Searches For New Physics

Gustaaf Brooijmans

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Meeting of the Division of Particles and Fields
of the American Physical Society
University of California, Riverside
2004

Too Much To Talk About

- I'd like to cover
  - Direct searches, indirect searches and future prospects
- Sounds simple enough, but looking at the parallel session agendas...
  - 31 talks in “Direct Searches”
  - 10 talks in “Muon g-2, LFV, EDMs”
  - 9 talks in “LHC-LC Comparison”
  - 43 talks in non-top “Heavy Flavor Physics”

I apologize

The Standard Model in Words

- Matter is built of spin ½ particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions
- There are 3 generations of matter particles
- The 4 different matter particles in each generation carry different combinations of (quantified) charges characterizing their couplings to the interaction bosons
- The matter fermions and the weak bosons have "mass"
- Gravitation is presumably mediated by spin 2 gravitons
- (There appear to be 3 macroscopic space dimensions)

Many Fundamental Questions

- What exactly *is* (weak iso)spin? Or color? Or electric charge? Why are they quantified?
- Are there only 3 generations? If so, why?
- Why is there no matter that doesn't interact weakly?
- What is mass?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- Is "our universe" the unique solution?

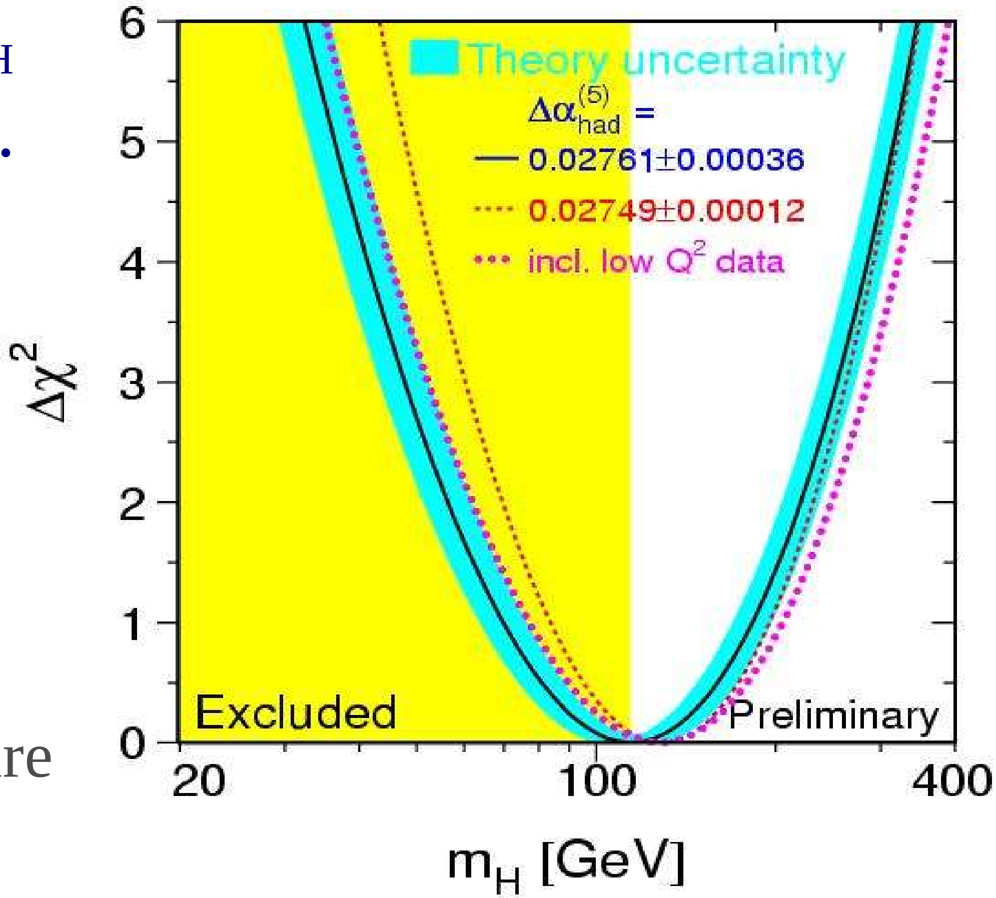
The One We Think We May Have a Handle On: Mass

- The addition of a naïve M^2WW mass term to generate the gauge boson masses (luckily) not only breaks gauge invariance, but also destroys renormalizability of the Standard Model
  - At high energy (sqrt(s) ~ 1.7 TeV), $W_L W_L$ scattering violates unitarity
- An elegant solution is provided by the Higgs mechanism: the "Standard Model Higgs" generates both boson and fermion masses, and "restores" unitarity (if $m_H <$ ~1 TeV).

Standard Model Higgs Mass

- Yellow shaded: excluded by LEP2 direct search (m_H > 114.4 GeV @ 95% CL).
- Curve: m_H inferred from precision measurements, very sensitive to m_{top}, m_W (best fit value shifted up ~18 GeV with 4 GeV increase in m_{top} – DØ, Nature 429: 638, 2004)

Best fit now 114 GeV

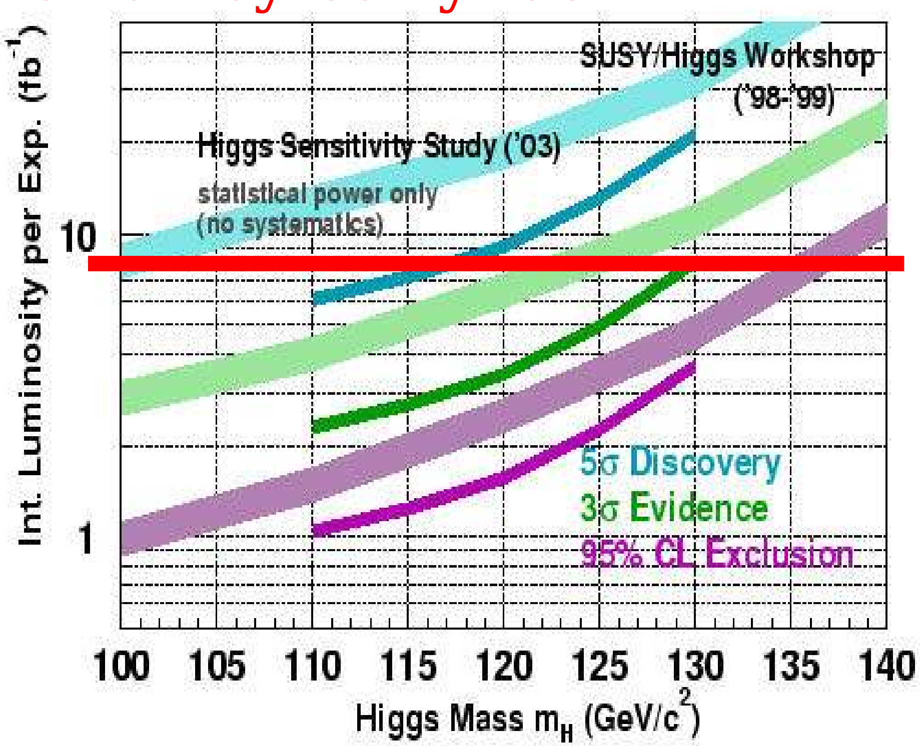


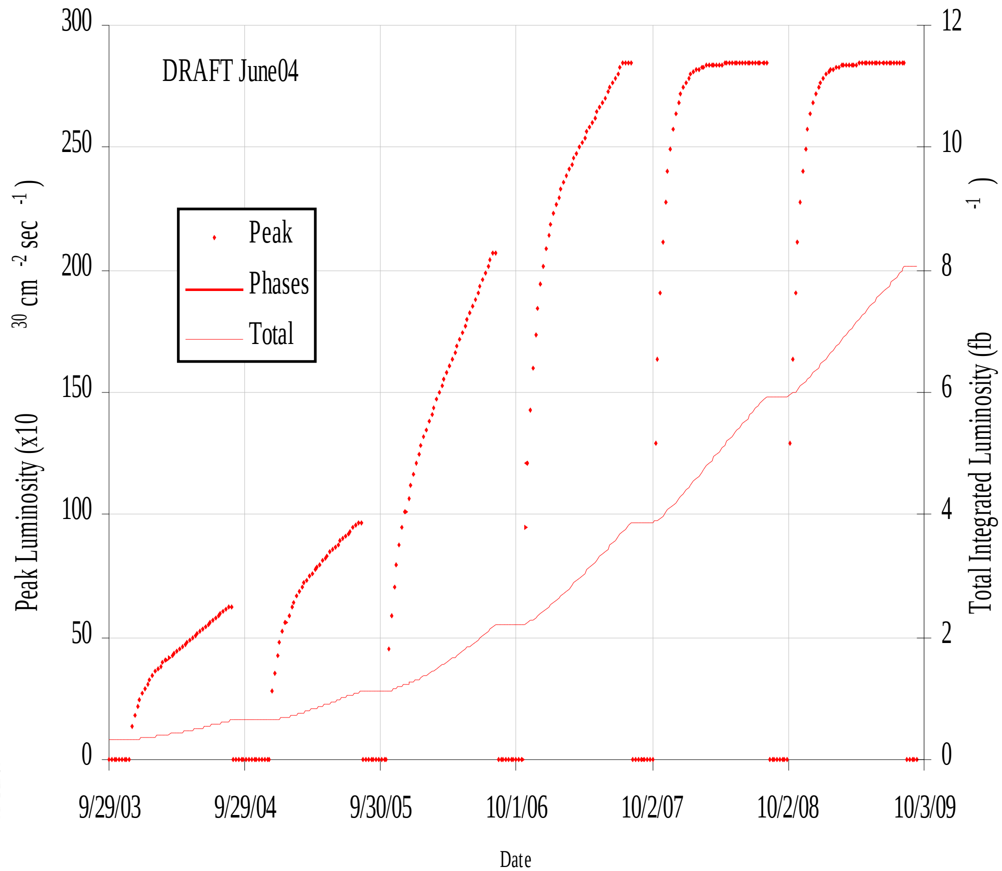
LEP EWWG, Summer 04

Prospects for SM Higgs Discovery

- Tevatron Higgs sensitivity study redone in 2003 with better knowledge of detector performance, 1999 results confirmed
- Detection through production of WH or ZH, leptonic W/Z decay and H decay to $b\bar{b}$

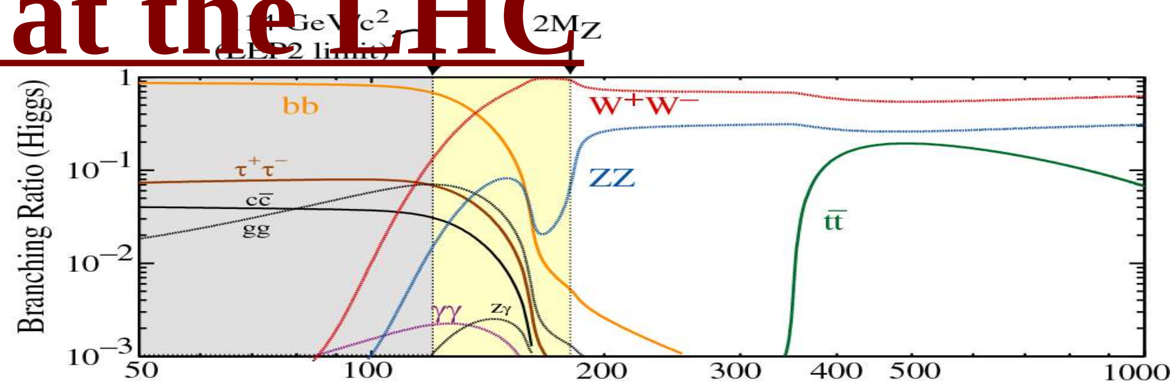
8 fb^{-1} by early '08



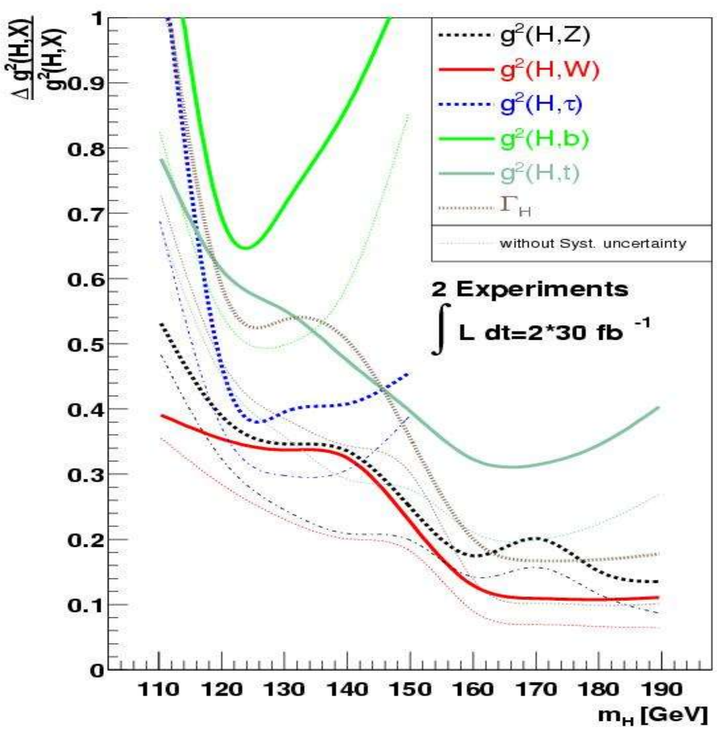


SM Higgs at the LHC

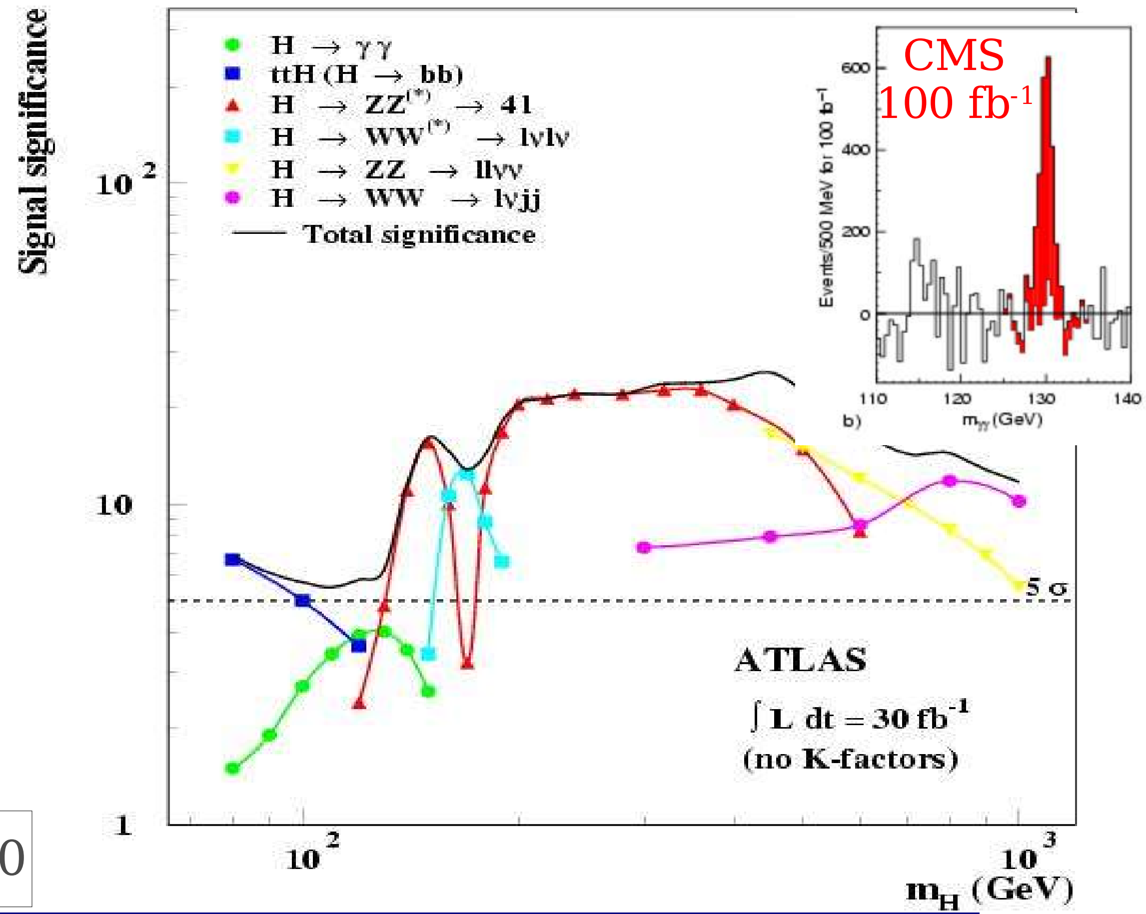
- If there is a Higgs with "Standard Model properties", discovery at LHC is "certain"



