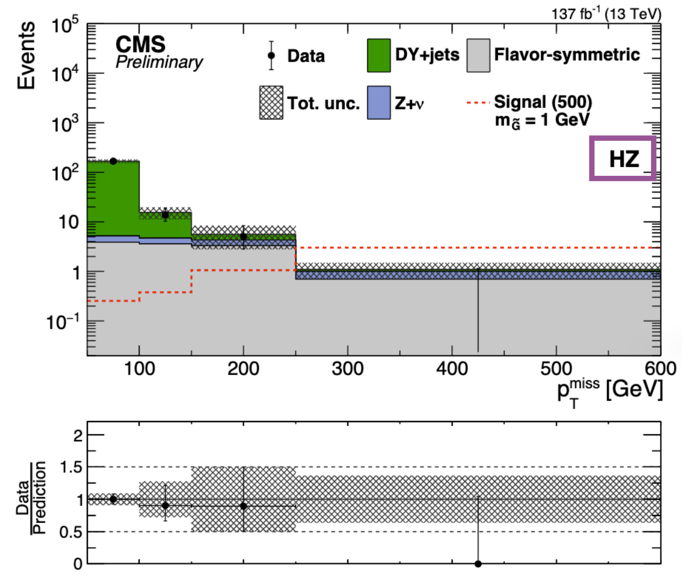




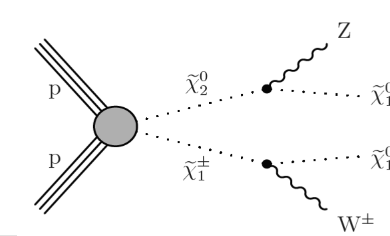
Electroweakinos: 2 e/μ OSSF on-Z

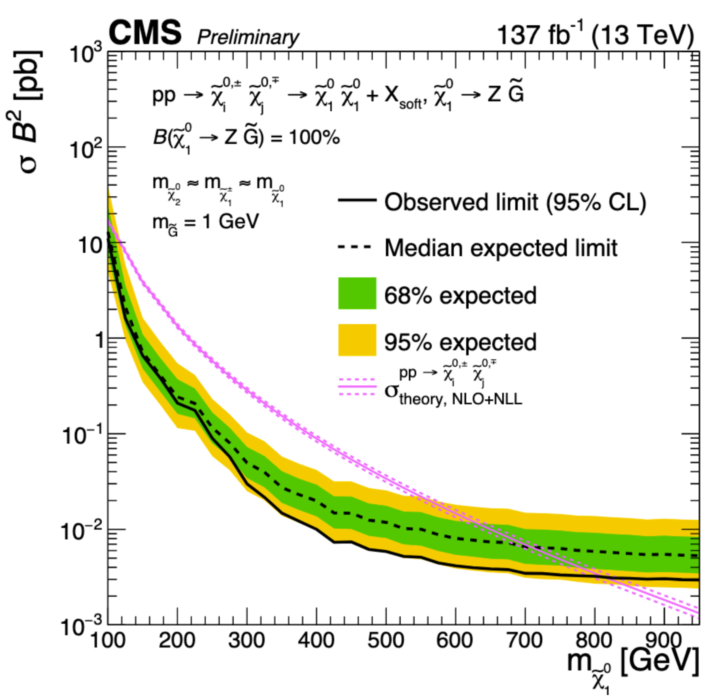
- **Tag one leptonically decaying Z with high p_T leptons (25,20 GeV), dilepton trigger, two additional jets and moderate E_T^{miss}**
  - E_T^{miss} SR for Z+hadronically decaying V(Z/W) in **resolved** or **boosted** regime, Z+H(bb)



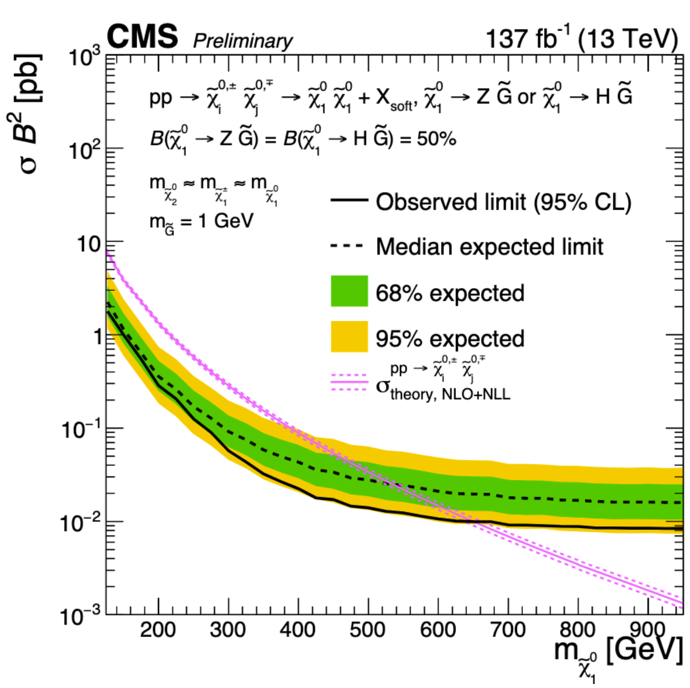


CMS 2012.08600

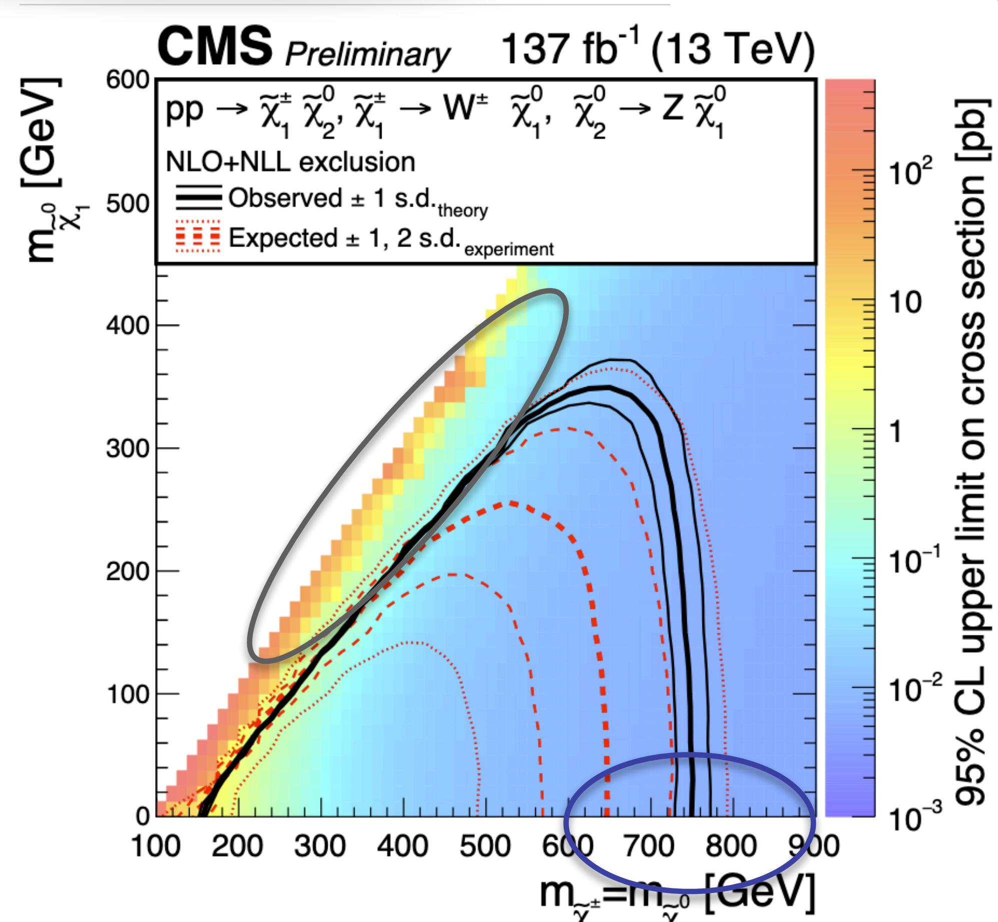




ZZ, Gravitino LSP



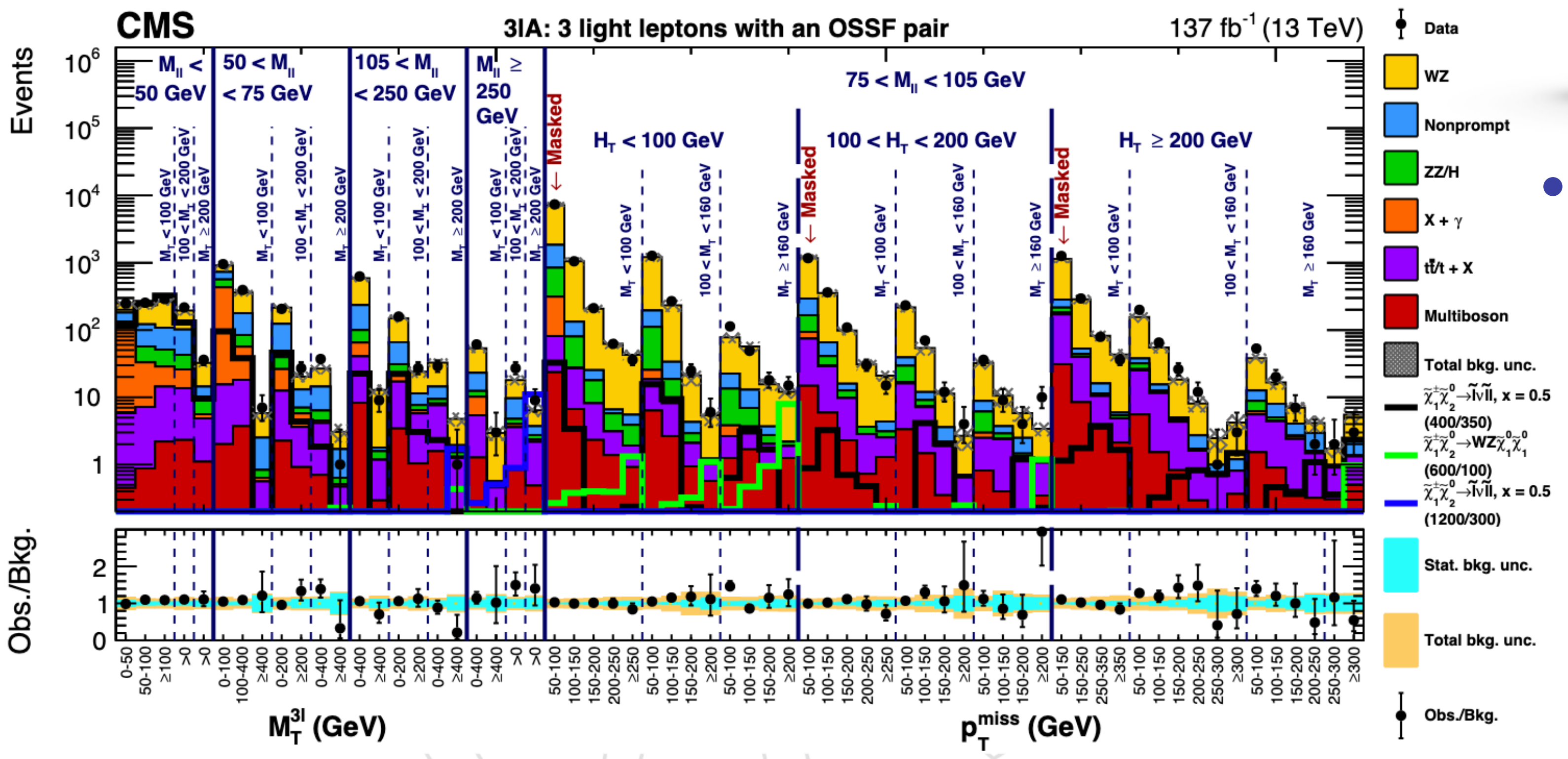
ZH, Gravitino LSP



WZ, Wino NLSP, Bino LSP

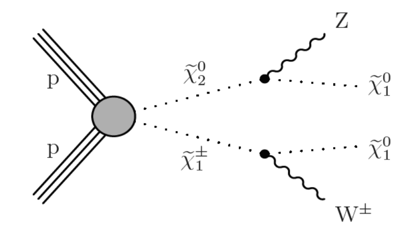
Electroweakinos: 3 lepton search (e/μ/τ)

- 3 leptons and moderate E_T^{miss}, target WZ leptonic decays (on- and off-shell)



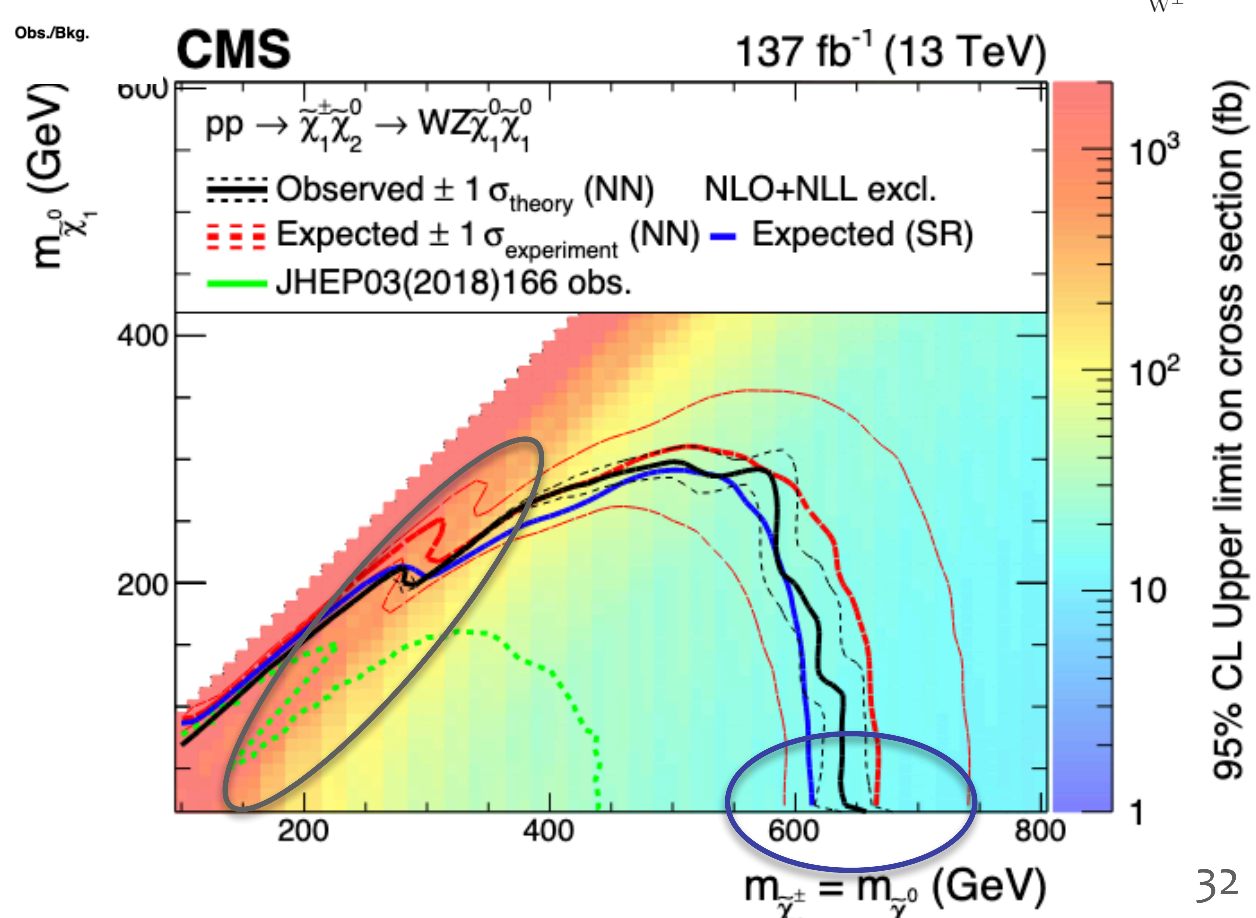
CMS 2106.14246

- 3 light lepton signal regions: preselected with $p_{Tl} > 20(25), 10(15), 10(10)$ GeV for μ/e, $E_T^{miss} > 50$ GeV, $m_{3l} > 100$ GeV



