Searching for Exotics at Hadron Colliders

Dan Tovey
University of Sheffield

Exotics from the Energy Frontier

- Exotics: Anything not described by the Standard Model
  - Does not include the SM Higgs boson (Beate)
  - Here: does not include non-SM Higgs (Beate)

- Not just ad hoc models
  - Supersymmetry **
  - Extra Dimensions **
  - GUTs
  - Little Higgs, etc.
- Despite success of SM motivation for Exotics is strong …

Why Exotics?

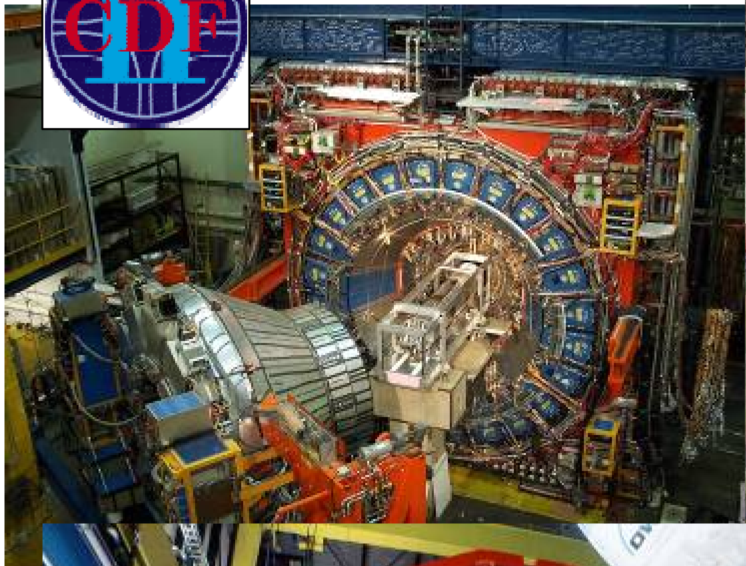
- Gauge hierarchy problem: why is the EW scale so small?
  - In SM, Higgs mass driven to high scale by loop corrections
- Dark matter problem: what is the nature most of the matter in the Universe?
  - WMAP/ BBN: only 15% can be baryonic
- Unification hypothesis: do the forces unify at a high scale?
  - Running couplings suggest unification of Strong, EM and Weak at GUT scale ~10^{16} GeV
  - GUT gauge group broken into SM at one scale?
  - What about gravity?
- Completeness arguments: new symmetry (breaking)
  - New continuous symmetries
  - New fermions
  - New gauge groups
  - Symmetry breaking (e.g. baryon/lepton number, CP-violation etc.)
- Ascetics: Nature abhors a vacuum ➔ physics abhors a 'desert'

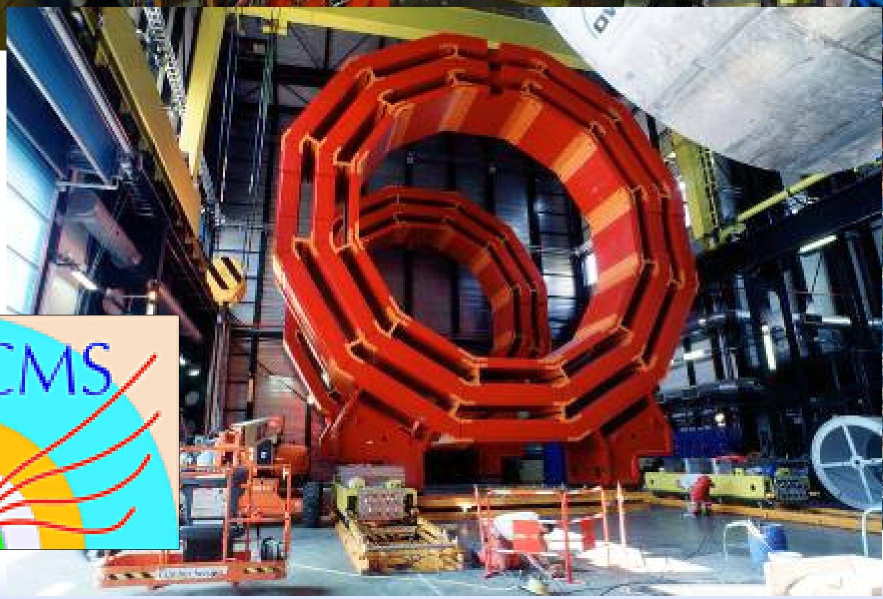
Plotting a Course

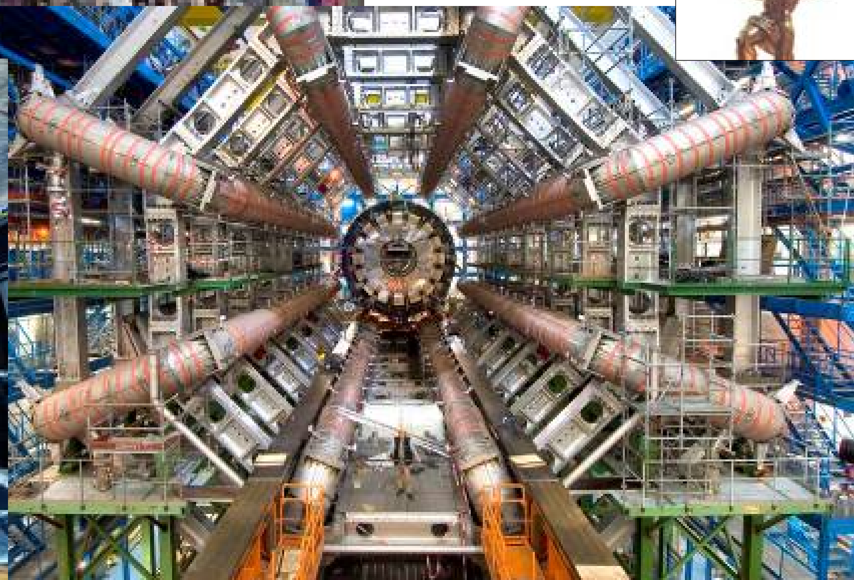
- **If exotics were easy to find they would not be exotic …**
  - Standard Model was once exotic
  - Now closer to home (LEP, SLD, B-factories, Tevatron, etc, etc, etc)

- **Exotics must have:**
  1. High mass scale and/or
  2. Small/exotic couplings to SM
- **Two complementary strategies**
  1. High energies ➔ Tevatron, LHC, (LC)
  2. Large statistics ➔ Large lumi, rare decays, precision tests of SM
- **Some overlap through Uncertainty Principle (e.g. proton decay)**

Transport to the Frontier





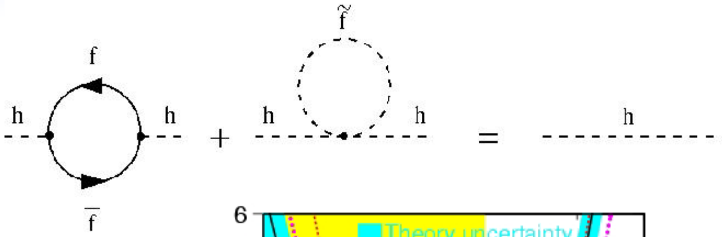


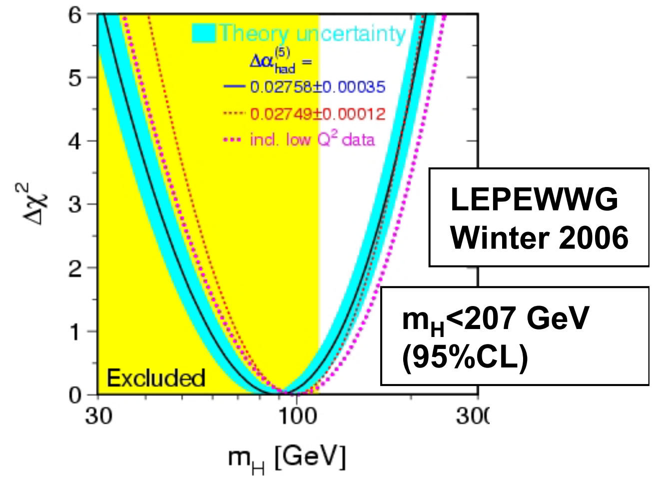
Supersymmetry

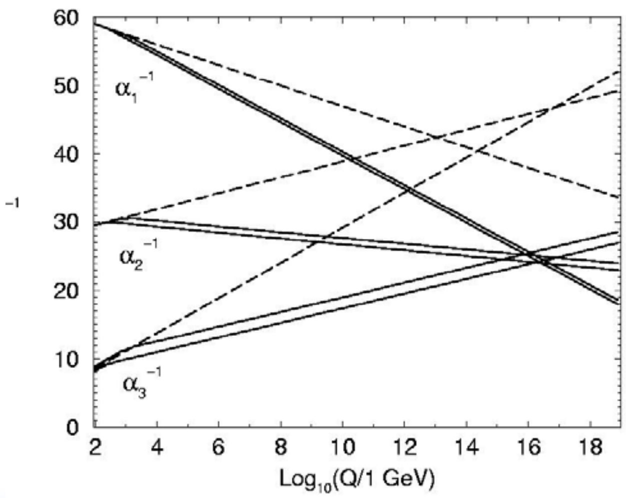
- Supersymmetry (SUSY) fundamental continuous symmetry connecting fermions and bosons

$$Q_\alpha|F\rangle = |B\rangle, \qquad Q_\alpha|B\rangle = |F\rangle$$

- $\{Q_\alpha, Q_\beta\} = -2\gamma^\mu_{\alpha\beta} p_\mu$: generators obey anti-commutation relations with 4-mom
  - Connection to space-time symmetry
- SUSY stabilises Higgs mass against loop corrections (gauge hierarchy/fine-tuning problem)
  - Leads to Higgs mass ≤ 135 GeV
  - Good agreement with LEP constraints from EW global fits
- SUSY modifies running of SM gauge couplings 'just enough' to give Grand Unification at single scale.



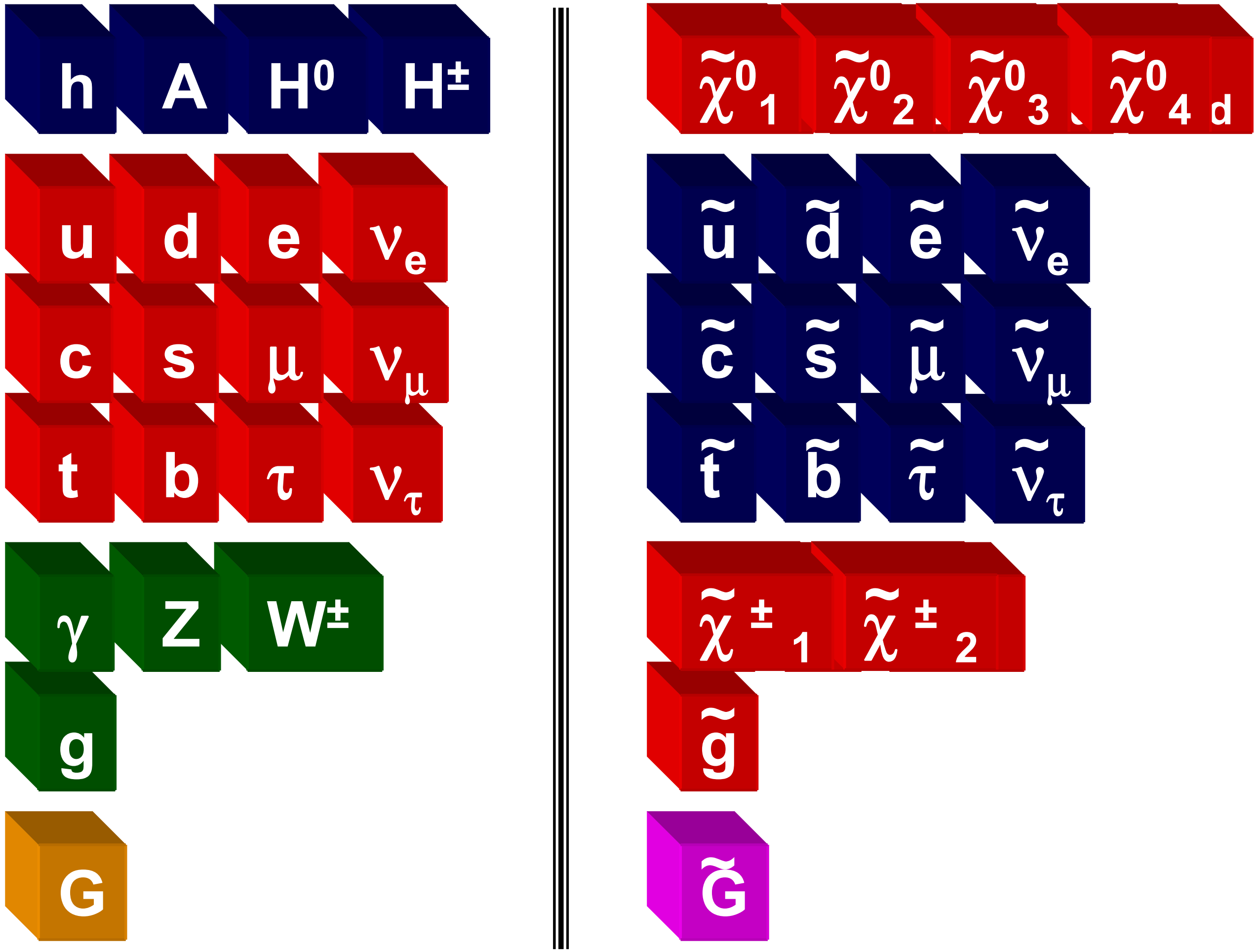




SUSY Spectrum

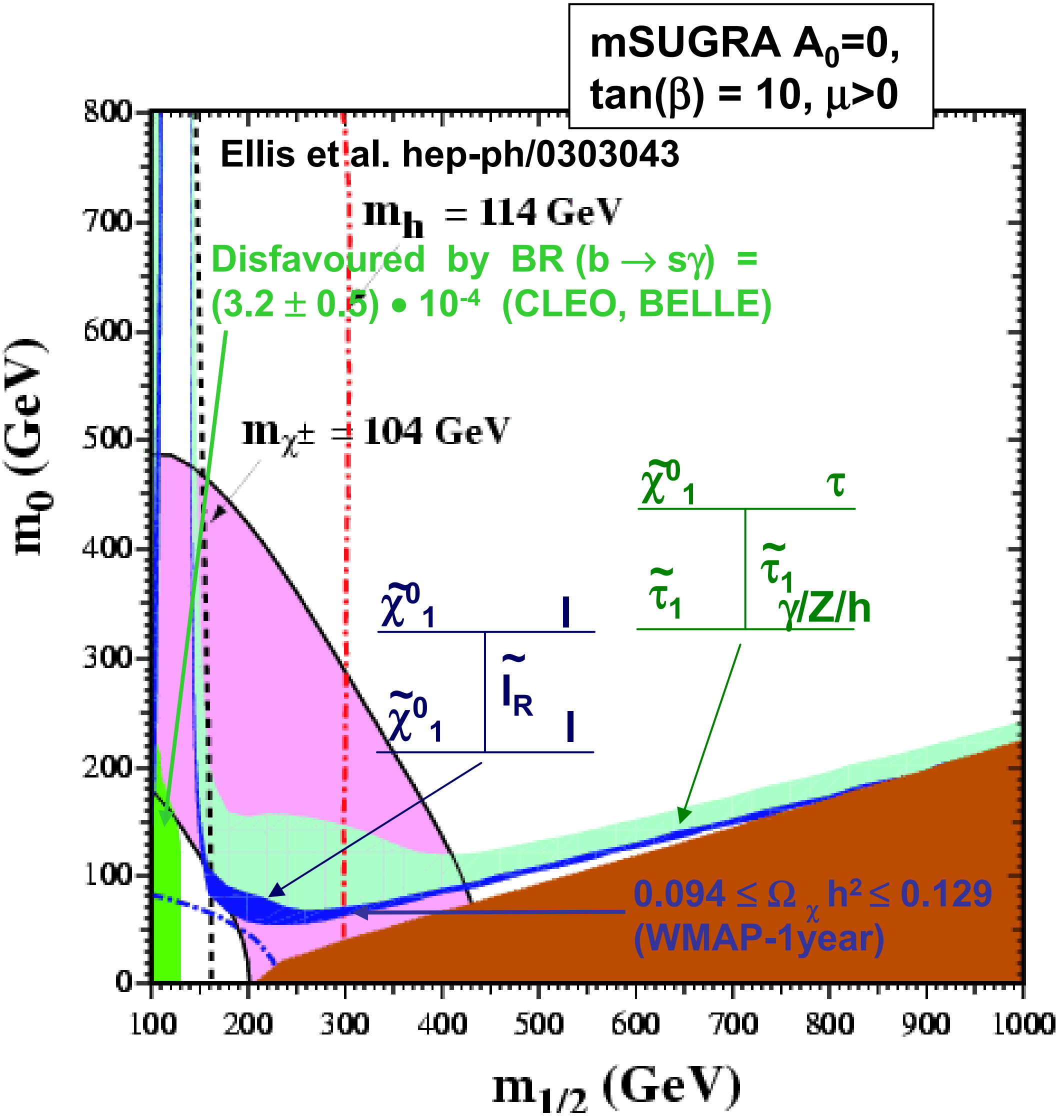
- SUSY gives rise to partners of SM states with opposite spin-statistics but otherwise same Quantum Numbers.

- Expect SUSY partners to have same masses as SM states
  - Not observed (despite best efforts!)
  - SUSY must be a broken symmetry at low energy
- Higgs sector also expanded



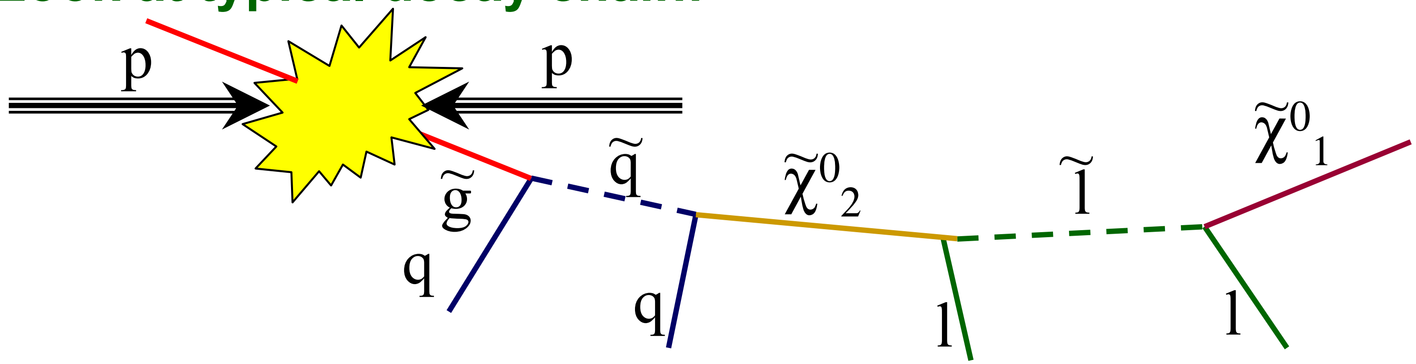
SUSY & Dark Matter

- R-Parity $R_p = (-1)^{3B+2S+L}$
- Conservation of R_p (motivated e.g. by string models) attractive
  - e.g. protects proton from rapid decay via SUSY states
- Causes Lightest SUSY Particle (LSP) to be absolutely stable
- LSP neutral/weakly interacting to escape astroparticle bounds on anomalous heavy elements.
- Naturally provides solution to dark matter problem
- R-Parity violating models still possible ➔ not covered here.



SUSY Signatures

- Q: What do we expect SUSY events @ hadron colliders to look like?
- A: Look at typical decay chain:

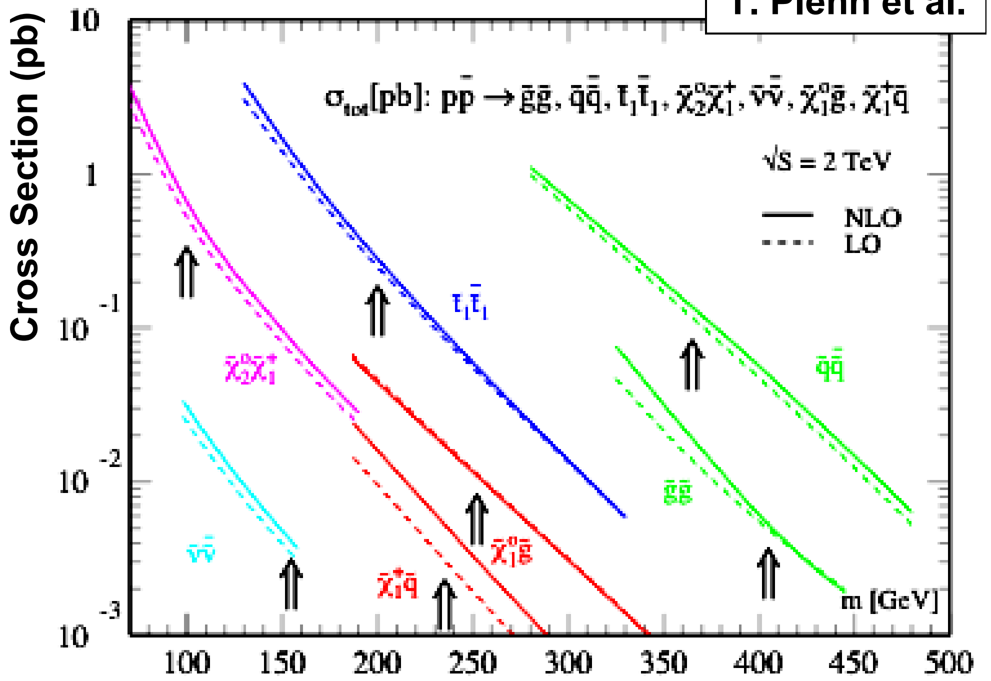


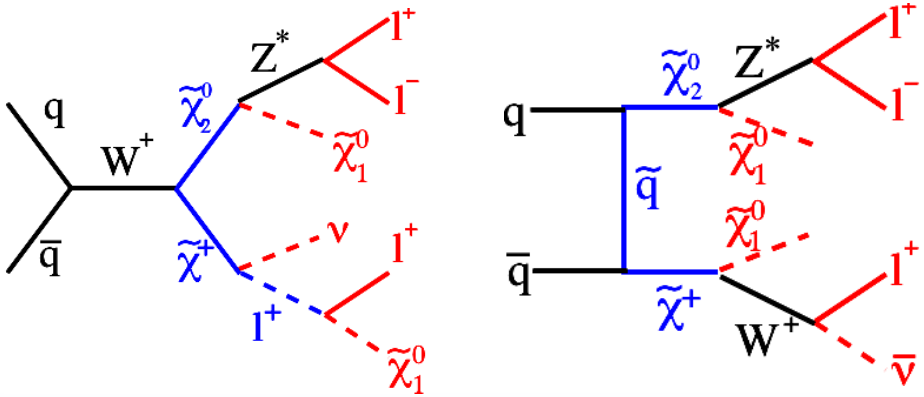
- Strongly interacting sparticles (squarks, gluinos) dominate production.
- Heavier than sleptons, gauginos etc. → cascade decays to LSP.
- Potentially long decay chains and large mass differences
  - Many high p_T objects observed (leptons, jets, b-jets).
- If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced.
  - Large E_T^{miss} signature (c.f. $W \rightarrow l\nu$).
- Closest equivalent SM signature $t \rightarrow Wb$.

SUSY @ Tevatron

- SUSY searches key goal of Tevatron experiments
- Hadron collider ➔ large cross-section for producing strongly interacting sparticles
  - Jets + E_T^{miss} searches
- But small kinematic reach:
  - Limited p_T separation from SM hadronic backgrounds
  - Short decay chains give limited signal multiplicity (jets, leptons)
- Alternative: lower backgrounds
  - Trilepton searches (gaugino production)
- Alternative: rare decays
  - $B_s \rightarrow \mu\mu$

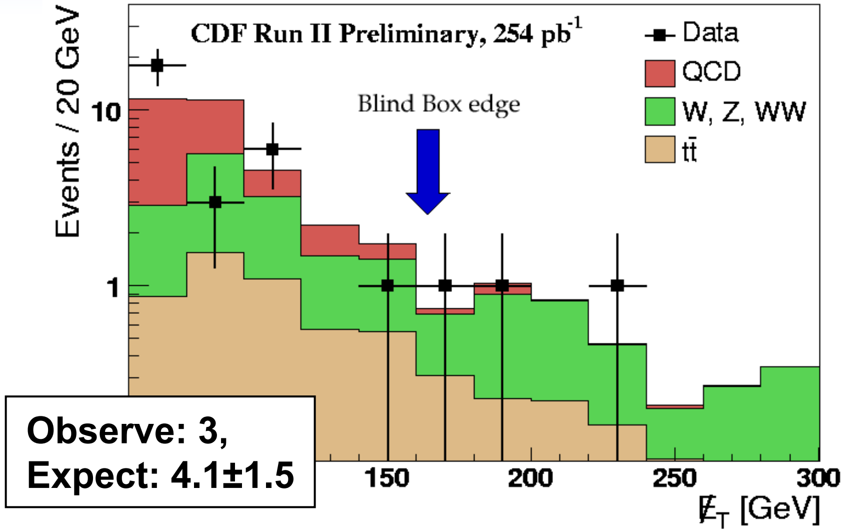
T. Plehn et al.

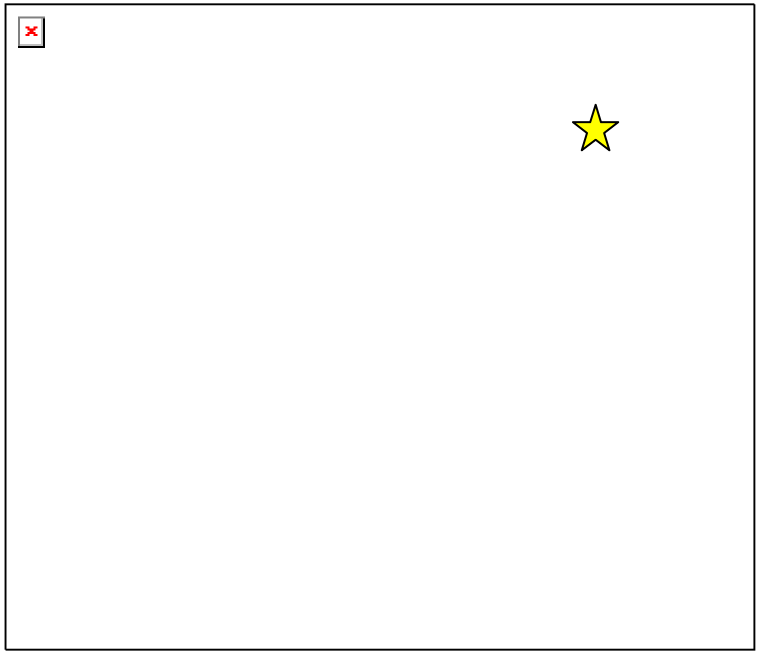




Run II: Jets + E_T^{miss}

- **E.g. CDF Selection:**
  - 3 jets with E_T>125 GeV, 75 GeV and 25 GeV
  - Missing E_T>165 GeV
  - $H_T=\sum$ jet E_T > 350 GeV
  - Missing E_T not along a jet direction:
    - Avoid jet mismeasurements

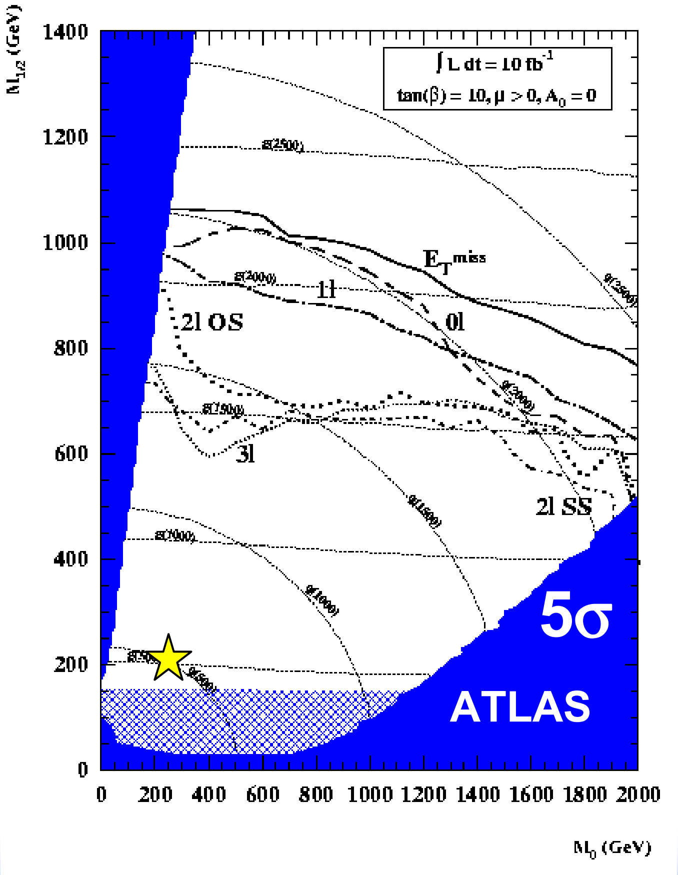


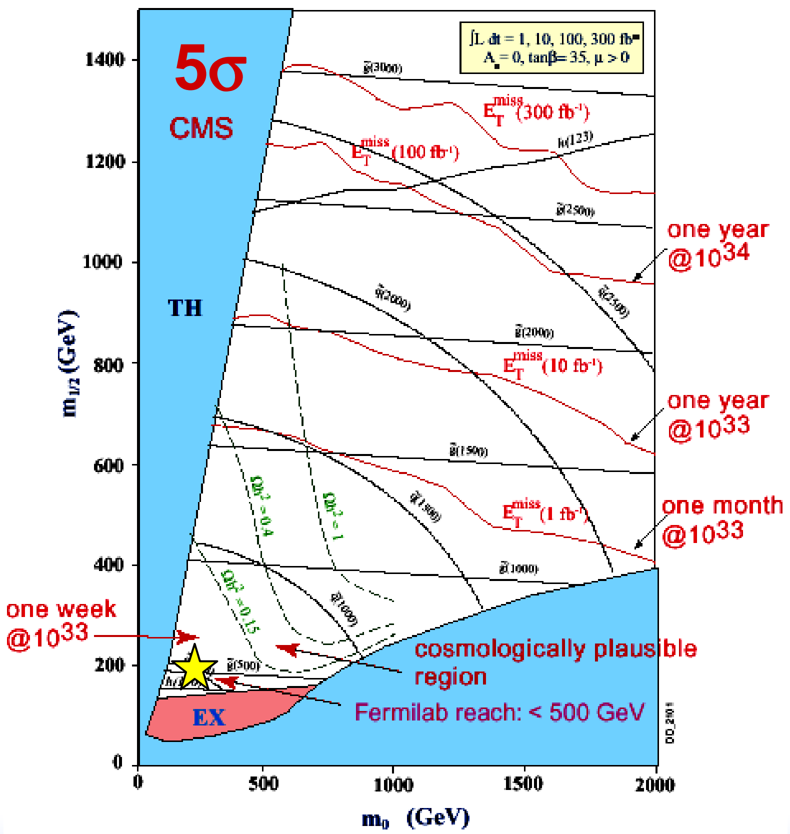


- **Background:**
  - W/Z+jets with W→lν or Z→νν
  - Top
  - QCD multijets
    - Mismeasured jet energies lead to missing E_T
- **No excess observed**
  - Exclude regions of squark / gluino mass plane (mSUGRA projection)

LHC: Jets + E_T^{miss}

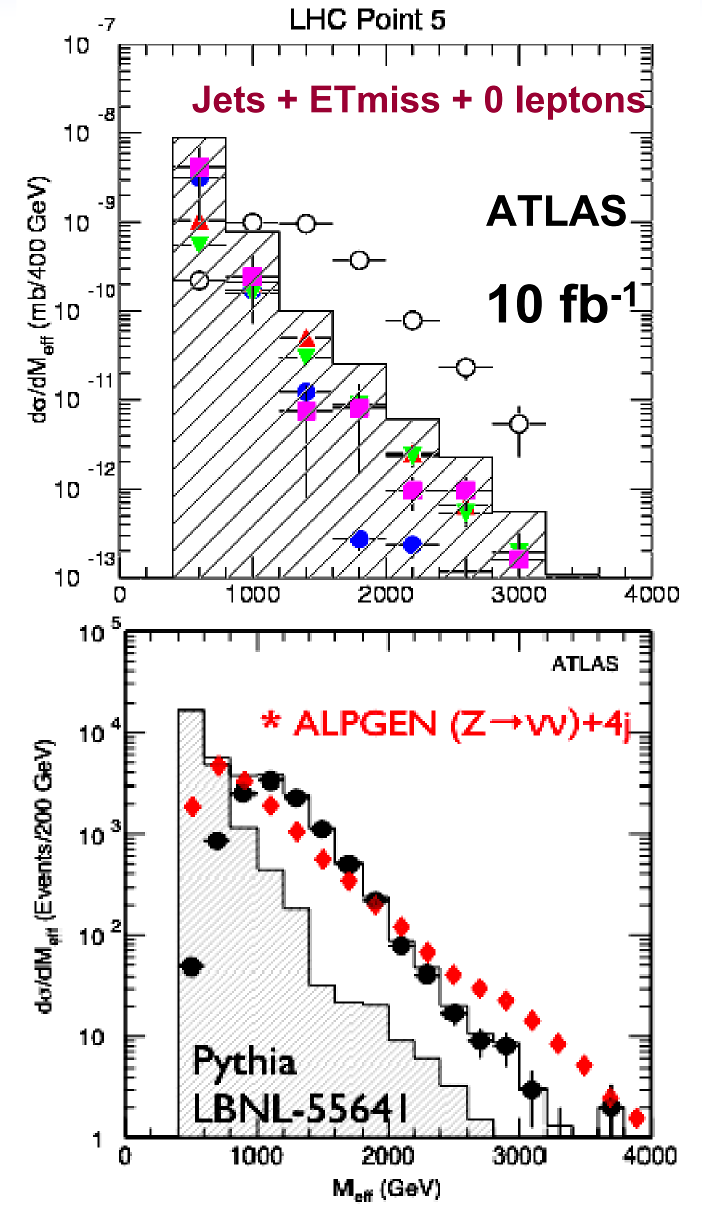
- Inclusive searches with Jets + n leptons + E_T^{miss} channel.
- Map <u>statistical</u> discovery reach in mSUGRA m_0-$m_{1/2}$ parameter space.
- Sensitivity only weakly dependent on A_0, tan(β) and sign(μ).
- Syst.+ stat. reach harder to assess: focus of current & future work.





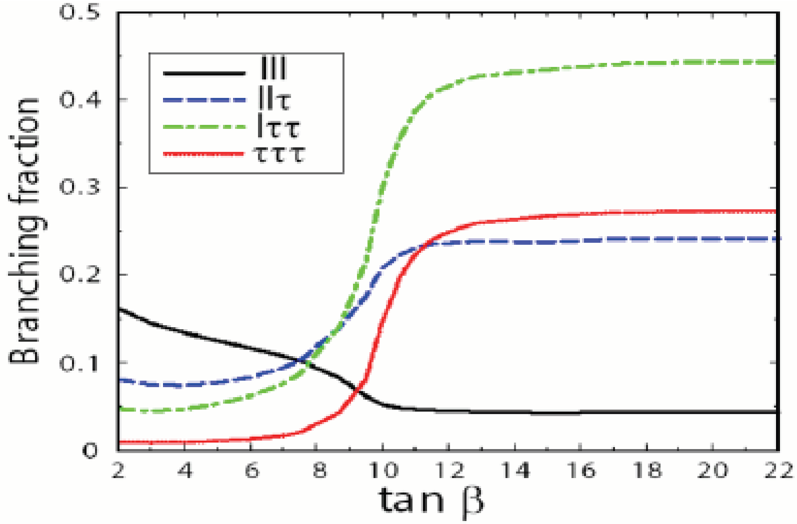
LHC: Jets + E_T^{miss}

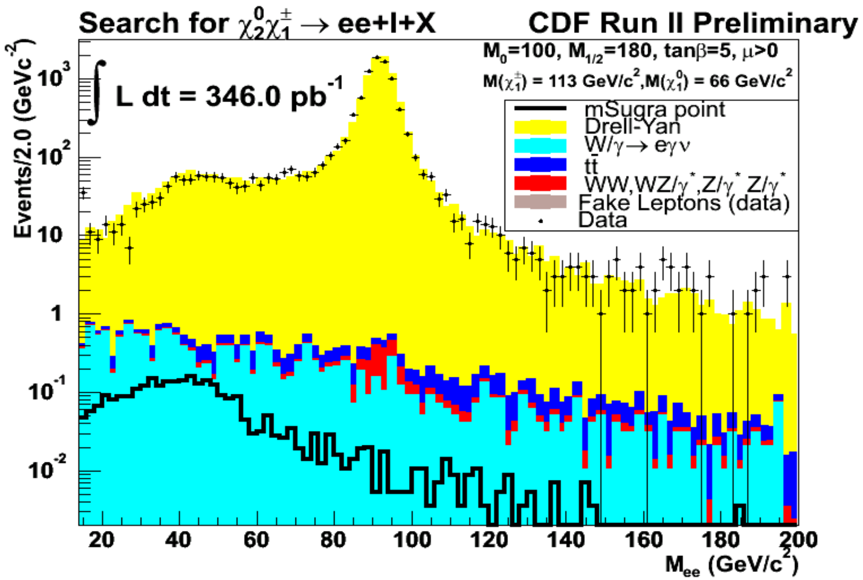
- **First SUSY parameter to be measured may be mass scale:**
  - **Cross-section weighted mean of masses of initial sparticles.**
- **Calculate distribution of 'effective mass' variable defined as scalar sum of jet p_T and E_T^{miss}.**
- **Distribution peaked at ~ twice SUSY mass scale for signal events.**
- **Pseudo 'model-independent' measurement.**
- **Typical measurement error (syst+stat) ~10% for mSUGRA models for 10 fb^{-1} using parton-shower MC.**
- **Errors much greater with matrix element calculation ➔ an important lesson …**



Run II: Trileptons

- **Alternative approach at Tevatron: reduce hadronic background with multi-lepton requirement**
- **Sensitive to gaugino (chargino/neutralino) production**
- **Analyses depend on SUSY model:**
  - **Low tanβ:**
    - **2e+e/μ**
    - **2μ+e/μ**
  - **High tanβ (BR(τ) enhanced):**
    - **2e+isolated track (1-prong τ)**
- **Other requirements (typical):**
  - **Large E_T^{miss}**
  - **m_{ll}>15 GeV, $m_{ll} \neq m_Z$**
  - **Njet < 2**
- **Also under study for LHC (large m_0 / Focus Point scenarii)**

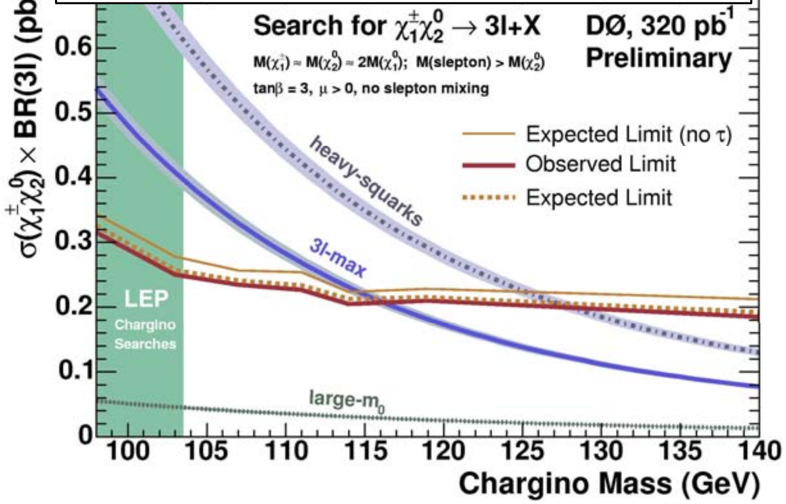


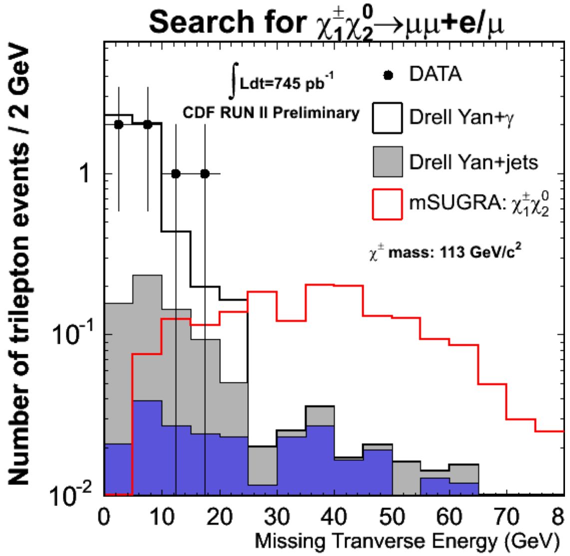


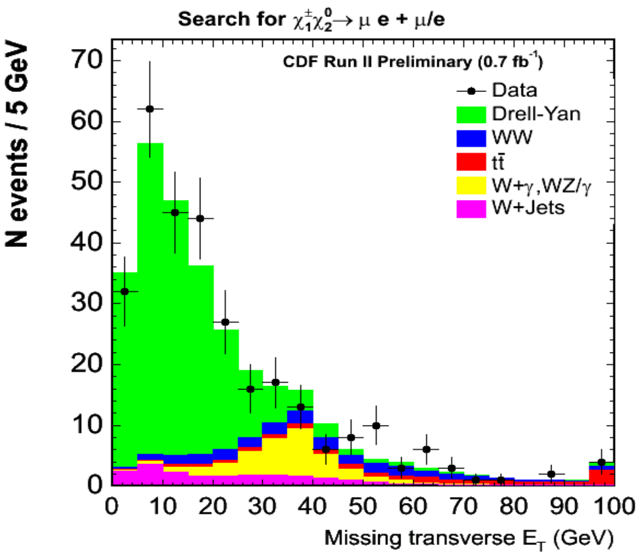
Run II: Trileptons

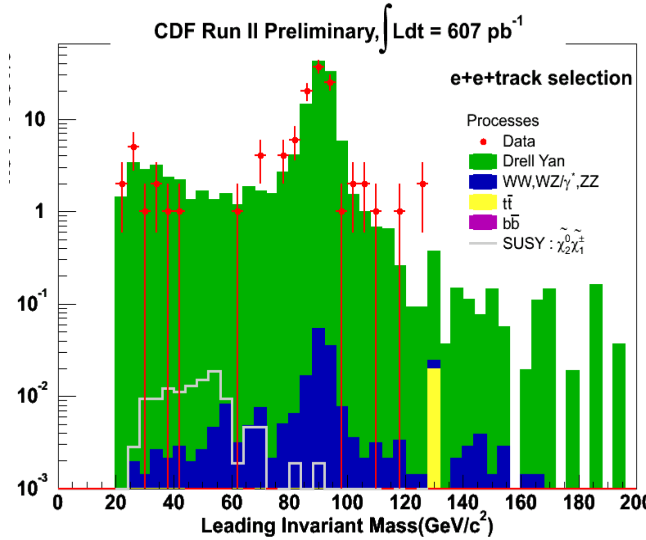
CDF Channel	Example signal	SM expected	Obs
μμ/e +l (0.7fb^{-1})	2.3±0.3	1.2±0.2	1
ee+l (350pb^{-1})	0.5±0.06	0.2±0.05	0
μμ+l (low pt) (320pb^{-1})	0.2±0.03	0.1±0.03	0
ee+trk (600pb^{-1})	0.7±0.03	0.5±0.1	1

DØ: 6 channels, 3.85±0.75 exp, 4 obs







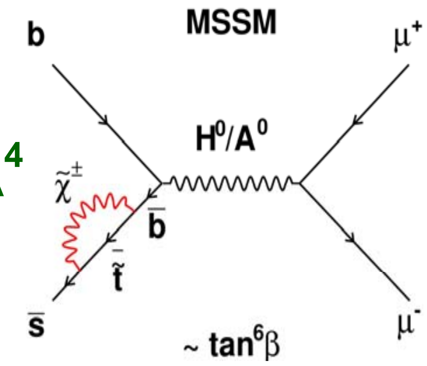


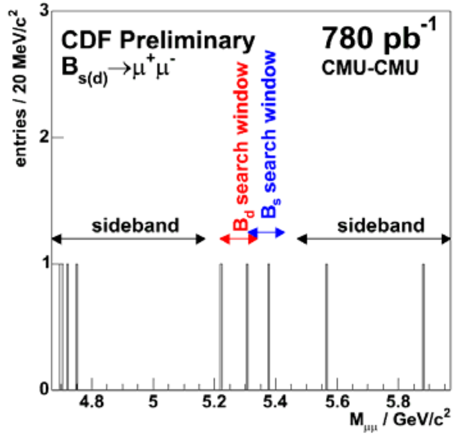
Run II: $B_s \rightarrow \mu\mu$

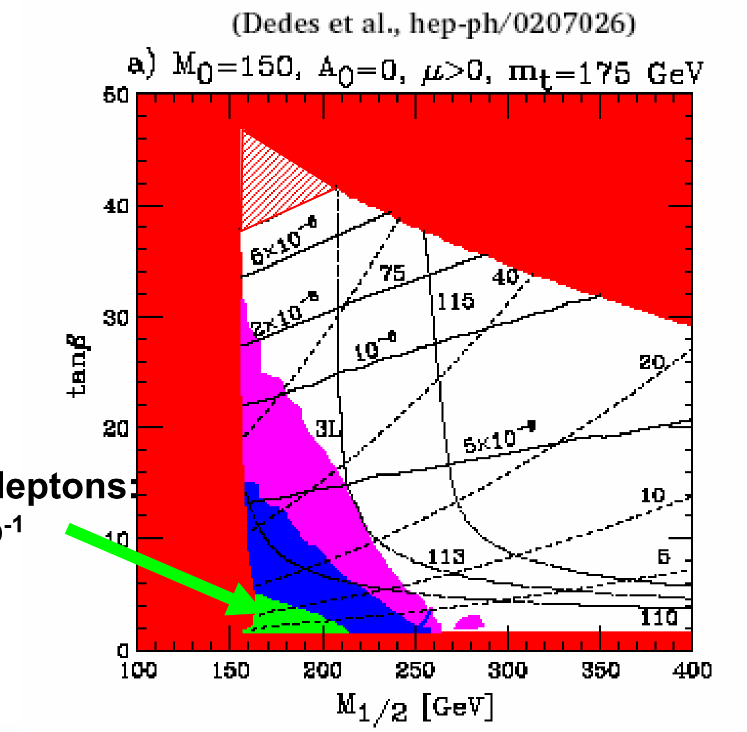
- **SM BR heavily suppressed:**

  $$BR(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

- **SUSY enhancements ~ $\tan^6(\beta)/m_A^4$**
- **Preselection (CDF):**
  - **Two muons with p_T>1.5 GeV/c**
  - **Displaced dimuon vertex**





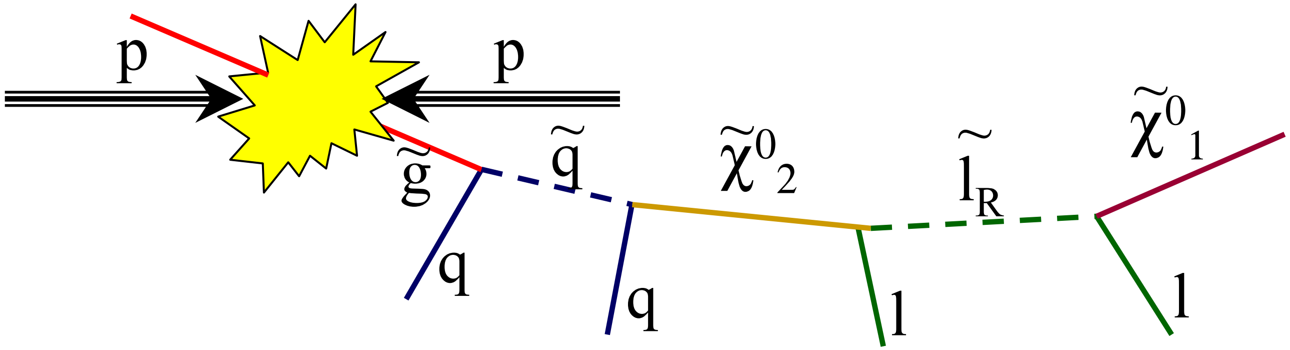


Trileptons: 2fb^{-1}

- **Complementary to trilepton searches**
- **Search for excess in B_s (also B_d) mass window**
- **Sideband based background estimate normalised to data $B^+ \to \mu^-\mu^+ K^+$**
  - **1(0) CMU(CMX) events observed,**
  - **0.88± 0.30(0.39 ± 0.21) CMU(CMX) exp.**
- **Combined Limit:**
  - **$BR(B_s \to \mu\mu) < 1.0 \times 10^{-7}$ at 95%C.L.**
- **Future Run II limit ~2×10^{-8} (8 fb^{-1})**

LHC: Exclusive Studies

- Prospects for kinematic measurements at LHC: measure weak scale SUSY parameters (masses etc.) using exclusive channels.
- Different philosophy to TeV Run II (better S/B, longer decay chains) → aim to use model-independent measures.



