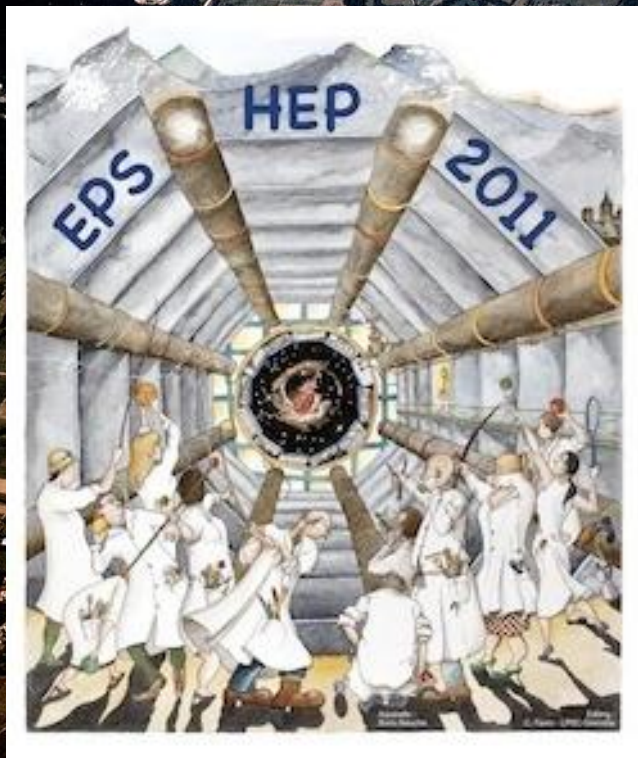


Searches for New Physics Beyond the Standard Model

Albert De Roeck
CERN, Geneva, Switzerland
August 2 2011



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

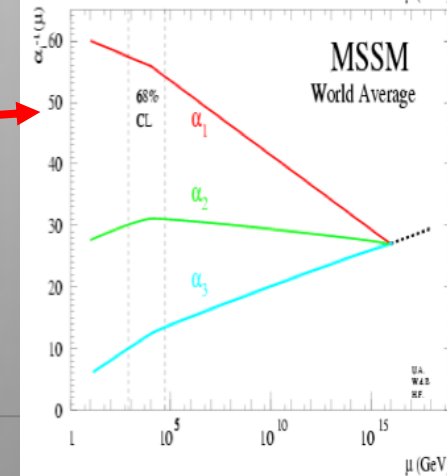
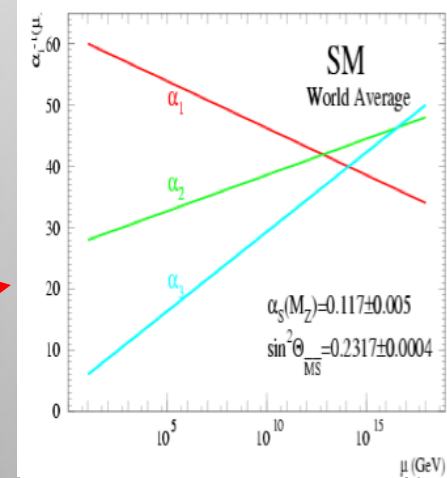
If a Higgs field exists:

- **Supersymmetry**
- **Extra space dimensions**

If there is no Higgs below ~ 700 GeV

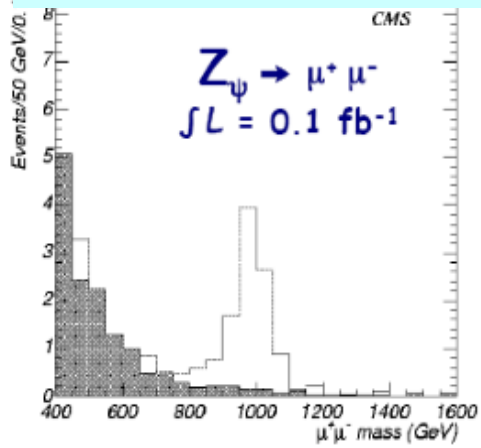
- **Strong electroweak symmetry breaking around 1 TeV**

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

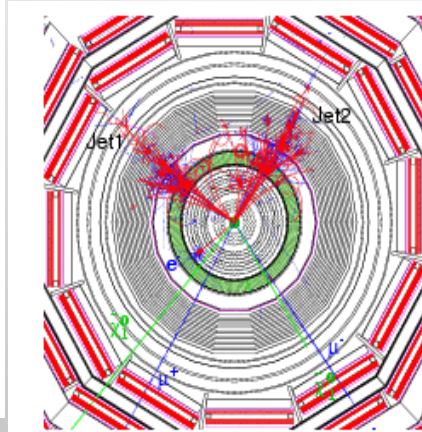


New Physics at High Energies?

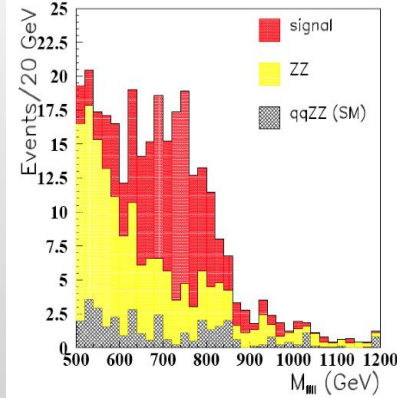
New Gauge Bosons?



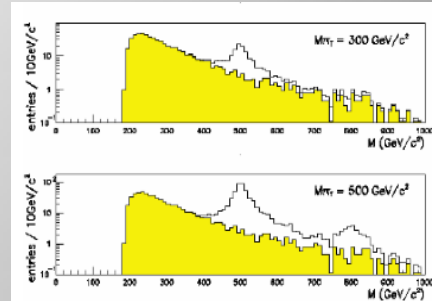
Supersymmetry



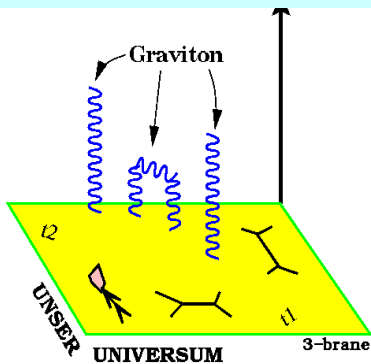
ZZ/WW resonances?



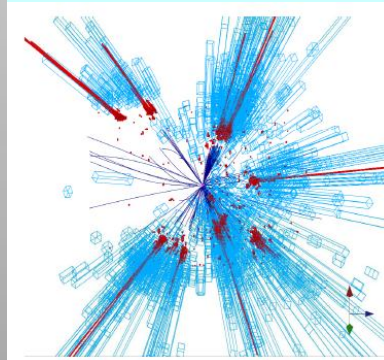
Technicolor?



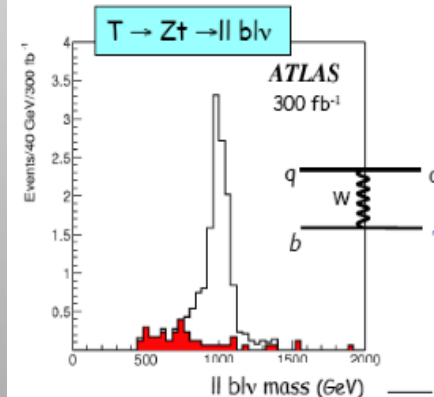
Extra Dimensions?



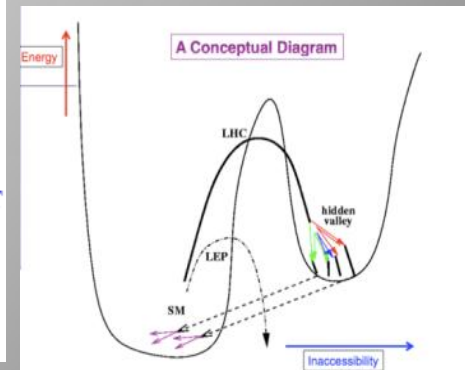
Black Holes???



Little Higgs?



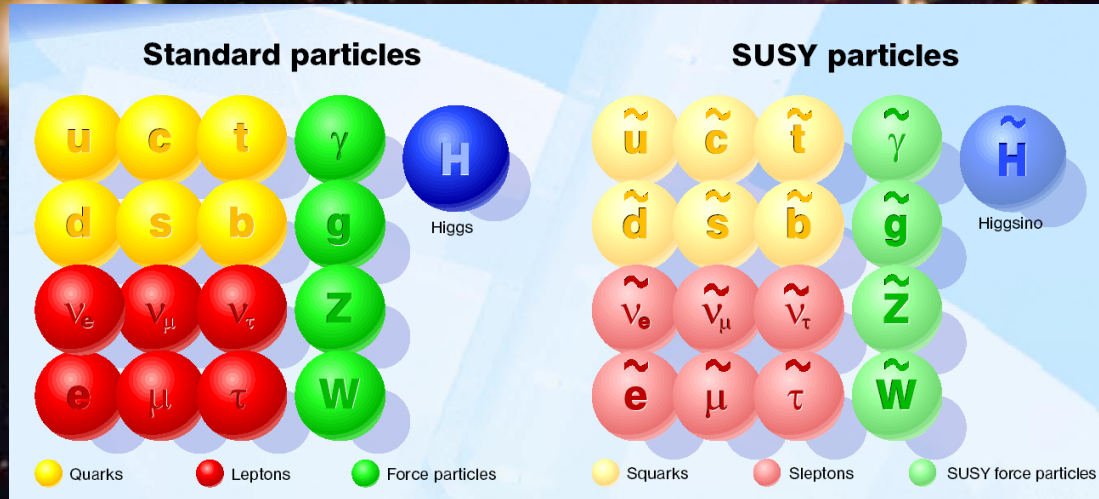
Hidden Valleys?



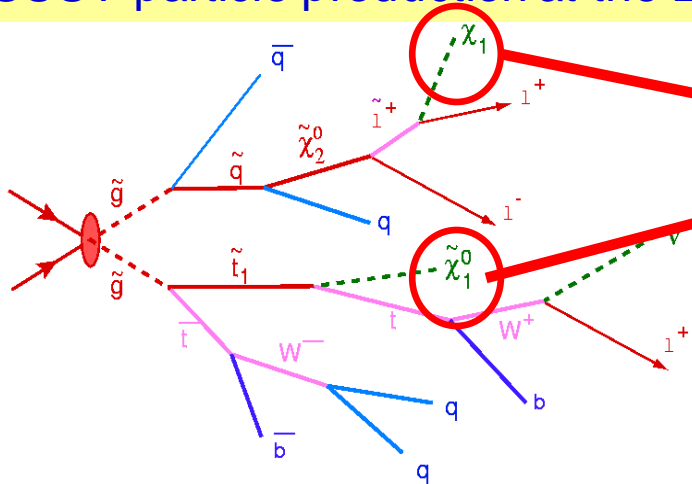
We do not know what is out there for us...

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

Supersymmetry: a new symmetry of Nature?



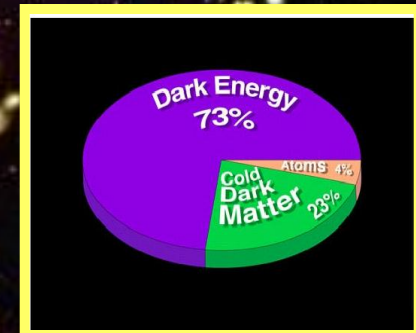
SUSY particle production at the LHC



Candidate particles for Dark Matter

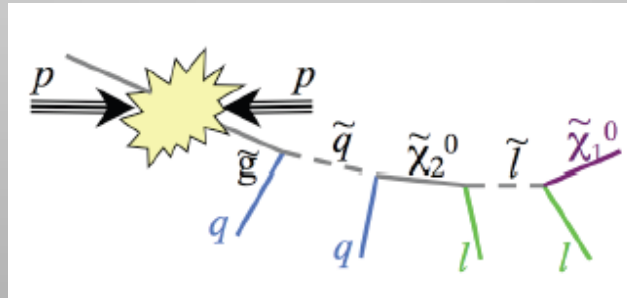
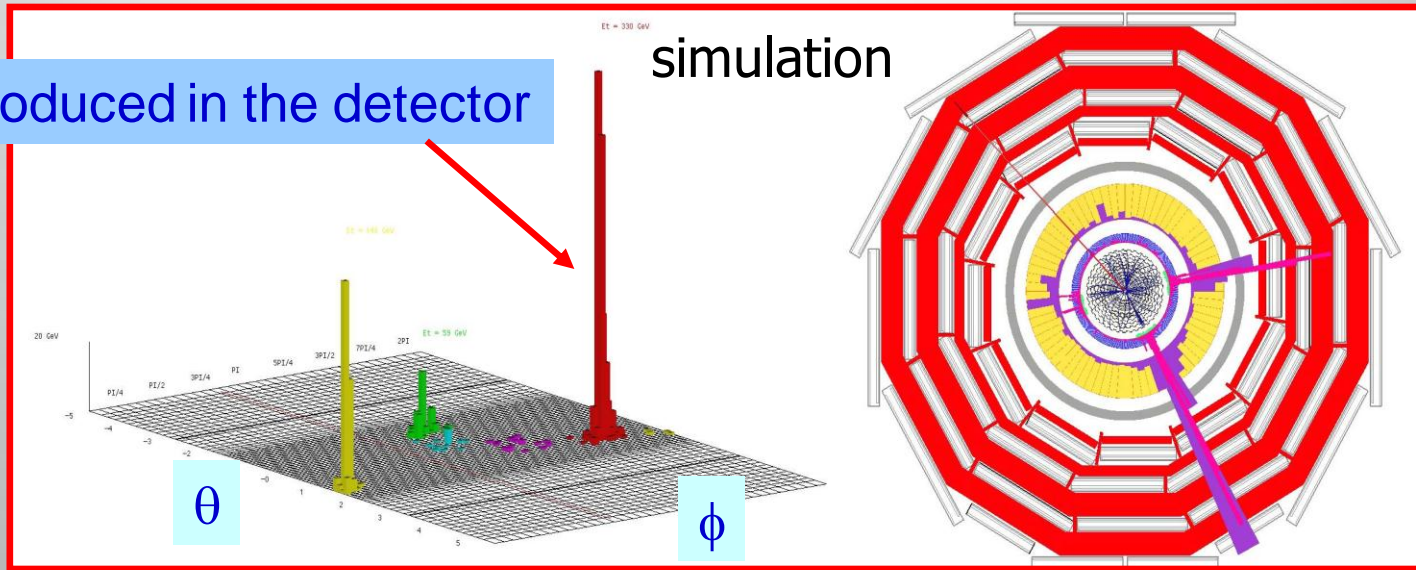
⇒ Produce Dark Matter in the lab

Assume "R-Parity" Conservation



Detecting Supersymmetric Particles

Energy produced in the detector



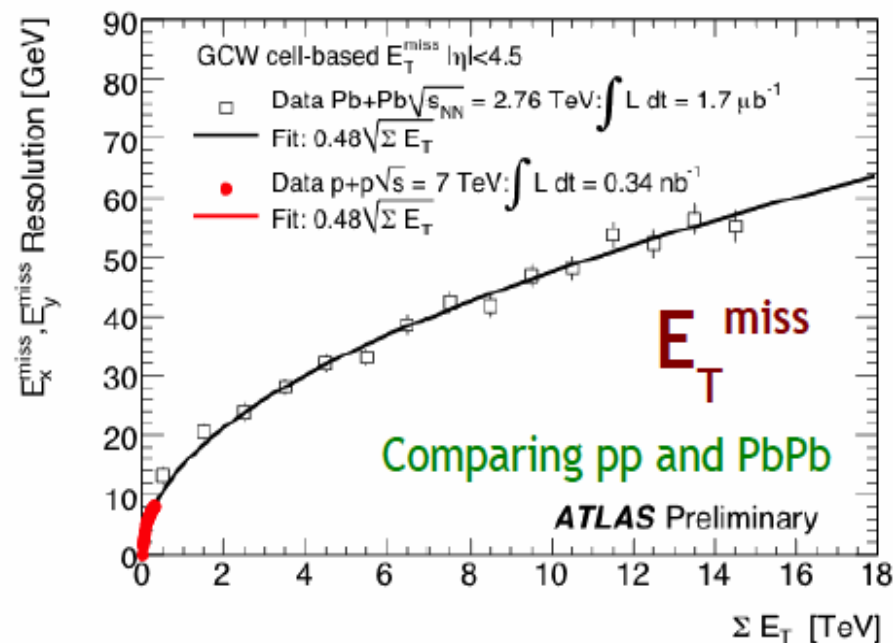
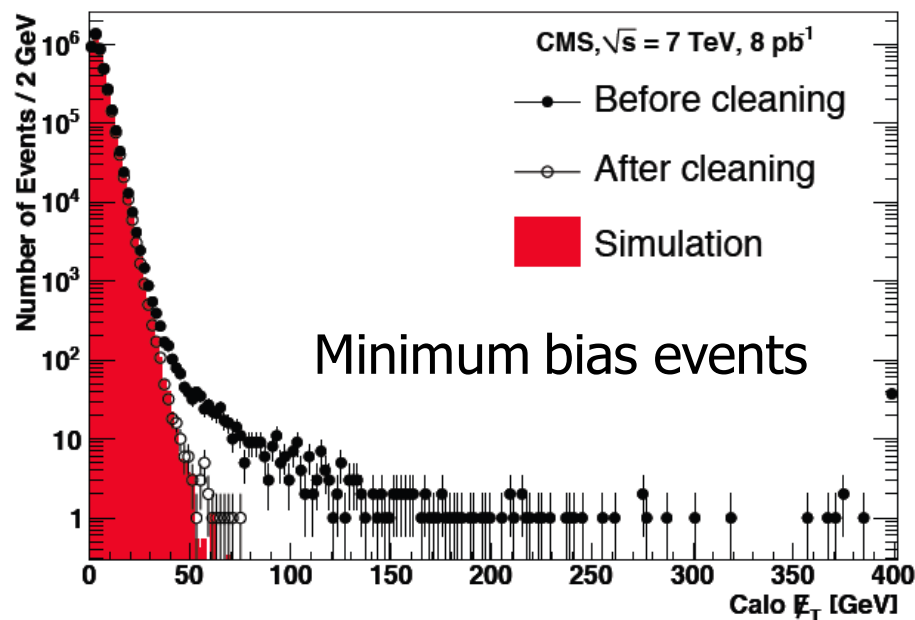
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

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

Large

SM backgrounds

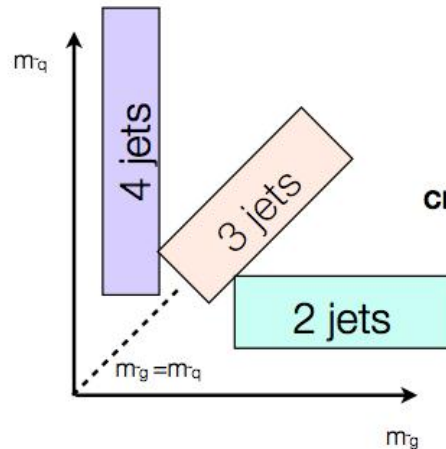
Low

sensitivity to strongly produced SUSY

sensitivity to gauge-mediated SUSY

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

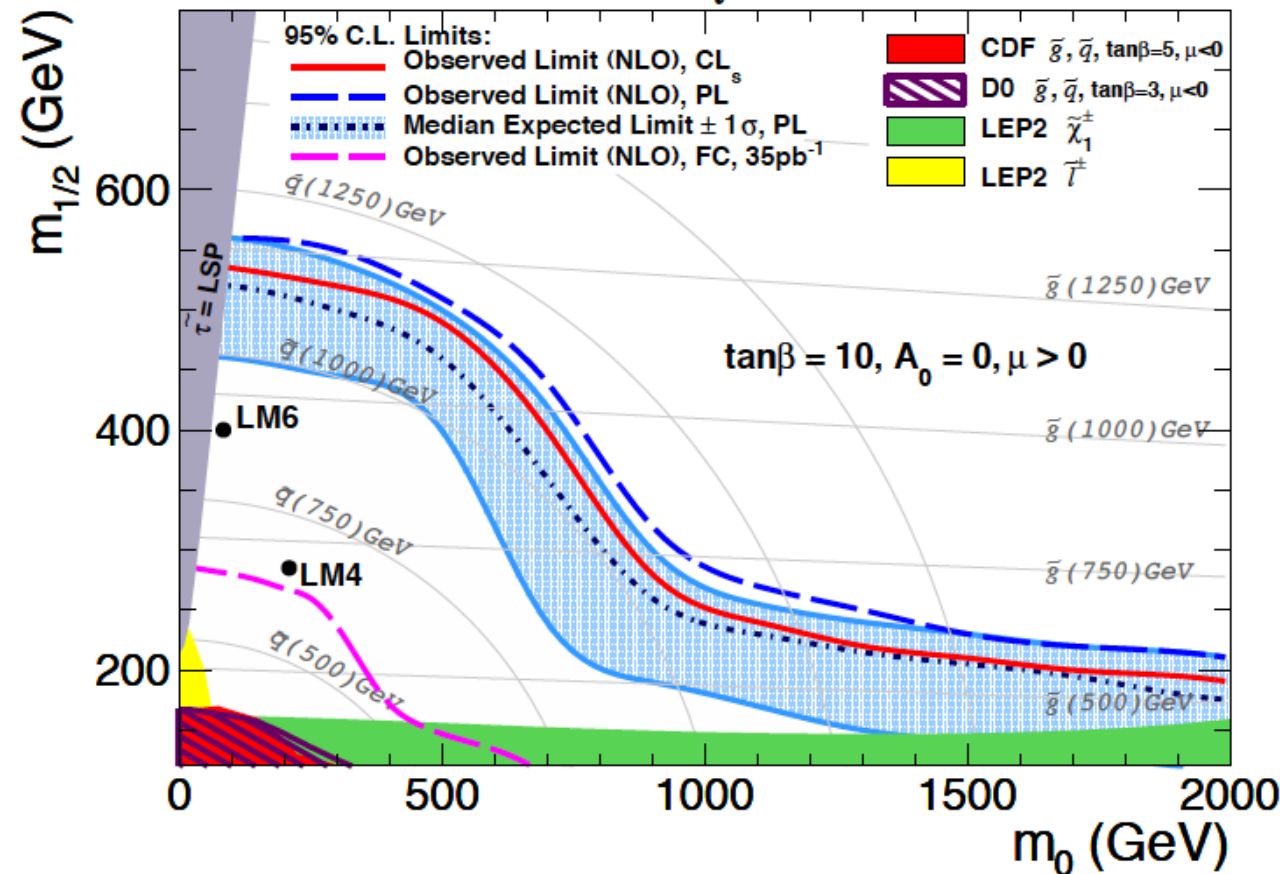
SUSY Search: Jets + Missing E_T Channel

CMS-SUS-11-003

Using 1 fb^{-1}

C. Autermann

CMS preliminary $\alpha_T \int L dt = 1.1 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV}$



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
- $\tan\beta$: vev ratio for 2 Higgs doublets
- A_0 : trilinear coupling and the sign of Higgs mixing parameter μ

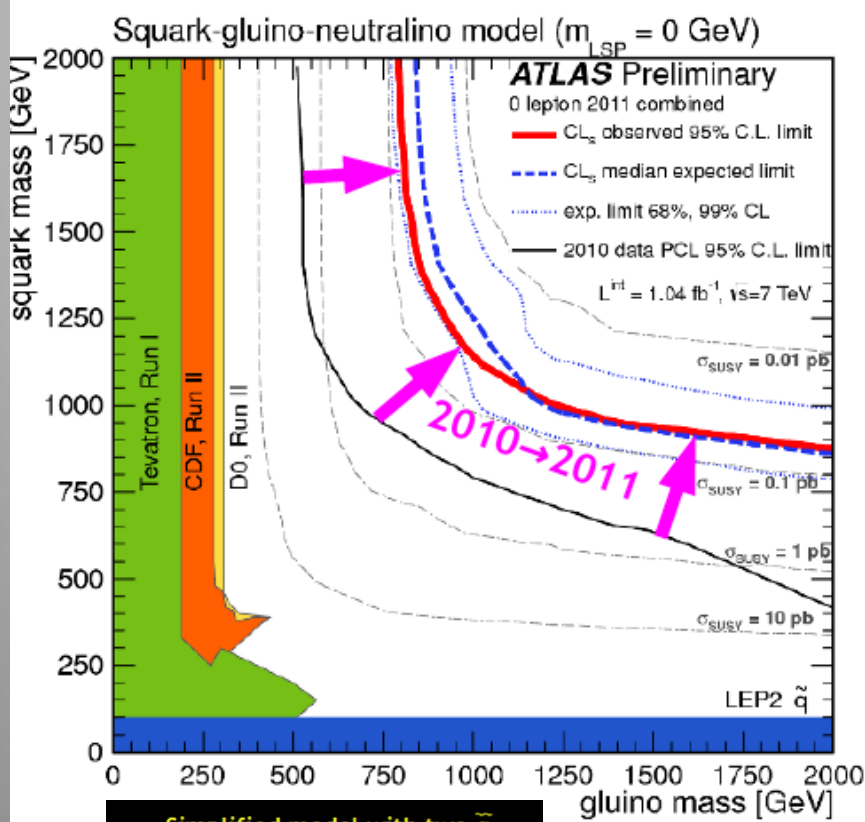
SUSY Search: Jets + Missing E_T Channel

Limits in a simplified model

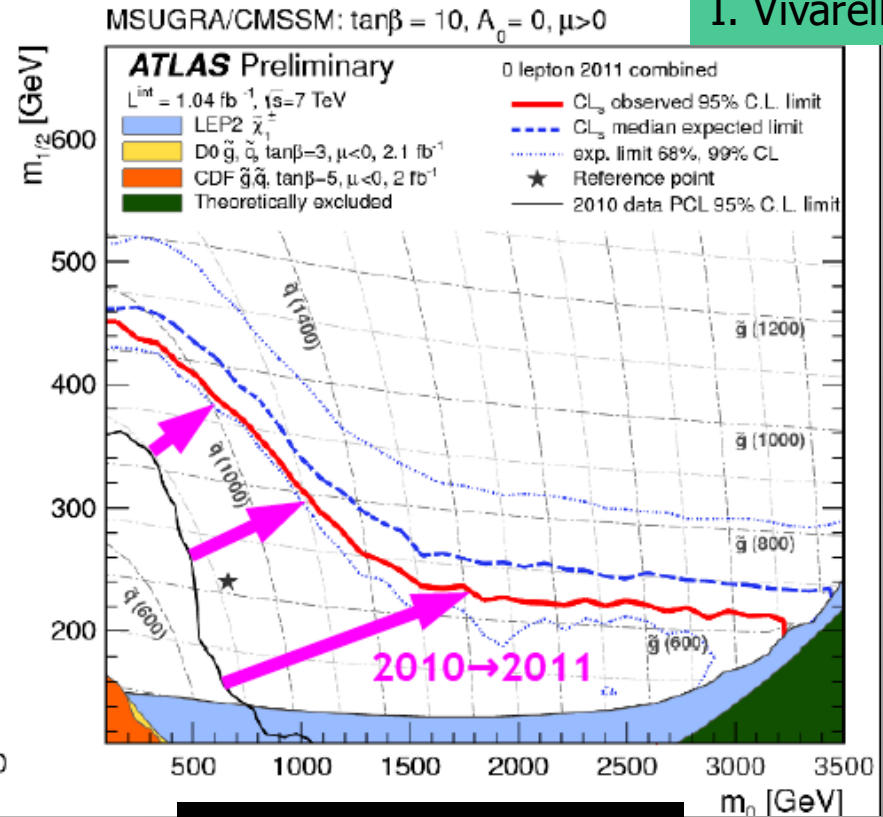
Using 1 fb^{-1}

Limits in CMSSM

I. Vivarelli



Simplified model with two \tilde{q} generations, $m(\tilde{\chi}_1^0) = 0$
 $m_{\tilde{g}} > 800 \text{ GeV}$ $m_{\tilde{q}} > 850 \text{ GeV}$
 Equal mass case: $m_{\tilde{g}} = m_{\tilde{q}} > 1.075 \text{ TeV}$



