Beyond the Standard Model Searches @ the LHC

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5th School on LHC Physics - 2016

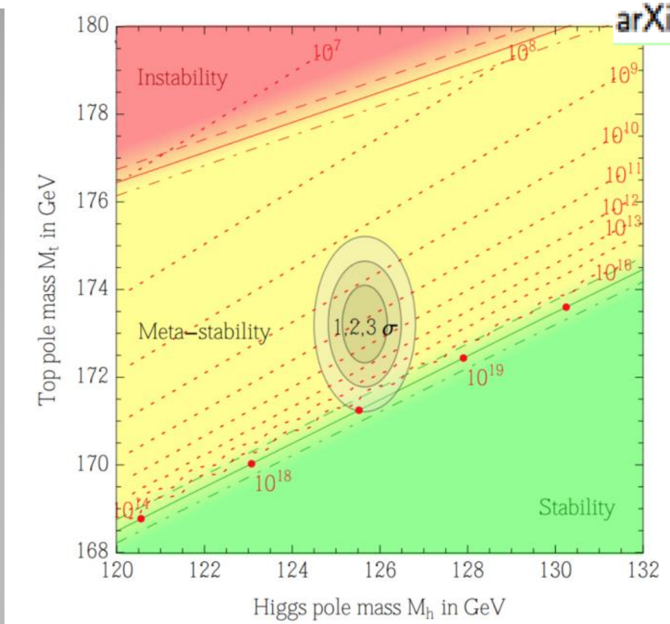
Lecture Plan

Overview of the 3 lectures in the next days

- Lecture 1:
  - Introduction to searches for new physics
  - Searches for exotica and new phenomena
- Lecture 2:
  - Searches for supersymmetry
  - Searches for real exotic particles
- Lecture 3:
  - The hunt for dark matter
  - Outlook for the LHC and for the Future

Physics Beyond the Standard Model?

Important SM parameter → stability of EW vacuum

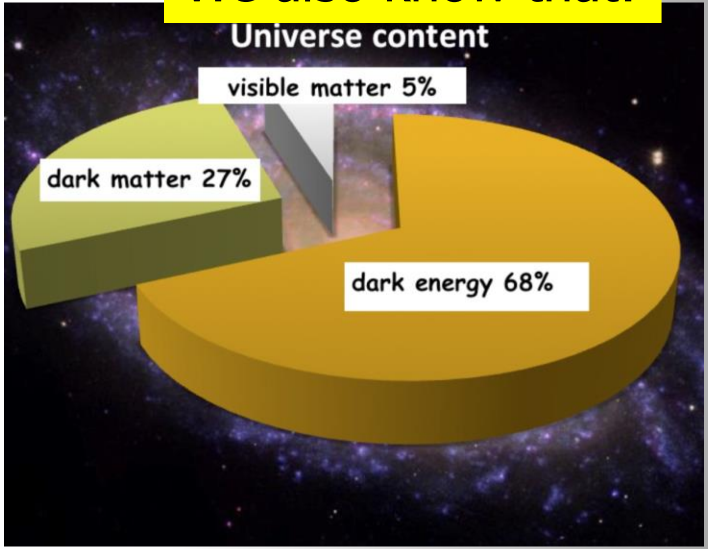


arXiv:1403.6535

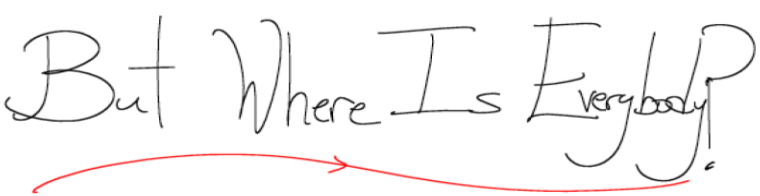
A Higgs at 125 GeV

Precise measurements of the top quark and the Higgs mass

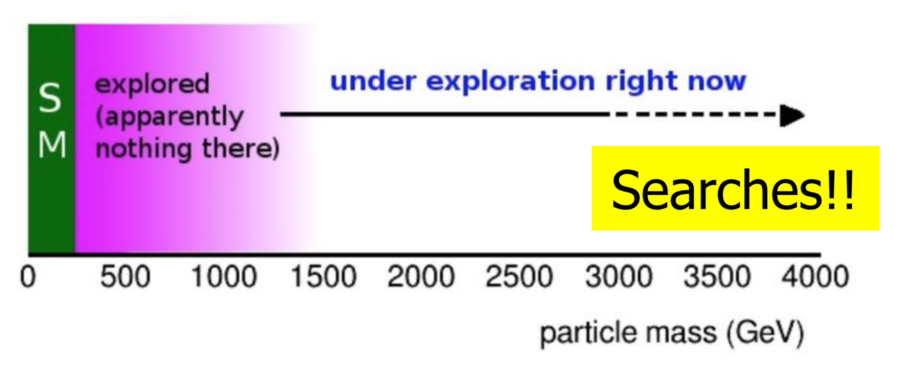
We also know that:



New Physics inevitable?
But at which scale/energy?



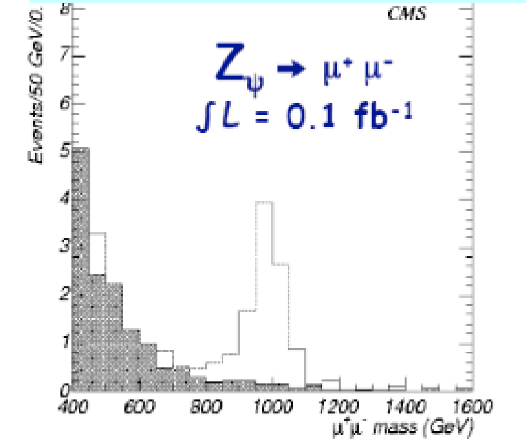
N. Arkani-Hamed



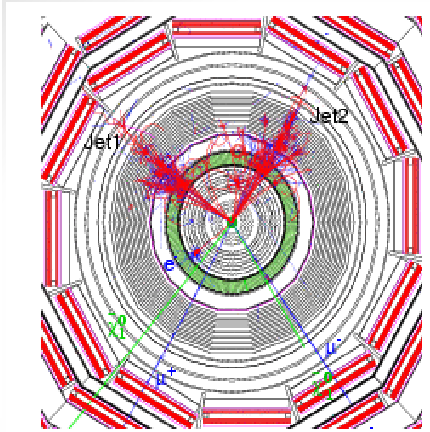
Searches!!

New Physics?

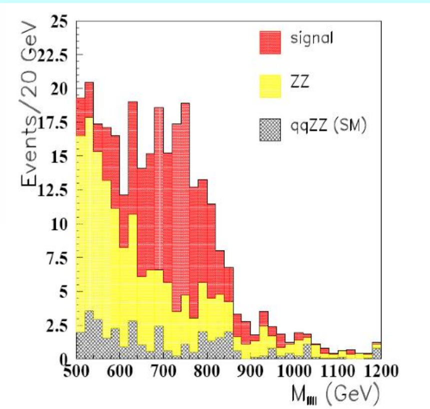
New Gauge Bosons?



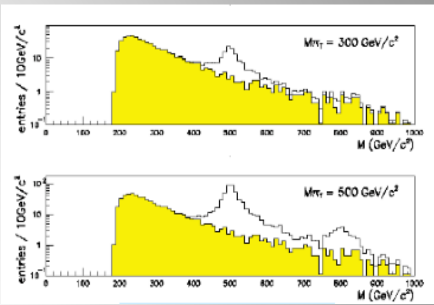
Supersymmetry



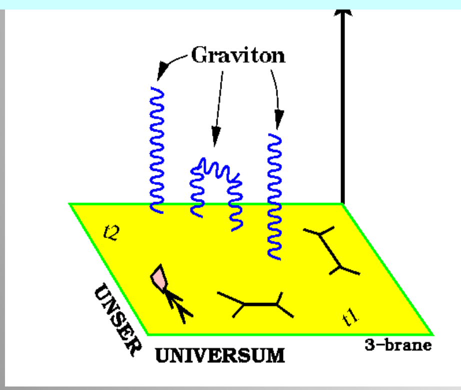
ZZ/WW resonances?



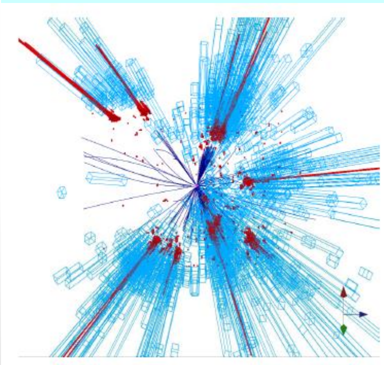
Technicolor?



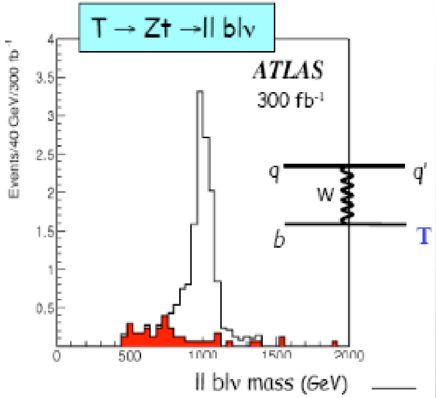
Extra Dimensions?



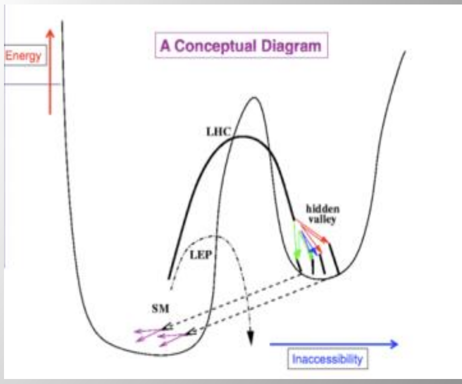
Black Holes???



Little Higgs?



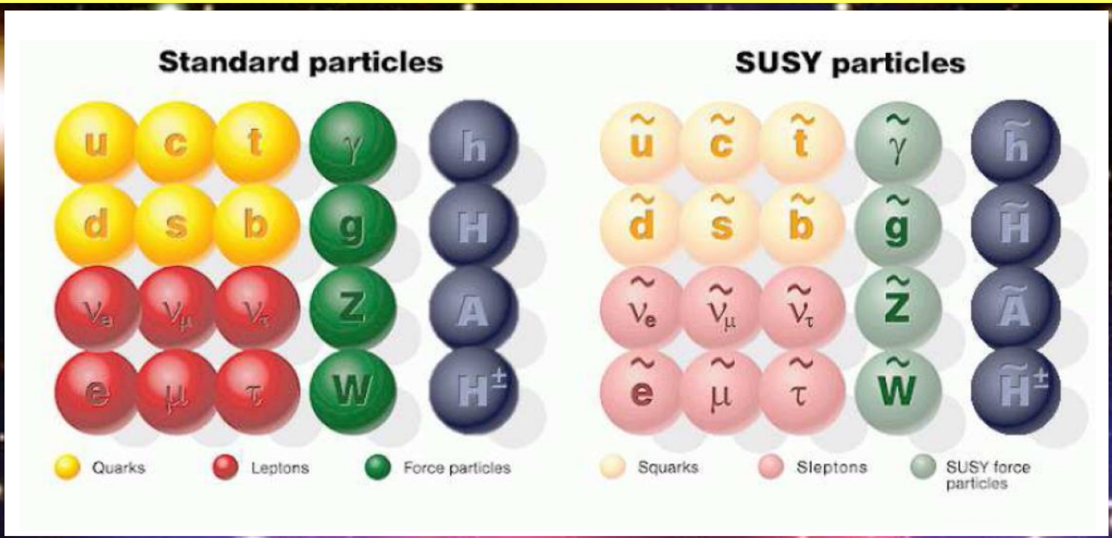
Hidden Valleys?



What stabelizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

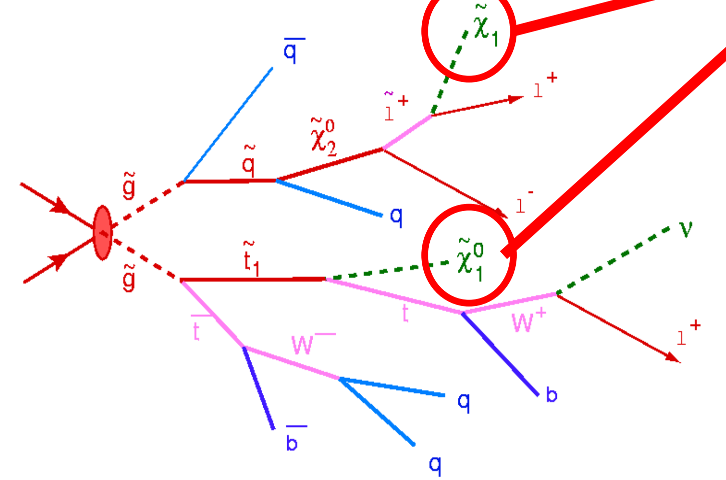
Supersymmetry: a new symmetry in Nature?



Candidate particles for Dark Matter

⇒ Produce Dark Matter in the lab

“One day all these trees will be SUSY phenomenology papers”

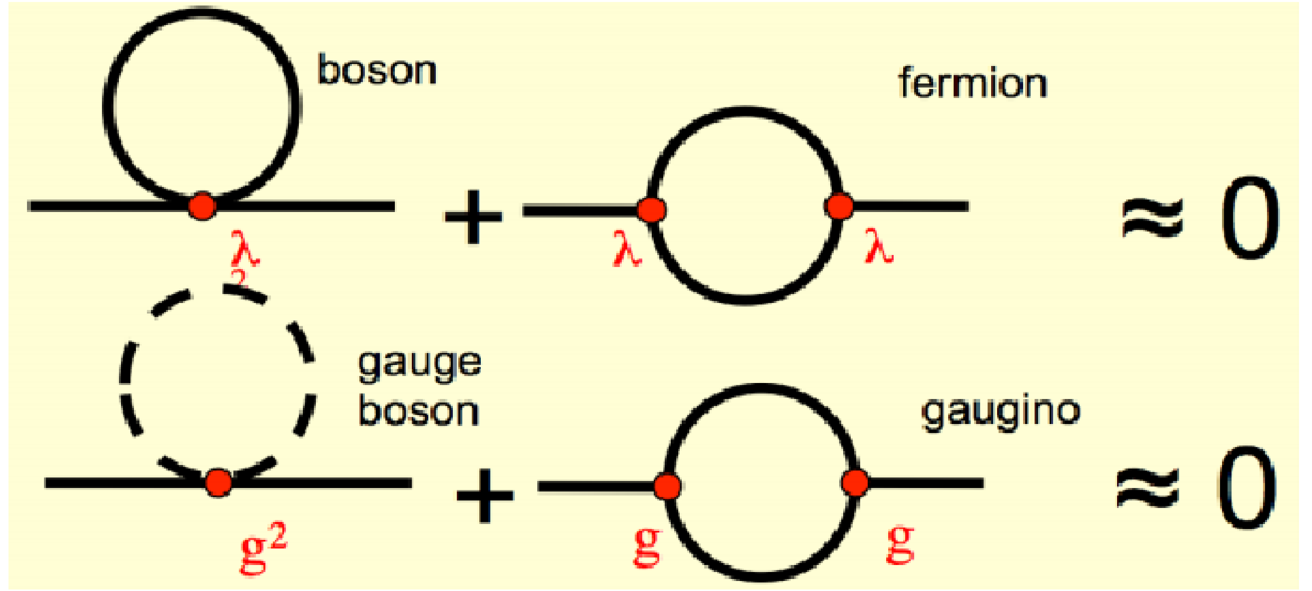


SUSY particle production at the LHC

adac

Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin). Can stabelize the Higgs mass up to the Planck scale



Fermion and boson loops cancel, provided $m_{\tilde{f}} \leq$ TeV.

Barbieri & Giudice (1988): Natural Models!

Why weak-scale SUSY ?

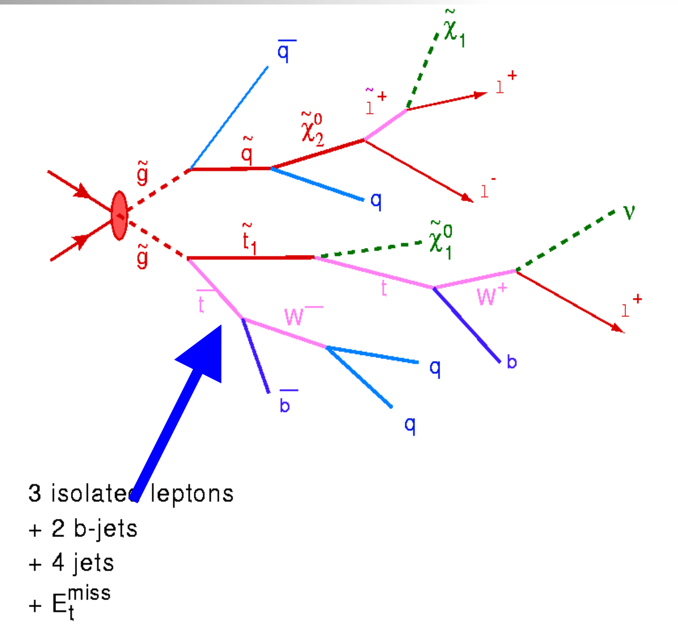
- stabilises the EW scale: $|m_F - m_B| < O(1\ \text{TeV})$
- predicts a light Higgs $m_h < 130$ GeV
- accomodates gauge unification
- accomodates heavy top quark
- dark matter candidate: neutralino, sneutrino, gravitino, ...
- consistent with EW precision tests

Discovering SUSY – A revolution in particle physics!!

Supersymmetry

Supersymmetry (SUSY) □ assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin) to explain the Hierarchy problem (Planck □ Electro-weak scale)

⇒Lots of new particles (squarks, sleptons,…) predicted with masses in the range from 10’s of GeV’s up to several TeV range



Supersymmetry is broken
We don’t see the superpartners

E.g. Minimal supersymmetric model

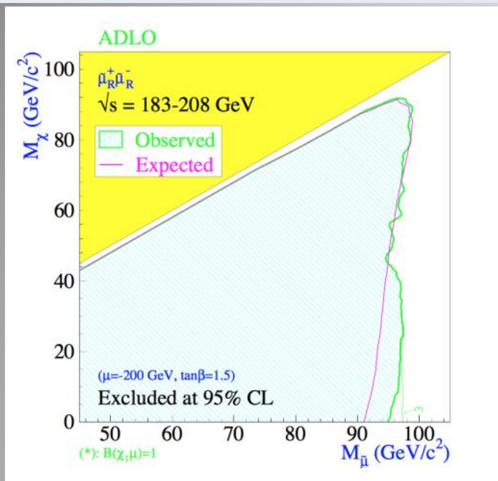
□ 105 new parameters! :masses, mixing angles…

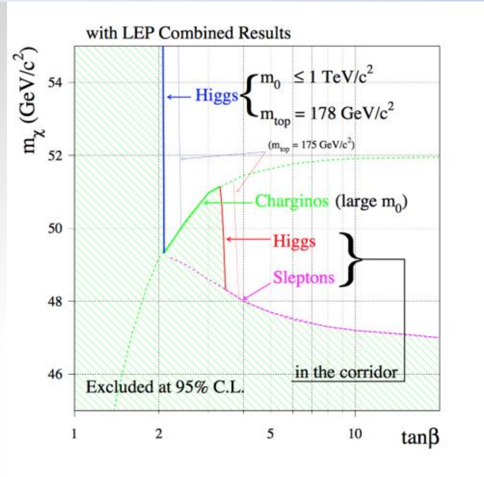
SUSY breaking mechanisms: reduces # of param.

