LHC: Searches for New Physics Beyond the Standard Model

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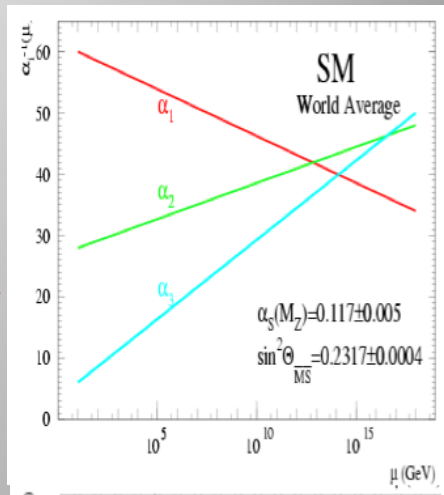
Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy

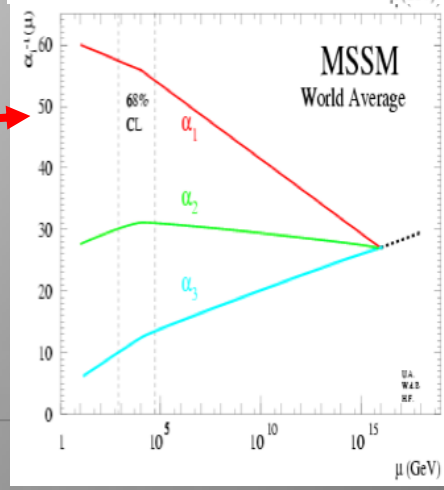


Most popular extensions these days

If a Higgs field exists:
- Supersymmetry
- Extra space dimensions

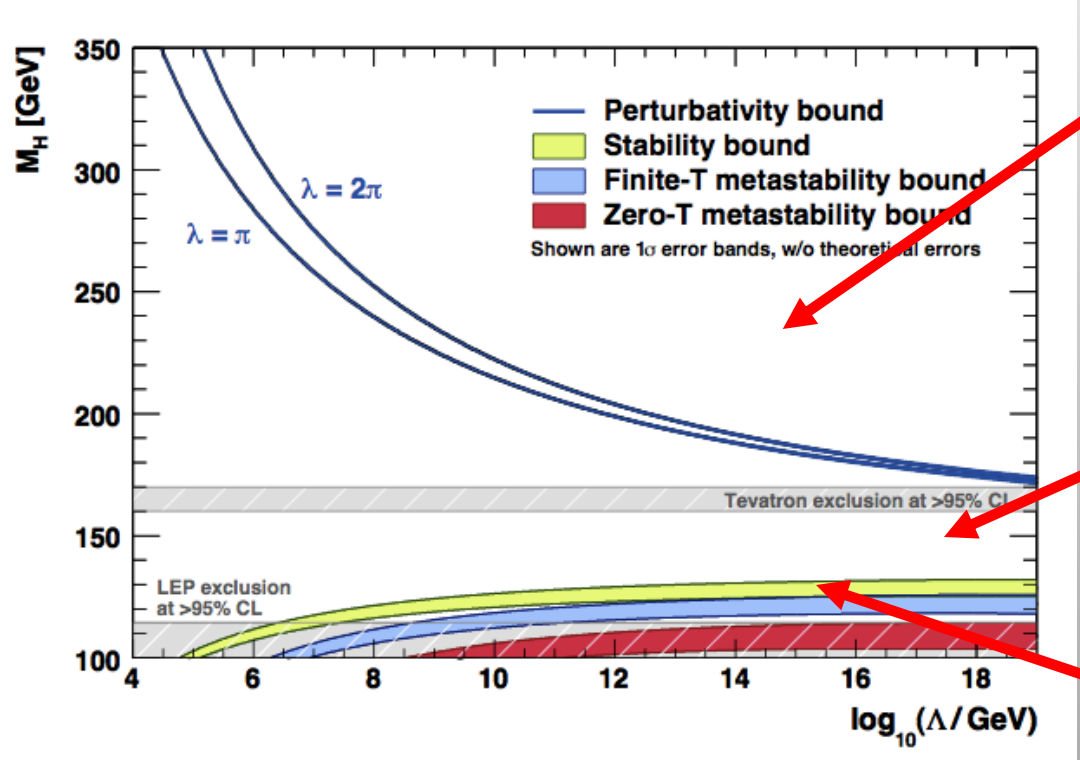
If there is no Higgs below ~ 700 GeV
- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more symmetry & gauge bosons, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys…



A Light Higgs: Consequences

A light Higgs implies that the Standard Model cannot be stable up to the GUT or Planck scale (10^{19} GeV)



The effective potential blows up, due to heavy top quark mass

Allowed corridor but needs strong fine-tuning…

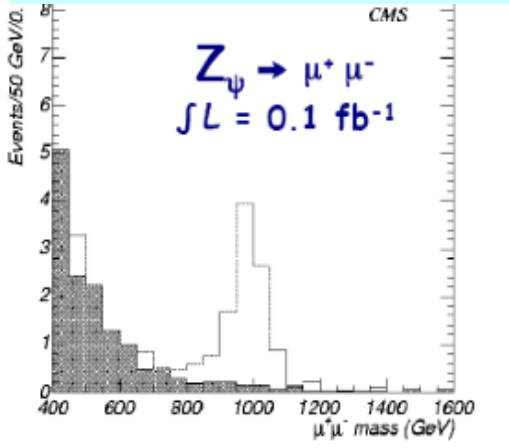
The electroweak vacuum is unstable to corrections from scales Λ >> v= 246 GeV

New physics expected in TeV range

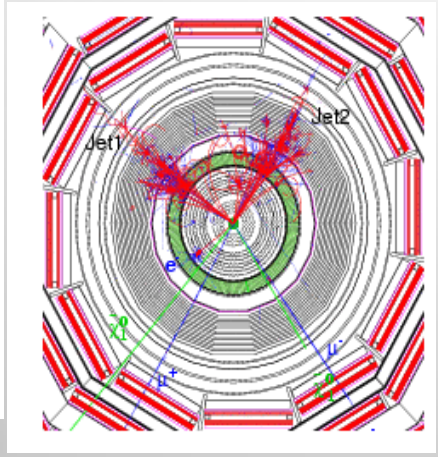
Hambye
Riesselmann

New Physics at High Energies?

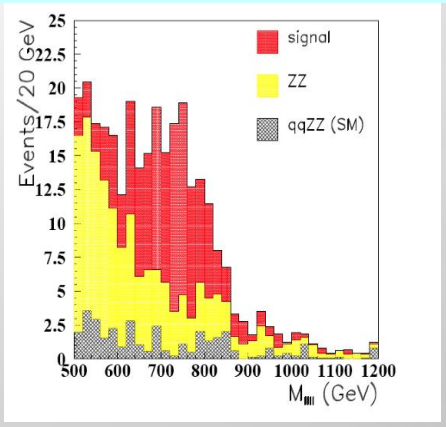
New Gauge Bosons?



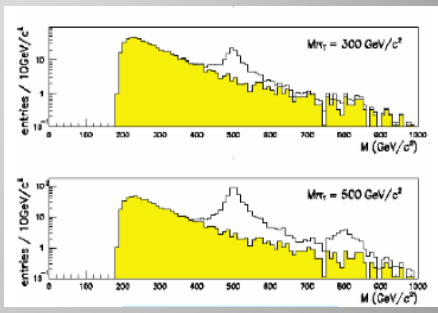
Supersymmetry



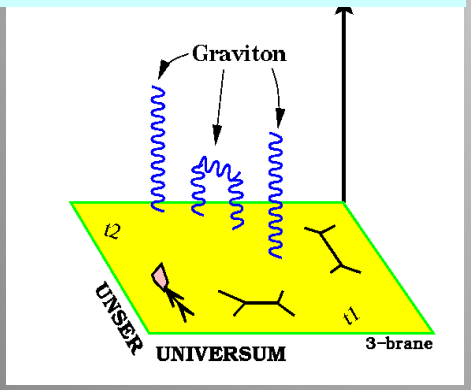
ZZ/WW resonances?



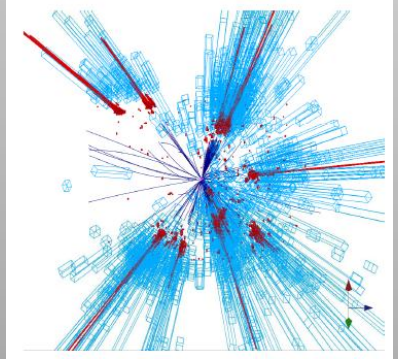
Technicolor?



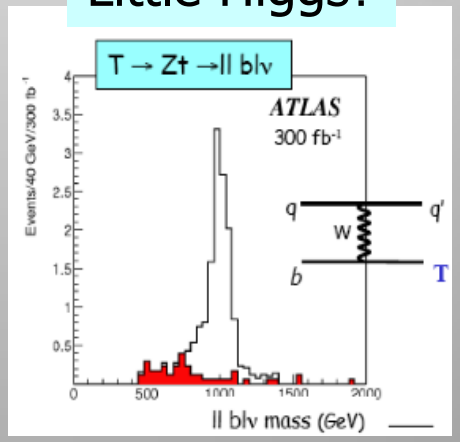
Extra Dimensions?



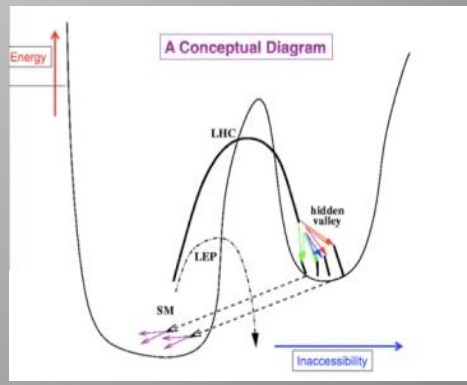
Black Holes???



Little Higgs?

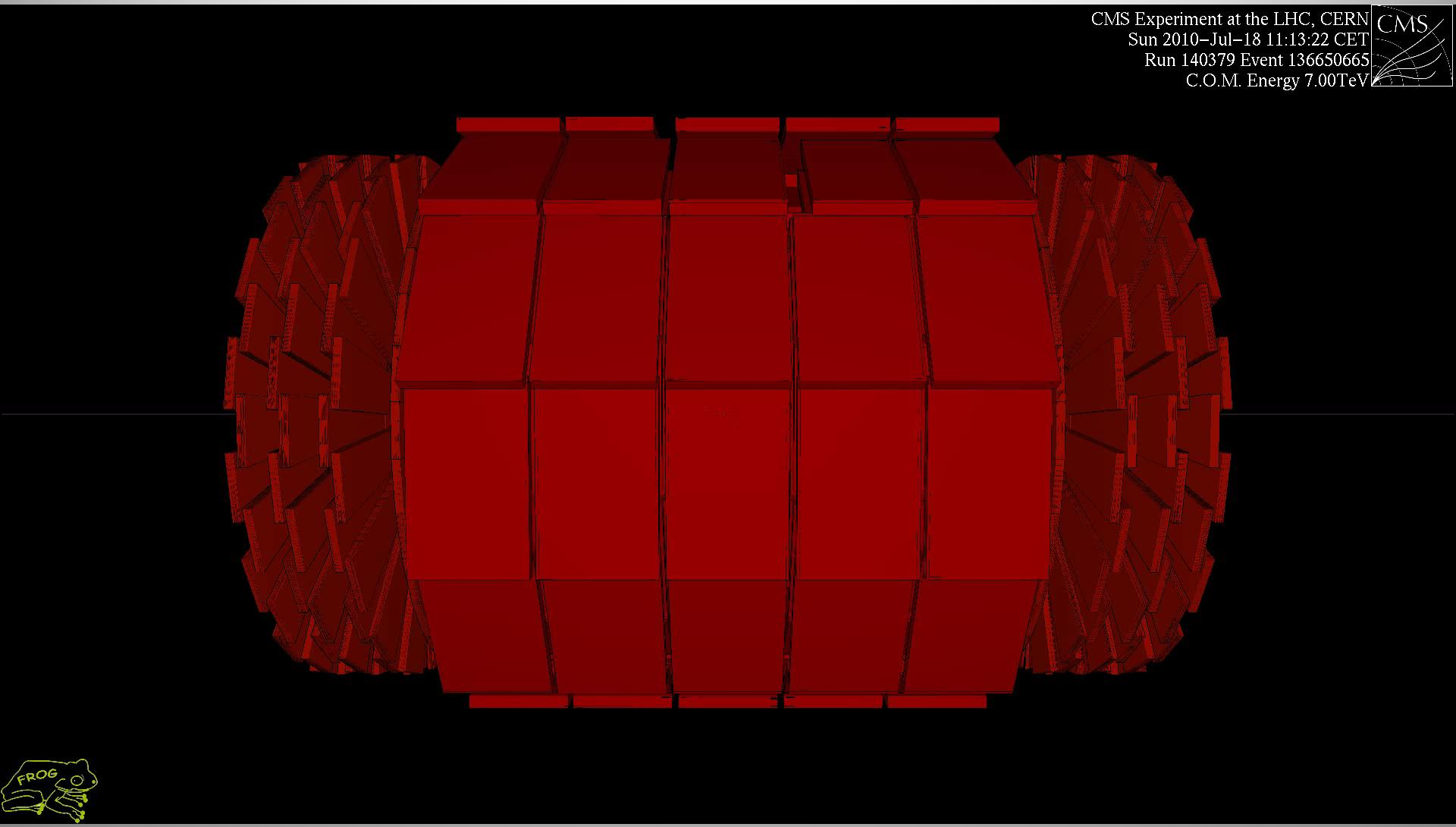


Hidden Valleys?



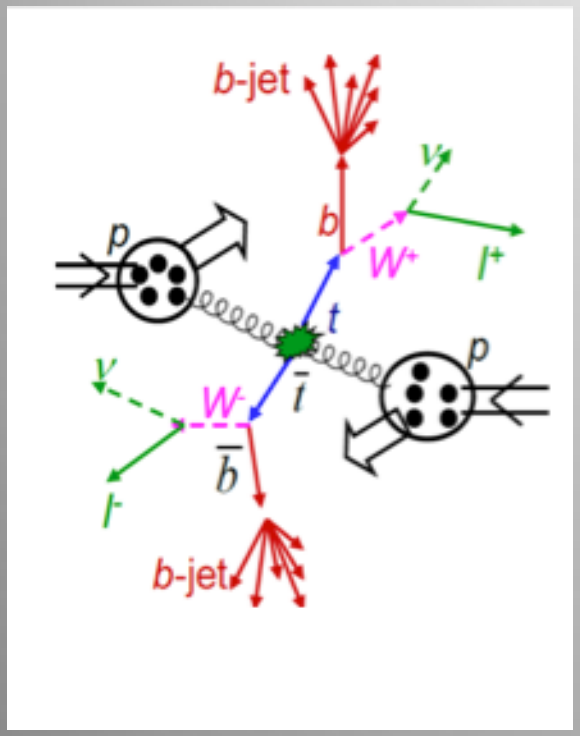
We do not know what is out there for us…
A large variety of possible signals. We have to be ready for that

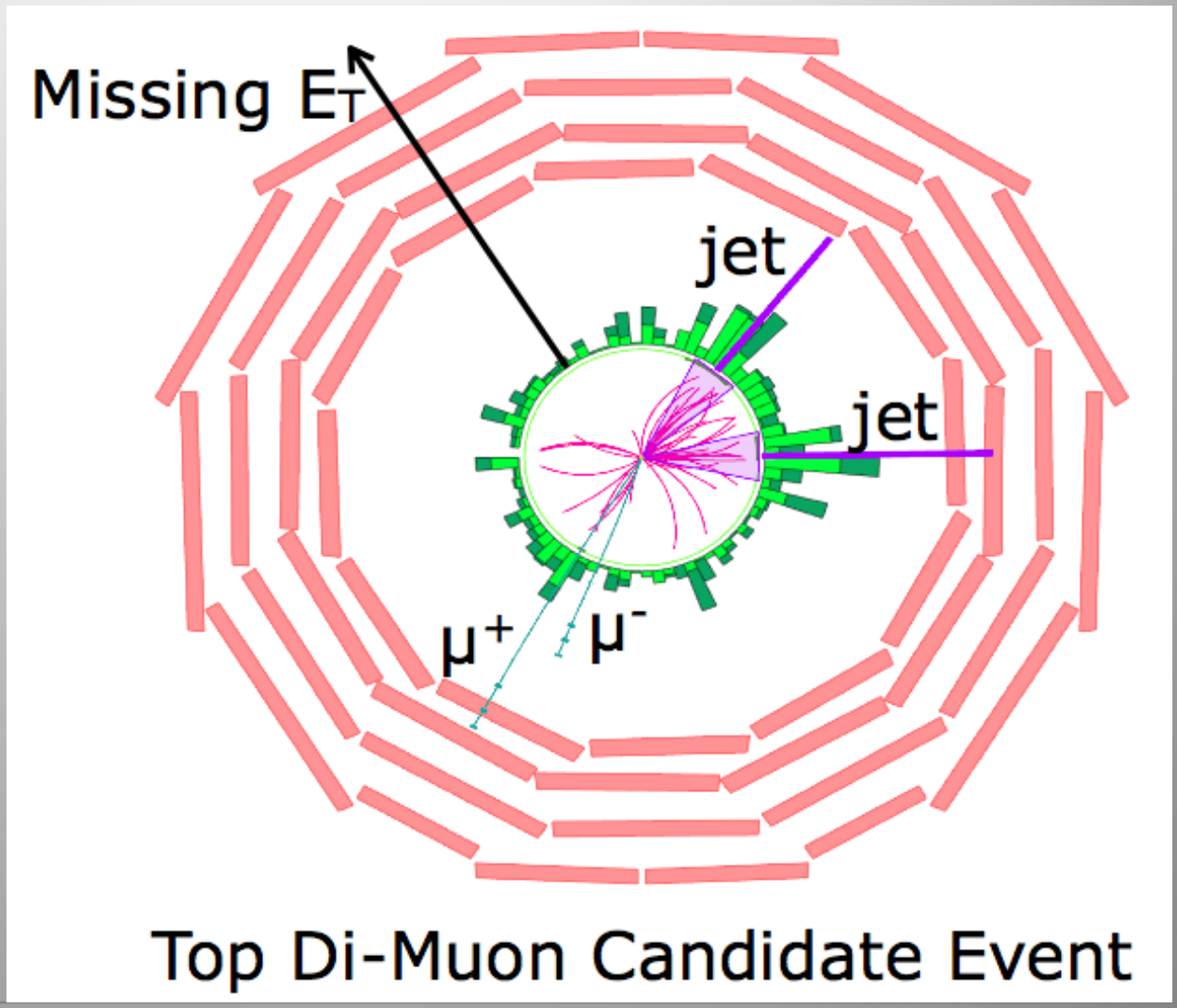
7 TeV pp Collisions



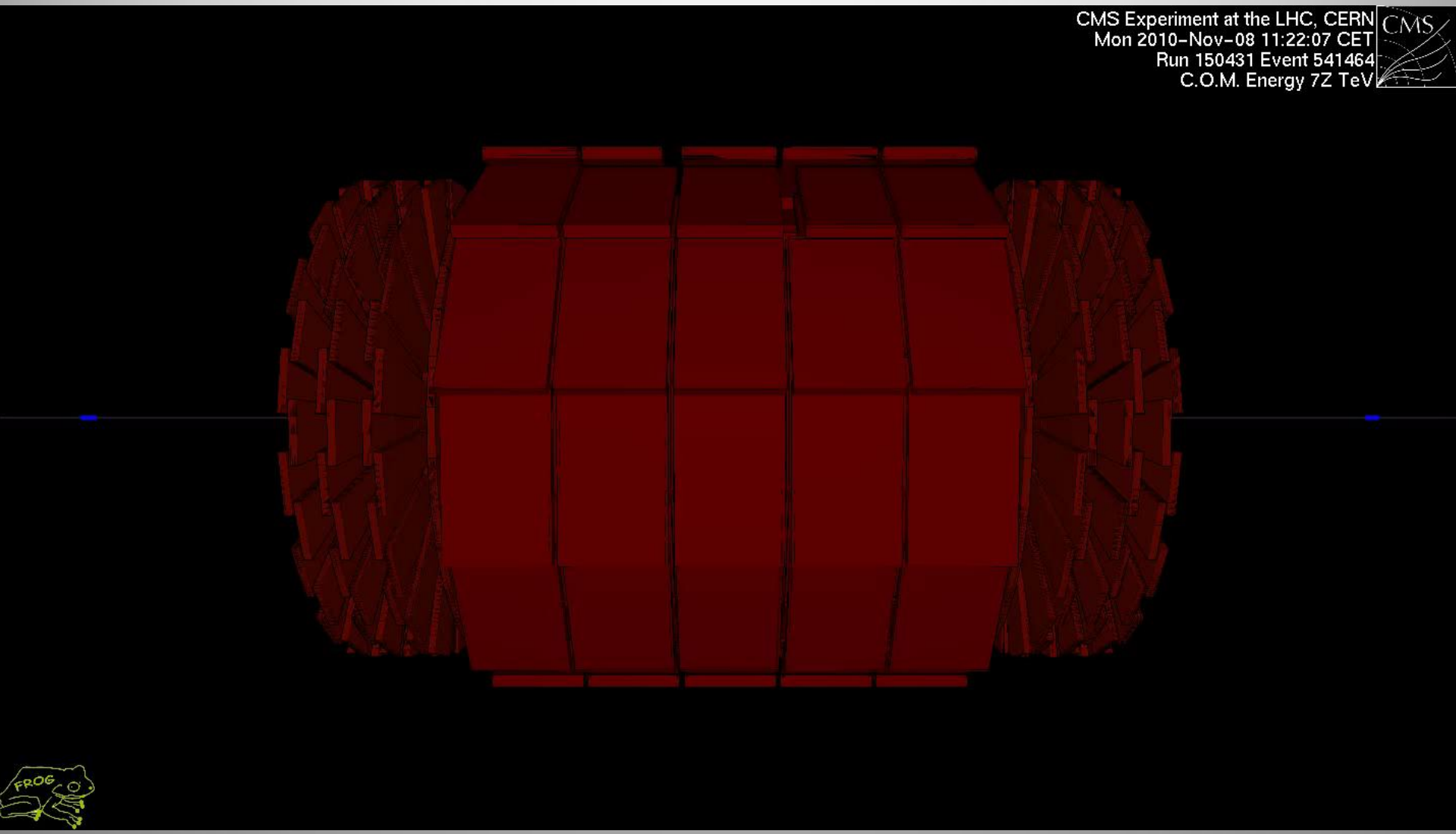
An event containing “top” quarks

Candidate Event for Top Production

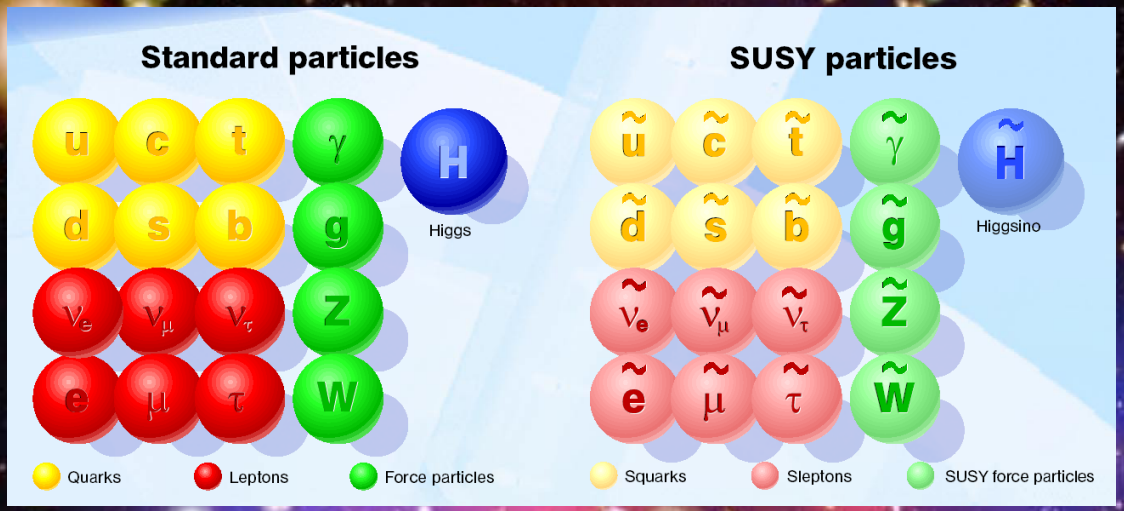




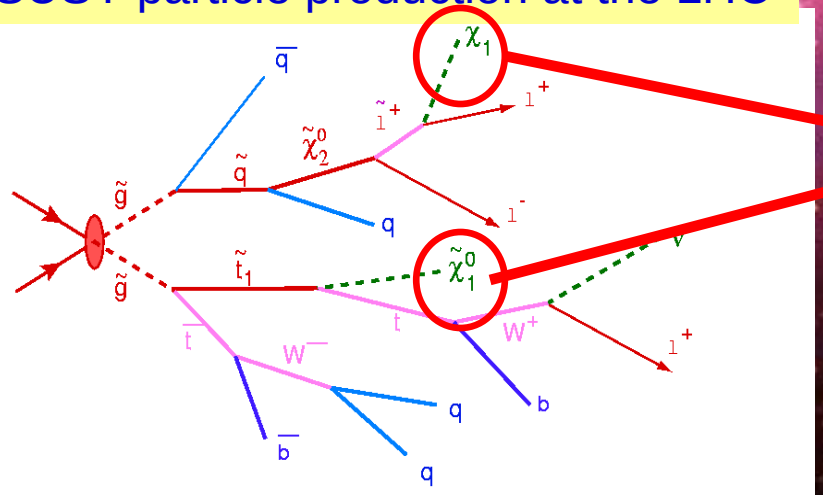
A Recorded Heavy Ion Collision



Supersymmetry: a new symmetry of Nature?

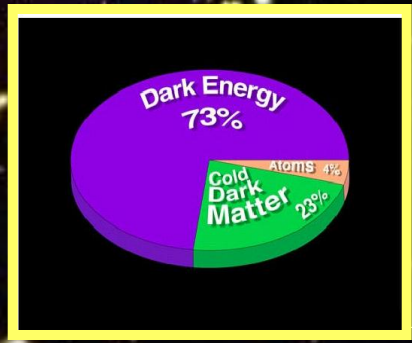


SUSY particle production at the LHC



Assume “R-Parity” Conservation

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



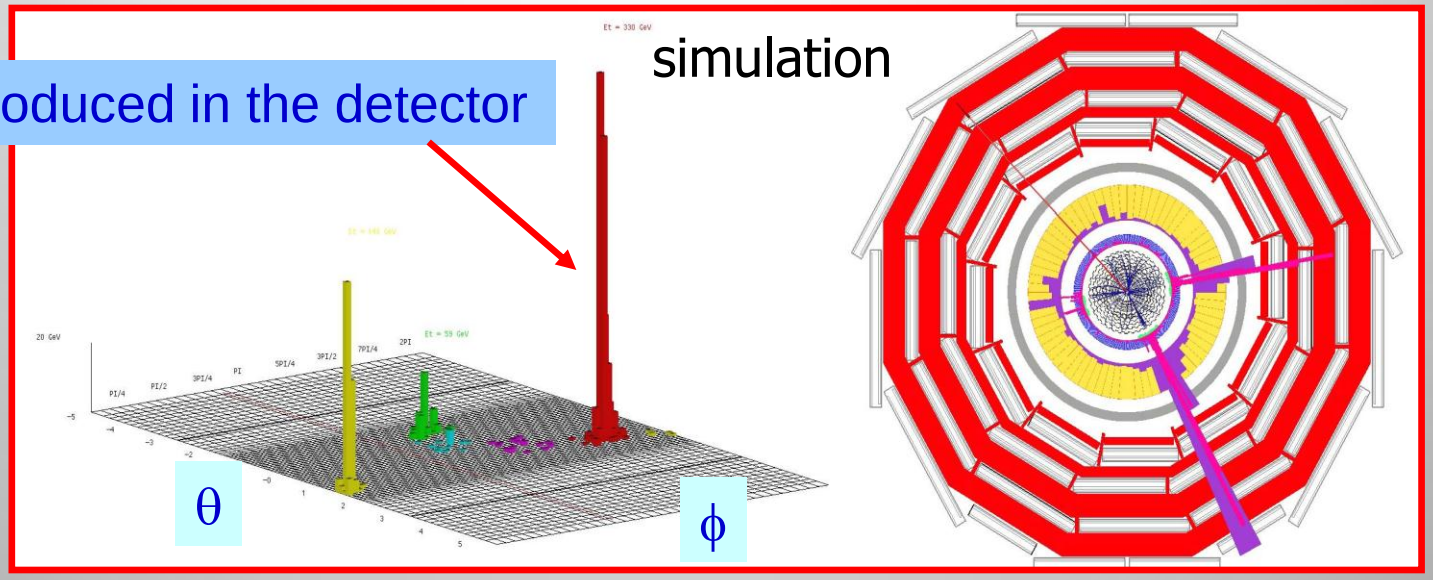
Why weak-scale SUSY ?

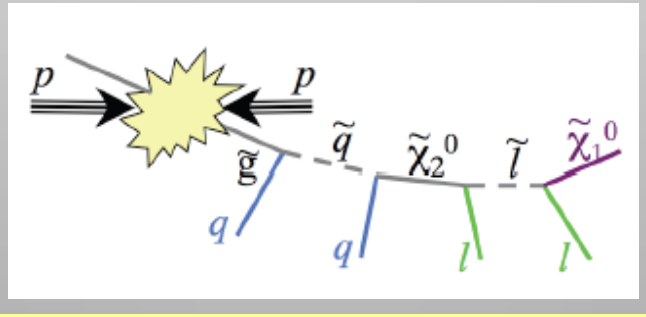
- stabilises the EW scale: $|m_F - m_B| < O(1\ \text{TeV})$
- predicts a light Higgs $m_h \lesssim 130$ GeV
- Predicts/allows gauge unification
- accomodates heavy top quark
- dark matter candidate: neutralino, sneutrino, gravitino, ...
- consistent with Electro-Weak precision data

Discovering SUSY – A revolution in particle physics!!

Detecting Supersymmetric Particles

Energy produced in the detector





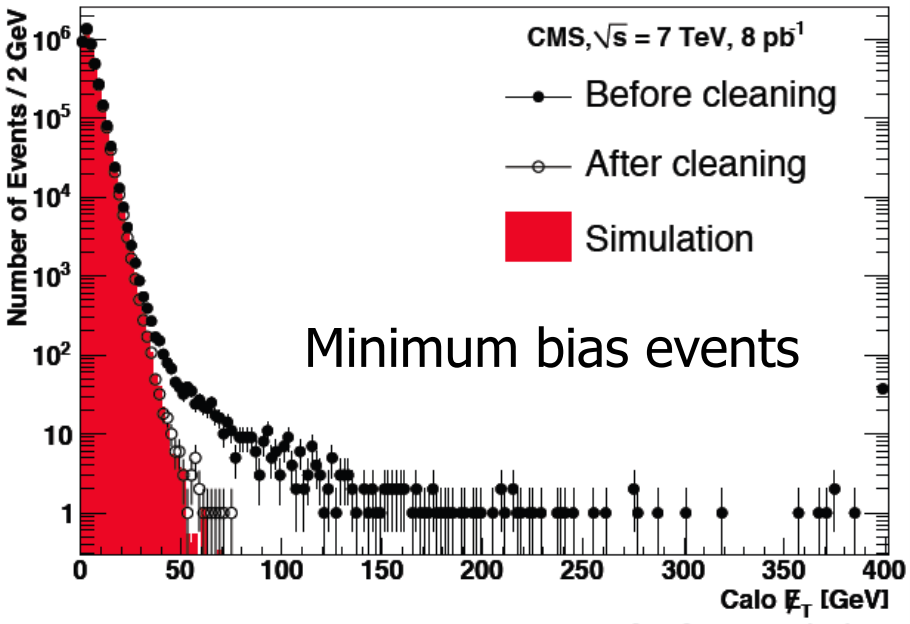
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

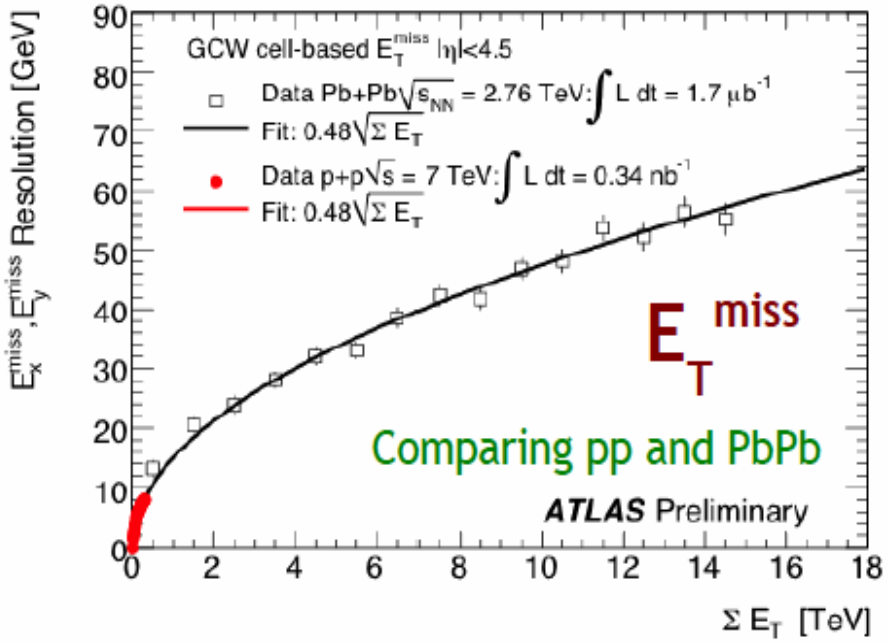
→ Very prominent signatures in CMS and ATLAS

Missing Transverse Energy

Total transverse momentum imbalance

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



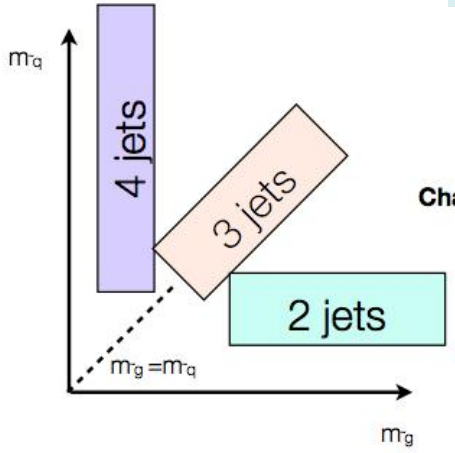


- In practice, rather well under control, from the start
- Good resolution using 'particle flow' ie maximally identifying particles
- More Pile-up in future will NOT make this simpler

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

All Analyses (CMS)



JET+MET (ATLAS)

	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

Note: Strong effort to get background (tail) estimates from data itself

Example: Search for SUSY

Take one example to show steps involved:

- Define event selection criteria
- Go through ~2.000.000.000 events triggered and stored on-line, to select candidates
- Use eg kinematical cuts to suppress background
- “Predict” backgrounds in signal region
- Determine efficiencies and systematics
- Excess or no excess?