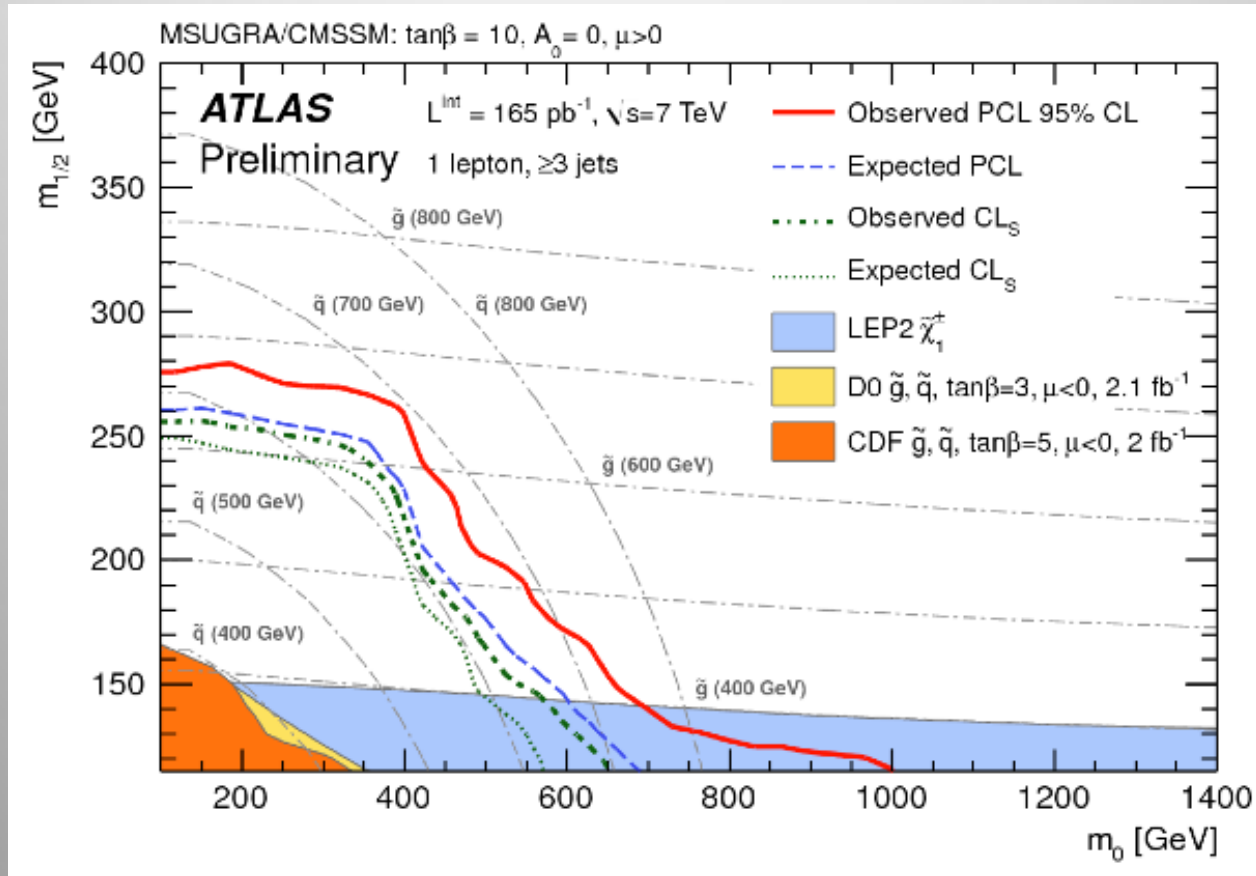
MSUGRA/CMSSM: $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$
 Equal mass case: $m_{\tilde{q}} = m_{\tilde{g}} > 980 \text{ GeV}$

Up to masses of 1 TeV excluded for equal gluino-squark masses
 Extends the 2010 data limits by $\sim 250 \text{ GeV}$

SUSY Search: 1 Lepton + jets + MET

ATLAS-CONF-2011-90

H. Hayward



Base on 165 pb^{-1}

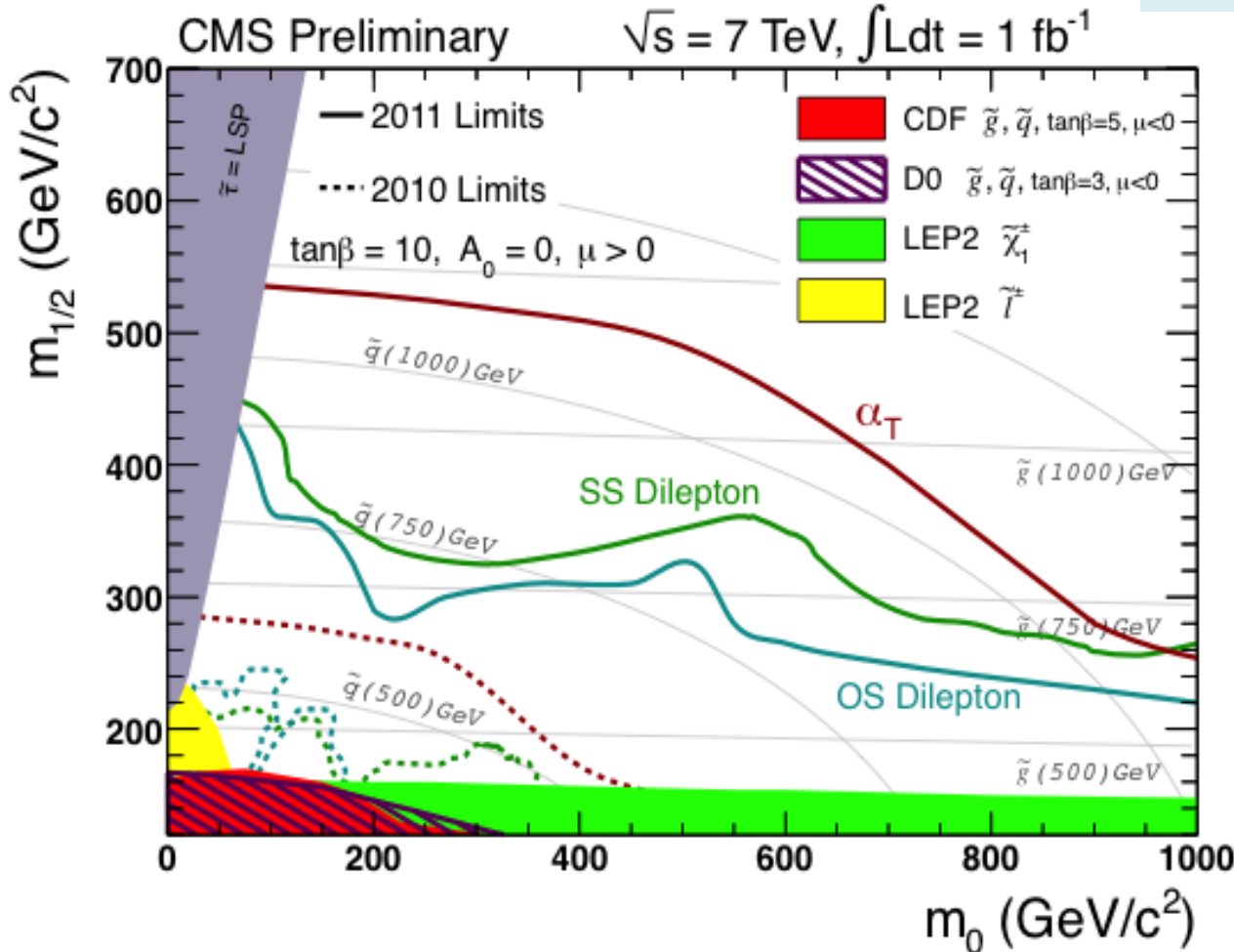
In CMSSM: less strong limits

SUSY Search: lepton and hadronic channels

CMS summary of channels with new data

Using 1 fb^{-1}

C. Autermann
S. Padhi

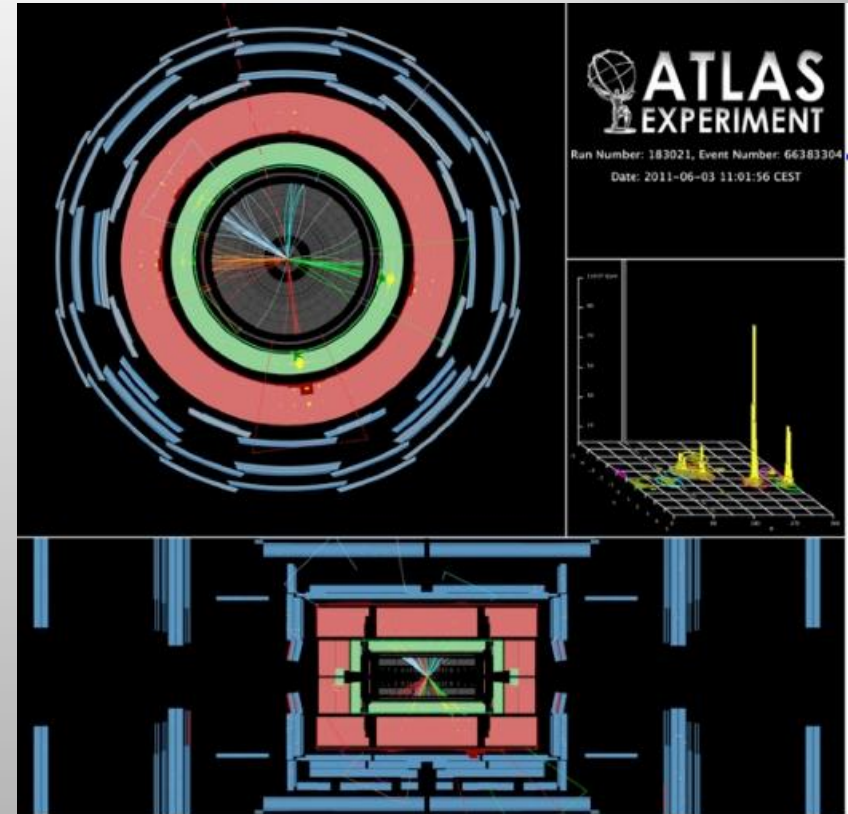
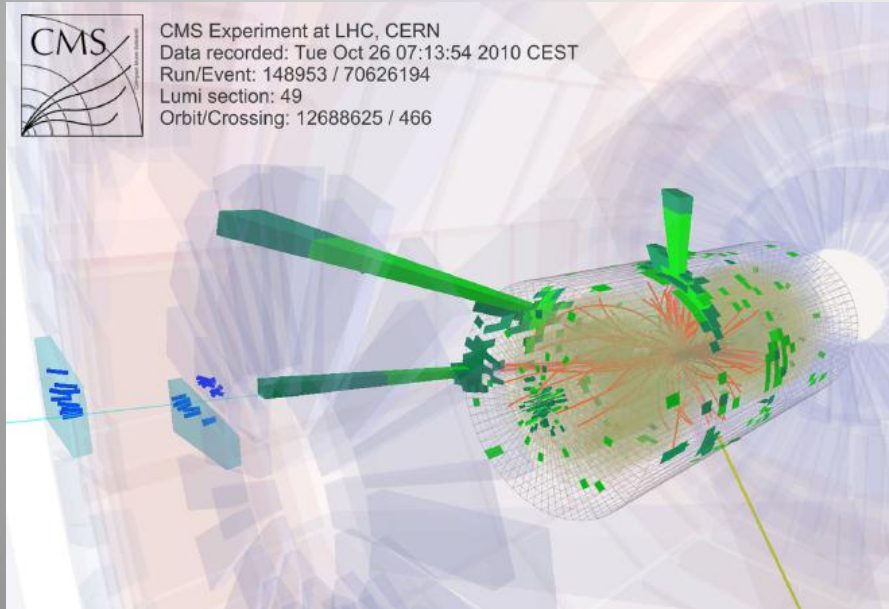


Results of three SUSY analyses completed on full summer 2011 data (α_T , Same Sign and Opposite Sign dileptons).

CMS-SUS-11-003
CMS-SUS-11-010
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

...Some Interesting Events...



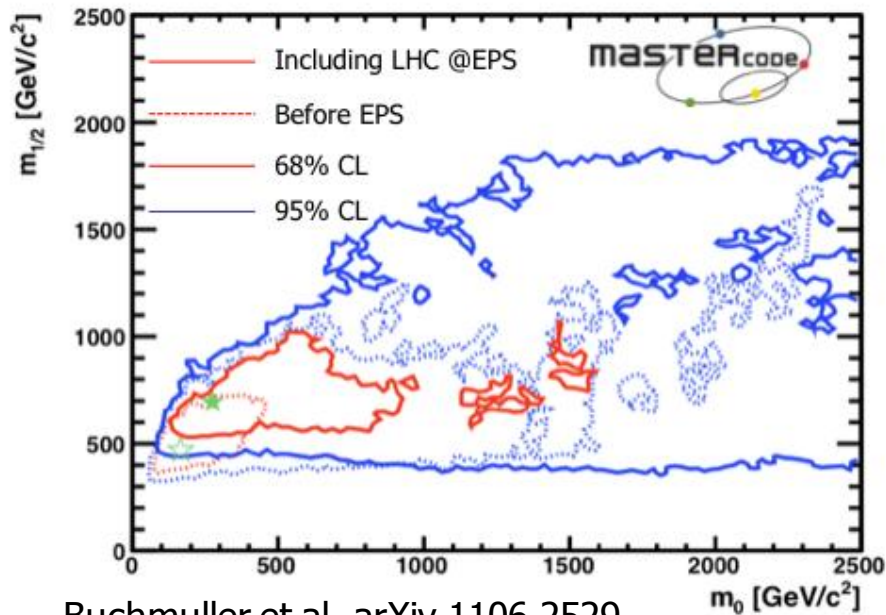
- Events with five jets and large missing transverse energy
- CMS: Total sum of transverse momentum $H_T = 1132 \text{ GeV}$ and missing transverse energy $H_{T\text{Miss}} = 693 \text{ GeV}$

Impact of LHC EPS Results on SUSY

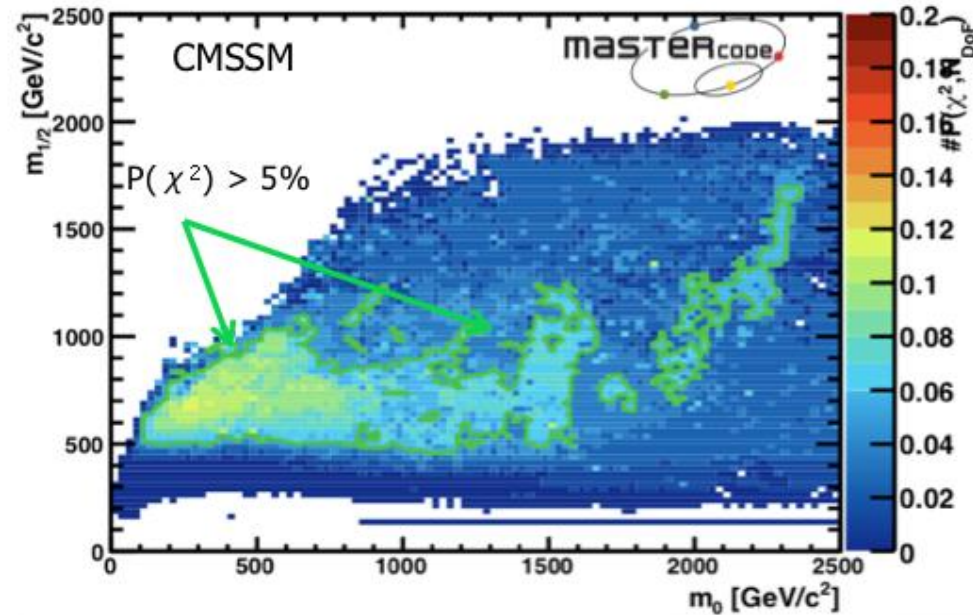
Simultaneous fit of CMSSM parameters m_0 , $m_{1/2}$, A_0 , $\tan\beta$ ($\mu > 0$) to more than 30 collider and cosmology data (e.g. M_W , M_{top} , $g-2$, $BR(B \rightarrow X\gamma)$, relic density)

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

S. Rogerson



Buchmuller et al. arXiv 1106.2529



χ^2 probability: $P(\chi^2)$ for CMSSM

Before EPS: 16%

Including CMS@EPS: 11%

LHC direct searches significantly constrain allowed CMSSM parameter space!

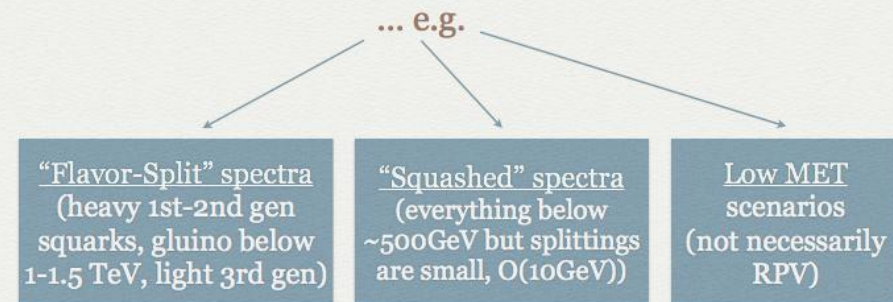
What is Next?

- 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
- LPCC Workshop @ CERN
August 28-September 2

M. Papucci

Missing something?

- Important to **push limits up**, but with more statistics **more important** to systematically **close windows** for light particles with suppressed xsec...



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

$\tilde{g}\tilde{g}(\text{production})$

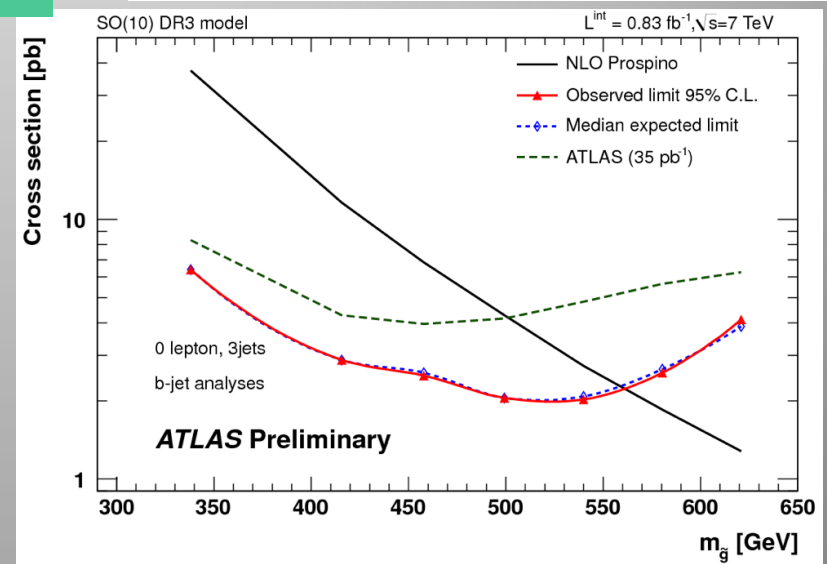
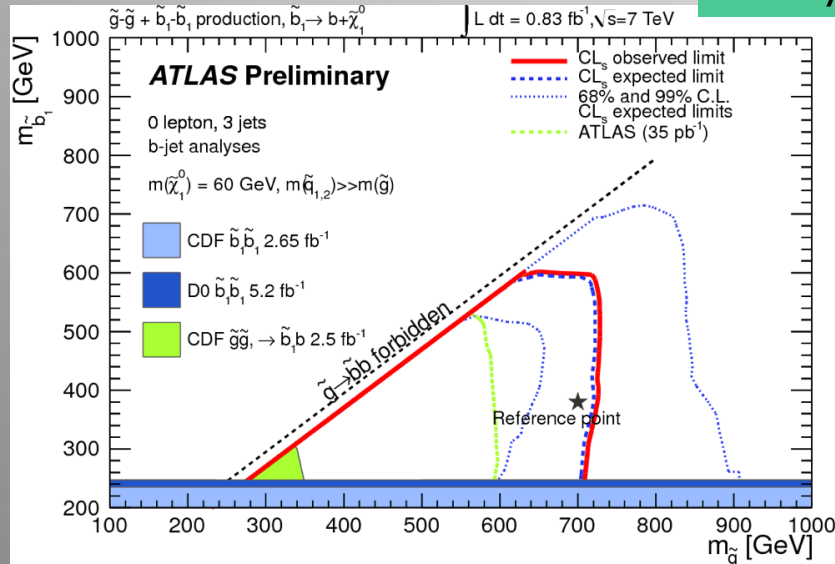
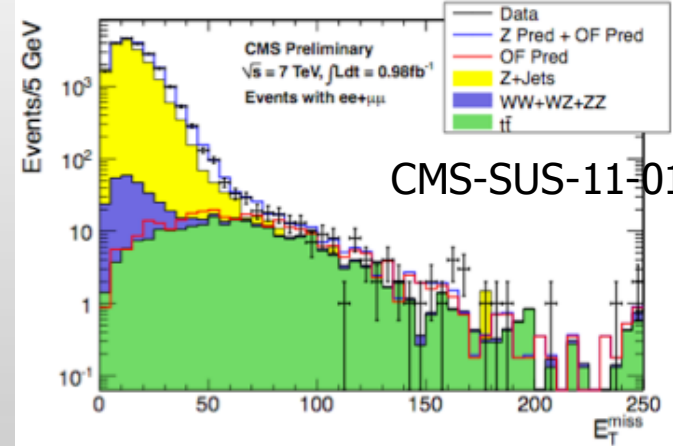
$\tilde{g} \rightarrow b\tilde{b}_1$

$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$

H. Hayward

ATLAS-CONF-2011-98

Z+2 or more jets and missing transverse energy.

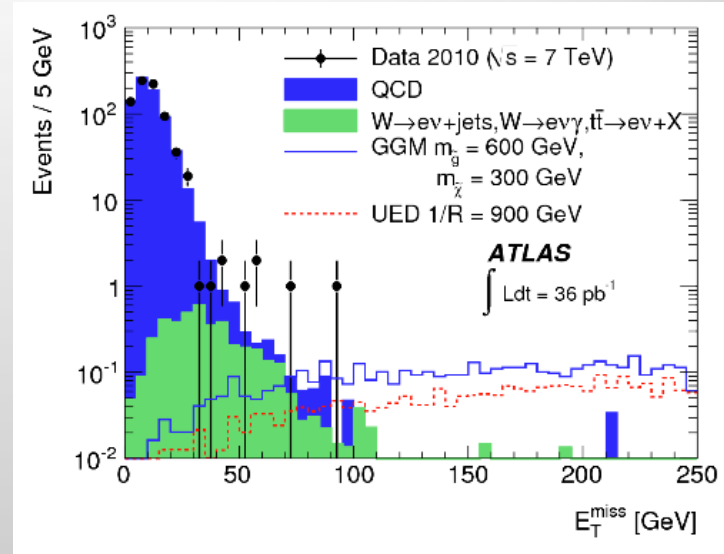


Gluinios heavier than $\sim 550 \text{ GeV}$ in this search

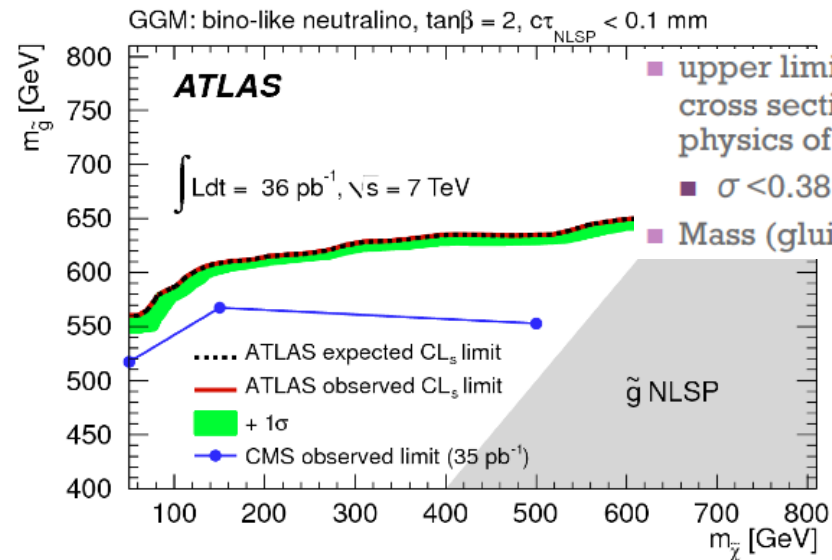
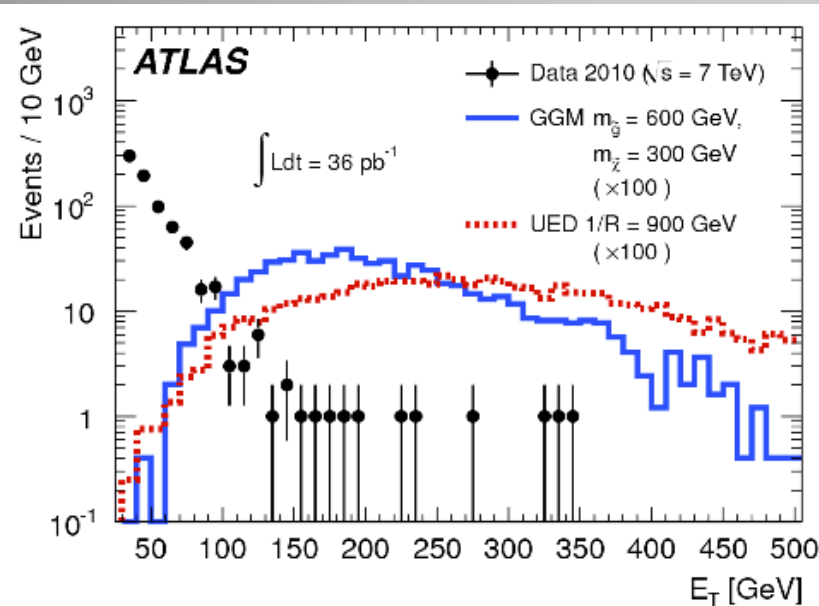
Search for Gauge Mediated SUSY

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

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



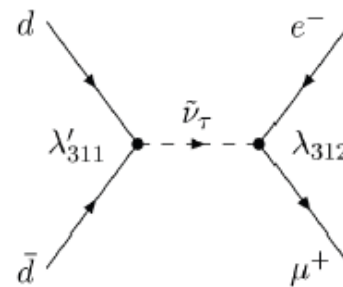
H. Hayward



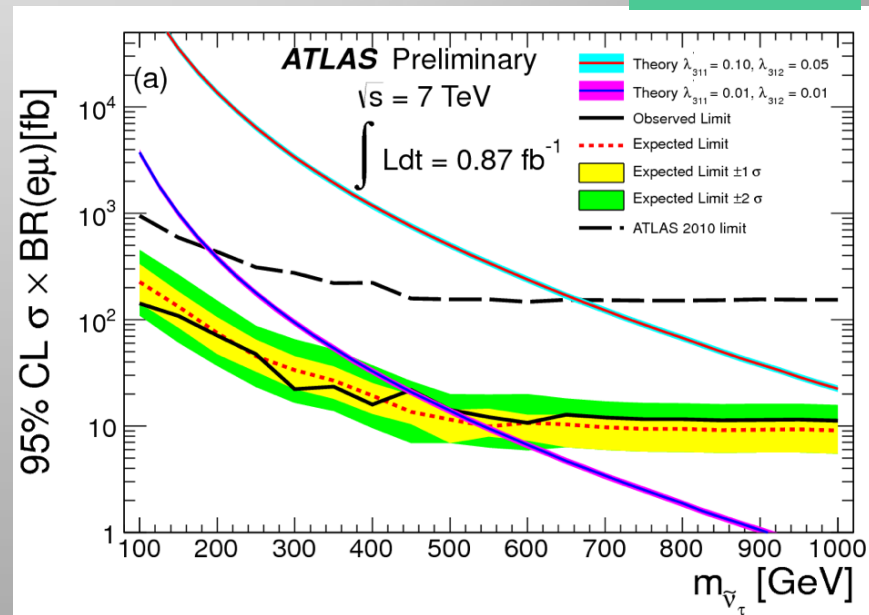
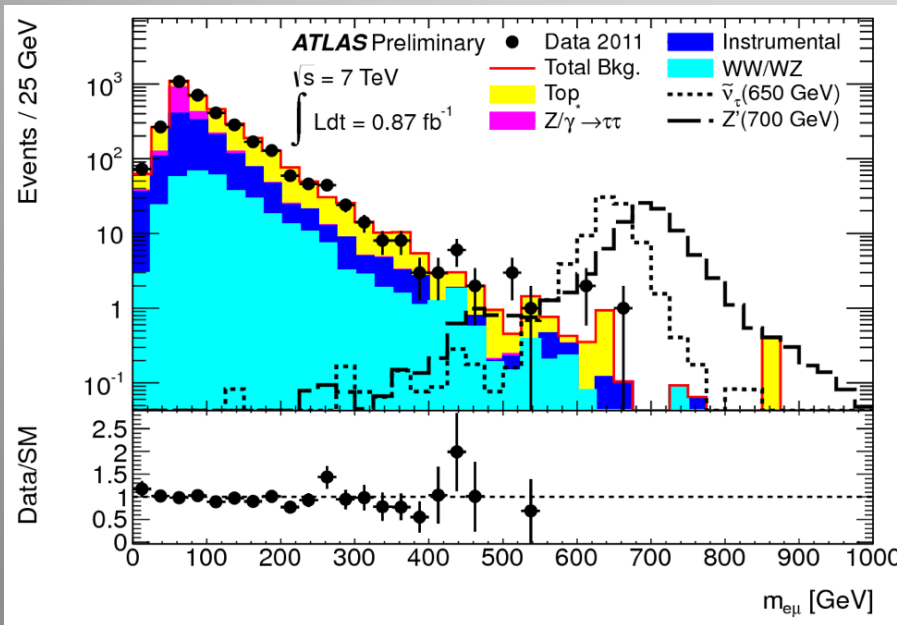
RP Violating SUSY Searches

$e\mu$ 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 p_T electron and muon
- Using 0.87 fb^{-1} of 2011 dataset to update analysis published in PRL analyzing 2010 data