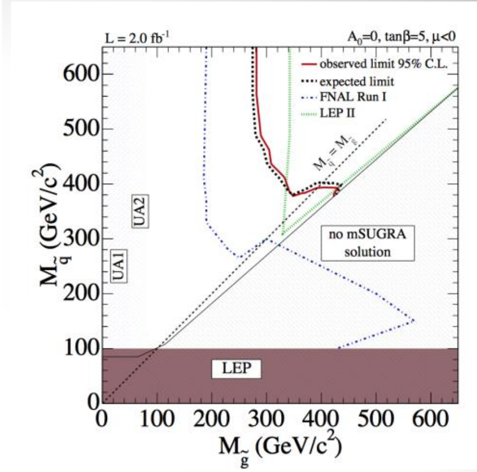
- Minimal SUSY Gravity (mSUGRA)
- Gauge mediated SUSY breaking
- Anomaly mediated SUSY breaking
- Gravitino mediated SUSY breaking… etc.

LHC is expected to have access to at least some part of the SUSY spectrum!

SUSY Searches in 2009: Pre-LHC

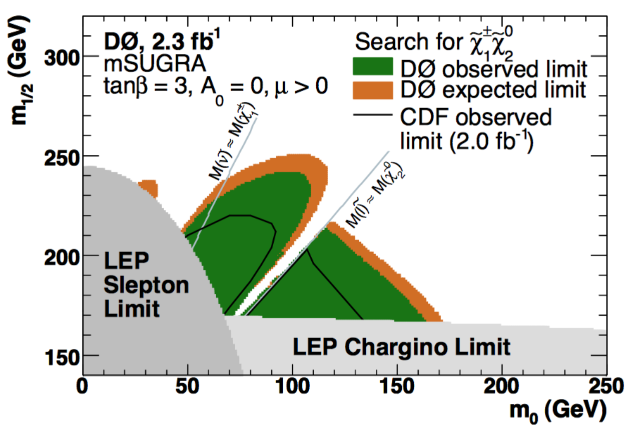


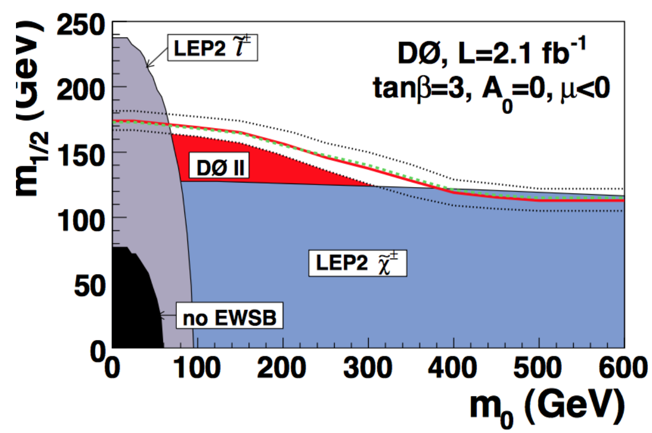


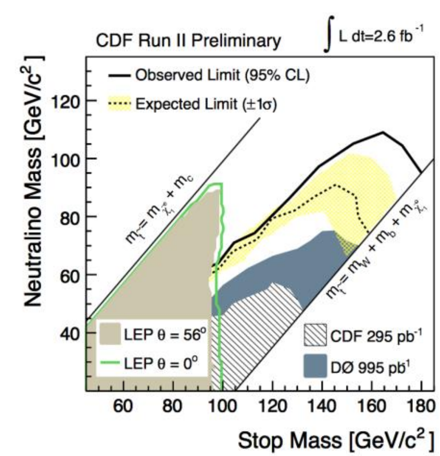


PDG 2009

LEP: mostly model independent
Tevatron: mostly mSUGRA interpret.
HERA: mostly RPV







Squark/gluino limits: 300-400 GeV
Electroweakinos (except LSP): >100 GeV

1993: Early Tevatron SUSY Searches

The New York Times

Science

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

ENVIRONMENT SPACE & COSMOS

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE
Published: January 5, 1993

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Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

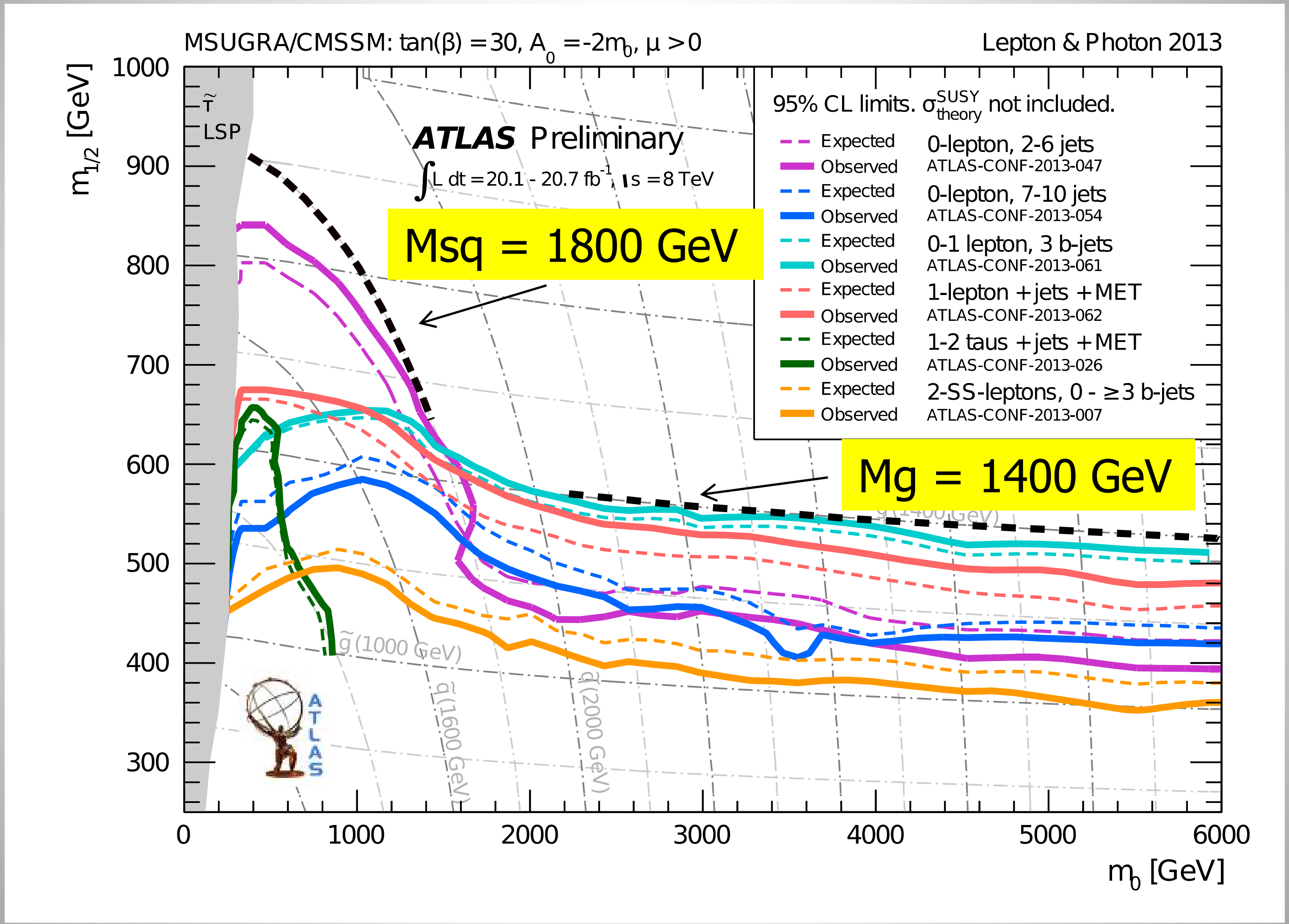
But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

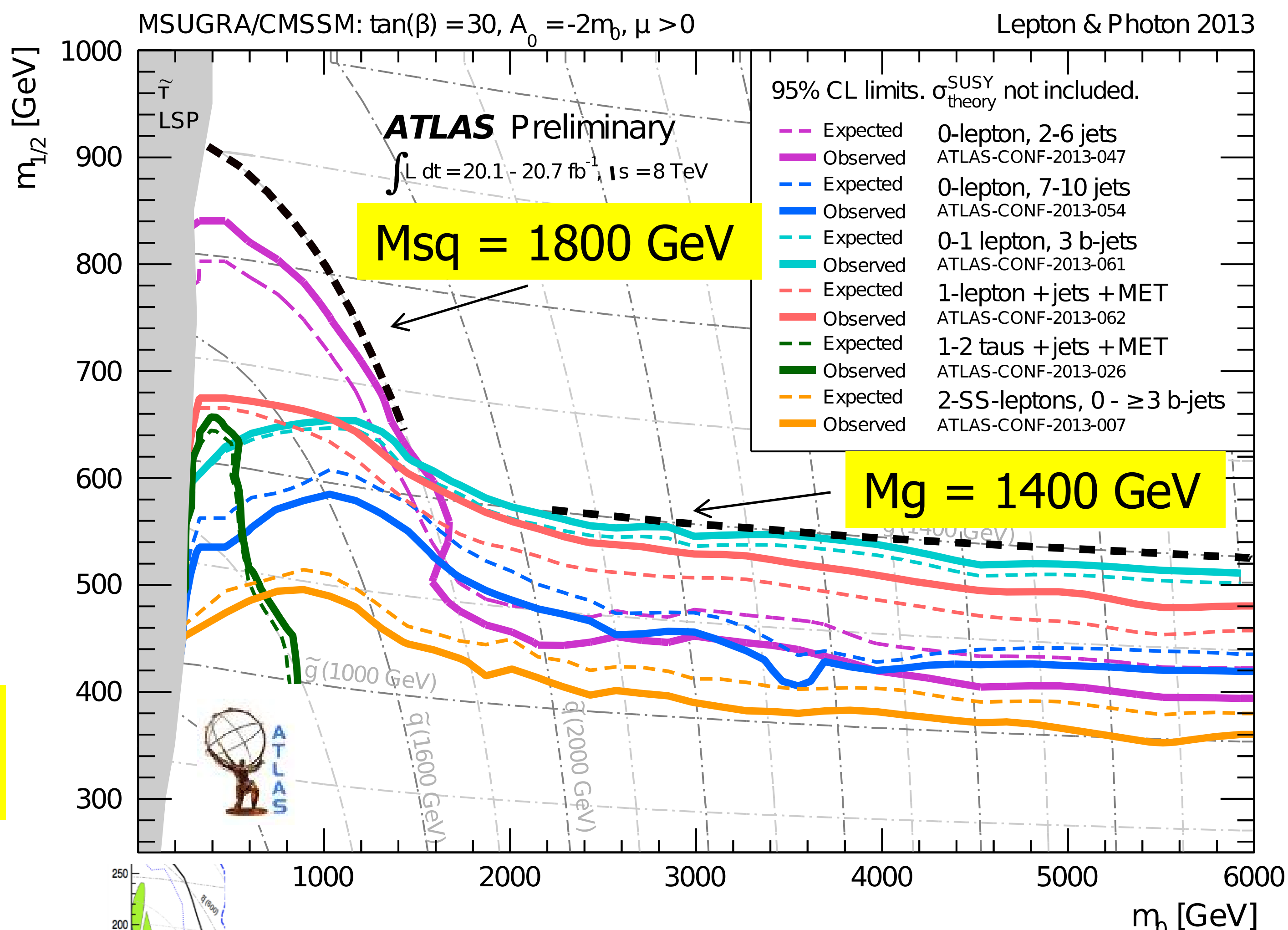
The press does not always find the 'correct' words…

They did not find any…

Inclusive SUSY Searches by 2013

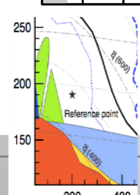


Inclusive SUSY Searches by 2013



Compared to 2009…

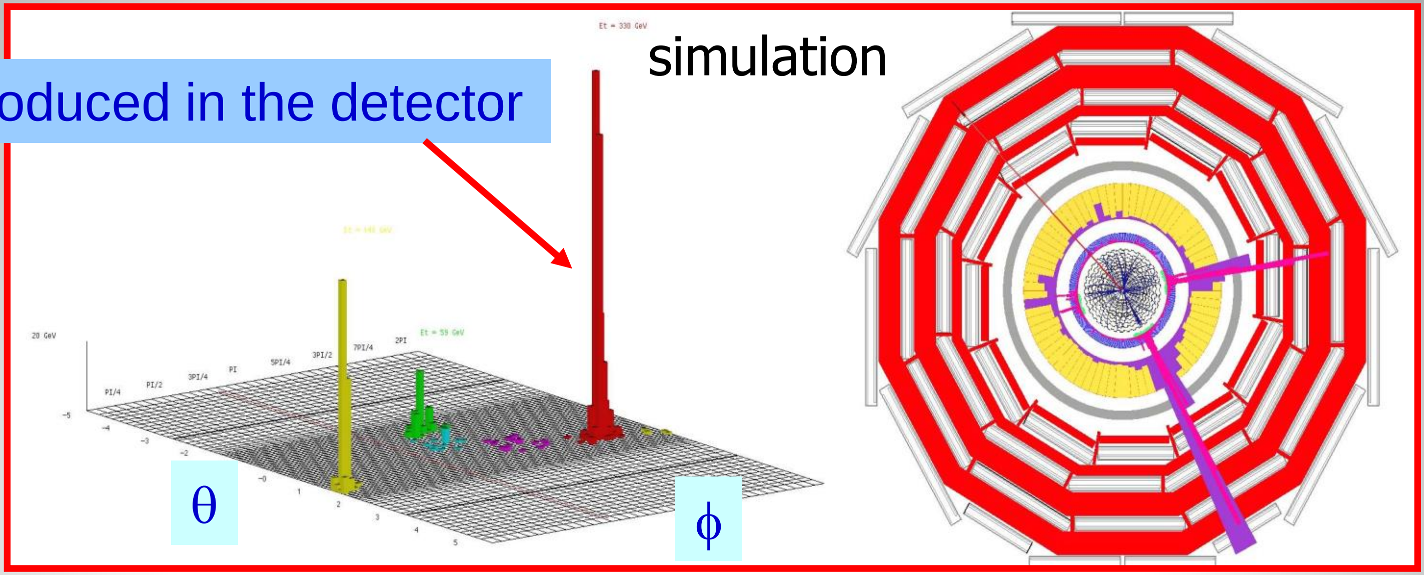
LEP & Tevatron

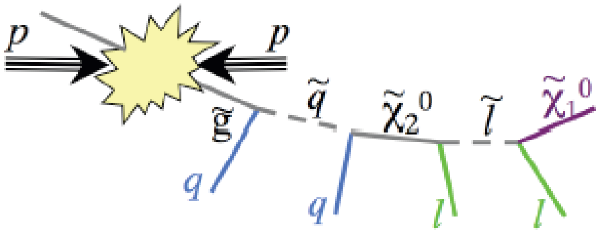


The LHC has pushed the mass scale in constraint SUSY models to a new level!

Detecting Supersymmetric Particles

Energy produced in the detector





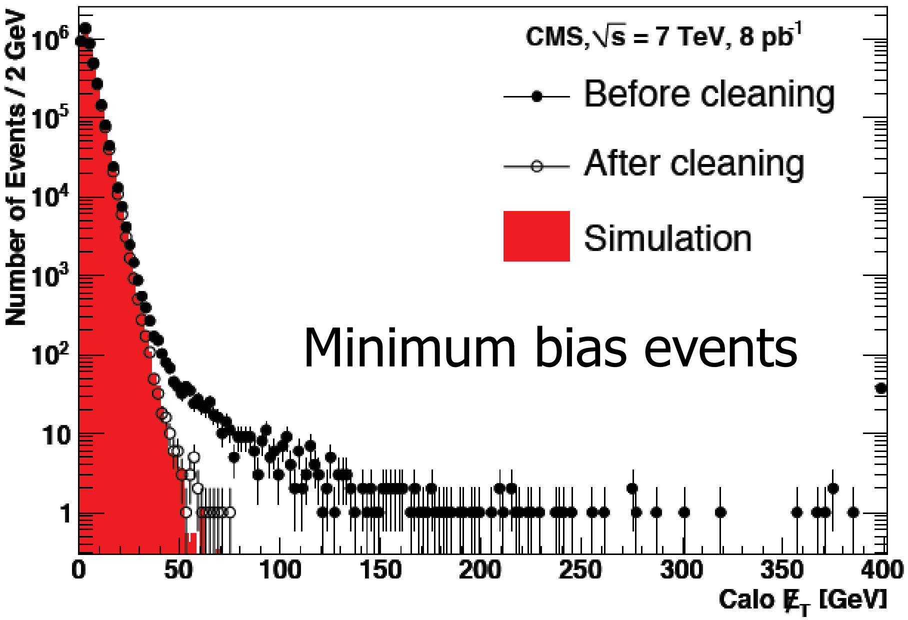
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

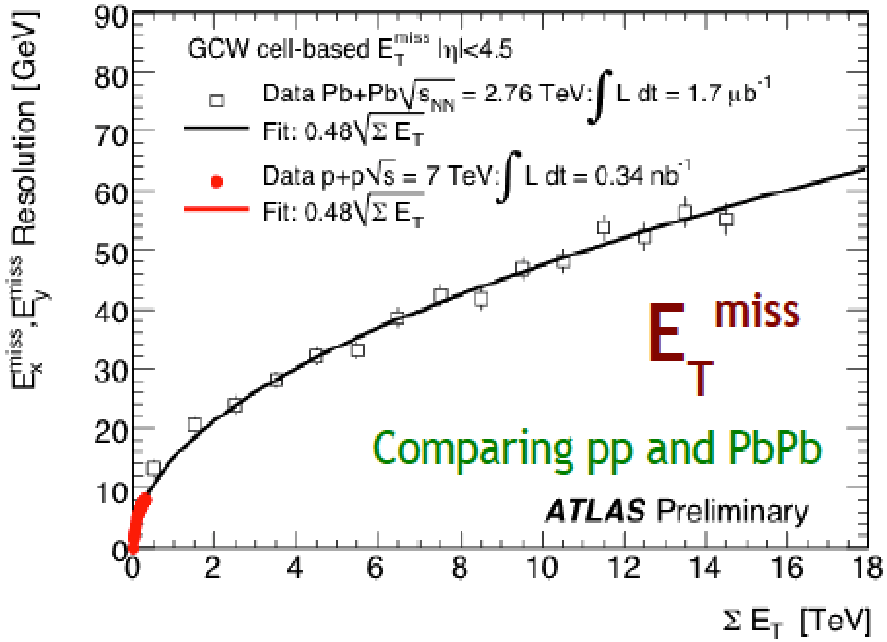
Very prominent signatures in CMS and ATLAS

Missing Transverse Energy

Total transverse momentum imbalance

Generally appreciated to be a difficult quantity to measure
Very sensitive to fluctuations, miss-measurements, noise, backgrounds