Jets+Missing E_T channel

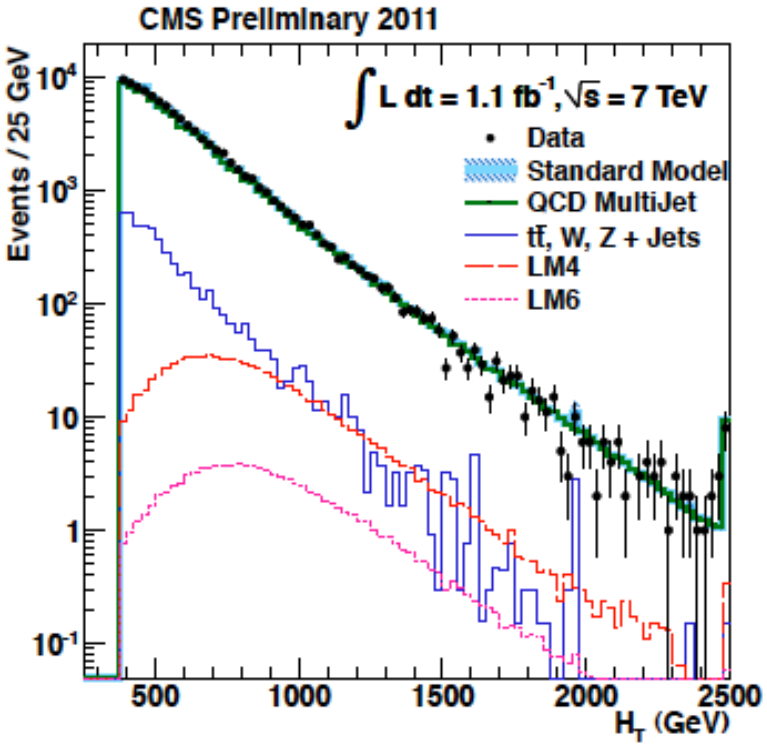
Kinematic Glossary

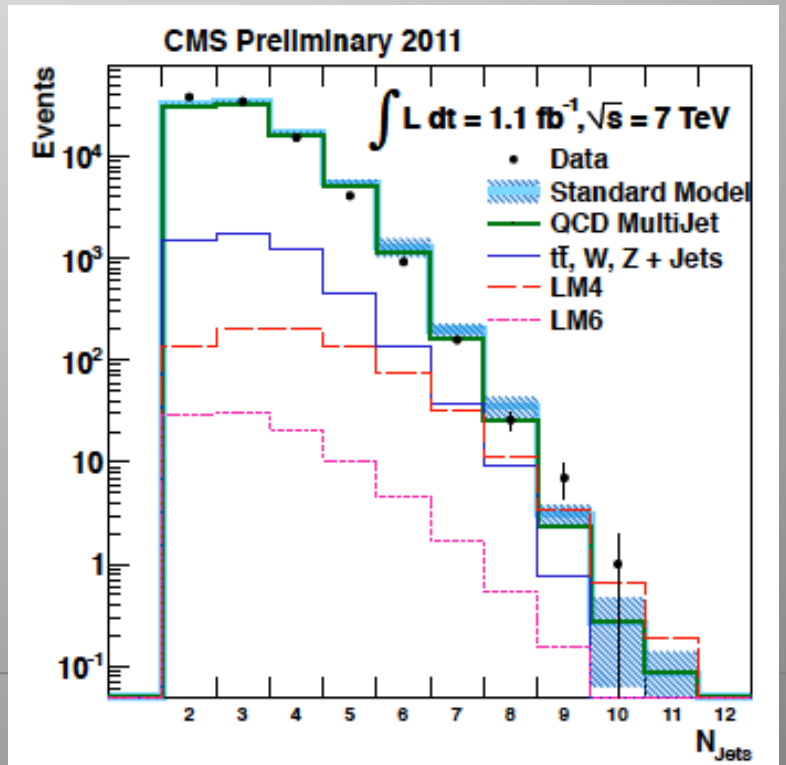
- $HT = \Sigma_j E_T$ Jets with $p_T > 50$ GeV
- $MHT = |- \Sigma_j \vec{p}_T|$ Jets with $p_T > 50$ GeV
- $\Delta\varphi^* = \min_j \Delta\varphi(\text{jet}, \vec{MHT}$ computed without the jet)

Select events with (main cuts)

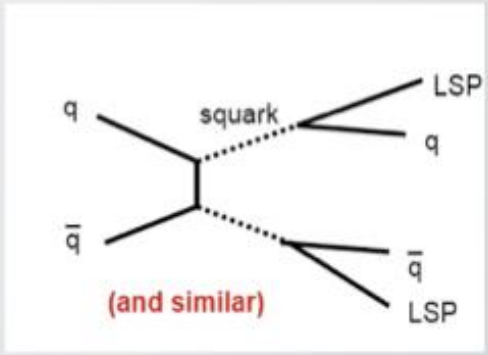
- At least 2 jets with pt>50 GeV;|η|<3
- No leptons (e,μ) present
- $\alpha_T > 0.55$
- HT> 275 GeV

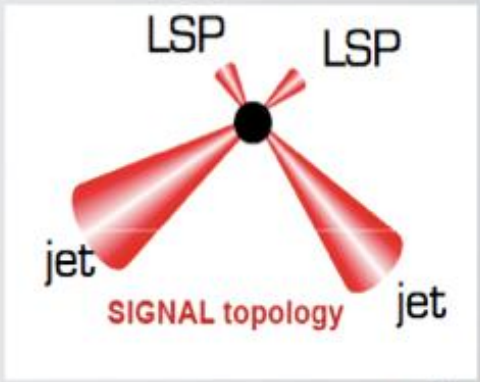
Dominated by background!!

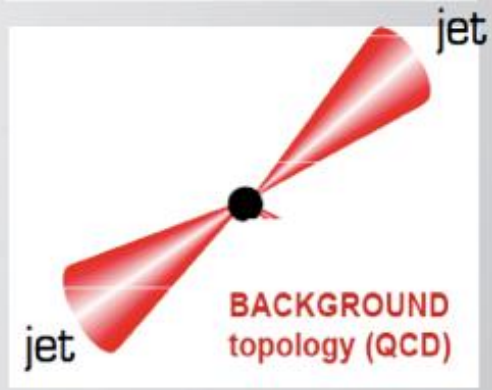




Example: Jets+Missing E_T channel







Simplest topology: 2 jets + missing E_T

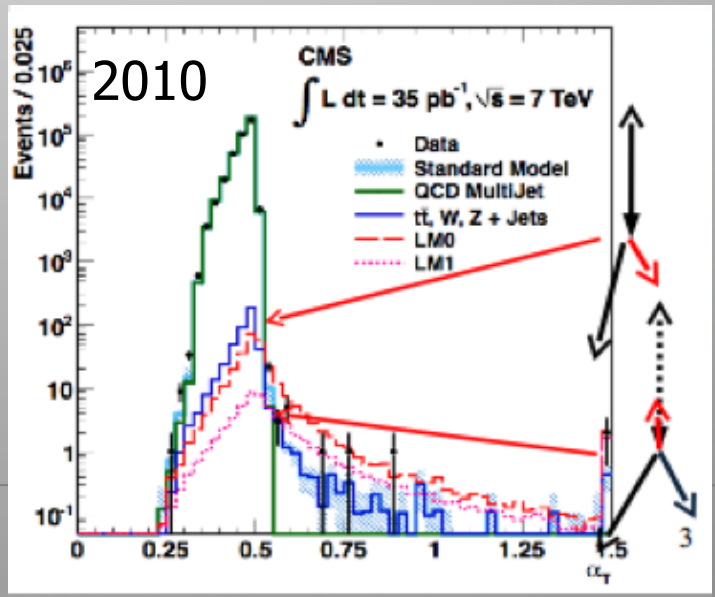
Signal topology is different from the background topology

We define a variable α_T defined as

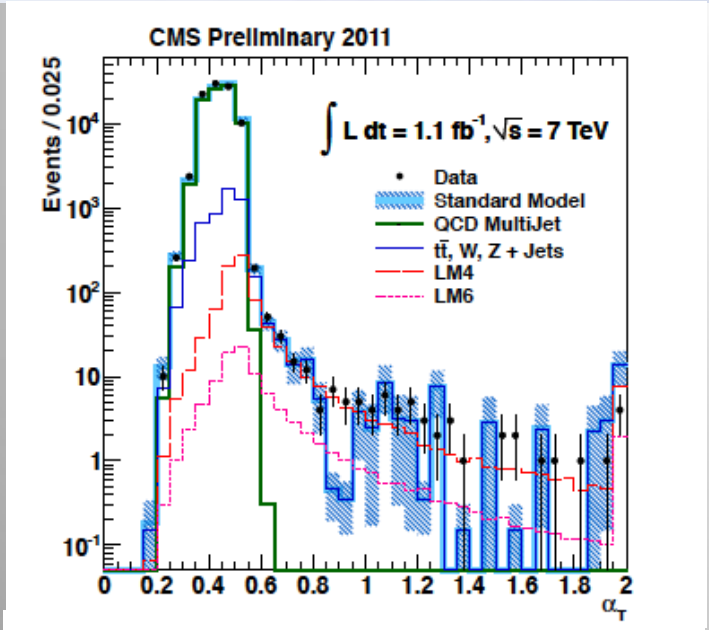
$$\alpha_T = \frac{E_T^{jet_2}}{M_T} = \frac{E_T^{jet_2}}{\sqrt{\left(\sum_{i=1}^{2} E_T^{jet_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{jet_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{jet_i}\right)^2}},$$

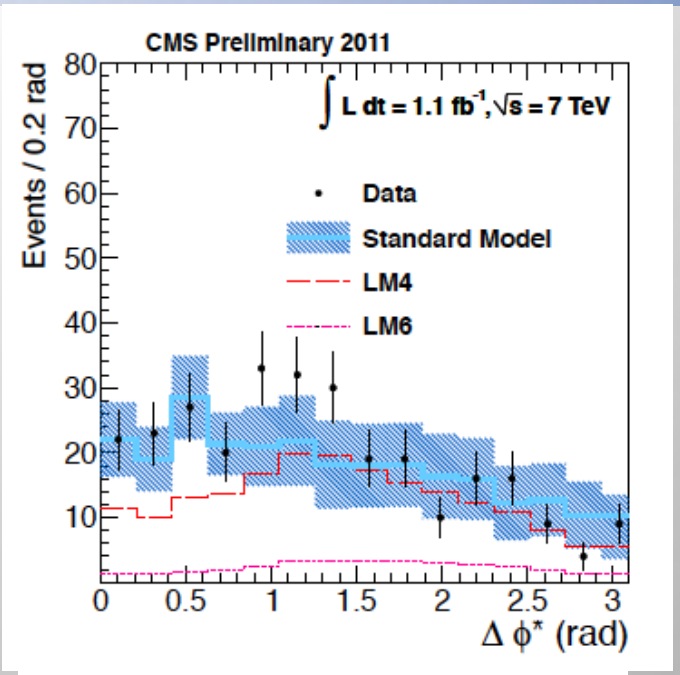
We know from MC studies that α_T <0.5 for QCD

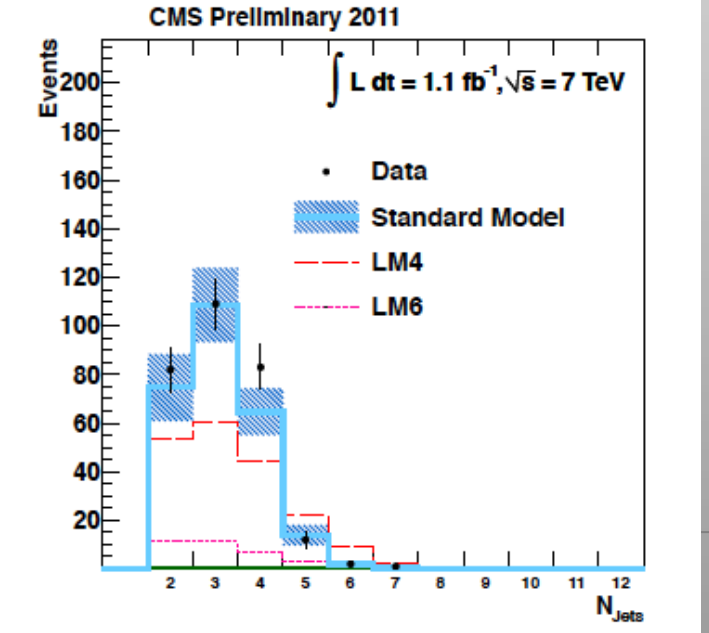
We will select events with α_T >0.55!

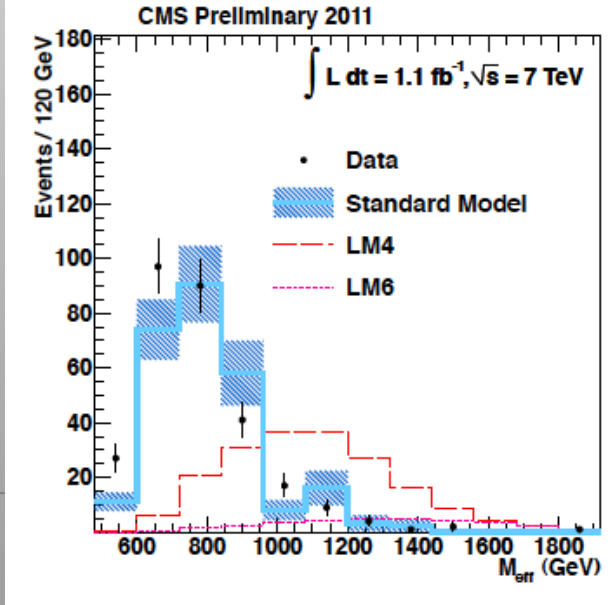


Several Control Variables







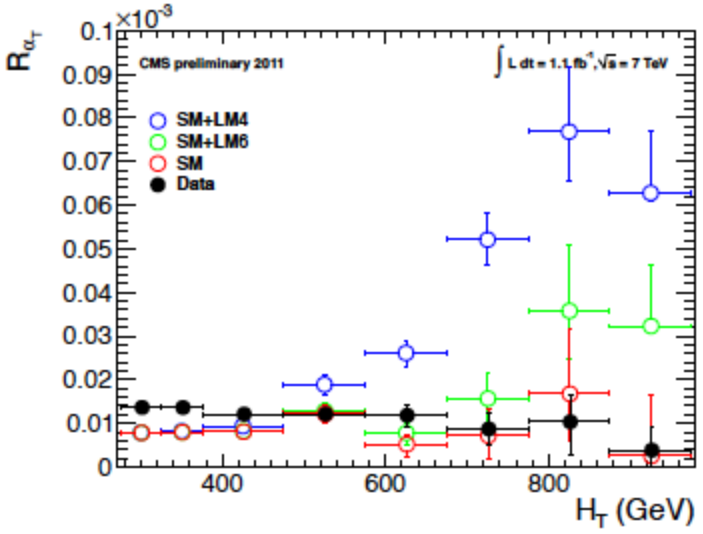


Jets + Missing E_T Channel

H_T Bin (GeV)	275–325	325–375	375–475	475–575
$p_T^{leading}$ (GeV)	73	87	100	100
p_T^{second} (GeV)	73	87	100	100
p_T^{other} (GeV)	37	43	50	50
$\alpha_T > 0.55$	782	321	196	62
$\alpha_T < 0.55$	$5.73 \cdot 10^7$	$2.36 \cdot 10^7$	$1.62 \cdot 10^7$	$5.12 \cdot 10^6$
$R_{\alpha_T}(10^{-5})$	$1.36 \pm 0.05_{stat}$	$1.36 \pm 0.08_{stat}$	$1.21 \pm 0.09_{stat}$	$1.21 \pm 0.15_{stat}$
H_T Bin (GeV)	575–675	675–775	775–875	875–∞
$p_T^{leading}$ (GeV)	100	100	100	100
p_T^{second} (GeV)	100	100	100	100
p_T^{other} (GeV)	50	50	50	50
$\alpha_T > 0.55$	21	6	3	1
$\alpha_T < 0.55$	$1.78 \cdot 10^6$	$6.89 \cdot 10^5$	$2.90 \cdot 10^5$	$2.60 \cdot 10^5$
$R_{\alpha_T}(10^{-5})$	$1.18 \pm 0.26_{stat}$	$0.87 \pm 0.36_{stat}$	$1.03 \pm 0.60_{stat}$	$0.39 \pm 0.52_{stat}$

- Define 8 bins in HT
- Add requirements on the leading and sub-leading jet p_T values

Expect different HT shape for SM background only and signal



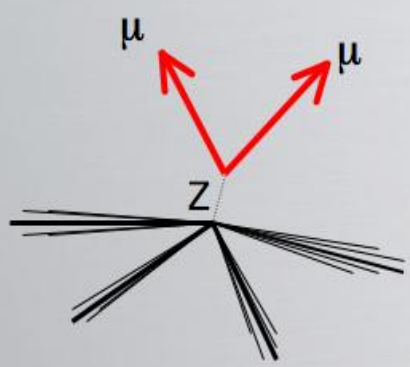
Data Driven Background Estimates

An illustrative example: $Z \rightarrow \nu\nu$+jets

Irreducible background for Jets+E_t^{mis} search

Data driven strategy:

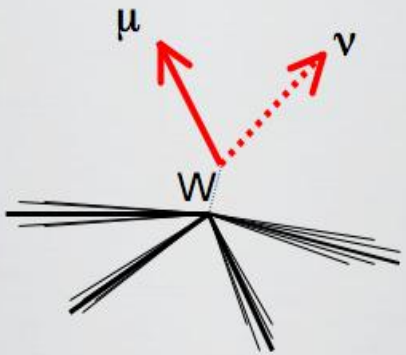
- define control samples and understand their strength and weaknesses



$Z \rightarrow ll$+jets

Strength:
- very clean, easy to select

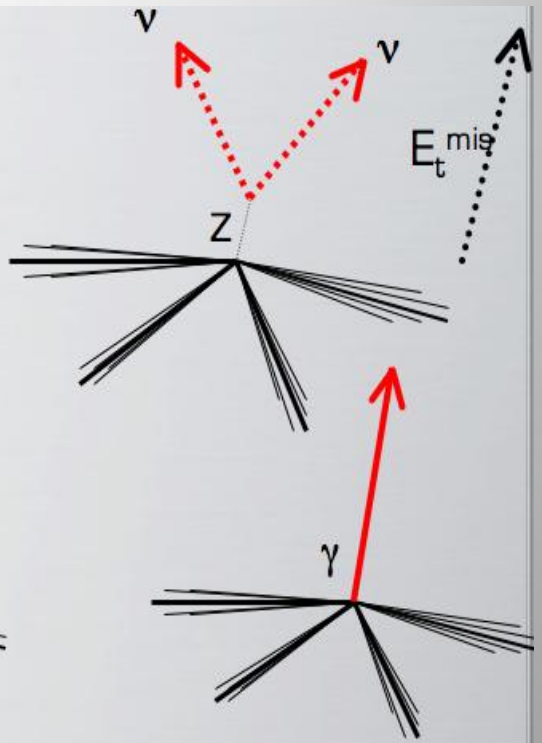
Weakness:
- low statistic: factor 6 suppressed wrt. to $Z \rightarrow \nu\nu$



$W \rightarrow l\nu$+jets

Strength:
- larger statistic

Weakness:
- not so clean, SM and signal contamination



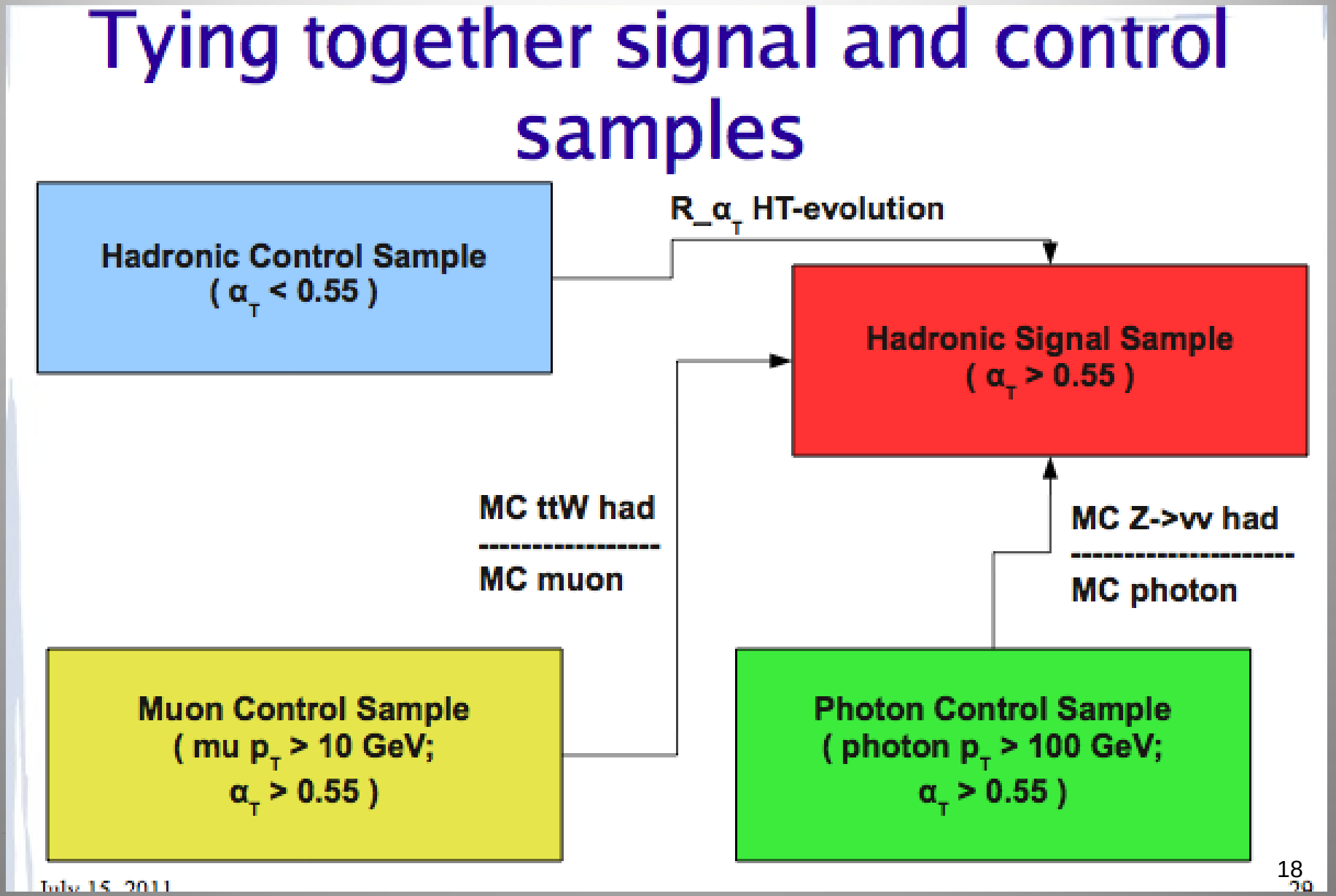
γ+jets

Strength:
- large stat, clean for high E_γ

Weakness:
- not clean for E_γ<100 GeV,
- possible theo. issues for normalization (u. investigation)

All have been used in the data analysis

Analysis Flow



Results

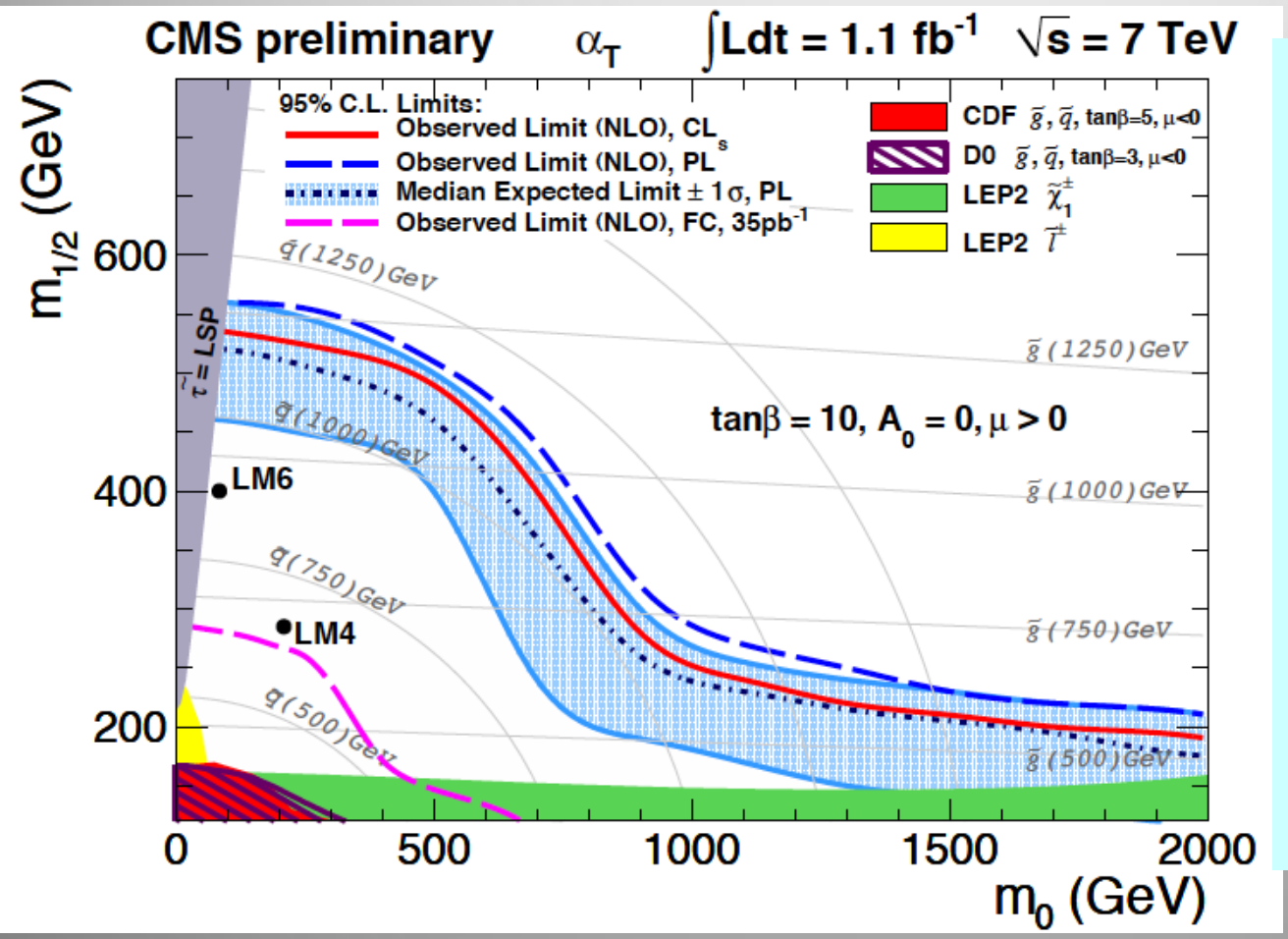
H_T Bin (GeV)	275–325	325–375	375–475	475–575
W + $t\bar{t}$ background	363.7	152.2	88.9	28.8
$Z \to \nu\bar{\nu}$ background	251.4	103.1	86.4	26.6
QCD background	172.4	55.1	26.9	5.0
Total Background	787.4	310.4	202.1	60.4
Data	782	321	196	62
H_T Bin (GeV)	575–675	675–775	775–875	875–∞
W + $t\bar{t}$ background	10.6	3.1	0.6	0.6
$Z \to \nu\bar{\nu}$ background	8.7	4.3	2.5	2.2
QCD background	1.0	0.2	0.1	0.0
Total Background	20.3	7.7	3.2	2.9
Data	21	6	3	1

No excess seen in data compared to predicted background

SUSY Search: Jets + Missing E_T Channel

CMS-SUS-11-003

Using 1 fb^{-1}



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

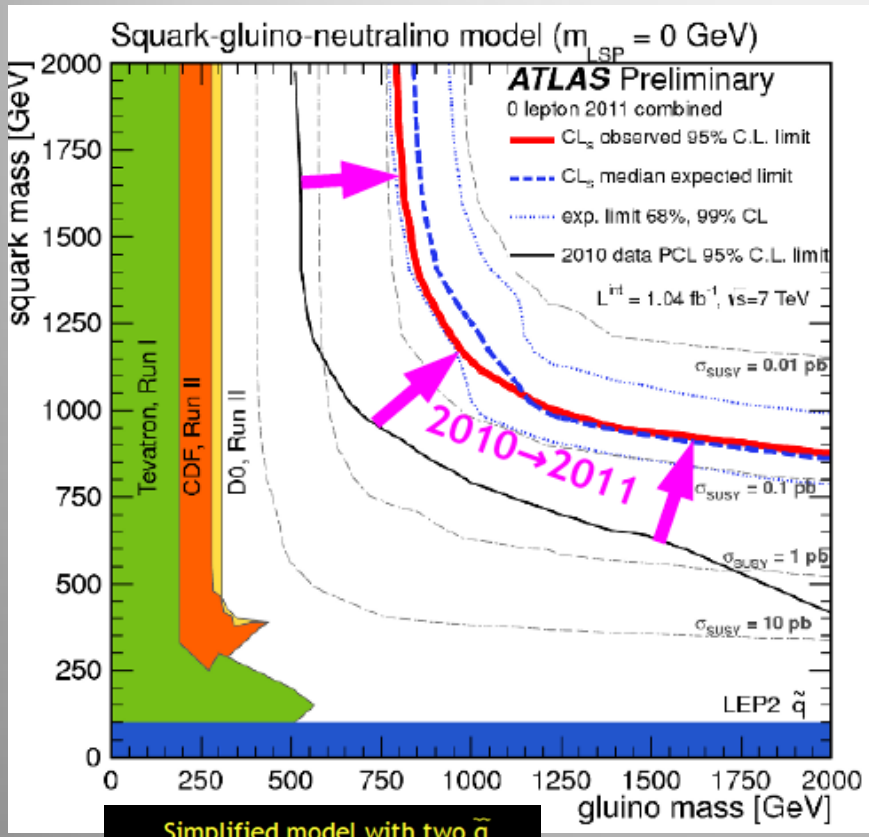
and the sign of Higgs mixing parameterμ

SUSY Search: Jets + Missing E_T Channel

Limits in a simplified model

Using 1 fb^{-1}

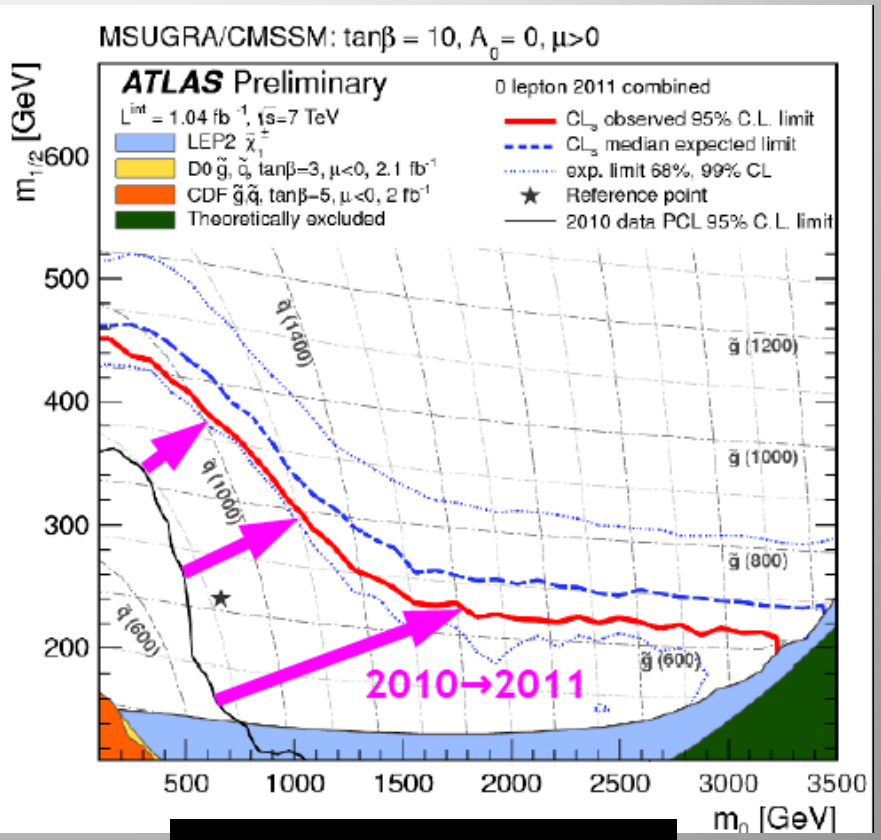
Limits in CMSSM



Simplified model with two $\tilde{q}$ generations, $m(\tilde{\chi}_1^0)$~0

$m_{\tilde{g}}$>800 GeV $m_{\tilde{q}}$>850 GeV

Equal mass case: $m_{\tilde{g}}=m_{\tilde{q}}$>1.075 TeV



MSUGRA/CMSSM: tanβ=10, A_0=0, μ>0

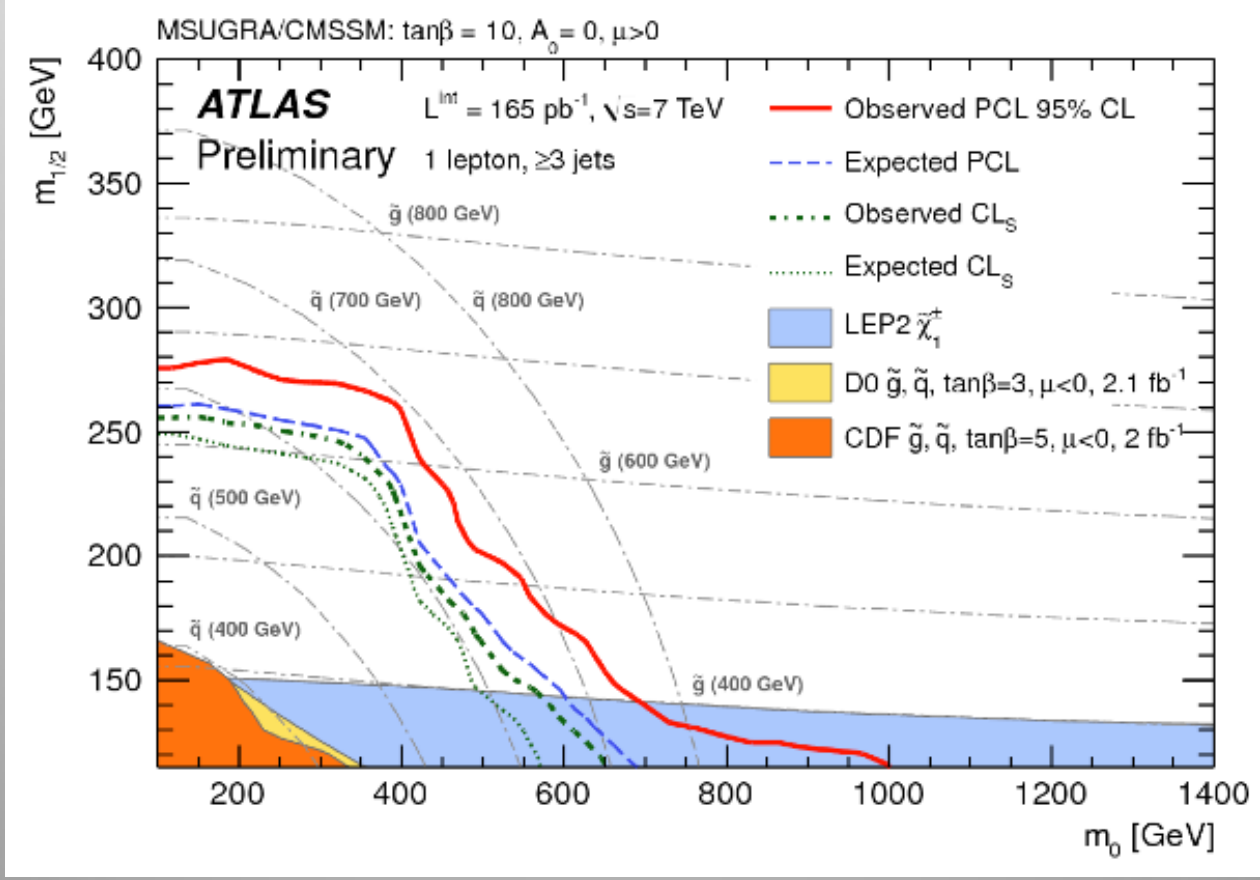
Equal mass case: $m_{\tilde{q}}=m_{\tilde{g}}$ > 980 GeV

