Physics at the Tevatron

Lecture IV

Beate Heinemann

University of California, Berkeley

Lawrence Berkeley National Laboratory

CERN, Academic Training Lectures, November 2007

Outline

- Lecture I:
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
- Lecture II:
  - The W boson mass, the Top Quark and the Higgs Boson
    - Lepton calibration, jet energy scale and b-tagging
- Lecture III:
  - Lifetimes, B_s^0 and D^0 mixing, and $B_s \rightarrow \mu\mu$ rare decay
    - Vertex resolution and particle identification
- Lecture IV:
  - Supersymmetry and High Mass Resonances
    - Missing E_T and tau-leptons

All lectures available at:

http://www-atlas.lbl.gov/~heinemann/homepage/publictalk.html

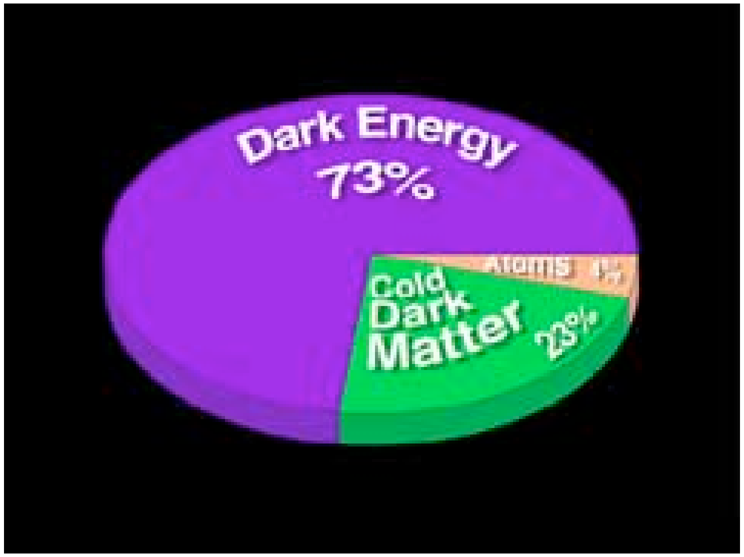
Does the Standard Model work?

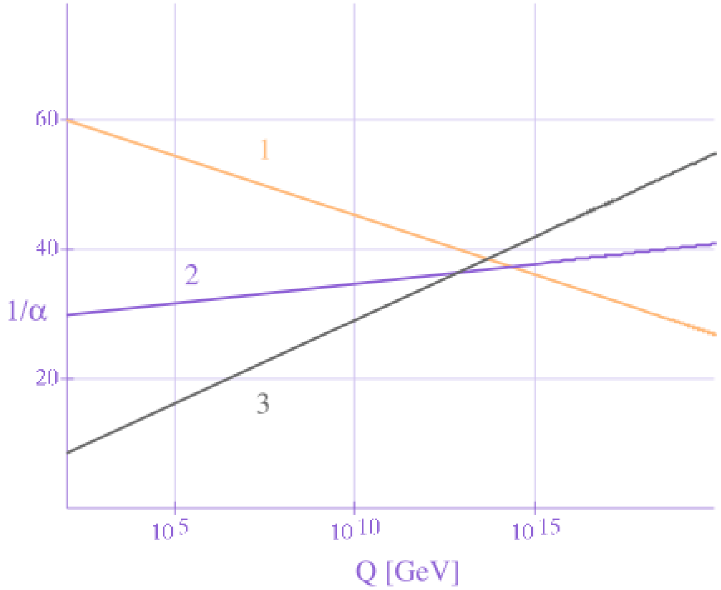
pro's:

- Is consistent with electroweak precision data

con's:

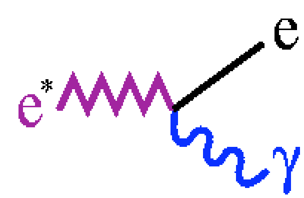
- Accounts for only 4% of energy in Universe
- Lacks explanation of mass hierarchy in fermion sector
- does not allow grand unification of forces
- Requires fine-tuning (large radiative corrections in Higgs sector)
- Where did all the antimatter go?
- Why do fermions make up matter and bosons carry forces?

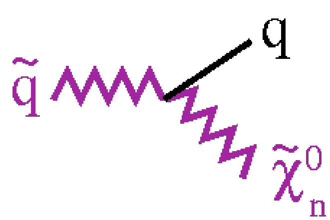


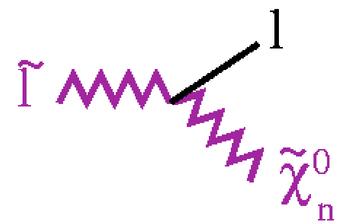


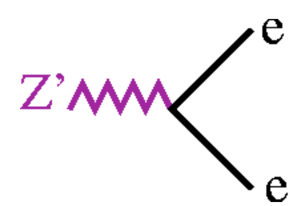
The Unknown beyond the Standard Model

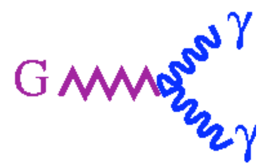
- Many good reasons to believe there is as yet unknown physics beyond the SM:
  - Dark matter + energy, matter/anti-matter asymmetry, neutrino masses/mixing +many more (see later)
- Many possible new particles/theories:
  - Supersymmetry:
    - Many flavours
  - Extra dimensions (G)
  - New gauge groups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

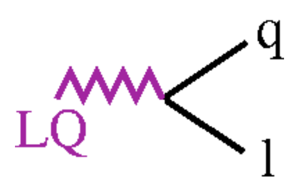


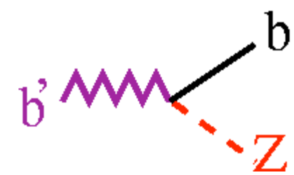




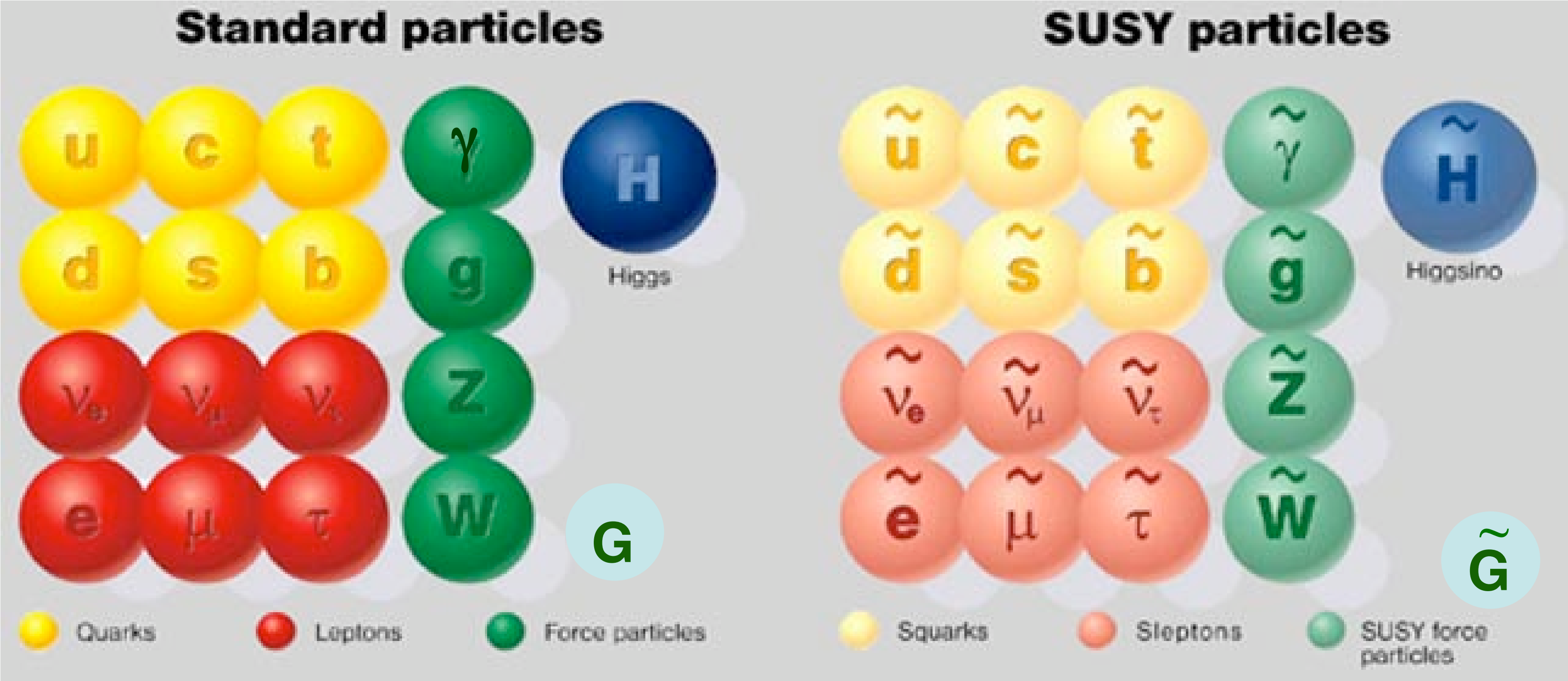








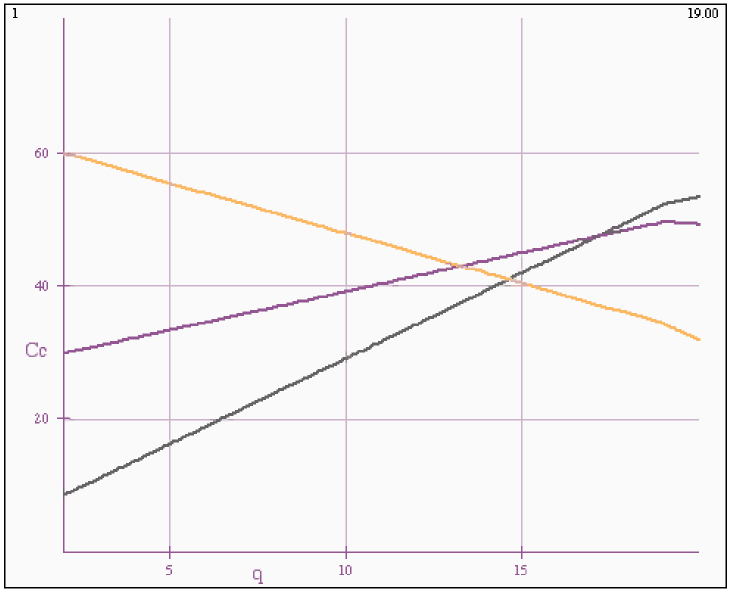
Supersymmetry (SUSY)



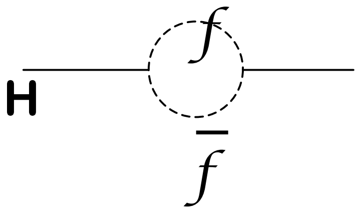
- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squarks, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology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

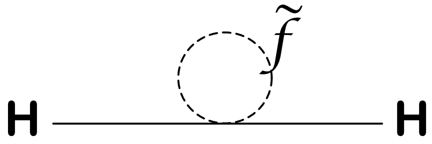
What's Nice about SUSY?

- 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



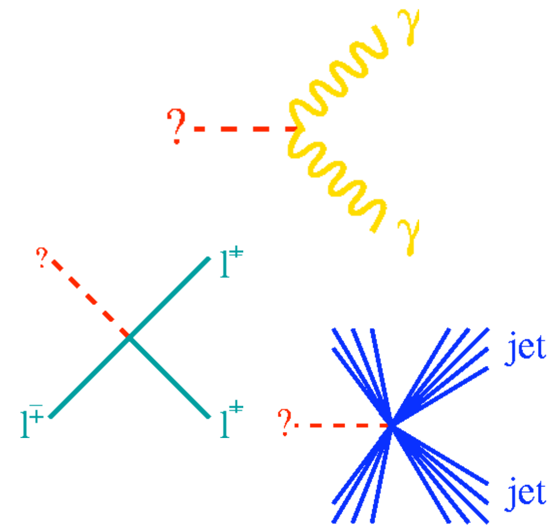
From C. Quigg





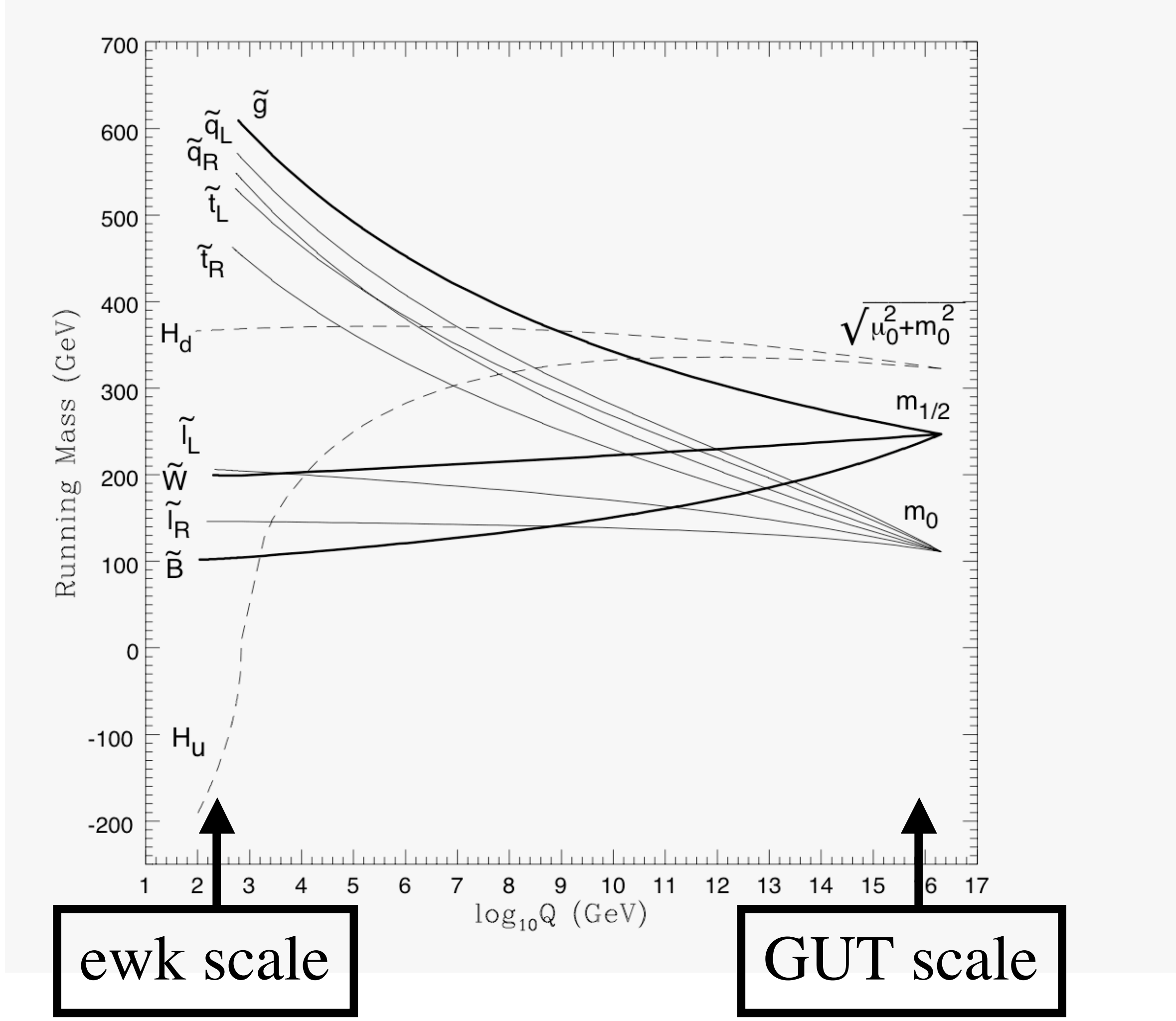
SUSY Comes in Many Flavors

- 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



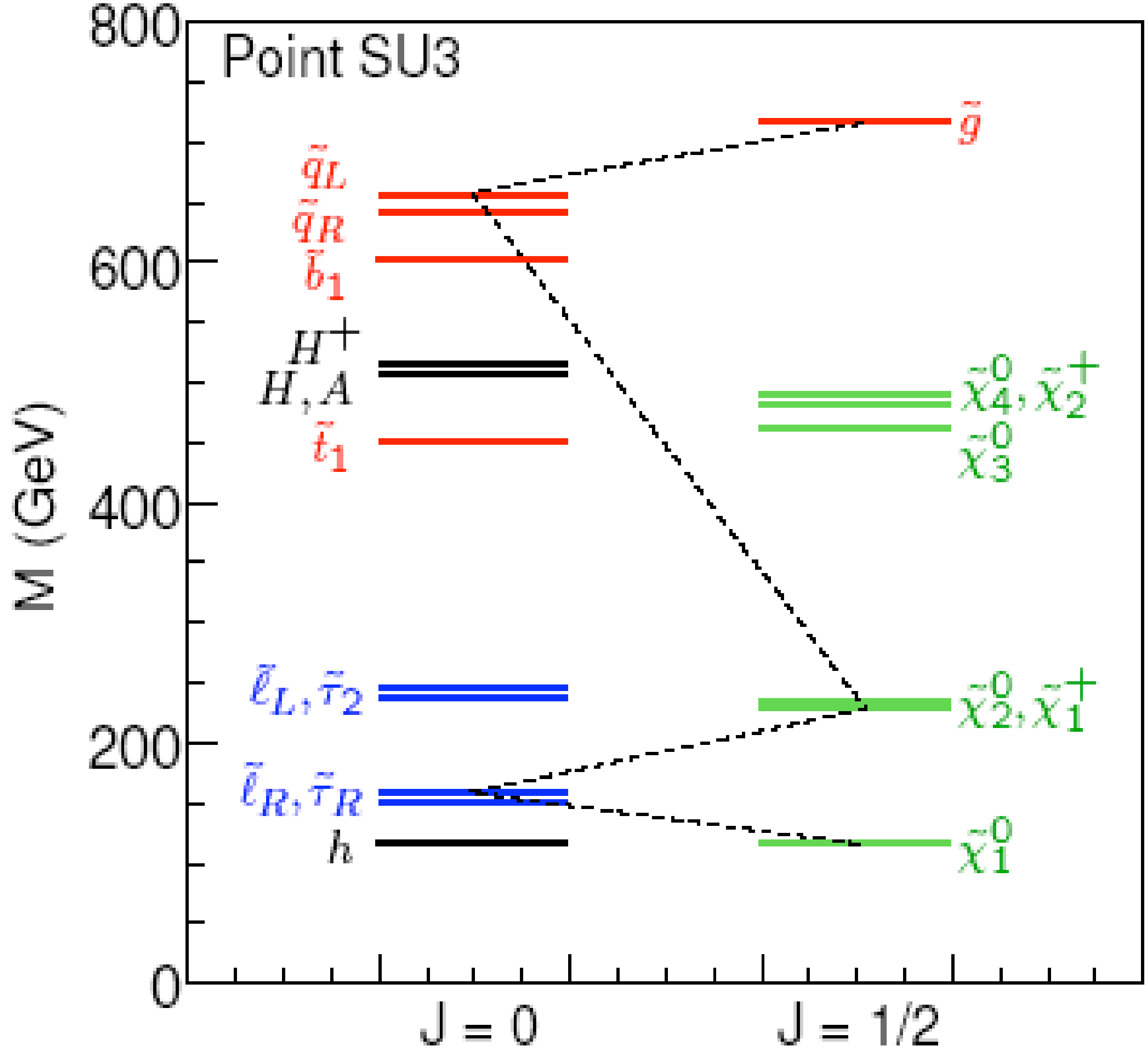
- R-parity
  - Conserved: Sparticles produced in pairs
    - natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector
    - Could explain neutrino oscillations if violation in lepton sector

