Searches for New Physics at the LHC

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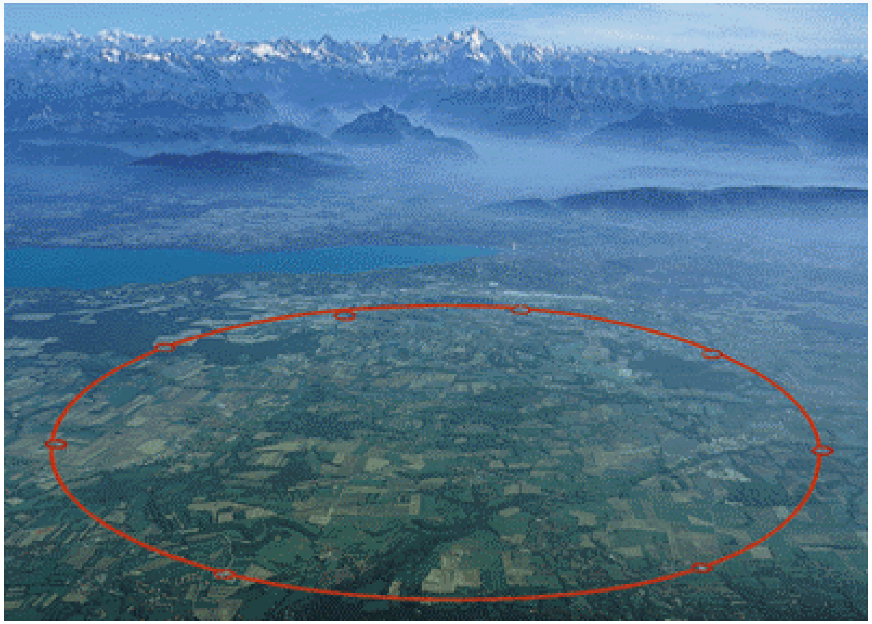
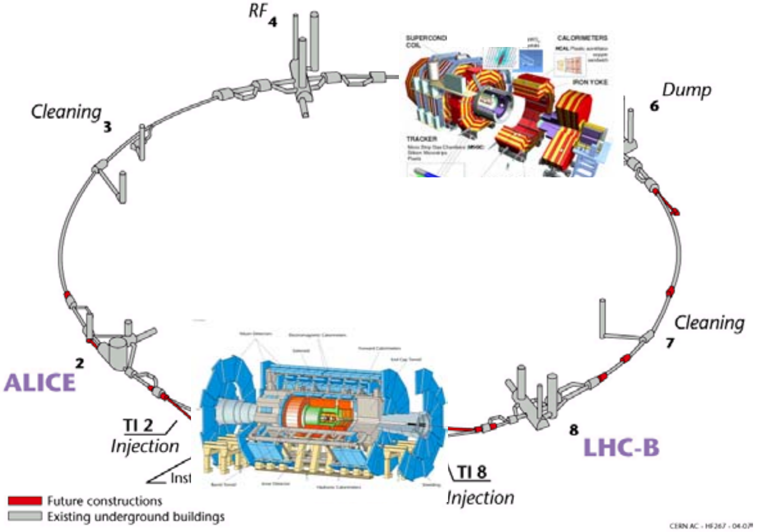
On behalf of the ATLAS and CMS Collaborations

Large Hadron Collider

- **LHC will be a 14 TeV proton-proton collider located inside the LEP tunnel at CERN.**
- **Luminosity goals are 10 fb^{-1} / year (first 3 years) and 100 fb^{-1}/year (subsequently).**





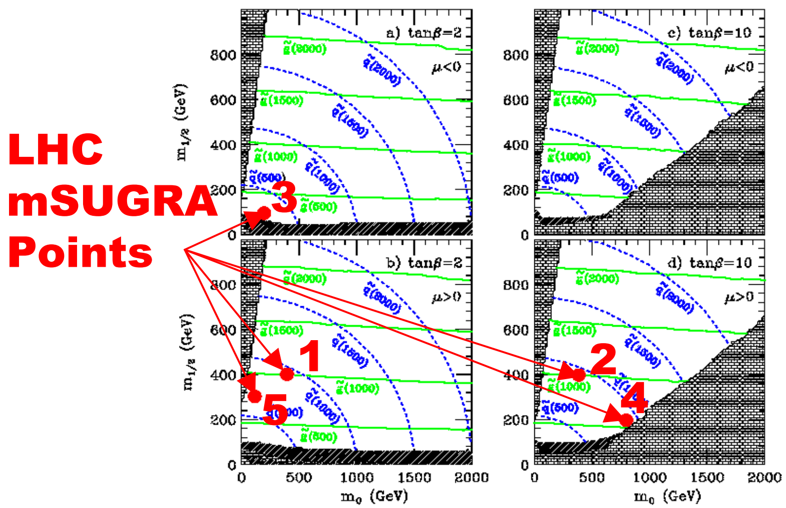
- **First data in 2007.**
- **Higgs, SUSY and Exotics searches a main goal of ATLAS and CMS GPDs.**

Recent Physics Studies

- **ATLAS Physics and Detector Performance TDR published May 1999**
  - **Summarised all physics studies up to that point.**
  - **Contained large SUSY and Exotics chapters.**
  - http://atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html
  - **Work also presented at Physics Workshop (Lund, September 2001)**
- **Major CMS SUSY paper recently published**
  - S. Abdullin et al., J. Phys. **G28** (2002) 469
  - **Summarises CMS SUSY activities up to ~ 1999**
  - **Also recent Compositeness and Extra Dimensions work**
- **Will concentrate on a few selected topics**
- **No GMSB, RPV SUSY, SUSY Higgs , ……**