Up to masses of 1 TeV excluded for equal gluino-squark masses

Extends the 2010 data limits by ~ 250 GeV

SUSY Search: 1 Lepton + jets + MET

ATLAS-CONF-2011-90



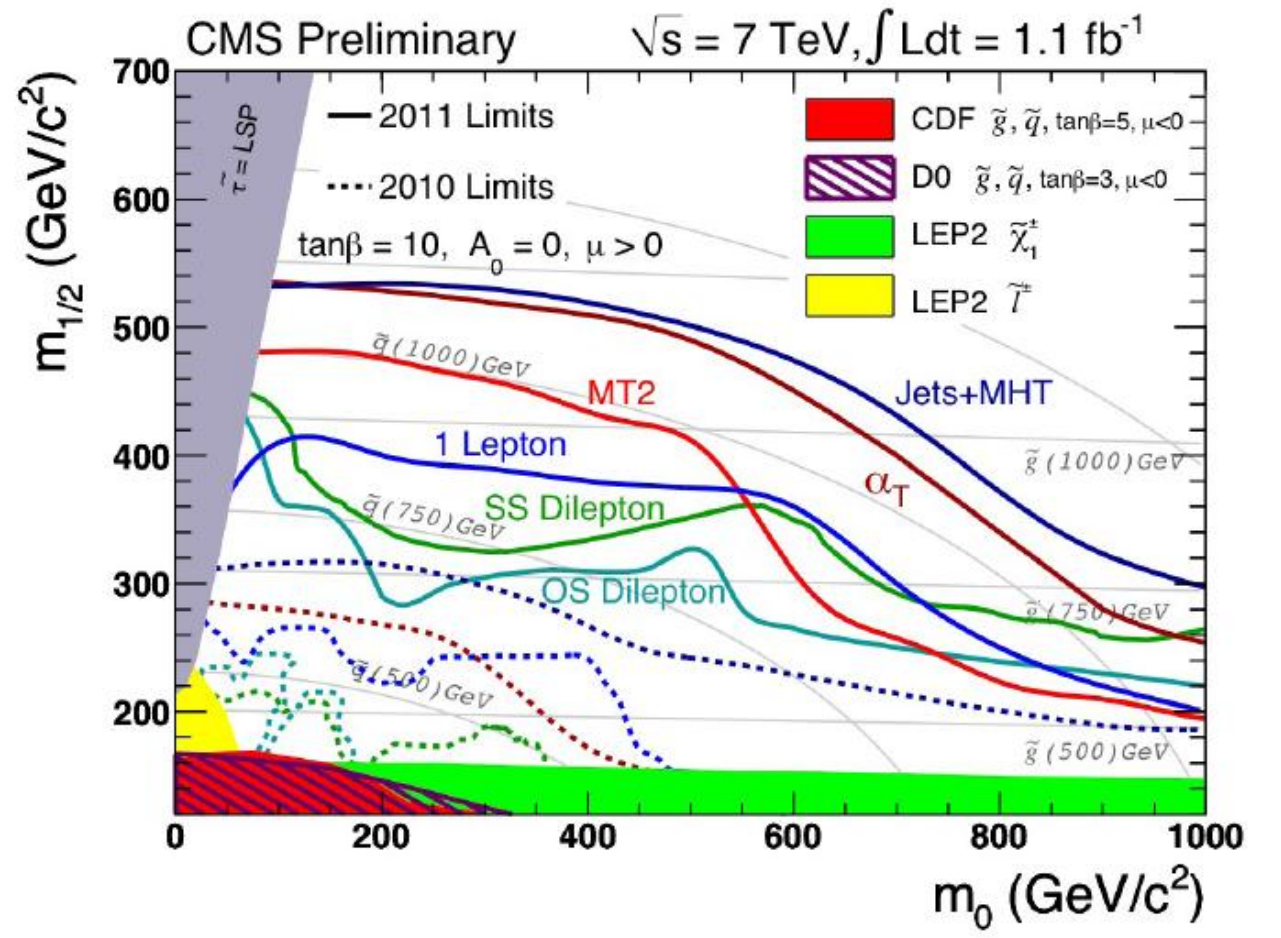
Base on 165 pb^{-1}

In CMSSM: less strong limits

SUSY Search: lepton and hadronic channels

CMS summary of channels with new data

Using 1 fb^{-1}

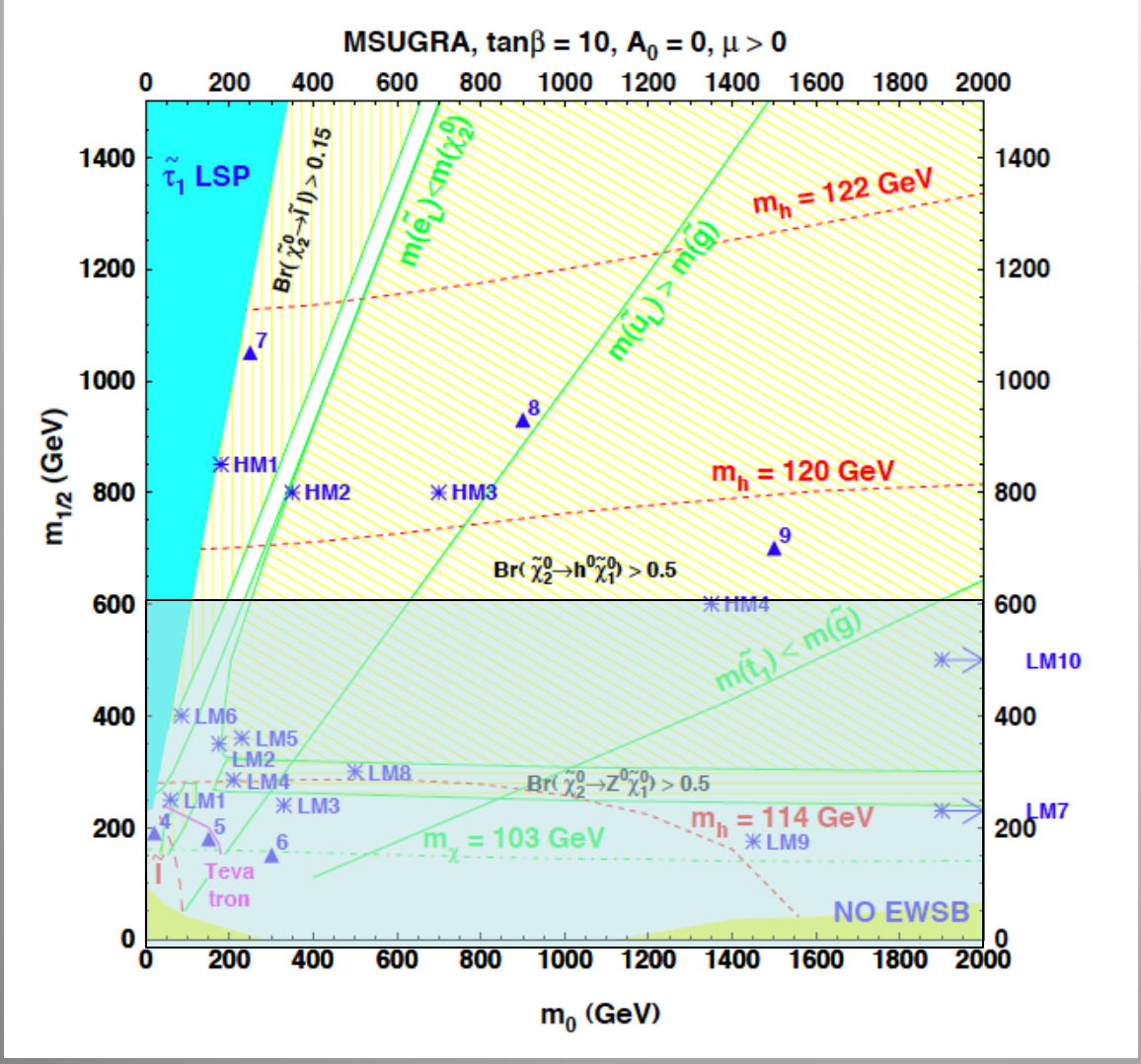


Results of three SUSY analyses completed on full summer 2011 data (α_T , Same Sign and Opposite Sign dileptons).

CMS-SUS-11-003
CMS-SUS-11-004
CMS-SUS-11-010
CMS-SUS-11-011

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

Previous Benchmark Points

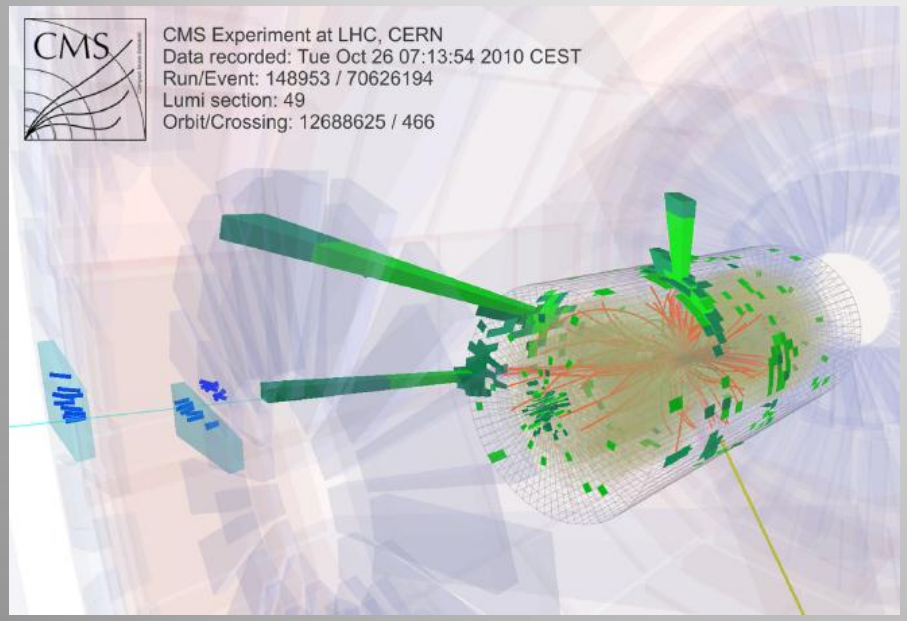


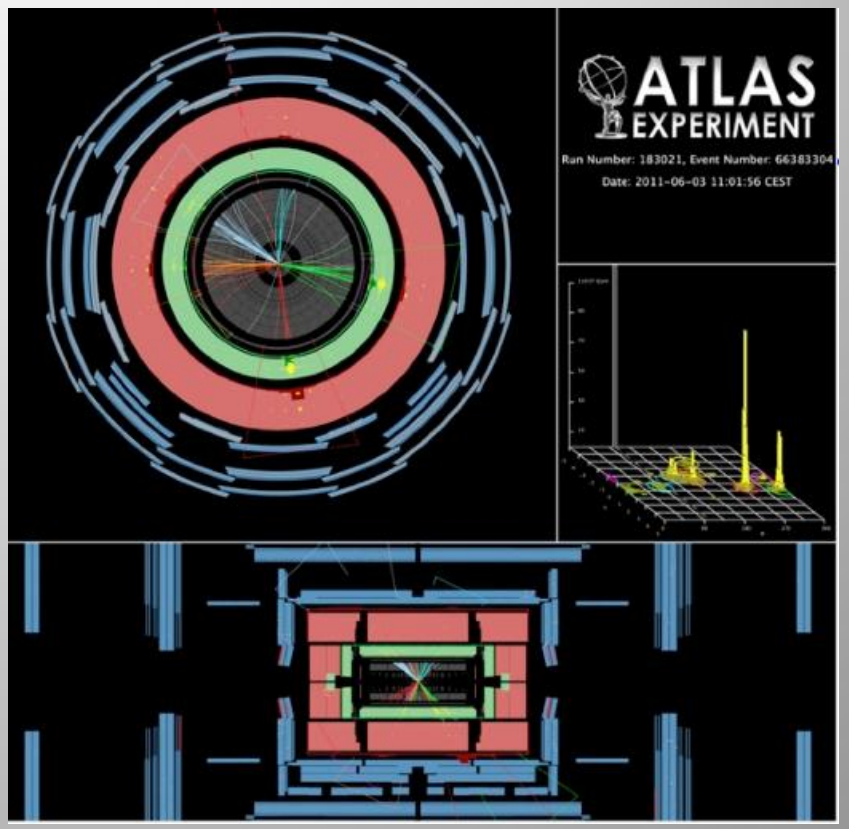
Example CMS

For our 2006 studies we chose 13 benchmark points (LMx, HMx…)

9 of these points are already washed away by the "tsunami" of data this year

…Some Interesting Events…



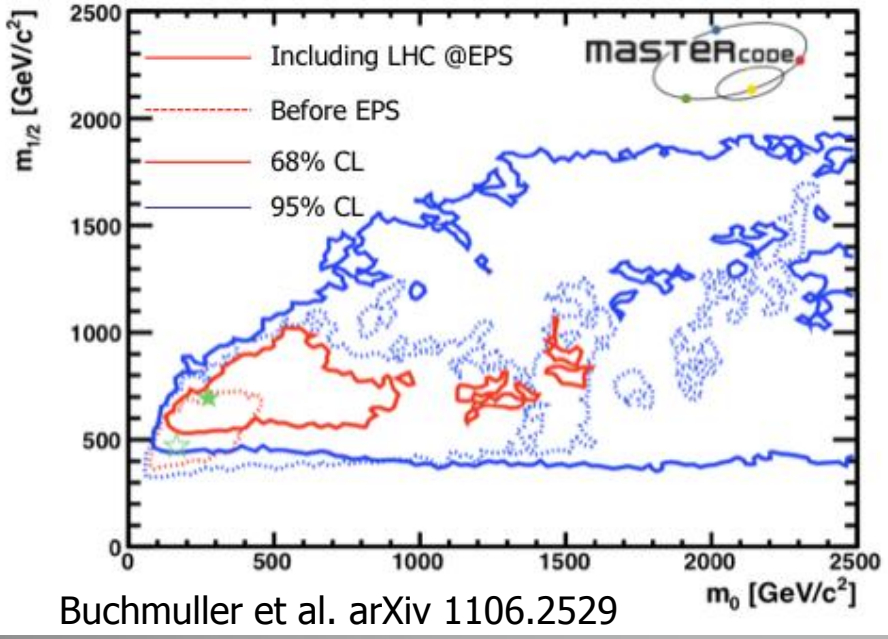


- Events with five jets and large missing transverse energy
- CMS: Total sum of transverse momentum H_T= 1132 GeV and missing transverse energy H_{TMiss} = 693 GeV

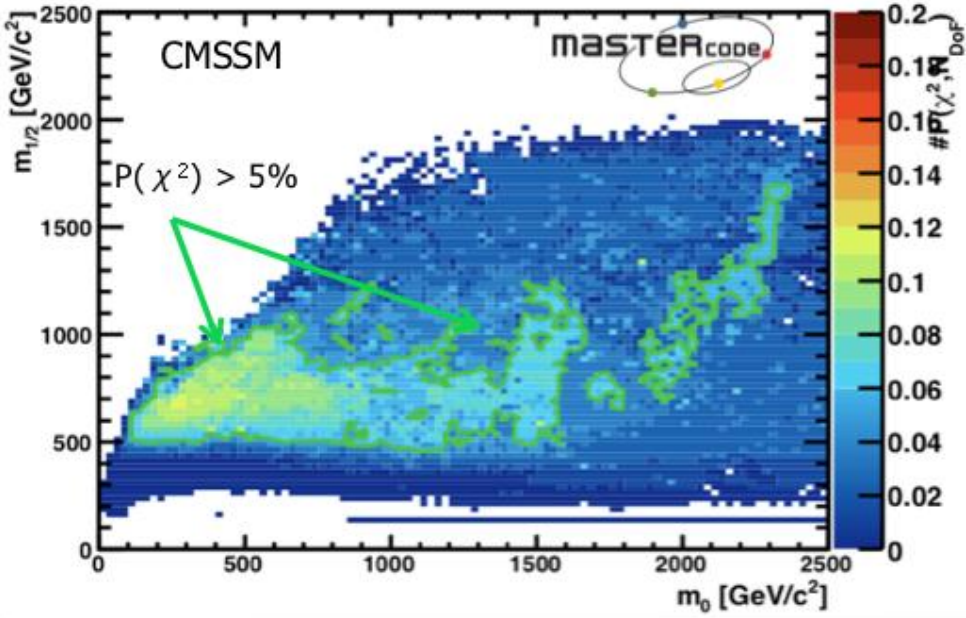
Impact of LHC EPS Results on SUSY

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

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



Buchmuller et al. arXiv 1106.2529



χ^2 probability: P(χ^2) for CMSSM
Before EPS: 16% Including EPS results: <10%

LHC direct searches significantly constrain allowed CMSSM parameter space!

The way the Press sees it (Example)

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27 August 2011 Last updated at 06:41 GMT

5,753 Share

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

Theorists working in the field have told BBC News that they may have to come up with a completely new idea.

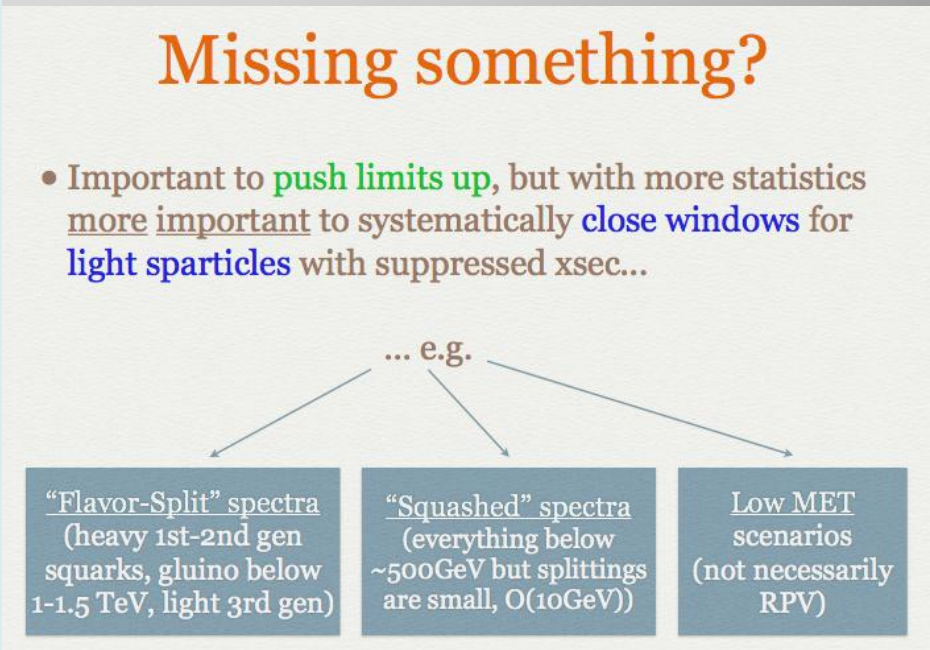
Supersymmetry predicts the existence of mysterious super particles.

A slight wave of panic?

What is Next?

- Think beyond the simplest or most constrained models and optimize searches
  - pMSSM
  - NMSSM
  - Degenerate mass spectra
  - Light 3rd generation
  - Split SUSY
  - RPV SUSY
  - …
- How much of the "theory space" do we really cover? May have to revise our searches for other scenarios
- More ideas at the LPCC Workshop@CERN last week

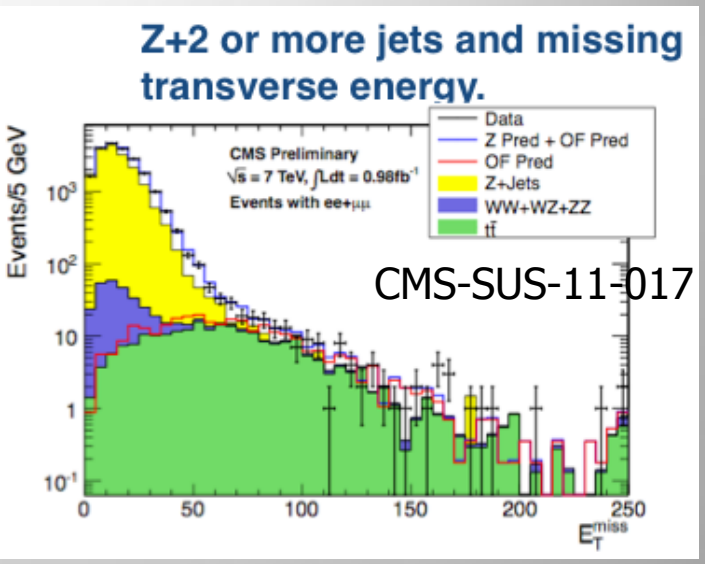
A lot!!



Searches in Different Channels

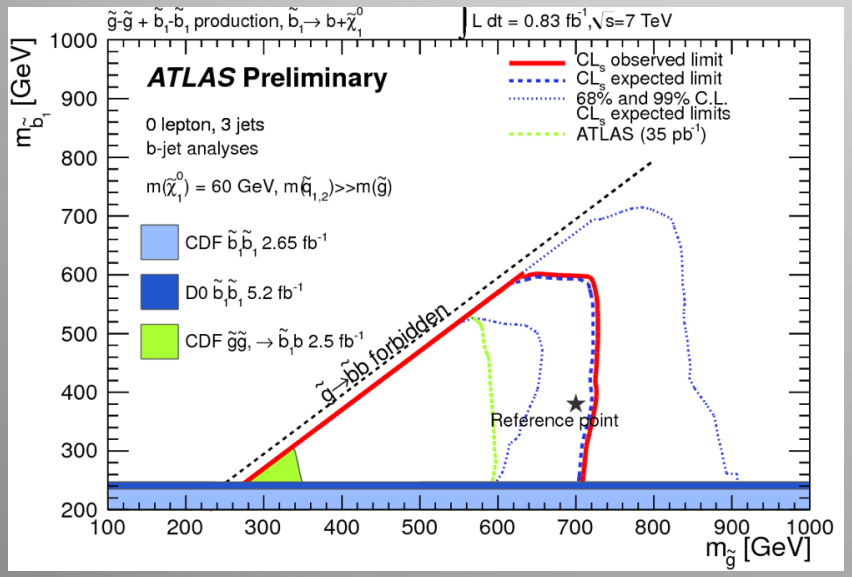
- Extend the searches using also to leptons and jets coming from b-quarks or Z bosons
- Sensitive to different part of the SUSY phase space

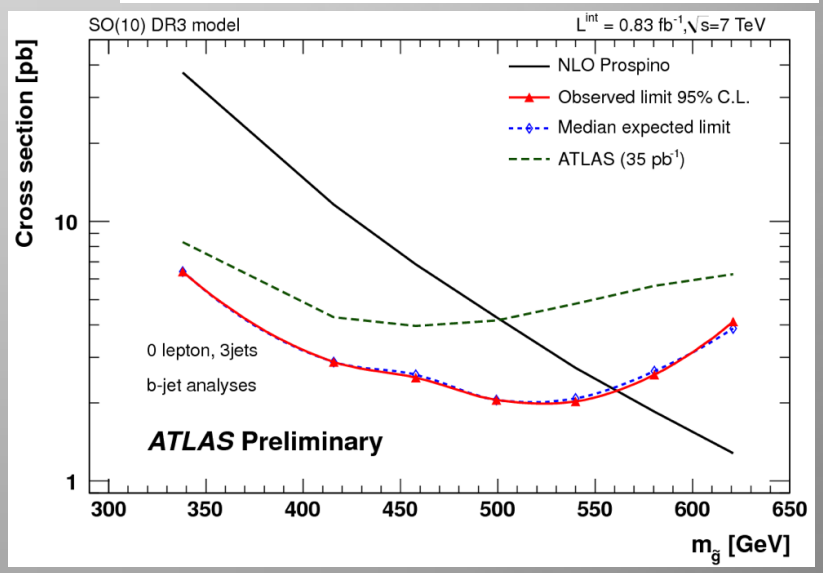
$$\tilde{g}\tilde{g}(production)$$
$$\tilde{g} \rightarrow b\tilde{b}_1$$
$$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$$



CMS-SUS-11-017

ATLAS-CONF-2011-98



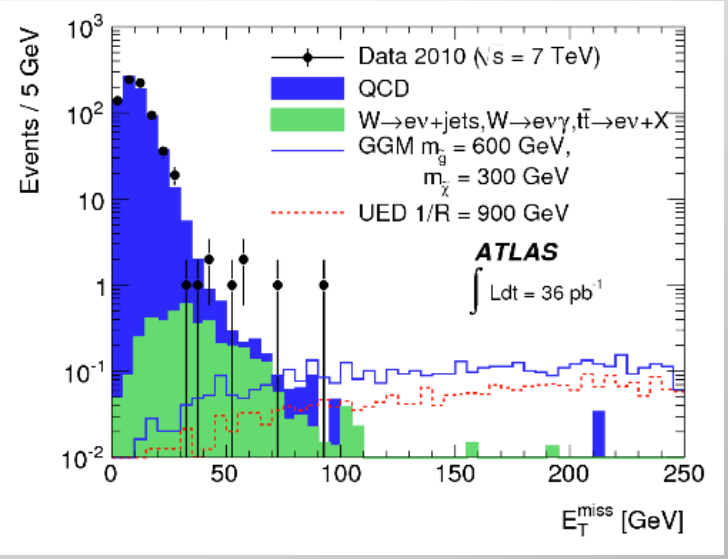


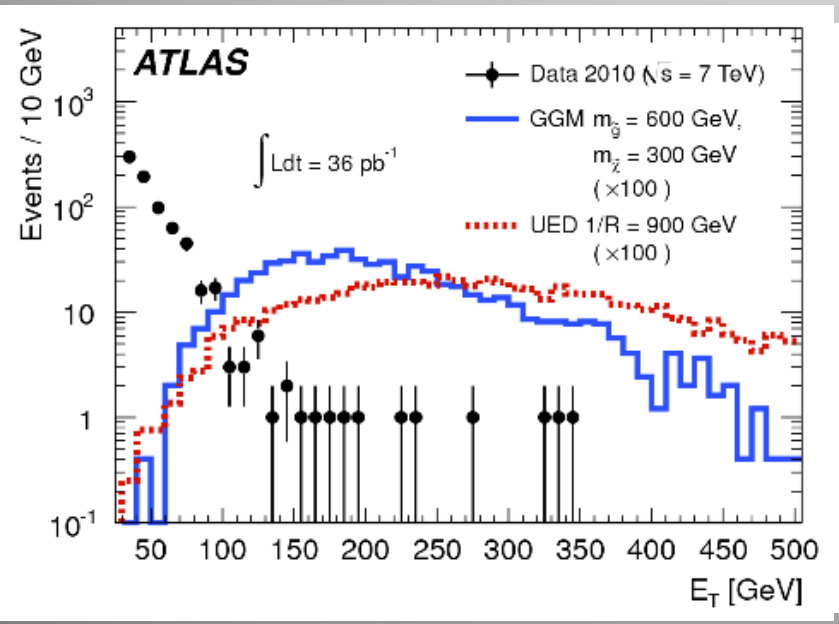
Gluinos have to be heavier than ~ 550 GeV from this search

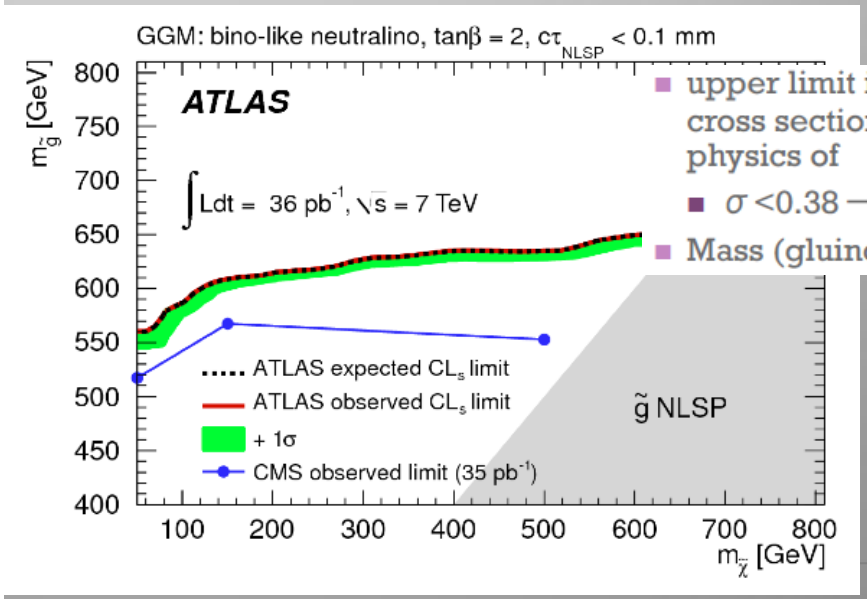
Search for Gauge Mediated SUSY

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$

- 2 photons (p_T>30,20GeV)
- E_T^{miss} > 125 GeV
- N_{signal}=0
- $N_{background}$=0.10 ±0.04(stat) ±0.05(syst)





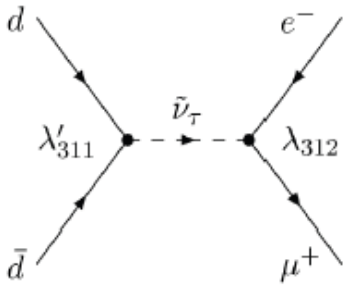


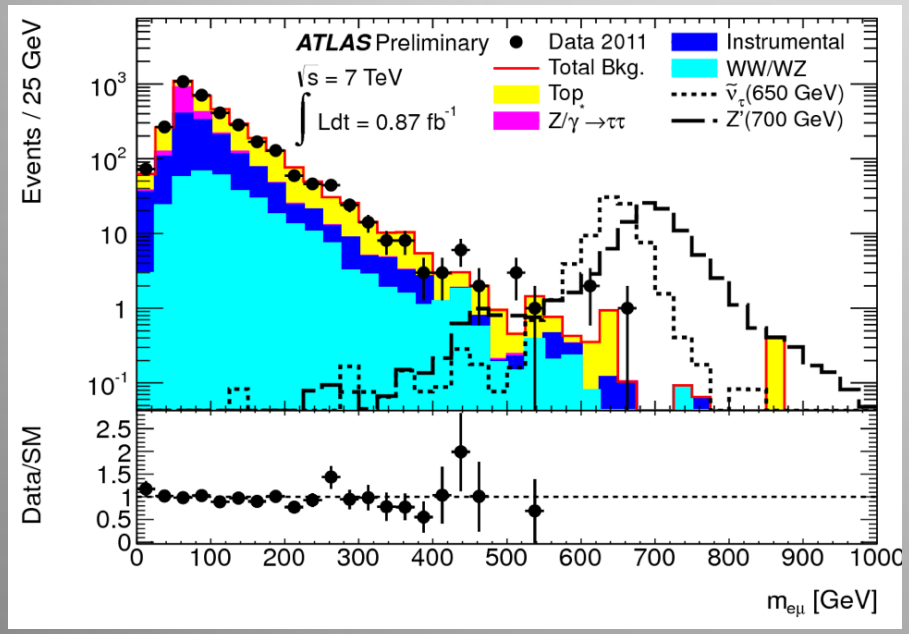
- upper limit is set on the cross section for new physics of
  - σ <0.38 –0.65pb.
  - Mass (gluinos)>560 [GeV]

