Physics at Hadron Colliders

Lecture IV

Beate Heinemann

University of California, Berkeley
Lawrence Berkeley National Laboratory

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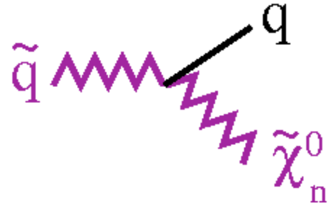
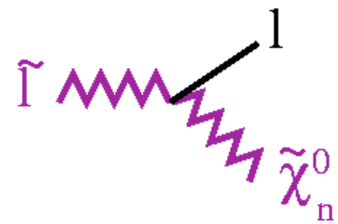
Outline

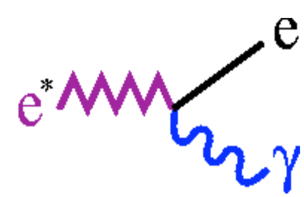
- **Lecture I: Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current colliders: Tevatron and LHC
  - Hadron-hadron collisions
- **Lecture II: Standard Model Measurements**
  - Tests of QCD
  - Precision measurements in electroweak sector
- **Lecture III: Searches for the Higgs Boson**
  - Standard Model Higgs Boson
  - Higgs Bosons beyond the Standard Model
- **Lecture IV: Searches for New Physics**
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)

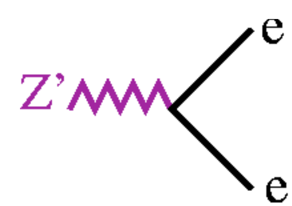
The Unknown beyond the Standard Model

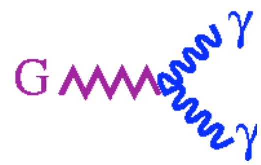
- Many good reasons to believe there is as yet unknown physics beyond the SM:
  - Dark matter + energy, matter/anti-matter asymmetry, neutrino masses/mixing +many more (see 1st lecture)
- Many possible new particles/theories:
  - Supersymmetry:
    - Many flavours
  - Extra dimensions (G)
  - New gauge groups (Z', W',…)
  - New fermions (e*, t', b', …)
  - Leptoquarks
- Can show up!
  - As subtle deviations in precision measurements
  - In direct searches for new particles

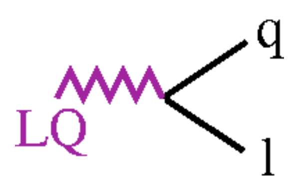


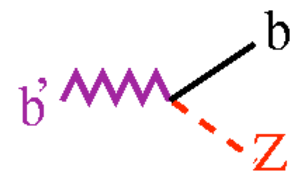




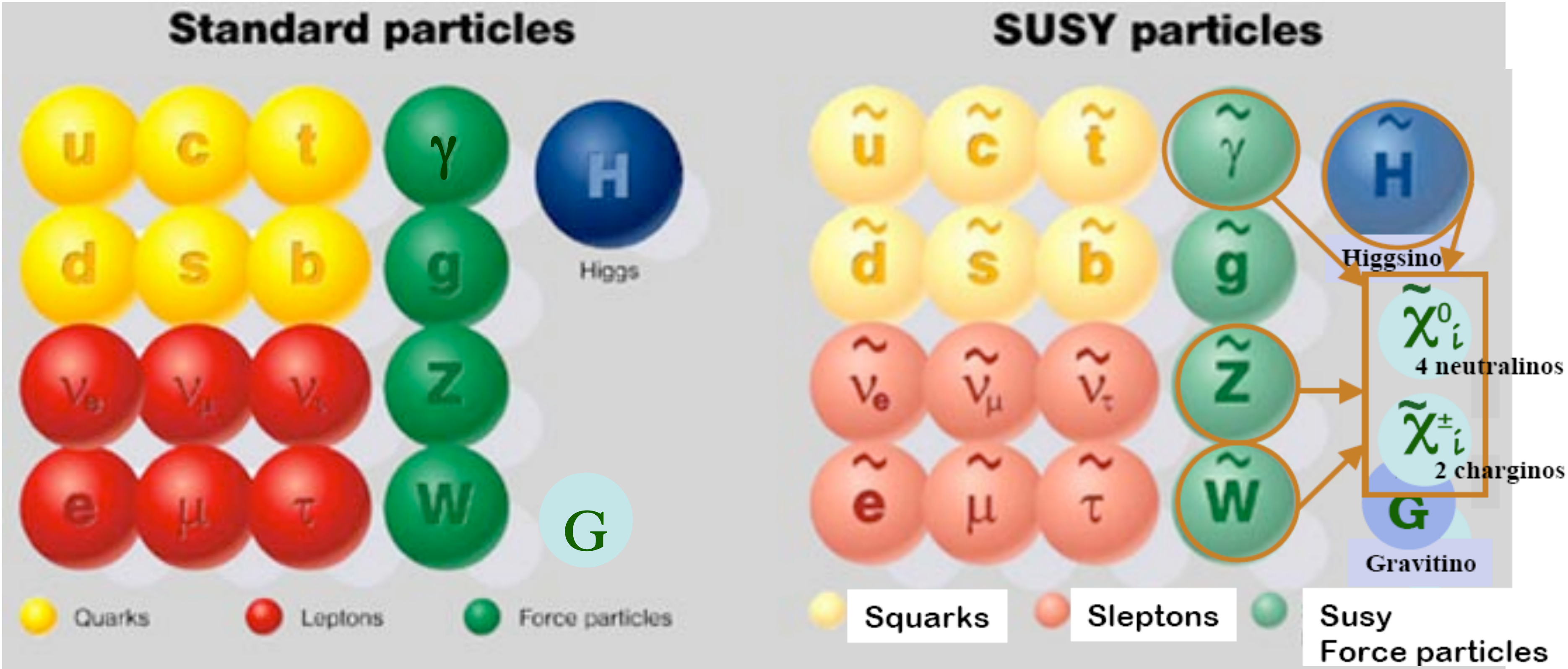








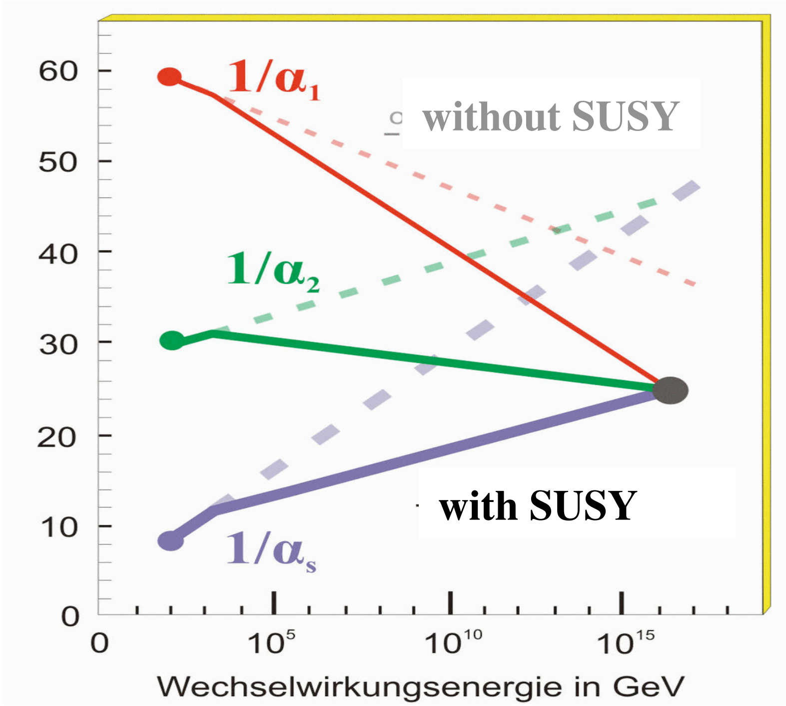
Supersymmetry (SUSY)

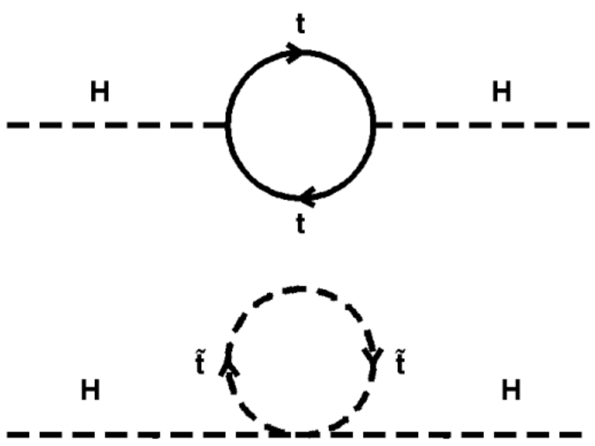


- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squark, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in “minimal” models!

What's Nice about SUSY?

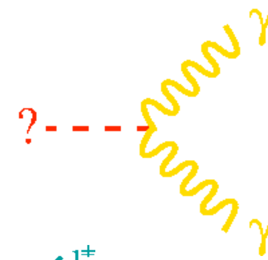
- Introduces symmetry between bosons and fermions
- Unifications of forces possible
  - SUSY changes runnning of couplings
- Dark matter candidate exists:
  - The lightest neutral gaugino
  - Consistent with cosmology data
- No fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops
- Also consistent with precision measurements of M_W and M_{top}
  - But may change relationship between M_W, M_{top} and M_H

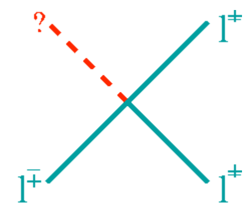


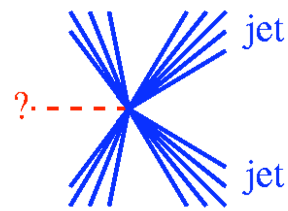


SUSY Comes in Many Flavors

- Breaking mechanism determines phenomenology and search strategy at colliders
  - GMSB:
    - Gravitino is the LSP
    - Photon final states likely
  - mSUGRA
    - Neutralino is the LSP
    - Many different final states
    - Common scalar and gaugino masses
  - AMSB
  - Split-SUSY: sfermions very heavy