Inclusive SUSY Searches

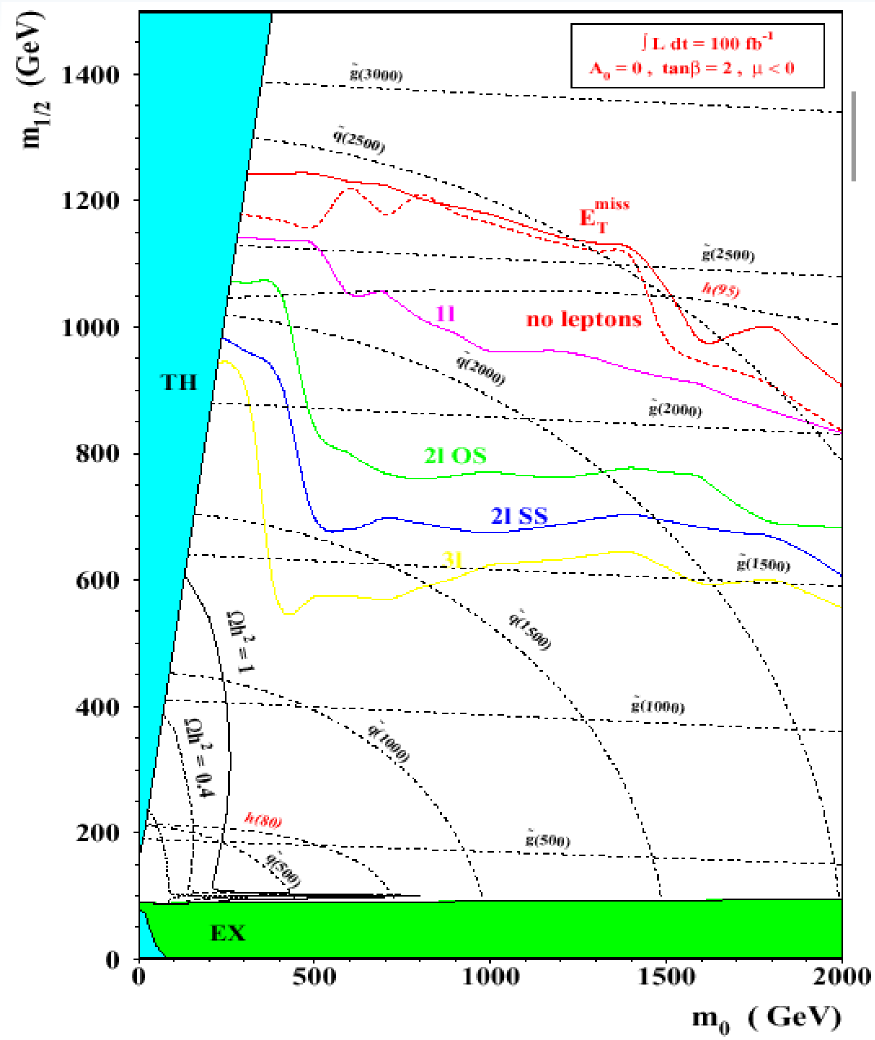
- Discovery reach mapped in mSUGRA parameter space: unified masses and couplings at the GUT scale → 5 free parameters (m_0, $m_{1/2}$, A_0, $\tan(\beta)$, $\text{sign}(\mu)$).
- Uses 'golden' Jets + n leptons + E_T^{Miss} discovery channel.
  - Heavy strongly interacting sparticles produced in initial interaction
  - Cascade decay with emitted jets and leptons
  - R-Parity conservation gives stable LSP (neutralino) at end of chain.
- Assess sensitivity in m_0-$m_{1/2}$ plane.
- Sensitivity weakly dependent on A_0, $\tan(\beta)$ and $\text{sign}(\mu)$.
  - Choose 'reasonable' values
- R-Parity assumed to be conserved.