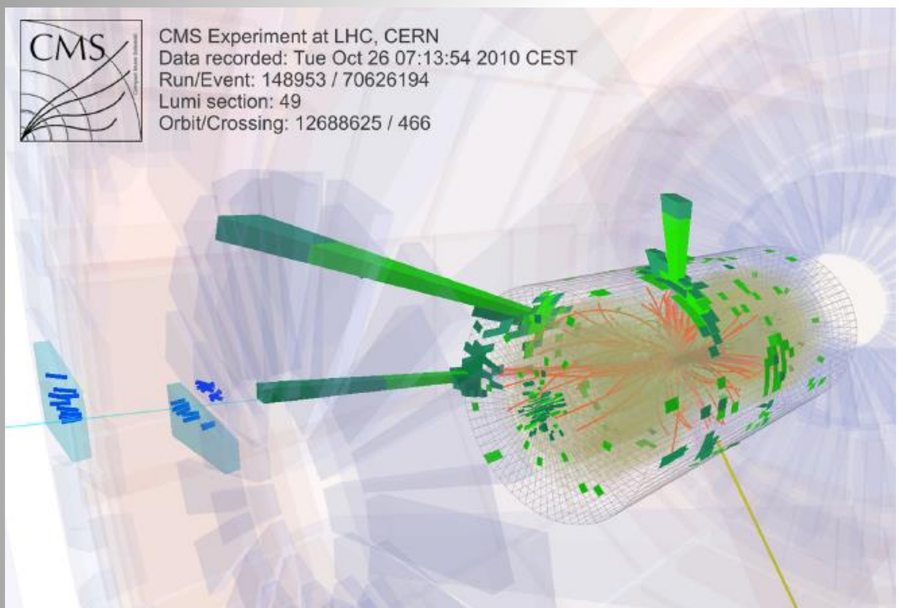


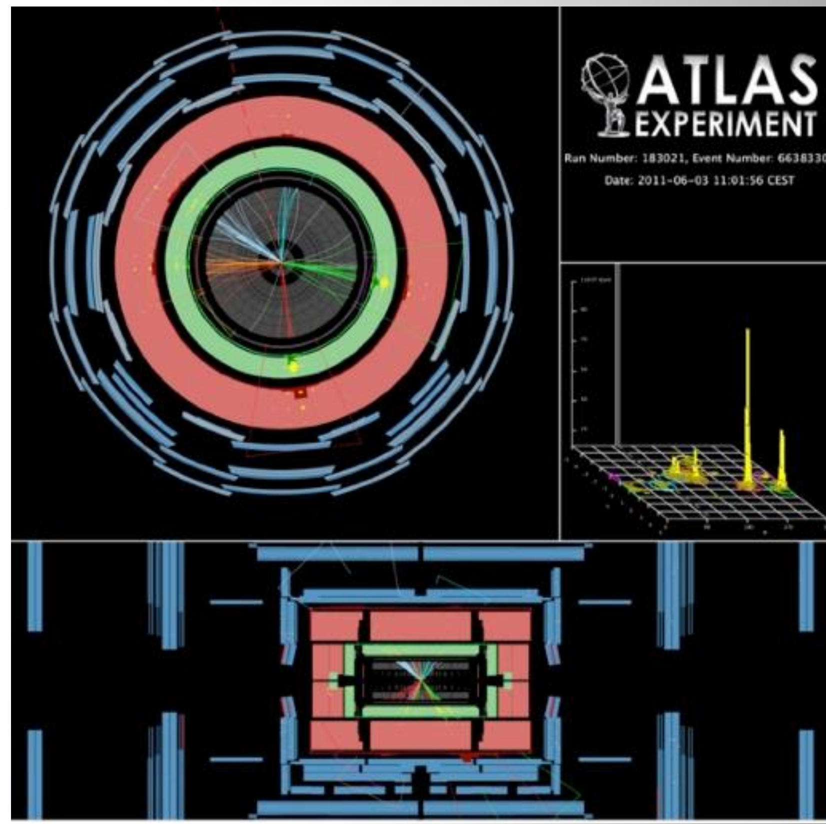


- In practice, rather well under control, from the start (2010)
- Good resolution using 'particle flow' ie maximally identifying particles
- More pile-up in future will NOT make this simpler

…Some Interesting Collisions…

…already in 2010…





- Events with five jets of particles and large missing energy which could come from a possible dark matter particle
- But a few events is not enough too prove we have something new No visible excess has been building up with time…

General SUSY Searches

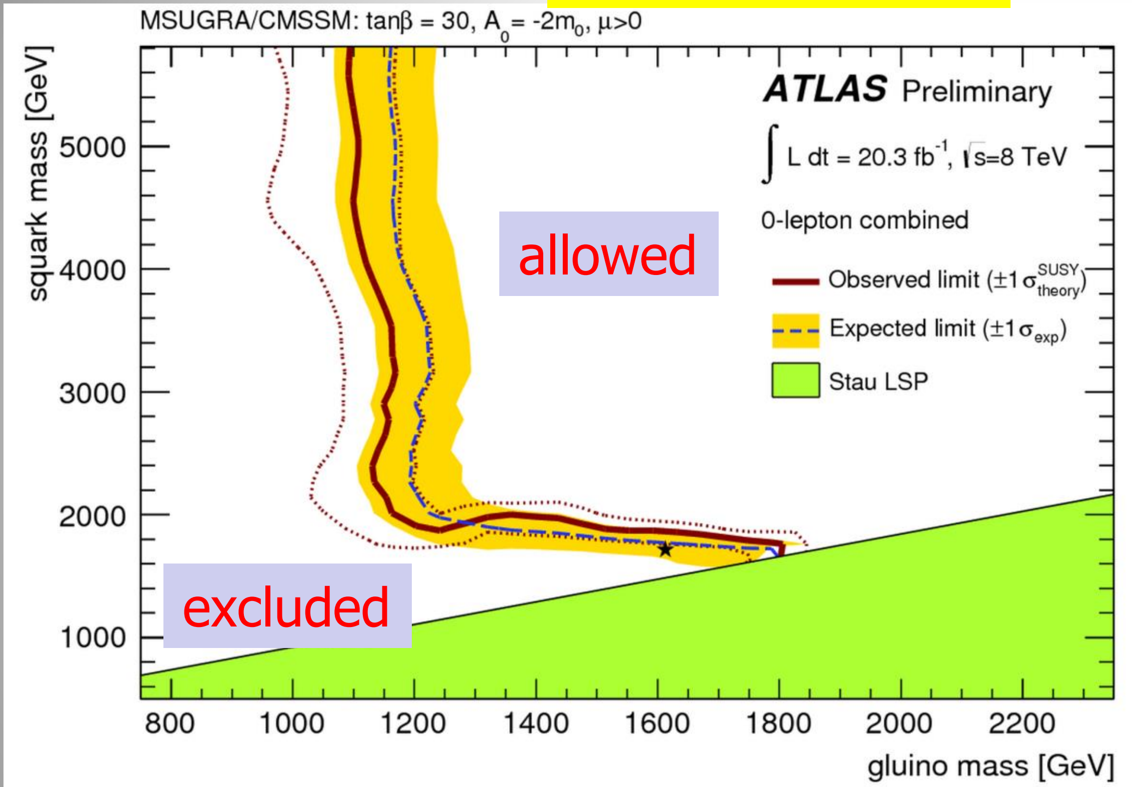
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

Early on SUSY searches at the LHC:

- Divide the searches in different categories
- The zero lepton (all hadronic) search has typically a wide reach and is done early on with the new data.
- Several hadronic searches are performed as independent searches? (MHT, MT, MT2, MCT, α_T, razor). Make use of specific kinematic properties
- New analyses in categories as above have already been performed for 13 TeV data

SUSY in Run-1: No Significant Signals

Status with Run-1



mSUGRA/CMSSM scenarios

- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches now continue with the higher energy in Run-2

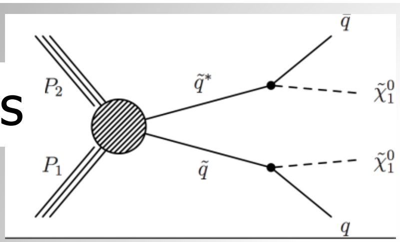
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

Also special searches for more contrived model regions

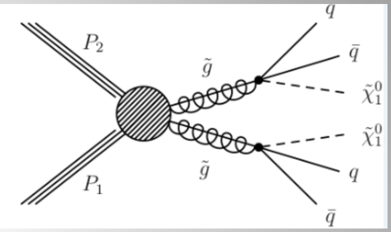
Run-1: Limits on Squarks and Gluinos

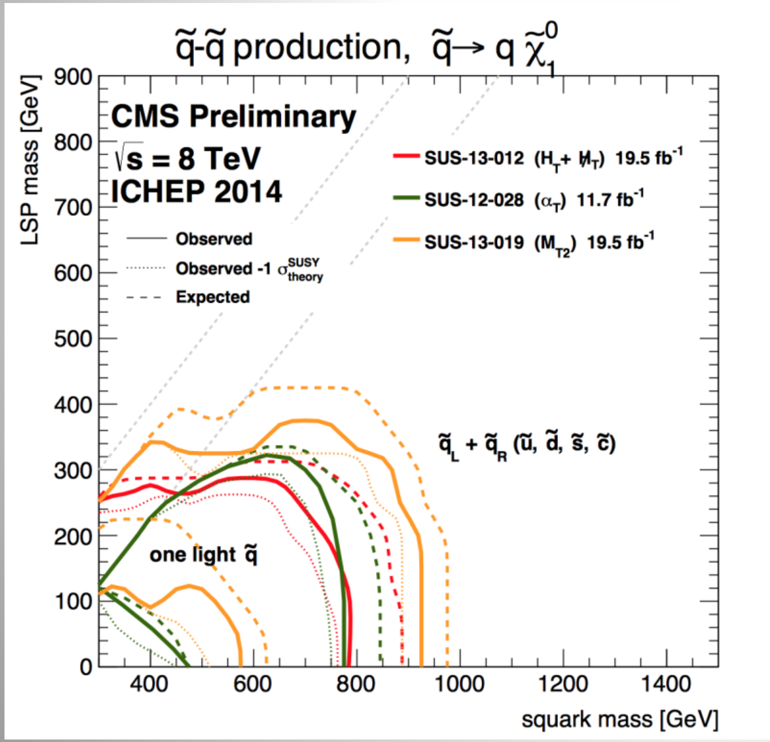
Results depend on the topologies studies, assumed mass of the LSP etc.

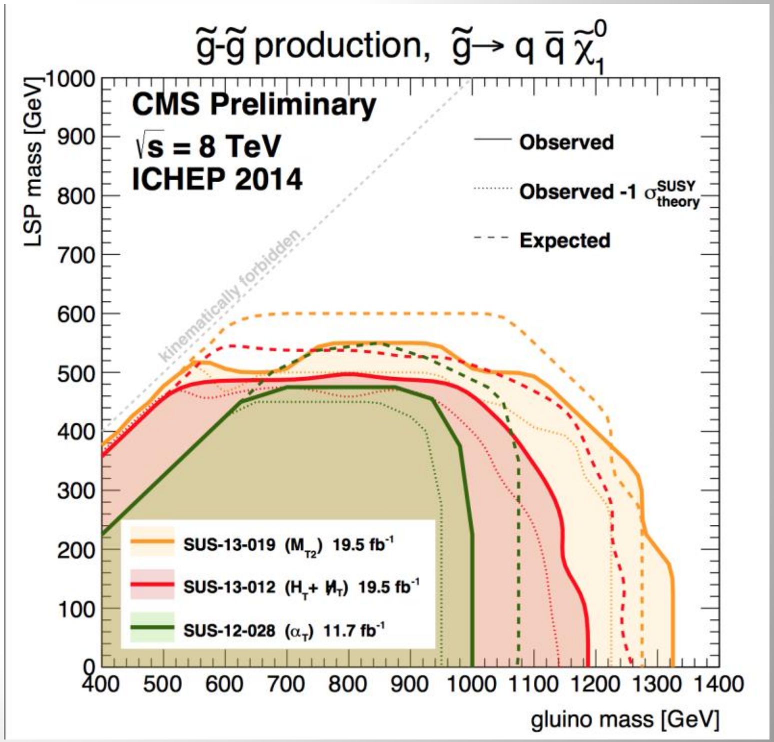
Examples



Popular presentation of data:
Simplified ModelS (SMS)







Combined limits typically > 1-1.3 TeV on sparticle masses

Simplified Models

Simplified models are a language for experimental results to theorists…

W. Adam

THE interpretation tool for SUSY searches @ LHC

Pros

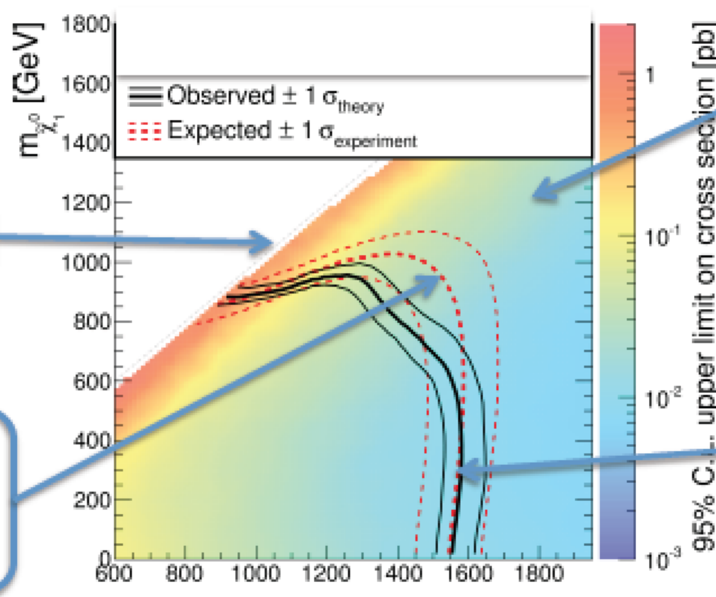
- closely related to exp. observables
  - understand features
- limited number of parameters
  - results as 2D scans
- "easy" reinterpretation (cross-section limit)

Cons

- no complete model
  - consistency, higher-order corrections?
- application to other (full) models
  - ignores details of production, spin structure, …

A short interpretation guide

Kinematic limit



Map of observed cross section limits

- under assumption BR=1

Expected (median) mass limit

- at nominal production cross section
- 1σ variations due to stat+syst

Observed mass limit

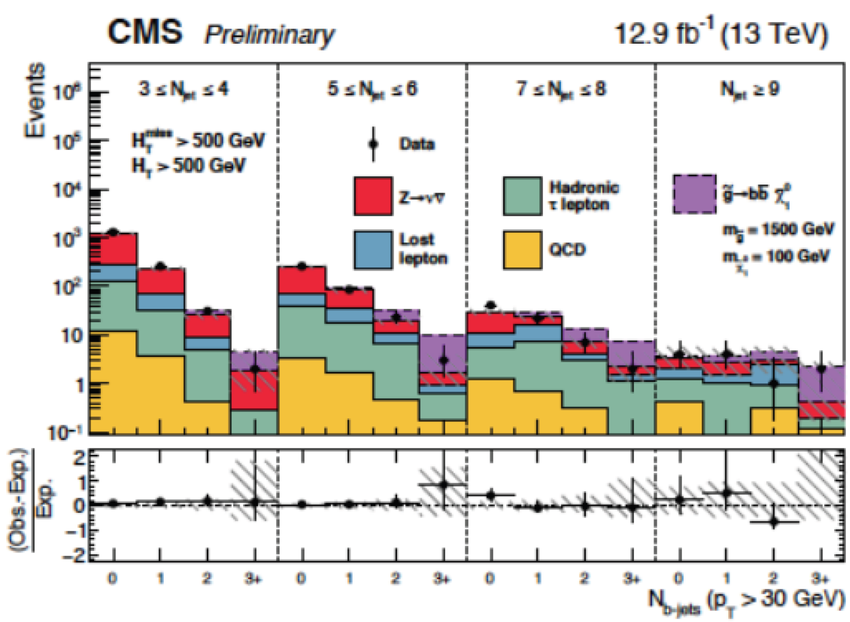
- variations correspond to ±1σ uncertainty on the total production cross section

All Hadronic Searches

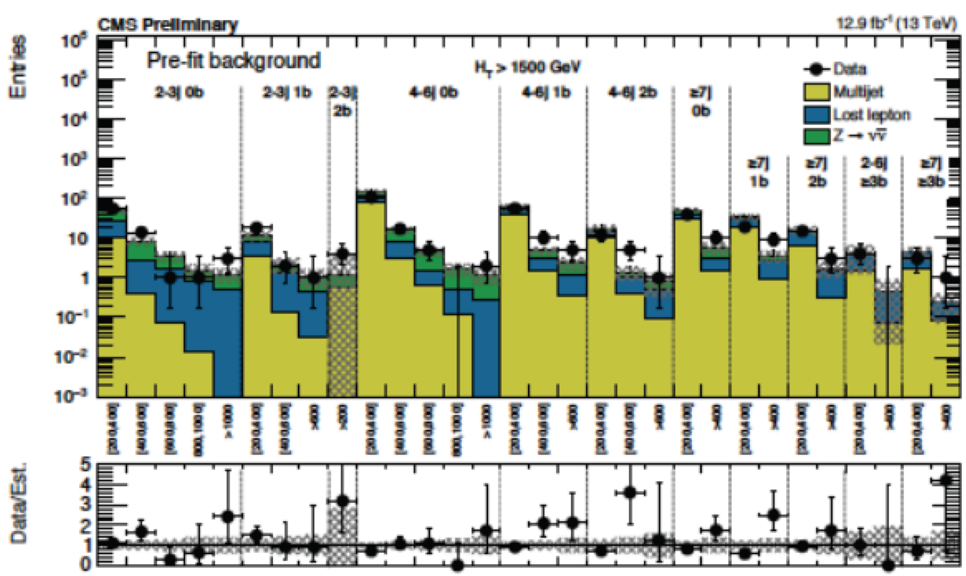
Searches with 12.9 fb^{-1} data: examples

- Divide data in many different classes, eg depending on the number of jets, the number of b-jets,…
- Optimize class for background estimate with data driven methods
- Combine classes for optimal sensitivity to SMS channel

H_T/H_T^{miss} method



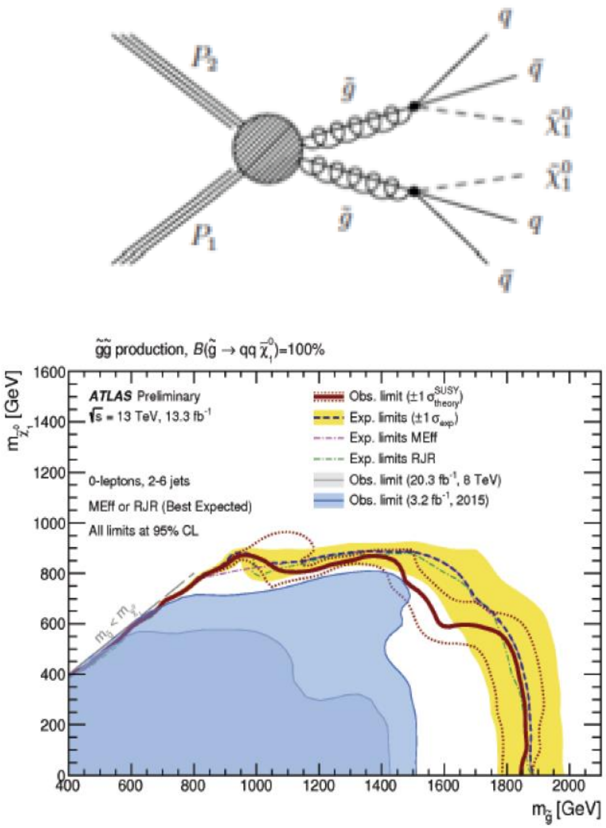
M_{T2} method



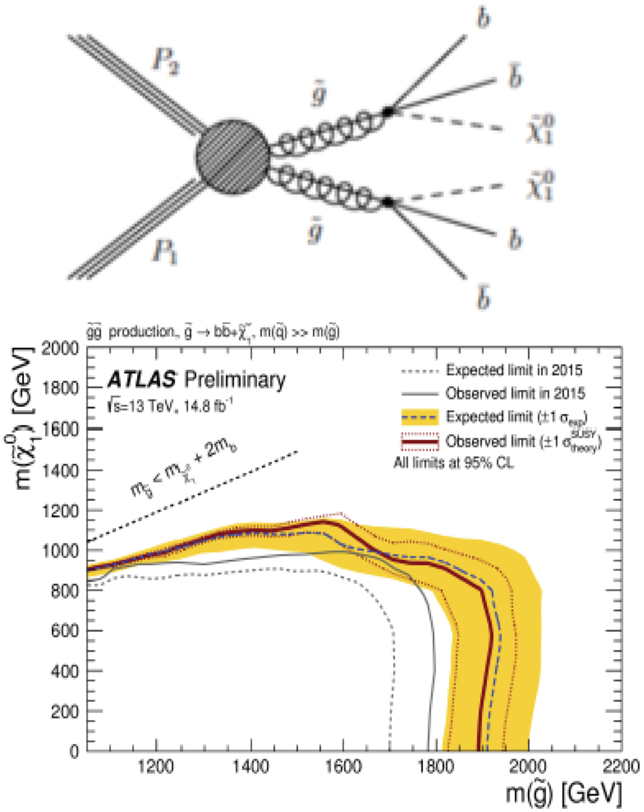
No significant excess observed over background prediction