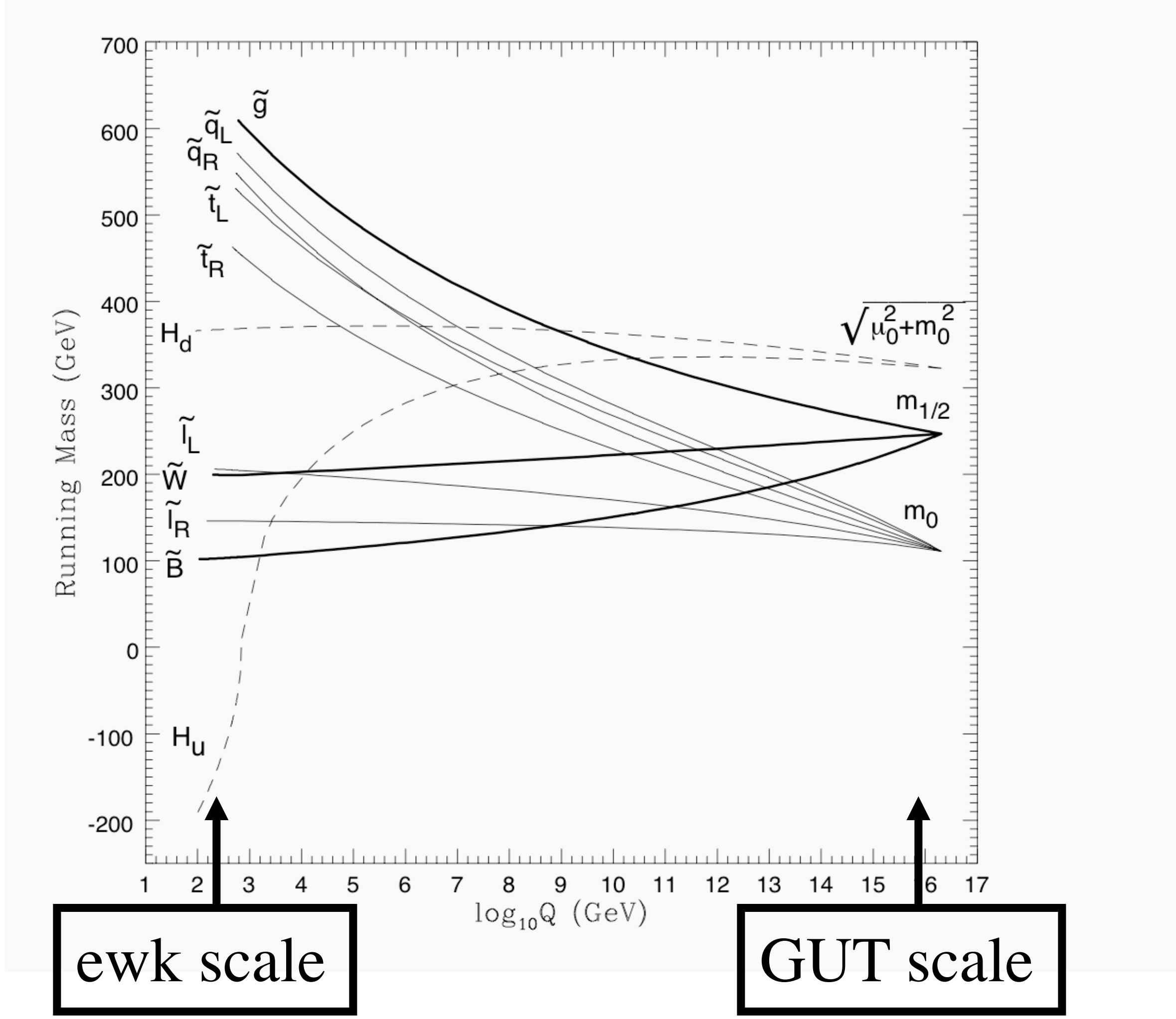






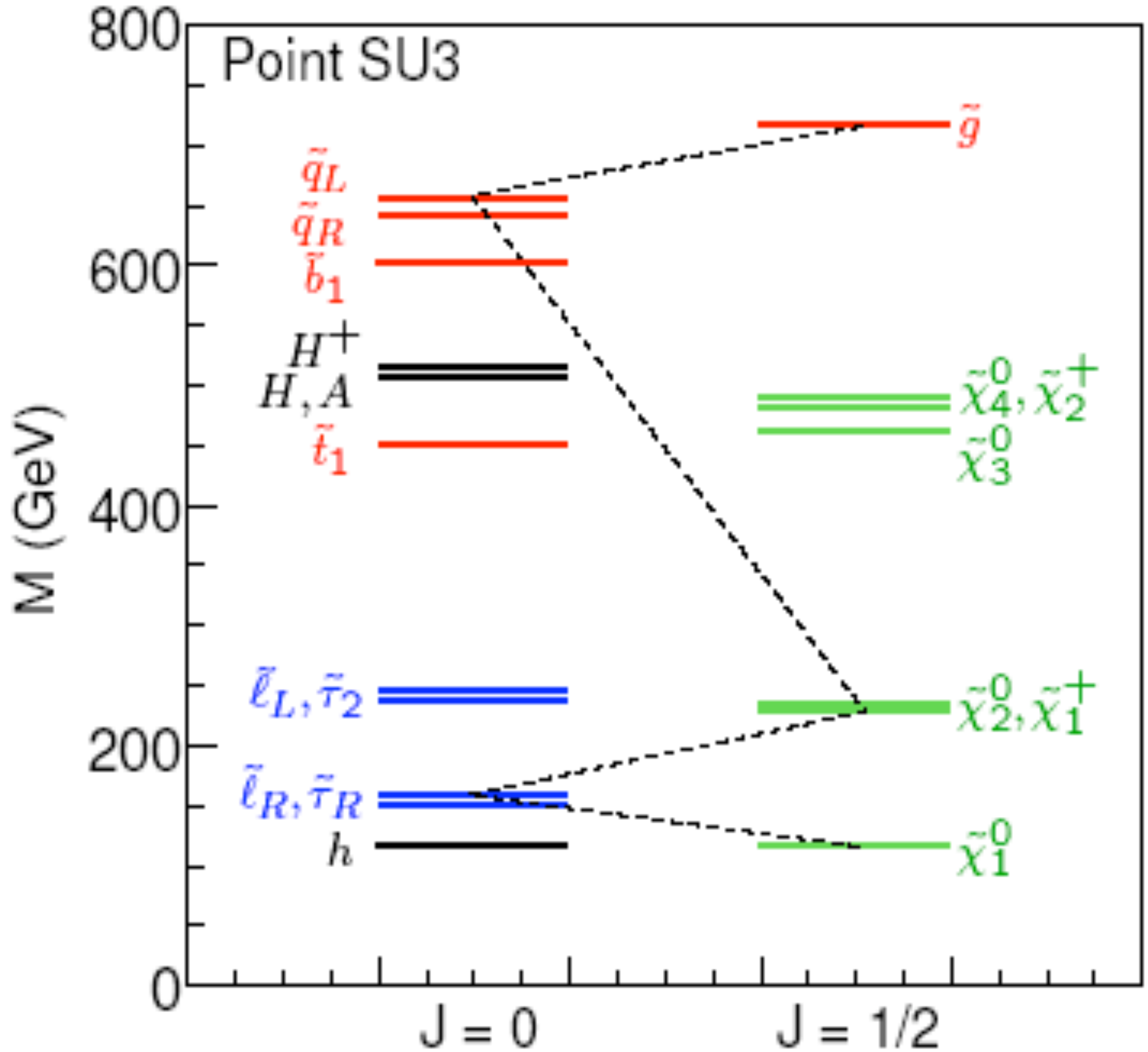
- R-parity
  - Conserved: Sparticles produced in pairs
    - Yields natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector
    - Could explain neutrino oscillations if violation in lepton sector

Mass Unification in mSUGRA

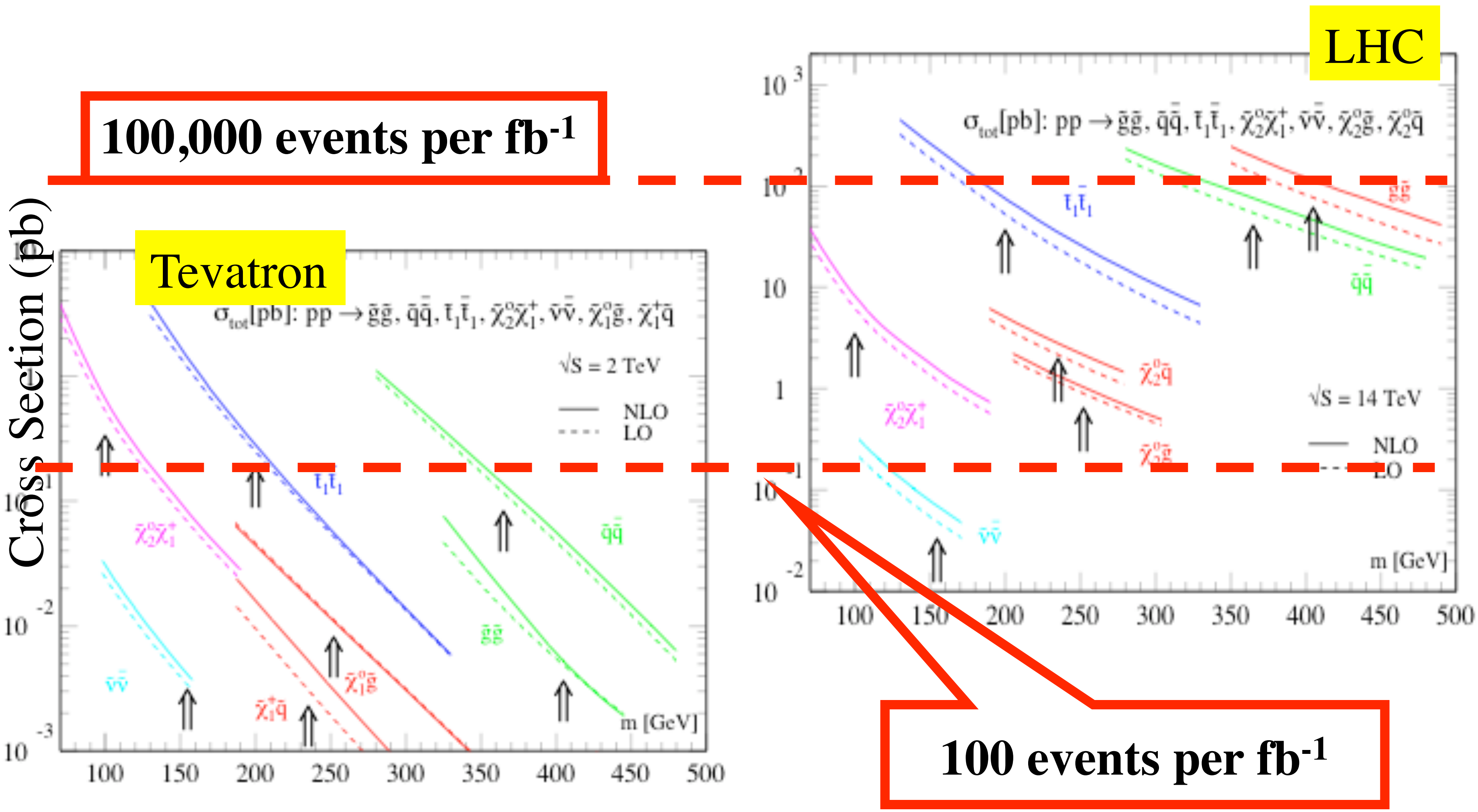


- Common masses at GUT scale: m_0 and $m_{1/2}$
  - Evolved via renormalization group equations to lower scales
  - Weakly coupling particles (sleptons, charginos, neutralions) are lightest

A Typical Sparticle Mass Spectrum

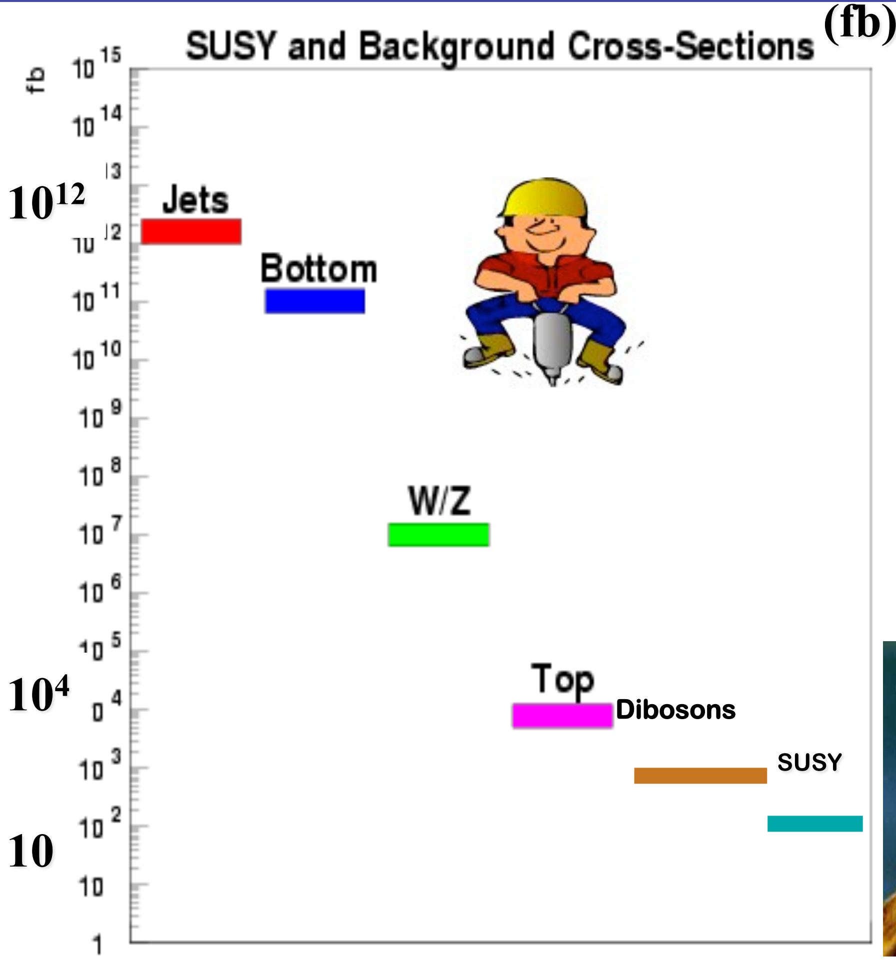


Sparticle Cross Sections



T. Plehn, PROSPINO

SUSY compared to Background



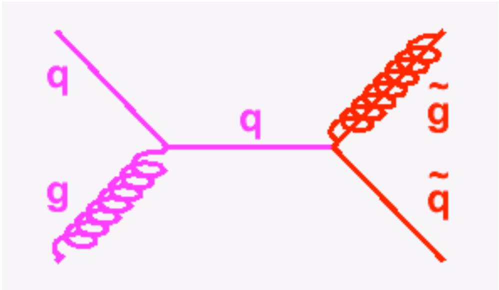
- Cross sections rather low
  - Else would have seen it already!
- Need to suppress background efficiently

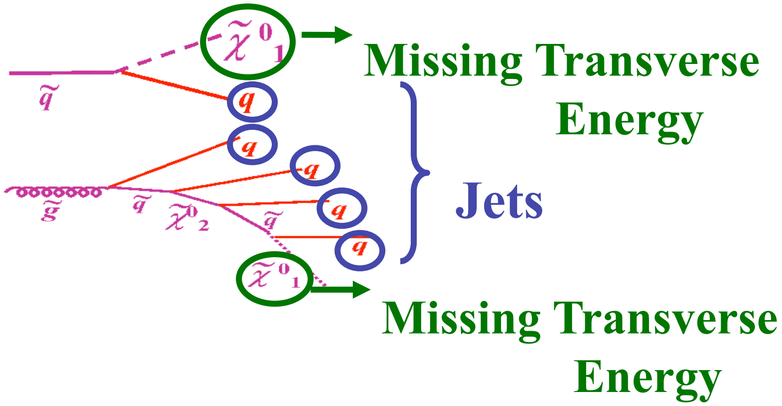
Strategy for SUSY Searches

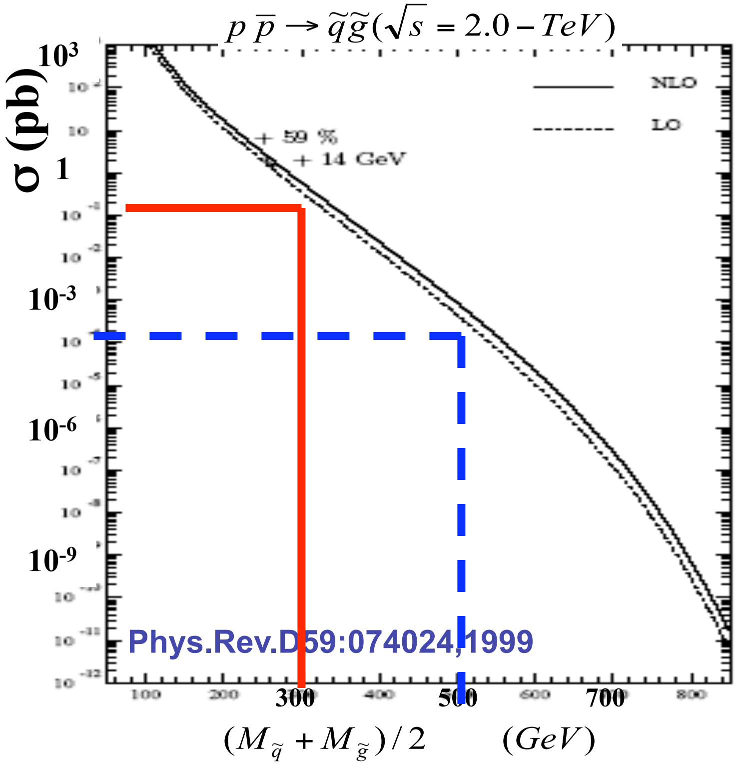
- *Minimal Supersymmetric Standard Model* (MSSM) has more than 100 parameters
  - Impossible to scan full parameter space
  - Many constraints already from
    - Precision electroweak data
    - Lepton flavour violation
    - Baryon number violation
    - …
- Makes no sense to choose random set
  - Use simplified well motivated "benchmark" models
    - Ease comparison between experiments
- Try to make interpretation model independent
  - E.g. not as function of GUT scale SUSY particle masses but versus EWK scale SUSY particle masses
  - Limits can be useful for other models