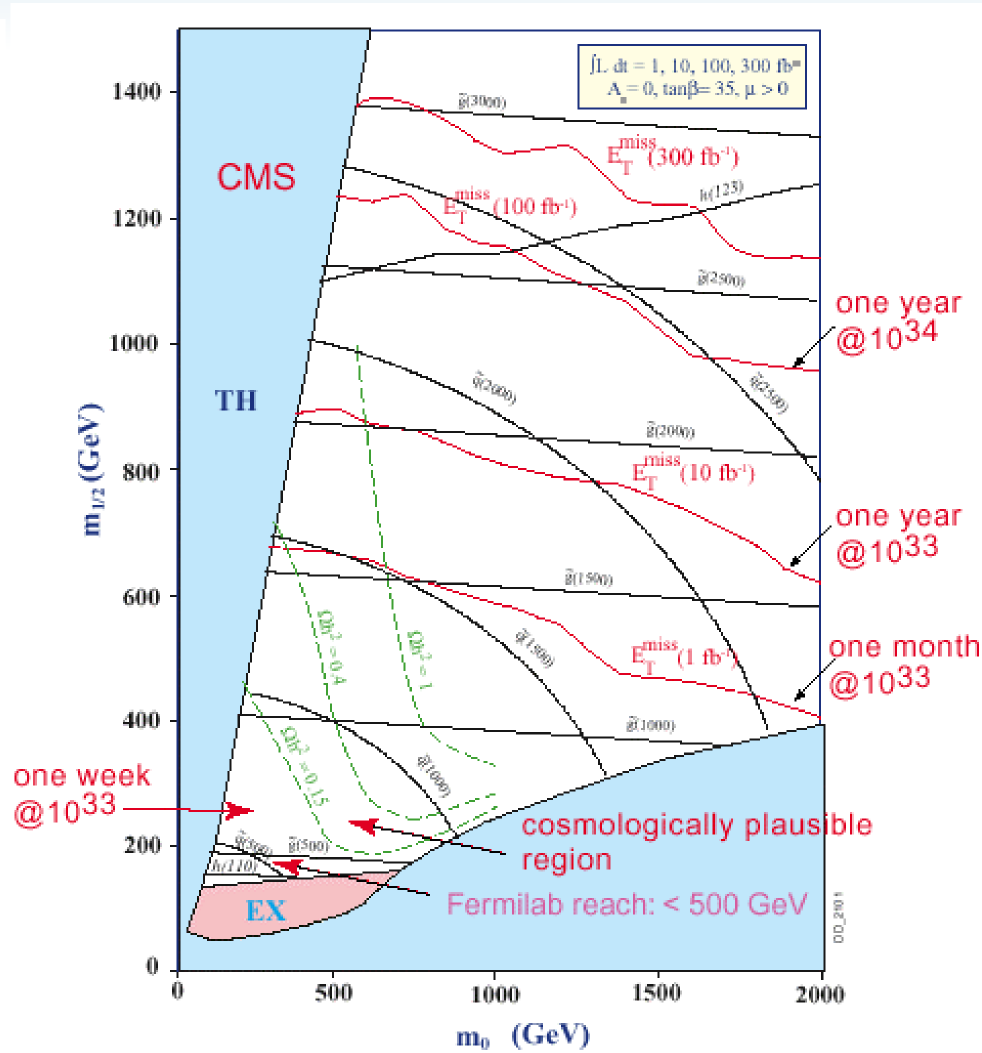


mSUGRA Reach

Abdullin and Charles, Nucl. Phys. B547 (1999) 60

CMS



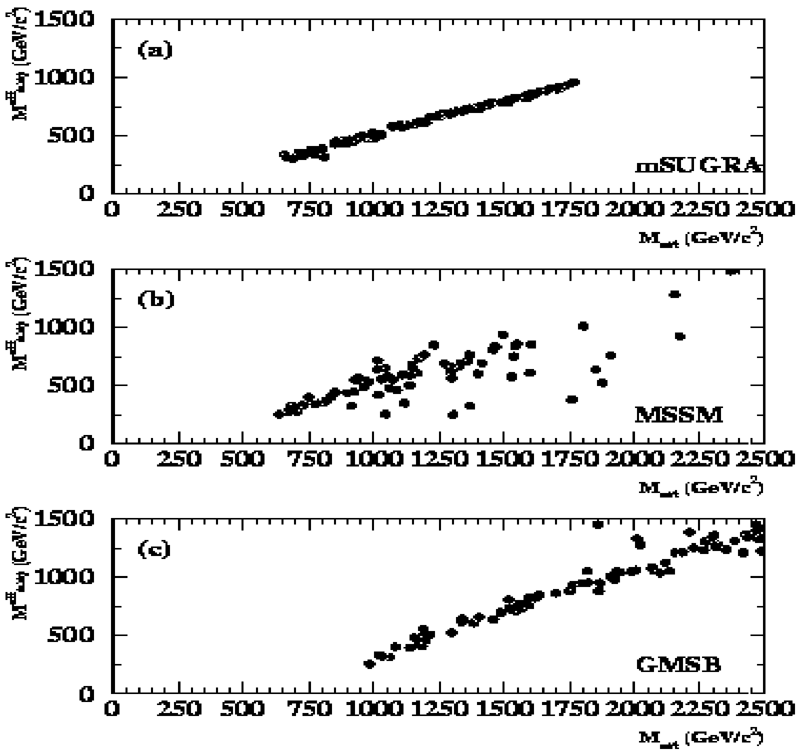


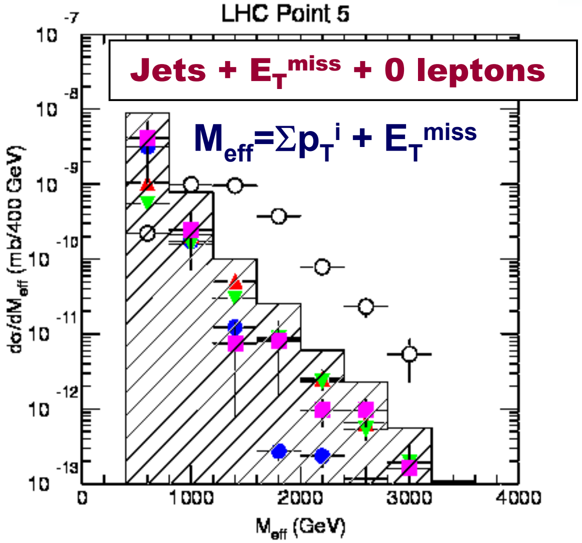
SUSY Mass Scale

Hinchliffe, Paige et al., Phys. Rev. D55 (1997) 5520; DRT, Phys. Lett. B498 (2001) 1

ATLAS

- **First measured SUSY parameter likely to be mass scale.**
- **Effective mass signal peak position ~ 2x SUSY mass scale.**





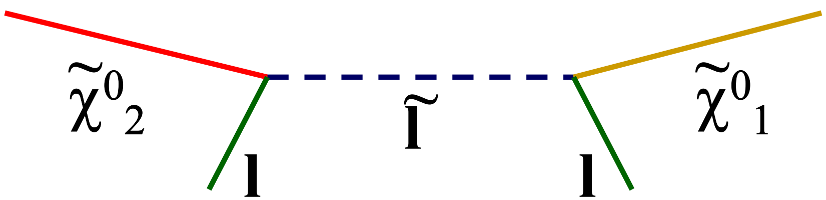
- **Peak position strongly correlated with mass scale for mSUGRA, GMSB etc.**
- **Pseudo model-independent**
- **Measurement error ~10% for mSUGRA after 1 year low lumi.**

Mass Measurements

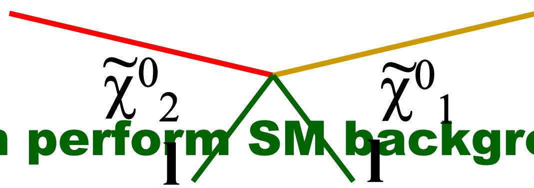
Hinchliffe, Paige et al., Phys. Rev. D55 (1997) 5520

ATLAS

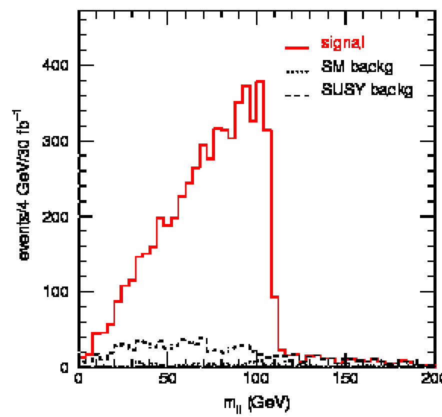
- **Starting point: OS SF dilepton edges.**
- **Important in regions of parameter space where two and three body decays of χ^0_2 to leptons dominate (e.g. LHC Point 5).**

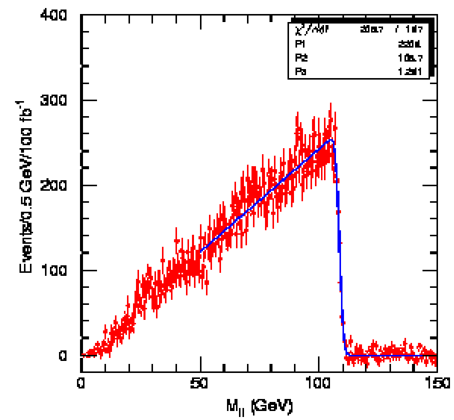


Elsewhere 2-body possible:



$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}} = 108.93\ \mathrm{GeV}$$





- **Can perform SM background s**

e^+e^- ·

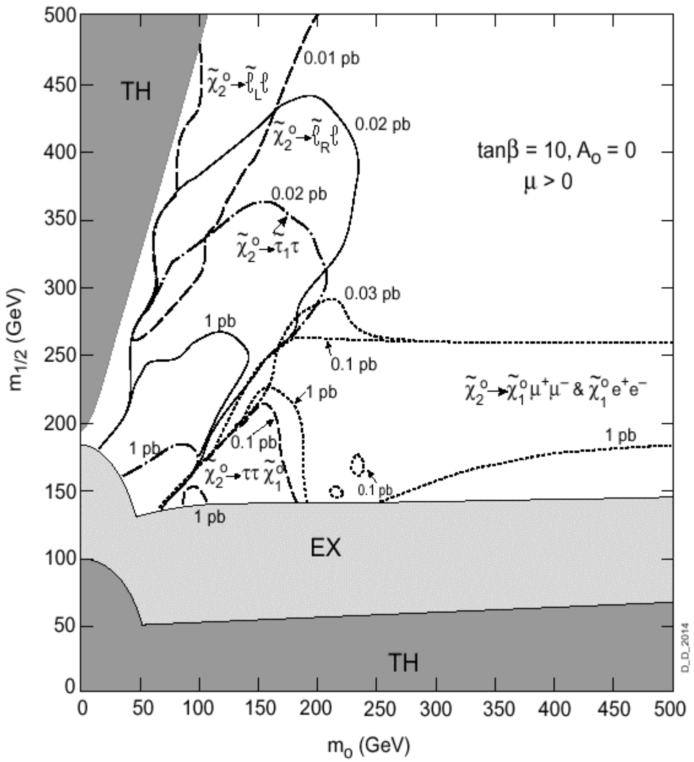
- **Position of edge can measure mass combinations to ~ 0.1%.**