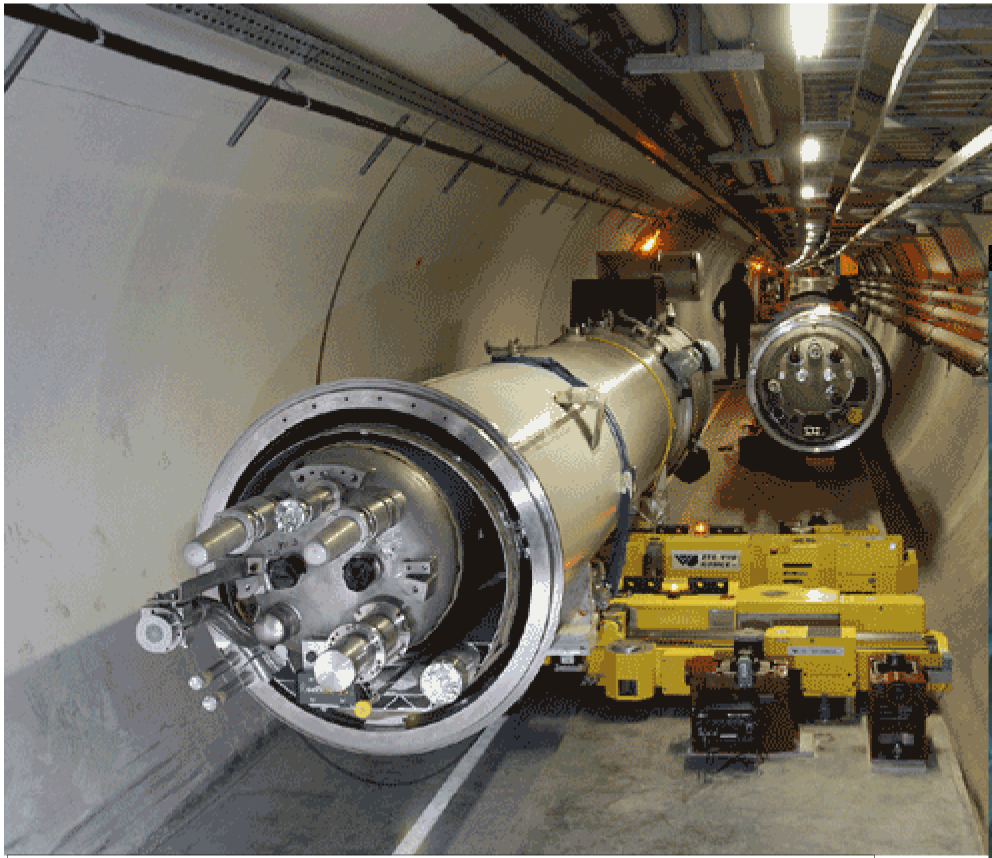
- Measurement of properties:



Duehrssen et al., hep-ph/0407190



The LHC is Real!



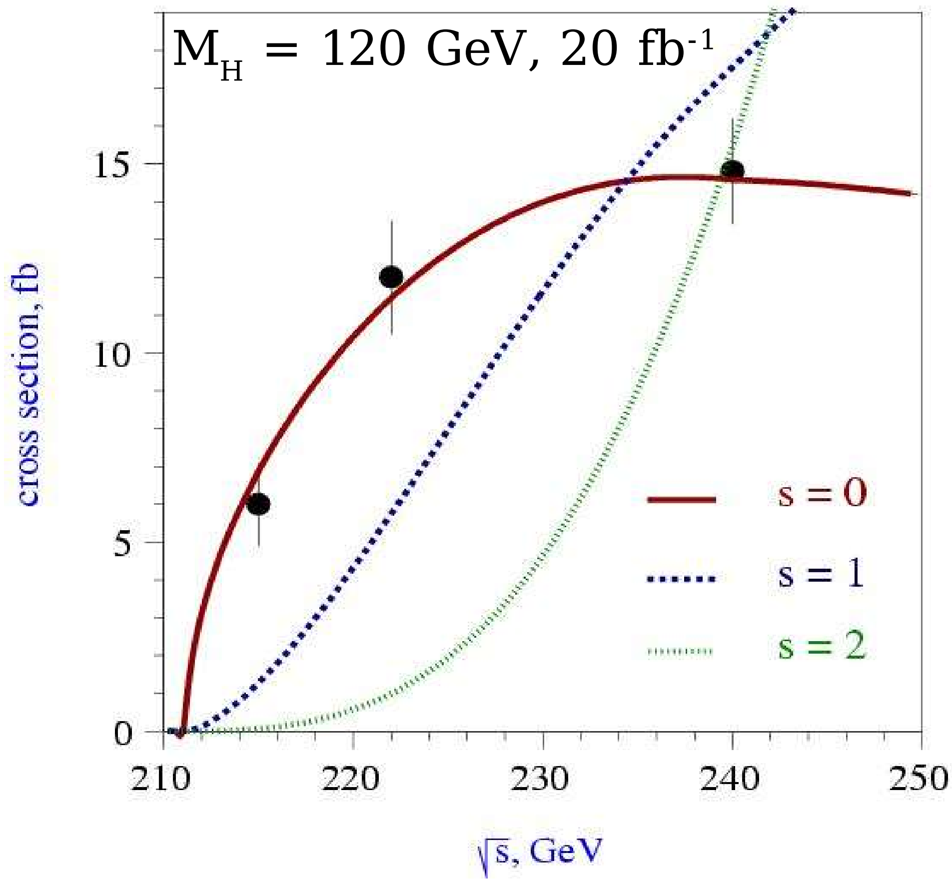
Real Magnets in Tunnel!

Atlas Cavern

Studying The Higgs at a LC

- Couplings: Dawson & Oreglia hep-ph/0403015
  - b: <1 - 10% for m_H = 115-200 GeV
  - c, tau: 12% for m_H < 160 GeV
  - t: through ttH production (10-20%, as LHC) for m_H < 350 GeV
  - W: 2 – 0.5% for m_H = 115-200 GeV
  - photon :5 – 25% for m_H = 115-200 GeV
  - Z: 1% at m_H = 200 GeV
- Spin:
  - (Angular distributions in) decays
  - Production cross-section

Dova, Garcia-Abia and Lohmann hep-ph/0302113



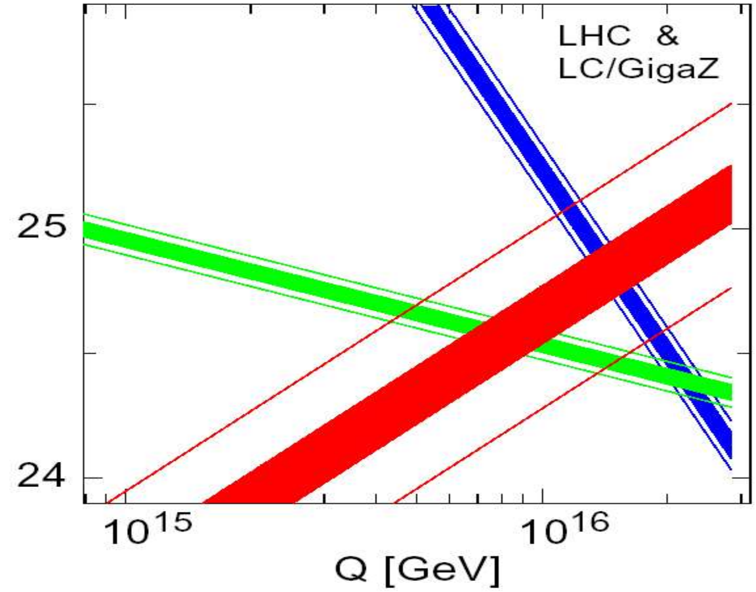
Higgs Drawbacks

- Higgs by itself is very unsatisfactory:
  - Why are the Yukawa couplings what they are?
  - What is the link to gravity?
  - Why exactly *is* $(\mathrm{mu})^2$ negative?
- Higgs mechanism introduces new problems (or benefits):
  - Higgs mass is "naturally" the next energy scale, so if we have a "Standard Model Higgs", that's about 200 GeV
- Two approaches:
  - Fix by addition (SUSY, ... at ~ 200 GeV – 1 TeV)
  - Fix by subtraction (forget about Higgs)

Low Scale Supersymmetry

- For each boson/fermion, there is an associated fermion/boson
  - All quantum numbers (except spin), and all couplings are the same, masses appear to be different
  - Then, what is spin?
- Fermionic and bosonic loop corrections to the Higgs mass cancel each other, so Higgs mass is ~SUSY mass scale
- Requires 2 Higgs doublets, get 5 physical Higgses

Gauge Coupling Unification - MSSM



Allanach et al., hep-ph/0407067

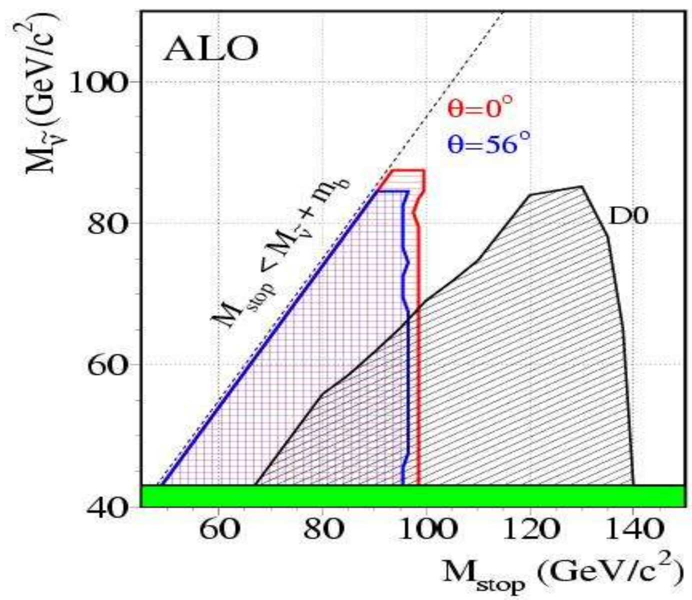
Minimal Supersymmetric SM

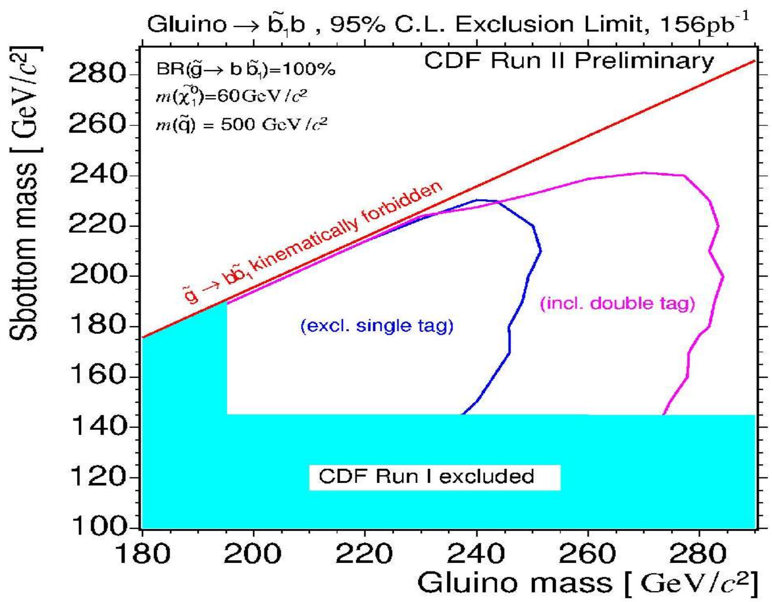
- Minimally constrained means 105 parameters (superpartner masses, mixing angles,…)

These analyses assume LSP is the lightest neutralino, process BR

LEP, D0 limits on stop and sneutrino mass assuming stop -> b l sneutrino

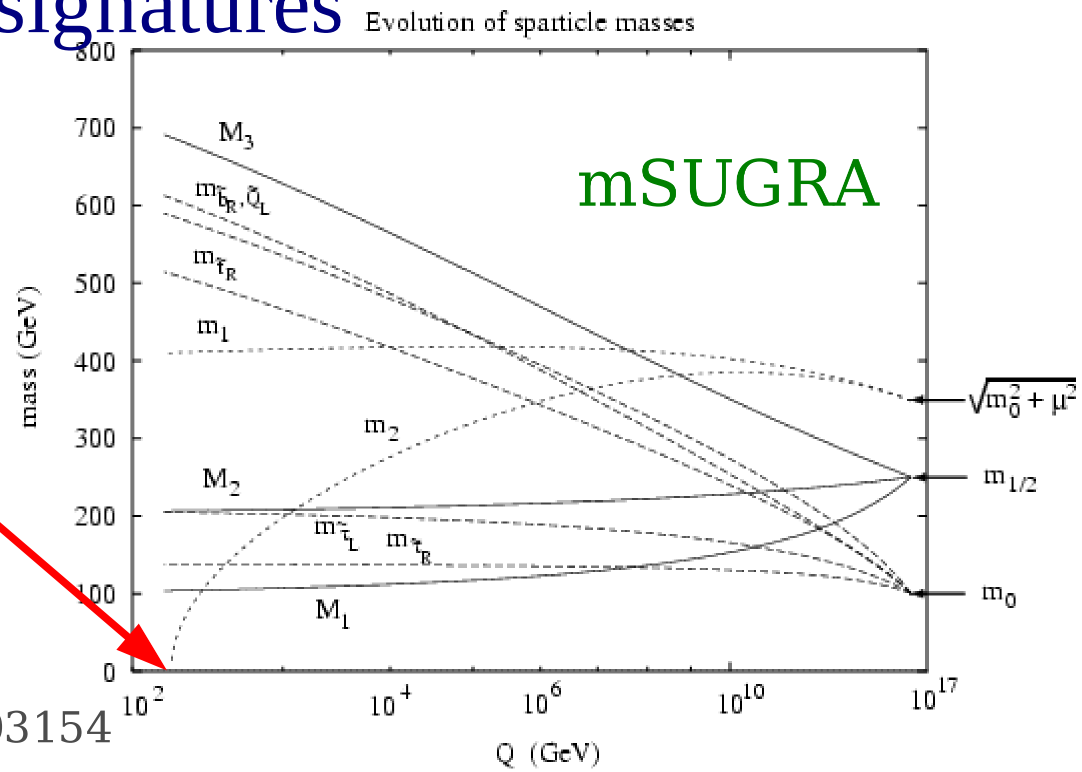
CDF limits on gluino and sbottom mass assuming gluino -> sbottom bottom





SUSY Breaking

- Sparticle masses are different from particle masses, so SUSY must be broken
- Various breaking models, with different phenomenological signatures



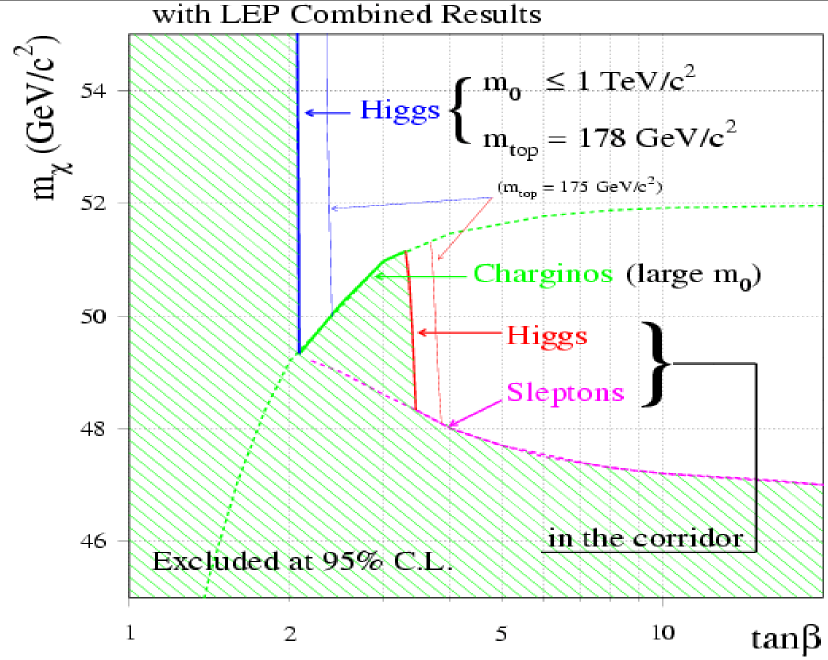
Explain Electroweak Symmetry Breaking! (Mass!)