Generic Squarks and Gluinos

- Squark and Gluino production:
  - Signature: jets and $\not{E}_T$







Strong interaction => large production cross section

for M(g) ≈ 300 GeV/c^2:

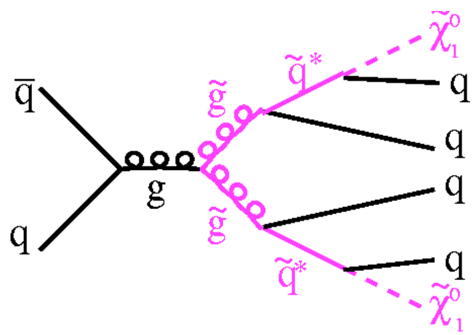
1000 event produced/ fb^{-1}

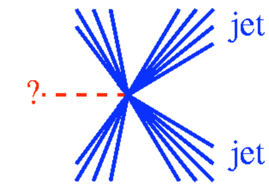
for M(g) ≈ 500 GeV/c^2:

1 event produced/ fb^{-1}

Signature depends on $\tilde{q}$ and $\tilde{g}$ Masses

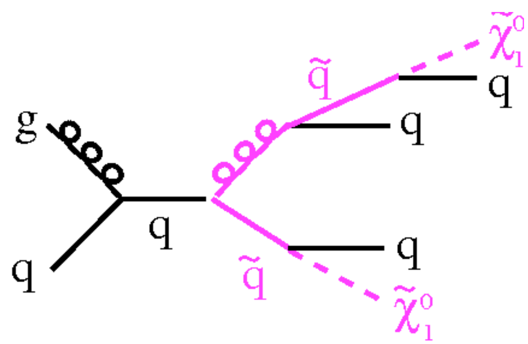
- Consider 3 cases:
  1. m($\tilde{g}$)<m($\tilde{q}$)

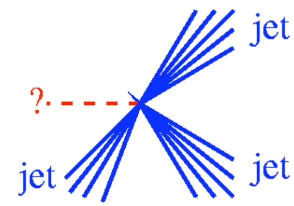




4 jets + E_T^{miss}

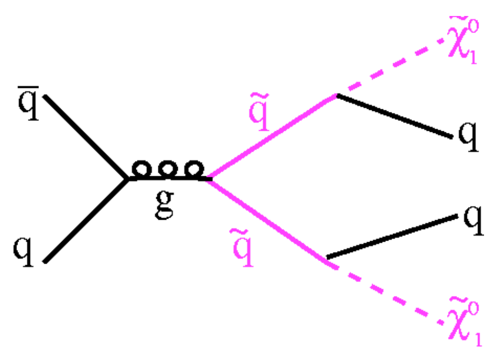
  2. m($\tilde{g}$)≈m($\tilde{q}$)

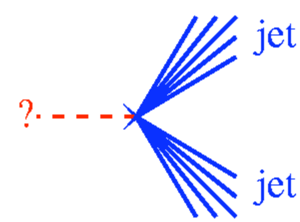




3 jets + E_T^{miss}

  3. m($\tilde{g}$)>m($\tilde{q}$)





2 jets + E_T^{miss}

Optimize for different signatures in different scenarios

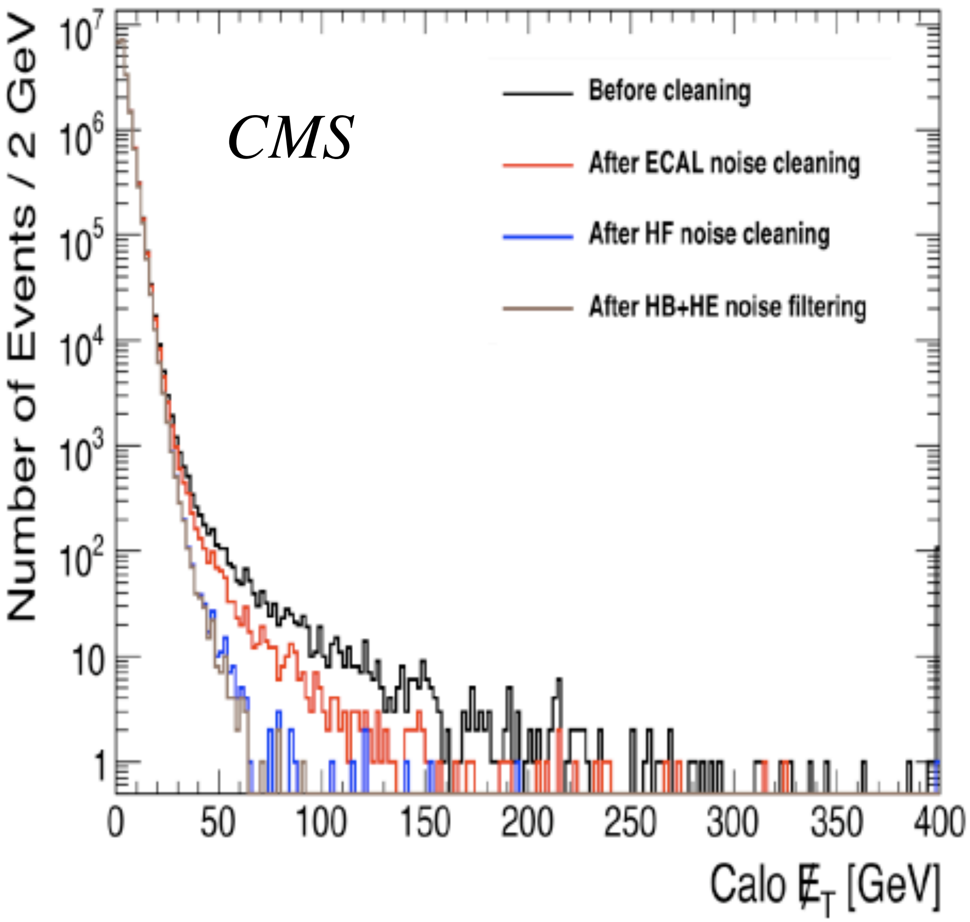
Selection and Procedure

- Selection:
  - Large missing E_T
    - Due to neutralinos
  - Large H_T
    - $H_T = \sum E_T^{jet}$
  - Large $\Delta\phi$
    - Between missing E_T and jets and between jets
    - Suppress QCD dijet background due to jet mismeasurements
  - Veto leptons:
    - Reject W/Z+jets, top

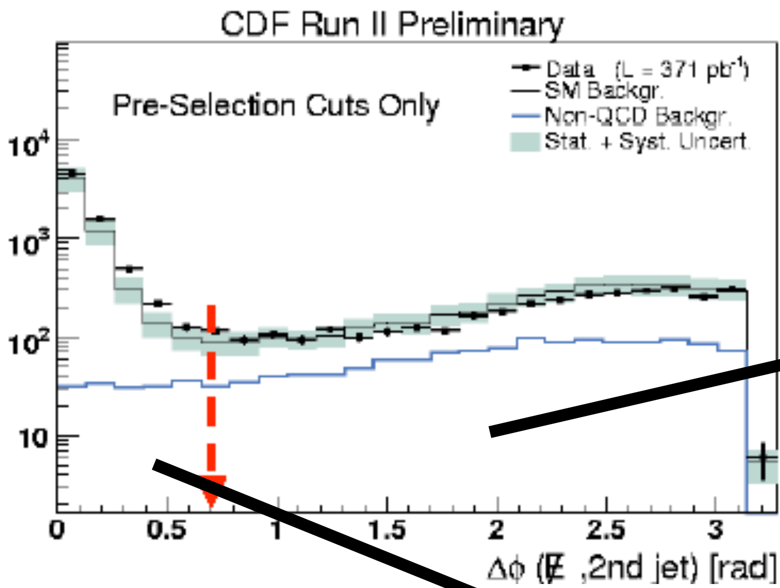
- Procedure:
  1. Define signal cuts based on background and signal MC studies
  2. Select control regions that are sensitive to individual backgrounds
  3. Keep data "blind" in signal region until data in control regions are understood
  4. Open the blind box!

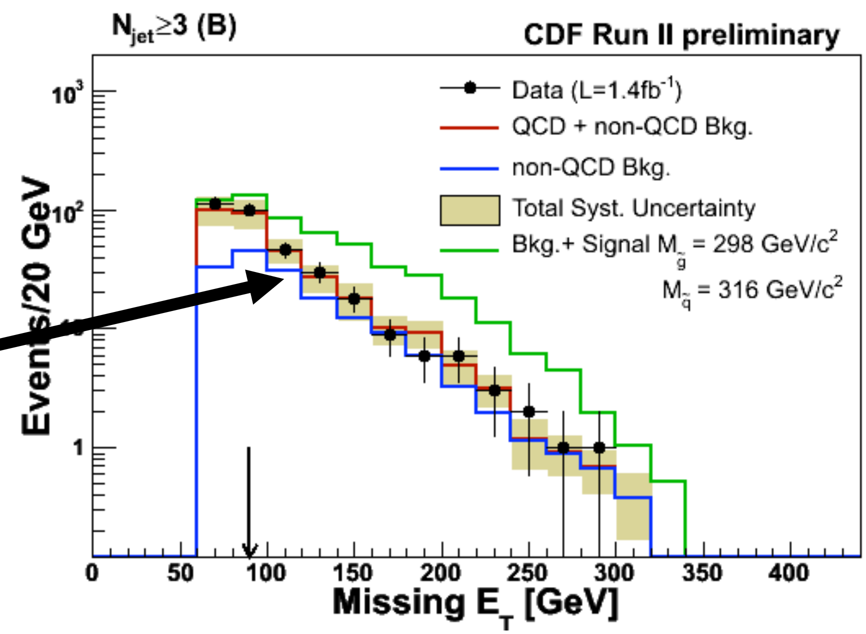
Missing Energy can be caused by Problems

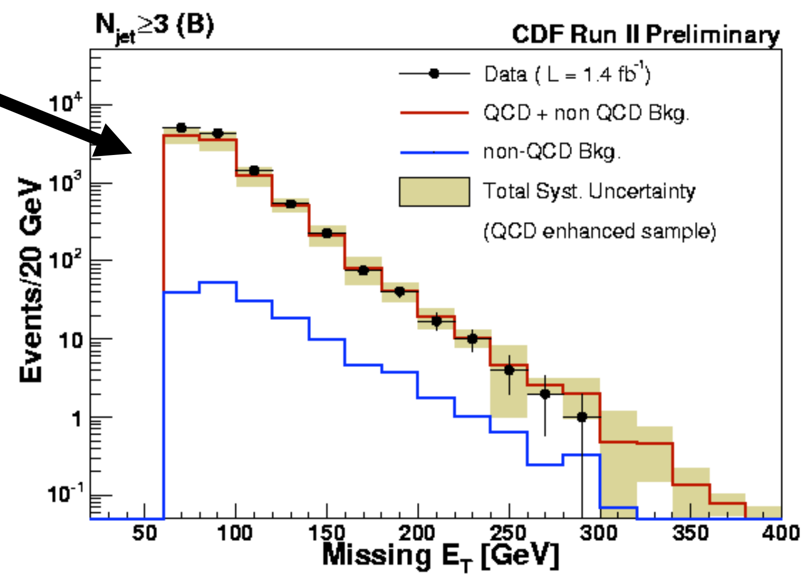
- Data spectrum contaminated by
  - Noise
  - Cosmic muons showering
  - Beam halo muons showering
- Needs "cleaning up"!
  - Noise rejection
  - Topological cuts
  - Requiring a track
  - …