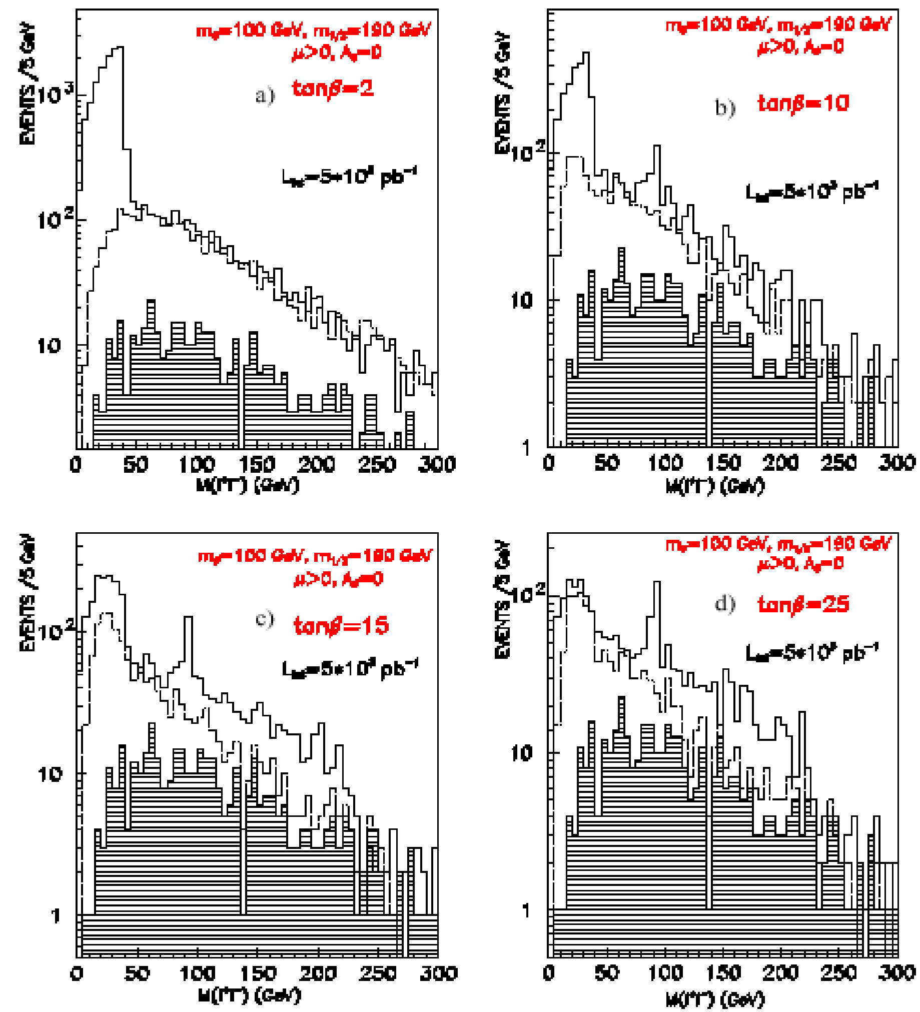
Dilepton Edge

Denegri et al., Phys. Rev. D60 (1999) 035008

CMS

- **CMS study of observability of edge over mSUGRA parameter space.**





Slepton Chain

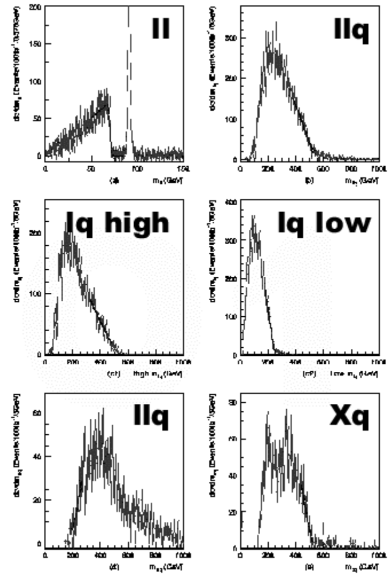
Lester et al., JHEP 0009 (2000) 004

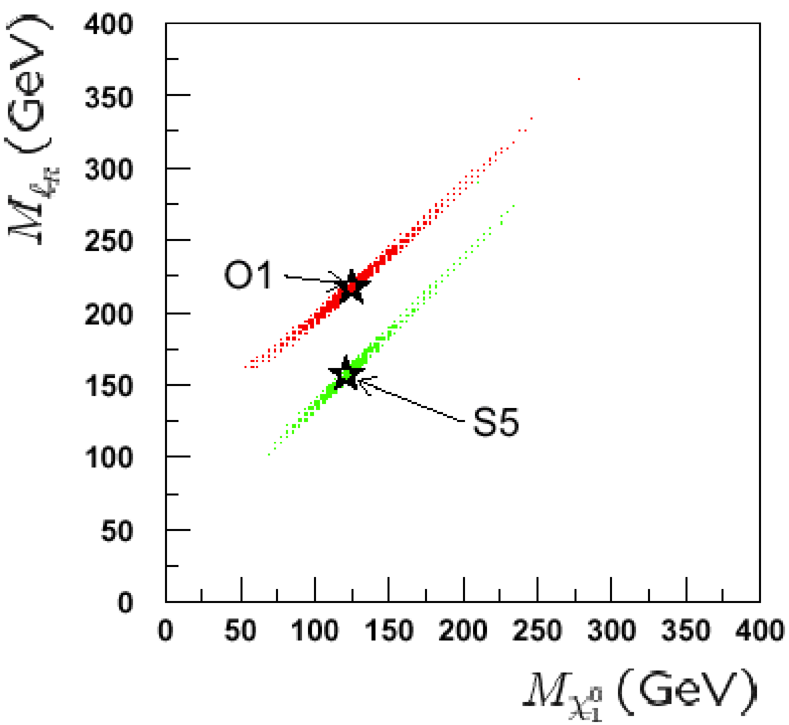
ATLAS

- **Use constraints from variety of edge measurements to measure absolute masses (e.g. LHC Point 5).**