P. Jackson

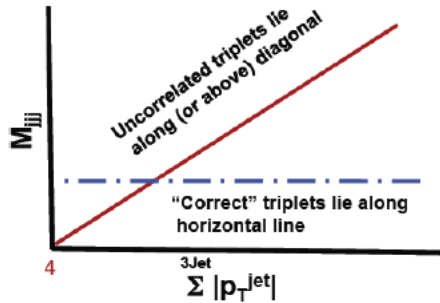


Limits on sneutrino mass between 0.5 and 1 TeV depending on the couplings

RP Violating SUSY Searches



Sparticle decays into 3 jets

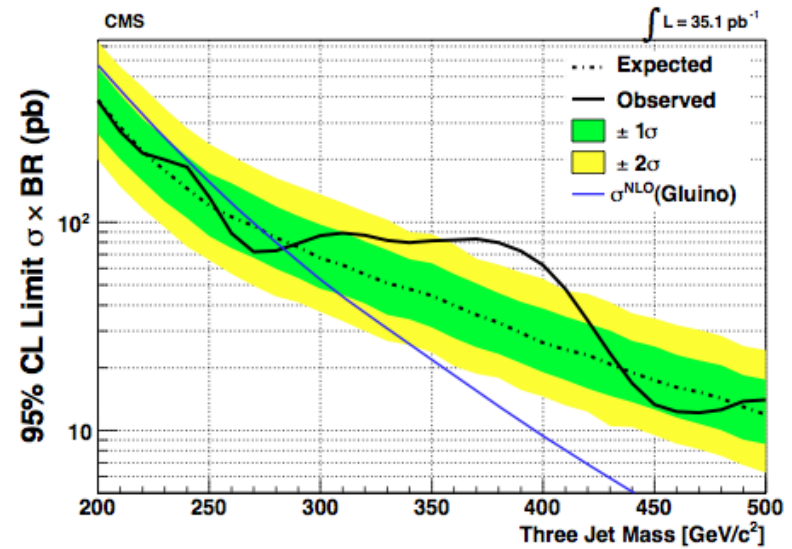
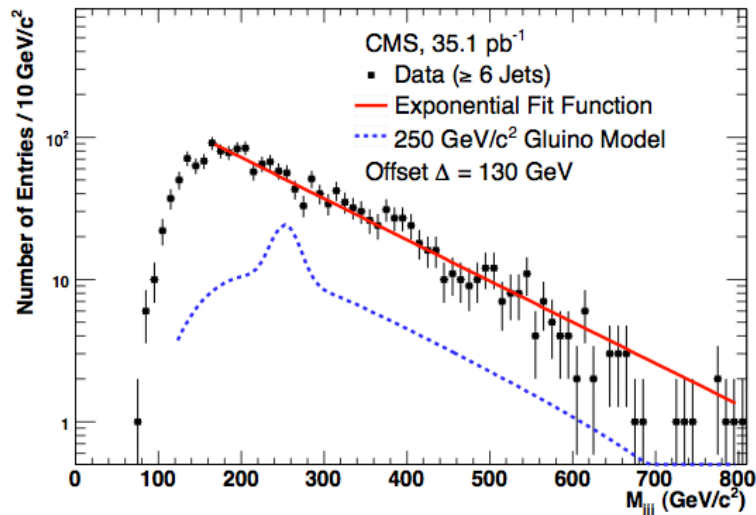


- Use a diagonal cut to remove combinatorial background as well as QCD background:

$$m_{jjj} < \sum |p_T(\text{triplet})| - \alpha \text{ (Offset)}$$

K. Yi

arXiv:1107.3084



No signal for gluino masses up to 280 GeV

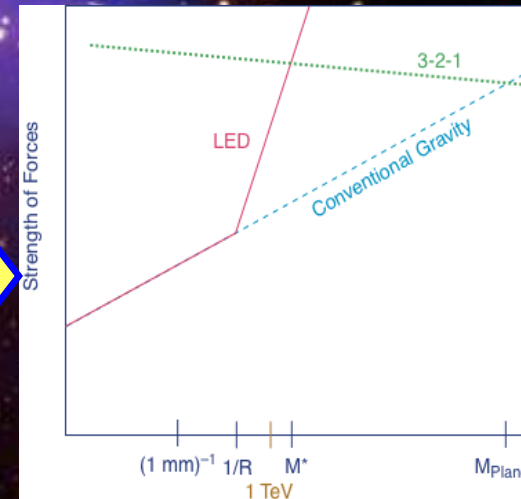
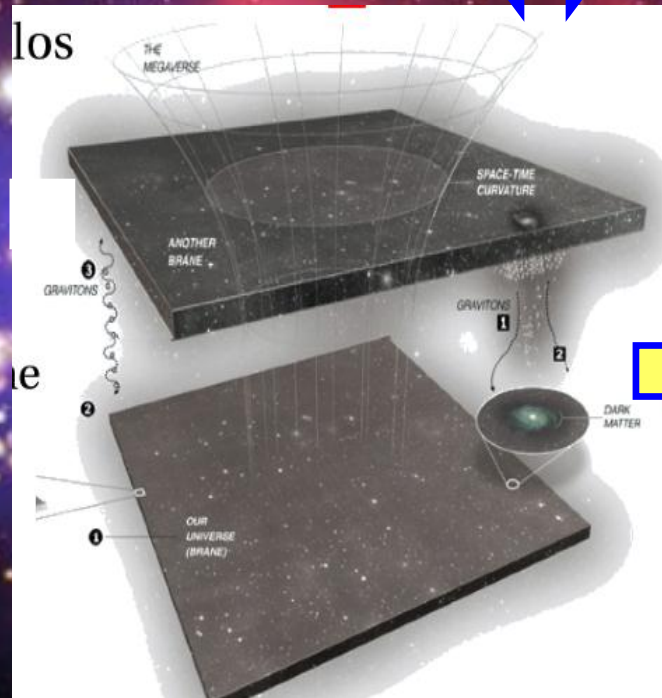
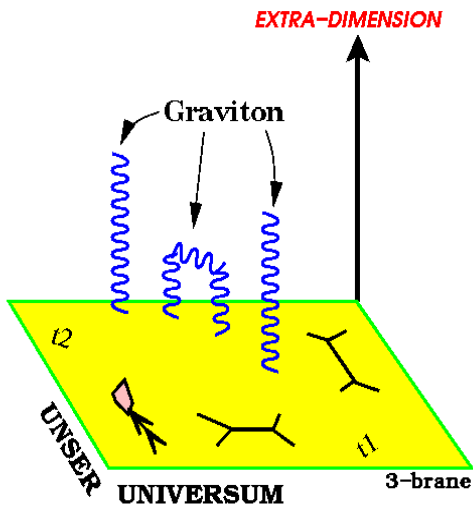
High mass excursion is less than 2σ taking into account look elsewhere effect

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) \sim TeV

Size: \gg 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)]

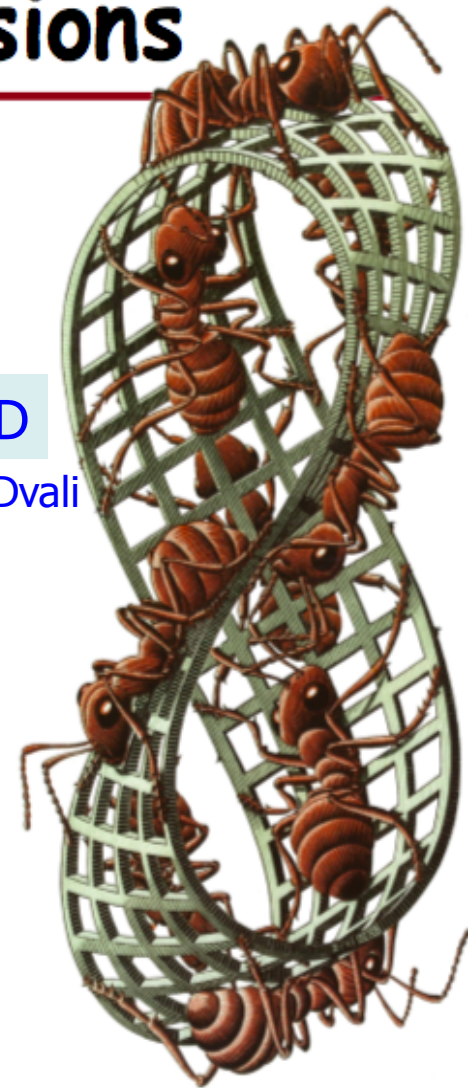
nUED : KK excitations of gauge bosons

UED

Universal Extra Dimensions

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...

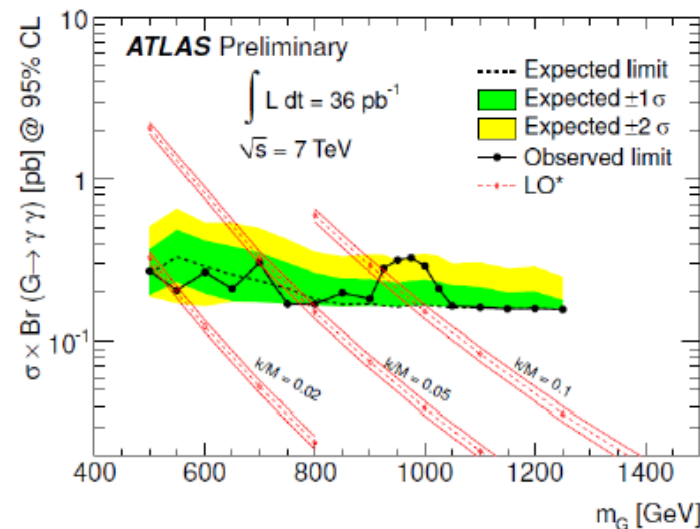
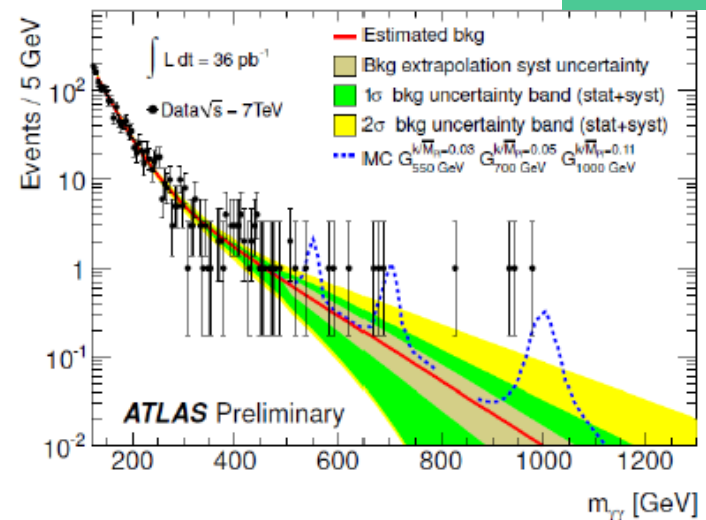


Search for Extra Dimensions

2-photon resonance (RS)

T. Berger Hryn'ova

- 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 $k/M_{Pl} = 0.1(0.02)$



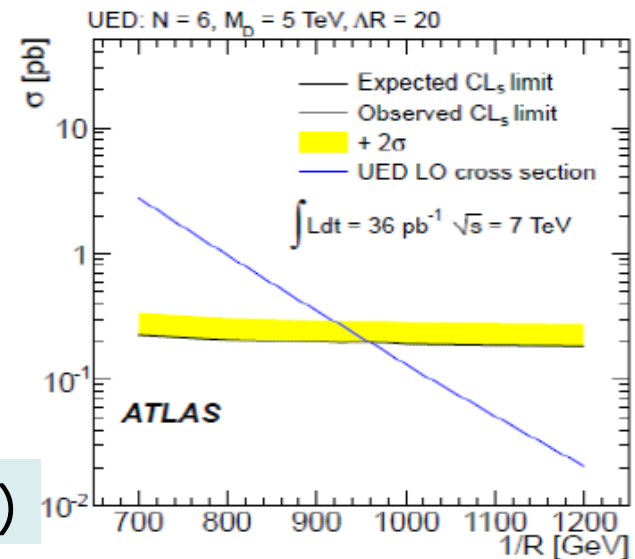
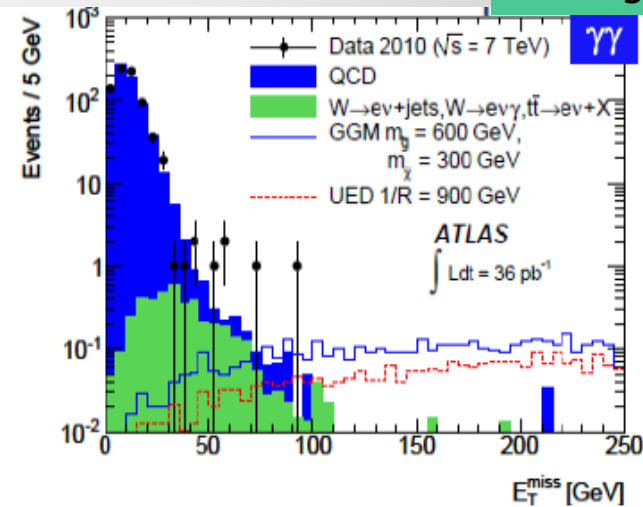
Search for Extra Dimensions

Two Photons and Missing E_T (UED)

T. Berger Hryn'ova

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

Same analysis as before !! (GMSB)

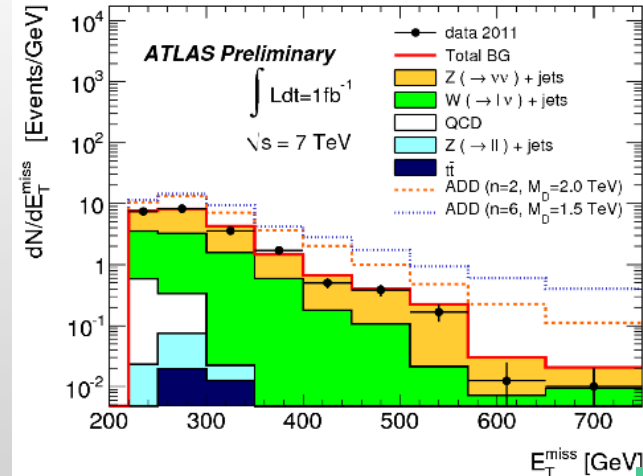
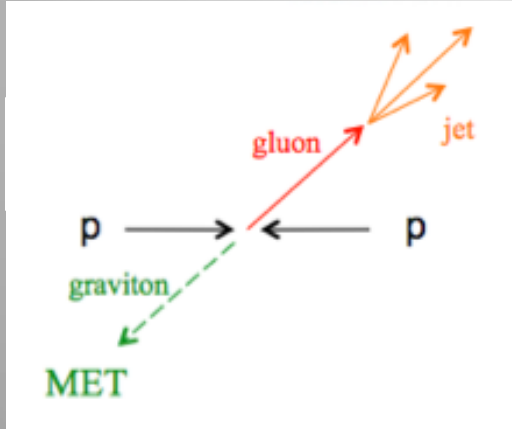


Search for Extra Dimensions

Mono-jet final state +MET (ADD)

ATLAS-CONF-2011-95

$p_T \text{ jet} > 250 \text{ GeV}$
 $\text{MET} > 220 \text{ GeV}$



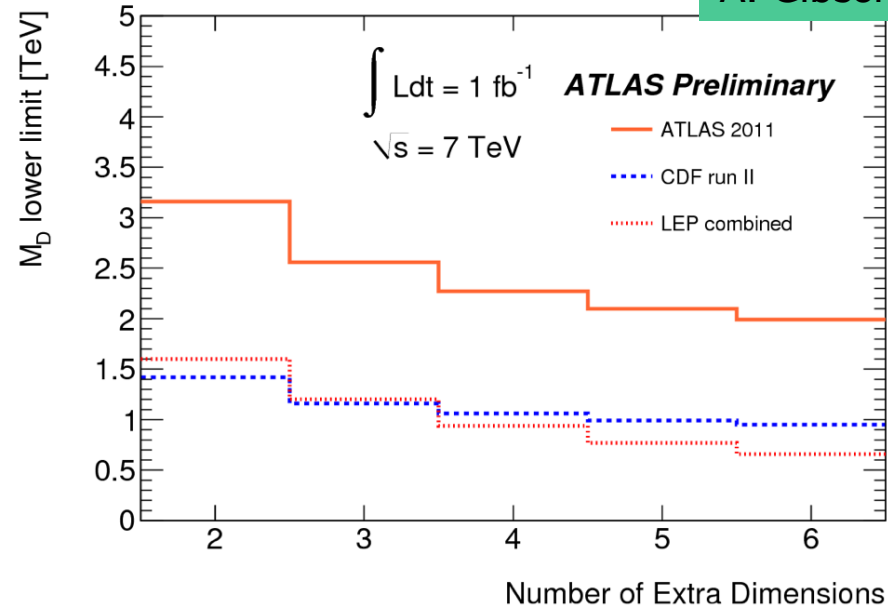
Lower Limit on the Planck Scale versus number of extra dimensions

CMS 35 pb^{-1}

CMS-EXO-11-003

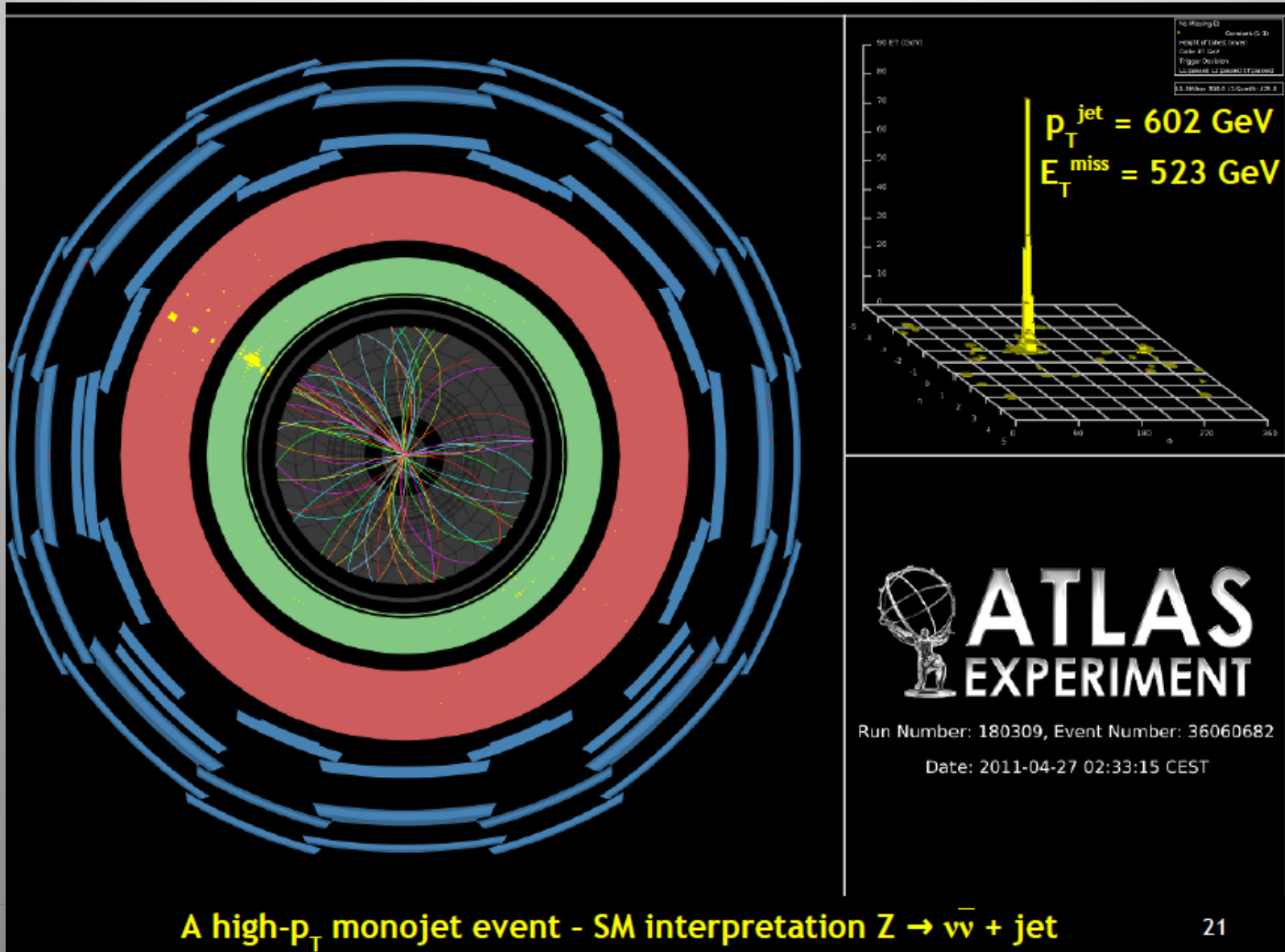
δ	K factor	LO Exp.	LO Obs.	NLO Exp.	NLO Obs.
2	1.5	2.17	2.29	2.41	2.56
3	1.5	1.82	1.92	1.99	2.07
4	1.4	1.67	1.74	1.78	1.86
5	1.4	1.59	1.65	1.68	1.74
6	1.4	1.54	1.59	1.62	1.68

A. Gibson



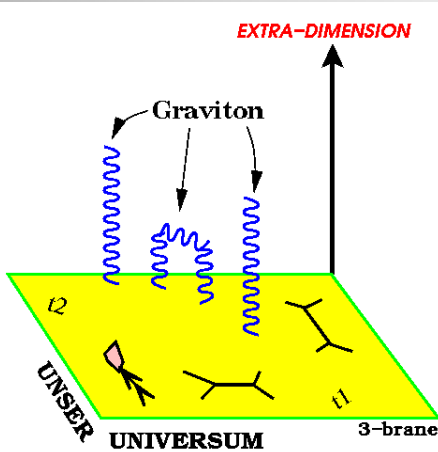
Limits on M_D between 2 and 3 TeV

A High p_T Mono-jet event



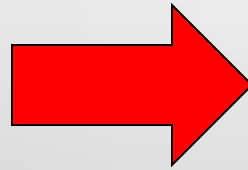
A high- p_T monojet event - SM interpretation $Z \rightarrow \bar{\nu}\nu + \text{jet}$

Search for Micro Black Holes

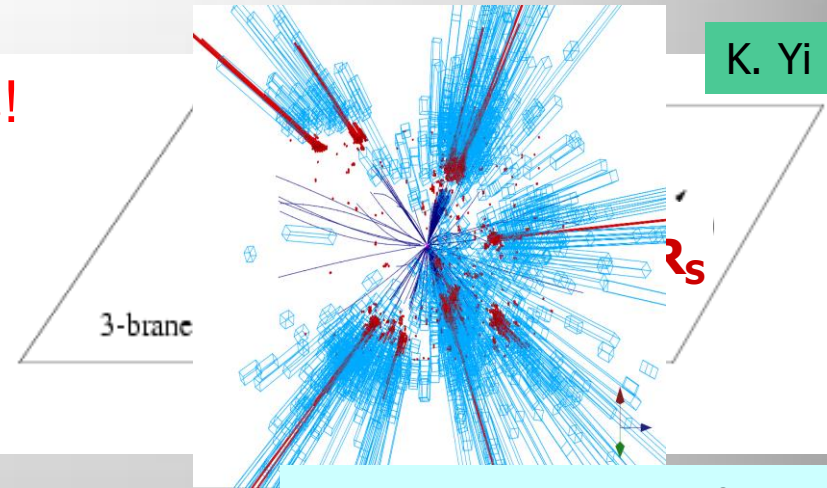


CMS-EXO-11-071

Extra Dimensions!



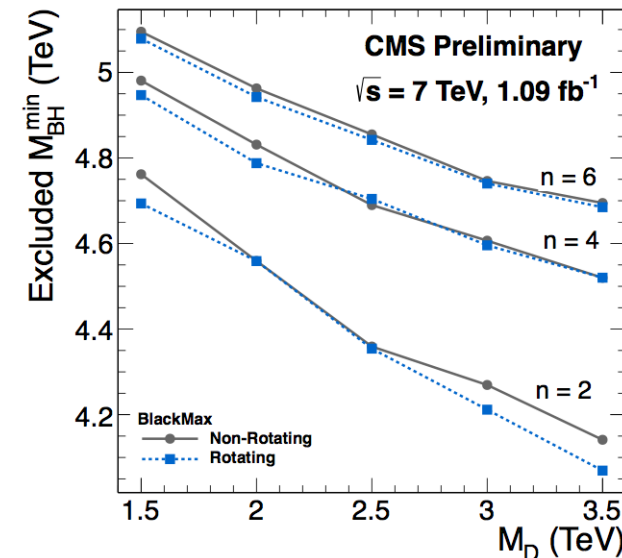
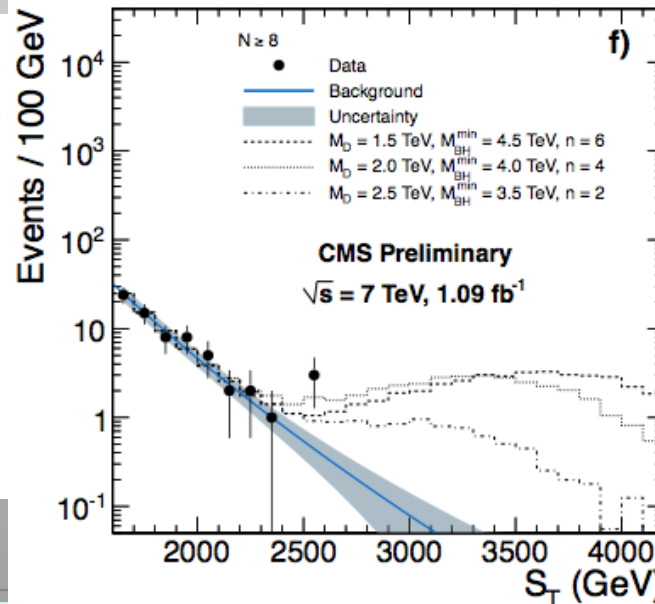
Planck scale
a few TeV?