Mass Unification in mSUGRA

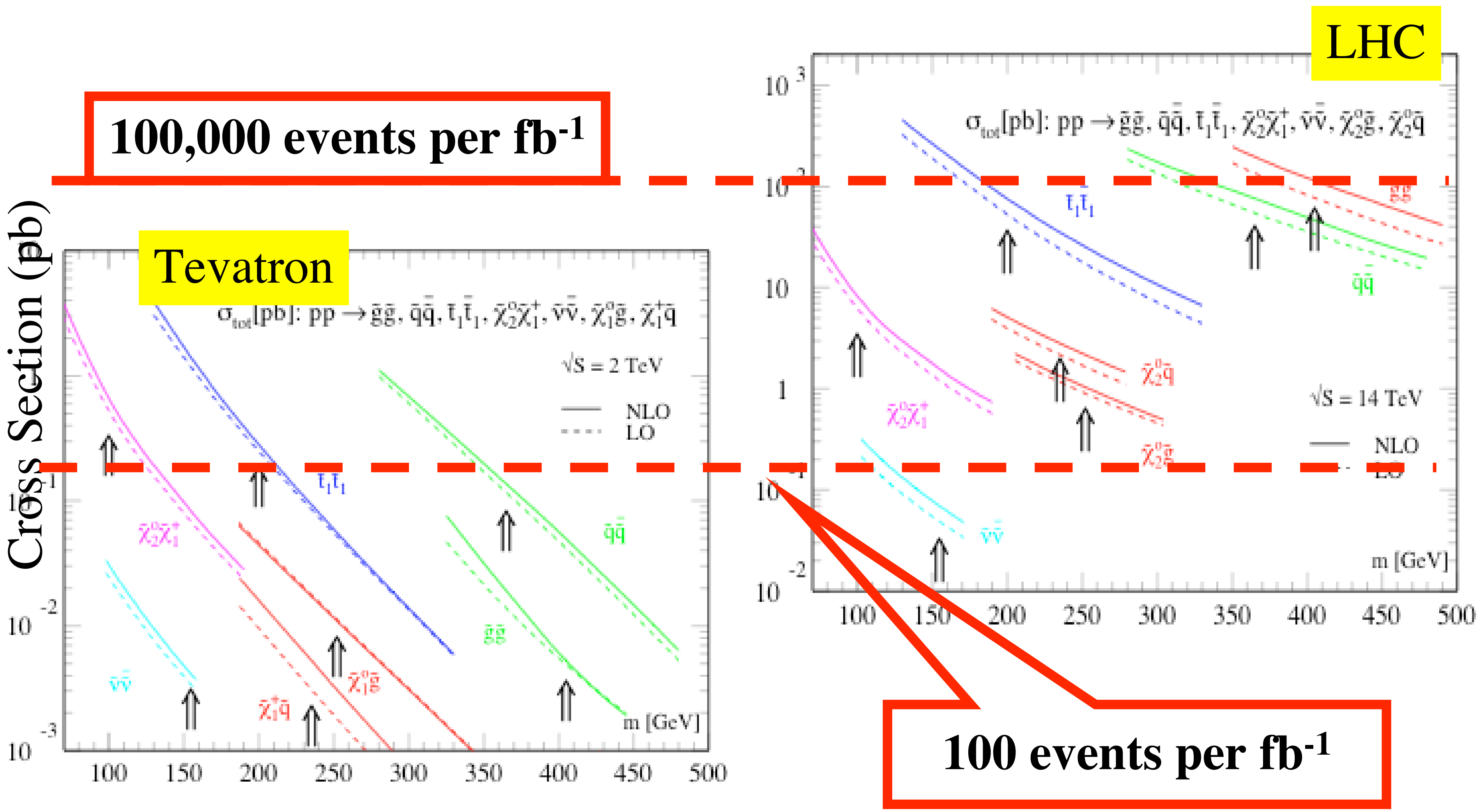


- Common masses at GUT scale: m_0 and $m_{1/2}$
  - Evolved via renormalization group equations to lower scales
  - Weakly coupling particles (sleptons, charginos, neutralions) are lightest

A Typical Sparticle Mass Spectrum

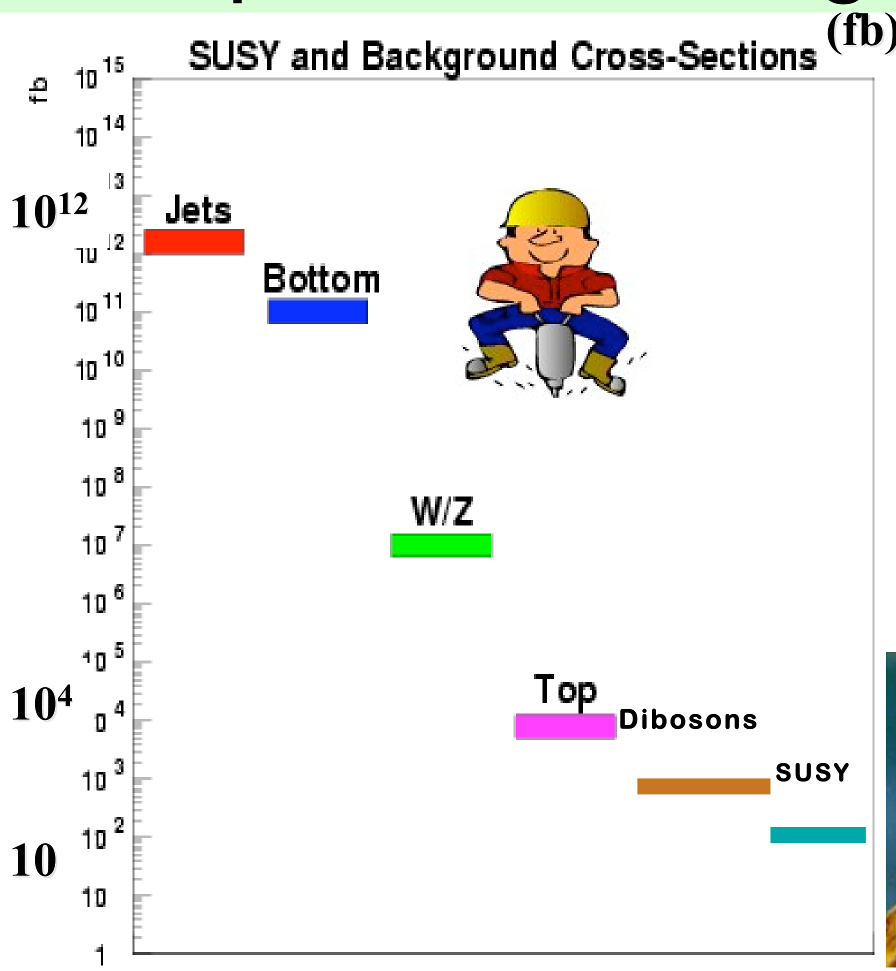


Sparticle Cross Sections



T. Plehn, PROSPINO

SUSY compared to Background



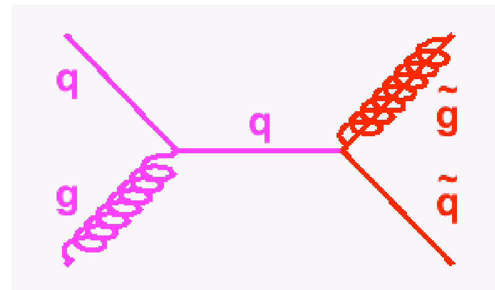
- Cross sections rather low
  - Else would have seen it already!
- Need to suppress background efficiently

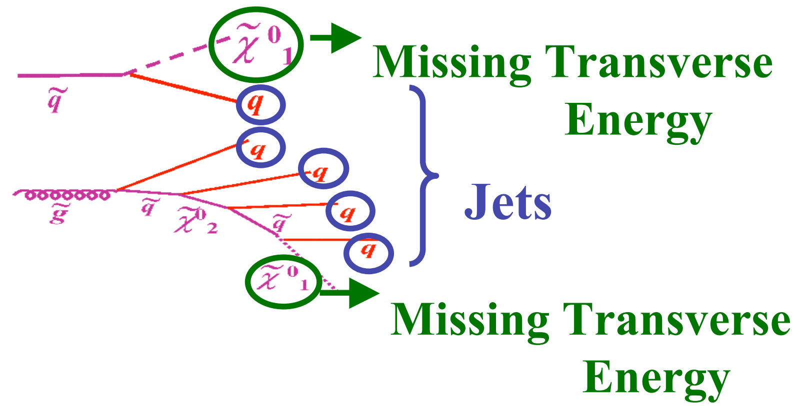
Strategy for SUSY Searches

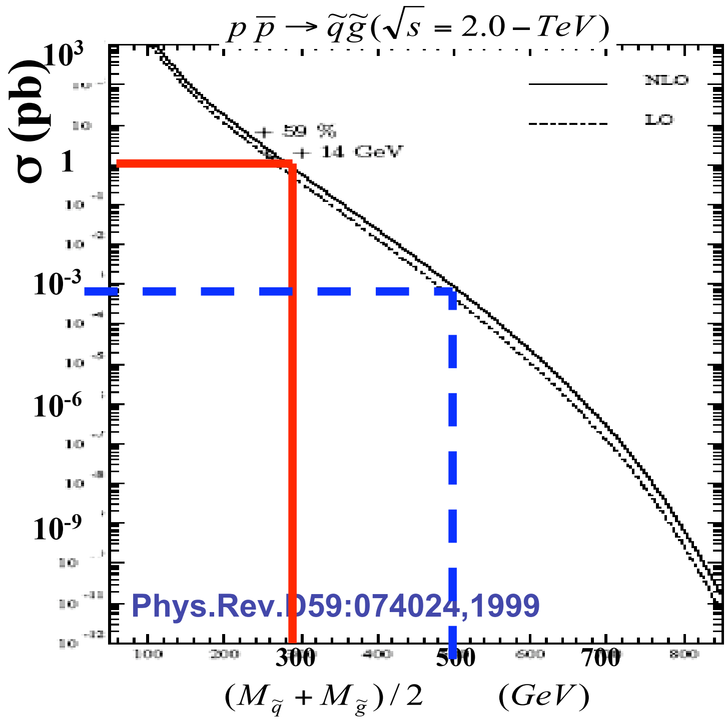
- MSSM has more than 100 parameters
  - Impossible to scan full parameter space
  - Many constraints already from
    - Precision electroweak data
    - Lepton flavour violation
    - Baryon number violation
    - …
- Makes no sense to choose random set
  - Use simplified well motivated "benchmark" models
    - 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 $\not{E}_T$



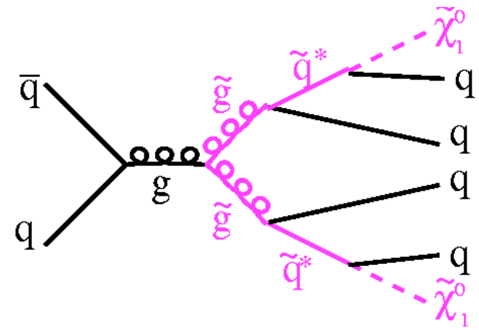


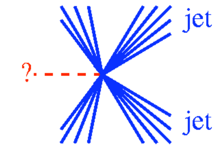


- Strong interaction => large production cross section
  - for M($\tilde{g}$) ≈ 300 GeV/c^2:
    - 1000 event produced/ fb^{-1}
  - for M($\tilde{g}$) ≈ 500 GeV/c^2:
    - 1 event produced/ fb^{-1}

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

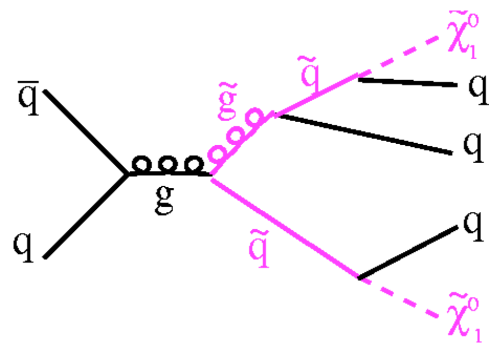
- Consider 3 cases:
  1. $m(\tilde{g})<m(\tilde{q})$

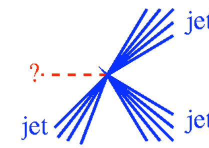




4 jets + E_T^{miss}

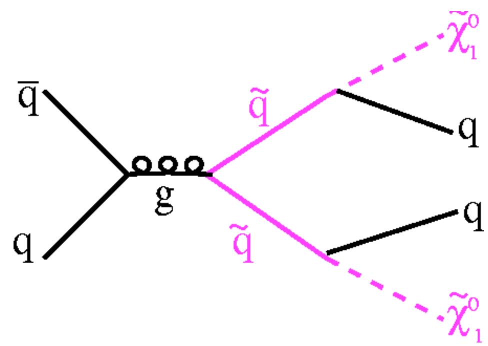
  2. $m(\tilde{g})\approx m(\tilde{q})$

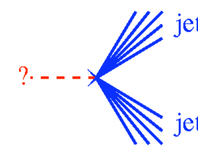




3 jets + E_T^{miss}

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





2 jets + E_T^{miss}

Optimize for different signatures in different scenarios

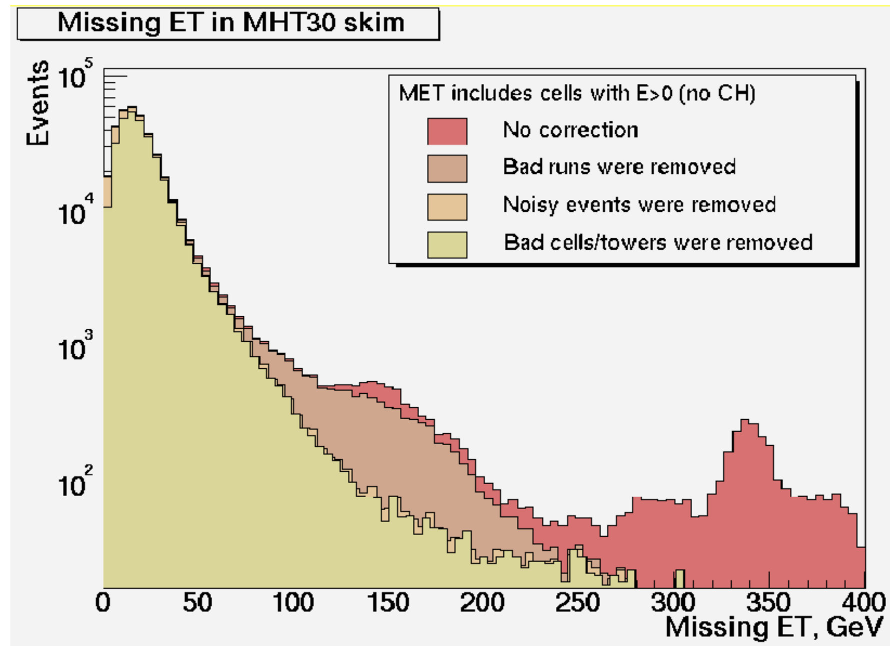
Selection and Procedure

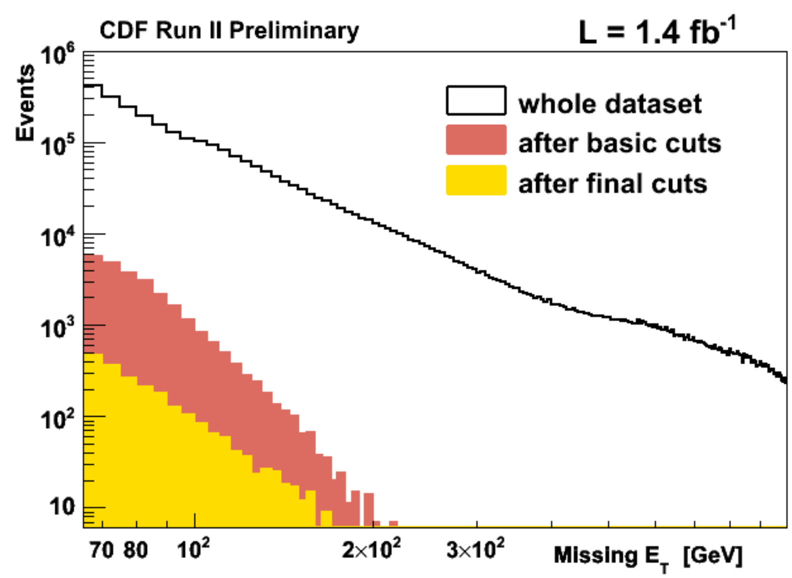
- Selection:
  - Large missing E_T
    - Due to neutralinos
  - Large H_T
    - $H_T = \sum E_T^{jet}$
  - Large $\Delta\phi$
    - Between missing E_T and jets and between jets
    - Suppress QCD dijet background due to jet mismeasurements
  - Veto leptons:
    - Reject W/Z+jets, top

- 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!