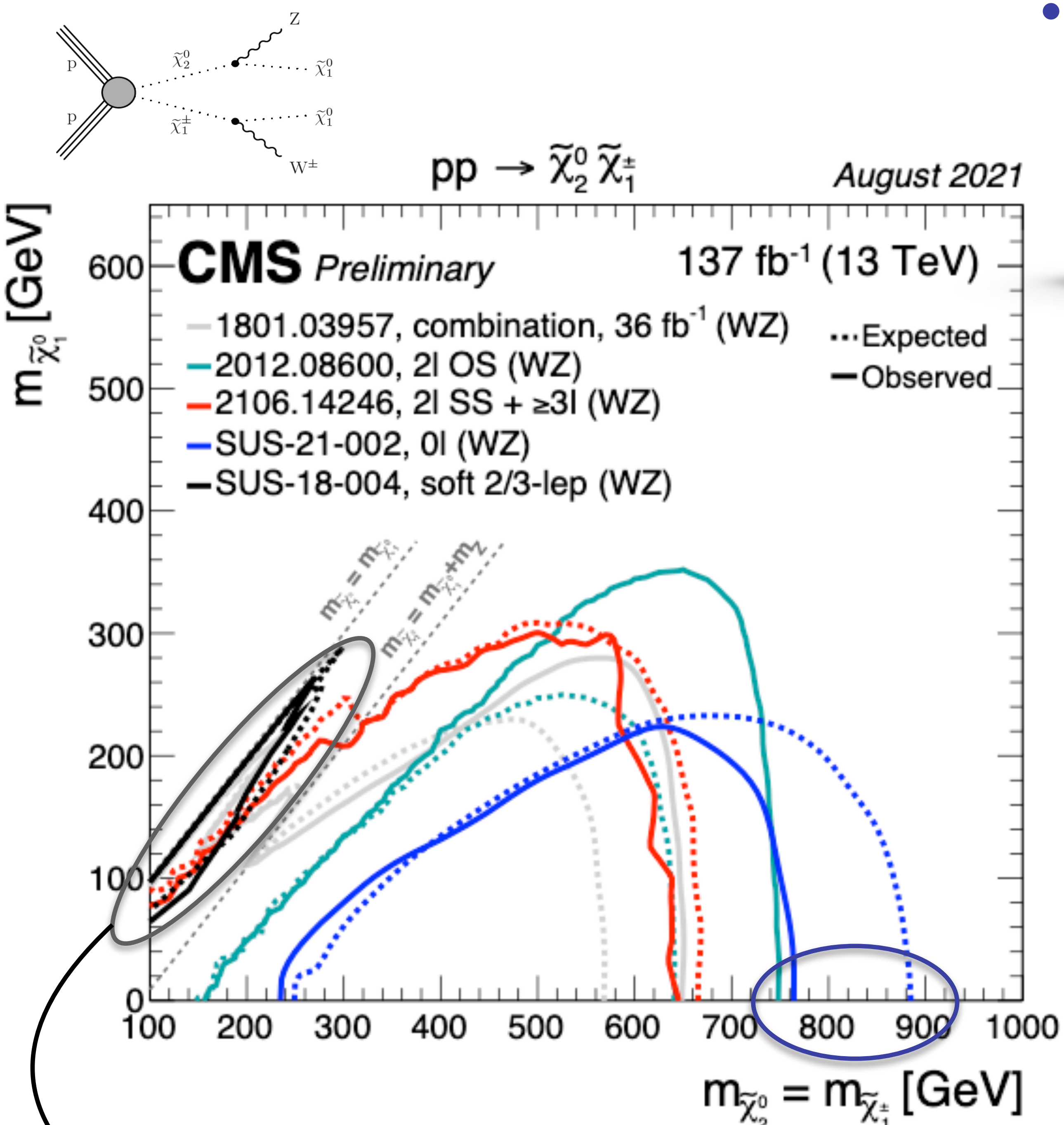
- Signal extraction performed with parametric Neural Network, training variables: m_{ll}, M_T^W, M_T^{3l}, E_T^{miss}, H_T, m_{3l}

- "WZ corridor": Δm=90 GeV, difficult regions due to WZ-bkg-like signal behaviour

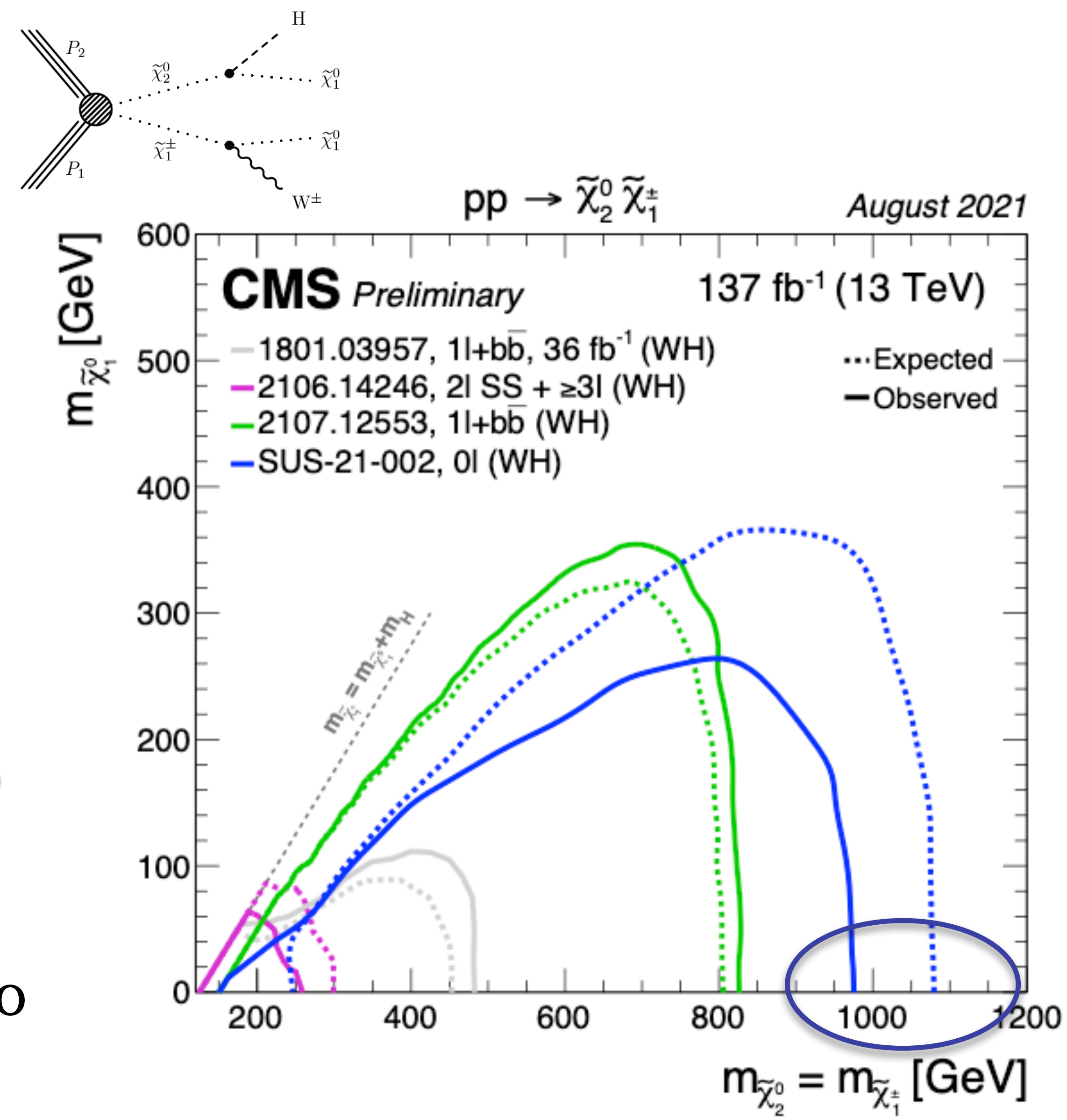


Electroweakinos: WZ/WH final states

- Hadronic final states are also used to target higher masses and large Δm
  - boosted topologies targeted with fat jets (AK8) and Deep W/Z/H(bb) taggers



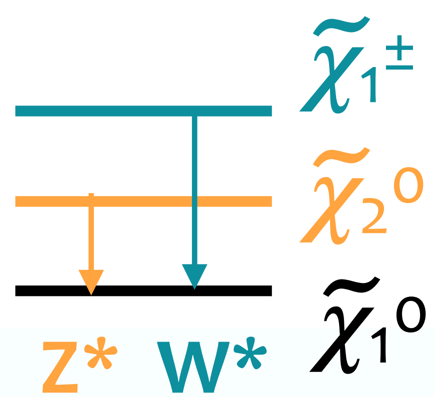
CMS SUSY Summary results



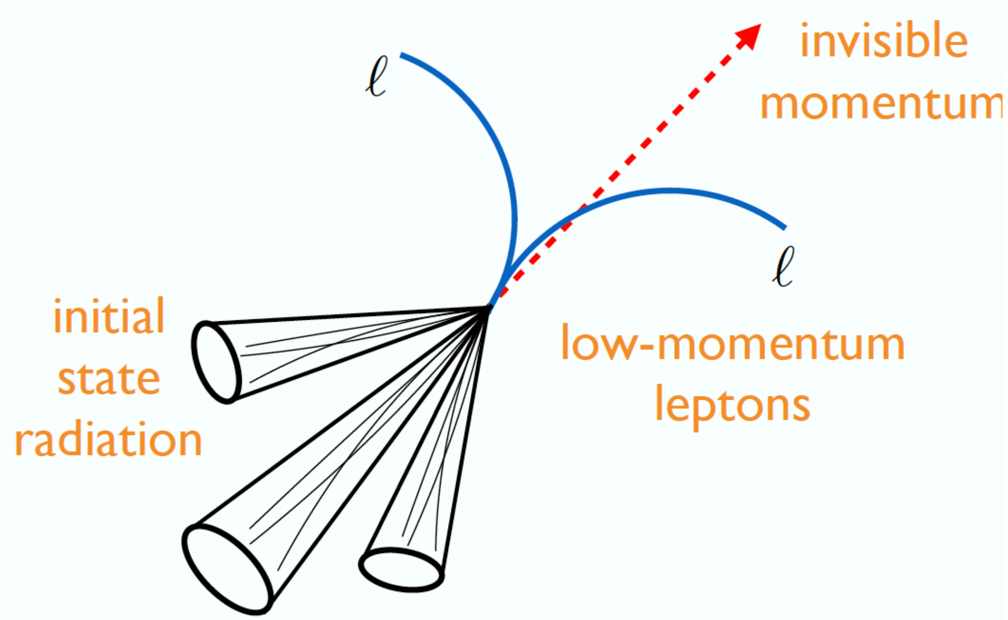
- In last years a lot of developments to target very compressed regions

Electroweakinos: compressed spectra

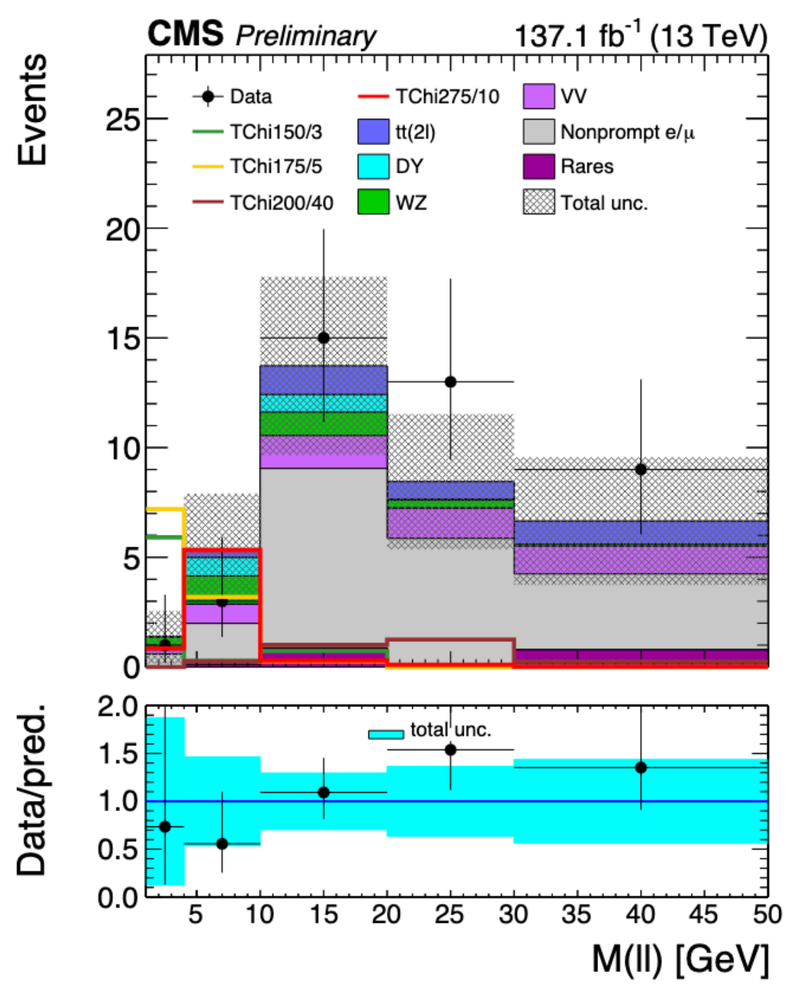
- Dedicated analysis strategy to target scenarios with Δm~few–tens of GeV