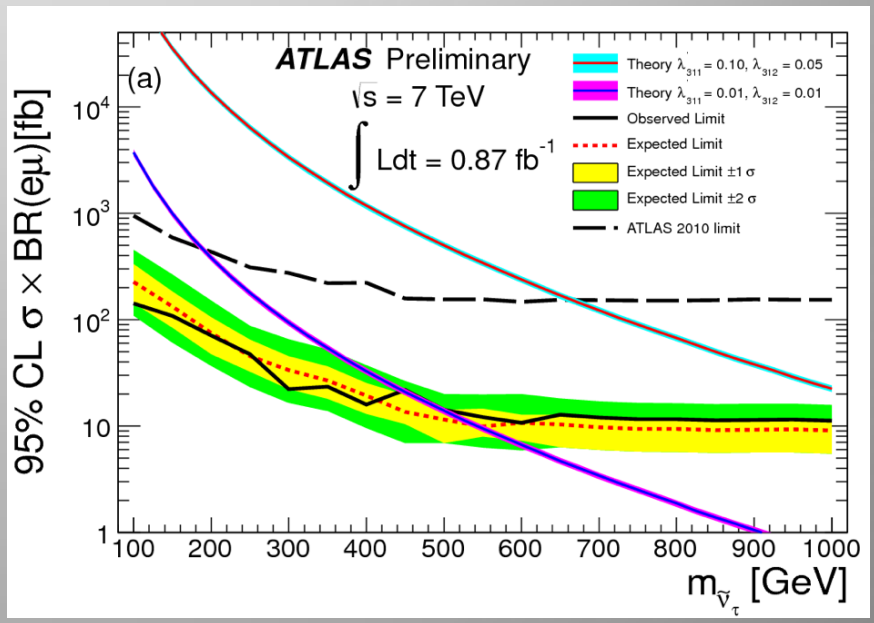
RP Violating SUSY Searches

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

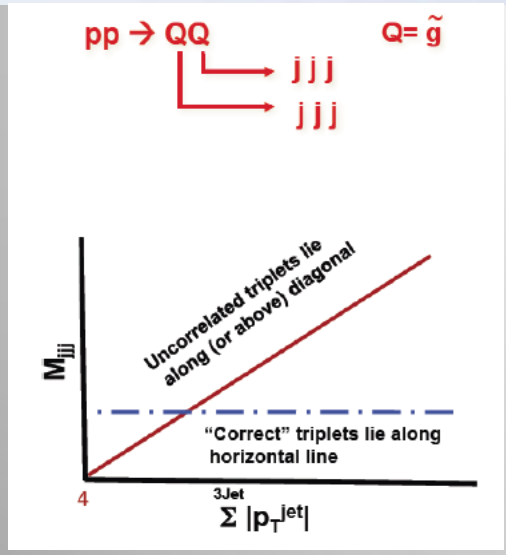






Limits on sneutrino mass between 0.5 and 1 TeV depending on the couplings

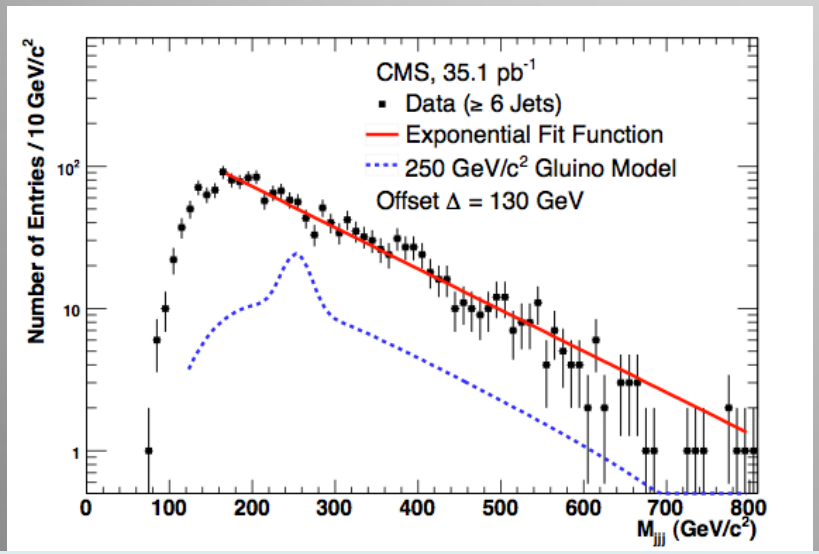
RP Violating SUSY Searches

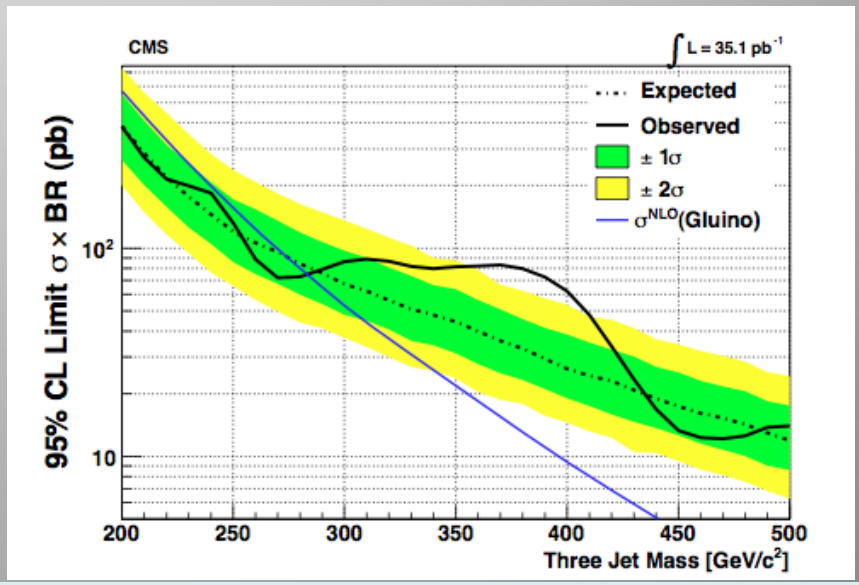


Sparticle decays into 3 jets

- 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



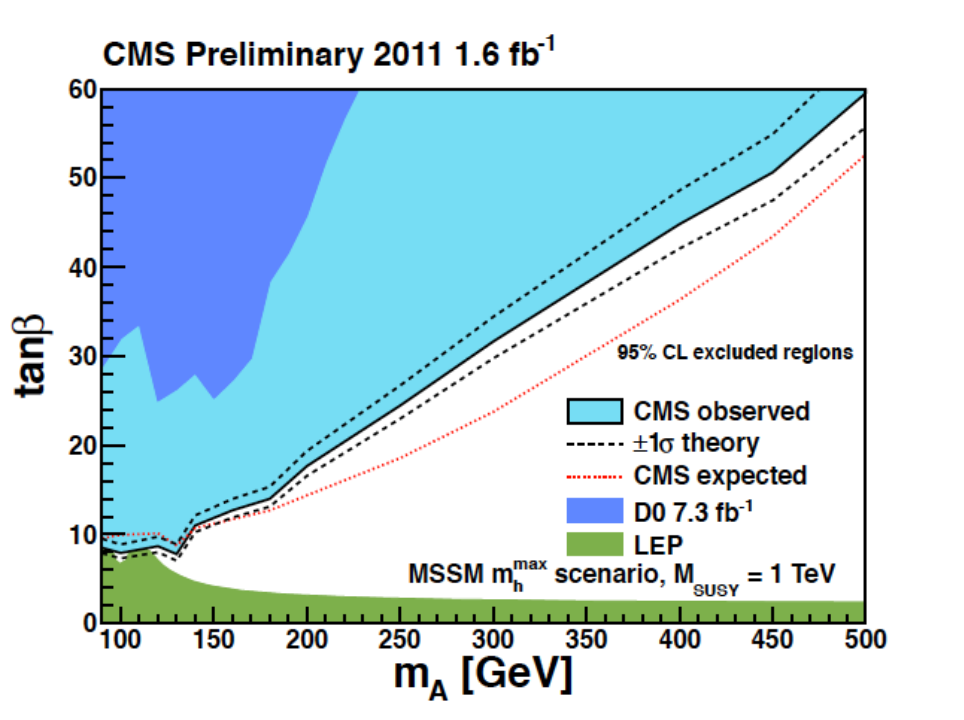


No signal for gluino masses up to 280 GeV

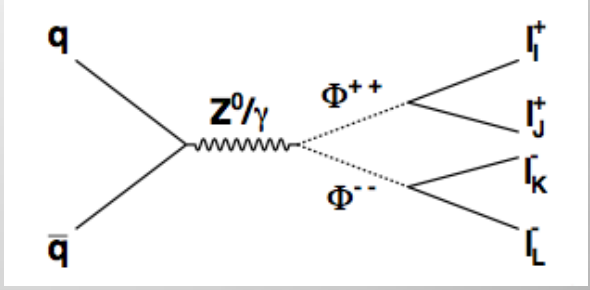
High mass excursion is less than 2σ taking into account look elsewhere effect

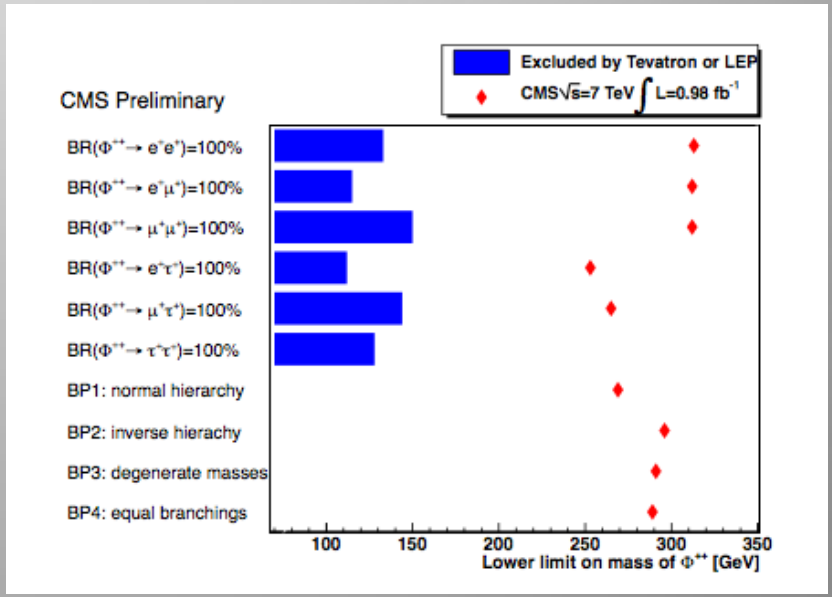
Search for BSM Higgses

MSSM Higgs $\rightarrow \tau\tau$



Double Charged Higgs





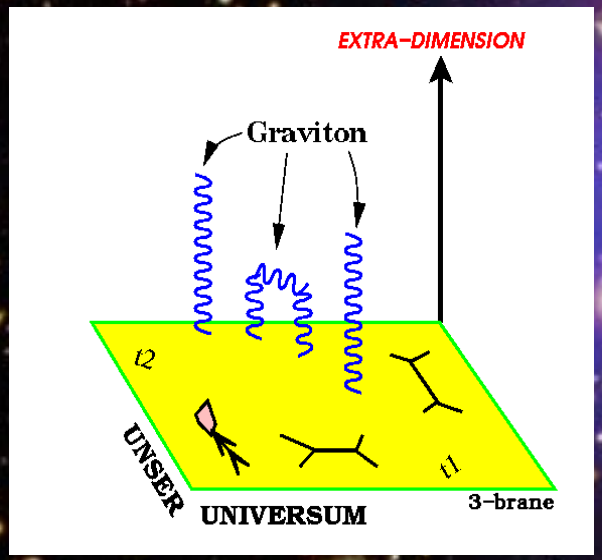
Impressive Exclusion Limits

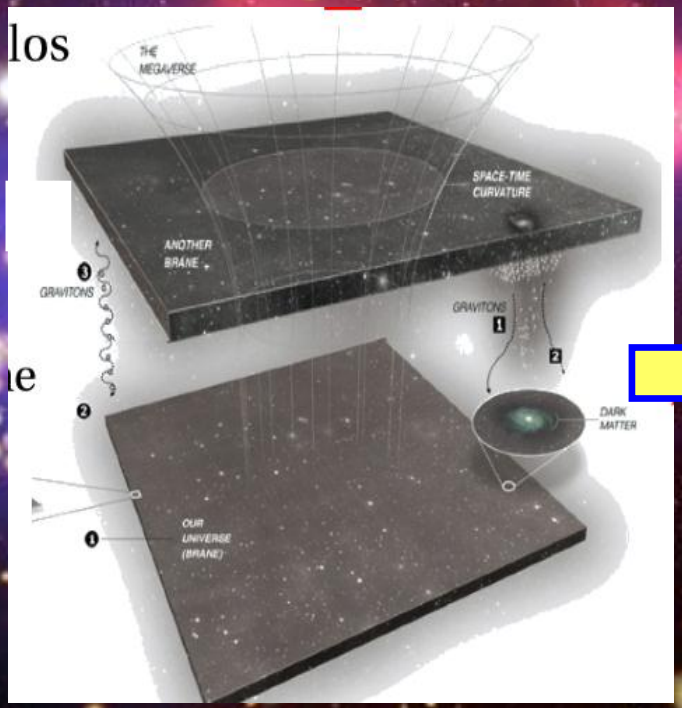
Extra Space Dimensions

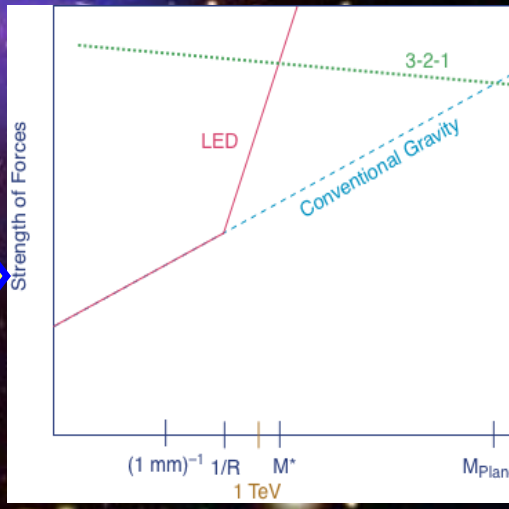
Problem:

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

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







Gravity becomes strong!

Models with Extra Dimensions

Large Extra Dimensions

Planck scale (M_D) ~ TeV

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk

KK-towers (small spacing); KK-exchange; graviton prod.

Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

ADD

Arkani-Hamed Dimopoulos Dvali

Warped Extra Dimensions

RS

Randall Sundrum

5-dimensional spacetime with warped geometry

Graviton KK-modes (large spacing); graviton resonances

Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions

look-like SUSY

SM particles allowed to propagate in ED of size TeV^{-1}

[scenarios: gauge fields only (nUED) or all SM particles (UED)]

Antoniadis

UED

Universal Extra Dimensions

nUED : KK excitations of gauge bosons

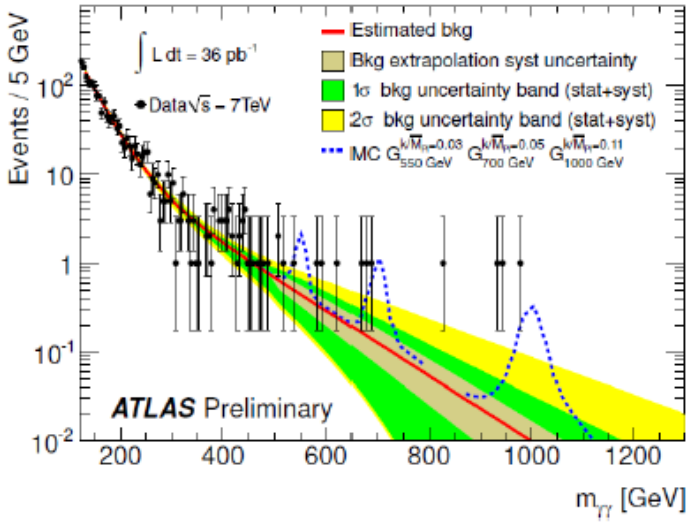
UED : KK number conservation; KK states pair produced (at tree-level) ...

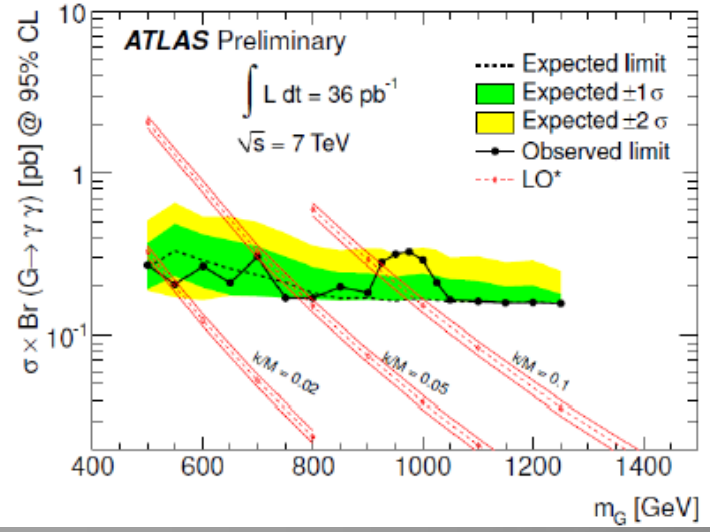
Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

Search for Extra Dimensions

2-photon resonance (RS)

- Benchmark Signal RS Gravitons (G)
- 5-D space-time bound by two 3+1D branes with SM particles localized on one and gravity on the other
- Only G propagate in bulk resulting in massive spin- 2 Kaluza-Klein (KK) excitations
- Narrow intrinsic width if $k/M_{Pl}<0.1$ (k is space-time curvature in ED)
- Graviton decays to SM fermions or bosons: Diphoton branching fraction is twice higher than dilepton one
- Data consistent with SM predictions
- Limit @ 95% CL >920(545) GeV for $k/M_{Pl}=0.1(0.02)$

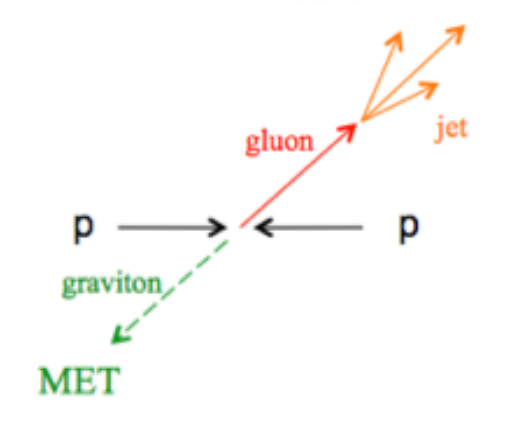




ATLAS-CONF-2011-044

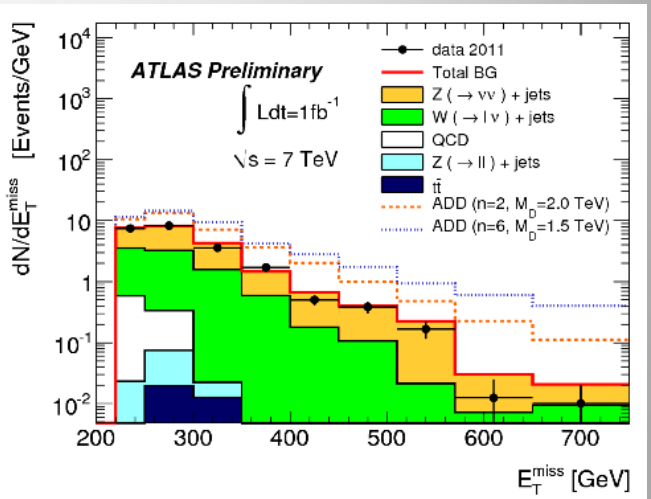
Search for Extra Dimensions

Mono-jet final state +Missing E_T (ADD)

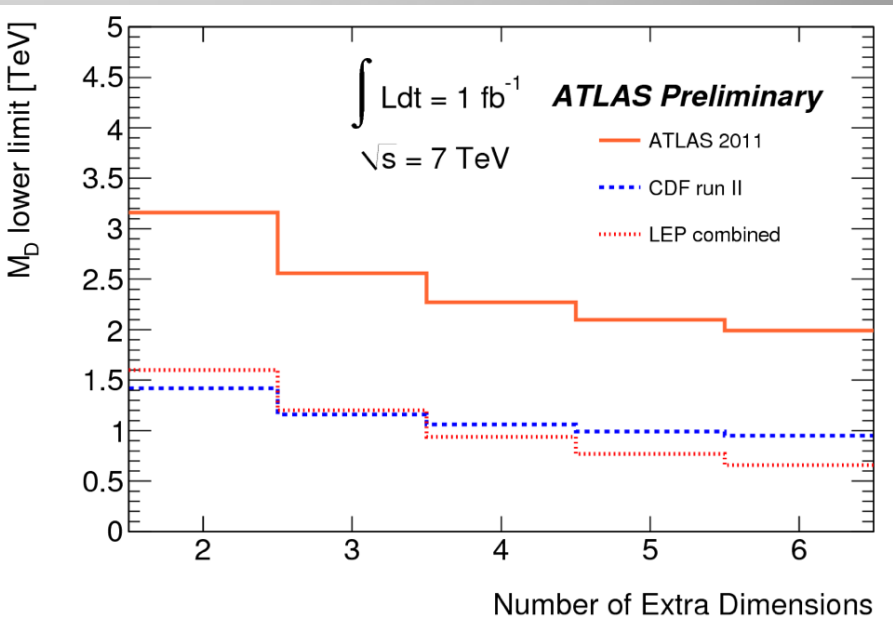


ATLAS-CONF-2011-95

p_T jet > 250 GeV
MET > 220 GeV

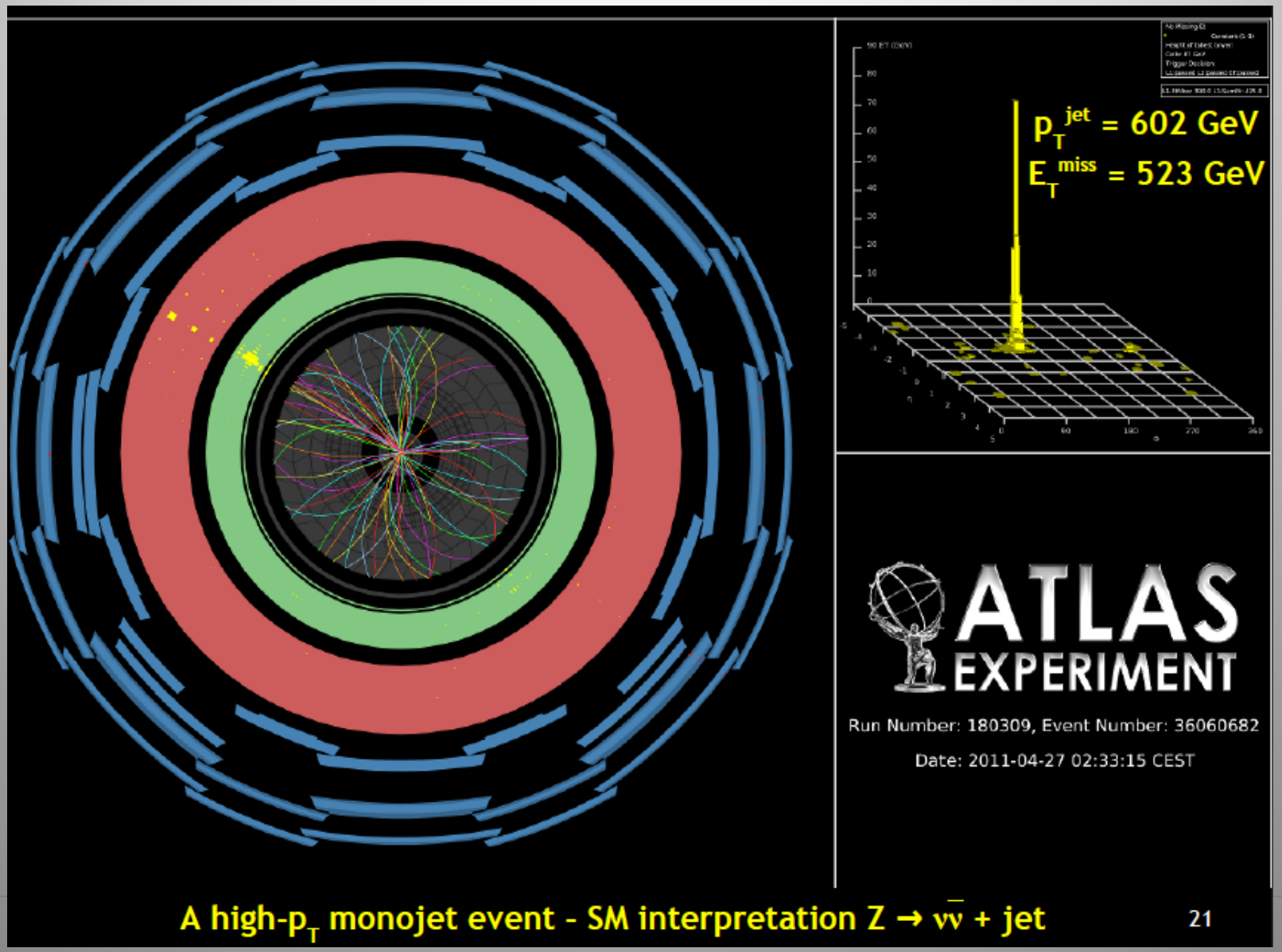


Lower Limit on the Planck Scale versus number of extra dimensions



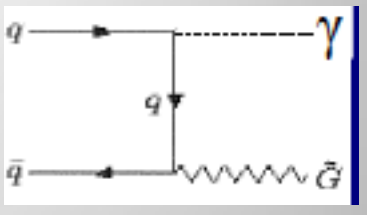
Limits on M_D between 2 and 3 TeV

A High p_T Mono-jet event



Search for Extra Dimensions

Mono-photon final state +Missing E_T (ADD)

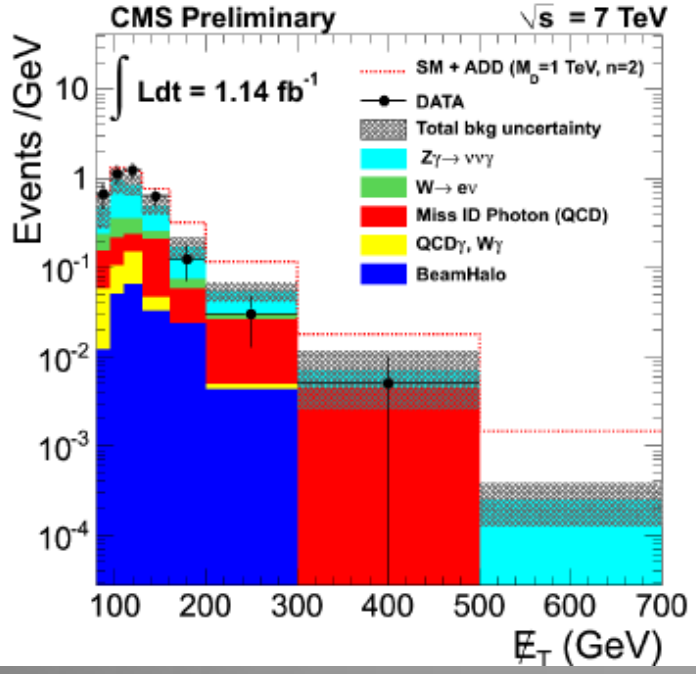


- Large Extra-D (ADD):
  - → Graviton escape detector
- Similarly to monojet:

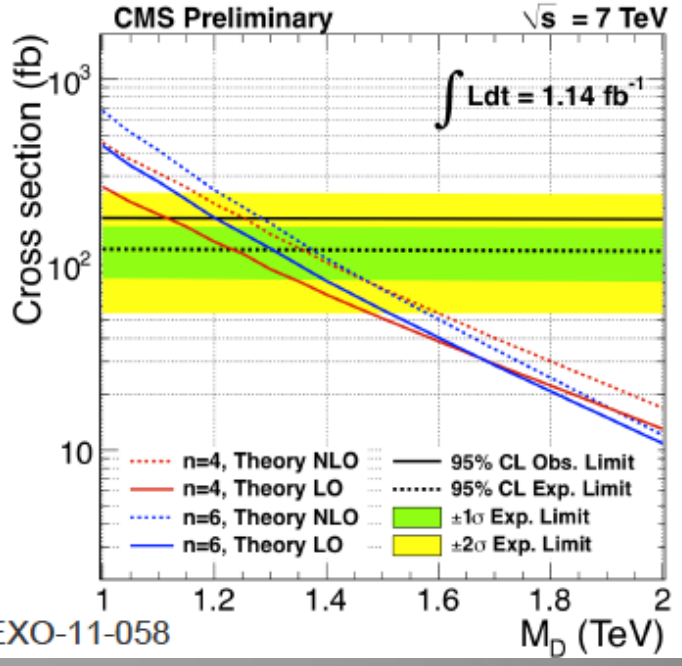
  Look for a photon and ~ nothing else

For n = 2-6:

M_D > 1.25 – 1.31 TeV



NEW!



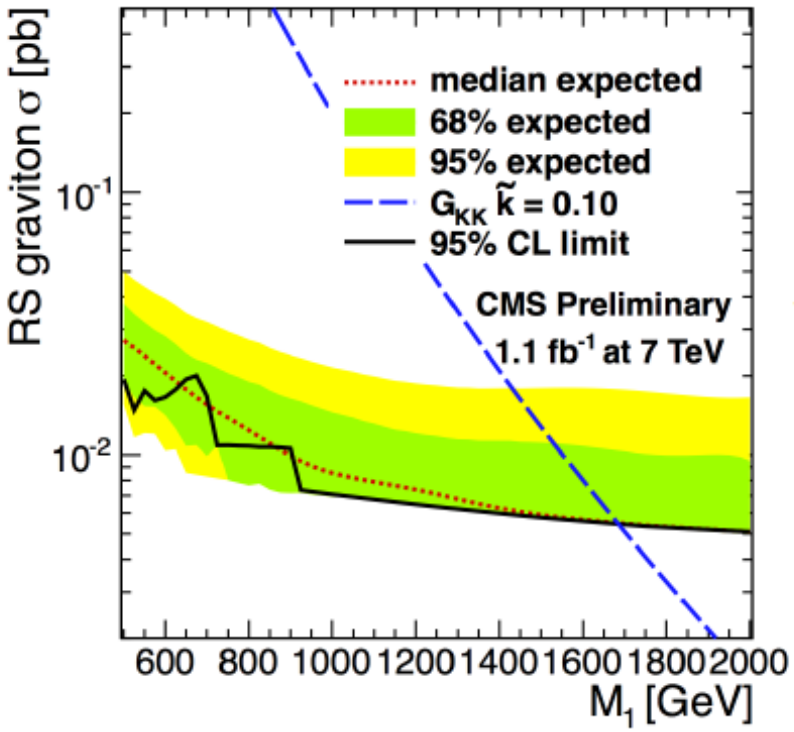
CMS-EXO-11-058

Search for Extra Dimensions

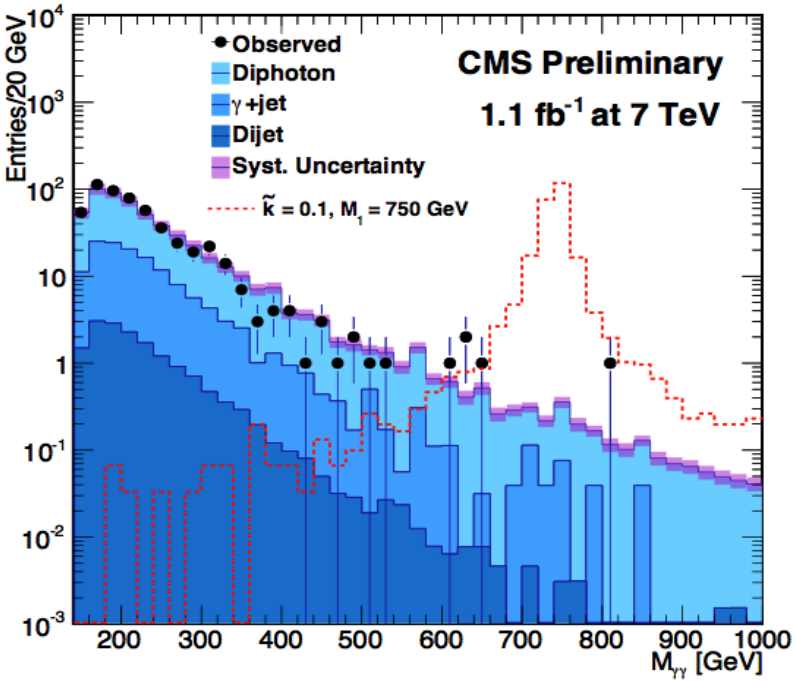
Two Photons Resonances (RS)

- Randall-Sundrum KK graviton excitation

RS graviton (k/MPl = 0.1):
m(G) > 1.7 TeV at 95% C.L.