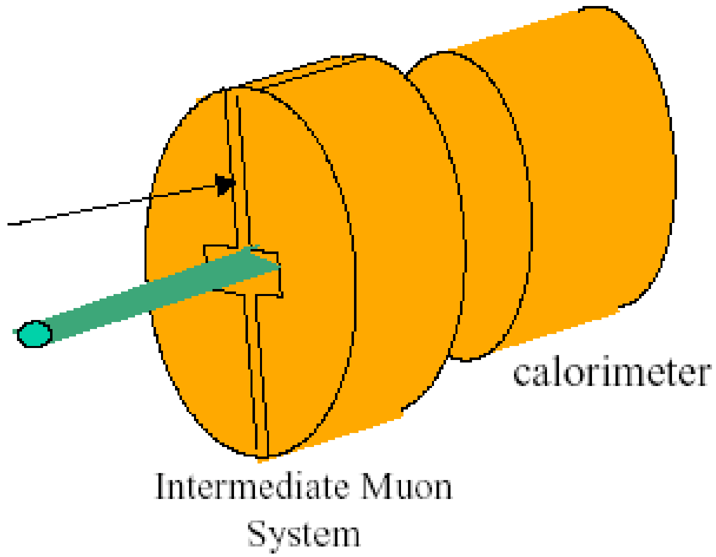
Missing Energy

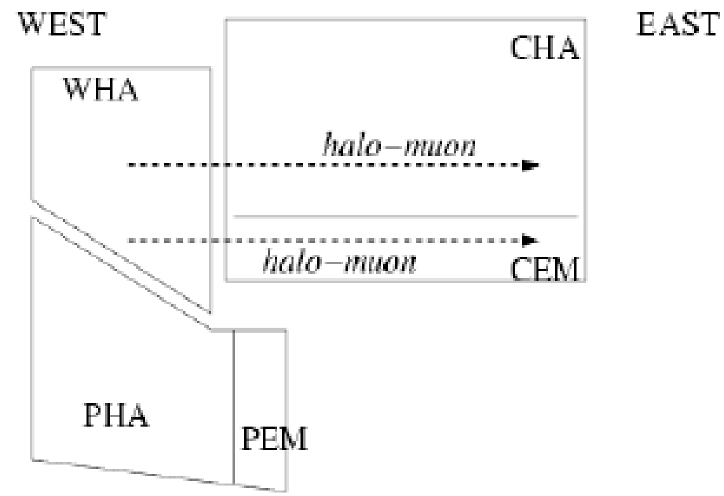
- Data spectrum contaminated by
  - Noise
  - Cosmic muons showering
  - Beam halo muons showering
- Needs "cleaning up"!
  - track matched to jet
  - electromagnetic energy fraction
  - Removal of hot cells
  - Topological cuts against beam-halo



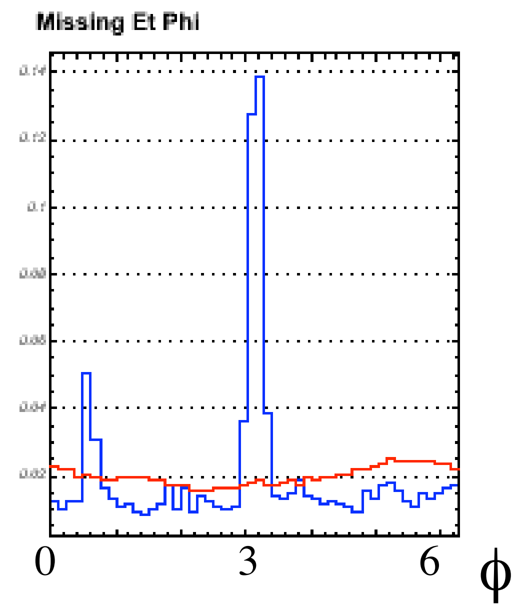


Beam-Halo Muon Background

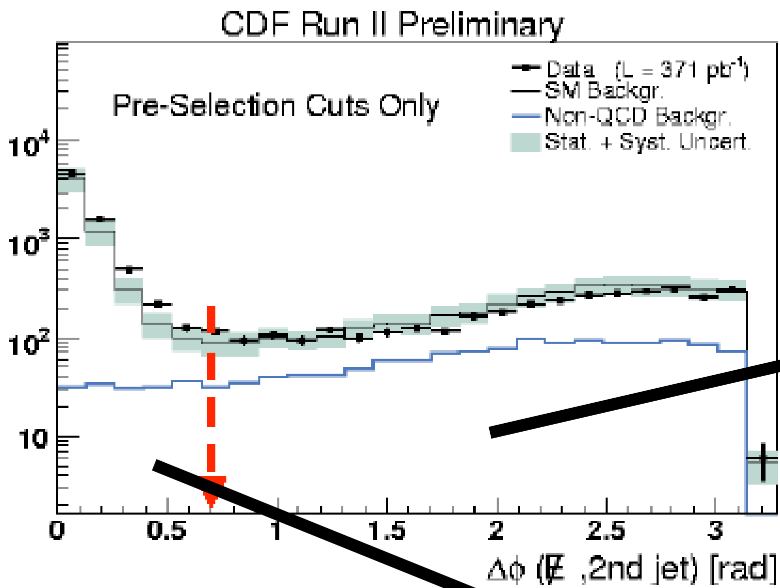


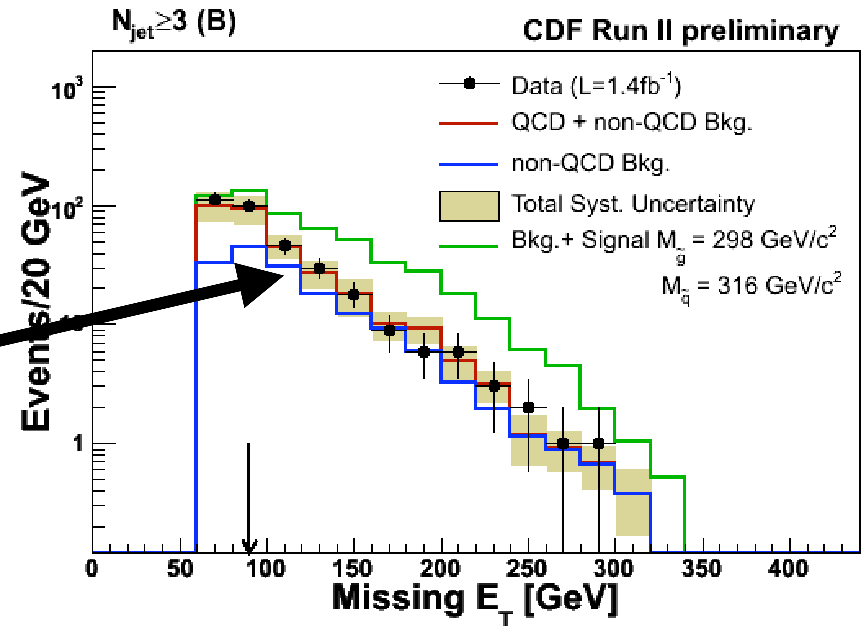


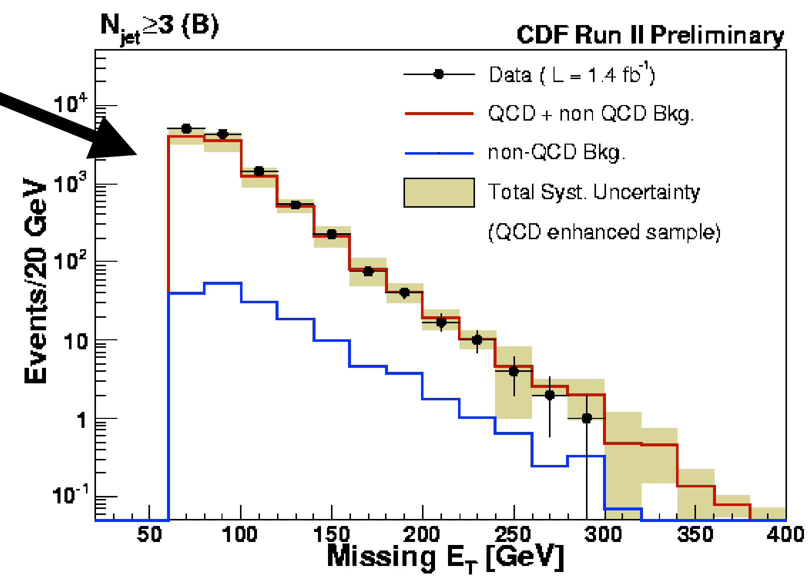
- Muon that comes from beam and goes through shielding
- Can cause showers in calorimeters
  - Shower usually looks not very much like physics jet
    - Often spike at certain azimuthal angles: π
  - But there is lots of those muons!
  - Can cause problem for trigger rate



QCD Dijet Rejection Cut



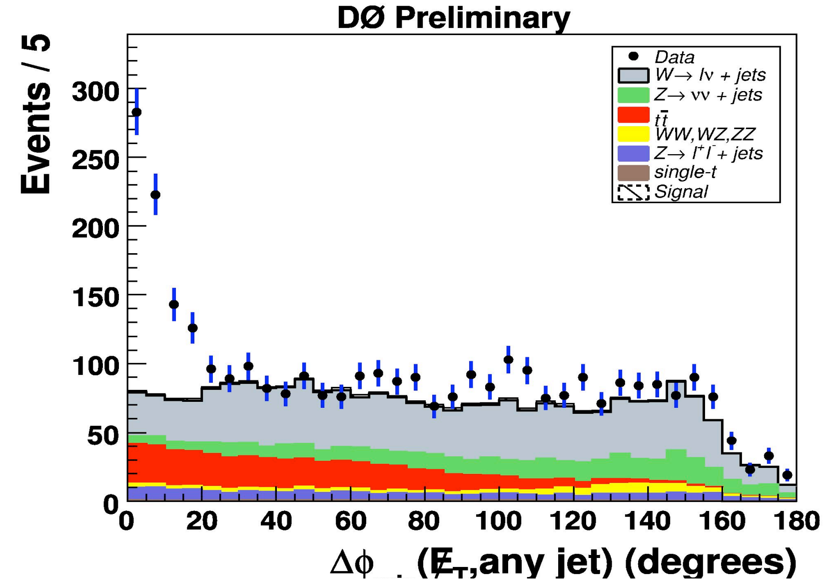


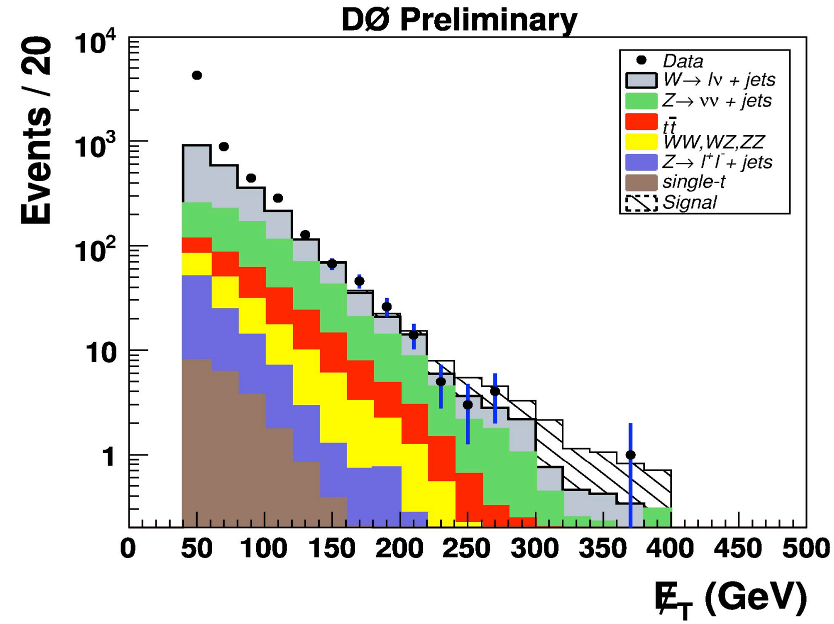


- Cut on $\Delta\phi$(jet, E_T^{miss})
- Used to suppress and to understand QCD multi-jet background
  - Extreme test of MC simulation

QCD Background at DØ

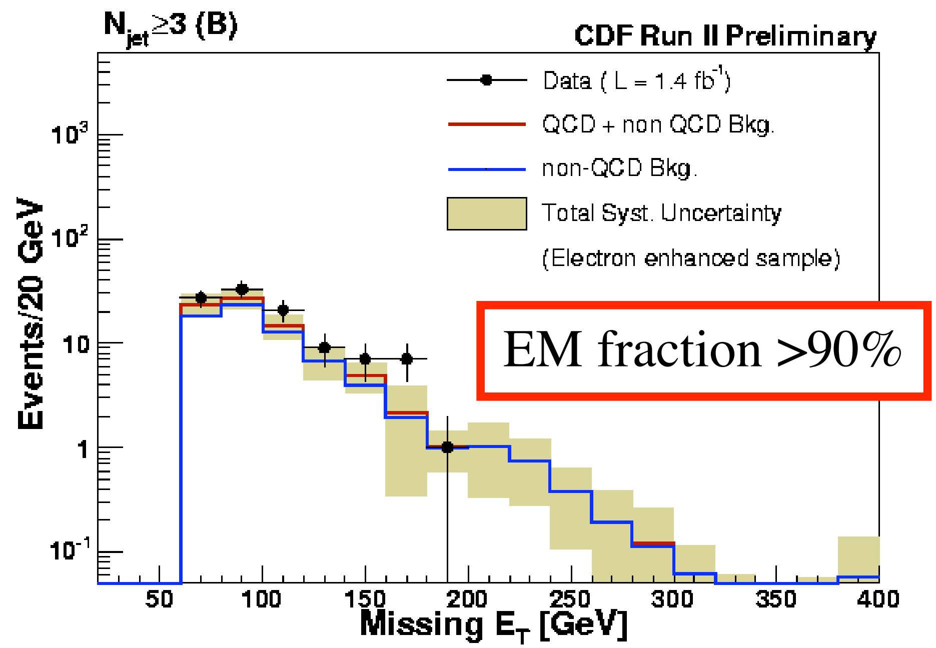
- DØ calorimeter very hermetic and compact
  - Excellent coverage and resolution
- QCD background extrapolated by exponential function
  - Only works if there are no non-Gaussian tails
    - E.g. not true in CDF
- Works in DØ!
  - This simplifies the analysis enormously if it can be done!
- Remaining backgrounds:
  - Top, W/Z+jets