Barger et al., hep-ph/0003154

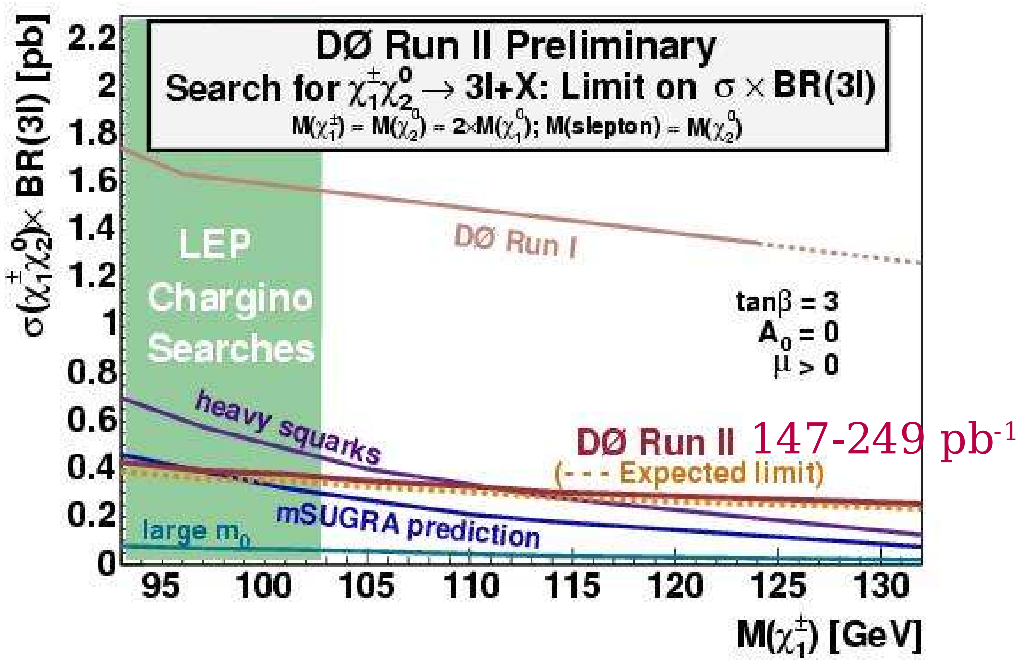
SUperGRAvity

- SUSY breaking is transmitted from a hidden sector through gravity – this reduces the number of free parameters to 5 (in mSUGRA)

LEP combined lower bound on neutralino mass in SUGRA-like model
(LEPSUSYWG/04-07.1)

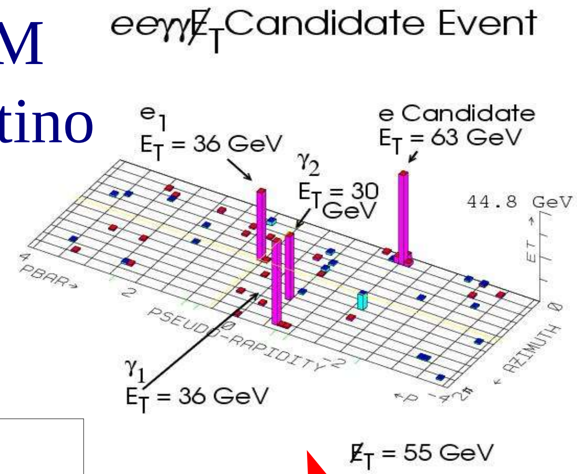


D0 bound on associated chargino - neutralino production in mSUGRA
(Trileptons: "Golden" channel at Tevatron)

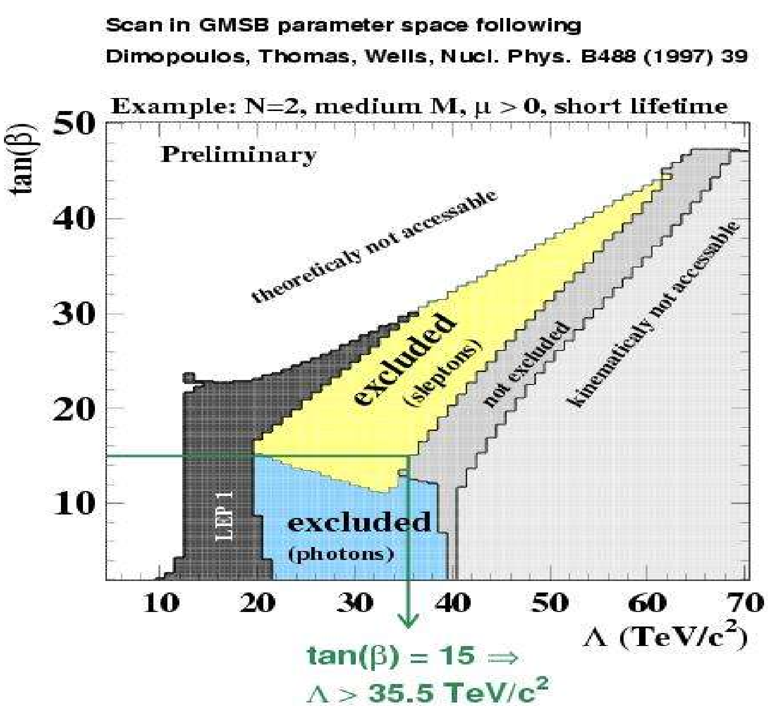


Gauge Mediated Susy Breaking

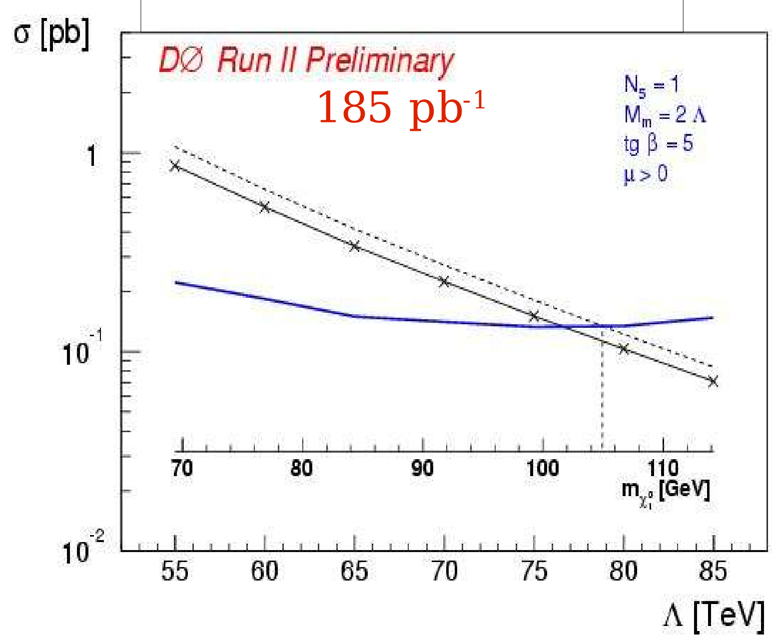
- SUSY breaking messengers participate in SM gauge interactions, LSP is a very light gravitino so phenomenology is driven by NLSP



LEP combined slepton and bino NLSP

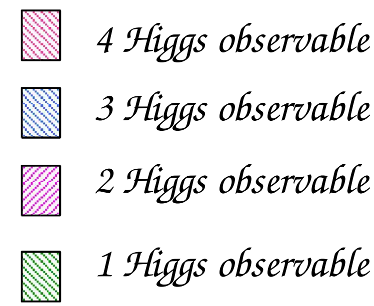


D0 bino NLSP

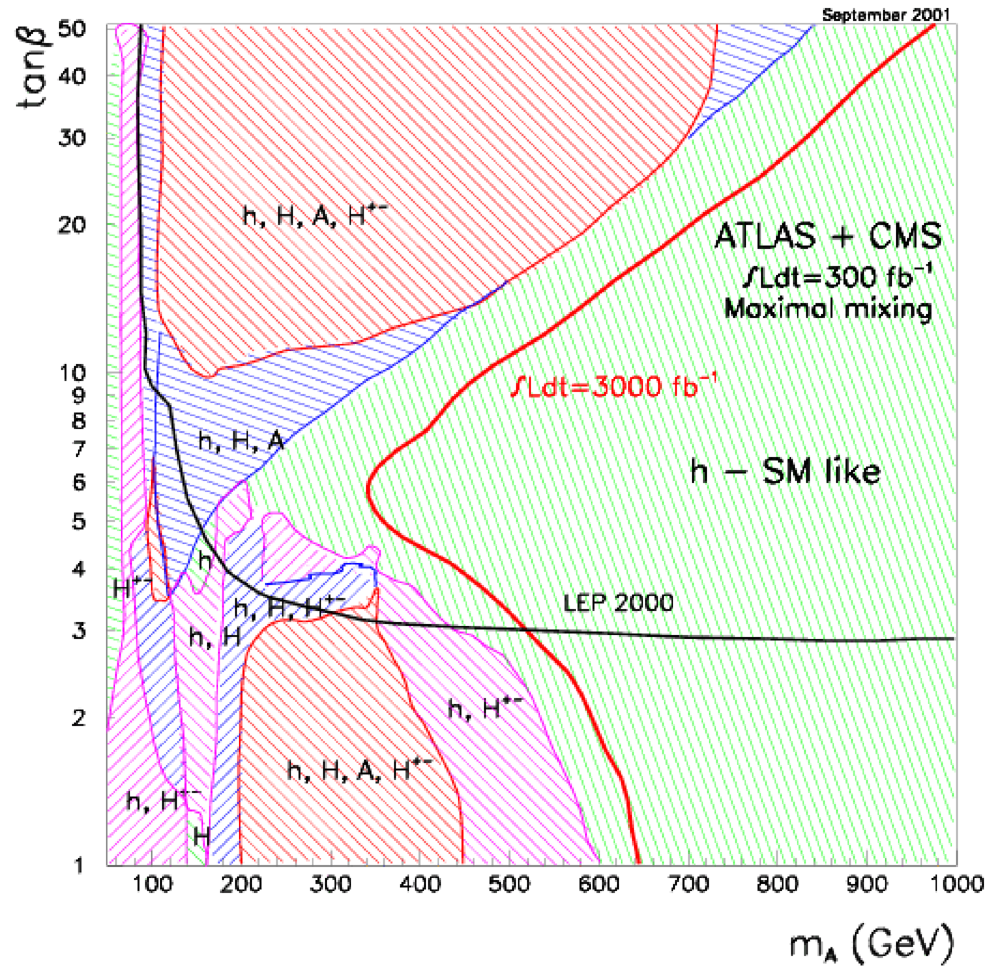


"The" CDF Run 1 Event

SUSY at the LHC - Higgses



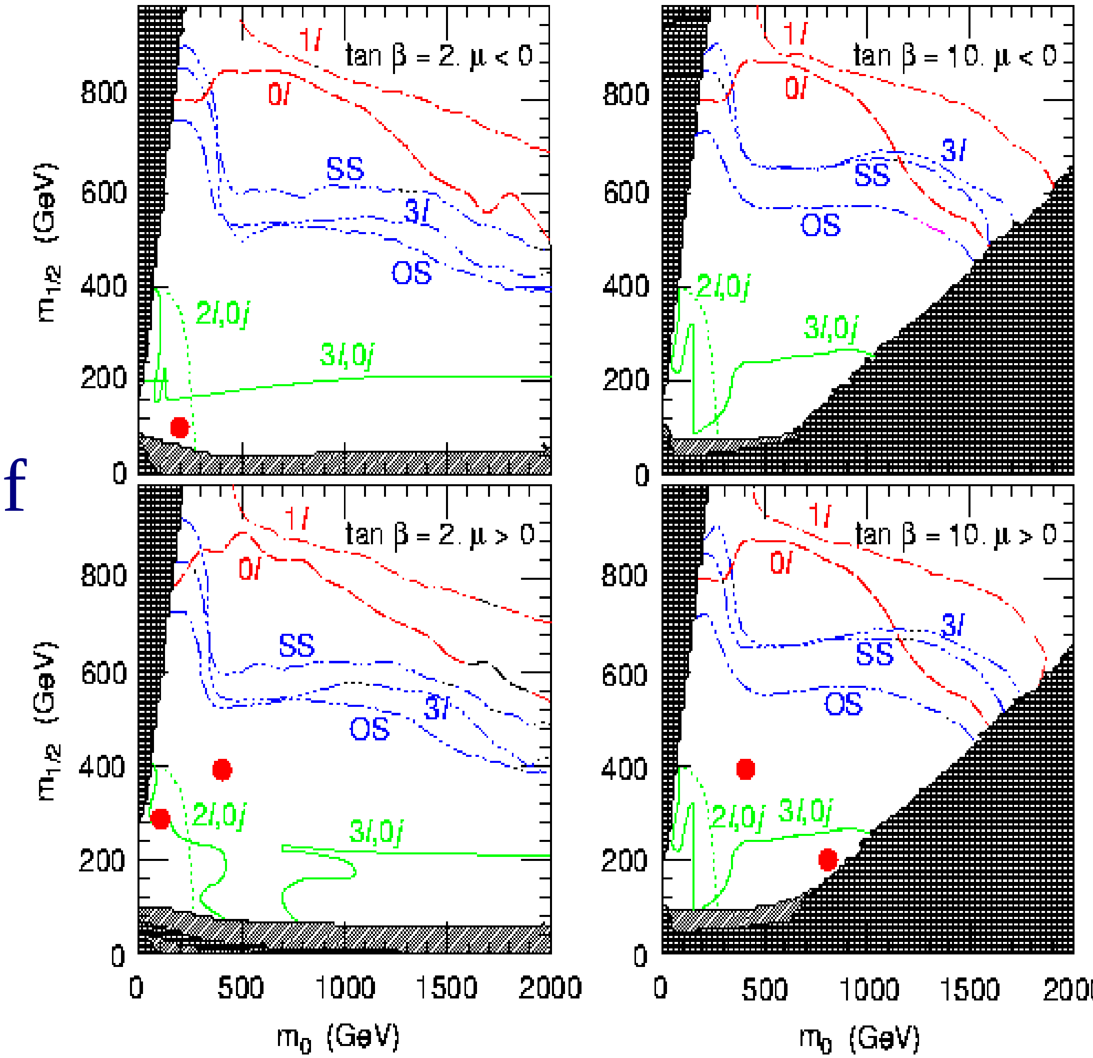
- Always at least one of 5 physical Higgses observable
  - At large m_A, distinguishing SUSY from SM based on Higgs alone is difficult, but in that region, other SUSY signatures are usually present



SUSY at the LHC - Sparticles

- Plethora of signatures
  - Jets + missing ET
  - Trileptons
  - ....
- Detect cascade decays of heavier particles, with LSP escaping -> use endpoints of kinematic distributions to determine masses

Atlas Physics TDR, 10 fb^{-1}

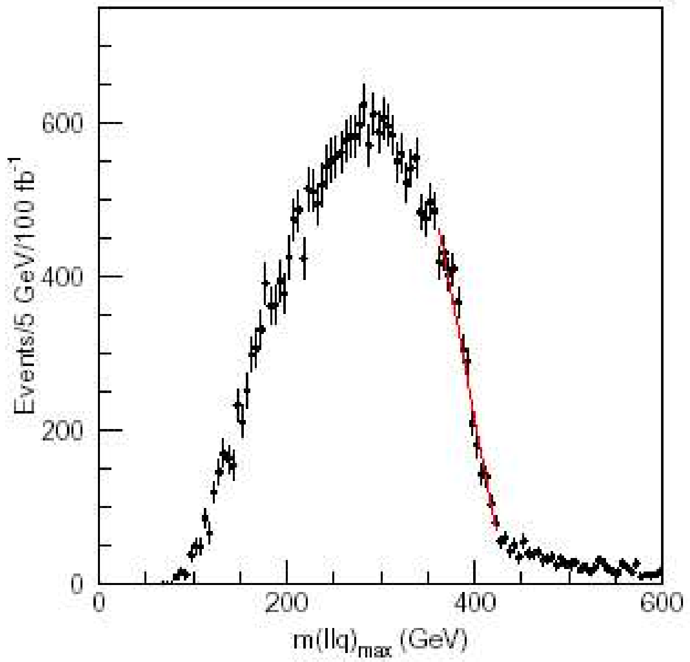


SUSY Measurements

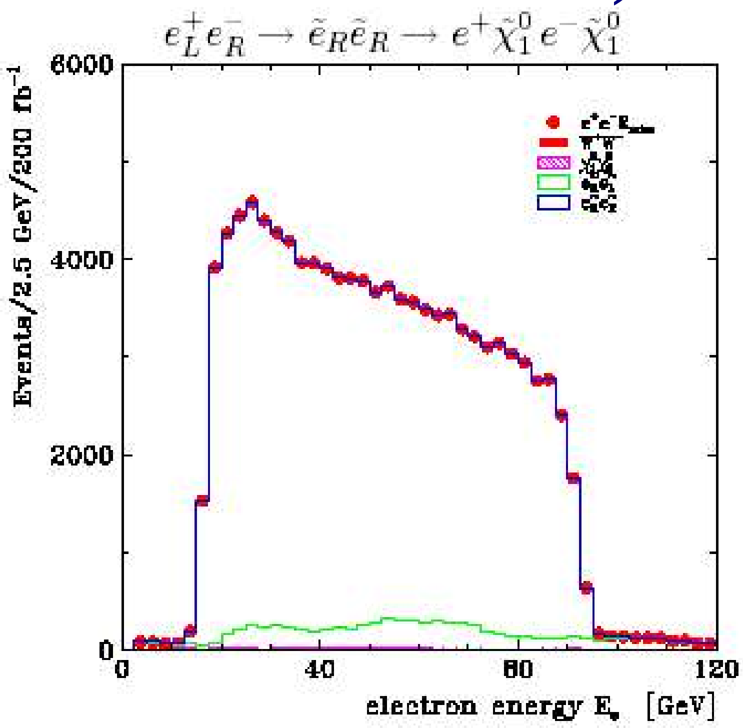
- If there is low-scale SUSY, it will be discovered at the LHC, then move to measurement phase
  - Verify it is SUSY (measure couplings and quantum numbers)
  - Measure pattern of sparticle masses, deduce the pattern of SUSY breaking
- How much of this will be accessible at the LHC and, later, LC depends on the sparticle masses themselves