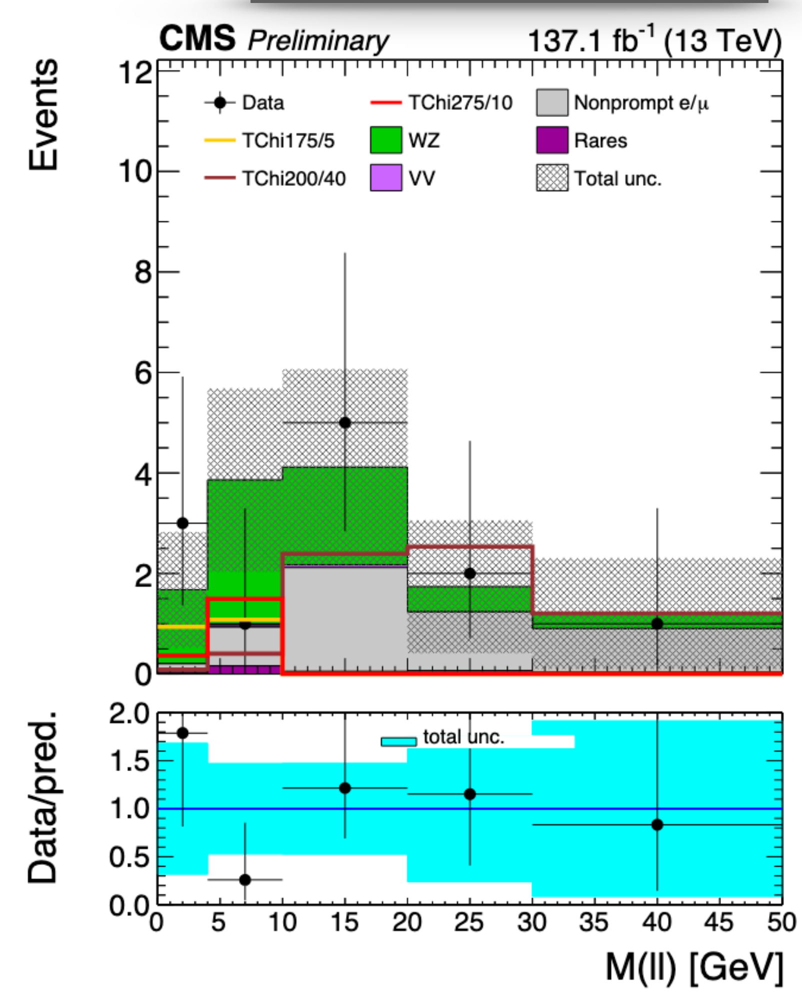
- ISR jet to boost superparticle pair system and **induce E_T^{miss}**, and other decay product remains soft (E_T^{miss} > 120 GeV)
- Exploit leptonic decays of W* and Z* to reduce bkg: 2 OSSF or 3 soft μ(e), down to 3(5) GeV
- SR bins: $m_{ll}^{(min)}$ down to 1 GeV, proxy of the Δm



CMS PAS-SUS-18-004



2 OSSF leptons SR

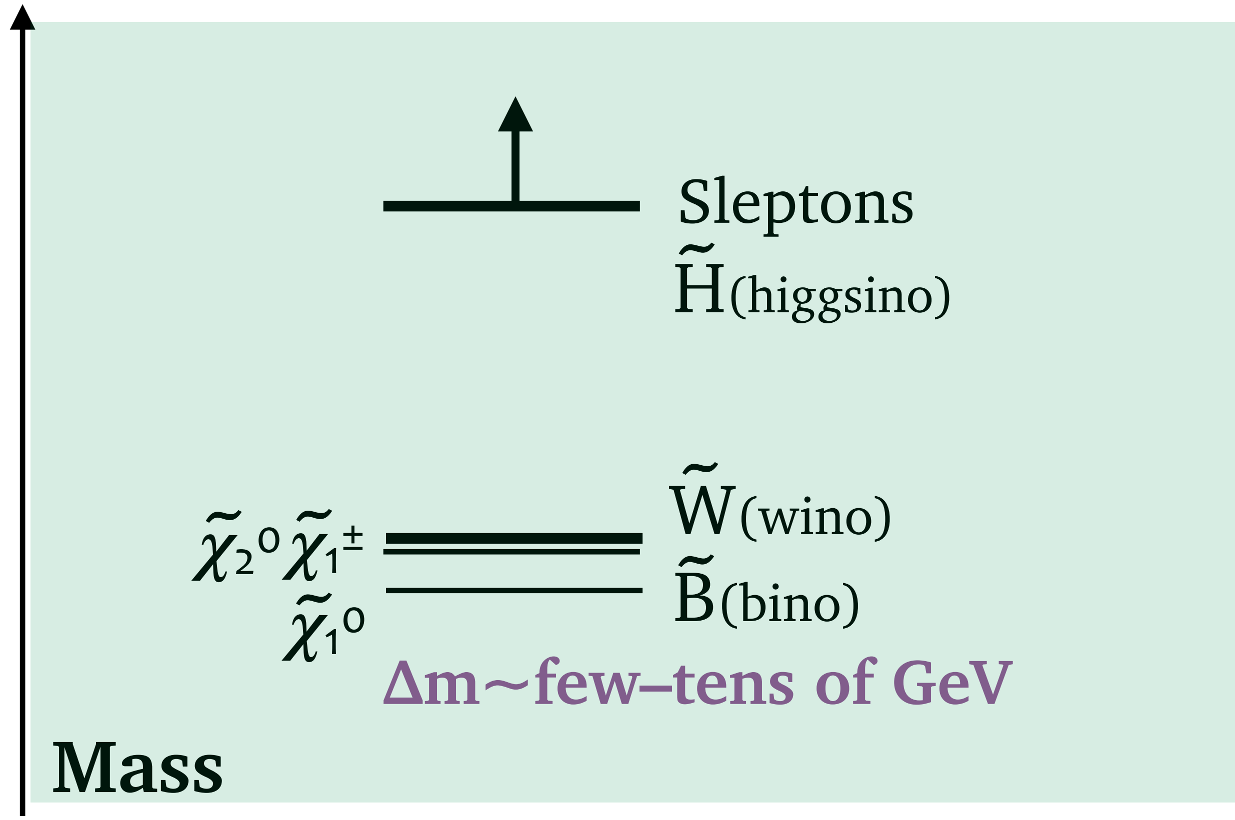


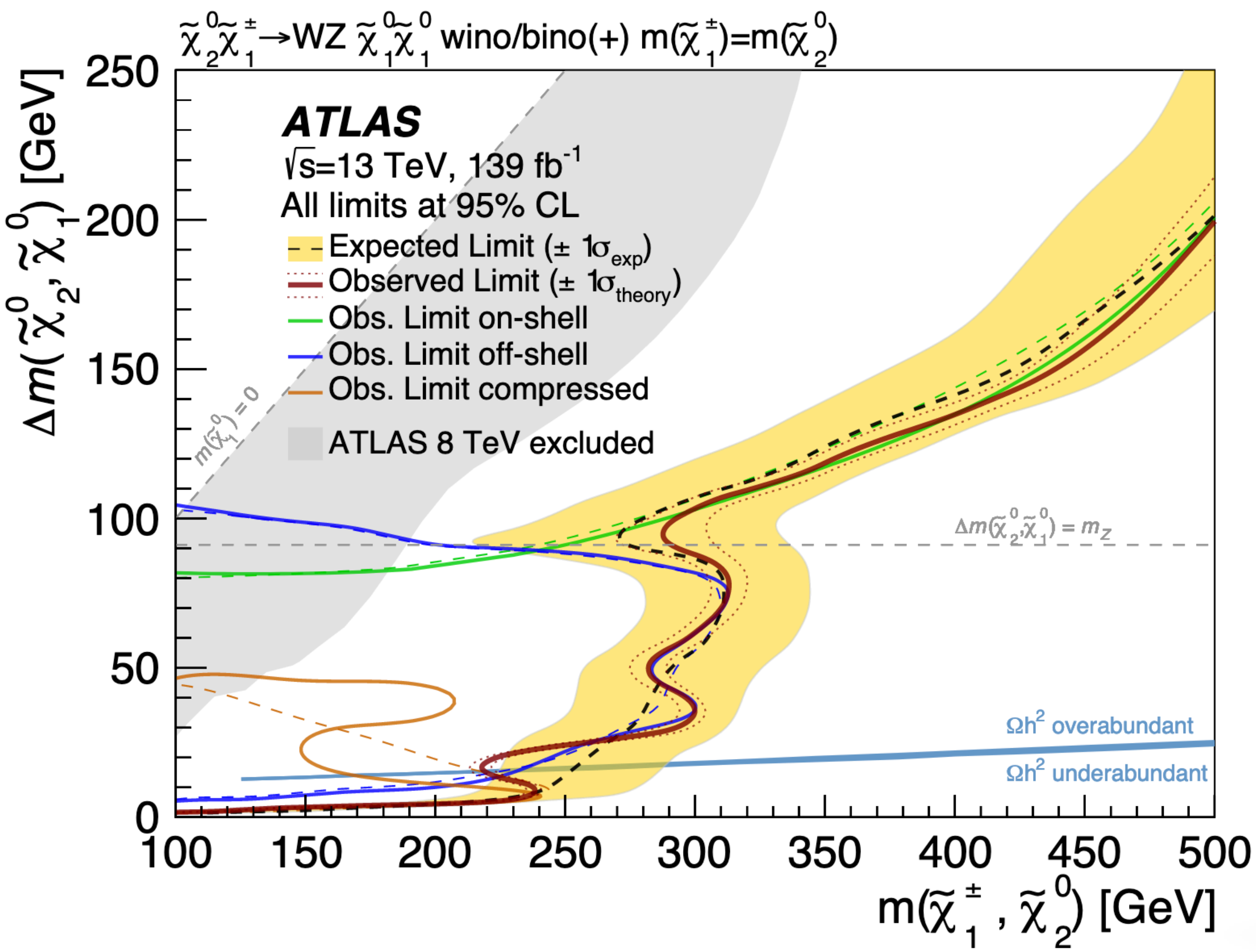
3 leptons SR

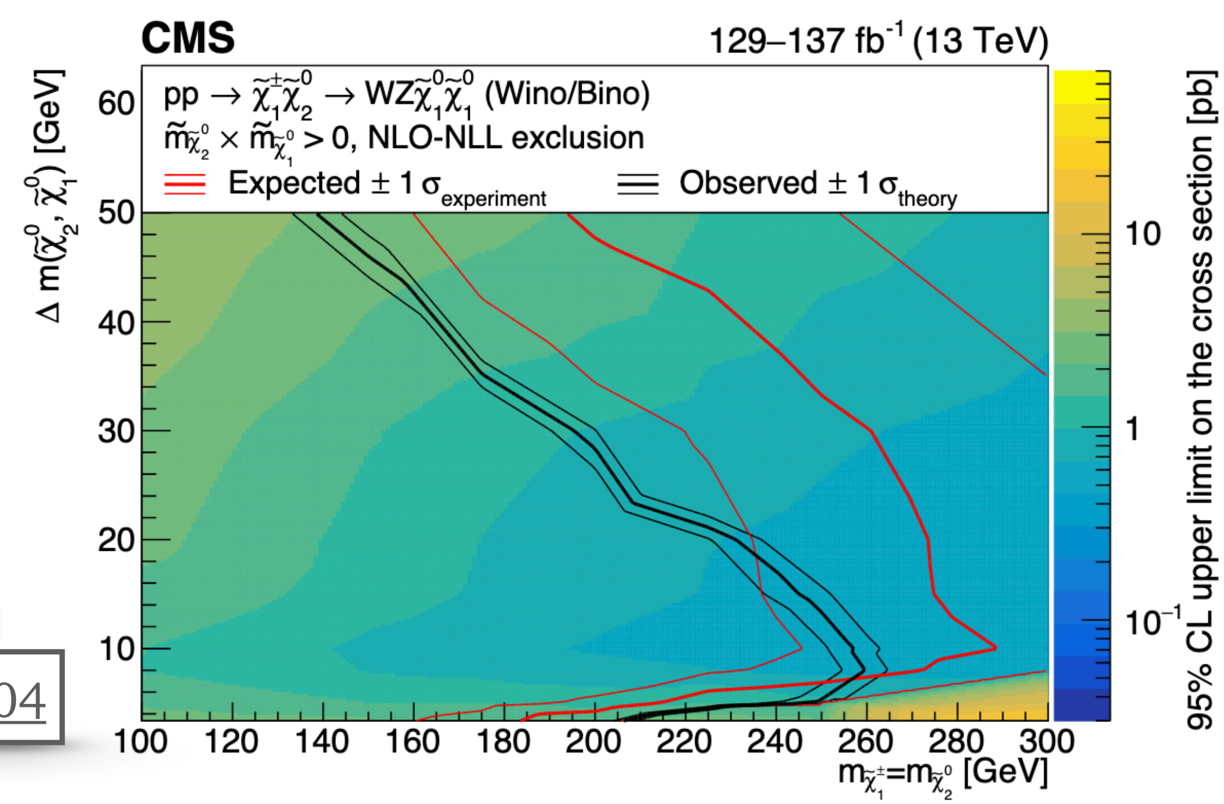
- Very low signal acceptance
- Analysis statistically limited
- Signal to emerge slowly as more integrated luminosity accrues

Electroweakinos: compressed spectra

- **Regions particularly appealing for theoretical considerations**
  - Sensitivity to Δm of few GeV with **Wino cross section**
  - **motivated by bino-wino cohannihilation:** LSP can reproduce the correct DM abundance