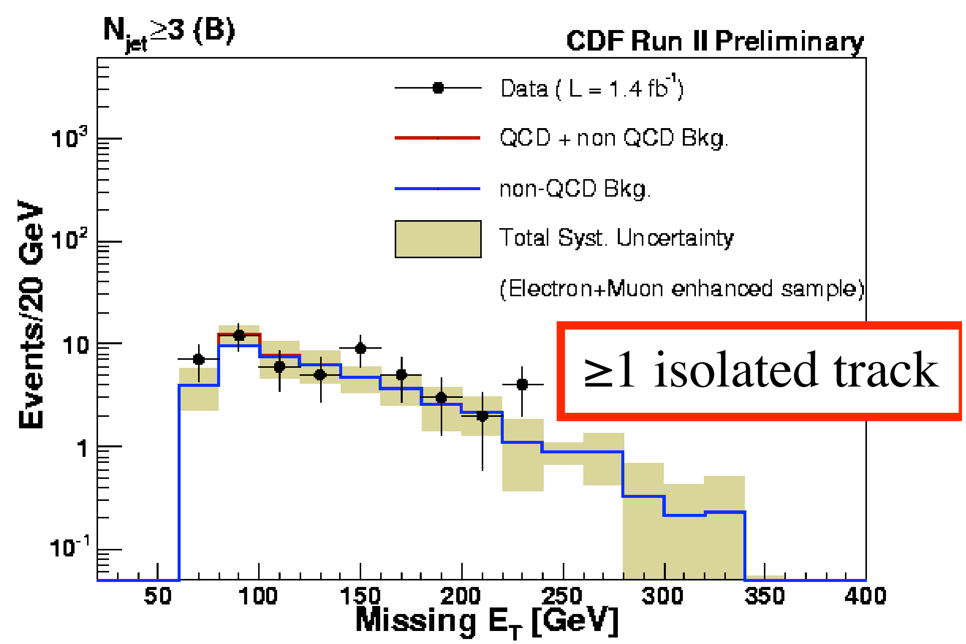




W+jets, Z+jets and Top background

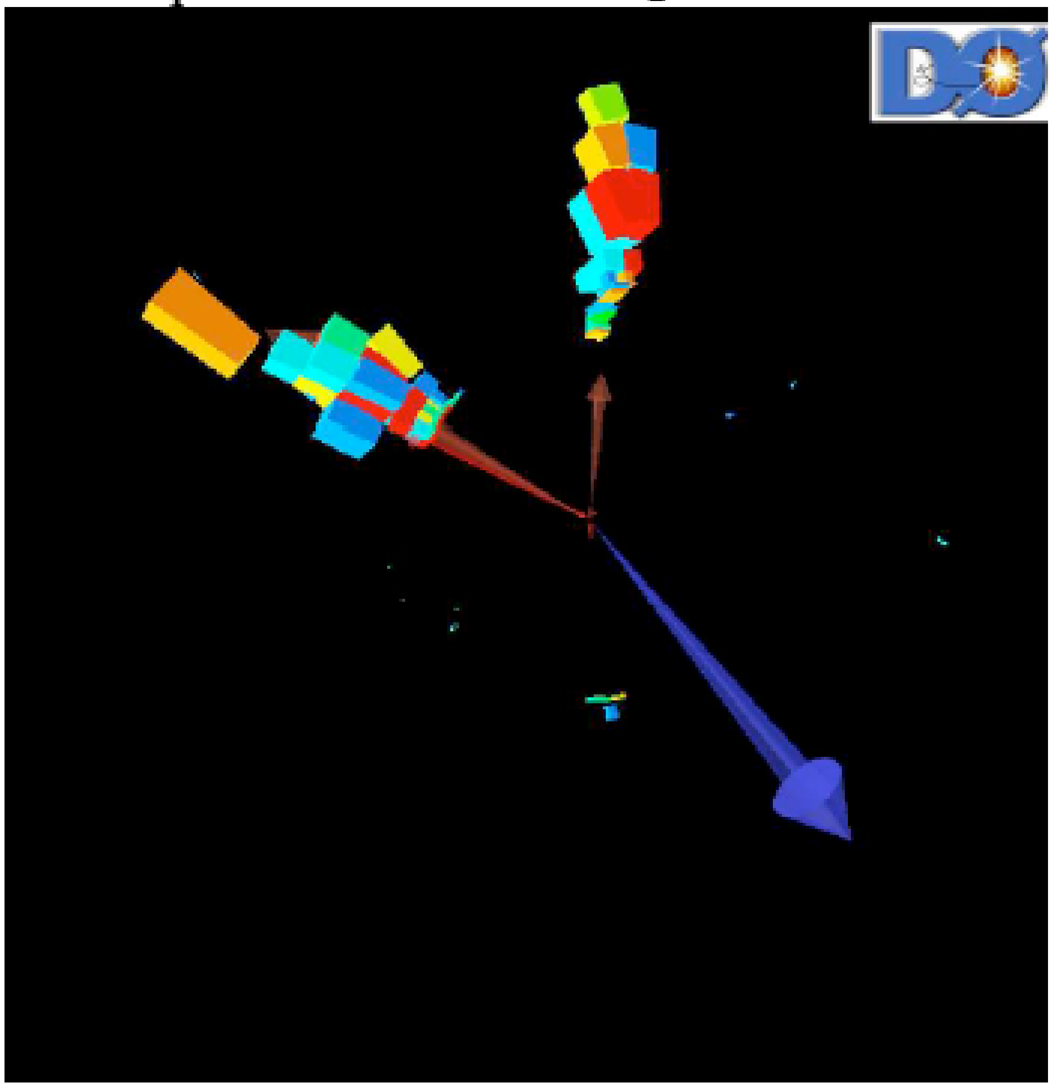
- Background sources:
  - W/Z+jets, top
  - Suppresssed by vetoes:
    - Events with jet with EM fraction>90%
      - Rejects electrons
    - Events with isolated track
      - Rejects muons, taus and electrons
- Define control regions:
  - W/Z+jets, top
    - Make all selection cuts but invert lepton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



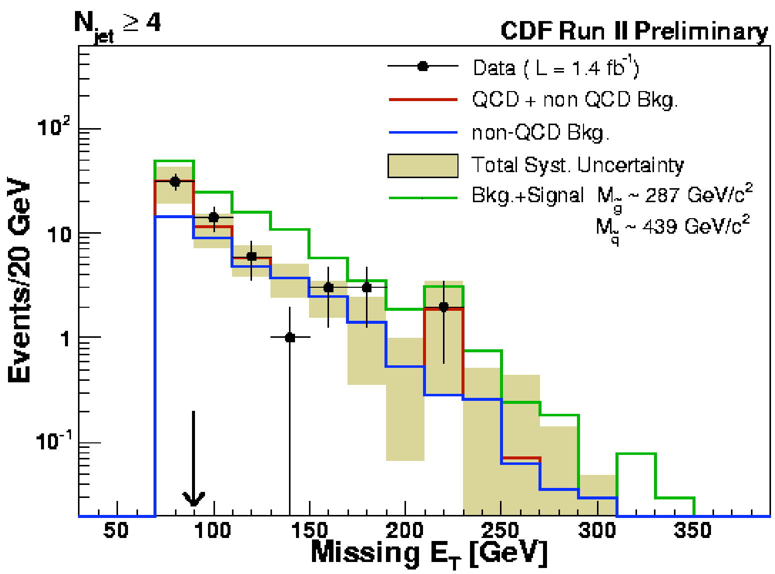


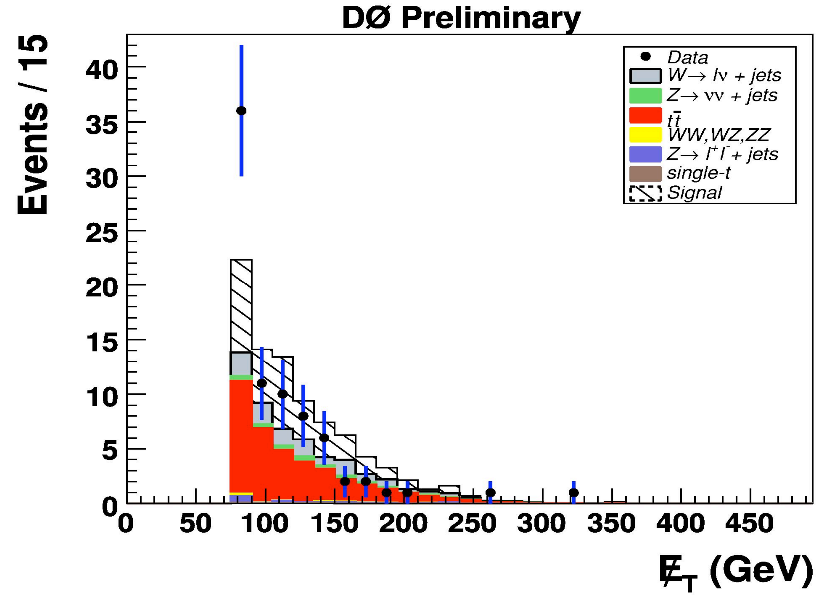
A Nice Candidate Event!