NEW

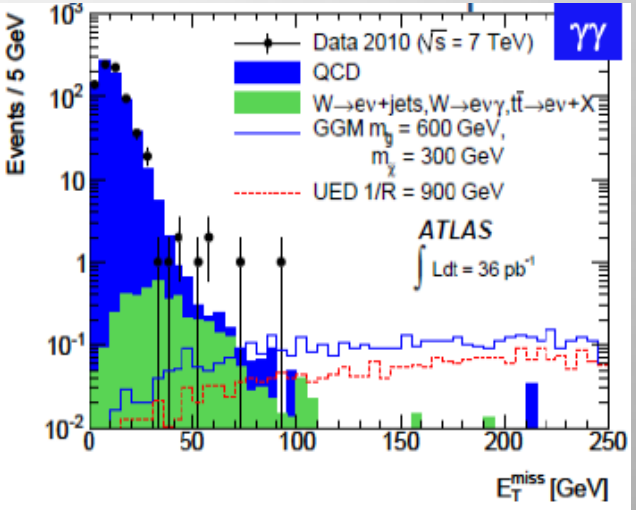


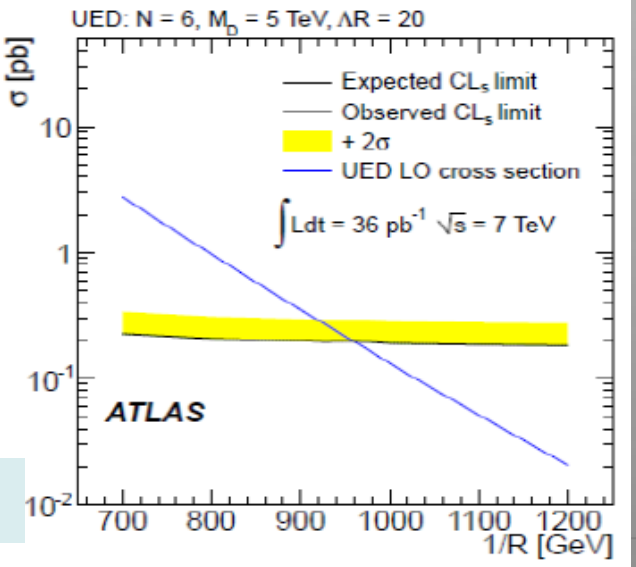
CMS-EXO-11-038

Search for Extra Dimensions

Two Photons and Missing E_T (UED)

- Benchmark: effective theory of one TeV^{-1} size UED valid at $\Lambda > 1/R$ (R = ED size)
  - SM particles in bulk ⇒ KK excitations
  - Mass degeneracy of KK excitations broken by radiative corrections
  - Lowest KK particle γ^* decays to γ+Graviton
- Expect excess of UED events at high E_T^{Miss}:
  - No events observed in $E_T^{Miss} > 125$GeV
  - Background events expected $0.10 \pm 0.04(stat) \pm 0.05(syst)$
- UL @ 95% CL on $\sigma < 0.18$-0.23pb for 1/R=700-1200GeV in UED model
- At 36pb^{-1} exclude @95% CL 1/R<961GeV

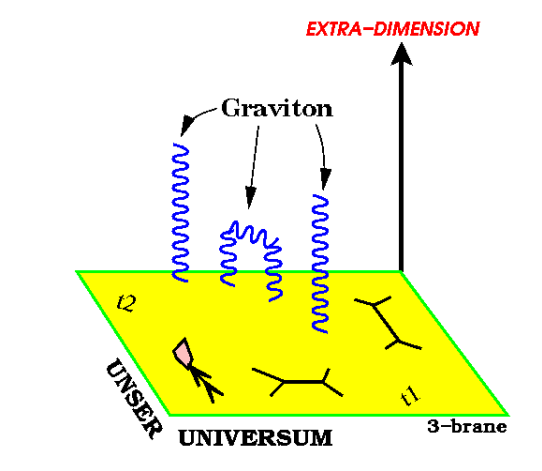




Same analysis as before !! (GMSB)

arXiv:1107.05661, submitted to EPJC

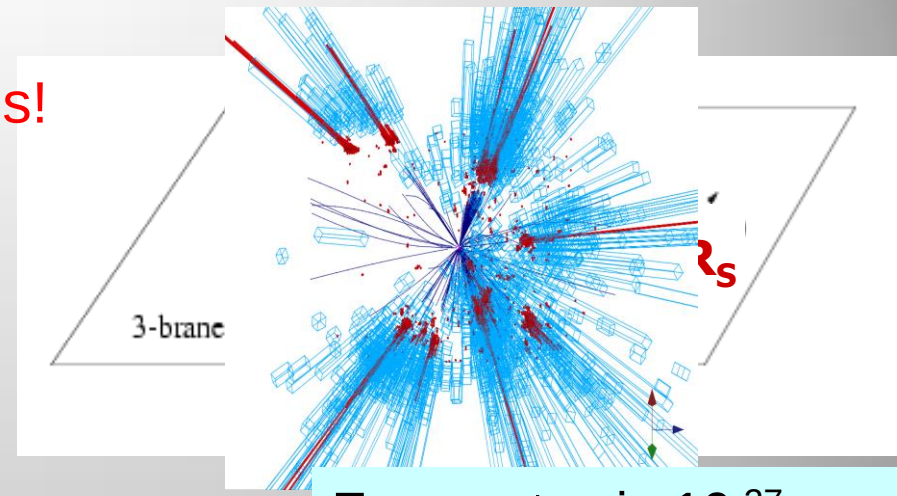
Search for Micro Black Holes



CMS-EXO-11-071

Extra Dimensions!

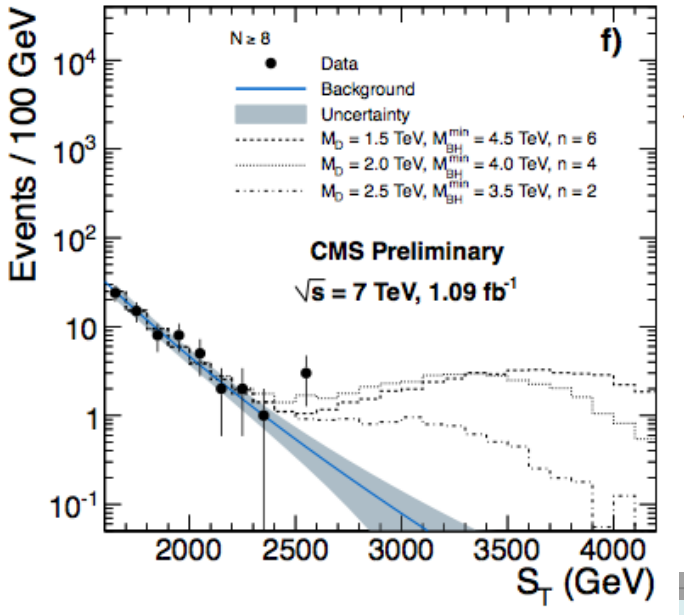
Planck scale
a few TeV?

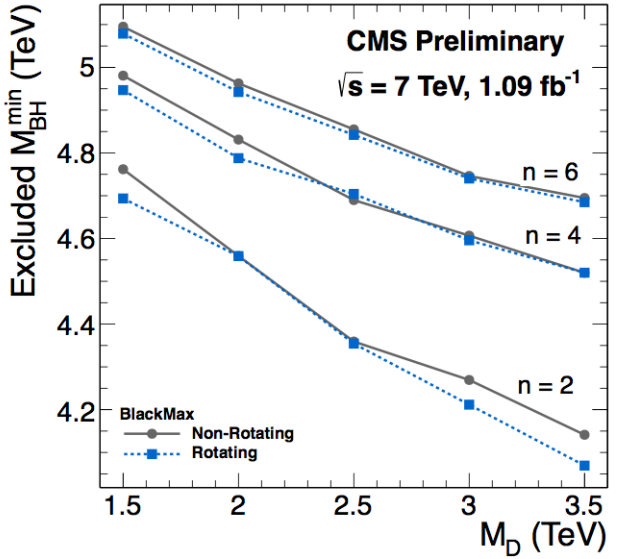


Evaporates in 10^{-27} sec

Look for the decay producs of an evaporating black hole

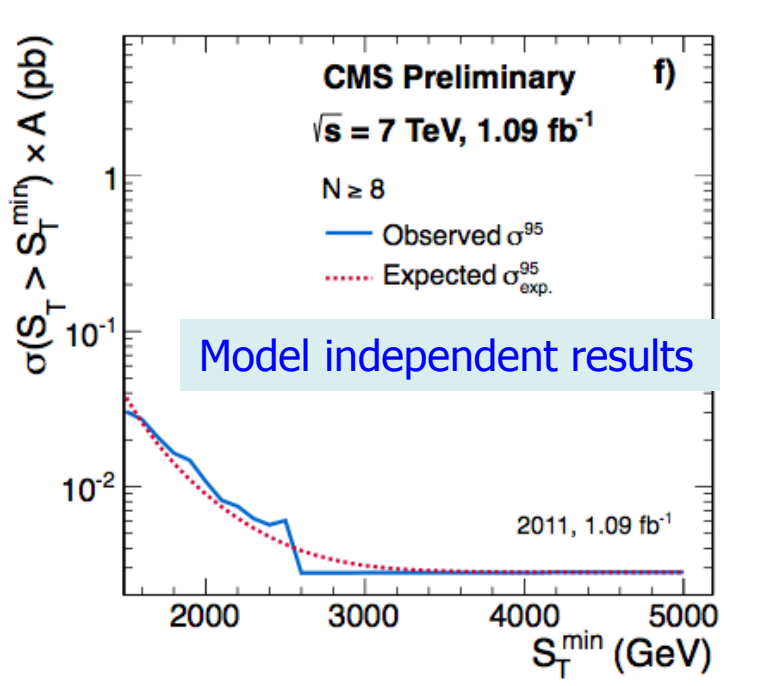
- Define S_T to be the scalar sum of all high p_T objects found in the event
- Look for deviations at high S_T



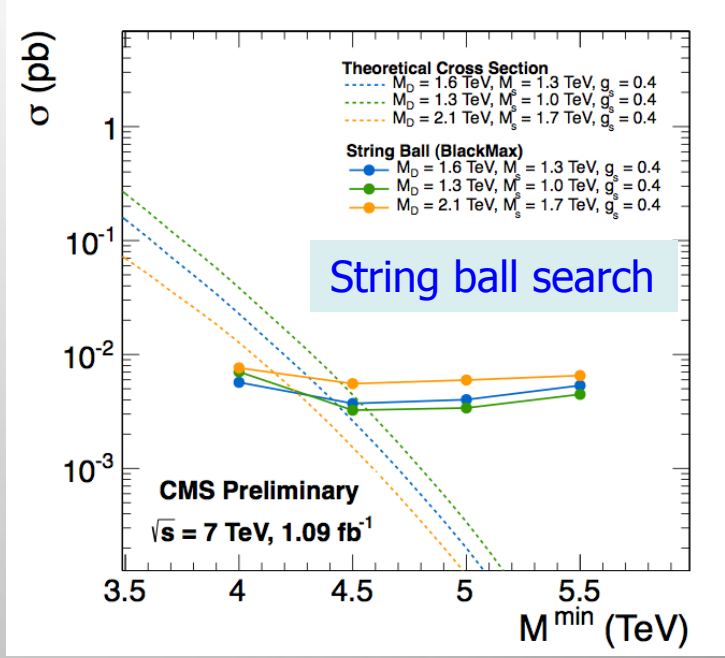


Black hole masses excluded in range ~5 TeV depending on assumptions

Search for Micro Black Holes

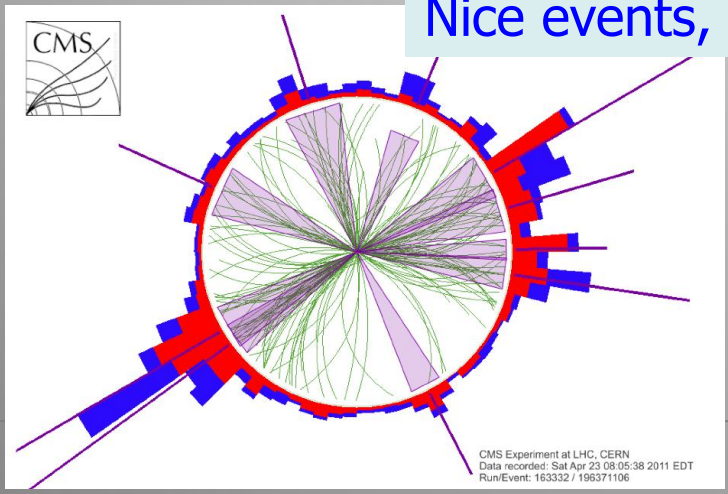


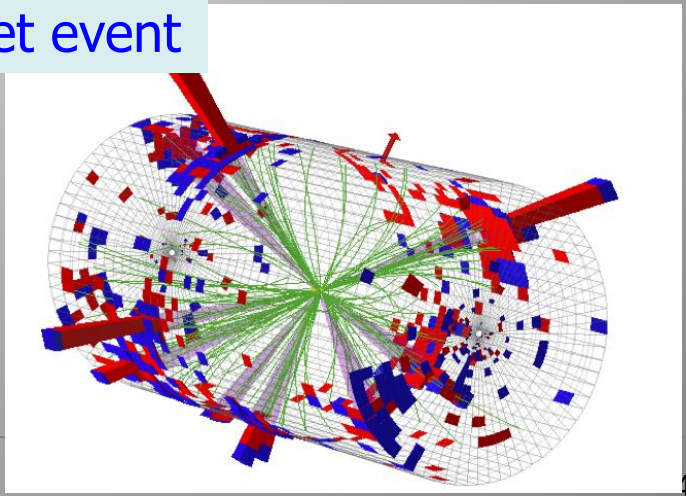
Model independent results



String ball search

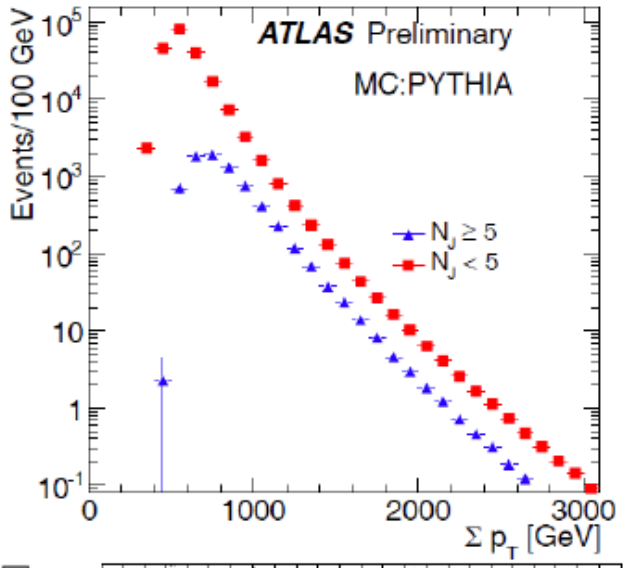
Nice events, eg this 10 jet event

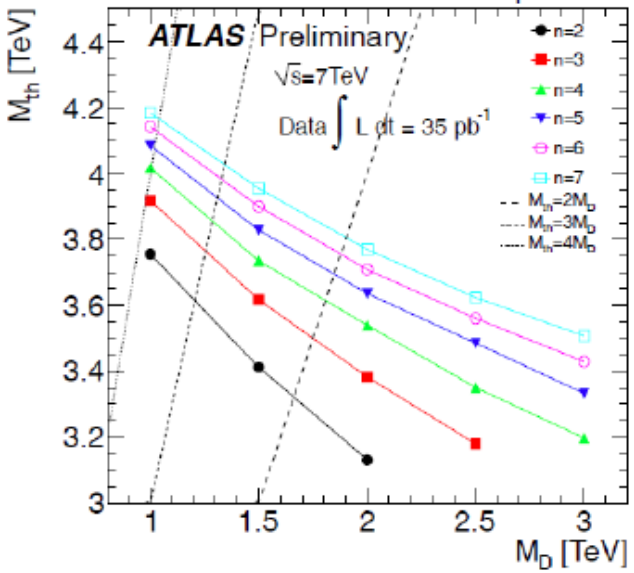




Search for Micro Black Holes

Multi-jet search

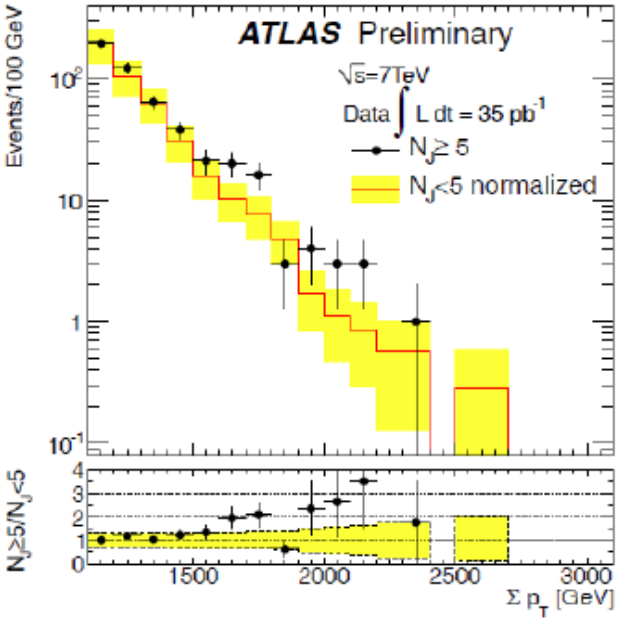




Require $E_T^{j1} > 250$ GeV for good trigger efficiency

For N_J, count jets with $p_T > 50$ GeV

To good approximation, the shape of Σp_T is the same in QCD for $N_J < 5$ and $N_J \geq 5$.



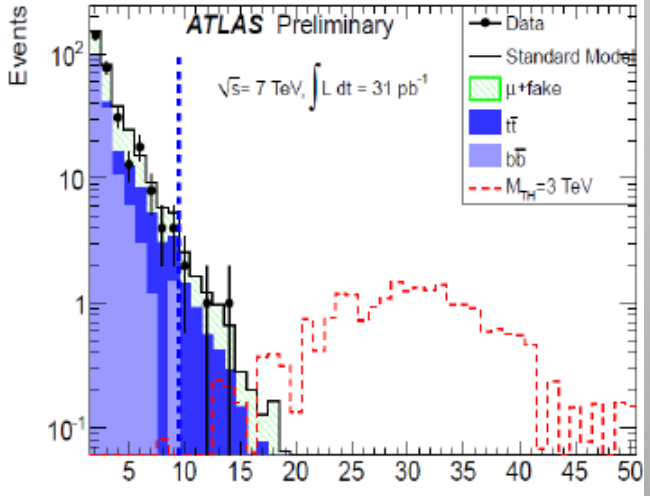
- Use 1.1 TeV < Σp_T < 1.2 TeV region for normalization, then compare the $N_J < 5$ shape to $N_J > 5$ data
- Predict number of events in **signal region: $N_J \geq 5$, $\Sigma p_T > 2$ TeV**
  - 3.7 ± 1.0 (stat) ± 1.1 (syst) compared to 7 data
  - Largest syst is 24% due to QCD modelling
- At **95% CL cross section × acceptance < 0.29 pb**
- Set model-dependent limits in M_D, M_{th}, n space

Search for Micro Black Holes

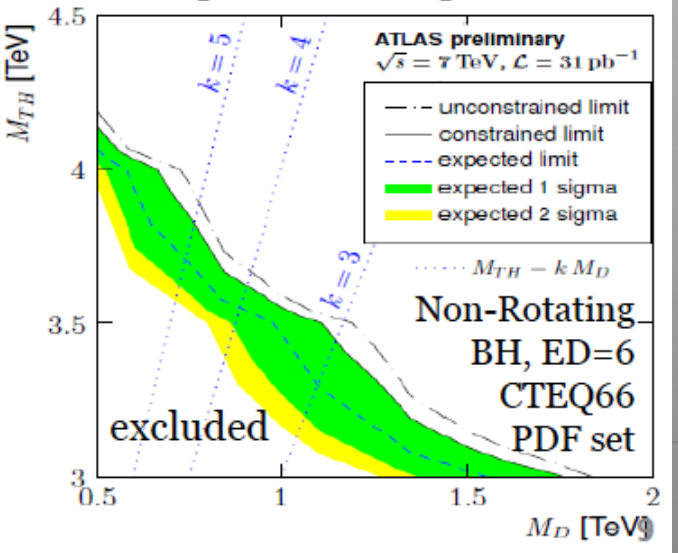
Same sign dimuon search

- Benchmark Model: Large ED ADD Model
- M_D is the Planck scale in n+4 D ($M_D << M_{Pl}$)
- If there are ED and M_D~1TeV, microscopic black holes (BH) can be produced at LHC
- Assume continuous BH production from M_D to LHC $\sqrt{s}$=7TeV, but remove mass region (M_{TH}) close to M_D where classical BH production and semi-classical BH decay approximations are not valid
- Strategy:
  - Select events with same sign di muons, with at least one being isolated, to minimize SM bkgs
  - Look at track multiplicity distribution
- No excess over SM expectations seen
- 95% CL limit on σ×A×BF of new physics in this final state is 0.184pb
- Exclusion plots in low scale gravity model

ATLAS-CONF-2011-065



Sample exclusion plot:

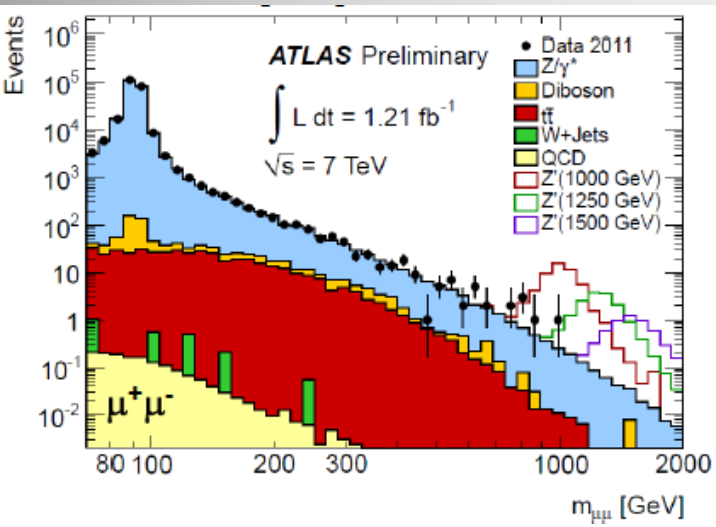


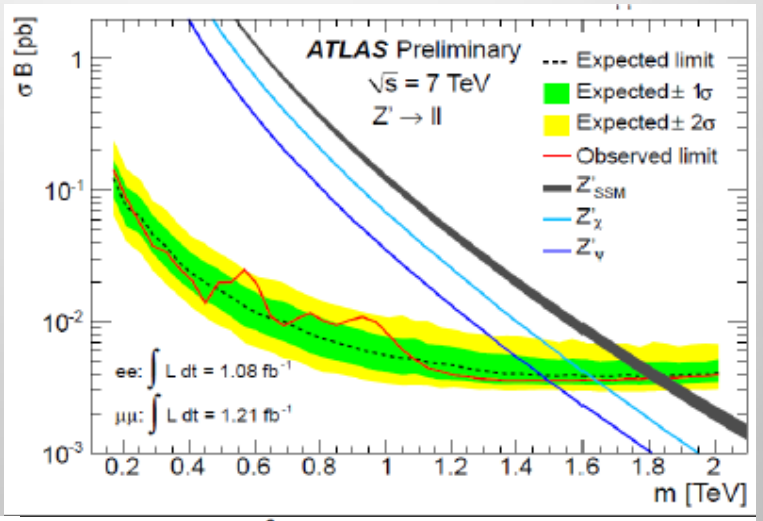
Other Searches

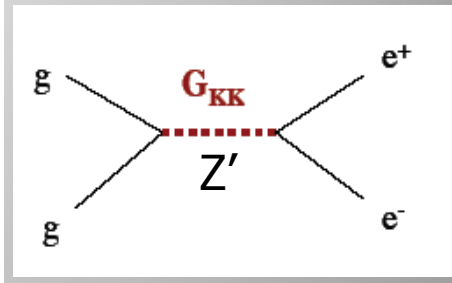
- New Gauge bosons
- Colored resonances
- Objects decaying into top quarks
- Strong EW symmetry breaking eg topcolor
- 4^{th} Generation of quarks and leptons
- Substructure /contact interactions
- Technicolor
- Long lived particles
- Dark/Hidden Sector particles
- …and more…

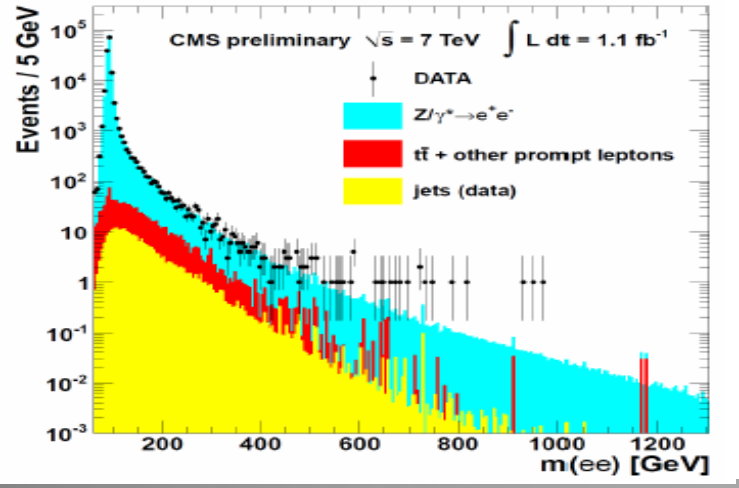
Search for G_{KK} or Z' Gauge Bosons

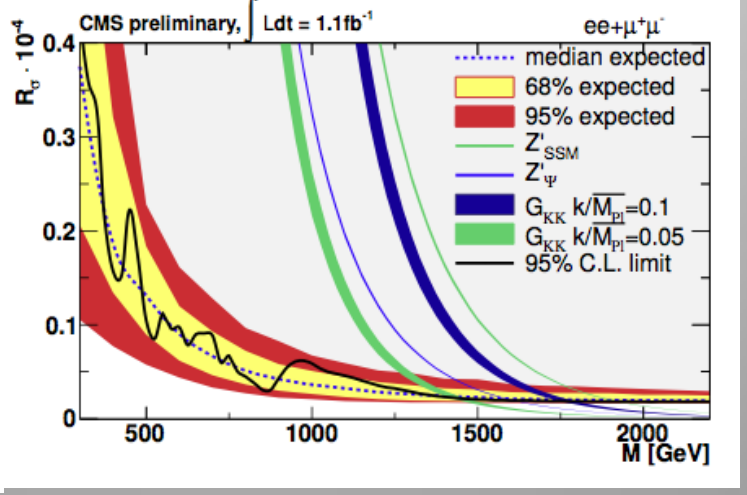
Study of the channels $Z' \rightarrow \mu\mu$, ee











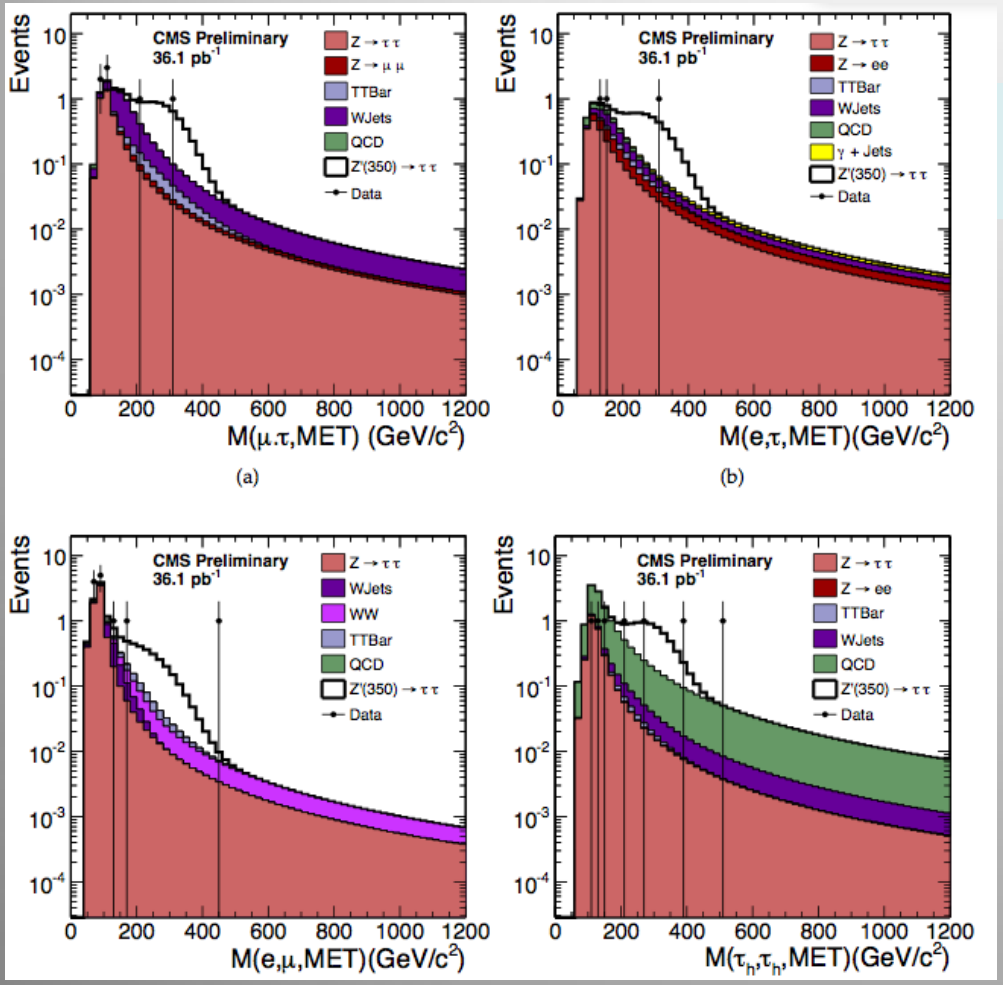
CMS-EXO-11-019

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

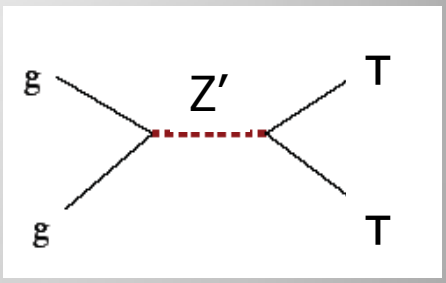
Exclude (SSM) Z' up to 1.94 TeV and G_{KK} up to 1.7 TeV or @ 95% CL

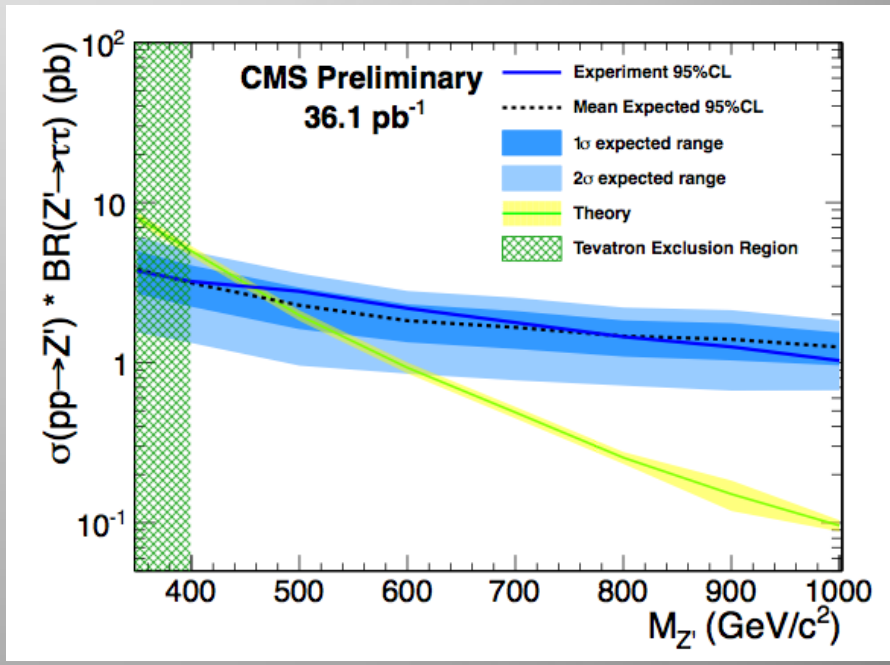
Search for Z' Gauge Bosons

Study of the channels $Z' \to \tau\tau$



Using 4 different tau-tau channels



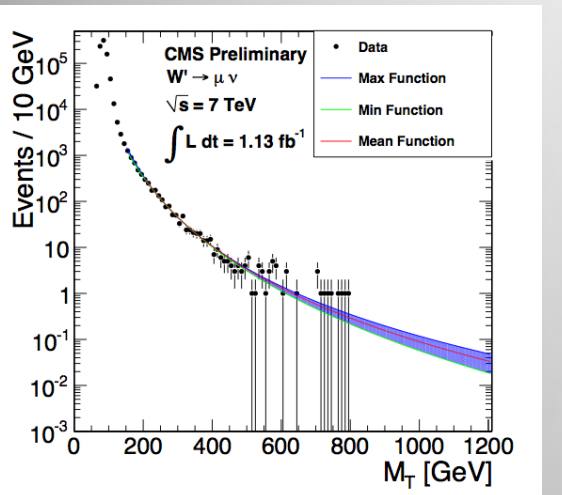


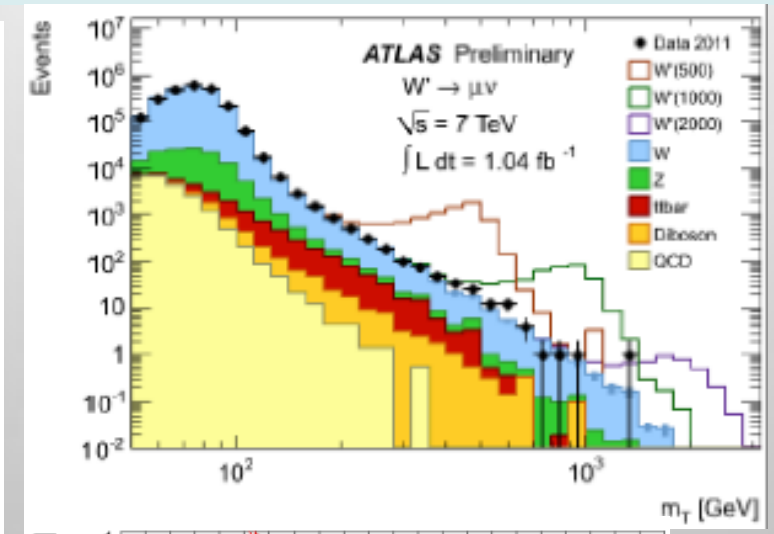
CMS-EXO-11-022

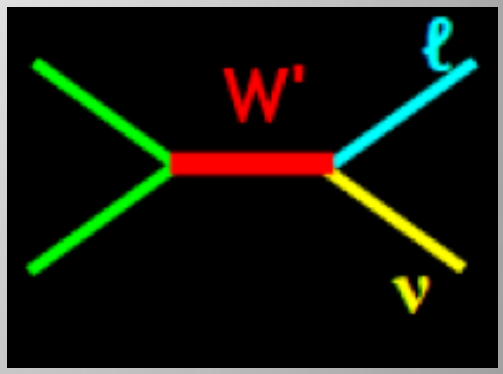
Exclude (SSM) Z' up to 468 GeV @ 95% CL

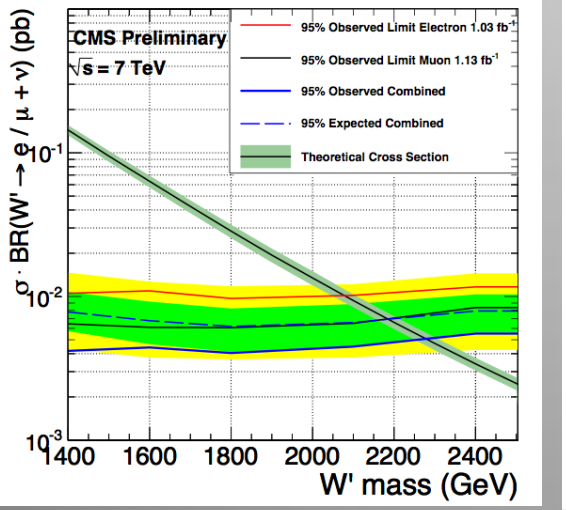
Search for W' Gauge Bosons

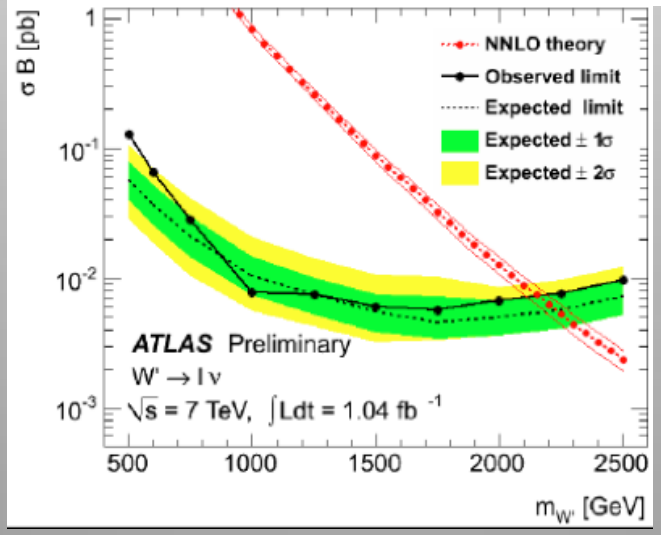
Study of the channels W'→μν,eν











$$M_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos \Delta\phi_{l, E_T^{miss}})}$$