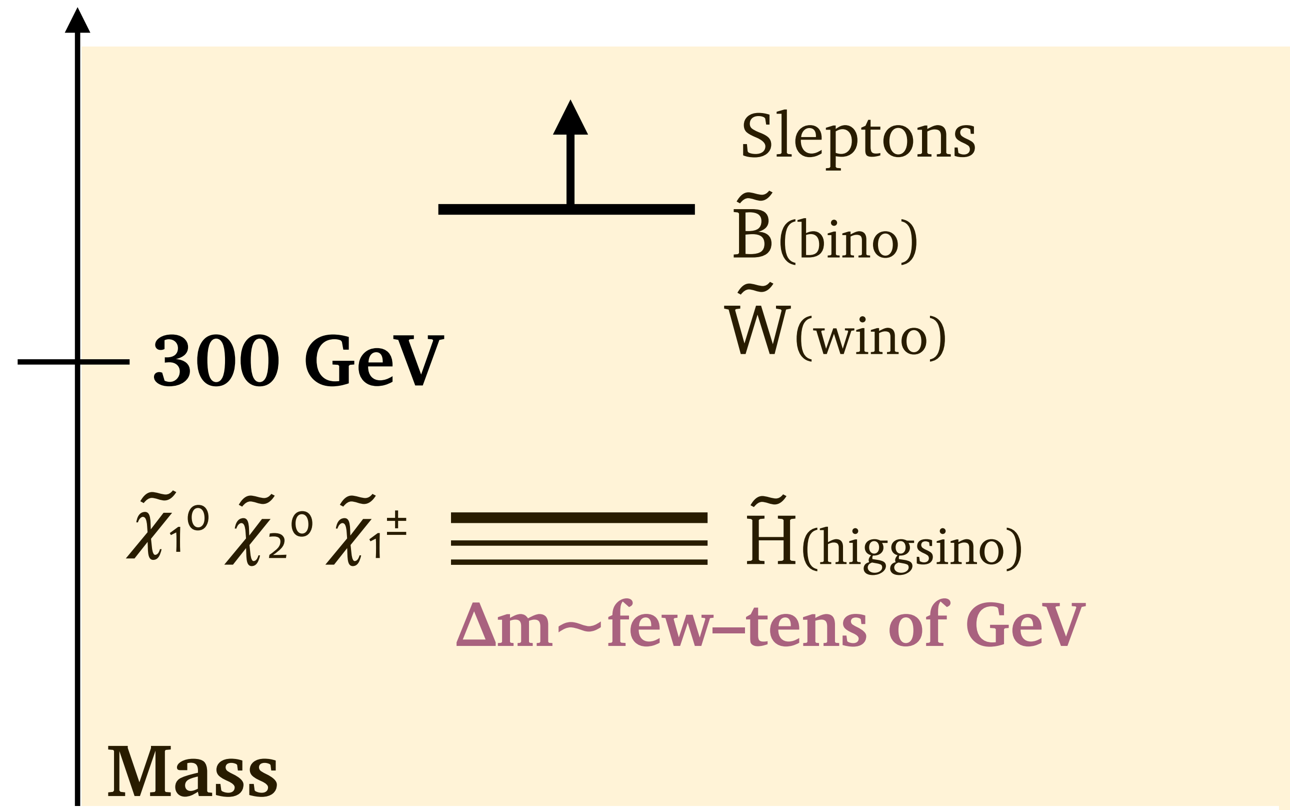


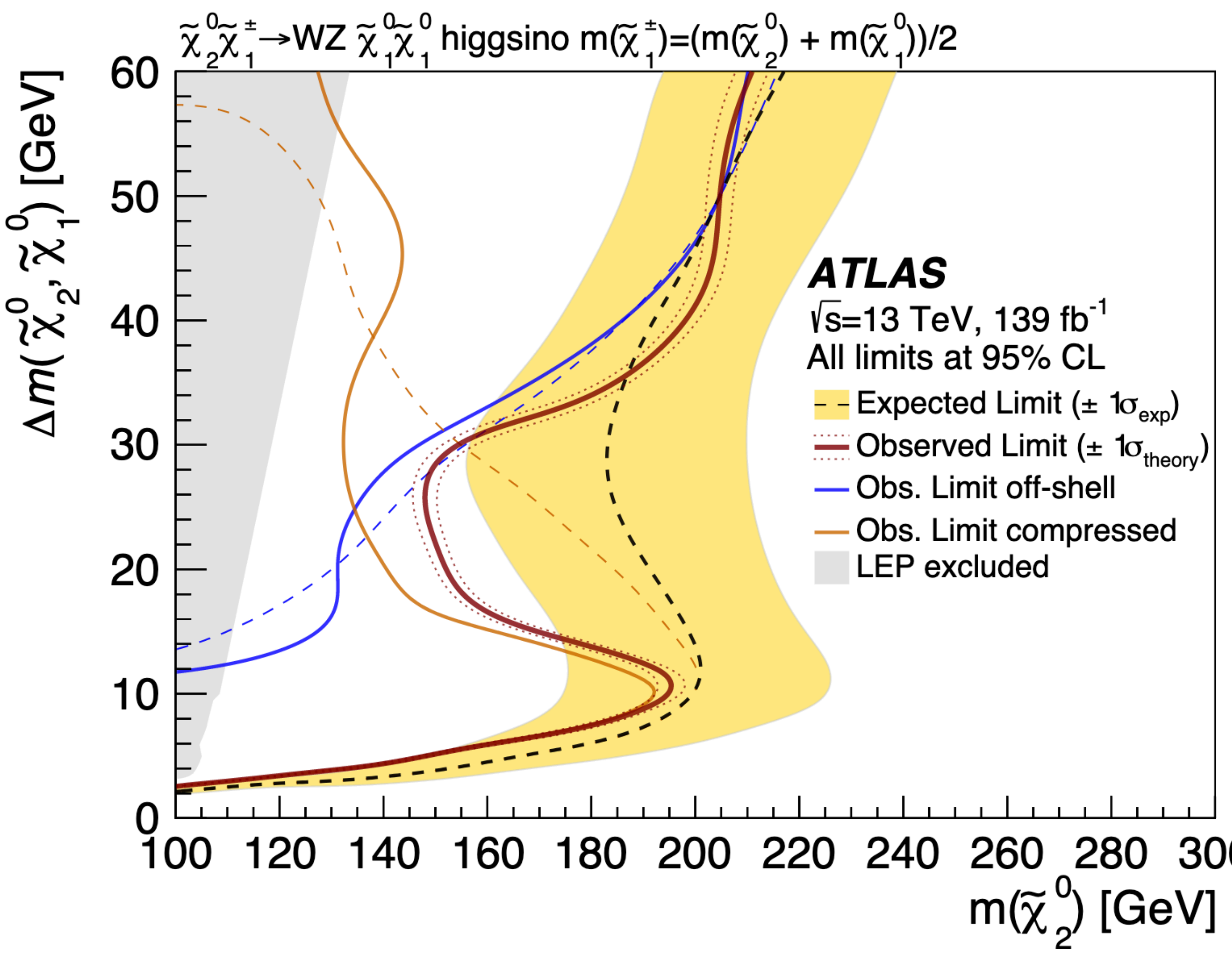
ATLAS 2106.01676

CMS PAS-SUS-18-004

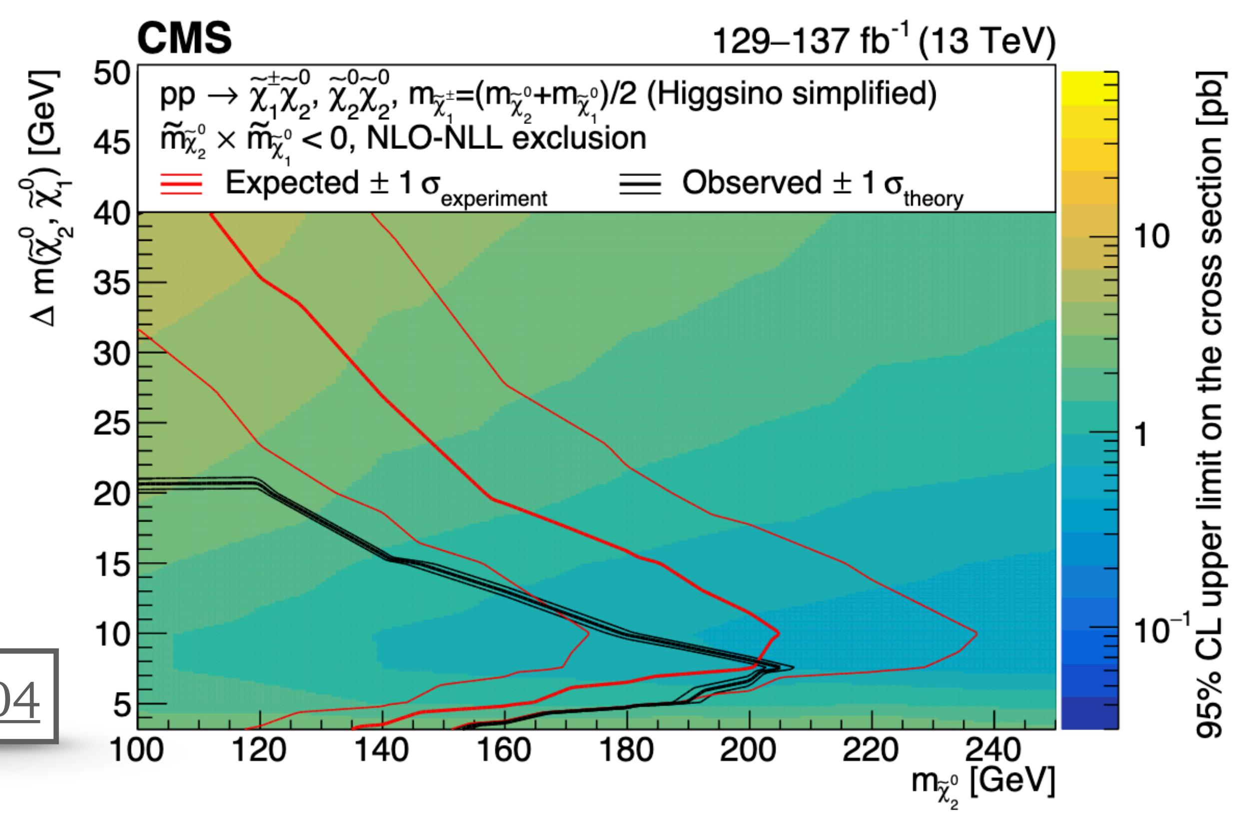
Electroweakinos: compressed spectra

- **Regions particularly appealing for theoretical considerations**
  - Reached sensitivity also to **Higgsinos LSP** cross section
  - **motivated by naturalness:** naturally compressed Higgsino **can still be light**