Evaporates in 10^{-27} sec

Look for the decay products
of an evaporating black hole

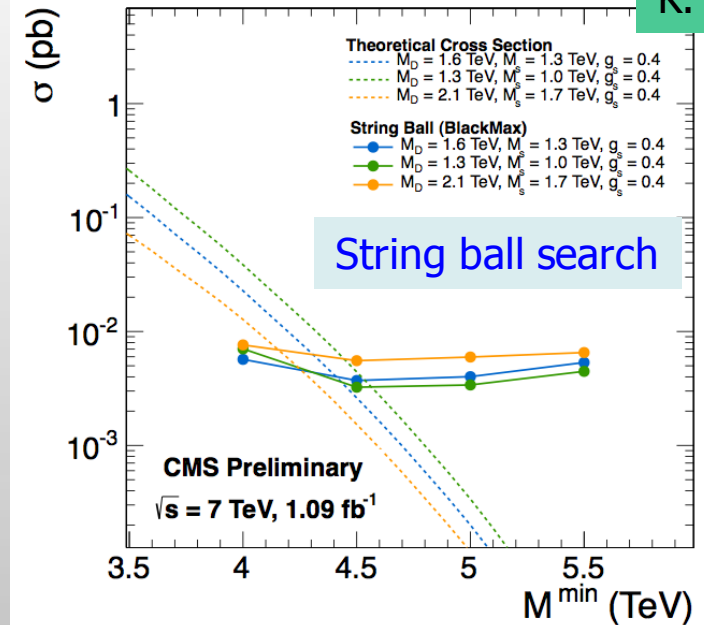
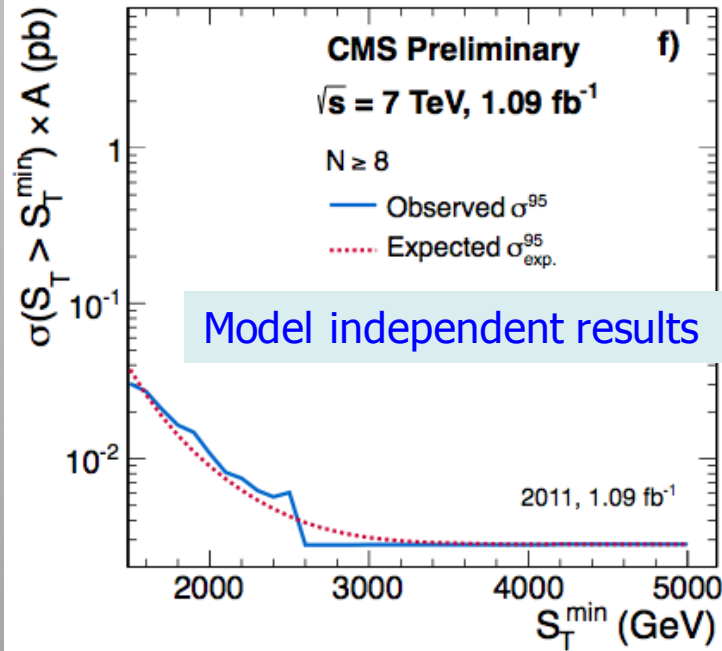
- Define S_T to be the scalar sum of all high p_T objects found in the event
- Look for deviations at high S_T



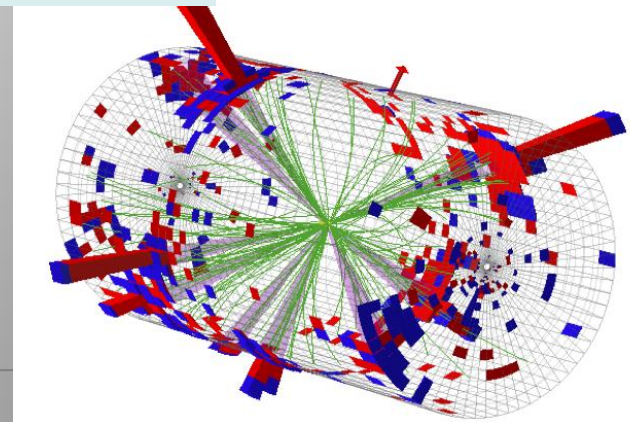
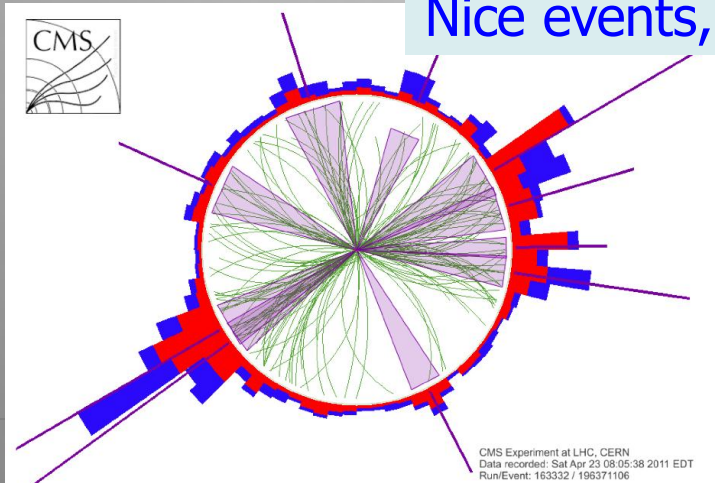
Black hole masses excluded in range ~ 5 TeV depending on assumptions

Search for Micro Black Holes

K. Yi



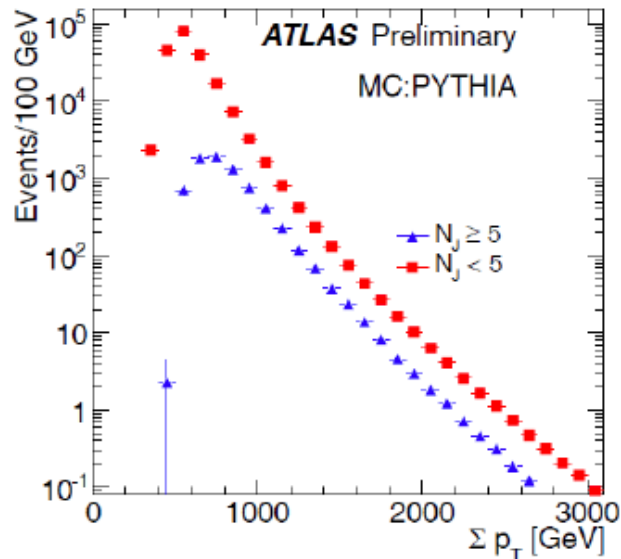
Nice events, eg this 10 jet event



Search for Micro Black Holes

Multi-jet search

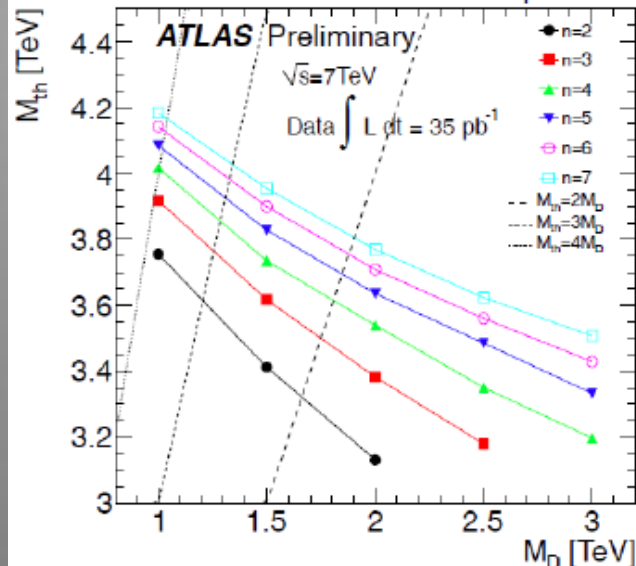
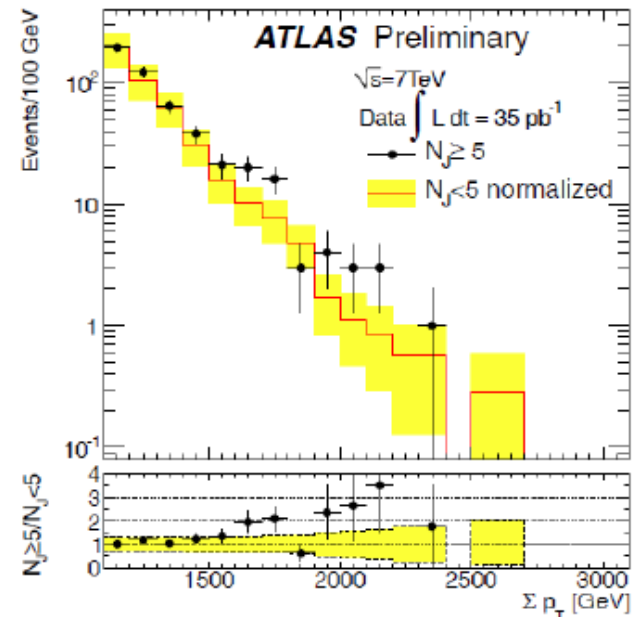
A. Gibson



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 $N_J \geq 5$.



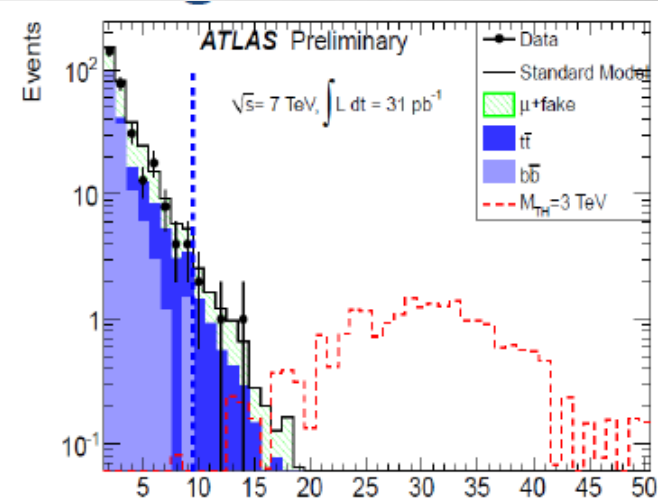
- Use $1.1 \text{ TeV} < \Sigma p_T < 1.2 \text{ TeV}$ region for normalization, then compare the $N_J < 5$ shape to $N_J \geq 5$ data
- Predict number of events in **signal region: $N_J \geq 5$, $\Sigma p_T > 2 \text{ TeV}$**
 - 3.7 ± 1.0 (stat) ± 1.1 (syst) compared to 7 data
 - Largest syst is 24%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

Search for Micro Black Holes

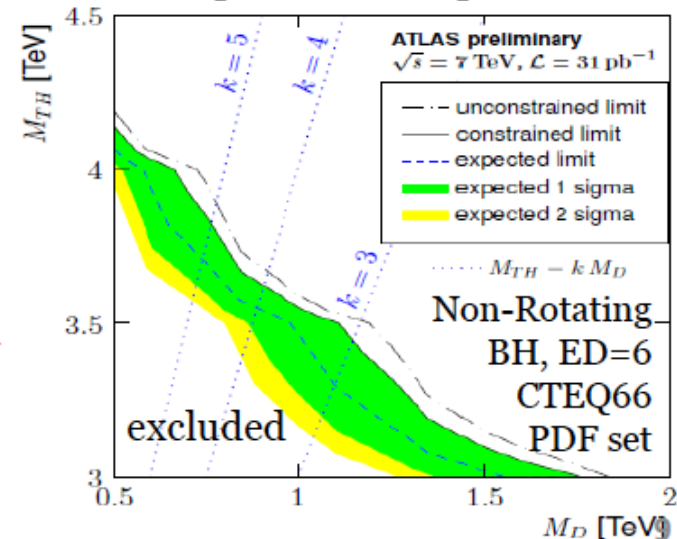
Same sign dimuon search

T. Berger Hryn'ova

- Benchmark Model: Large ED ADD Model
- M_D is the Planck scale in $n+4$ D ($M_D \ll M_{Pl}$)
- If there are ED and $M_D \sim 1$ TeV, microscopic black holes (BH) can be produced at LHC
- Assume continuous BH production from M_D to LHC $\sqrt{s}=7$ TeV, 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 bkg
 - Look at track multiplicity distribution
- No excess over SM expectations seen
- 95% CL limit on $\sigma \times A \times BF$ of new physics in this final state is 0.184 pb
- Exclusion plots in low scale gravity model



Sample exclusion plot: NTracks

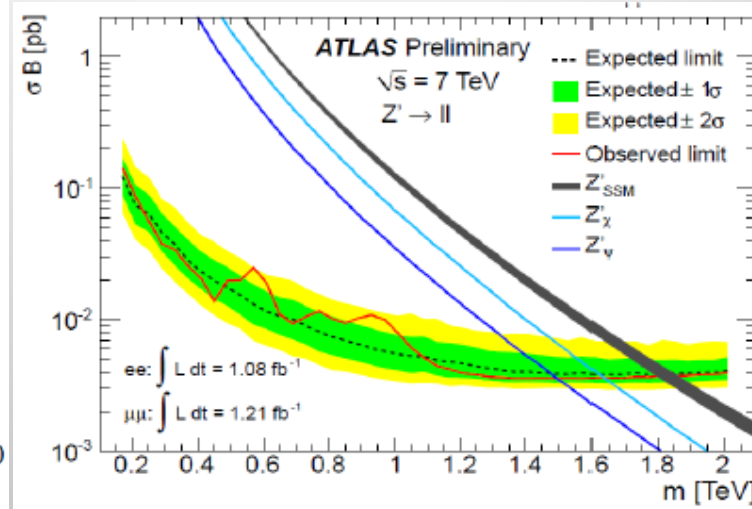
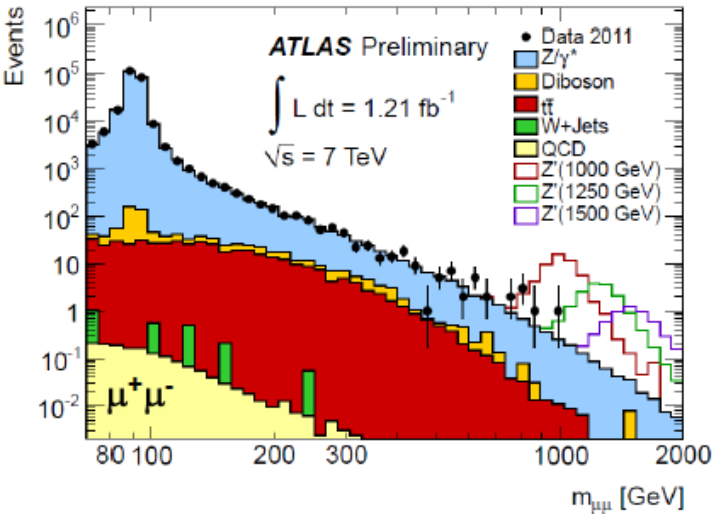


Other Searches

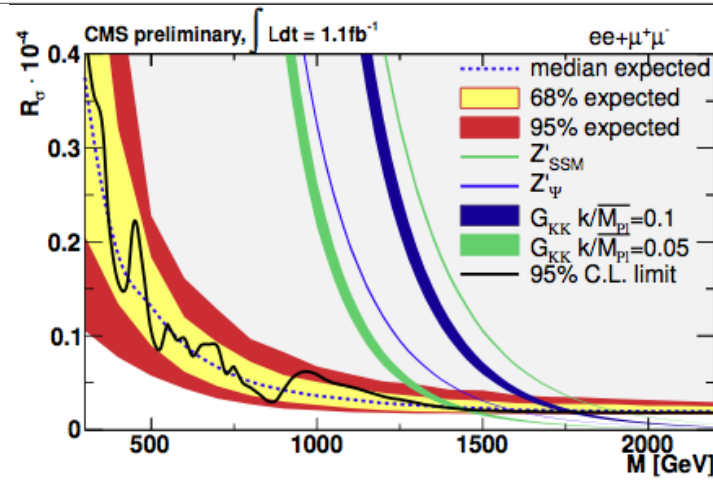
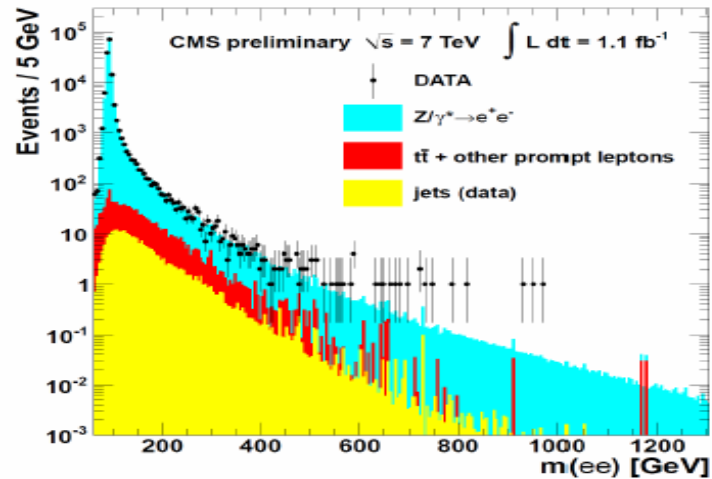
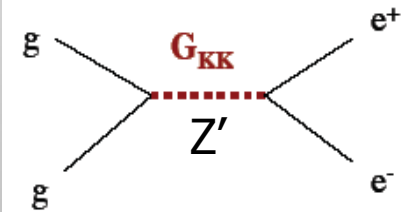
- New Gauge bosons
- Colored resonances
- Objects decaying into top quarks
- Strong EW symmetry breaking eg topcolor
- 4th Generation of quarks and leptons
- Substructure /contact interactions
- Long lived particles
- Dark/Hidden Sector particles
- And more...

Search for G_{KK} or Z' Gauge Bosons

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



T. Berger Hryn'ova
J. Tucker



CMS-EXO-11-019

$G^* (k/m_p = 0.1)$

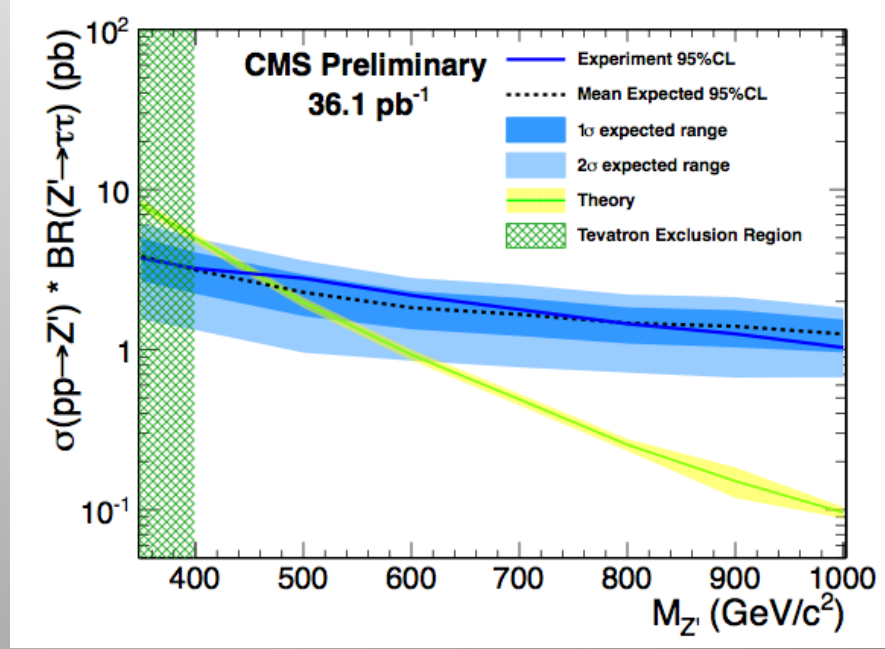
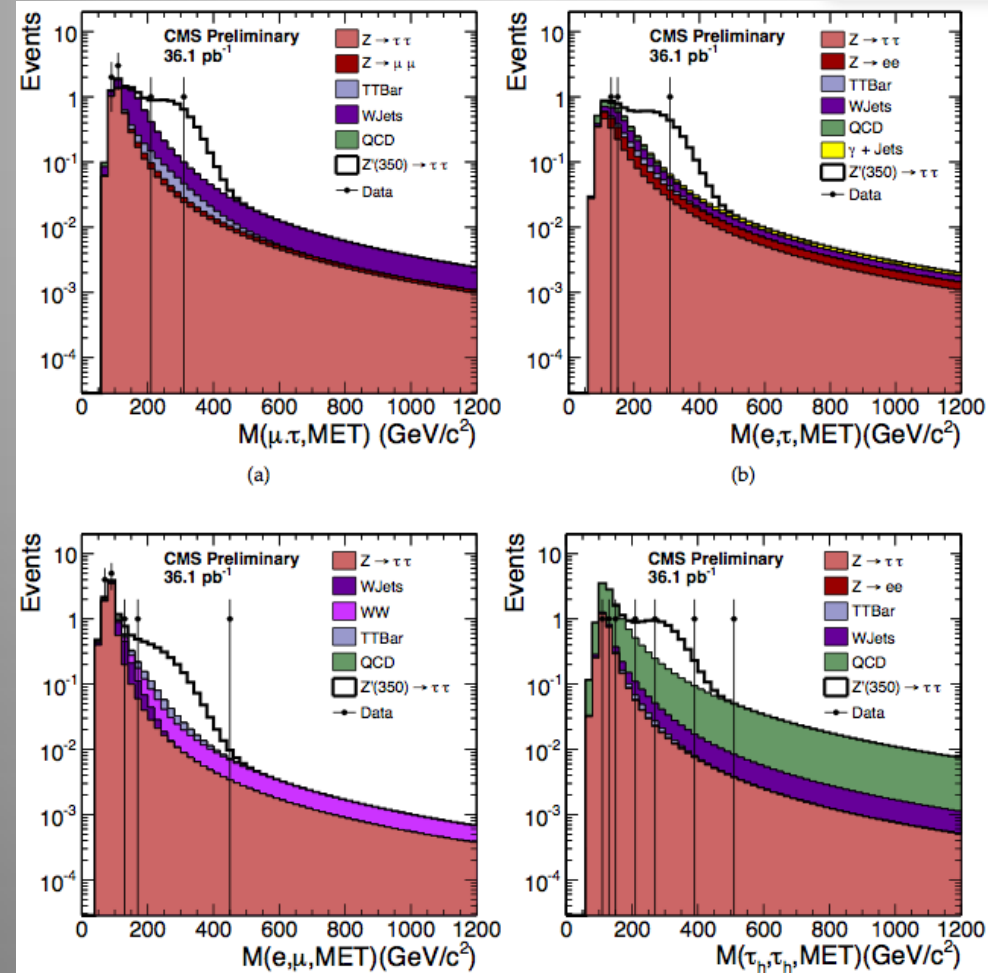
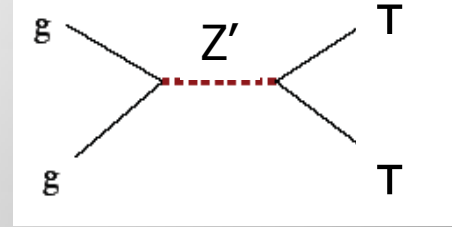
Exclude (SSM) Z' up to 1.94 TeV and G_{KK} up to 1.7 TeV or @ 95% CL

Search for Z' Gauge Bosons

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

J. Tucker

Using 4 different tau-tau channels



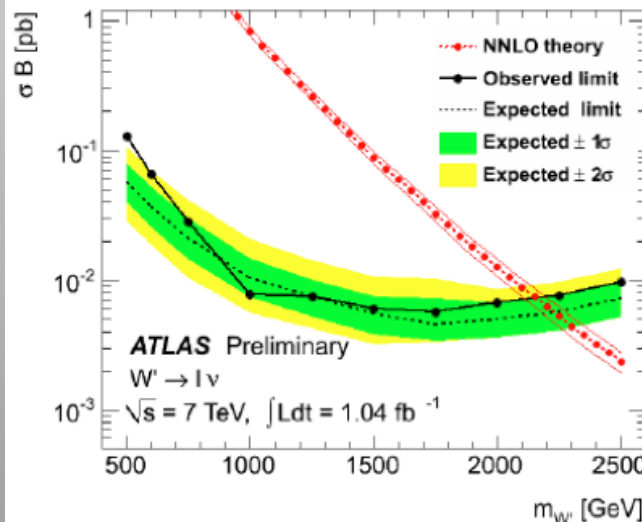
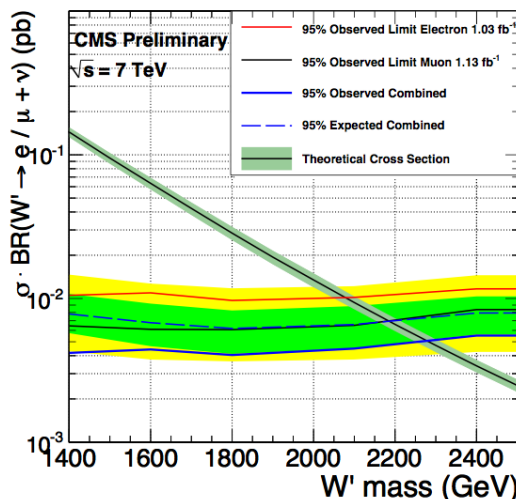
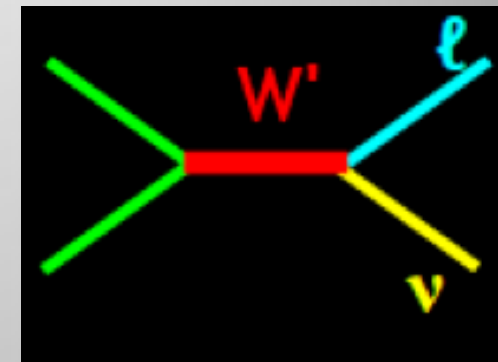
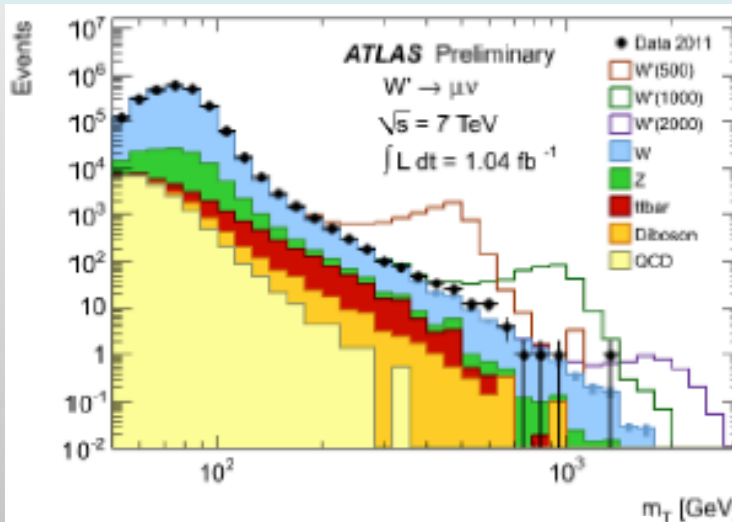
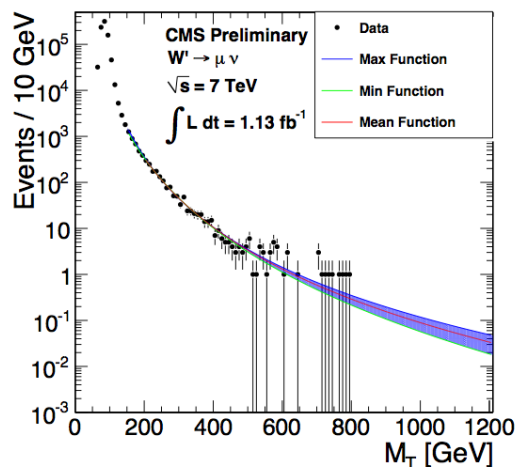
Exclude (SSM) Z' up to 468 GeV @ 95% CL

CMS-EXO-11-022

Search for W' Gauge Bosons

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

C. Leonidopoulos
T. Berger Hryn'ova



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

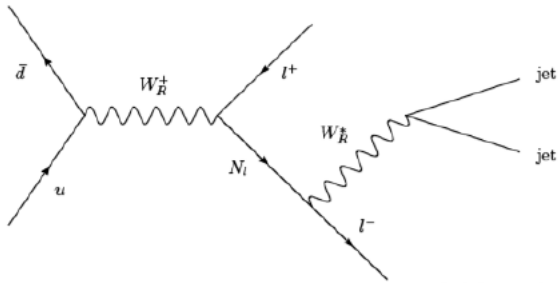
CMS-EXO-11-024

Exclude new W' bosons up to $\sim 2.27 \text{ TeV}$ @ 95% CL

Heavy Neutrinos in W_R decays

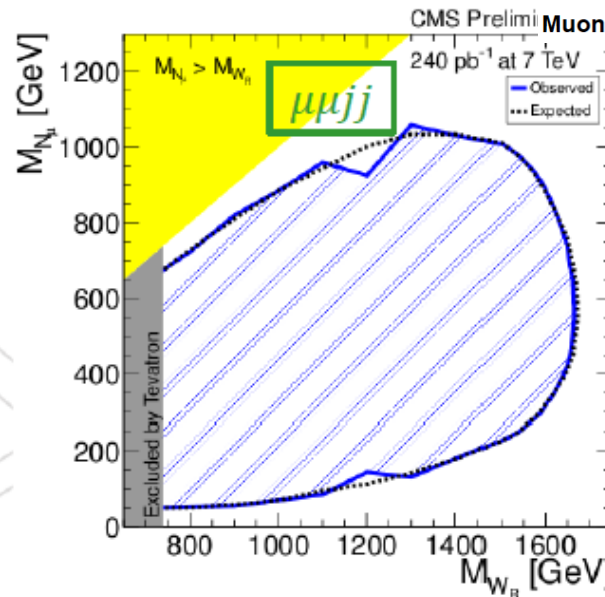
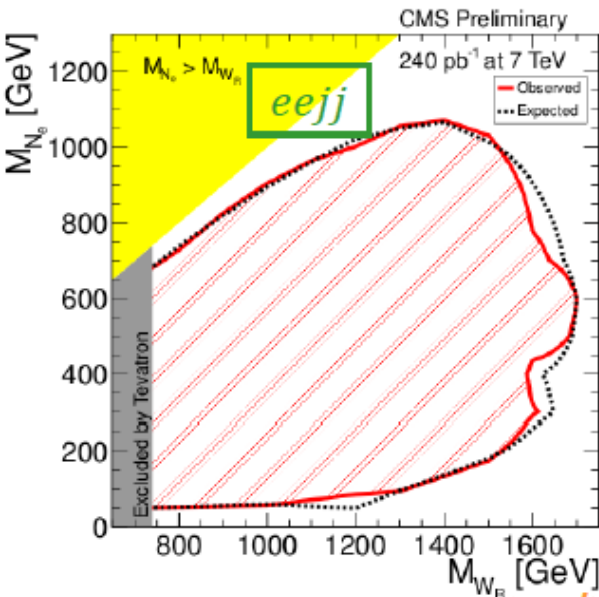
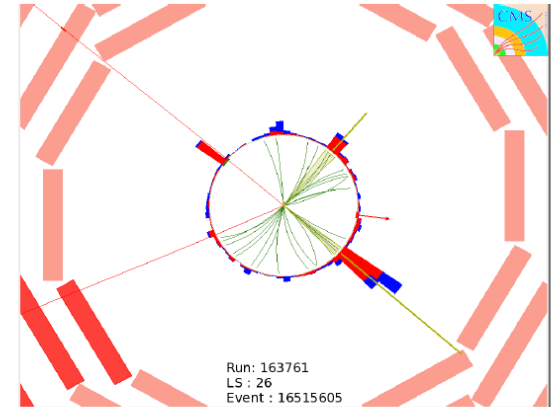
C. Leonidopoulos

Left-right symmetric extension of the Standard Model



CMS-EXO-11-002

Select events with
2 leptons and 2 jets



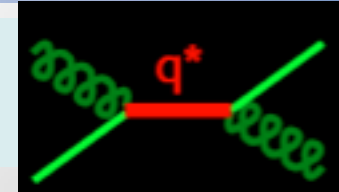
Muon channel: Event with $M_{\mu\mu} = 331$ GeV, $M_{\mu\mu jj} = 881$ GeV