Run-2: Gluino Searches

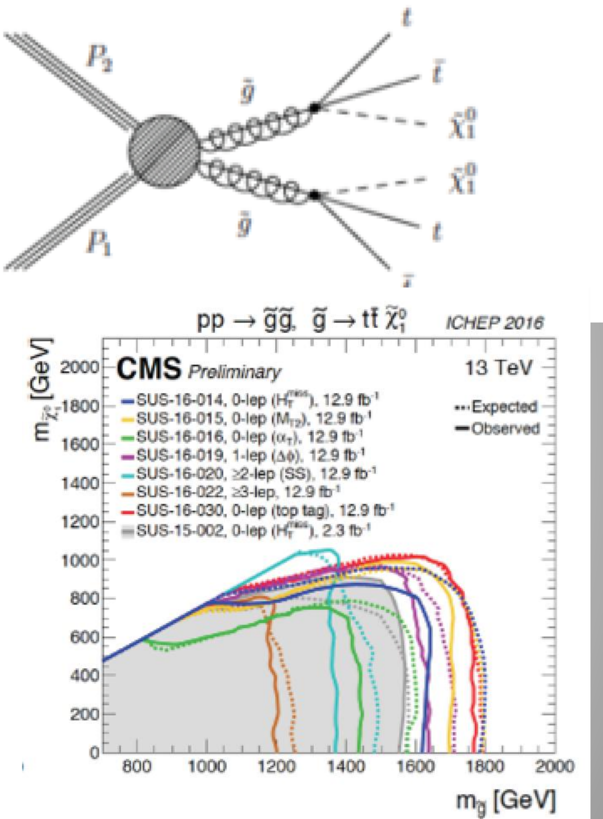
CONF-2016-078



CONF-2016-052



CMS Summary



Within the context of the SMS:

Exclude with masses up to 1900 GeV for neutralino masses up to 800 GeV

Sensitivity is like 400-500 GeV better than Run-1 reach

What is really needed from SUSY?

End 2011: Revision!

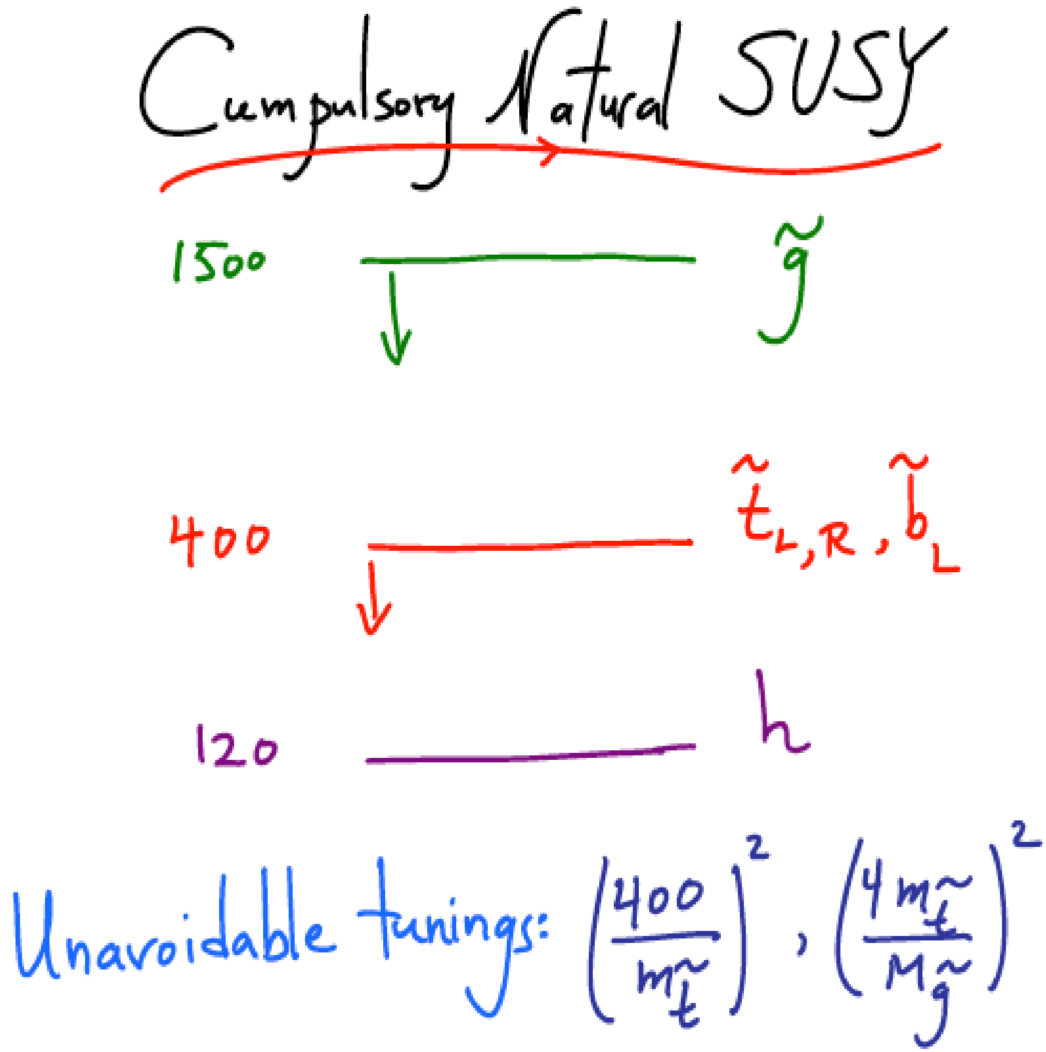
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman,
Weiler arXiv:1110.6926

LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

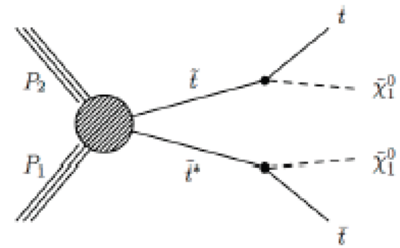
Moving away from constrained SUSY models to ‘natural’ models

Natural SUSY survived LHC so far, but we are getting close to push it to its limits!



Top Quark Searches

Top squarks



W. Adam

Low-mass top squarks required for natural models

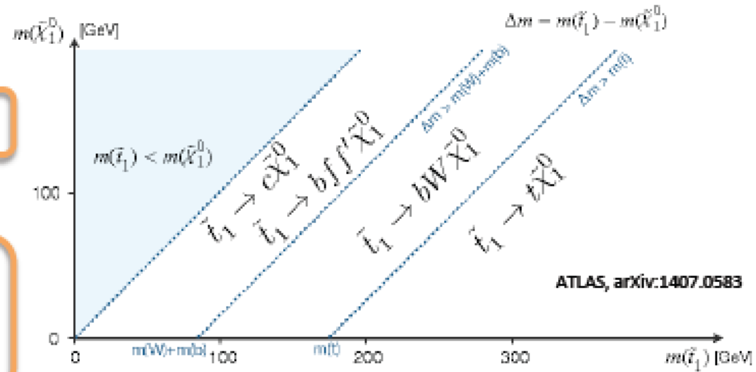
- could be the 2nd lightest SUSY particle (and the first detectable sparticle at the LHC)

Signature

- favored decay via $t^{(*)}$ and LSP: final states classified according to W decay mode
- approaches SM tt signature for Δm≈m(t) and low LSP mass

4-body decay

alternative: flavor-changing decays via charm



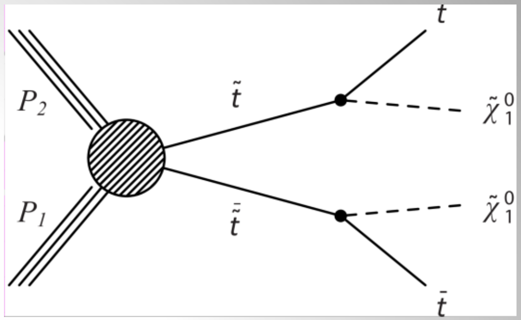
Decay via on-shell top quarks (2 body)

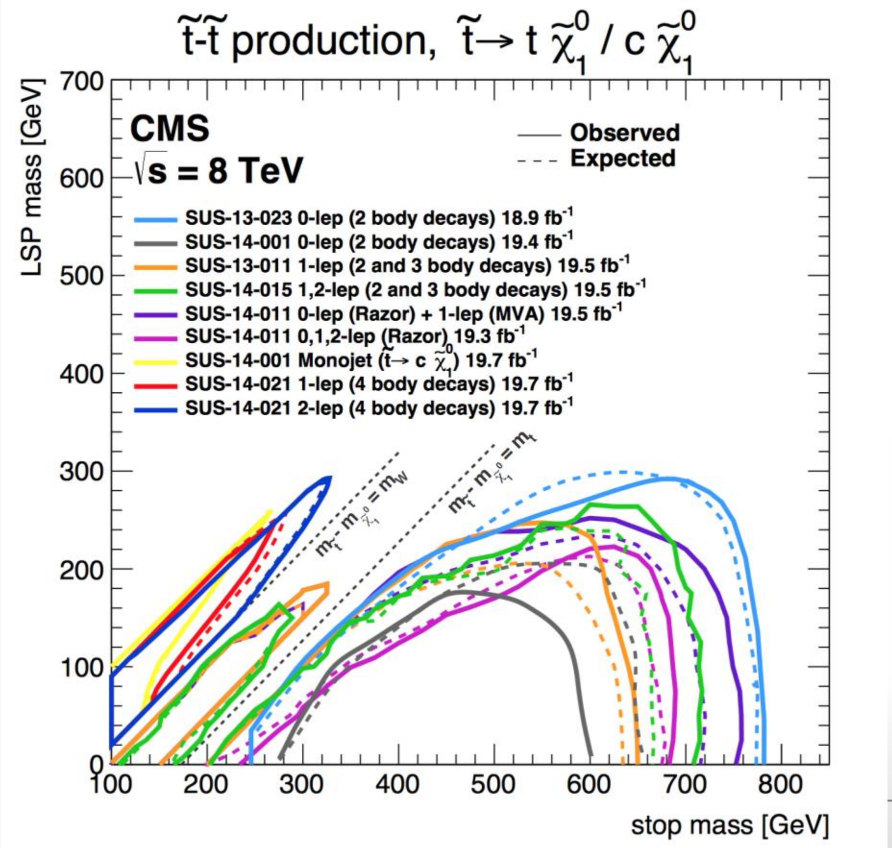
Decay via on-shell W (3 body)

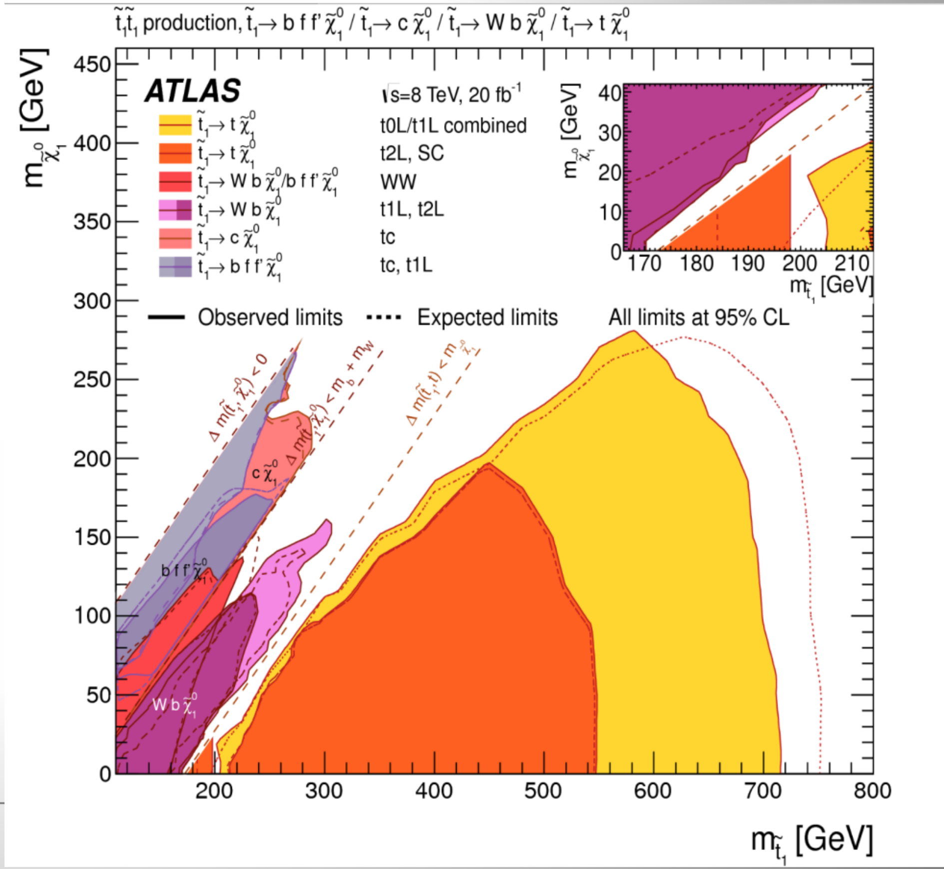
if chargino is accessible: alternative decay to b-chargino

Stop Searches @ 8 TeV

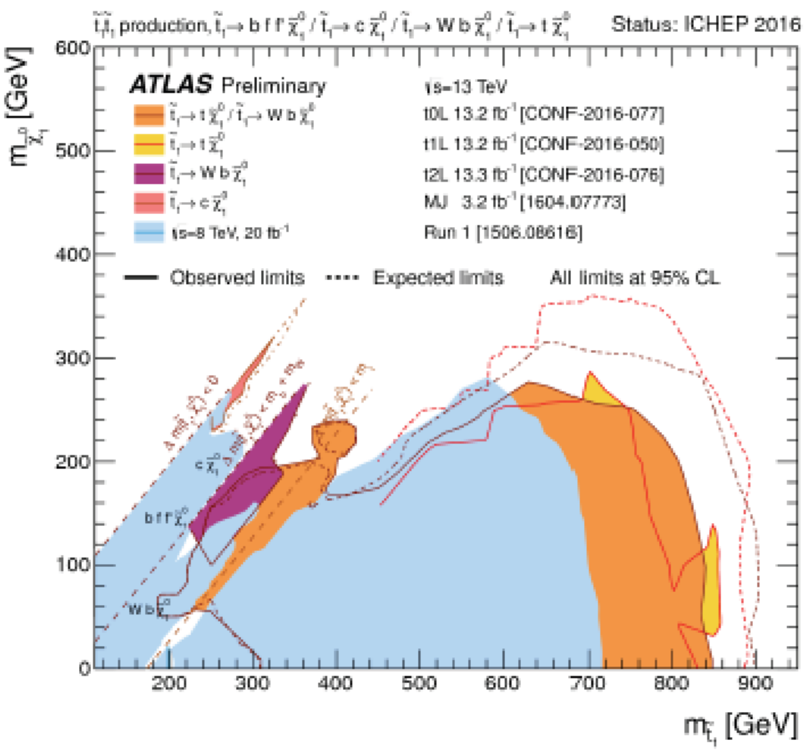
Run-1 summaries

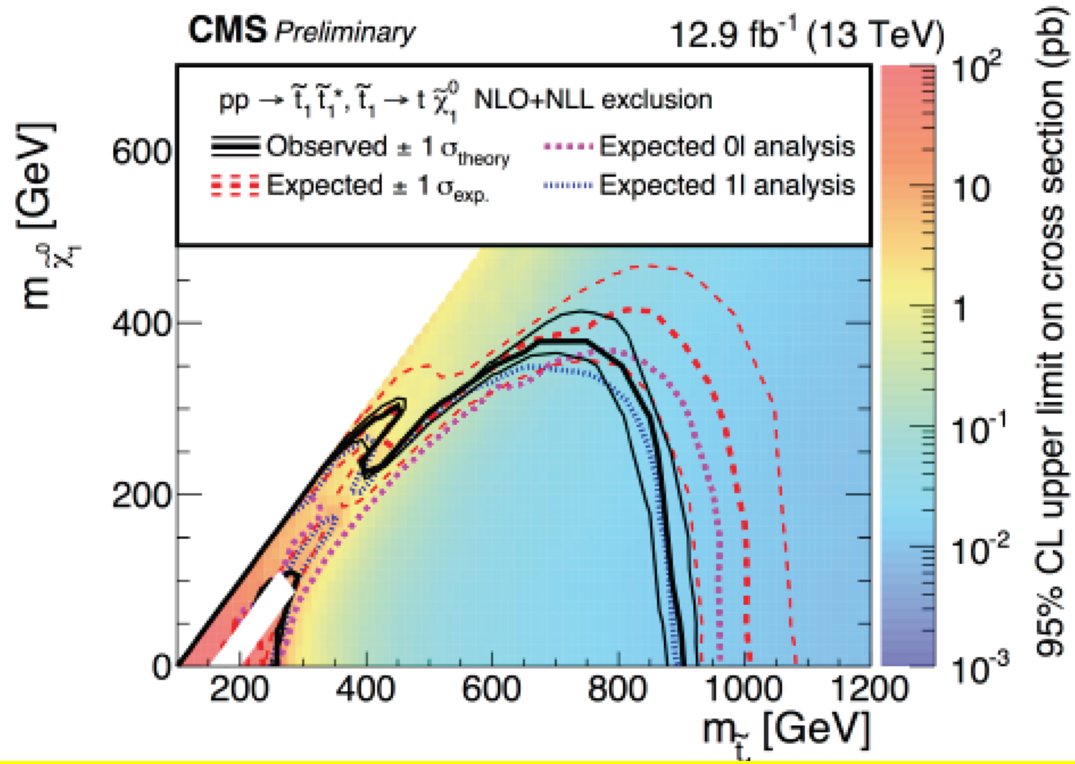






Top Squark Search Summaries





Within the context of the SMS:

Exclude with masses up to 900 GeV for neutralino masses up to 400 GeV

Sensitivity is like 100-200 GeV better than Run-1 reach & gaps being covered

Is this getting critical for Natural Models??

