Searches for New Physics at the Large Hadron Collider

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CERN, Geneva, Switzerland
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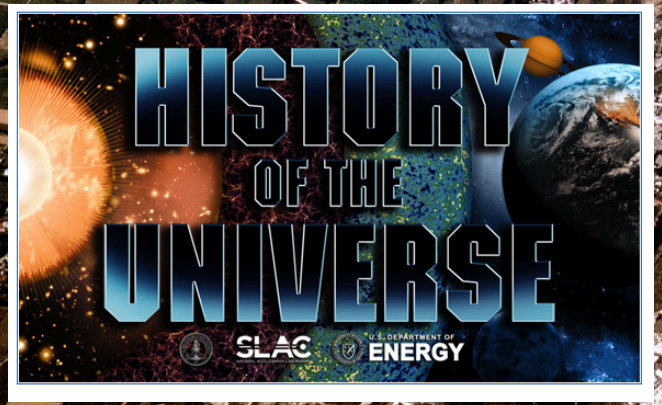
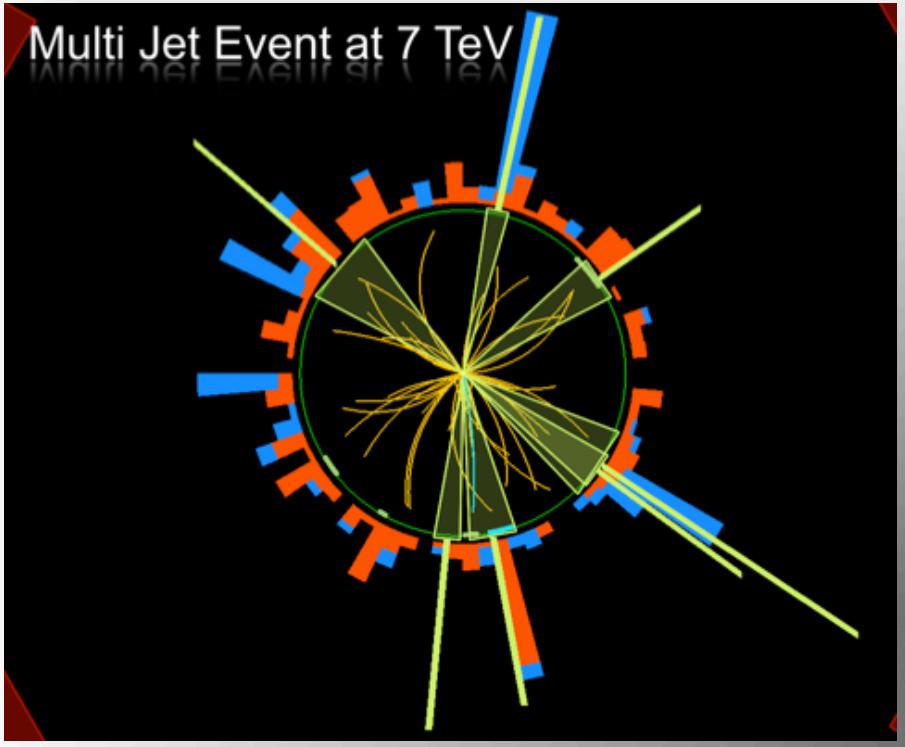
27 July 2011



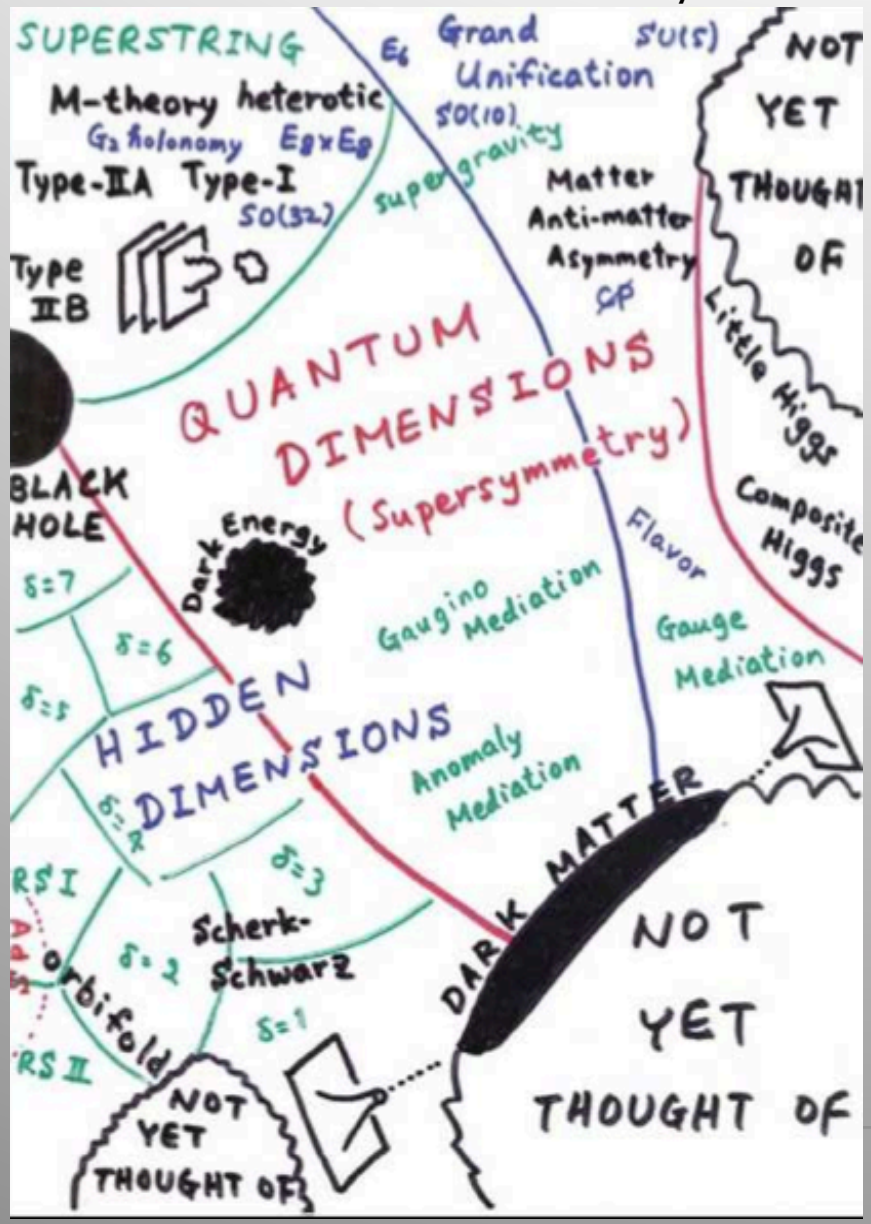


Outline

- Introduction
- Recent Search Results at 7 TeV from ATLAS and CMS
  - Supersymmetry
  - Exotica
- Summary

Physics Beyond the Standard Model

H. Murayama



No lack of ideas!!

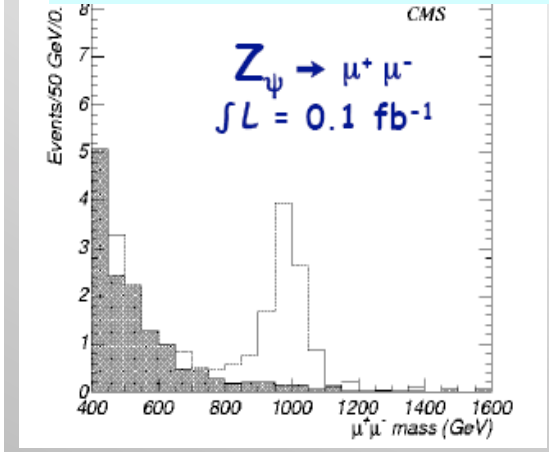
During the last ~10 years LHC experimentalists got more models to deal with than we needed…

Some of the latest: heavy stable charged particles, hidden valley models, Quirks, the dark sector…

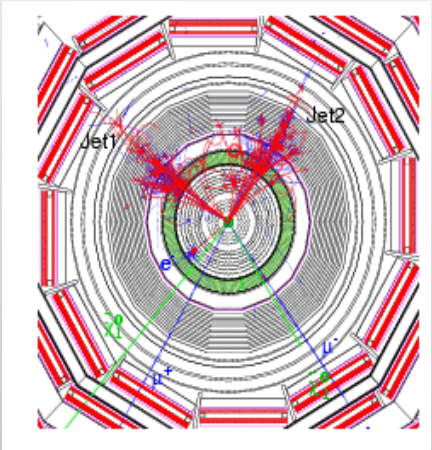
Many give particular signatures that we can search for CMS and ATLAS are designed for searches…

New Physics at High Energies?

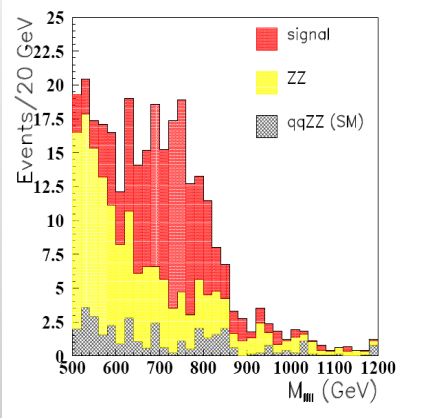
New Gauge Bosons?



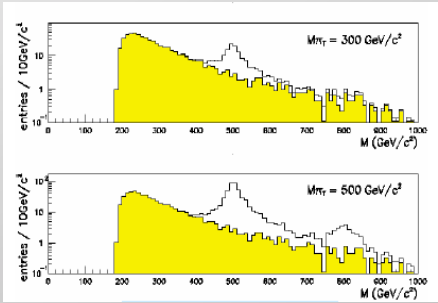
Supersymmetry



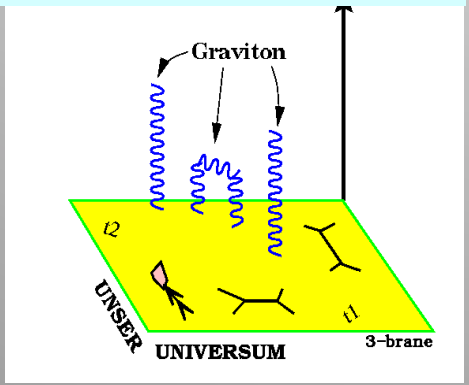
ZZ/WW resonances?



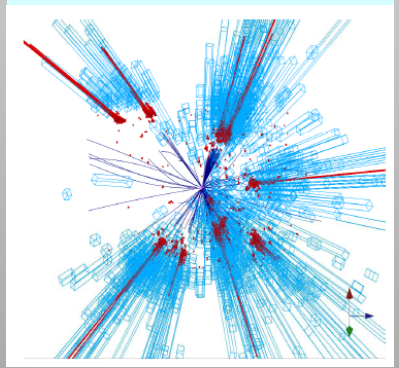
Technicolor?



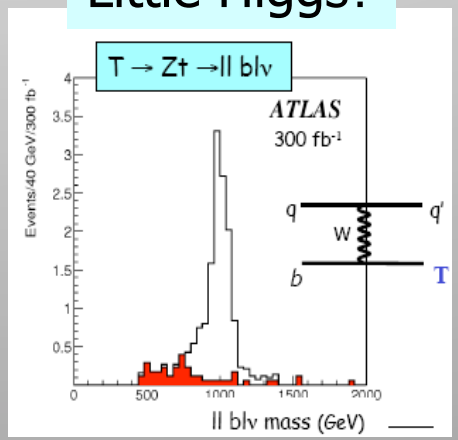
Extra Dimensions?



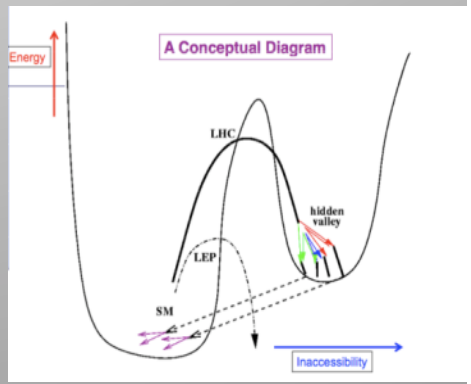
Black Holes???



Little Higgs?



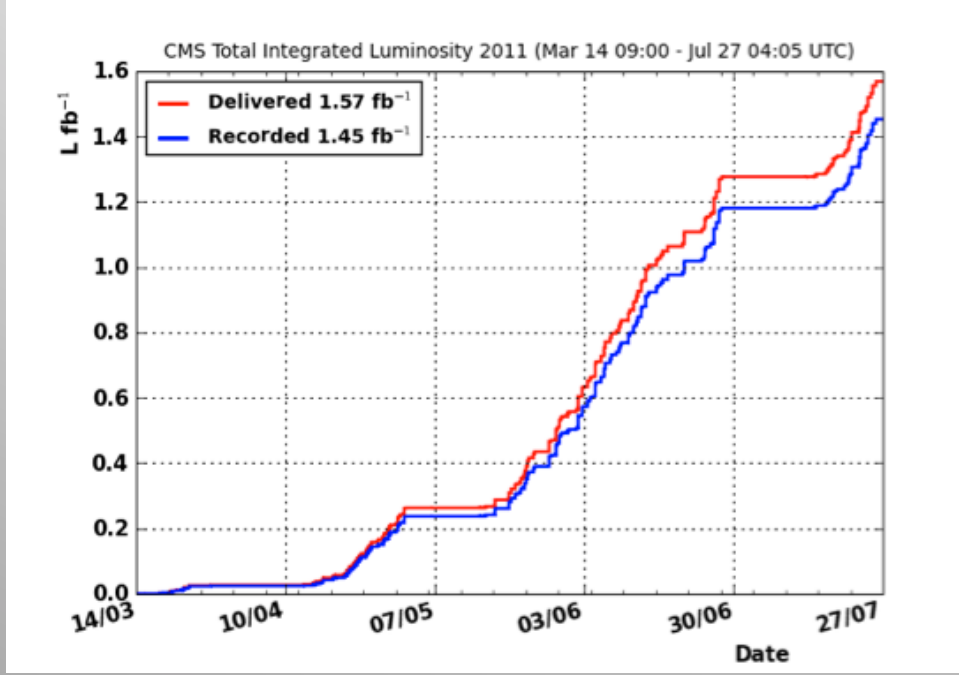
Hidden Valleys?



We do not know what is out there for us…
A large variety of possible signals. We have to be ready for that

Luminosity in 2011 & Operation

Total luminosity



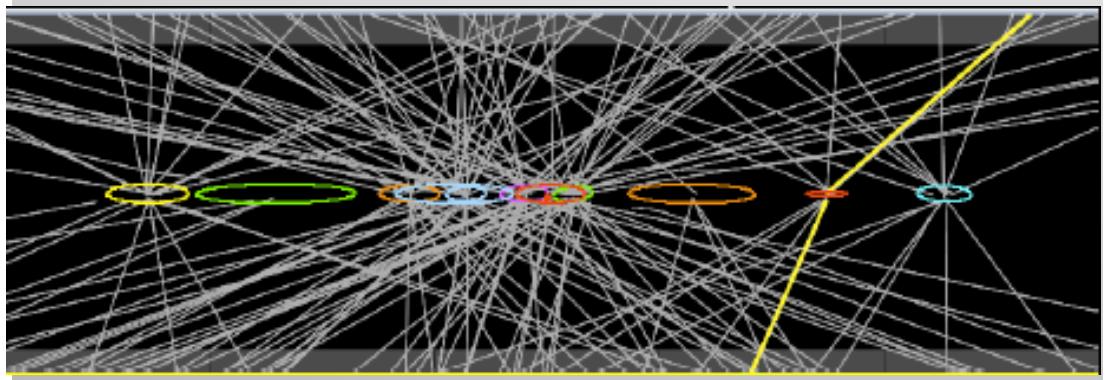
Fraction of ATLAS live channels

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	96.8%
SCT Silicon Strips	6.3 M	99.1%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.8%
Tile calorimeter	9800	97.5%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	97.7%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	98.1%

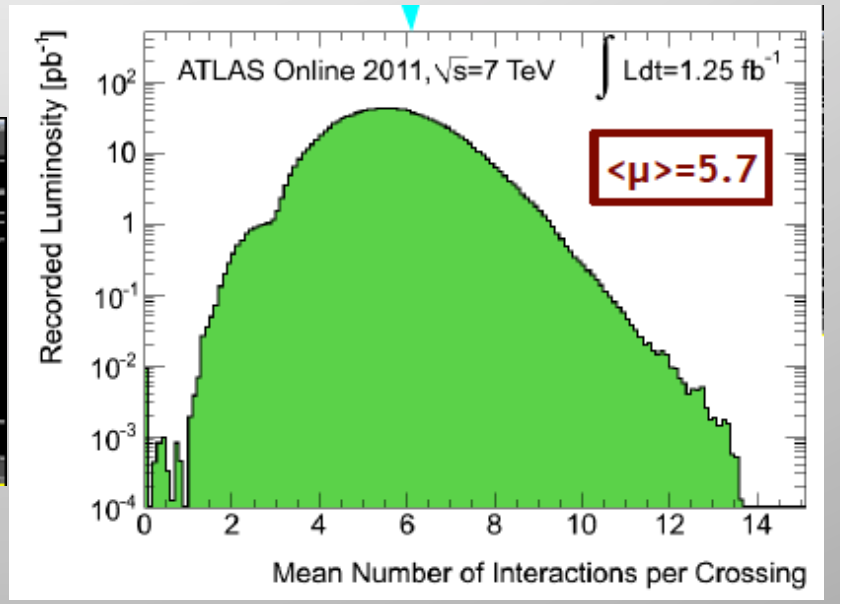
- CMS is up and running with high efficiency
- The LHC has produced already ~40 times more luminosity compared to 2010
- LHC running now with 1380 bunches and $>1.5 \cdot 10^{33} cm^{-2} s^{-1}$ luminosity

→ 1 fb^{-1} now, ~5 fb^{-1} by the end of the year

New Challenges at the LHC



Z→ μ μ event with 11 vertices



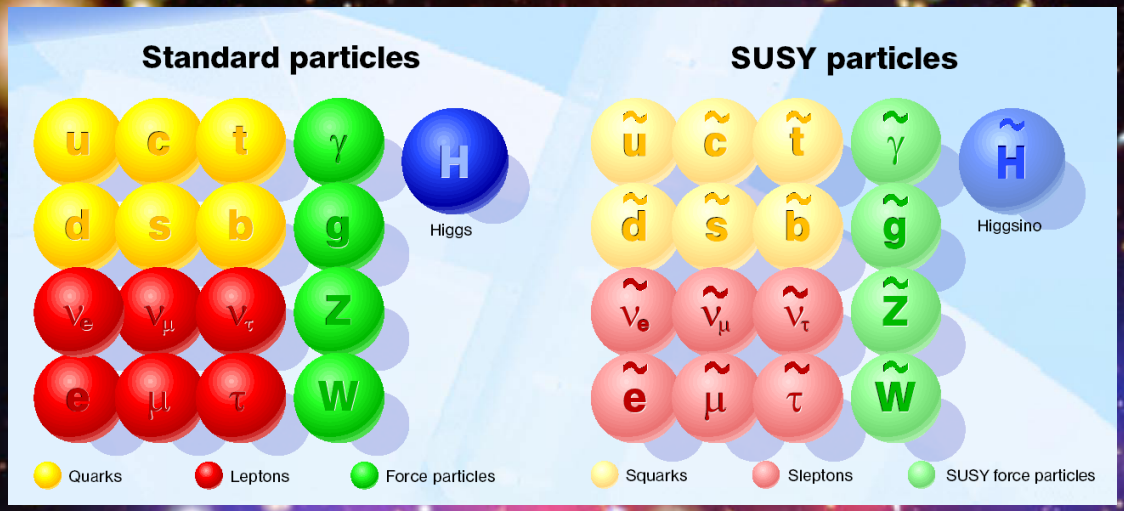
…many collisions in one bunch crossing!

On average now we have 5-8 events per bunch crossing

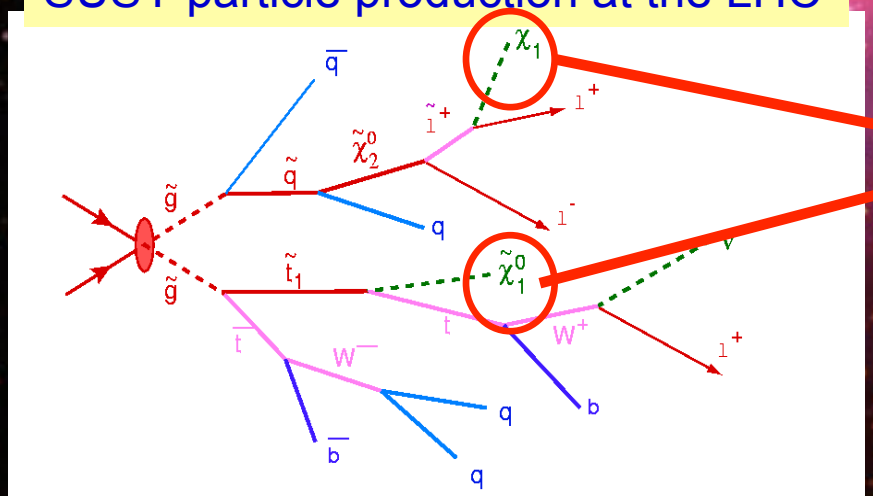
Expect this to increase to ~ 15-30 events during the year

Pile-up!!!