Large exclusion range
in mass of the W_R and
heavy neutrino

Tevatron excludes
 $W_R \sim 780$ GeV

Search for Dijet Resonances

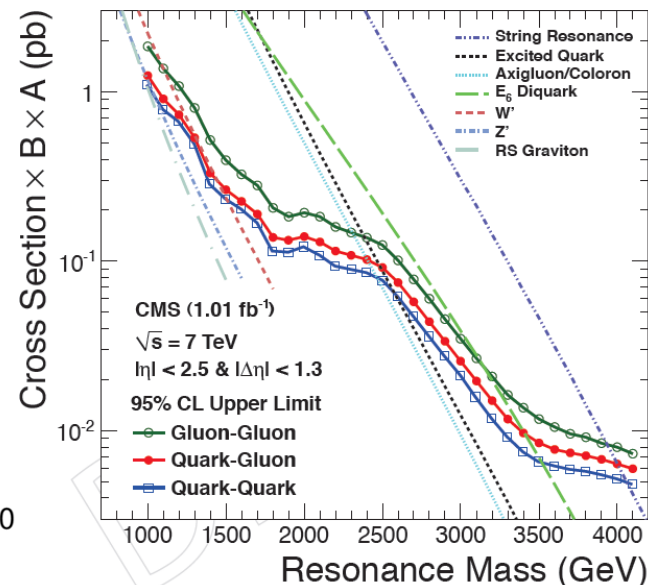
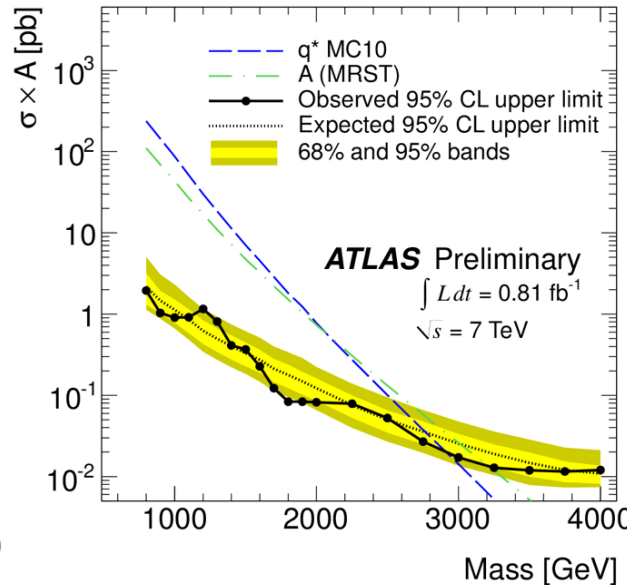
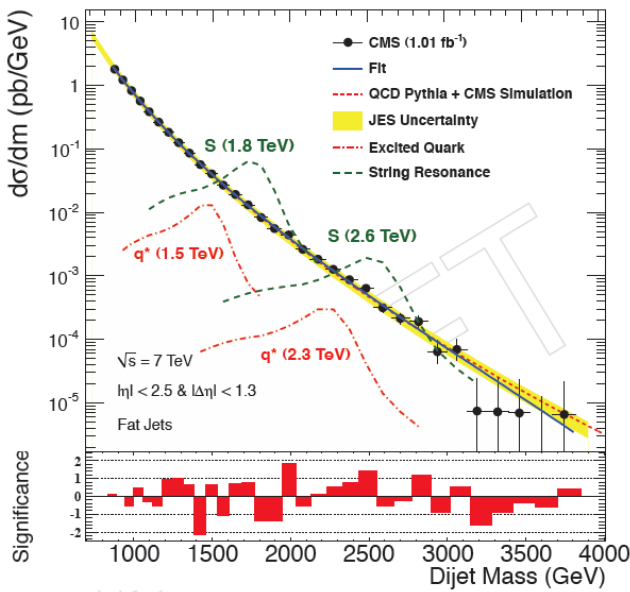
Select events with 2 jets with $p_T > 180$ GeV (ATLAS)
 Search for a bump in the invariant jet jet mass



K. Yi
 A. Gibson

No bump found Limits $\rightarrow \sim 1-4$ 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 $M(S) < 4.00$ TeV, E_6 diquarks with $M(D) < 3.52$ TeV, excited quarks with $M(q^*) < 2.49$ TeV, axigluons and colorons with $M(A,C) < 2.47$ TeV, and W' bosons with $M(W') < 1.51$ TeV

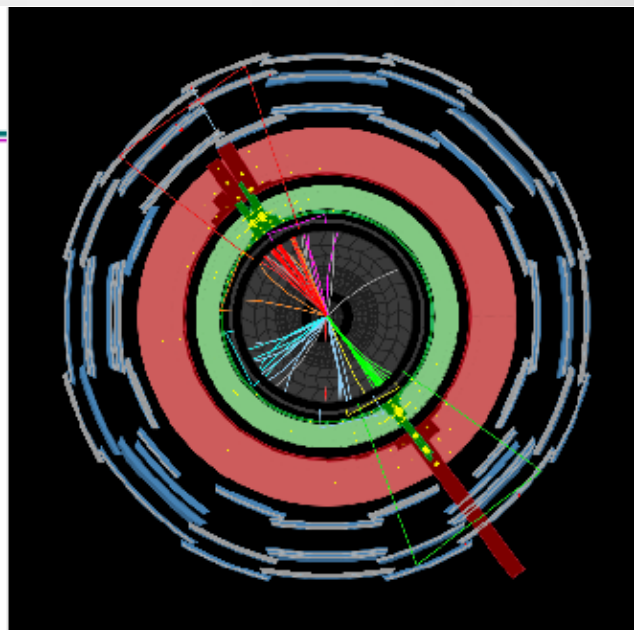
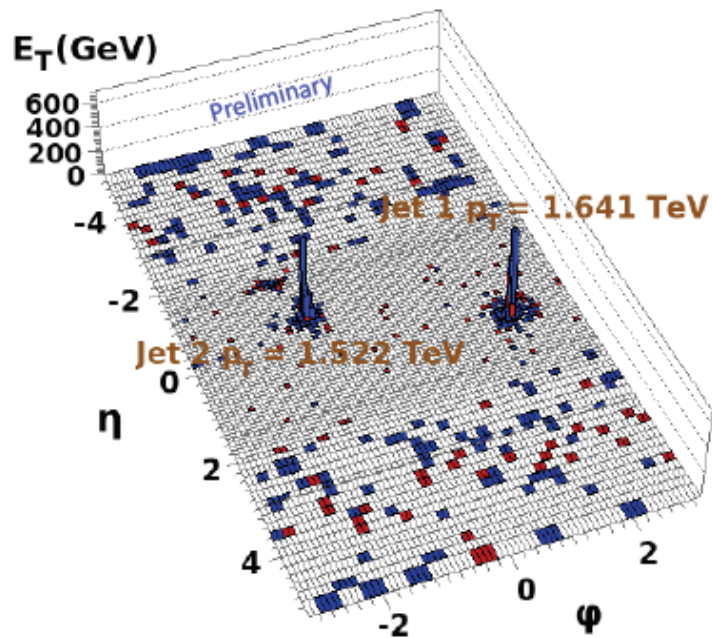
ATLAS

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



Run : 166895
Event : 367873378
Dijet Mass : 3.835 TeV



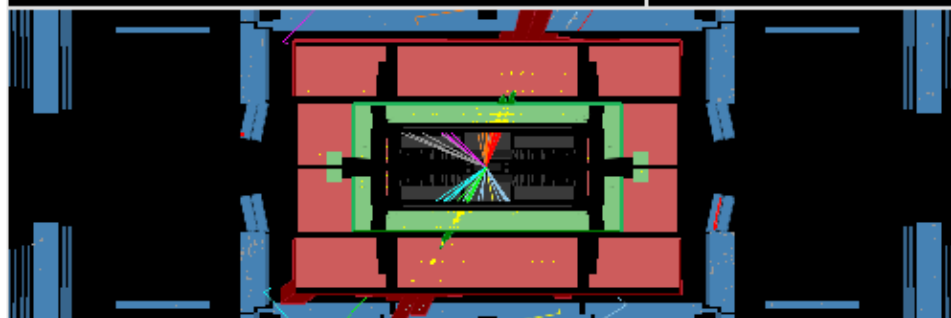
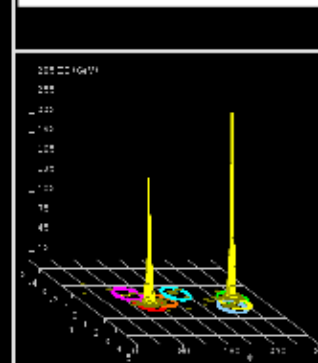
Very high energy jet event

$$m_{jj} = 4040 \text{ GeV}$$

$$p_T^{j1} = 1850 \text{ GeV}$$

$$p_T^{j2} = 1840 \text{ GeV}$$

ATLAS-CONF-2011-081



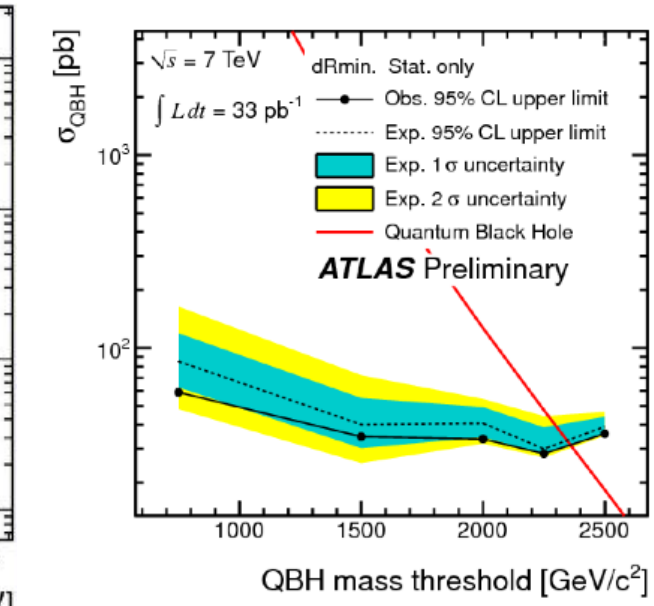
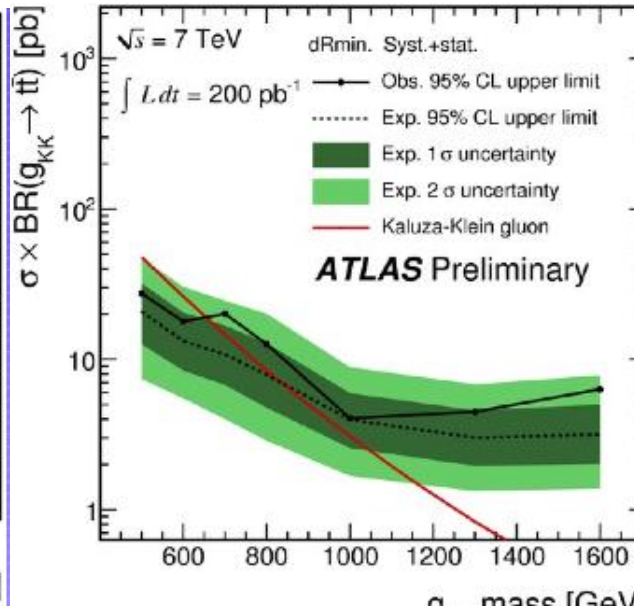
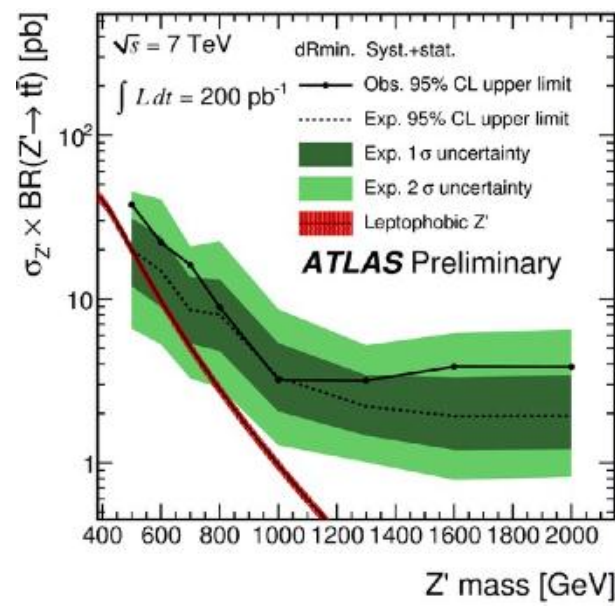
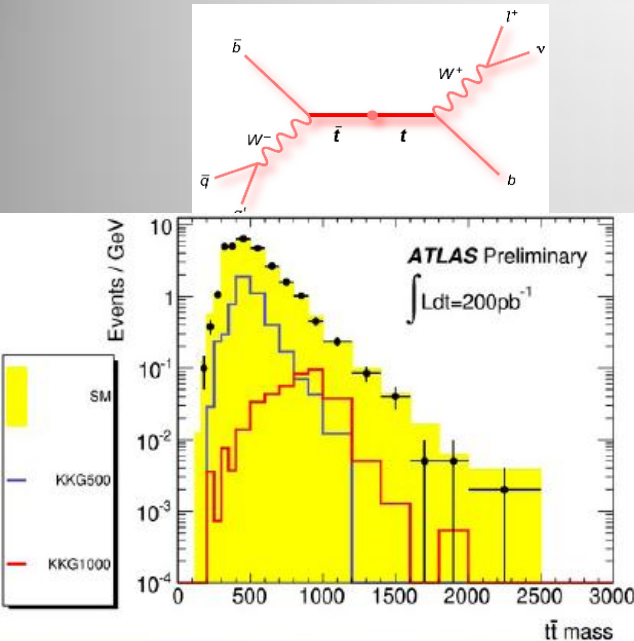
Well balanced dijet event

Top Resonances

ATLAS-CONF-2011-87

T. Kuhl

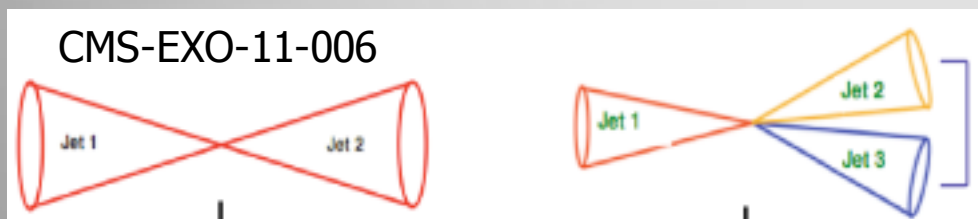
- Select semi-leptonic $t\bar{t}$ event
- Inspect the $t\bar{t}$ invariant mass spectrum
- Search for narrow topcolor Z' and wider KK gluons
- Limit on KK-gluons < 700 GeV 95 % CL
- Black holes near threshold $\rightarrow t\bar{t}$? arXiv:0708.3017
- Limit on 2 body $t\bar{t}$ decay black holes ~ 2.35 TeV



Z' → tt Search

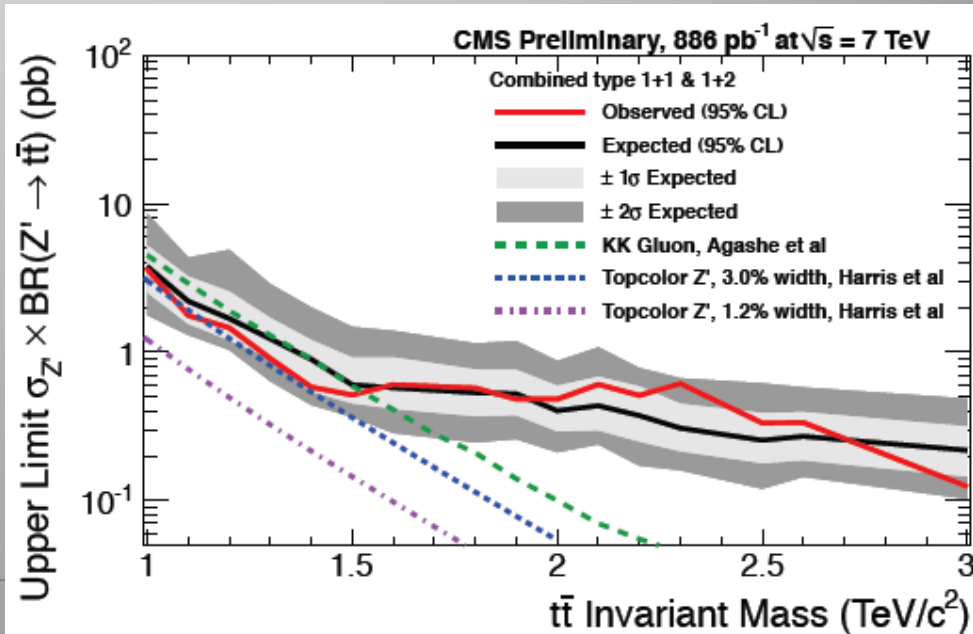
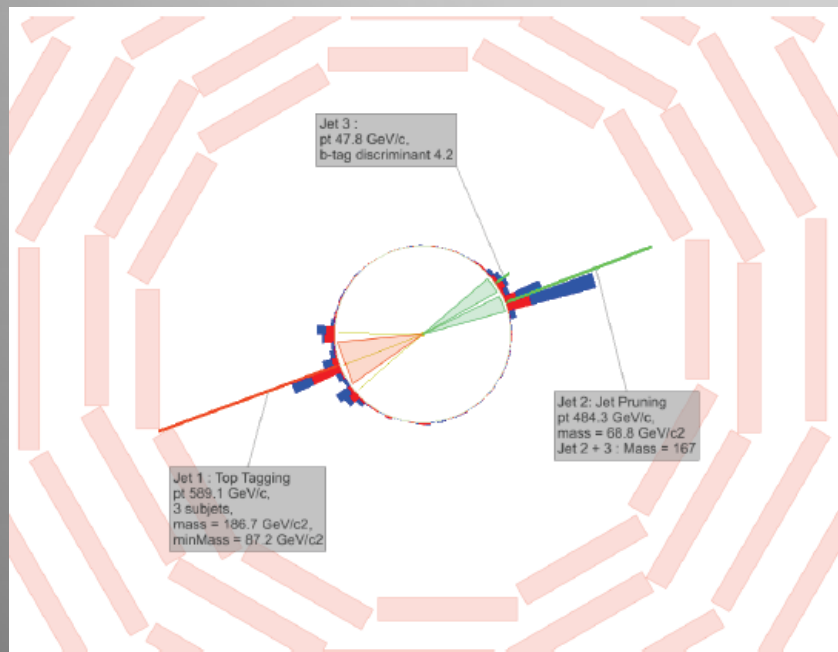
M. Mulders

- 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 $1 < M < 1.5$ GeV

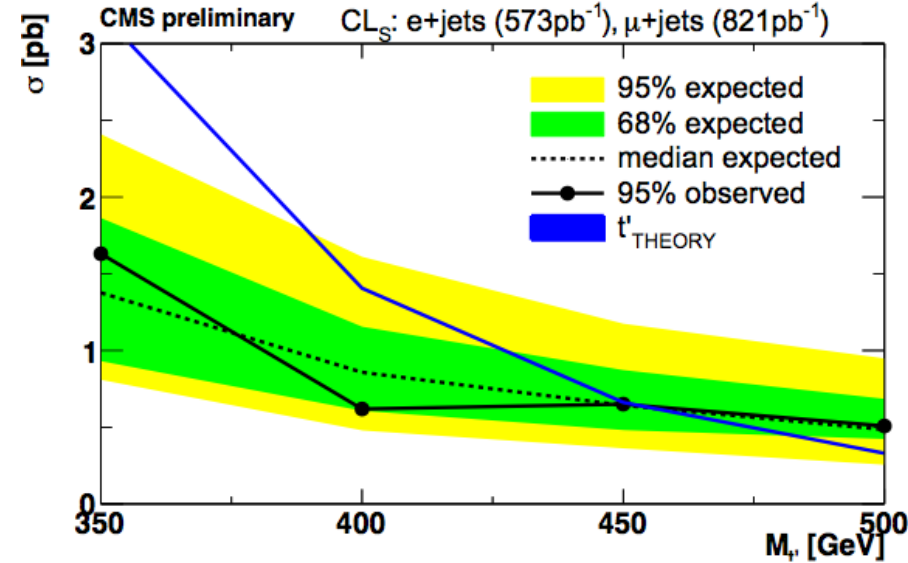
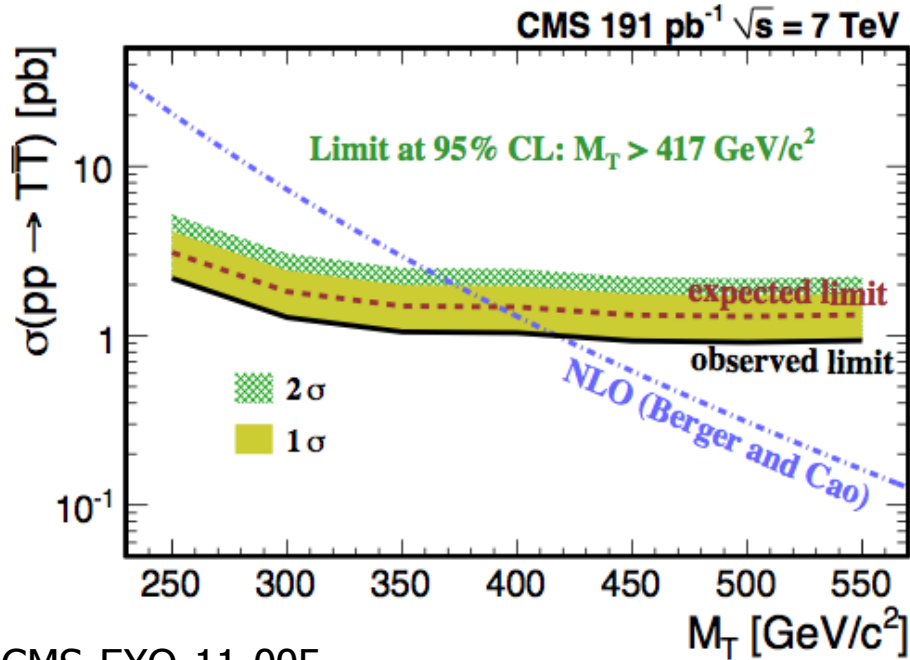


4th Generation: Top partners

G. Tonelli

$$T \rightarrow tZ$$

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



CMS-EXO-11-0051

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

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

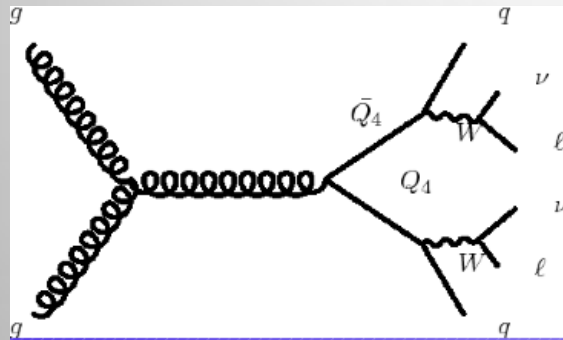
No top-like quark with tZ decay found with mass < 417 GeV at 95% CL

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

No b' with $255 < \text{mass} < 361$ GeV

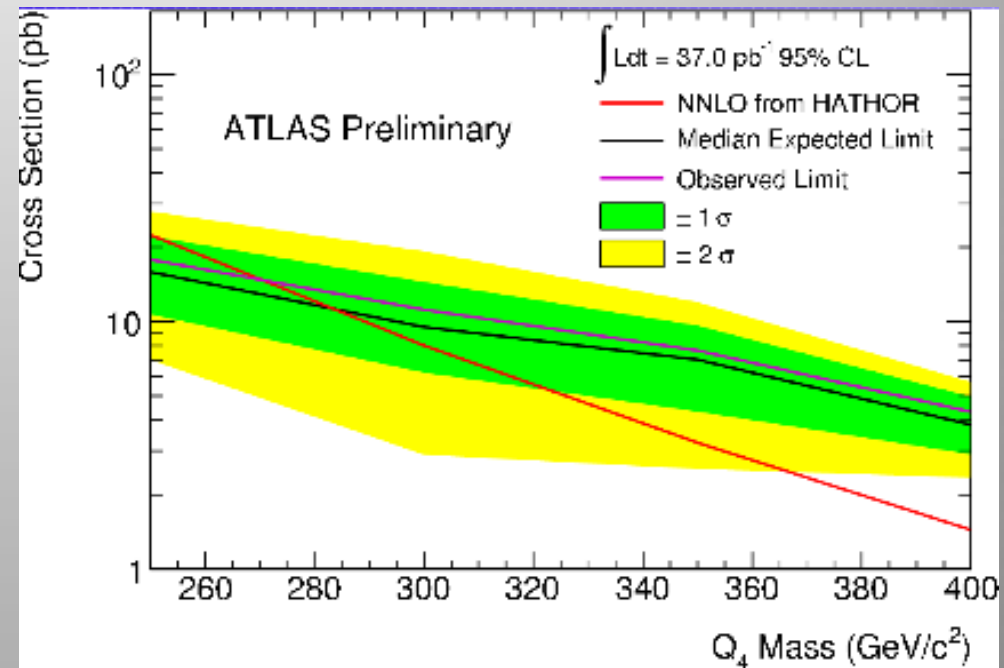
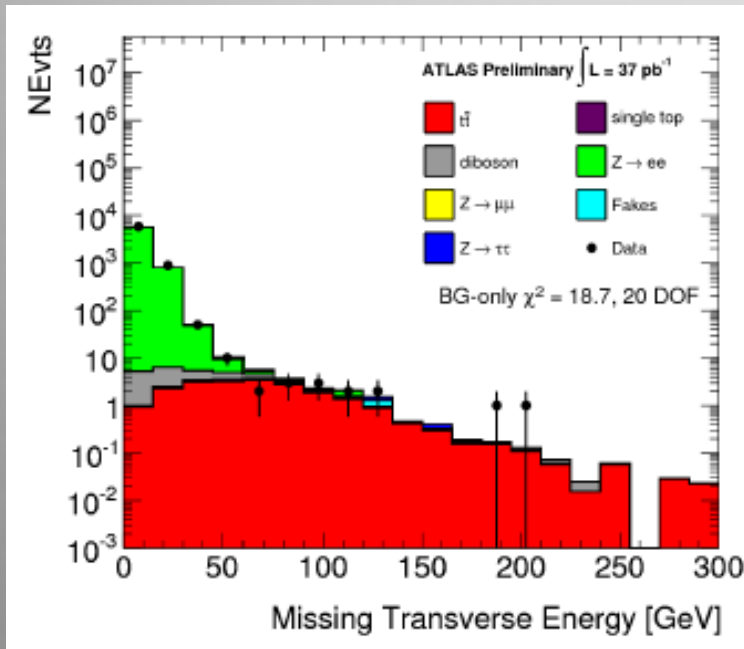
4th Generation

A. Gibson



Final state has heavy top pair signature:

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



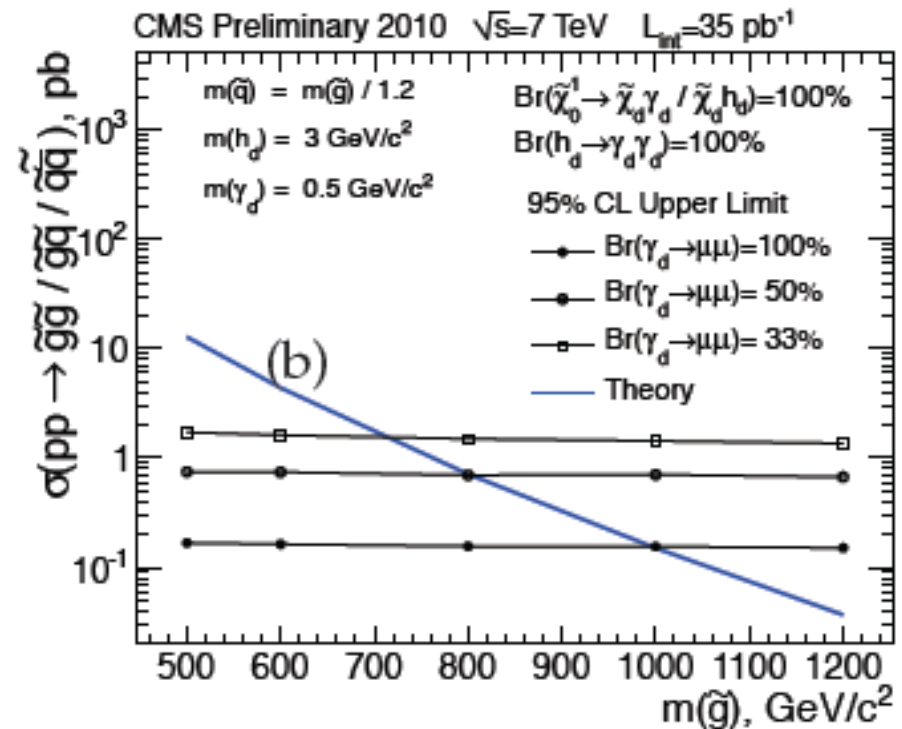
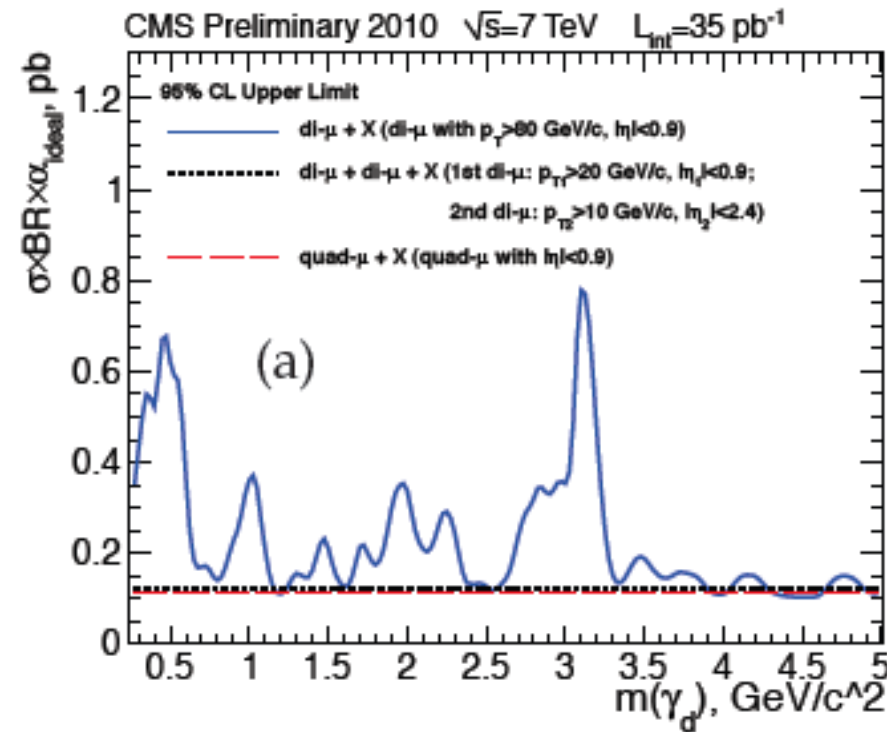
Limit on production cross section of Q_4 for 37 pb^{-1} :
 \rightarrow Translates to lower mass limit: $M_{Q_4} > 270 \text{ GeV}$
 (Best Tevatron limits (CDF, 4.6 fb^{-1} : $m_{Q_4} > 335 \text{ GeV}$))