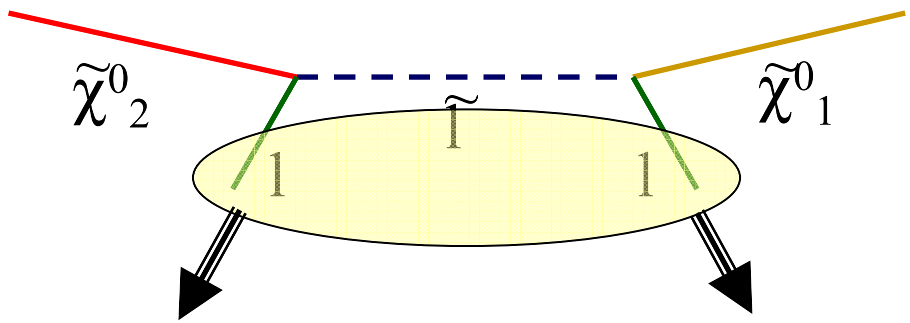
- Two neutral LSPs escape from each event
  - Impossible to measure mass of each sparticle using one channel alone
- Use kinematic end-points to measure combinations of masses.
- Old technique used many times before (ν mass from β decay spectrum, W (transverse) mass in W→lν).
- Difference here is we don't know mass of neutral final state particles.

LHC: Dilepton Edge

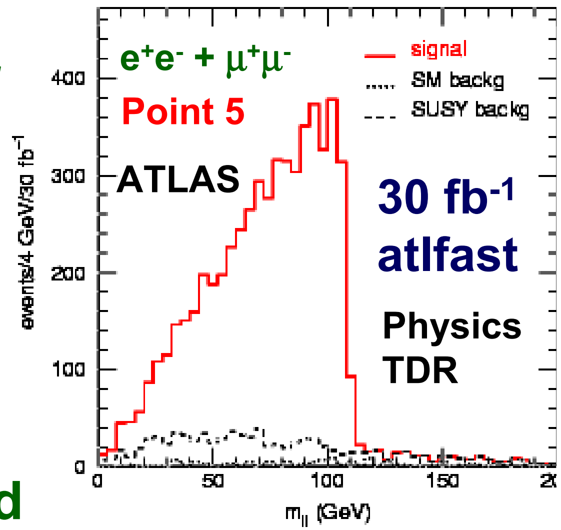
- When kinematically accessible $\tilde{\chi}^0_2$ can undergo sequential two-body decay to $\tilde{\chi}^0_1$ via a right-slepton (e.g. LHC Point 5).
- Results in sharp OS SF dilepton invariant mass edge sensitive to combination of masses of sparticles.
- Can perform SM & SUSY background subtraction using OF distribution

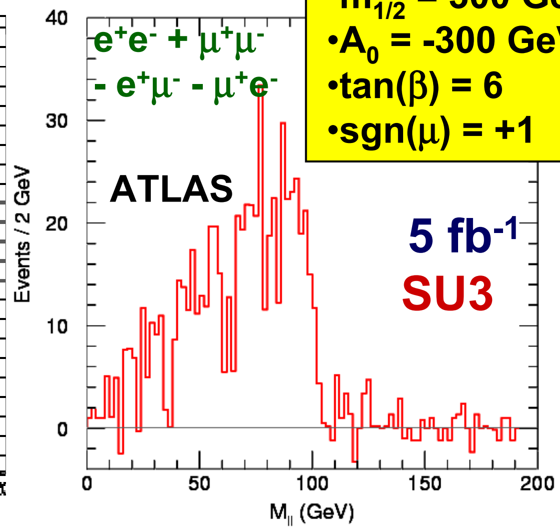
  $e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$

- Position of edge measured with precision ~ 0.5% (30 fb^{-1}).



- m_0 = 100 GeV
- $m_{1/2}$ = 300 GeV
- A_0 = -300 GeV
- tan(β) = 6
- sgn(μ) = +1

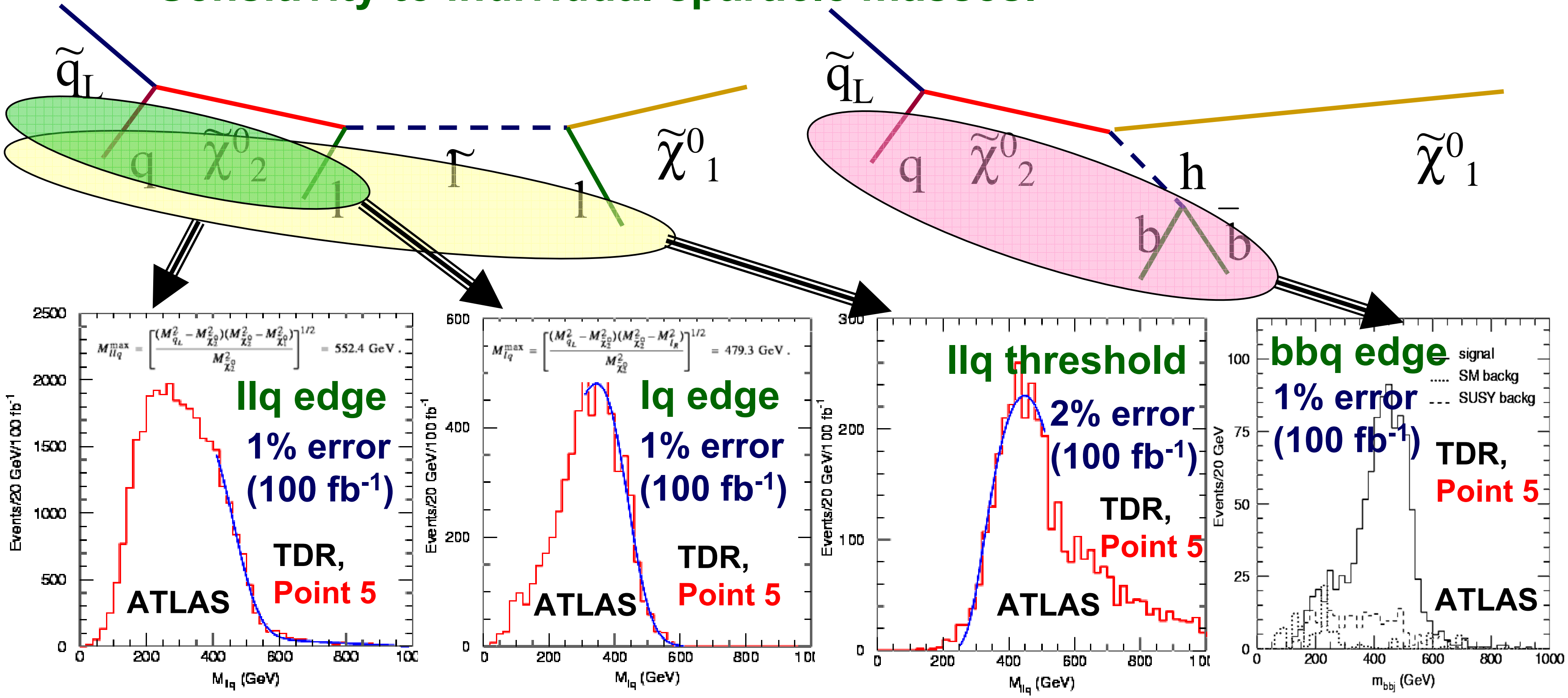




$$M_{ll}^{max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}} = 108.93 \text{ GeV}$$

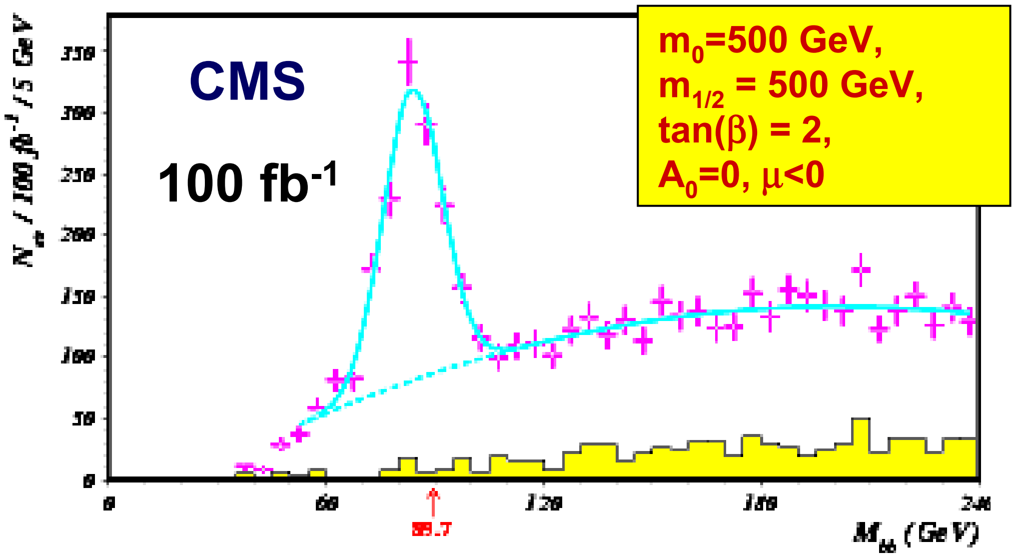
LHC: Endpoint Measurements

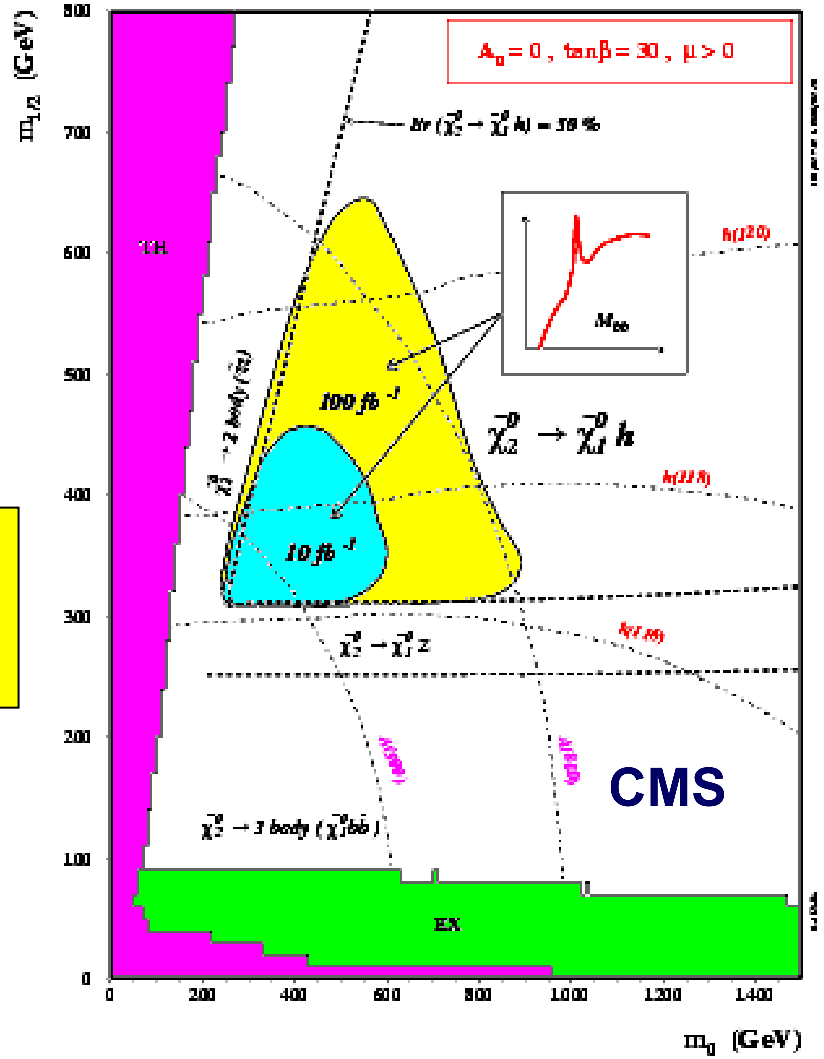
- Dilepton edge starting point for reconstruction of decay chain.
- Make invariant mass combinations of leptons and jets.
- Gives multiple constraints on combinations of four masses.
- Sensitivity to individual sparticle masses.



LHC: Higgs Signatures

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



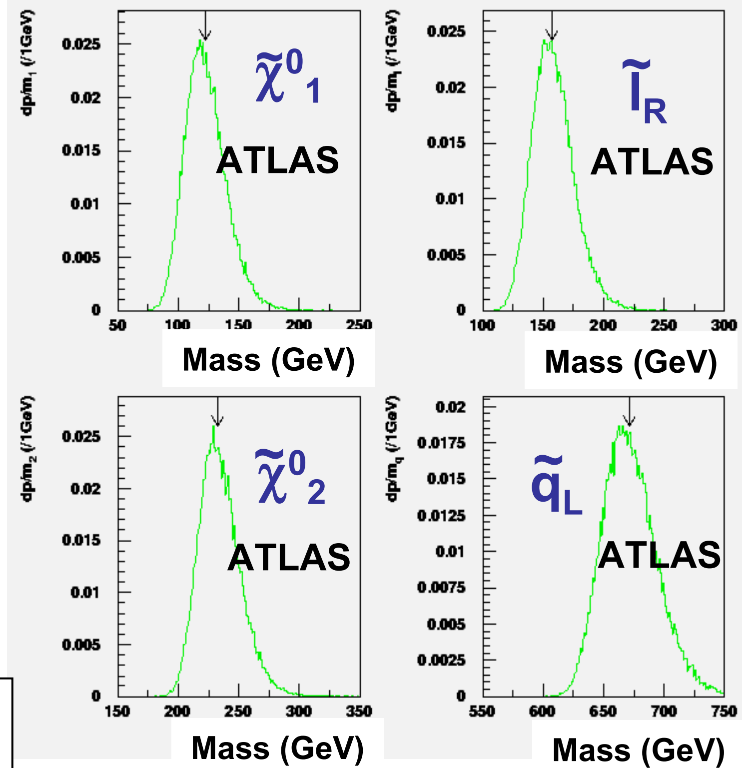


LHC: Sparticle Masses

- **Combine measurements from edges from different jet/lepton combinations to obtain 'model-independent' mass measurements.**

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	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})}{\tilde{\xi}}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\tilde{\chi})}{\tilde{l}}, \frac{(\tilde{q}\tilde{l}-\tilde{\xi}\tilde{\chi})(\tilde{\xi}-\tilde{l})}{\tilde{\xi}\tilde{l}}\right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\tilde{\chi} < \tilde{\xi}^2 \text{ and} \\ \tilde{\xi}^2\tilde{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}} - m_{\tilde{\chi}_1^0})^2. \end{cases}$
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	$\Delta M = m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$

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: $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}$, $\tilde{l} = m^2_{\tilde{l}_R}$, $\tilde{\xi} = m^2_{\tilde{\chi}_2^0}$, $\tilde{q} = m^2_{\tilde{q}}$ and X is $m^2_{\tilde{\chi}}$ or $m^2_{\tilde{g}}$ depending on which particle participates in the "branched" decay.



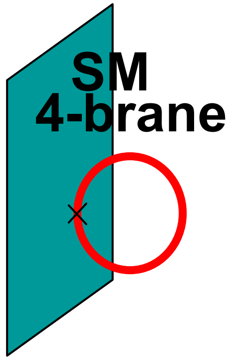
LHCC Point 5

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	± 3%
$\tilde{\chi}^0_2$	± 6%
$\tilde{l}_R$	± 9%
$\tilde{\chi}^0_1$	± 12%

- **Also measurements of spin (Barr)**

Extra Dimensions

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

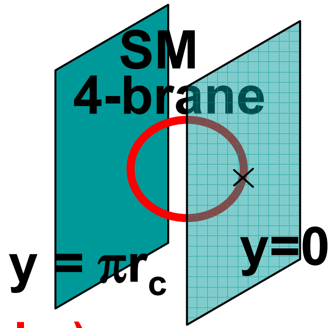


Large (>> TeV^{-1})

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

TeV^{-1}

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



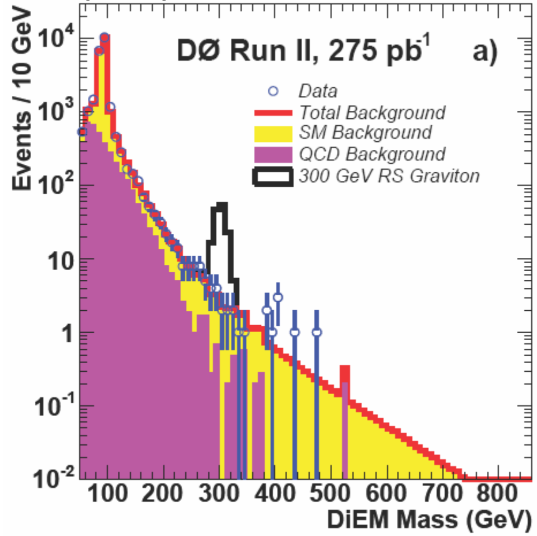
Warped

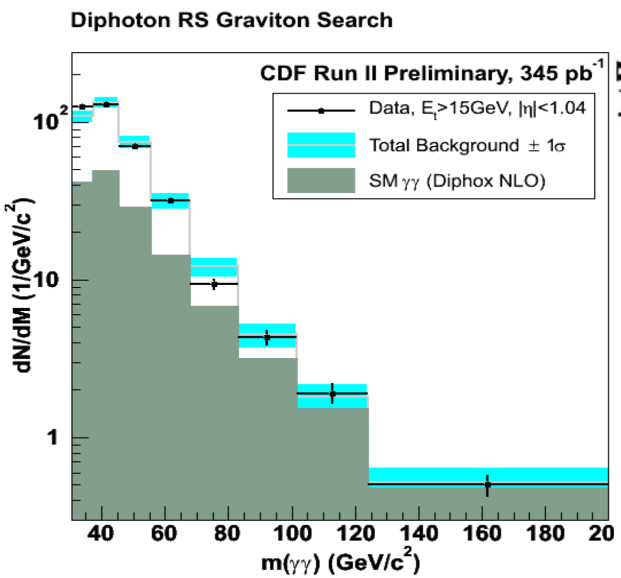
- Warped metric with 1 ED
- $M^{eff}_{Planck} \sim M_{weak}$
- Signature: 4D KK excitations of Graviton (also Radion scalar)

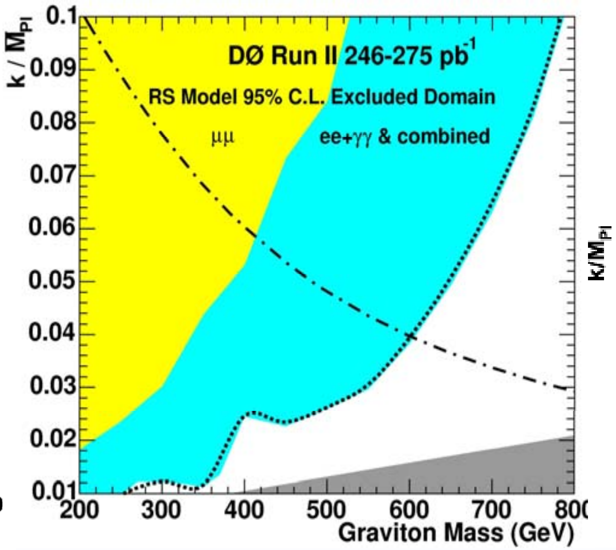
Run II: Warped ED

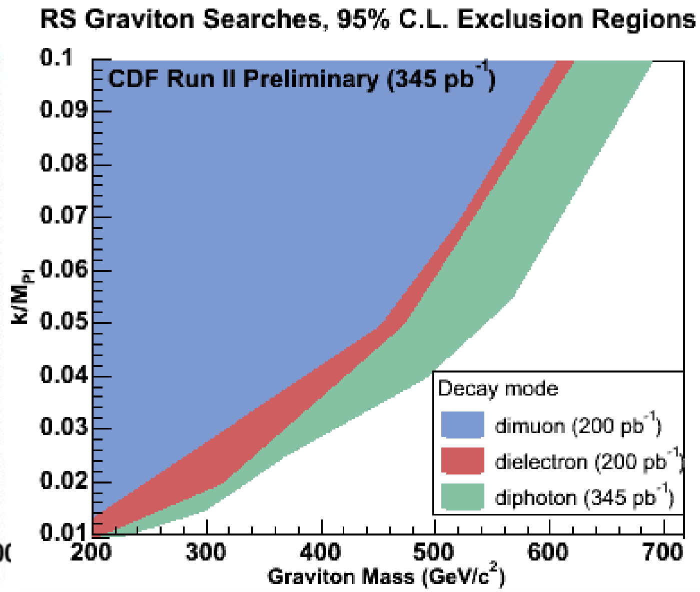
L.Randall and R.Sundrum, Phys.Rev.Lett. 83 (1999) 3370-3373; Phys.Rev.Lett.83 (1999) 4690-4693

- Concentrate on graviton decaying to two electrons or two photons
- Backgrounds:
  - Drell-Yan ee, direct $\gamma\gamma$ production
  - Jets: fake e, $\pi^0 \rightarrow \gamma\gamma$,
- Data consistent with background
- Limits on coupling (k/M_{Pl}) vs m(1st KK- mode)





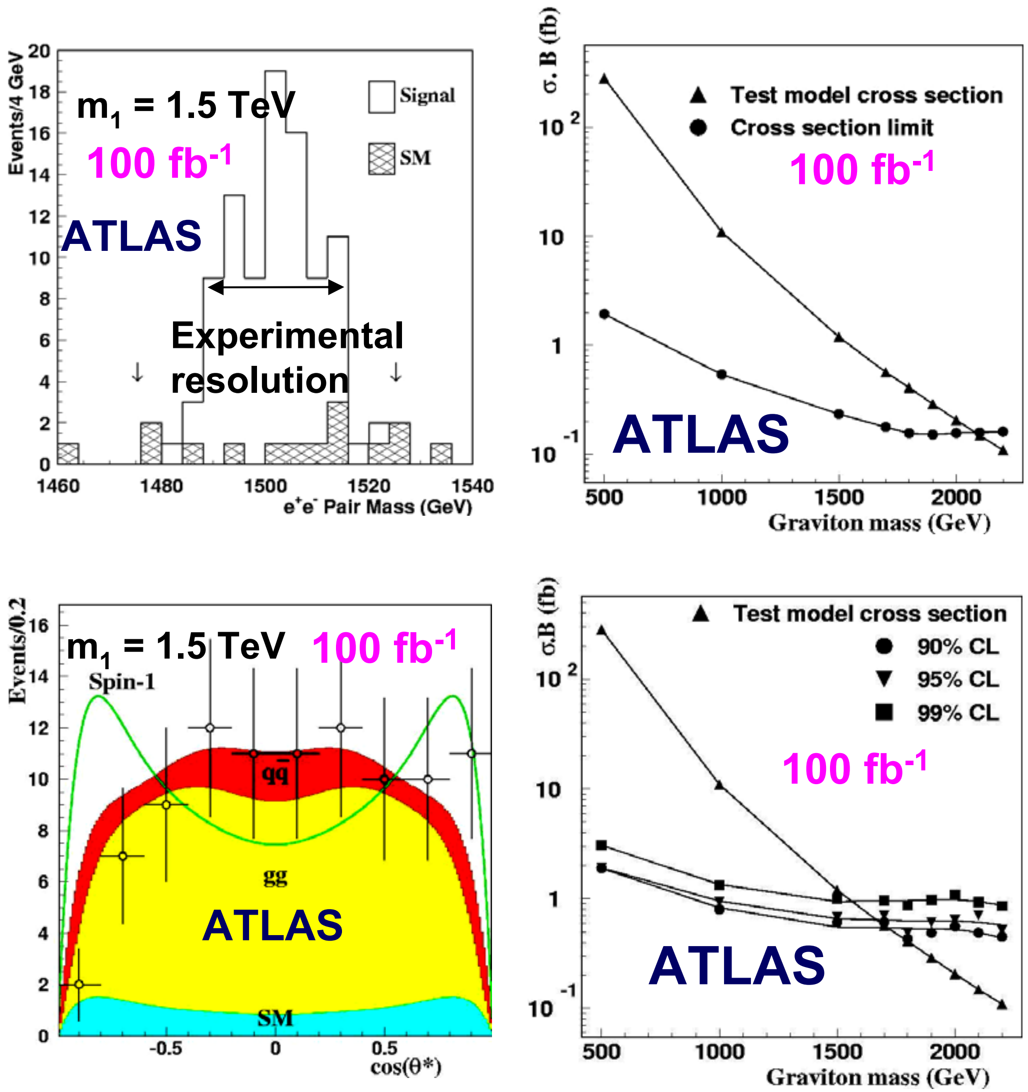




LHC: Warped ED

L.Randall and R.Sundrum, Phys.Rev.Lett. 83 (1999) 3370-3373; Phys.Rev.Lett.83 (1999) 4690-4693

- Search for gg(qq) → $G^{(1)}$ → e^+e^-. ATLAS study using test model with k/M_{Pl}=0.01 (narrow resonance).
- Signal seen for mass in range [0.5,2.08] TeV for k/M_{Pl}=0.01.
- Measure spin (distinguish from Z') using polar angle distribution of e^+e^-.
- Measure shape with likelihood technique.
- Can distinguish spin 2 vs. spin 1 at 90% CL for mass up to 1.72 TeV.



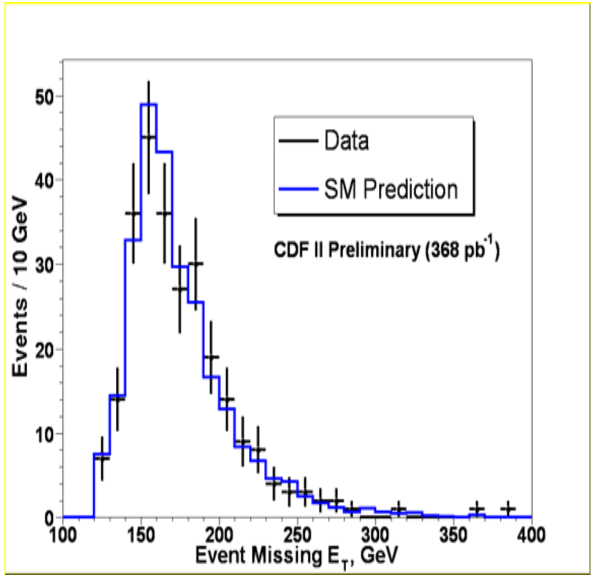
Run II: Large ED

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

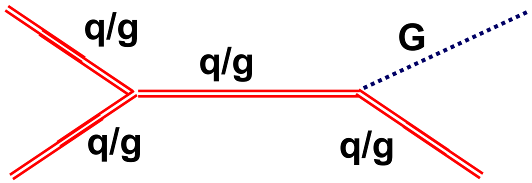
- With δ EDs of size R, observed Newton constant related to fundamental scale of gravity M_D:

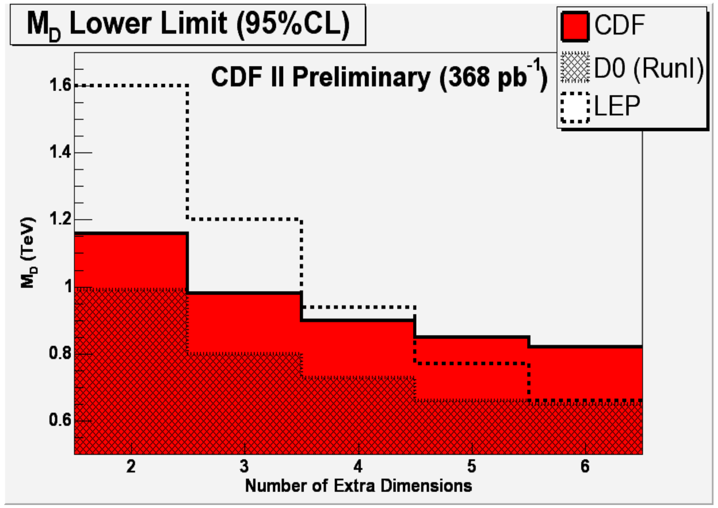
$$G_N^{-1} = 8\pi R^\delta M_D^{2+\delta}$$

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



Signal : graviton + 1 jet production
Main background: Jet + Z(W) [$Z \rightarrow \nu\nu$, $W \rightarrow l\nu$]





- E_T(j1) >150GeV, ET(j2)<60 GeV,
- E_T^{miss}>120 GeV,
- no leptons,
- E_T^{miss} isolation

Expected: 265±30, Observed: 263
M_D> 0.85, 0.83 TeV (95%CL) for δ=5,6

LHC: Large ED

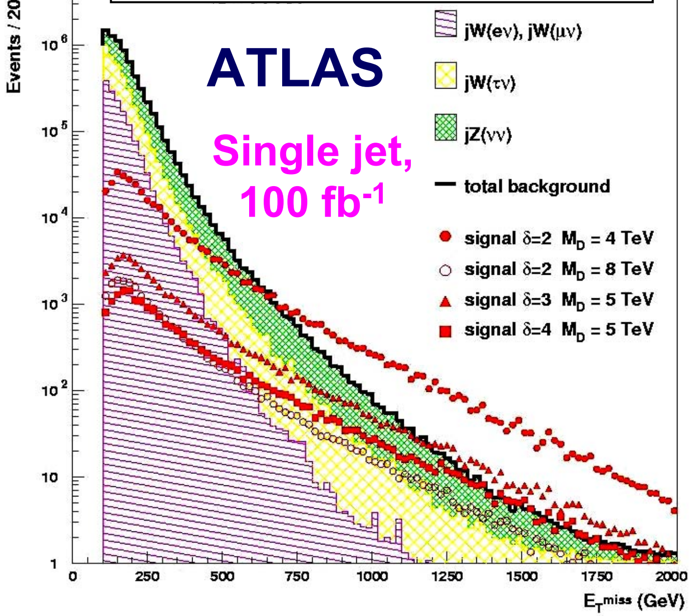
Antoniadis, Benakli and Quiros, PLB331 (1994) 313; Arkani-Hamed, Dimopoulos and Dvali, PLB429 (1998) 263

- 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.

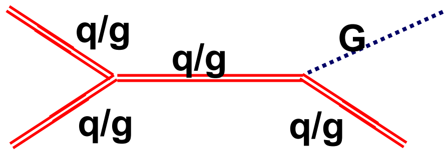
Gg → gG, qg → qG, qq → Gg



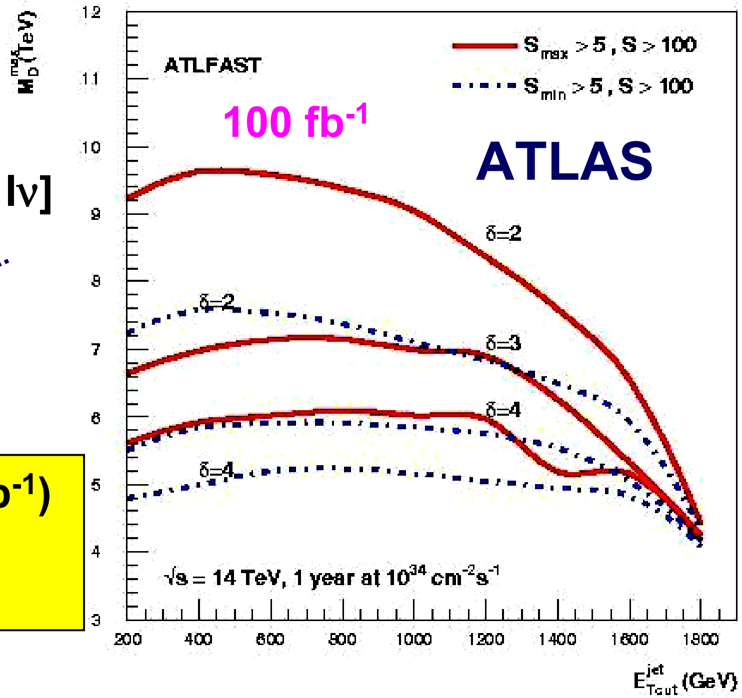
Signal : graviton + 1 jet production

Main background:

Jet + Z(W) [Z → νν, W → lν]



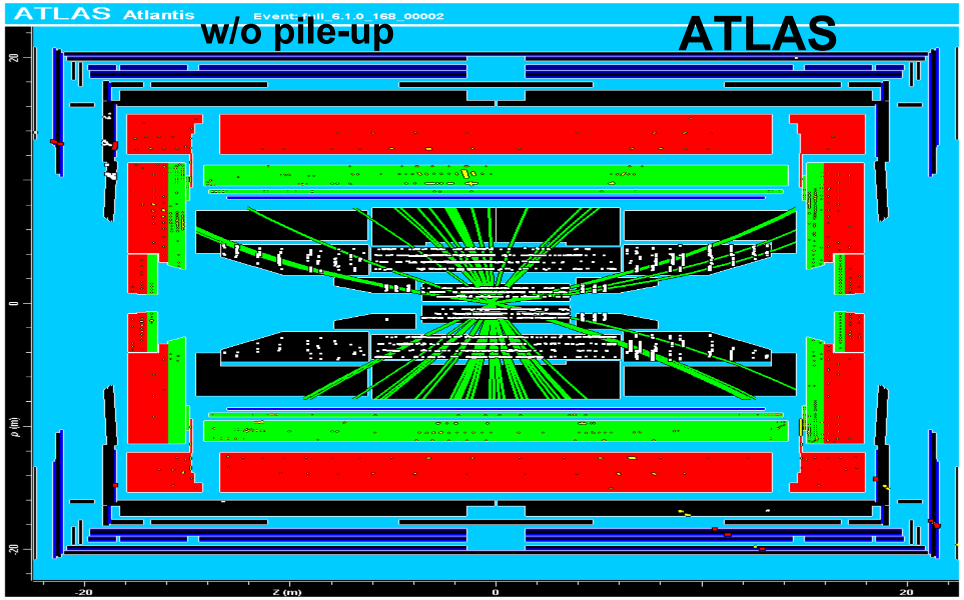
M_D^{max} (E_T>1 TeV, 100 fb^{-1}) = 9.1, 7.0, 6.0 TeV for δ=2,3,4

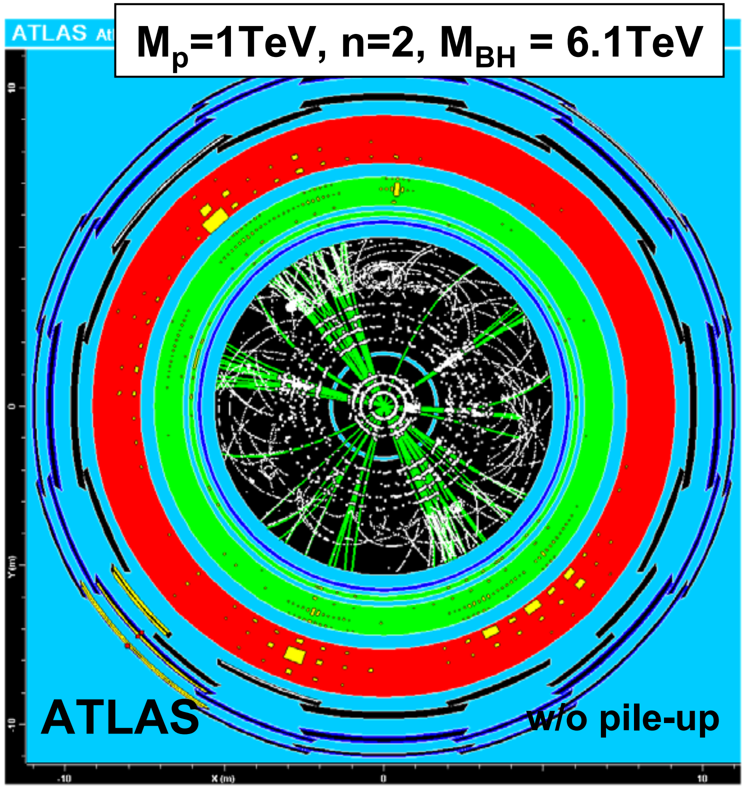


LHC: Black Hole Signatures

Dimopoulos and Landsberg PRL87 (2001) 161602

- In large ED (ADD) scenario, when impact parameter smaller than Schwartzschild radius Black Hole produced with potentially large x-sec (~100 pb).
- Decays democratically through Black Body radiation of SM states – Boltzmann energy distribution.





- Discovery potential (preliminary)
  - M_p < ~4 TeV → < ~ 1 day
  - M_p < ~6 TeV → < ~ 1 year
- Studies continue …

News from the Frontier

- Exotics searches well underway at Tevatron
- Many new results improving on Run I / LEP sensitivity
- Statistics increasing rapidly now
- So far no sight of land

- New searches commencing next year at LHC
- Good prospects for exciting discoveries
- Exciting times ahead!