QCD Dijet Rejection Cut



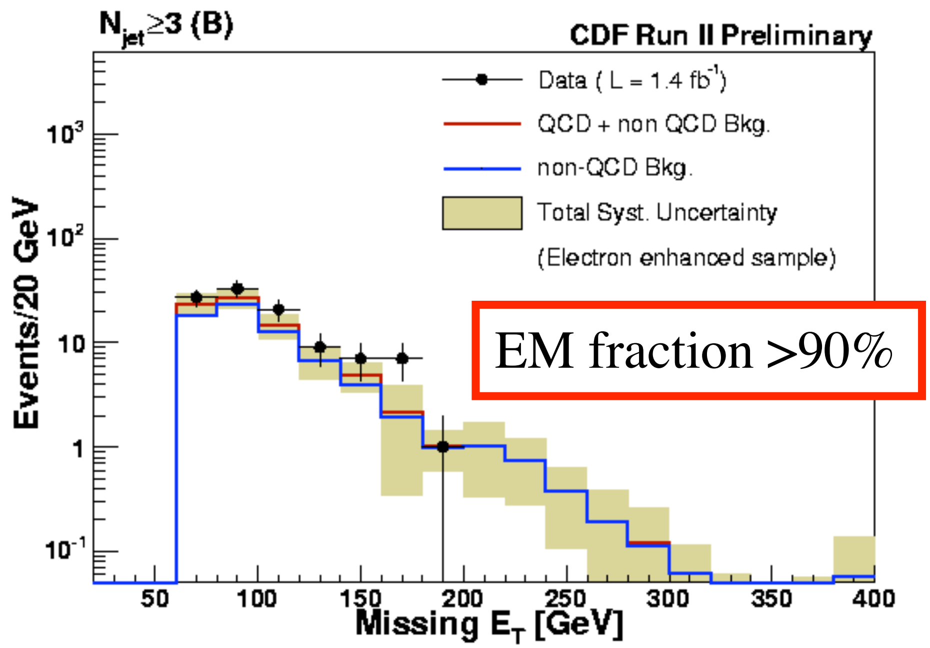


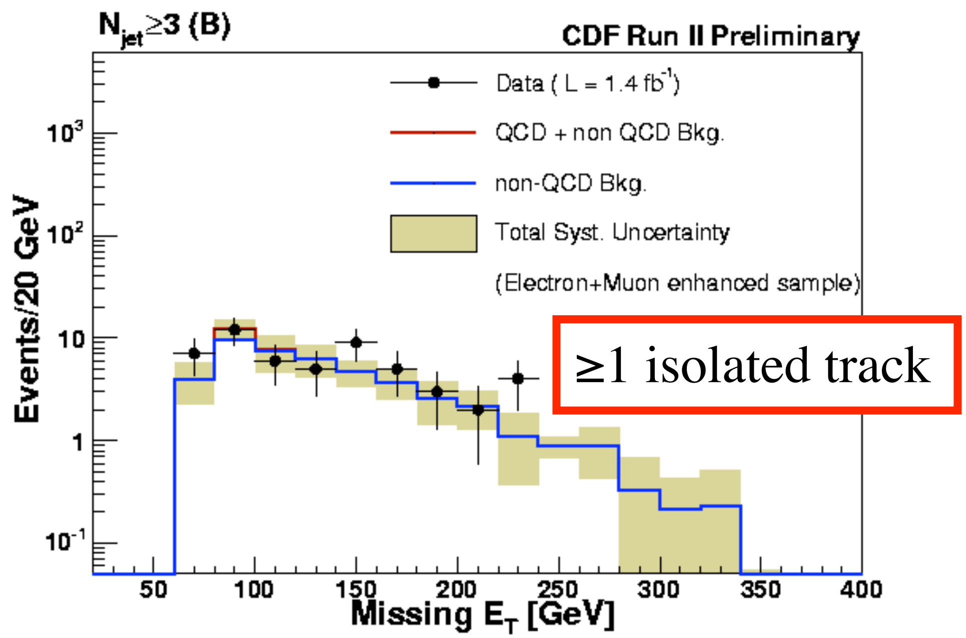


- Cut on $\Delta\phi(\text{jet}, E_T^{miss})$
- Used to suppress and to understand QCD multi-jet background
  - Extreme test of MC simulation

W+jets, Z+jets and Top background

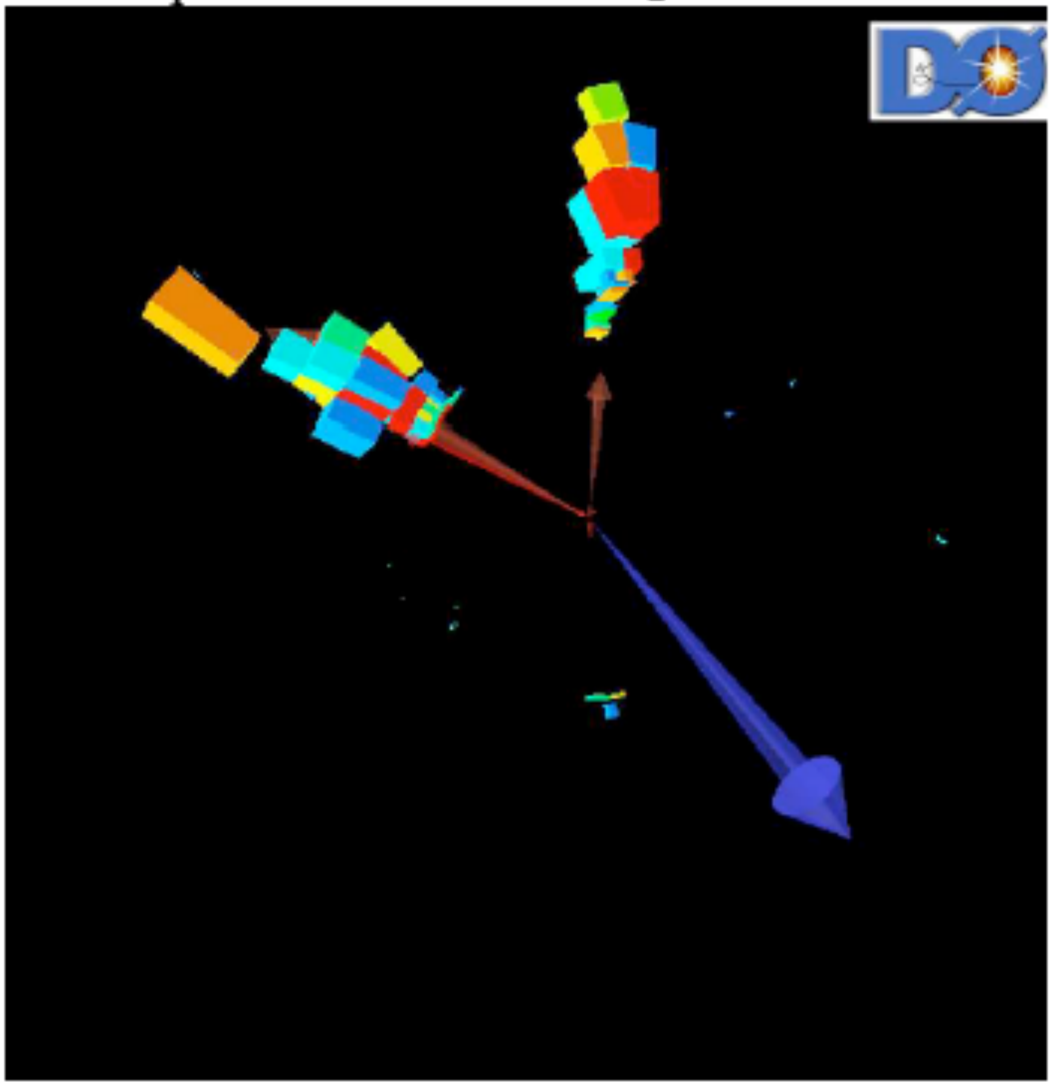
- Background sources:
  - W/Z+jets, top
  - Suppressed by vetoes:
    - Events with jet with EM fraction>90%
      - Rejects electrons
    - Events with isolated track
      - Rejects muons, taus and electrons
- Define control regions:
  - W/Z+jets, top
    - Make all selection cuts but invert lepton vetoes
  - Gives confidence in those background estimates



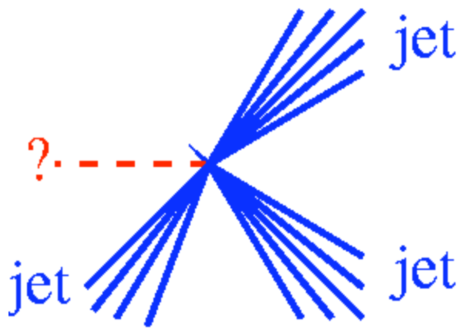


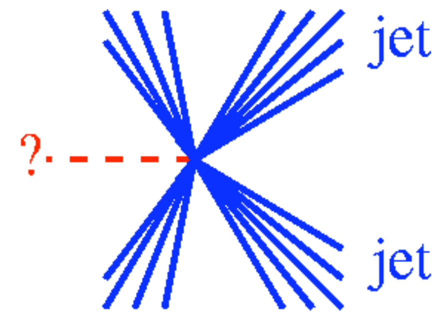
A Nice Candidate Event!