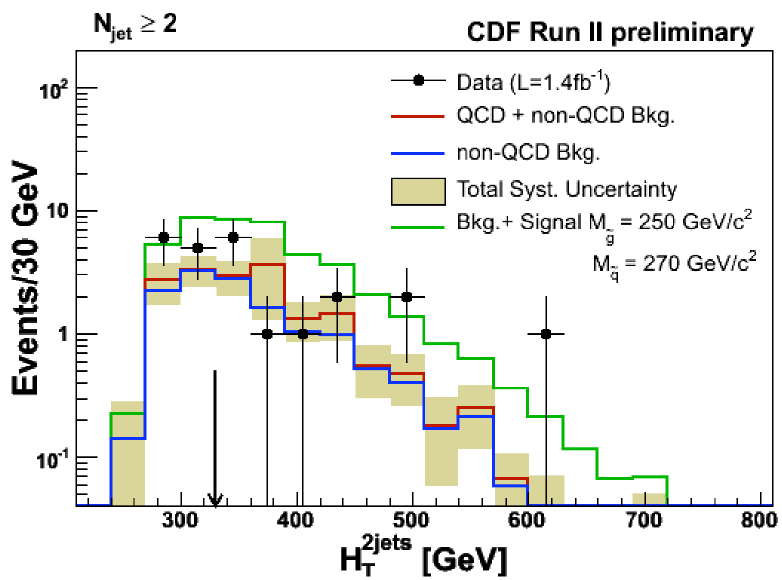
Squark Candidate: $\not{E}_T$=381 GeV

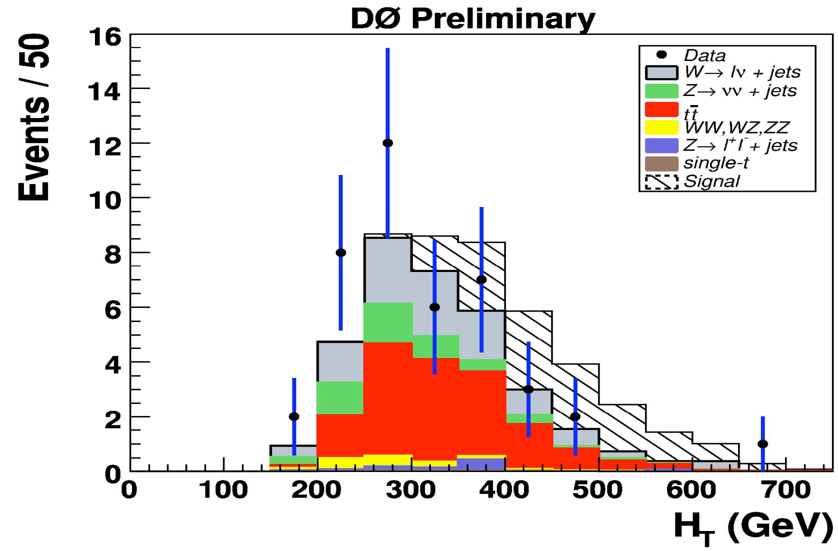


But there is no clear signal…

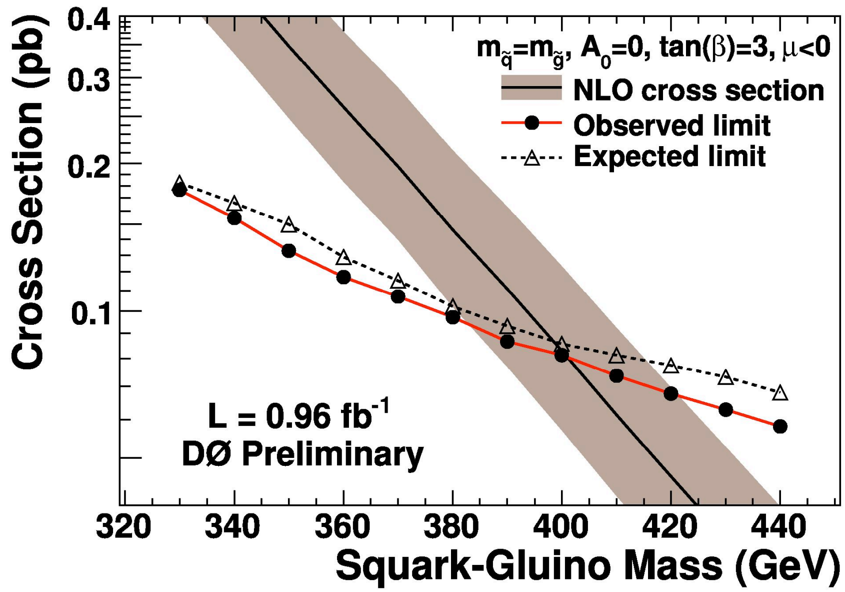


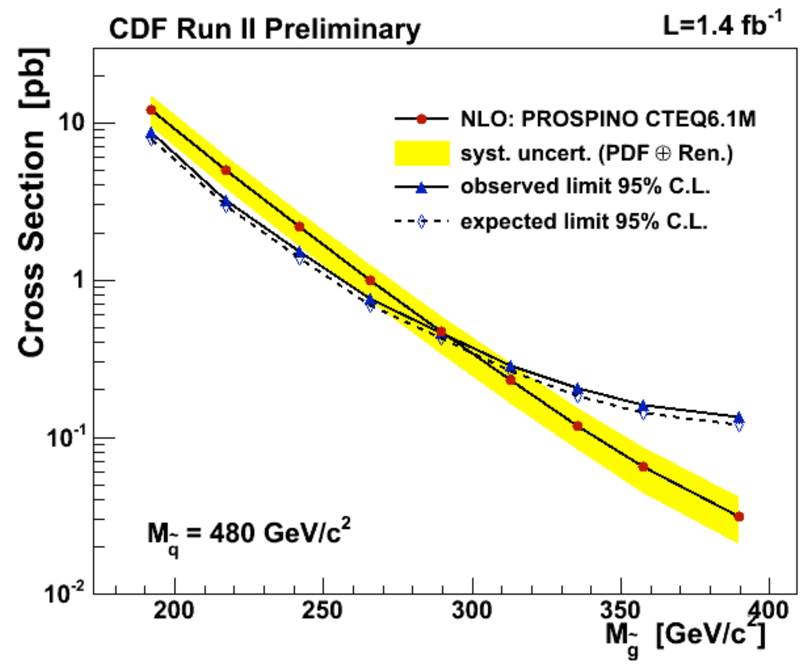






Cross Section Limits

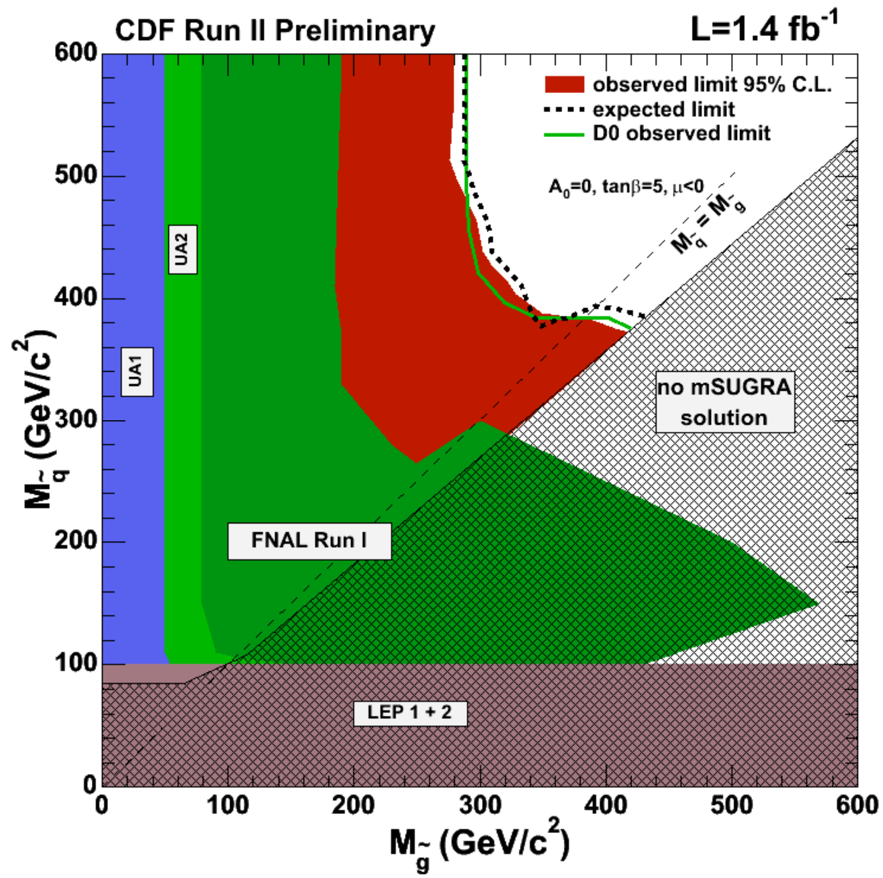




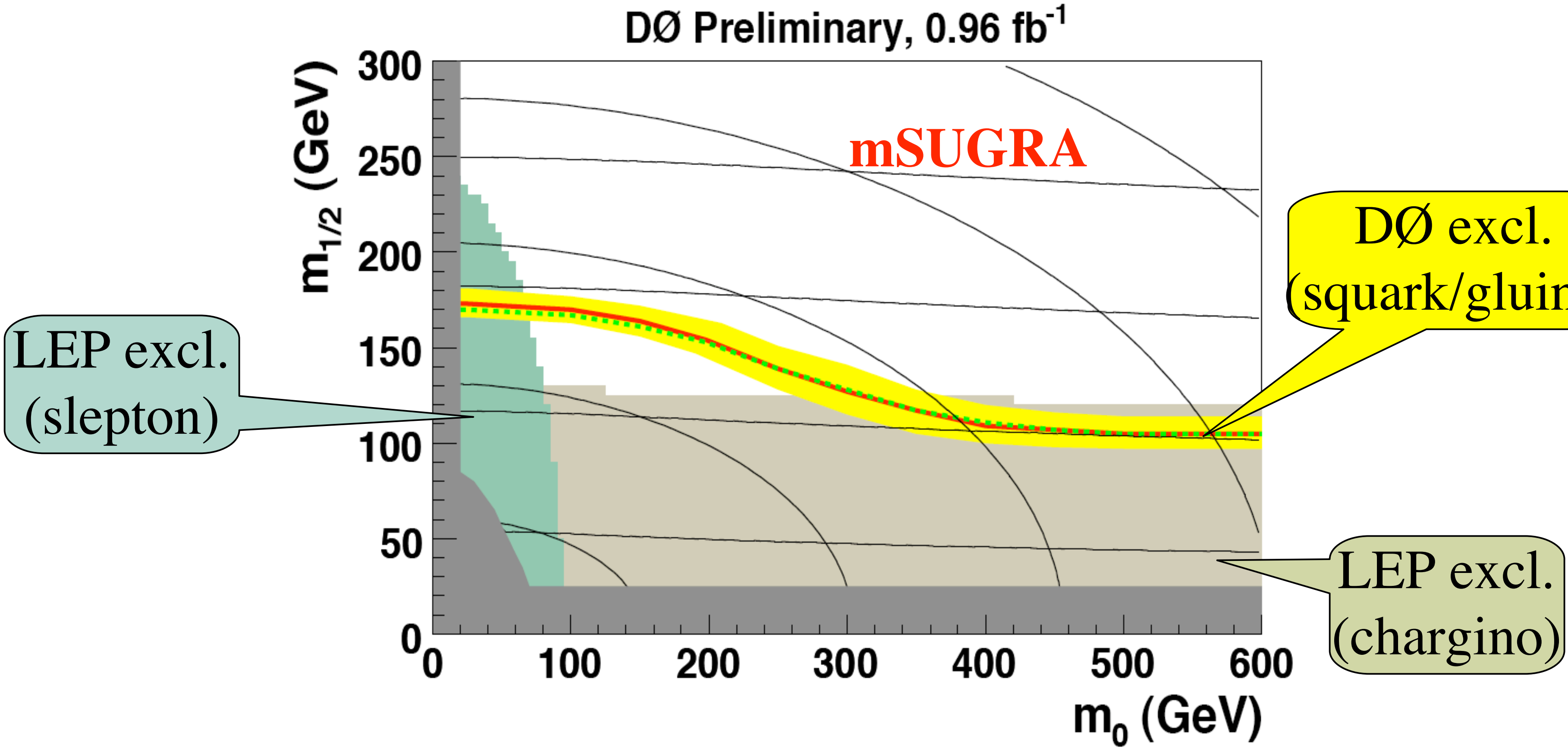
- No excess in data
  - Evaluate upper limit on cross section
  - Find out where it crosses with theory
- Theory has large uncertainty: ~30%
  - Crossing point with theory lower bound ~ represents limit on squark/gluino mass

Squark and Gluino Mass Limits

- No evidence for excess of events:
  - Excluding gluino masses
    - >280 GeV independently of squark masses
    - >400 GeV for m(q̃) ≈ m(g̃)
- Represented in this plane:
  - Rather small model dependence as long as there is R-parity violation
- Stop and sbottom quarks are excluded/negligible in analyses:
  - They introduce model dependence and are better looked for directly

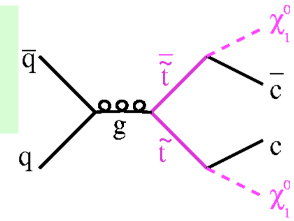


Exclusion of GUT scale parameters



- 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

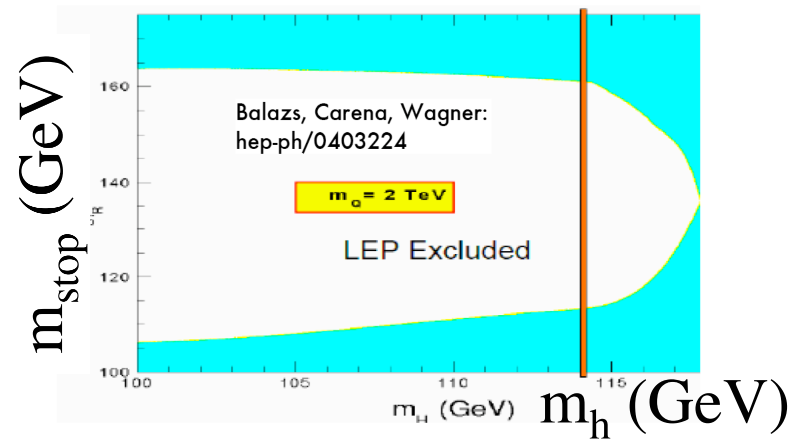
Third Generation Squarks



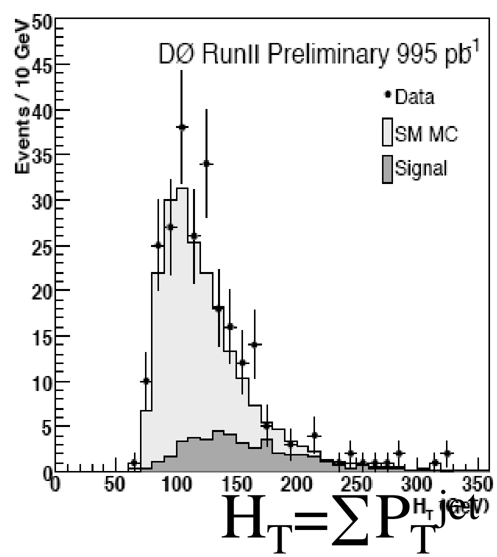
- The lightest q̃'s:

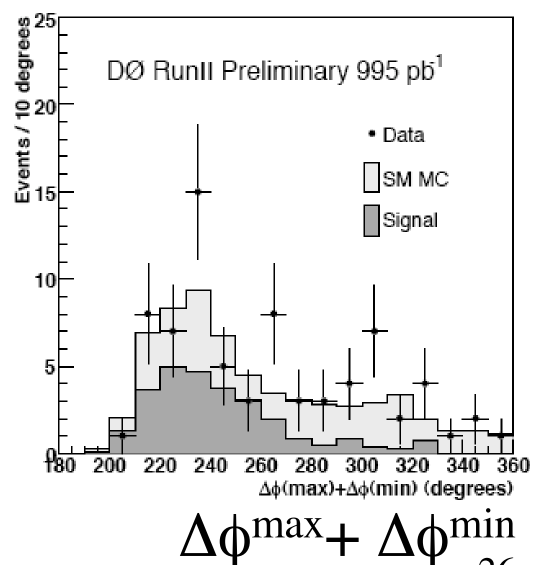
$$m^2_{\tilde{t}_{1,2}} = \frac{1}{2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}) \mp \frac{1}{2}\sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4m^2_t(A_t - \mu \tan\beta)^2}$$

  - Due to large SM top mass
- Dedicated searches for stop and sbottom:
  - $\tilde{t} \to c\tilde{\chi}^0_1$ and $\tilde{b} \to b\tilde{\chi}^0_1$
- Signature:
  - Two heavy flavor jets + large missing E_T

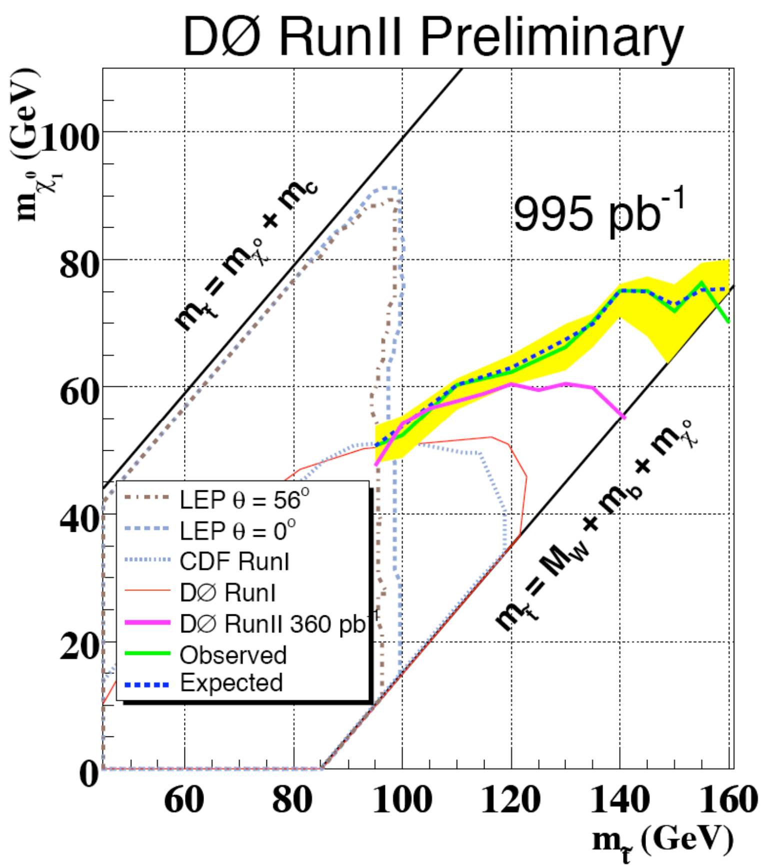


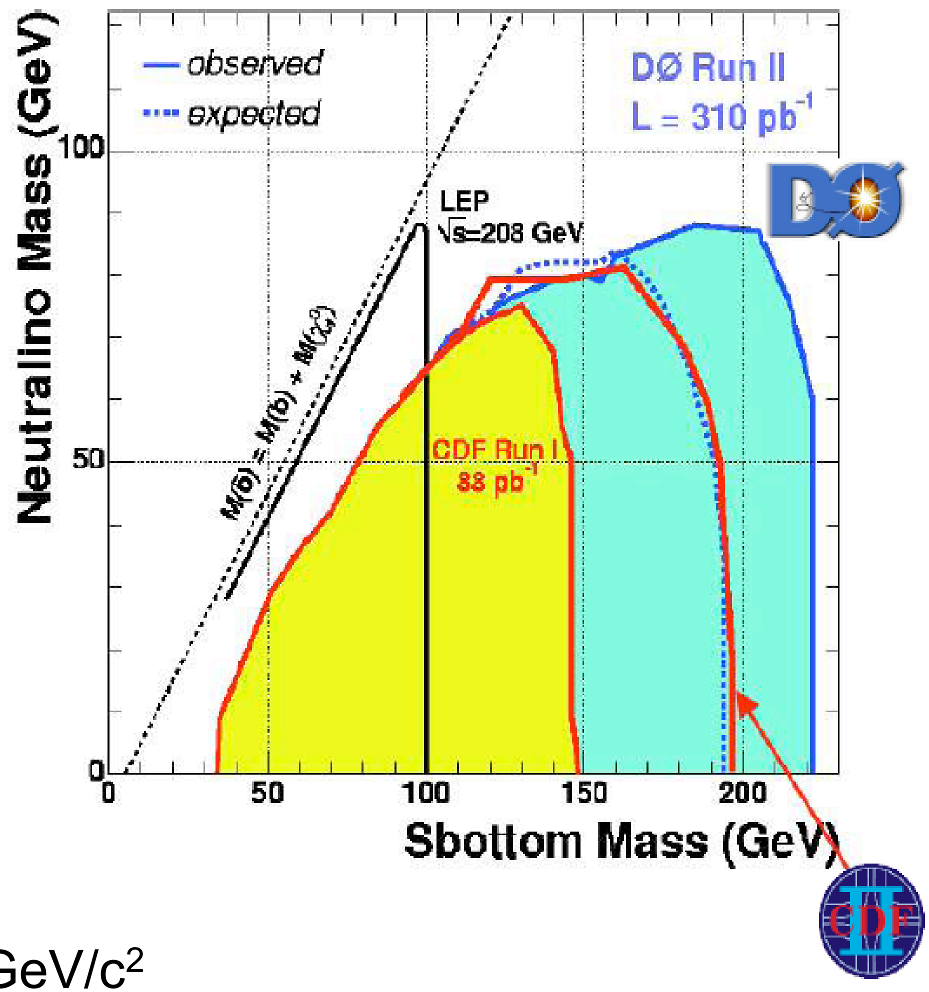
H_T	P	# observed	#Expected
> 100	< 260	83	$81.9 \pm 4.0^{+13.9}_{-14.1}$
> 140	< 300	57	$57.1 \pm 3.1^{+8.6}_{-8.6}$
> 140	< 320	66	$64.2 \pm 3.2^{+9.0}_{-9.1}$





Stop and Sbottom Mass Exclusion

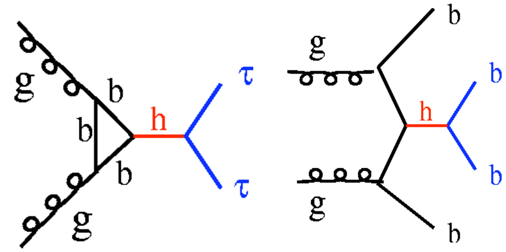




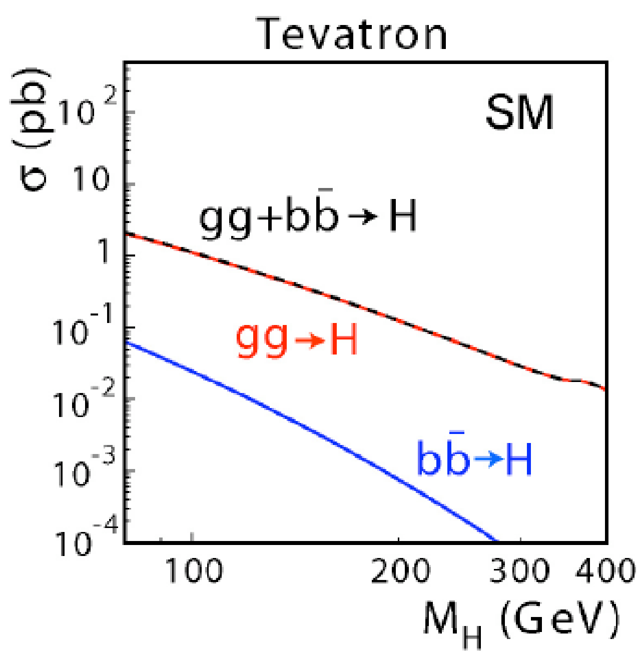
- Stop masses excluded up to 150 GeV/c^2
  - If $m(\tilde{t})-m(\tilde{\chi}^0_1)>60$ GeV/c^2
- Sbottom masses excluded up to 220 GeV/c^2
  - If $m(\tilde{\chi}^0_1)<80$ GeV/c^2

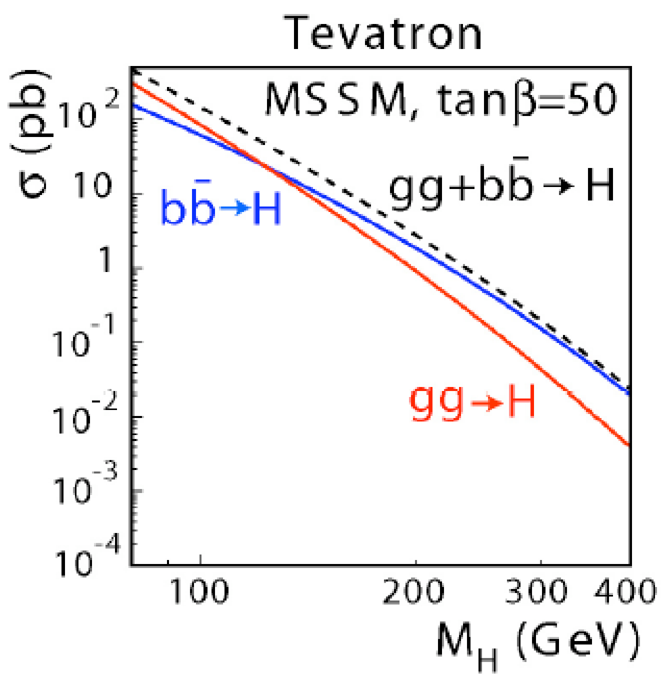
Higgs in the MSSM

- Minimal Supersymmetric Standard Model:
  - 2 Higgs-Fields: Parameter $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
- Neutral Higgs Boson:
  - Pseudoscalar A
  - Scalar H, h
    - Lightest Higgs (h) very similar to SM