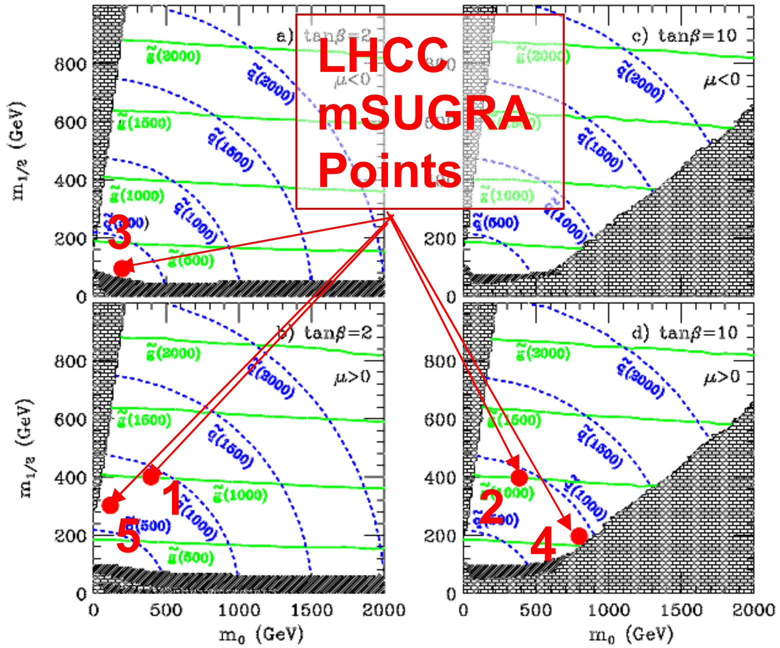
BACK-UP SLIDES


NON STANDARDS


03-TRACE FUNCTION
04-THE INVISIBLE WITNESS
bonus tracks!
11-EXCLUSIONS (JAPAN EXCLUSIVE)

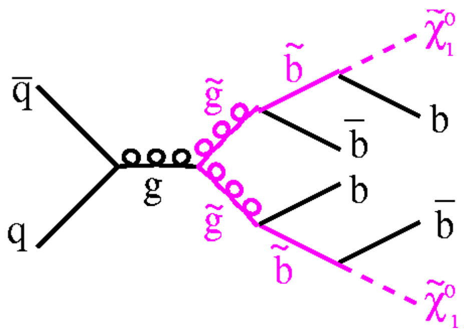
Model Framework

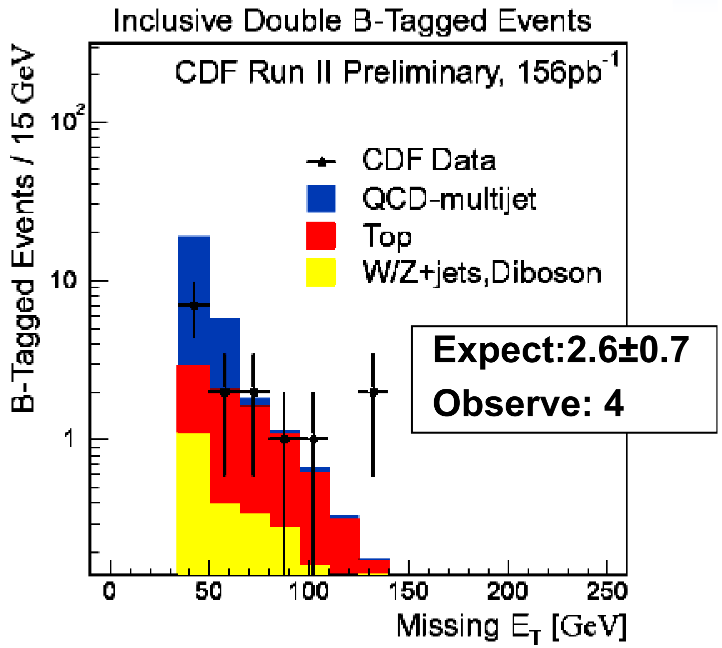
- Minimal Supersymmetric Extension of the Standard Model (MSSM) contains > 105 free parameters, NMSSM etc. has more → difficult to map complete parameter space!
- Assume specific well-motivated model framework in which generic signatures can be studied.
- Often assume SUSY broken by gravitational interactions → mSUGRA/CMSSM framework : unified masses and couplings at the GUT scale → 5 free parameters (m_0, $m_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$).
- R-Parity assumed to be conserved.
- Exclusive studies use benchmark points in mSUGRA parameter space:
  - LHCC Points 1-6;
  - Post-LEP benchmarks (Battaglia et al.);
  - Snowmass Points and Slopes (SPS);
  - etc…

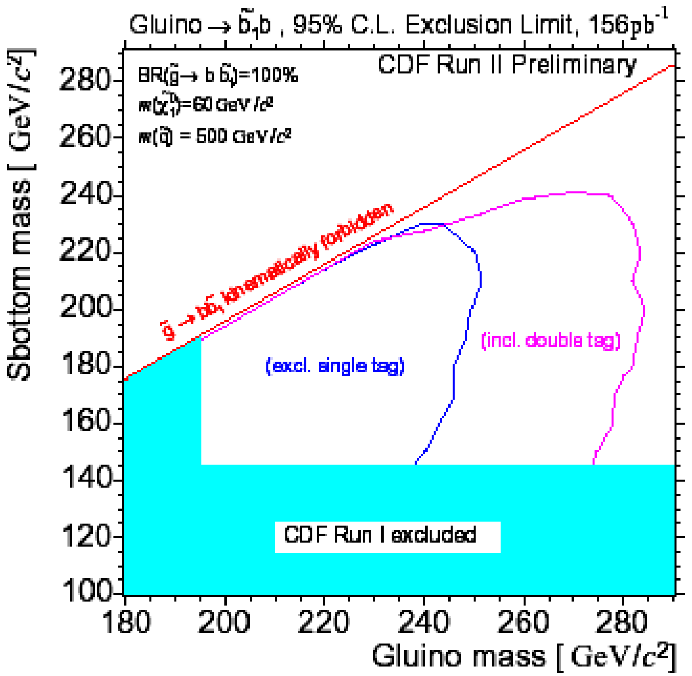


Run II: Stop/Sbottom

- **Lower mass than 'light' squarks / gluinos esp. at large tan(β) / A_0**
- **Dedicated searches complementary to generic jets + E_T^{miss} channel**



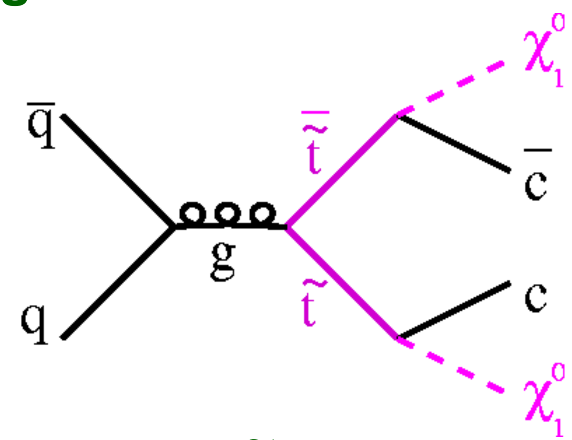




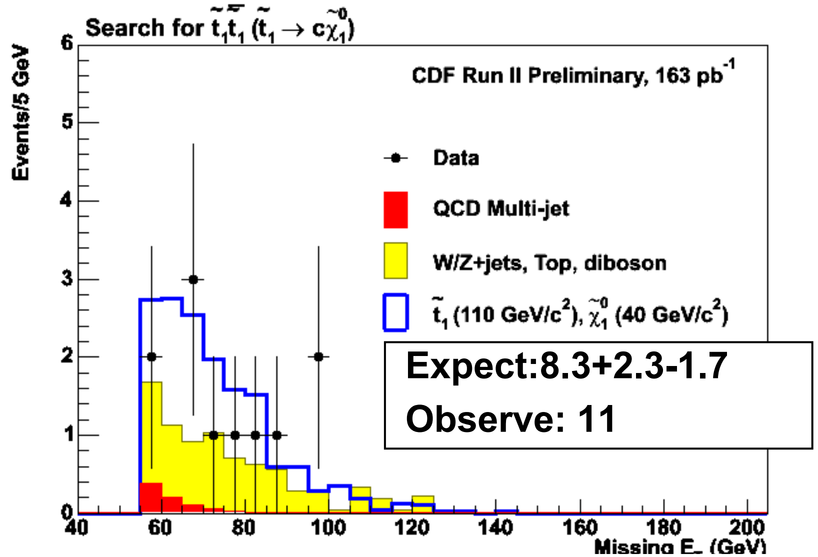
- **CDF sbottom search**
- **Sbottom signature: b production + E_T^{miss}> 80 GeV**
- **Assume:**
  - **light gluino: sbottom produced in cascade**
  - **BR(g->bb)=100%**

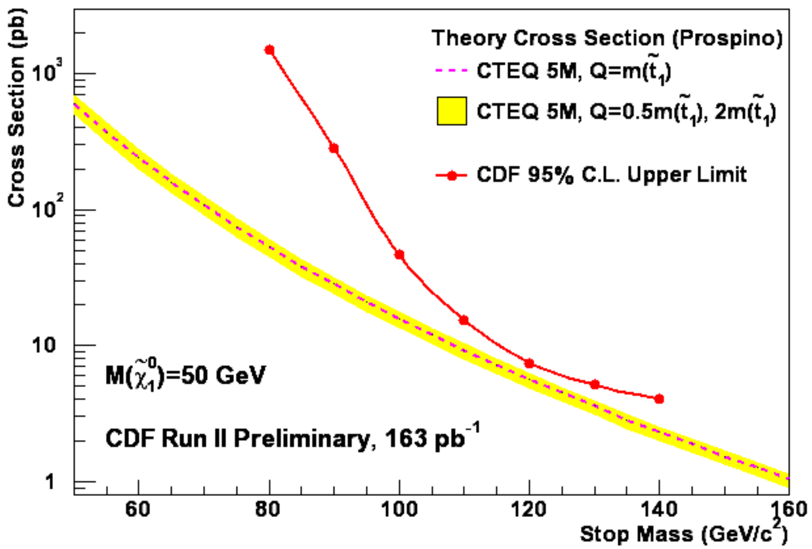
DØ: Stop Searches

- **Low mass stop squarks well-motivated: can co-annihilate with $\tilde{\chi}^0_1$ to give observed DM density**



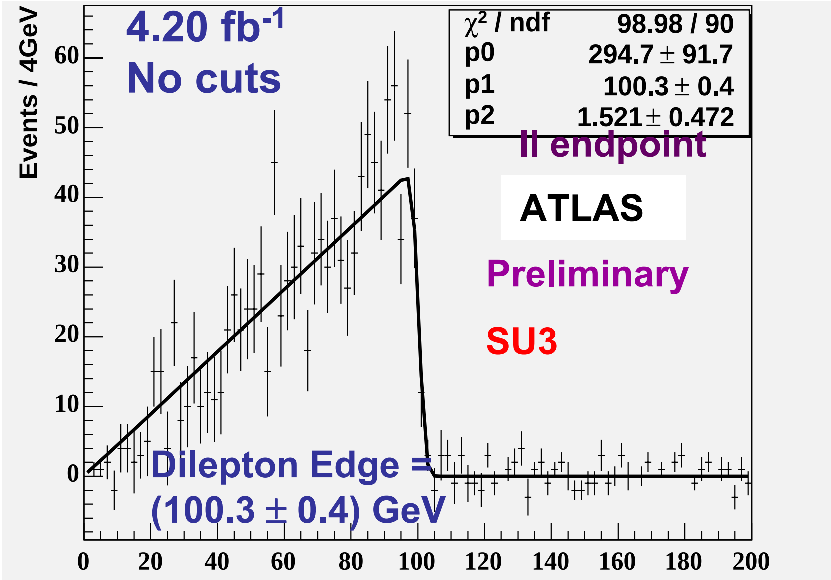
- **Requires small $\tilde{t}_1$ - $\tilde{\chi}^0_1$ mass difference ➔ decays to charm**
- **Search for 2 c-jets and large E_T^{miss}:**
  - E_T(jet)>35, 25 GeV
  - E_T^{miss}>55 GeV
- **Main backgrounds:**
  - Z+jj ➔ ννjj, W+jj ➔ τνjj

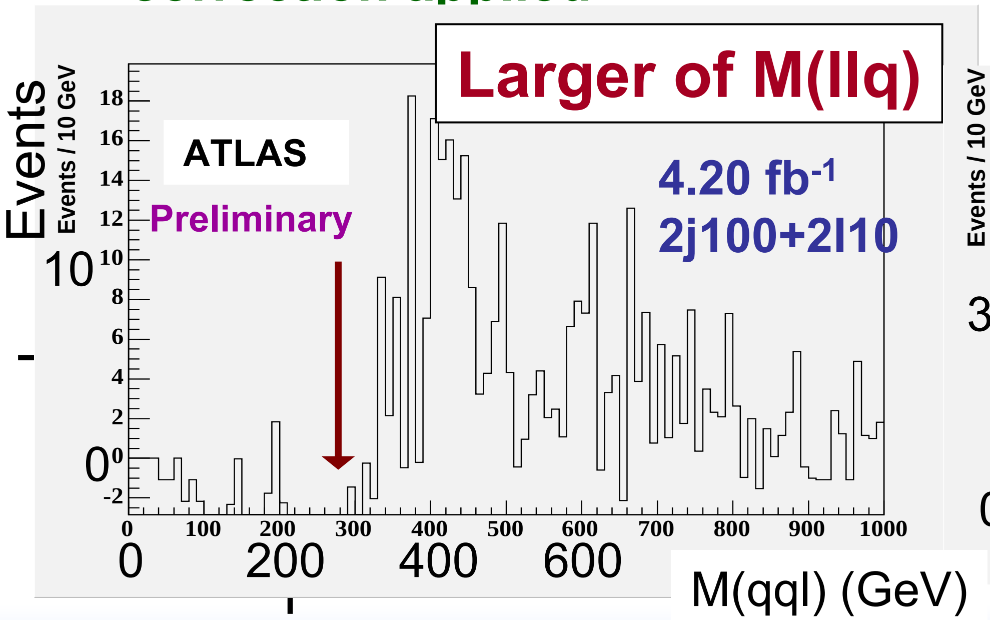


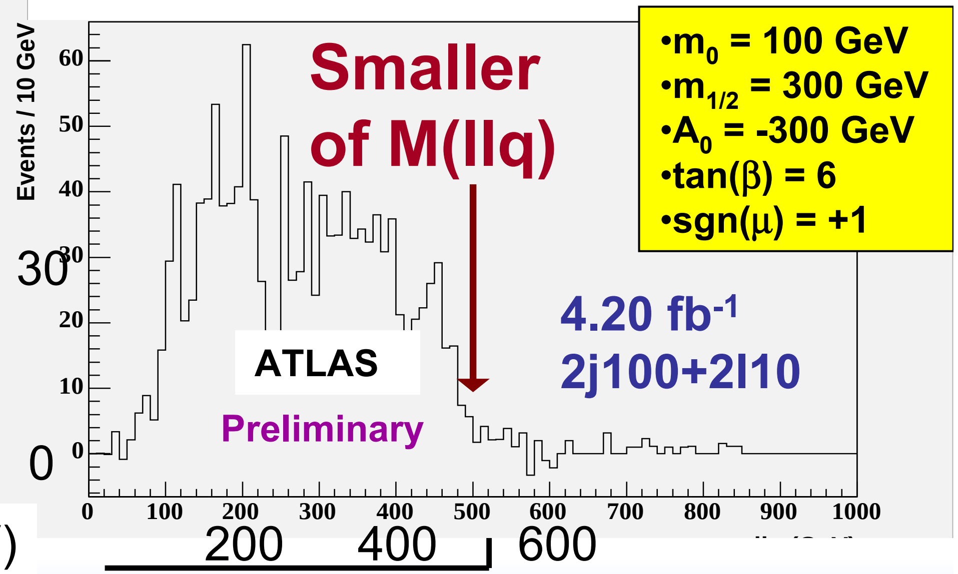


Full Simulation

- Full Geant4 simulation of signals + backgrounds now priority.
- Invariant mass of dilepton+jet bounded by M_{llq}^{min}=271.8 GeV and M_{llq}^{max} =501 GeV.
- Leptons combined with two jets with highest p_T
- Flavour subtraction & efficiency correction applied

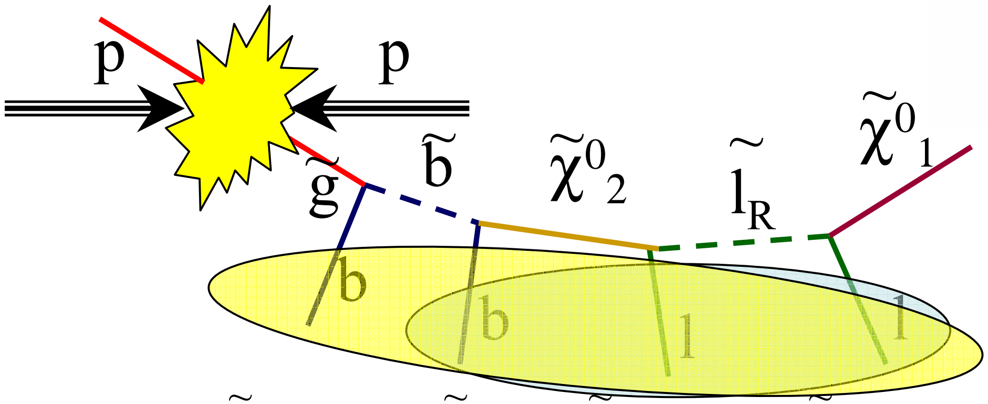


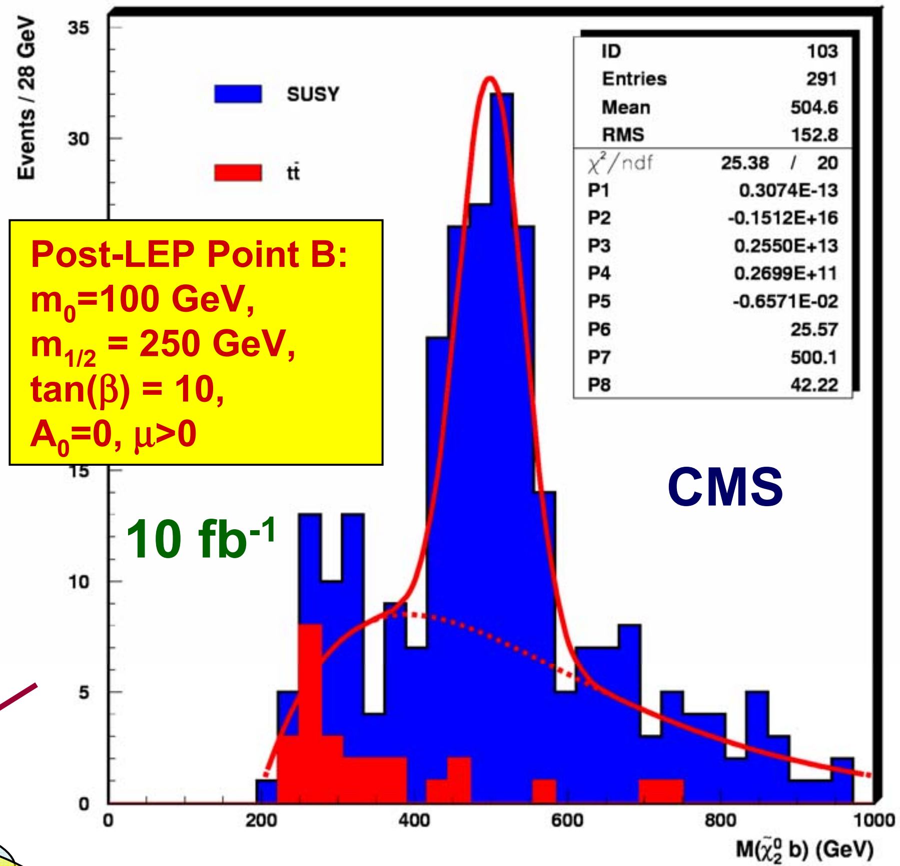




Sbottom Mass

- Following measurement of squark, slepton and neutralino masses move up decay chain and study alternative chains.
- One possibility: require b-tagged jet in addition to dileptons.
- Give sensitivity to sbottom mass (but actually two peaks).



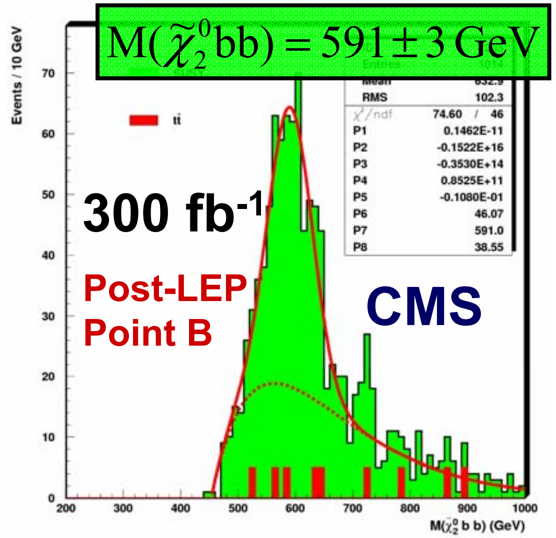


$$\overline{M}(\tilde{b}) = \frac{M(\tilde{b}_1)\bullet\sigma\times BR(\tilde{b}_1) + M(\tilde{b}_2)\bullet\sigma\times BR(\tilde{b}_2)}{\sigma\times BR(\tilde{b}_1) + \sigma\times BR(\tilde{b}_2)} = 503.9\ \text{GeV}$$

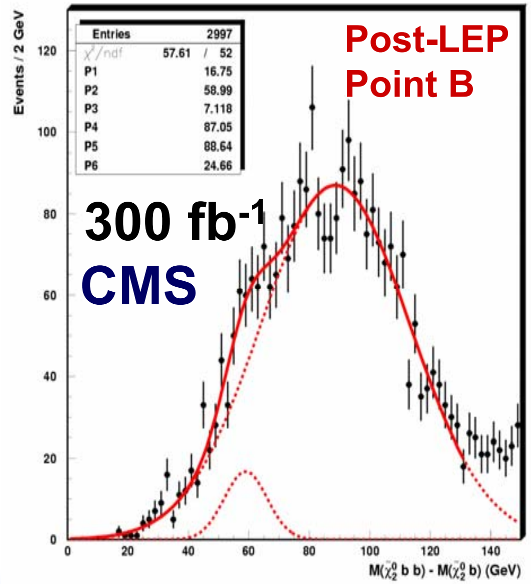
$$M(\tilde{\chi}^0_2 b) = 500 \pm 7\ \text{GeV}$$

Gluino Mass

- Can also move further up the decay chain to gain sensitivity to gluino mass.
- Can use either light squark decay or sbottom (as here).
- Problem with large error on input $\tilde{\chi}^0_1$ mass remains → solve by reconstructing difference of gluino and squark/sbottom masses.
- Allows separation of $\tilde{b}_1$ and $\tilde{b}_2$ with 300 fb^{-1}.



	Sbottom Chain				Squark Chain		
	10 fb^{-1}	60 fb^{-1}	300 fb^{-1}		10 fb^{-1}	60 fb^{-1}	300 fb^{-1}
M(sbottom)	500±7	502±4	497±2	M(squark)	536±10	532±2	536±1
σ(sbottom)	42±5	41±4	36±3	σ(squark)	60±9	36±1	31±1
M(gluino)	594±7	592±4	591±3	M(gluino)	592±7	595±2	590±2
σ(gluino)	42±7	46±3	39±3	σ(gluino)	75±5	59±2	59±2
M(gl)-M(sb)	92±3	88±2	90±2	M(gl)-M(sq)	57±3	47±2	44±2
σ(gl-sb)	17±4	20±2	23±2	σ(gl-sq)	9±3	16±5	11±2



LHC: Model Parameters

- Alternative use for SUSY observables (invariant mass end-points, thresholds etc.).
- Here assume mSUGRA/CMSSM model and perform global fit of model parameters to observables
  - So far mostly private codes but e.g. SFITTER, FITTINO now on the market;
  - c.f. global EW fits at LEP, ZFITTER, TOPAZ0 etc.

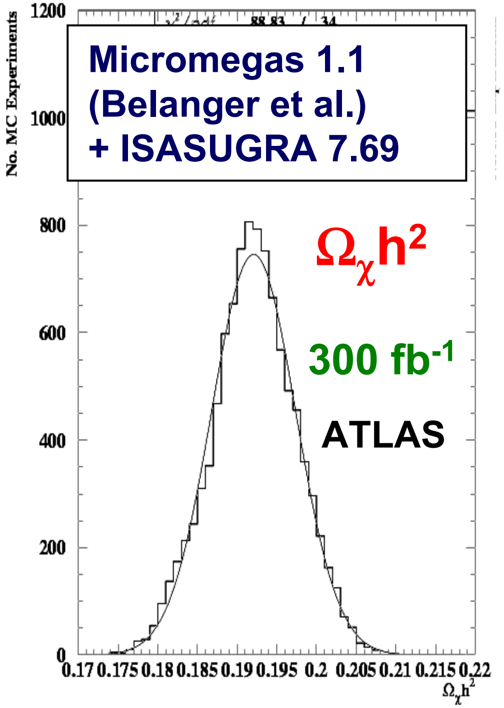
Point	m_0	$m_{1/2}$	A_0	$\tan(\beta)$	sign(μ)
LHC Point 5	100	300	300	2	+1
SPS1a	100	250	-100	10	+1

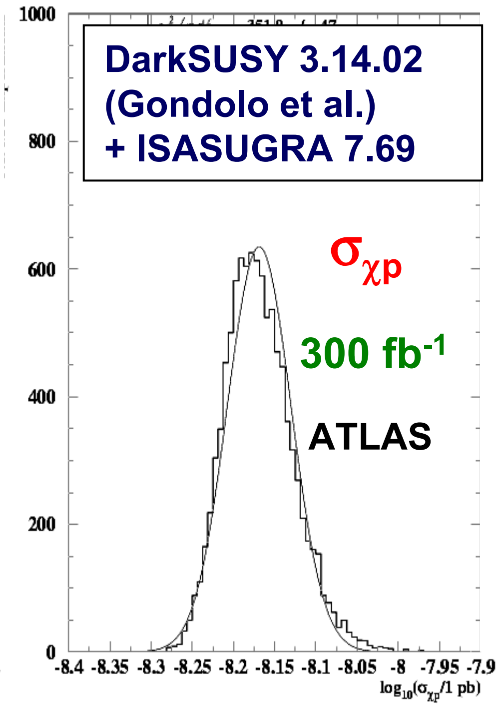
Variable	Value (GeV)	Errors Stat. (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

Parameter	Expected precision (300 fb^{-1})
m_0	± 2%
$m_{1/2}$	± 0.6%
$\tan(\beta)$	± 9%
A_0	± 16%

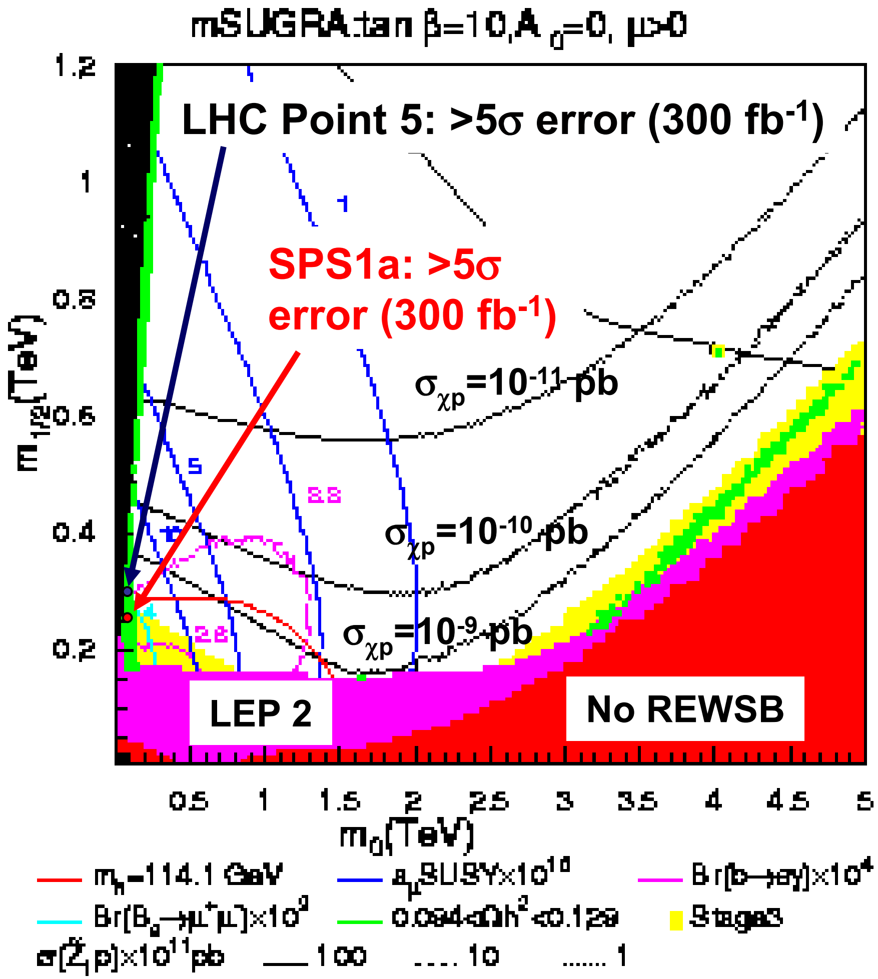
LHC: SUSY Dark Matter

- Can use parameter measurements for many purposes, e.g. estimate LSP Dark Matter properties (e.g. for 300 fb^{-1}, SPS1a)
  - $\Omega_\chi h^2 = 0.1921 \pm 0.0053$
  - $\log_{10}(\sigma_{\chi p}/pb) = -8.17 \pm 0.04$

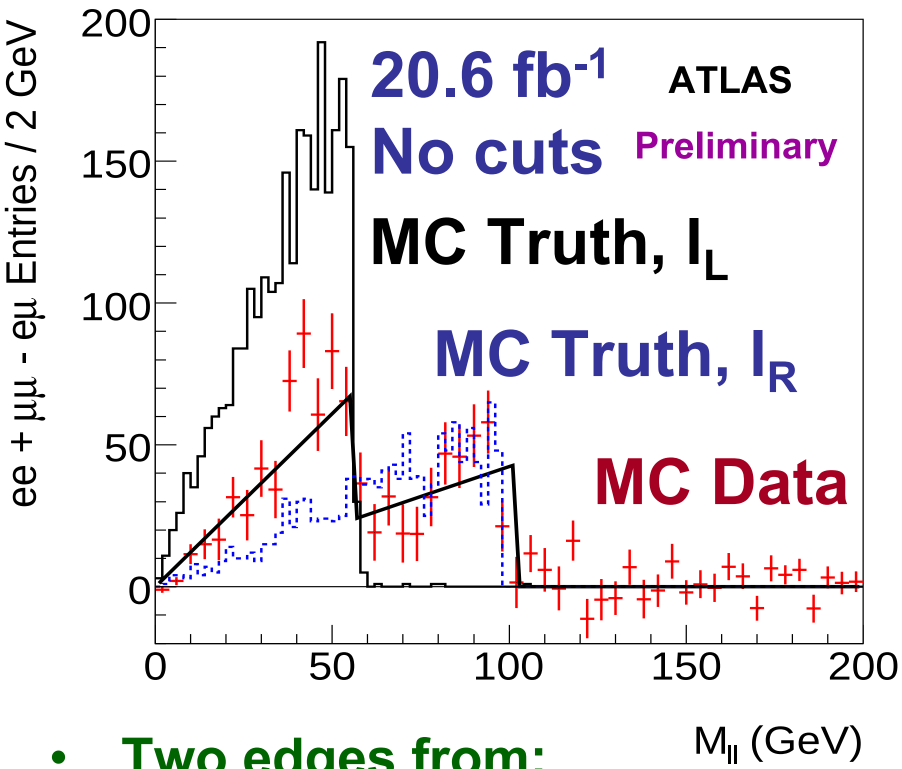


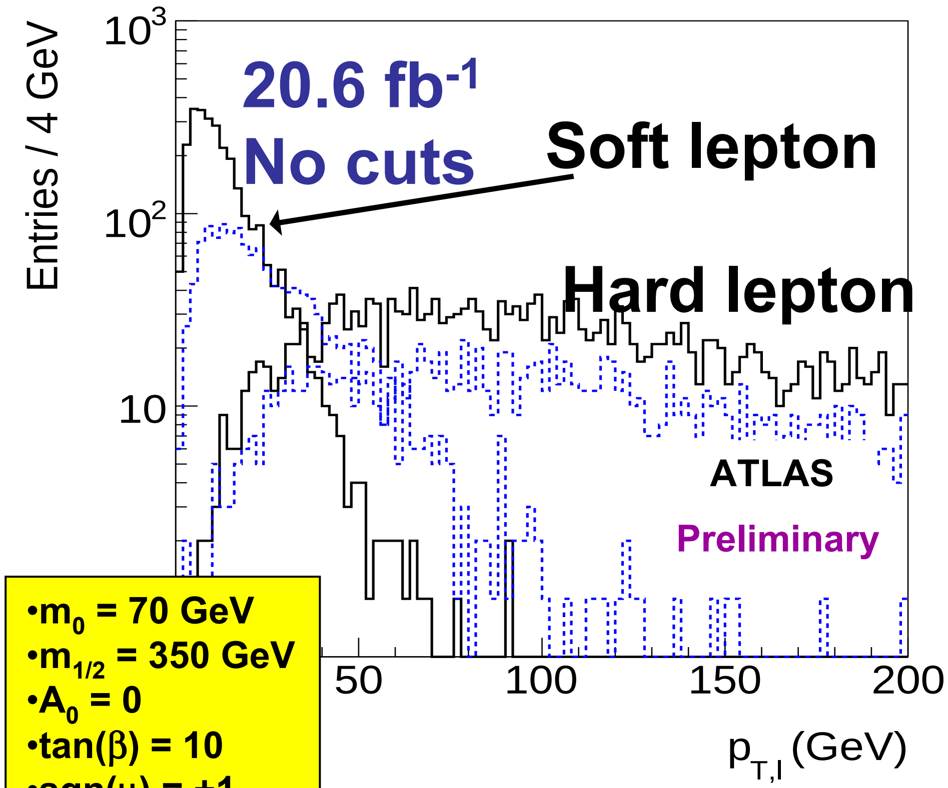


Baer et al. hep-ph/0305191



Full Simulation





- m_0 = 70 GeV
- $m_{1/2}$ = 350 GeV
- A_0 = 0
- $\tan(\beta)$ = 10
- $\mathrm{sgn}(\mu)$ = +1

- Two edges from:

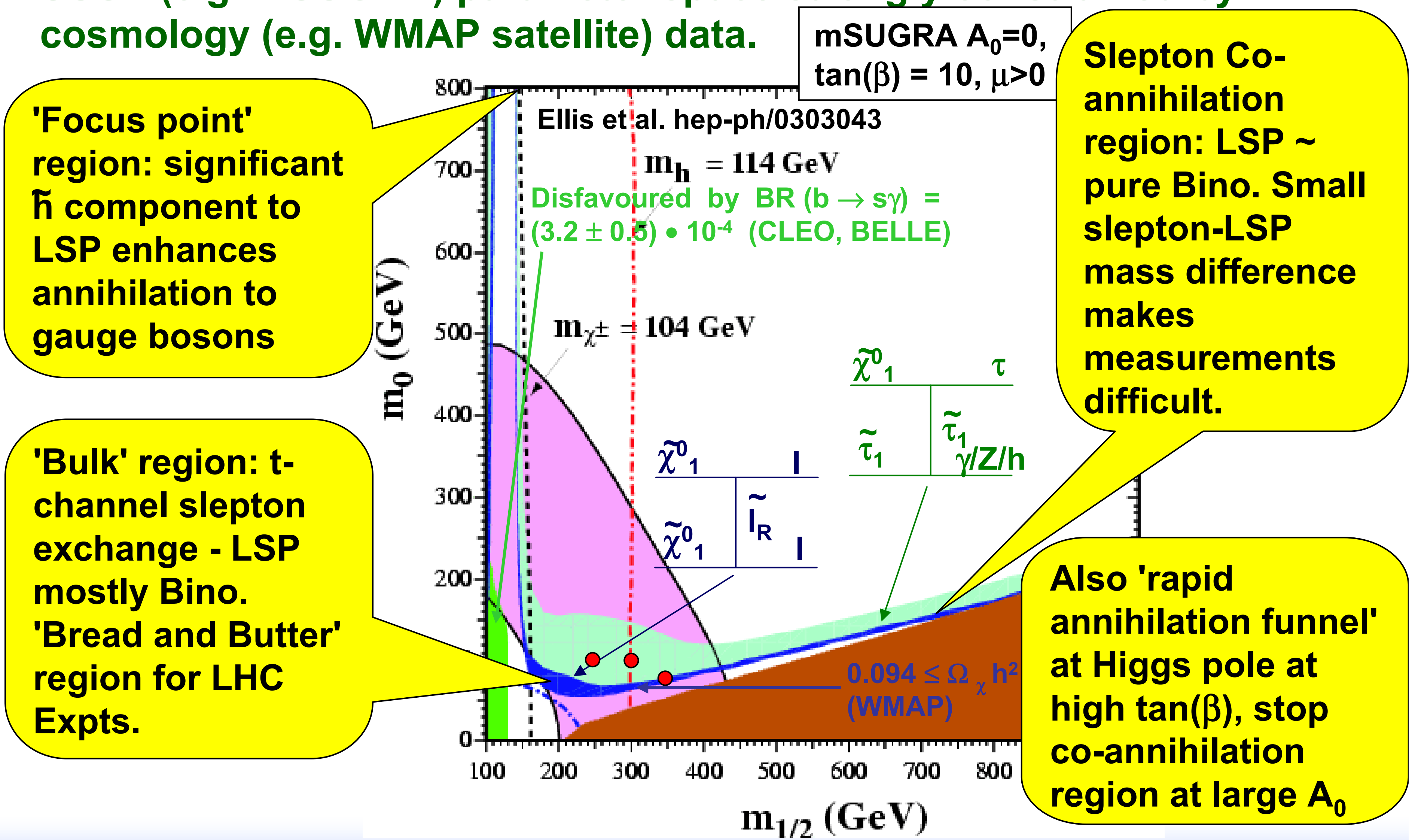
$$\chi_2^0 \rightarrow l\tilde{l}_L \rightarrow ll\chi_1^0$$

$$\chi_2^0 \rightarrow l\tilde{l}_R \rightarrow ll\chi_1^0$$

Each slepton is close in mass to one of the neutralinos – one of the leptons is soft

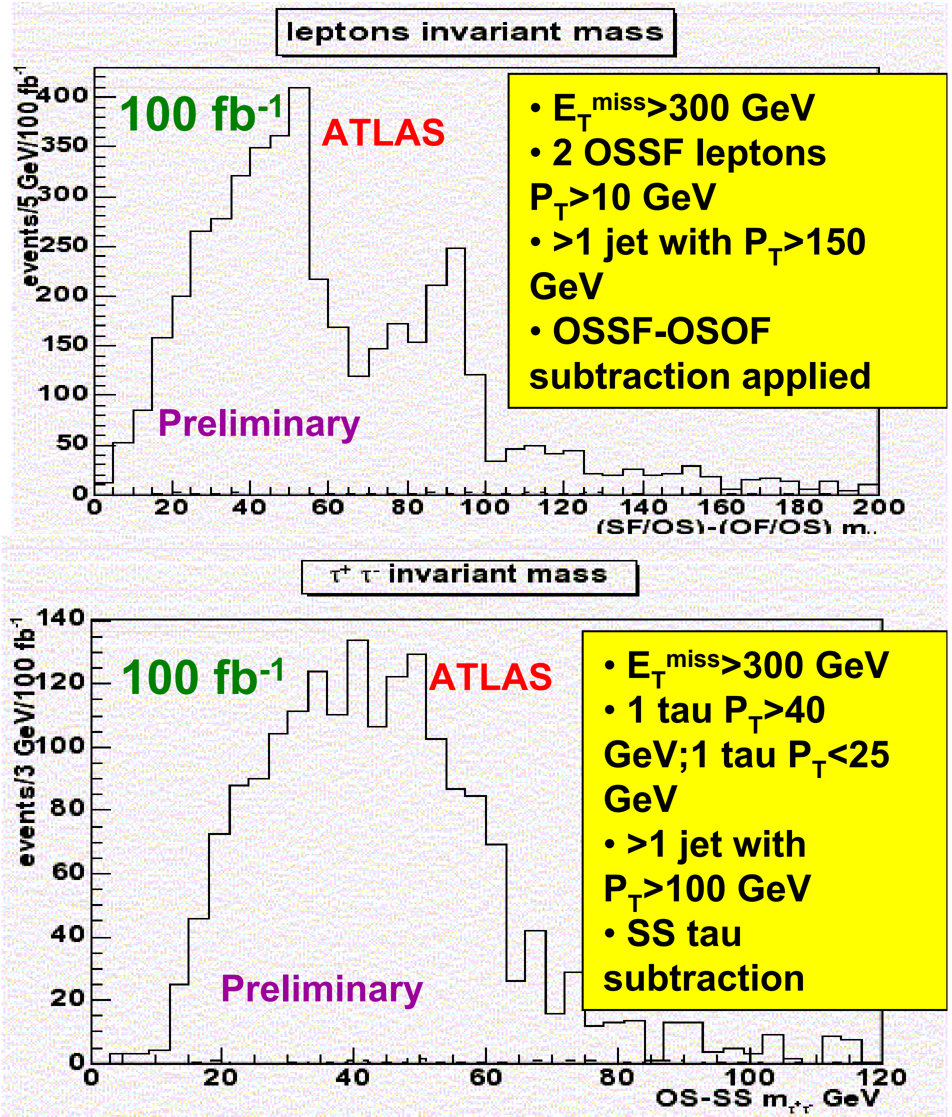
LHC: SUSY Dark Matter

- **SUSY (e.g. mSUGRA) parameter space strongly constrained by cosmology (e.g. WMAP satellite) data.**



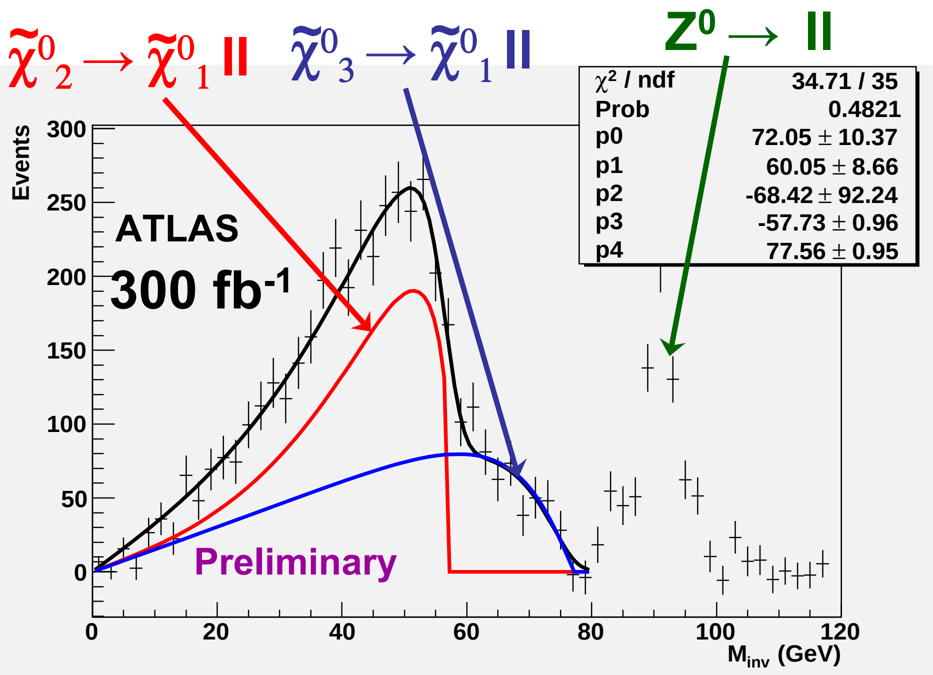
LHC: Coannihilation Models

- Small slepton-neutralino mass difference gives soft leptons
  - Low electron/muon/tau energy thresholds crucial.
- Study point chosen within region:
  - m_0=70 GeV; $m_{1/2}$=350 GeV; A_0=0; tanß=10 ; μ>0;
  - Same model used for DC2 study.
- Decays of $\tilde{\chi}^0_2$ to both $\tilde{l}_L$ and $\tilde{l}_R$ kinematically allowed.
  - Double dilepton invariant mass edge structure;
  - Edges expected at 57 / 101 GeV
- Stau channels enhanced (tanβ)
  - Soft tau signatures;
  - Edge expected at 79 GeV;
  - Less clear due to poor tau visible energy resolution.