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{max})^2 = (\tilde\xi - \tilde l)(\tilde l - \tilde\chi)/\tilde l$
l^+l^-q edge	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)}{\tilde\xi}, \frac{(\tilde q-\tilde l)(\tilde l-\tilde\chi)}{\tilde l}, \frac{(\tilde q\tilde l-\tilde\xi\tilde\chi)(\tilde\xi-\tilde l)}{\tilde\xi\tilde l}\right] \\ \text{except for the special case in which } \tilde l^2 < \tilde q\tilde\chi < \tilde\xi^2 \text{ and} \\ \tilde\xi^2\tilde\chi < \tilde q\tilde l^2 \text{ where one must use } (m_{\tilde q} - m_{\tilde\chi^0_1})^2. \end{cases}$
Xq edge	$(m_{Xq}^{max})^2 = X + (\tilde q - \tilde\xi)\left[\tilde\xi + X - \tilde\chi + \sqrt{(\tilde\xi - X - \tilde\chi)^2 - 4X\tilde\chi}\right]/(2\tilde\xi)$
l^+l^-q threshold	$(m_{llq}^{min})^2 = \begin{cases} [\ 2\tilde l(\tilde q - \tilde\xi)(\tilde\xi - \tilde\chi) + (\tilde q + \tilde\xi)(\tilde\xi - \tilde l)(\tilde l - \tilde\chi) \\ \ -(\tilde q - \tilde\xi)\sqrt{(\tilde\xi + \tilde l)^2(\tilde l + \tilde\chi)^2 - 16\tilde\xi\tilde l^2\tilde\chi}\ ]/(4\tilde l\tilde\xi) \end{cases}$
$l^{\pm}_{near}q$ edge	$(m_{l_{near}q}^{max})^2 = (\tilde q - \tilde\xi)(\tilde\xi - \tilde l)/\tilde\xi$
$l^{\pm}_{far}q$ edge	$(m_{l_{far}q}^{max})^2 = (\tilde q - \tilde\xi)(\tilde l - \tilde\chi)/\tilde l$
$l^{\pm}q$ high-edge	$(m_{lq(high)}^{max})^2 = \max\left[(m_{l_{near}q}^{max})^2, (m_{l_{far}q}^{max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(low)}^{max})^2 = \min\left[(m_{l_{near}q}^{max})^2, (\tilde q - \tilde\xi)(\tilde l - \tilde\chi)/(2\tilde l - \tilde\chi)\right]$
M_{T2} edge	$\Delta M = m_{\tilde l} - m_{\tilde\chi^0_1}$

Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde\chi = m^2_{\tilde\chi^0_1}$, $\tilde l = m^2_{\tilde l_R}$, $\tilde\xi = m^2_{\tilde\chi^0_2}$, $\tilde q = m^2_{\tilde q}$ and X is $m^2_{\tilde X}$ or $m^2_{\tilde g}$ depending on which particle participates in the "branched" decay.





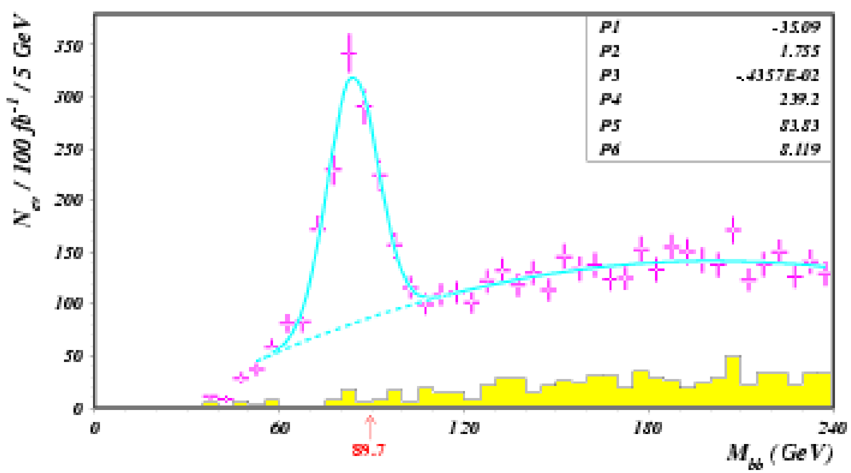
- **Can discriminate between mSUGRA point S5 and similar optimised string model O1.**
- **Powerful technique applicable to wide variety of RPC models.**

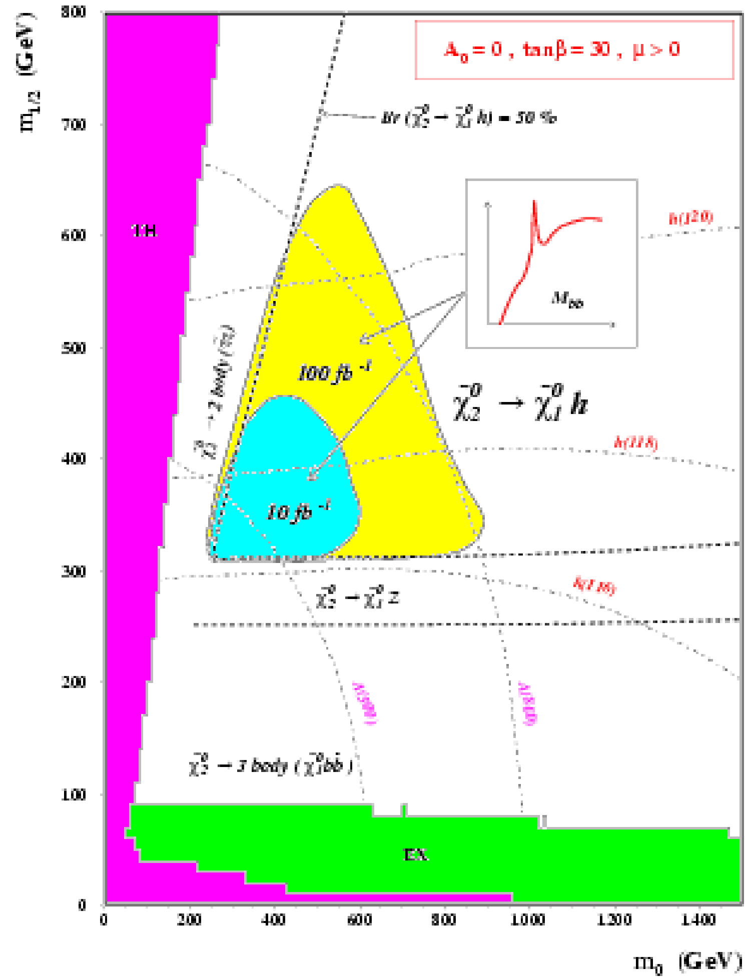
Higgs Signatures

S. Abdullin et al., J. Phys. G28 (2002) 469

CMS

- **Lightest Higgs particle produced copiously in $\tilde{\chi}^0_2$ decays if kinematically allowed.**
- **Prominent peak in bb invariant mass distribution.**
- **Possible discovery channel.**



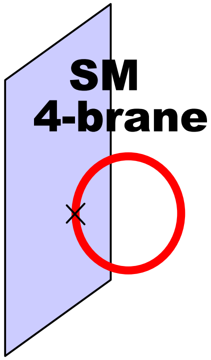


Extra Dimensions

- **M-theory/Strings → compactified Extra Dimensions (EDs)**
- **Q: Why is gravity weak compared to gauge fields (hierarchy problem)?**
- **A: It isn't, but gravity 'leaks' into EDs.**
- **Possibility of Quantum Gravity effects at TeV scale colliders!**
- **Variety of ED models proposed:**