Search for Dark Photons

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

Arkani-Hamed, Weiner

CMS-SUS-11-13



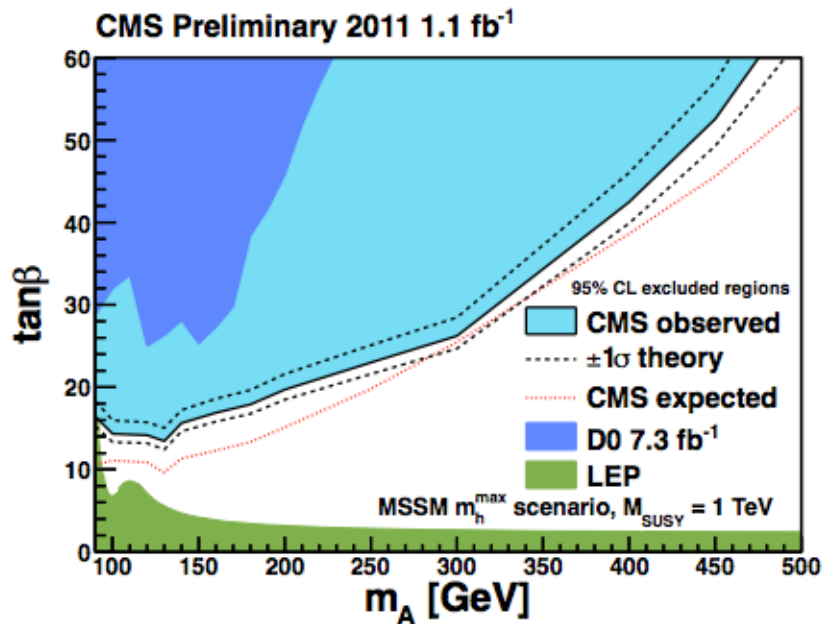
$$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_{dark} \gamma_{dark} + \tilde{\chi}_{dark} h_{dark} (\rightarrow \gamma_{dark} \gamma_{dark})$$

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

Search for BSM Higgses

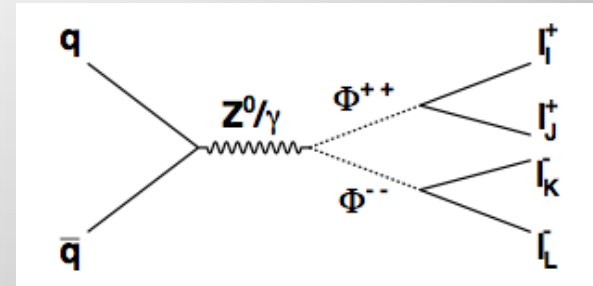
S. Gennai

MSSM Higgs $\rightarrow \tau\tau$



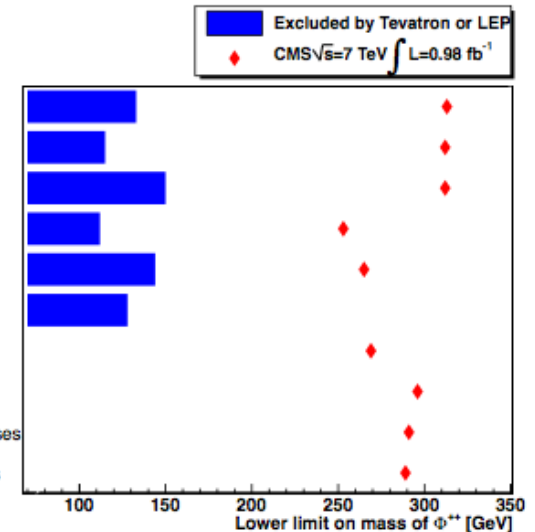
Impressive Exclusion Limits

Double Charged Higgs



CMS Preliminary

- BR($\Phi^{++} \rightarrow e^+e^+$)=100%
- BR($\Phi^{++} \rightarrow e^+\mu^+$)=100%
- BR($\Phi^{++} \rightarrow \mu^+\mu^+$)=100%
- BR($\Phi^{++} \rightarrow e^+\tau^+$)=100%
- BR($\Phi^{++} \rightarrow \mu^+\tau^+$)=100%
- BR($\Phi^{++} \rightarrow \tau^+\tau^+$)=100%
- BP1: normal hierarchy
- BP2: inverse hierarchy
- BP3: degenerate masses
- BP4: equal branchings



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

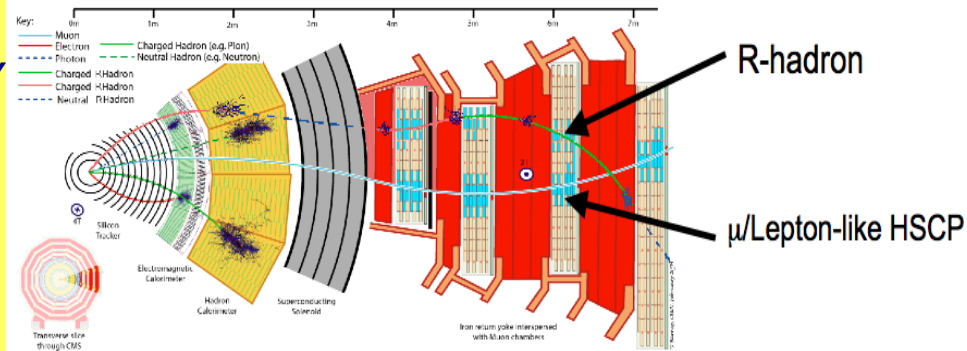
Unusual interactions with material

eg. with the calorimeters of the experiments!

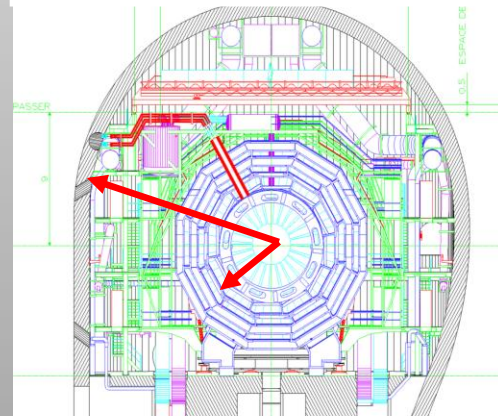
Gravitino Dark Matter and GMSB

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

⇒ Challenge to the experiments!



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



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

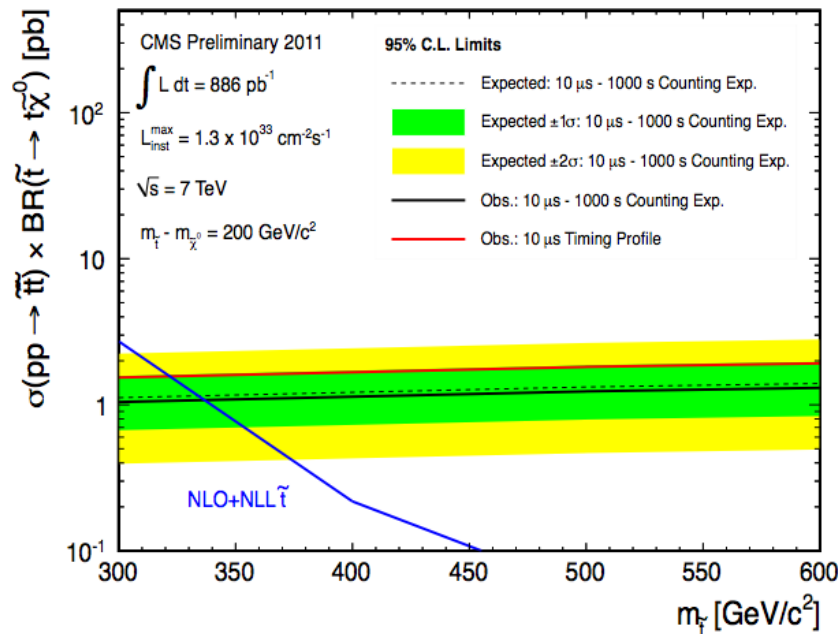
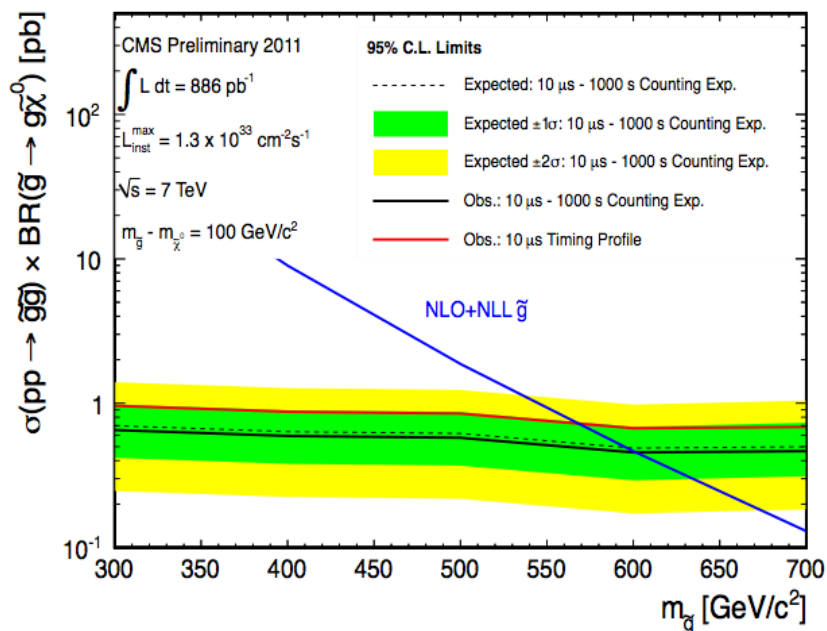
Search for Stopped Gluinos

Y. Chen

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

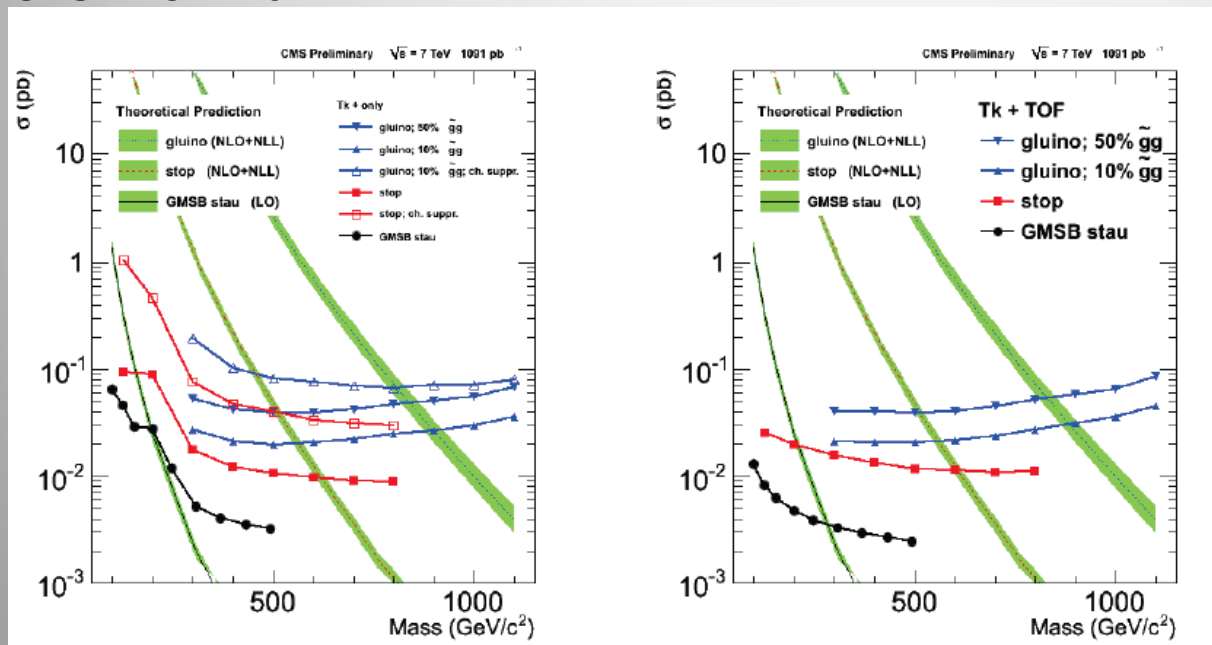


95% CL Limits: Stopped Gluinos > 600 GeV, Stopped Stop quarks > 337 GeV

Heavy Stable Charged Particles

CMS-EXO-11-022

Y. Chen



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

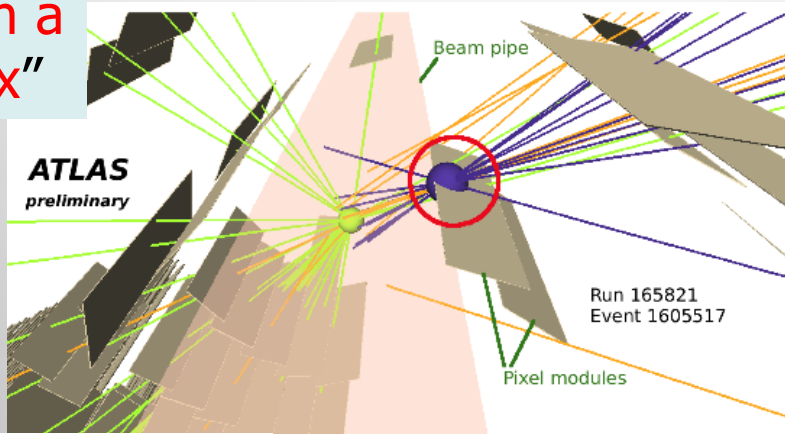
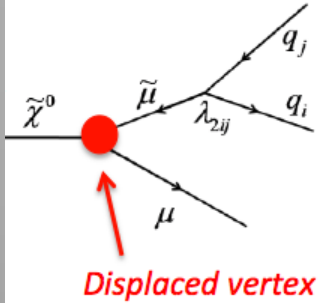
95% C.L. mass limits are set for

- Cloud model interaction scenario
 - Gluino (10% $\tilde{g}\tilde{g}$): 899 GeV, Gluino (50% $\tilde{g}\tilde{g}$): 839 GeV
 - Stop: 620 GeV GMSB Stau: 293 GeV ← NEW Addition
- Charge suppression interaction scenario
 - Gluino (10% $\tilde{g}\tilde{g}$): 808 GeV, Stop: 515 GeV

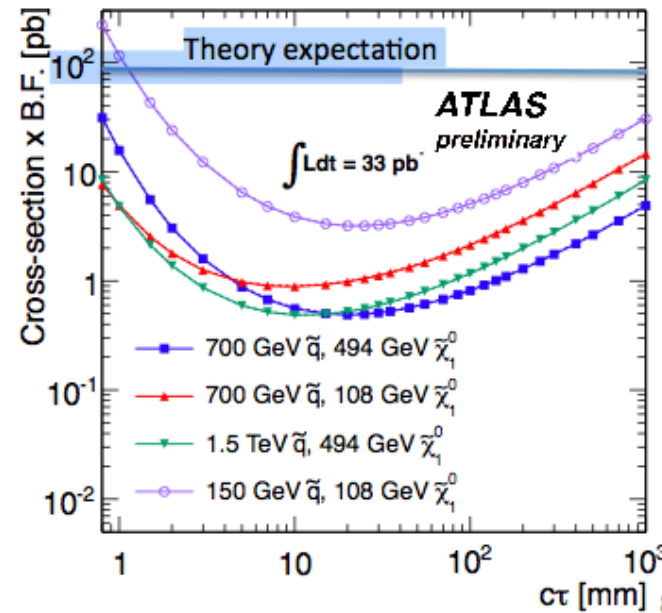
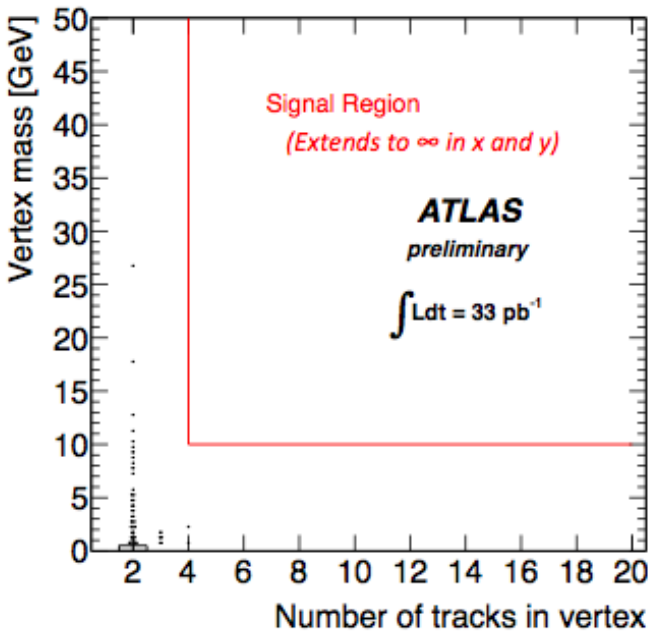
Search for RPV SUSY

P. Jackson

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

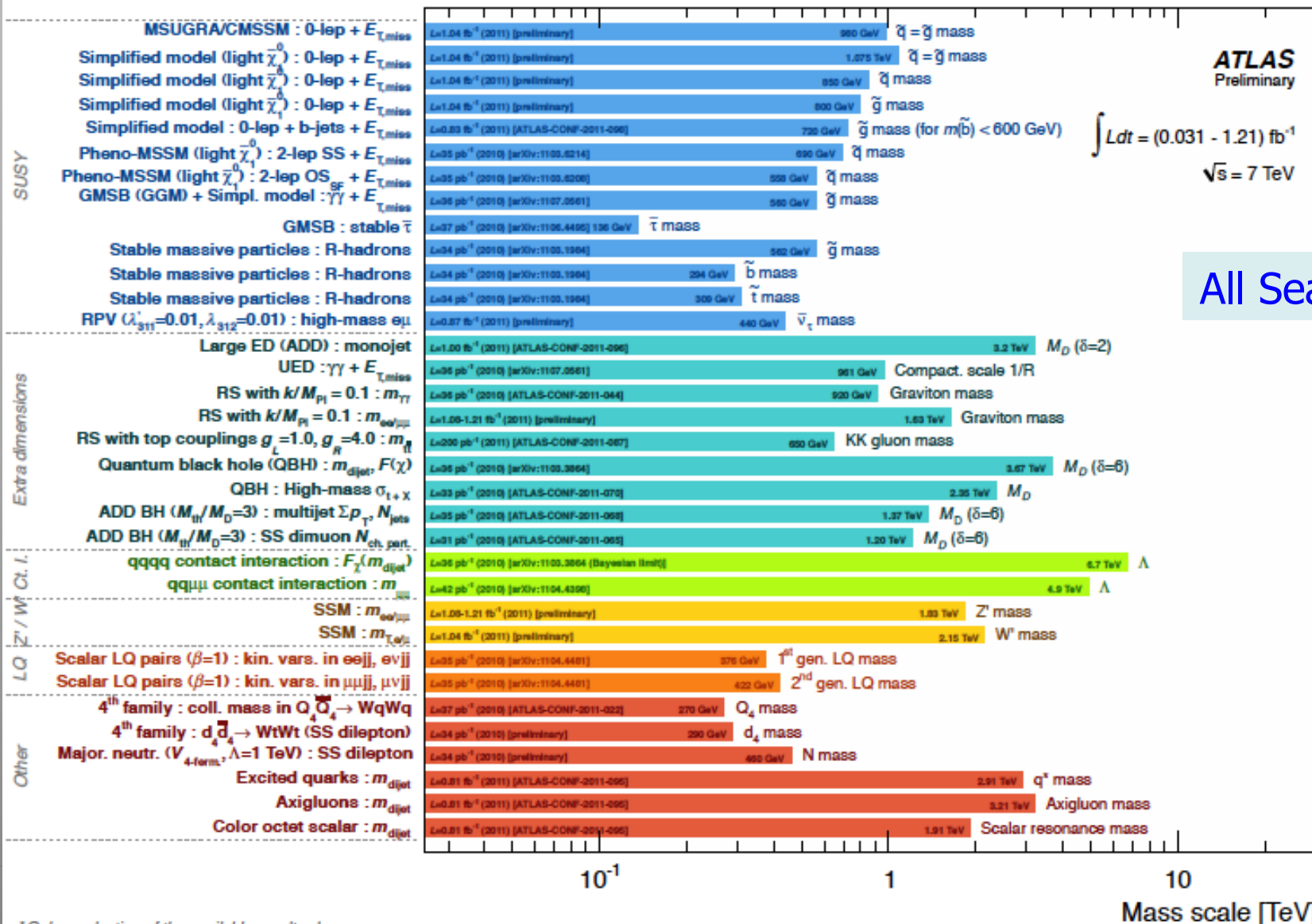


No signal found

- $\sigma * \text{detector acceptance} * \epsilon < 0.09 \text{ pb @95\% Confidence level}$

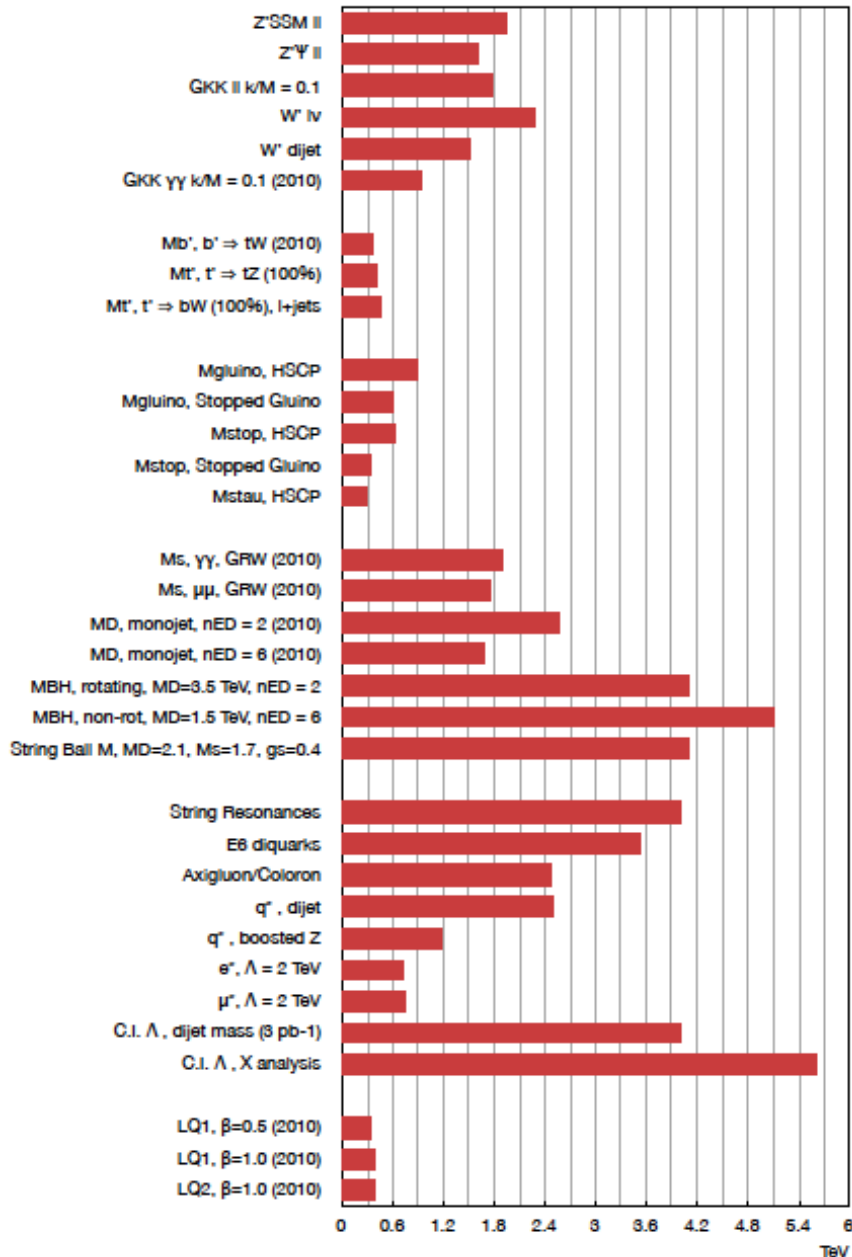
The Search Overview (ATLAS)

ATLAS Searches* - 95% CL Lower Limits (EPS-HEP 2011)



*Only a selection of the available results shown

The Search Overview (CMS)

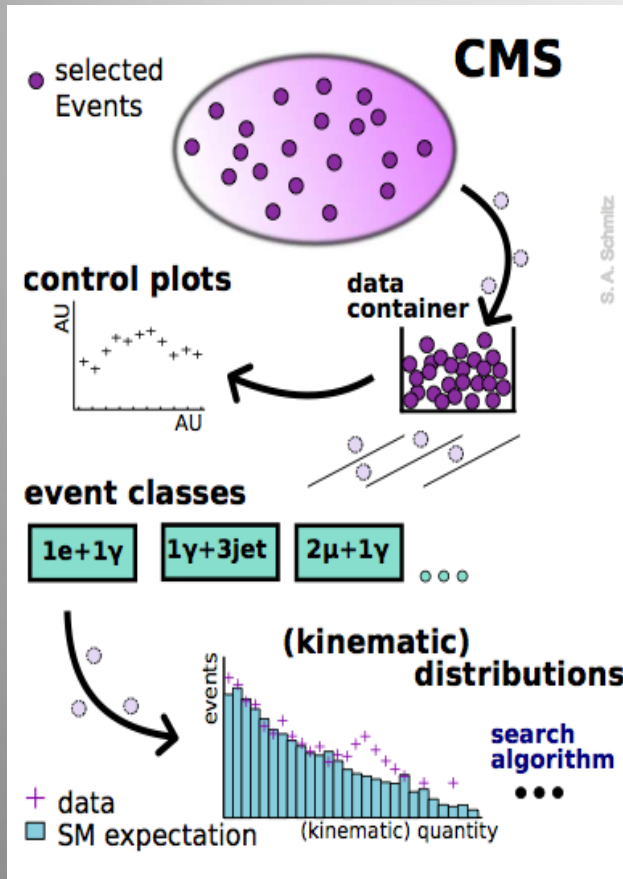


Exotica
Searches

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

Can we miss something?