LHC: Focus Point Models

- Large m_0 ➔ sfermions are heavy
- Most useful signatures from heavy neutralino decay
- Study point chosen within focus point region :
  - m_0=3550 GeV; $m_{1/2}$=300 GeV; A_0=0; tanß=10 ; μ>0
- Direct three-body decays $\tilde{\chi}^0_n \rightarrow \tilde{\chi}^0_1$ ll
- Edges give $m(\tilde{\chi}^0_n)-m(\tilde{\chi}^0_1)$: flavour subtraction applied



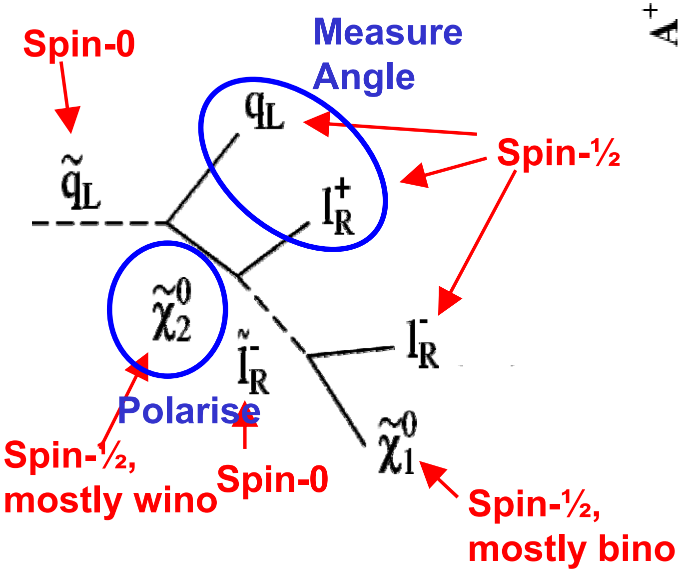
$$\frac{d\Gamma}{dM_{\rm inv}} = C_{\rm Norm} M_{\rm inv} \frac{\sqrt{M_{\rm inv}^4 - M_{\rm inv}^2(\mu^2+M^2)+(\mu M)^2}}{(M_{\rm inv}^2 - m_Z^2)^2} \cdot \left[-2M_{\rm inv}^4 + M_{\rm inv}^2(2M^2+\mu^2)+(\mu M)^2\right].$$

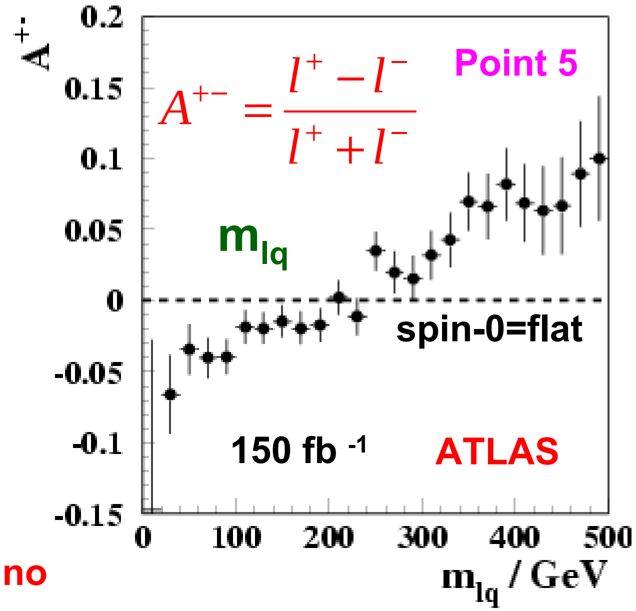
$M = m_A + m_B \quad \mu = m_A - m_B$

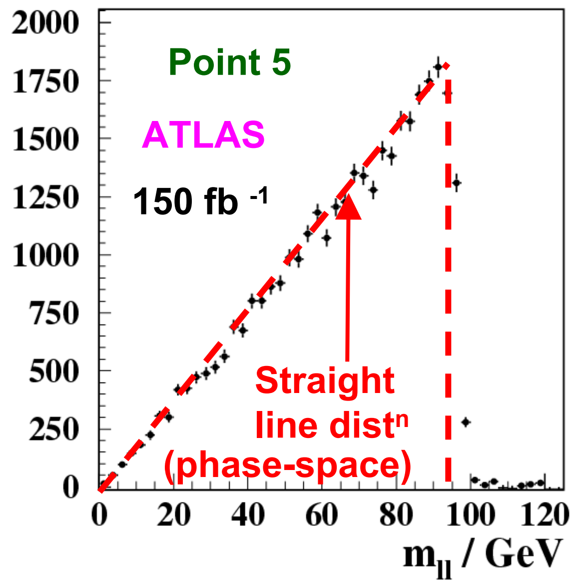
Parameter	Without cuts	Exp. value
M_1	68±92	103.35
M_2-M_1	57.7±1.0	57.03
M_3-M_1	77.6±1.0	76.41

LHC: SUSY Spin Measurement

- Q: How do we know that a SUSY signal is really due to SUSY?
  - Other models (e.g. UED) can mimic SUSY mass spectrum
- A: Measure spin of new particles.
- One proposal – use 'standard' two-body slepton decay chain
  - charge asymmetry of lq pairs measures spin of $\tilde{\chi}^0_2$
  - relies on valence quark contribution to pdf of proton (C asymmetry)
  - shape of dilepton invariant mass spectrum measures slepton spin

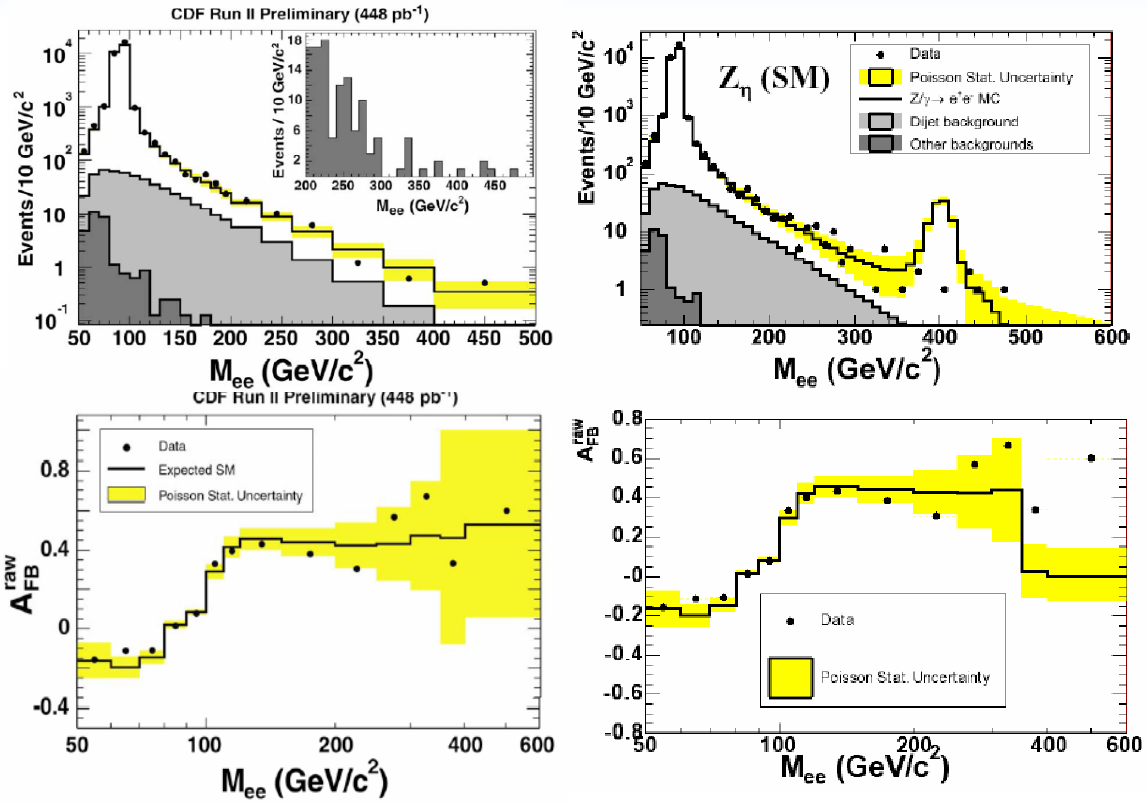






Run II: Resonances

- **Generic signature:**
  - **Resonances: Higgs, Sneutrino (Spin-0), Spin-1: Z', W' (Spin-1), Randall-Sundrum Graviton (Spin-2),**
  - **Enhancements: Large ED (ADD), contact interactions**
- **Dielectron mass and A_{FB} show no evidence of excess**
- **Limits on Z' (peak) from 650 GeV (Z_I) – 850 GeV (SM)**
- **Limit qqee couplings:**



Contact interactions $qqee$ $\sum_q \sum_{i,j=L,R} \frac{4\pi\eta}{\Lambda_{ij}^2} \bar{e}_i \gamma^\mu e_i \bar{q}_j \gamma_\mu q_j$

CDF RunII Preliminary (448 pb^{-1})

Interaction	LL	LR	RL	RR	VV	AA
Λ^+_{qe} limit (TeV/c^2)	3.7	4.7	4.5	3.9	5.6	7.8
Λ^-_{qe} limit (TeV/c^2)	5.9	5.5	5.8	5.6	8.7	7.8

Fo

VV=LL+LR+RL+RR; AA = LL+RR-RL-LR

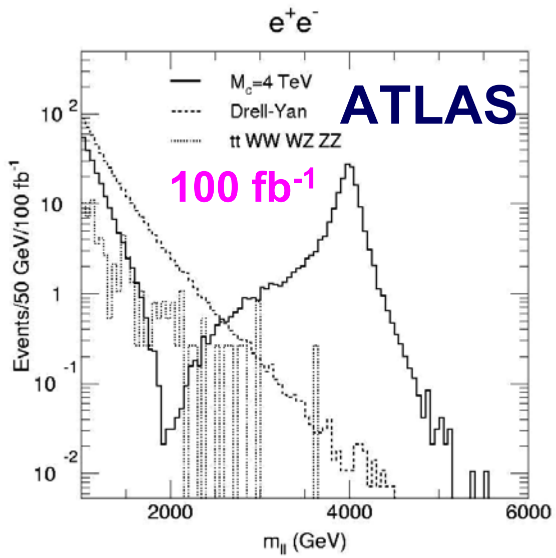
LHC: TeV^{-1} Scale ED

- 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:

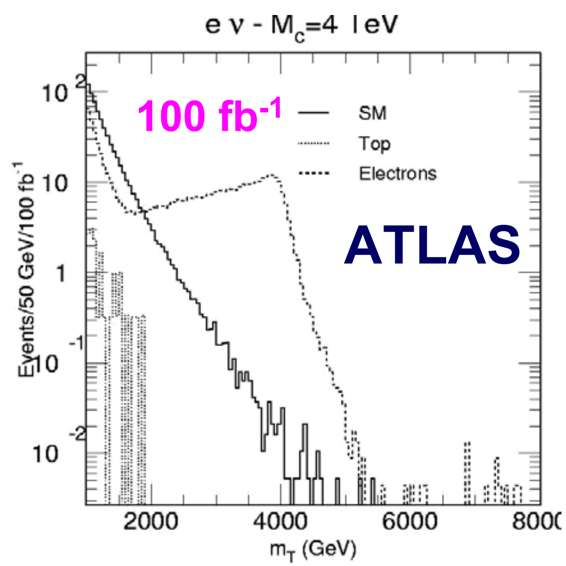
$$M_n^2=(nM_c)^2+M_0^2$$

for compactification scale M_c and SM mass M_0

- Look for l^+l^- decays of γ and Z^0 KK modes.
- Also $l\nu$ decays (m_T) of $W^{+/-}$ KK modes.

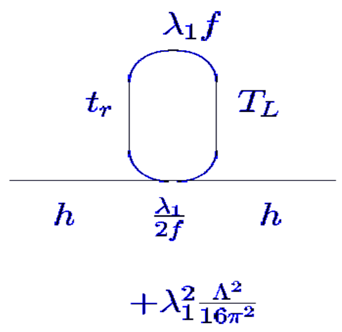


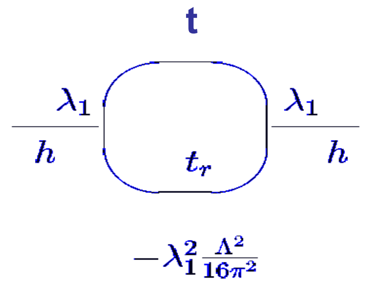
- 5σ reach for 100 fb^{-1} ~ 5.8 TeV (Z/γ)
  ~ 6 TeV (W)
- For 300 fb^{-1} l^+l^- peak detected if M_c < 13.5 TeV (95% CL).



Little Higgs Models

- Solves hierarchy problem by cancelling loop corrections (top, W/Z, Higgs loops) to the Higgs mass with new states.
- New states derived from extended gauge group rather than new continuous symmetry (c.f. SUSY).
- 'Littlest Higgs' model contains 'not too little, not too much, but just enough' extra gauge symmetry $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$:
  - Electroweak singlet T quark (top loop) – mixes with top;
  - New gauge bosons W_H, A_H, Z_H (W/Z loops);
  - New $SU(2)_L$ triplet scalars, including neutral, singly charged, doubly charged ϕ (Higgs loops).
- Requirement that these states protect Higgs from large corrections limits their masses:
  - T quark ~ 1 TeV;
  - W_H, A_H, Z_H ~ 1 TeV;
  - ϕ^0, $\phi^{+/-}$, $\phi^{+/-+/-}$ ~ 10 TeV.

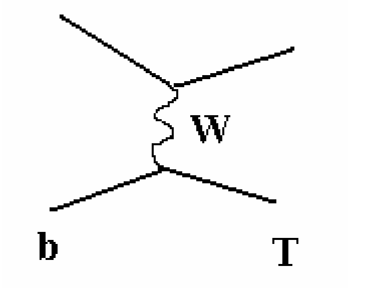




Littlest Higgs Model

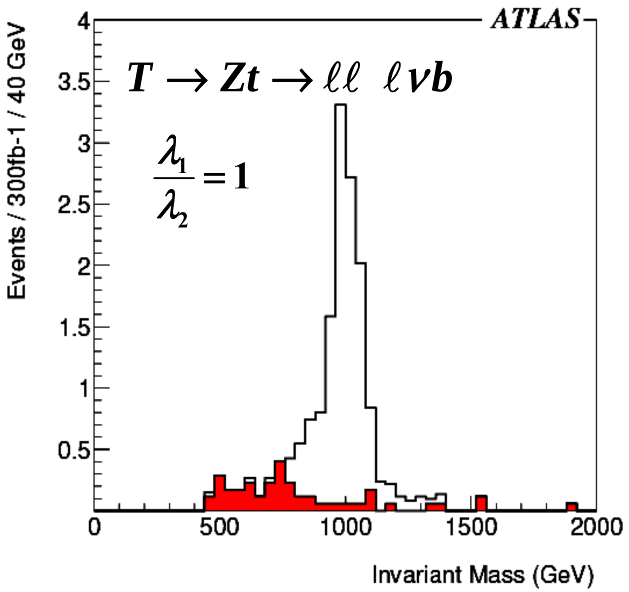
Azuelos et al., SN-ATLAS-2004-038

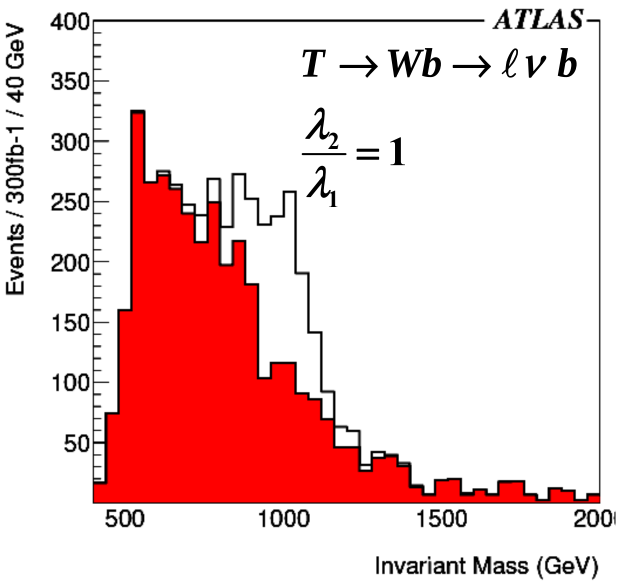
- **Searches for/measurements of new particles studied.**
- **For T quark single production assumed.**
- **Yukawa couplings governed by 3 parameters (m_t, m_T, λ_1/λ_2) – top mass eigenstate is mixture of t and T:**

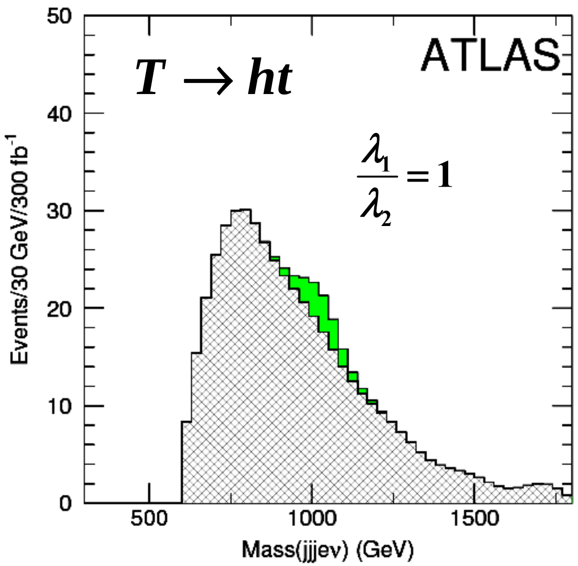


$$\lambda_1(iQht_r + fT_L t_r hh^\dagger) + \lambda_2 f(T_L T_R)$$

- **Decays:** $\Gamma(T \to th) = \Gamma(T \to tZ) = \frac{1}{2}\Gamma(T \to bW) = \frac{\kappa^2}{32\pi} M_T$ $\qquad \kappa = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$





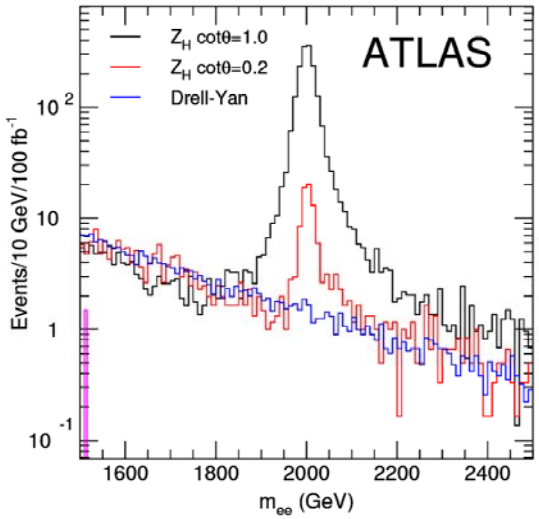


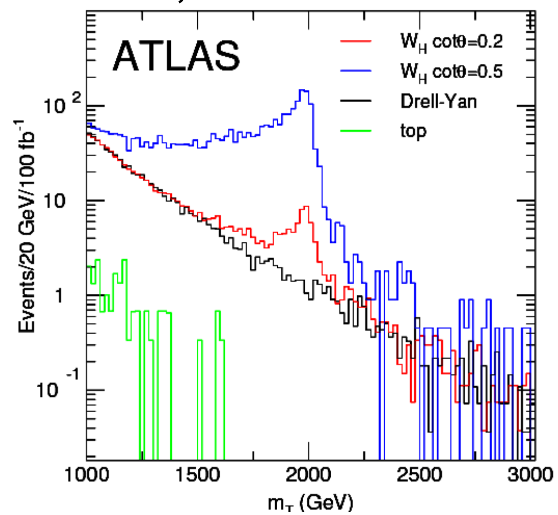
Heavy Gauge Bosons

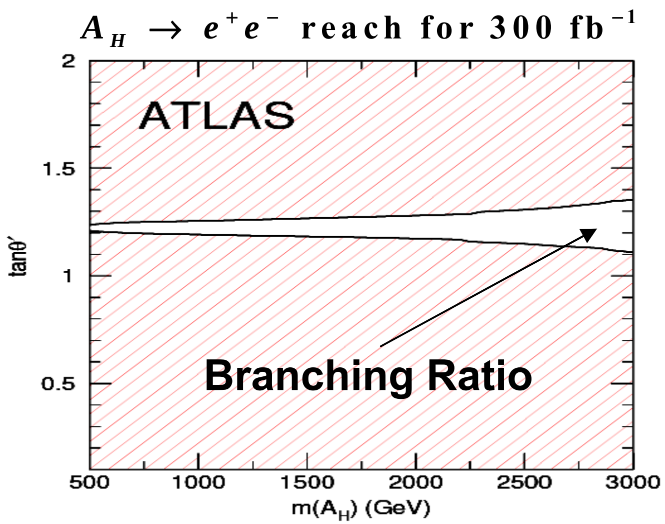
Azuelos et al., SN-ATLAS-2004-038

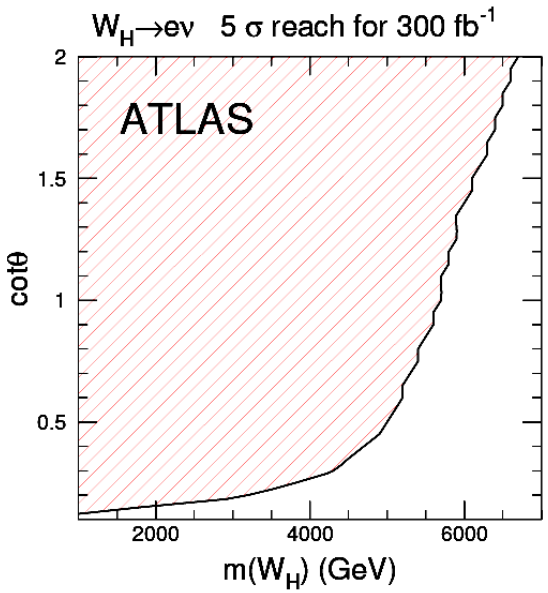
- W_H, Z_H, A_H arise from $[SU(2) \otimes U(1)]^2$ symmetry

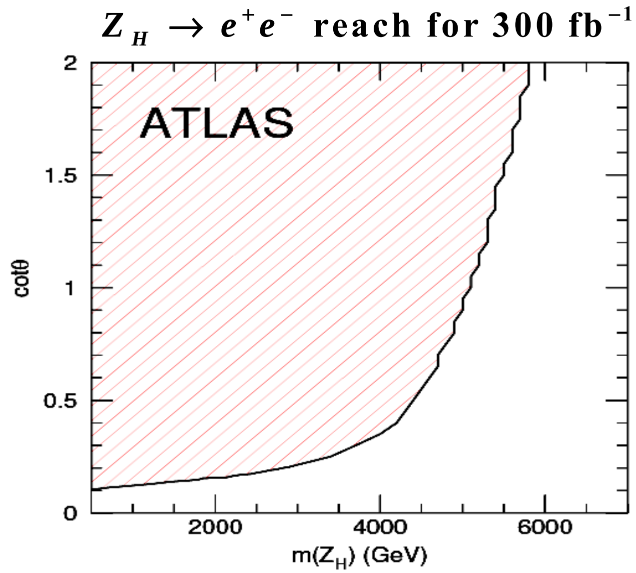
$\rightarrow$ 2 mixing angles (like θ_W): θ for Z_H, θ' for A_H





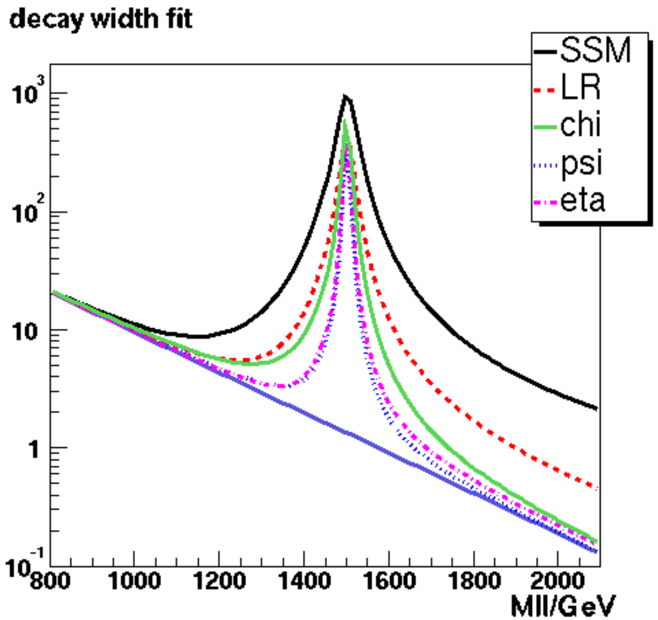


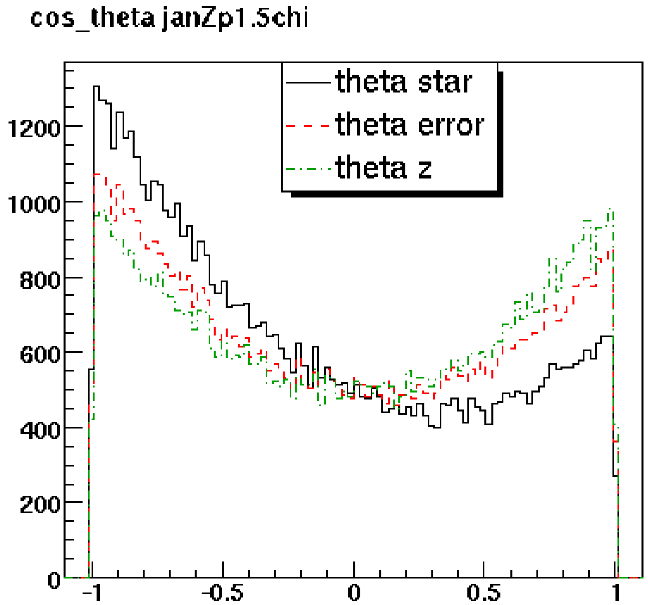




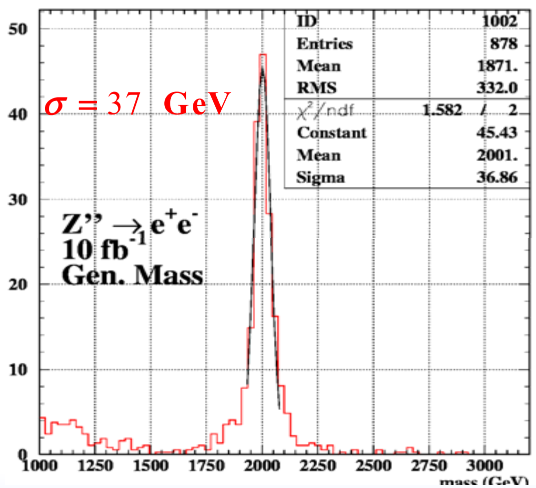
Z', W' studies

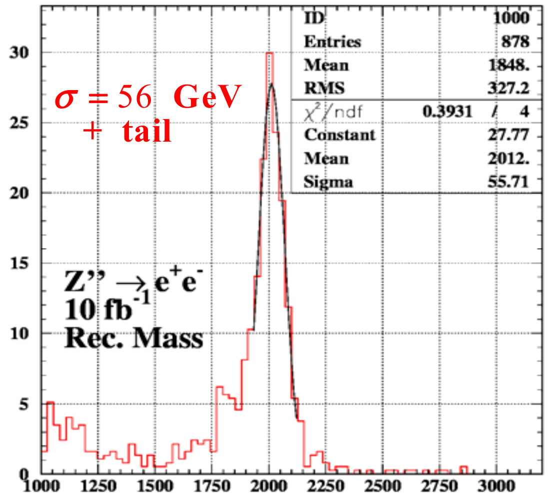
M. Schaefer
different models
full sim. in progress





O. Gaumer
full simulation

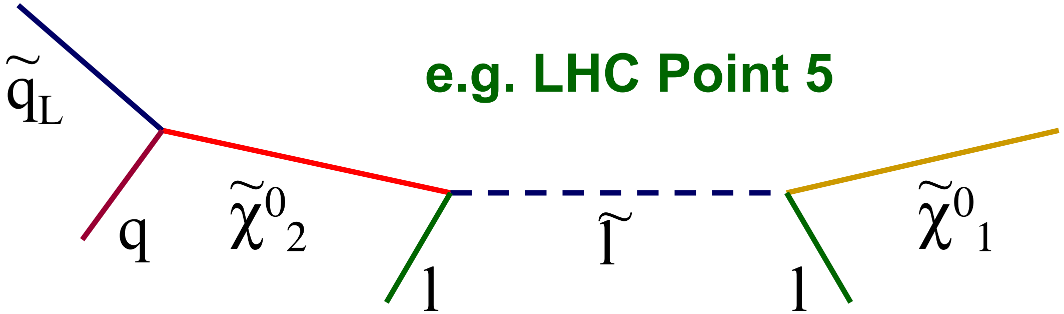




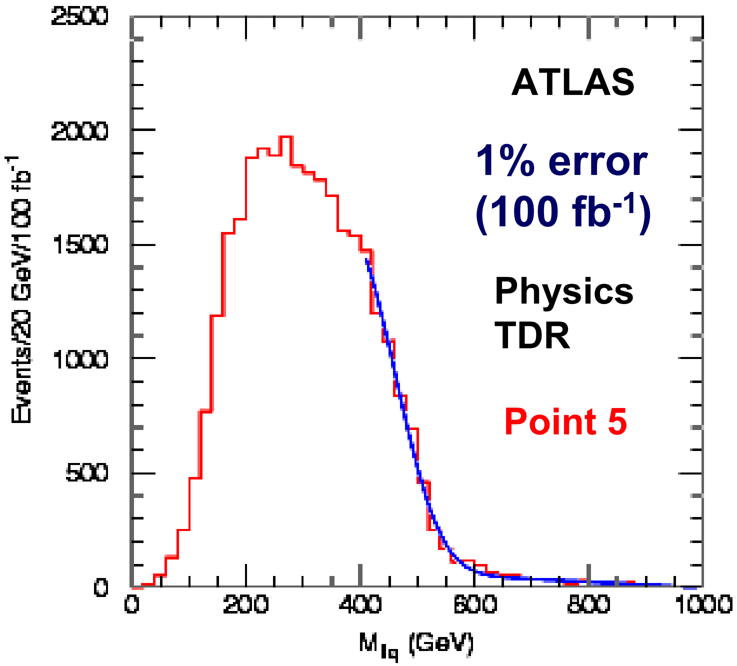
llq Edge

- Dilepton edges provide starting point for other measurements.
- Use dilepton signature to tag presence of $\tilde{\chi}^0_2$ in event, then work back up decay chain constructing invariant mass distributions of combinations of leptons and jets.

e.g. LHC Point 5



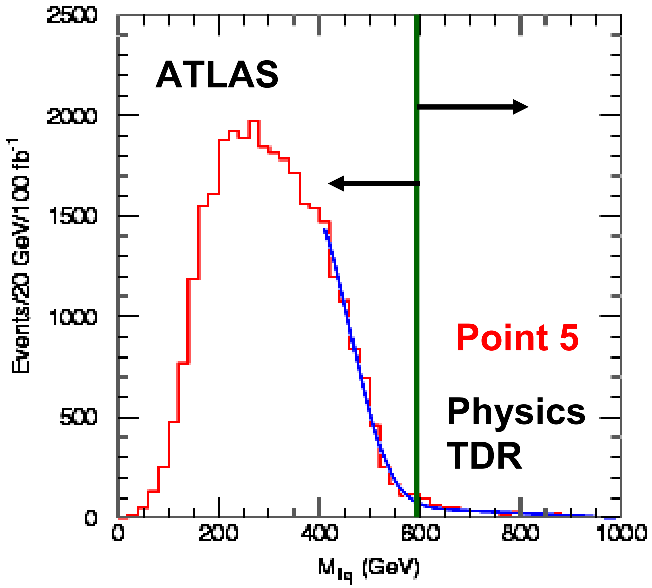
$$M_{llq}^{\max} = \left[\frac{(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2})(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{\chi}^0_2}}\right]^{1/2} = 552.4 \text{ GeV} .$$

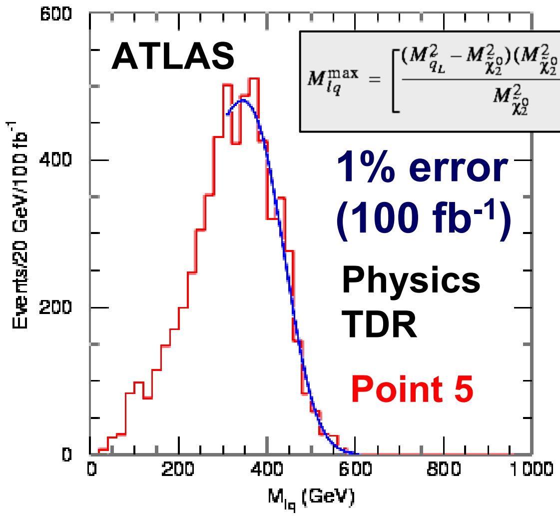


- Hardest jets in each event produced by RH or LH squark decays.
- Select smaller of two llq invariant masses from two hardest jets
  - Mass must be < edge position.
- Edge sensitive to LH squark mass.

lq Edge

- Complex decay chain at LHC Point 5 gives additional constraints on masses.
- Use lepton-jet combinations in addition to lepton-lepton combinations.
- Select events with only one dilepton-jet pairing consistent with slepton hypothesis
  - → Require one llq mass above edge and one below (reduces combinatorics).



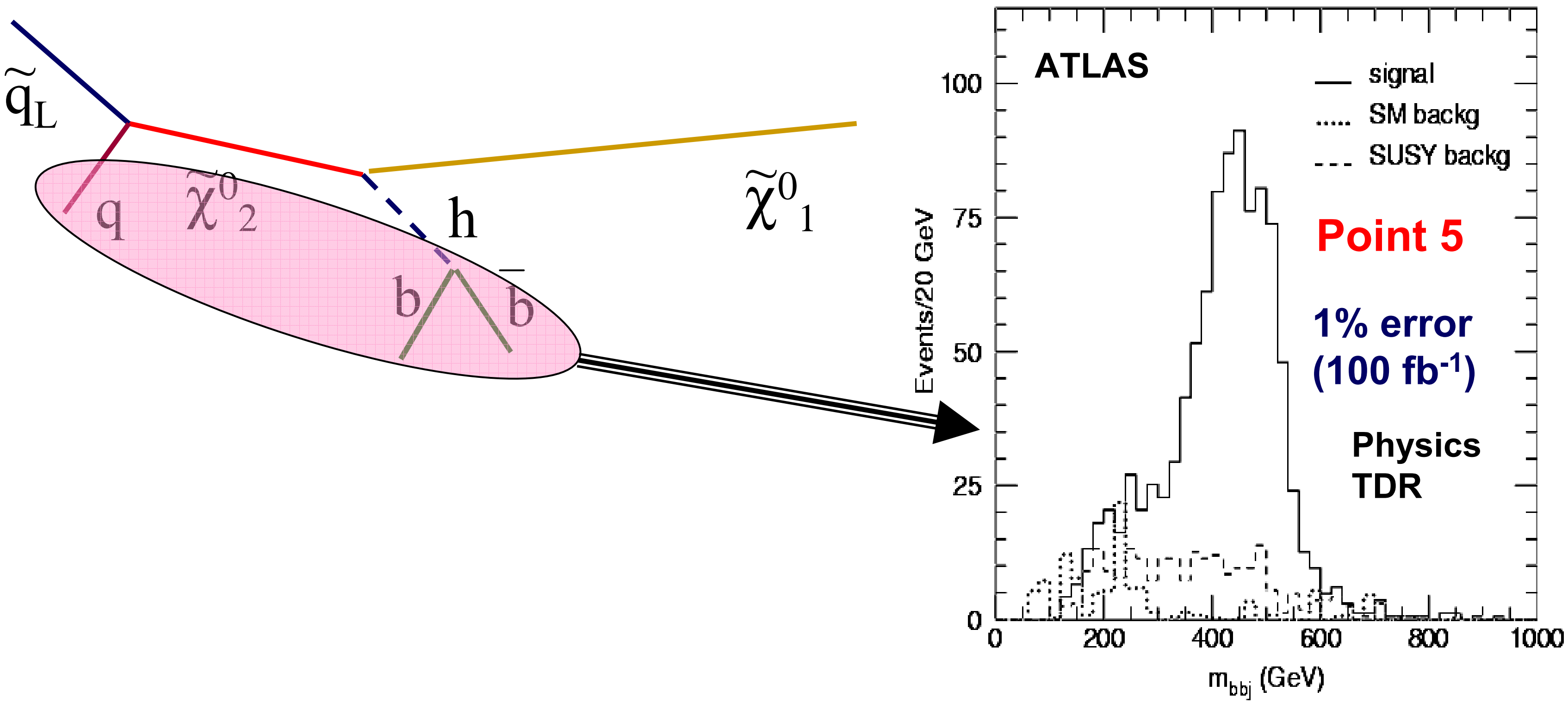


$$M_{lq}^{\max} = \left[\frac{(M_{q_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{l_R}^2)}{M_{\tilde{\chi}_2^0}^2}\right]^{1/2} = 479.3\ \text{GeV}.$$

- Construct distribution of invariant masses of 'slepton' jet with each lepton.
- 'Right' edge sensitive to slepton, squark and $\tilde{\chi}^0_2$ masses ('wrong' edge not visible).

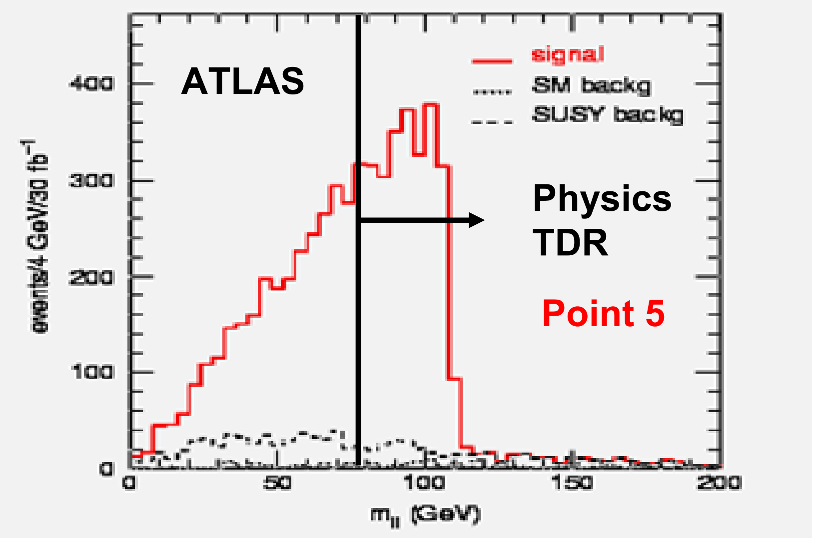
hq edge

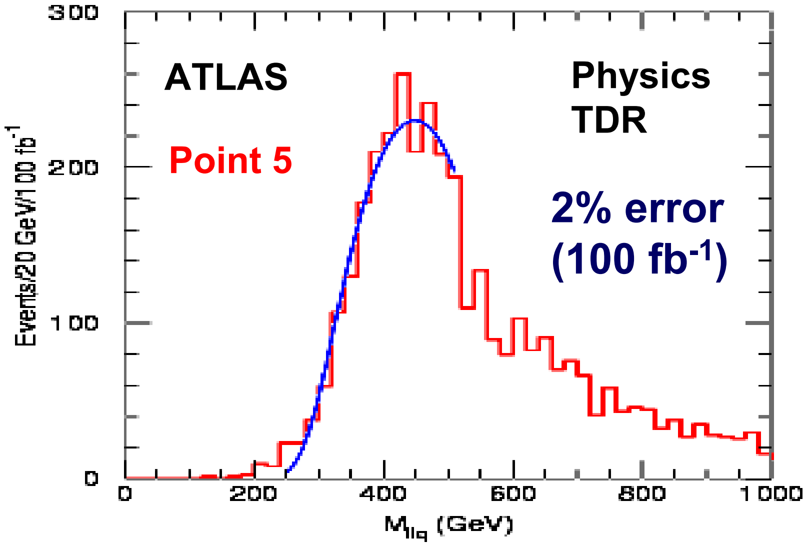
- If tan(β) not too large can also observe two body decay of $\tilde{\chi}^0_2$ to higgs and $\tilde{\chi}^0_1$.
- Reconstruct higgs mass (2 b-jets) and combine with hard jet.
- Gives additional mass constraint.



llq Threshold

- Two body kinematics of slepton-mediated decay chain also provides still further information (Point 5).
- Consider case where $\tilde{\chi}^0_1$ produced near rest in $\tilde{\chi}^0_2$ frame.
  - ➜ Dilepton mass near maximal.
  - ➜ p(ll) determined by p($\tilde{\chi}^0_2$).





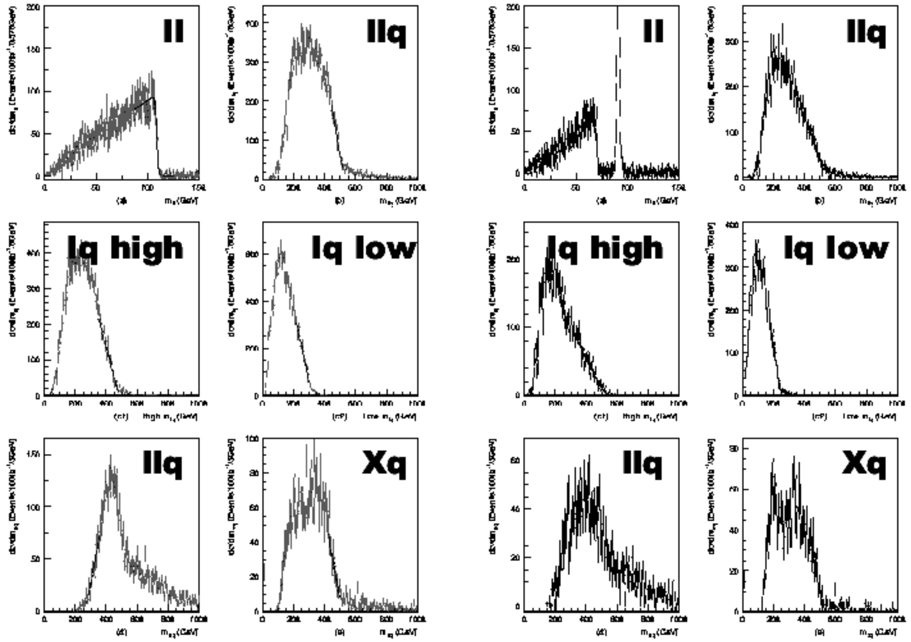
- Distribution of llq invariant masses distribution has maximum and <u>minimum</u> (when quark and dilepton parallel).
- llq threshold important as contains new dependence on mass of lightest neutralino.

Mass Reconstruction

- **Combine measurements from edges from different jet/lepton combinations.**

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	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})}{\tilde{\xi}}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\tilde{\chi})}{\tilde{l}}, \frac{(\tilde{q}\tilde{l}-\tilde{\xi}\tilde{\chi})(\tilde{\xi}-\tilde{l})}{\tilde{\xi}\tilde{l}}\right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\tilde{\chi} < \tilde{\xi}^2 \text{ and} \\ \tilde{\xi}^2\tilde{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}} - m_{\tilde{\chi}_1^0})^2. \end{cases}$
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	$\Delta M = m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$

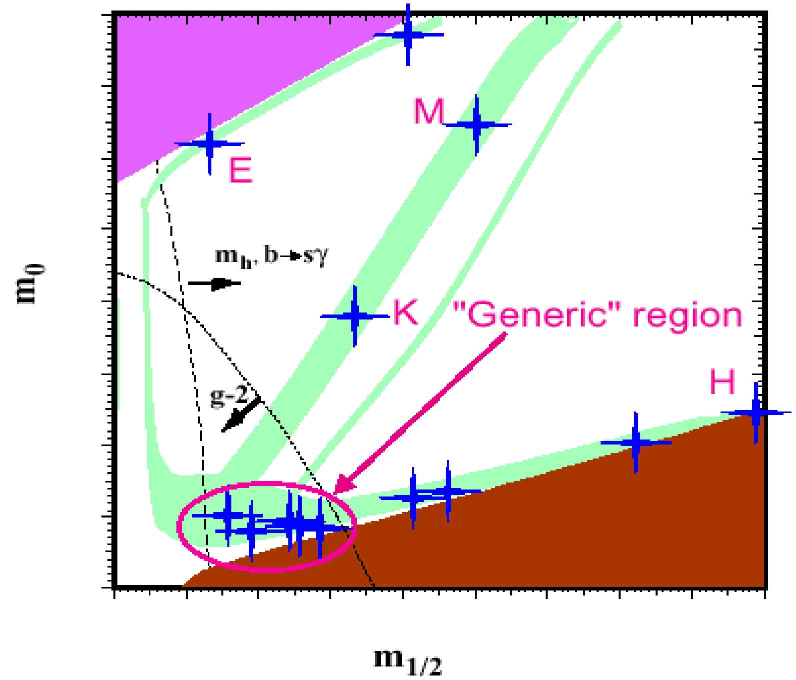
Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}$, $\tilde{l} = m^2_{\tilde{l}_R}$, $\tilde{\xi} = m^2_{\tilde{\chi}_2^0}$,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

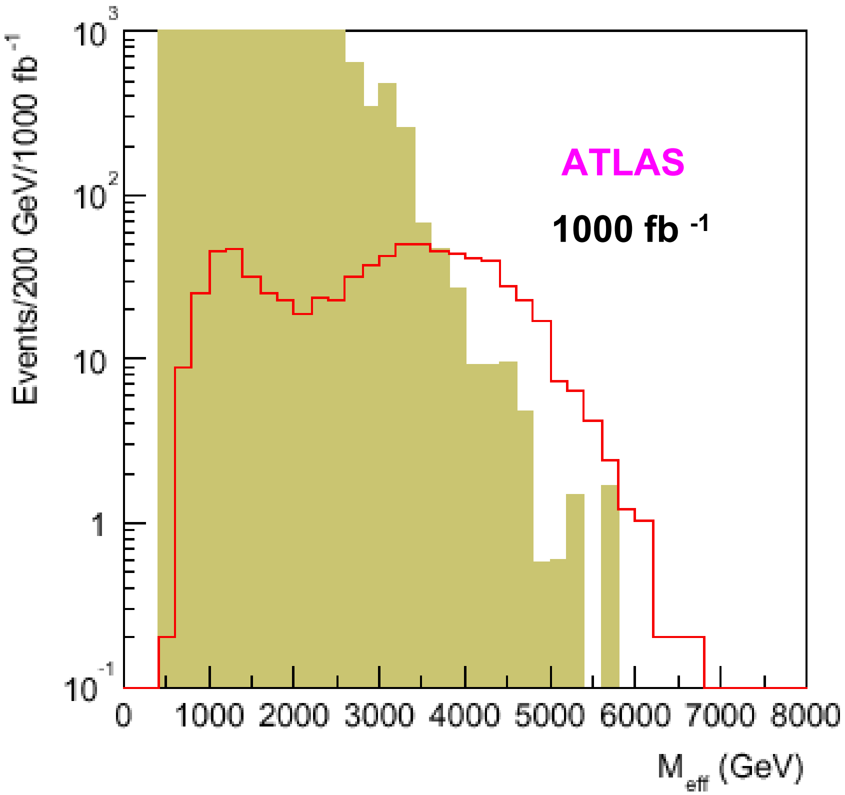


- **Gives sensitivity to masses (rather than combinations).**

High Mass mSUGRA

- ATLAS study of sensitivity to models with high mass scales
- E.g. CLIC Point K ➔ Potentially observable … but hard!

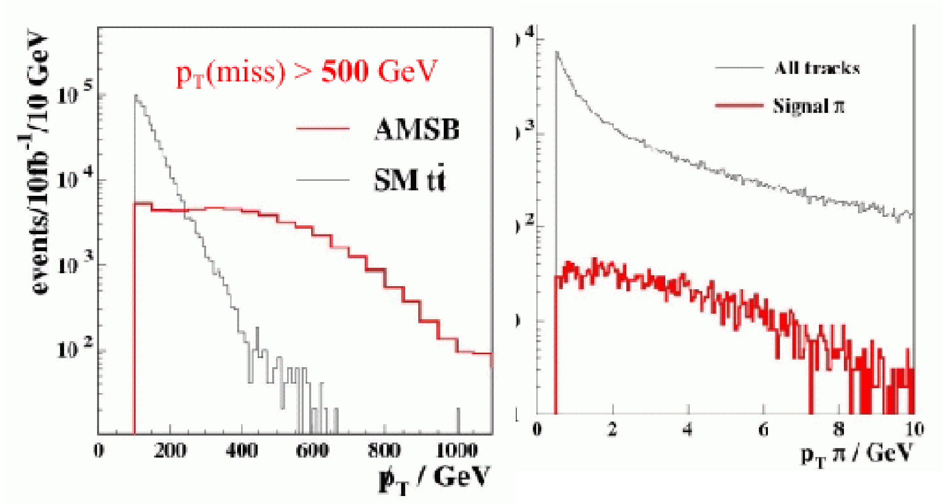


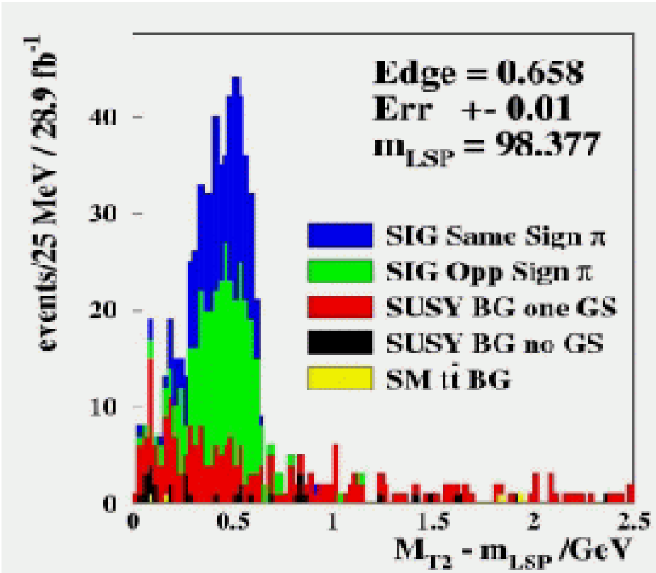


- Characteristic double peak in signal M_{eff} distribution (Point K).
- Squark and gluino production cross-section reduced due to high mass.
- Gaugino production significant

AMSB

- Examined RPC model with $\tan(\beta) = 10$, $m_{3/2}=36$ TeV, $m_0=500$ GeV, sign(μ) = +1.
- $\tilde{\chi}^{+/-}_1$ near degenerate with $\tilde{\chi}^0_1$.
- Search for $\tilde{\chi}^{+/-}_1 \rightarrow \pi^{+/-}\tilde{\chi}^0_1$ (Δm = 631 MeV → soft pions).