Supersymmetry: a new symmetry of Nature?



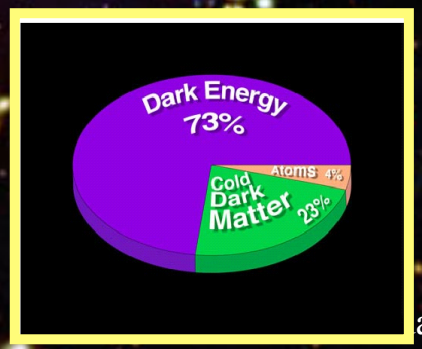
SUSY particle production at the LHC



Assume "R-Parity" Conservation

+ 2 b-jets
+ 4 jets

Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab



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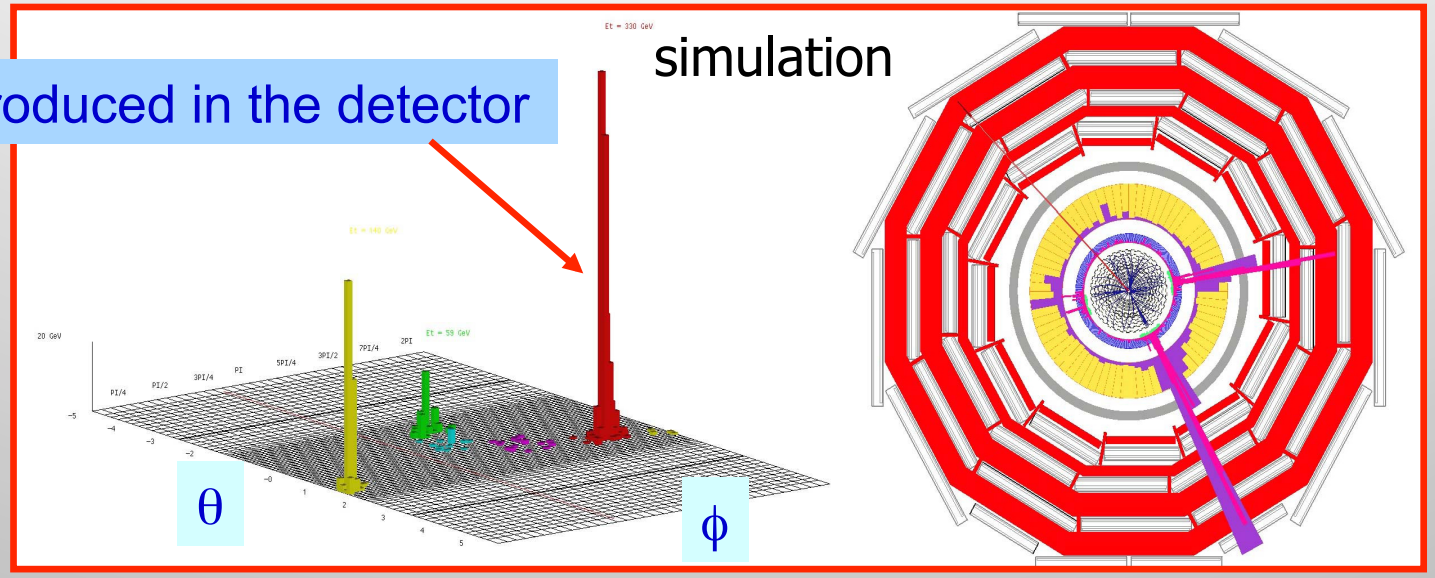
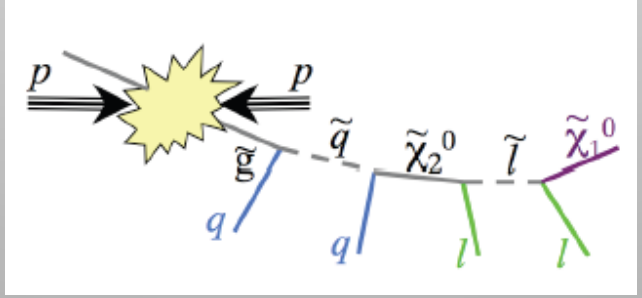
Detecting Supersymmetric Particles





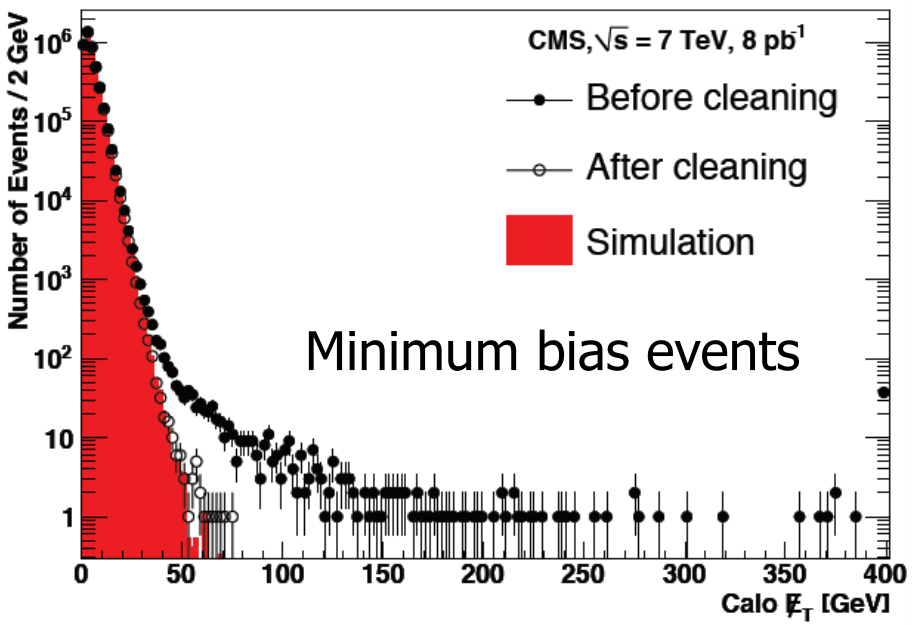
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

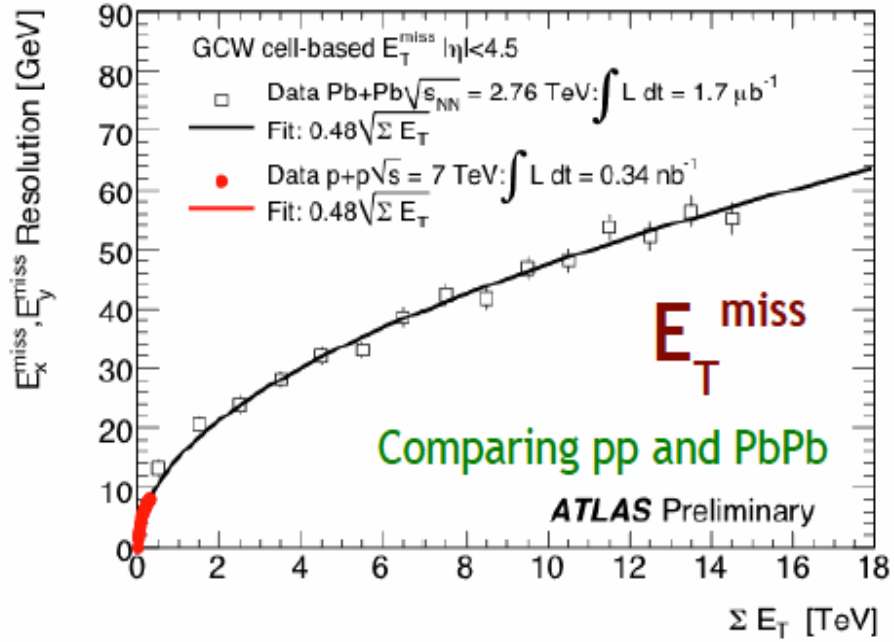
→ Very clear signatures in CMS and ATLAS

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
- Good resolution using 'particle flow' ie maximally identifying particles
- More Pile-up will NOT make this simpler

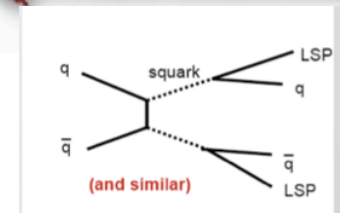
SUSY Searches

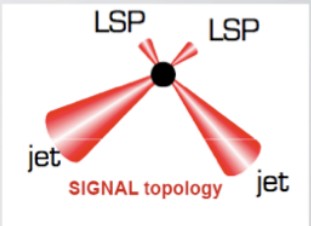
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

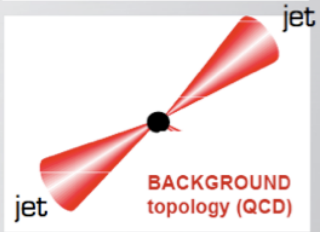
Large SM backgrounds Low

sensitivity to strongly produced SUSY

sensitivity to gauge-mediated SUSY



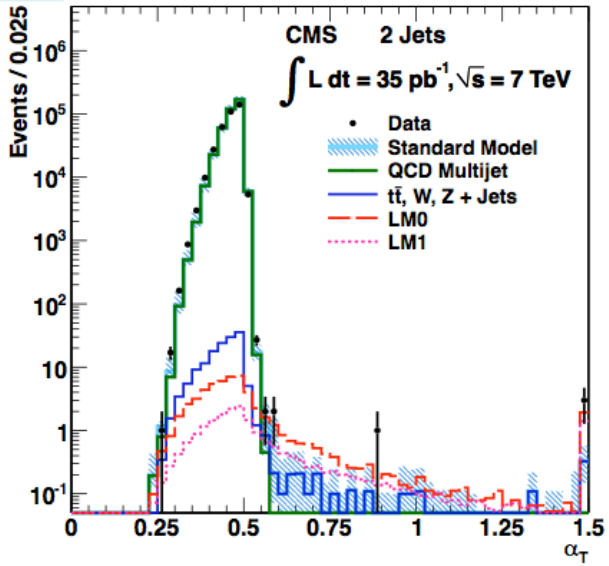




Example: Jets plus MET channel

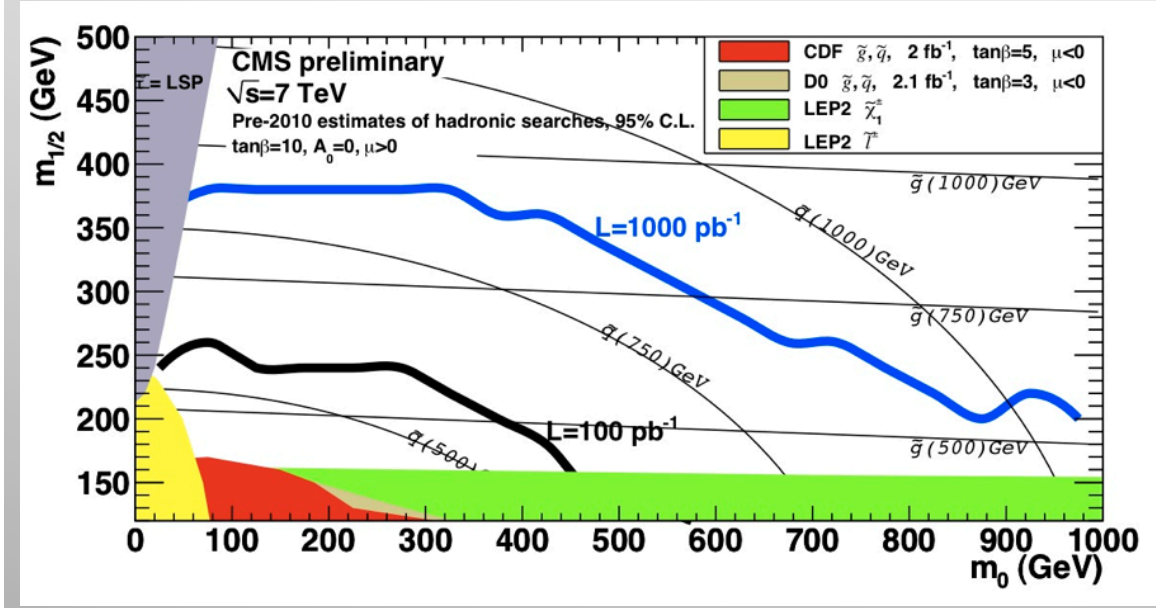
$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

- Control jet SM background with the α_T variable
- No jet SM background expected for $\alpha_T > 0.5$



SUSY Searches @ LHC

Prospects 2009



So far Constrained Minimal Supersymmetric Standard Model CMSSM is often used as a benchmark model for presenting the search results…

The CMSSM has 4 parameters

-$m_{1/2}$: universal gaugino mass at GUT scale

- m_0: universal scalar mass at GUT scale

-tanβ: vev ratio for 2 Higgs doublets

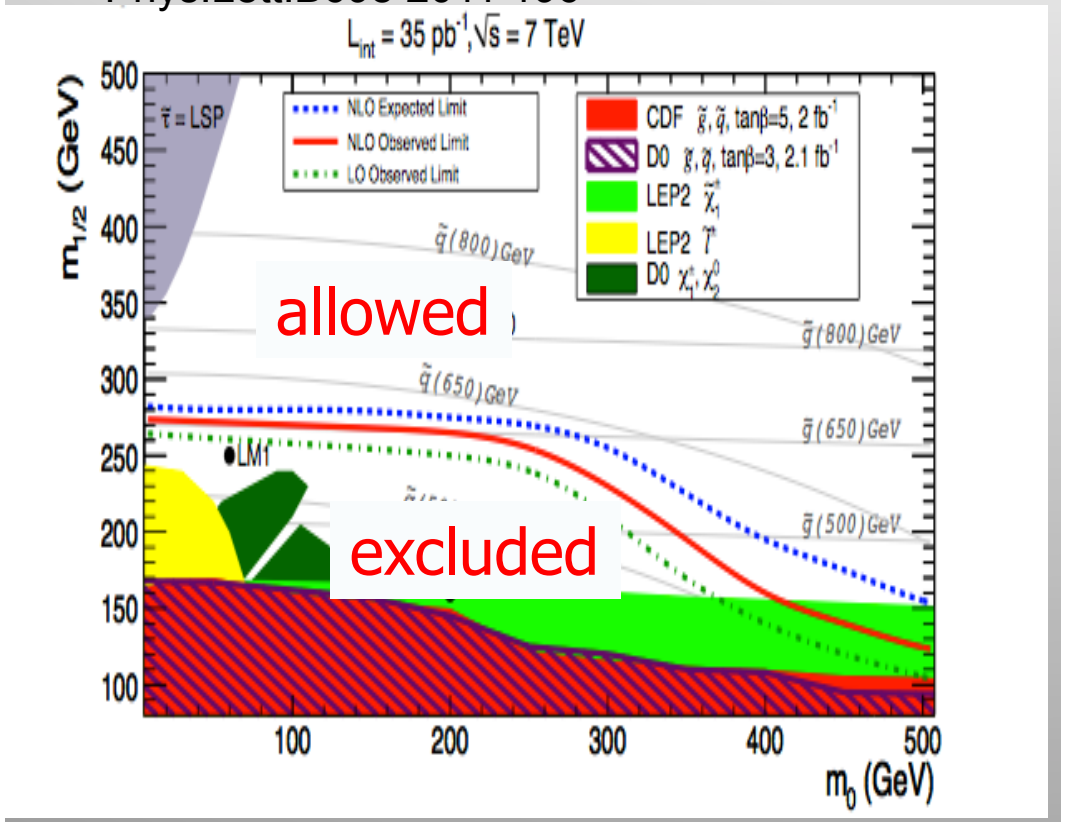
-A_0: trilinear coupling and the sign of Higgs mixing parameter μ

- If low energy Supersymmetry exists, LHC will almost certainly observe it
- Masses up to 800-900 GeV already detectable with 1 fb^{-1}
- Squarks and Gluinos detectable up to 2.5-3 TeV mass with a ~100 fb^{-1}

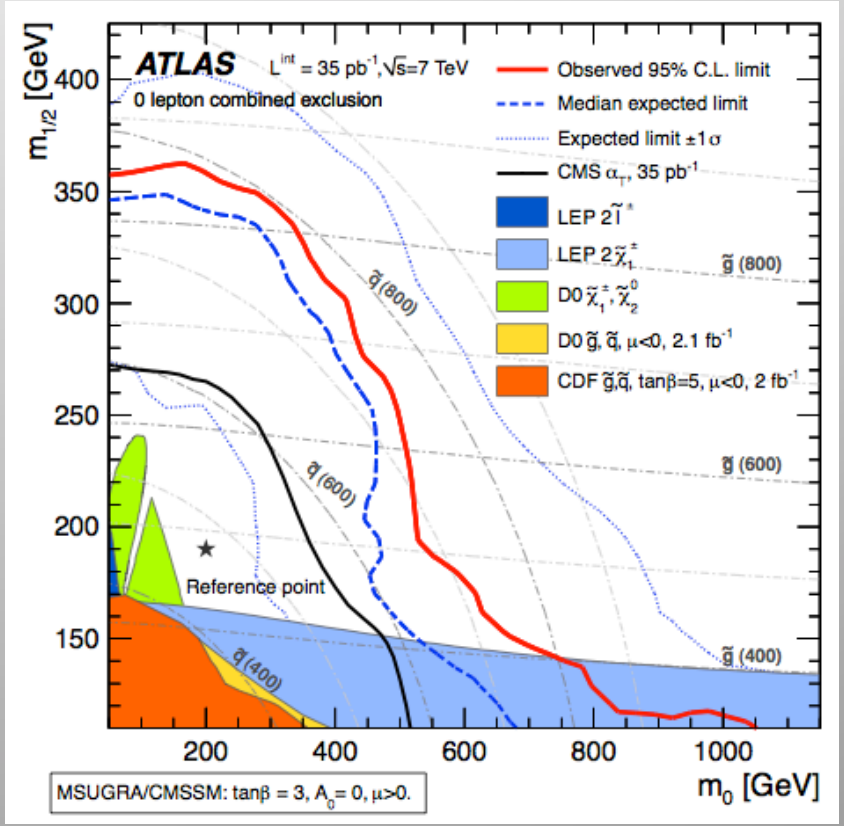
First SUSY Search Results

No discovery of supersymmetry… Stronger exclusion limits

Phys.Lett.B698 2011 196



arXiv:1102.5290

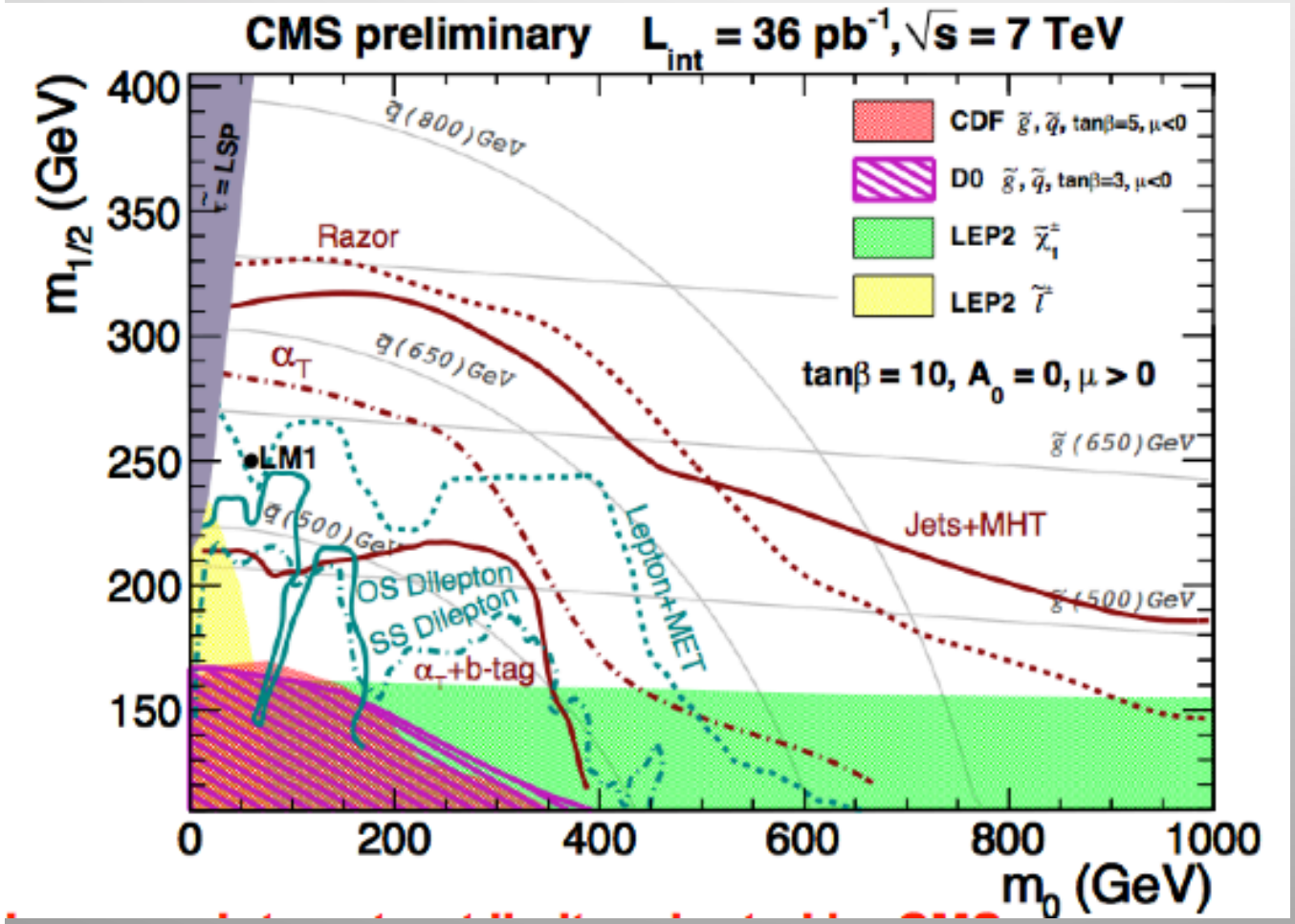


Masses of squarks/gluinos > ~600-700 GeV!!! (in the CMSSM)