Large (>>TeV^{-1})

- **Only gravity propagates in the EDs, $M^{Eff}_{Planck} \approx M_{weak}$**
- **Signature: Direct or virtual production of Gravitons**

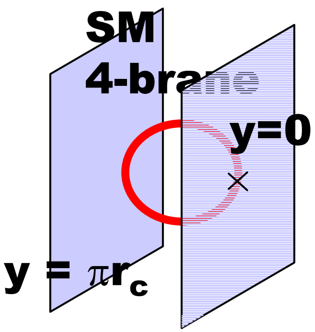


TeV^{-1}

- **SM gauge fields also propagate in EDs**
- **Signature: 4D Kaluza-Klein excitations of gauge fields**

Warped

- **Warped metric with 1 ED**
- **$M^{Eff}_{Planck} \approx M_{weak}$**
- **Signature: 4D KK excitations of Graviton, Radion scalar**



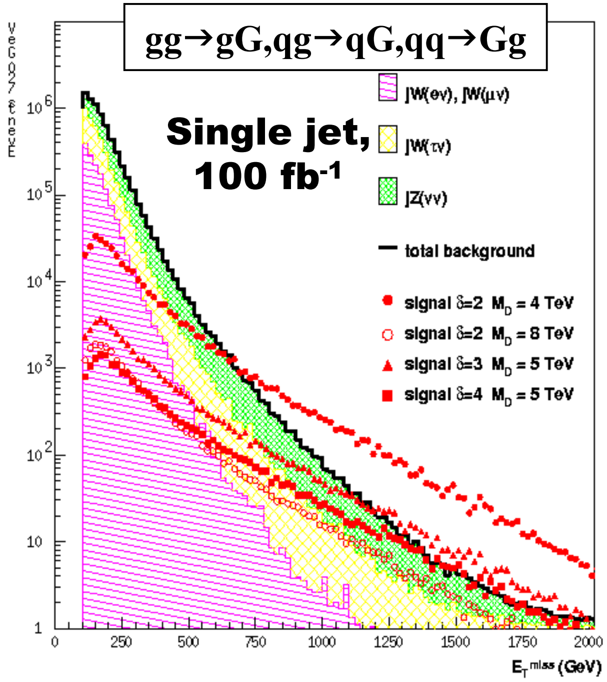
Large Extra Dimensions

Antoniadis, Benakli and Quiros PLB331 (1994) 313; Arkani-Hamed, Dimopoulos and Dvali PLB429 (1998) 263 ATLAS

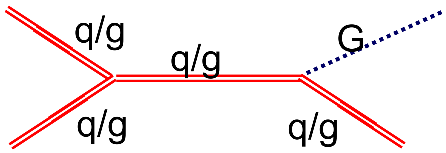
- With δ EDs of size R, observed Newton constant related to fundamental scale of gravity M_D:

$$G_N^{-1}=8\pi R^{\delta}M_D^{2+\delta}$$

- Search for direct graviton production in jet(γ) + E_T^{miss} channel.

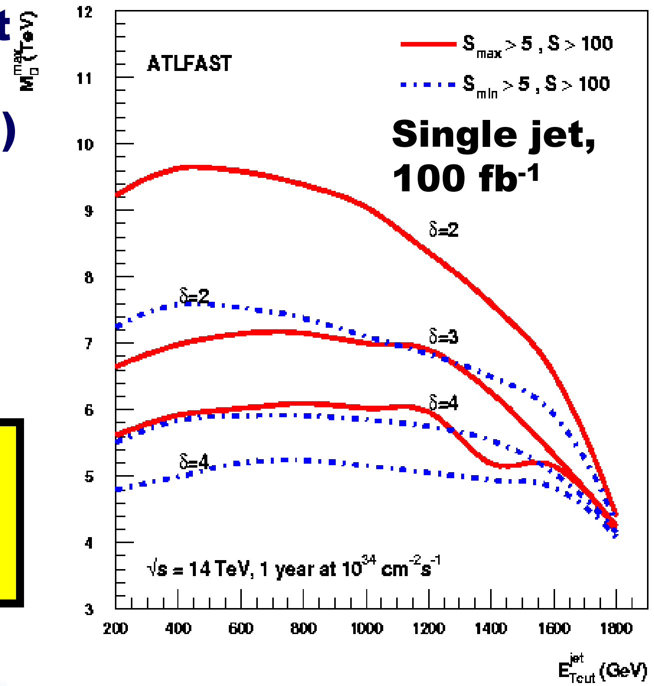


Signal : Graviton + 1 jet
Main background :
jet + Z(W) ($Z \rightarrow \nu\nu$, $W \rightarrow l\nu$)



M_D^{max} (100 fb^{-1}) = 9.1, 7.0, 6.0 TeV for δ=2,3,4

Hinchliffe and Vacavant, 2000



TeV^{-1} Scale ED

Azuelos and Polesello, 2001

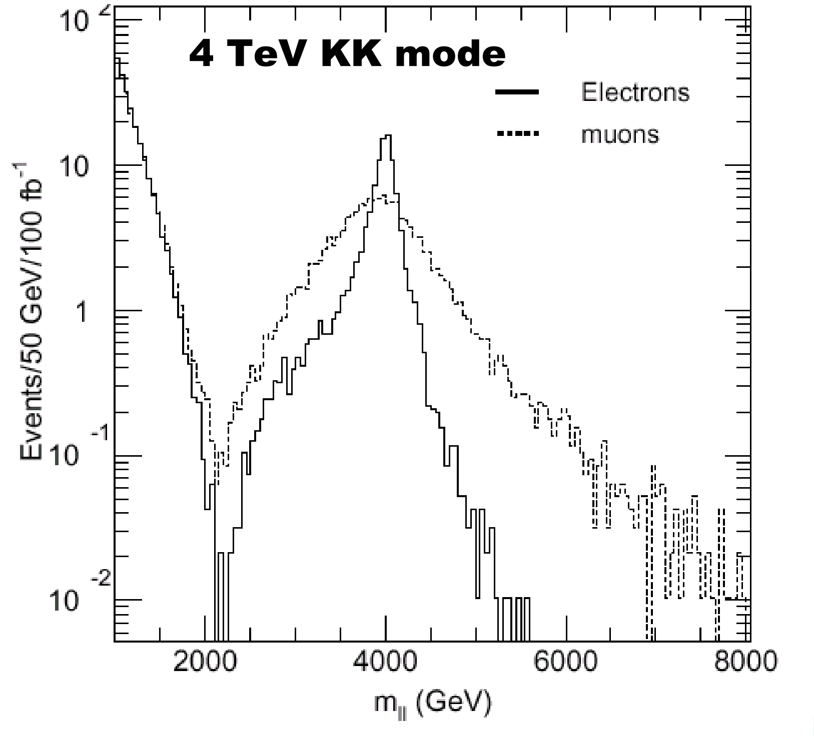
ATLAS

- Usual 4D + Small (TeV^{-1}) EDs + Large EDs (>>TeV^{-1})
- SM Fermions on 3-brane, SM gauge bosons on 4D+Small EDs, gravitons everywhere.
- 4D Kaluza-Klein excitations of SM gauge bosons (here assume 1 small ED)
- Masses of KK modes given by:

  $$M_n^2 = (nM_c)^2 + M_0^2$$

  for compactification scale M_c
- Look for e^+e^-, $\mu^+\mu^-$ decays of γ and Z KK modes.