Phenomenological MSSM analysis

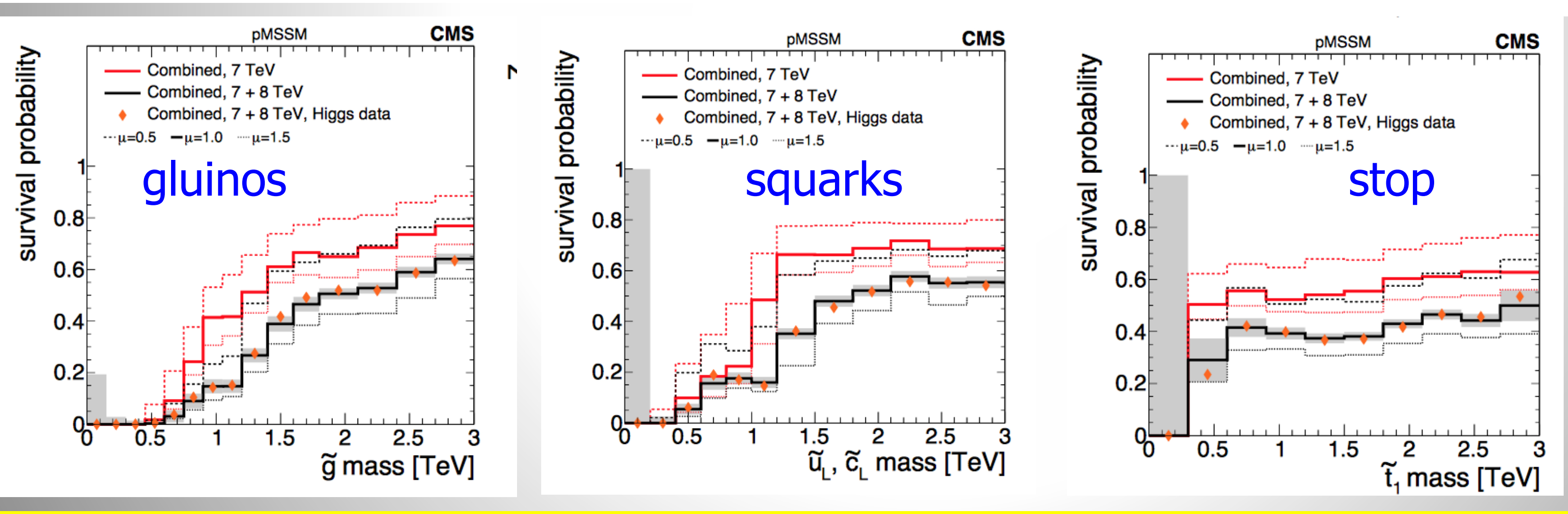
SMS don't always fully cover signatures…
-> the 19 parameter phenomenological MSSM (pMSSM) analyses

arXiv:1606.03577

ATLAS: arXiv: 1508.06608

- three independent gaugino mass parameters M_1, M_2, and M_3,
- the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$,
- the higgsino mass parameter μ and the pseudoscalar Higgs boson mass m_A,
- 10 independent sfermion mass parameters $m_{\tilde{F}}$, where $\tilde{F} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{E}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3$ (for the 2nd generation we take $m_{\tilde{Q}_2} \equiv m_{\tilde{Q}_1}, m_{\tilde{L}_2} \equiv m_{\tilde{L}_1}, m_{\tilde{U}_2} \equiv m_{\tilde{U}_1}, m_{\tilde{D}_2} \equiv m_{\tilde{D}_1}$, and $m_{\tilde{E}_2} \equiv m_{\tilde{E}_1}$; left-handed up- and down-type squarks are by construction mass degenerate), and
- the trilinear couplings A_t, A_b and A_τ.

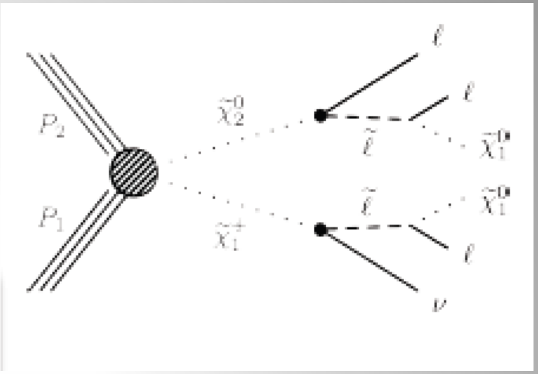
$$-3 \le M_1, M_2 \le 3\,\text{TeV},$$
$$0 \le M_3 \le 3\,\text{TeV},$$
$$-3 \le \mu \le 3\,\text{TeV},$$
$$0 \le m_A \le 3\,\text{TeV},$$
$$2 \le \tan\beta \le 60,$$
$$0 \le m_{\tilde{Q}_{1,2}}, m_{\tilde{U}_{1,2}}, m_{\tilde{D}_{1,2}}, m_{\tilde{L}_{1,2}}, m_{\tilde{E}_{1,2}}, m_{\tilde{Q}_3}, m_{\tilde{U}_3}, m_{\tilde{D}_3}, m_{\tilde{L}_3}, m_{\tilde{E}_3} \le 3\,\text{TeV},$$
$$-7 \le A_t, A_b, A_\tau \le 7\,\text{TeV},$$



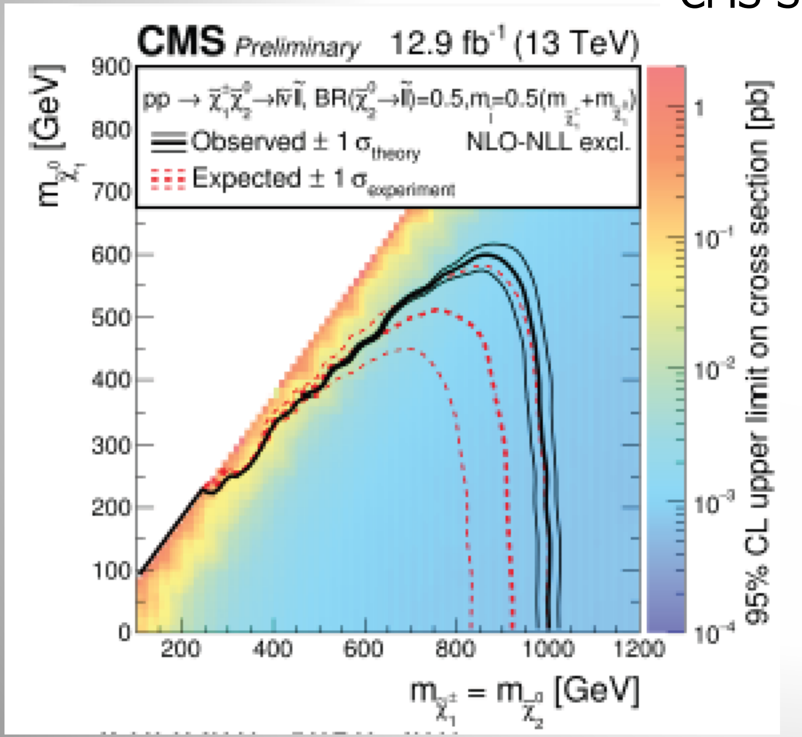
10^8 points sampled: Leads to softer limits on the sparticles masses
Gluinos > 500 GeV, stops > 250 GeV => there is still low mass phase space left!

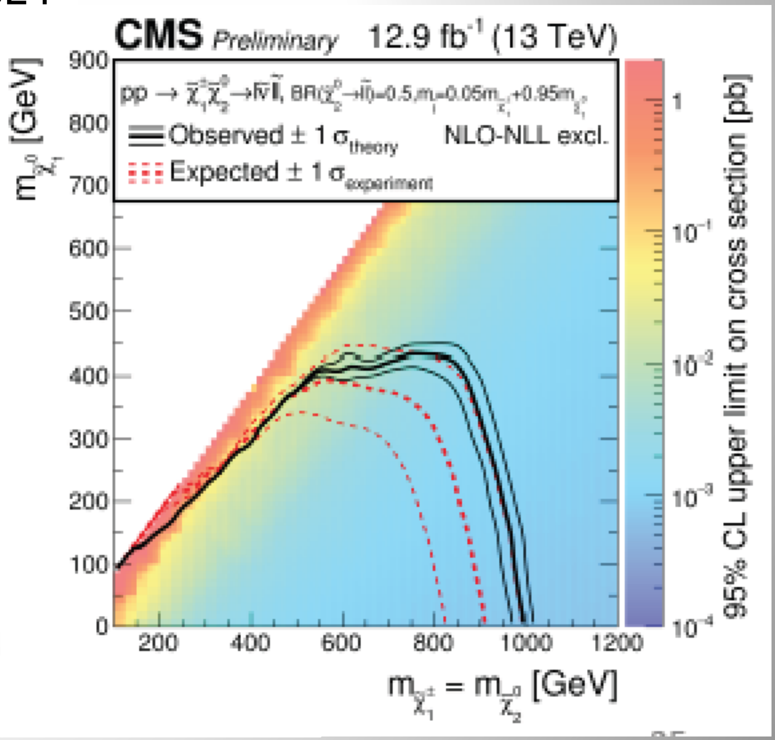
Chargino and Neutralino Production

Direct production of "electroweakino pairs
- Decays via sleptons /sneutrinos
- Using benchmarks to illustrate different scenarios
- Multilepton searches (incl.taus)



CMS-SUS-16-024





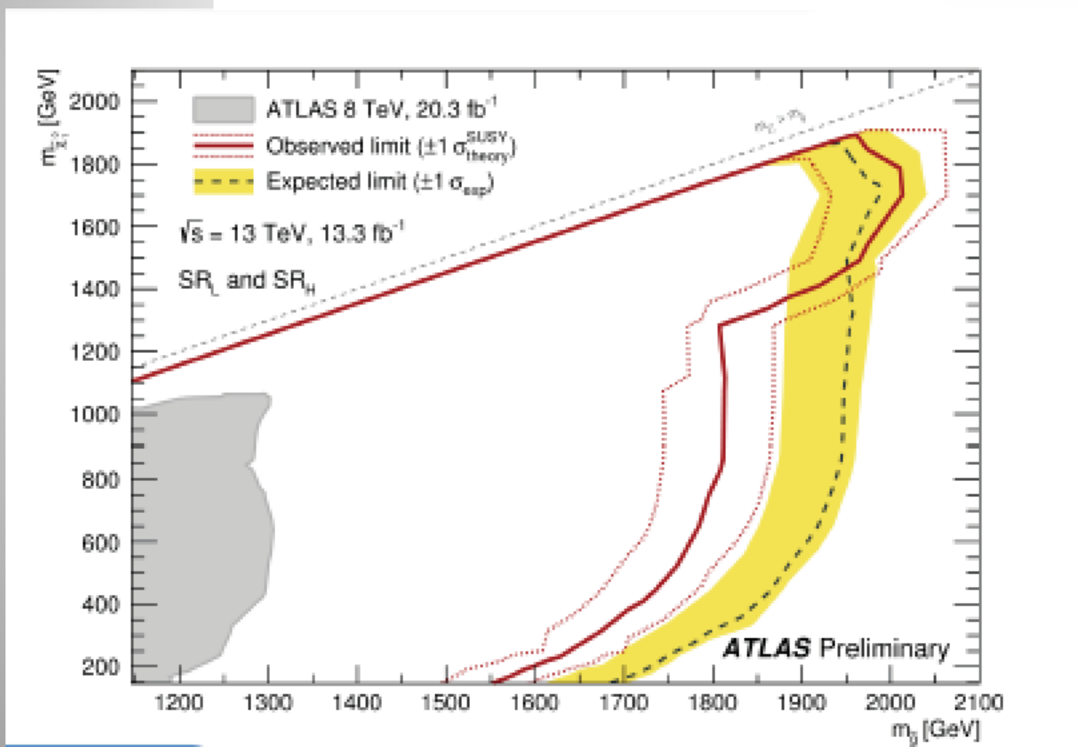
Exclude masses up to 1000 GeV for neutralino masses up to 400 GeV

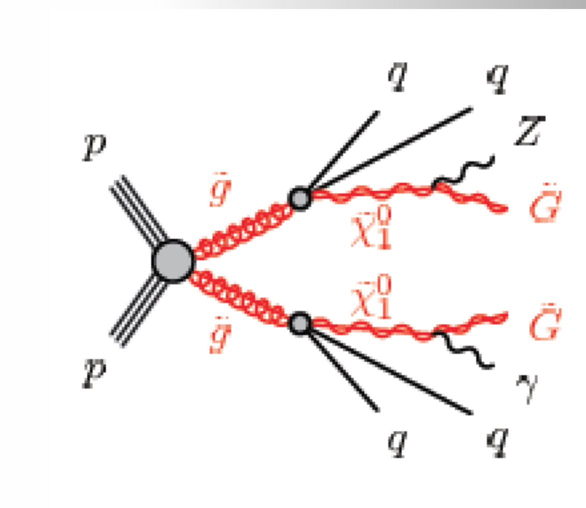
GMSB Scenario

Gluino induced Z/γ+ gravitino final state

Photons + jet +MET search

ATLAS-CONF-2016-048



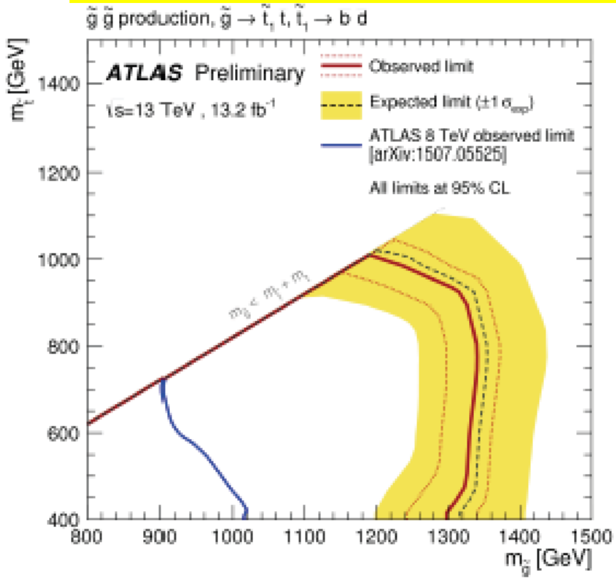


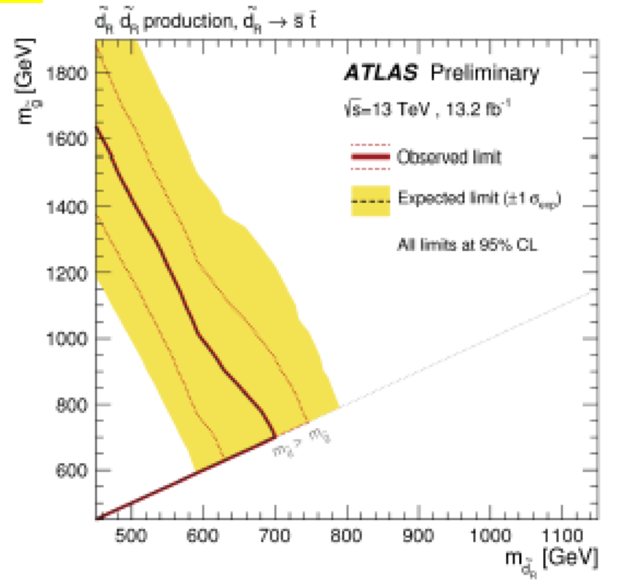
More GMSB searches in ATLAS-CONF-2016-048 and CMS-SUS-16-021

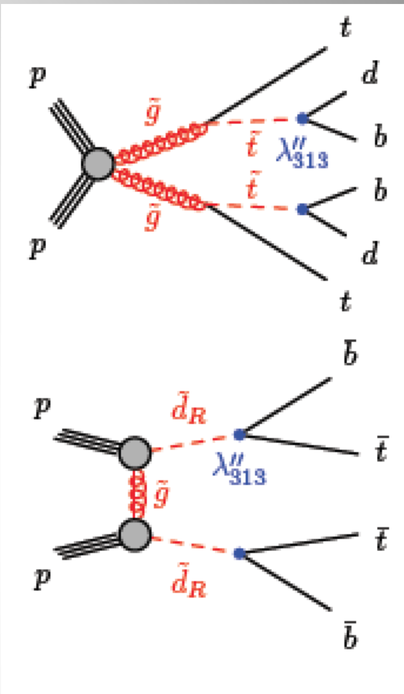
RPV Violating Searches

Squark and gluino decays

ATLAS-CONF-2016-037

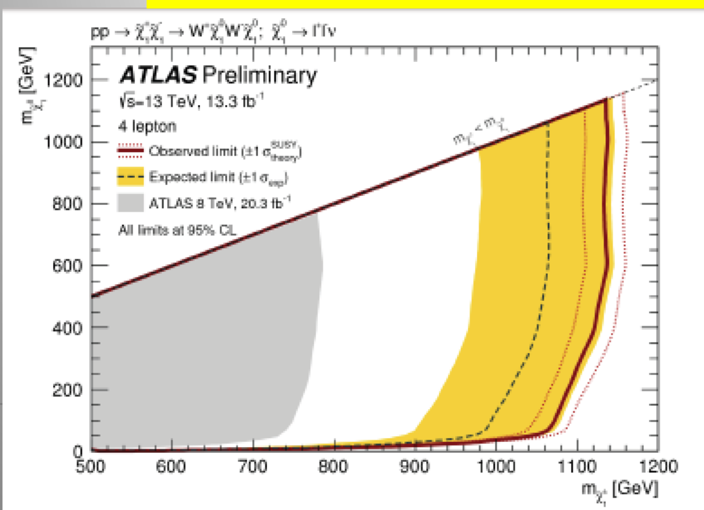


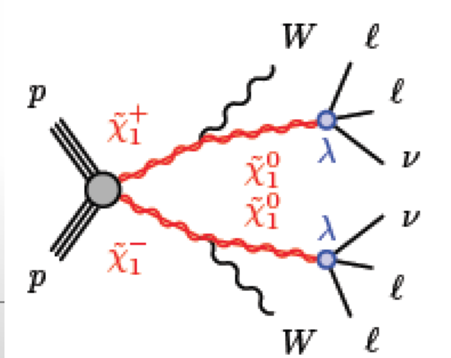




Electroweakino production

ATLAS-CONF-2016-075





RPV Scenarios without "neutralino" missing E_T

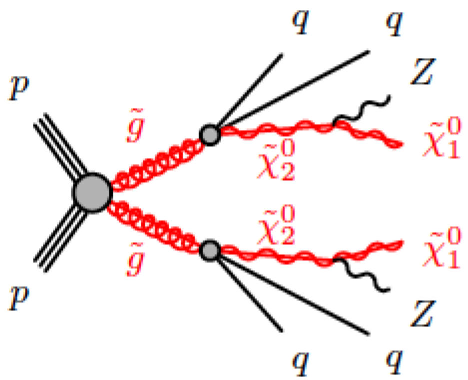
No dark matter candidate

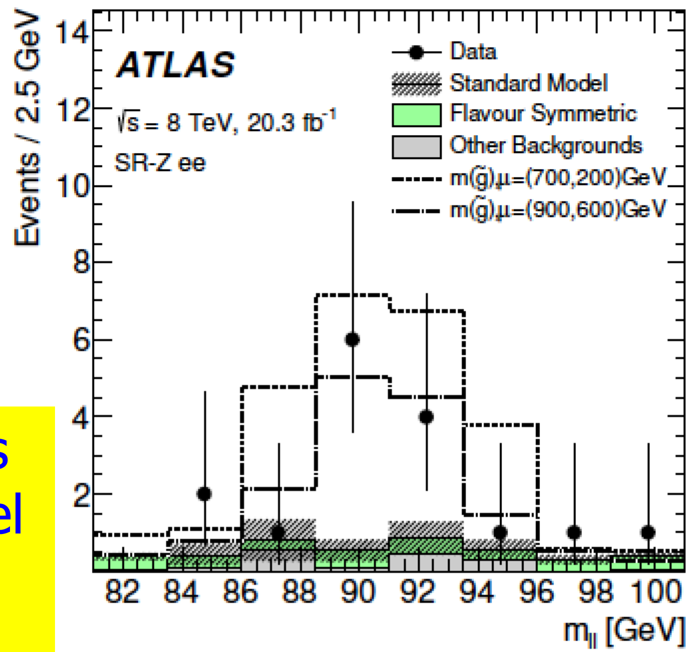
What about analyses that showed some excess in Run-1?