m_0 amd $m_{1/2}$ are universal scalar and gaugino masses at the GUT scale

Summary Search Channels

CMS summary of channels

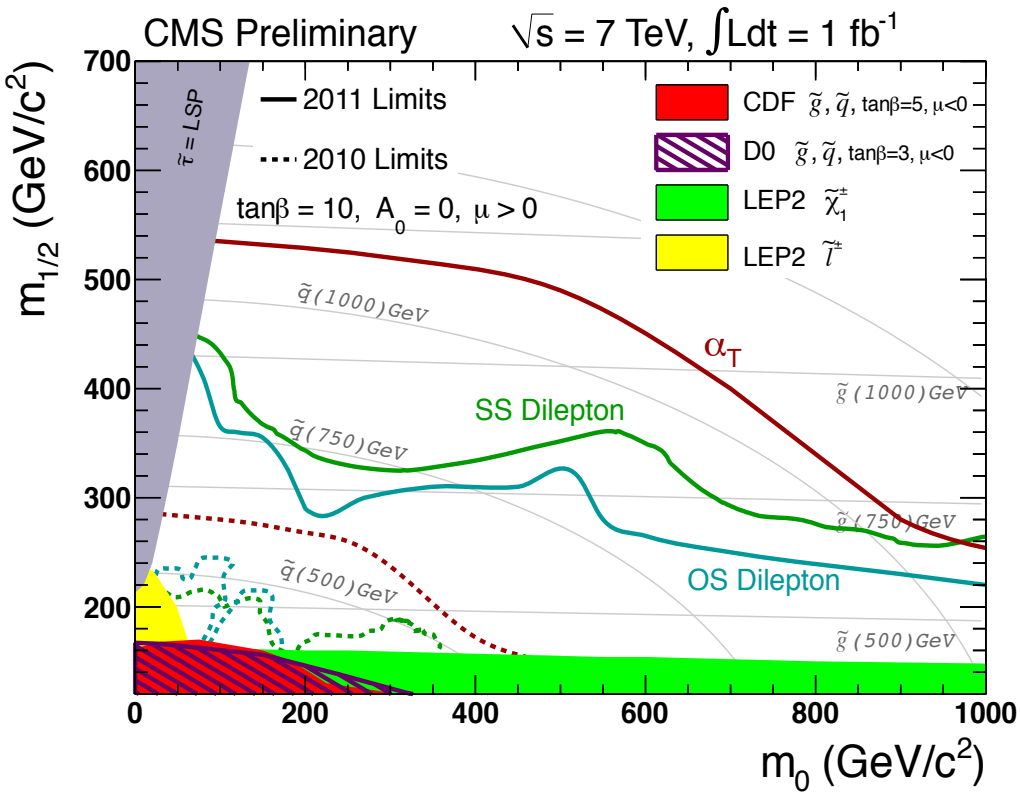


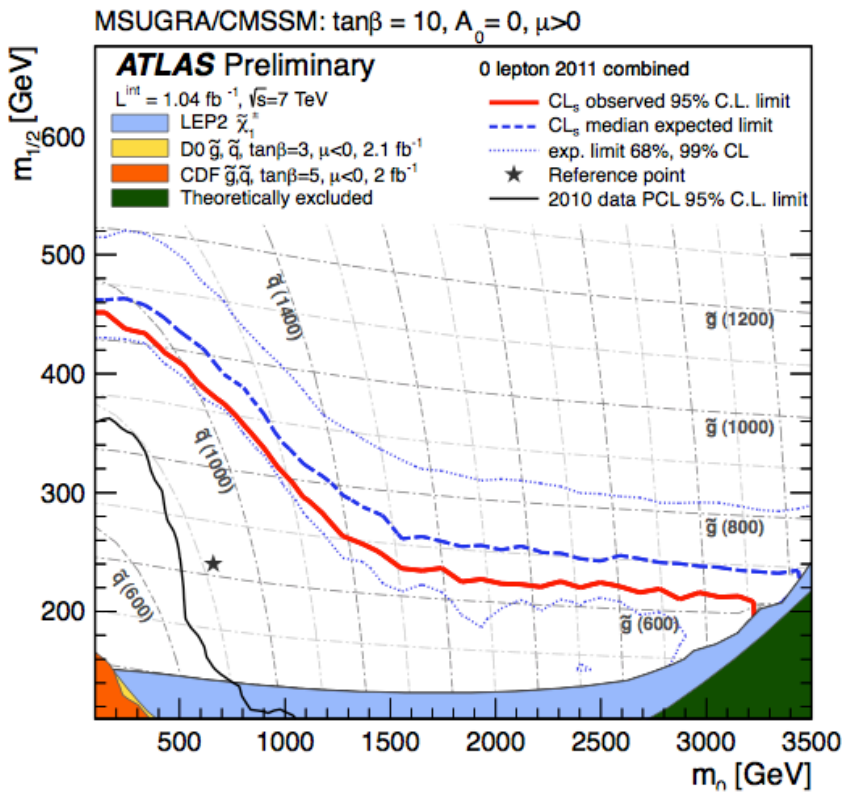
Channels with

- Jets only
- Single leptons
- Di-leptons
- Photons
- b-quarks

Squarks/gluinos are excluded for masses below 600-800 GeV in constrained models

1 fb^{-1} Search: Hadronic Channel

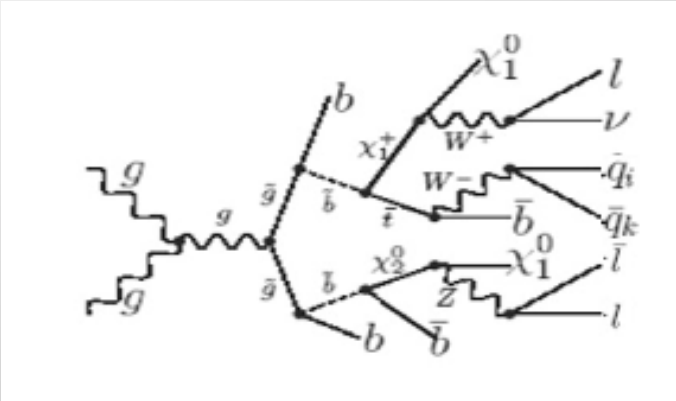


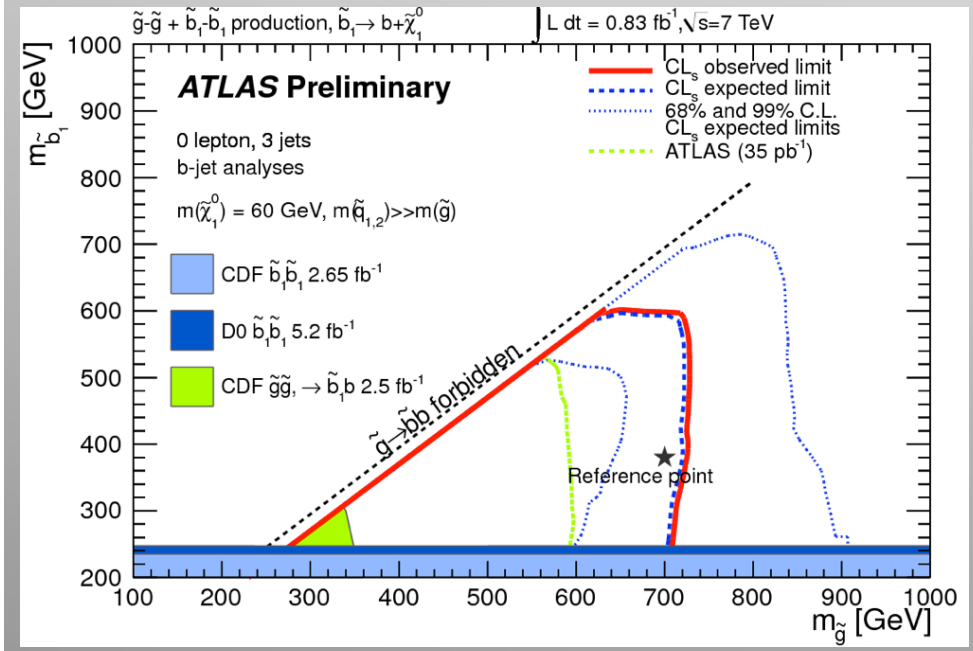


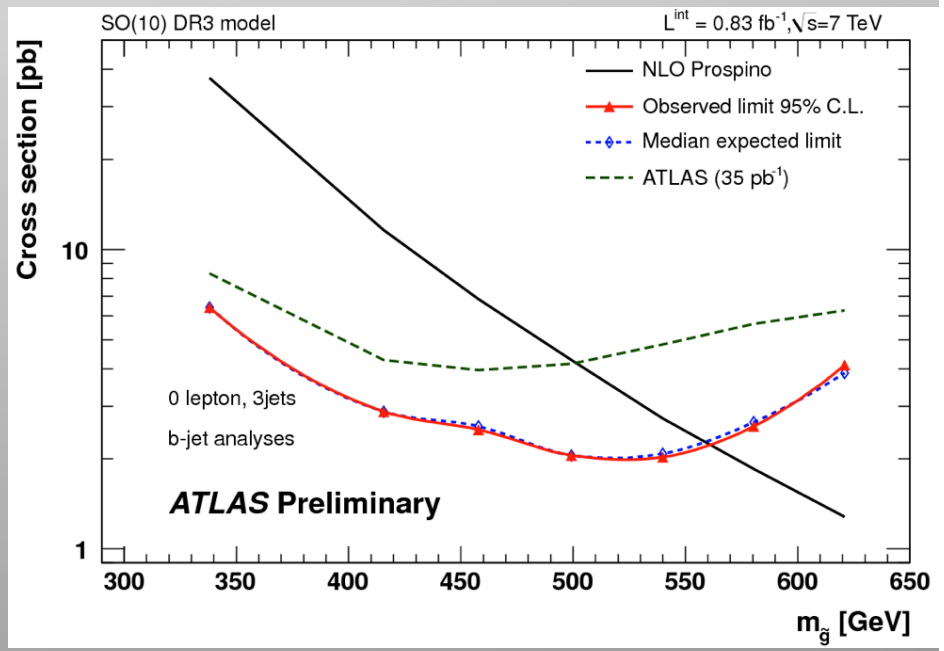
Within the Constrained MSSM model we are crossing the border of excluding gluinos up to 1TeV and squarks up to 1.25TeV

Searches in Different Channels

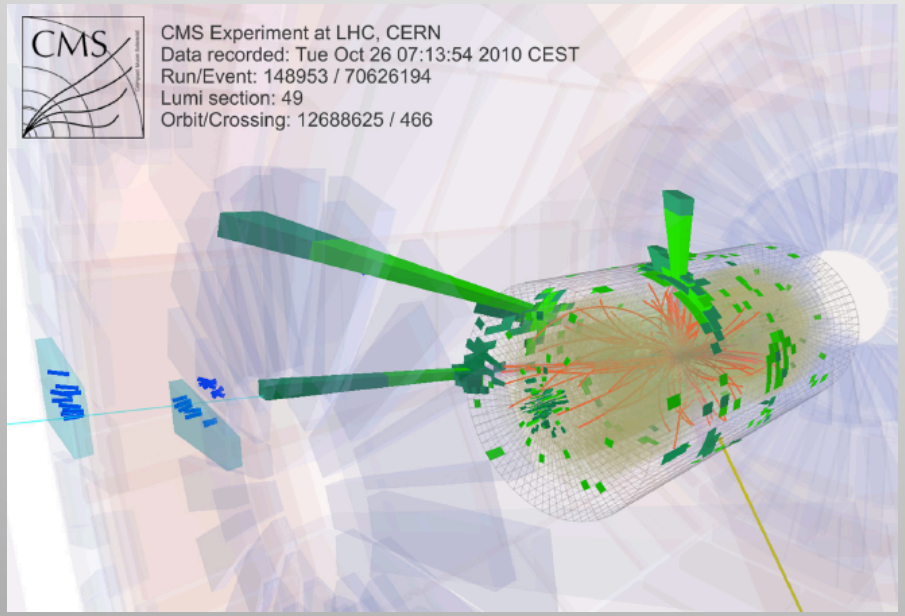
- Extend the searches using also to leptons and jets coming from b-quarks
- Sensitive to different part of the SUSY phase space

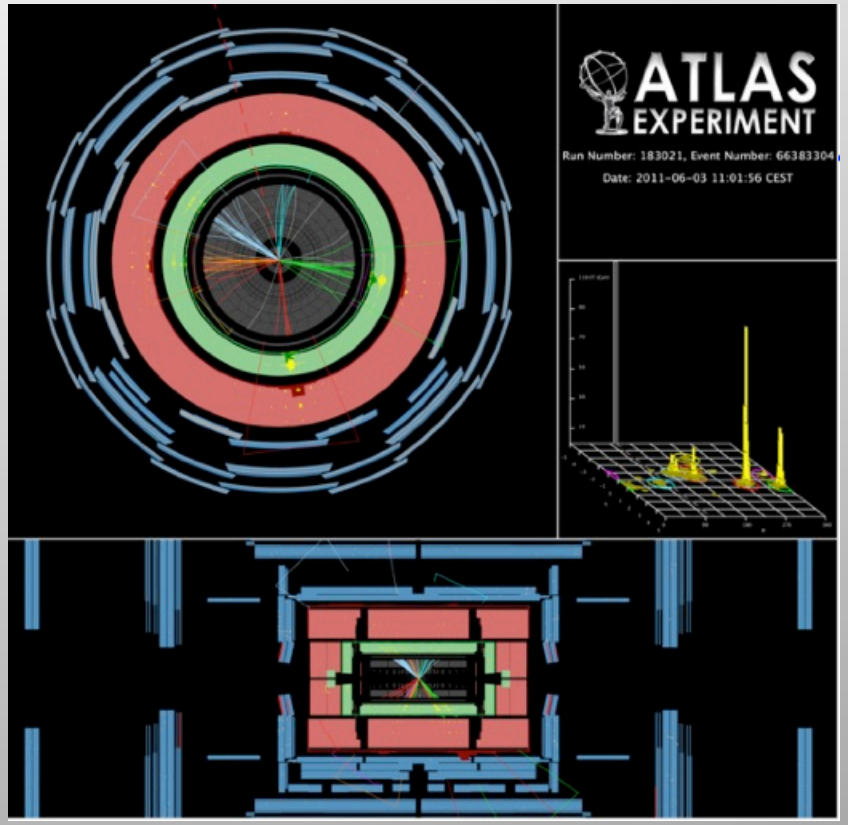






…Some Interesting Events…





- Events with five jets and large missing transverse energy
- CMS: Total sum of transverse momentum H_T= 1132 GeV and missing transverse energy H_{TMiss} = 693 GeV

Where do we expect SUSY?

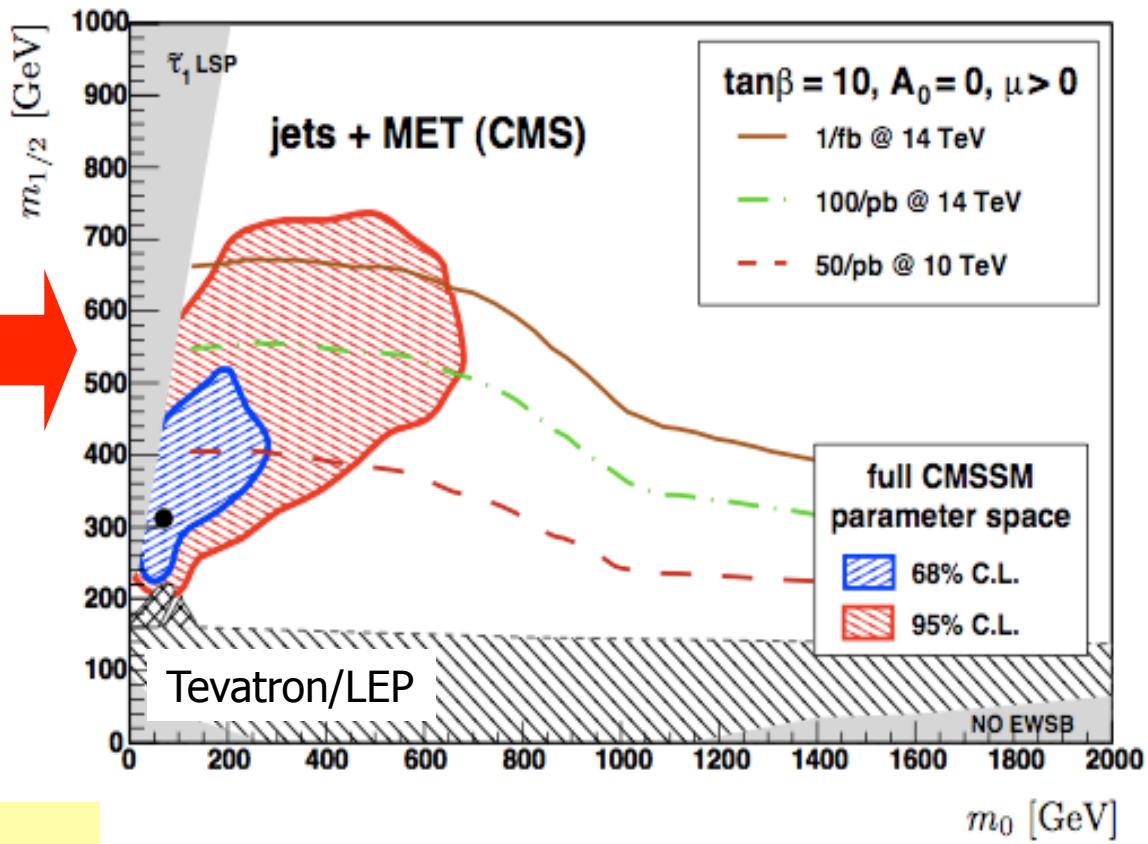
O. Buchmuller et al
arXiv:0808.4128

OB, R.Cavanaugh, A.De Roeck,
J.R.Ellis, H.~Flaecher, S.~Heinemeyer
G.Isidor, K.A.Olive, P.Paradisi,
F.J.Ronga, G.Weiglein

Precision measurements
Heavy flavour observables

Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, $\tan\beta$ (μ>0) to more than 30 collider and cosmology data (e.g. M_W, M_{top}, g-2, BR(B→Xγ), relic density)

"LHC Weather Forecast"



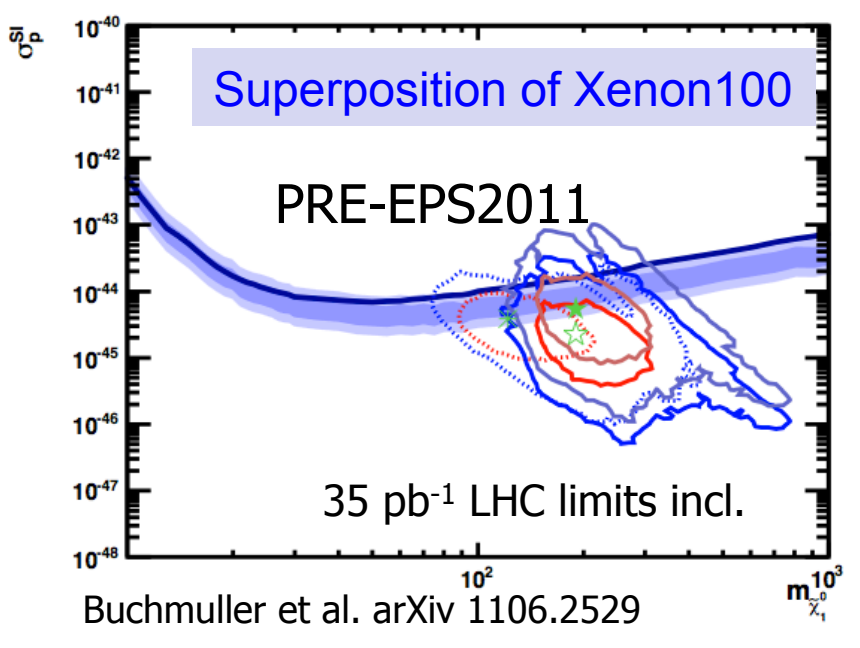
"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

"Predict" on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)

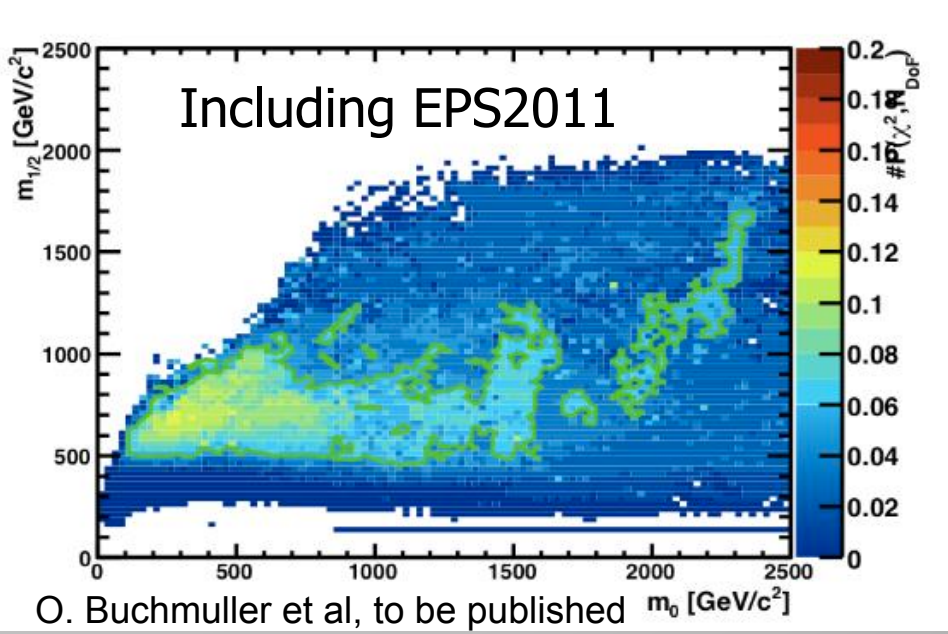
Many other groups attempt to make similar predictions

Impact of LHC Data on Constrained SUSY

Preferred region for (CMSSM) SUSY, Including the results from ATLAS and CMS



Buchmuller et al. arXiv 1106.2529



O. Buchmuller et al, to be published

Pre-LHC: dots, ×, post-LHC, solid ★
Original :dotted lines +CMS+ATLAS: Solid lines

Fits including heavy flavor measurements, G-2,relic density,M_W, M_{top}...