LHC vs LC

- LC obviously gives better precision (ingoing longitudinal momentum is known)



LHC: llq mass (squark decay)



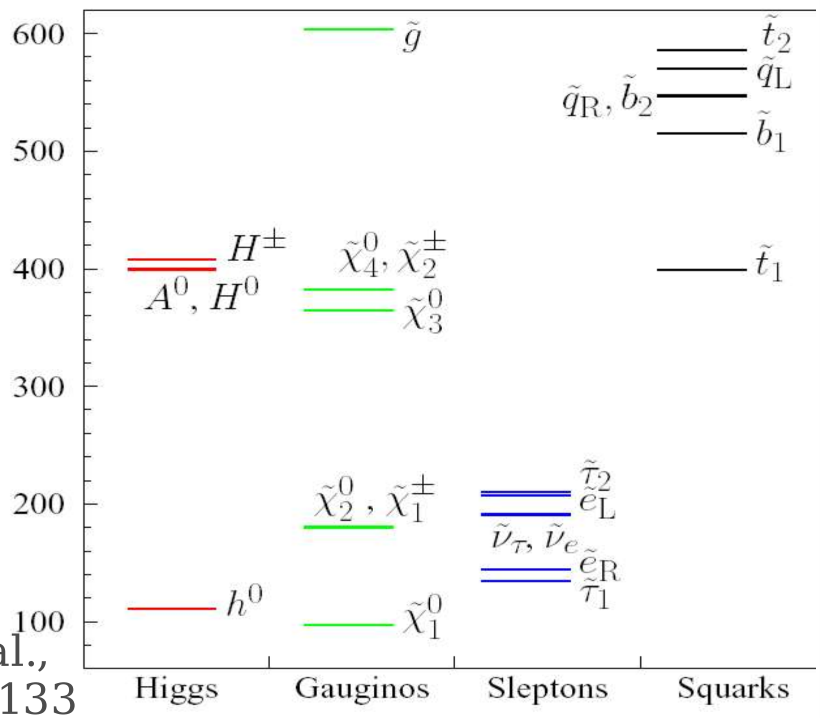
LC: lepton spectrum (slepton decay)

At LC, can also perform threshold scans

Allanach et al., hep-ph/0403133

Comparison For Snowmass Pt 1a

- LC clearly improves mass determination
- But SPS point 1a is very good for the LC (masses are ~low):



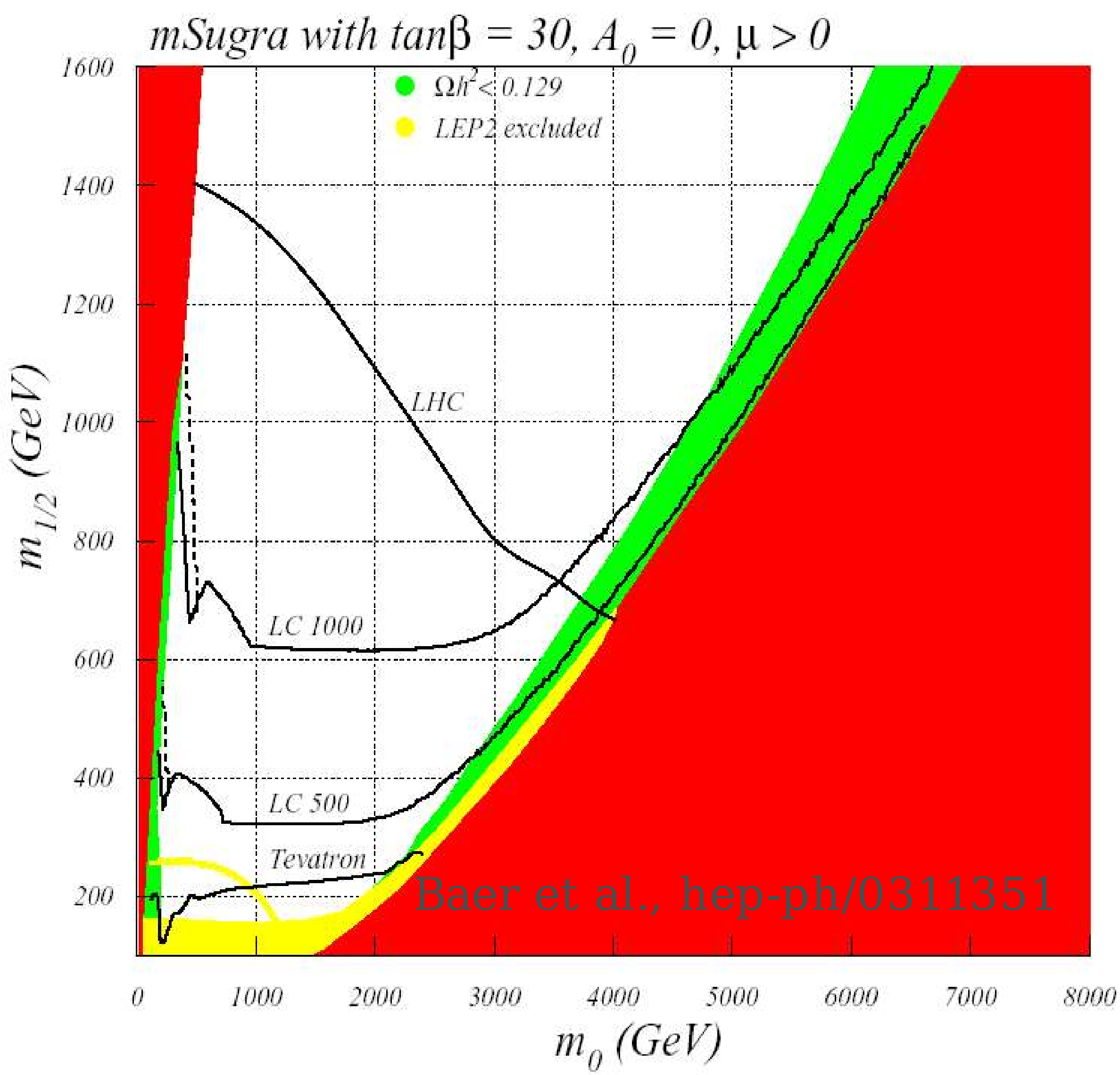
Allanach et al., hep-ph/0403133

	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^{\pm}$	179.7		0.55	0.55
$\tilde{\chi}_2^{\pm}$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{\chi}_3^0$	364.7		3-5	3-5
$\tilde{\chi}_4^0$	381.9	5.1	3-5	2.23
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\mu}_L$	207.1	5.0	0.5	0.5
$\tilde{\nu}_\mu$	191.3	–		
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{\nu}_\tau$	190.4	–	–	–
$\tilde{q}_R$	547.6	7-12	–	5-11
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{b}_1$	515.1	7.5	–	5.7
$\tilde{b}_2$	547.1	7.9	–	6.2
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
H^0	399.8		1.5	1.5
A^0	399.4		1.5	1.5
$H^{\pm}$	407.7	–	1.5	1.5

(in GeV)

Combined mSUGRA Reach

- Red: theoretically not accessible
- Yellow: LEP 2 excluded
- Green: preferred region from WMAP dark matter measurement
- Note area accessible to LC but not LHC

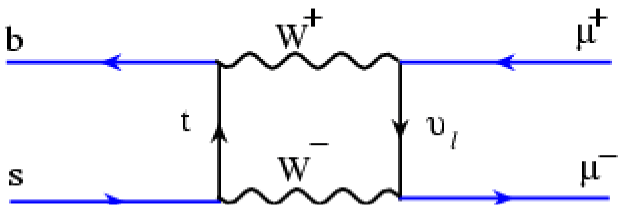


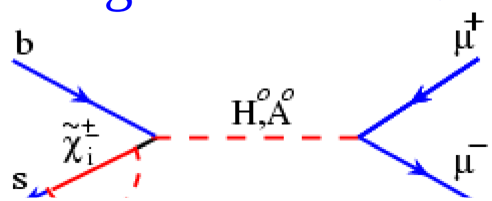
SUSY, Rare Decays and Precision Measurements

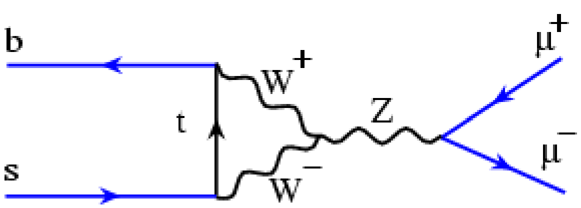
- Rare decays are processes in which the tree-level SM process is forbidden (for example because it is a FCNC)
  - At 1 loop level often still involve a weak process
  - These often provide a relatively background-free means of probing physics at the 1 or 2 loop level
- Other processes are measured with stunning precision, and theoretical precision is just as impressive
- In many cases, these drive limits on new couplings (like R-Parity Violation in SUSY)

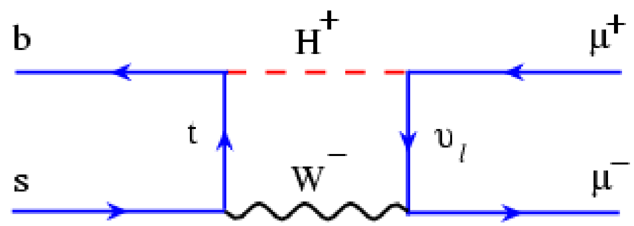
At the Tevatron...

- Tevatron is a copious source of B_s, search for decays to muons
  - In the SM BR = 3.8 10^{-9} (Buchalla & Buras, NPB400 (1993) 225)
  - Could be up to 3 orders of magnitude higher in SUSY:









(This one is present in all 2HDM models...)

New Limits from D0 and CDF (240 and 171 pb^{-1}), combined by M. Herndon: BR < 2.7 10^{-7} @ 90% CL

Or at SLAC (and KEK) ...

Similarly with measurement of $B \to X_S$ gamma, rare tau decays

- BABAR searches for $B_d \to l^+l^-$ decays in ~120 fb^{-1} of on- and off-resonance: (BABAR, hep-ex/0408096)
  - $BR(B_d \to ee) < 6.1\ 10^{-8}$ (SM: $1.9\ 10^{-15}$)
  - $BR(B_d \to mu\ mu) < 8.3\ 10^{-8}$ (SM: $8.0\ 10^{-11}$)
  - $BR(B_d \to e\ mu) < 18\ 10^{-8}$ (SM: 0)
- Allows them to put limits on MSSM parameters using Bobeth et al., PRD 66, 074021 (2002)
  - e.g. $M_H > 138$ GeV @ 90% CL for tan(beta) = 60

Or at Brookhaven...

- New result from E949:
  - BR (K^+ -> pi^+ nu nubar) = 1.47 $^{+1.30}_{-0.89}$ 10^{-10}

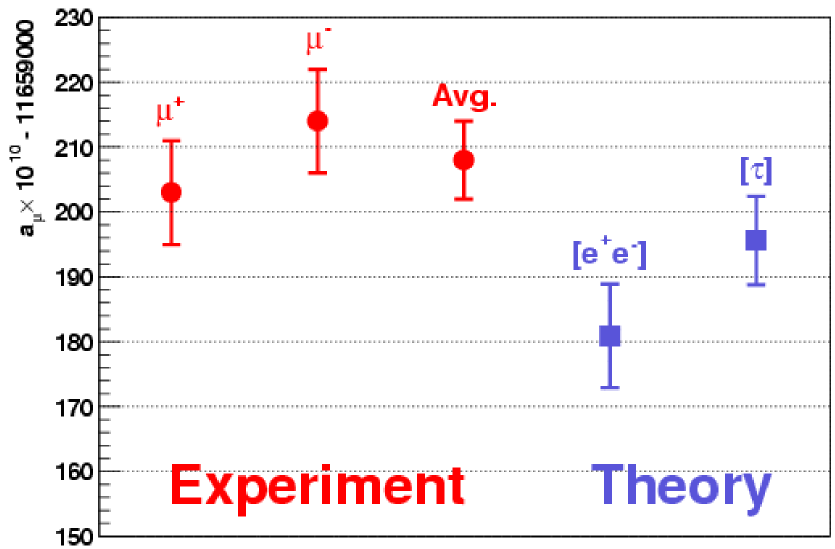
    (E949, hep-ex/0403036)
  - Current SM estimate: BR^{SM} = 8.18 +- 1.22 10^{-11}

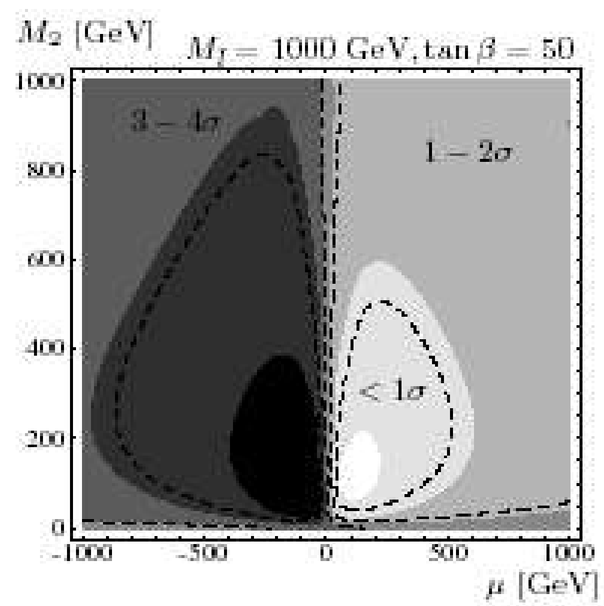
    (Deandrea et al., hep-ph/0407216)
  - SUSY contribution without R-Parity violation is maximum 50% of SM (with current bounds), but use to set limits on some RPV couplings which are the most stringent to date (same authors)

Muon g-2

- Motivation:
  - Difficult, but well-understood experiment, done to a precision of 0.5 ppm (!), sensitive to 2-loop corrections – potential to see effects from heavy new particles
  - Theoretical value well known (0.7 ppm!), although some variation in calculations, and always 2 results, depending on input to hadronic vacuum polarization. (In one of those, issue with uncertainties due to isospin breaking effects)

- Current situation:
  - Discrepancy is 2-3 sigma
- This discrepancy is larger than the effect of weak interactions by 30%! (de Troconiz & Yndurain hep-ph/0402285)
- Can be used to put strong constraints on new physics that contributes in other direction