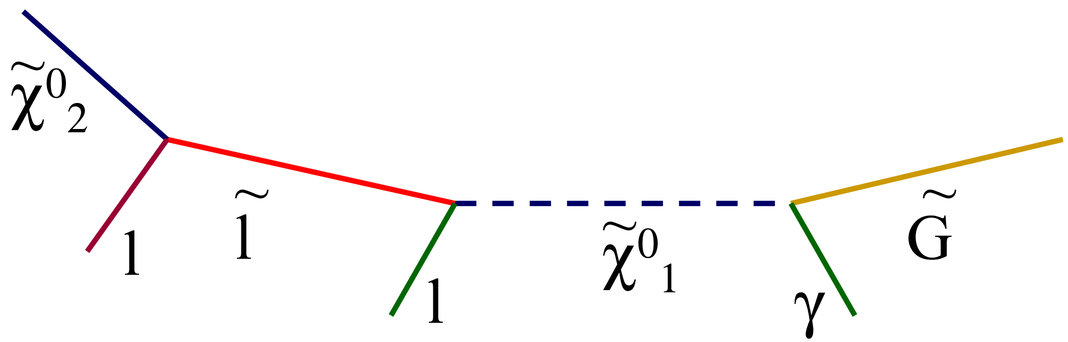




- Also displaced vertex due to phase space ($c\tau$=360 microns).
- Measure mass difference between chargino and neutralino using m_{T2} variable (from mSUGRA analysis).

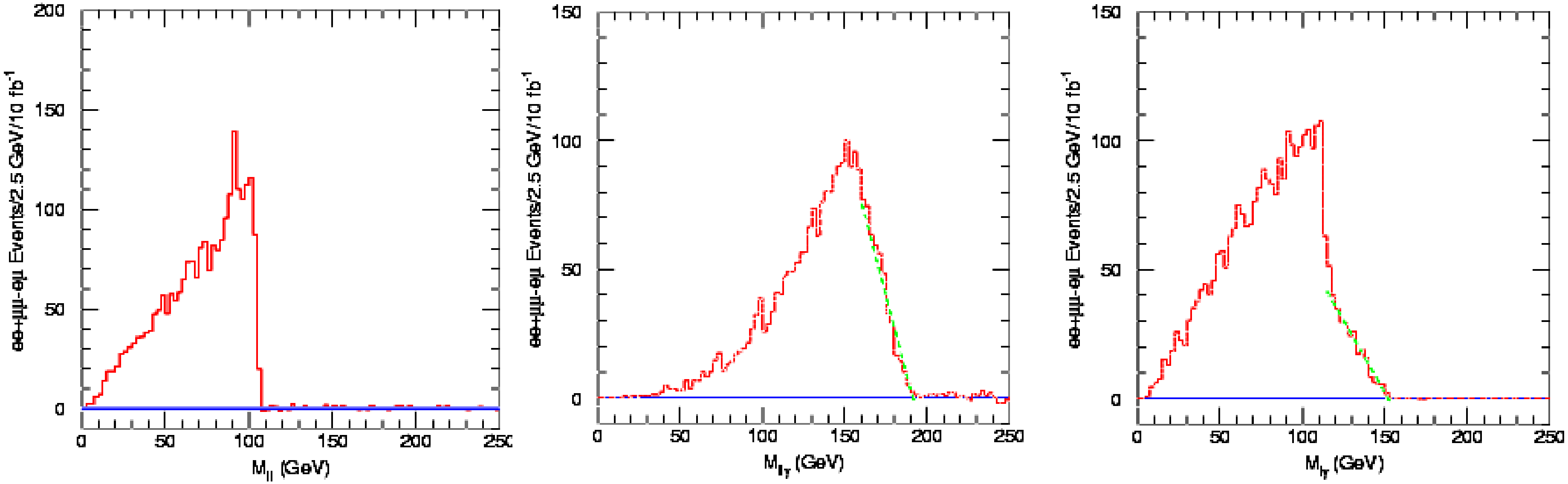
GMSB

- Kinematic edges also useful for GMSB models when neutral LSP or very long-lived NLSP escapes detector.
- Kinematic techniques using invariant masses of combinations of leptons, jets and photons similar.
- Interpretation different though.
- E.g. LHC Point G1a (neutralino NLSP with prompt decay to gravitino) with decay chain:



GMSB

- Use dilepton edge as before (but different position in chain).
- Use also lγ, llγ edges (c.f. lq and llq edges in mSUGRA).
- Get <u>two</u> edges (bonus!) in lγ as can now see edge from 'wrong' lepton (from χ^0_2 decay). Not possible at LHCC Pt5 due to masses.

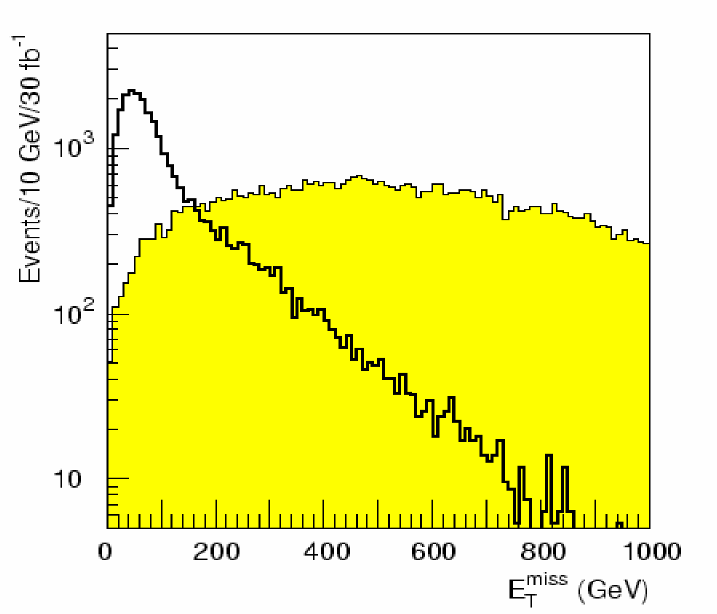


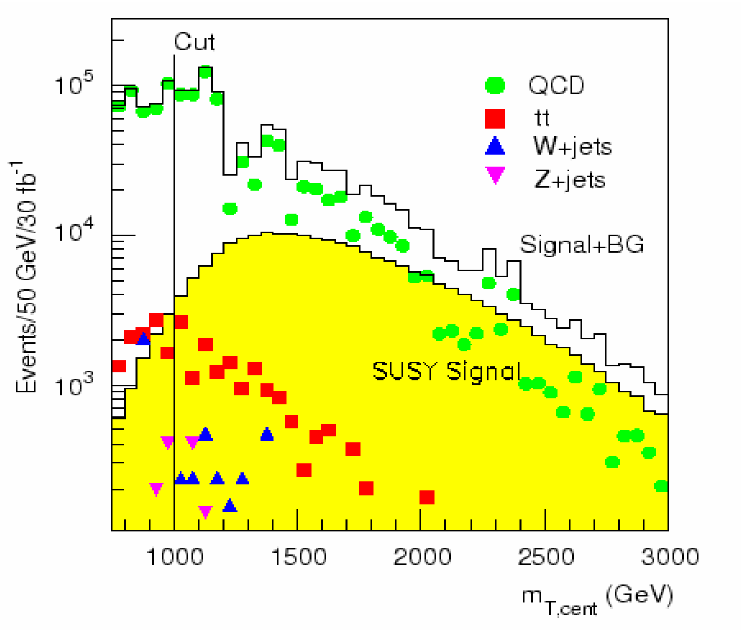
- Interpretation easier as can assume gravitino massless:

$$M^2_{\tilde{l}_R} = \frac{(M^{(1)}_{l\gamma})^2 (M^{(2)}_{l\gamma})^2}{(M^{\max}_{ll})^2} \quad M^2_{\tilde{\chi}^0_1} = M^2_{\tilde{l}_R} - (M^{(1)}_{l\gamma})^2 \quad M^2_{\tilde{\chi}^0_2} = M^2_{\tilde{l}_R} + (M^{(2)}_{l\gamma})^2 \quad (M^{\max}_{ll\gamma})^2 = (M^{(1)}_{l\gamma})^2 + (M^{(2)}_{l\gamma})^2 \,.$$

R-Parity Violation

- Missing E_T for events at SUGRA point 5 with and without R-parity violation
- RPV removes the classic SUSY missing E_T signature





- Use modified effective mass variable taking into account p_T of leptons and jets in event

$$m_{T,cent} = \sum_{\eta<2} p_T^{jet,lepton}$$

R-Parity Violation

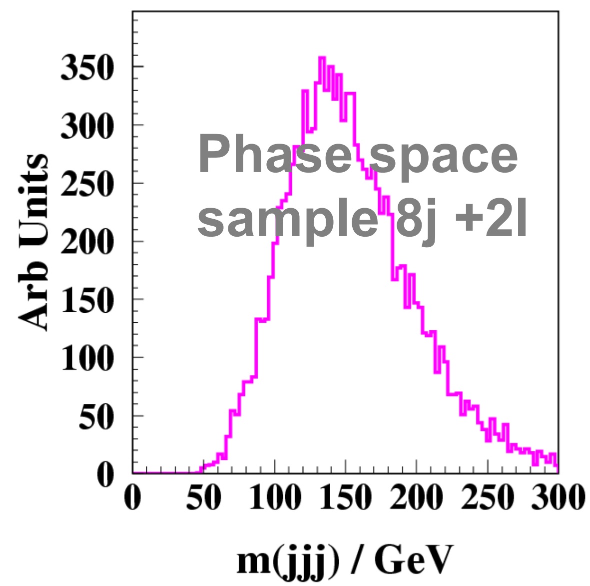
- **Baryon-Parity violating case hardest to identify (no leptons).**
  - **Worst case: λ''_{212} - no heavy-quark jets**
- **Test model studied with decay chain:**

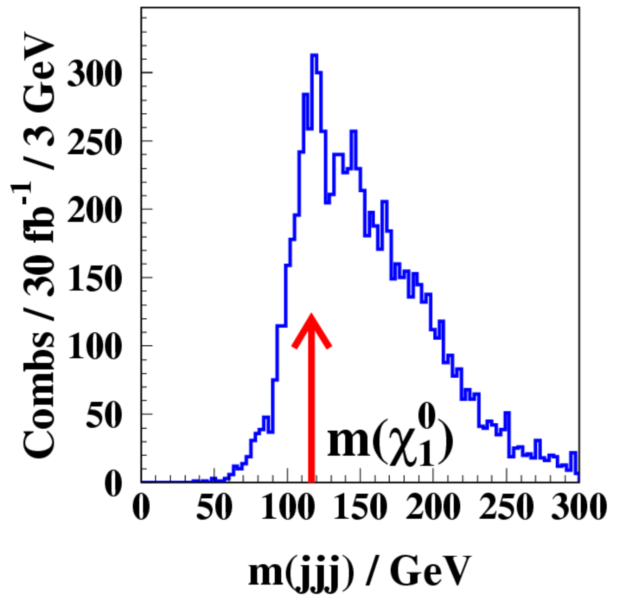
$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R l q \to \tilde{\chi}_1^0 l l q$$

- **Lightest neutralino decays via BPV coupling:**

$$\tilde{\chi}_1^0 \to cds$$

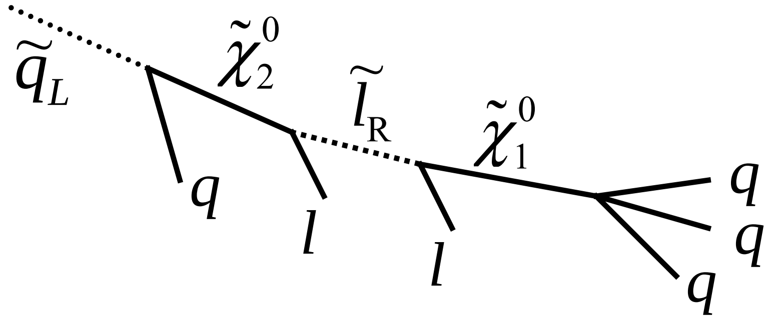
- **Reconstruct neutralino mass from 3-jet combinations (<u>but</u> large combinatorics : require > 8 jets!)**



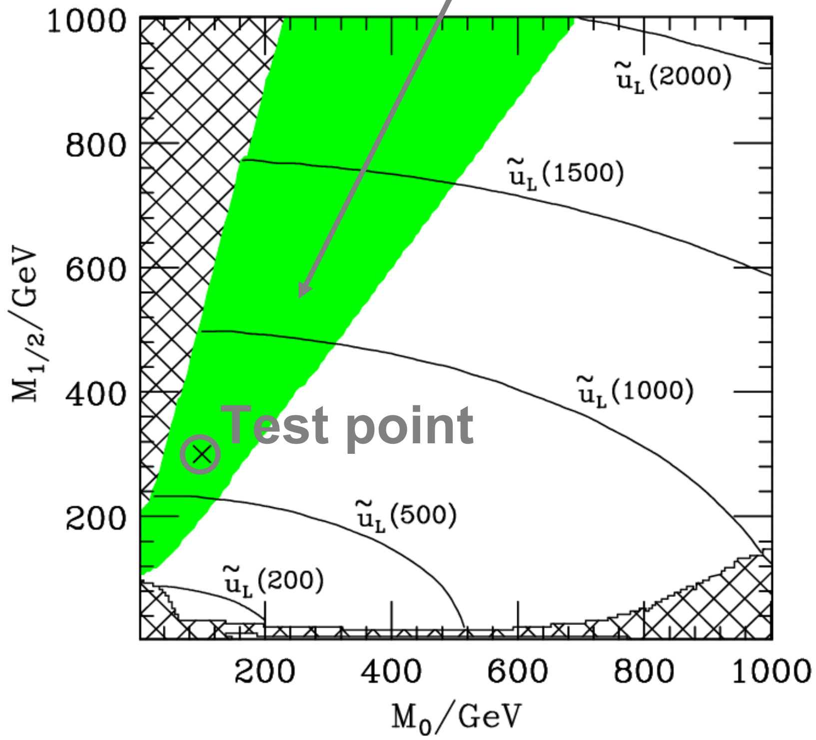


R-Parity Violation

- **Use extra information from leptons to decrease background.**
- **Sequential decay of $\tilde{q}_L$ to $\tilde{\chi}_1^0$ through $\tilde{\chi}_2^0$ and $\tilde{l}_R$ producing Opposite Sign, Same Family (OSSF) leptons**

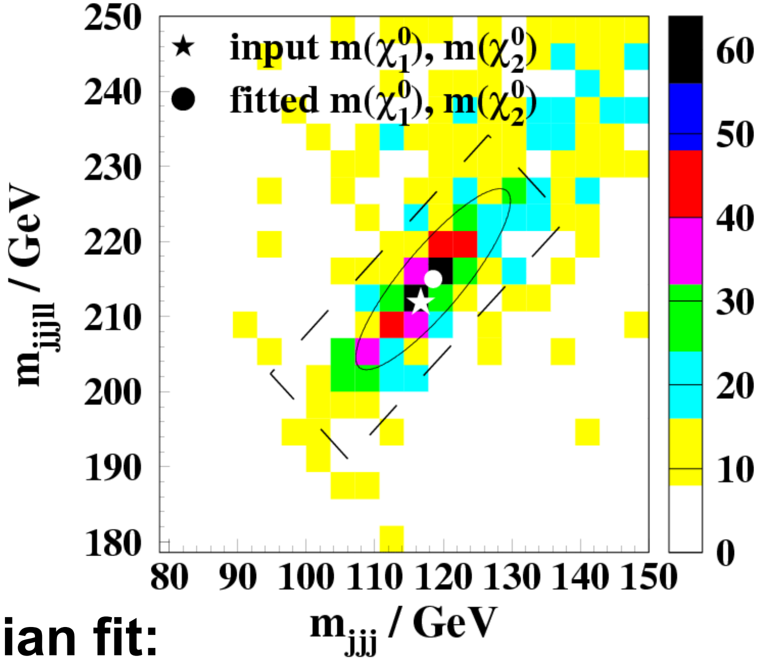


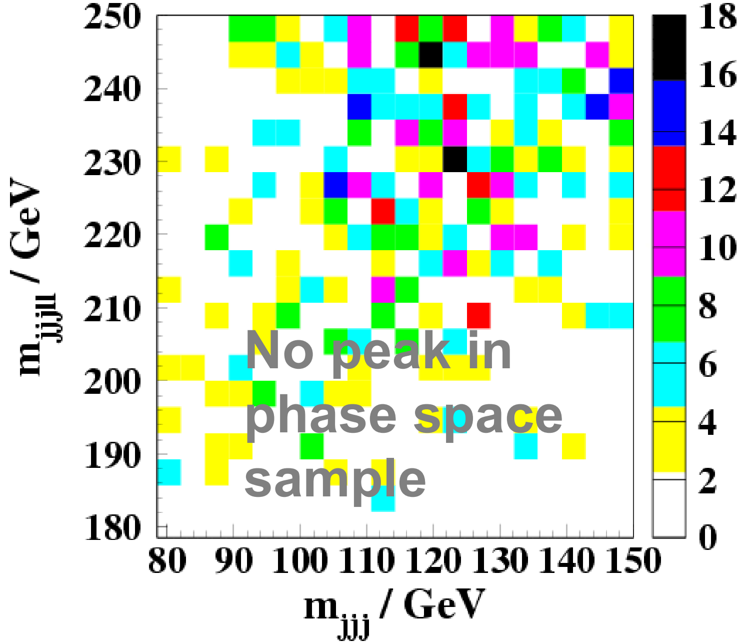
Decay via $\tilde{l}_R$ allowed where $m(\tilde{\chi}_2^0) > m(\tilde{l}_R)$



R-Parity Violation

- Perform simultaneous (2D) fit to 3jet and 3jet + 2lepton combination (measures mass of $\tilde{\chi}^0_2$).





Gaussian fit:

$m(\tilde{\chi}_1^0)$ = 118.9 ± 3 GeV, (116.7 GeV)

$m(\tilde{\chi}_2^0)$ = 218.5 ± 3 GeV (211.9 GeV)

- Jet energy scale uncertainty ≈ 3% ⇒ 3 GeV systematic

- Can also measure squark and slepton masses.

R-Parity Violation

- **Different λ"$_{ijk}$ RPV couplings cause LSP decays to different quarks:**

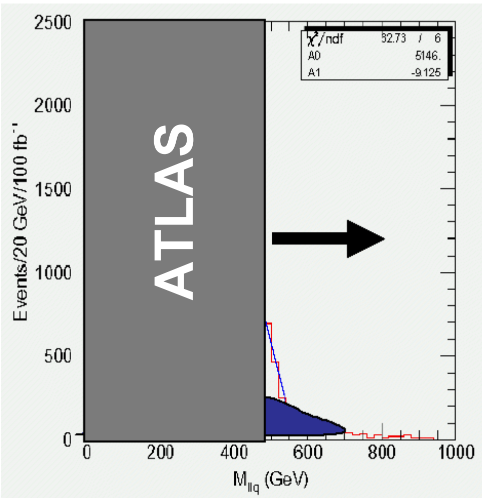
$$\tilde{\chi}_1^0 \rightarrow q_1 q_2 q_3$$

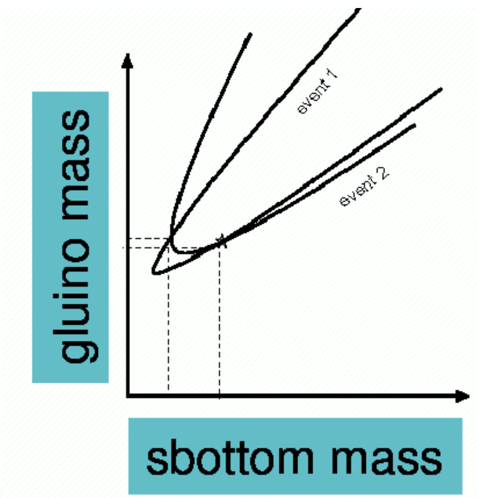
- **Identifying the dominant λ" gives insight into flavour structure of model.**
- **Use vertexing and non-isolated muons to statistically separate *c*- and *b*- from light quark jets.**
- **Remaining ambiguity from *d*↔*s***
- **Dominant coupling could be identified at > 3.5 σ**

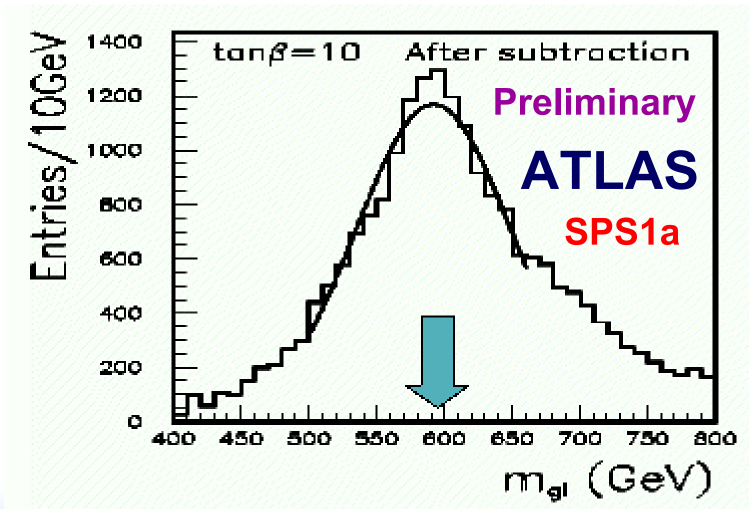
Distinguishing		Vertexing		Muons		Combined
λ''_{ijk} from λ''_{lmn}		χ^2 / df	P / %	χ^2 / df	P / %	σ
uds	udb	59.1/1	-	28.7/1	-	9.4
	usb	73.0/1	-	31.7/1	-	10.2
	cds	30.5/1	-	4.0/1	4	5.9
	cdb	106.9/1	-	47.2/1	-	12.4
	csb	113.4/1	-	49.2/1	-	12.8
udb	usb	1.6/2	44	0.4/1	54	1.4
	cds	10.3/2	1	13.0/1	-	4.8
	cdb	18.3/2	-	6.8/2	3	5
	csb	16.3/2	-	5.1/2	8	4.6
usb	cds	17.5/2	-	17.2/1	-	5.9
	cdb	12.1/2	-	5.1/1	2	4.2
	csb	9.9/2	1	3.1/1	8	3.6
cds	cdb	56.1/2	-	37.4/1	-	9.7
	csb	55.8/2	-	35.3/1	-	9.5
cdb	csb	0.6/2	72	1.3/2	51	1.4

Mass Relation Method

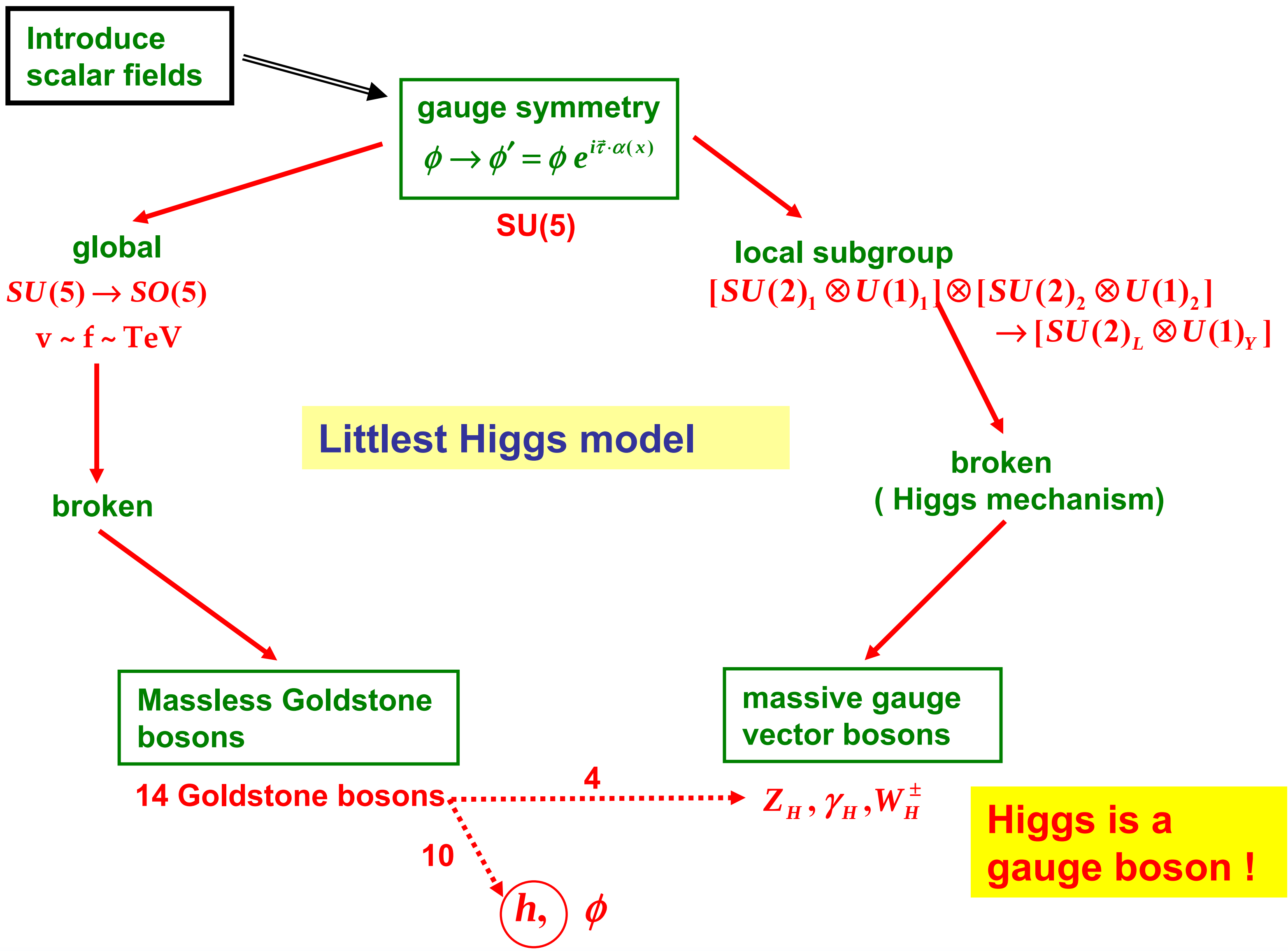
- New(ish) idea for reconstructing SUSY masses!
- 'Impossible to measure mass of each sparticle using one channel alone' (Slide 10).
  - Should have added caveat: Only if done event-by-event!
- Assume in each decay chain 5 inv. mass constraints for 6 unknowns (4 $\tilde{\chi}^0_1$ momenta + gluino mass + sbottom mass).
- Remove ambiguities by combining different events analytically → 'mass relation method' (Nojiri et al.).
- Also allows all events to be used, not just those passing hard cuts (useful if background small, buts stats limited – e.g. high scale SUSY).







Little Higgs



Littlest Higgs Model

In $SU(2)_L \times U(1)_Y$ basis, $(2\tau+1)_{Y/2}$

X	Y	1_0	3_0

$\rightarrow$ eaten $\Rightarrow$ 4 heavy bosons: $Z_H, \gamma_H, W_H^{\pm}$

$Q = \tau_3 + \frac{Y}{2}$

h	$h^\dagger$
$2_{1/2}$	$2_{-1/2}$

$\rightarrow$ complex higgs doublet, massless

vev for h $\rightarrow$ triggers EW symm. breaking $\rightarrow$ mass to Z, W, h massless

ϕ	$\phi^\dagger$
3_1	3_{-1}

$\rightarrow$ complex triplet

acquires mass from one-loop gauge interactions

$W_H^{\pm}, Z_H, \gamma_H : \sim 1$ TeV

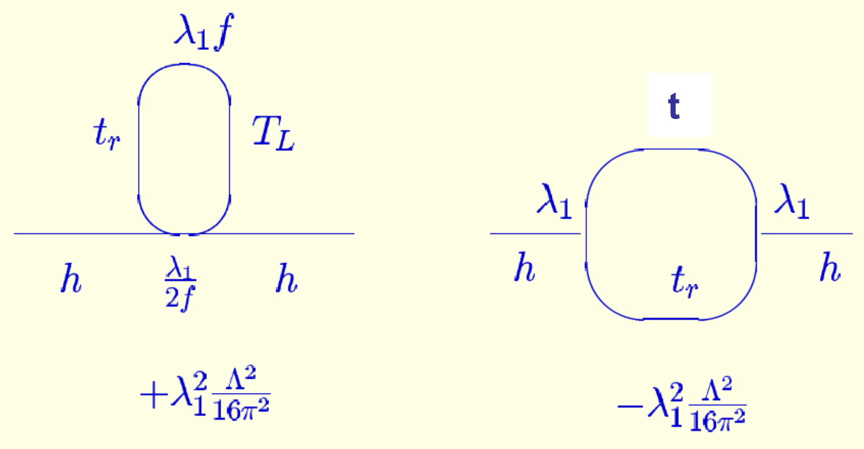
$T : \sim 1$ TeV

$\phi^{\pm\pm}, \phi^{\pm}, \phi^0 : \sim 10$ TeV

1-loop gauge interactions:

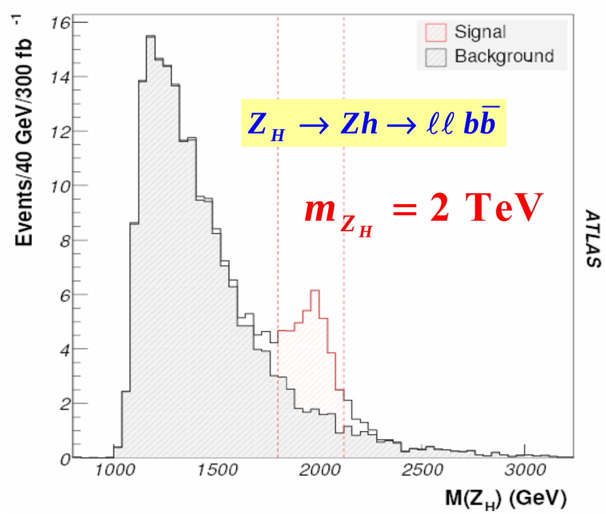
To cancel the top loop, introduce $SU(2)_L$ singlet quark T_L, and T_R $\rightarrow$

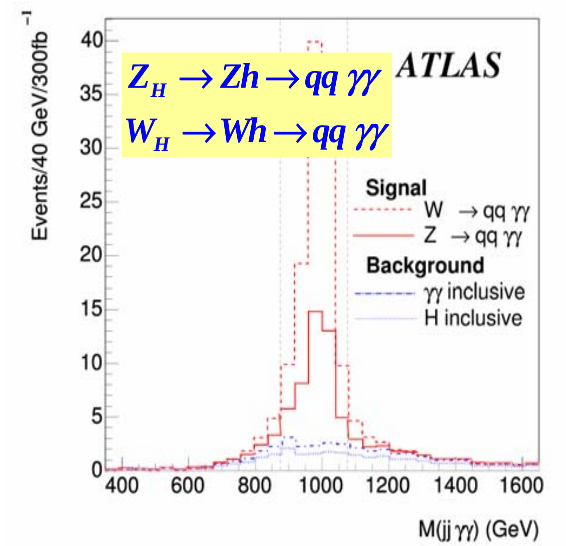
$$\lambda_1 (iQht_r + fT_L t_r hh^\dagger) + \lambda_2 f (T_L T_R)$$

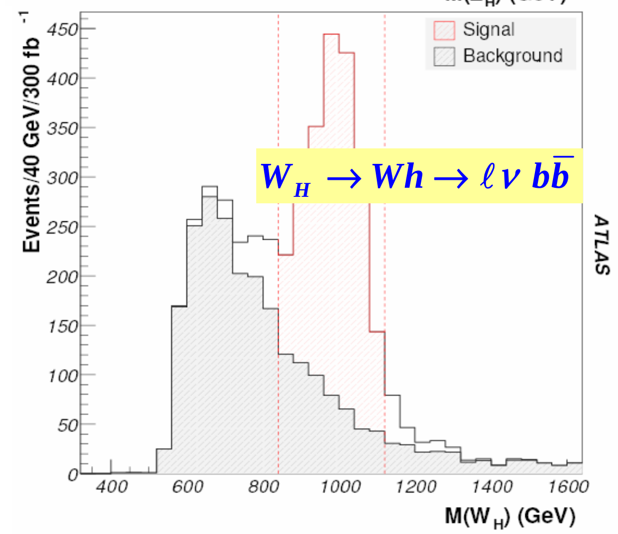


Higgs-Gauge Boson Couplings

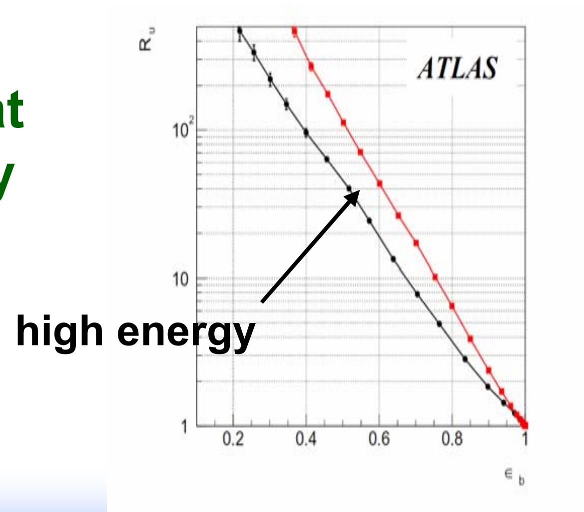
- **Measurement of $Z_H Zh$ and $W_H Wh$ couplings needed to test model**





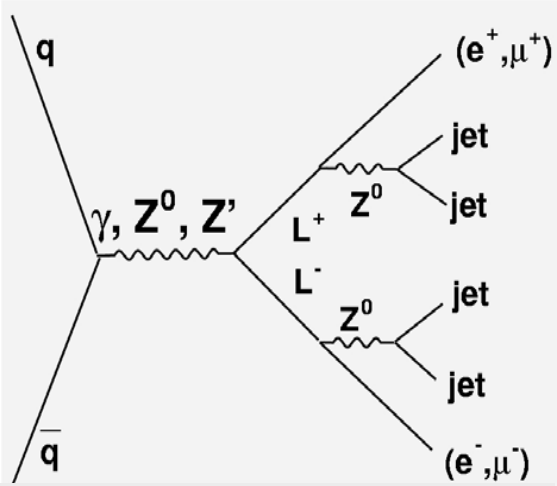


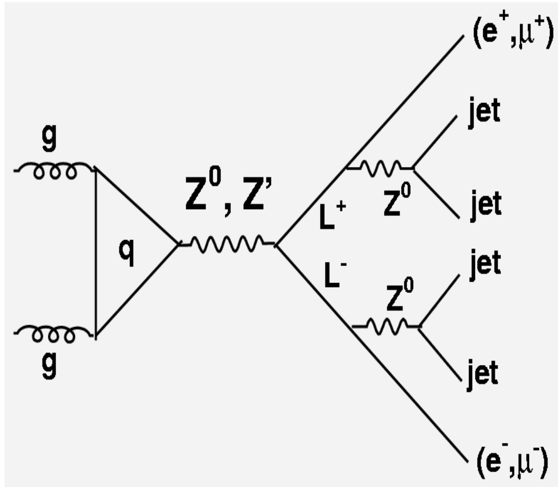
B-tagging at high energy needed



Heavy Leptons

- Extra heavy leptons present in many extended gauge models.
- Study l^+l^-+4j channel.
- Backgrounds from ttbar, WZ, WW, ZZ.
- Also 6 lepton channel.





Experimental considerations:
- high energy leptons, jets

Systematics:
- large NLO corrections

conclusion:

ATLAS can discover sequential charged heavy leptons up to M_L = 0.9 / 1.0 TeV (low/high luminosity)

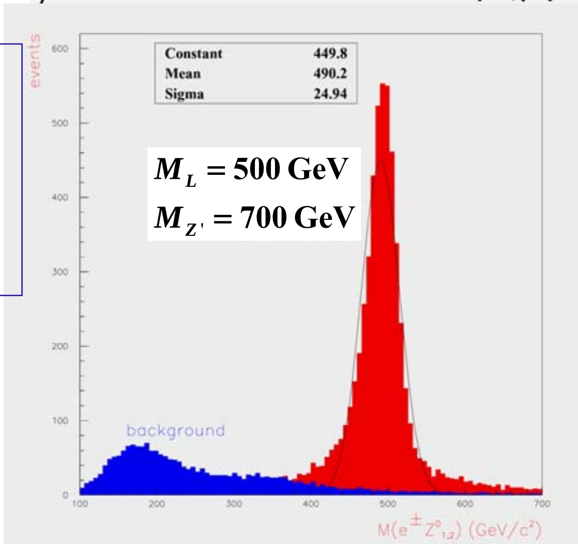
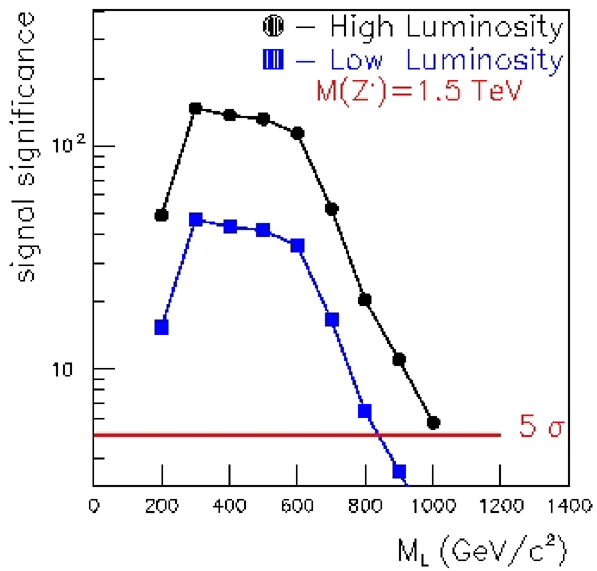
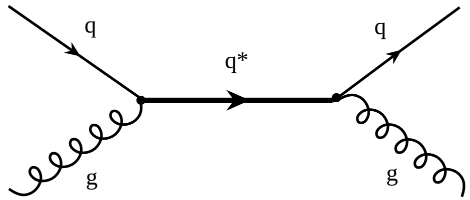


Figure 13: Signal to background comparison for M_L = 0.5 TeV/c^2 and $M_{Z'}$ = 0.7 TeV/c^2, for $L \to e + Z^0$ channel.