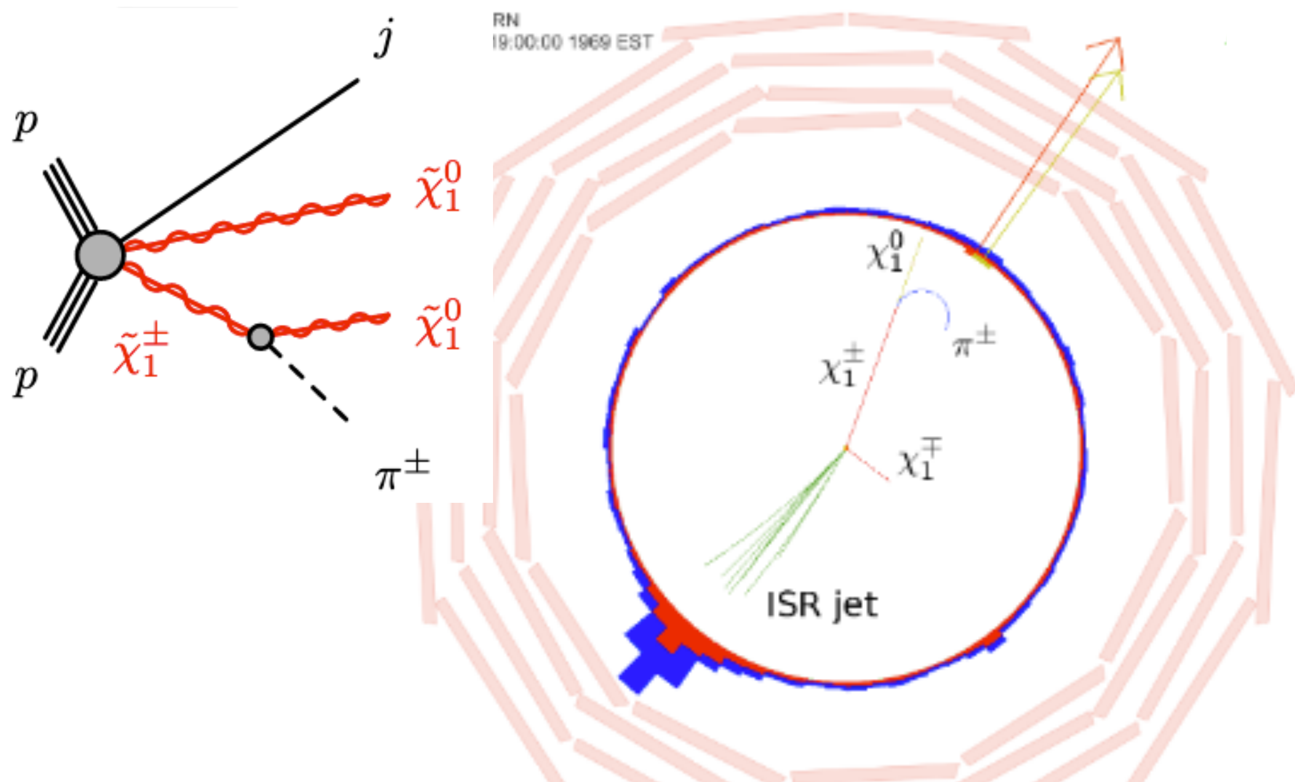
ATLAS 2106.01676

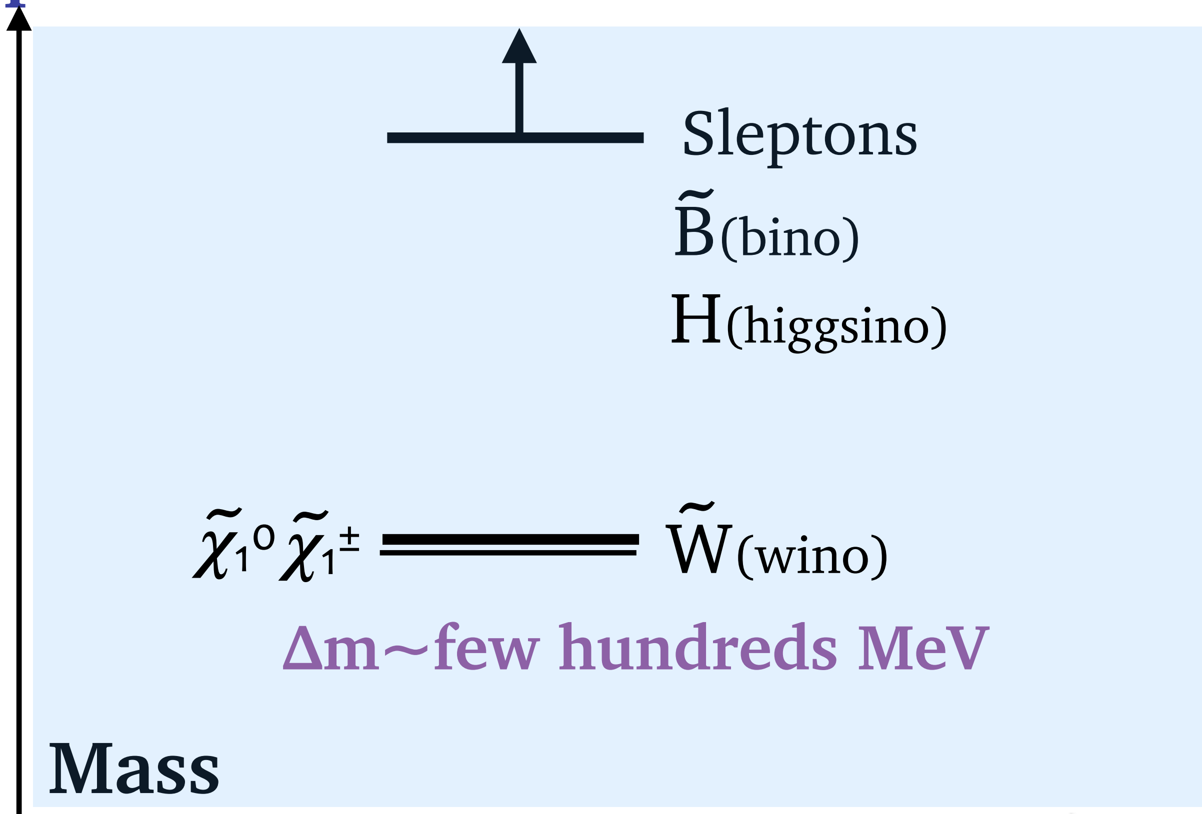


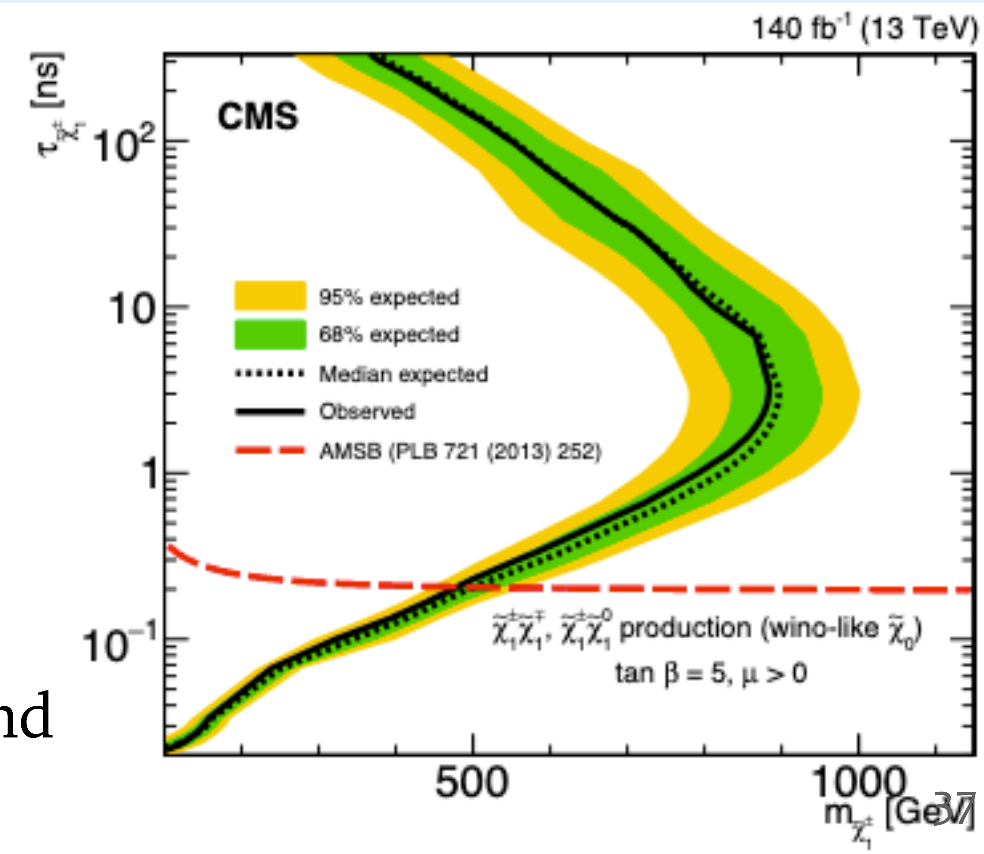
CMS PAS-SUS-18-004

Electroweakinos: compressed spectra

- **Very small mass splitting, O(100)MeV, expected in scenarios with wino-like LSP and other SUSY particles decoupled**
  - **chargino is long lived (cτ of ~10s cm),** and decays into a soft pion and neutralino
  - ISR jet to induce E_T^{miss}
  - identification of **disappearing tracks** inside the tracker volume (<1m)



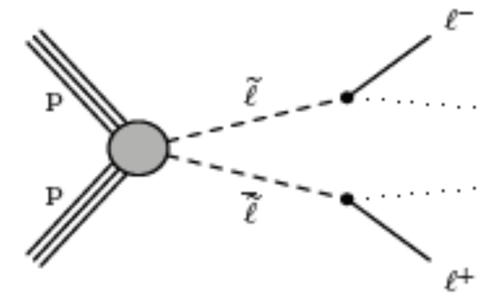


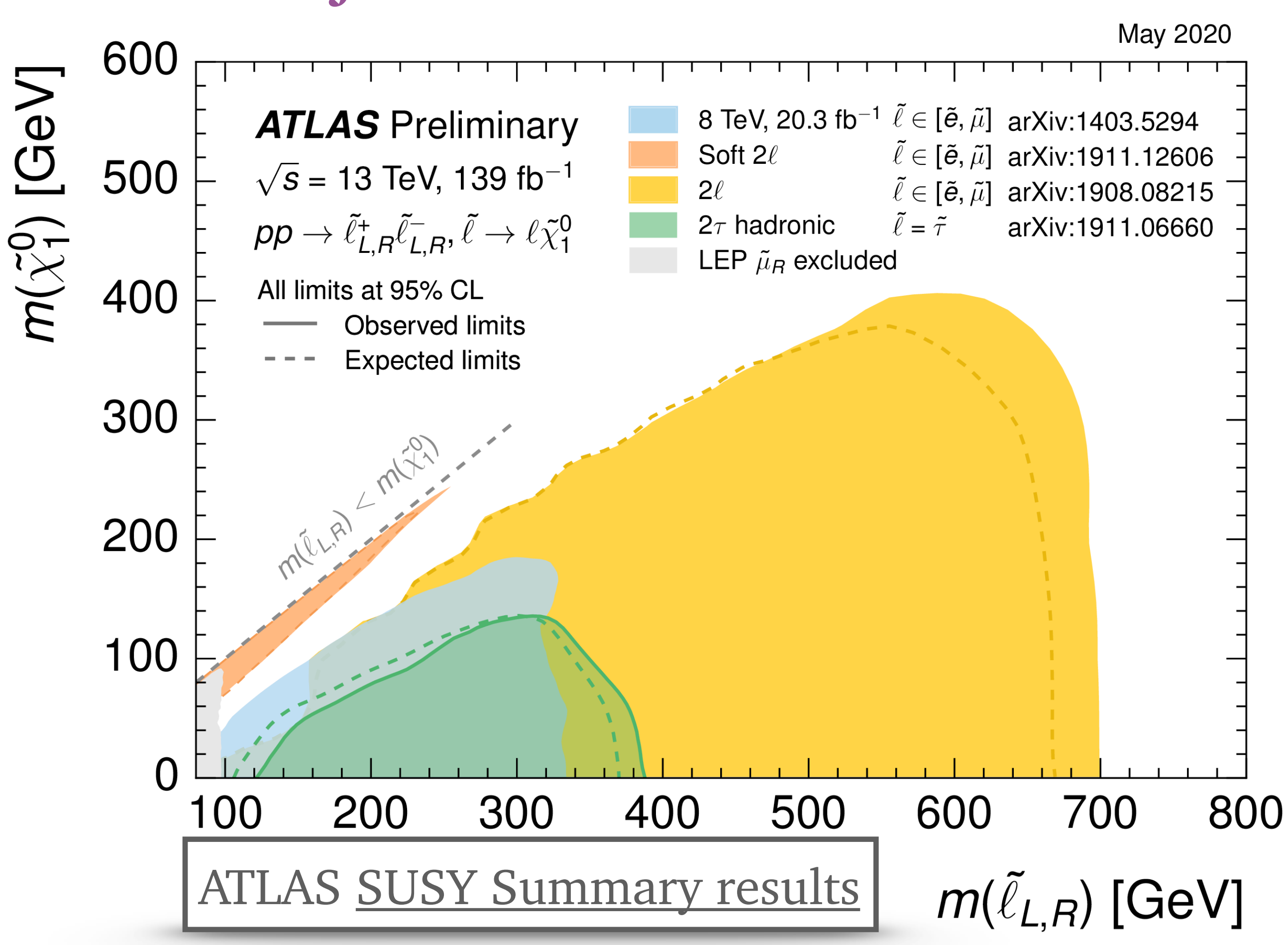


- Pure **wino exclusion up to 490 GeV** (σ~46.4 fb)
- **Exclude chargino masses up to 884 GeV for τ of 3 ns**
- Reach at high/low lifetimes mix of detector geometry and analysis optimization

Sleptons, the rarest

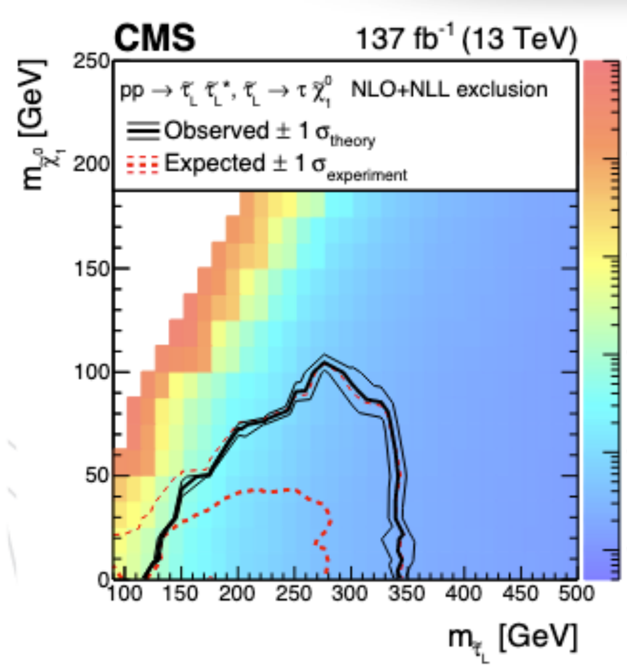
- **Direct slepton production: scalar partners of left- and right-handed e/μ/τ**
  - mass degeneracy: $m(\tilde{e}_L)=m(\tilde{e}_R)=m(\tilde{\mu}_L)=m(\tilde{\mu}_R)$, $m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$
  - **2 OSSF high p_T e/μ to target high Δm**
    - moderate E_T^{miss} and hadronic activity ($N_{jets}<2$ to allow ISR), Z-veto
  - **2 soft OSSF e/μ recoiling against ISR to target small Δm**
    - SR binned in M_{T2}^{ll}
  - **Final states with hadronic taus**
    - **lower signal acceptance:** tight τ_h ID and p_T, large background from **jets→τ_h misidentification**

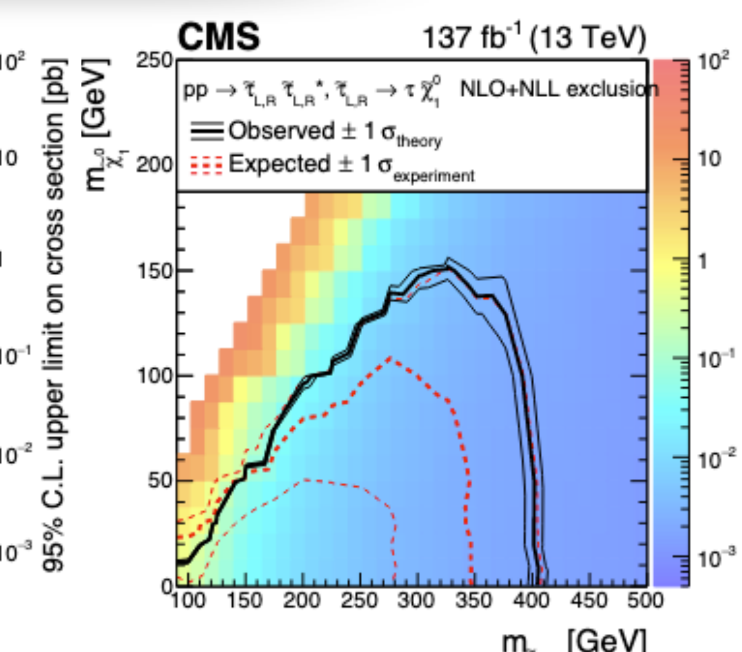




ATLAS SUSY Summary results

CMS PAS-SUS-21-001





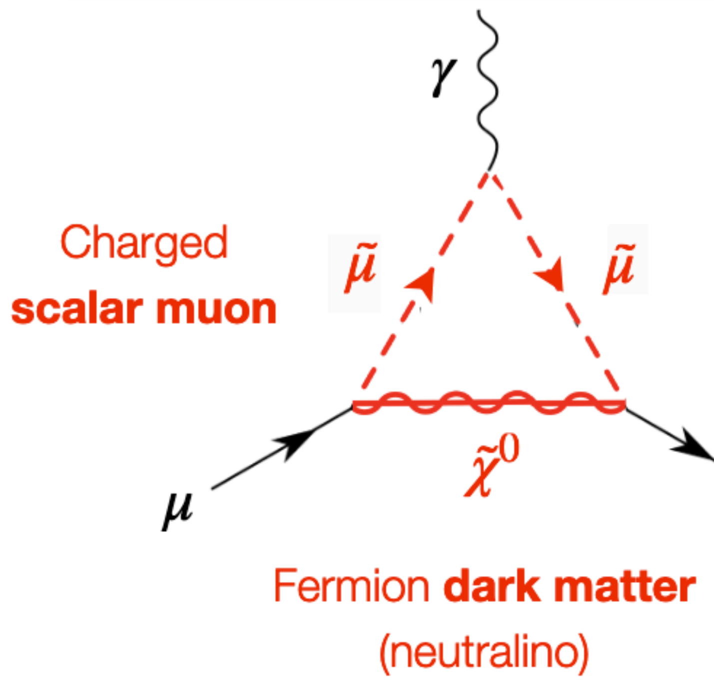
cross section for degenerate

cross section for

Sleptons and Muon g-2?