SUSY and g-2

Heinemeyer et al., hep-ph/0405255

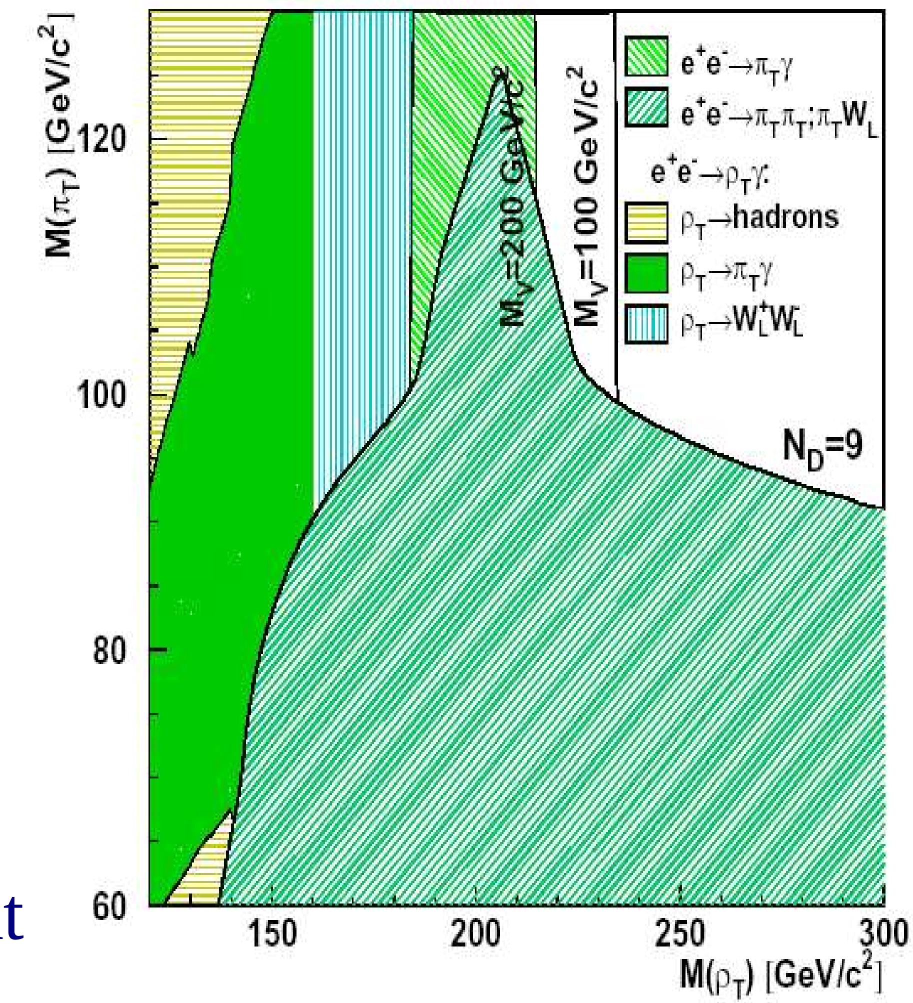
Maybe There is No Low Scale SUSY

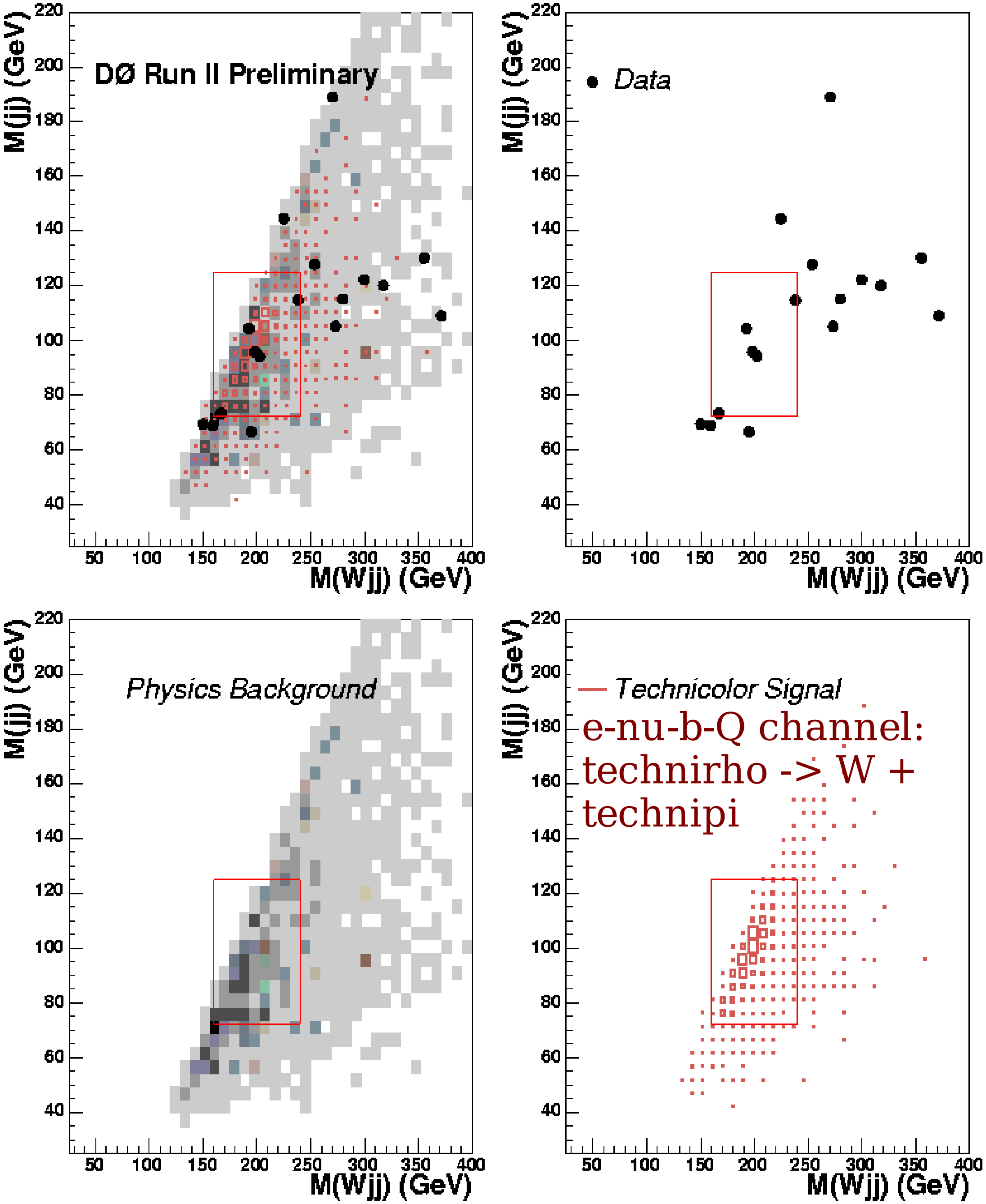
- Quite a few alternatives have been explored, most address hierarchy problem first and foremost:
  - Technicolor
  - Extra space dimensions
  - Complex group-theoretical constructions
- Others argue fine-tuning may be part of nature:
  - "Split" SUSY (Arkani-Hamed & Dimopoulos, hep-th/0405159)

Technicolor Searches

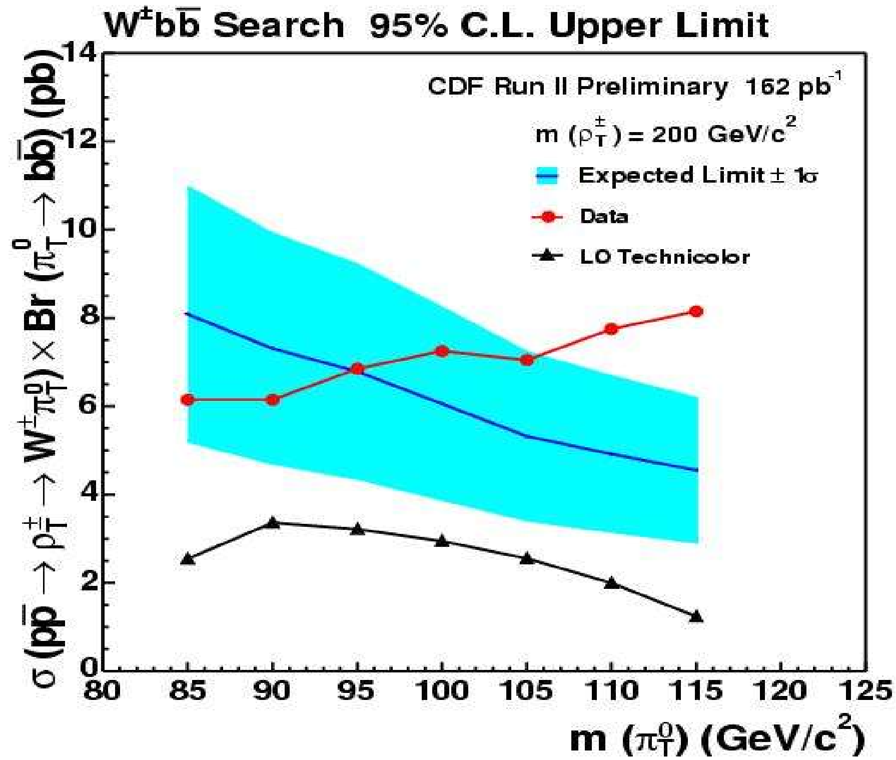
- QCD-inspired, strongly coupled theory
  - Hierarchy explained as a confinement phenomenon
  - No fundamental scalars
- Strong coupling makes it difficult to satisfy constraints from precision data, now have *topcolor-assisted walking technicolor*
- Also makes predictions difficult

Delphi, 2001 LEP Jamboree

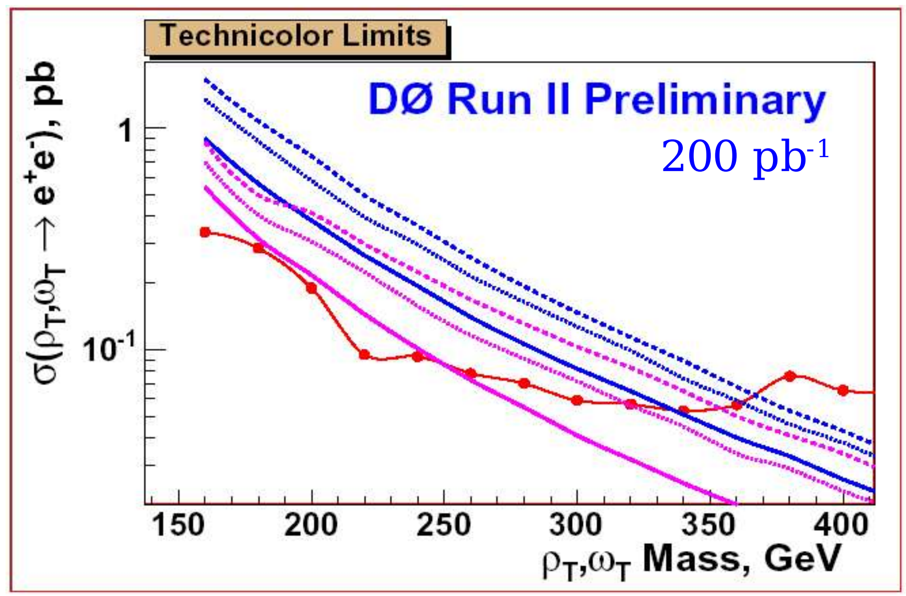




DØ Run II Preliminary
Data
Physics Background
Technicolor Signal
e-nu-b-Q channel:
technirho -> W +
technipi
M(jj) (GeV)
M(Wjj) (GeV)



W±bb̄ Search 95% C.L. Upper Limit
CDF Run II Preliminary 162 pb-1
m (ρ±T) = 200 GeV/c2
Expected Limit ± 1σ
Data
LO Technicolor
m (π0T) (GeV/c2)

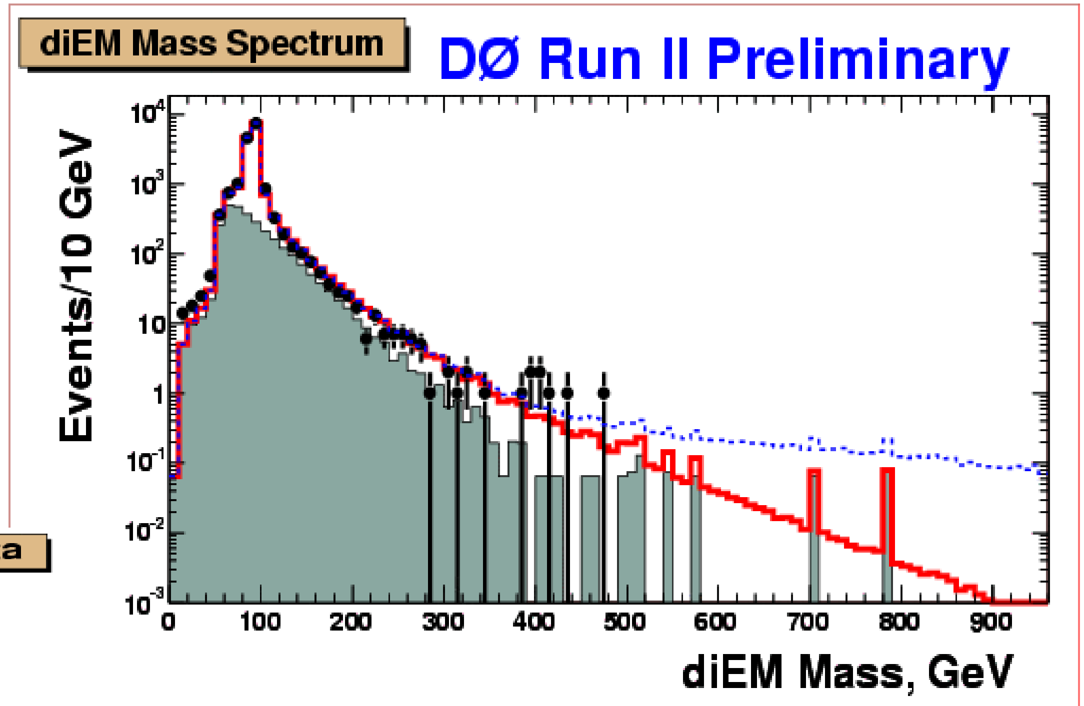


Technicolor Limits
DØ Run II Preliminary
200 pb-1
ρT,ωT Mass, GeV

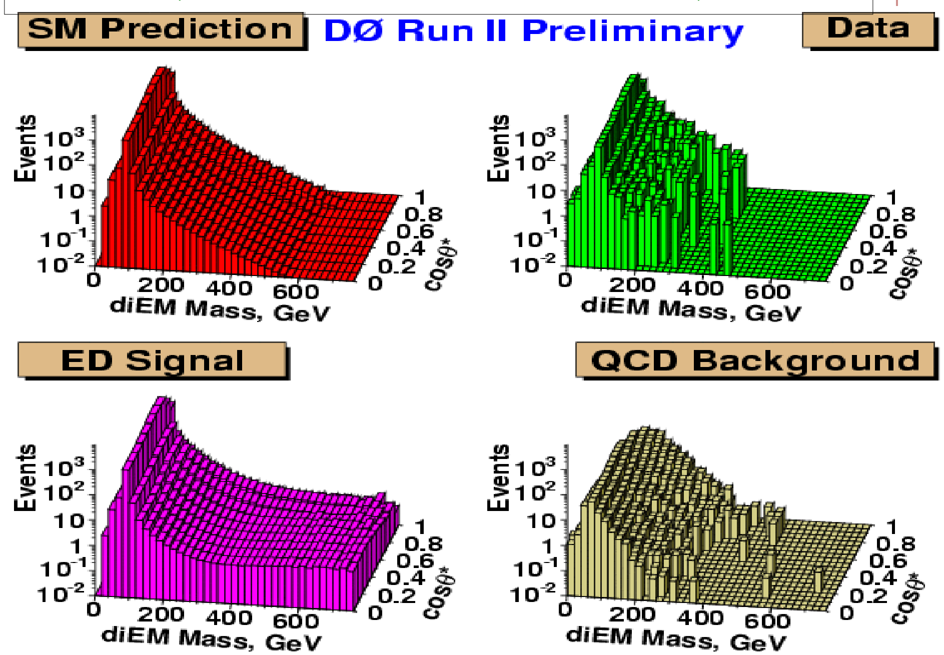
Large Extra Dimensions

- In original Arkani-Hamed, Dimopoulos & Dvali (ADD) scenario, SM particles are confined to a 3-brane, with gravity propagating in more dimensions
- Hierarchy problem solved by bringing down Planck scale (only "appears" high in 3D)
- Two main types of signatures:
  - Interference from KK graviton excitations in SM processes
    - Look at high energy/mass, and angular behavior
  - On-shell KK graviton excitation production
    - Missing energy (graviton goes back to non-SM dimensions)

- D0 search in dielectron (Drell-Yan) and diphoton events



Leads to Most Stringent Limits to Date on Fundamental Planck Scale:
M_S > 1.43 TeV @ 95% CL
(GRW Convention)