Excited Quarks

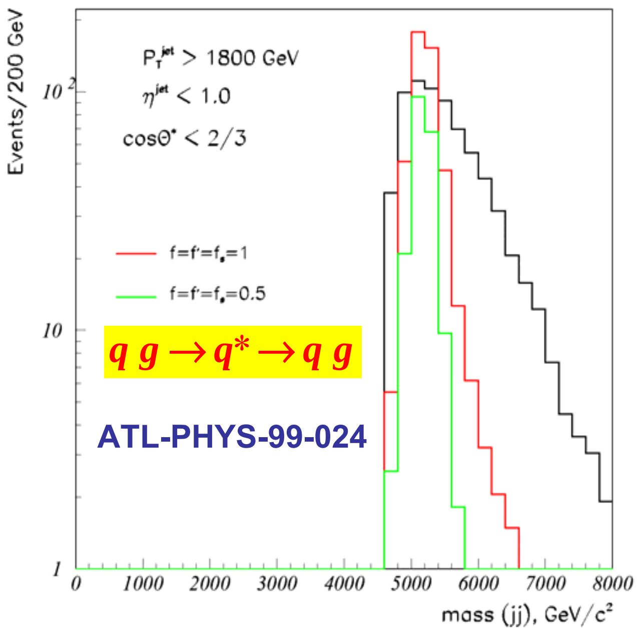


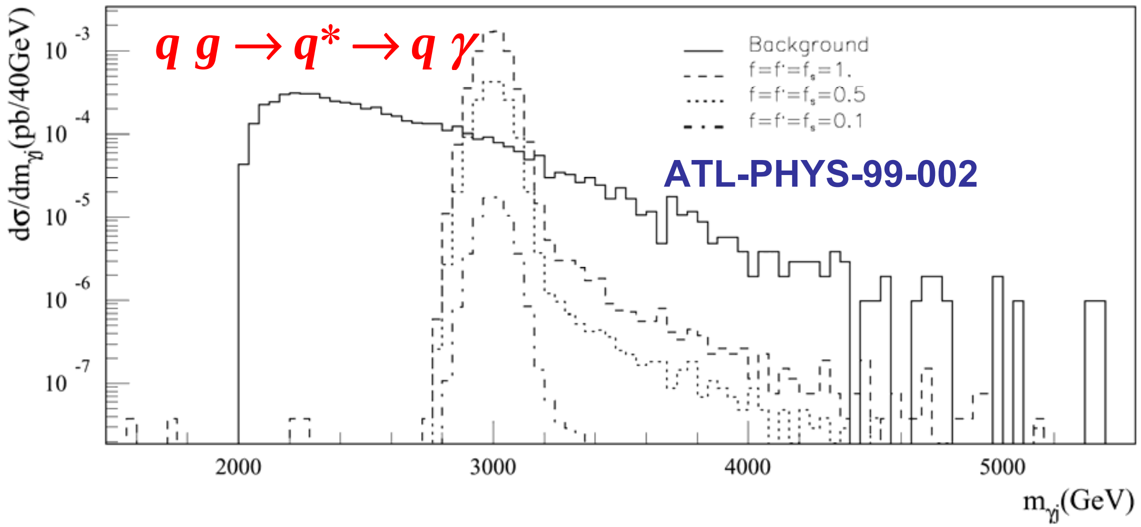
$$L = \frac{1}{2\Lambda} \bar{q}^*_R \sigma^{\mu\nu} \left(g_s f_s G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) q_L + h.c.$$

take as reference : $\Lambda = m^*, \quad f_s = f = f' = 1$

O. Çakir, C. Leroy, R. Mehdiyev,
ATL-PHYS-2002-014

m^*(GeV)	Δm_{jj}(GeV)	S	B	S/B	$S/\sqrt{B}$
1000	170	12396806	16870000	0.73	3018
2000	320	858214	525000	1.63	1184
3000	445	37635	23500	1.60	245
5000	705	601	325	1.85	33
6000	880	75	60	1.25	9.6

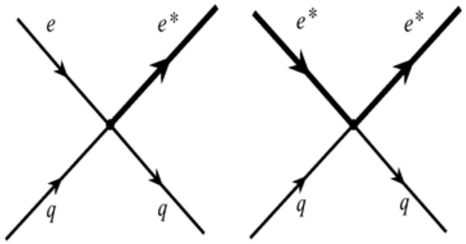




Also : $q^* \to qZ; \quad q^* \to \bar{q}'W$

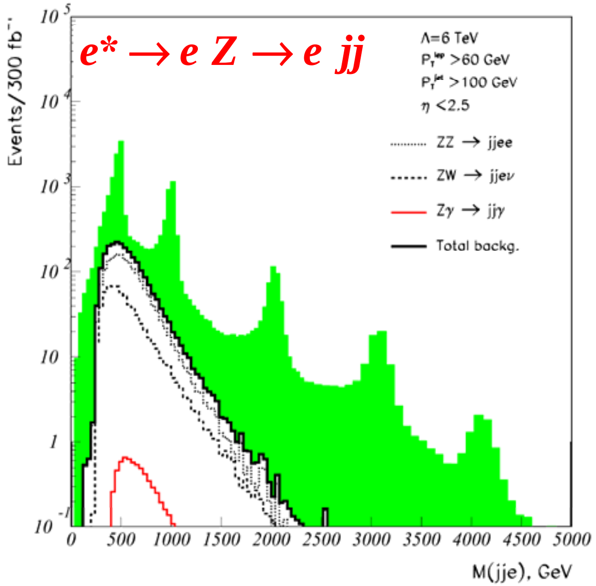
Excited Leptons

contact interaction : $L_C = \frac{g_*^2}{2\Lambda^2} J_\mu J^\mu$

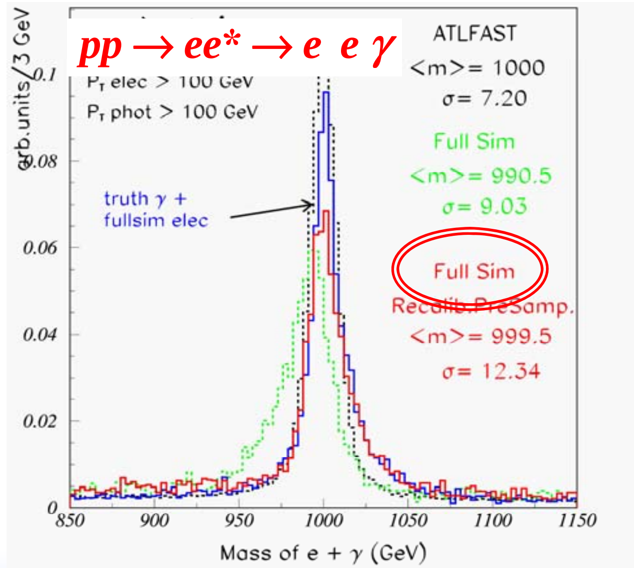


Experimental considerations:
- **high energy e, γ**
- **Z → jj, W → jj**

L = 300 fb^{-1}, Λ = 6 TeV



$m^\star \to$	500	1 TeV	2 TeV	3 TeV	4 TeV
$q\bar{q} \to e^\star e \to Zee \to eeee$					
ΔM, GeV	20	38	63	84	
S	242	121	17	2	
S/B	25	76	283	333	
$S/\sqrt{B}$	77	96	69	26	
$q\bar{q} \to e^\star e \to Zee \to eejj$					
ΔM, GeV	40	60	106	180	200
S	4725	2388	358	54	6
S/B	3	16	48	67	-
$S/\sqrt{B}$	121	192	131	60	-

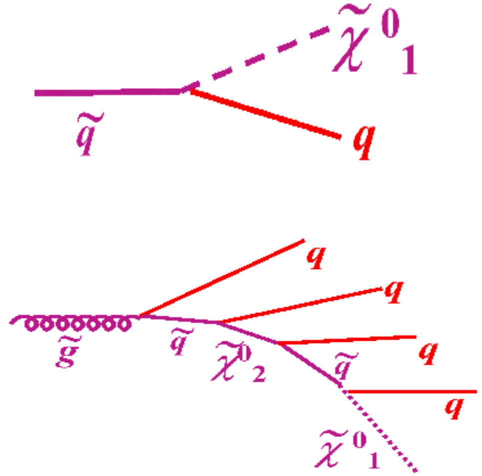


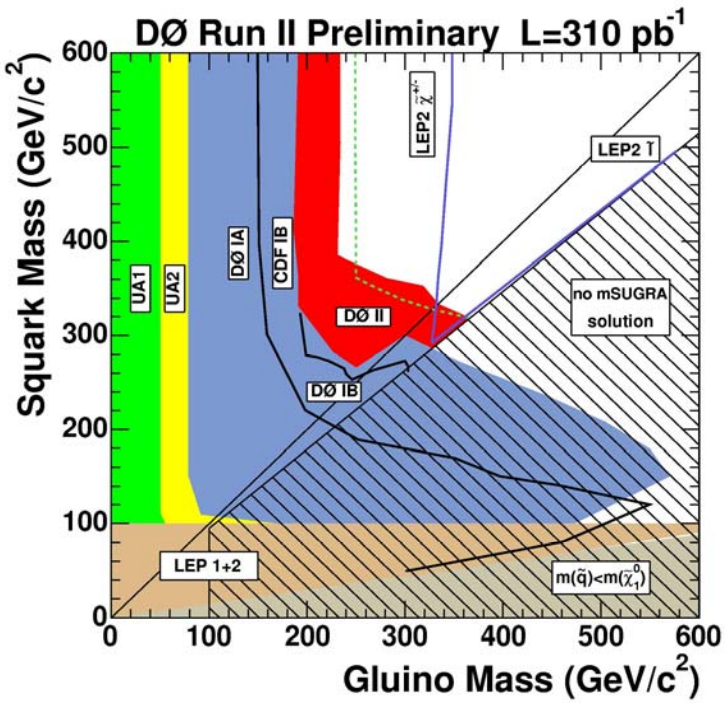
MET + jets: squark and gluino

Generic squarks and gluinos strongly produced
Cross section @ Tevatron: ~ a few pb

Expect cascade decays

Signature: lots of MET and ≥ 2 jets





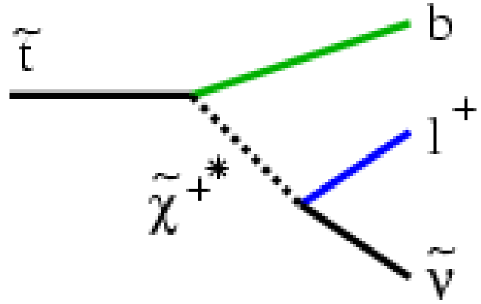
Results from D0: (310 pb^{-1}) 2, 3, or 4 jets
CDF: (250 pb^{-1}) ≥ 3 jets
Dominant backgrounds
Z+jets, W+jets, tt, QCD

- QCD fitted or cross checked with data
- MET cut > [75;175] GeV

Both experiments see no hints of SUSY

Search for Scalar top

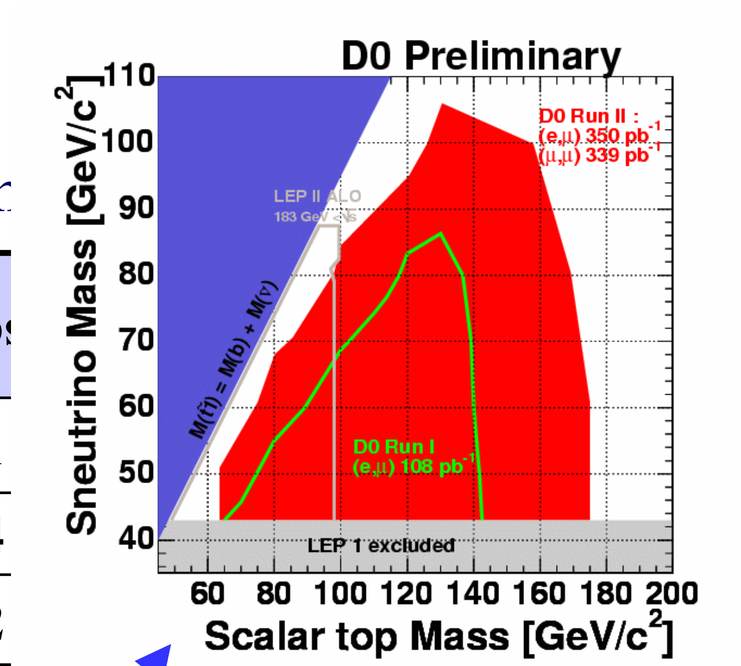
Look for pair production of lightest stop quark
Assume equal BR to e, μ,τ, and $\tilde{\nu} \to \nu \tilde{\chi}^0_1$
LEP limit: $m_{\tilde{\nu}} \geq 45$ GeV
Event signature:



cut on N non-iso tracks → 2 b-jets, $e^{\pm}\mu^{\mp}$ + MET

Signal regions optimized for $\Delta M = m_{\tilde{t}}$ - m

L=350 pb^{-1}	Signal	SM expected	Obs
ΔM: 20-40 GeV	16.43±1.07	22.99±3.10	21
ΔM: 50-60 GeV	18.28±0.72	34.63±3.96	34
ΔM: > 70 GeV	16.70±0.51	40.66±4.38	42



Limit combining with previous result in the μμ channel

Stopped gluinos

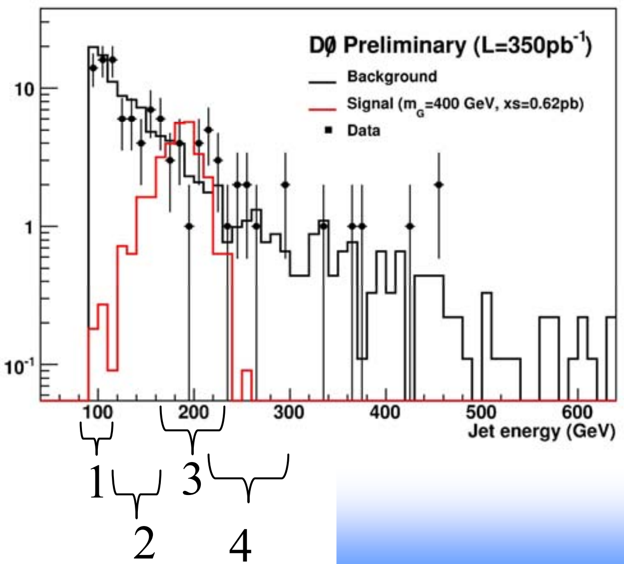
Assume M_{SUSY}(scalars) >> M_{SUSY}(fermions)

$\Rightarrow$ gluino can have long lifetime and hadronize ("R-hadrons")

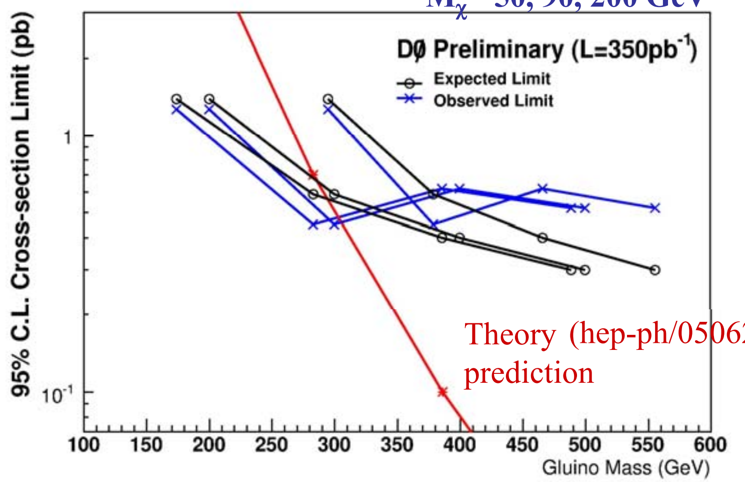
If lifetime > 10 μs:

- fraction of $\tilde{g}$'s stopped in calorimeters
- stopped gluino $\rightarrow g + \tilde{\chi}_1^0$ — no good vertex
- later bunch crossing: single high E_T shower and high MET

Background: cosmic muons

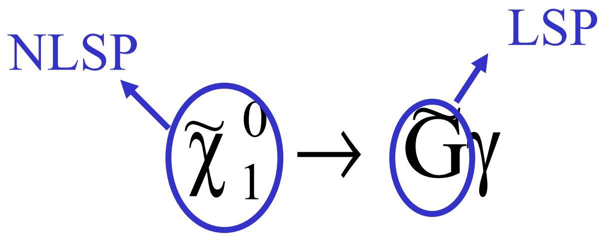


	Bkg	Obs
1	48	46
2	38	32
3	22	27
4	10	14



MET + photons

In Gauge Mediated SUSY breaking models, LSP is gravitino.
Typical signature from χ decay:

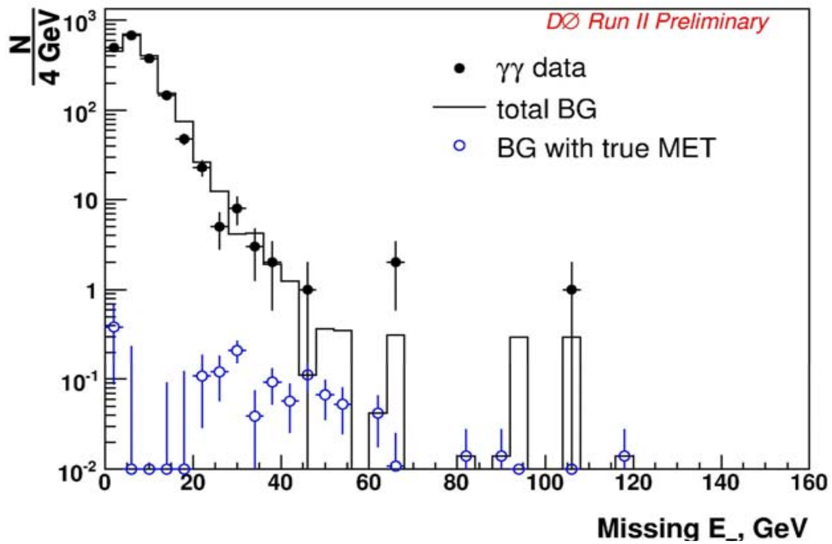


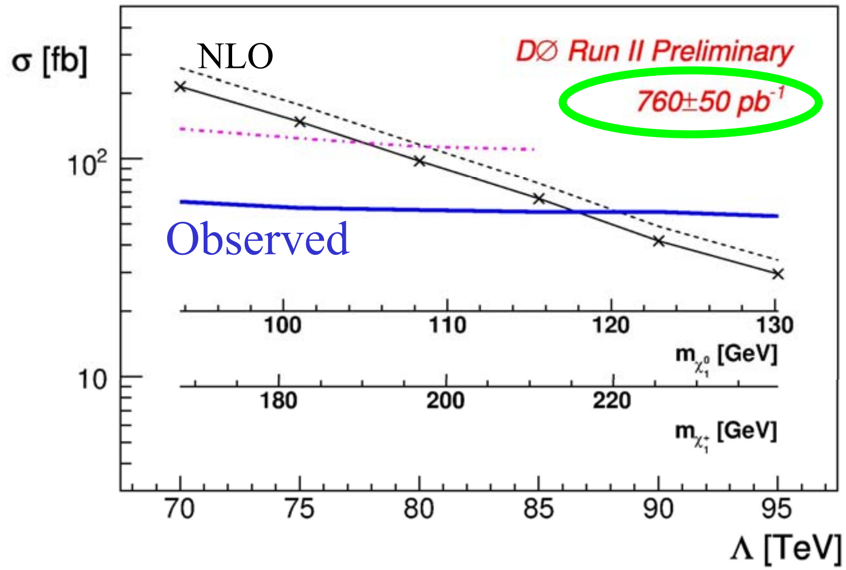
Assume prompt decay

Signature: 2 energetic photons + MET

QCD background normalized to data below MET of 12 GeV
Observe 4 events with MET≥45 GeV
Expecting 2.1±0.7 with 760pb^{-1}

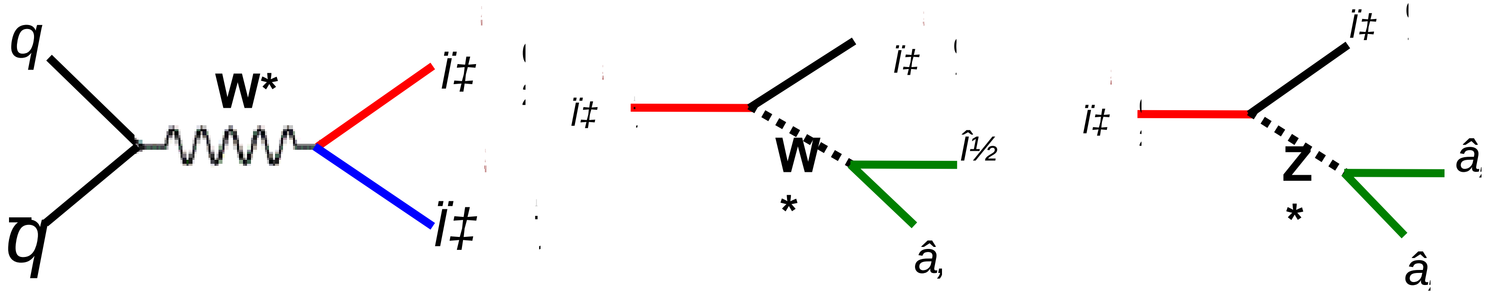
New limit: m($\tilde{\chi}_1^{\pm}$)≥ 220 GeV
Previous limit (CDF + D0): 209 GeV



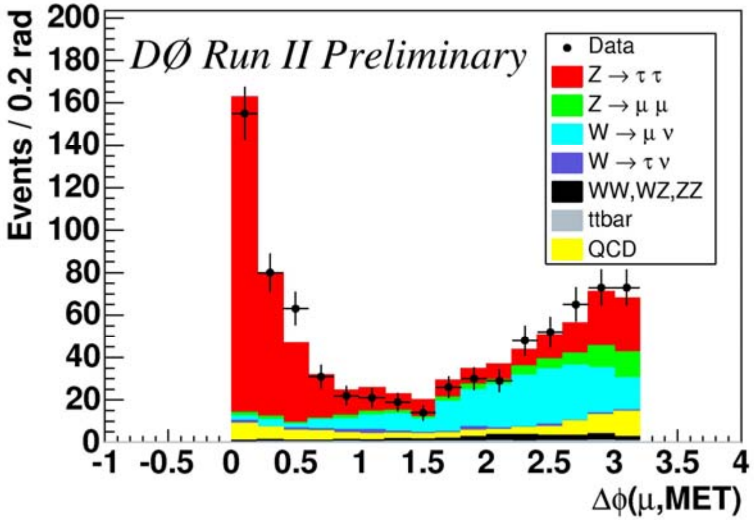


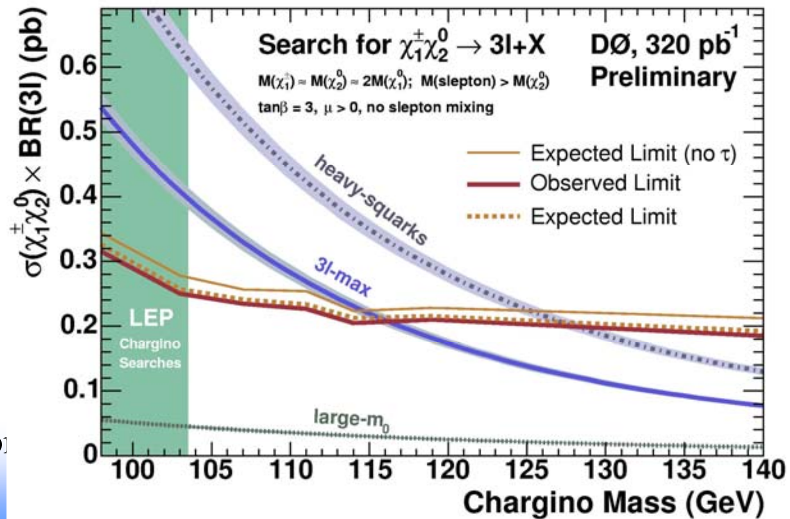
MET + 3 leptons

Expected signature from chargino-neutralino production
Clean signature very attractive for the Tevatron



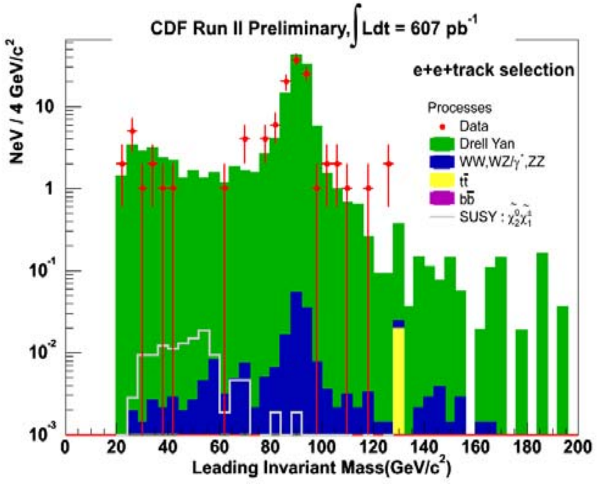
D0, 6 channels: **Expects: 3.85±0.75, Observes : 4. Signal would be 3-10 events**

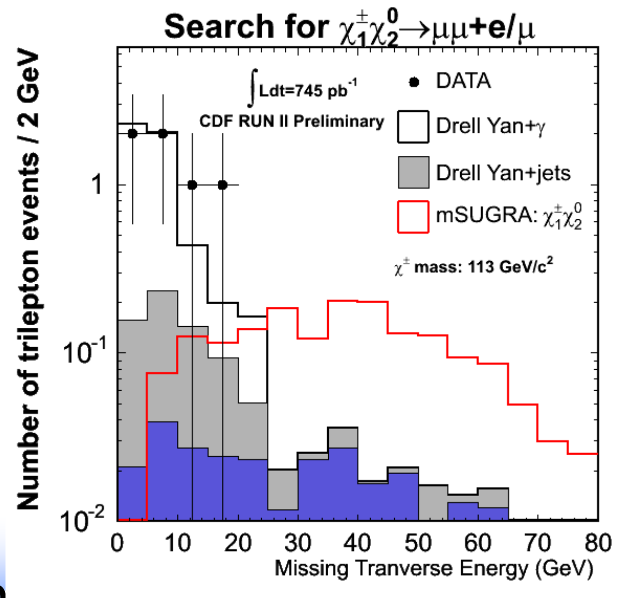




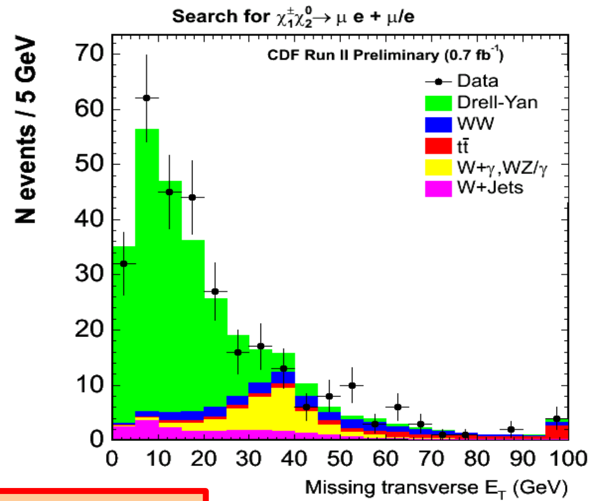
3 leptons: continued

Channel	Example signal	SM expected	Obs
μμ/e +l (0.7fb^{-1})	2.3±0.3	1.2±0.2	1
ee+l (350pb^{-1})	0.5±0.06	0.2±0.05	0
μμ+l (low pt) (320pb^{-1})	0.2±0.03	0.1±0.03	0
ee+trk (600pb^{-1})	0.7±0.03	0.5±0.1	1





CDF:
All observations in agreement with SM predictions



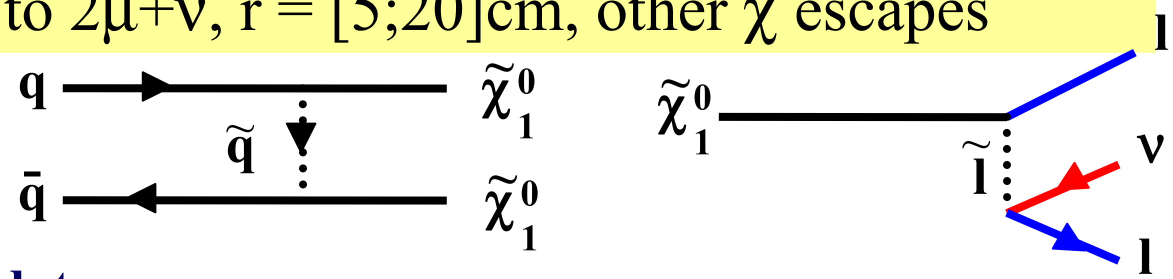
Stay tuned for updated limits!

76

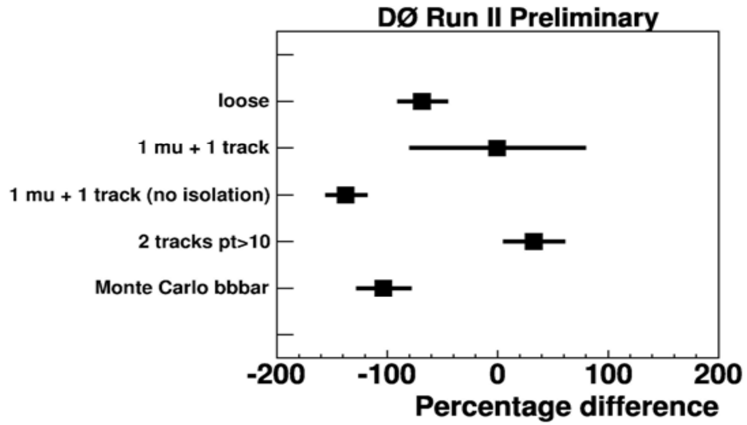
$\not{R}_P$ SUSY: Long-lived LSP

Scenario: Weak R_P violation (inspired by NuTeV dimuon excess)
Low mass LSP decays to $2\mu+\nu$, r = [5;20]cm, other χ escapes

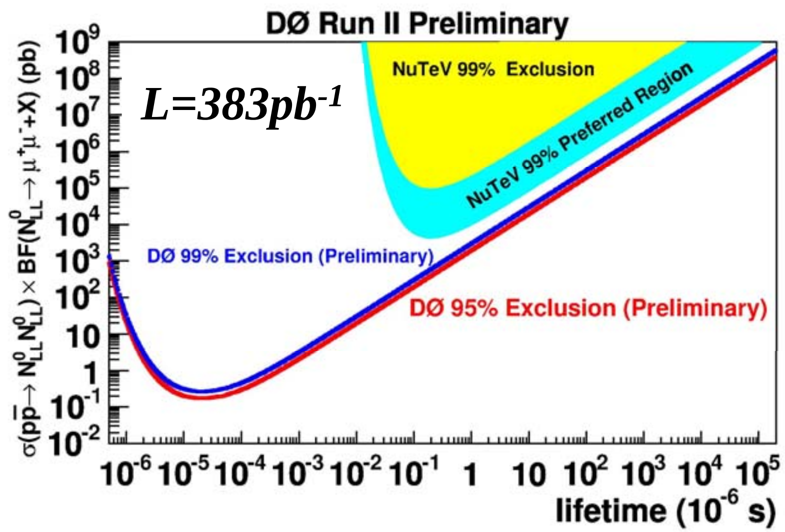
(~5 GeV)



- ✓Bkg estimated from data
- ✓Several cross checks
- ✓Diff as systematics



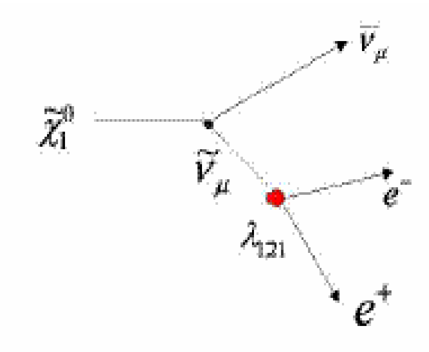
Now excluding that these events are SUSY χ :



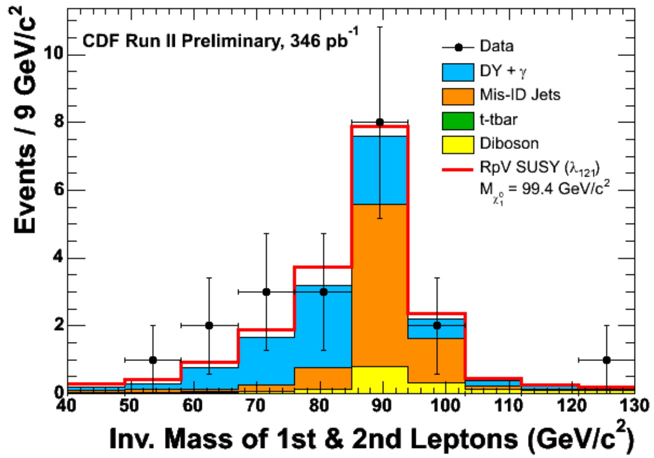
Expect 0.8±1.5 events, observe 0

$\not{R}_P$: 4 leptons

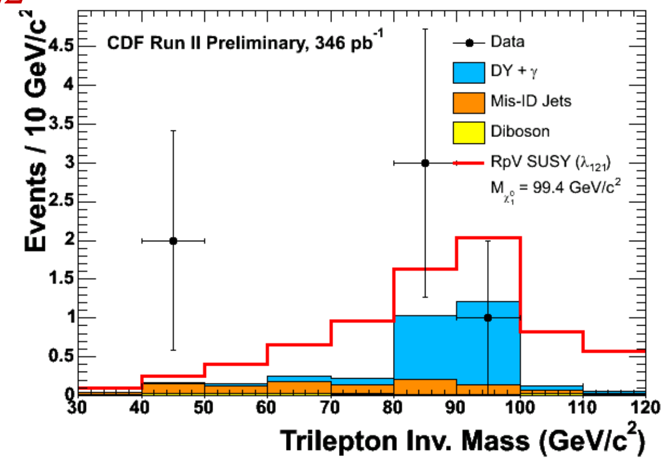
Now assume prompt decay
$\geq$4 leptons from $\tilde{\chi}\tilde{\chi}$ decays
Analysis also looked at 3 leptons



Yukawa term:
$\lambda_{ijk}L_iL_jE_k$
Analysis accepts e and μ
$\Rightarrow$ sensitive to λ_{121} and λ_{122}



Trilepton control regions

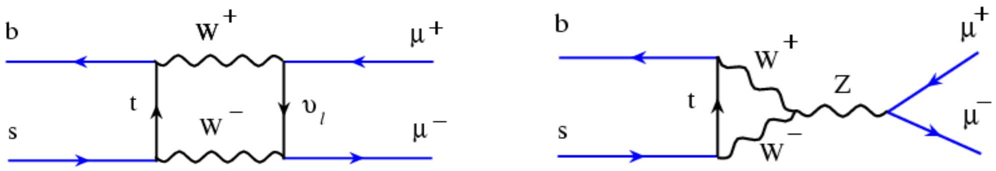


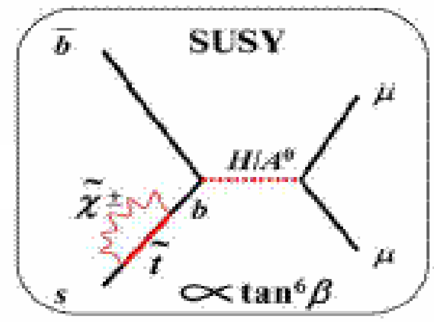
Striking signature, virtually no SM background
No cut on MET or N jets
Expects 1.5±0.2 signal, <0.01 SM, observes 0

$\Rightarrow$ Limits on λ_{121}: $\sigma < 0.21$ pb
λ_{122} : $\sigma < 0.11$ pb

Else Lytken, Moriond QCD 2006 78

Indirect constraint: $B_s \to \mu\mu$

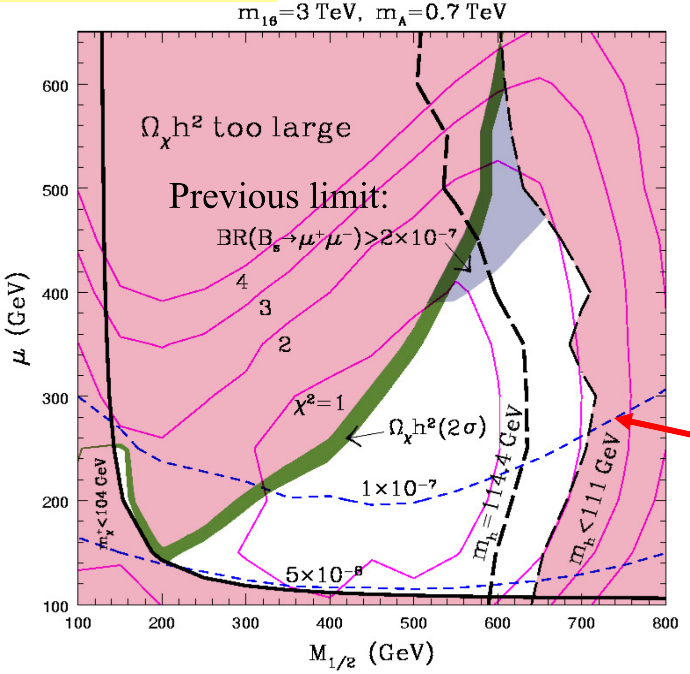




Important at high tanβ

Rare decay, SM branching frac $\sim 10^{-9}$
$\to$Loop diagrams with sparticles (or direct decay if RPV) enhance orders of magnitude

hep-ph/0507233

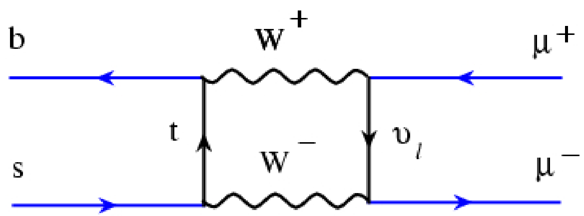


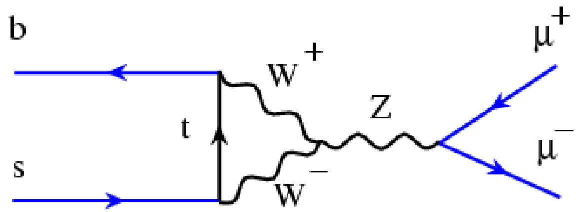
- Look for excess of μμ events in B_s and B_d mass windows
- Background estimation: linear extrapolation from sidebands
- Results compatible with SM backgrounds

  $Br(B_s \to \mu\mu) < 1.0\times10^{-7}$ @ 95%CL

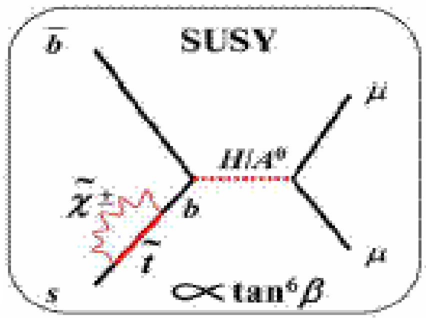
  --- Closing in on SUSY! ---

Indirect constraint: $B_s \to \mu\mu$

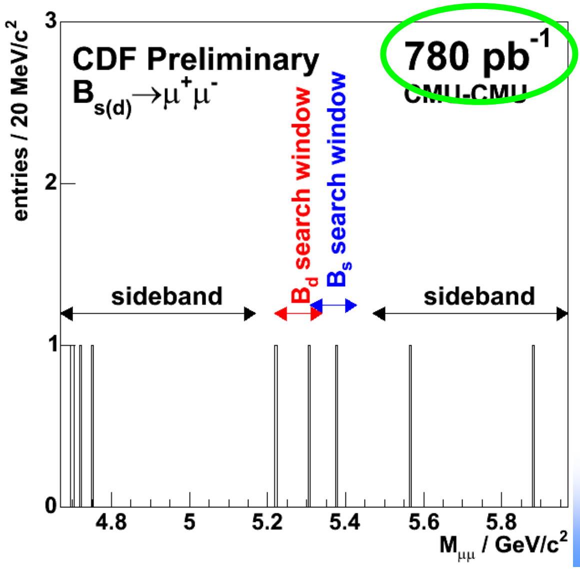




Rare decay, in SM branching frac $\sim 10^{-9}$
Loop diagrams with sparticles (or direct decay if RPV) enhance orders of magnitude



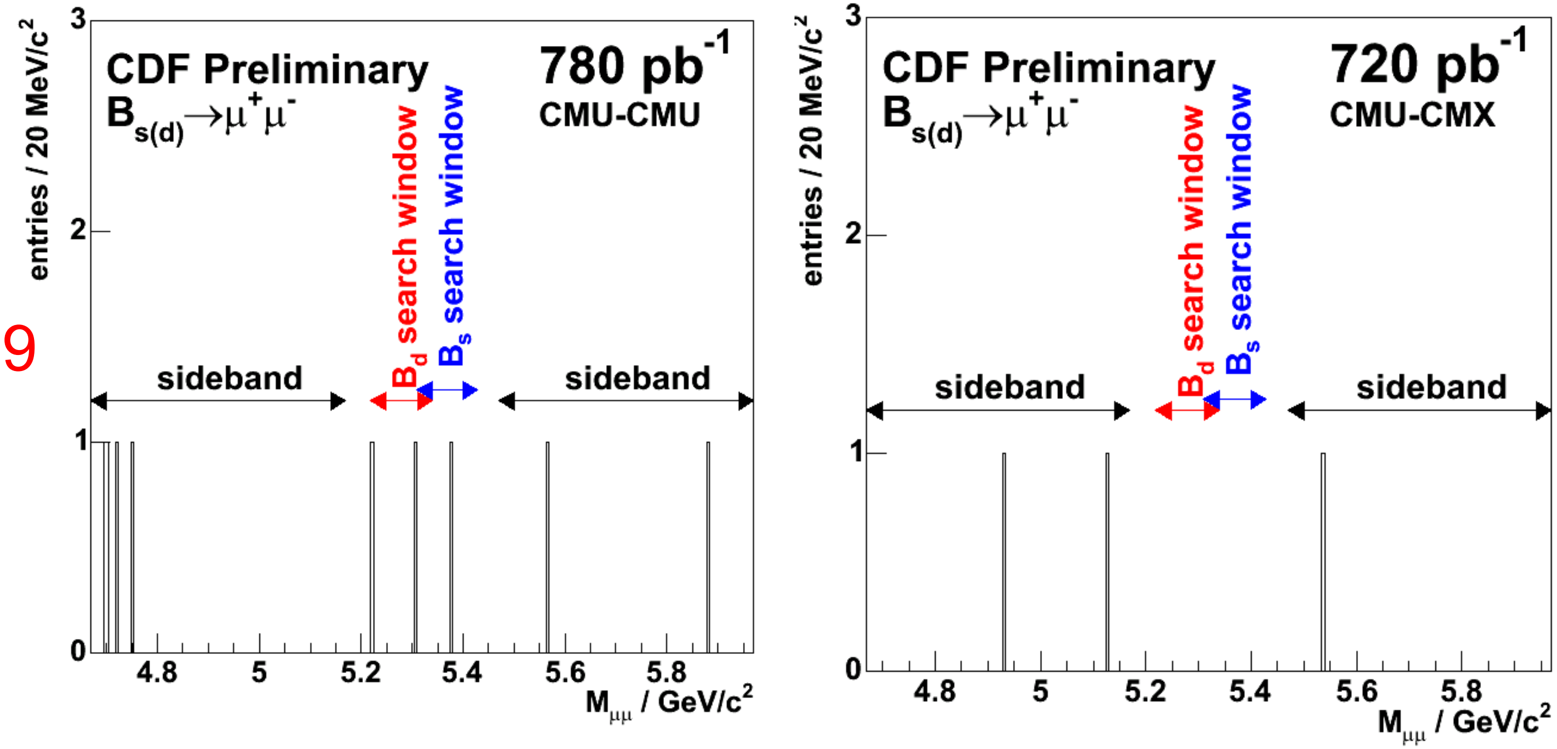
Important at high tanβ



CDF also looks at $B_d \to \mu\mu$
Background estimation: linear extrapolation from sidebands
Normalizing using $B^+ \to \mu^- \mu^+ K^+$
- Results compatible with SM backgrounds

Look in the Bs and Bd Signal Window

$L_R > 0.99$



CMU-CMU Channel:

	Expect	Observed	Prob
B_s	0.88±0.30	1	67%
B_d	1.86±0.34	2	63%

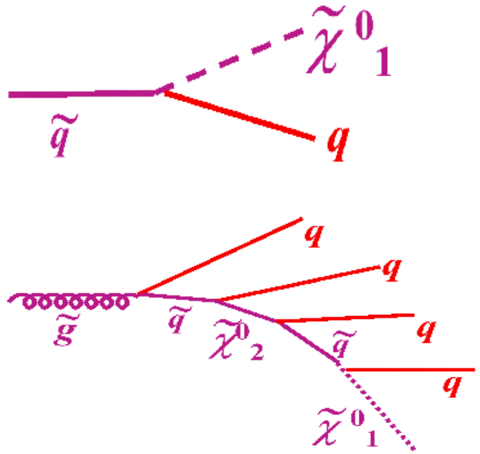
CMU-CMX Channel:

	Expect	Observed	Prob
B_s	0.39±0.21	0	68%
B_d	0.59±0.21	0	55%

MET + jets: squark and gluino

Generic squarks and gluinos strongly produced
Cross section @ Tevatron: ~ a few pb

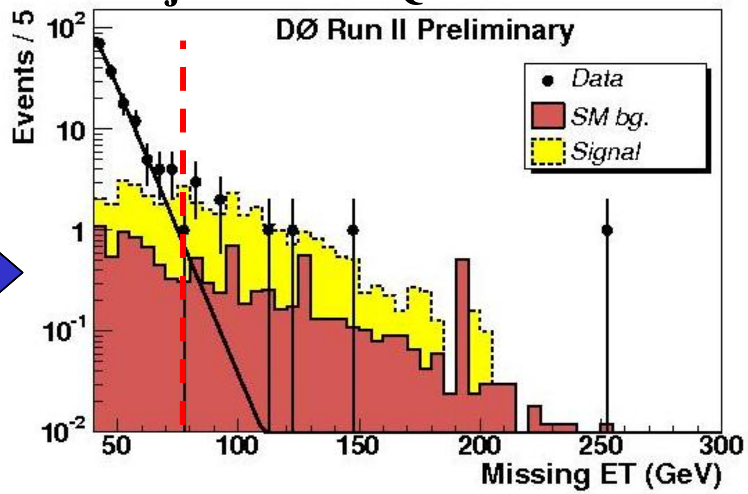
Expect cascade decays
Signature: lots of MET and ≥ 2 jet



<u>D0 result:</u>

- 2, 3, or 4 jets for the cases:
  $M_{\tilde{g}} > M_{\tilde{q}}$ $M_{\tilde{g}} \sim M_{\tilde{q}}$ and $M_{\tilde{g}} < M_{\tilde{q}}$
- Dominant background differ
  Z+jets, W+jets, tt, QCD
- MET > [75, 100, 175] GeV
- Lepton veto

4 jets: Fit to QCD



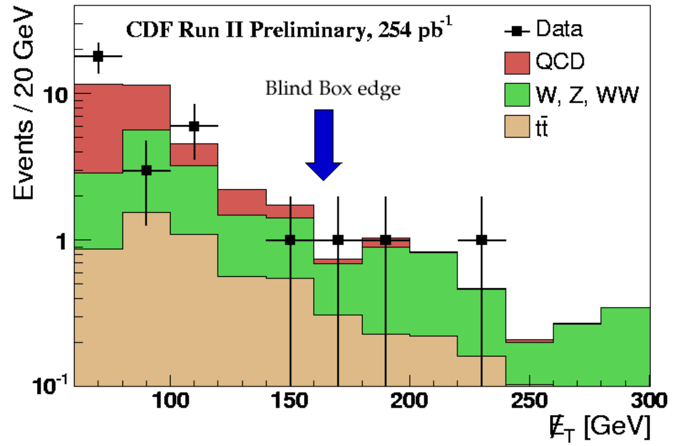
Else Lytken, Moriond QCD

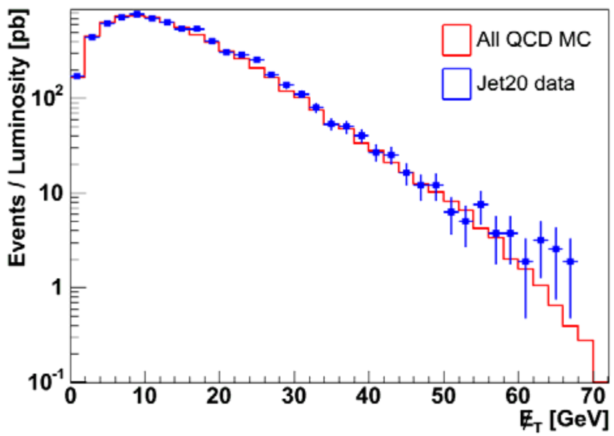
MET+jets continue

CDF:

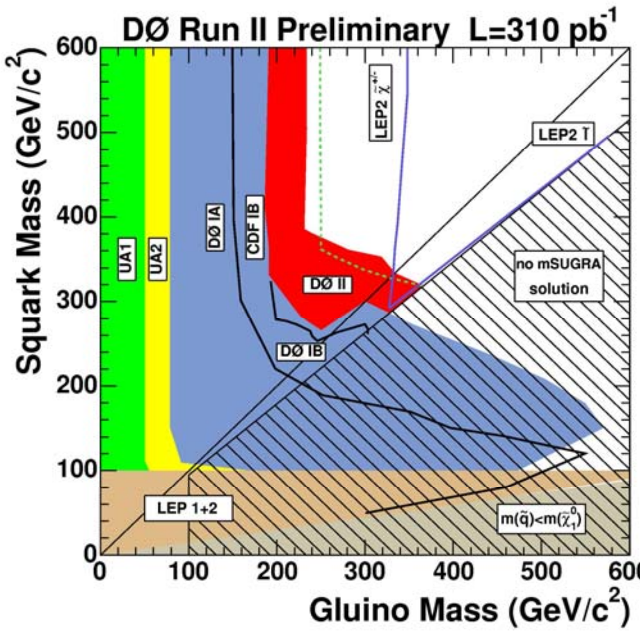
- Req. ≥ 3 jets and MET>165 GeV
- Bkg dominated by $Z \to \nu\nu$ + jets
- Check: compare data and QCD MC in jet domimated region

Expect 4.1 events, observe 3





Else Lytken, Moriond QCD 2006



D0 STRATEGY

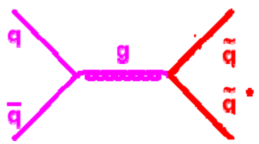
Data pre-selection: 2 jets $\quad |\sum_{jets} \vec{p}_T| > 40\ \mathrm{GeV}$ $\quad \mathrm{MET} > 40\ \mathrm{GeV}$ $\quad H_T \equiv \sum_{jets} |\vec{p}_T| > 50$

Luminosity: **310 pb^{-1}**

ANALYSIS STRATEGY

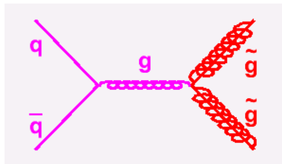
Distinguishes 3 approaches (dominant σ)

$M_{\tilde{g}} > M_{\tilde{q}}$



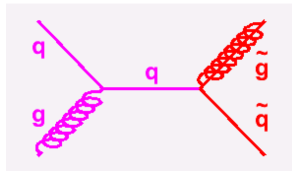
Search for acoplanar dijet events (squark → jet + MET dominant)

$M_{\tilde{g}} < M_{\tilde{q}}$



Search for events with at least 4 jets (gluino → 2 jets + MET dominant)

$M_{\tilde{g}} \sim M_{\tilde{q}}$

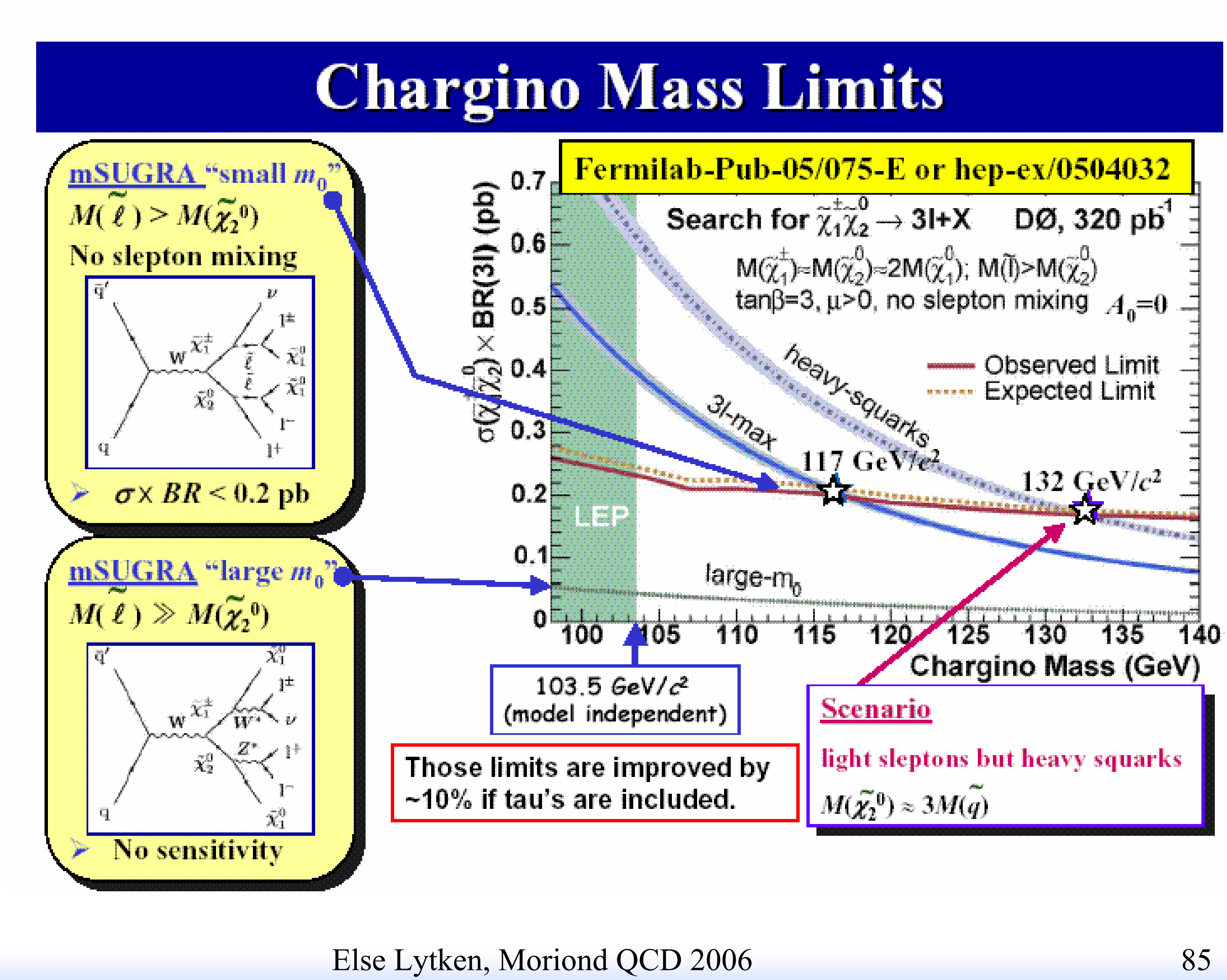


Search for events with at least 3 jets (2 jets from gluino and one from squark)

JET BACKGROUND STRATEGY

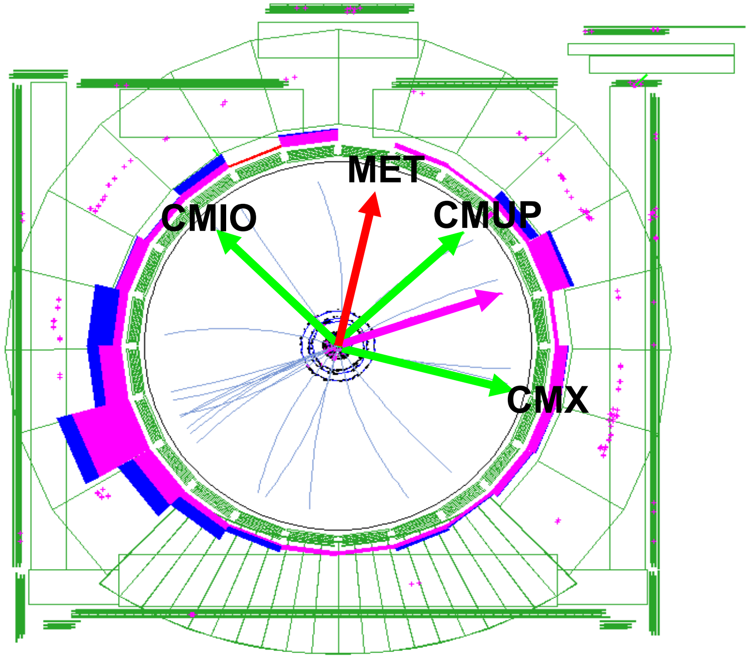
Cuts will remove its contribution.