χ^2 probability: P(χ^2) for CMSSM
Before EPS: 16% Including LHC@EPS: 11%

CMS searches significantly constrain allowed SUSY parameter space.
The air is getting very thin for constrained SUSY models but it needs more data to be fully conclusive.

What is Next?

- Think beyond the simplest/ most constrianed models
  - pMSSM
  - NMSSM
  - Degenerate mass spectra
  - Light 3rd generation
  - Split SUSY
  - RPV SUSY
  - …
- May have to revise our searches for other models
- DAMA/COGENT signals? How compatible are these with our present searches?
- LPCC Workshop @ CERN August 28-September 2

Nature Feb 2011

Beautiful theory collides with smashing particle data

Latest results from the LHC are casting doubt on the theory of supersymmetry.

Geoff Brumfiel

"Wonderful, beautiful and unique" is how Gordon Kane describes supersymmetry theory. Kane, a theoretical physicist at the University of Michigan in Ann Arbor, has spent about 30 years working on supersymmetry, a theory that he and many others believe solves a host of problems with our understanding of the subatomic world.

"Any squarks in here?" The ATLAS detector (above) at the Large Hadron Collider has failed to find predicted 'super partners' of fundamental particles.

C. MARCELLONI/CERN

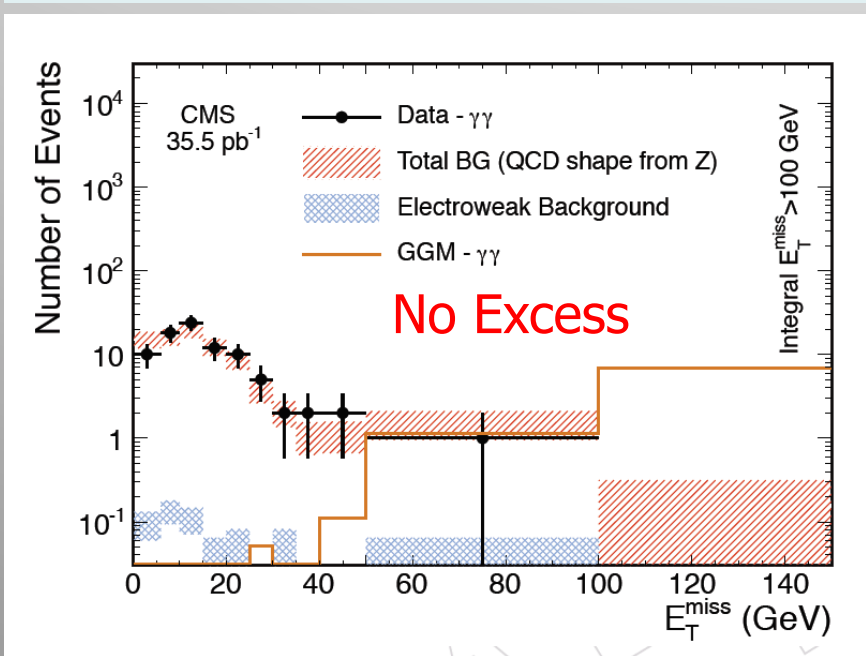
GMSB SUSY Searches

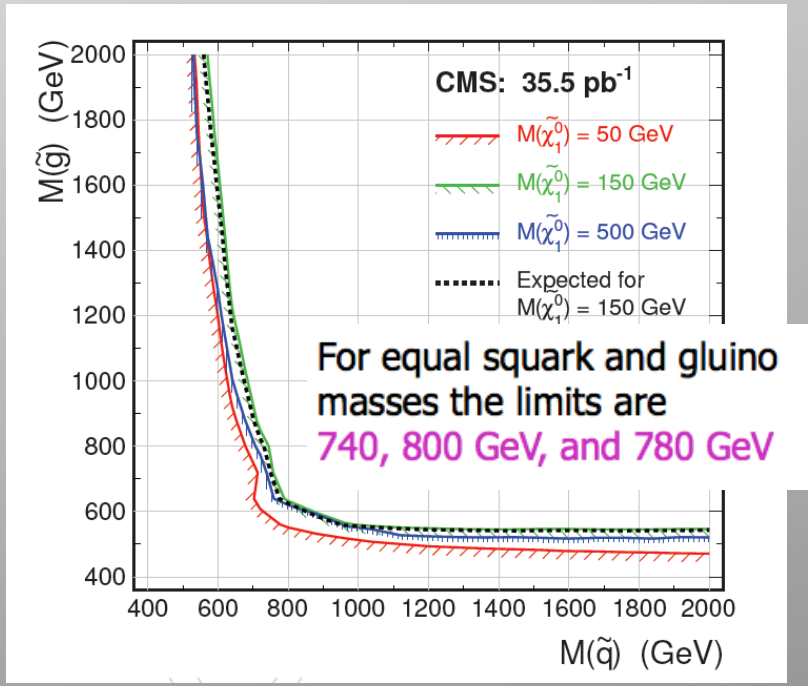
Gauge Mediated SUSY breaking: LSP is the Gravitino

- Phenomenology depends on NLSP
  - if neutralino, decays into gravitino and γ, Z^0, or h^0 (depending on neutralino mixing)

PRL.106 211802,2011

Here analyse collisions with:
two hard photons (30 GeV) , missing transverse momentum and jets



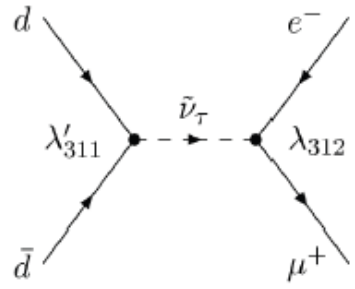


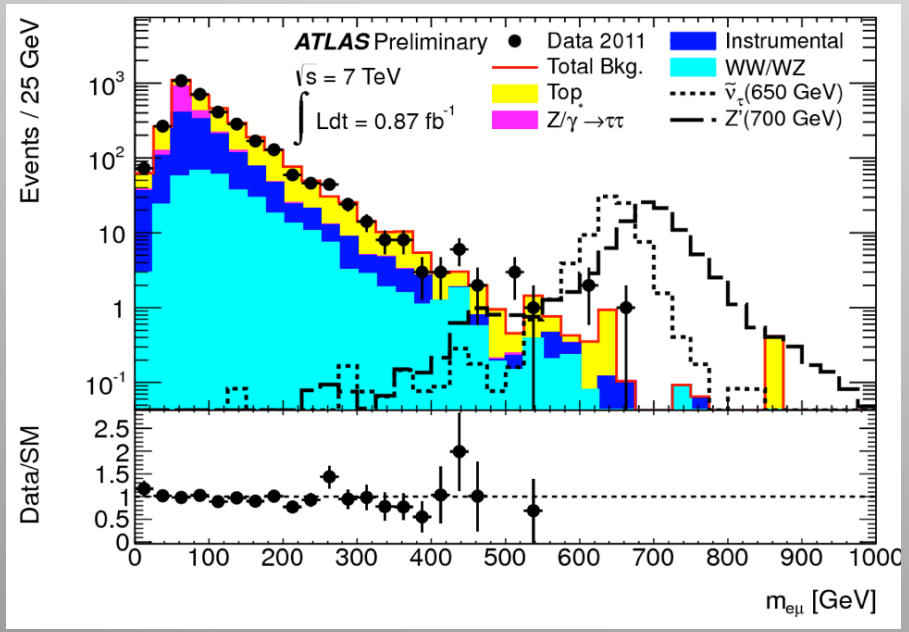
These results can be reinterpreted in Universal Extra Dimensions

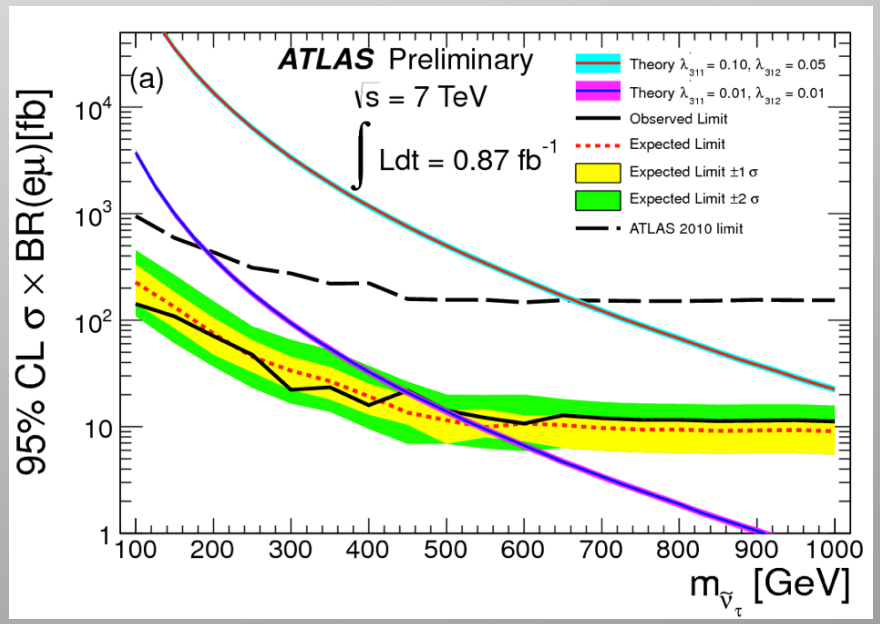
RP Violating SUSY Searches

eμ resonance

- With λ' RPV coupling, resonant sneutrino (or Z') can decay into an electron-muon pair
- Use single lepton triggers and select signal candidates with exactly one high pT electron and muon
- Using 0.87 fb^{-1} of 2011 dataset to update analysis published in PRL analyzing 2010 data

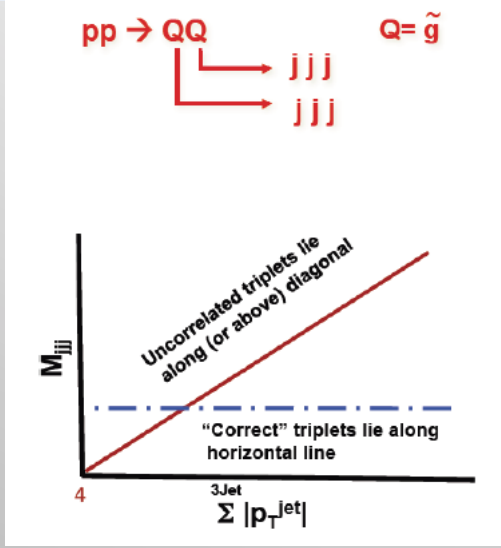






Limits on sneutrino mass between 0.5 and 1 TeV depending on the theory

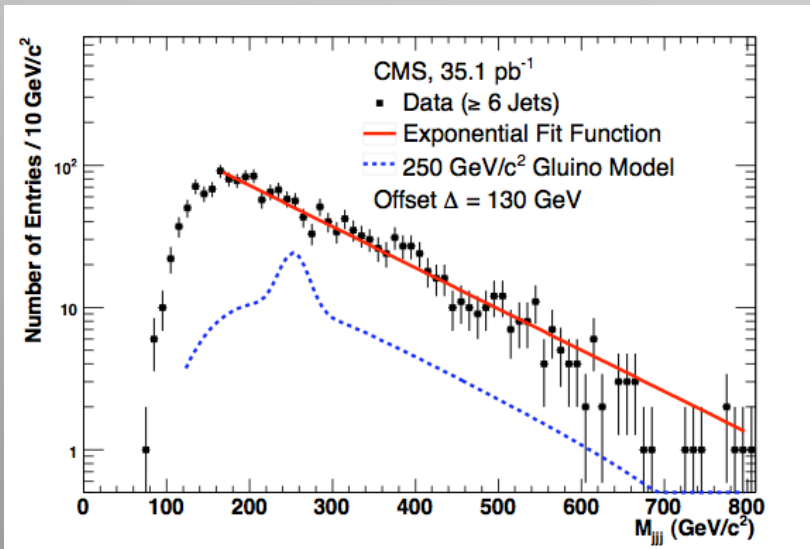
RP Violating SUSY Searches

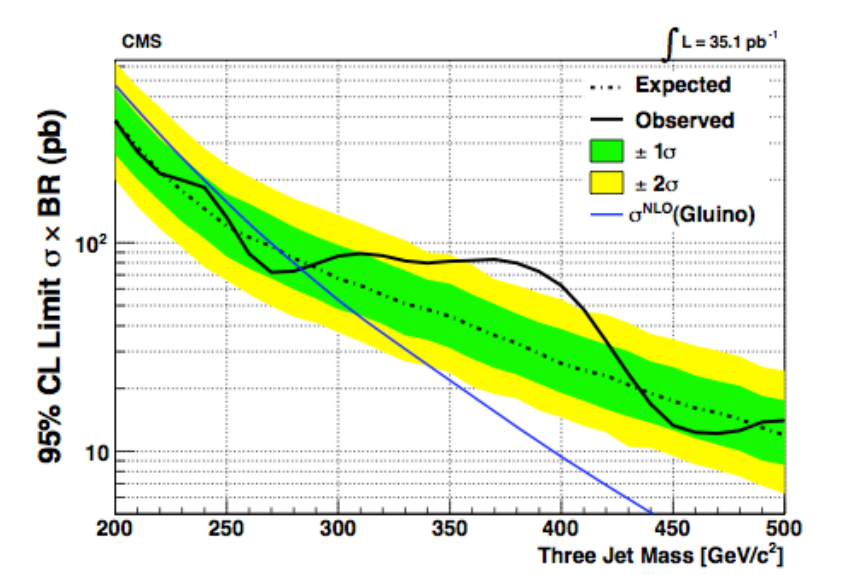


Sparticle decays into 3 jets

- Use a diagonal cut to remove combinatorial background as well as QCD background:
  - $m_{jjj} < \Sigma\ |p_T(\text{triplet})| - \alpha\ (\text{Offset})$

arXiv:1107.3084





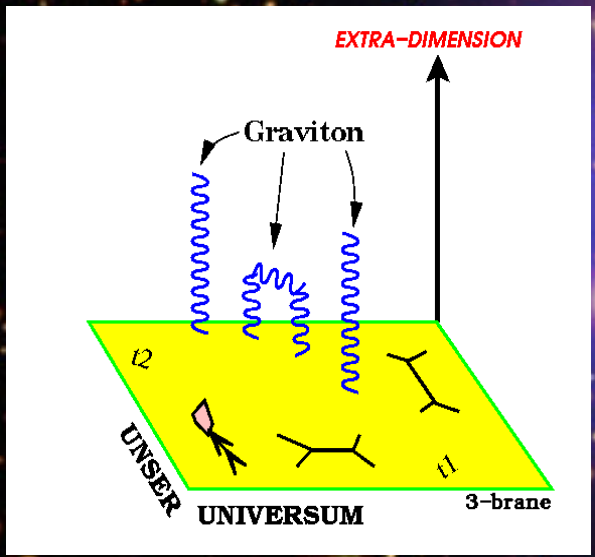
No signal for gluino masses up to 280 GeV
High mass excursion is less than 2 σ taking into account look elsewhere effect

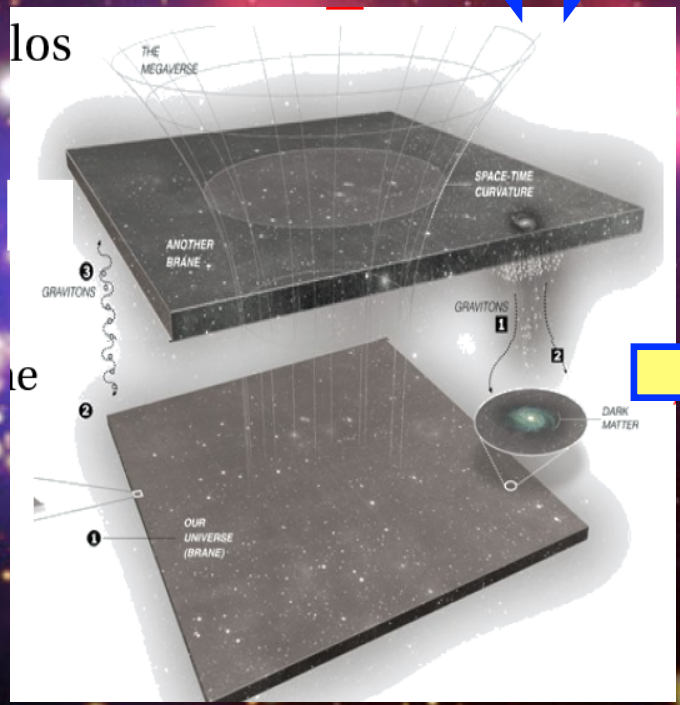
Extra Space Dimensions

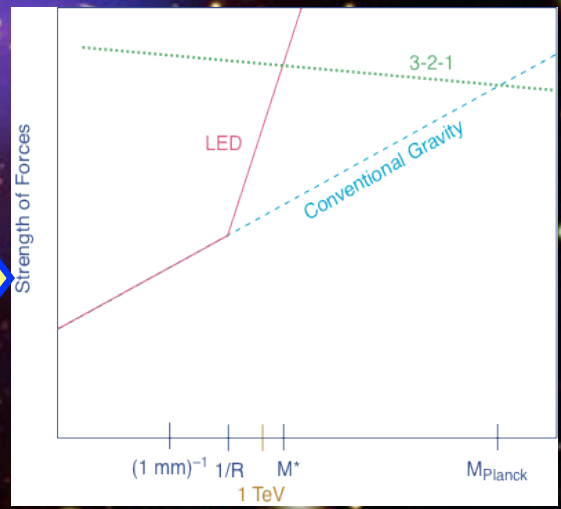
Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\,\text{GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\,\text{GeV}$$







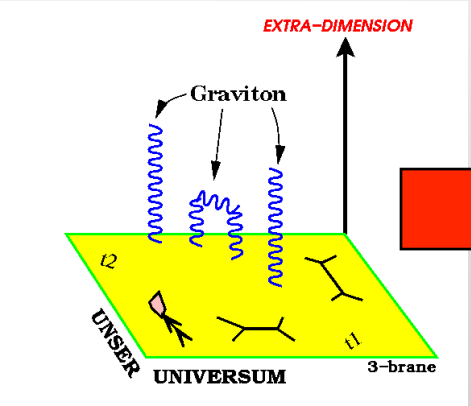
Gravity becomes strong!