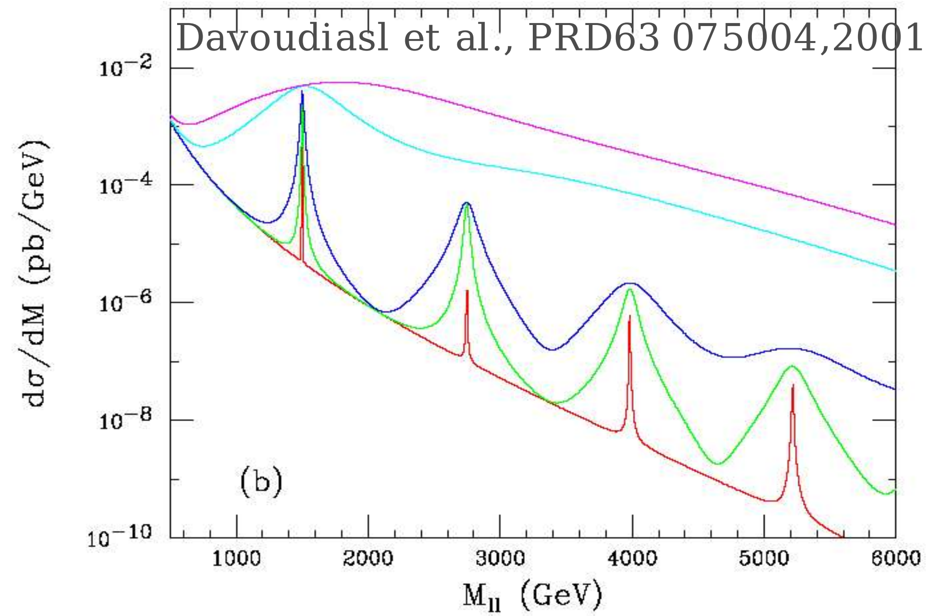
LHC reach is up to 9 TeV (depending on number of dimensions)
Atlas & CMS
hep-ex/0310020

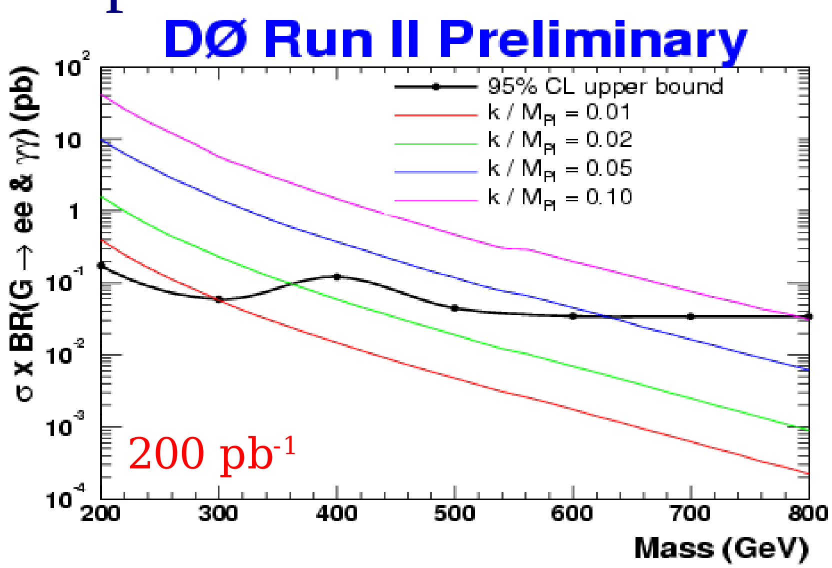
Resonances

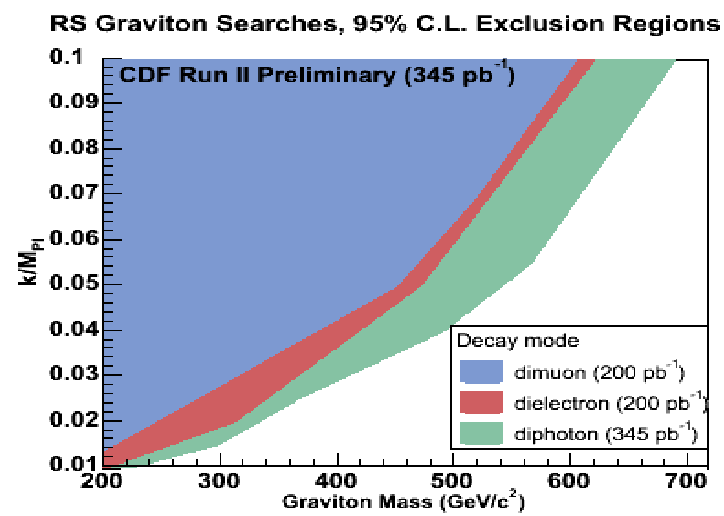
- Many of the non-SUSY models predict resonances:
  - “Warped” extra dimensions (Randall-Sundrum and variations)
    - Graviton resonances
    - Gauge boson KK excitations
  - Little Higgs and other models with extended group structures
    - Z', W' bosons with various coupling strengths
- Experimentally, one analysis gets reinterpreted multiple ways...

Randall Sundrum Gravitons

- Masses correspond to zeros of Bessel function (ratio k/M_{Pl} changes cross-section and width of resonances)
- Search in all dilepton and diphoton channels

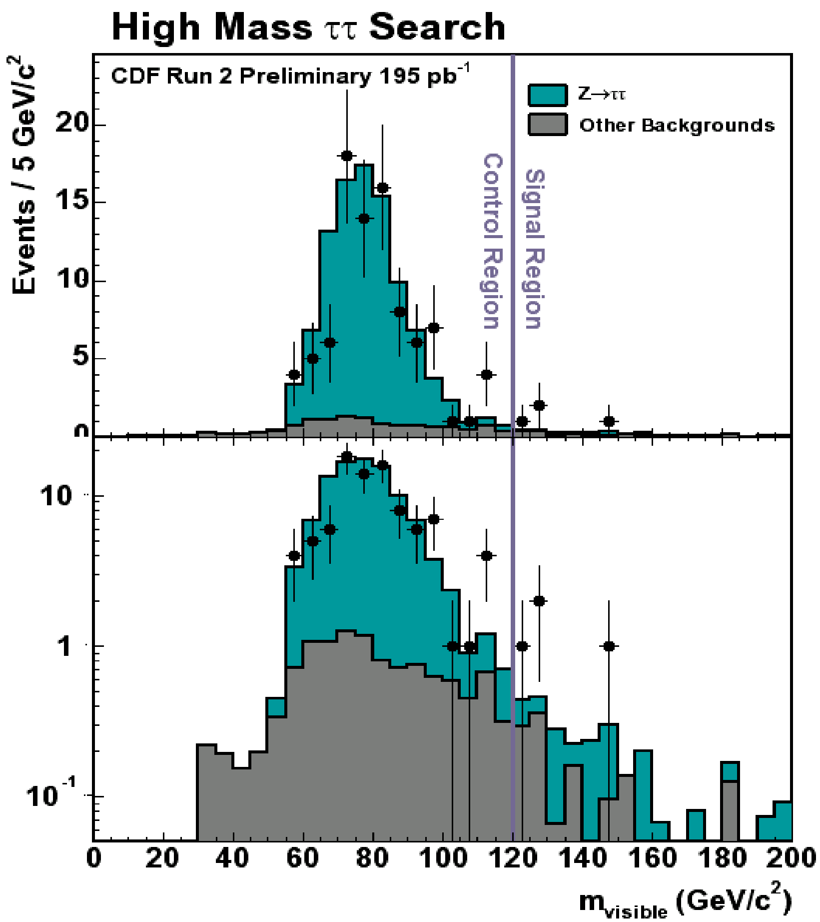


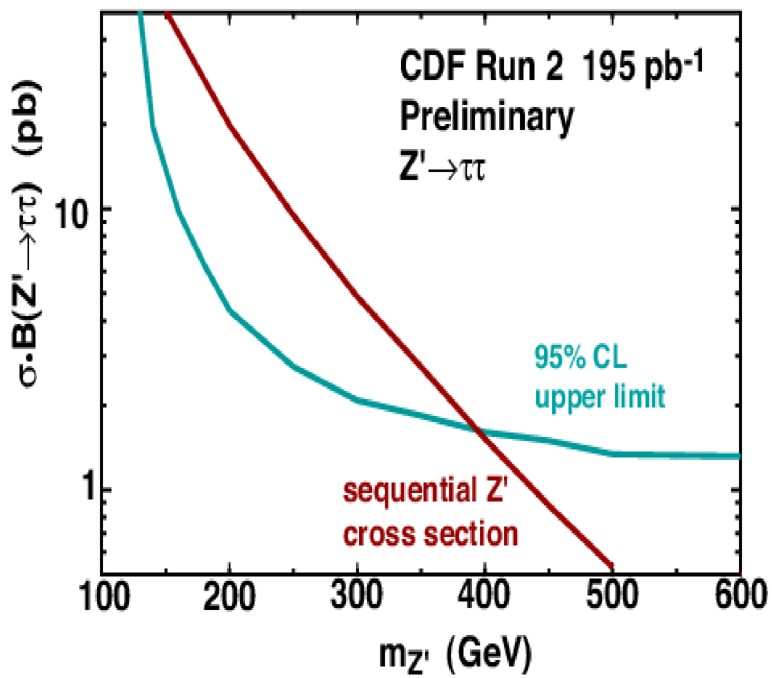


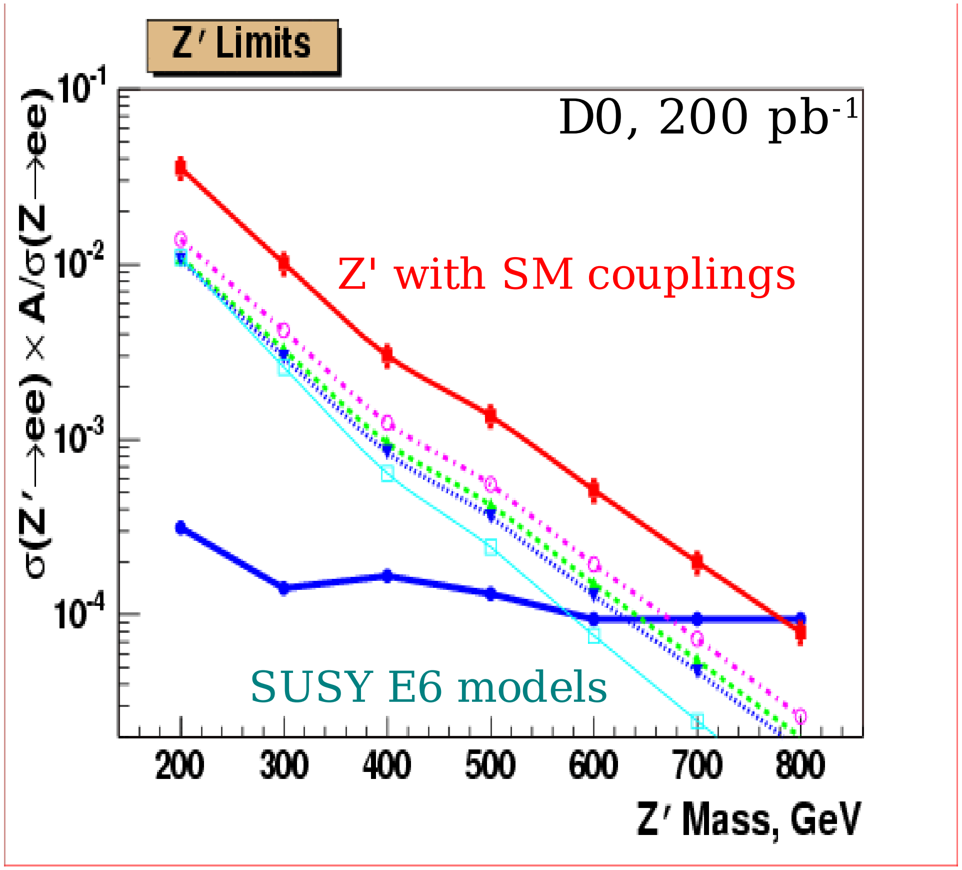


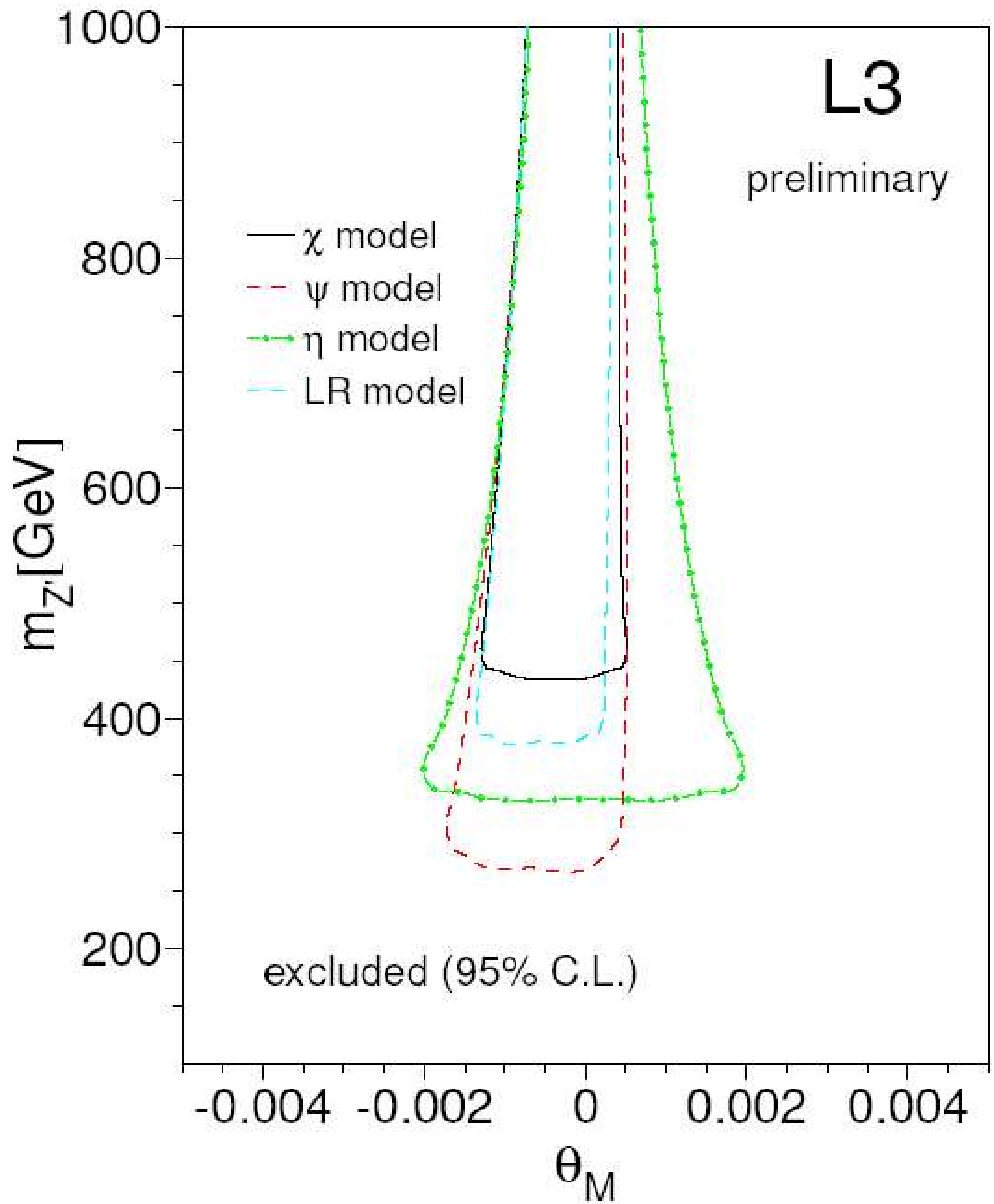
Extra Gauge Bosons

- CDF search in ditaus
  - In some models, dominant coupling is to 3rd generation