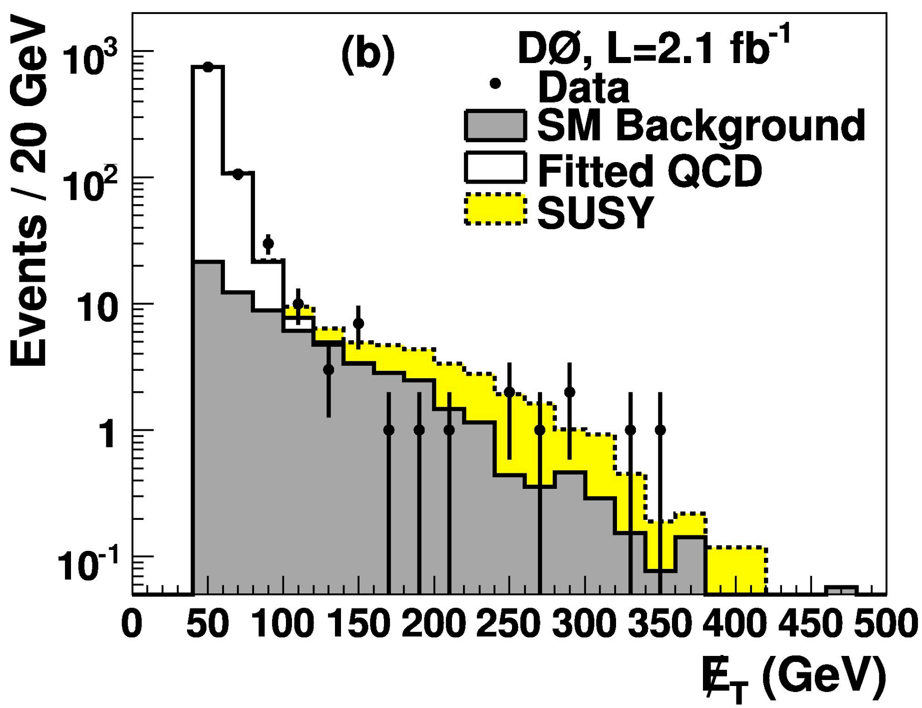
Squark Candidate: $\not{E}_T$=381 GeV

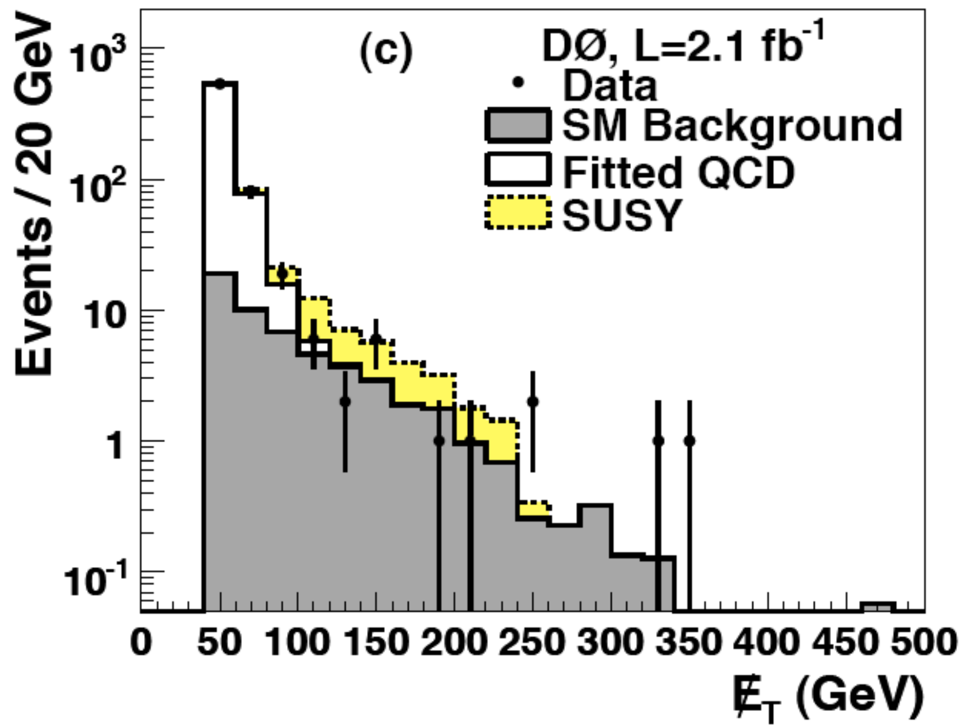


But there is no clear signal…

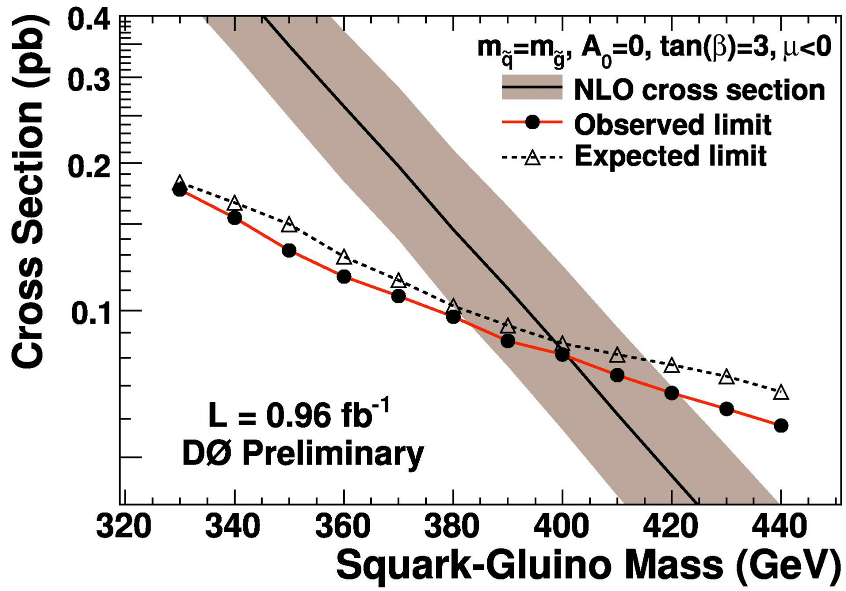


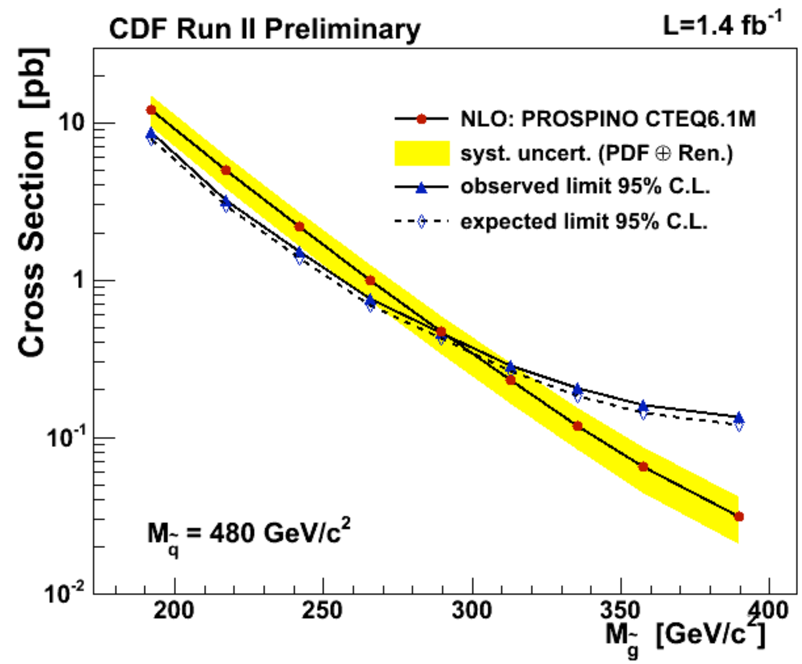






Cross Section Limits

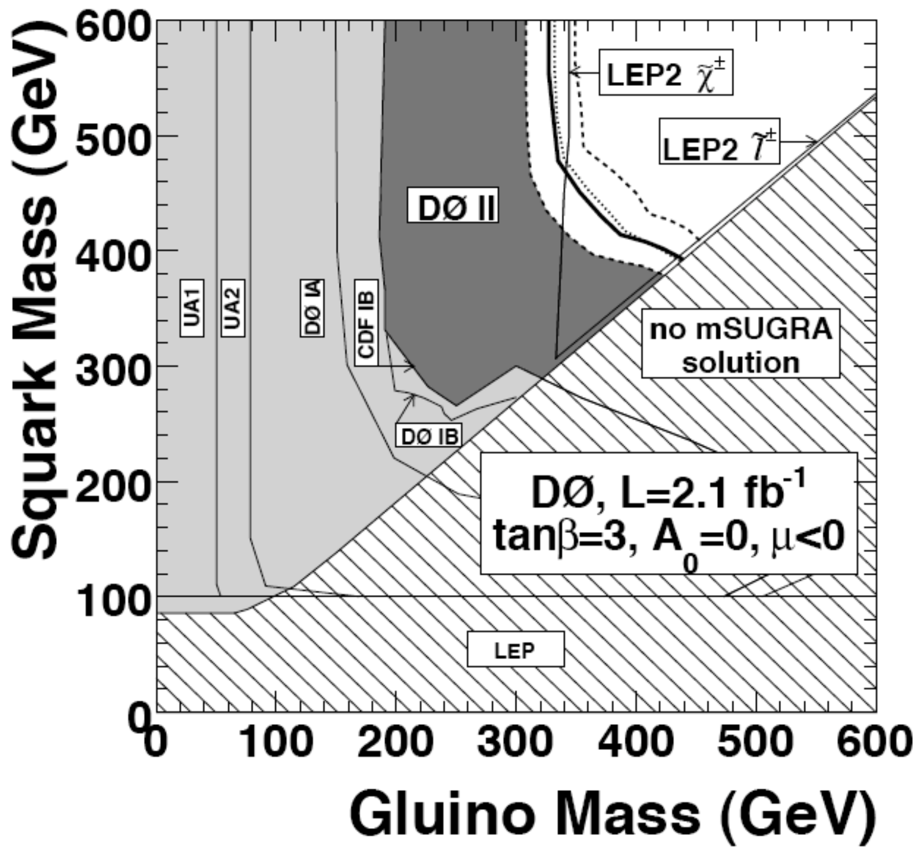




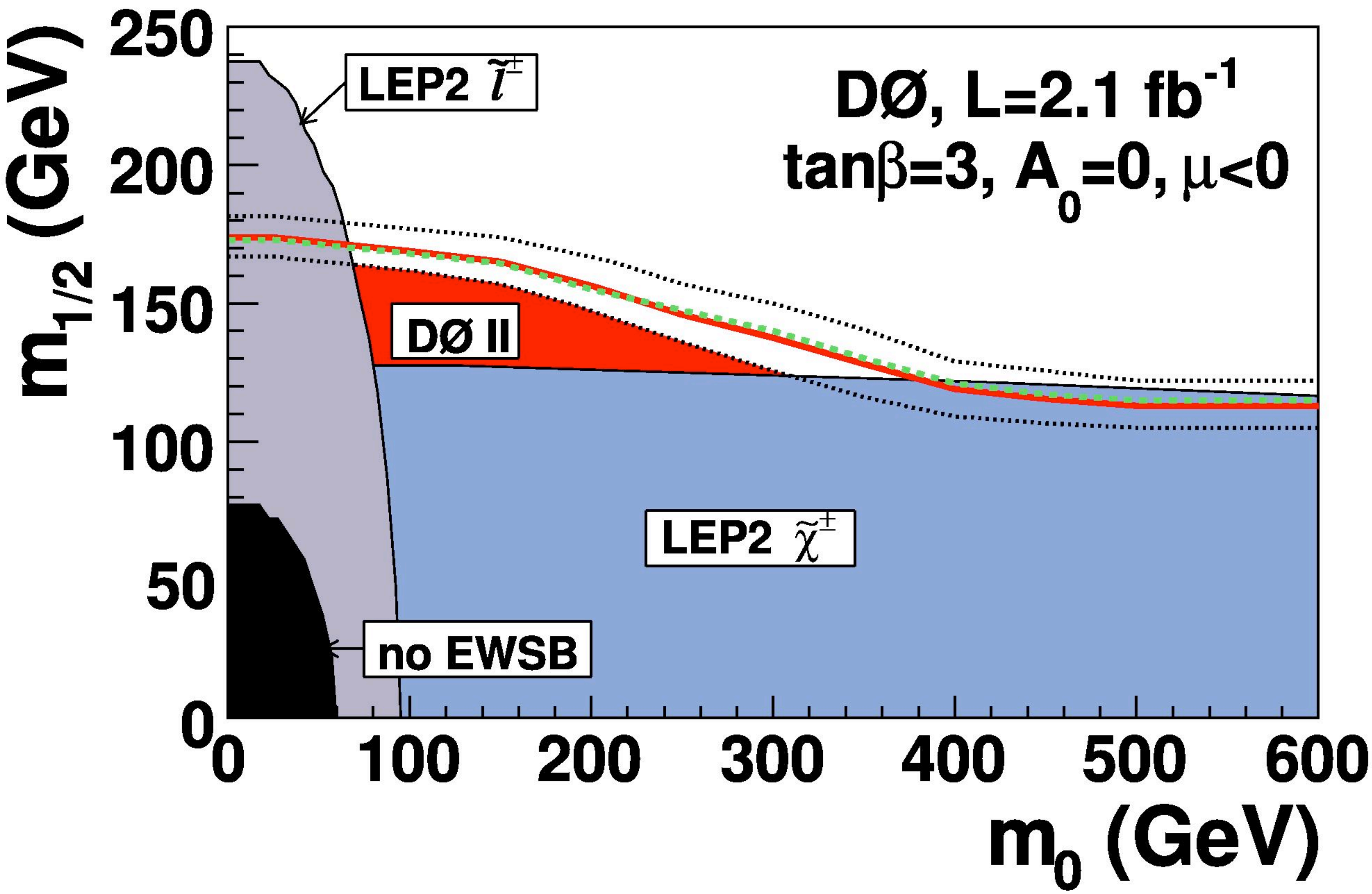
- No excess in data
  - Evaluate upper limit on cross section
  - Find out where it crosses with theory
- Theory has large uncertainty: ~30%
  - Crossing point with theory lower bound ~ represents limit on squark/gluino mass

Squark and Gluino Mass Limits

- No evidence for excess of events:
  - Constraints on masses
    - M($\tilde{g}$)>308 GeV
    - M($\tilde{q}$)>379 GeV
- Represented in this plane:
  - Rather small model dependence as long as there is R-parity conservation



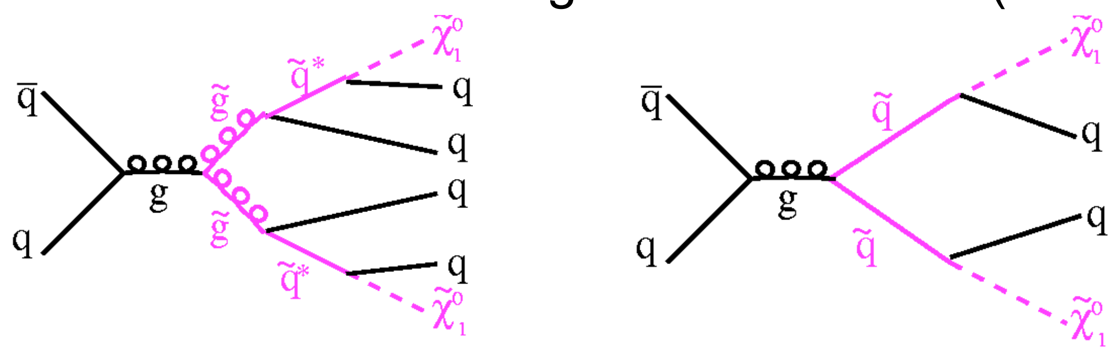
Exclusion of GUT scale parameters



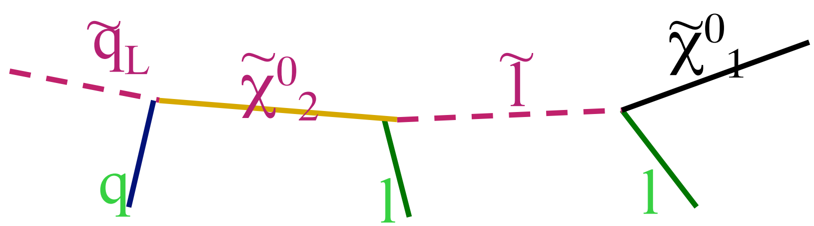
- Nice interplay of hadron colliders and e^+e^- colliders:
  - Similar sensitivity to same high level theory parameters via very different analyses
  - Tevatron is starting to probe beyond LEP in mSUGRA type models

SUSY at the LHC

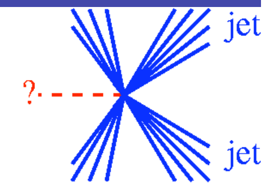
- Cross section **much** higher, e.g.
  - for m(g̃)=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g})/\ \sigma_{Tevatron}(\tilde{g}\tilde{g}) \approx 20{,}000$
  - for m(q̃)=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g})/\ \sigma_{Tevatron}(\tilde{g}\tilde{g}) \approx 1{,}000$
    - Since there are a lot more gluons at the LHC (lower x)



- At higher masses more phase space to decay in cascades
  - Results in additional leptons or jets