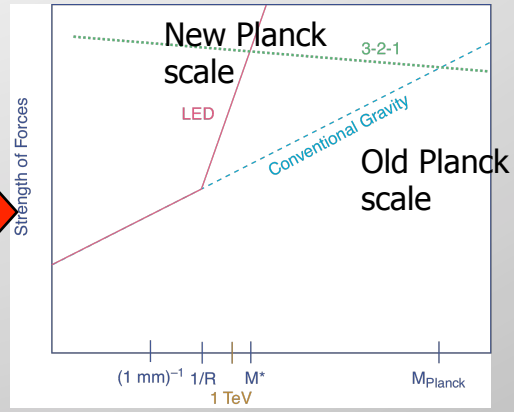
Search for Extra Dimensions

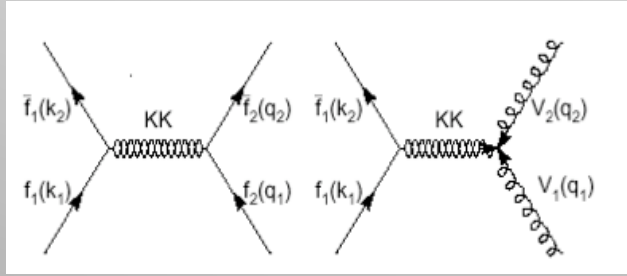
Are there extra space dimensions that open at higher energies?

Example: Experimental signature affects the di-fermion production

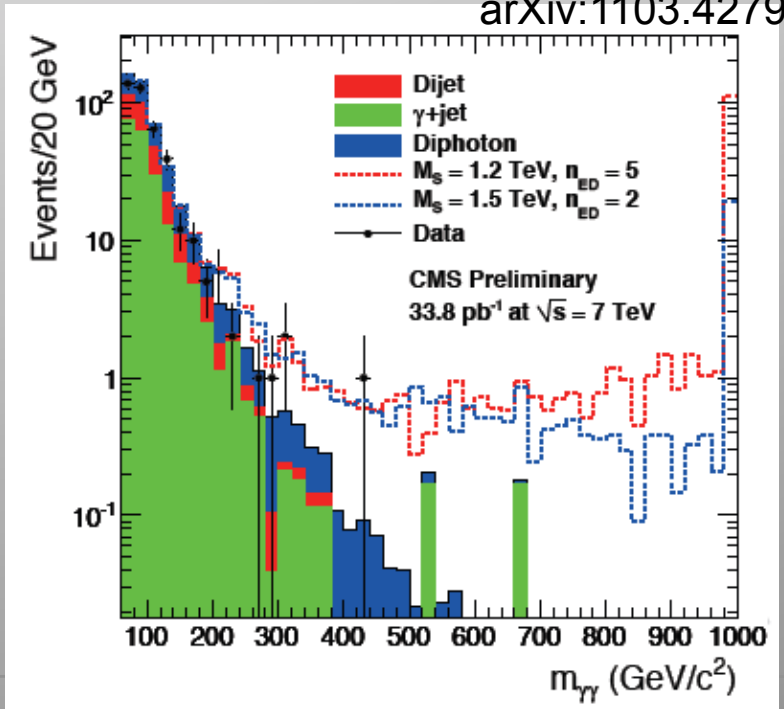
Study here: di-photon production







arXiv:1103.4279



Results (TeV)

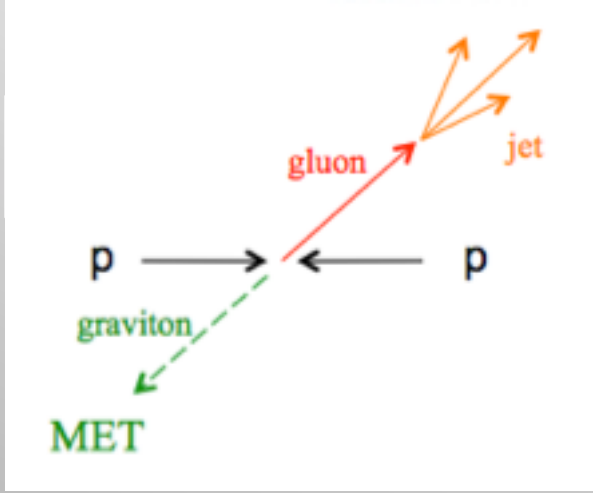
$n_{ED} = 2$	$n_{ED} = 3$	$n_{ED} = 4$	$n_{ED} = 5$	$n_{ED} = 6$	$n_{ED} = 7$
1.88	2.29	1.93	1.74	1.62	1.53

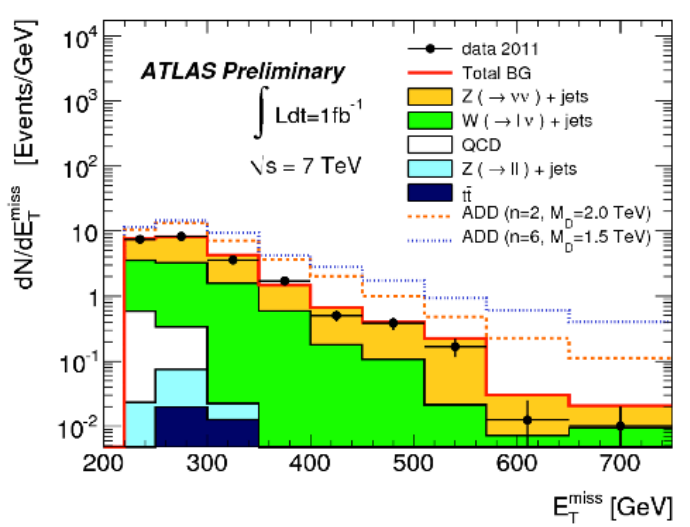
New mass scale larger than 1.5-2.3 TeV depending on the number of extra dimensions (similar in the μμ channel)

Tighter limits than from the Tevatron

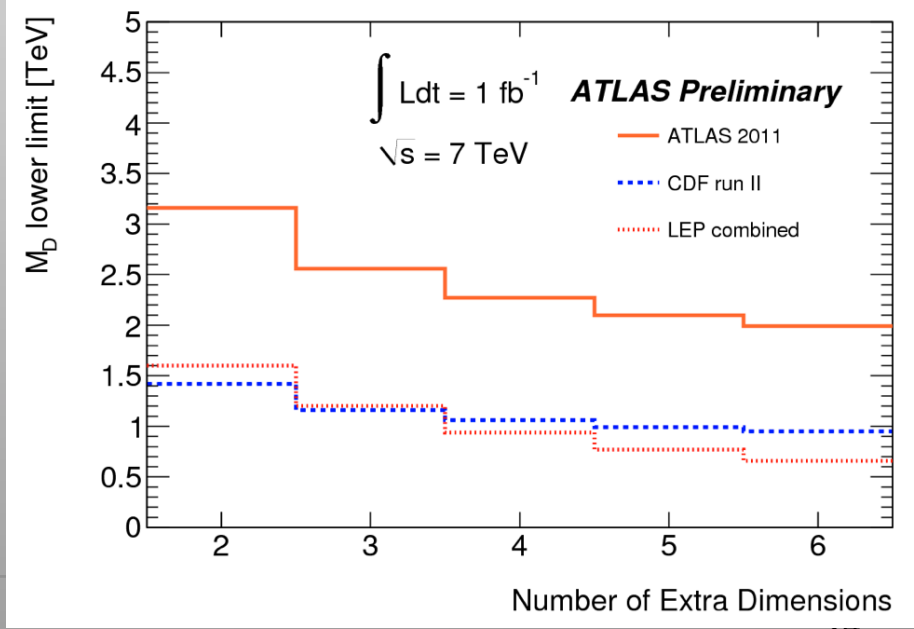
Searches for Extra Dimensions

Mono-jet final states (+MET)





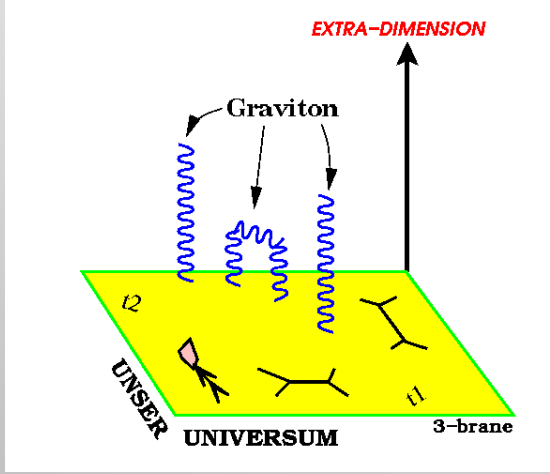
Lower Limit on the Planck Scale versus number of extra dimensions



Limits between 2 and 3 TeV

Best limits on extra dimensions from the LHC

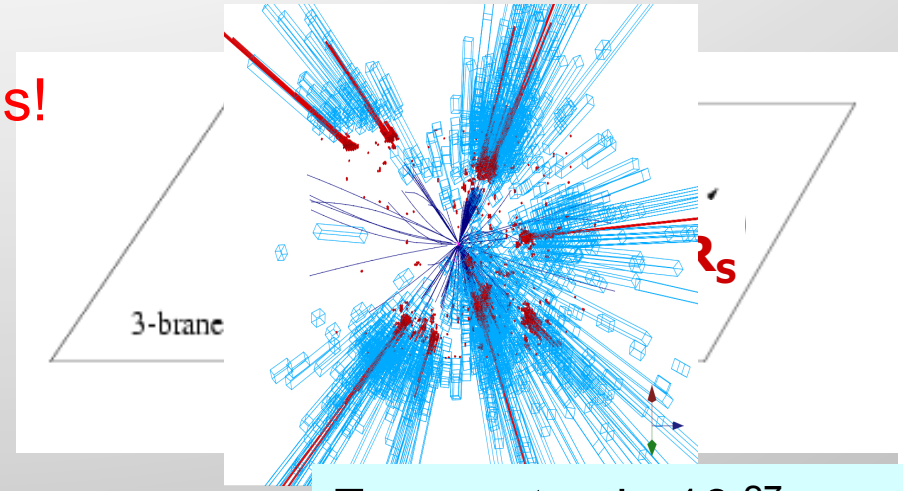
Search for Micro Black Holes



CMS-EXO-11-071

Extra Dimensions!

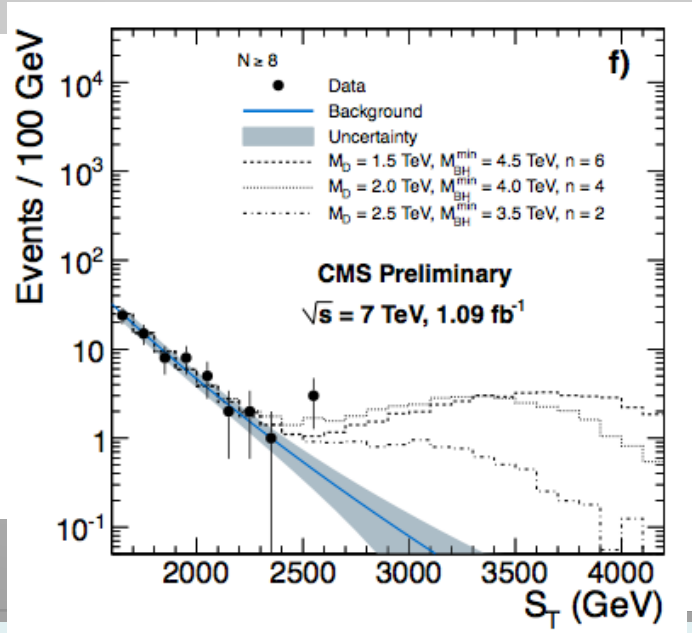
Planck scale
a few TeV?

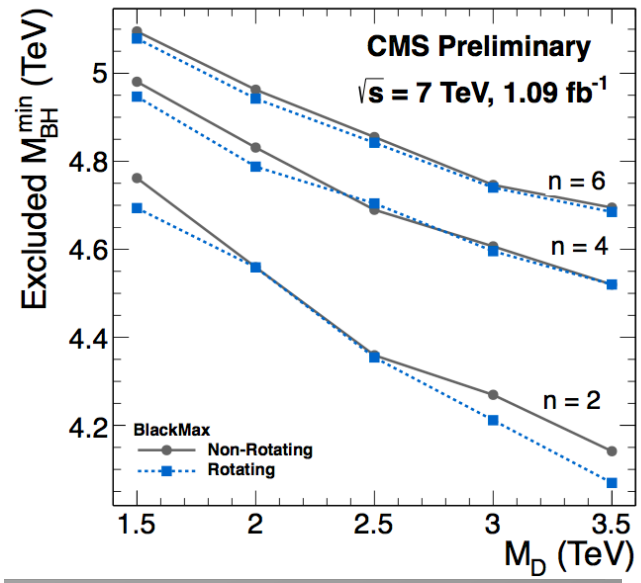


Evaporates in 10^{-27} sec

Look for the decay producs
of an evaporating black hole

- Define S_T to be the scalar sum of all high p_T objects found in the event
- Look for deviations at high S_T

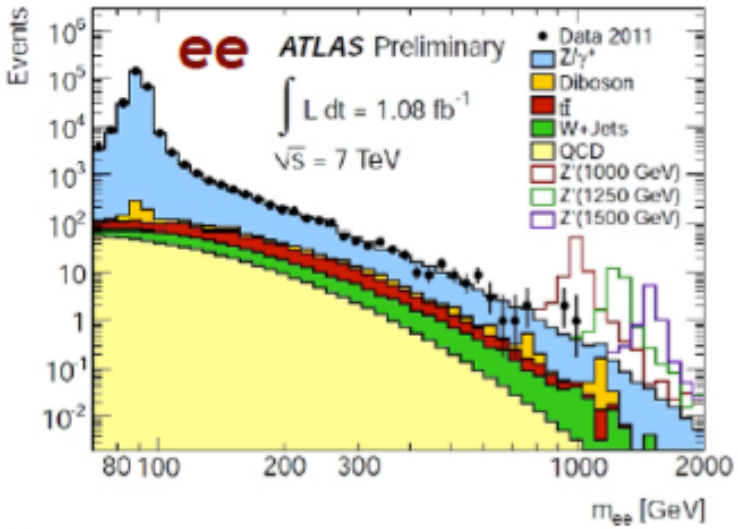


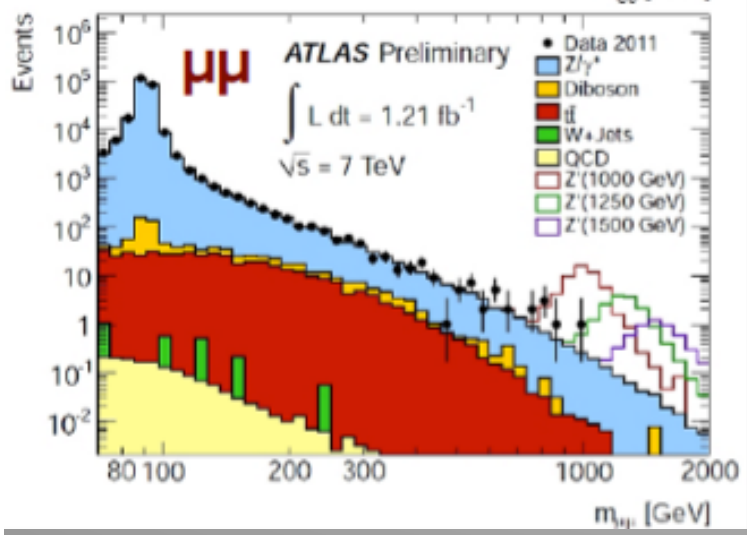


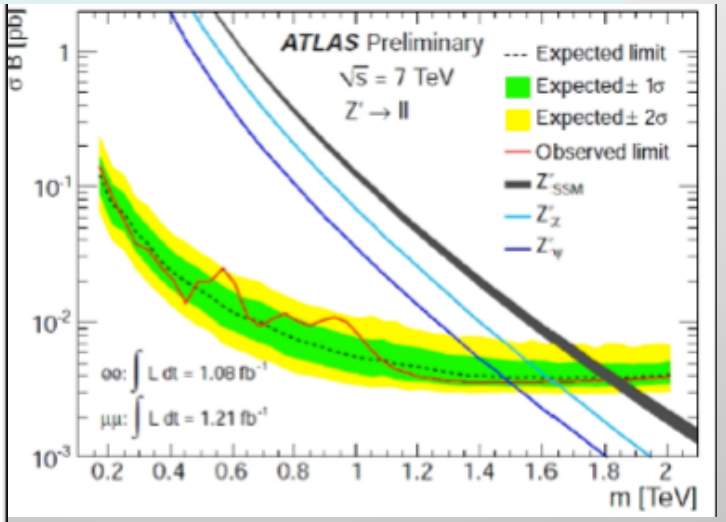
Black hole masses excluded in range ~5 TeV depending on assumptions

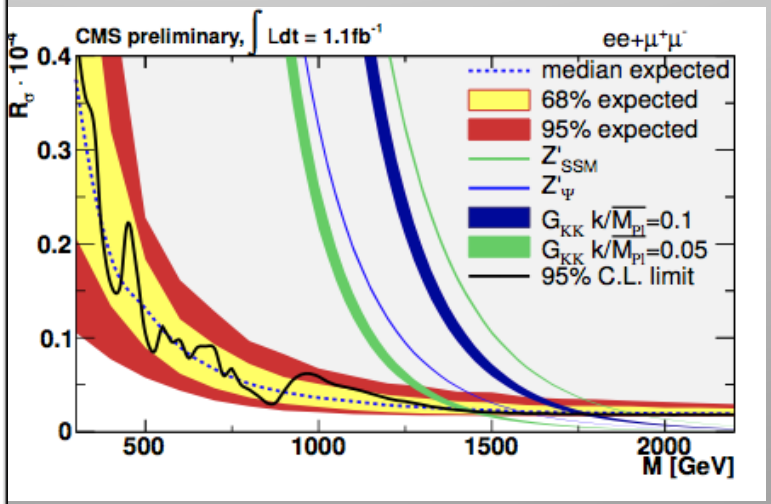
Search for G_{KK} or Z' Gauge Bosons

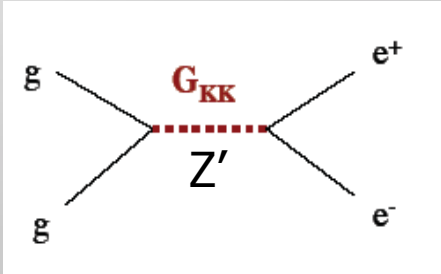
Study of the channels $Z' \rightarrow \mu\ \mu$, ee











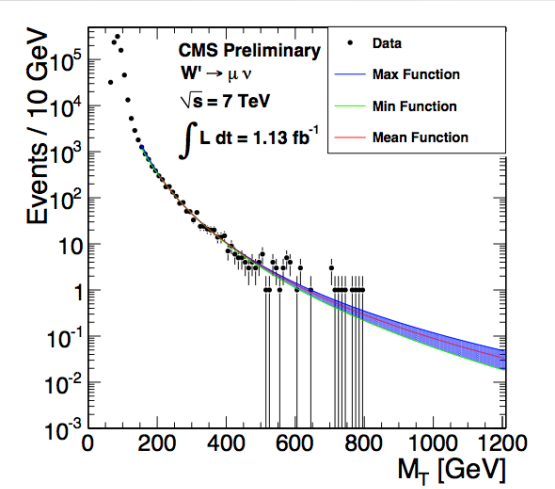
CMS-EXO-11-024
CMS-EXO-11-019

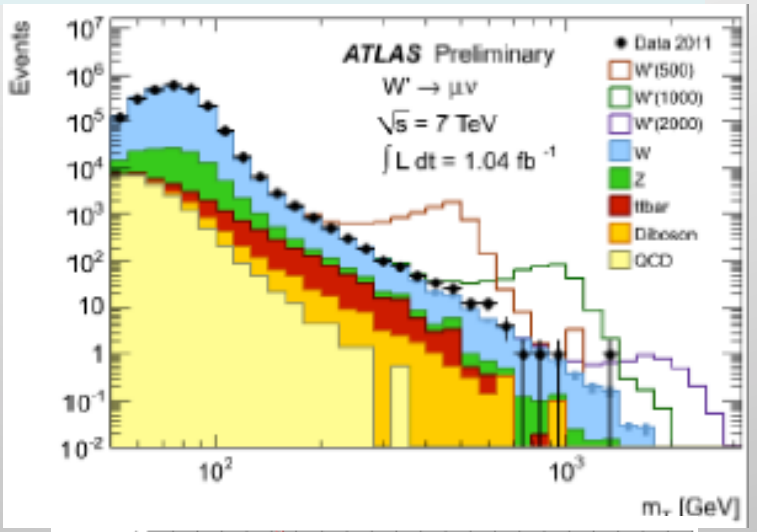
G^* (k/m_{Pl}=0.1)