Search in the Z+Jets+MET Channel

ATLAS-CONF-2015-082

Search for gluino or squark production with Z in decay chain



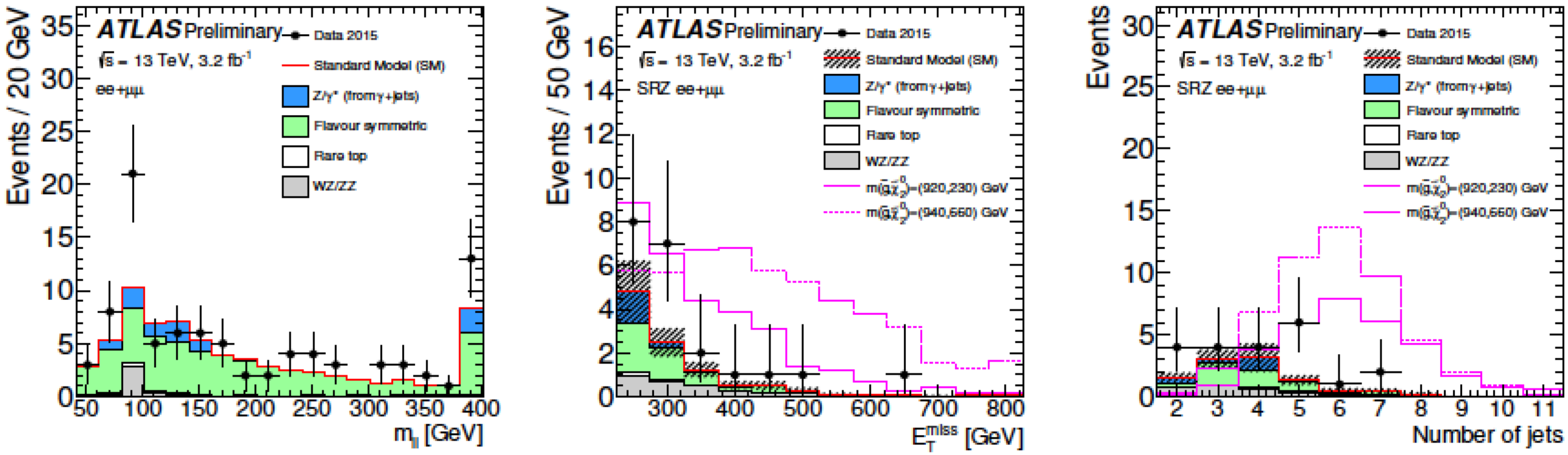


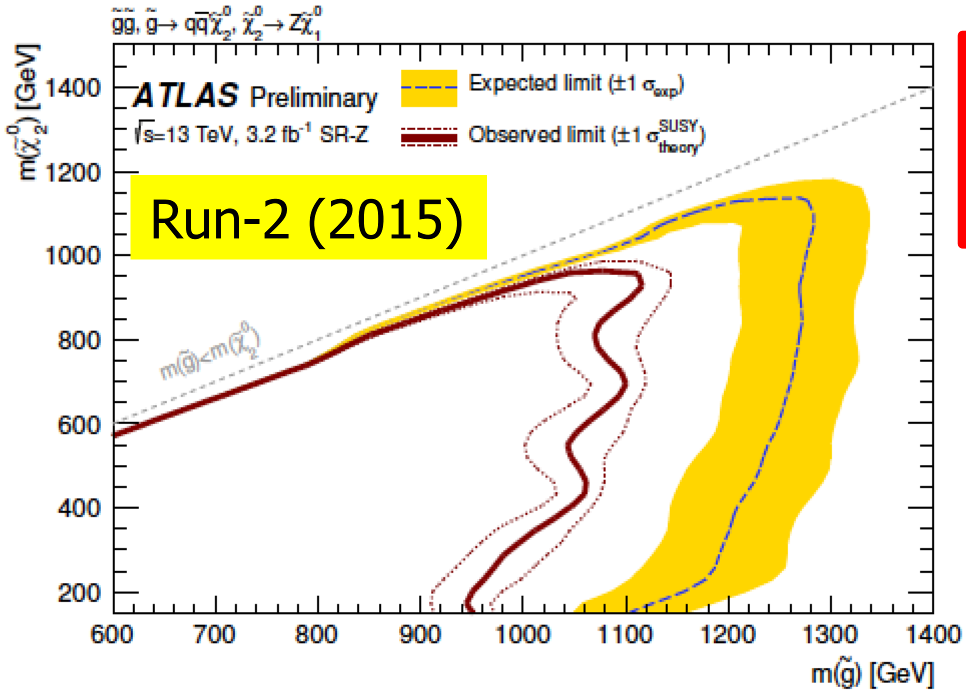
- In Run-1 ATLAS observed an excess in this channel: 3 (1.7) σ excess in ee (μμ) channel
- No excess observed in CMS in Run-1

Reproduce the Run-1 analysis in Run-2:

- 2 ℓ (e^+e^- or $\mu^+\mu^-$) with $p_T > 50{,}25$ GeV and $81 < m(\ell\ell) < 101$ GeV
- $\geqslant 2$ jets with $\Delta\phi_{\min}(\not{E}_T, jets) > 0.4$
- $\not{E}_T > 225$ GeV and $H_T > 600$ GeV

Search in the Z+Jets+MET Channel





10.3 ± 2.3 events expected

21 observed (10 ee + 11 $\mu\mu$)

- Local excess of 2.2σ

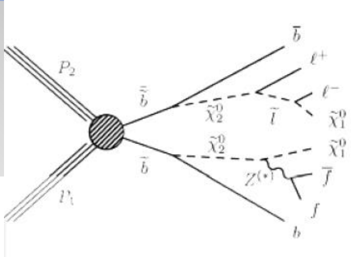
CMS result : Exp = $12^{+4.0}_{-2.8}$, obs = **14**

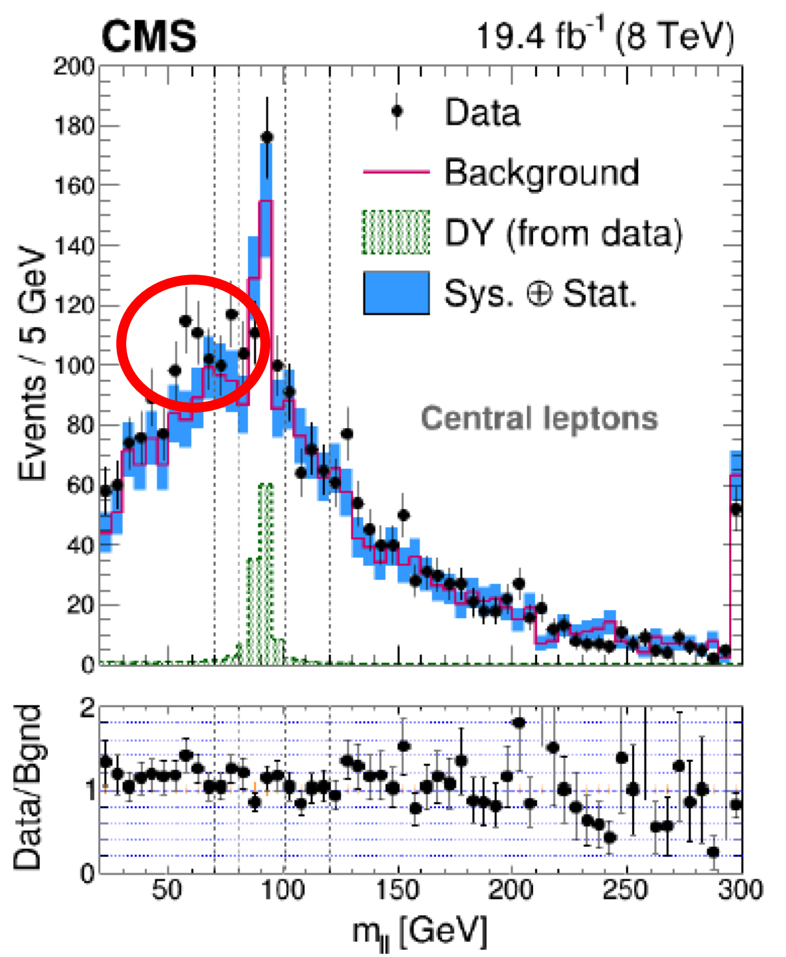
- ATLAS continues to observe an excess in the 2015 data
- CMS remains consistent with the background expectation.

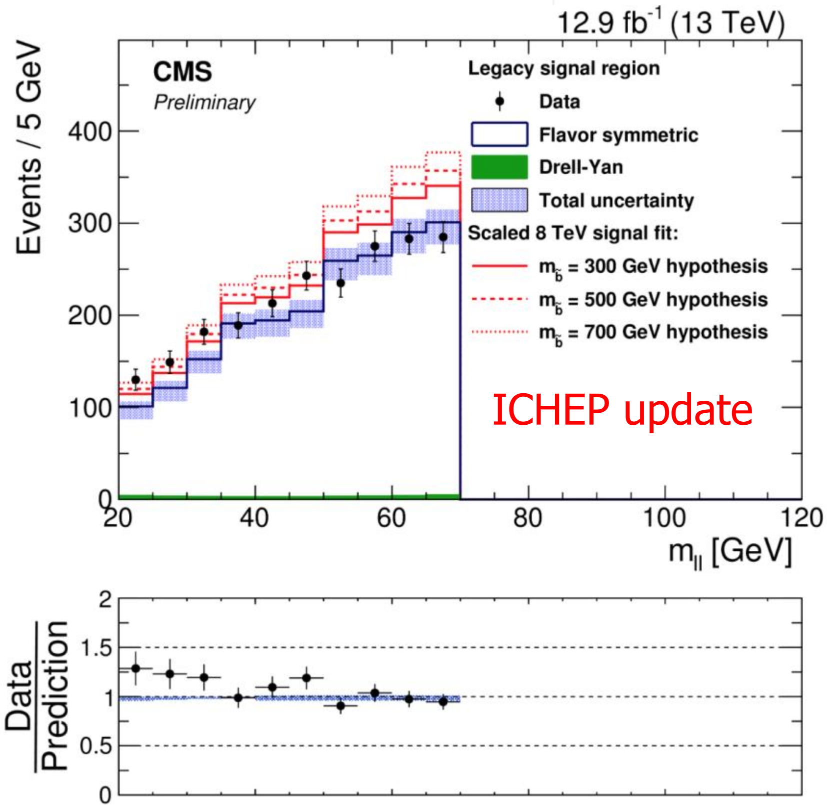
No new ATLAS result@ICHEP…

Opposite Sign Dilepton Analysis

CMS had "it's own" mild excess in run-1 dileptons in the Region below the Z at 8 TeV. The local excess was 3.4σ







CMS-SUS-16-021

The new 2015 data so far does not confirm this excess…

Many Other Searches for SUSY

- Searches with many jets (8 or more)
- Searches with hard photons
- Searches for electroweakinos in multi-lepton final states
- Searches with soft leptons
- Searches fort sbottoms and staus
- Specific analyses for compressed spectra
- RPV analyses without missing E_T requirement
- VBF production of sparticles
- SUSY with long lived particles
- …

-> So far no outstanding surviving signal!!

Real Exotic Objects!

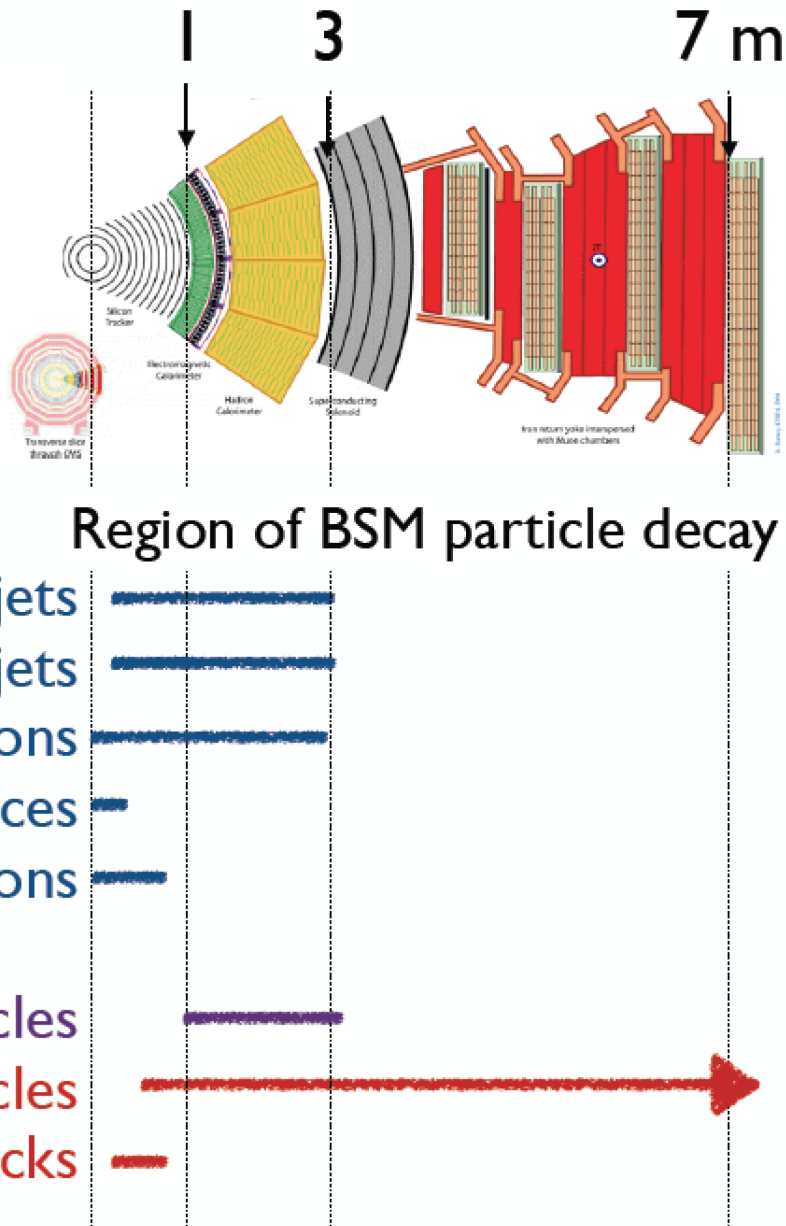
Many new searches for truly exotic particles, ie long-lived particles or other unusual signatures

Searches for Unusual Particles

Long-lived searches are signature-driven.

W. Wulsin

LL particle may be neutral or charged (or both)



displaced jets

lepton jets

displaced leptons

displaced vertices

displaced / delayed photons

stopped particles

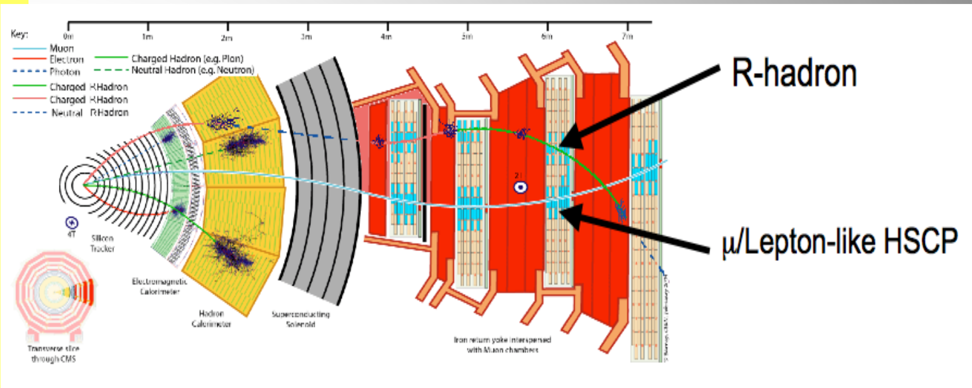
heavy stable charged particles

disappearing tracks

Very Long Lived Particles

Split Supersymmetry

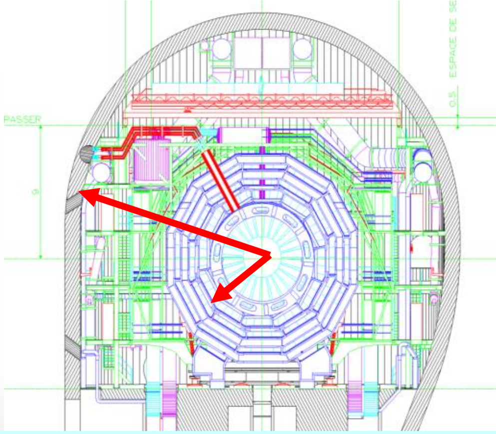
- The only light particles are the Higgs and the gauginos
  - Gluino can live long: sec, min, years!
  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles



Gravitino Dark Matter and GMSB

- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live ‘long’: “heavy muon-like?
- ⇒ non-pointing photons

EG: K. Hamaguchi,M Nojiri,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198



Hidden Valley modes!…

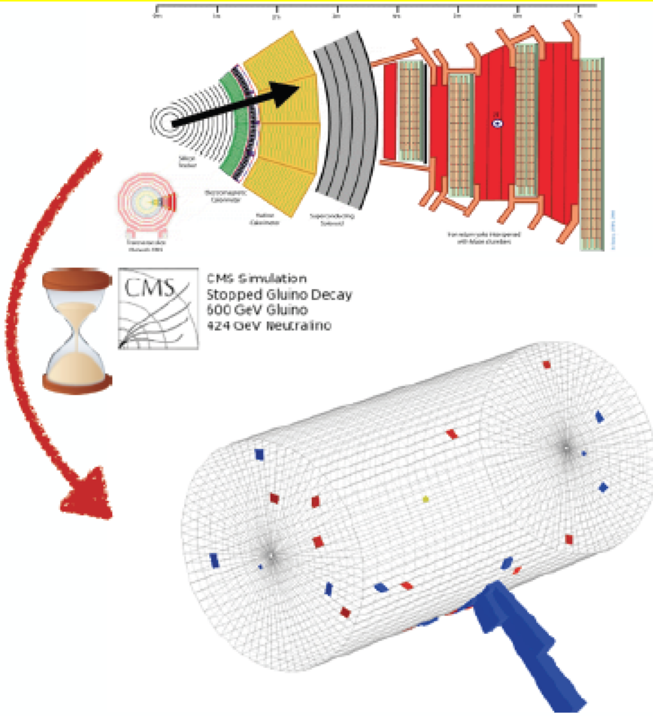
Plethora of possibilities for long lived neutrals

Sparticles stopped in the detector,walls of the cavern, or dense ‘stopper’ detector. They decay after hours---months…

⇒Challenges to the experiments!