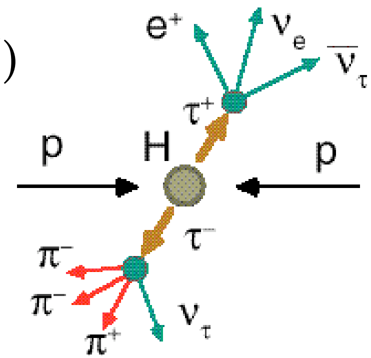
$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

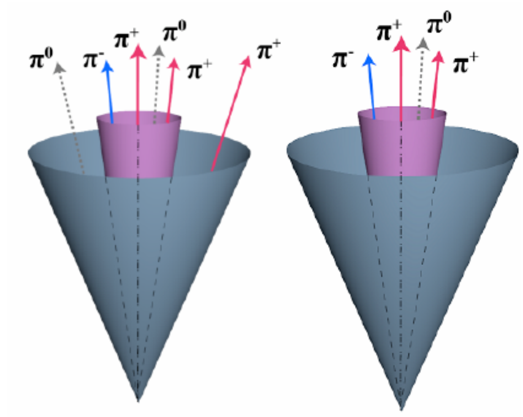


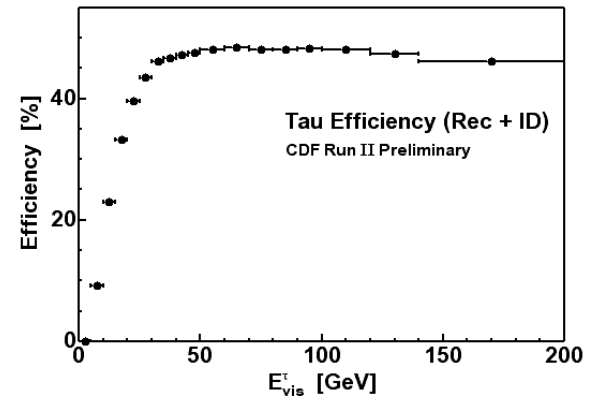


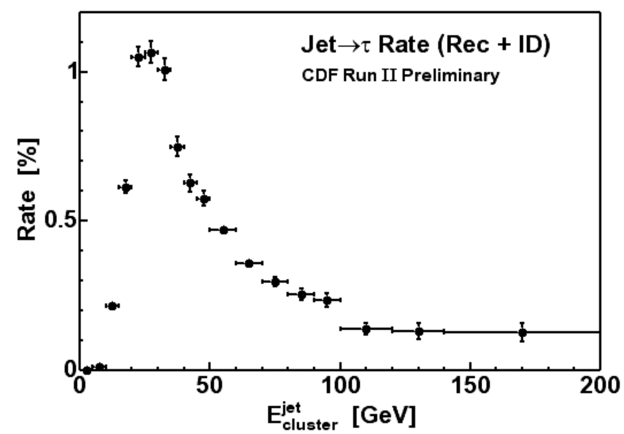
Heavy Object could couple mostly to τ's

- Maybe the third generation is special?
  - E.g. Higgs bosons couple to mass!
  - Search for Z' or Higgs boson decaying to two τ's
- Selection:
  - one electron or muon ("τ_e ,τ_μ ")
    - From leptonic tau-decay
  - one hadronic tau ("τ_h ")
    - From hadronic tau-decay
  - Both should be isolated
- Hadronic Tau ID:
  - Select 1- and 3-prong decays
  - Efficiency: ~20-50%
  - Jet fake rate: ~1-0.1%
    - 100-10 times higher than for electrons or muons!

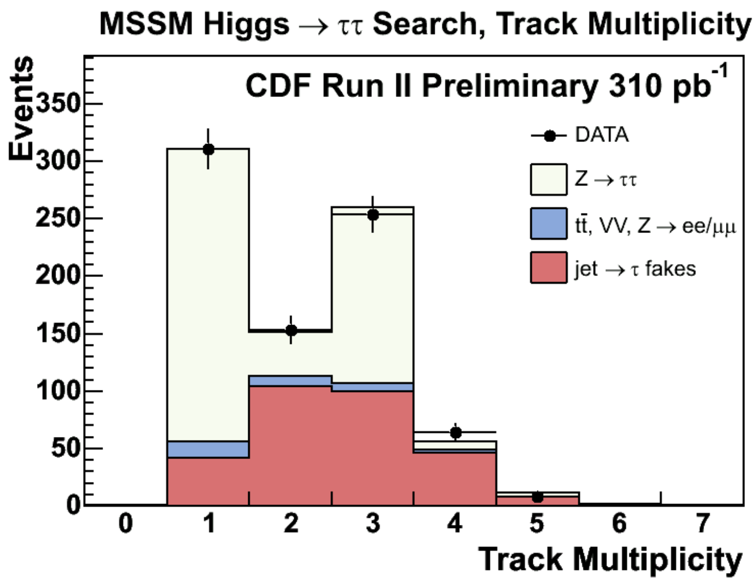


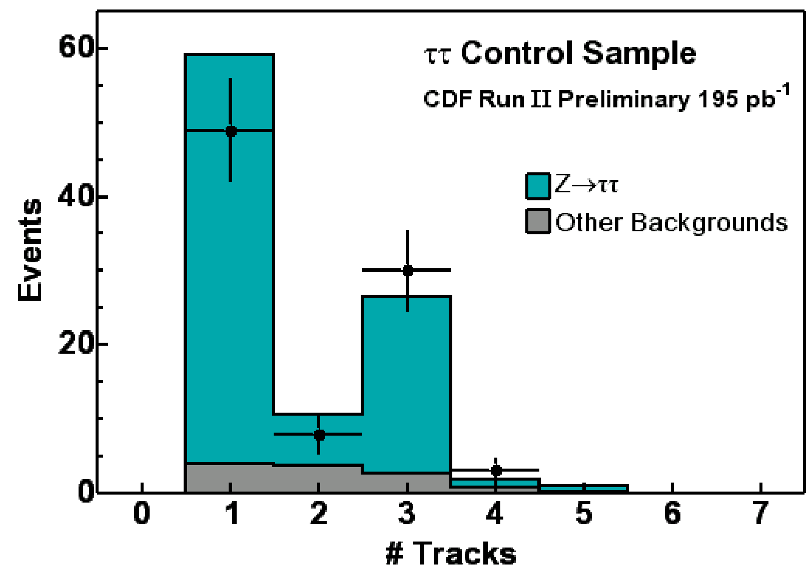




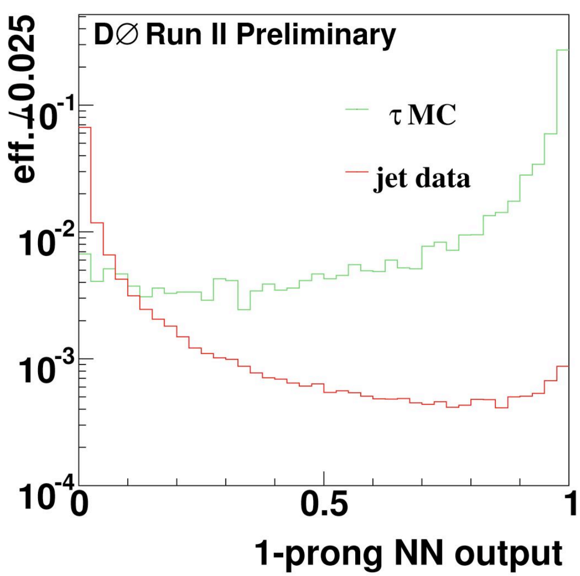


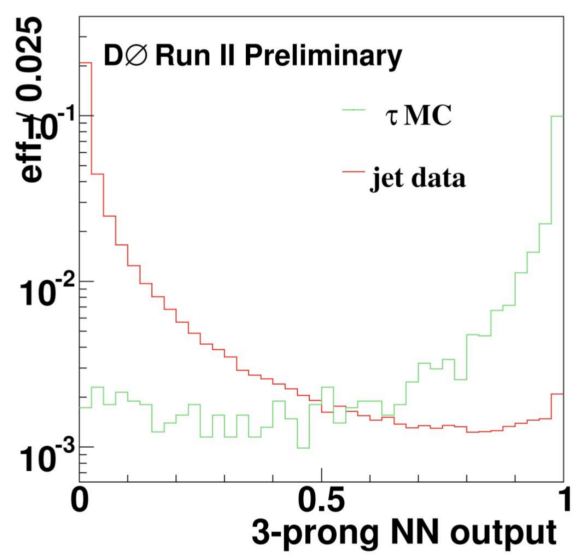
Tau Signals!



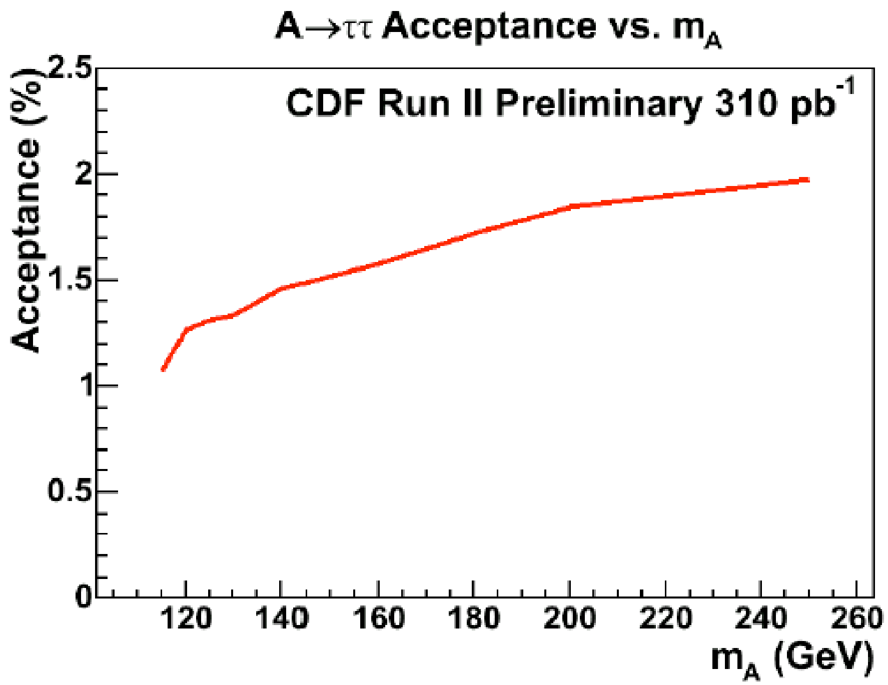


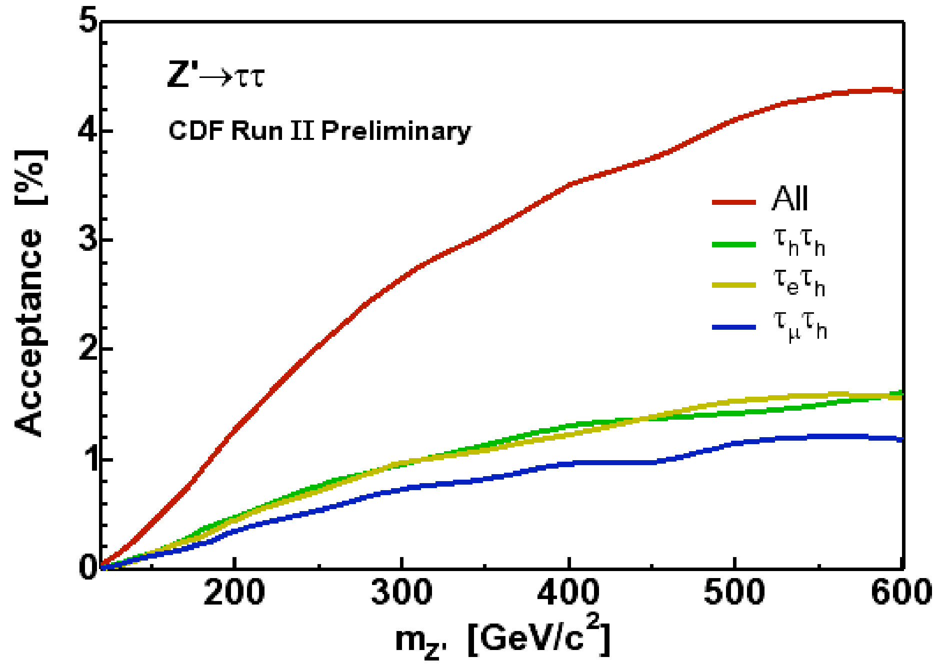
- Clear peaks at 1 and 3 tracks:
  - Typical tau signature
- DØ use separate Neural Nets for the two cases:
  - Very good separation of signal and background





Acceptance for di-tau events

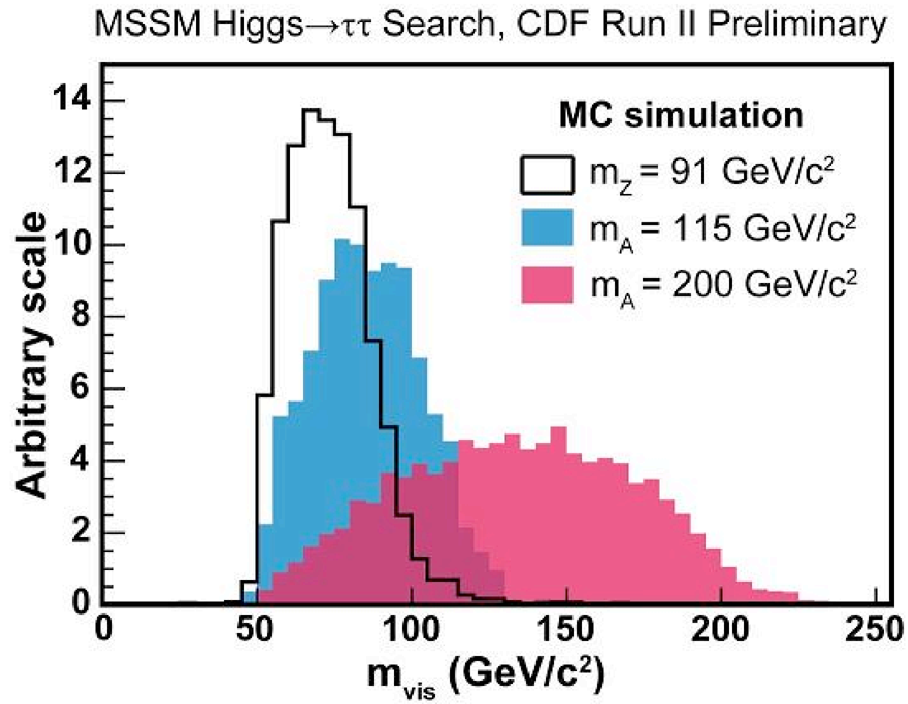




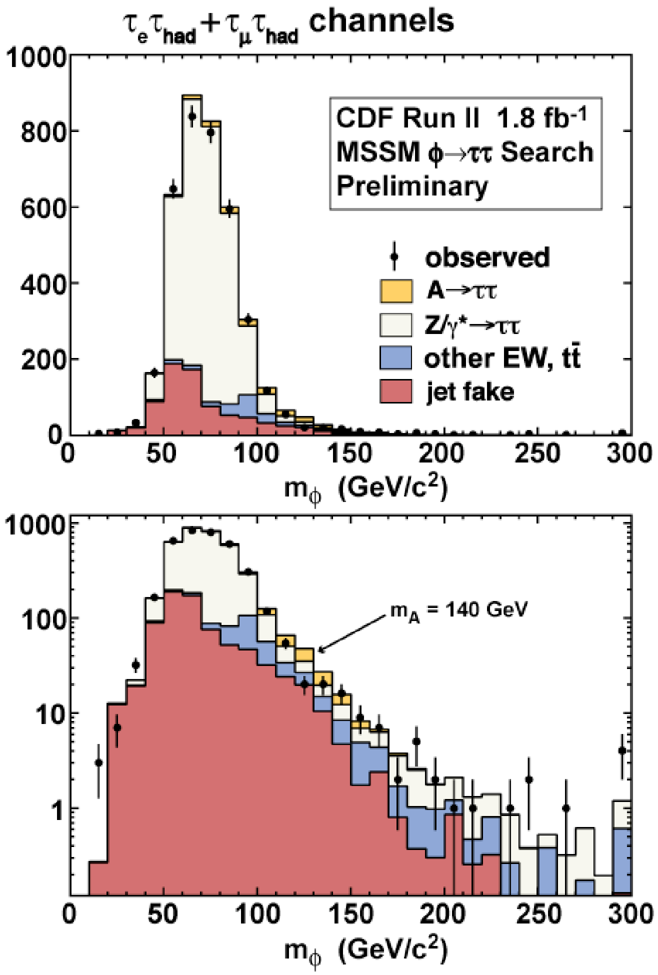
- Typical acceptance 1-4%
  - Factor 10 lower than for electrons and muons