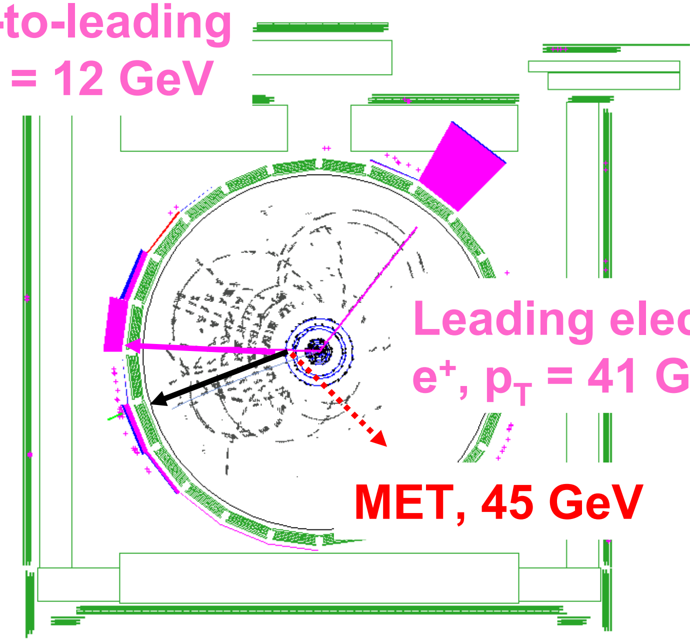
Otherwise, contribution extrapolated from data behavior at low missing ET region.


Chargino Mass Limits
mSUGRA "small m_0"
$M(\tilde{\ell}) > M(\tilde{\chi}_2^0)$
No slepton mixing
$\sigma \times BR < 0.2$ pb
mSUGRA "large m_0"
$M(\tilde{\ell}) \gg M(\tilde{\chi}_2^0)$
No sensitivity
Fermilab-Pub-05/075-E or hep-ex/0504032
Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3l+X$ DØ, 320 pb^{-1}
$M(\tilde{\chi}_1^{\pm}) \approx M(\tilde{\chi}_2^0) \approx 2M(\tilde{\chi}_1^0)$; $M(\tilde{l}) > M(\tilde{\chi}_2^0)$
tanβ=3, μ>0, no slepton mixing $A_0=0$
Observed Limit
Expected Limit
heavy-squarks
3l-max
large-m_0
LEP
117 GeV/c^2
132 GeV/c^2
$\sigma(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0) \times$ BR(3l) (pb)
Chargino Mass (GeV)
103.5 GeV/c^2 (model independent)
Those limits are improved by ~10% if tau's are included.
Scenario
light sleptons but heavy squarks
$M(\tilde{\chi}_2^0) \approx 3M(\tilde{q})$
Else Lytken, Moriond QCD 2006
85

CDF Trilepton events

Isolated track, p_T = 4 GeV
Muon?





	run=203347; event=513922
Leading lepton	CMX μ^-, p_T= 52 GeV , η = -0.9, ϕ = -0.26, Z_0 = 30 cm
Next Leading lepton	CMIO μ^+, p_T= 27 GeV , η = -0.5, ϕ = 2.33, Z_0 = 30 cm
Third lepton	CMUP μ^- , p_T= 8 GeV, η = -0.16, ϕ = 0.79, Z_0 = 30 cm
Other leptons	Electron E_T 4.3 GeV, η = -0.2, ϕ = 0.411, Z_0 = 7 cm
Missing Transverse Energy	15.5 GeV, ϕ = 1.42
Vertices	Z_1 = 31 cm, Z_2 = 7 cm, vertex $Z_3 = -29$ cm
N. Jets L5 E_T > 20 GeV	1
Leading jet	L5 E_T = 47 GeV , η = -0.13, ϕ = -0.279, Z_0 = 19.4 cm
Invariant mass of OS Muons	$m_{CMX-CMIO}$ = 72.5 GeV
Transverse mass	$m_{T(CMUP-MET)}$ = 7 GeV

Mass OS1	41.6 GeV
Mass OS2	27.0 GeV

Limits

Combine 3 lepton and 4+ lepton signal regions to set limits.

Observed Limits (95% C.L.)	
λ_{121}	λ_{122}
$\sigma \leq 0.21$ pb	$\sigma \leq 0.11$ pb

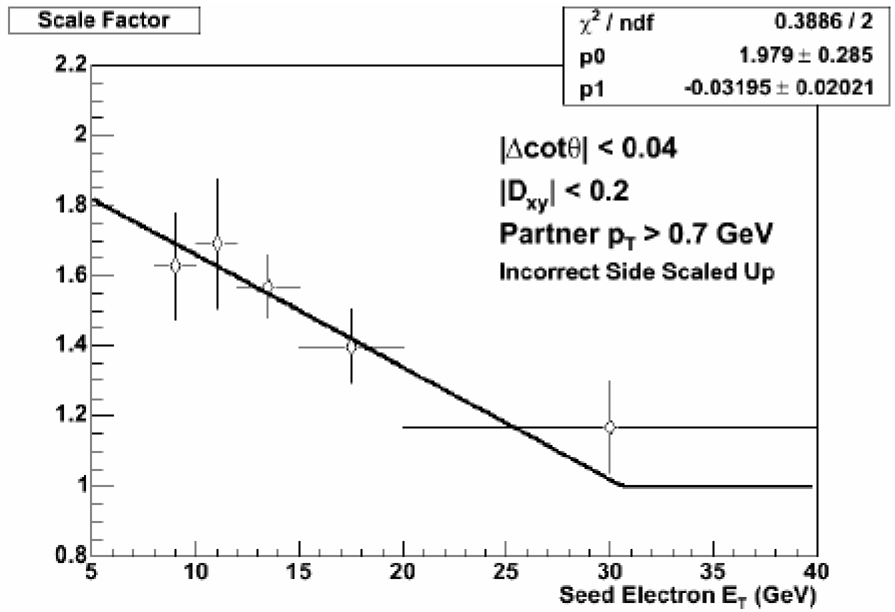
Signal Point: $M_0 = 250$, $M_{1/2} = 260$, $\tan\beta = 5$, $\mu > 0$, $\sigma = 0.143$

Excluded by DØ: $\sigma \leq 0.116$ (λ_{121}) with 238 pb^{-1}

$\sigma \leq 0.239$ (λ_{122}) with 160 pb^{-1}

Conversion removal SF

$$SF = \frac{1-\varepsilon_{Data}}{1-\varepsilon_{MC}}$$



- Apply scale factor to all electrons in MC that originate from photon conversions that are not rejected by the conversion tagger.
- In order to use SF, ignore tracks with $p_T < 0.7$ GeV in conversion filter.

Models and Final States

- Go beyond the Standard Model without introducing SUSY

	Models	Final States
Lepton-quark substructure	compositeness excited fermions Leptoquarks	ee, γγ, μμ μμγ, eej eejj, μμjj, eνjj , μνjj ,ννjj,ννbb
EWSB without Higgses	technicolor	lνbb, lνbc
New Heavy gauge bosons	Z' W'	ee, μμ, ττ eν, bblν
Hierarchy problem ($M_{Planck} >> M_{EW}$)	Extra Dimensions: Large Extra Dimensions (ADD LED) Randall-Sundrum gravitons (RS gravitons)	ee, γγ, μμ (resonant or not) jet+ME_T (monojet)

→ Three final states: leptons/photons , leptons+jets (+ME_T) , jets+ME_T

Dilepton/Diphoton

dielectron/diphoton

- E_T>15-25 GeV
- isolated, fraction EM
- EM shower shape
- Track match (ee)

EM Calorimeter

Tracker

- Main background:
  - ...nts and direct photon events -> estimated from data

EMid: ε~ 80 to 90%

- syst signal: ~9% (cross section, EMid, acceptance, e/γ)

dimuon

- P_T > 15 GeV
- Isolated
- Track quality req. (hits…)
- Cosmic ray bkgd cuts

μ chambers +tracker

- Main background:
  - Drell-Yan -> μμ

μid: ε~ 80 to 90%

- syst signal: 8% (acceptance)

syst SM background: 9 to 13% (efficiency, momentum smearing, PDF,…)

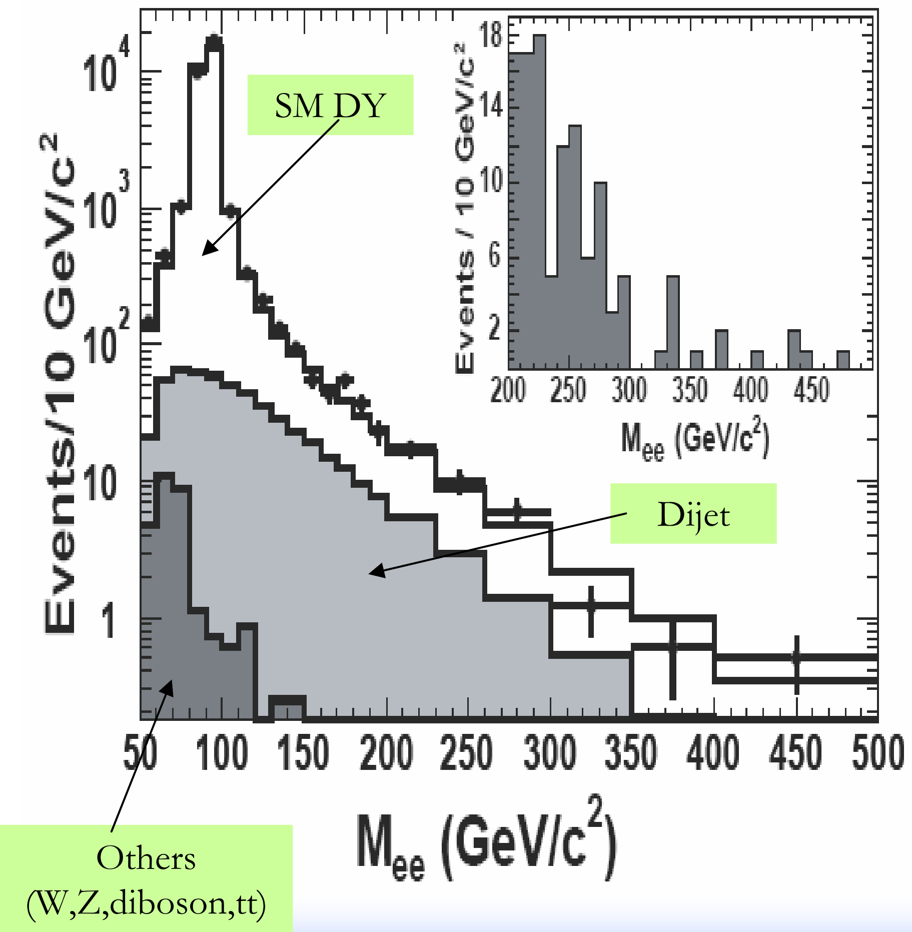
→ **Direct search (mass peak: Z', RS graviton) and indirect search (LED, compositness)**

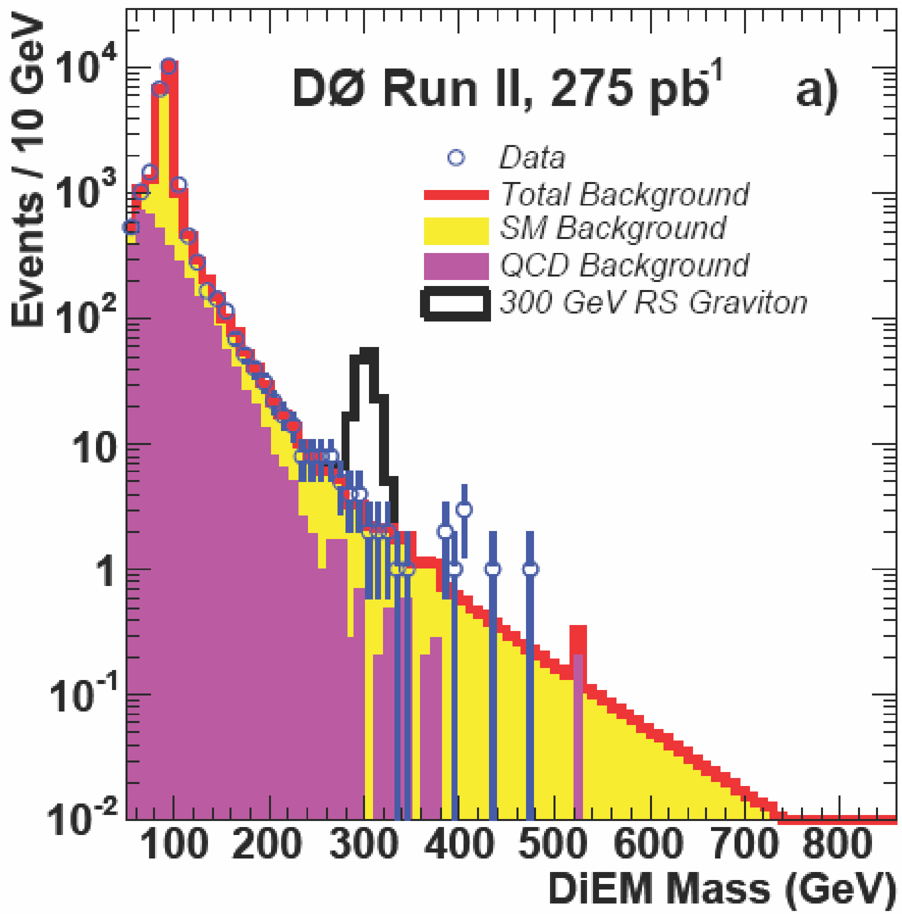
Data/MC Comparison

Z'-> ee

RS graviton – ee,γγ

$\mathcal{L}$~450 pb^{-1}





Dilepton

- *No excess wrt SM -> limits (95% CL) on the models*

Compositeness: ee, μμ

$$L_{ql} = \frac{g_0^2}{\Lambda^2}\{\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_L\gamma_\mu\mu_L) + \eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_R\gamma_\mu\mu_R) + \eta_{RL}(\bar{u}_R\gamma_\mu u_R)(\bar{\mu}_L\gamma^\mu\mu_L) + \eta_{RL}(\bar{d}_R\gamma_\mu d_R)(\bar{\mu}_L\gamma^\mu\mu_L) + \eta_{RR}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_R\gamma_\mu\mu_R) + \eta_{RR}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_R\gamma_\mu\mu_R)\}$$

Λ: compositness scale(TeV)

μμ 250pb [-1]

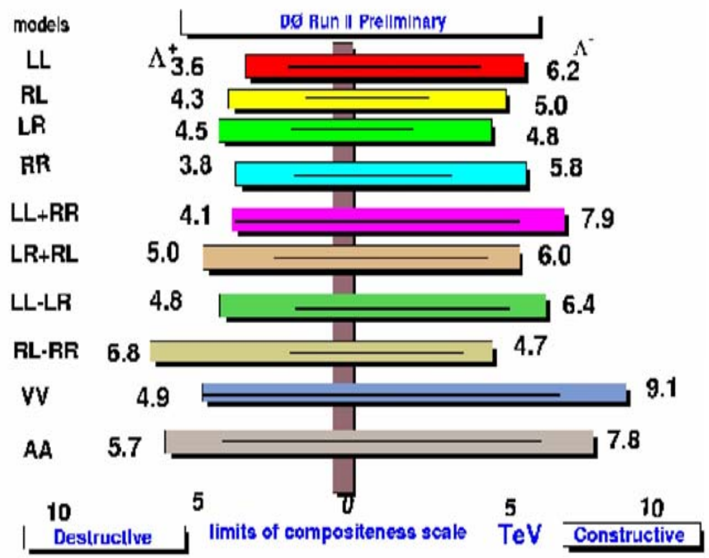
Model	Λ^+(TeV)	Λ^-(TeV)
LL	4.19	6.98
RR	4.15	6.74
LR	5.32	5.10
RL	5.31	5.17
LL+RR	5.05	9.05
LR+RL	6.45	6.12
LL-LR	4.87	7.74
RL-RR	5.07	7.41
VV	6.88	9.81
AA	5.48	9.76

Z'->ee CDF 450 pb $^{-1}$

Z' Model	Z_{SM}	Z_χ	Z_ψ	Z_η
Exp. limit (GeV/c^2)	860	735	725	745
Obs. limit (GeV/c^2)	850	740	725	745

$m_{Z'_{SM}}$ > 850 GeV @95% CL

ee 200 pb $^{-1}$



combination in progress

Dilepton/Diphoton

ADD LED

cross section: $\sigma = f(\eta_G, \eta_G^2)$
parameter: $\eta_G = \mathcal{F}/M_S$
M_S: *fundamental Planck scale*
$\mathcal{F} \sim 1$: *model dependent*

Limits are in TeV

$\mathcal{L}$ (pb^{-1})	Final state	GRW [1]	HLZ[2] n=2	n=3	n=4	n=5	n=6	n=7	Hewett[3] Λ=+1/λ=-1
200 CDF	ee	1.10	-	1.31	1.10	0.999	0.929	0.879	0.987/0.959
246 D0	μμ	1.07	1.09	1.27	1.07	0.97	0.90	0.85	0.96/0.93
275 D0	ee+γγ	1.48	1.74	1.76	1.48	1.33	1.24	1.17	1.32/1.21

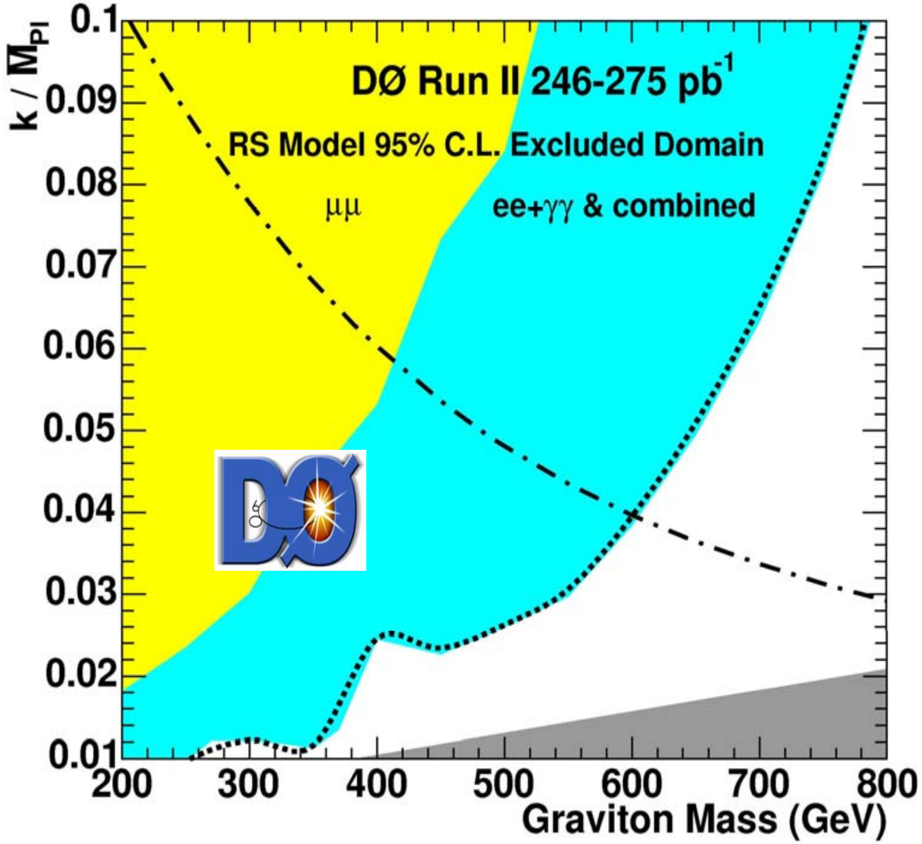
RunI+RunII

World Best Limit

[1] Giudice, Rattazzi, Wells NPB 544,3 (1999)
[2] Han, Lykken, Zhang PRD59,105006 (1999)
[3] Hewett PRL 82, 4765 (1999)

RS graviton: ee, γγ, μμ combined

parameters:
-graviton mass
- $k/\overline{M}_{PL}$: *coupling to the SM fields*



Lepton/photon(s)+X

Signature of excited particles which decay to l/γ+X

γγ+X

diphoton trigger: E_T>12 (isolated), E_T>18 GeV
2 central photons |η| < 1 E_T >13 GeV

γγ+e,μ $\mathcal{L}$ ~ 683 pb^{-1}	γγ+γ $\mathcal{L}$ ~ 1020 pb^{-1}
one electron E_T > 20 GeV	A third photon
one muon p_T > 20 GeV	|η| < 1 E_T >13 GeV

1 fb^{-1}

Source	electron	muon
$Z\gamma\gamma$	$0.535 \pm 0.014 \pm 0.049$	$0.307 \pm 0.011 \pm 0.028$
$W\gamma\gamma$	$0.117 \pm 0.008 \pm 0.011$	$0.048 \pm 0.005 \pm 0.004$
Fake $l+\gamma\gamma$	$0.093 \pm 0.004 \pm 0.038$	$0.006 \pm 0.005 \pm 0.003$
$l\gamma + \text{jet} \to \gamma$	$0.386 \pm 0.021 \pm 0.220$	$0.093 \pm 0.011 \pm 0.114$
$l\gamma + e \to \gamma$	$3.363 \pm 0.272 \pm 0.760$	$0.017 \pm 0.017 \pm 0.004$
Total	4.49 ± 0.84	0.47 ± 0.12
Data	2	0

lγγ

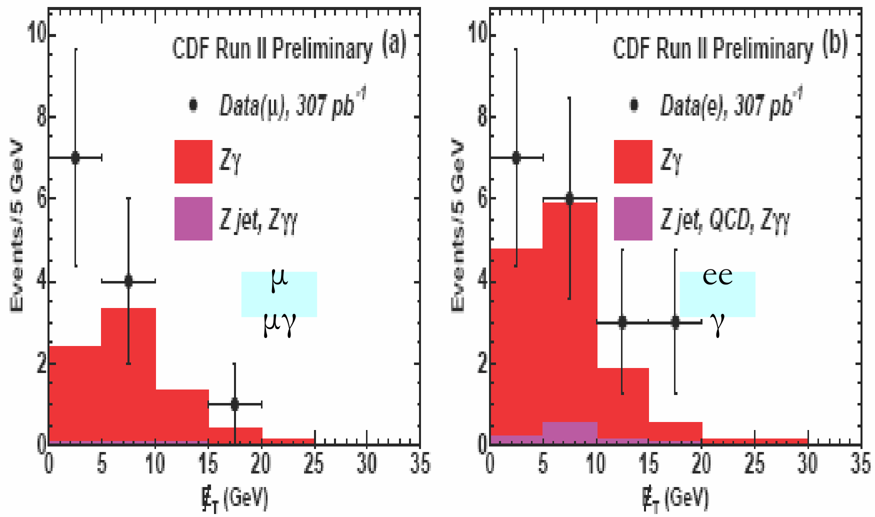
High Luminosity

γγγ: exp: 1.9±0.6
observ: 4

γl+X

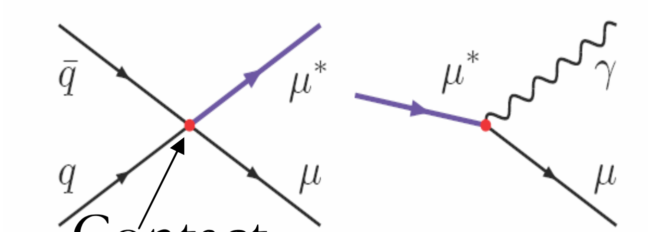
One isolated γ E_T >25 GeV
One isolated « tight » central lepton E_T >25 GeV

lγ+ME_T $\mathcal{L}$ ~ 307 pb^{-1}	lγ+l $\mathcal{L}$ ~ 307 pb^{-1}
ME_T> 25 GeV	Loose lepton E_T>25 GeV
Obs: 43 Exp: 35.1±5.3	Obs: 31 Exp: 21.2±4



No excess wrt SM

Excited muons



Contact Interaction (CI)

Main background:
Zγ,WZ, ZZ
Z+jet (fakes)

	CDF L=371 pb^{-1}	DØ L=377 pb^{-1}
2 isolated muons	p_T>20 GeV	p_T>15 GeV
1 isolated photon	E_T>25 GeV	E_T>16 GeV

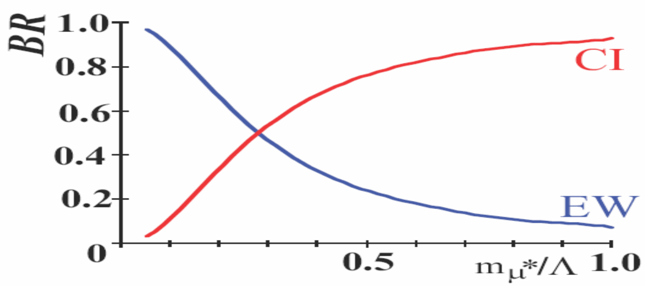
Systematics:
fakes(jet misid as photon)

Compositness models:
Quarks and leptons are composed of a scalar and a spin ½ particles
Large spectrum of excited states

DØ E_T^{γ}>27 GeV + $M_{\mu\gamma}$ mass cut

m_{μ^*} [GeV]	$m_{\mu\gamma}$ cut [GeV]	Data	SM expectation	Signal eff. [%]
100	200	0	0.170 ± 0.126	7.5 ± 1.0
200	200	0	0.170 ± 0.126	12.5 ± 1.5
300	280	0	0.041 ± 0.023	12.1 ± 1.5
400	330	0	0.016 ± 0.011	14.7 ± 1.8
500	440	0	0.003 ± 0.001	11.9 ± 1.5
600	440	0	0.003 ± 0.001	14.4 ± 1.8
700	440	0	0.003 ± 0.001	13.6 ± 1.7
800	440	0	0.003 ± 0.001	14.5 ± 1.8
900	440	0	0.003 ± 0.001	14.7 ± 1.8
1000	440	0	0.003 ± 0.001	14.4 ± 1.8

Excited muons

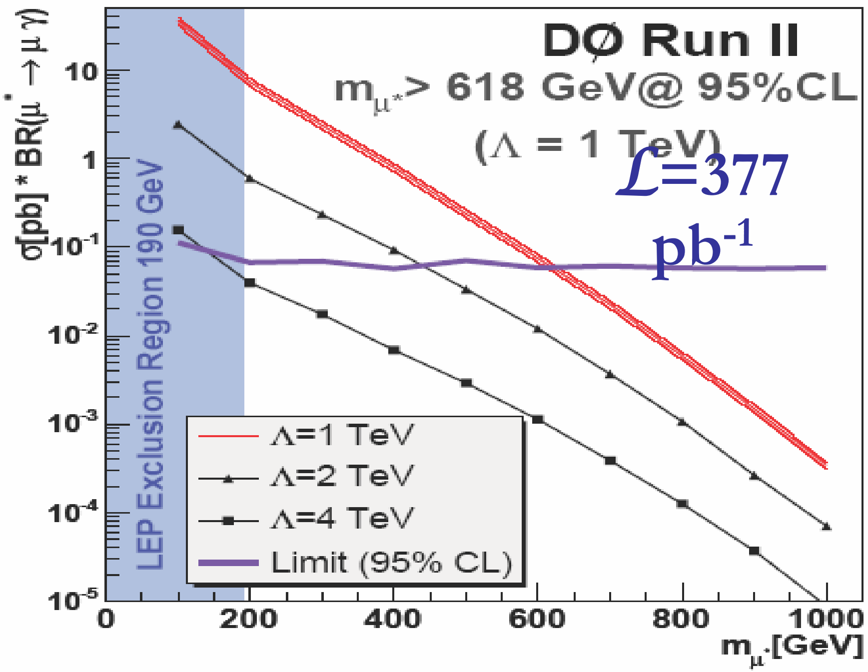


EW decays: μ* -> μ + gauge boson

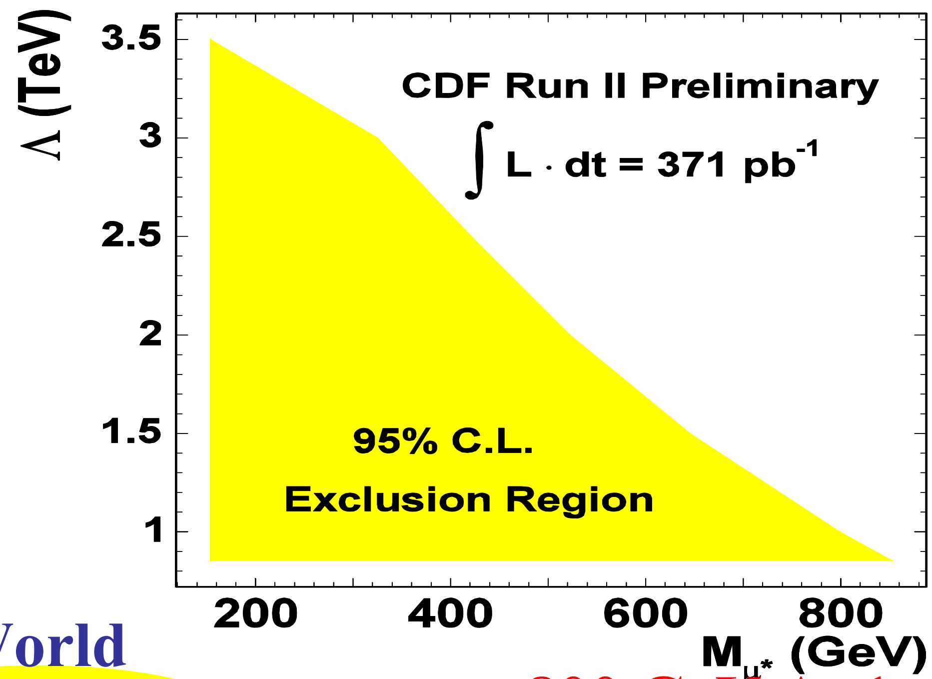
CI decays: μ* -> μ + ff

Three parameters:

- m_{μ^*}
- BR(μ* -> μγ)
- Λ: compositness scale



$\mathcal{L}$=377 pb^{-1}



m_{μ^*} > 618 GeV Λ=1 TeV

World Best Limit

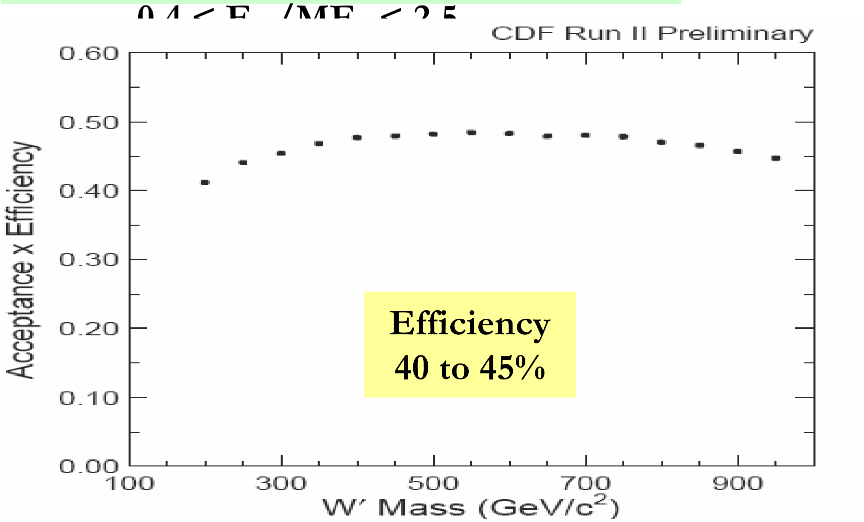
m_{μ^*} > 800 GeV Λ=1 TeV

Only EW decays

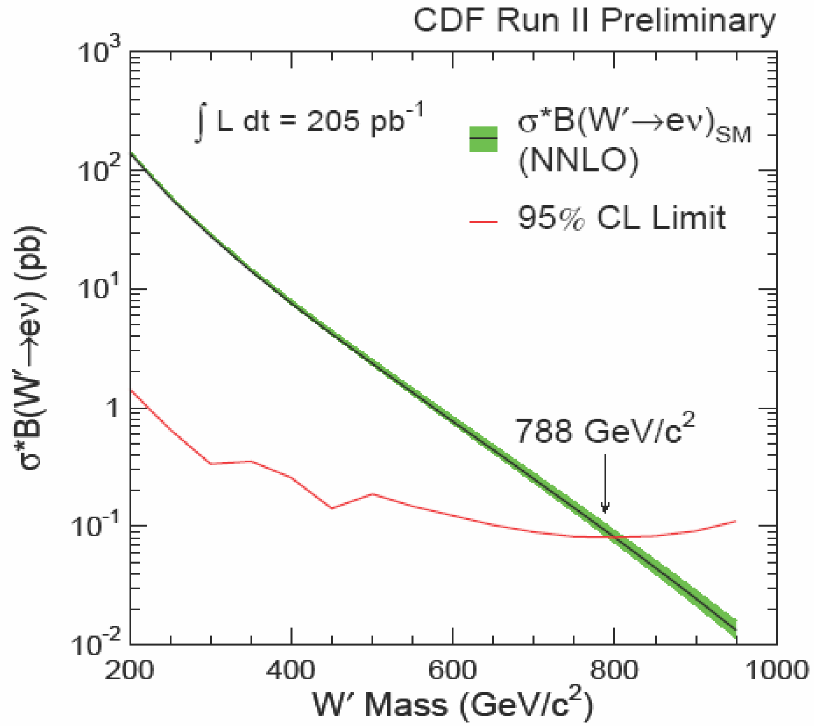
W' -> eν

Trigger: inclusive electron E_T >18 GeV
Selection
- One isolated electron E_T >25 GeV
- ME_T > 25 GeV
- $0.4 < E_T/ME_T < 2.5$

Background:
W->eν, W-> τν,
Multijet (fakes)



Efficiency
40 to 45%



	Events in Each M_T Bin (GeV/c^2)				
	200 - 250	250 - 350	350 - 500	500 - 700	700 - 1000
$W \to e\nu$	30.8 ± 5.7	17.0 ± 4.0	3.52 ± 1.70	0.27 ± 0.45	0.00 ± 0.00
Multijet	2.7 ± 6.1	0.0 ± 3.3	0.00 ± 0.29	0.00 ± 0.01	0.00 ± 0.00
Other Backgrounds	5.2 ± 1.0	3.0 ± 0.9	0.51 ± 0.22	0.06 ± 0.08	0.00 ± 0.03
Total Background	38.7 ± 8.9	20.0 ± 5.9	4.03 ± 1.97	0.33 ± 0.53	0.01 ± 0.03
Data	41	21	9	1	0

$M_{W'}$ > 788 GeV @95% CL

Systematics:
- JES
- PDF
- EM scale, ISR

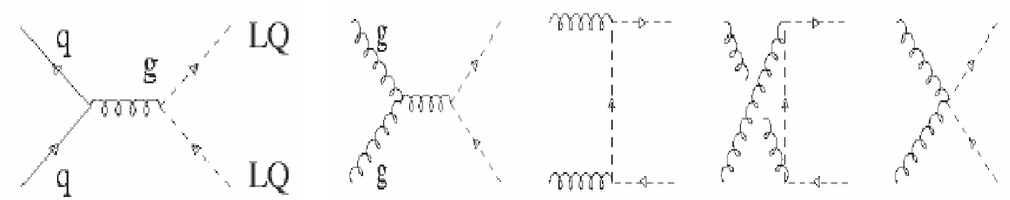
World Best Limit

Leptoquarks

2nd generation: LQ 2 LQ 2-> μμjj (CDF+D0)
LQ 2 LQ 2-> μνjj (CDF)

LQ: bosons carrying the quantum numbers of a quark-lepton system

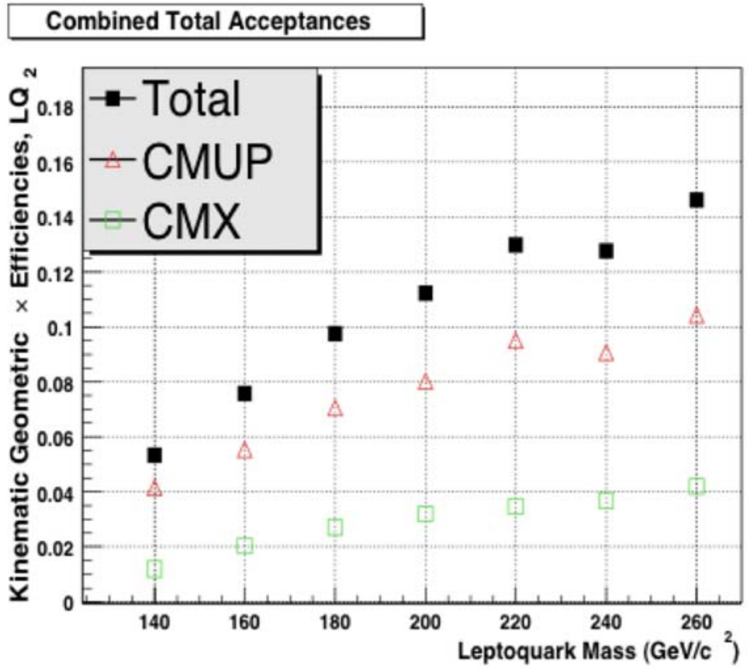
2 isolated energetic jets + one (two) isolated high pT muons



Background:
DY: Z/γ*(μμ) +jets

	D0	CDF	
	L~ 294 pb $^{-1}$	L ~ 200 pb $^{-1}$	
		μμjj	μνjj
2 isolated muons	p_T > 15 GeV	p_T > 25 GeV	p_T > 25 GeV
2 isolated jets	E_T > 25 GeV	E_T (jet1) > 30 GeV E_T (jet2) > 15 GeV	E_T > 30 GeV
M(μμ)	> 105 GeV	15 GeV< < 75 GeV > 105	
ME_T			> 60 GeV

+additional cuts: scalar sum of transverse energies of objects (μμjj), angular selections and mass cut around M_{LQ} (μνjj)