- **Supersymmetric interpretation of the Muon g-2 Anomaly:**

Measured by the Fermilab and BNL experiments



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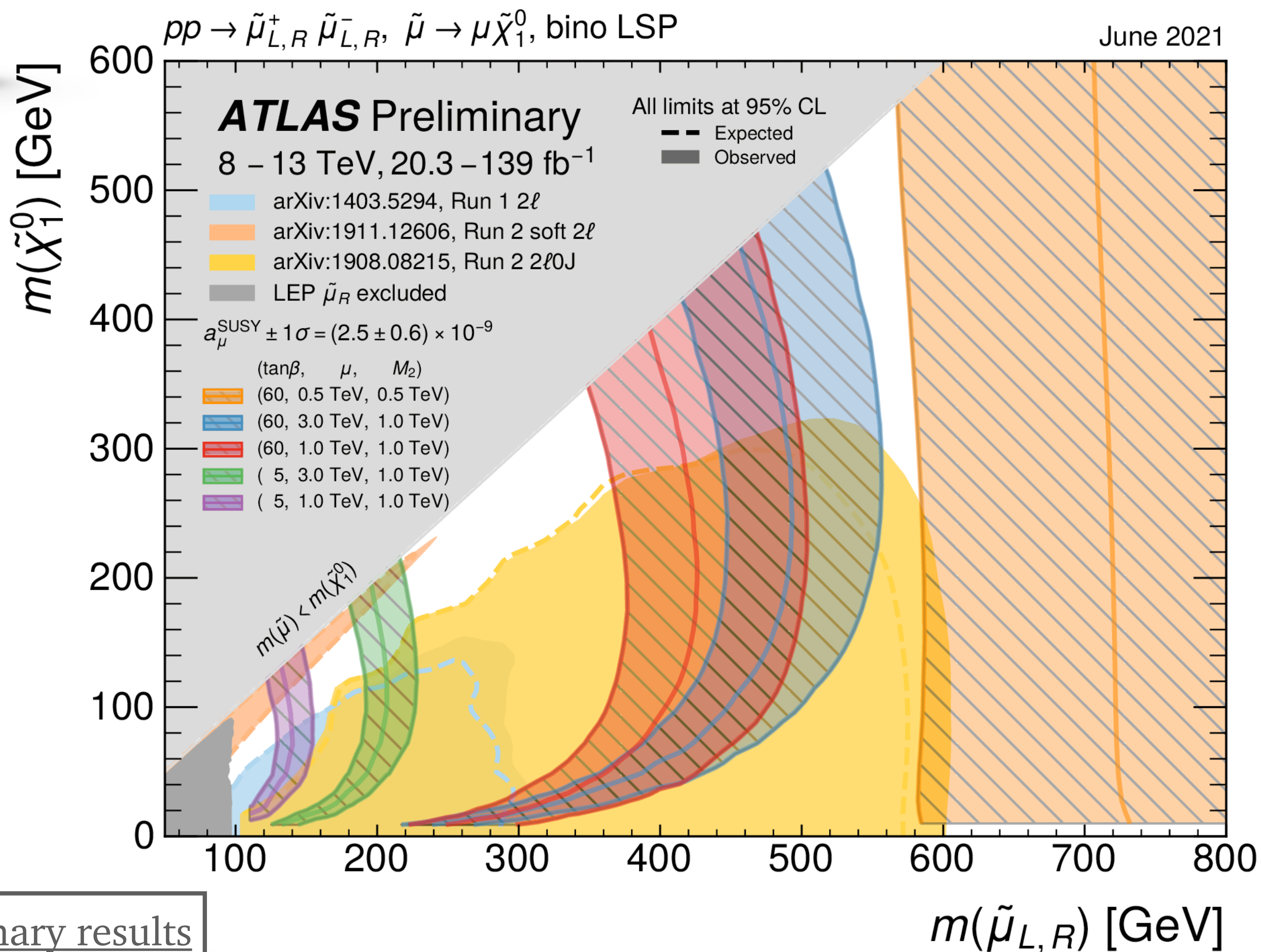


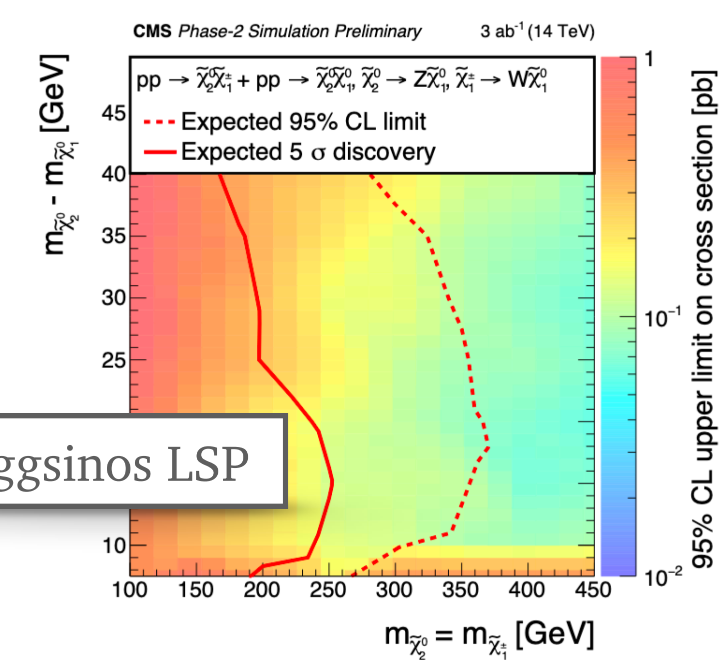
ATLAS SUSY Summary results

- The hatched bands indicate **a few examples of regions that are compatible with the observed muon g-2 anomaly** at the ±1σ level, corresponding to the pMSSM parameters specified in the legend.

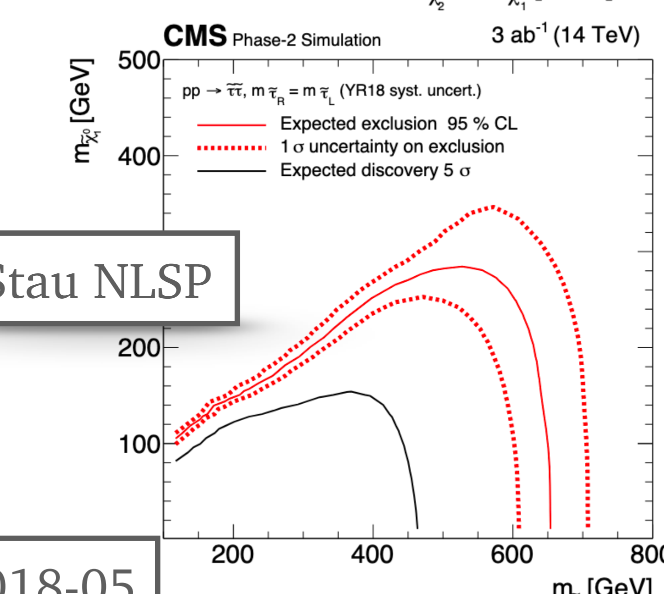
Future prospects for SUSY searches

- **ATLAS and CMS have provided legacy Run2 results (~140 fb^{-1})**
  - **"reinterpretation friendly" results:**
    - **ATLAS** has started publishing **full likelihoods** [see here]
    - **CMS** has published **simplified likelihoods** for multi-bins analyses [see here]

- **Standard analyses (energetic jets/leptons and E_T^{miss}) have highly constrained RPC natural SUSY in the bulk**
  - NLSP gluinos excluded up to **~2 TeV**, NLSP top squarks up to **~1.2 TeV**, NLSP charginos (Wino) up to **~700 GeV**



- **In the past years designed searches to cover the difficult corners where "SUSY" can still be "light"**
  - **sensitivity reached** to compressed gluinos and top squarks, light Higgsinos, direct stau production, several RPV final states, final states with long lived sparticles…



- **Need high statistical power dataset to cover all the allowed parameter space:**
  - prepare **LHC Run3** data-taking and detectors upgrade for **HL-LHC** to be able to perform same or extended searches in the future

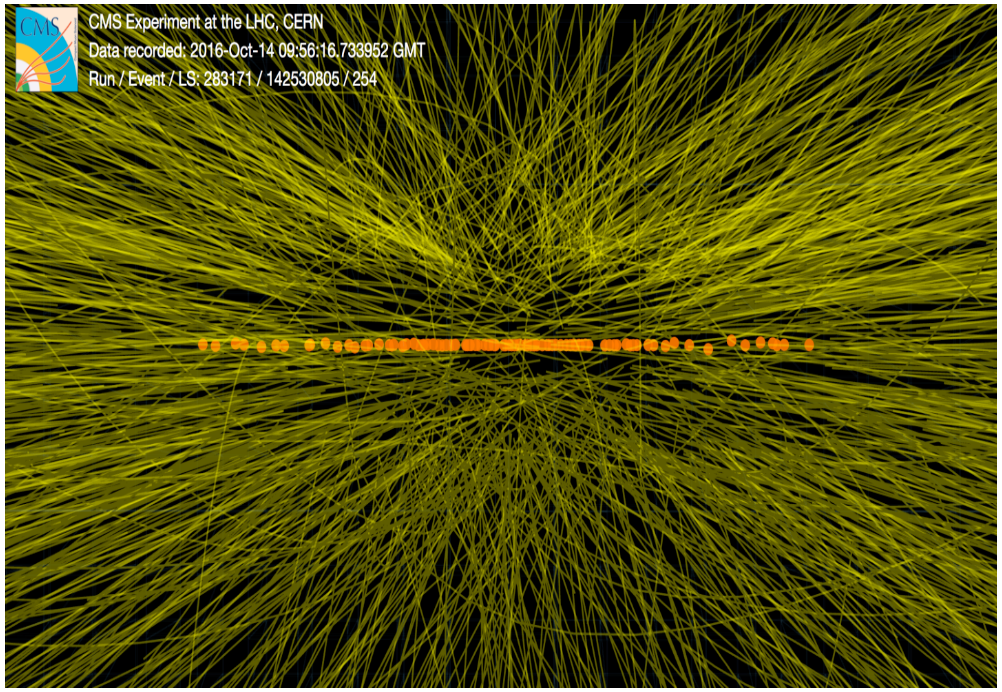
CERN-LPCC-2018-05

HL-LHC and Trigger Systems

- **Keep exploring the EWK scale with high statistical power dataset:**
  - **HL-LHC to provide 4000 fb^{-1} by ~2040: x40 data we have today, obtained with peak $\mathscr{L}$ = 7.5×10^{34} $cm^{-2}s^{-1}$**

Large statistics → **High Luminosity** → **Pile-up increase** → **Trigger rate increase**

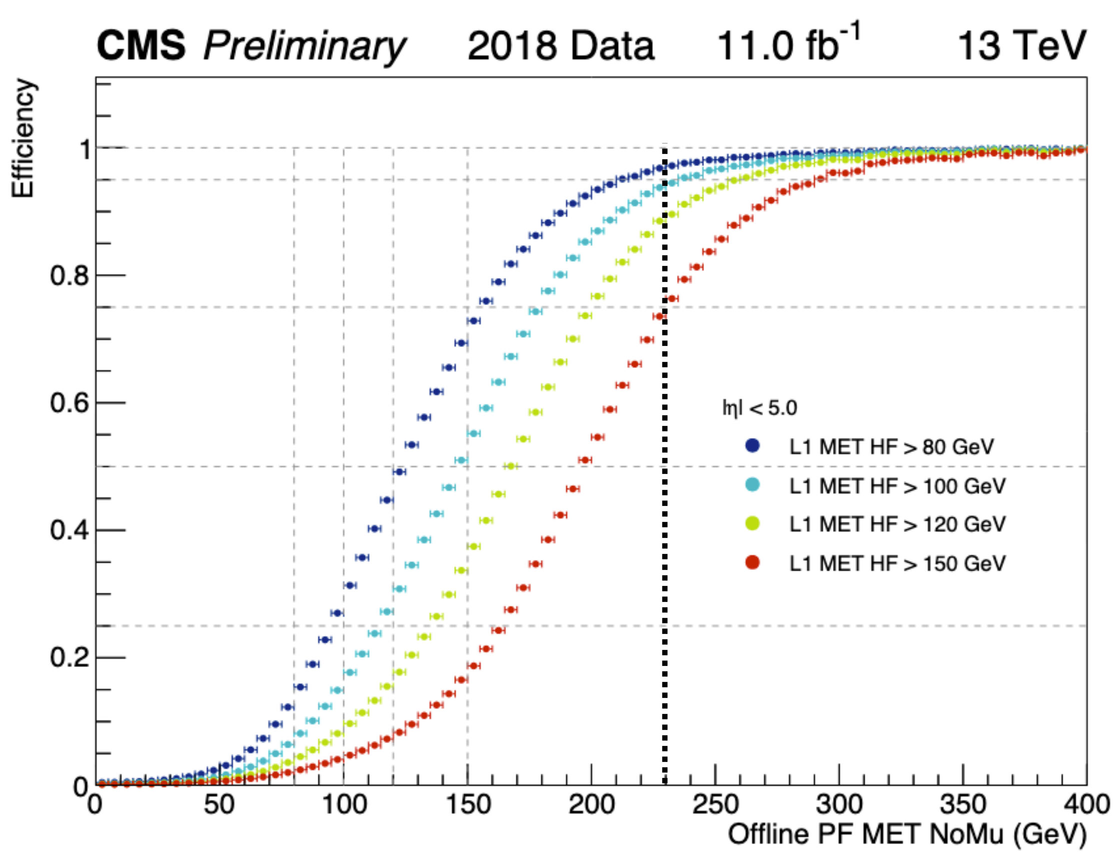
- **Pile-up: pp interactions per bunch crossing**
  - small fraction of 'hard' collisions but increase particle multiplicities
  - from **50 to 200** at HL-LHC