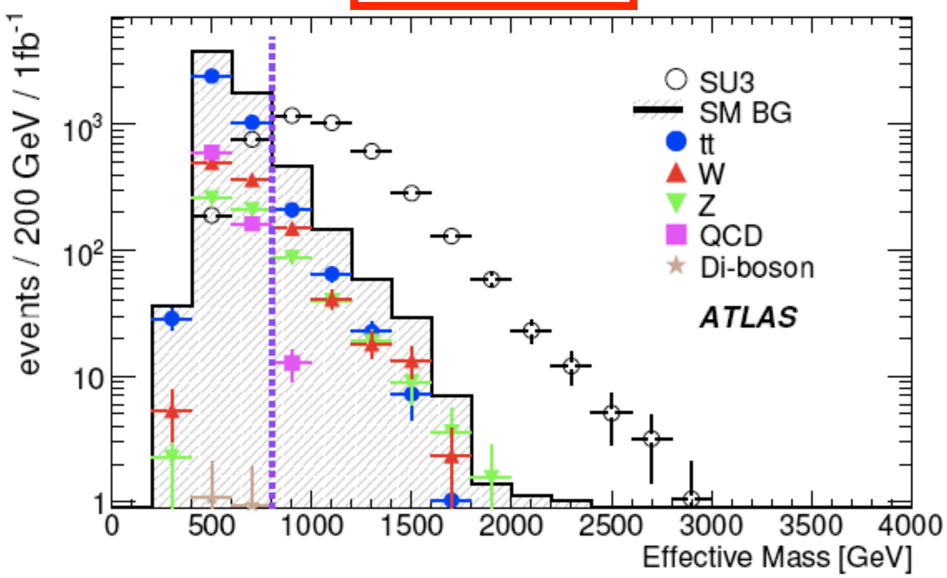


SUSY at the LHC

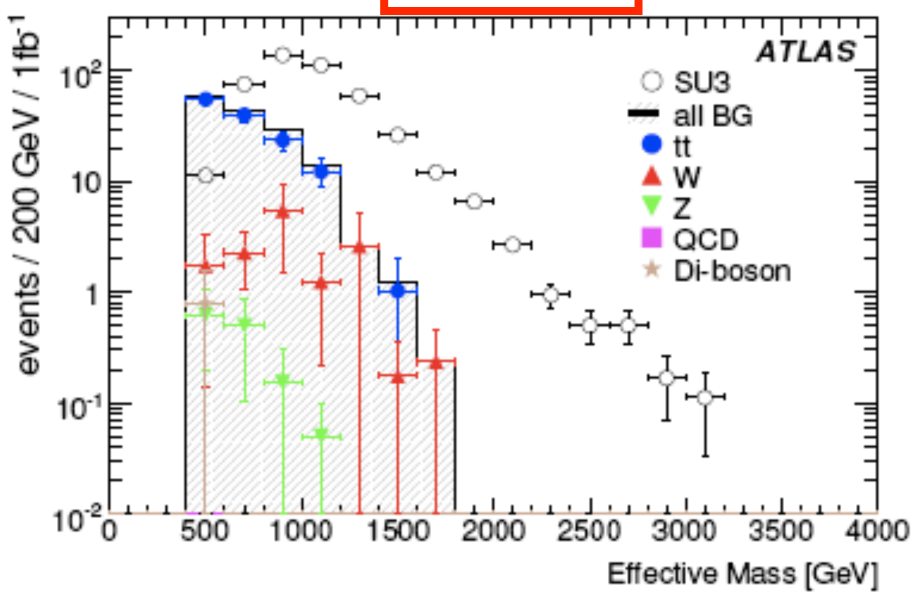


- Example: m($\tilde{q}$)~600 GeV, m($\tilde{g}$)~700 GeV
- Require 4 jets, large missing E_T and 0 or 1 lepton

0 leptons

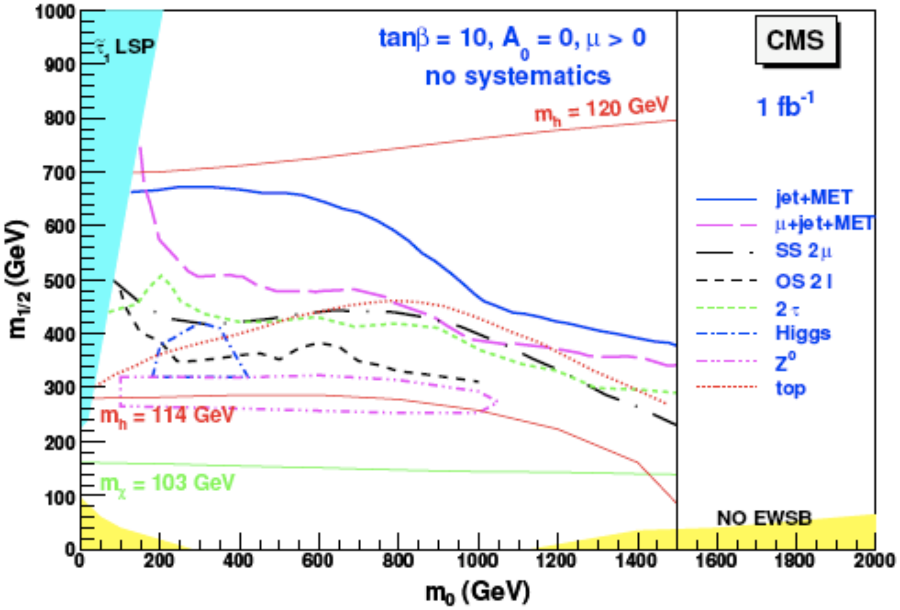


1 lepton

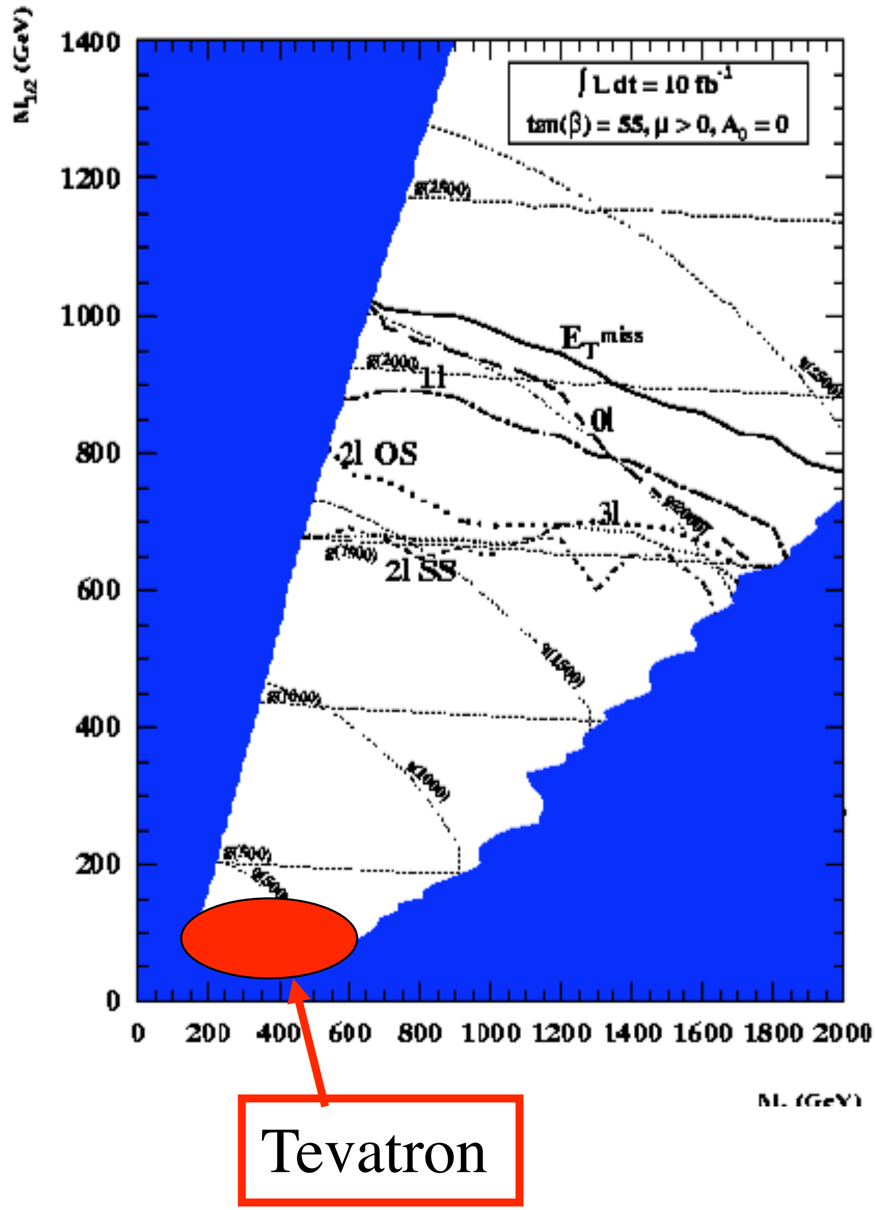


- "Effective Mass" = sum of p_T of all objects
- Similar and great (!) sensitivity in both modes

SUSY Discovery Reach

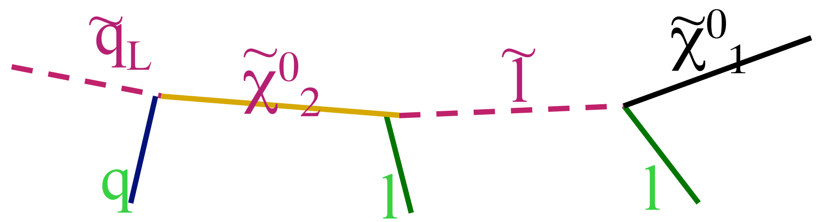


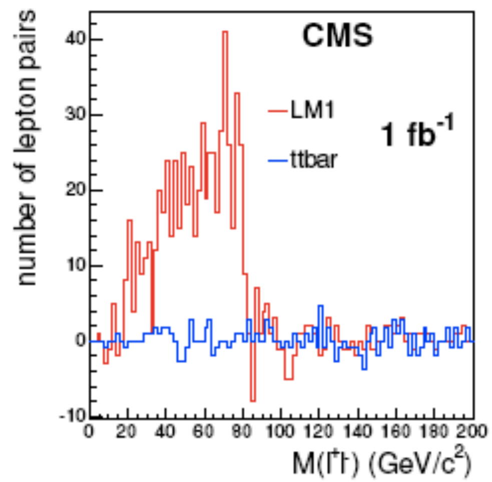
- With 1 fb^{-1}:
  - Sensitive to m($\tilde{g}$)≲1000 GeV/c^2
- With 10 fb^{-1}:
  - Sensitive to m($\tilde{g}$)≲1800 GeV/c^2
- Amazing potential!
  - If data can be understood
  - If current MC predictions are ≈ok

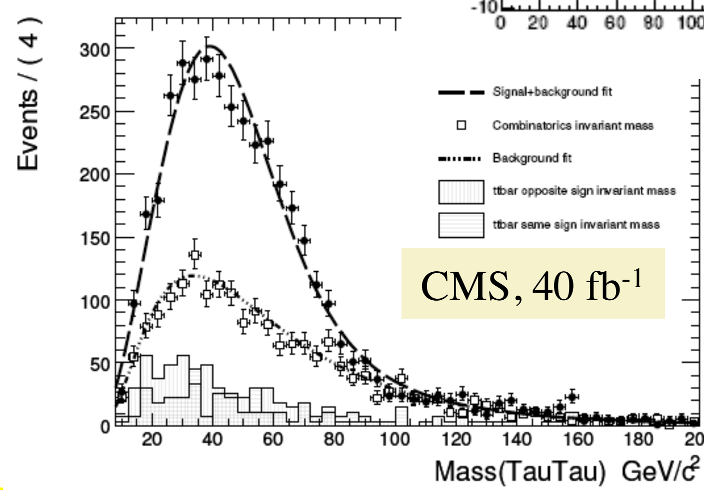


What kind of SUSY is it?

- We will need to do SUSY spectroscopy!
  - Rate of 0 vs 1 vs 2 vs n leptons
    - Sensitive to neutralino masses
  - Rate of tau-leptons:
    - Sensitive to tanβ
  - Kinematic edges
    - obtain mass values
  - Detailed examination of inclusive spectra
  - ….

