Physics Landscape

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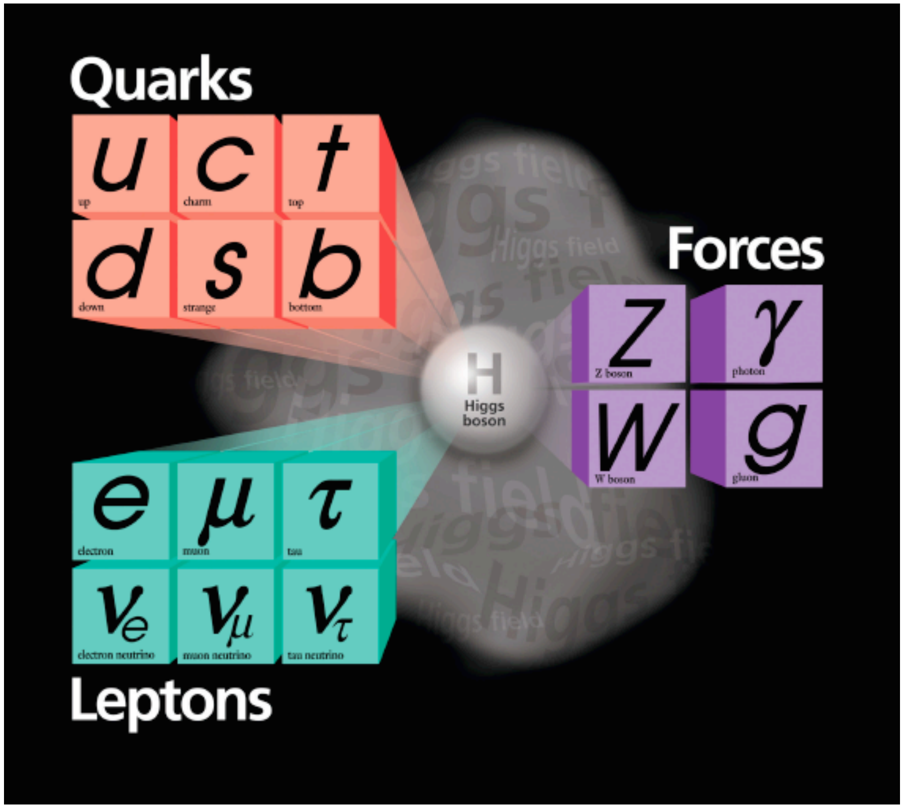
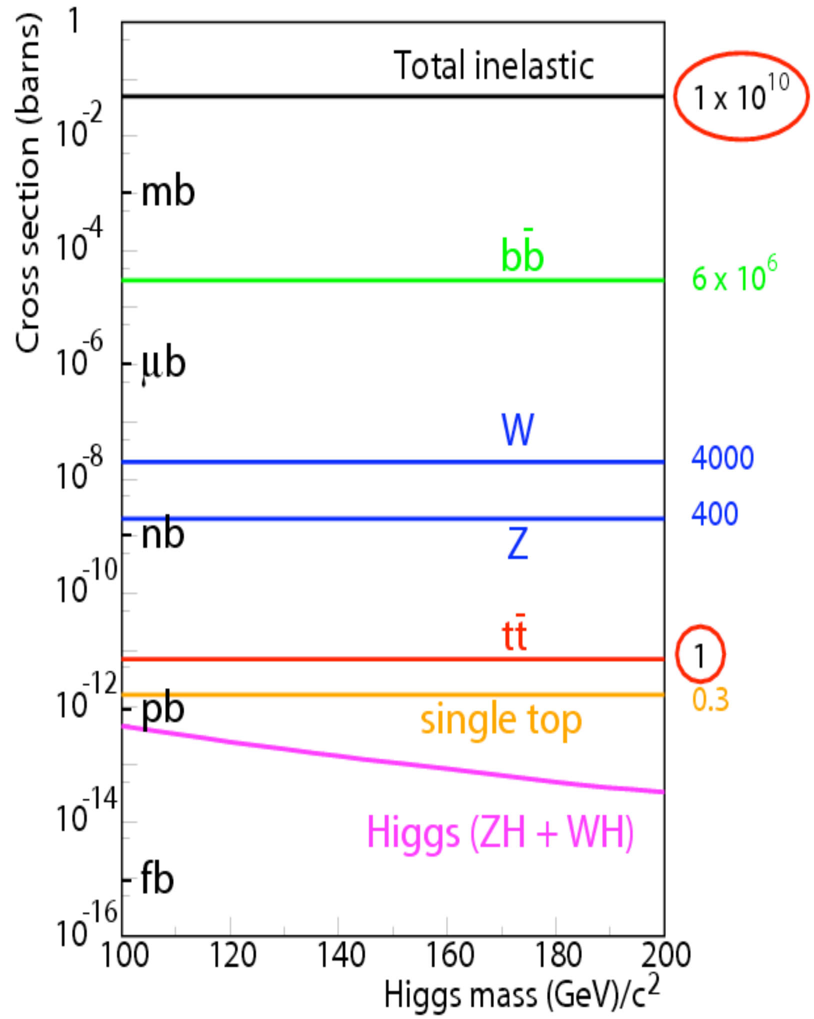
The Standard Model and the Questions Hadron Colliders can (maybe) answer