- **First drastic effect: increase of trigger rate**
- **Trigger system: real-time decision to accept or discard a collision event**
  - **necessary due to real-world limitation** in computing power, data storage capacity
  - **CMS L1 Trigger:** implemented in custom hardware processors, 40 MHz to 100 KHz with **thresholds on physics objects reconstructed with coarse information** from Calorimeter and Muon systems
  - **with 200 pile-up: 100 KHz→ 4000 KHz**, simply beyond technical feasibility

Trigger thresholds and SUSY

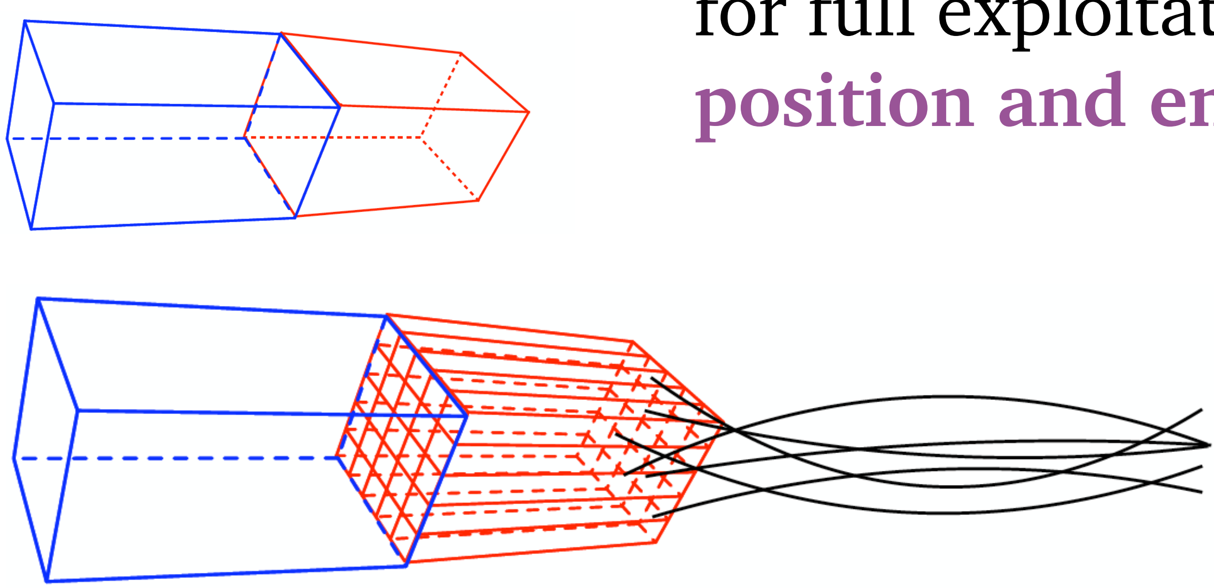
- **In light of the future plans for SUSY (target compressed spectra, small couplings, off-shell decays) CMS must retain the same physics acceptance as of today: no higher thresholds**
- **Previous searches rely on following triggers:**
  - **E_T^{miss}:** most of RPC standard searches
  - **H_T or multiple jets:** RPV searches, and to recover low E_T^{miss} events in strong SUSY decays
  - **Single, Double, Triple lepton triggers:** EWKinos and Sleptons searches
  - **cross triggers of E_T^{miss} and other objects:** compressed spectra



CMS L1 Trigger: Lowest threshold unprescaled E_T^{miss} trigger in 2018: L1_ETMHF100 which reach **95% plateau efficiency wrt offline E_T^{miss} at 230 GeV**

The CMS L1 Trigger and its upgrade

- **Upgraded sub-detectors to provide more and better information to the L1 system**
  - **Inclusion of Tracking at L1 (p_T>2 GeV, |η|<2.4)** to be combined with Calo and Muon
  - **Upgrades to the L1 Calorimeter and Muon trigger systems** for full exploitation of the Track trigger requires **improved position and energy resolution**



Barrel: replacement of electronic systems to reach **ECAL crystal-level energies** (25x increase over current input data); full exploitation of **spacial DT resolution**

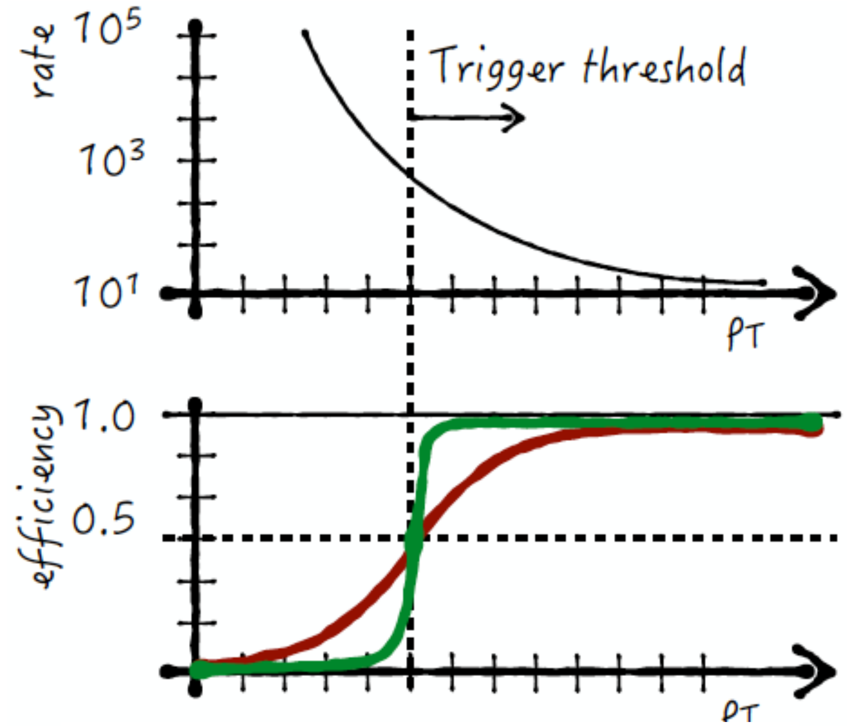
Endcap: 3D High Granularity calorimeter with unprecedented spacial resolution and shower shape separation; **new endcap muon chambers up to |η|<2.8**

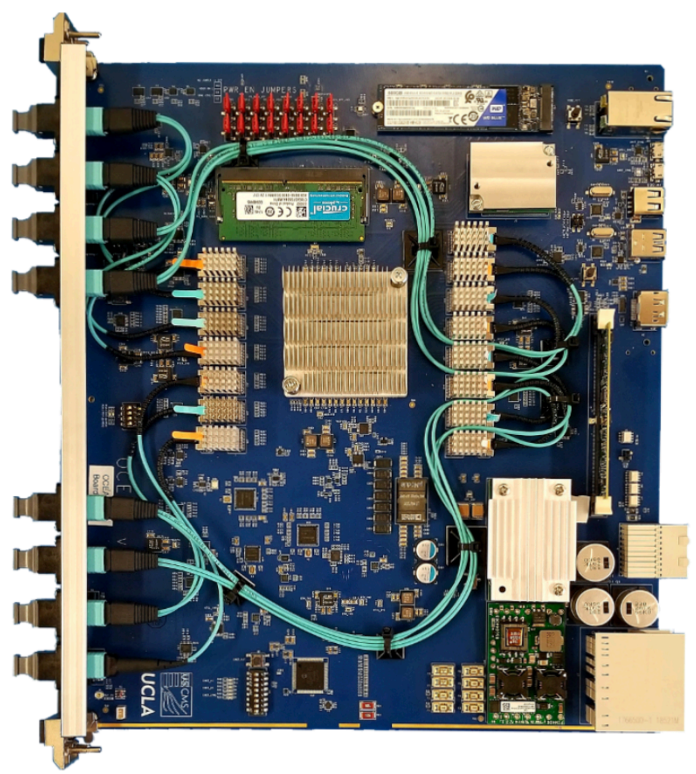
- **Longer latency (12.5 μs vs 3 μs) and a flexible and modular architecture for processor boards**
- **Full advantage of much more powerful Field Programmable Gate Array (FPGA) and optical link technologies**

Technical Design Report: The Phase2 Upgrade of the CMS L1 Trigger

The CMS L1 Trigger and its upgrade

- Door opened for state-of-the-art reconstruction techniques used offline: reduce rate matching the performance of offline algorithms
  - Tracking used to confirm Muon/Calo objects, significant improvements with simple design: L1 tracks provides sharpened efficiency turn-on for **muons, as well as electron identification, photon and lepton isolation**
  - L1 Tracks also used for reconstructing vertices, PV then used for **Pile-Up Per Particle Identification (PUPPI)**
  - Particle Flow + PUPPI techniques provide ultimate performance improvement for **jets, τ_h, E_T^{miss}**, combining information from all subdetectors,
  - For the first time these complex algorithms are being implemented in firmware



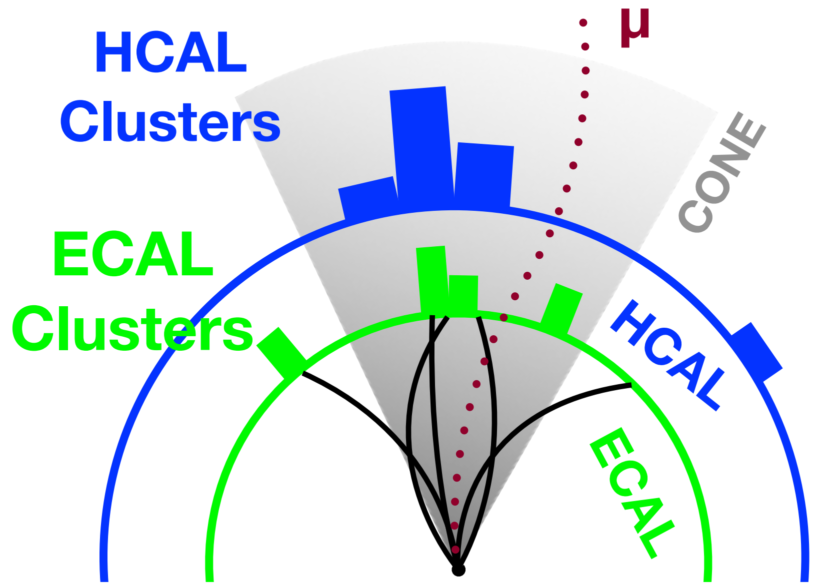


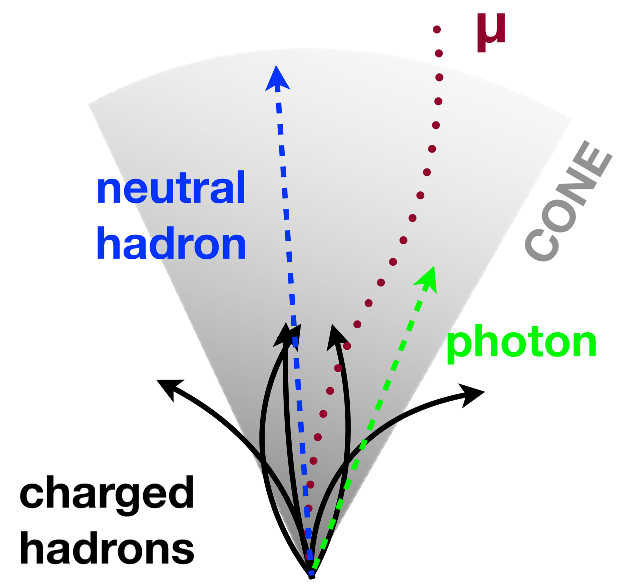
[Technical Design Report: The Phase2 Upgrade of the CMS L1 Trigger]

Particle Flow for L1 Trigger

- **PF reconstruction aim at reconstruct and identify all particles in an event using all subdetector information**
- **Implementable for the first time at L1 thanks to:**
  - efficient reconstruction of **charged particles in the tracker**
  - **fine granularity calorimetry** to resolve the contributions from neighboring particles

Inputs:
L1 Tracks, STA μ, HGCAL 3D clusters, ECAL crystals HCAL towers





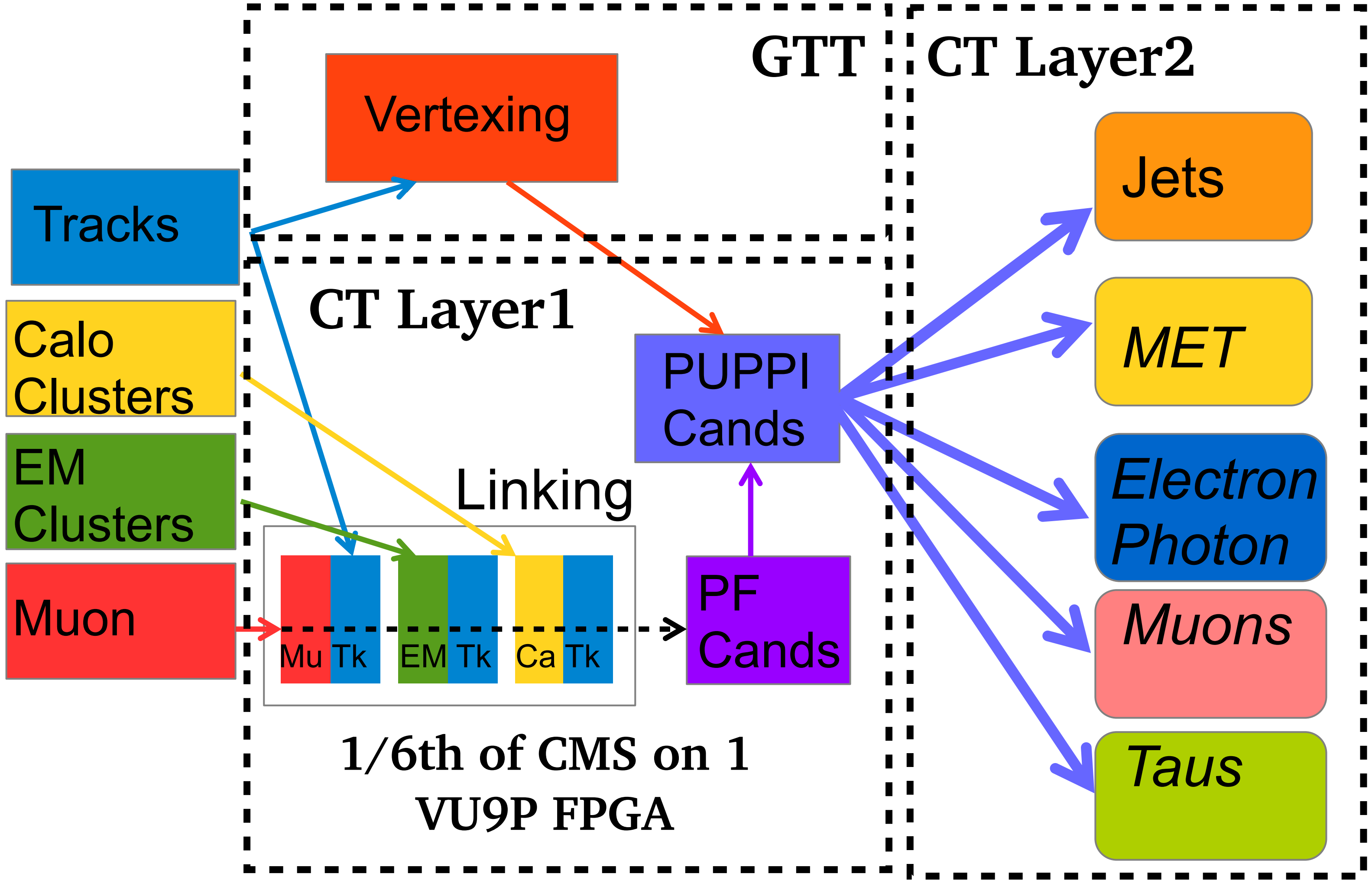
Output:
Neutral Hadrons, Charged Hadrons Photons, Electrons, Muons