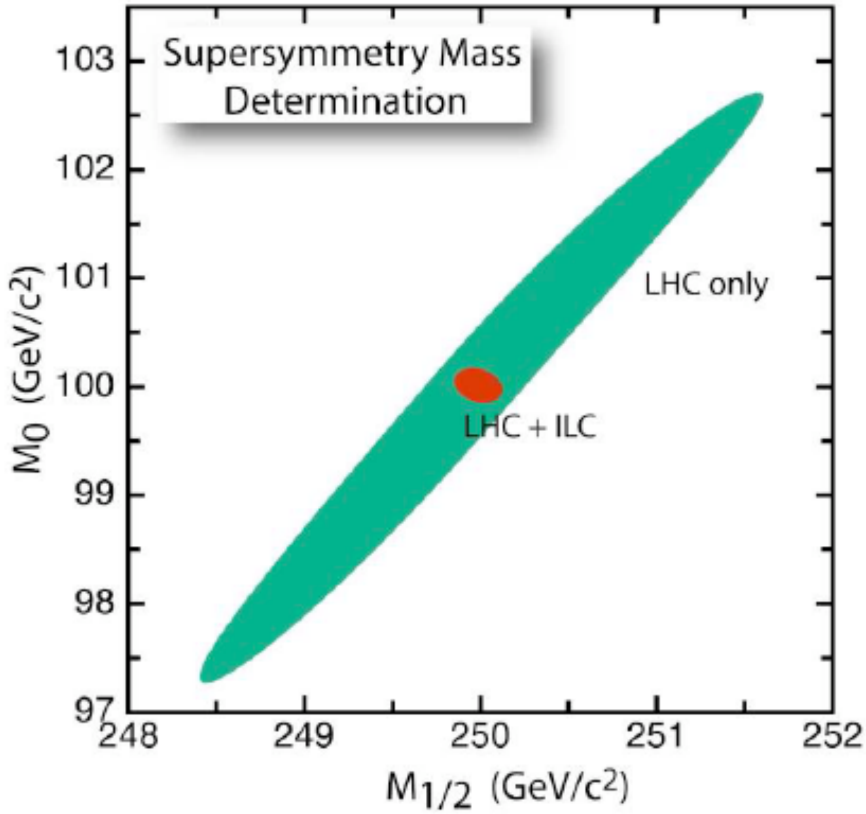


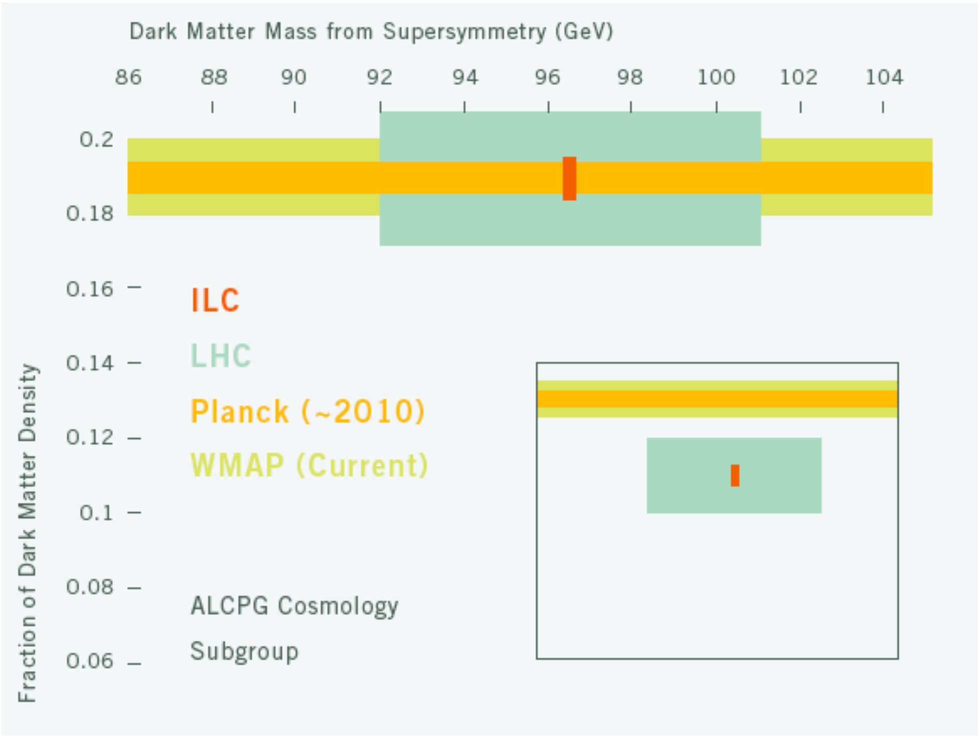




That would be my dream scenario! It's where the real fun starts!!

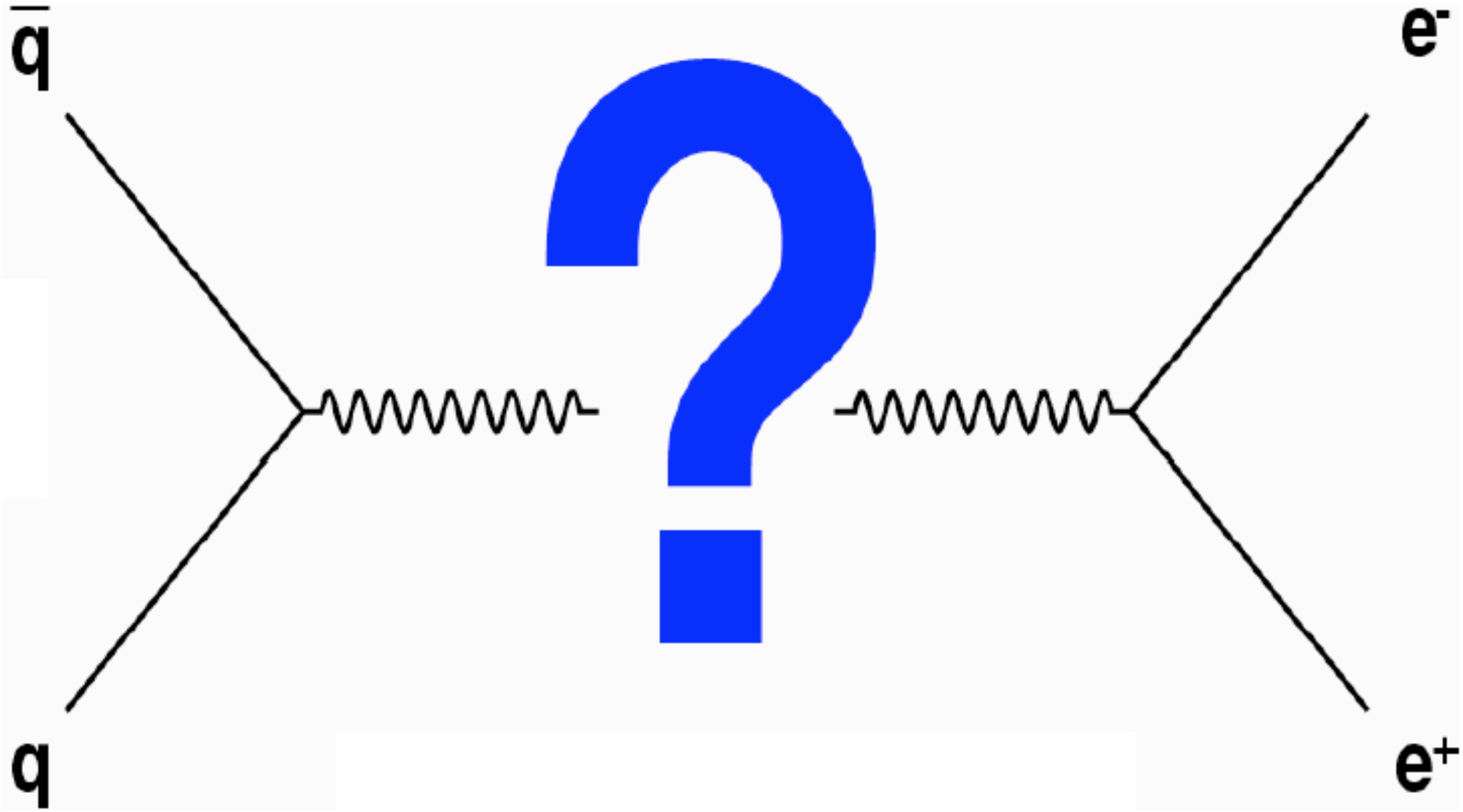
If SUSY gets discovered at the LHC…





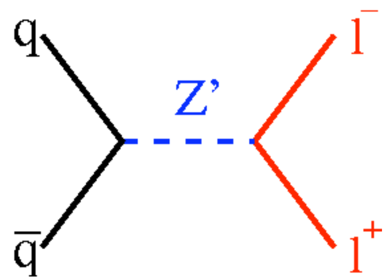
- Measure dark matter particle mass with ~5 GeV precision?
  - Rather model-dependent… need to understand the model we are in!
- May need the ILC to really understand SUSY!

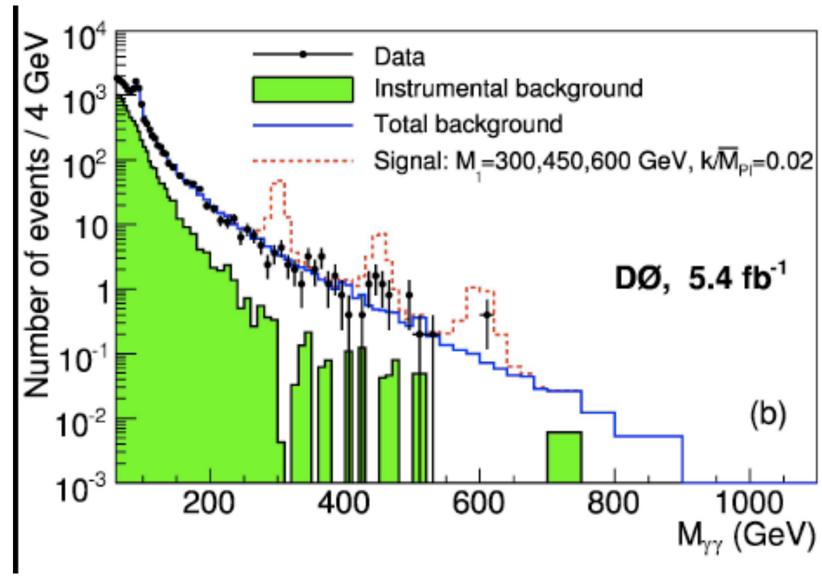
High Mass Resonances

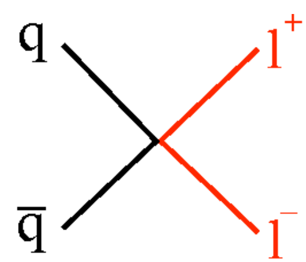


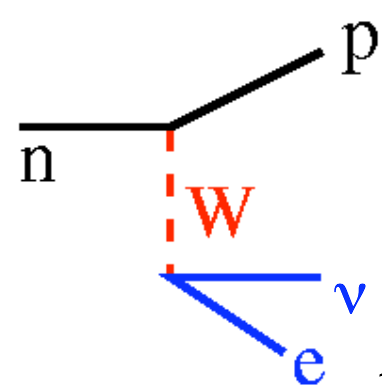
Resonances or Tails

- New resonant structure:
  - New gauge boson:
    - Z' →ee, μμ, ττ, tt
    - W' →eν, μν, τν, tb
  - *Randall-Sundrum* Graviton:
    - G→ee, μμ, ττ, γγ, WW, ZZ,…
- Tail:
  - Large extra dimensions *[Arkani-Hamed, Dvali, Dimopoulos (ADD)]*
    - Many many many resonances close to each other:
    - "Kaluza-Klein-Tower": ee, μμ, ττ, γγ, WW, ZZ,…
  - Contact interaction
    - Effective 4-point vertex
      - E.g. via t-channel exchange of very heavy particle
    - Like Fermi's β-decay