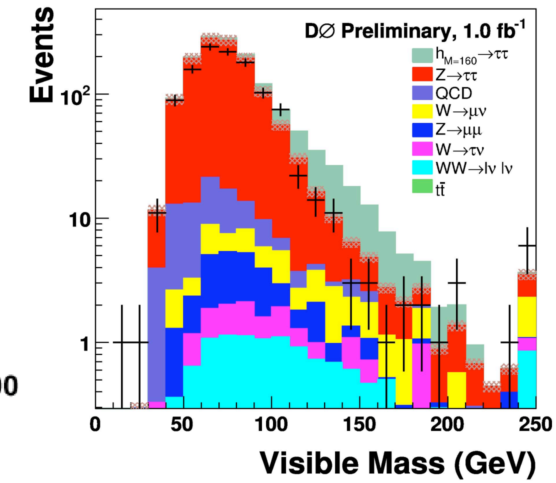
Di-tau Mass reconstruction

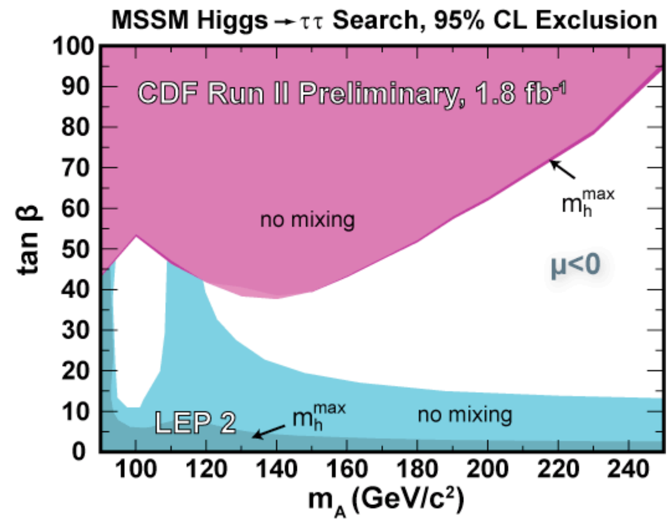
- Neutrinos from tau-decay escape:
  - No full mass reconstruction possible
- Use "visible mass":
  - Form mass like quantity: $m_{vis}=m(\tau, e/\mu, \not\!\!E_T)$
  - Good separation between signal and background
- Full mass reconstruction possible in boosted system, i.e. if $p_T(\tau, \tau)$>20 GeV:
  - Loose 90% of data statistics though!
  - Best is to use both methods in the future

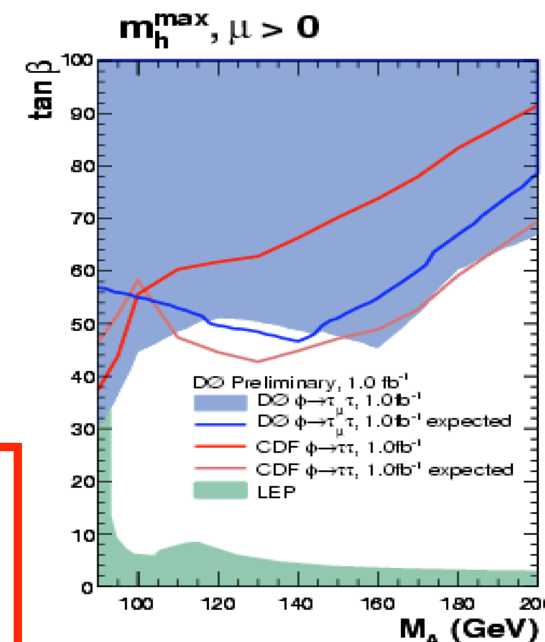


MSSM Higgs Boson Search Results



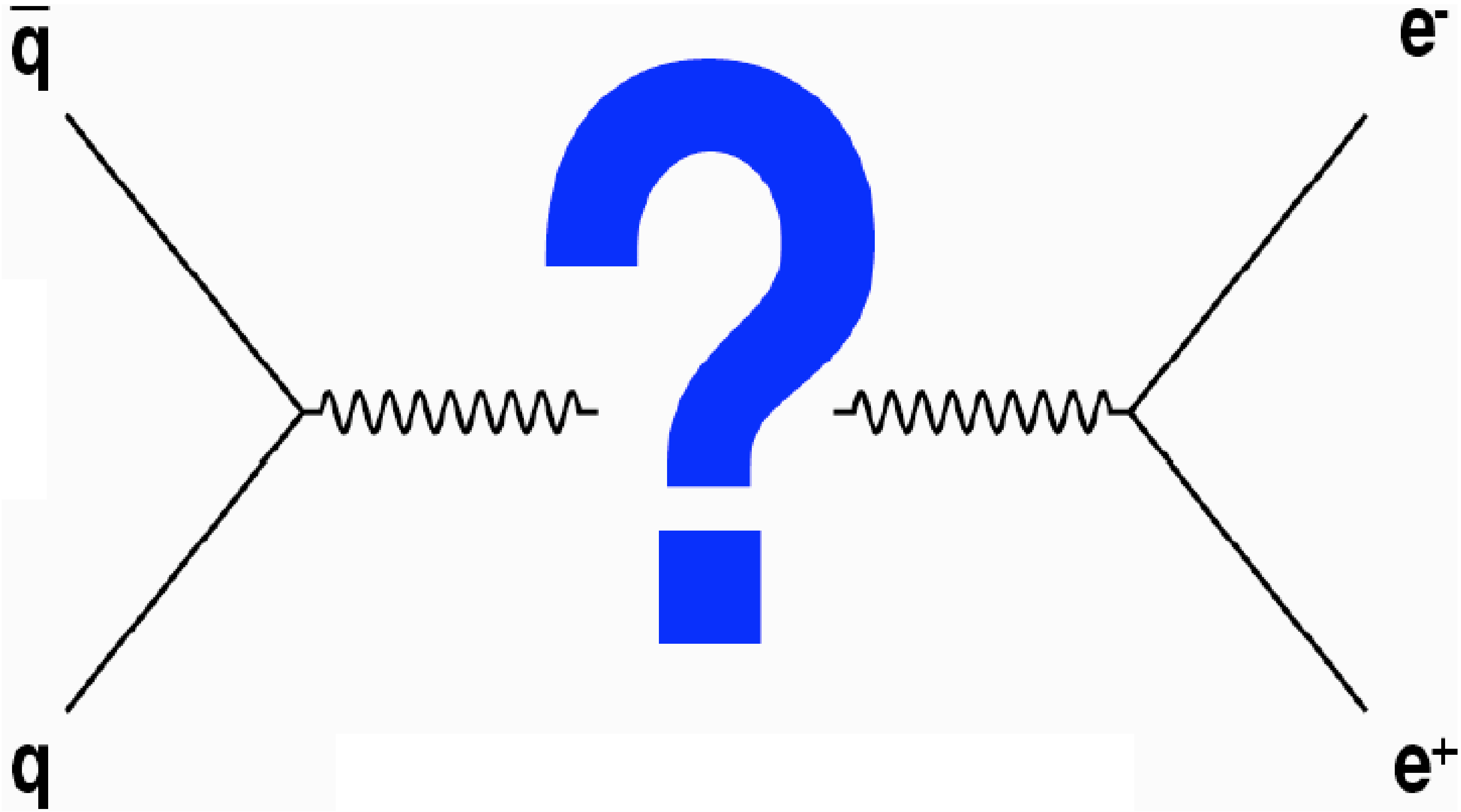






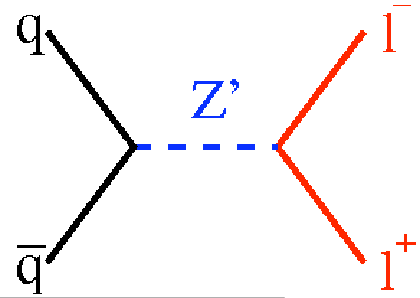
- Data mass distribution agrees with SM expectation
- Sensitive to tanβ≈50

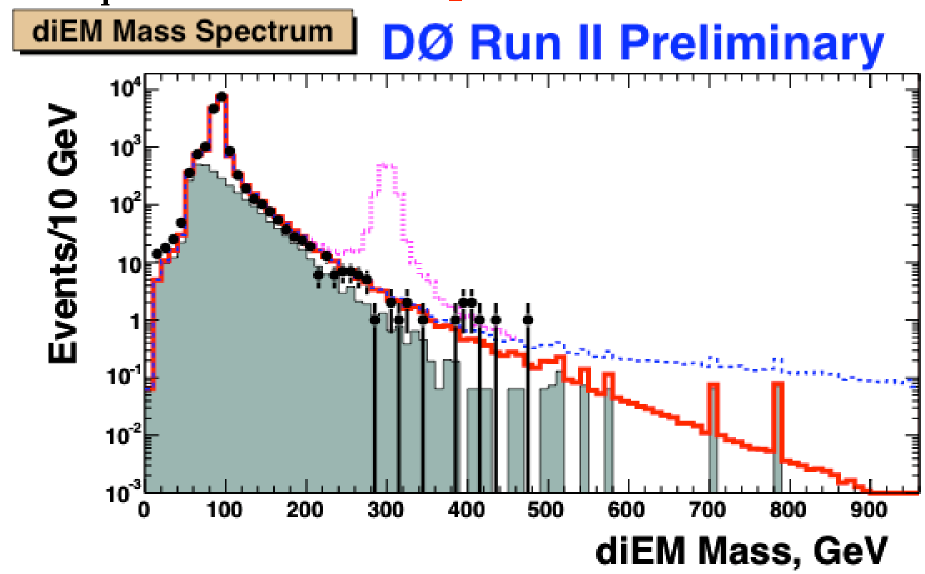
High Mass Resonances

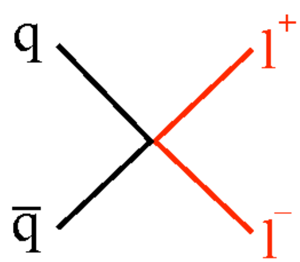


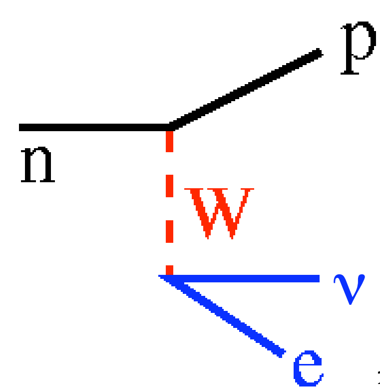
Resonances or Tails

- 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 (ADD model)
    - 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



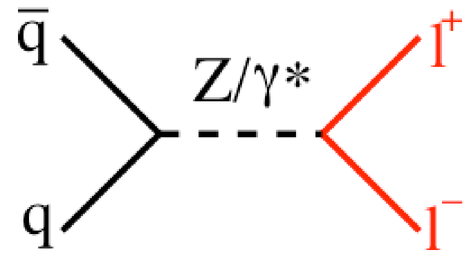


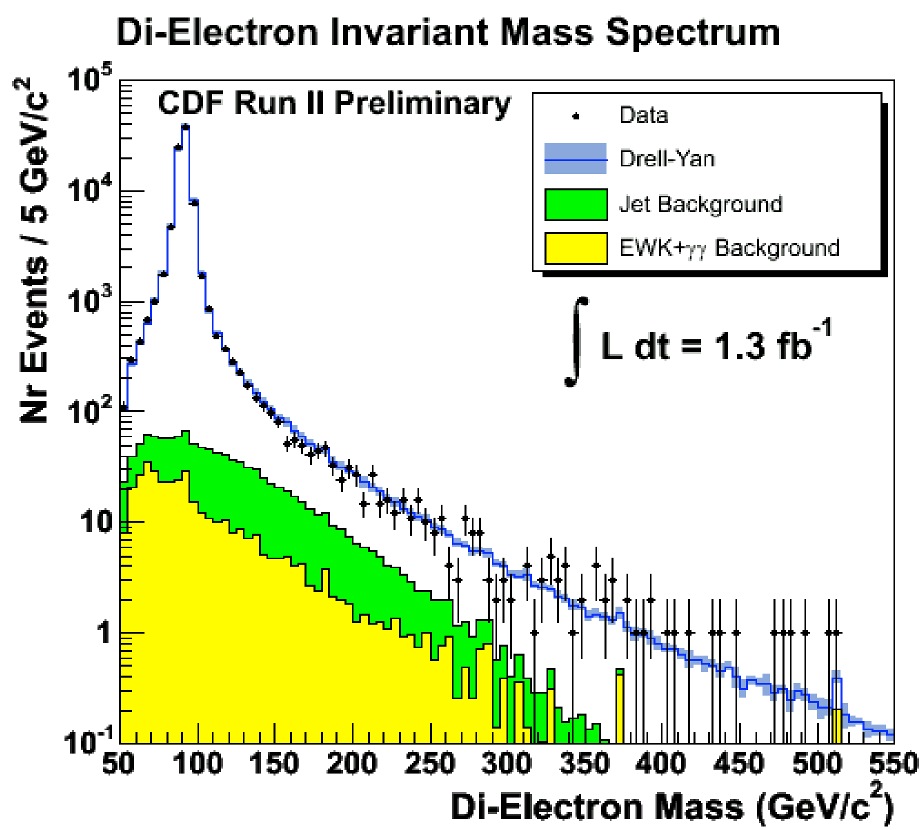




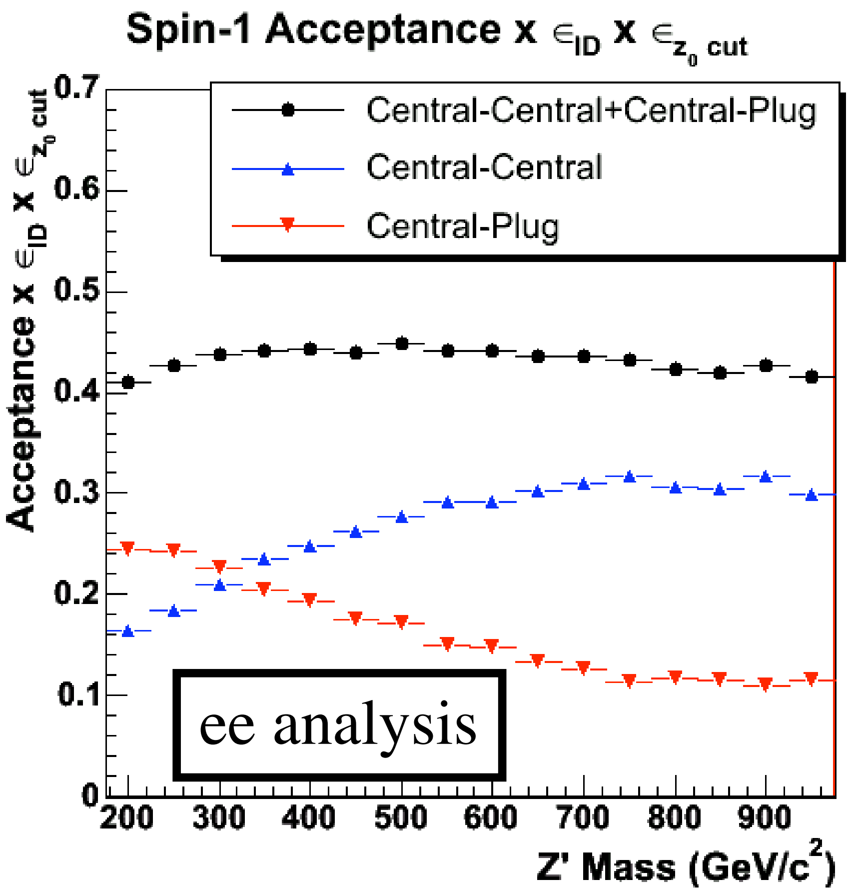
Dilepton Selection

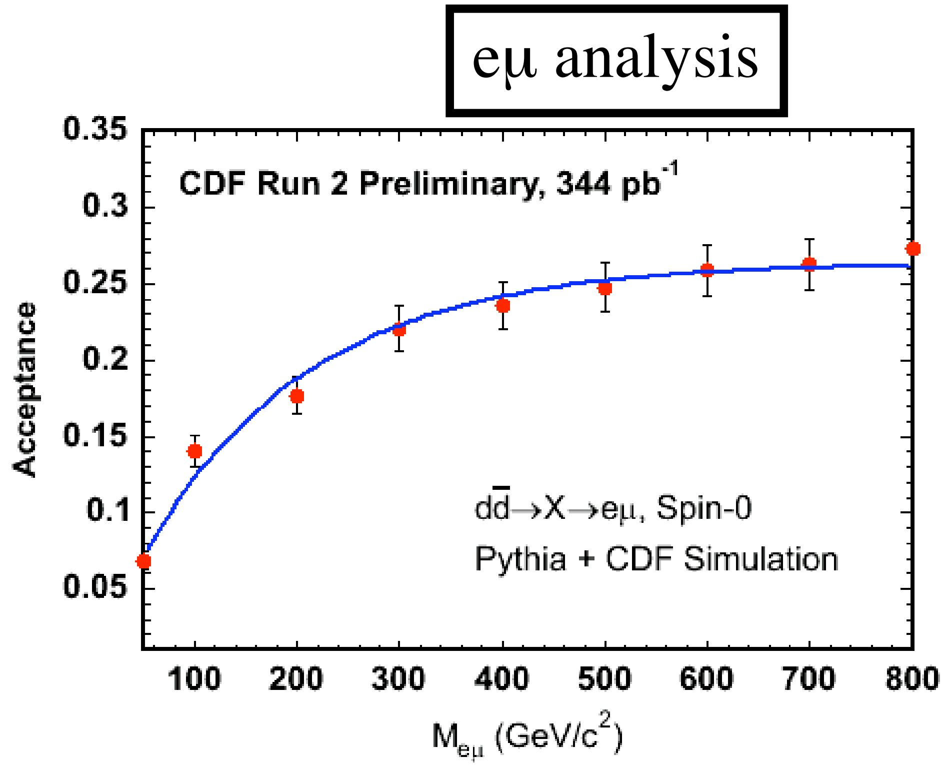
- Two high momentum leptons
  - irreducible background is Drell-Yan production
  - Other backgrounds:
    - Jets faking leptons: reject by making optimal lepton ID cuts
    - WW, diphoton, etc. very small
- Have searches for
  - Dielectrons
  - Dimuons
  - Ditaus
  - Electron+muon
    - flavor changing