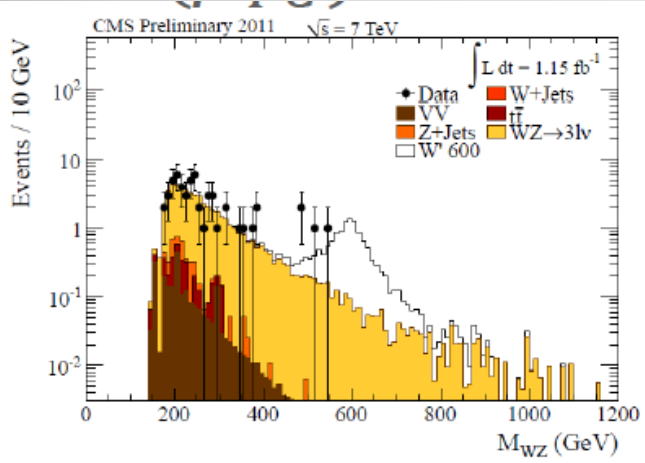
CMS-EXO-11-024

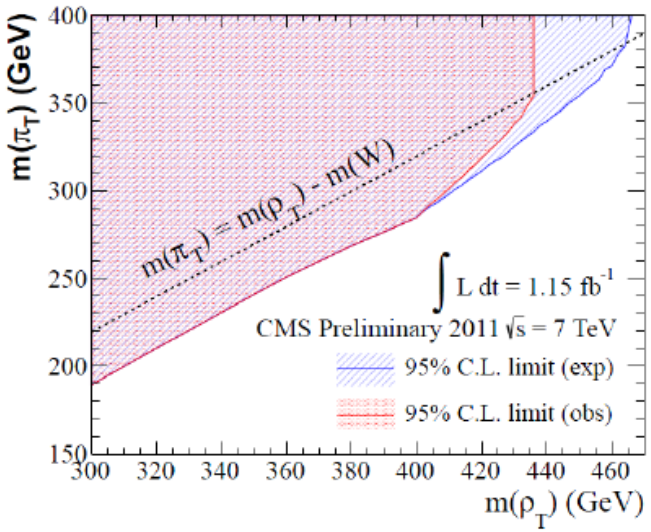
Exclude new W' bosons up to ~2.27 TeV @ 95% CL

Searching for Technicolor

$$W'(\rho_{TC}) \rightarrow WZ \rightarrow 3\ell\nu \; (\ell = e, \mu)$$

Technicolor ~ QCD (color force); Higgs is composite





W'_{SSM}: 784 GeV

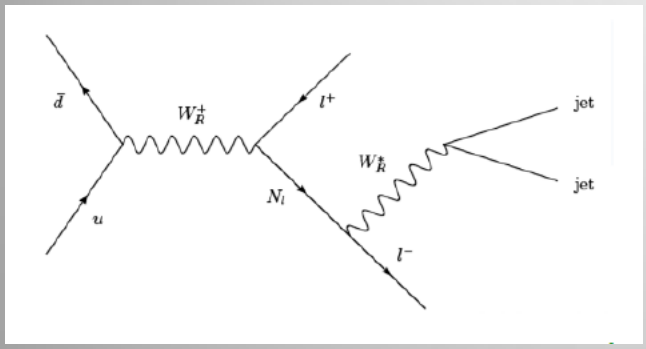
ρ_{TC}: 382 GeV ($M_{\pi_{TC}} = \frac{3}{4} M_{\rho_{TC}}$-25 GeV) **EXO-11-041**

ρ_{TC}: 436 GeV ($M_{\rho_{TC}} < M_{\pi_{TC}} + M_W$)

First search after TeVatron; Exclusion limits on SSM (784 GeV) and techni-color models (382-436 GeV)

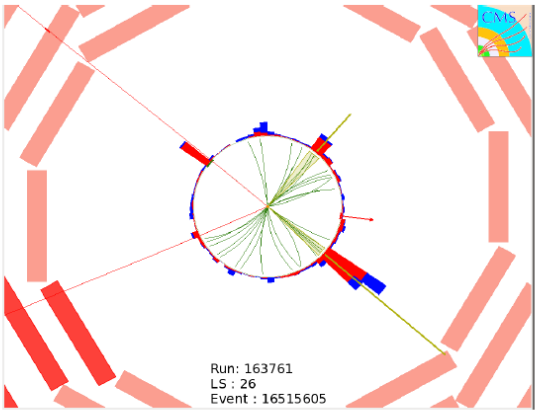
Heavy Neutrinos in W_R Decays

Left-right symmetric extension of the Standard Model

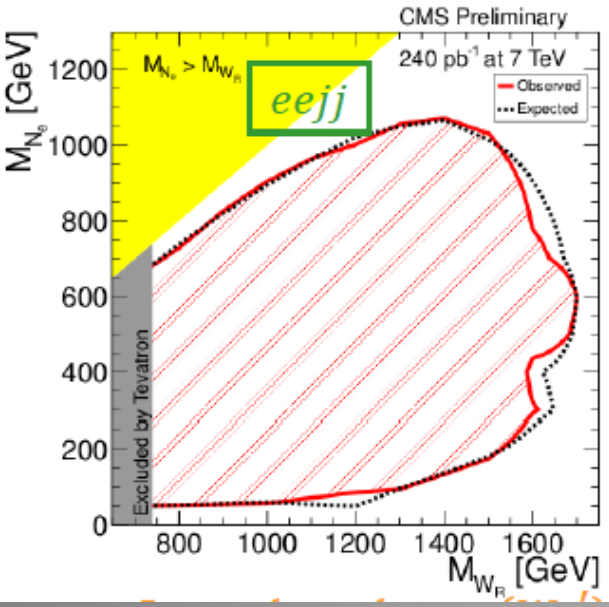


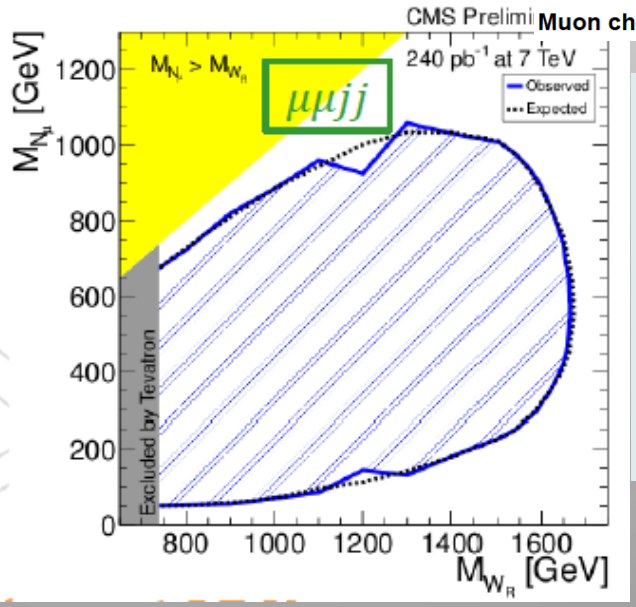
CMS-EXO-11-002

Select events with
2 leptons and 2 jets



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



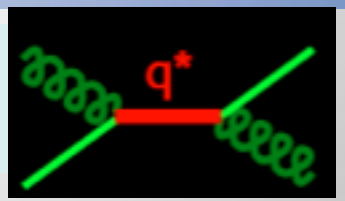


Large exclusion range in mass of the W_R and heavy neutrino

Tevatron excludes $W_R \sim$ 780 GeV

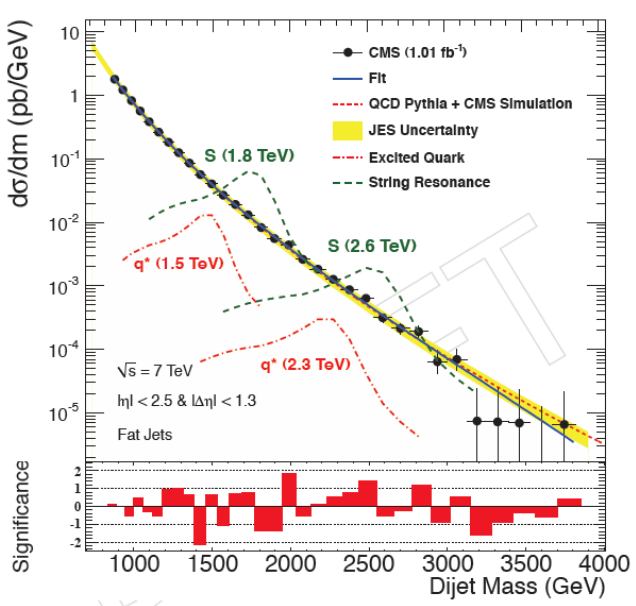
Search for Dijet Resonances

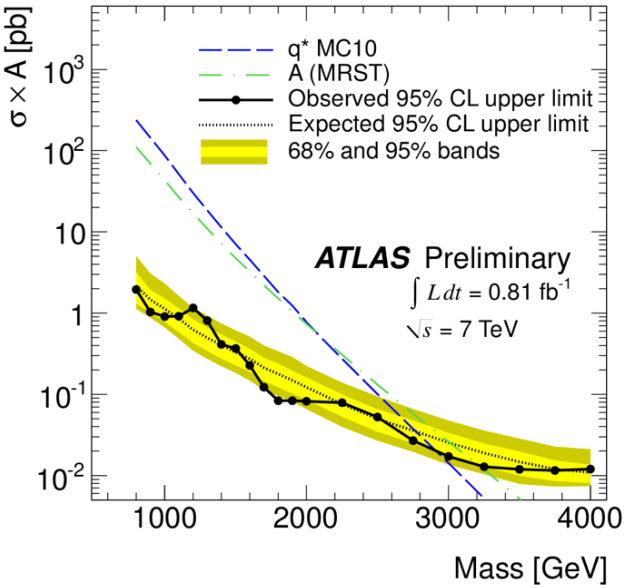
Select events with 2 jets with p_T> 180 GeV (ATLAS)
Search for a bump in the invariant jet mass

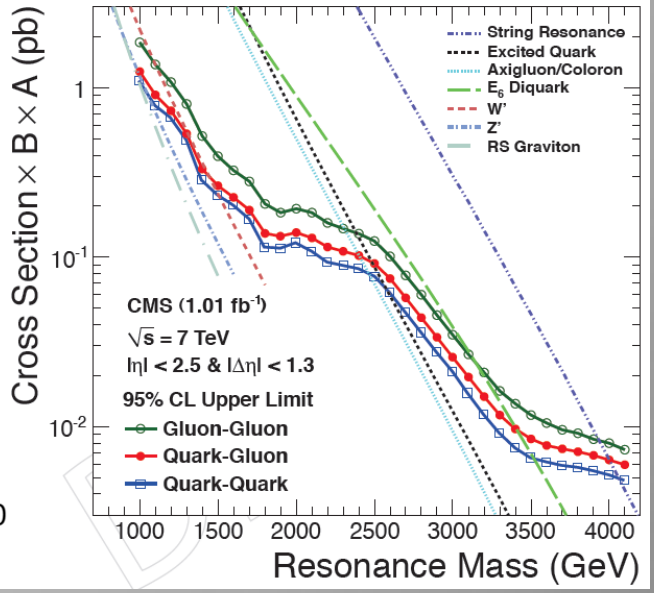


No bump found Limits →~1-4 TeV Range

CMS:arXiv:1107.4771: Sub. to PLB
ATLAS-CONF-2011-95





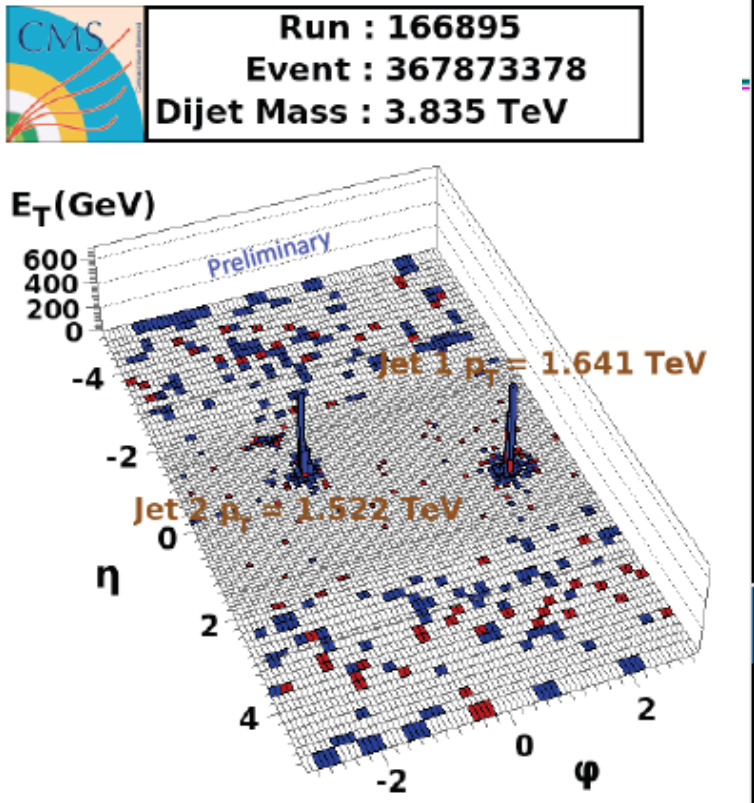


The data exclude new particles predicted in the following models at the 95%CL (CMS)
String resonances with mass M(S)<4.00TeV, E_6 diquarks with M(D) <3.52TeV, excited quarks with M(q∗)<2.49TeV, axigluons and colorons with M(A,C)<2.47TeV, and W' bosons with M(W') <1.51TeV

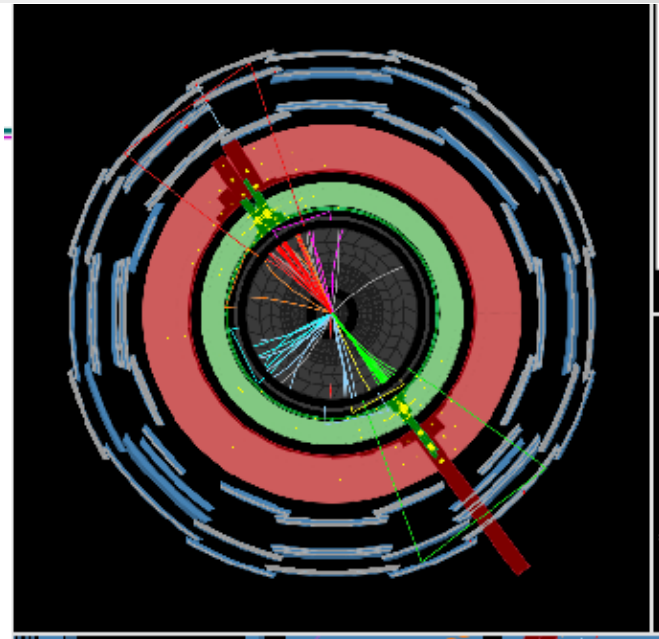
ATLAS

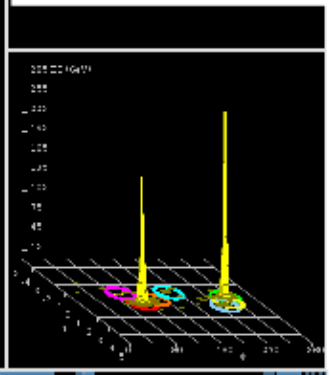
Model	95% CL Limits (TeV)	
	Expected	Observed
Excited Quark q^*	2.77	2.91
Axigluon	3.02	3.21
Color Octet Scalar	1.71	1.91

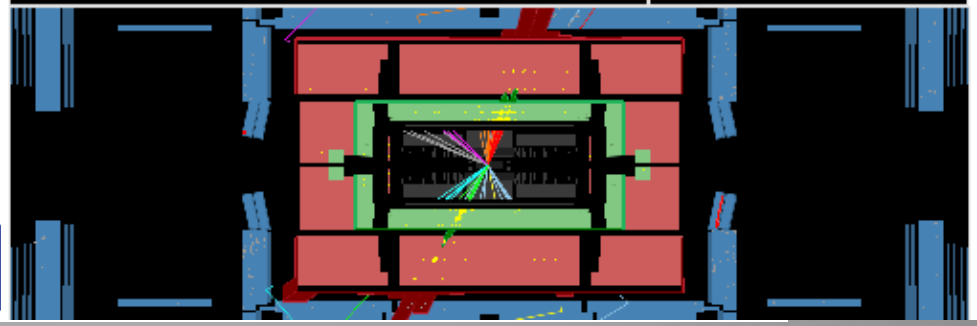
High p_T Dijet Events



❖ Well balanced dijet event



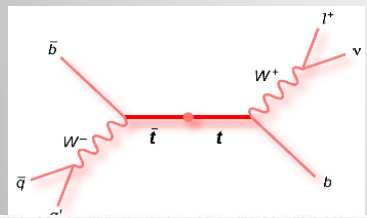




Very high energy jet event
m_{jj} = 4040 GeV
p_T^{j1} = 1850 GeV
p_T^{j2} = 1840 GeV
ATLAS-CONF-2011-081

p. 5

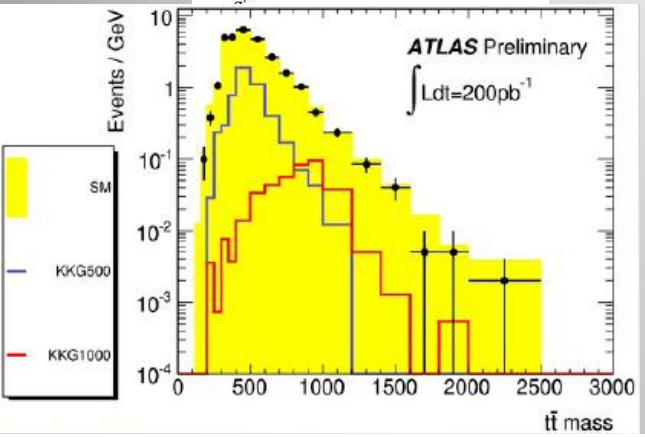
Top Resonances

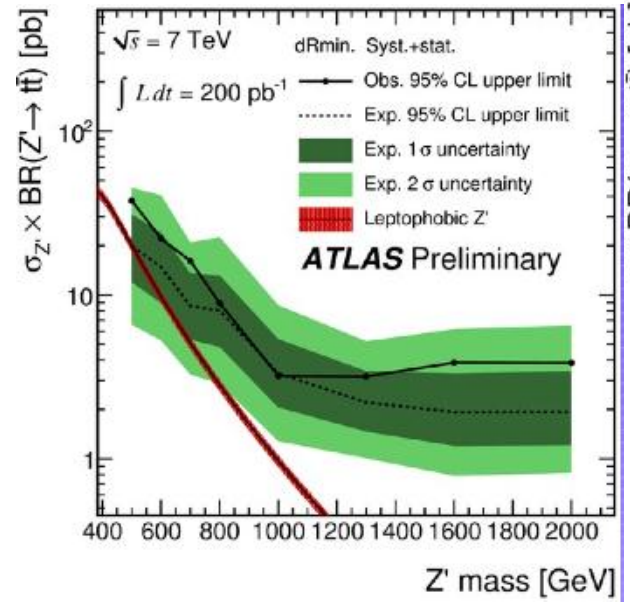


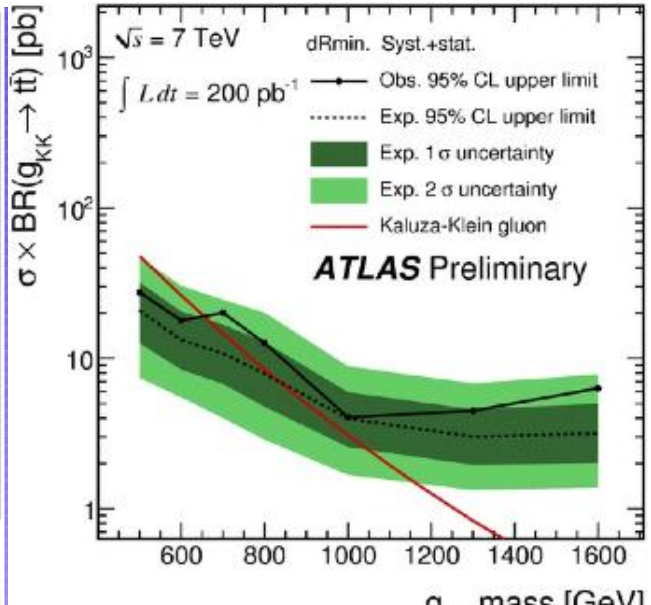
ATLAS-CONF-2011-87

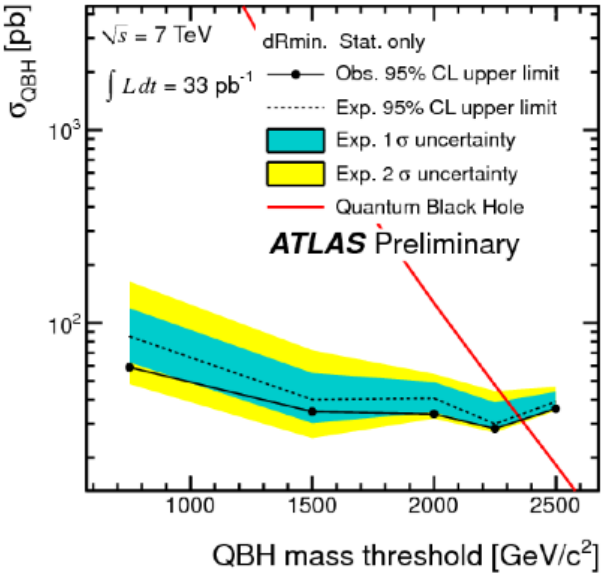
- Select semi-leptonic tt event
- Inspect the tt invariant mass spectrum
- Search for narrow topcolor Z' and wider KK gluons
- Limit on KK-gluons < 700 GeV 95 % CL

- Black holes near threshold -> tt? arXiv:0708.3017
- Limit on 2 body tt decay black holes ~ 2.35 TeV



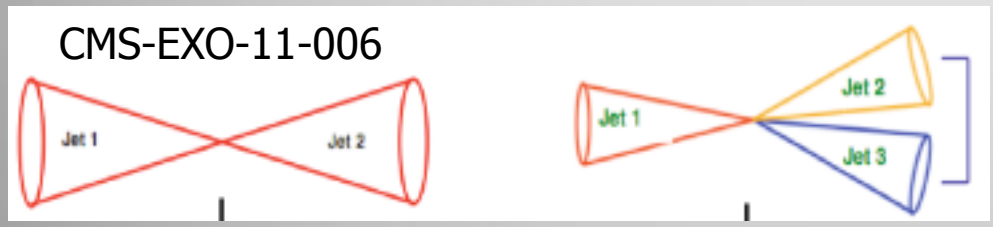






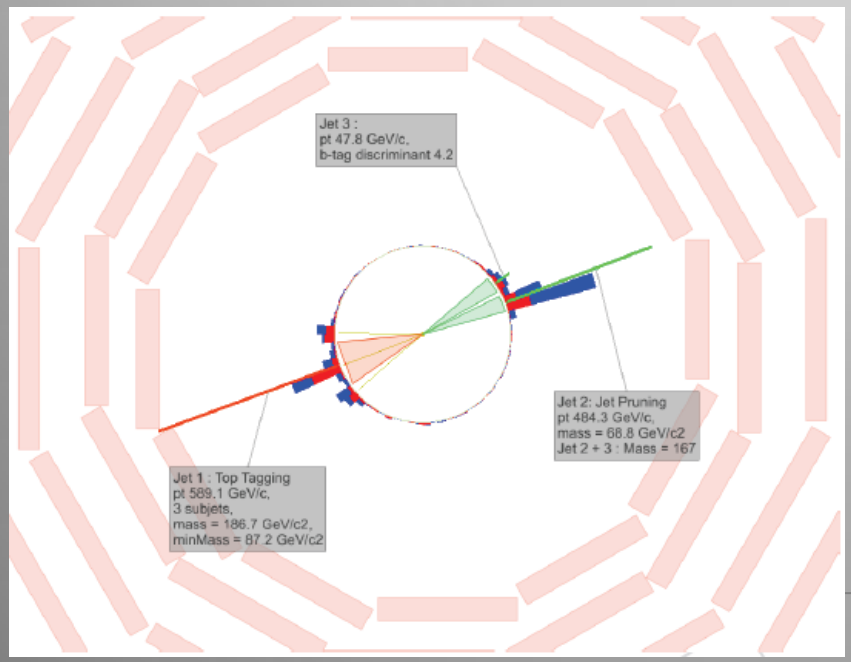
Z' → tt Search

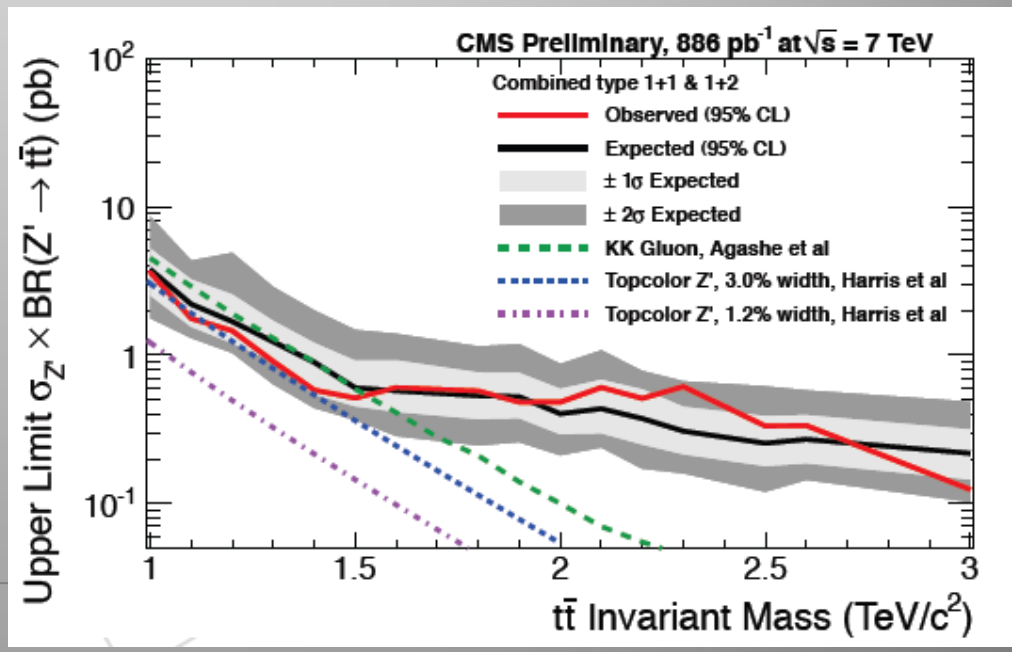
- Search in the all hadronic decay channel for the tops
- Tops are boosted for high mass Z', jets merge
- Start from Cambridge-Aachen FAT jets and apply jet pruning to find sub-jets
- QCD background estimate from data (mistag method)



Particle flow an asset for this study!

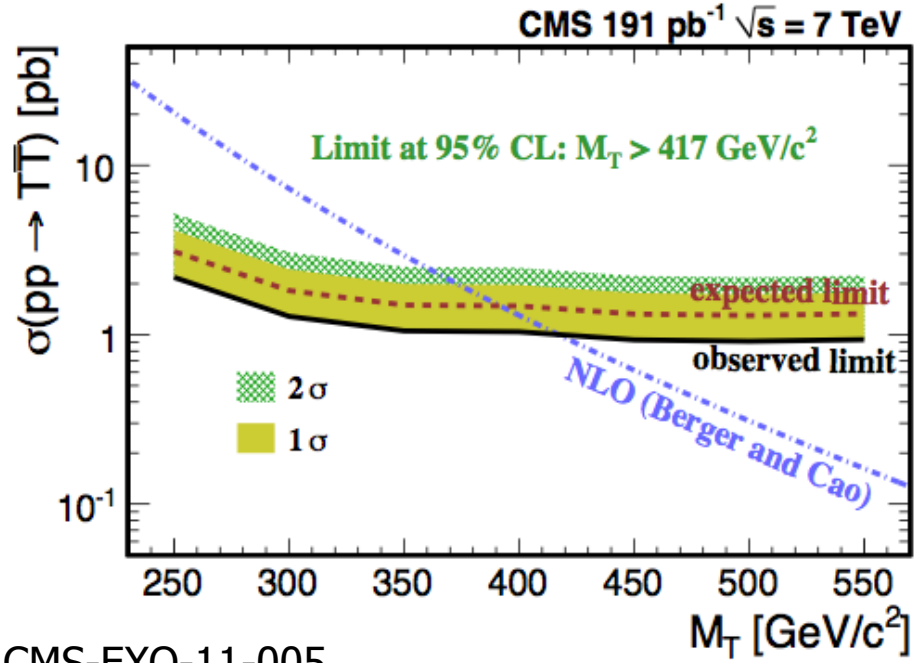
Exclude KK-Gluons 1<M<1.5 TeV





4th Generation: Top partners

$T \to tZ$

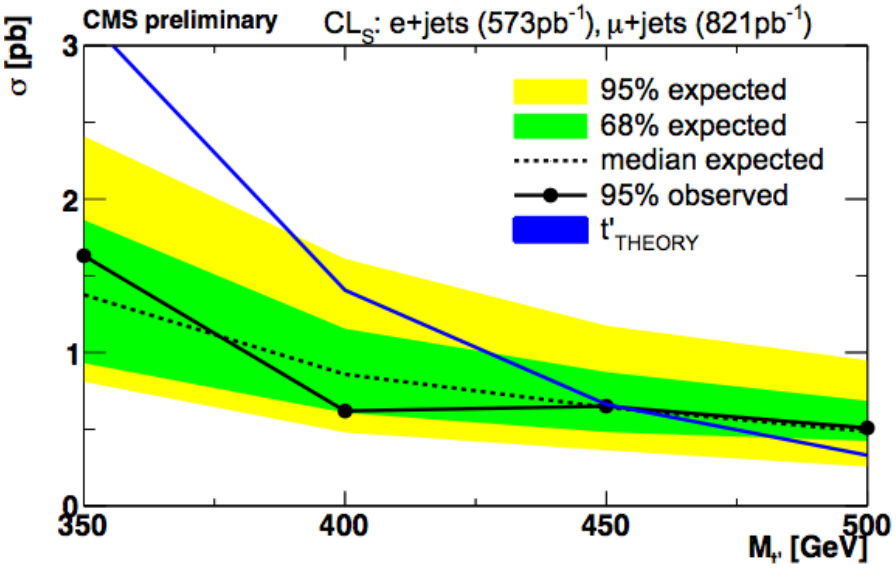


CMS-EXO-11-005

$M(T)$ [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

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



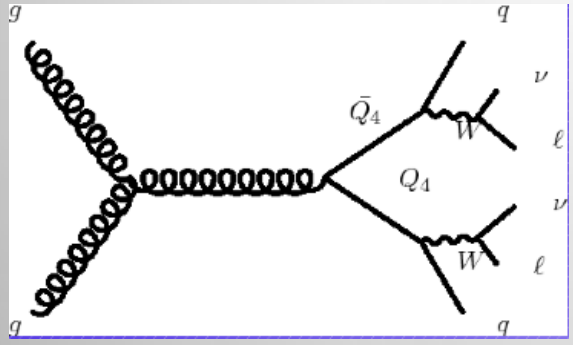
CMS-EXO-11-0051

No t′ with found in the region of mass < 450 GeV at 95% CL

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

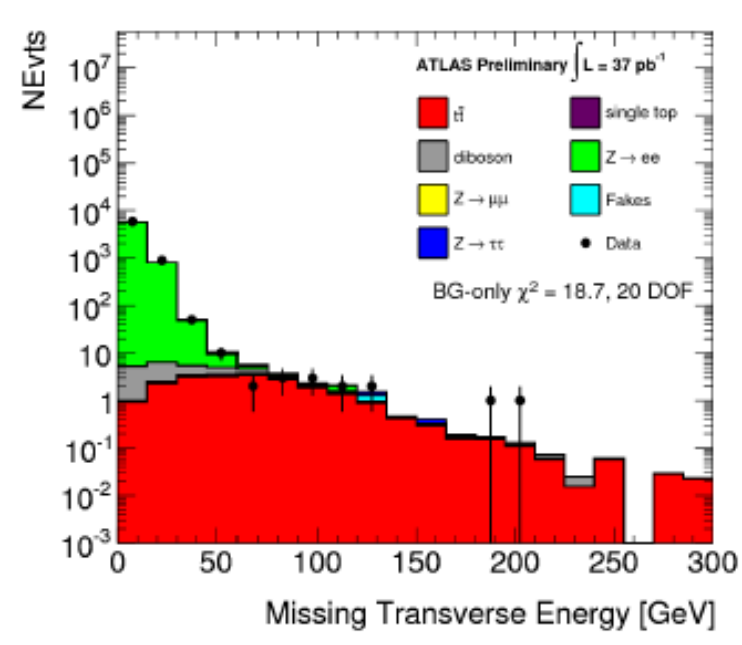
No b′ with 255<mass< 361 GeV

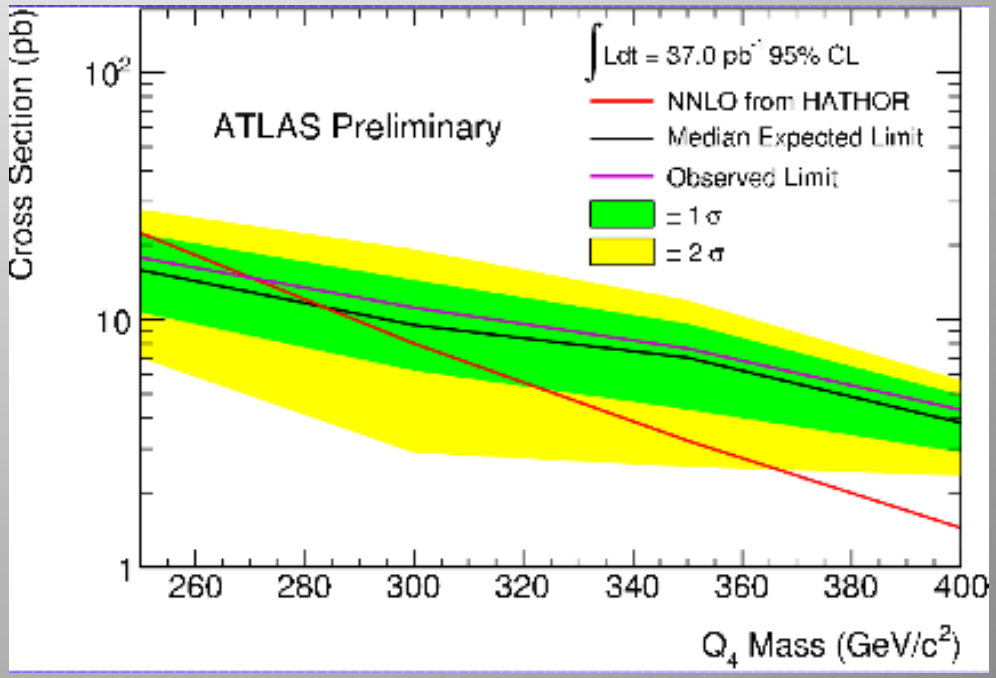
4th Generation



Final state has heavy top pair signature:

- 2 leptons
- 2 jets
- Missing E_T (→ plot for ee)
- higher boost of the decay products





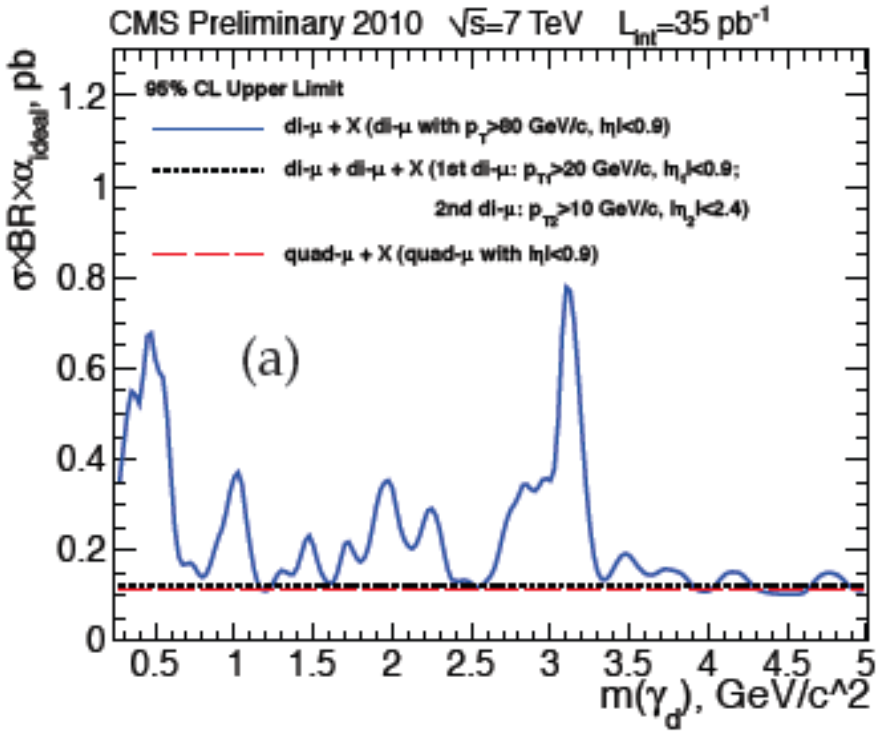
Limit on production cross section of Q_4 for 37 pb^{-1}:
→ Translates to lower mass limit: M_{Q4}>270 GeV
(Best Tevatron limits (CDF, 4.6 fb^{-1}: m_{Q4}>335 GeV))

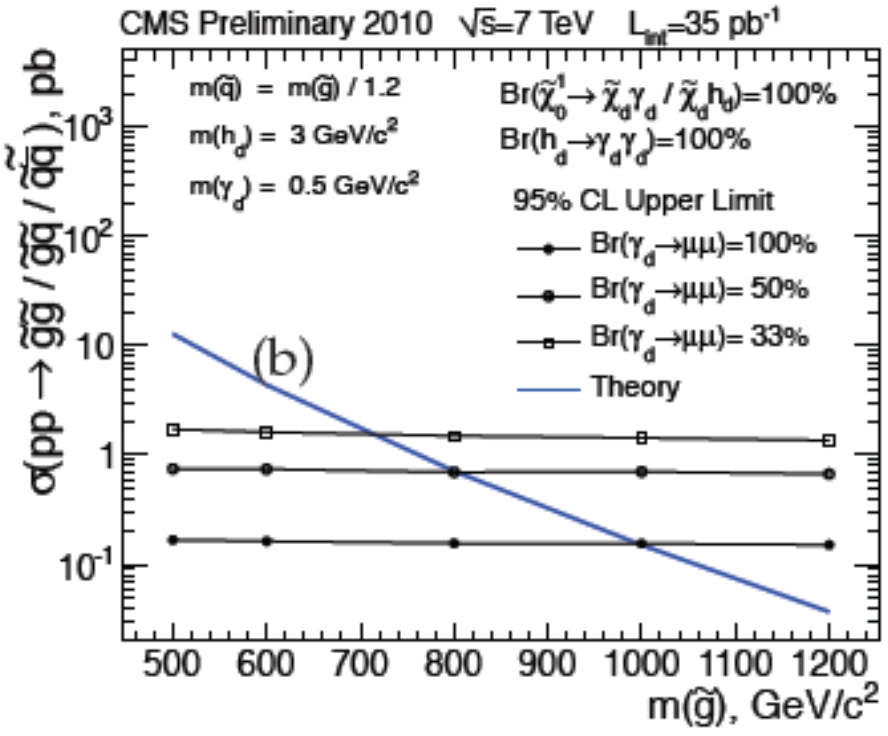
Search for Dark Photons

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

Arkani-Hamed, Weiner

CMS-SUS-11-13





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

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

Long Lived Particles

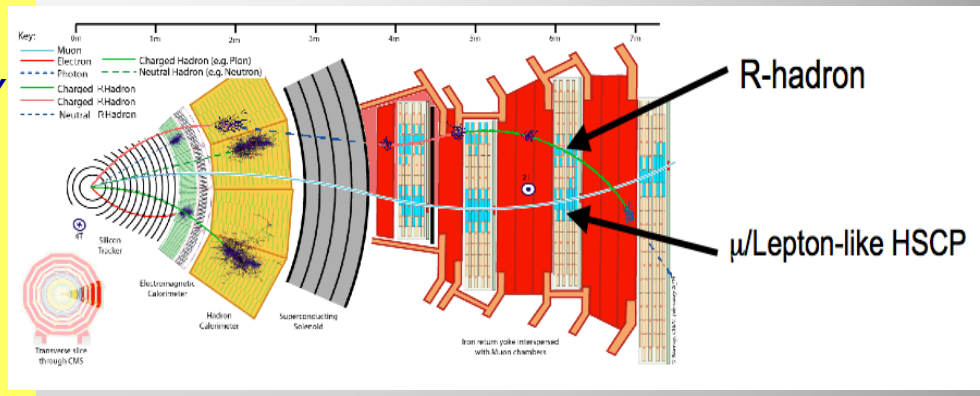
Split Supersymmetry

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

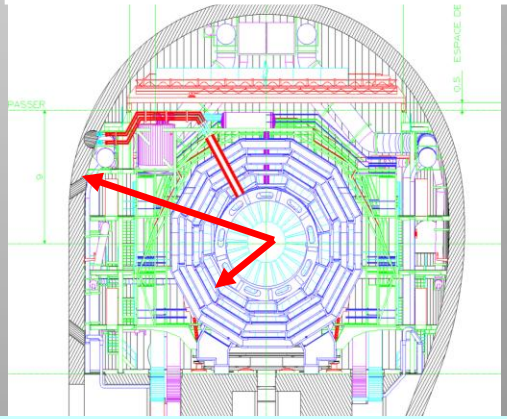
- Gluino can live long: sec, min, years!
- R-hadron formation (eg: gluino+ gluon): slow, heavy particles

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

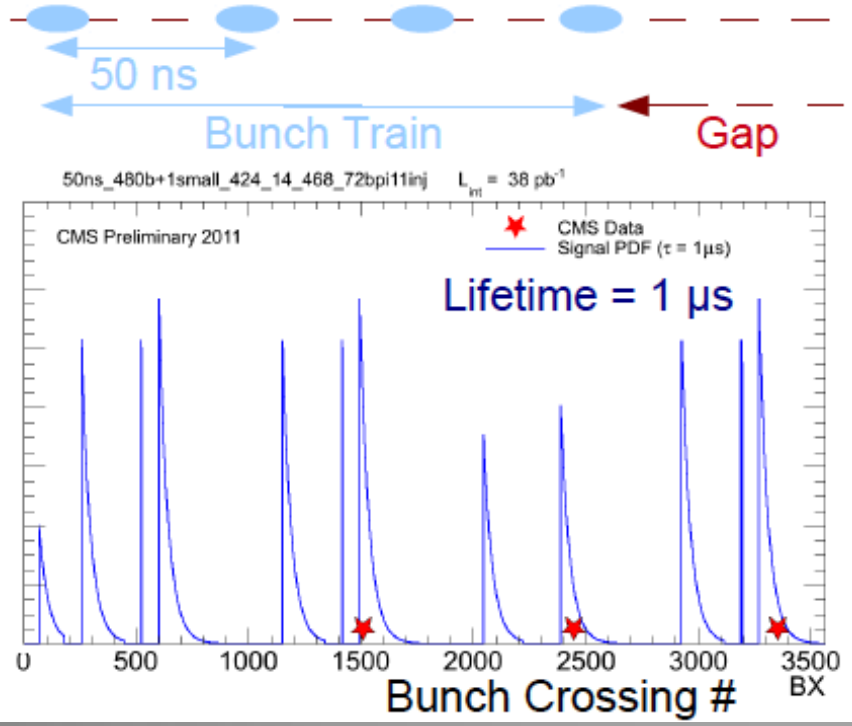
- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

⇒Challenge to the experiments!

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

Search for Stopped Gluinos

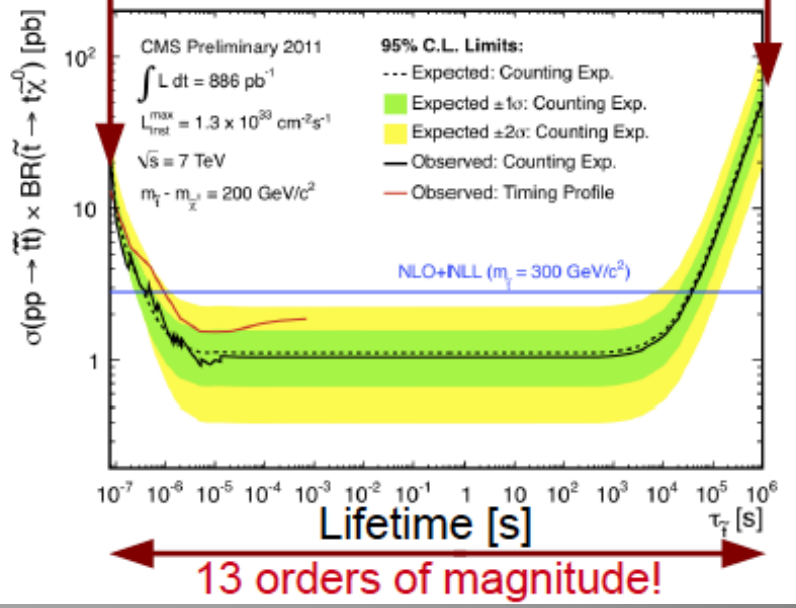
- Out-of-time decay of heavy particles stopped in the detector
- Look for signal **without** collisions:
  - → When no beam in the machine
  - → Between bunch trains



CMS-EXO-11-020

Too short-lived to be out-of-time 100 ns

Too long-lived to have decayed yet 1 month

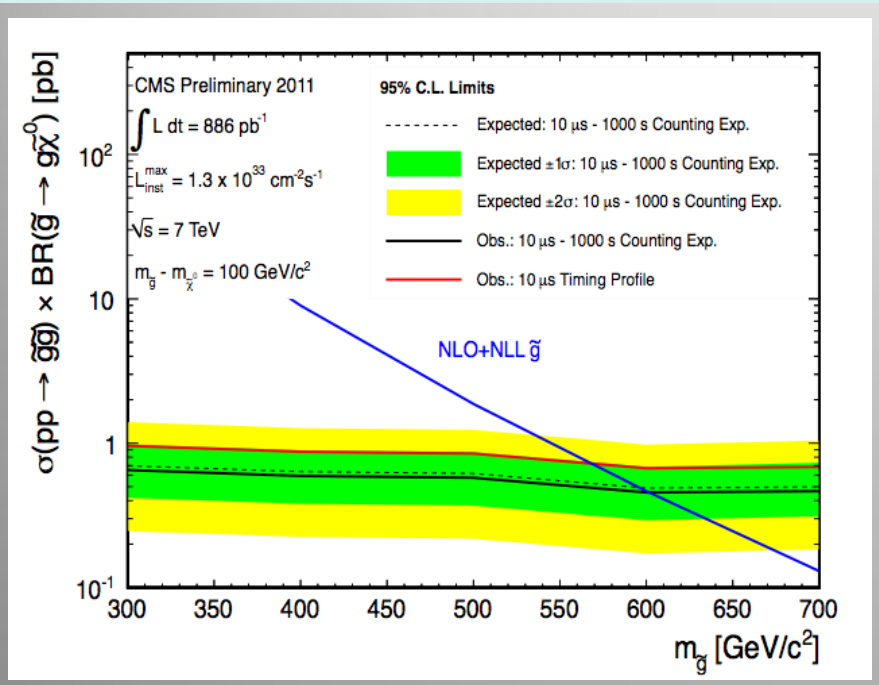


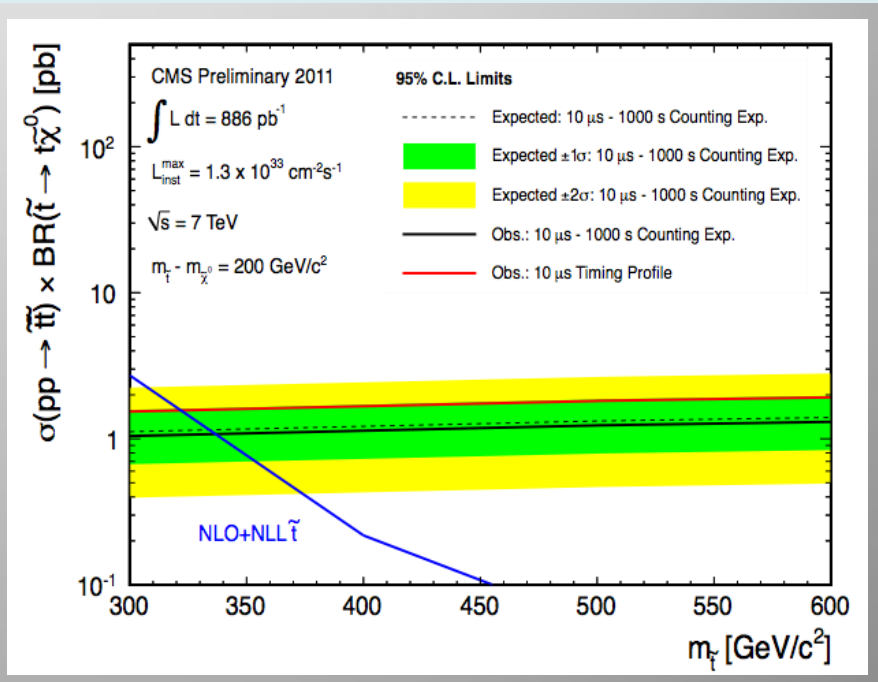
Search for Stopped Gluinos

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

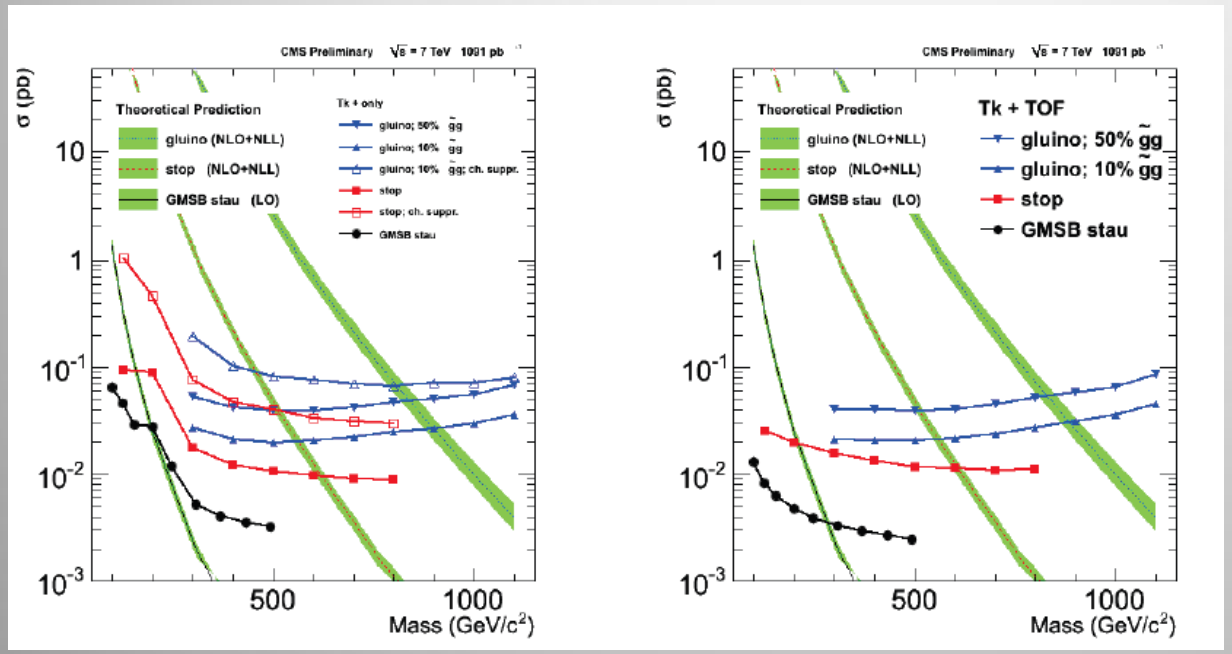




95% CL Limits: Stopped Gluinos > 600 GeV, Stopped Stop quarks> 337 GeV

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

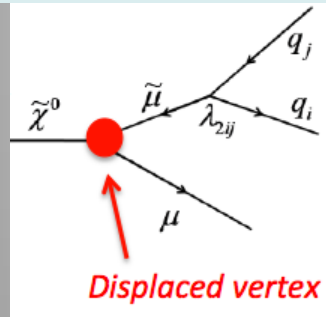
Result for 1 fb^{-1}: #Events consistent with estimated background

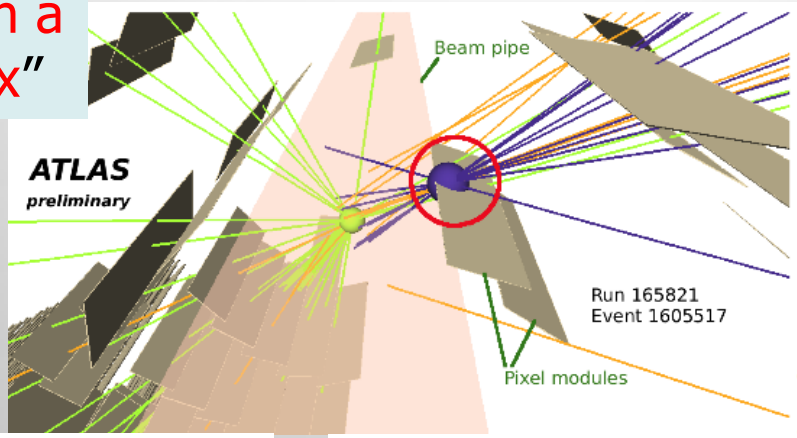
95% C.L. mass limits are set for

- 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

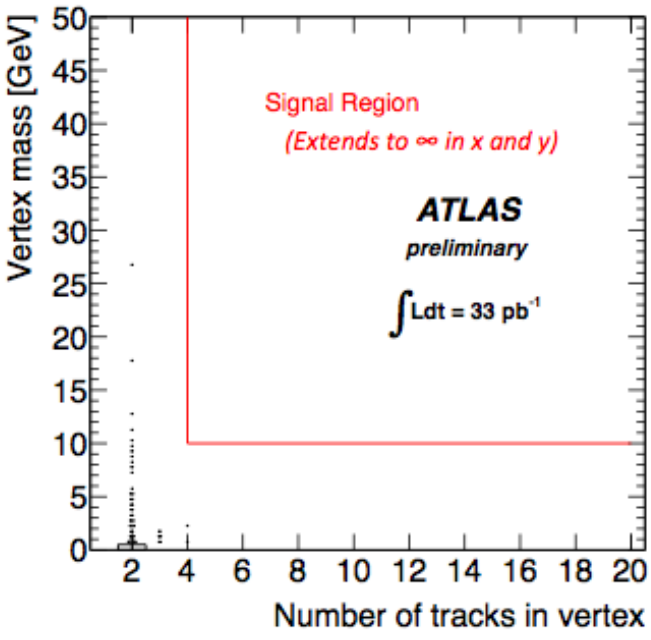
Search for RPV SUSY

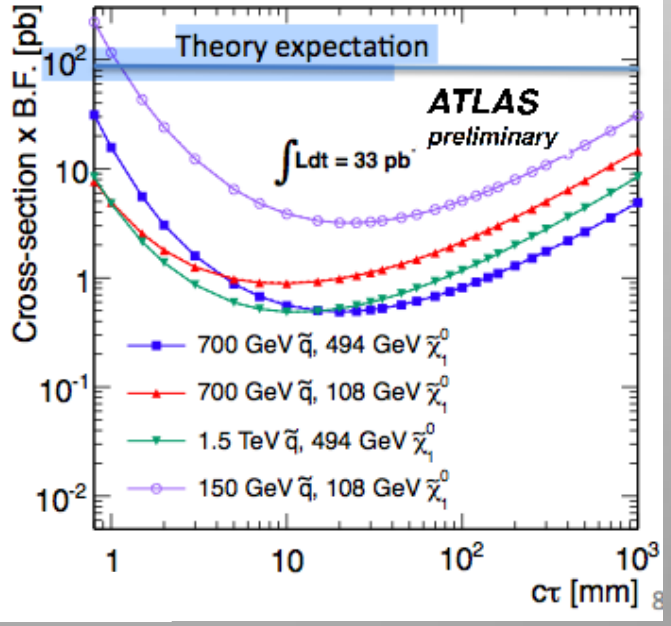
Using events with a "displaced vertex"





Event from a jet-trigger data sample, where a high-mass vertex (circled) is the result of an apparently random, large-angle intersection between a track and a low-mass hadronic-interaction vertex produced in a pixel module. The beampipe and some pixel modules are shown

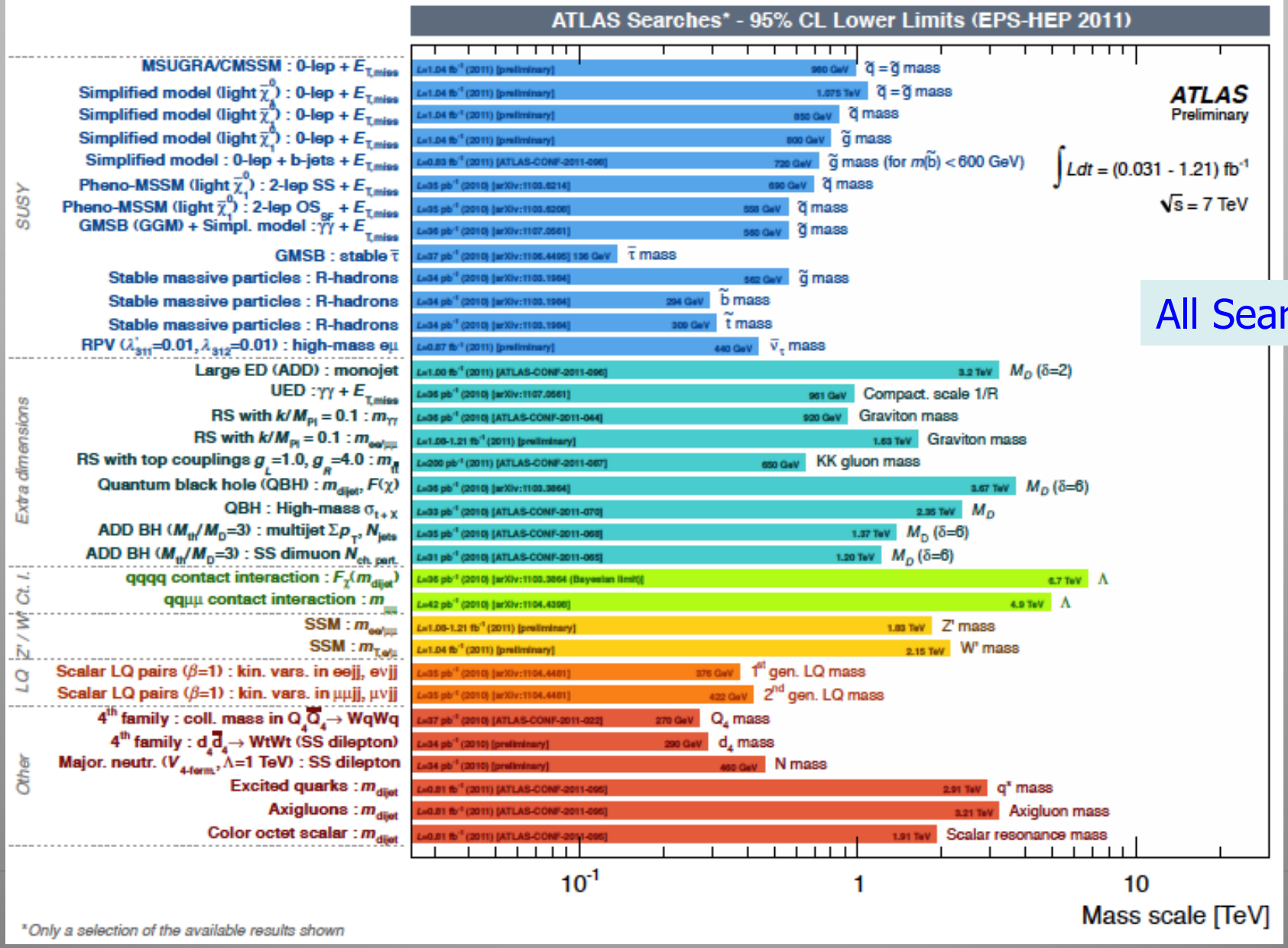




No signal found

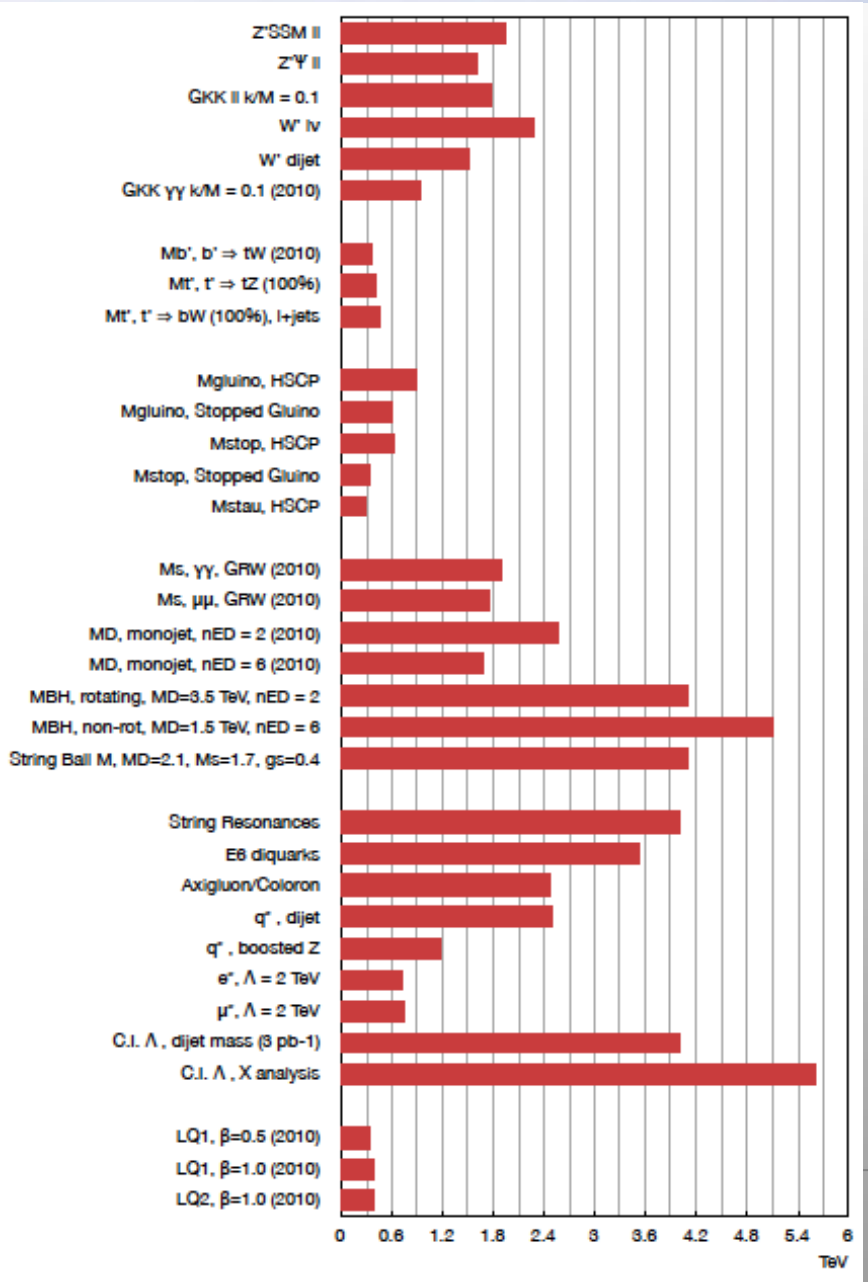
- σ * detector acceptance * ε <0.09pb @95% Confidence level

The Search Overview (ATLAS)



*Only a selection of the available results shown

The Search Overview (CMS)

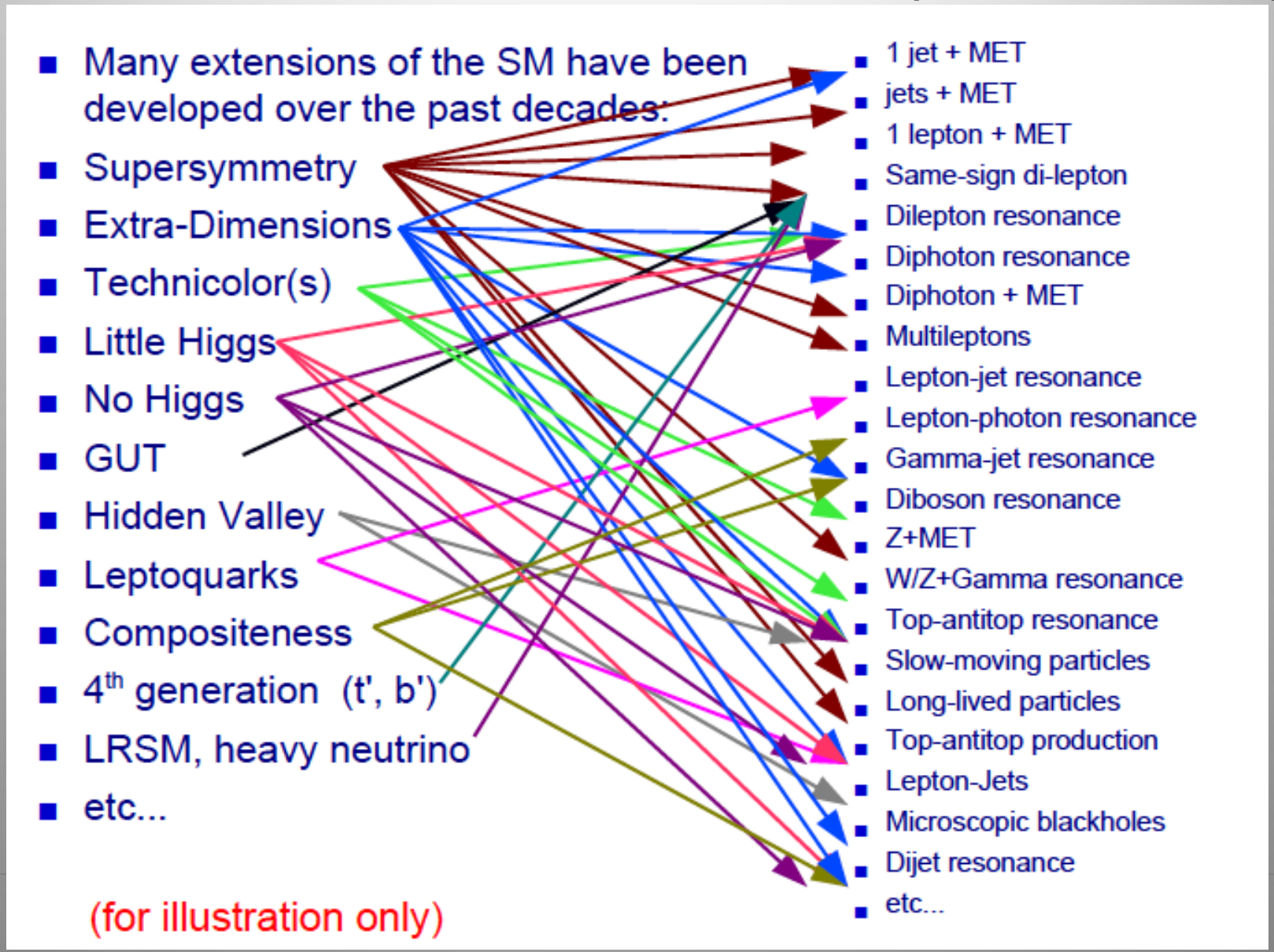


Exotica Searches

Bottom line: no evidence for new physics yet @ the LHC

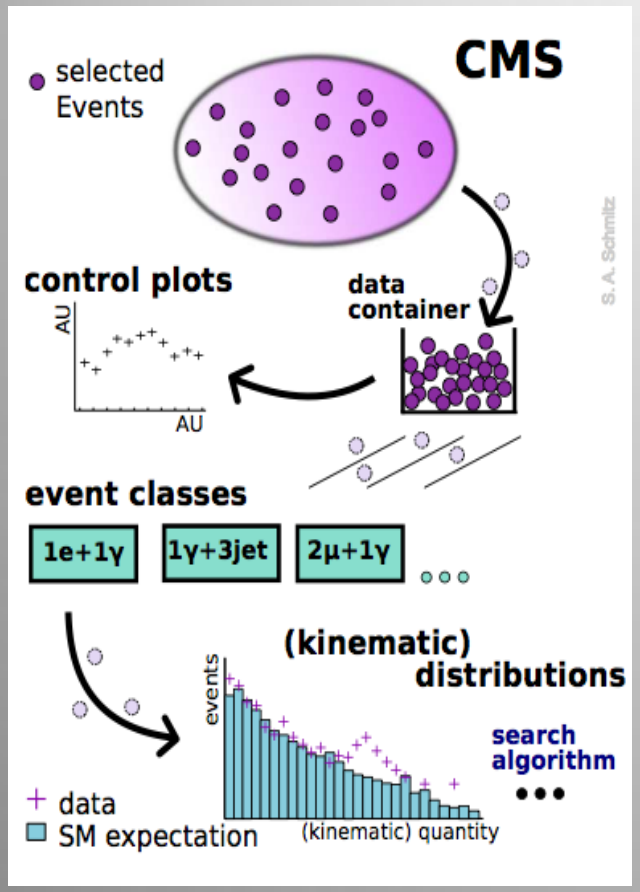
New Physics and signatures

(LP11: H. Bachacou)



Can we miss something?