CMS-EXO-10-021



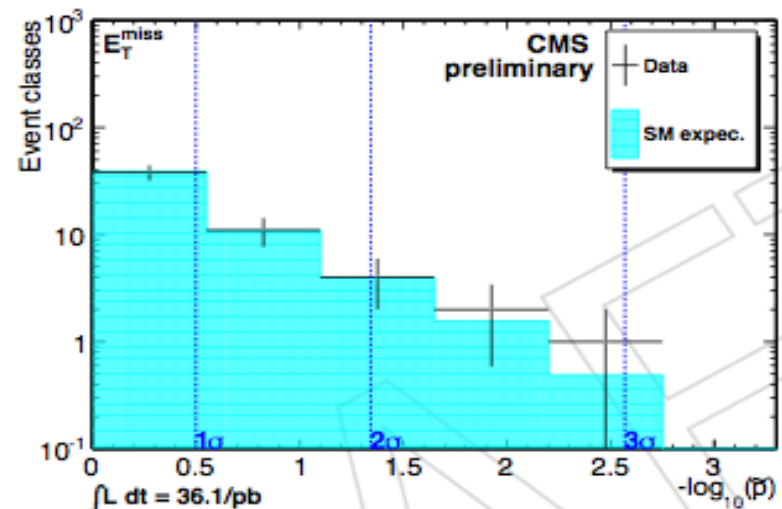
S. A. Schmitz

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



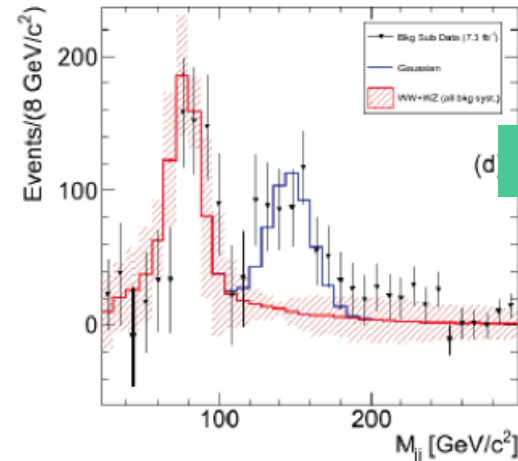
Probability distribution as expected for 35 pb⁻¹
Look at & watch the outliers...

Tevatron: W+2 jets bump??

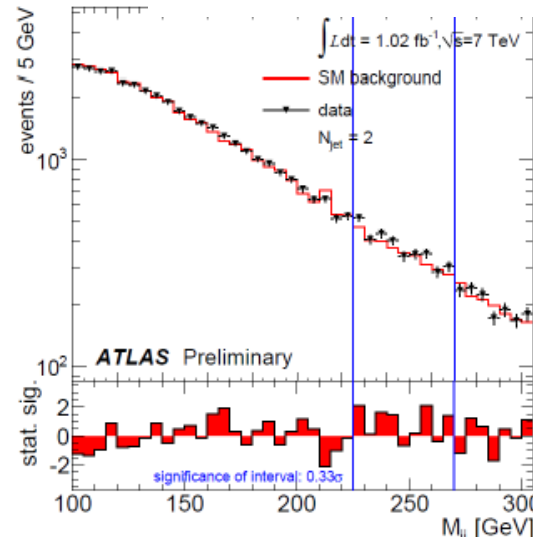
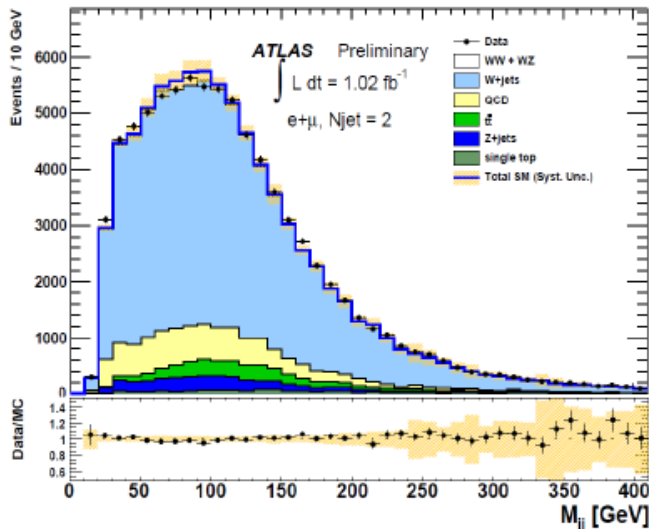
More on lvjj channel



- CDF has reported an excess of 4.1σ at $\sim 145\text{GeV}$ in jj mass distribution in lvjj channel with 7.3fb^{-1} of data
- This channel is not optimal at LHC with W+jet bkg 20 times higher, but this can be model dependent
- Selection: $p_T^j > 30\text{GeV}$, $p_T^e > 25\text{GeV}$, $p_T^\mu > 20\text{GeV}$, $p_T^{jj} > 40\text{GeV}$, $E_T^{\text{Miss}} > 25\text{GeV}$, $M_T^W > 40\text{GeV}$, $|\Delta\eta| < 2.5$, $|\Delta\phi^{j1,ET^{\text{Miss}}}| > 0.4\text{GeV}$
- Looked at $N_j=2$ (shown) and $N_j \geq 2$ (in backup)



T. Berger Hryn'ova



Not seen by D0
Tevatron jury
still out!

No significant excess over Standard Model processes seen in 1.02fb^{-1} of data

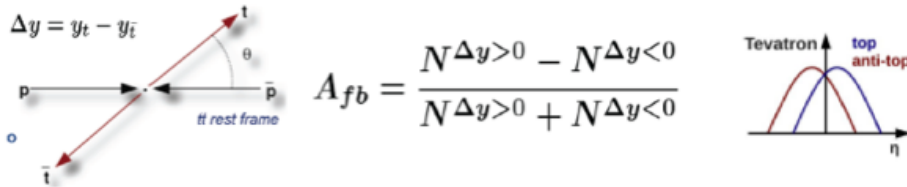
ATL-CONF-2011-097

15

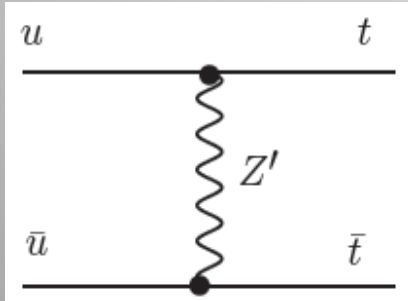
Note: for some of the possible new physics interpretations (eg Technicolor) perhaps $O(5)\text{fb}^{-1}$ is needed, and cuts should be re-optimized at the LHC

Tevatron: Top forward-backward asymmetry

color charge asymmetry A_{FB}



Is the Tevatron observation due to flavor changing neutral currents?



CMS-EXO-11-065

This would lead to to same sign top production at the LHC

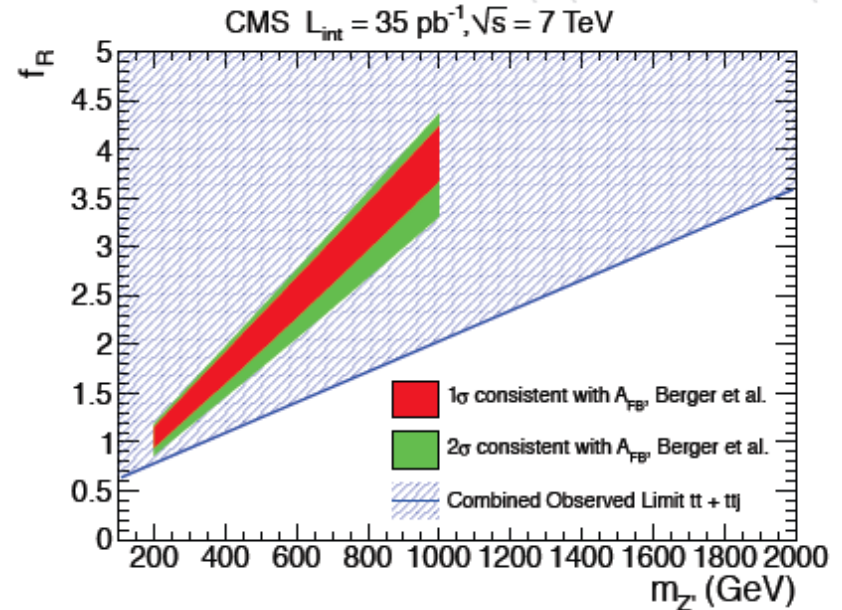
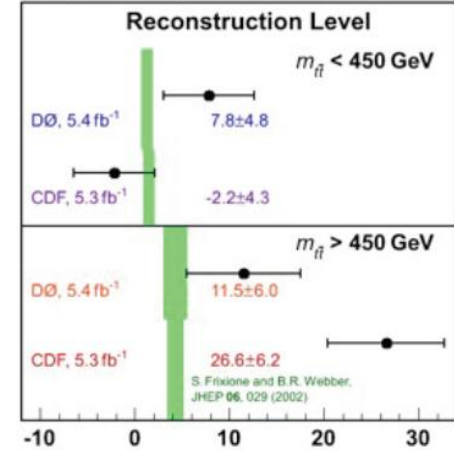
CMS search:

Two events found/one background expected

-> Exclusion limits!

Hypothesis excluded

Forward-Backward Top Asymmetry, %



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

Conclusions (D. Gross)

Keep up the hard work.

BE PATIENT

1 FB⁻¹ DOWN

2999 FB⁻¹ TO GO

ENJOY

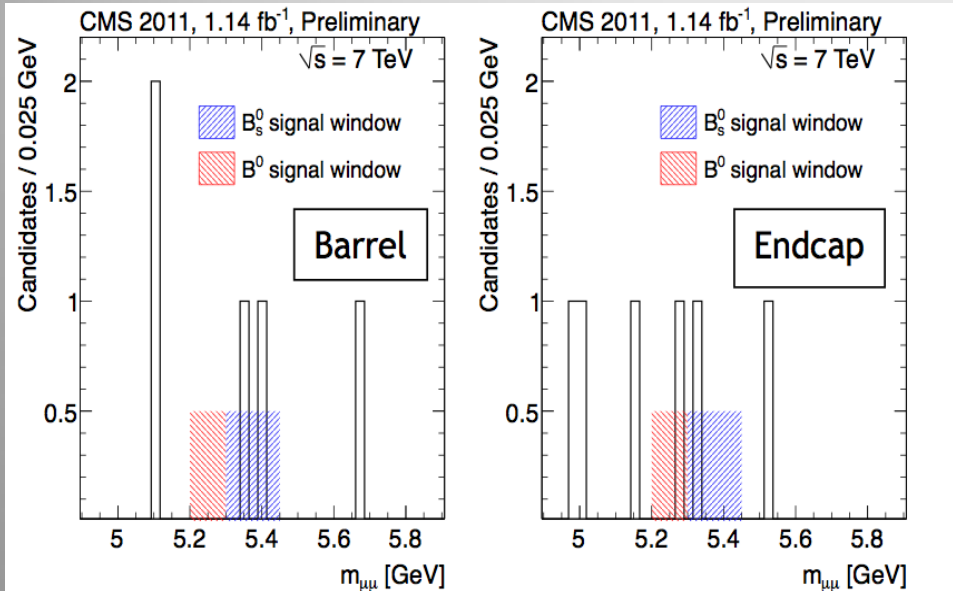
**THE
FUN
IS JUST
BEGINNING**

BACKUP

$B_s \rightarrow \mu^+ \mu^-$

Indirect sensitivity to new physics (MSSM: $BR \propto (\tan\beta)^6 \rightarrow$ sensitivity to extended Higgs boson sectors \rightarrow constraints on parameter region).

$$B_s \rightarrow \mu^+ \mu^- = (3.2 \pm 0.2) \times 10^{-9} ; B_d \rightarrow \mu^+ \mu^- = (1.0 \pm 0.1) \times 10^{-10}$$



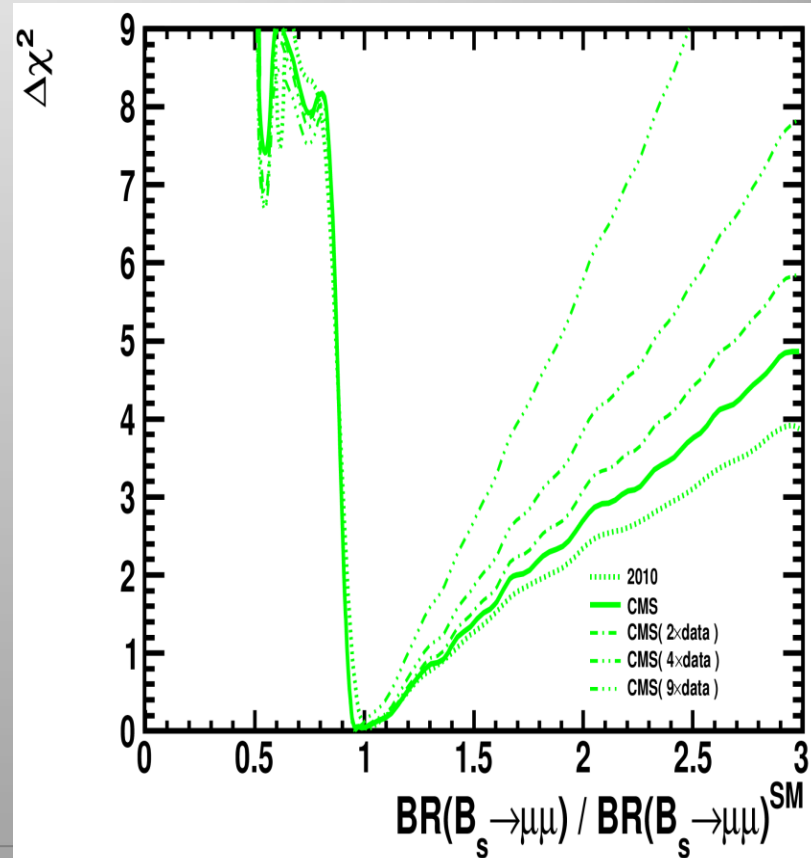
Events observed in the unblinded windows consistent with background plus SM expectations.

$$B_s \rightarrow \mu^+ \mu^- < 1.9 \times 10^{-8} \text{ (95\% CL)}$$

$$B_d \rightarrow \mu^+ \mu^- < 4.6 \times 10^{-9} \text{ (95\% CL)}$$

Impact on new models

arXiv:1106.2529



Bs to $\mu\mu$ in LHCb/CMS

- LHCb presents new preliminary results with 300pb^{-1} on $\text{BR}(B_{s/d} \rightarrow \mu^+\mu^-)$

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.3 \times 10^{-8} (1.6 \times 10^{-8}) @ 90 (95)\% \text{ CL}$$

$$\text{BR}(B_d \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-9} (5.2 \times 10^{-9}) @ 90 (95)\% \text{ CL}$$

- Combined results with 2010 data (37pb^{-1}):

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.2 (1.5) \times 10^{-8} @ 90 (95)\% \text{ CL}$$

- We do not confirm the excess seen by CDF

LHCb

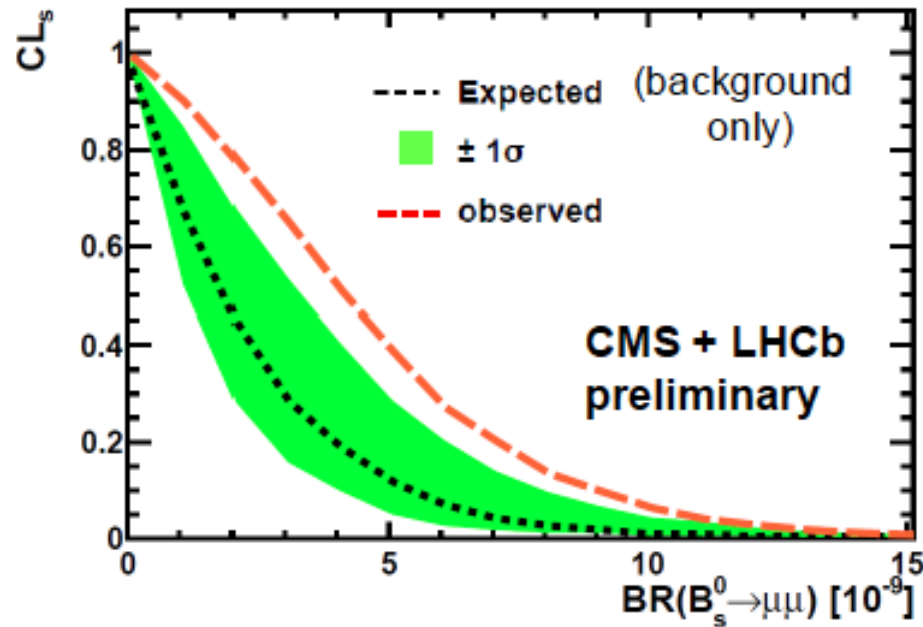
CMS

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-8} \quad (95\% \text{ C.L.})$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9} \quad (95\% \text{ C.L.})$$

LHCb-CMS Prelim. Combination

A preliminary CMS-LHCb combination on $BR(B_s \rightarrow \mu^+ \mu^-)$ has been performed, again using the CLs approach, & taking LHCb value of f_s/f_d as common input



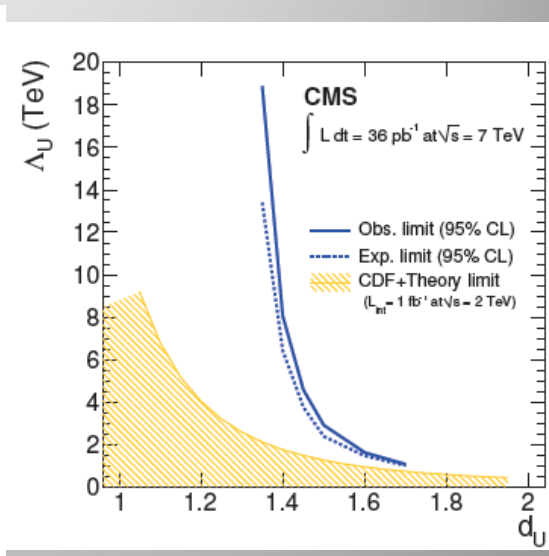
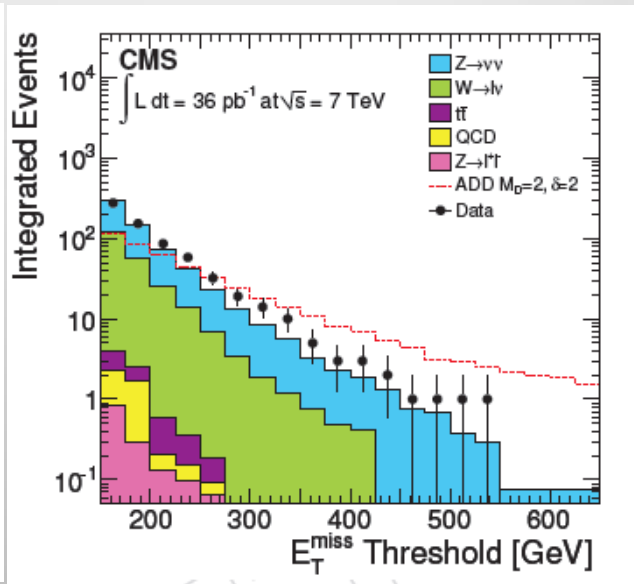
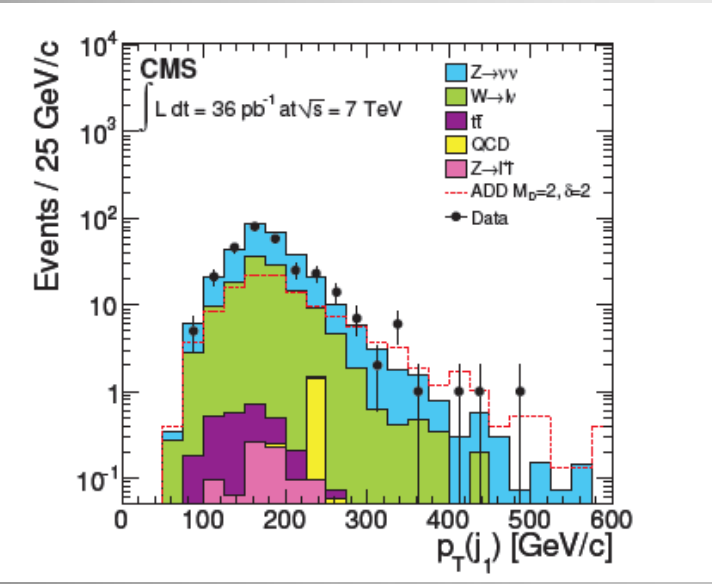
Observed limit at 95% (90%): 1.1 (0.9) $\times 10^{-9}$

This is 3.4 times the expected SM value

ABR of 1.8×10^{-8} has a CLs value of $\sim 0.3\%$

Monojets: ADD Extra Dimensions

Selection: max 2 jets in the event: 1 jet > 110 GeV, MET > 150 GeV

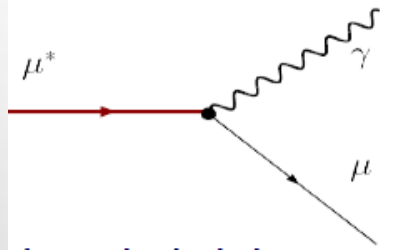
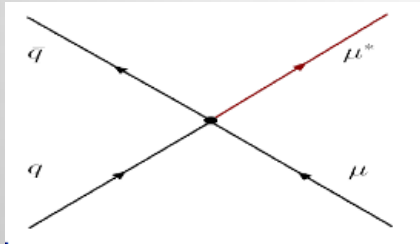


Results for ADD scale (with/without K-factor)

δ	K factor	LO Exp.	LO Obs.	NLO Exp.	NLO Obs.
2	1.5	2.17	2.29	2.41	2.56
3	1.5	1.82	1.92	1.99	2.07
4	1.4	1.67	1.74	1.78	1.86
5	1.4	1.59	1.65	1.68	1.74
6	1.4	1.54	1.59	1.62	1.68

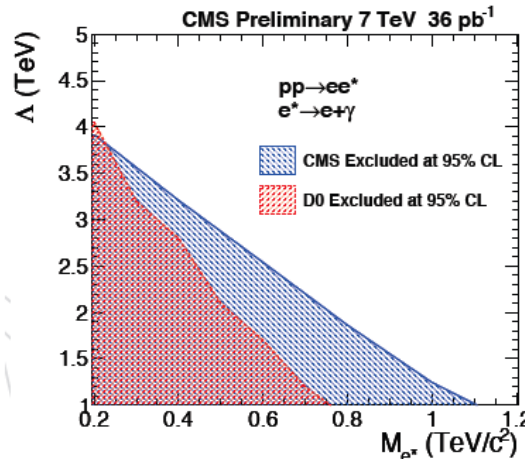
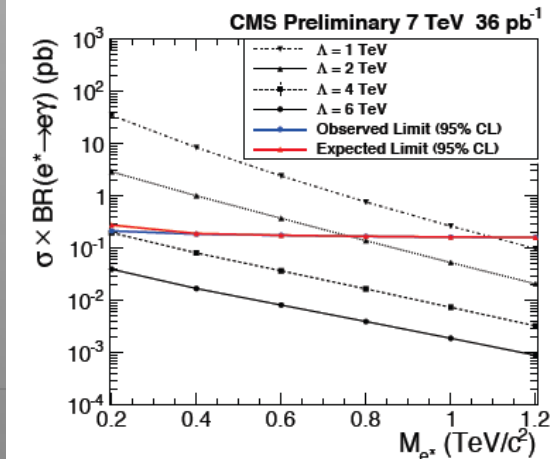
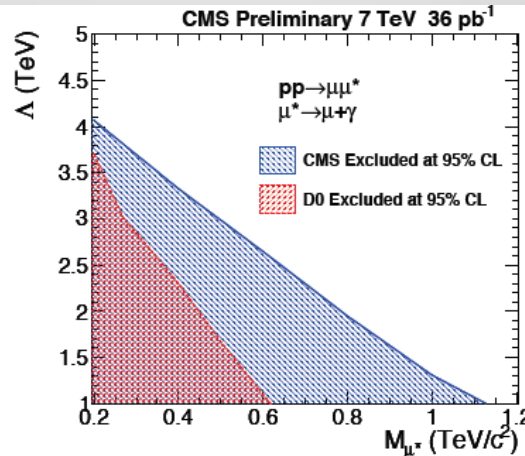
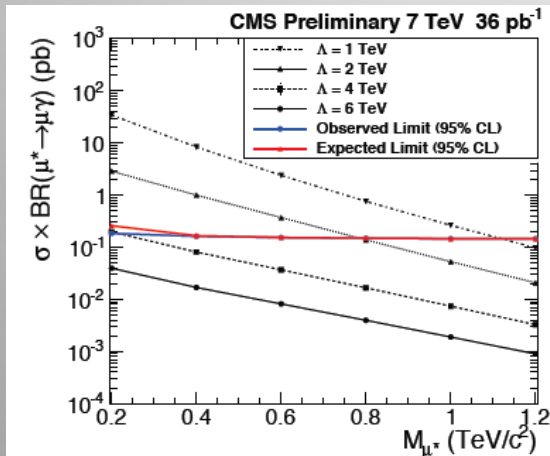
CMS-EXO-11-003

Excited Leptons



Contact interactions

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

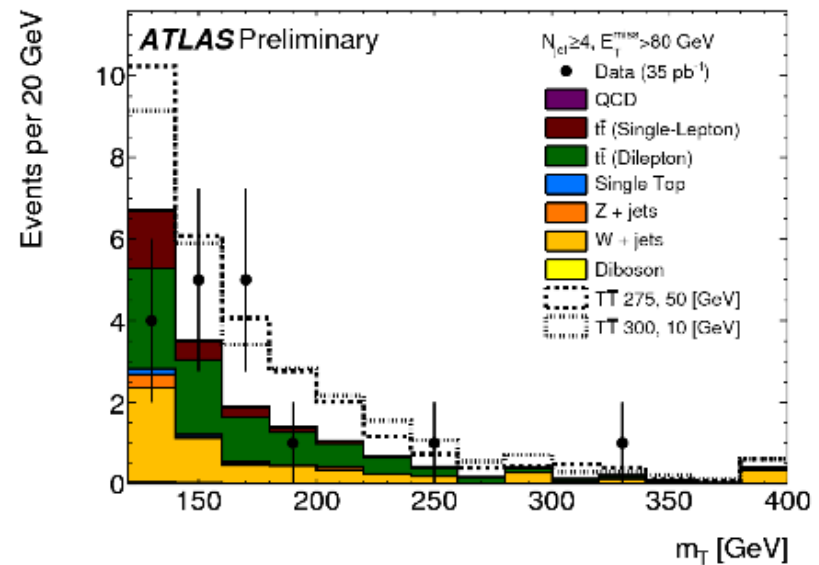
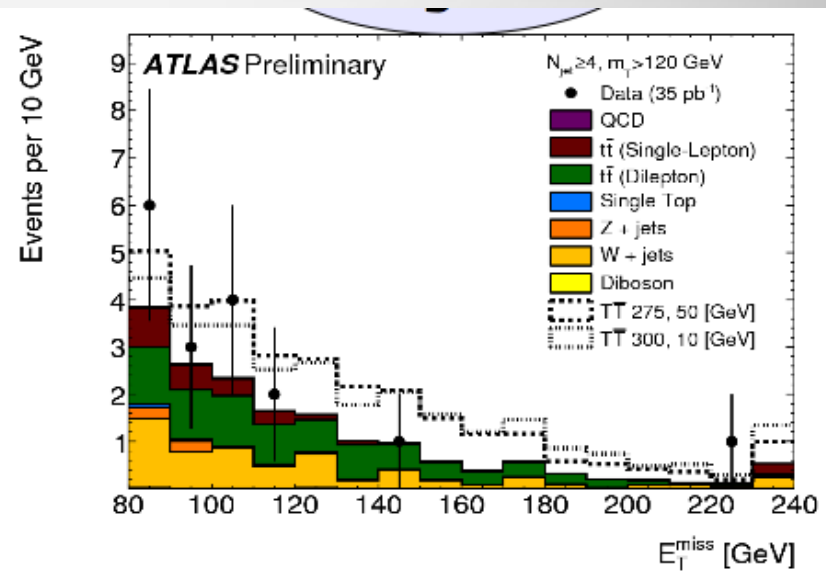