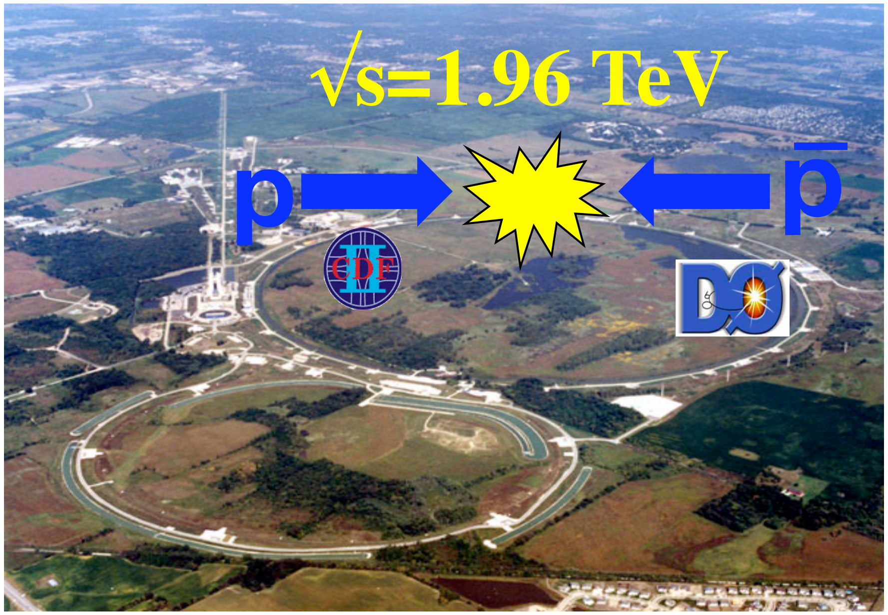
- Is **QCD** describing the data at highest energies?
  - Are the calculations adequate?
- What is the origin of **electroweak symmetry breaking**?
  - Is there a Higgs boson?
- Is the CKM matrix the only source of **CP violation**?
- What is the **Dark Matter**?
  - Is it produced it at colliders?
- Are there **new dimensions of space**?
  - Or e.g. extended gauge sectors, leptoquarks,…?
- Is there **anything that no one has thought of**?

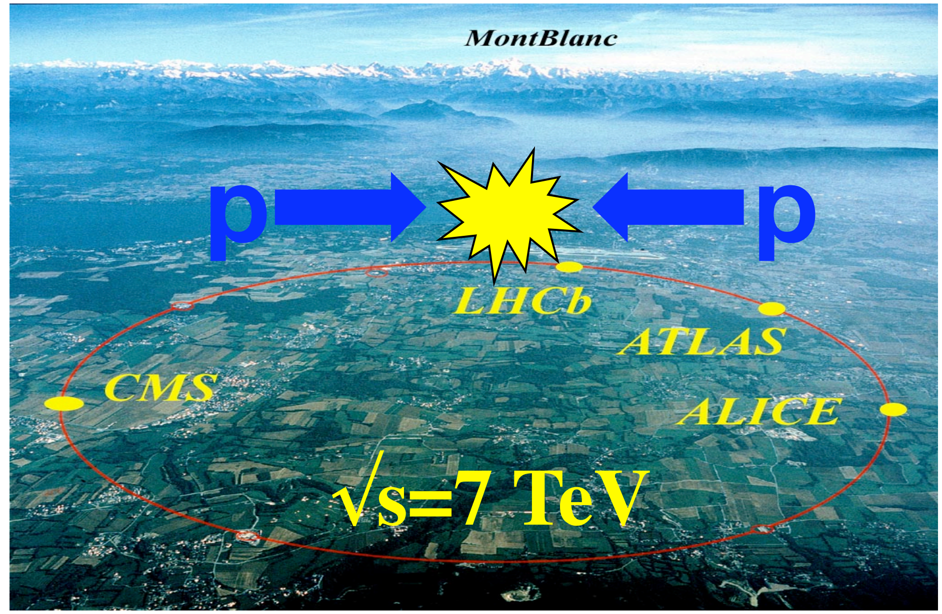
Outline

- **Testing Particle Production**
  - Jets, W's and Z's, top quarks
- **Electroweak Symmetry Breaking**
  - W boson mass
  - Top quark mass
  - Higgs boson search
- **Beyond the Standard Model**
  - Supersymmetry
  - Beyond SUSY
- **Conclusions**



Tevatron and LHC





- **Tevatron:**
  - pp collider operating since 1985, “Run 2” since 2001
  - $\sqrt{s}$=1.96 TeV, dataset collected 9 fb^{-1}
- **LHC:**
  - pp collider operating since March 2010 at high energy
  - $\sqrt{s}$=7 TeV, dataset collected 6.5 pb^{-1}

Production of Particles

Luminosity and Cross Sections

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p N_{\bar{p}}}{4\pi\, \sigma_x\, \sigma_y}$$