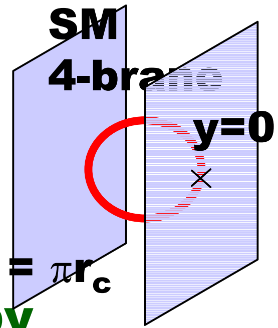
For 100 fb^{-1} m_{ll} peak detected if M_c < 5.8 TeV
For 300 fb^{-1} peak detected if M_c < 13.5 TeV (95% CL)



Warped Extra Dimensions

Randall and Sundrum, PRL 83 (1999) 3370; Giudice,Rattazzi and Wells, hep-ph/002178; Goldberger and Wise,PLB 475(2000)275

- Generates EW scale from Planck scale via warping of one small ED (rather than flat large ED as in ADD scenario).
- Universe → two 4D surfaces bound warped 5D bulk.
- SM fields live on TeV scale ($y=\pi r_c$) brane, gravity lives everywhere



$$ds^2 = e^{-2kr_c|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

(1/k curvature radius, k ~ M_{Pl}, r_c volume radius)

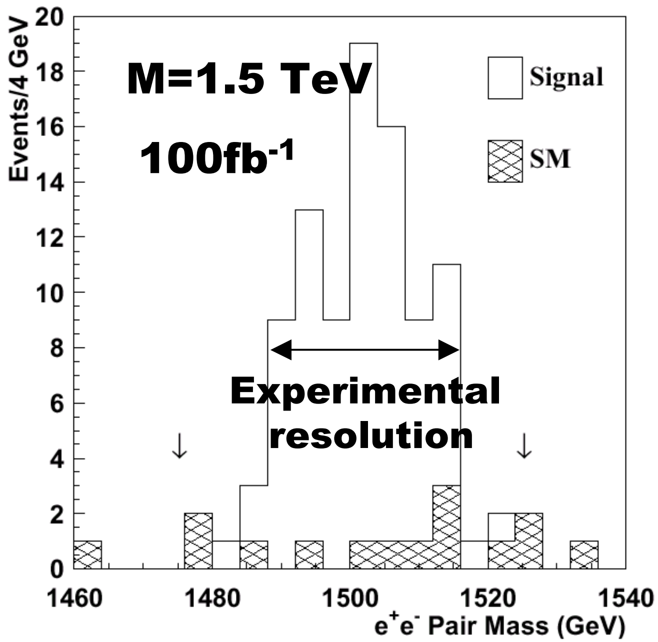
- Leads to two excitations: graviscalar radion and graviton
- Stabilise ED → Radion acquires mass $m=m_0e^{-kr\pi}$ governed by M_{weak}/M_{Pl} → $kr_c\pi$~35 (Goldberger and Wise).
- Radion ϕ radial excitation of compactified dimension.
- Radion can mix with SM Higgs scalar.

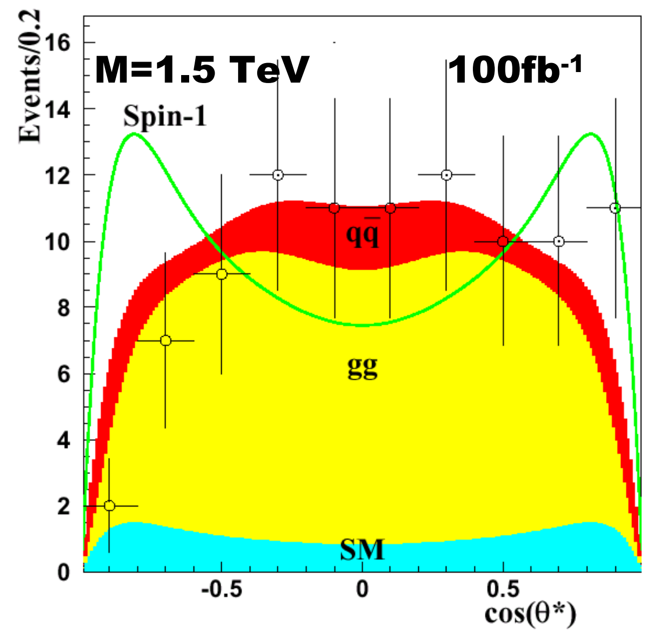
Warped Extra Dimensions

Allanach, Odagiri, Parker and Webber, JHEP 09 (2000) 019 – ATL-PHYS-2000-029

ATLAS

- Search for narrow graviton resonances (KK modes)
- Use gg (qq) → G → e^+e^-





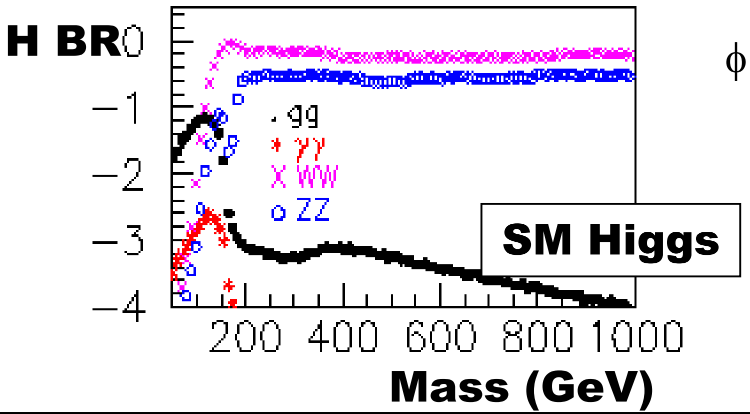
- Signal can be seen for M in the range [0.5, 2.08] TeV for worst case Randall-Sundrum Scenario (k/Λ_π=0.01).
- ATLAS can distinguish spin 2 vs 1 up to 1.72 TeV.