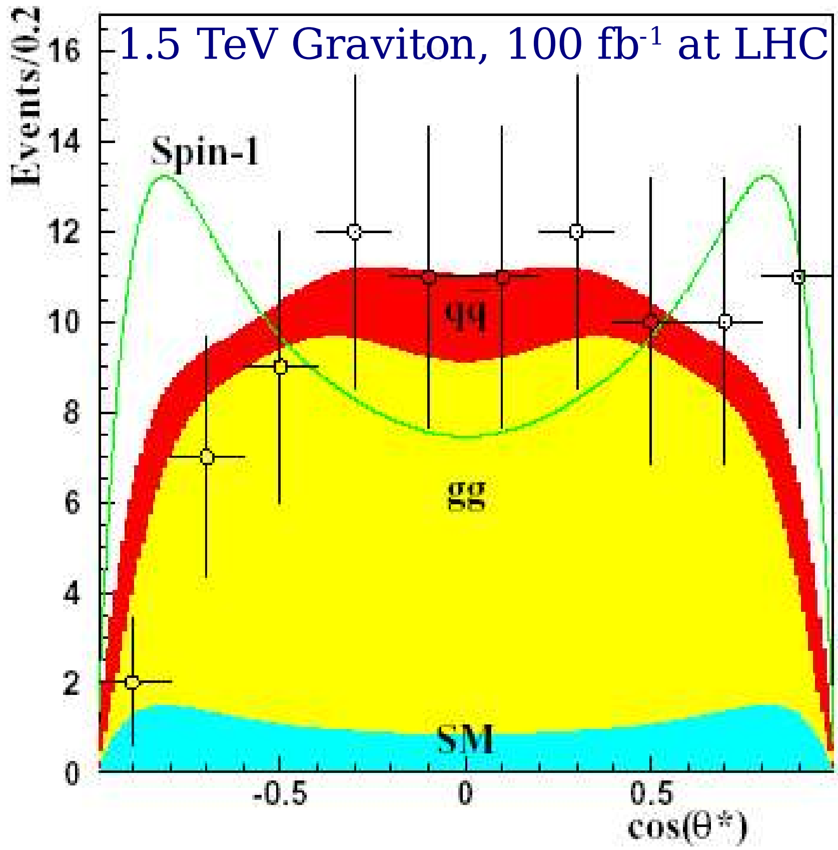




Note: Moller Scattering (E158) should be competitive

Distinguishing Gravitons from Z'

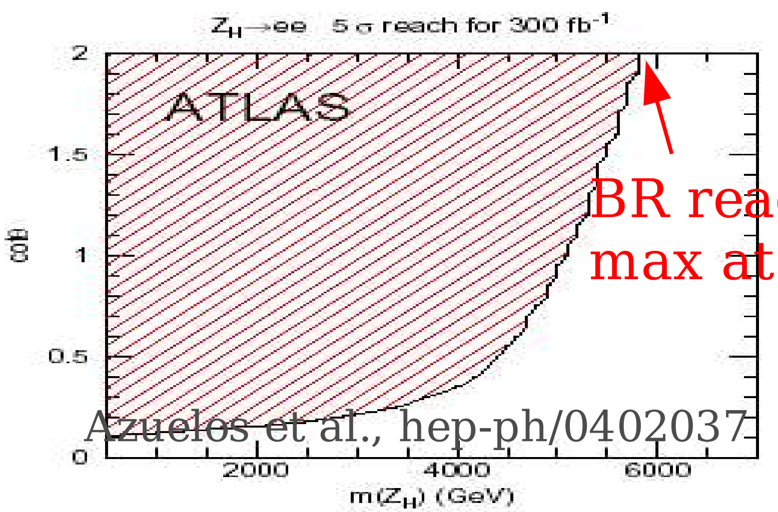
- Exploit the fact that the graviton is spin 2:
- But if parameters conspire, distinction may not be possible until LC (see for example Rizzo, hep-ph/0109179)
- If graviton, still need LC to distinguish between models using lineshape (Rizzo, hep-ph/0110202)



Allanach et al., JHEP 0009:019, 2000

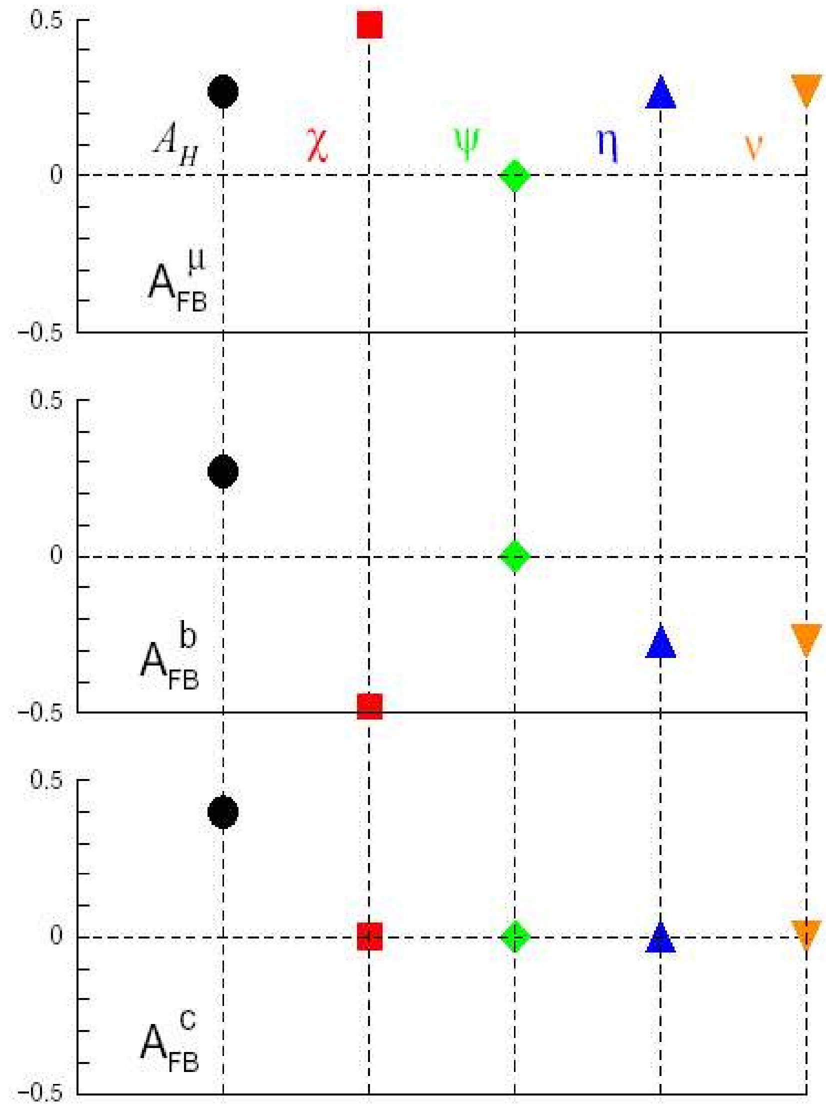
Z' At Future Colliders

- Mass reach at LHC reaches 5 TeV at high luminosity if model parameters cooperate
- If accessible at LC, use FB asymmetries to determine model



BR reaches max at 4%

Azuelos et al., hep-ph/0402037

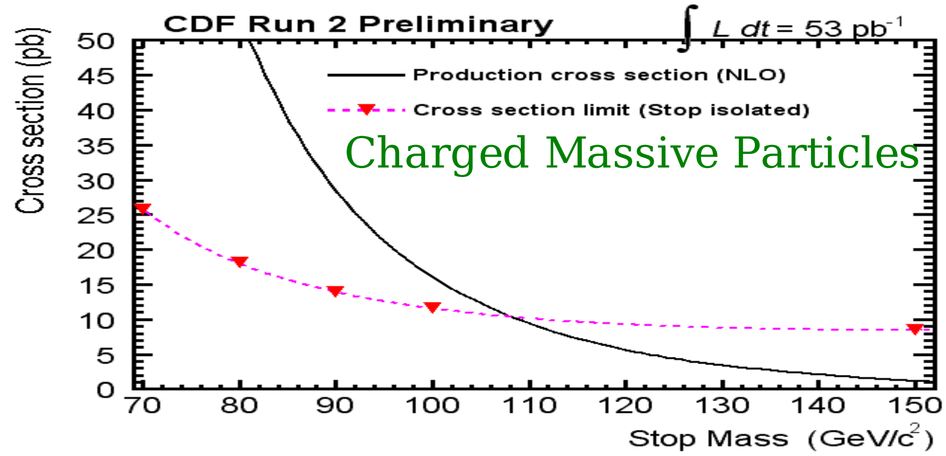


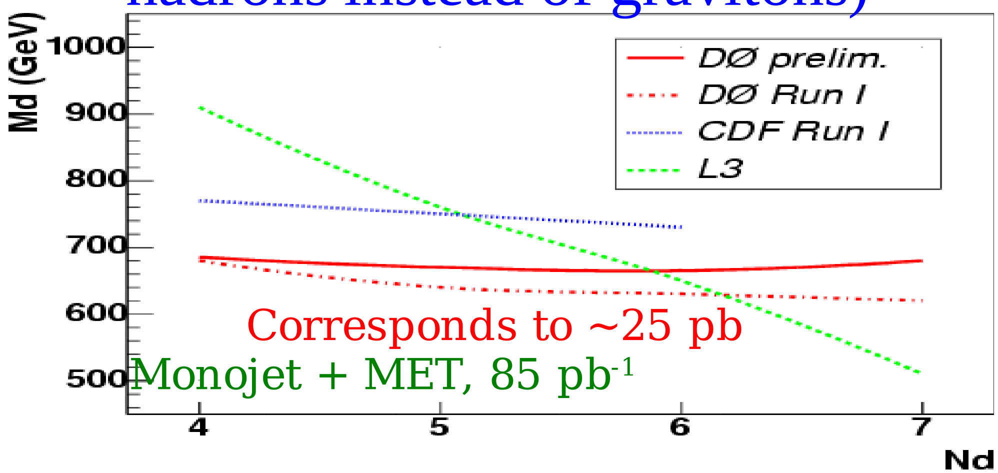
Split SUSY

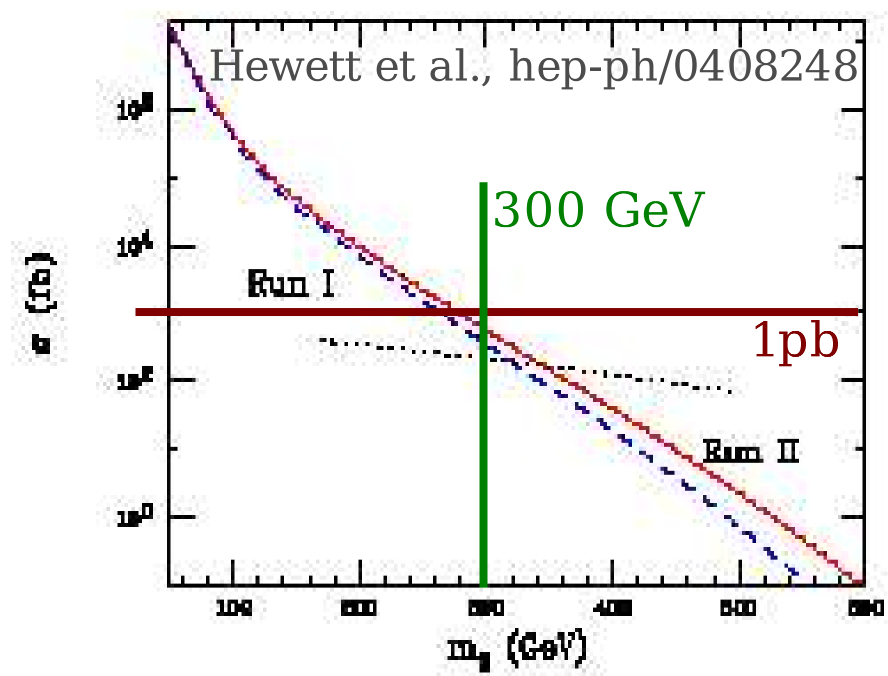
- Recent model which doesn't attempt to address EWK fine-tuning problem (Arkani-Hamed & Dimopoulos, hep-th/0405159)
  - Fermion partners are ultraheavy (SUSY scale)
  - Gauginos are light (use chiral symmetry), so still have trileptons
  - Still have gauge coupling unification
  - Still have light Higgs (although mass can now go up to 150 GeV)
  - Get long-lived gluino

New Model…

- … but long-lived gluino phenomenology gives signatures similar to
  - GMSB (long lived strongly interacting NLSP)
  - LED (monojet + missing ET due to escaping neutral gluino-hadrons instead of gravitons)







New Physics in Lepton Flavor Violation

- The generational structure of the SM fermions clearly suggests a link between the generations
  - LFV is therefore to be expected at some scale
  - And it's seen in the neutrino sector!
- Experimentally, LFV muon decays or conversions yield a very sensitive probe to high scale physics:

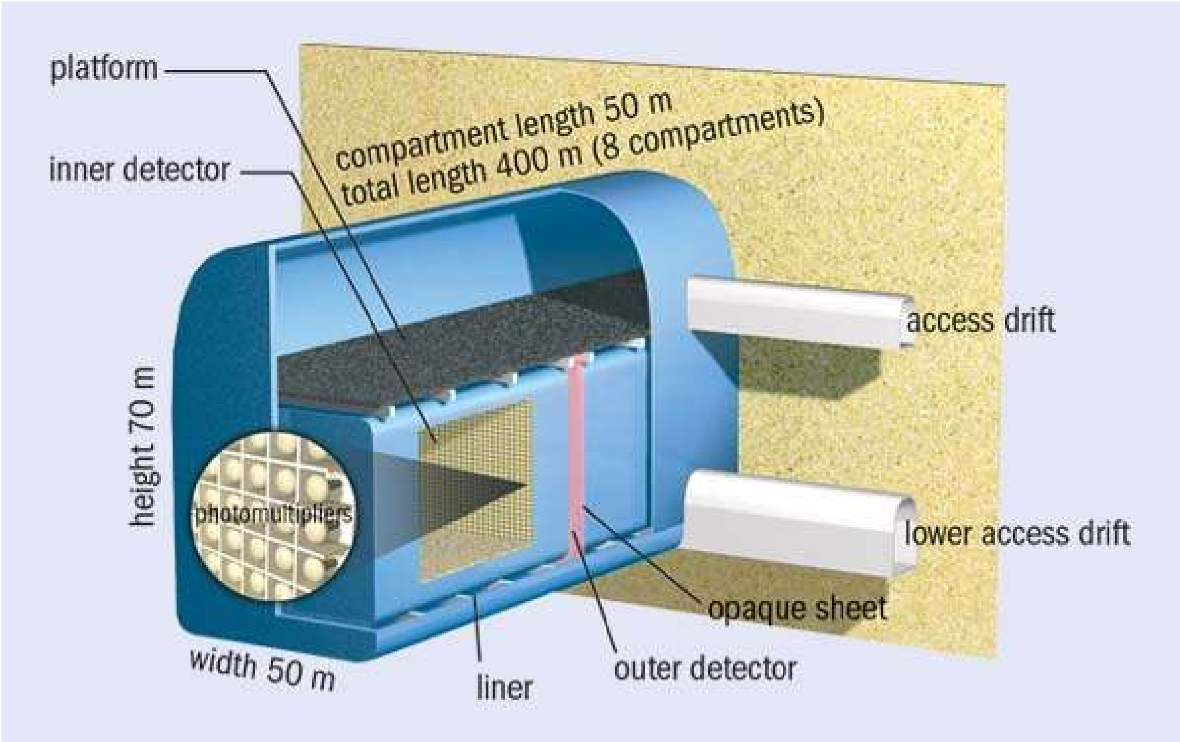
Process	Leading experiment	BR reach	Future experiment	BR reach
$\mu \to e\gamma$	MEGA (1999)	1.2×10^{-11} [3]	MEG (2005)	4.5×10^{-14} [4]
$\mu N \to eN$	SINDRUM II (1998)	6.1×10^{-13} [5]	MECO (2009)	$> 10^{-16}$ [6]
			PRIME (2008)	$\sim 10^{-18}$ [7]

- No signal yet, but ratios can be used to distinguish between processes:

Maybury & Murakami, hep-ph/0401170, also see talk by V. Cirigliano

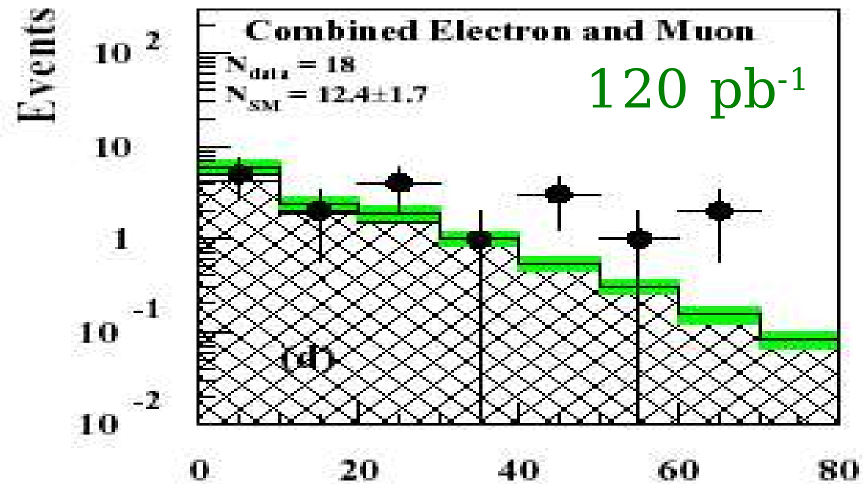
Proton Decay

- Quark-lepton unification leads to proton decay
  - Non-observation already imposes stringent constraints on models
  - Current limit is lifetime > 10^{31}-10^{33} years depending on decay mode
- Next generation detector should reach sensitivity ~10^{35} years
- Expect ~10^{36} years from GCU (see talk by D. Bourilkov)