CMS-EXO-10-021

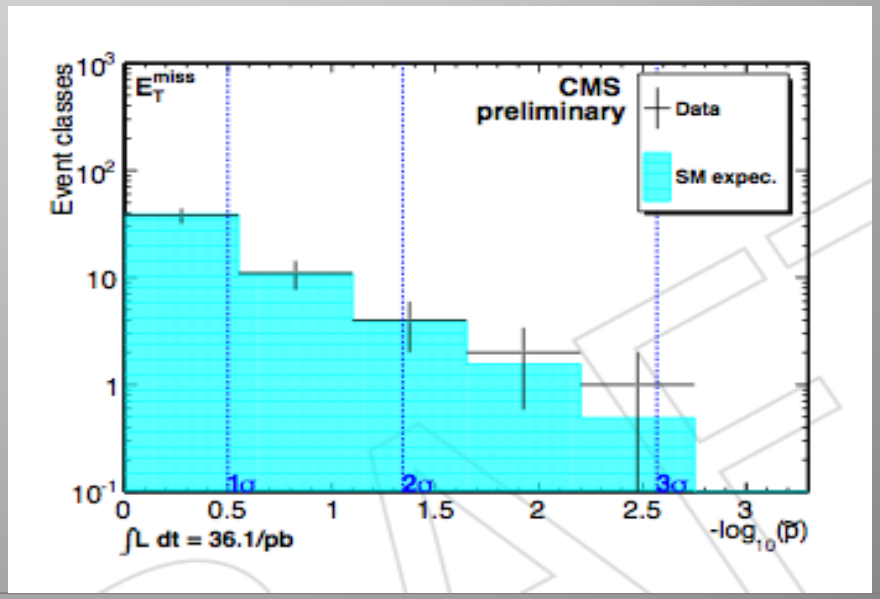


Model independent search

- 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

New signatures for new physics yet
→ Simple Summary (LP11: H. Bachacou)

	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV

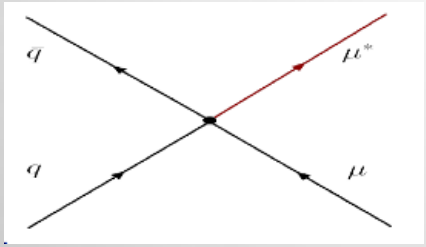
Summary: The Searches are on!

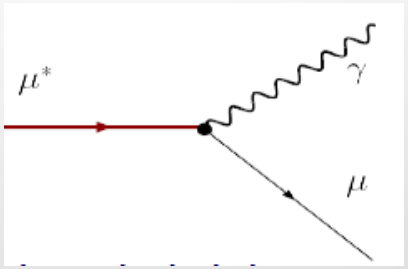
- The LHC has entered new territory. The ATLAS and CMS experiments are ready for searches for new physics. The most popular example is SUSY, but many other New Physics model searches are covered.
- No sign of new physics yet in the first 1 fb^{-1} at 7 TeV.

  Starts to cut into the 'preferred SUSY region'. The air for constrained models is getting very thin. We' ll need to dig deeper. Input from our theory colleagues welcome!
- Some analyses have been released only with 35 pb^{-1} so far so these have a lot of headroom left.
- 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 (optimistic), and maybe a higher energy in 2012,which would help for searches

BACKUP

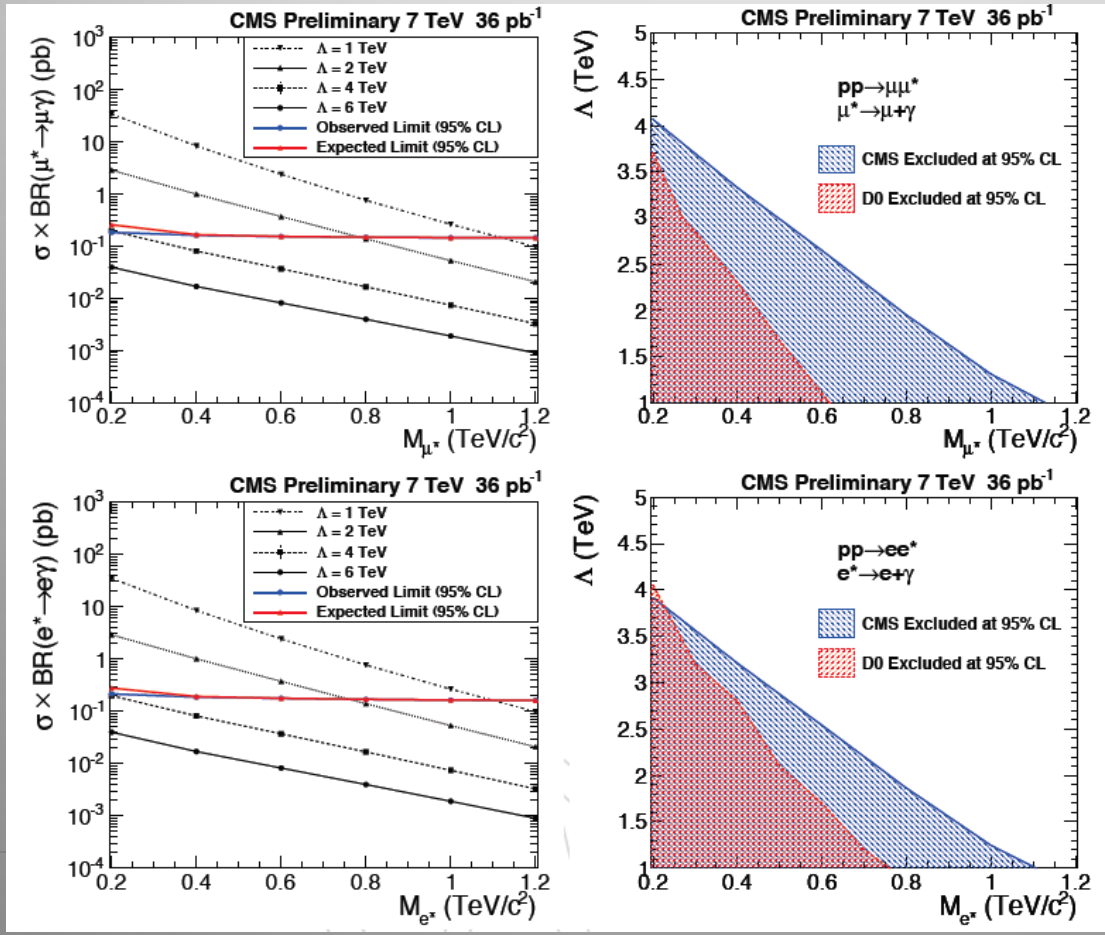
Excited Leptons





Contact interactions

$$\mathcal{L}_{CI} = \frac{g^{*2}}{2\Lambda^2} j^{\mu} j_{\mu},$$



No excited leptons with mass < 1 TeV for $\Lambda = M_{e^*}$

No excited squarks with mass < 1.17 TeV for $\Lambda = M_{q^*}$
From q-> qZ study

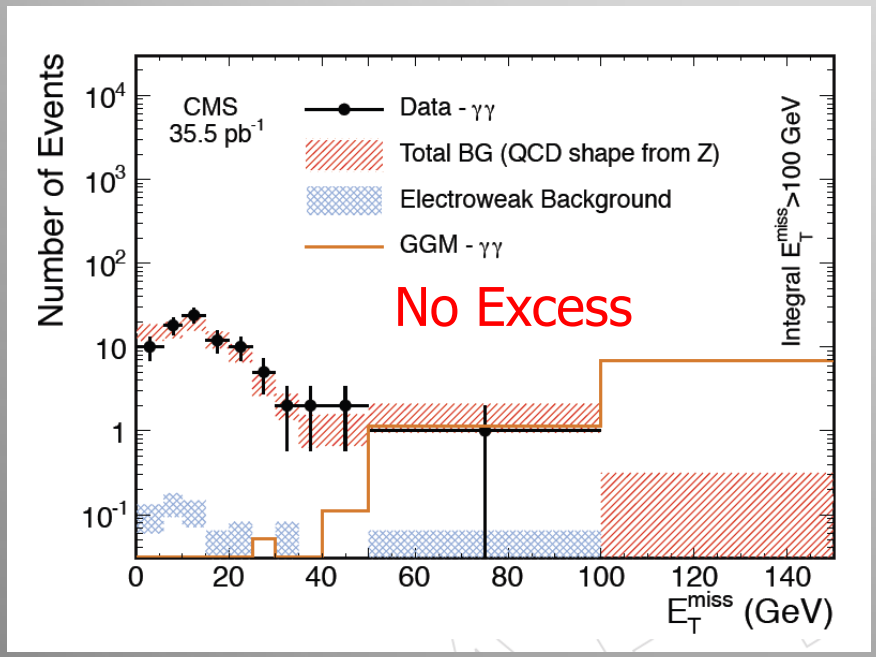
GMSB SUSY Searches

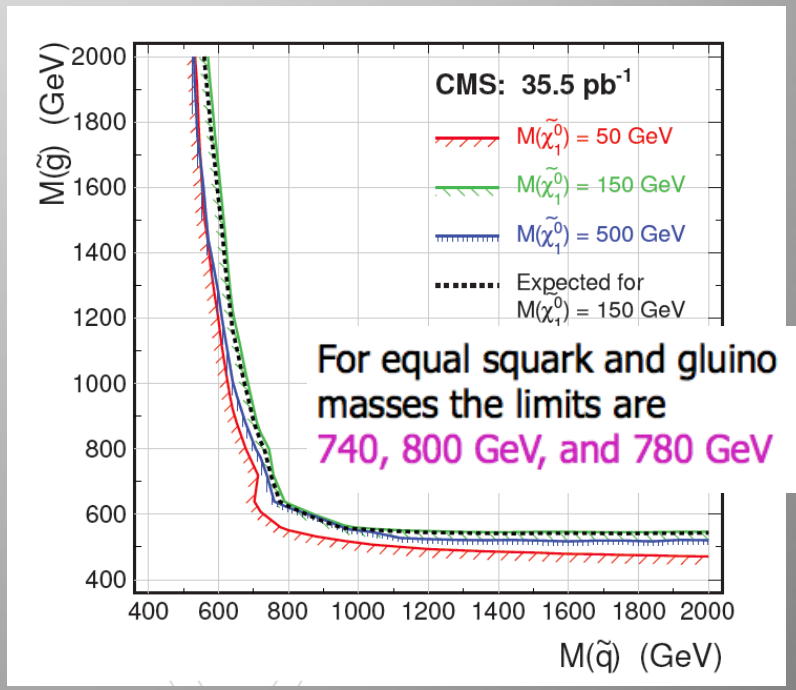
Gauge Mediated SUSY breaking: LSP is the Gravitino

- 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

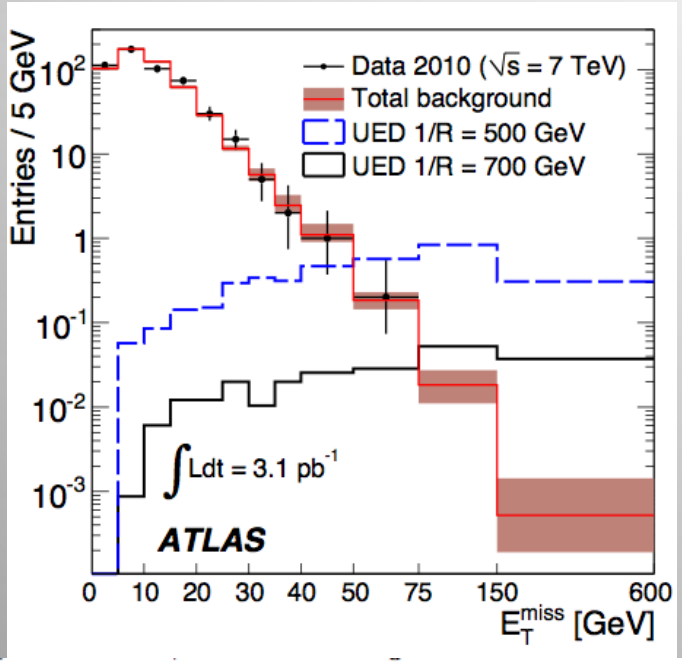


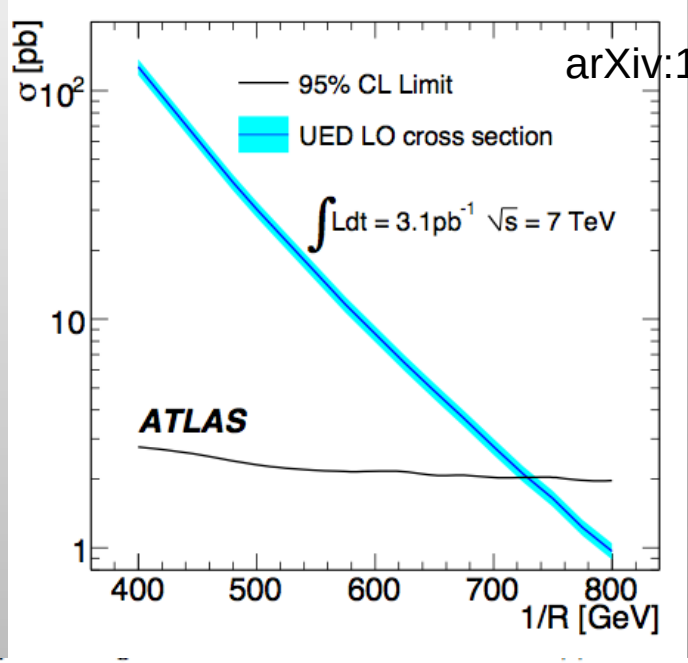


These results can be reinterpreted in Universal Extra Dimensions

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





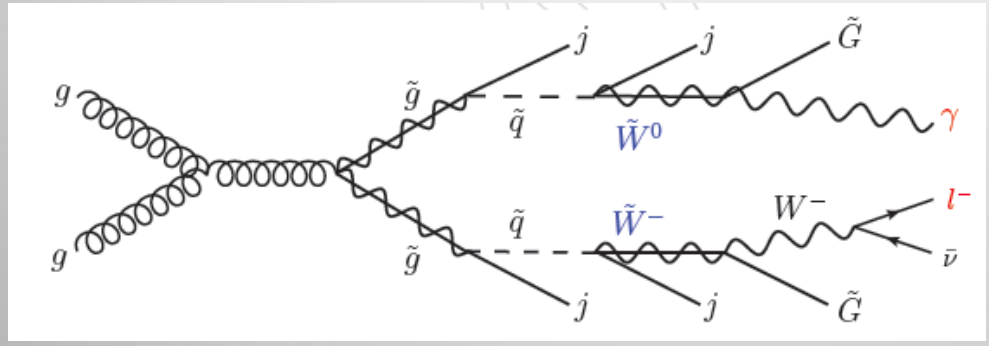
arXiv:1012.4272

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...

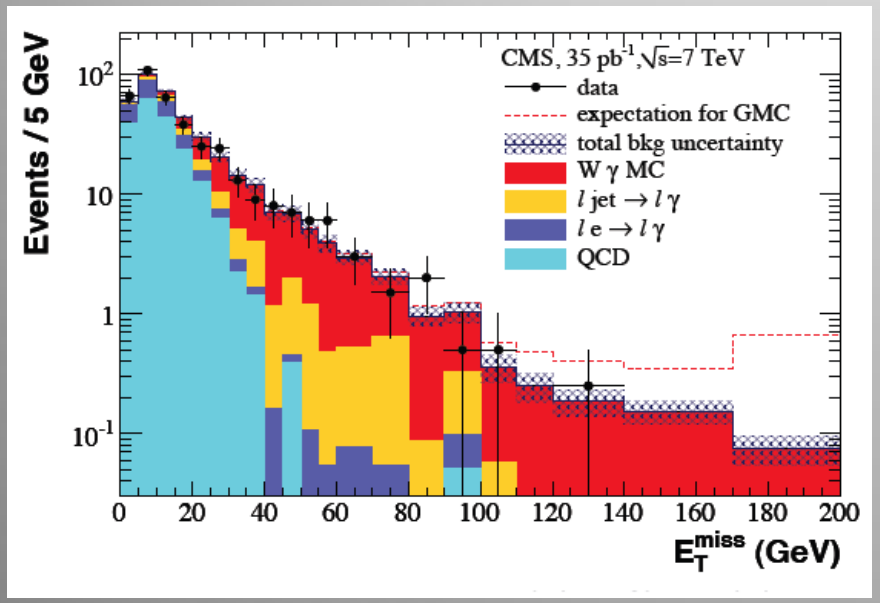
GMSB SUSY Searches

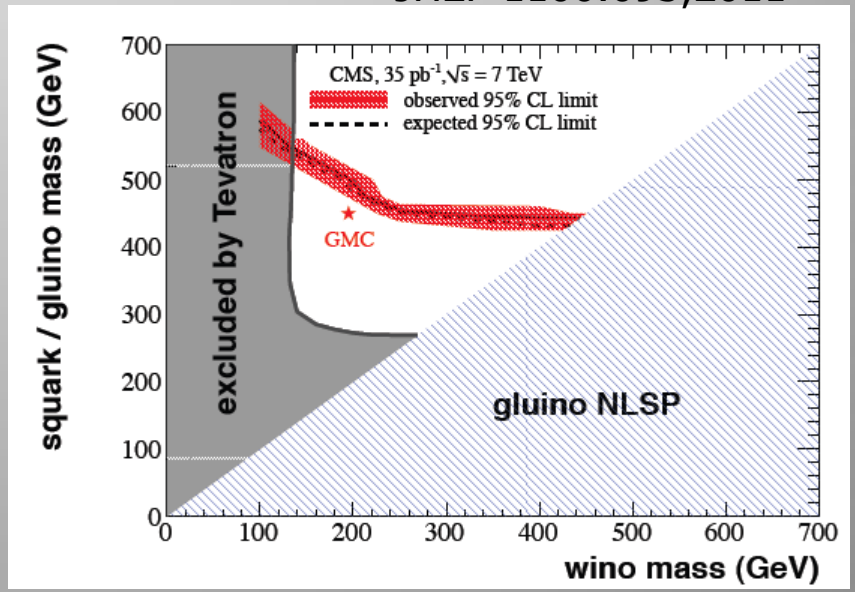
E.G. This channel: A lepton, a photon and Missing Transverse Energy



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

JHEP 1106:093,2011

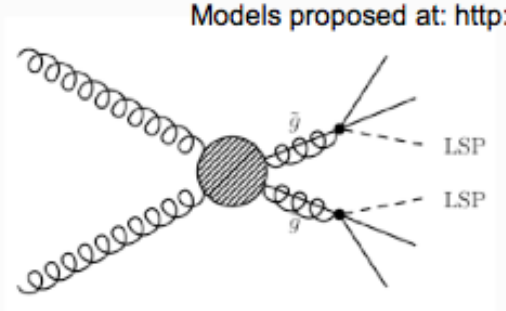


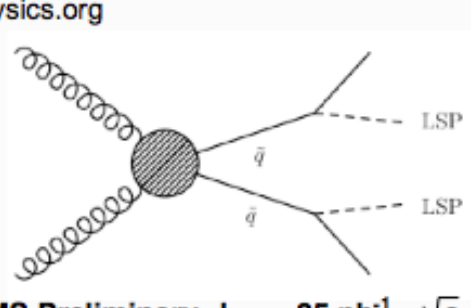


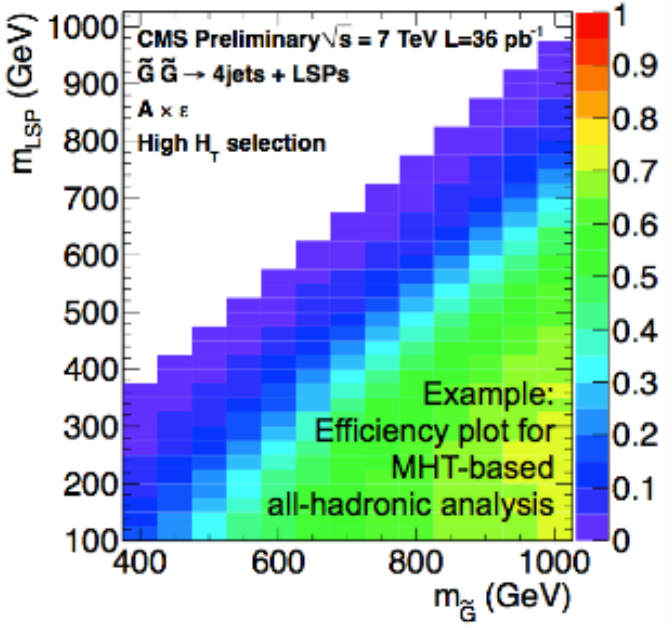
No excess found… Exclusion in the squark/gluino wino space

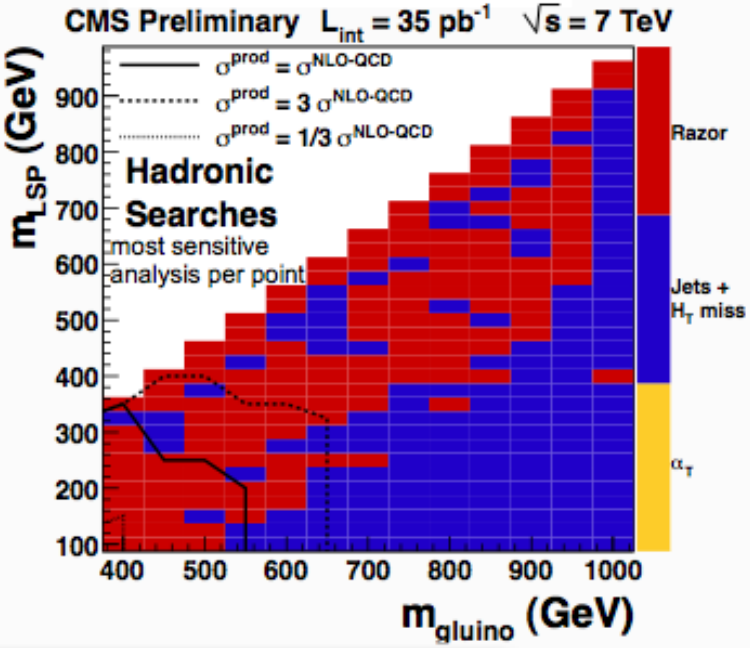
Results as Simplified Models

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?

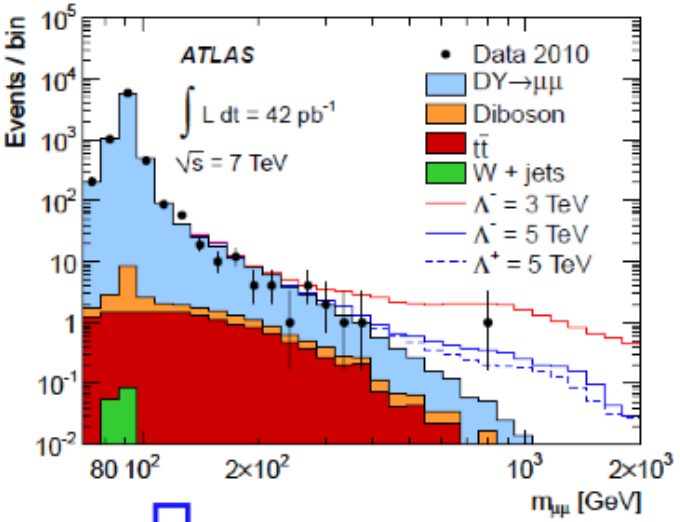
Contact Interactions

Contact Interactions

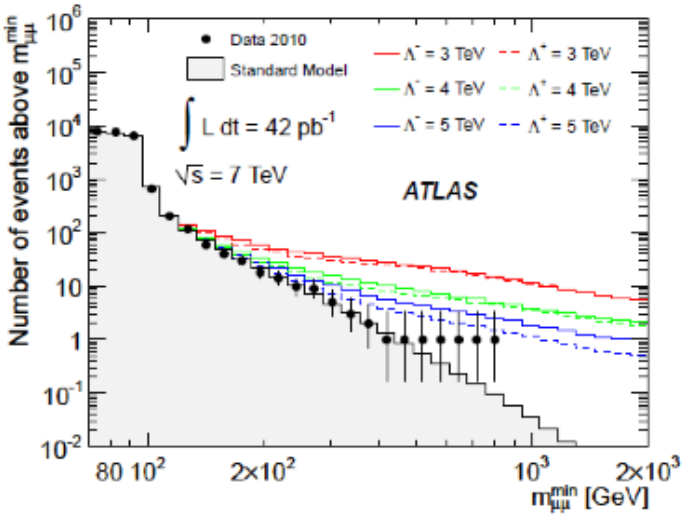
- Four-fermion contact interactions (CI) at low energy limit describe phenomena as:
  - Large Extra Dimension ADD Model
  - Quark-lepton compositeness
- Benchmark: left-left isoscalar model

$$\frac{d\sigma}{dm_{\mu\mu}} = \frac{d\sigma_{DY}}{dm_{\mu\mu}} - \eta_{LL}\frac{F_I(m_{\mu\mu})}{\Lambda^2} + \frac{F_C(m_{\mu\mu})}{\Lambda^4}$$

  - $F_{I(C)}$ is interference (CI) term, $_{LL}$= 1
  - is the energy scale (below which fermion constituences are bound)
- No excess, limits at 95% CL:
  - $^{-}$>4.9TeV for constructive interference
  - $^{+}$>4.5TeV for destructive interference



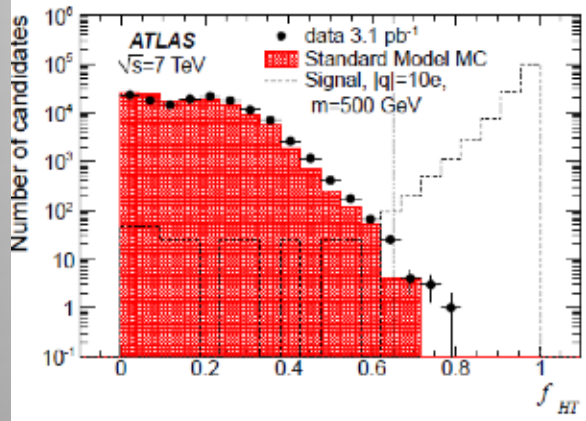
Taking an integral...

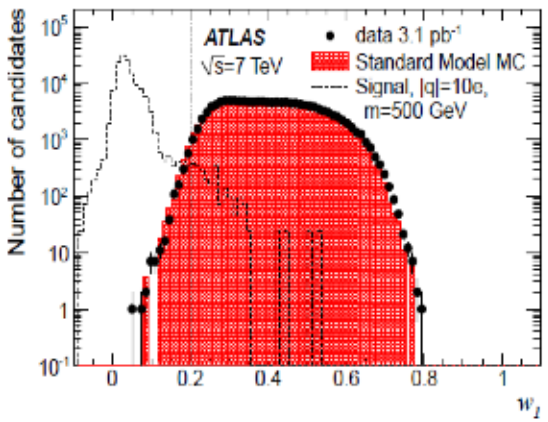


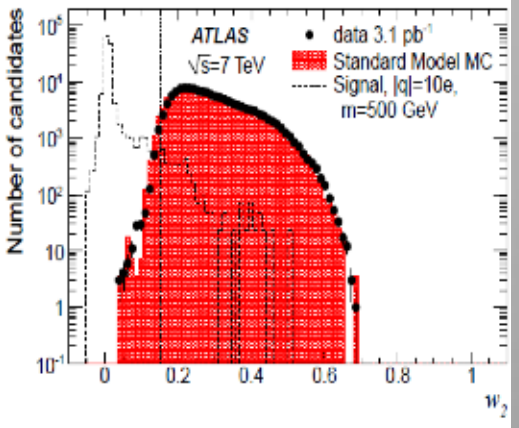
arxiv:1104.4398 accepted by PRD

Long Lived Particles

Search for Massive Long-Lived Highly Ionising Particles







- Search for massive long-lived HIP: concentrate on large mass (>100GeV), non-relativistic speed, charges 6-17e (Q-balls, stable micro black holes)
- Signal has high ionization in tracker, narrow calorimeter deposits
- No events pass selection shown above (96% efficient for signal)

Cross-section limits @ 95% CL in pb for any model

m [GeV]	$\|q\| = 6e$	$\|q\| = 10e$	$\|q\| = 17e$
200	1.4	1.2	2.1
500	1.2	1.2	1.6
1000	2.2	1.2	1.5

Cross-section limits at 95% CL in pb assuming Drell-Yan-like production mechanism

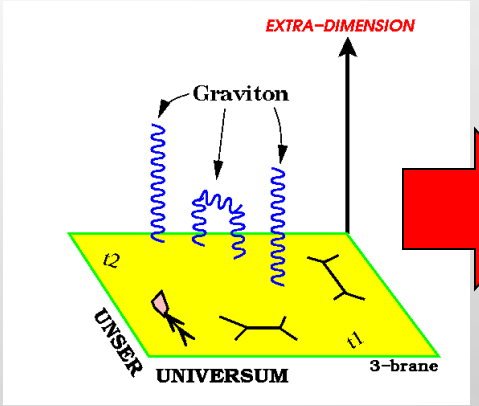
m [GeV]	$\|q\| = 6e$	$\|q\| = 10e$	$\|q\| = 17e$
200	11.5	5.9	9.1
500	7.2	4.3	5.3
1000	9.3	3.4	4.3

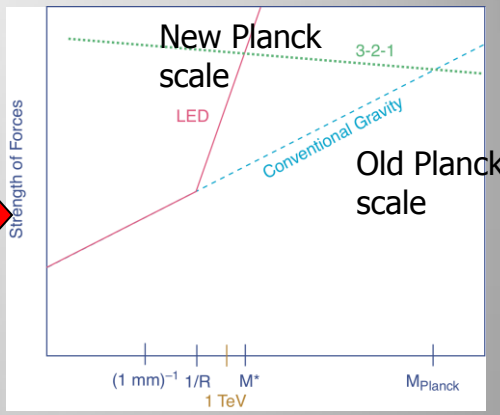
Search for Extra Dimensions

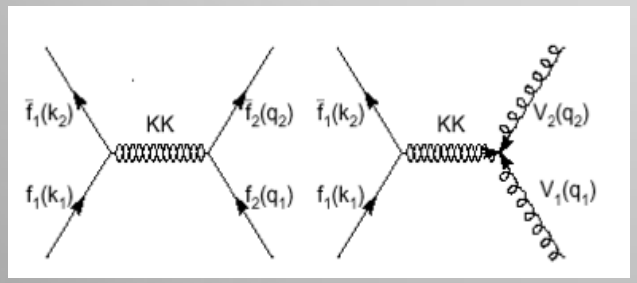
Are there extra space dimensions that open at higher energies?

Example: Experimental signature affects the di-fermion production

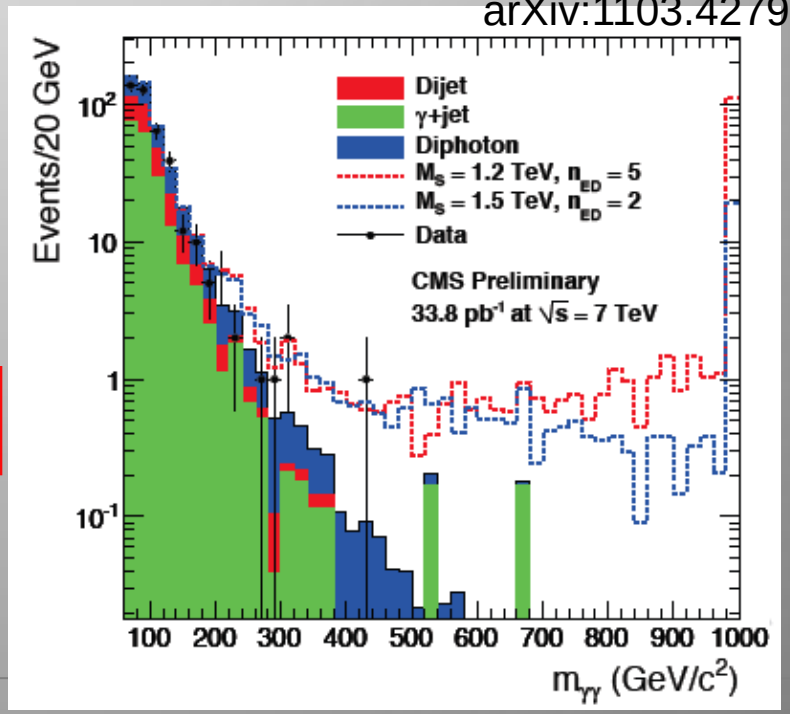
Study here: di-photon production







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