No excited leptons with mass < 1 TeV for $\Lambda = M_{e^*}$

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

New physics with top

• Example: $TT \rightarrow ttA_0A_0$



GMSB SUSY Searches

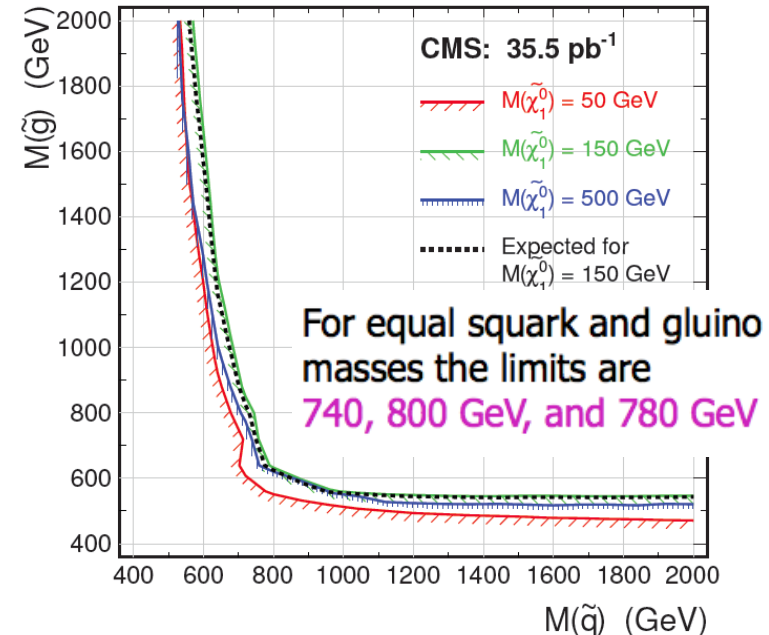
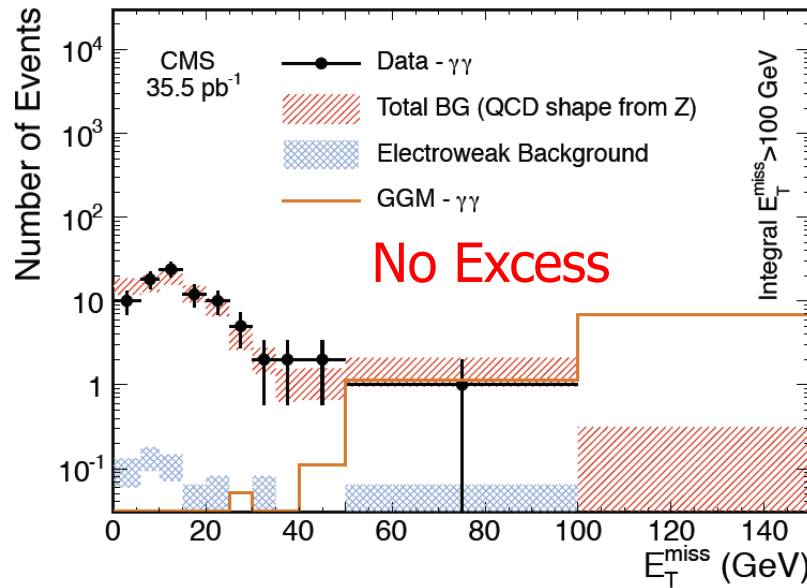
Gauge Mediated SUSY breaking: LSP is the Gravitino

● 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

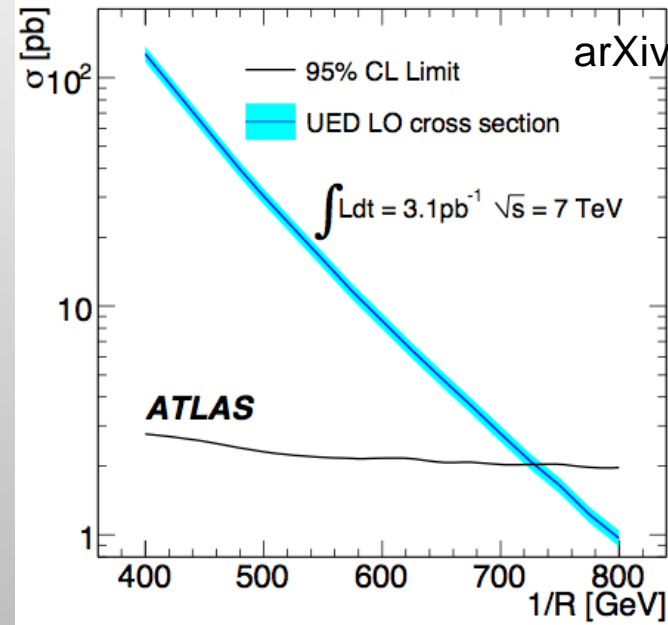
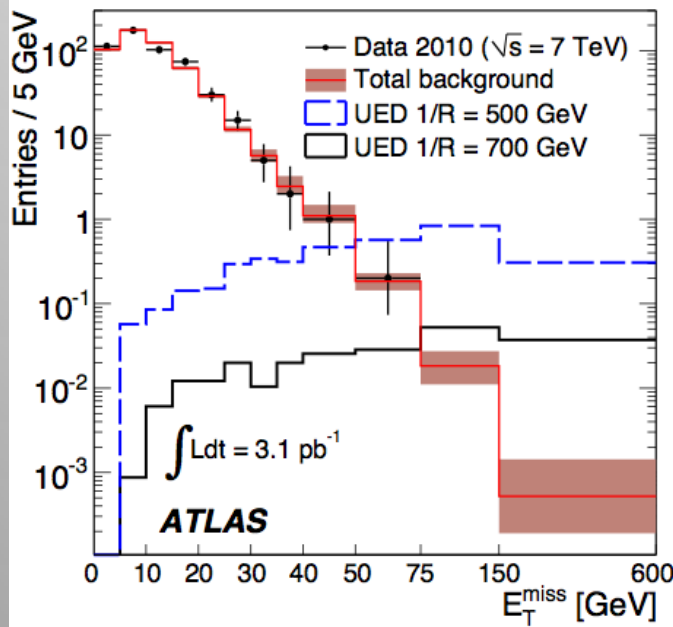


These results can be reinterpreted in Universal Extra Dimensions

Universal Extra Dimensions

Search for events with two photons and missing transverse energy

Limits set for events with two photons with $E_T > 25$ GeV and $MET > 75$ GeV

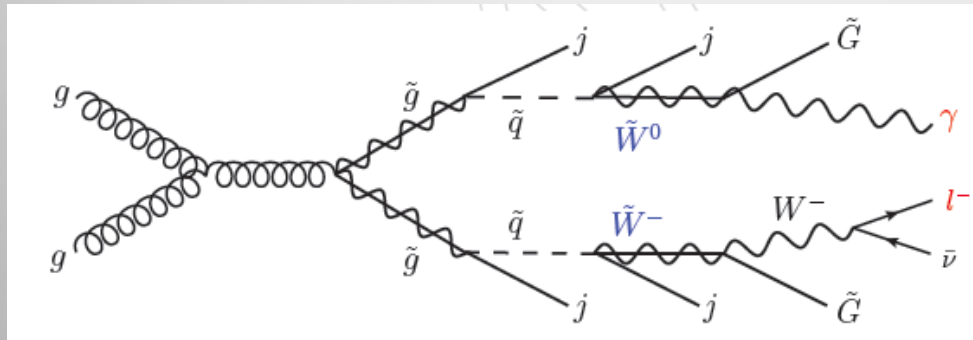


E_T^{miss} range (GeV)	Data events	Predicted background events			Expected UED signal events	
		Total	QCD	$W(\rightarrow e\nu) + \text{jets}/\gamma$	$1/R = 500$ GeV	$1/R = 700$ GeV
0 - 20	465	465.0 ± 9.1	465.0 ± 9.1	-	0.28 ± 0.06	0.02 ± 0.01
20 - 30	45	40.5 ± 2.2	40.41 ± 2.17	0.11 ± 0.07	0.45 ± 0.07	0.03 ± 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...

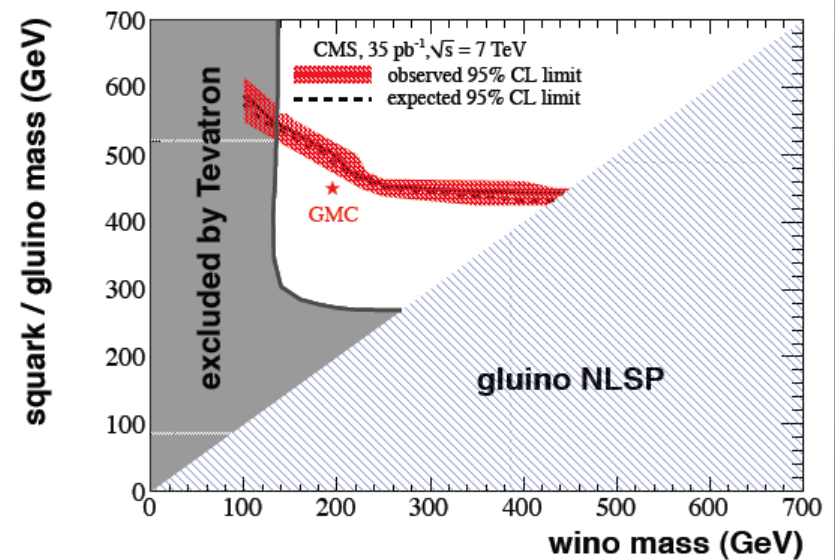
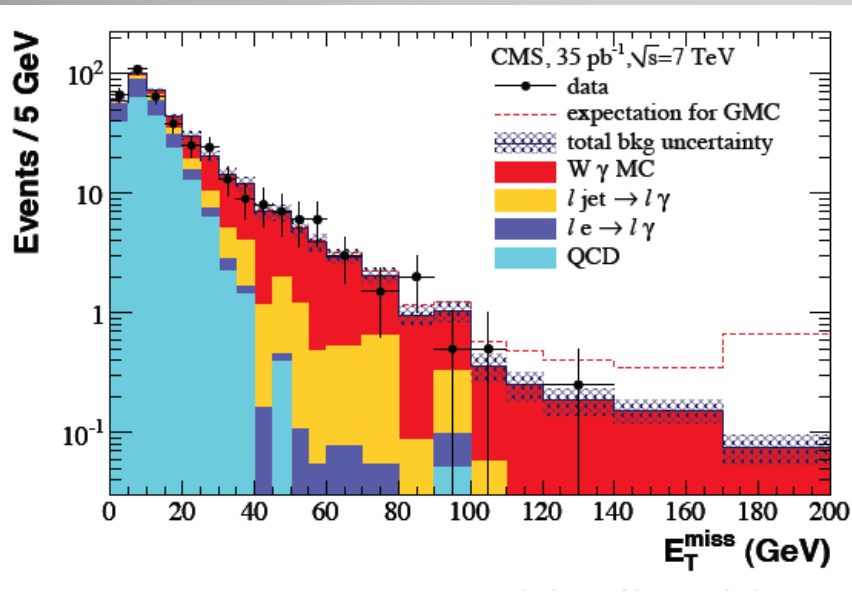
GMSB SUSY Searches

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

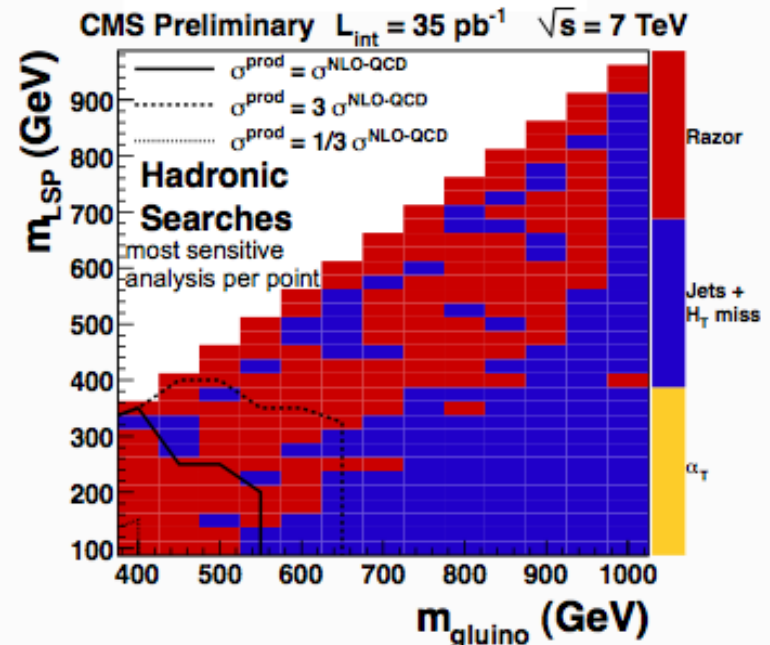
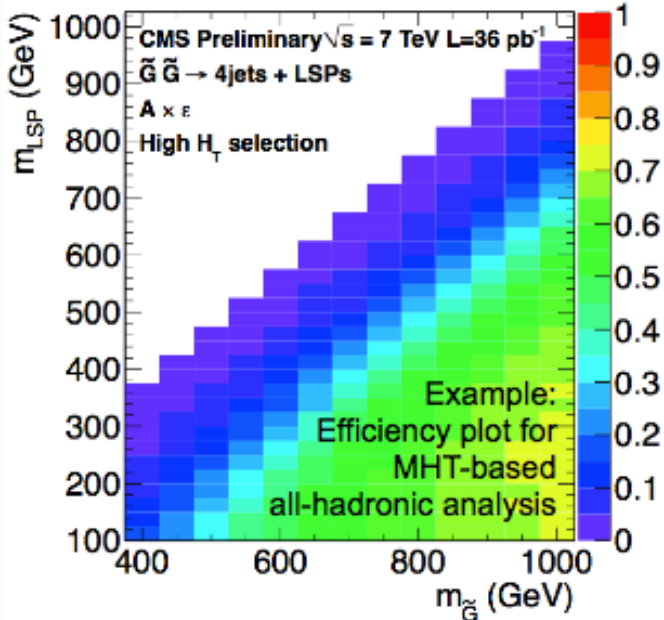
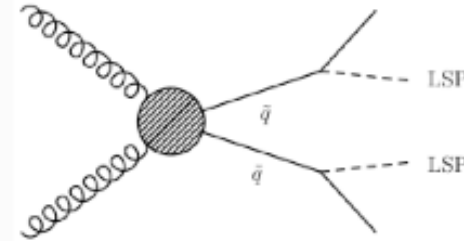
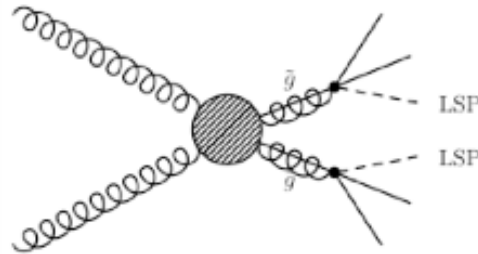
JHEP 1106:093,2011



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?

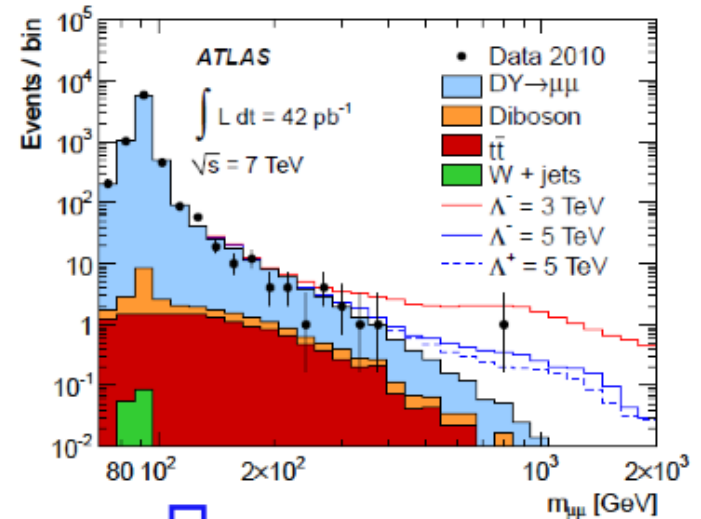
Contact Interactions

Contact Interactions

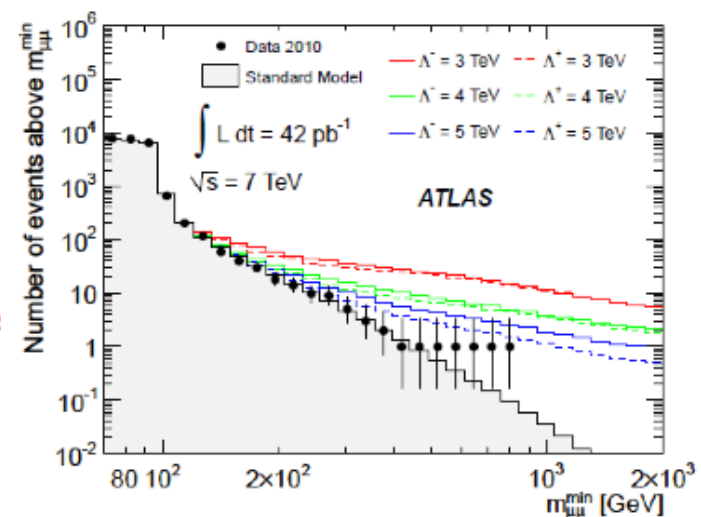
- Four-fermion contact interactions (CI) at low energy limit describe phenomena as:
 - Large Extra Dimension ADD Model
 - Quark-lepton compositeness
- **Benchmark: left-left isoscalar model**

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

- $F_{I(C)}$ is interference (CI) term, $\eta_{LL} = 1$
- Λ is the energy scale (below which fermion constituents are bound)
- No excess, **limits at 95% CL**:
 - $\Lambda > 4.9 \text{ TeV}$ for constructive interference
 - $\Lambda > 4.5 \text{ TeV}$ for destructive interference

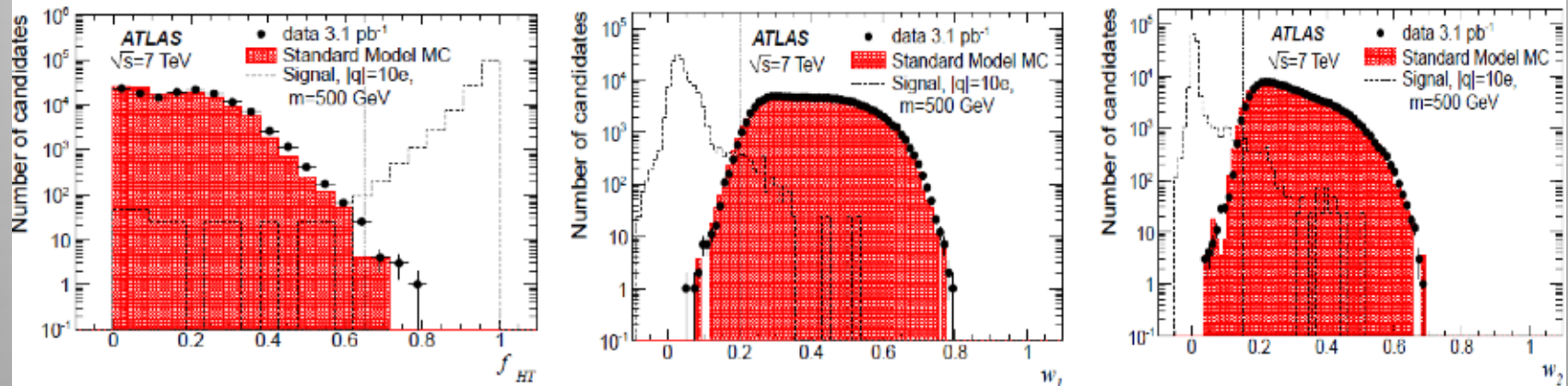


Taking an integral...



Long Lived Particles

Search for Massive Long-Lived Highly Ionising Particles



- Search for massive long-lived HIP: concentrate on large mass (>100 GeV), 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)

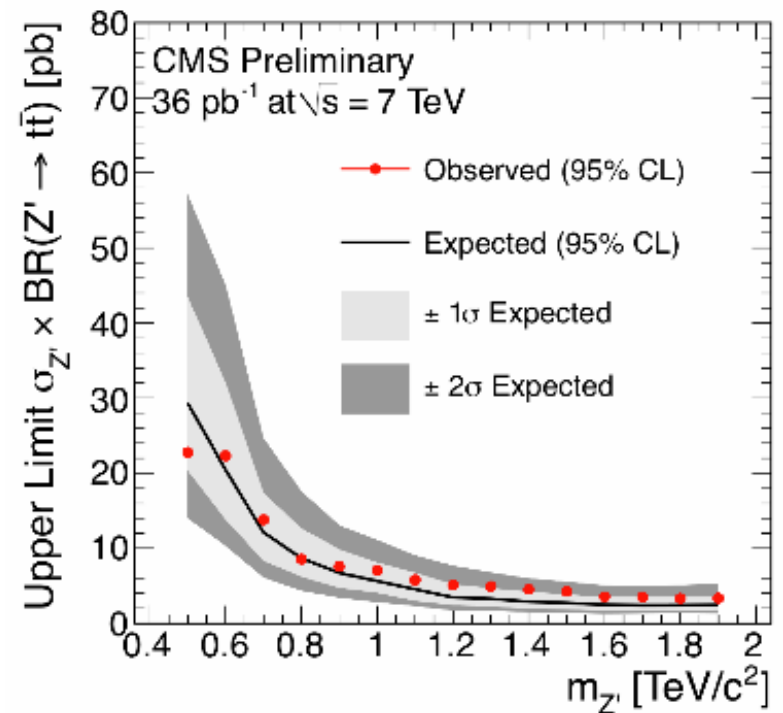
Cross-section limits @ 95% CL
in pb for any model

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

m [GeV]	$ q = 6e$	$ q = 10e$	$ q = 17e$	m [GeV]	$ q = 6e$	$ q = 10e$	$ q = 17e$
200	1.4	1.2	2.1	200	11.5	5.9	9.1
500	1.2	1.2	1.6	500	7.2	4.3	5.3
1000	2.2	1.2	1.5	1000	9.3	3.4	4.3

Z' -> top anti-top

- No significant deviations from SM expectation
- Set non-model-specific 95% CL upper limit on $\sigma(\text{narrow } Z' \text{ resonance}) \times \text{BR}$
 - ~7 pb at 1.0 TeV and
 - ~4 pb at 1.5 TeV



Z' -> top anti-top

Run 166864, Event 457688464

Ttbar mass = 1353 GeV

Jet 3 :
pt 47.8 GeV/c,
b-tag discriminant 4.2

Bonus: 3rd jet is b-tagged !

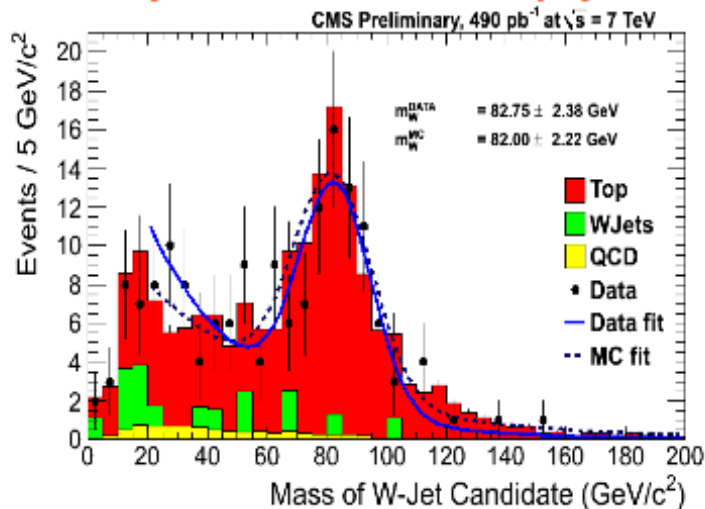
Jet 2: Jet Pruning
pt 484.3 GeV/c,
mass = 68.8 GeV/c²
Jet 2 + 3 : Mass = 167

Jet 1 : Top Tagging
pt 589.1 GeV/c,
3 subjets,
mass = 186.7 GeV/c²,
minMass = 87.2 GeV/c²

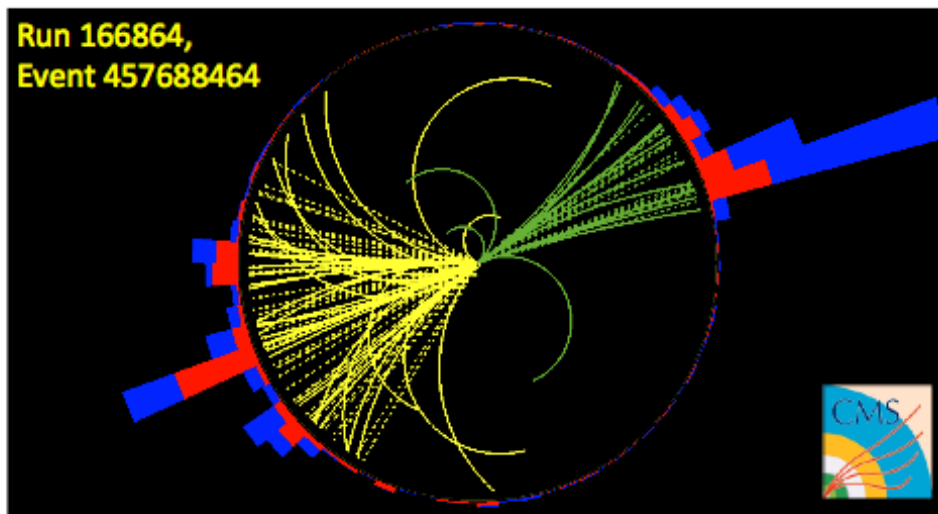


Z' -> top anti-top

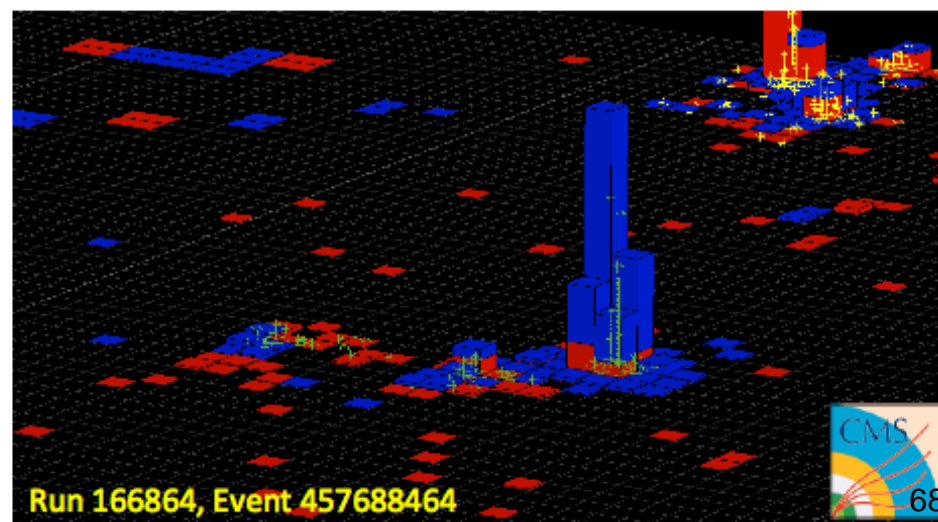
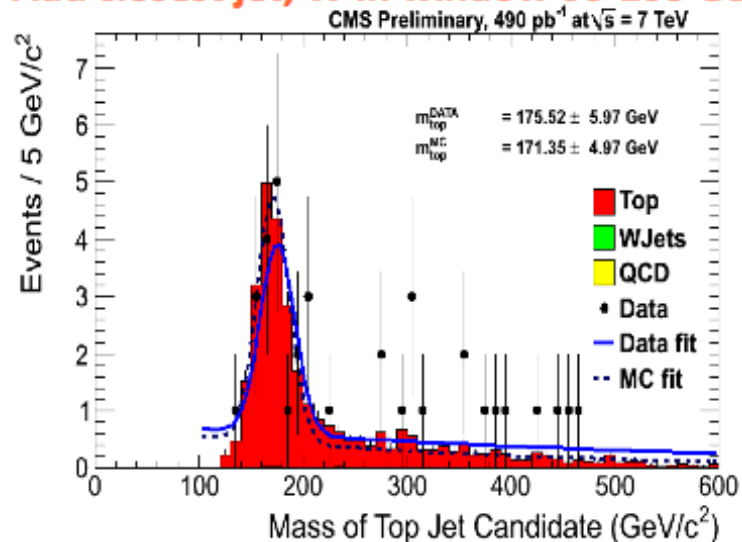
Test Subjet JES with boosted μ +jets events:



Particle Flow helps to resolve substructure:



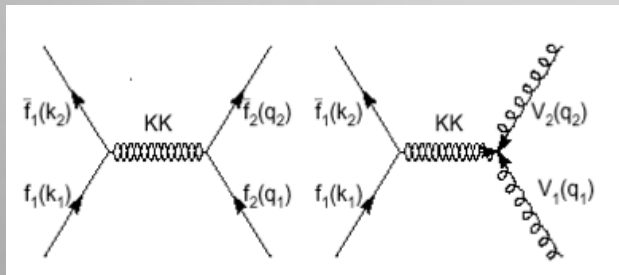
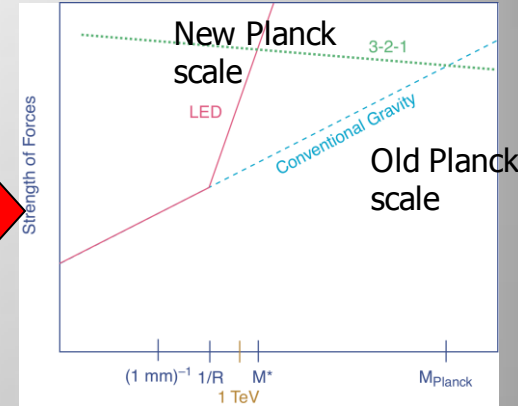
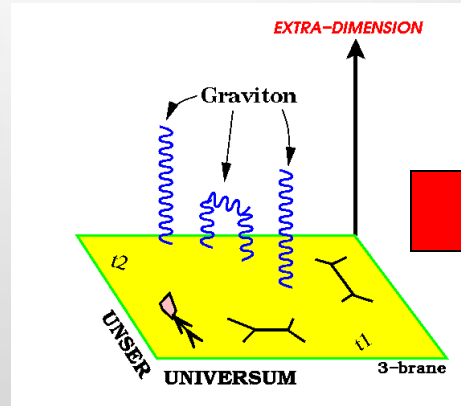
Add closest jet, W in window 60-100 GeV:



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



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 $\mu\mu$ channel)
 Tighter limits than from the Tevatron