Isolated Leptons at HERA

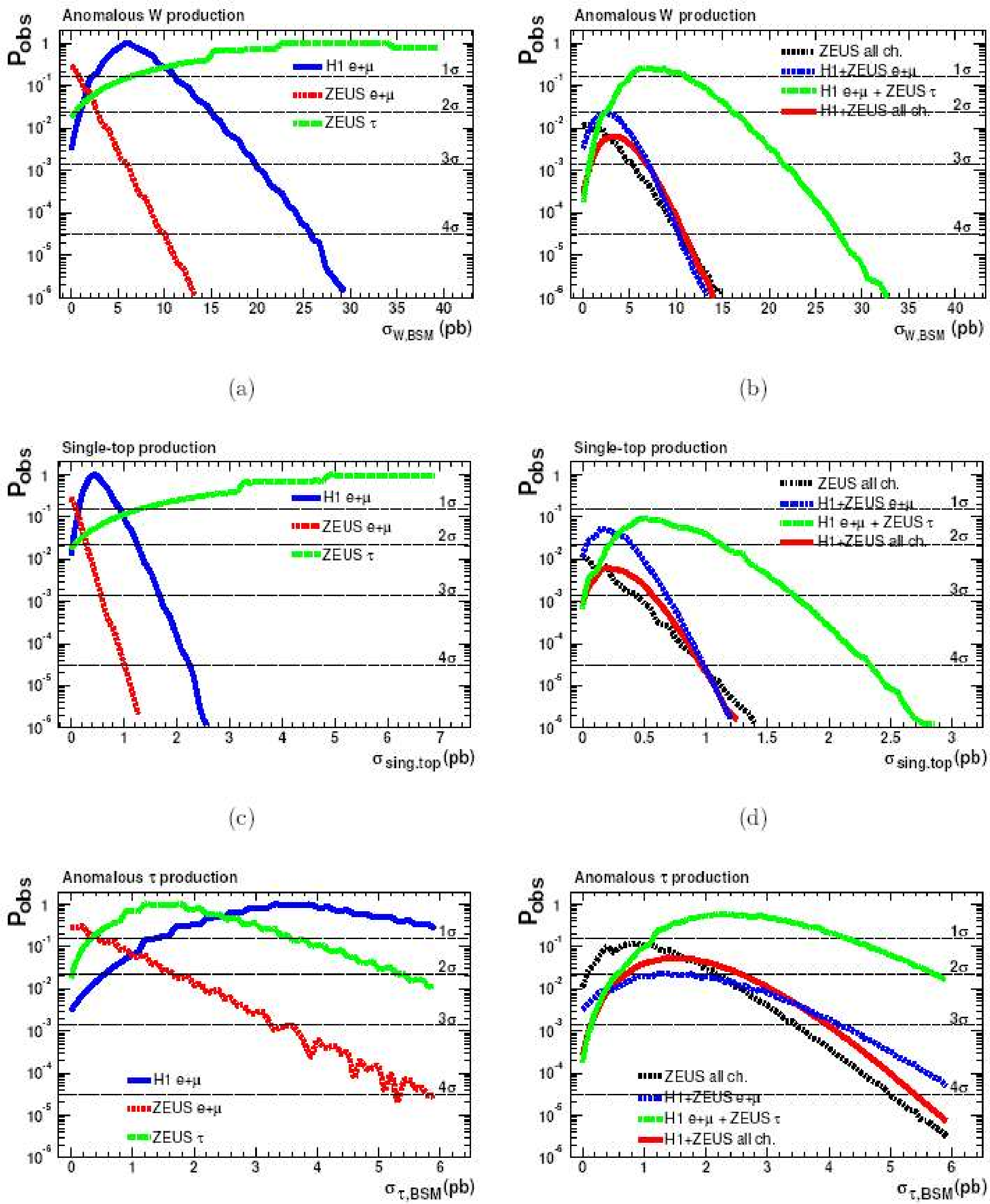
- Select W candidates in HERA data:
  - Isolated lepton
  - Missing Transverse Energy
- Total event count in reasonable agreement with SM, but if look at recoil p_T, apparent excess in H1 data
- ZEUS excess in tau channel only



H1, PLB 561(2003), 241

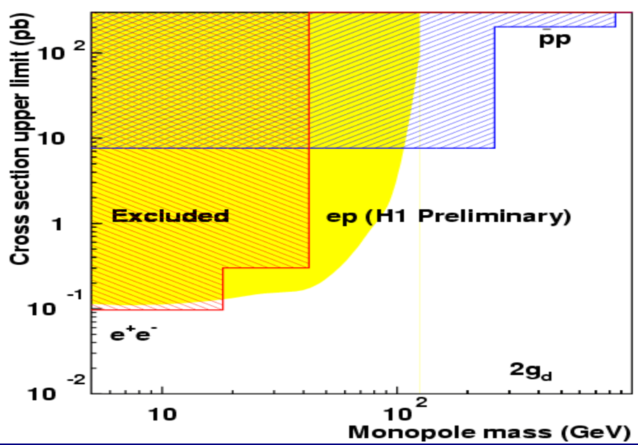
	$P_T^X > 25$ GeV			$P_T^X > 40$ GeV		
H1	Data	SM	$W^{\pm}$-contr.	Data	SM	$W^{\pm}$-contr.
electron	5	1.8 ± 0.3	82%	3	0.7 ± 0.1	80%
muon	6	1.7 ± 0.3	88%	3	0.6 ± 0.1	92%
combined	11	3.4 ± 0.6	85%	6	1.3 ± 0.3	86%
ZEUS	Data	SM	W-contr.	Data	SM	W-contr.
electron	2	$2.9^{+0.6}_{-0.3}$	45%	0	0.9 ± 0.1	61%
muon	5	2.8 ± 0.2	50%	0	1.0 ± 0.1	61%
combined	7	5.7 ± 0.6	47%	0	1.9 ± 0.2	61%

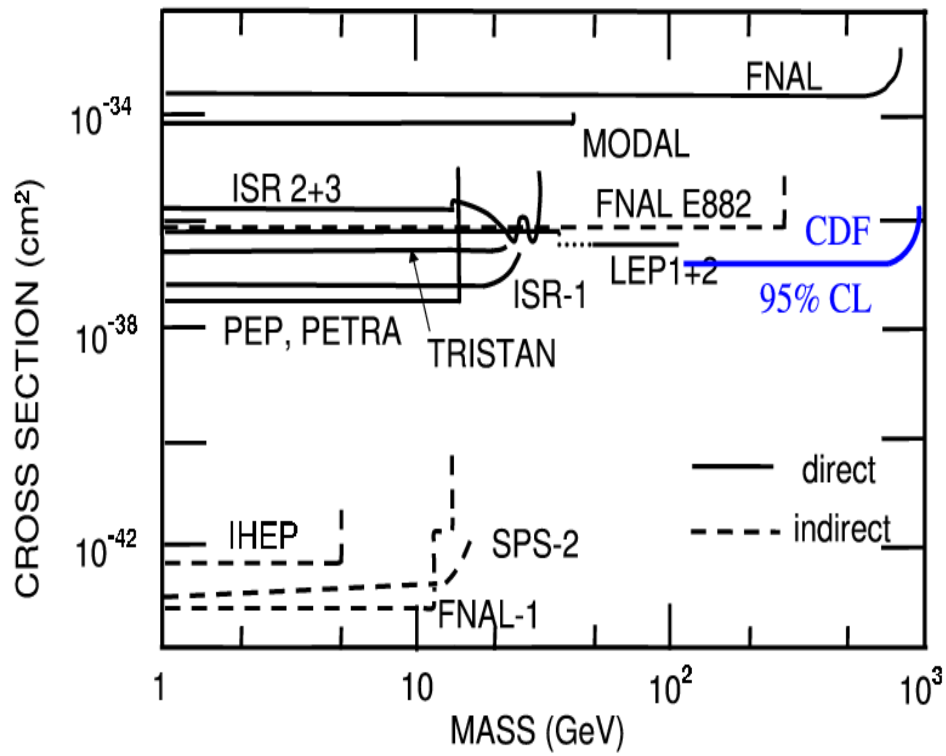
- Is this a signal? Are the two experiments compatible?
  - H1 electron+muon is a 2.8 sigma effect
  - Carli et al., MPLA 19, 1881, 2004 investigated compatibility under different scenarios: anomalous W, top or tau production
- HERA Run II, H1 result only:
  - 7 e events, 4.1 expected
  - 1 muon, 1 expected
  - 3 with $p_T^X > 25$ GeV, 1.5 exp



Magnetic Monopole(s)

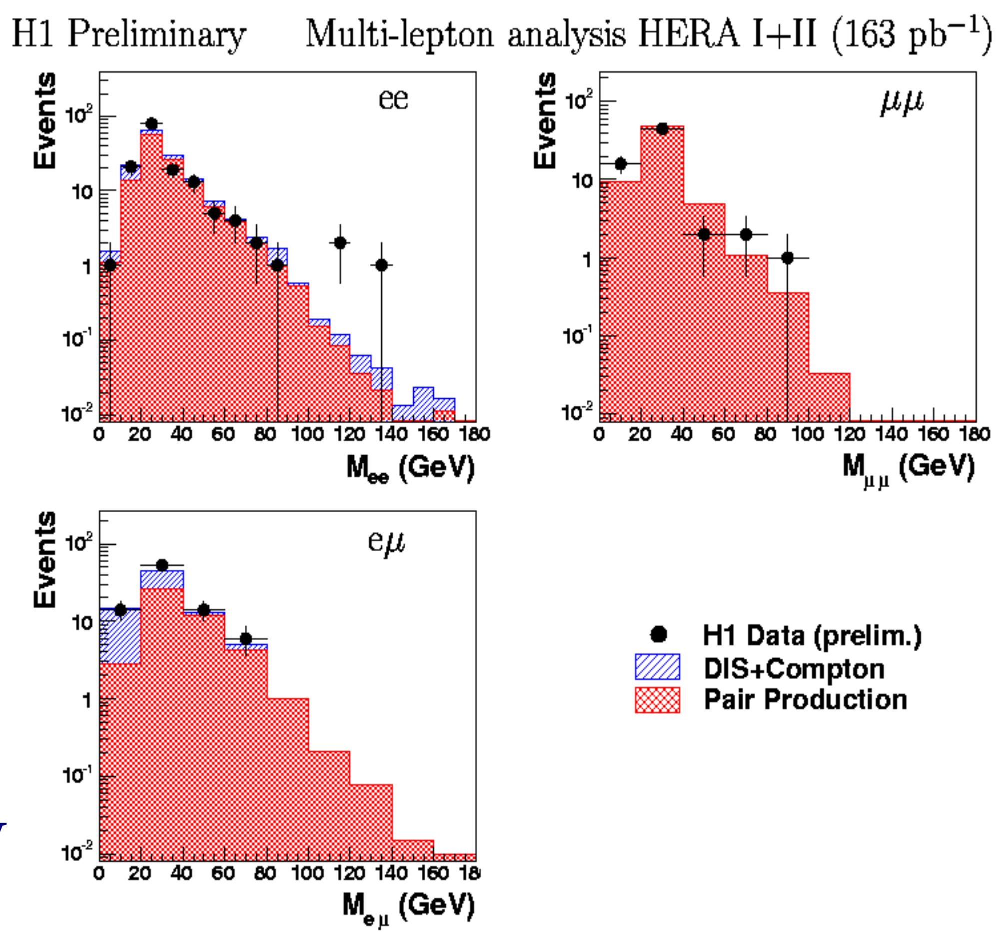
- Existence of even a single magnetic monopole would explain electric charge quantization (Dirac, 1931), no prediction for mass
- In GUTs, magnetic monopoles exist, with mass m > 10^{16} GeV
- Since magnetic charge is conserved, they are stable





Multilepton Events at HERA

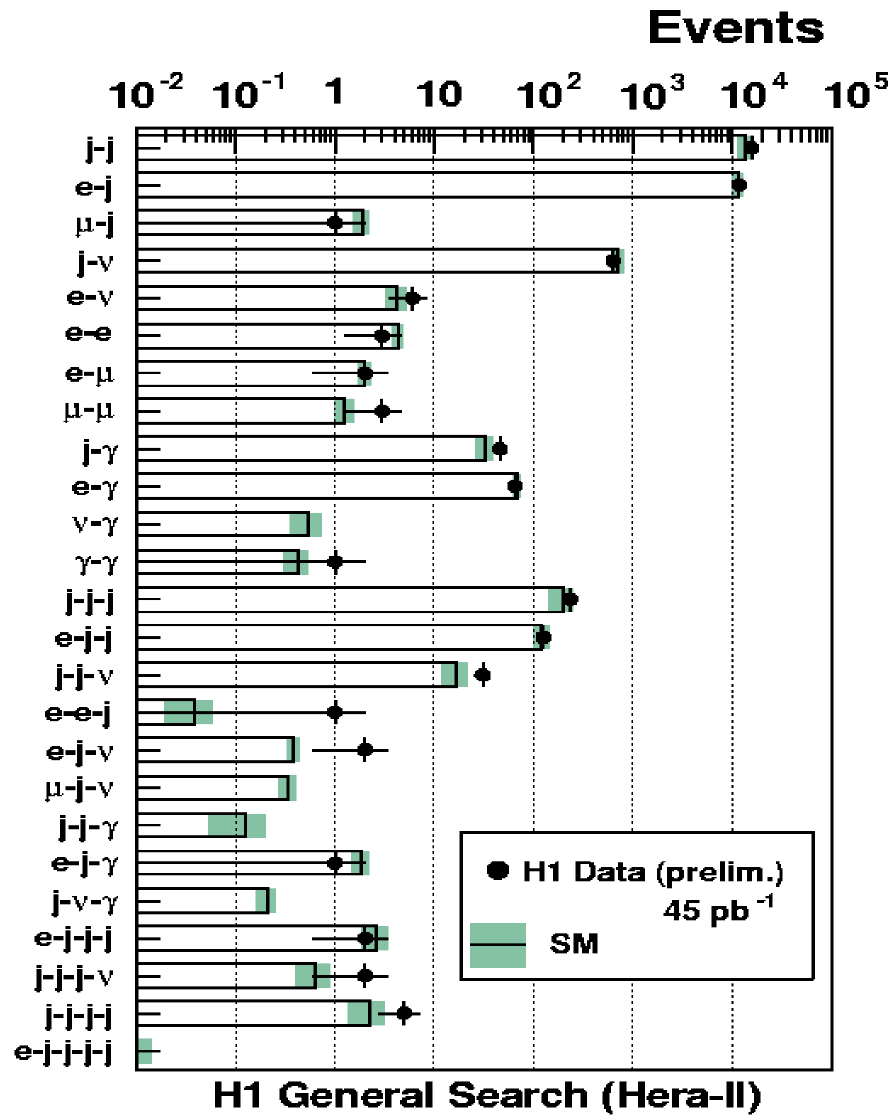
- H1 observed 3 dielectron events in HERA-RUNI with M_{ee} > 100 GeV, no new events are observed. The expected number is 0.44



- ZEUS does not see any excess

Model-Independent Searches

- In channels where backgrounds are sufficiently small and/or understood, can pursue model-independent searches
  - Typically counting experiments above pre-fixed thresholds
- Of course, these a-priori analyses do not exploit all information (shapes of distributions,...)



The Fundamental Questions

- Understanding EWSB explains mass
- If there is Grand Unification, understanding its breaking will tell us about electric charge, color and spin
  - Both direct (low scale) and indirect (high scale)data critical
- Manifestations of extra dimensions would lead to better understanding of space-time
- Hopefully, information about GUT breaking or extra dimensions will help understand why there are 3 generations

Conclusions

- Nothing convincing yet
  - (And beware of effects at the edge of sensitivity)
- Things would need to conspire to avoid detection at the LHC, LC (with sufficient c.o.m energy) needed for measurements
- Only SUSY deals with the hierarchy problem, gauge coupling unification and EWSB, but it comes at (IMHO) a significant price
- Most of the really fundamental questions are going to remain unanswered for a while longer

No-Lose at the LHC?

Haywood et al., hep-ph/0003275

- Suppose there is no Higgs, no resonances are seen, nothing
- Study $V_L V_L$ scattering to find what "saves" unitarity
- Start from effective chiral lagrangian

Heavy and Broad Scalar Resonance