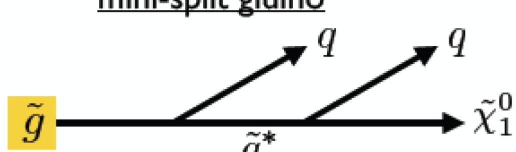
Stopped Particles

Data collected when there are no collisions in the IP



Look for calorimeter cluster **asynchronous** with p-p collisions. 281 hours of trigger livetime.

mini-split gluino

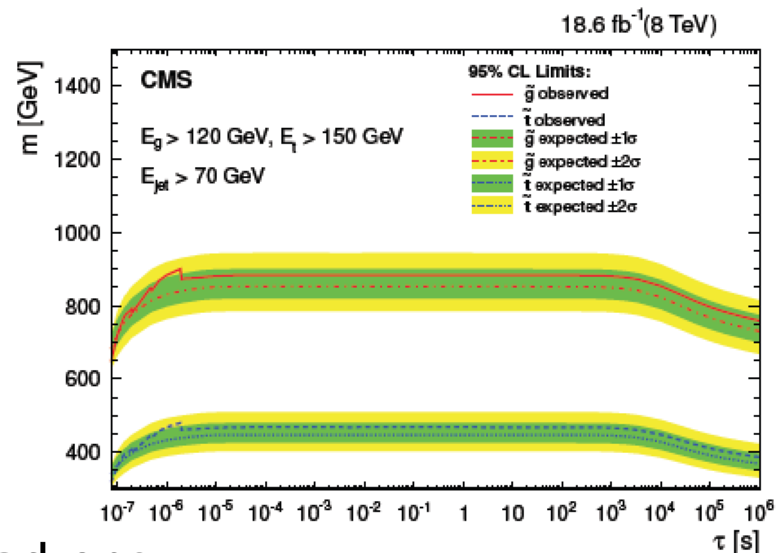


arXiv:1501.05603

Backgrounds: beam halo muons, cosmic rays, HCAL noise.

	Signal region
Expected bkgd	$13.2^{+3.6}_{-2.5}$
Observation	10

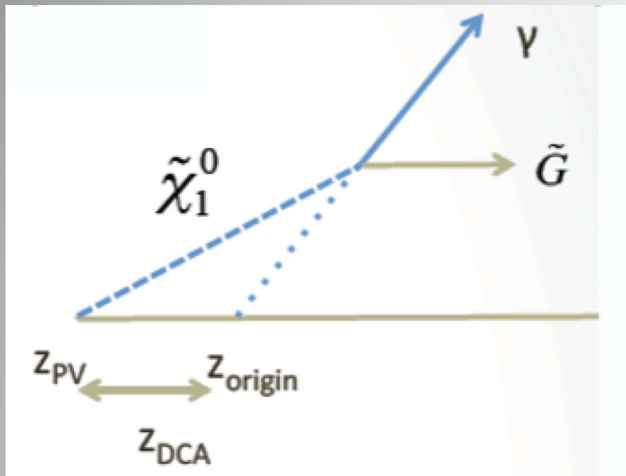
Limits on gluino, stop mass for **over 13 orders of magnitude!**



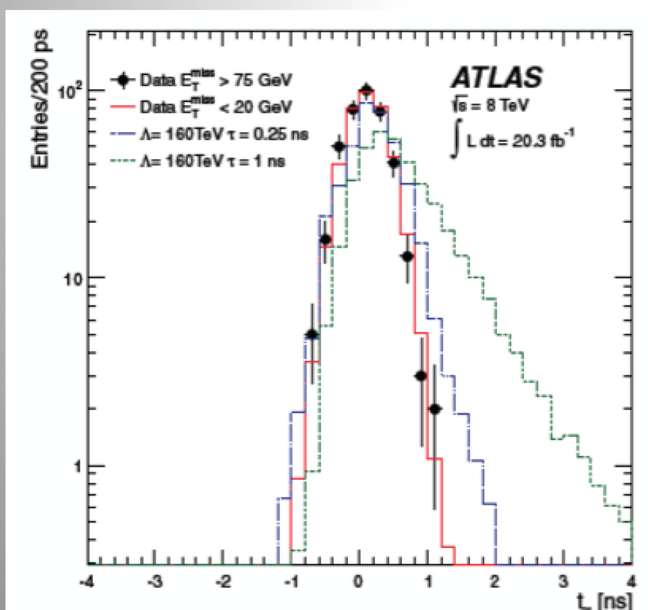
Eg. R-hadrons

Similar techniques employed in Phys. Rev. D 88, 112006 (2013) (ATLAS)

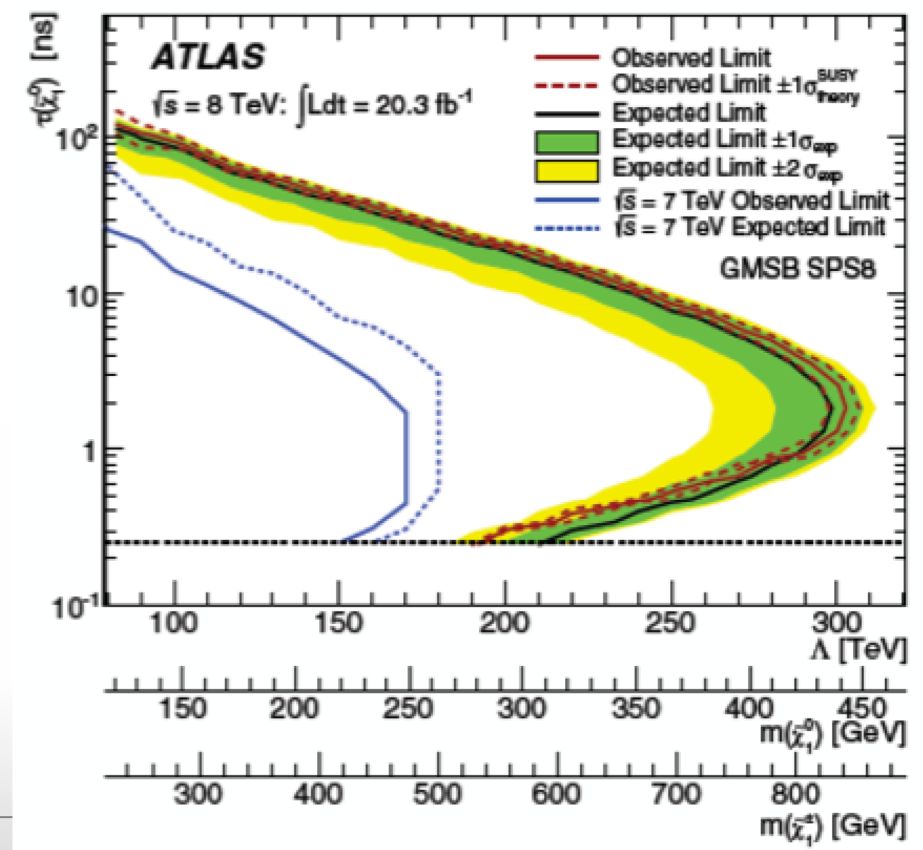
Displaced/Delayed Photons



Search for photons that do not point back to the primary vertex (via timing/pointing)

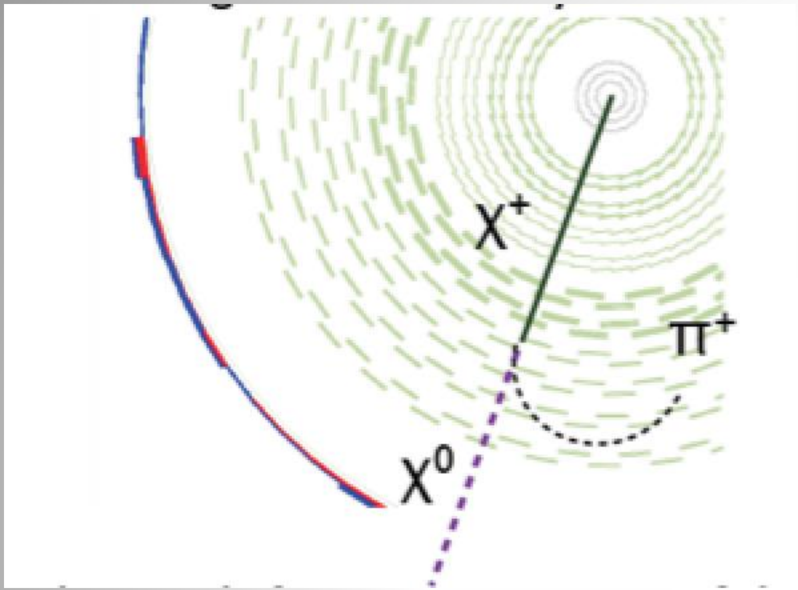


Set limits on GMSB SPS8 model.



Phys. Rev. D 90, 112005 (2014)

Disappearing Tracks



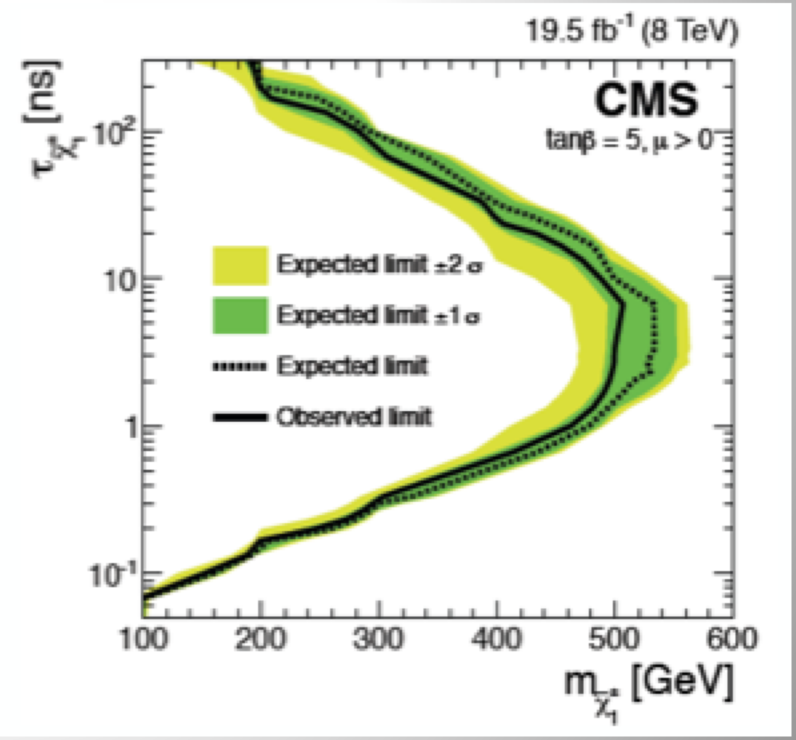
Tracks "appears" to stop
Decay results in a very slow pion that remains undetected

Typical for AMSB SYSY scenarios

JHEP 01 (2015) 096

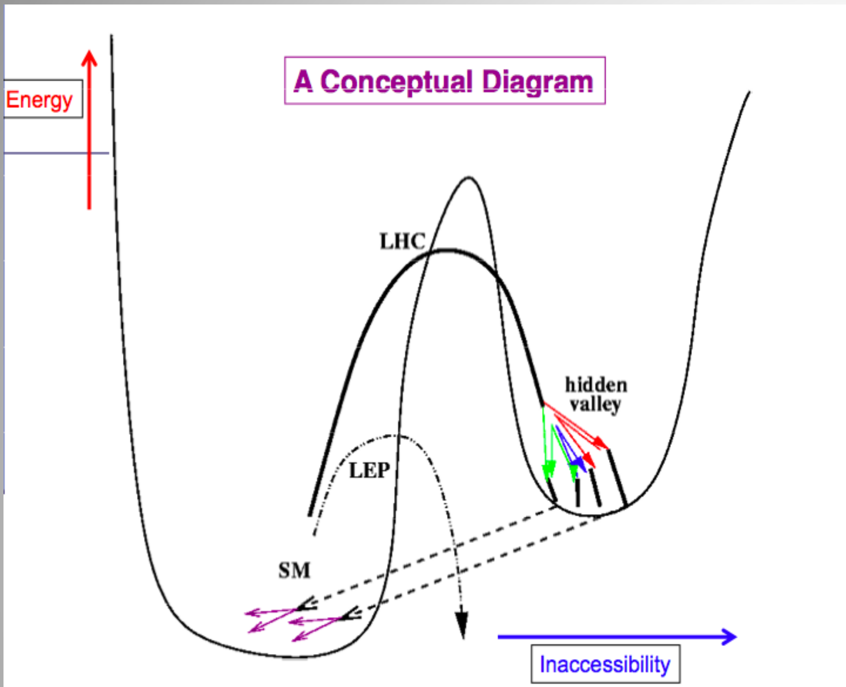
Search for high p_T stopping tracks

	Signal region
Expected bkgd	1.4 ± 1.2
Observation	2

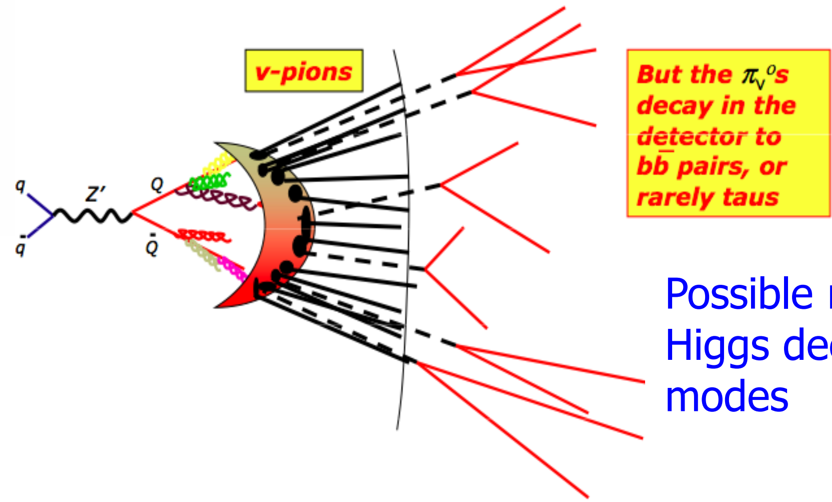


Similar constraint from
Phys. Rev. D 88, 112003 (2013) (ATLAS)

Hidden Valley Physics: New Signatures



M. Strassler, K. Zurek



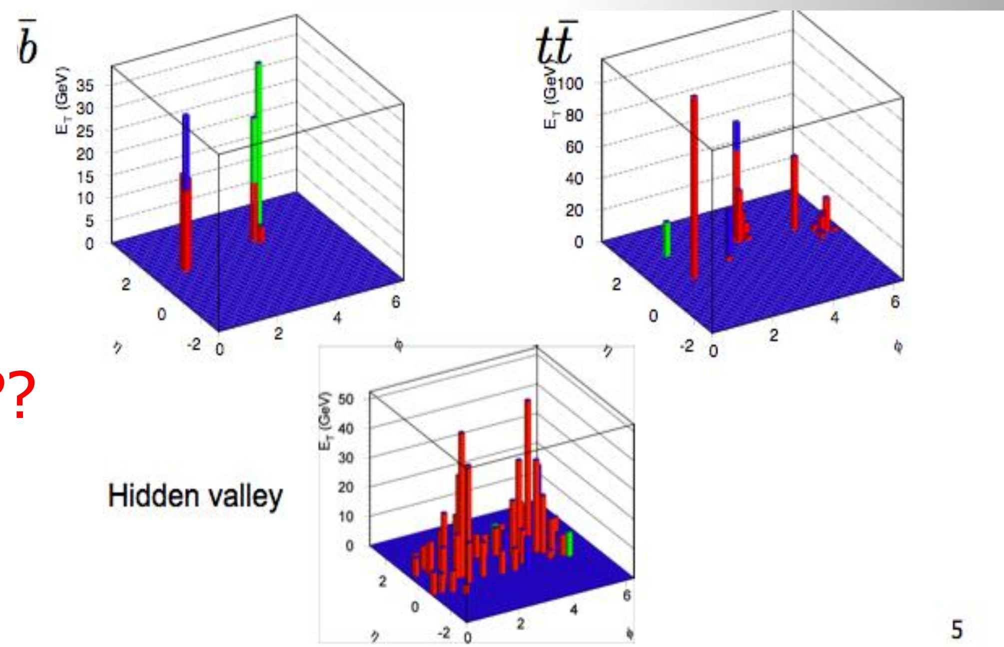
Possible new Higgs decay modes

Will produce "Weird Jets" and a lot of secondary vertices from b-quark jets

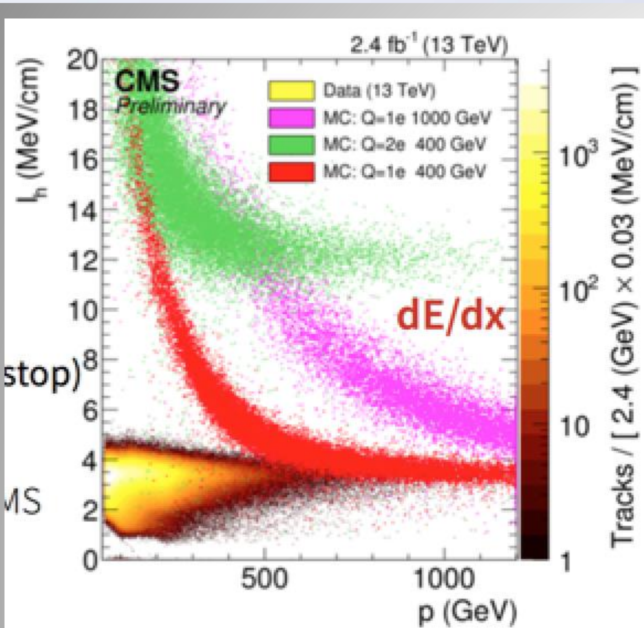
$\Rightarrow$ Difference with QCD jets??

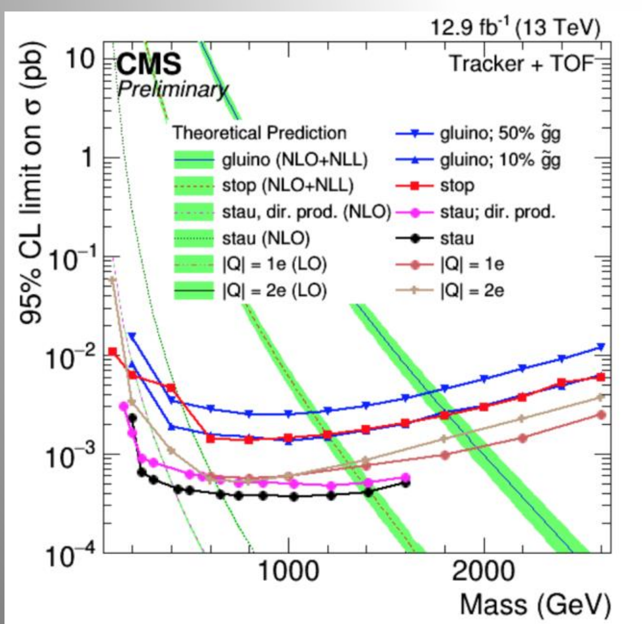
$\Rightarrow$Study SM jet structure!!