Systematics:
- CDF: lumi, PDF
- D0: JES, lumi, PDF

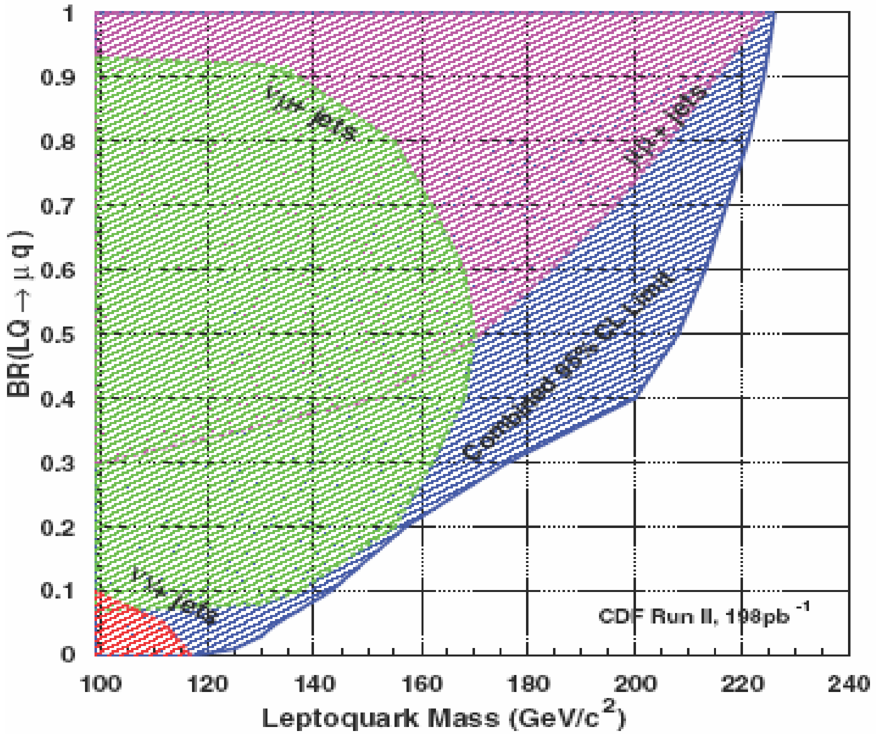
Leptoquarks

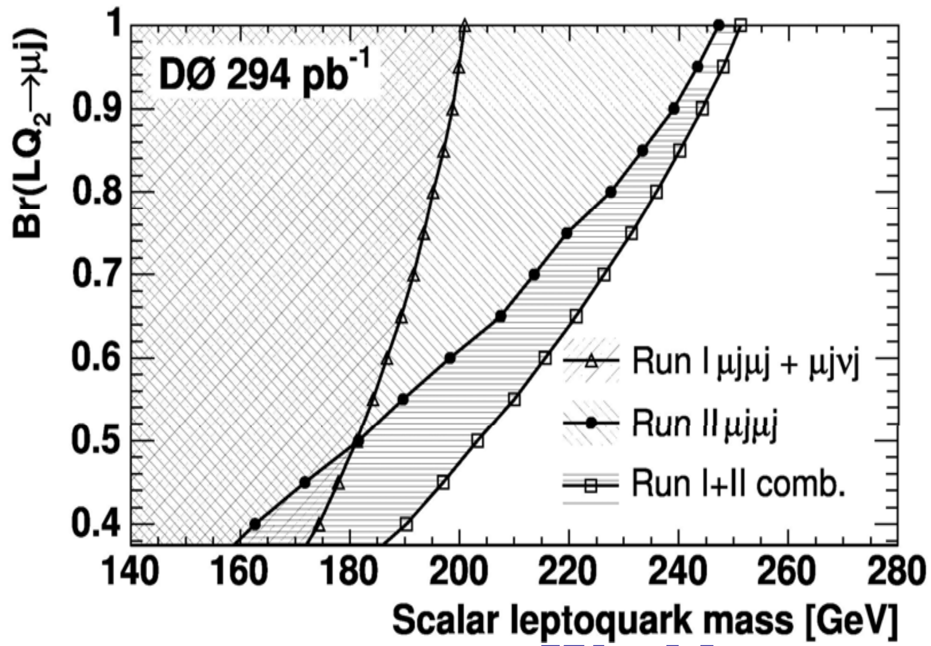
μμjj

	$\mathcal{L}$ ~ 200 pb^{-1} (CDF)	$\mathcal{L}$ ~ 294 pb^{-1} (DØ)
Data	2	6
MC	1.87± 1	6.8 ±2

μνj (CDF)

	140	160	180	200	220	240	260
W	0.92 ± 0.06	1.44 ± 0.10	1.44 ± 0.10	1.67 ± 0.11	1.65 ± 0.11	0.93 ± 0.06	0.44 ± 0.03
Top	1.69 ± 0.21	1.84 ± 0.23	1.35 ± 0.17	1.00 ± 0.39	0.80 ± 0.29	0.67 ± 0.08	0.52 ± 0.06
Z	0.18 ± 0.01	0.22 ± 0.02	0.19 ± 0.01	0.18 ± 0.01	0.14 ± 0.01	0.05 ± 0.00	0.04 ± 0.00
QCD	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.00
Total	3.09 ± 0.57	3.74 ± 0.62	3.22 ± 0.56	3.08 ± 0.53	2.83 ± 0.51	1.94 ± 0.44	1.30 ± 0.39
Data	3	3	2	0	0	0	0



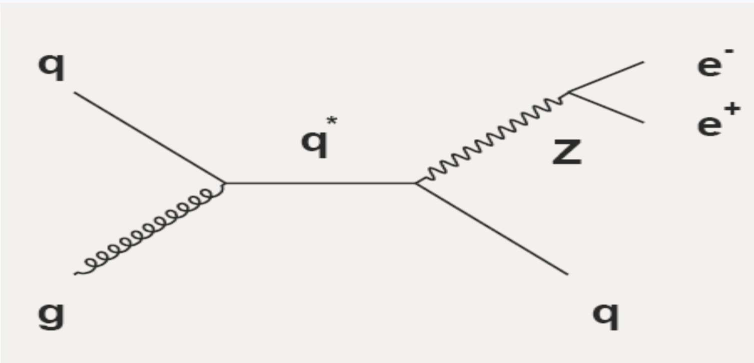


World Best Limit

2 parameters:
β: BR(LQ->l$^{\pm}$q)
M_{LQ}

β = 1 M_{LQ2} > 251 GeV @95% CL

Excited quarks



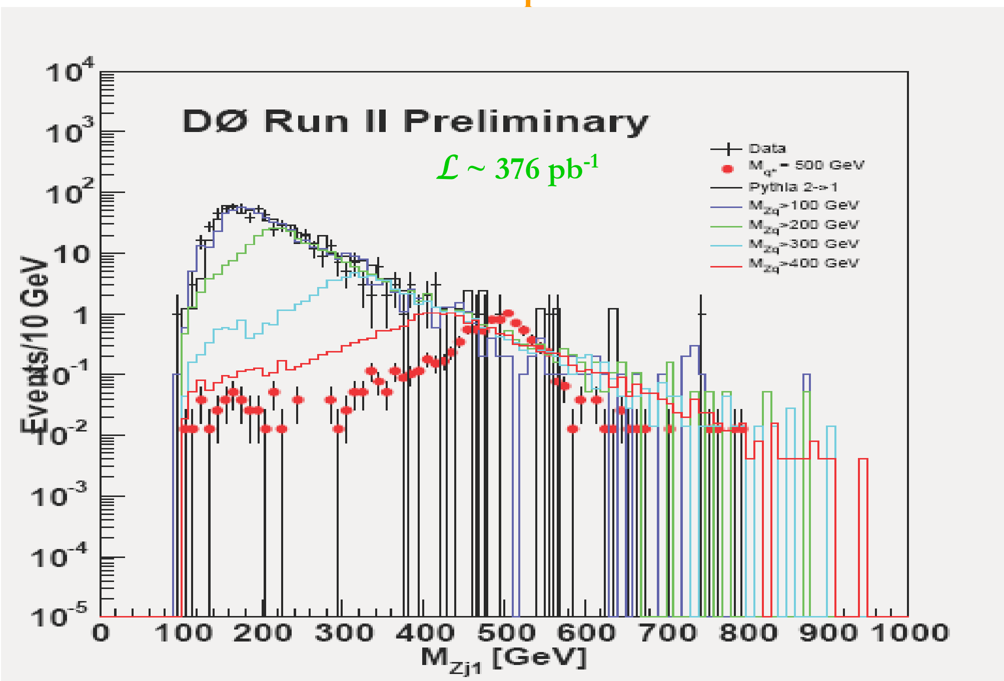
Signature: Z(ee)+jet

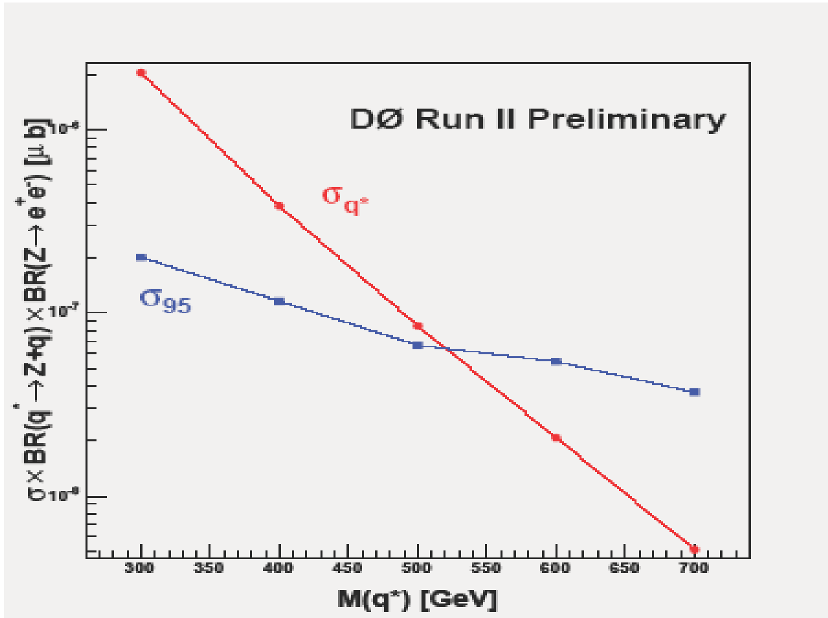
M_{Zq} resonant

Event selection:

- 2 electrons (E_T>30, 25 GeV): usual criteria
- $81 < M_{ee} < 101$ GeV
- 1 jet $p_T > 10$ GeV
- no matching jet – EM object

Main background: DY Z(ee)+jets





M_{q^*} > 520 GeV @ 95% CL

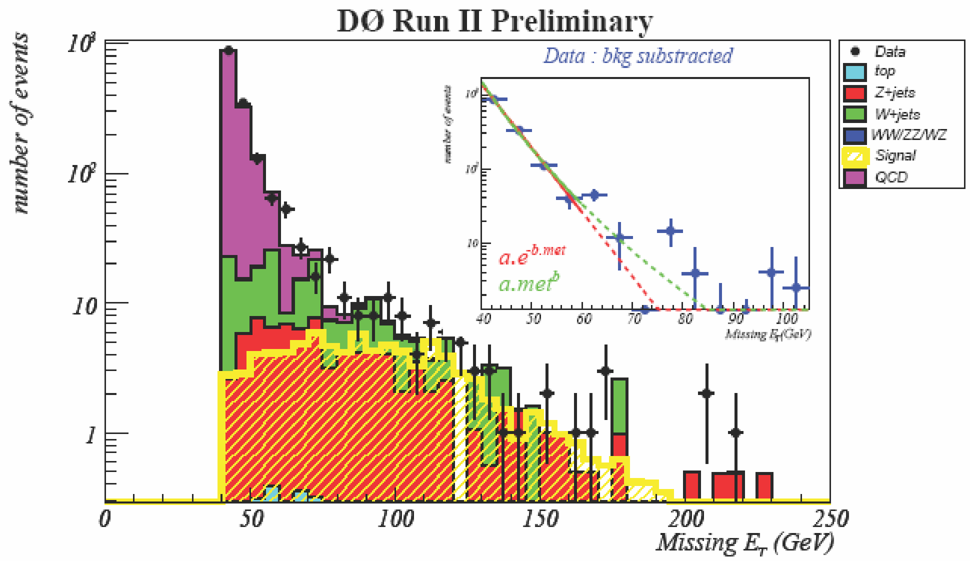
Scalar Leptoquarks

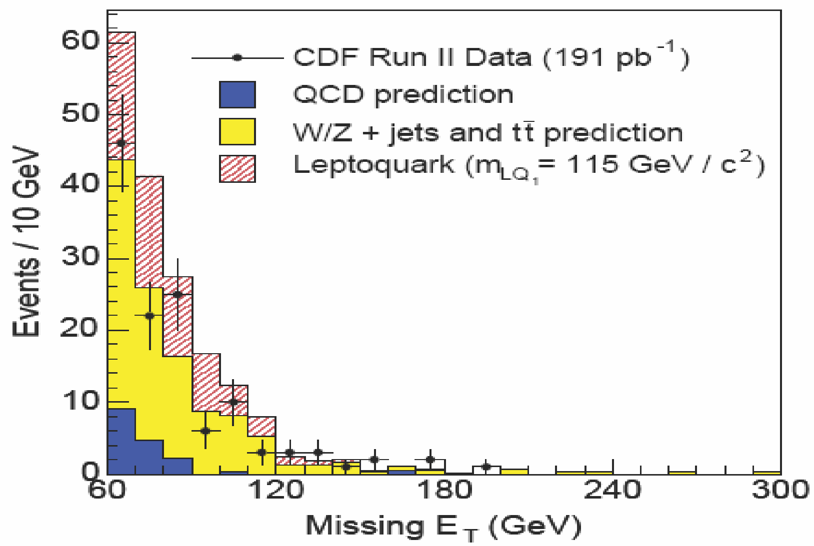
$p\bar{p}$ -> LQLQ -> ννjj : 2 acoplanar (light) jets + ME_T

Main background:

- Z(νν)+jets
- W(lν)+jets
- QCD multijets (instrumental) -> from data

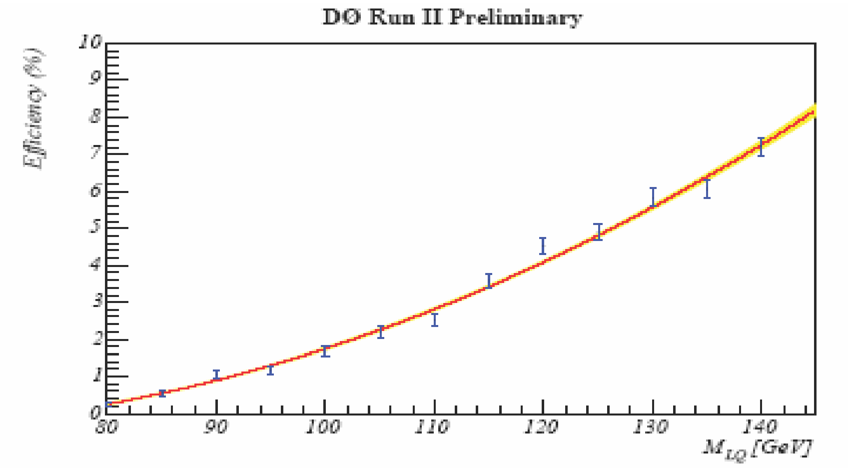
	CDF $\mathcal{L}$ ~ 191 pb^{-1}	DØ $\mathcal{L}$ ~ 310 pb^{-1}
Triggers	MET	jets+MET
2 central jets	p_T > 40, 25 GeV	p_T > 60, 50 GeV
MET	> 60 GeV	> 80 GeV
no isolated track, no electron or muon		
cuts on ΔΦ(MET, jet) to remove SM and QCD background		

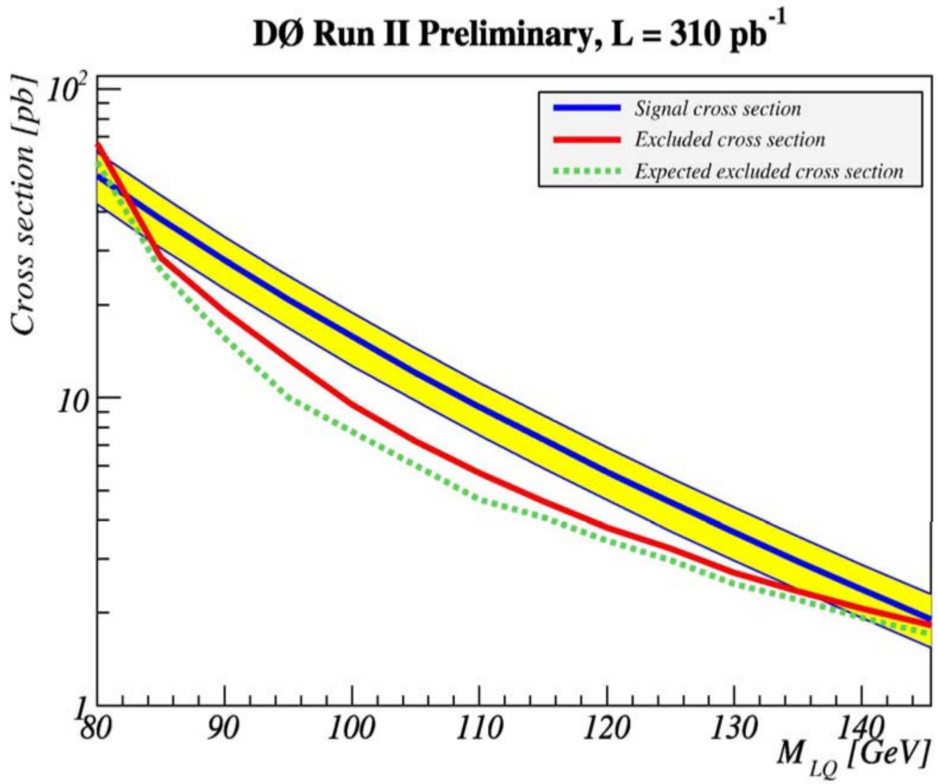




Scalar Leptoquarks

— pp -> LQLQ -> ννjj : 2 acoplanar (light) jets + ME_T





	CDF	DØ
	$\mathcal{L}$ ~ 191 pb^{-1}	$\mathcal{L}$ ~ 310 pb^{-1}
DATA	124	86
SM	118.3± 14.5	$75.2^{10.1}_{9.7}{}^{10.7}_{-12.2}$

Systematics: 14 to 16%
(luminosity, JES, Jet energy reso, PDFs)

CDF: = 0 M_{LQ} > 117 GeV @95% CL

DØ: = 0 M_{LQ} > 136 GeV @95% CL

World Best Limit

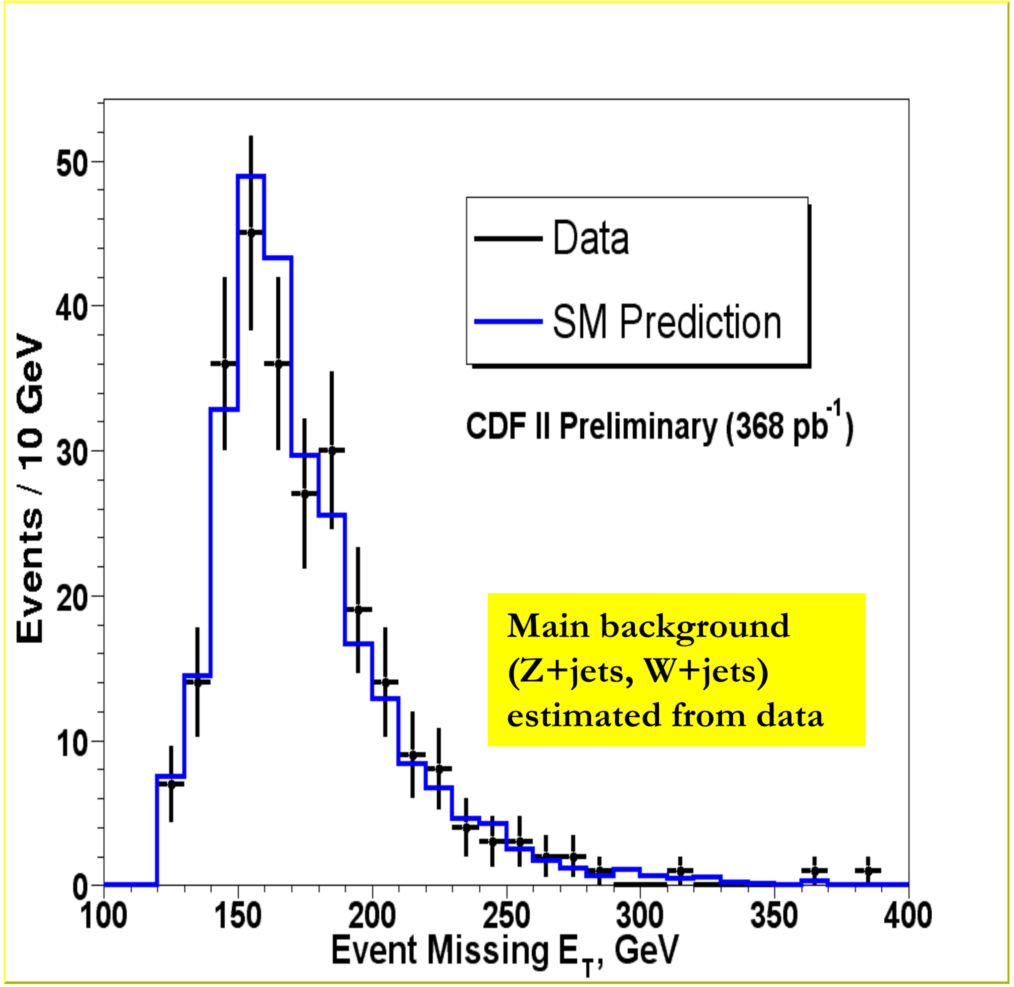
Extra Dimensions

qq, qg, gg-> gG, qG: a single energetic jet + large ME_T

Main background:
- Z(νν)+jets
- W(lν)+jets
- QCD multijets -> from data

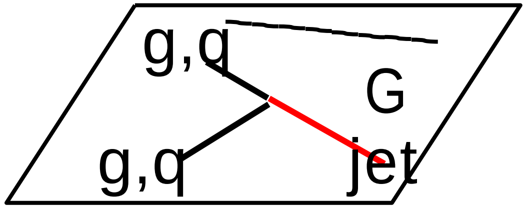
High sensitivity to Jet Energy Scale

	$\mathcal{L}$ ~ 368 pb^{-1}
Triggers	High E_T single jet
1 central jet (quality criteria)	p_T > 150 GeV
ME_T	> 120 GeV
2nd leading jet	p_T < 60 GeV
no isolated track, no electron or muon	
cuts on ΔΦ(MET, jet) to remove SM and QCD background	

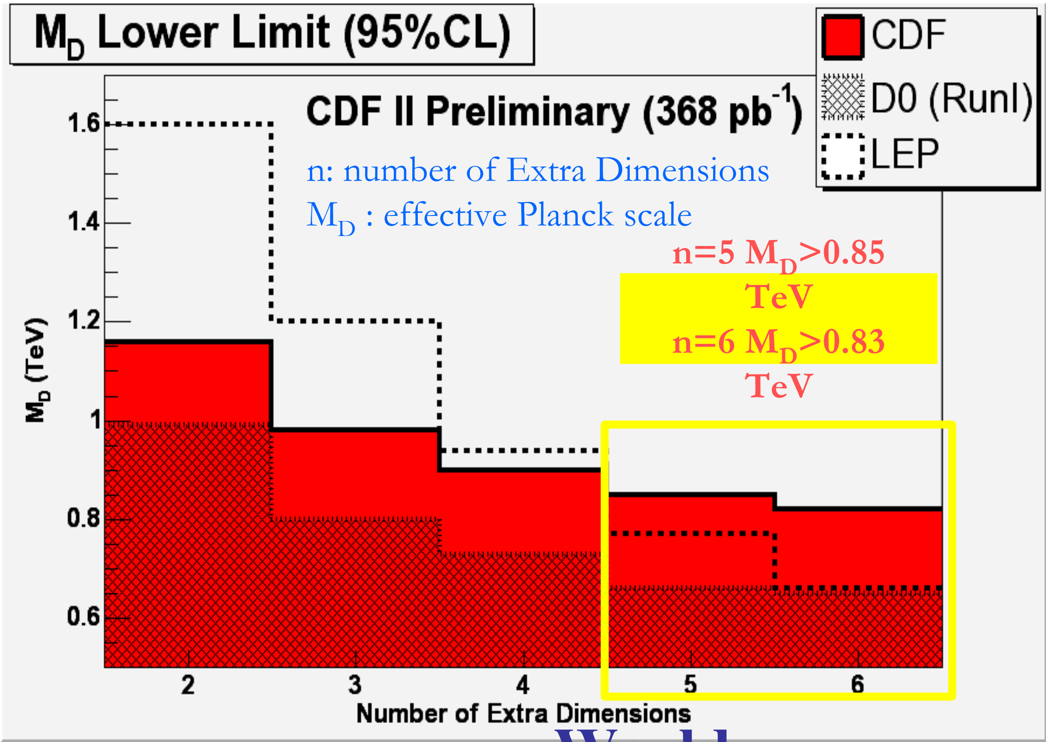


Extra Dimensions

qq, qg, gg-> gG, qG: a single energetic jet + large ME_T



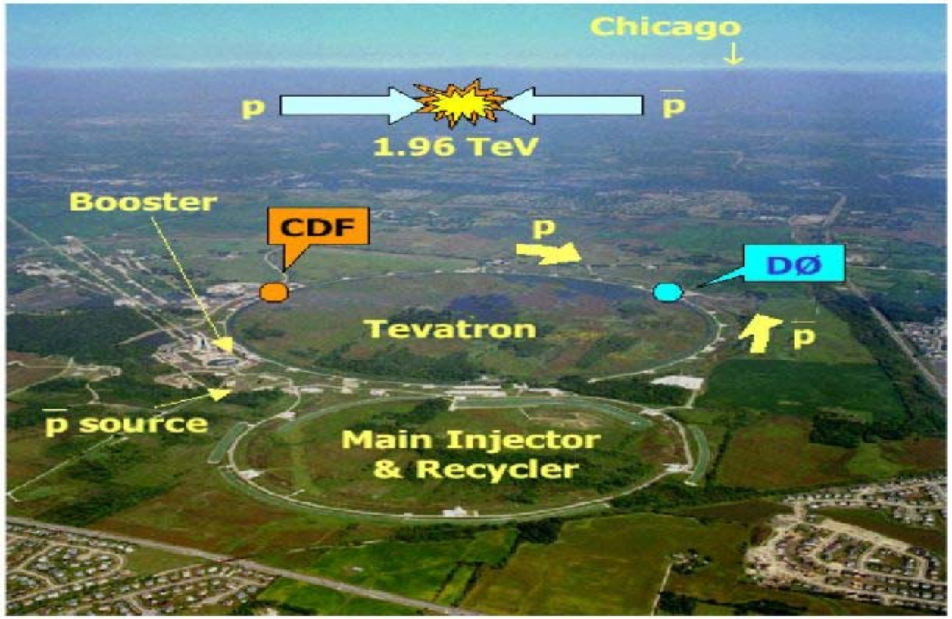
Background	
$Z \to \nu\bar{\nu}$	130 ± 14
$W \to \tau\nu$	60 ± 7
$W \to \mu\nu$	36 ± 4
$W \to e\nu$	17 ± 2
$Z \to \ell\ell$	3 ± 1
QCD	15 ± 10
Non-collision	4 ± 4
Total predicted	265 ± 30
Data observed	263



Uncertainties:
- stat+syst: 11% (bckgd from data)

World Best Limit

TeVatron

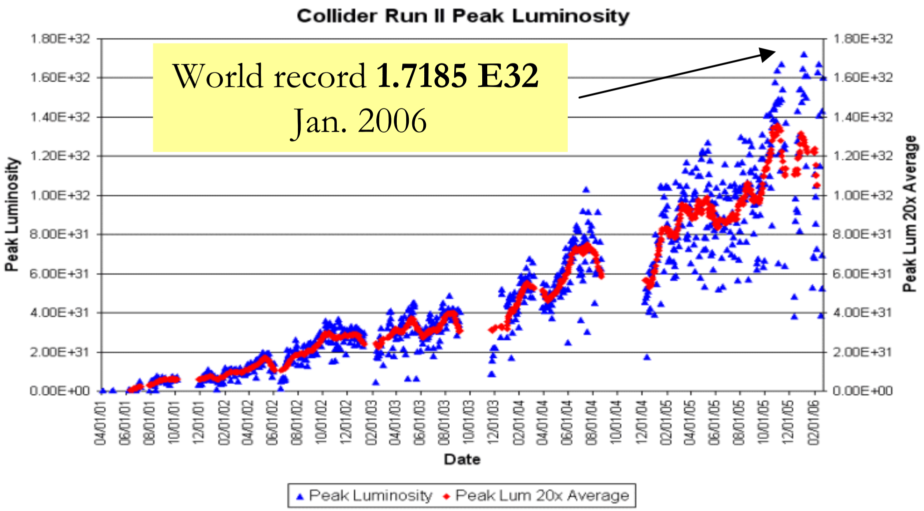


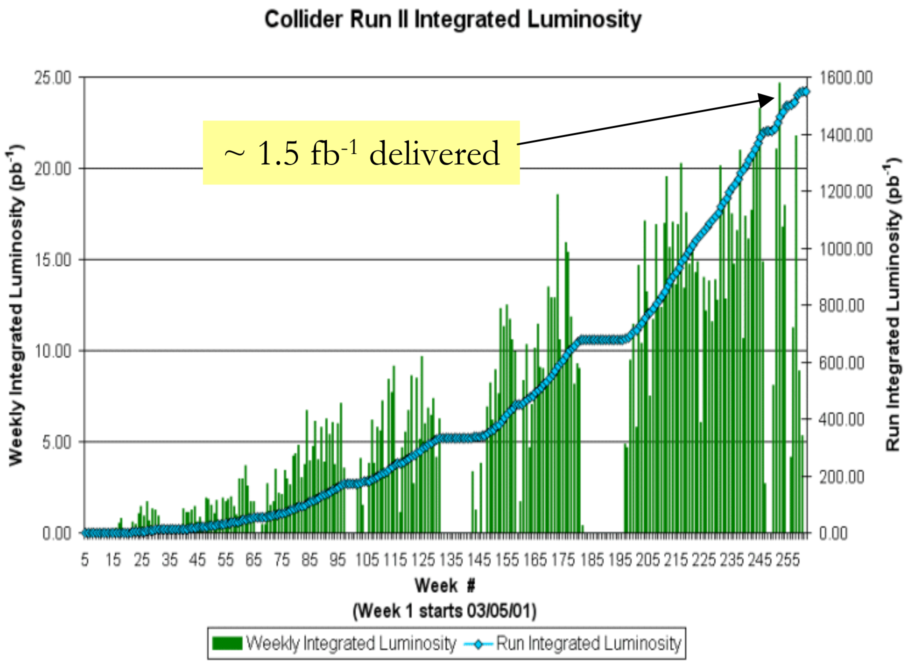
Typical « recorded » to « delivered » luminosity ratio: 80 to 90%

~1.2 fb^{-1} on tape for each experiment

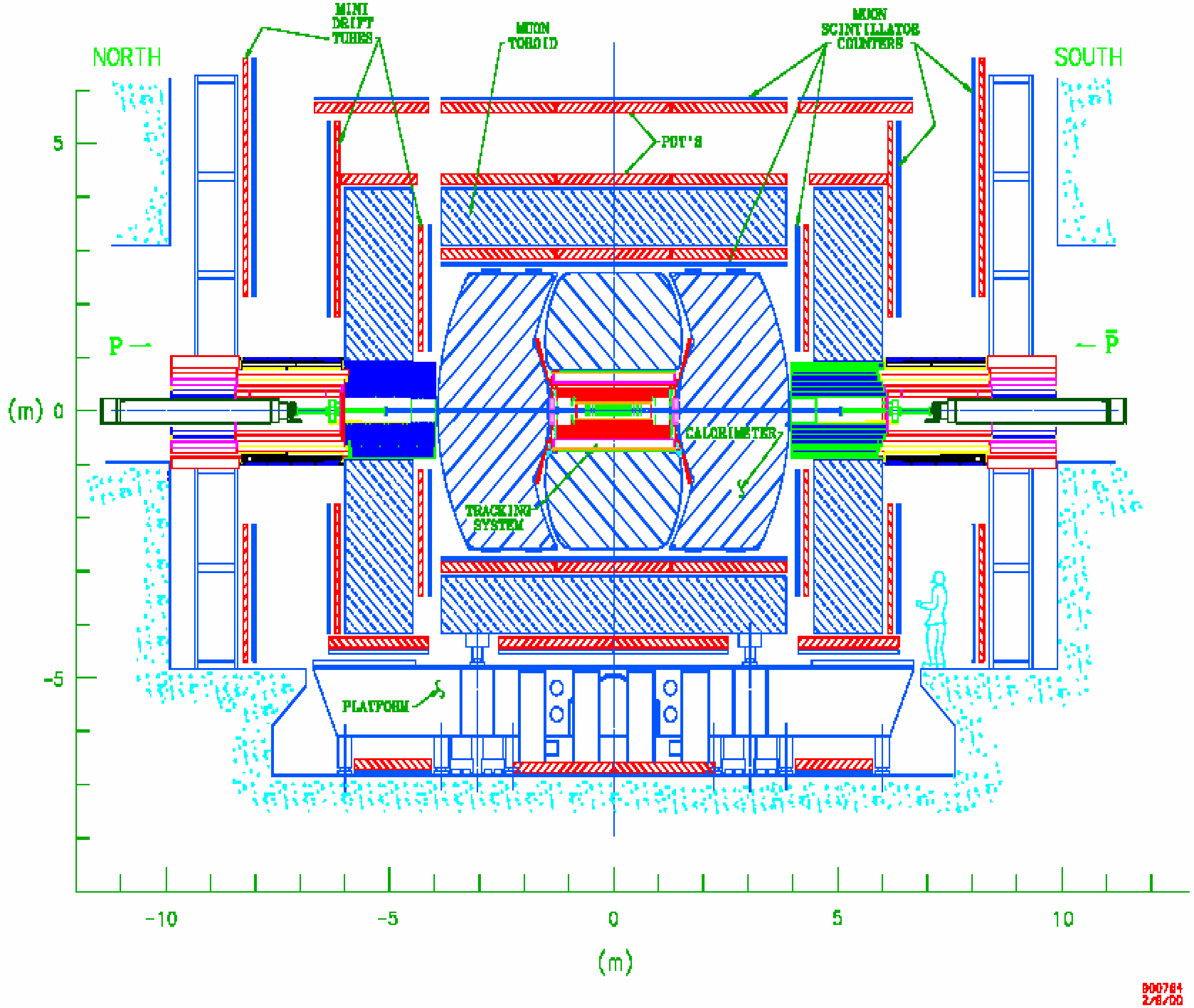
0.2 to 0.4 fb^{-1} for results presented here

4 to 8 fb^{-1} expected in 2009



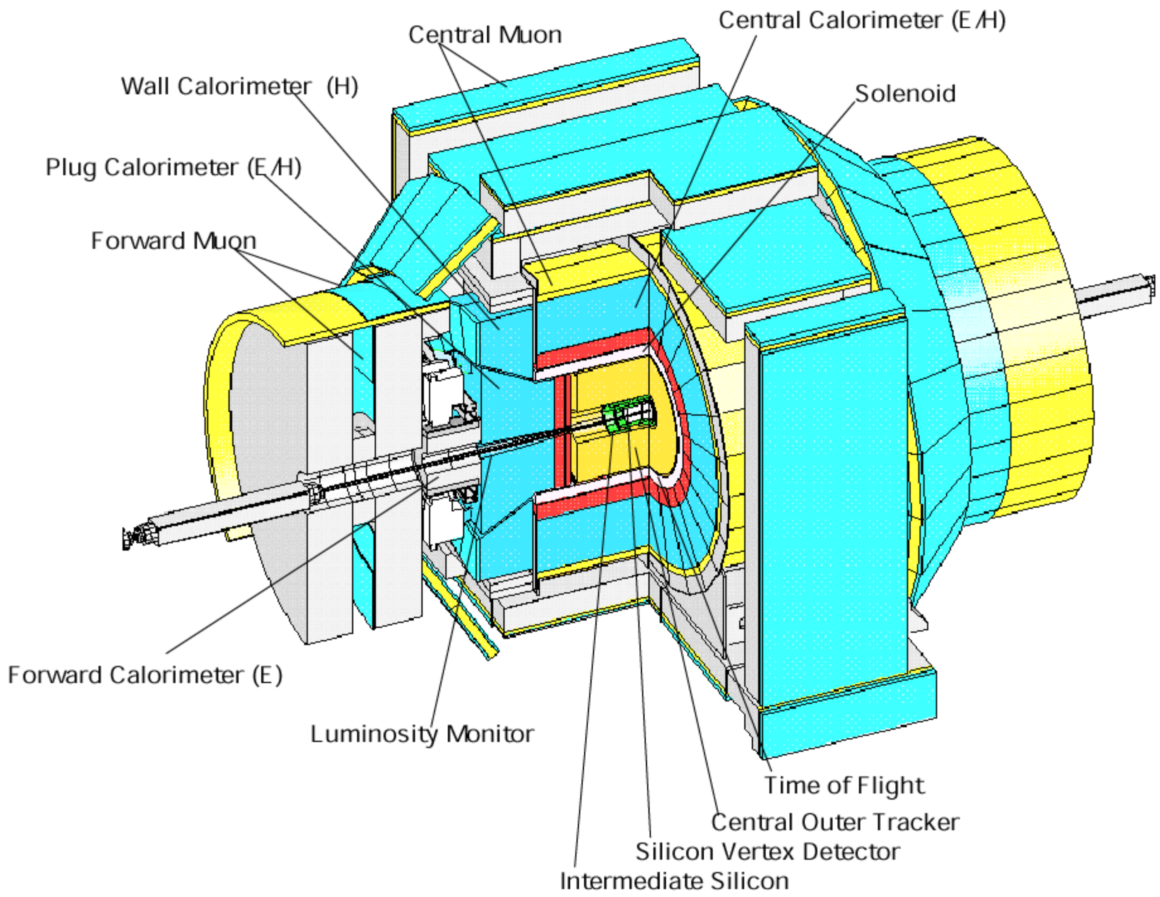


Do detector



- New silicon and fiber tracker
- Solenoid (2 Tesla)
- Upgrade of muon system
- Upgrade of Trigger/DAQ

CDF detector



- New silicon and drift chamber
- Upgrade of calorimeter and muon system
- Upgrade of Trigger/DAQ

Extra Dimensions

Hierarchy problem: Why $M_{PL} \sim 10^{16}$ TeV >> $M_{EW} \sim 1$ TeV ?

Arkani-Hamed, Dimopoulos Dvali (ADD)

- SM particles confined to a three-dimensional « brane »
- Gauge interactions: embedded in a « multiverse »: the three standard plus additionnal compact dimension
- Graviton can propagate in the multiverse
- Gravitons propagating in compact extra dimensions appear as a tower of Kaluza-Klein (KK) excited modes (point of view of the SM brane)
- Radius of compactification can be as large as 1 mm
- Gravitons are free to propagate in extra dimensions

  -> gravitational appears suppressed on the SM brane

  -> the apparent Planck scale is ~ 10^{19} GeV with respect to the 3+n dimensional space but the

Excited states with masses n/R^{δ}
(n=number of extra dimensions, R: compactification radius)
Coupling to matter α $1/M_{PL}$
Continuum of KK states -> cross section ~pb

Randall-Sundrum (RS)

- two branes (Planck and SM) in a slice of AntideSitter space-time (AdS_5)
- gravity originates on the Planck brane and the graviton wave function is exponentionnaly suppressed away from the brane along the extra dimension due to a warp factor (metric)

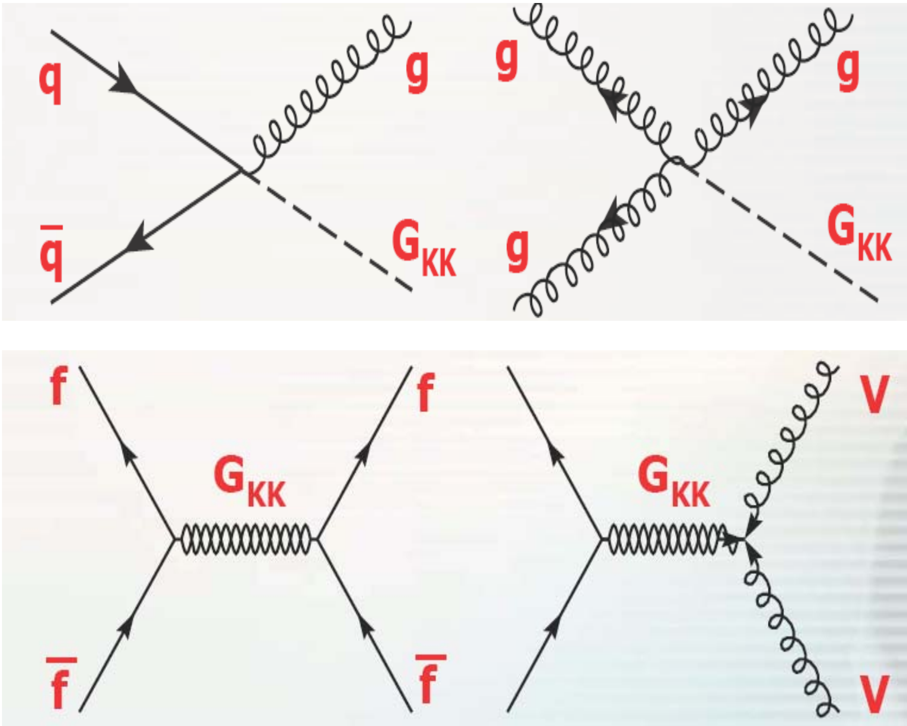
  -> low energy effects on the SM brane with a typical scale: $\Lambda_{\pi} \sim M_{PL} \exp(-k\pi R)$ $M_{PL} = M_{PL}/\sqrt{8\pi}$

  -> hierarchy problem solved if $\Lambda_{\pi} \sim 1$ TeV ie kR ~10

Only one dimension
Massive resonances not equidistant in mass
First excited state: cross section ~pb

Extra Dimensions

Signatures at the TeVatron



Real graviton emission
-> monojets

LED: Virtual graviton effect

RS: real graviton
-> fermion or vector boson pairs
(resonance in RS)

Jet Energy Scale in Do

- Jets are reconstructed from energy deposits in the calorimeter using a cone algorithm
- Jets are made of different kinds of particles (γ,π, K, p, n) for which calorimeter responses are different.
- Moreover: there are energy depositions in the calorimeter from spectator interactions, additionnal pp interactions, electronic noise, and noise due to radioactive decay of uranium.
- Furthermore: not always all particles in a jet deposit energy within algorithm cone.

-> all these effects produce a distorsion in the jet energy and the particle level jet energy can be obtained from the measured jet energy through:

$$E_{jet}^{ptcl} = \frac{E_{jet}^{meas} - E_0(R, \eta, L)}{R_{jet}(E_{jet}^{meas}, \eta) * R_{cone}(R, E_{jet}^{meas}, \eta)}$$

Offset energy(multiple interaction, underlying event energy, electronic noise, uranium noise and pile-up)

Calorimeter response to the hadronic jet

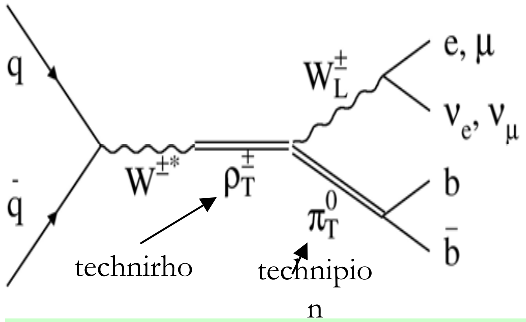
Fraction of pqrticle jet energy contained within the algorithm cone

γ+jet events (p_T imbalance)

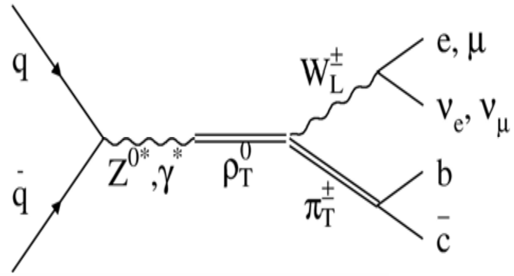
dijet events

Zero Bias (ZB) and Minimum Bias (MB) events

Technicolor



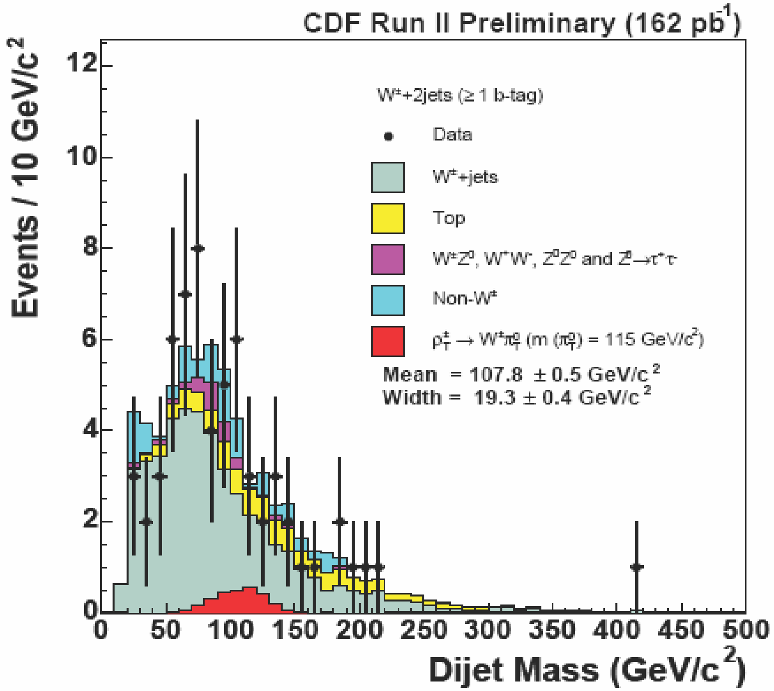
1 isolated lepton
2 jets flavoured tagged
(sim
for b



eνbQ (Q=b,c) $\mathcal{L}$ ~ 238 pb^{-1}

1 electron p_T >20 GeV
ME_T > 20 GeV
$M_T(W)$ > 30 GeV
2 jets p_T >20 GeV
1 jet b-tagged (ε_b ~ 35%; mistg~0.25%)
$\Delta\Phi$(jj) > 2.2, p_T (jj) < 75 GeV
HT= $p_T^e + p_T^j + p_T^j$ < 200 GeV
Invariant masses: m(jj) , m(Wjj)
Main bkground: Wbb, W+light (mistag)

Data: 4 MC: 6.6



Systematics:
-D0: JES, Jet reso, btag
-CDF: FSR, btag, ISR, JES

$m(\varrho_T, \pi_T) = (200,105)$ GeV $\sigma < 0.681$ pb @ 95% C

Projection Z'->ee