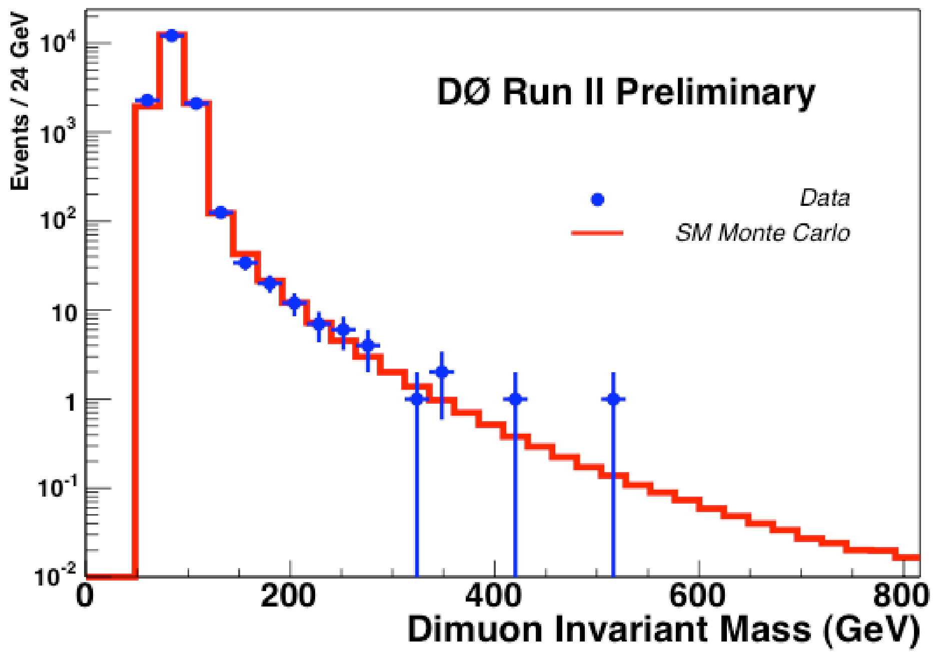
Dilepton Acceptance x Efficiency

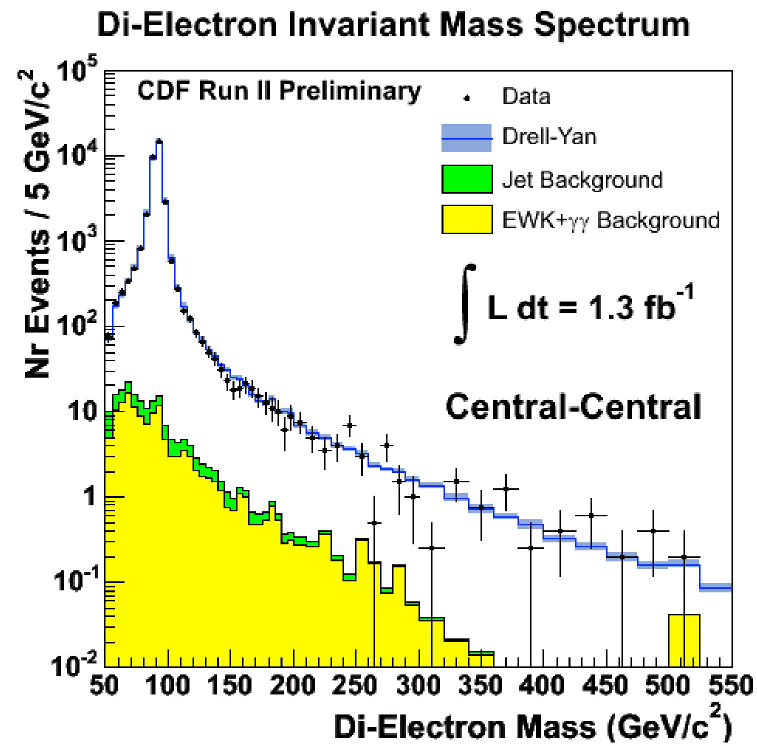




- Acceptance typically 20-40% for ee, μμ and eμ analyses

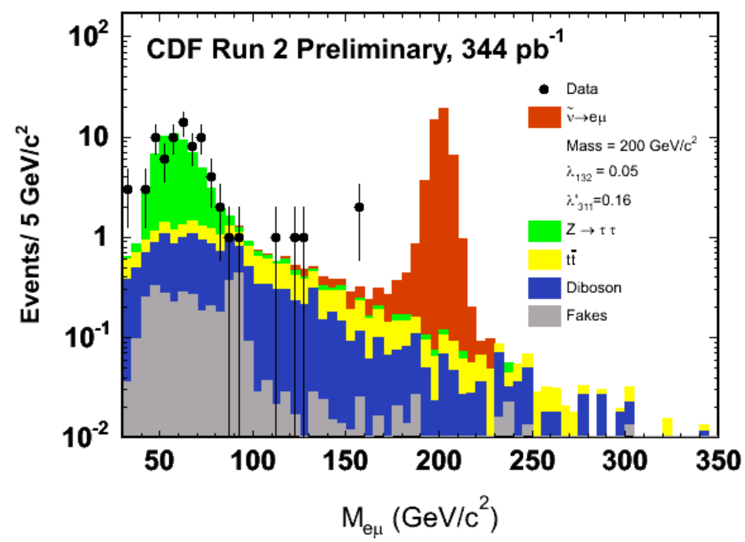
Neutral Spin-1 Bosons: Z’



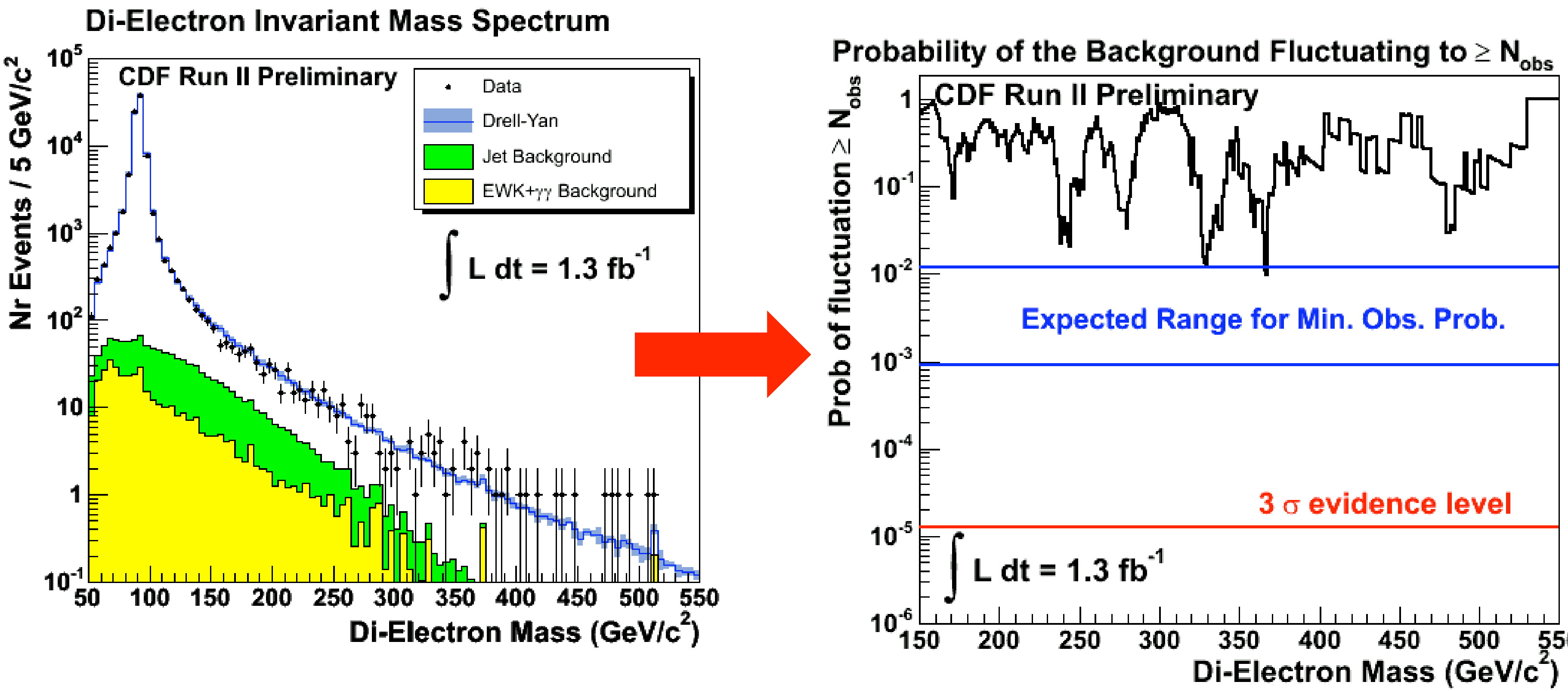


- 2 high P_T leptons: ee, μμ or eμ

- Data look like they agree well with background
  – Let’s evaluate this more closely!



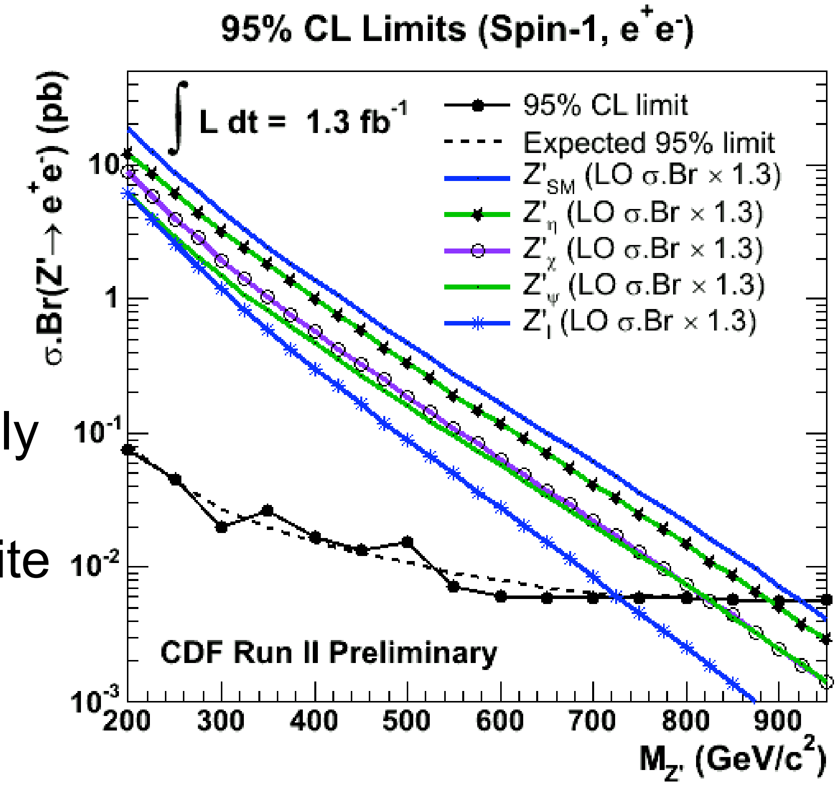
How consistent are the data with the SM?



- Calculate probability of data vs SM prediction at each mass:
  - Mass window size adapted to mass resolution (~3%)
- At 330 GeV the probability is only 1%!
  - But this happens very often when scanning over a large mass range
    - 10^{-5} would correspond to 3σ evidence

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
    - This is model independent, i.e. really what we measure
    - Any theorist can overlay their favorite curve
    - It remains valid independent of changes in theory
    - Always publish this!
  - can also set limits on Z' mass within certain models
    - This is model dependent
    - Nice though for comparing experiments, e.g. LEP vs Tevatron



For SM couplings:

	$Z' \rightarrow ee$	$Z' \rightarrow \mu\mu$
limit	>923 GeV	>735 GeV

Conclusions: Lecture IV

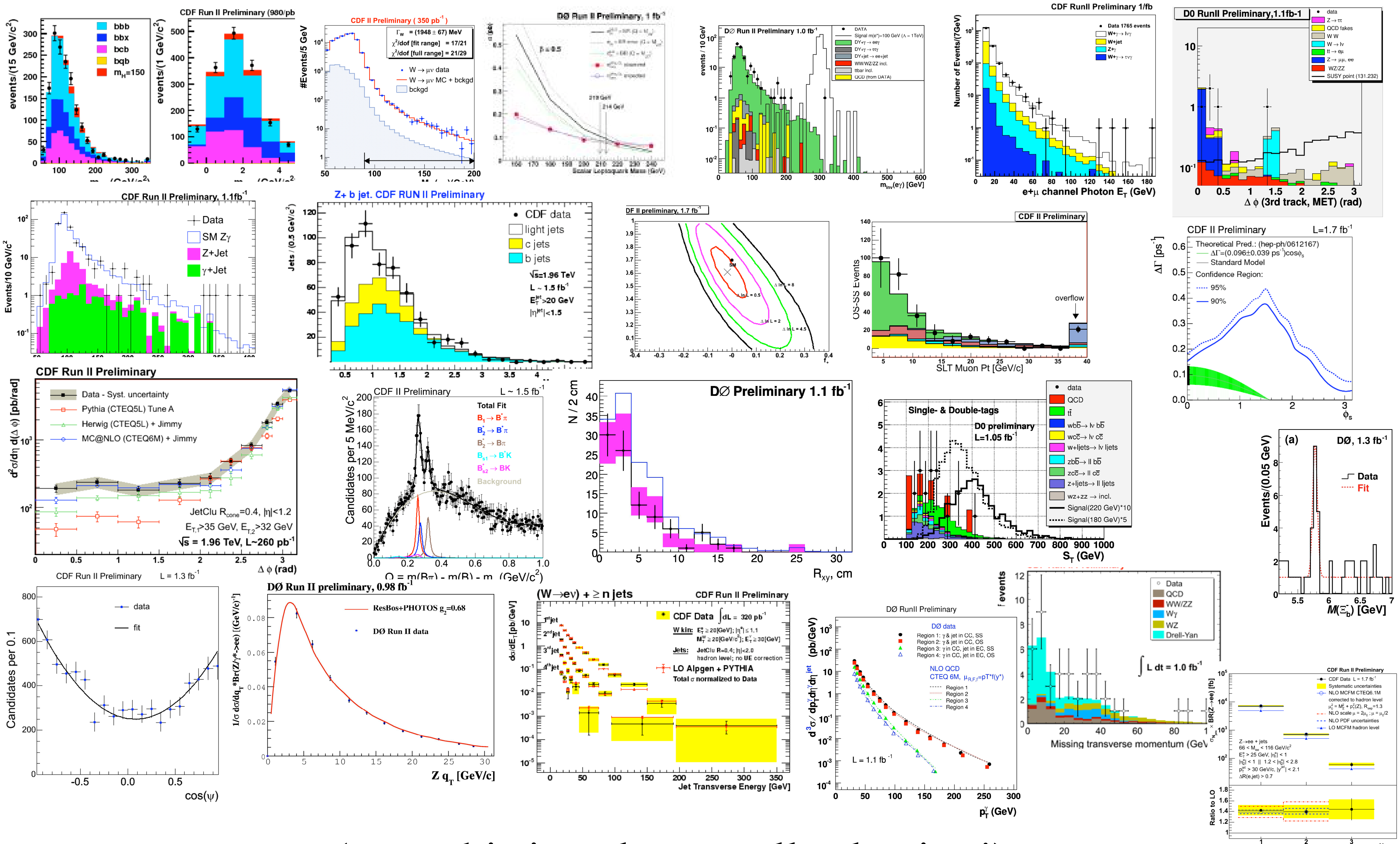
- Searches for Physics Beyond the Standard Model are extremely important
  - This can revolutionize our subject and solve many (or at least a few) questions
- I showed you:
  - Squarks and Gluinos:
    - Best to optimize for physical mass regions at electroweak scale
  - High mass resonances: Z’ and MSSM Higgs
- Most analyses done blindly
  - Avoid experimental bias
  - You get to have an exciting day!
  - Blind analysis does not mean “not looking at the data”
    - Look at data all the time in background dominated regions
- Not found any new physics (yet)
  - Tevatron ever improving and LHC coming soon!

Overall Conclusions

- The Tevatron physics program is very rich:
  - Probing the electroweak, the strong, the flavor sector of the Standard Model and looking for the unknown
  - Possible due to excellent detector and trigger capabilities
- The Tevatron is operating at the highest energies
  - And it is operating very well now: 3.1 fb^{-1} delivered
  - A hadron collider environment is challenging but doable!
- There is a lot I could not show you, see also
  - http://www-cdf.fnal.gov/physics/physics.html
  - http://www-d0.fnal.gov/Run2Physics/WWW/results.html

All the best to all of us for finding (spectacular) physics beyond the Standard Model in either precision measurements or in direct searches

And so many more beautiful measurements I could not show you…!



(even this is only a small selection!)