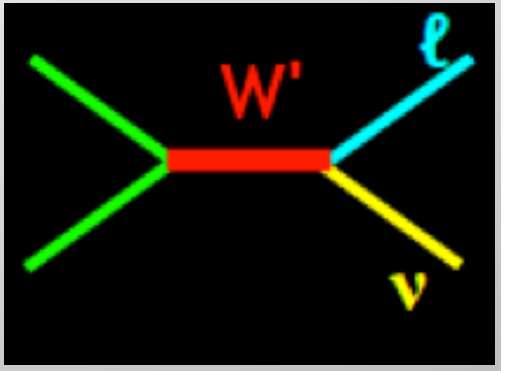
Exclude (SSM) Z' up to 1.94 TeV and G_{KK} up to 1.7 TeV or @ 95% CL

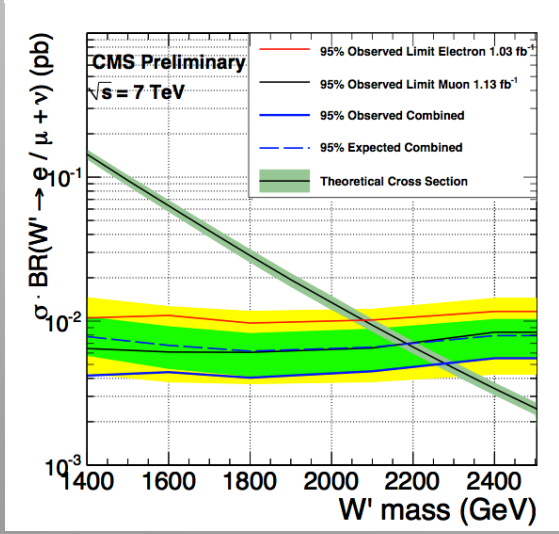
Search for W' Gauge Bosons

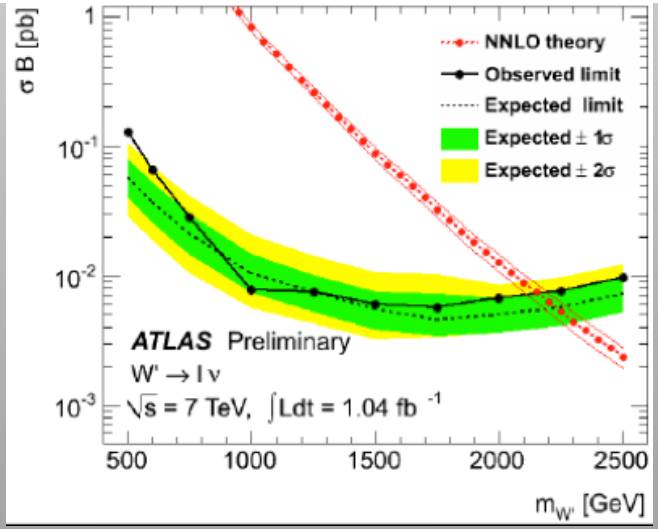
Study of the channels W'→ $\mu\ \nu$,e ν







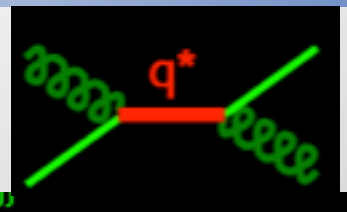




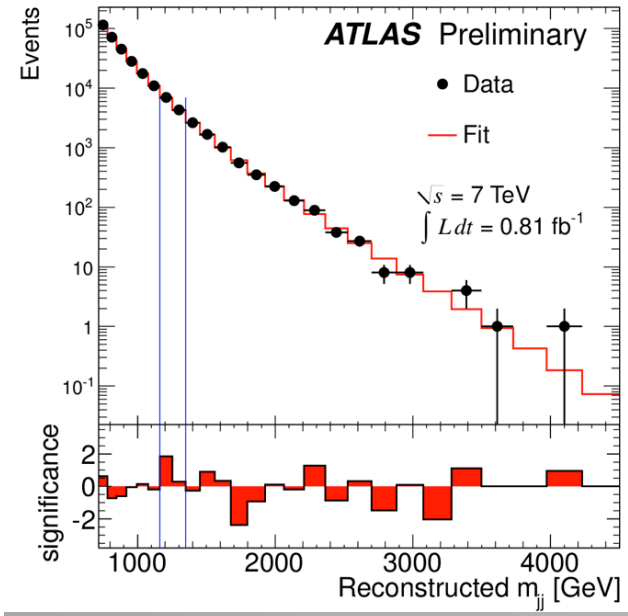
Exclude new W' bosons up to ~2.27 TeV @ 95% CL

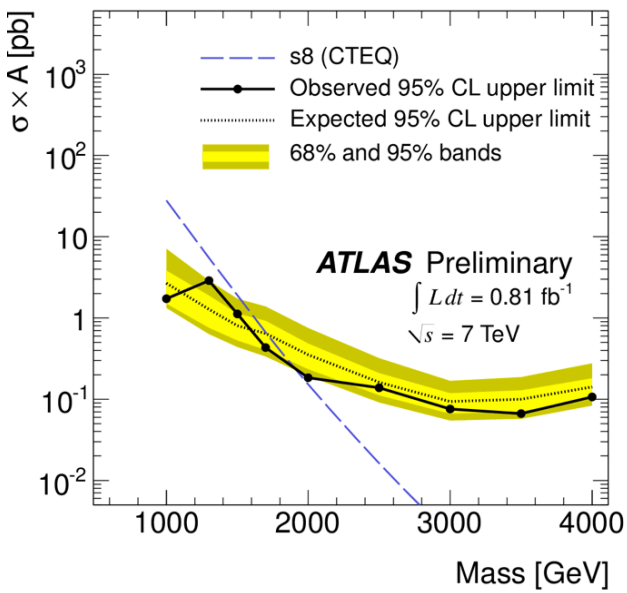
Search for Dijet Resonances

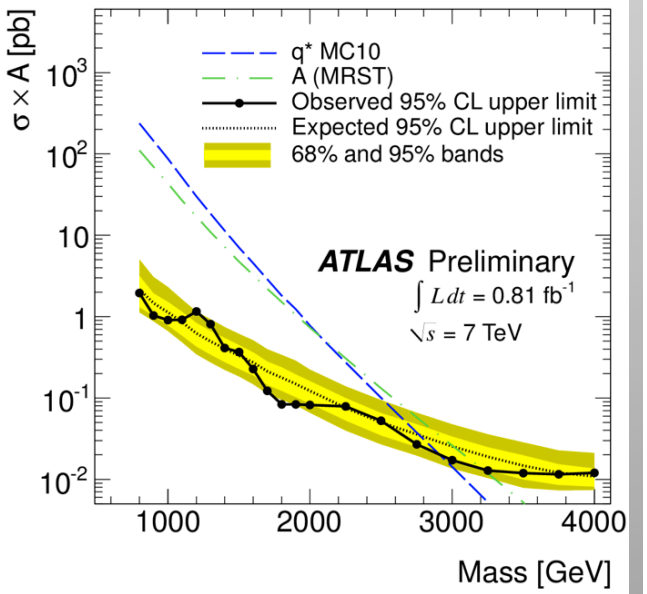
Select events with 2 jets with p_T> 180 GeV
Search for a bump in the invariant jet jet mass



Examples: q*, axigluon, colour-octet scalar models - also generic limits





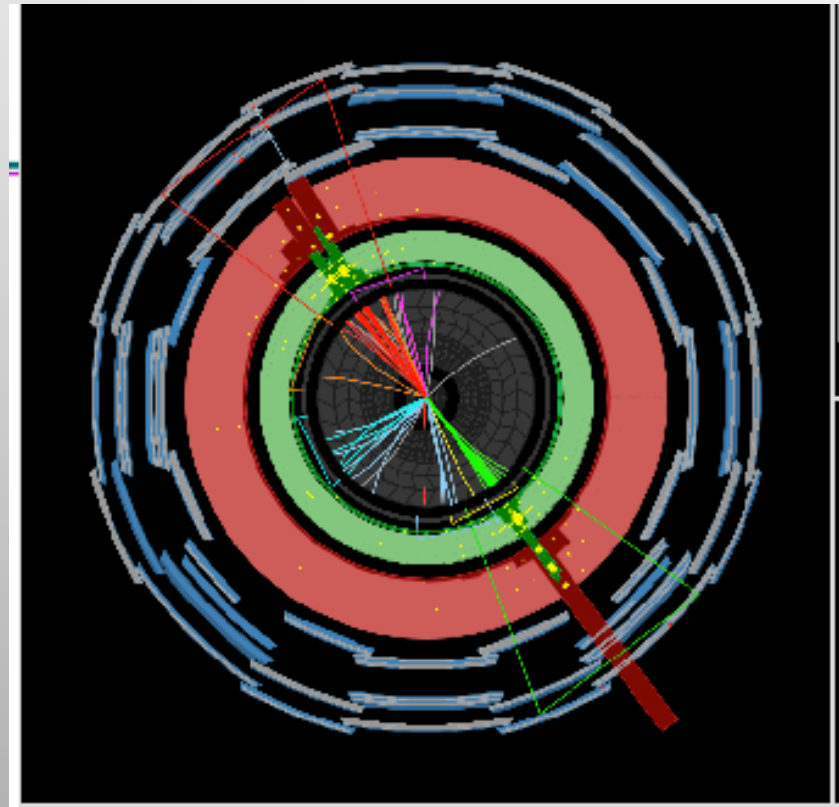


No bump found
Limits →

Model	Expected limit	Observed limit	Obs. 2010
q*	2.77	2.91	2.15
axigluon	3.02	3.21	2.10
c.o.s (s8)	1.71	1.91	-

95% CL limits in TeV

High p_T Dijet Event



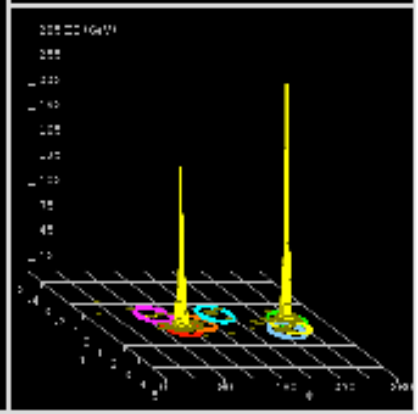
Very high energy jet event

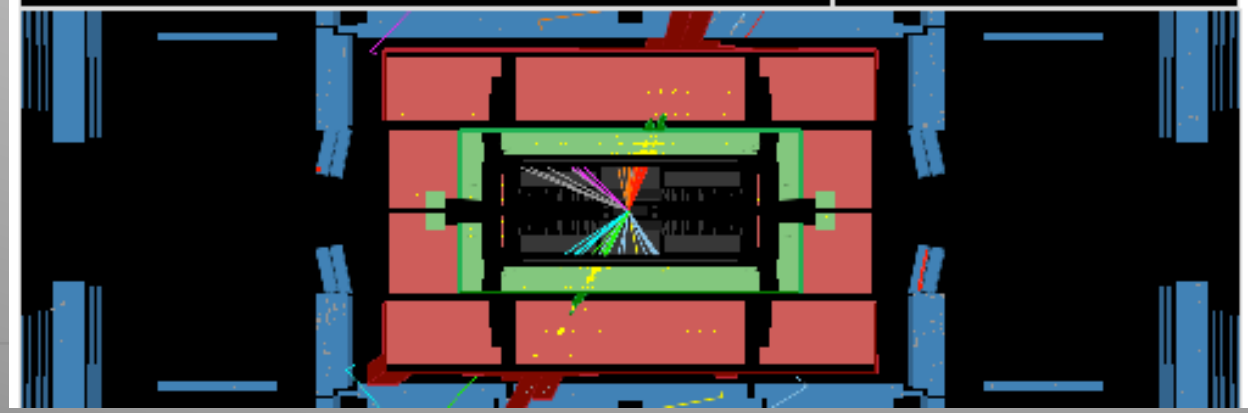
m_{jj} = 4040 GeV

p_T^{j1} = 1850 GeV

p_T^{j2} = 1840 GeV

ATLAS-CONF-2011-081



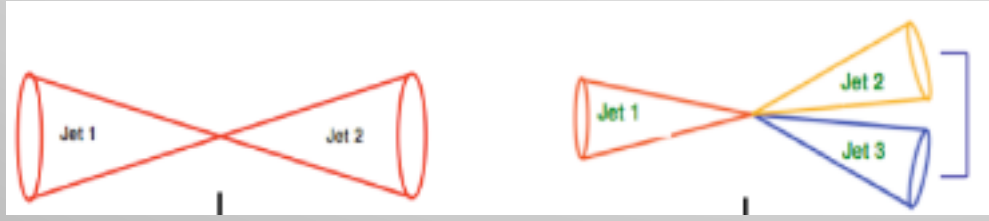


p. 5

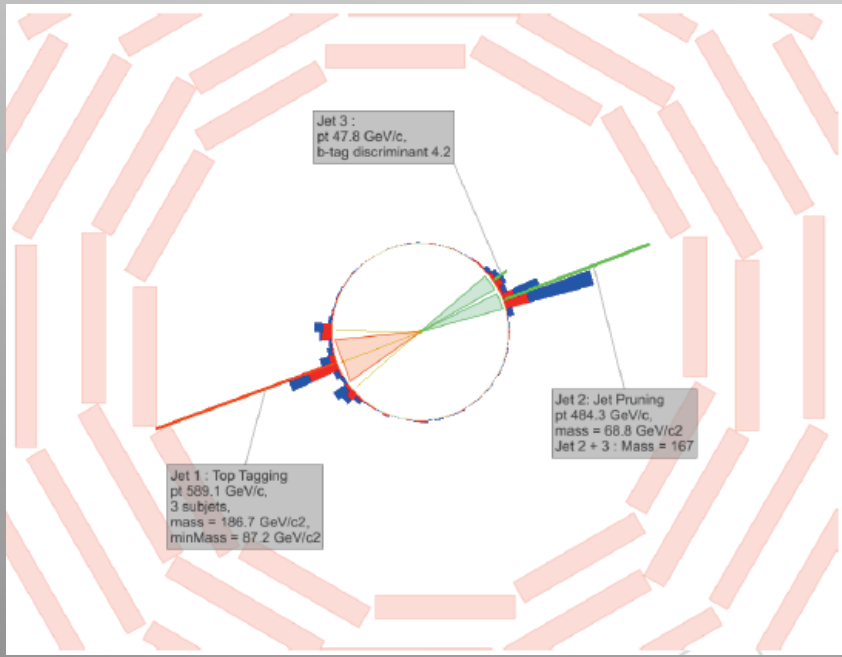
Z' → tt Search

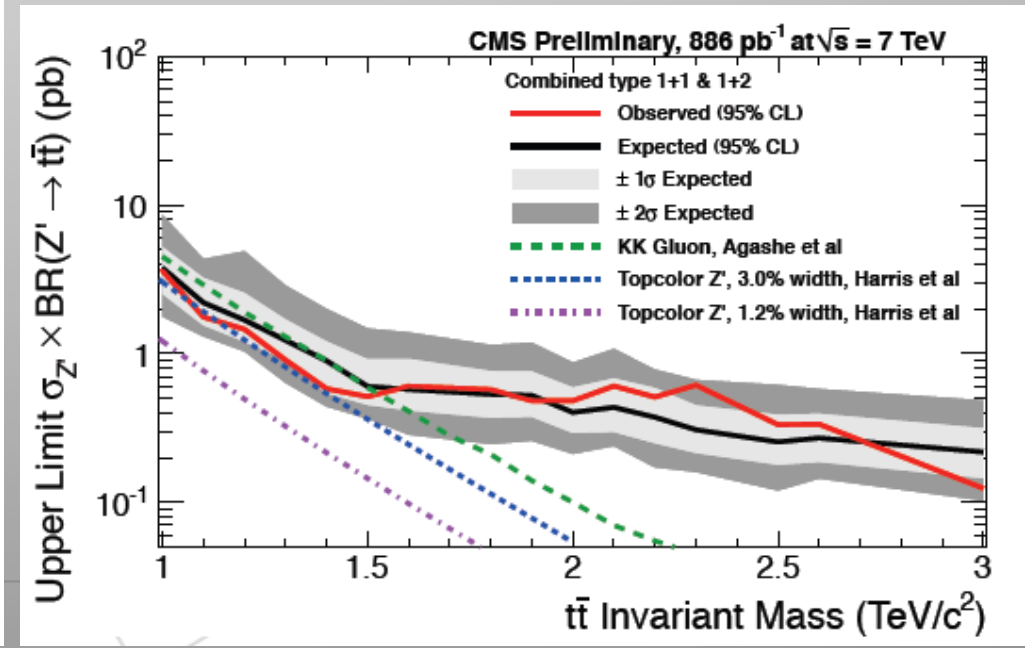
Search in the all hadronic decay channel for the tops
Tops are boosted for high mass Z', jets merge
Start from Cambridge-Aachen fat jets and apply jet pruning to find sub-jets
QCD background estimate from data (mistag method)

CMS-EXO-11-006



Exclude KK-Gluons 1<M<1.5 GeV





Long Lived Particles

Split Supersymmetry

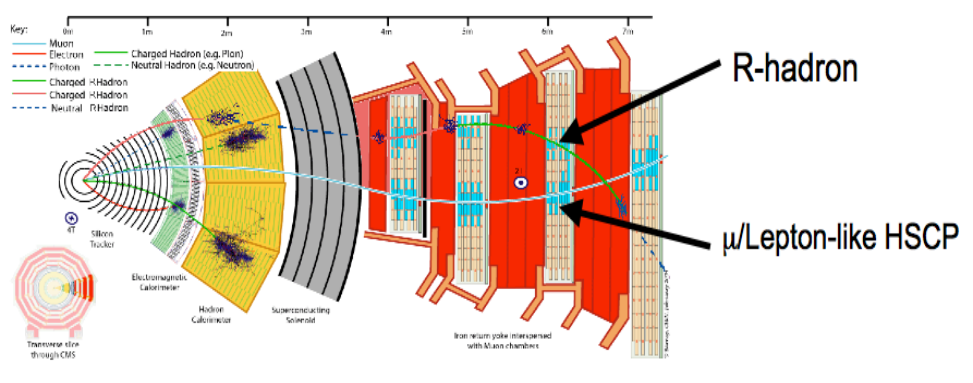
- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

  - Gluino can live long: sec, min, years!

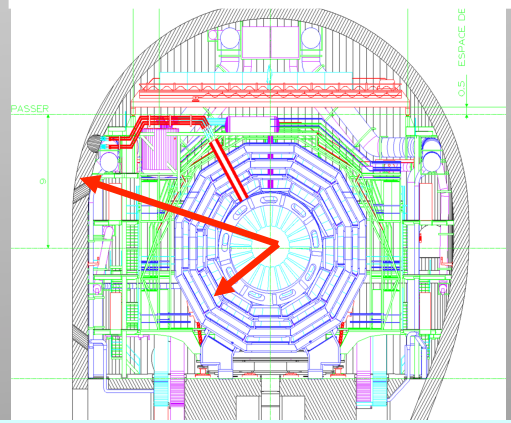
  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles

  Unusual interactions with material

  eg. with the calorimeters of the experiments!



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



Gravitino Dark Matter and GMSB

- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

⇒Challenge to the experiments!