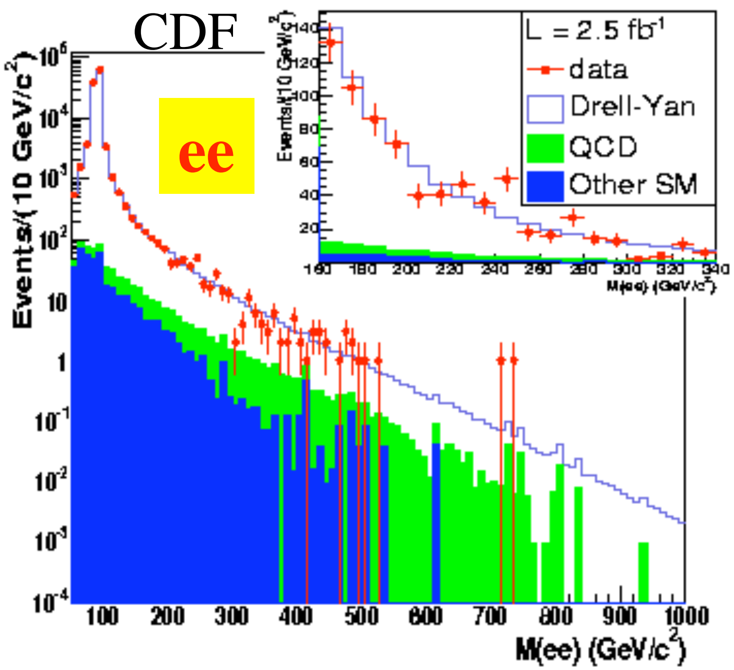


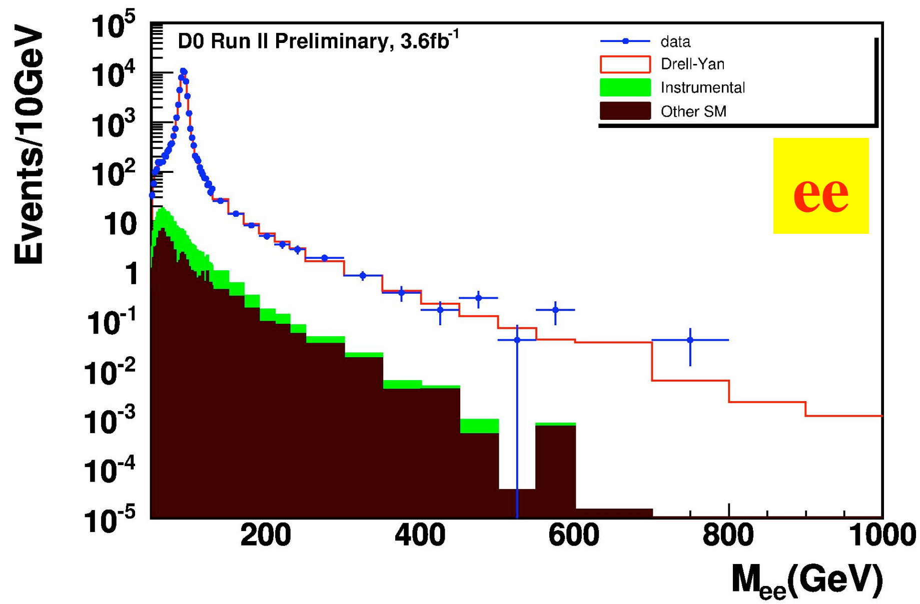




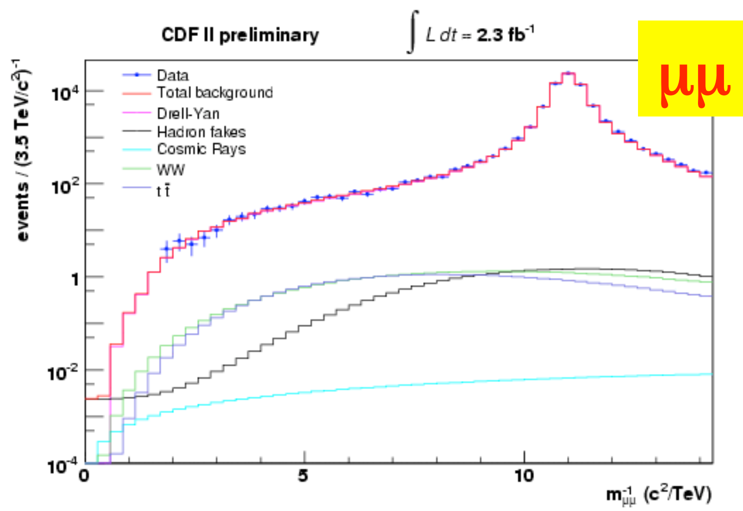


Neutral Spin-1 Bosons: Z′

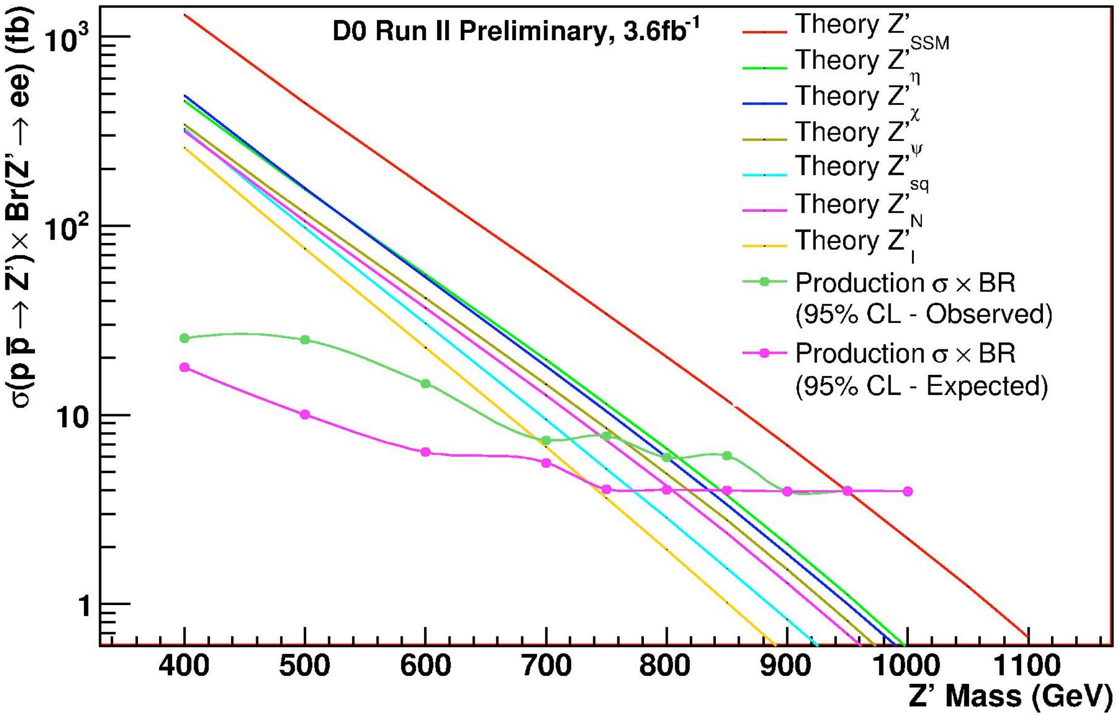




- 2 high P_T leptons: ee, μμ
- Slight excess in CDF dielectron data at 250 GeV
  - Not seen in dimuon channel and not seen by DØ



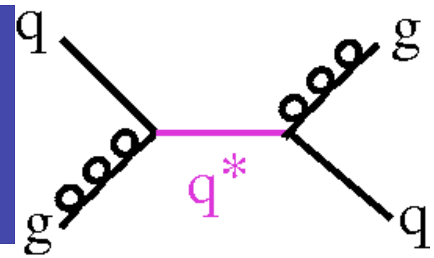
Interpreting the Mass plots

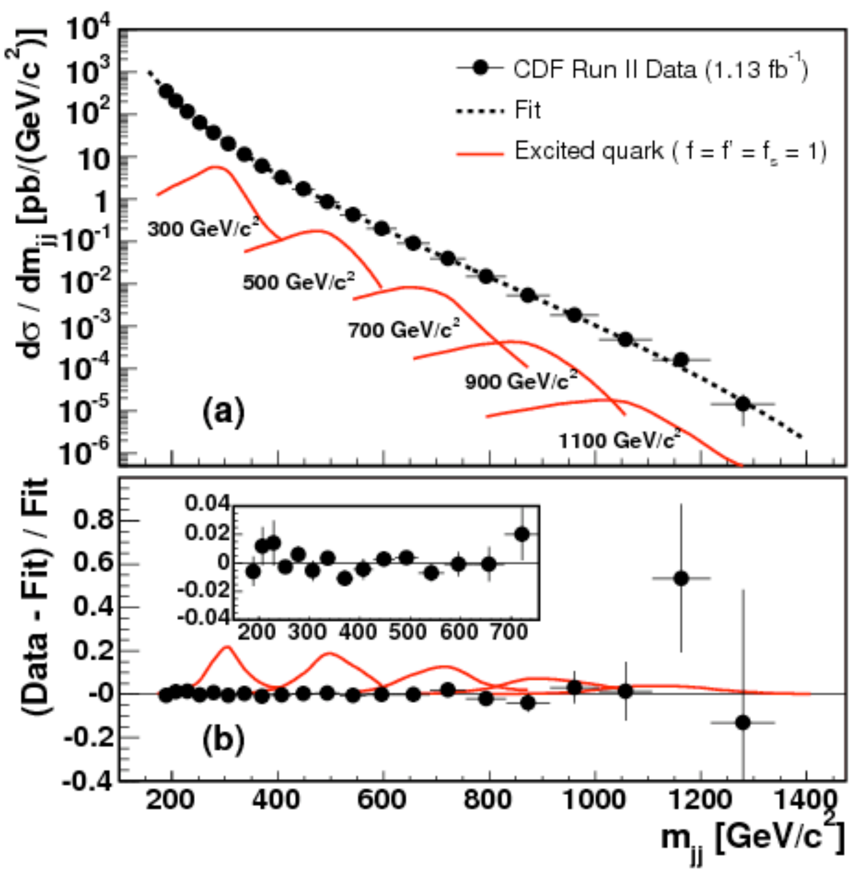


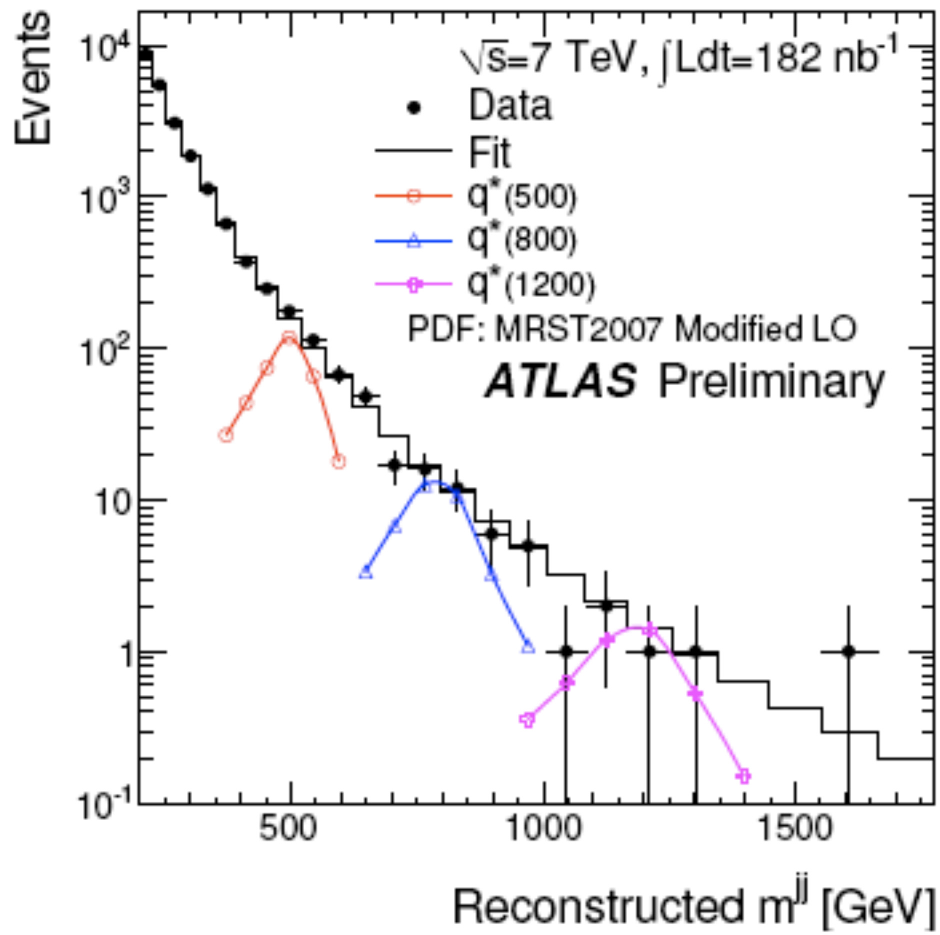
- No evidence for any deviation from Standard Model => Set limits on new physics
  - Set limits on cross section x branching ratio
  - Can also set limits on Z' mass within certain models
    - Approximately M>1 TeV for SM couplings

Limits for SM couplings:

Dijet Resonances: Tevatron and LHC

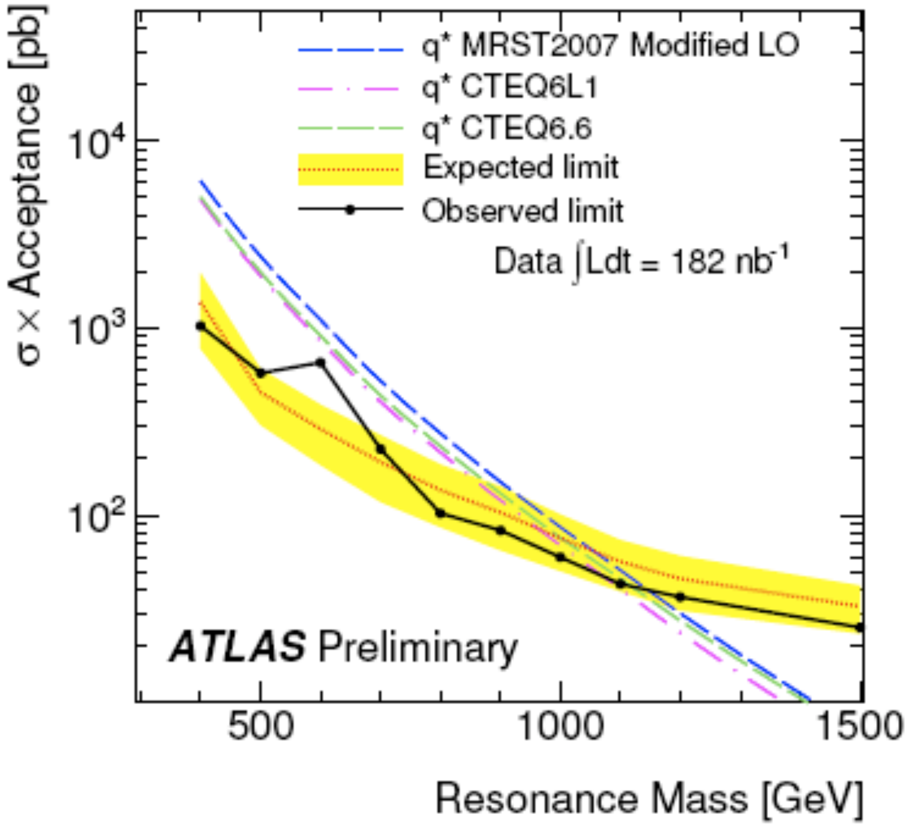






- Appear in many new physics models
  - e.g. "excited quark"

Limits on Excited Quarks



- ATLAS: M(q*)>1150 GeV (with L=0.2 pb^{-1})
- CDF: M(q*)>870 GeV (with L=1100 pb^{-1})
- LHC already probing new physics with so little luminosity

Conclusions: Lecture IV

- Searches for Physics Beyond the Standard Model are extremely important
  - This can revolutionize our subject and solve many (or at least a few) questions
- I showed you two classic/important examples:
  - SUSY
    - Squarks and Gluinos
    - If it exists we will have lots of fun understanding what we've found
  - High mass resonances
- Not found any new physics (yet)
  - Tevatron ever improving and LHC catching up!

If Supersymmetry solves indeed current problems in our theory it will be found at latest at the LHC

Overall Conclusions

- **Hadron colliders are powerful tools to understand Nature:**
  - Probing the **electroweak** and the **strong** sector of the Standard Model
  - Looking for the **unknown**
- **Tevatron**
  - has further established the Standard Model
- **We are entering a truly new regime with the LHC**
  - Probing distances of 10^{-19} m aka the *Tera*-scale
  - amazing discovery potential for
    - the Higgs boson (if it exists) or something new
    - Supersymmetry or other new physics at ~TeV masses

Stay tuned … in a few years we may have to rewrite the text books!

Finally…
enjoy your stay here at CERN and
all the best for your next steps!

Email me any time: *Beate.Heinemann@cern.ch*