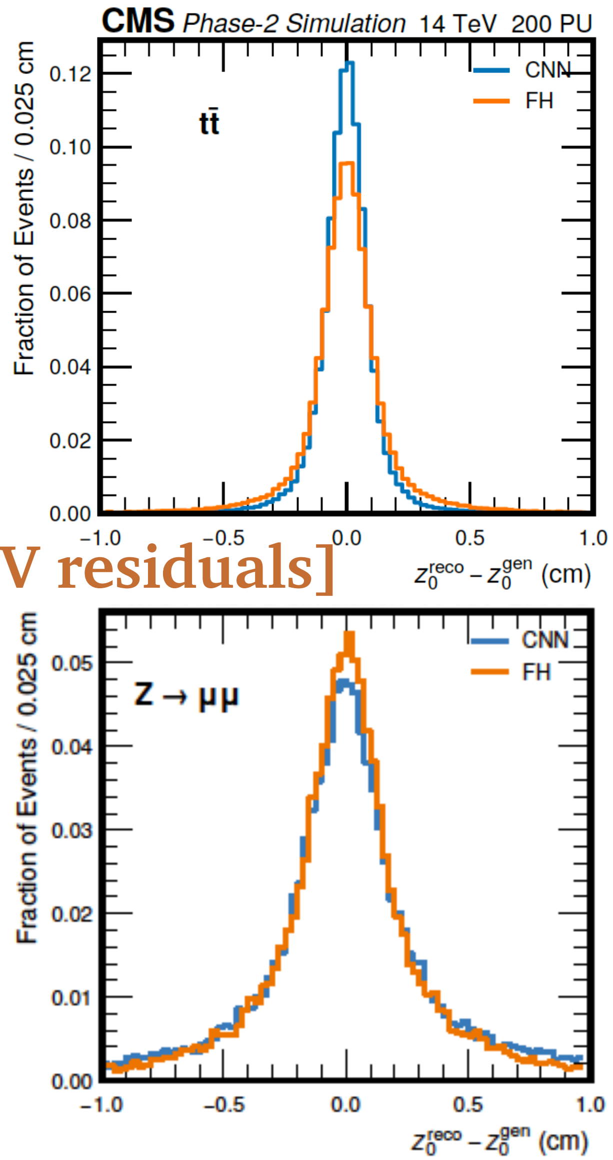
- **Clustering ID (e/γ vs $\pi^{\pm}$ vs PU) and track matching performed in a global event description logic**
  - semplification: reconstruction of a candidate can be performed relying only on detector input objects in the vicinity of the particle
  - **allow regions to be processed separately**

Technical Design Report: The Phase2 Upgrade of the CMS L1 Trigger

PUPPI for L1 Trigger

- **PF Candidates are then filtered with the PUPPI algorithm**
  - uses vertexing info and QCQ-based ansatz function to define a particle weight
  - **vertexing done in parallel w/PF from L1 Tracks in another processor board**
  - L1 PUPPI runs on global list of candidates from PF reconstruction step and **select prompt physics objects**





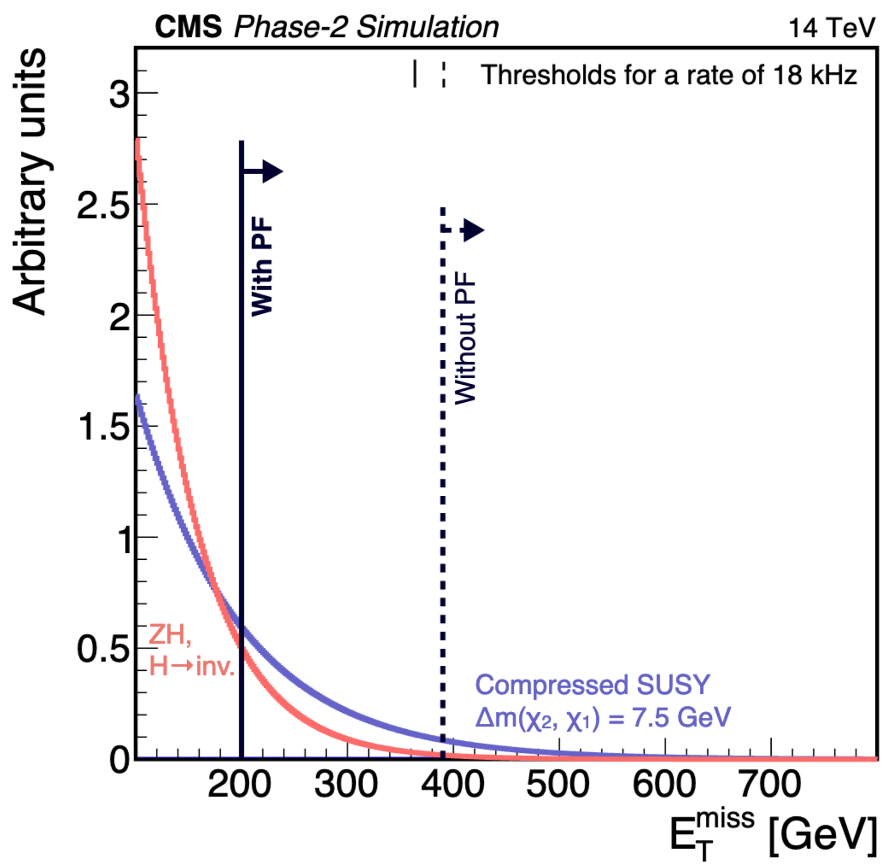
[PV residuals]

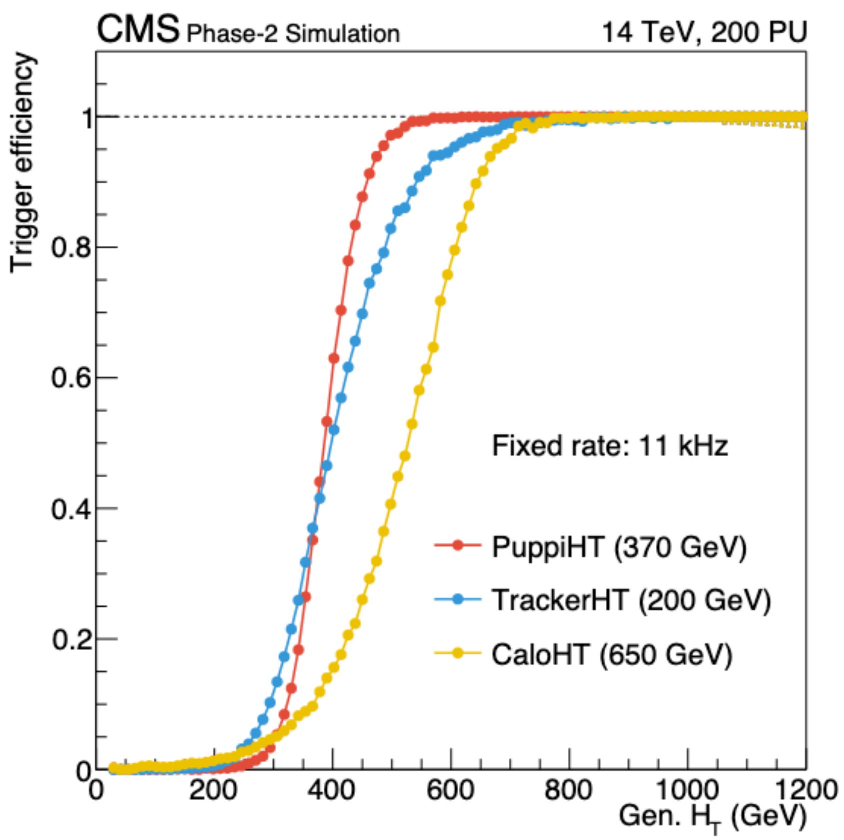
- **PUPPI drastically mitigates the PU effect and reduces by a factor 10 the PF candidates**
  - can all be sent to the next layer for jets, E_T^{miss}, τ_h algos

Technical Design Report: The Phase2 Upgrade of the CMS L1 Trigger

Is the acceptance preserved?

- **PF+PUPPI reconstruction significantly improves energy resolution of jets** (expecially at low p_T : important for cross-objects triggers), **E_T^{miss}, τ_h, allowing for lower sustainable trigger thresholds**



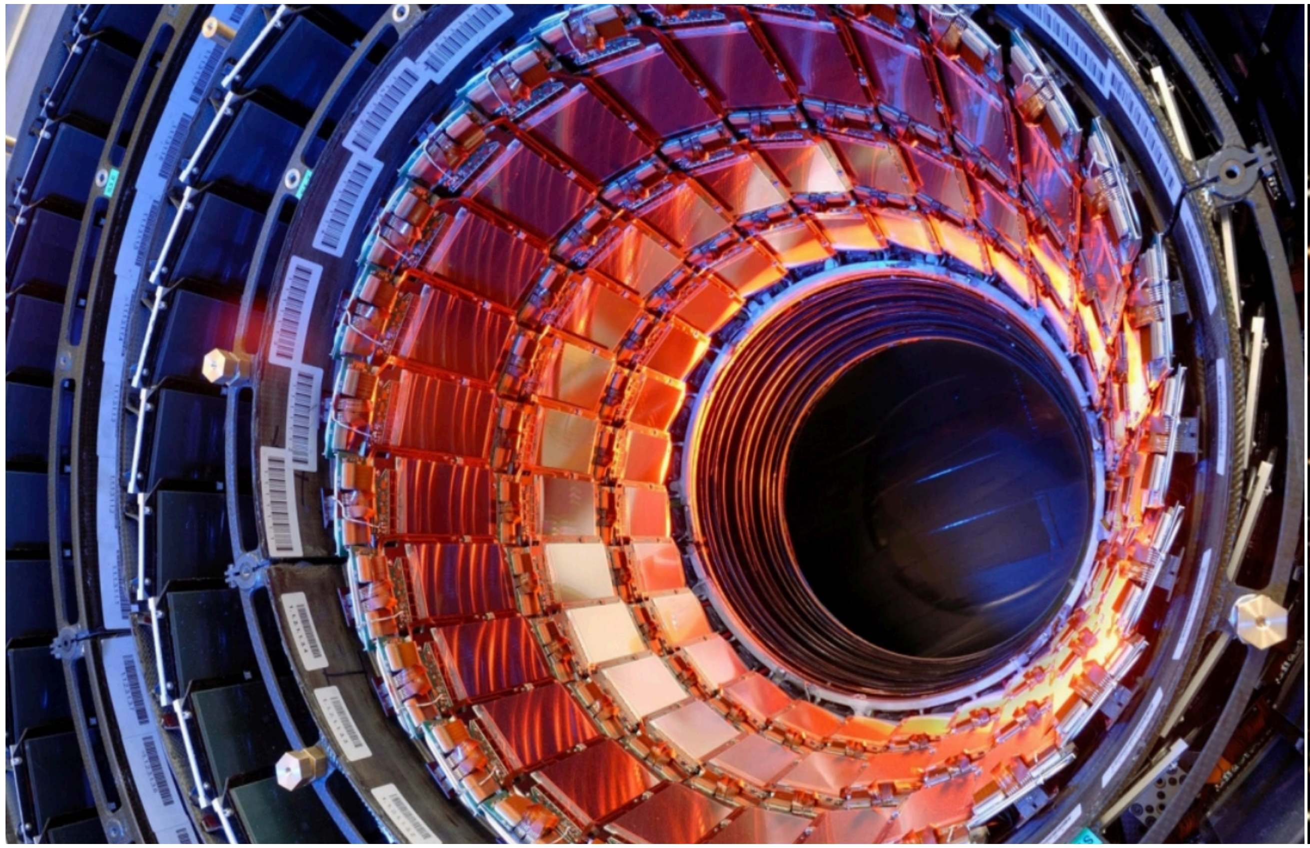


- **Test that CMS Phase1 acceptance is preserved with simplified Trigger Menu**
  - Designed a simplified Trigger Menu that covers 70% of Run2 CMS Trigger rate (~40 trigger paths) **making use of newly developed algorithms and Phase1 thresholds: total rate of about ~400kHz** which perfectly fit the total allowed bandwidth of 750 kHz

Technical Design Report: The Phase2 Upgrade of the CMS L1 Trigger

Can the acceptance be extended?

- **With the CMS Phase-2 L1 Trigger architecture and algorithms possible to explore new triggering strategies that could not be envisaged or sustained in terms of rate by the Phase-1 system**
  - Algorithms are being developed to improve efficiency and resolution for **muons and electrons at low p_T**: important for **cross objects or topological triggers**
  - **Multivariate discriminators** for specific signal topologies that currently suffer from high thresholds or for more sophisticated **E_T^{miss} and tau algorithms** that could allow the reduction of corresponding thresholds:
    - **tools to synthesise machine learning based algorithms into FPGA firmware have recently been made available.**
  - **Dedicated displaced jets/muons reconstruction** to increase acceptance and reduce thresholds when triggering on signatures with long-lived particles
- **Challenging corners of the phase space will therefore be accessible at HL-LHC, and no stone will be left unturned in the search for “SUSY-like” new physics manifestation**



Thank you for your attention

Cristina Botta, University of Zurich

LTP/PSI Thursday Colloquia

Backup