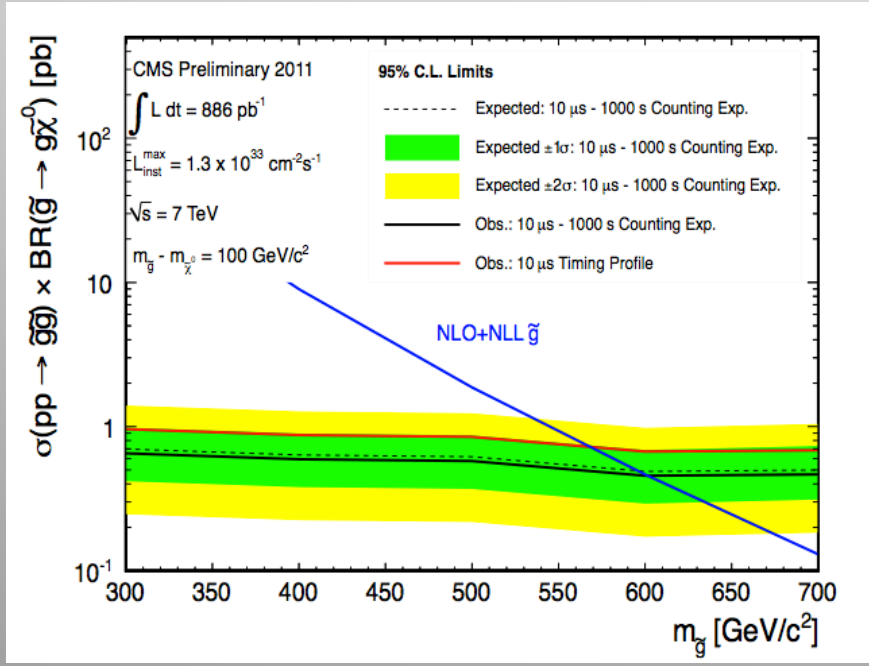
Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

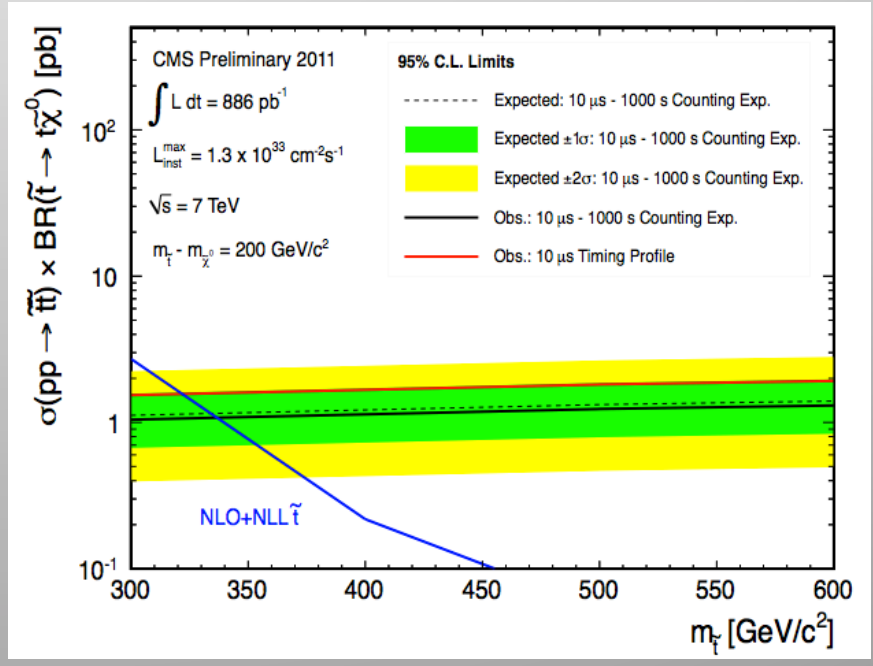
Searches: Stopped Gluinos

Search for Heavy Stable Charged Particles that stop in the detectors and decay a long time afterwards (nsec, sec, hrs…)

Special data taking after the beams are dumped and during beam abort gaps

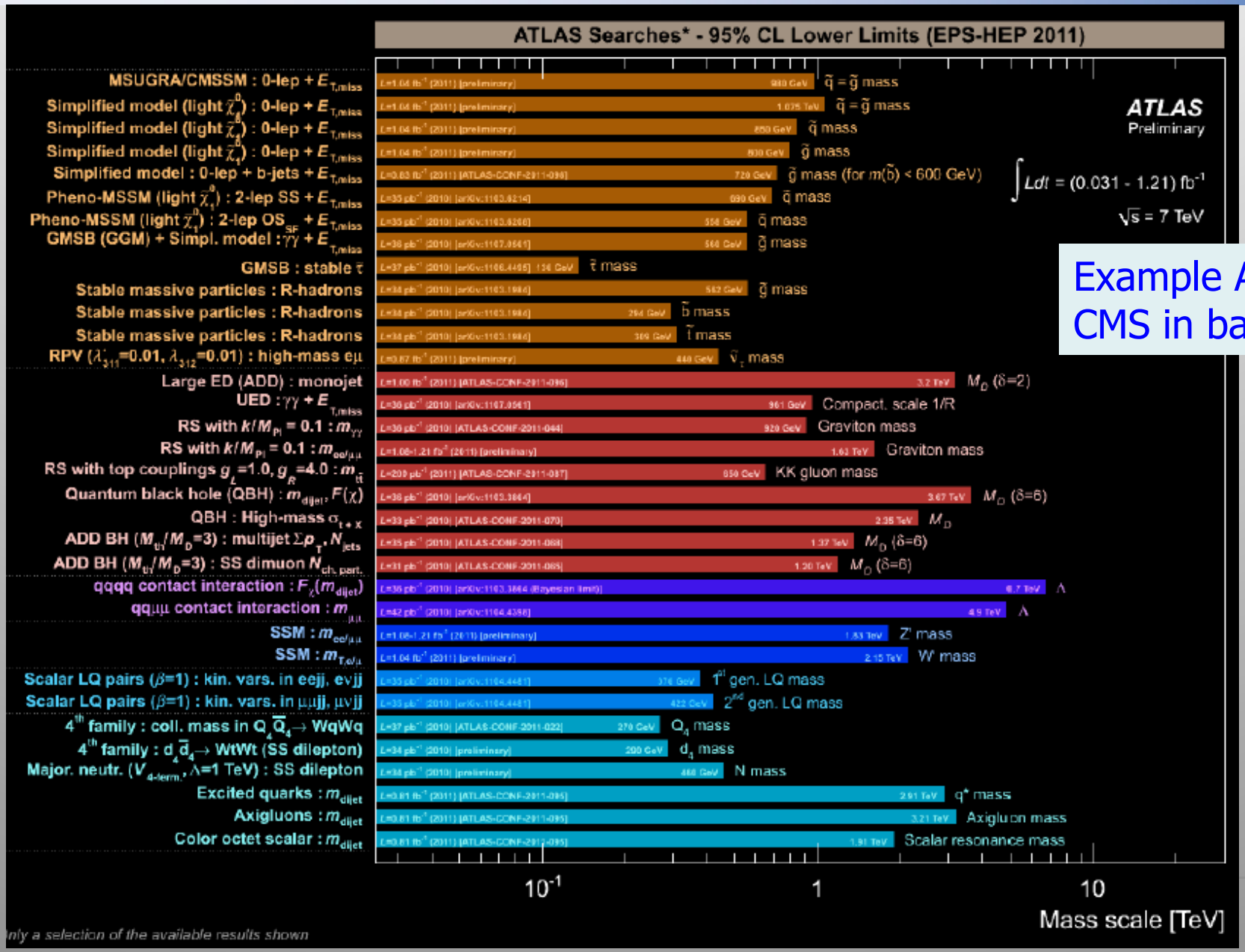
CMS-EXO-11-020





95% CL Limits: Stopped Gluinos > 600 GeV, Stopped Stop quarks> 337 GeV

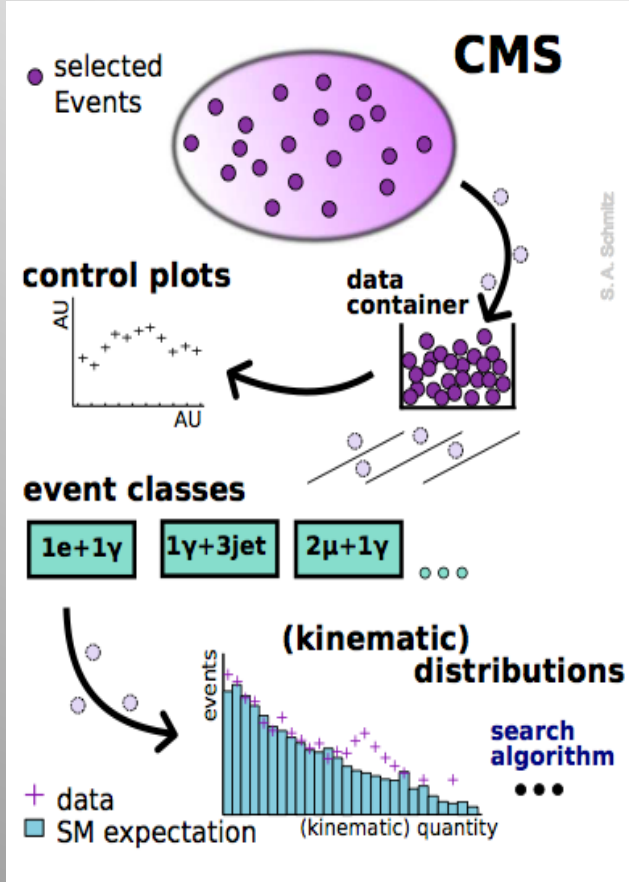
…and all the rest



Example ATLAS
CMS in backup

Can we miss something?

CMS-EXO-10-021

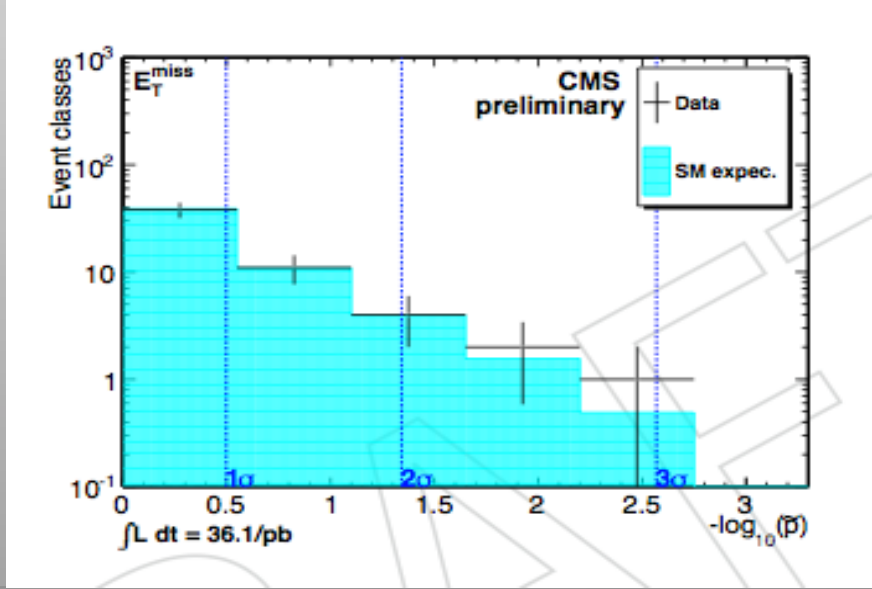


Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class

- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles



Probability distribution as expected for 35 pb^{-1}

Look at & watch the outliers…

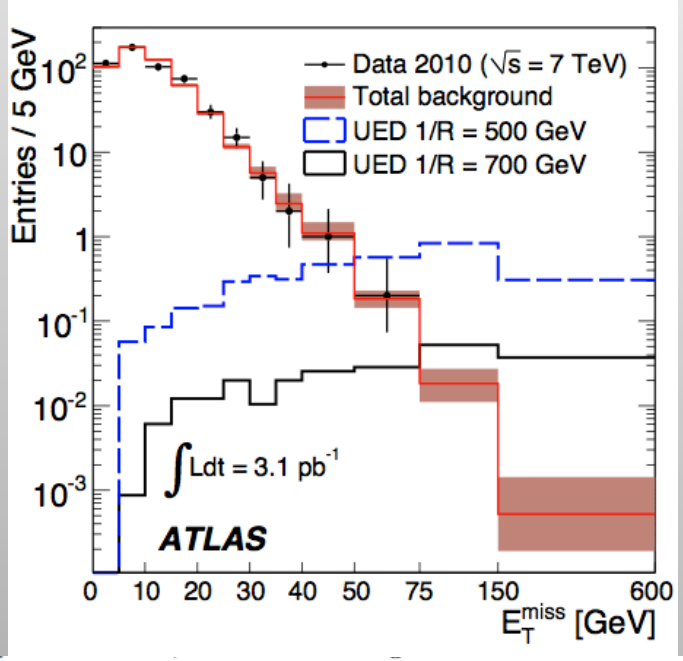
Summary: The Searches are on!

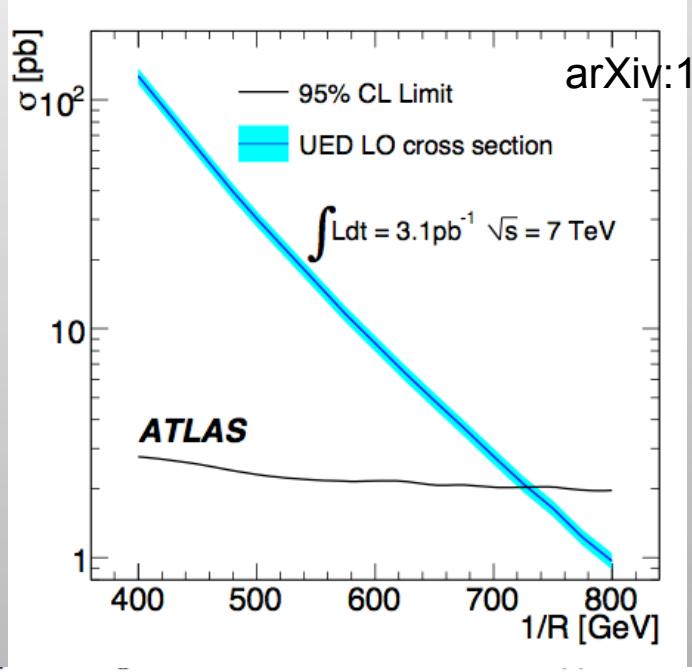
- The LHC has entered new territory. The ATLAS and CMS experiments are ready for searches for new physics. The most popular example is SUSY, but many other New Physics model searches are covered.
- No sign of new physics yet in the first 1 fb^{-1} at 7 TeV.

  Starts to cut into the 'preferred SUSY region'. The air for constrained models is getting very thin.
- We need to prepare to tackle the next, more difficult, cases experimentally. Guidance and ideas from our theory colleagues welcome!.
- The LHC did its part so far with a great first half in 2011 Expect between 10 and 20 fb^{-1} by end of 2012, and maybe a higher energy in 2012.

Universal Extra Dimensions

Search for events with two photos and missing transverse energy
Limits set for events with two photons with E_T> 25 GeV and MET > 75 GeV





arXiv:1012.4272

E_T^{miss} range (GeV)	Data events	Predicted background events Total	QCD	$W(\rightarrow e\nu)$ + jets/γ	Expected UED signal events $1/R = 500$ GeV	$1/R = 700$ GeV
0 - 20	465	465.0 ± 9.1	465.0 ± 9.1	-	0.28 ± 0.06	0.02 ± 0.01
20 - 30	45	40.5 ± 2.2	40.41 ± 2.17	0.11 ± 0.07	0.45 ± 0.07	0.03 ± 0.01
30 - 50	9	10.3 ± 1.3	10.13 ± 1.30	0.16 ± 0.10	1.60 ± 0.12	0.08 ± 0.01
50 - 75	1	0.93 ± 0.23	0.85 ± 0.23	0.08 ± 0.05	2.84 ± 0.16	0.14 ± 0.01
> 75	0	0.32 ± 0.16	0.28 ± 0.15	0.04 ± 0.03	40.45 ± 0.62	4.21 ± 0.06

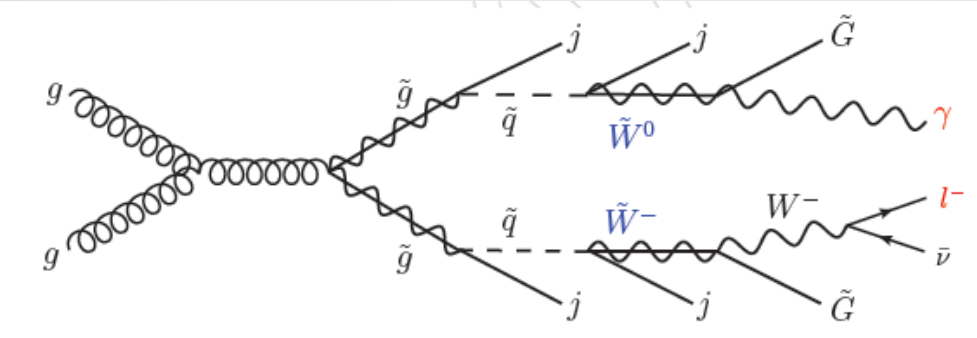
No evidence yet for Universal Extra Dimensions…

Summary of the Exotica searches

	Limits in TeV	
	Heavy Bosons	
Z'_{SSM} ll	1.94	2011
Z'_{ψ} ll	1.62	2011
G_{KK} ll k/M = 0.1	1.78	2011
W' lν	2.27	2011
W' dijet	1.51	2011
G_{KK} γγ k/M = 0.1 (2010)	0.945	2010
	4th Generation	
$M_{b'}$, b' ⇒ tW (2010)	0.361	2010
$M_{t'}$, t' ⇒ tZ (100%)	0.417	2011
$M_{t'}$, t' ⇒ bW (100%), l+jets	0.45	2011
	Heavy Stable Particles	
M_{gluino}, HSCP	0.899	2011
M_{gluino}, Stopped Gluino	0.601	2011
M_{stop}, HSCP	0.620	2011
M_{stop}, Stopped Gluino	0.337	2011
M_{stau}, HSCP	0.293	2011
	Large Extra Dimensions	
M_s, γγ, GRW (2010)	1.89	2010
M_s, μμ, GRW (2010)	1.75	2010
M_D, monojet, n_{ED} = 2 (2010)	2.56	2010
M_D, monojet, n_{ED} = 6 (2010)	1.68	2010
M_{BH}, rotating, M_D=3.5 TeV, n_{ED} = 2	4.1	2011
M_{BH}, non-rot, M_D=1.5 TeV, n_{ED} = 6	5.1	2011
String Ball M, M_D=2.1, M_s=1.7, g_s=0.4	4.1	2011
	Compositeness and Contact Interactions	
String Resonances	4.0	2011
E_6 diquarks	3.52	2011
Axigluon/Coloron	2.47	2011
q* , dijet	2.49	2011
q* , boosted Z	1.17	2010
e*, Λ = 2 TeV	0.720	2010
μ*, Λ = 2 TeV	0.745	2010
C.I. Λ , dijet mass (3 pb^{-1})	4.0	2010
C.I. Λ , X analysis	5.6	2010
	LeptoQuark	
LQ1, β=0.5 (2010)	0.340	2010
LQ1, β=1.0 (2010)	0.384	2010
LQ2, β=1.0 (2010)	0.394	2010

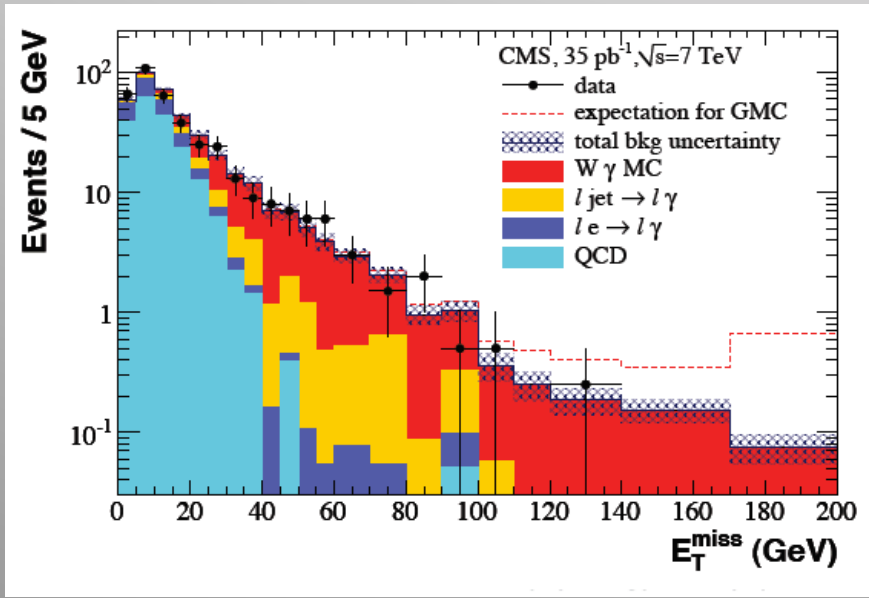
GMSB SUSY Searches

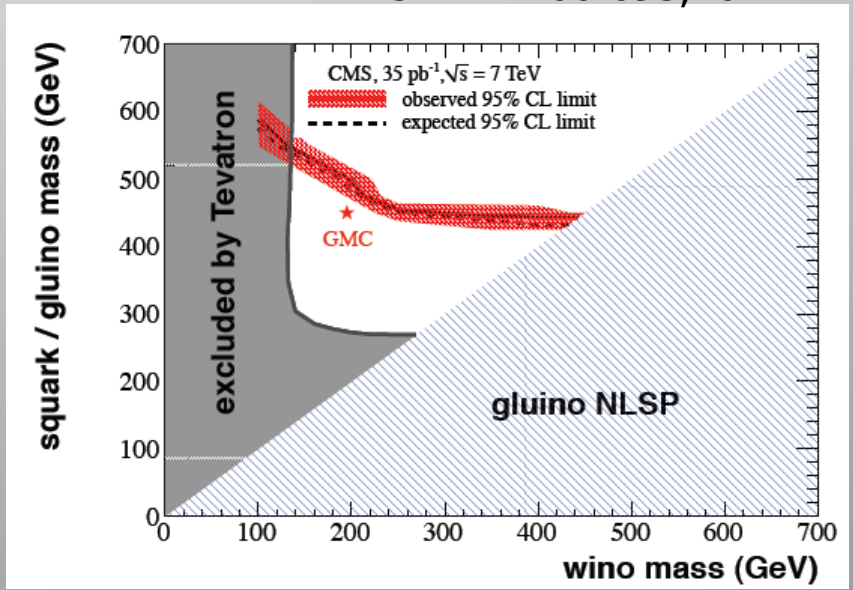
E.G. This channel: A lepton, a photon and Missing Transverse Energy