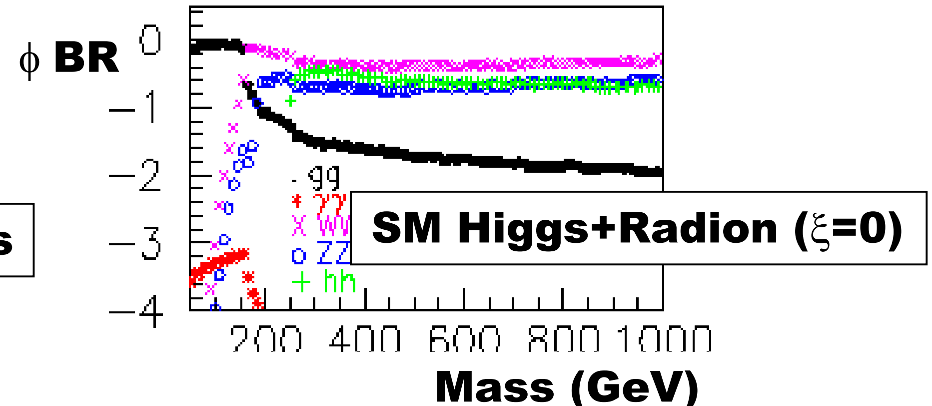
Warped Extra Dimensions

Azuelos, Cavalli, Vacavant and Przysiezniak (Proc. Physics at TeV Scale Colliders, 2001)

ATLAS

- **Described by 3 params: m_ϕ (mass), Λ_ϕ (scale), ξ (ϕ–H mixing)**
- **Study observability of radion as function of Λ_ϕ and m_ϕ**





Assuming 100fb^{-1}, ξ = 0, m_h=125 GeV, Λ_ϕ = 1(10) TeV for $\phi \to ZZ^{(*)} \to 4l$:
$S/\sqrt{B}$~100(1) (200<m_ϕ<600 GeV)

Assuming 30fb^{-1},ξ = 0,m_h=125 GeV for $\phi \to hh \to bb\gamma\gamma$:
Λ_ϕ^{max}=4.6 → 5.7 TeV (m_ϕ= 300 → 600 GeV)

Summary

- Much work on Beyond the Standard Model physics being carried out by both ATLAS and CMS.
- Lots of input from both theorists and experimentalists.
- LHC and detector performance should in general give access to energy scales ~ a few TeV.
- Many studies of methods for measuring SUSY mass spectrum following discovery (edges, combination of edges etc.)
- Discovery/study of a plethora of Extra Dimension models and signatures also looks feasible.
- BUT … we must never forget to

EXPECT THE UNEXPECTED!

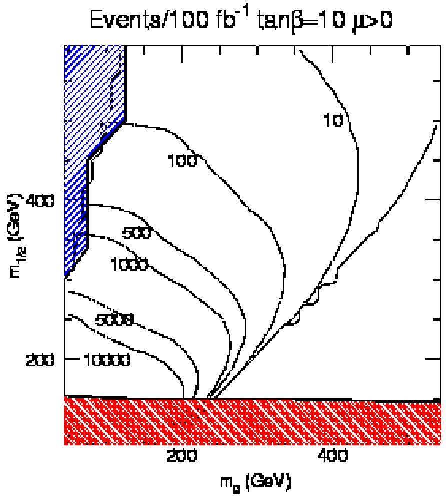
Gaugino Edges

Polesello, 2002

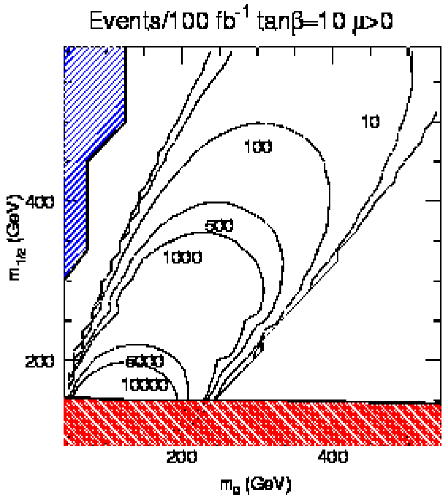
ATLAS

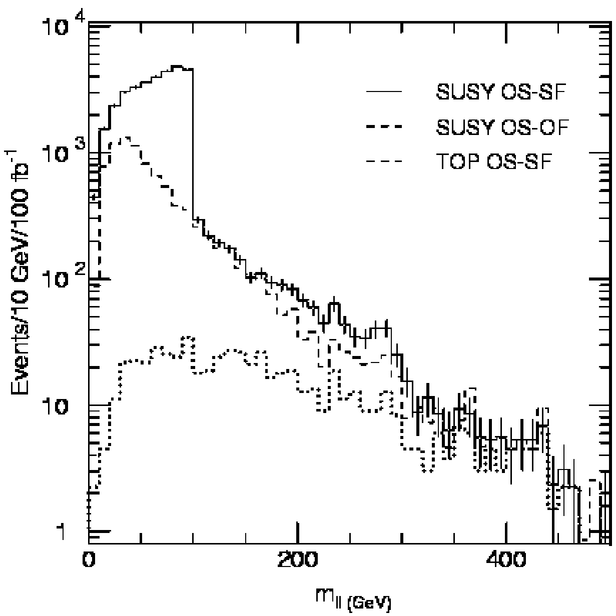
- **Recent work trying to identify dilepton edges from decays of heavy gauginos.**
- **Appears possible, but much harder than NL gauginos due to poor stats.**

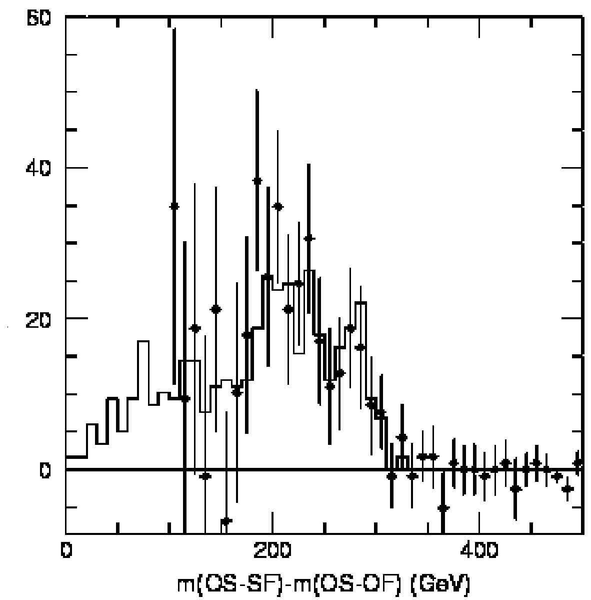
$\tilde{\chi}_4^0$



$\tilde{\chi}_2^\pm$







Large Extra Dimensions

Kabachenko, Miagkov, Zenin (ATL-PHYS-2001-012)

ATLAS

- **Alternatively, search for virtual graviton production in dilepton and diphoton invariant mass spectra.**

- **Superior results obtained with two channels combined.**

M_D^{max} (100 fb^{-1}) = 8.1, 7.9, 7.1, 7.0 TeV for δ=2,3,4,5