$\Rightarrow$Displaced letposn, jets…



Heavy Stable Ionizing Particles





Detection techniques used for (multiple/fractional) heavy stable charge particles

- Abnormal energy loss (de/dx)
- Slower than speed of light (lowβ) via time of flight measurements with the muon system

Time of flight $\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$

CMS-EXO-16-036

Model	Analysis	Mass Limits
Gluino $f = 0.1$	tracker-only	$M > 1850(1850)$ GeV
	tracker+TOF	$M > 1810(1810)$ GeV
Gluino $f = 0.1$ CS	tracker-only	$M > 1840(1840)$ GeV
Gluino $f = 0.5$	tracker-only	$M > 1760(1760)$ GeV
	tracker+TOF	$M > 1720(1720)$ GeV
Gluino $f = 0.5$ CS	tracker-only	$M > 1800(1800)$ GeV
Stop	tracker-only	$M > 1250(1250)$ GeV
	tracker+TOF	$M > 1200(1200)$ GeV
Stop CS	tracker-only	$M > 1220(1220)$ GeV
GMSB Stau	tracker-only	$M > 660(660)$ GeV
	tracker+TOF	$M > 660(660)$ GeV
Pair Prod. Stau	tracker-only	$M > 170(170)$ GeV
	tracker+TOF	$M > 360(360)$ GeV
DY $Q = 1e$	tracker-only	$M > 720(720)$ GeV
	tracker+TOF	$M > 730(730)$ GeV
DY $Q = 2e$	tracker-only	$M > 670(750)$ GeV
	tracker+TOF	$M > 890(890)$ GeV

Particles with Fractional Charge

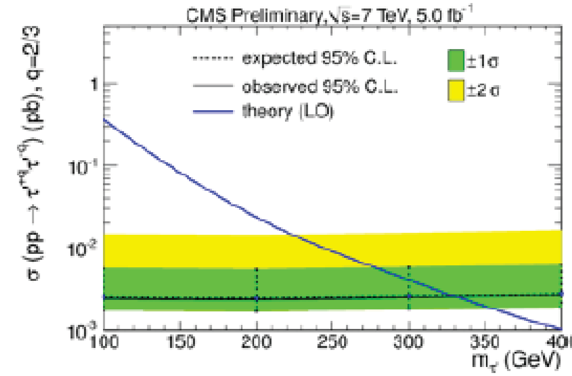
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

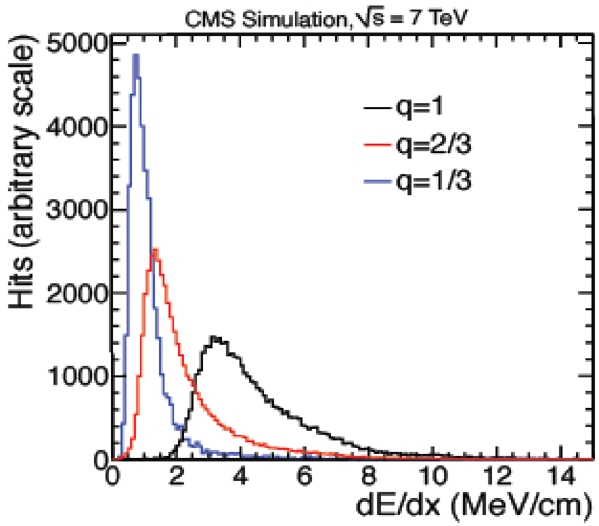
Free quarks?

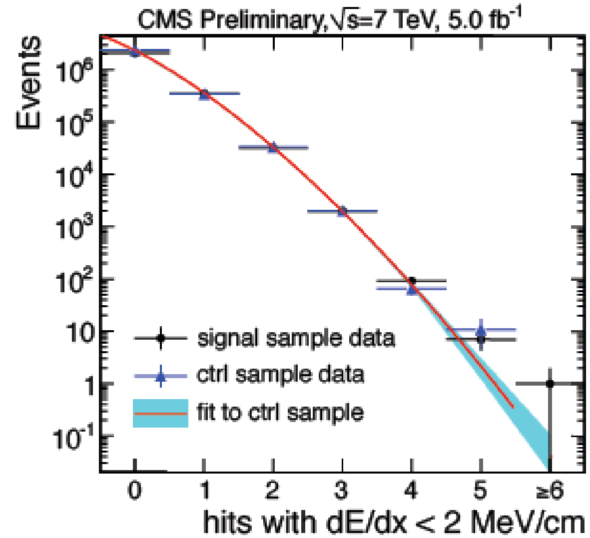
[CMS PAS EXO-11-074]

- Search for long-lived particles with fractional charge
- Backgrounds
  - Cosmics: estimate from d_{xy} sidebands
  - Collisions: using Z→μμ data, fit N_{hits} with low dE/dx
- Assume lepton-like spin=1/2 particle masses

Exclude: Q= e/3: m > 210 GeV
Q=2e/3: m > 330 GeV







Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac '31)

$$\nabla . \mathrm{E} = 4\pi \rho_e$$

$$\nabla . \mathrm{B} = 4\pi \rho_m$$

$$-\nabla \times \mathrm{E} = \frac{1}{c}\frac{\partial \mathrm{B}}{\partial t} + \frac{4\pi}{c}\mathrm{j_m}$$

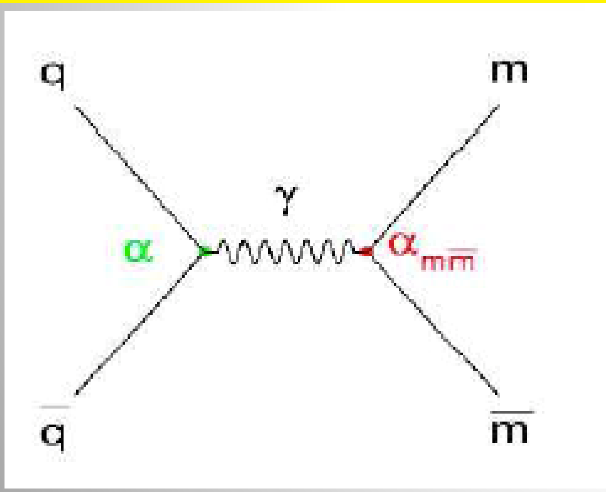
$$\nabla \times \mathrm{B} = \frac{1}{c}\frac{\partial \mathrm{E}}{\partial t} + \frac{4\pi}{c}\mathrm{j_e}$$

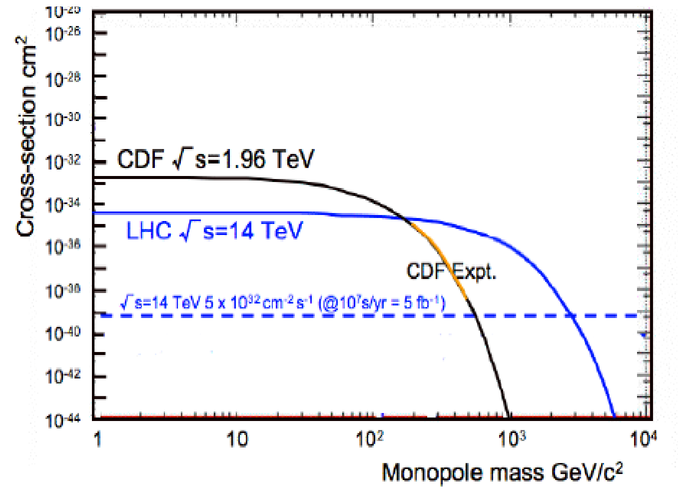
$$\mathrm{F} = q_e\left(\mathrm{E} + \frac{\mathrm{v}}{c} \times \mathrm{B}\right) + q_m\left(\mathrm{B} - \frac{\mathrm{v}}{c} \times \mathrm{E}\right)$$

$$eg = n\hbar c/2 = n g_D$$ = n 68.5e

$$\sigma_{D(m)} = \left(\frac{g_D}{e}\right)^2 \times \sigma_{\mu\mu}(> 2m) \times (1 - 4\frac{m^2}{s})$$

Symmetrizes Maxwell equations
Searched for at all colliders
Tevatron limits ~ 400-800 GeV





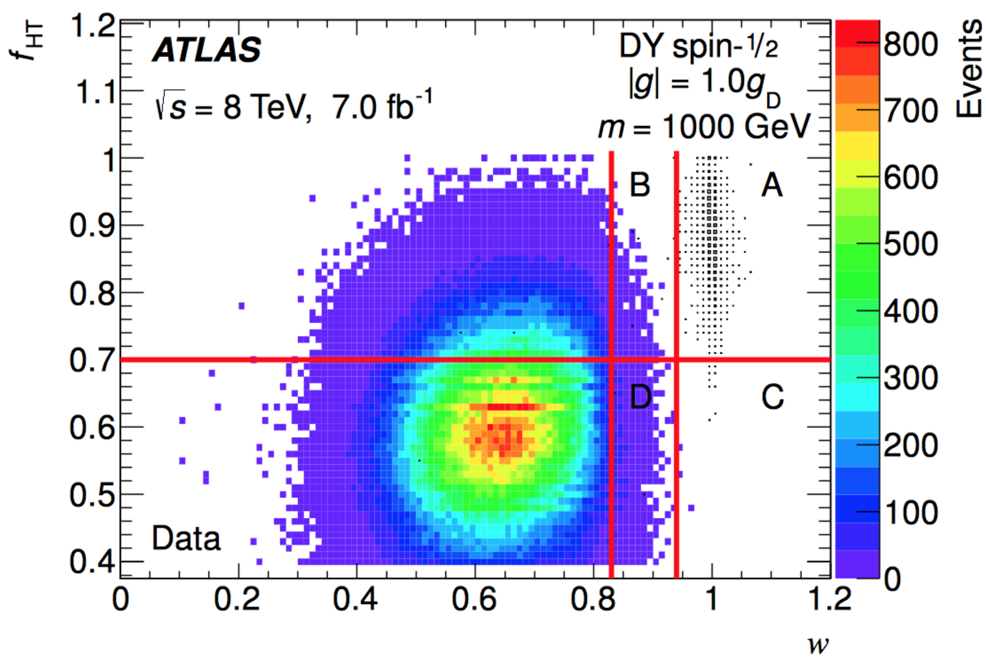
Sensitivity of LHC experiments to exotic highly ionising particles

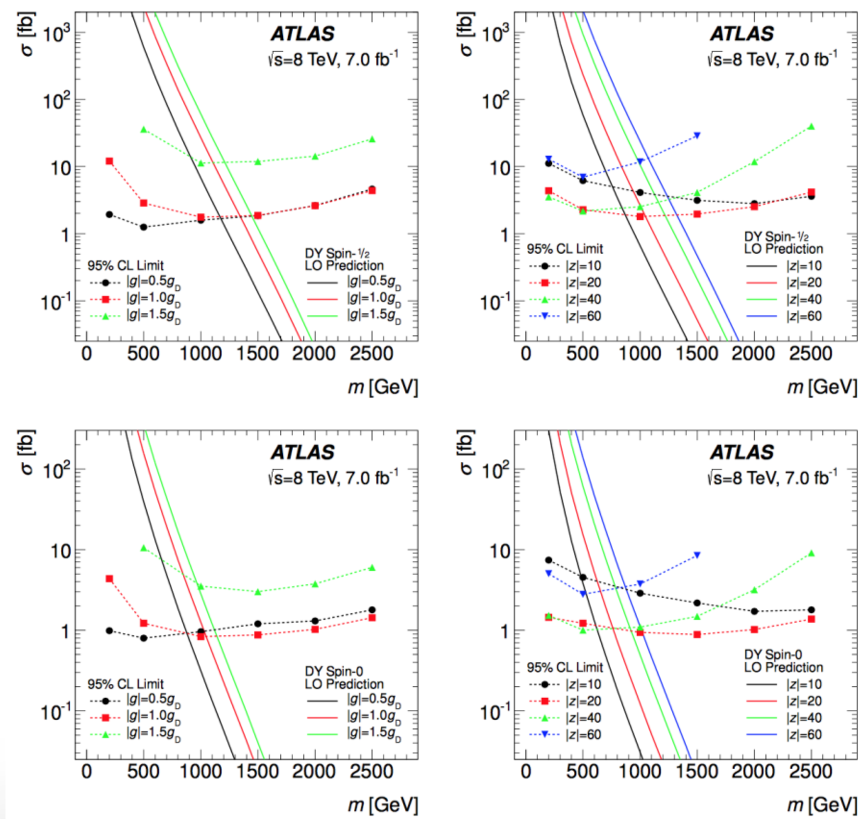
A. De Roeck[1,2,3], A. Katre[4], P. Mermod[a,4,5], D. Milstead[6], T. Sloan[7]

arXiv: 1112.2999

Monopole Searches: ATLAS

- For Monopoles, expect tacks with high de/dx and particle stopped in ECAL
- Use fraction of hits in TRT above a high threshold f_{HT} and narrowness *w* of the shower in ECAL   arXiv:1509.08059



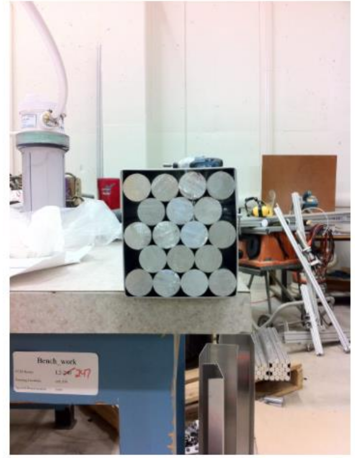


$$A^{\rm est}_{\rm bkg} = \frac{BC}{D} = 0.41 \pm 0.24\ (\text{stat.}) \pm 0.16\ (\text{syst.}).$$

Zero events observed

	Drell-Yan Lower Mass Limits [GeV]						
	$\lvert g\rvert = 0.5g_D$	$\lvert g\rvert = 1.0g_D$	$\lvert g\rvert = 1.5g_D$	$\lvert z\rvert = 10$	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert z\rvert = 60$
spin-1/2	1180	1340	1210	780	1050	1160	1070
spin-0	890	1050	970	490	780	920	880

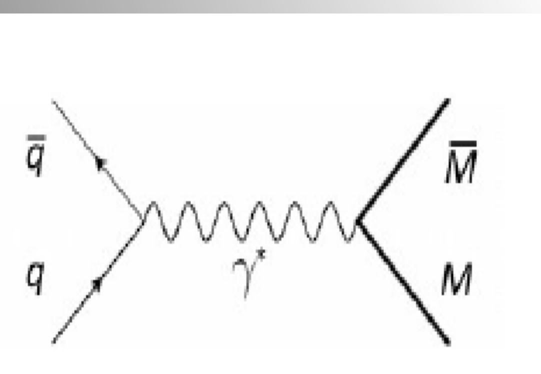
MoEDAL: Search for Monopoles

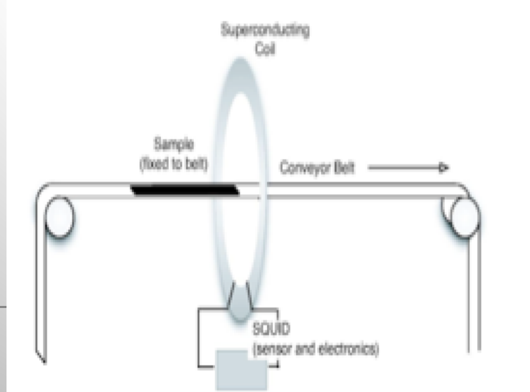


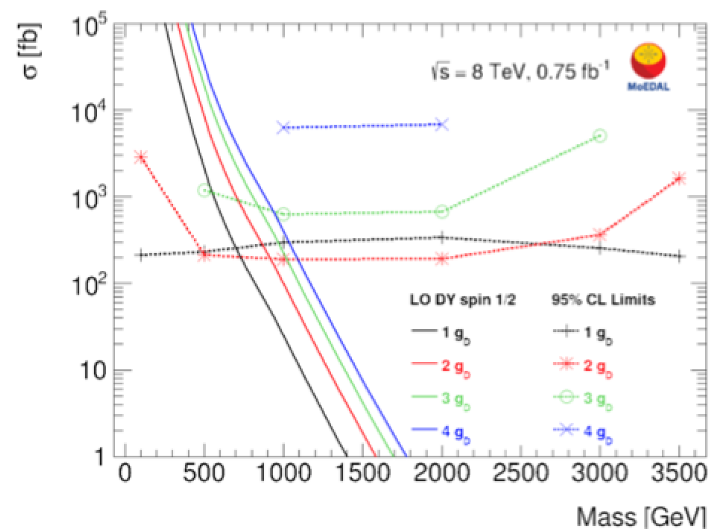
160 kg Magnetic Monopole Trapper prototype made of 198 aluminium rods of 2.5 cm diameter and 60 cm length (0.75 fb^{-1} @ 8 TeV)

No Monopoles found yet-> Limits!

arXiv:1604.06645

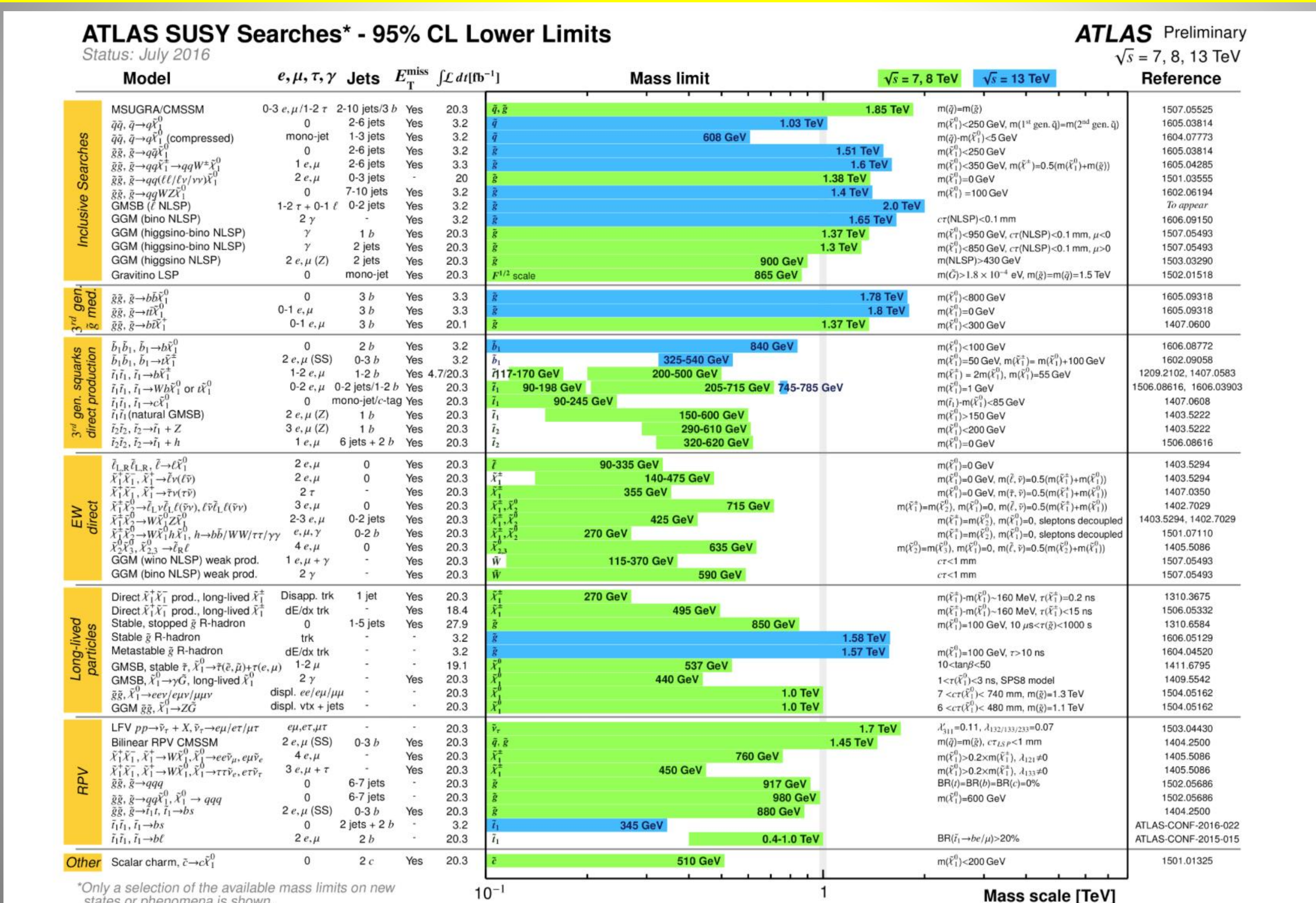






Summary of SUSY Searches

In short: no clear sign of SUSY with the data collected so far (similar for CMS)



End of Lecture II