P_T lepton> 20 GeV
P_T photon > 30 GeV
MET> 100 GeV

JHEP 1106:093,2011

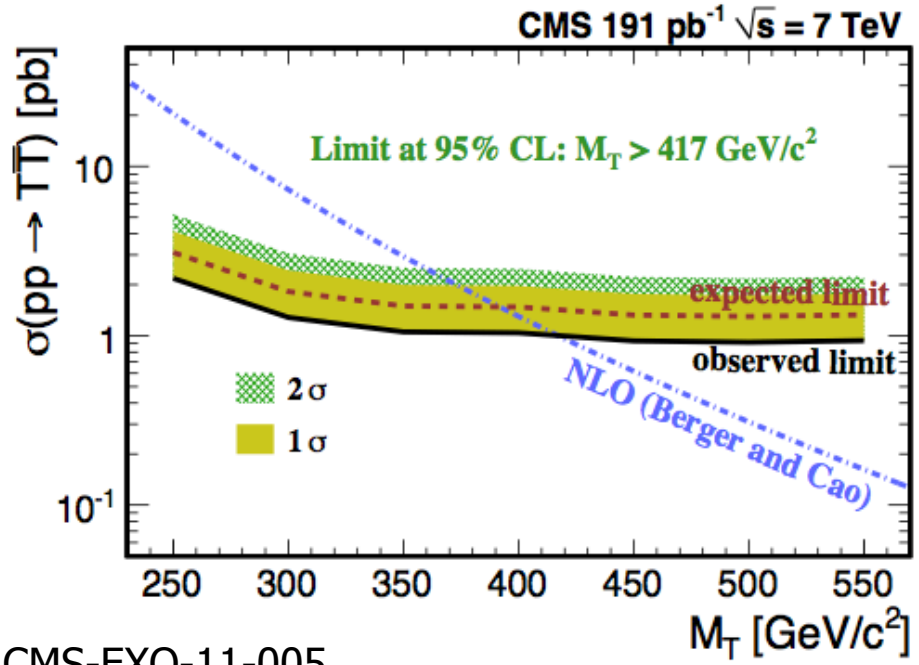




No excess found… Exclusion in the squark/gluino wino space

4th Generation: Top partners

$T \to tZ$

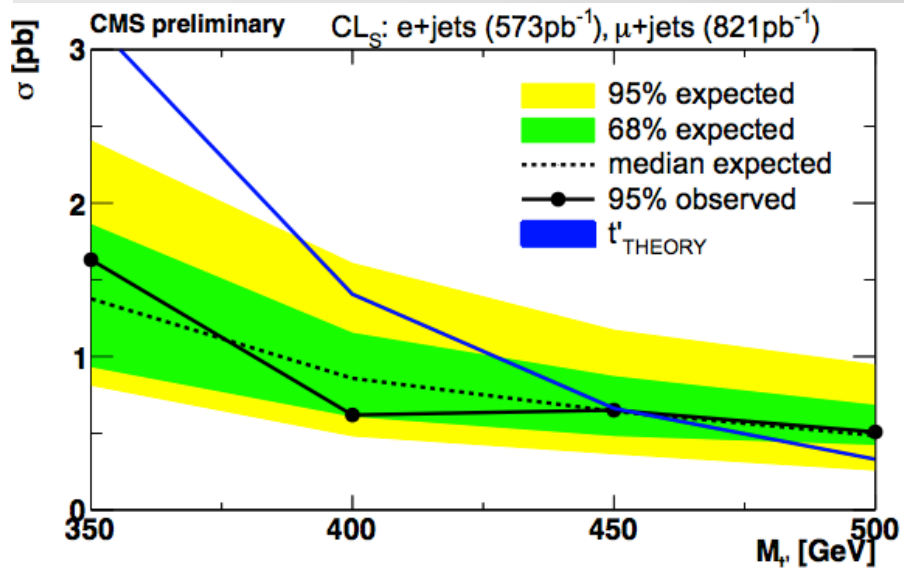


CMS-EXO-11-005

$M(T)$ [GeV/c^2]	250	300	350	400	450	500	550
Observed limit [pb]	2.18	1.28	1.05	1.04	0.93	0.91	0.94

No top-like quark with tZ decay found with mass < 417 GeV at 95% CL

$t'\bar{t}' \to WbW\bar{b} \to \ell\nu bq\bar{q}\bar{b}$



CMS-EXO-11-0051

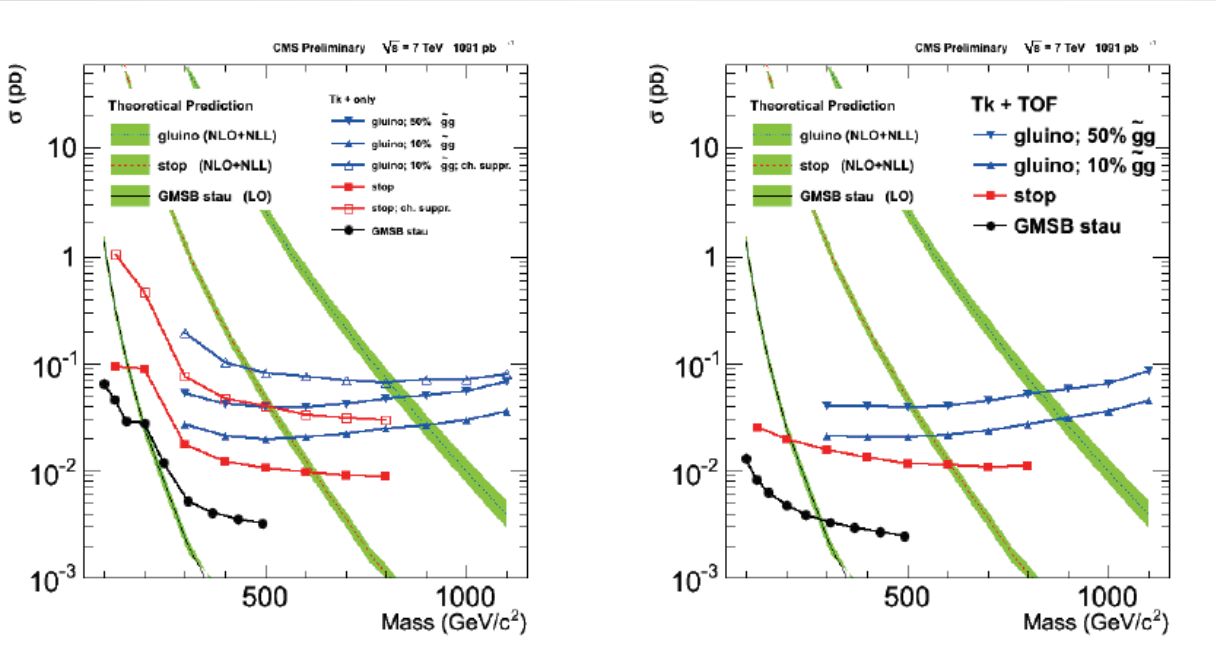
No t' with found in the region of mass < 450 GeV at 95% CL

$b'\bar{b}' \to tW^-\bar{t}W^+ \to bW^+W^-\bar{b}W^-W^+$

No b' with 255<mass< 361 GeV

Heavy Stable Charged Particles

CMS-EXO-11-022



Stable particles that traverse the detector, and move slowly

Eg heavy stable Gluino or stop/stau

Search limits using tracker de/dx and Muon TOF information

Result for 1 fb^{-1}:
0 events after all cuts

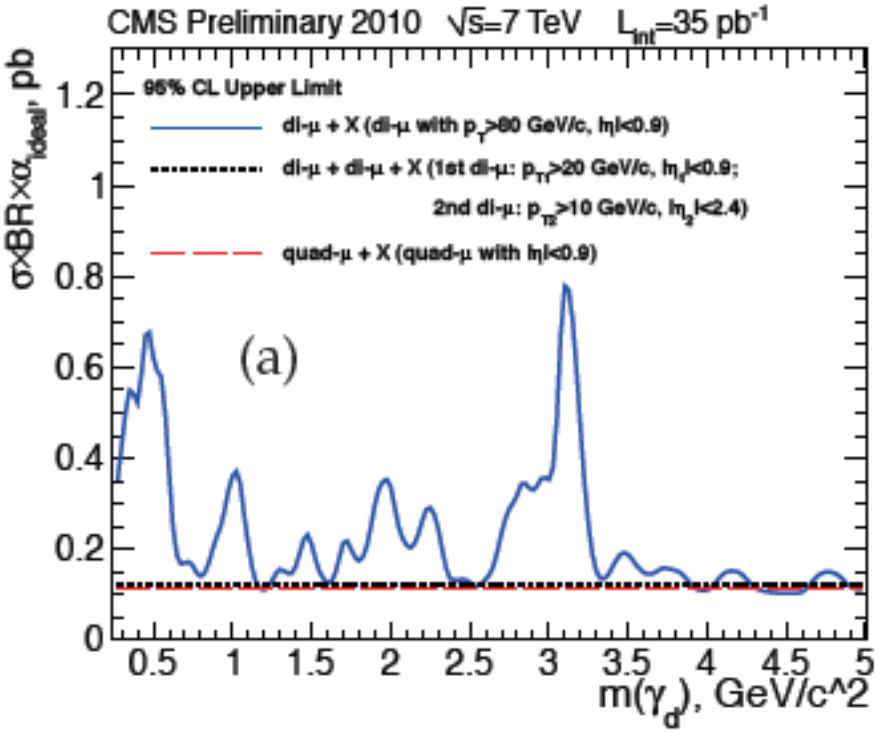
95% C.L. mass limits are set for

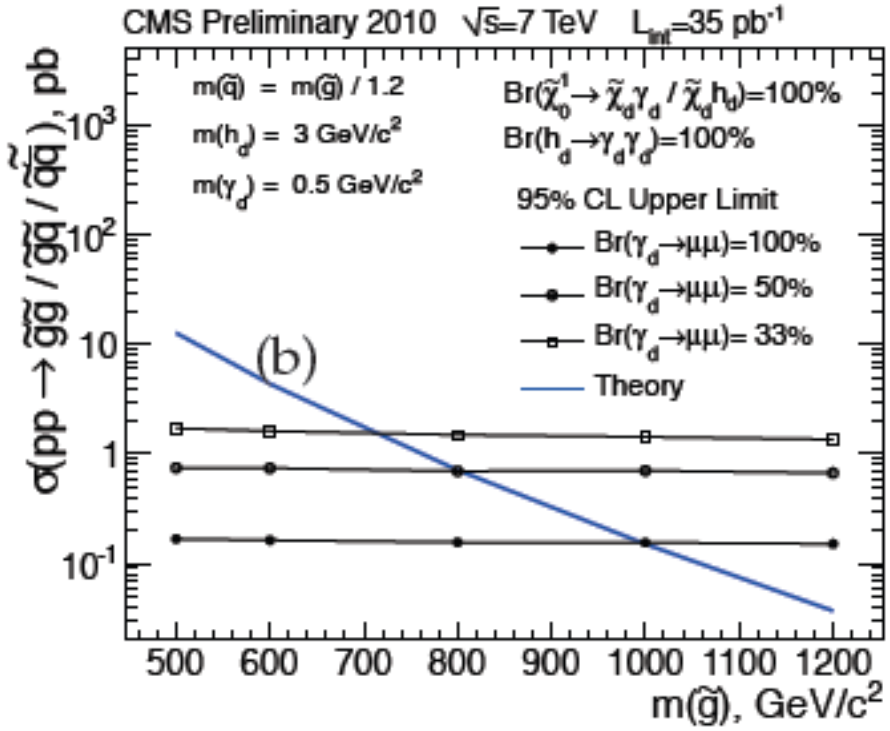
- Cloud model interaction scenario
  - Gluino (10% ~gg): 899 GeV, Gluino (50% ~gg): 839 GeV
  - Stop: 620 GeV GMSB Stau:293 GeV ← NEW Addition
- Charge suppression interaction scenario
  - Gluino(10% ~gg): 808 GeV, Stop: 515 GeV

Search for Dark Photons

Dark photons decaying into muons. Look for muon jets events in data

Arkani-Hamed, Weiner



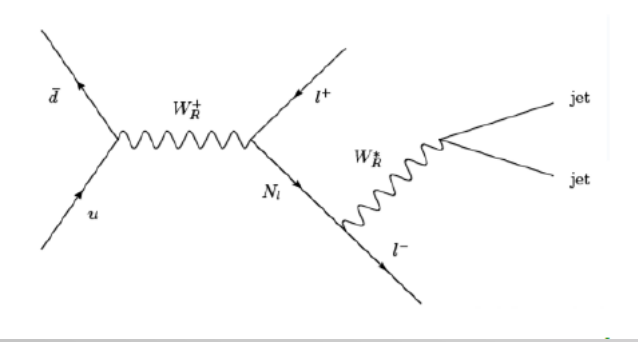


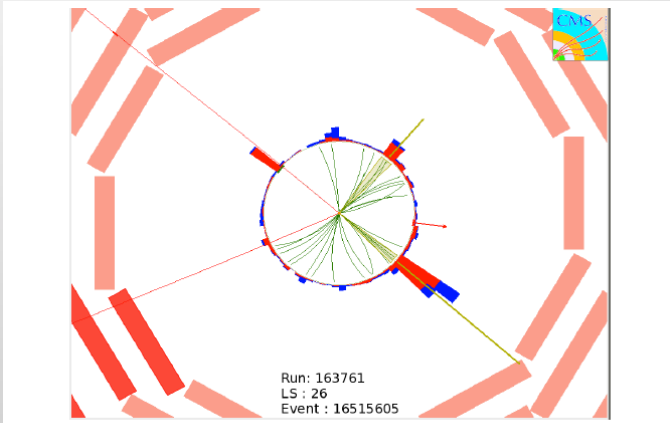
$$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_{dark}\gamma_{dark} + \tilde{\chi}_{dark}h_{dark}(\rightarrow \gamma_{dark}\gamma_{dark})$$

None found so far…. Limits set on production cross sections

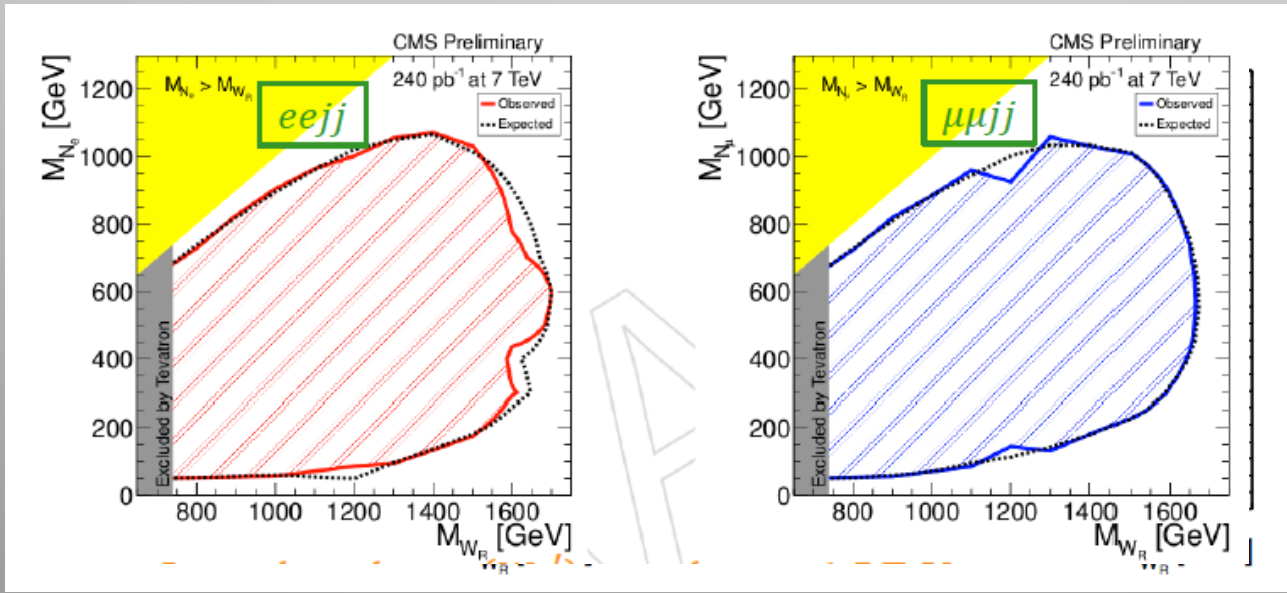
Heavy Neutrinos in W_R decays

Select 2 leptons and 2 jets





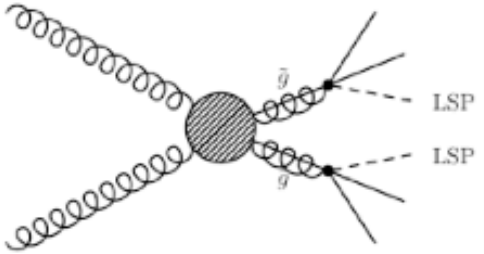
Muon channel: Event with $M_{\mu\mu}$ = 331 GeV, $M_{\mu\mu jj}$ = 881 GeV

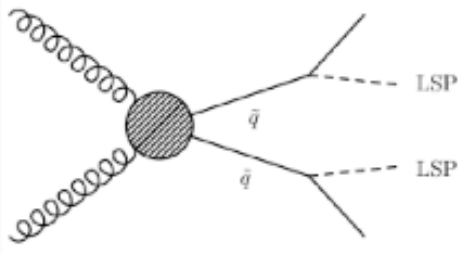


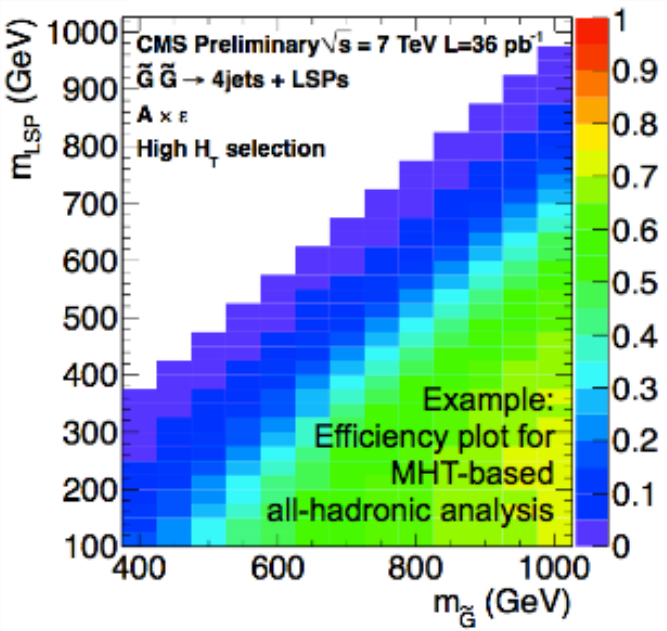
Large exclusion range
Tevatron ~ 780 GeV
Excluded on WR

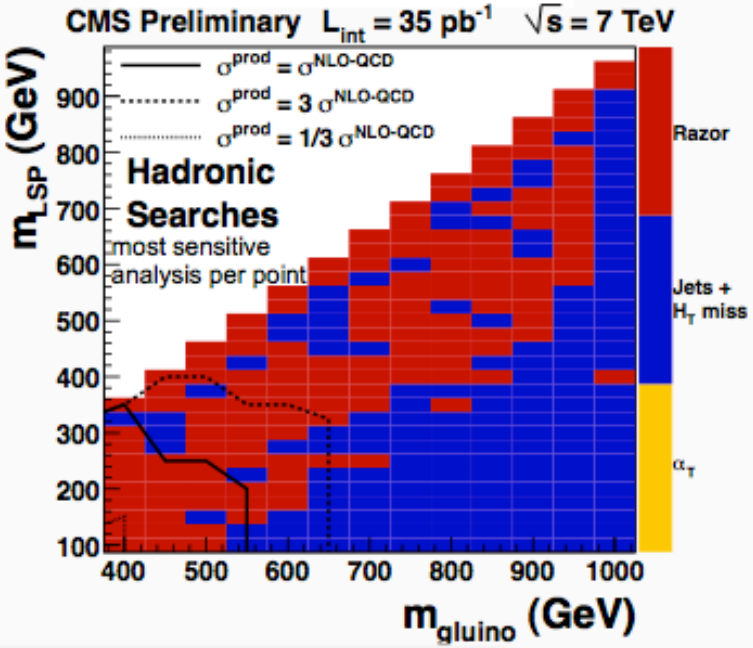
Results as Simplified Models

Models proposed at: http://www.lhcnewphysics.org









Shows complementarity of hadronic analyses.
CMS will provide these results electronically.
Feedback is welcome.

Are these result representations useful/used?