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

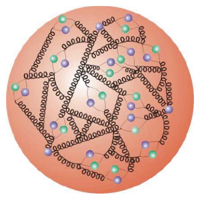
Efficiency: optimized by experimentalist

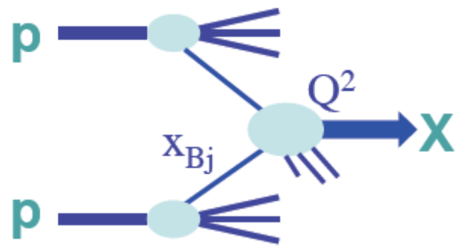
Cross section σ: Given by Nature (calc. by theorists)

Luminosity Uncertainty: 6% (Tevatron), 11% (LHC)

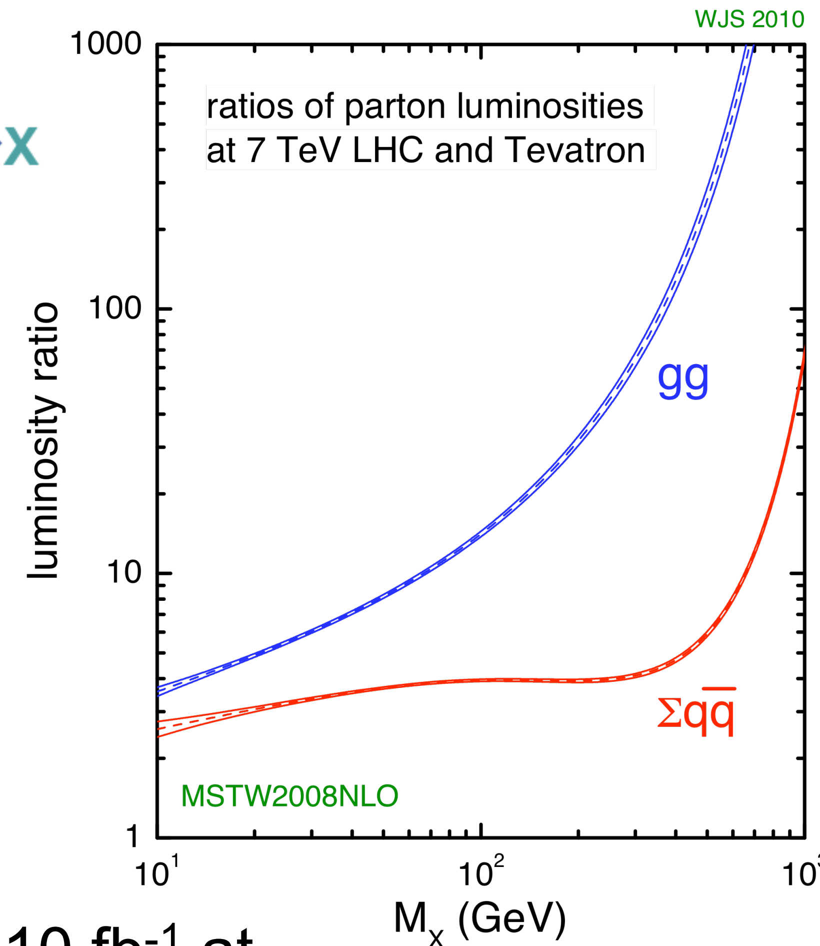
Physics Cross Sections

$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$



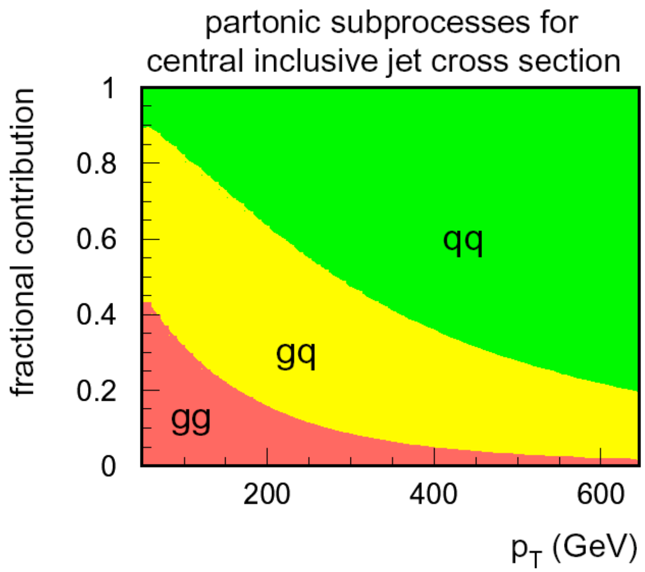


Process	M_X	σ(LHC @ 7 TeV) / σ(Tevatron)
$q\bar{q} \to W$	80 GeV	3
$q\bar{q} \to Z'_{SM}$	1 TeV	50
$gg \to H$	120 GeV	20
$q\bar{q}/gg \to t\bar{t}$	2x173 GeV	15
$gg \to \tilde{g}\tilde{g}$	2x400 GeV	1000

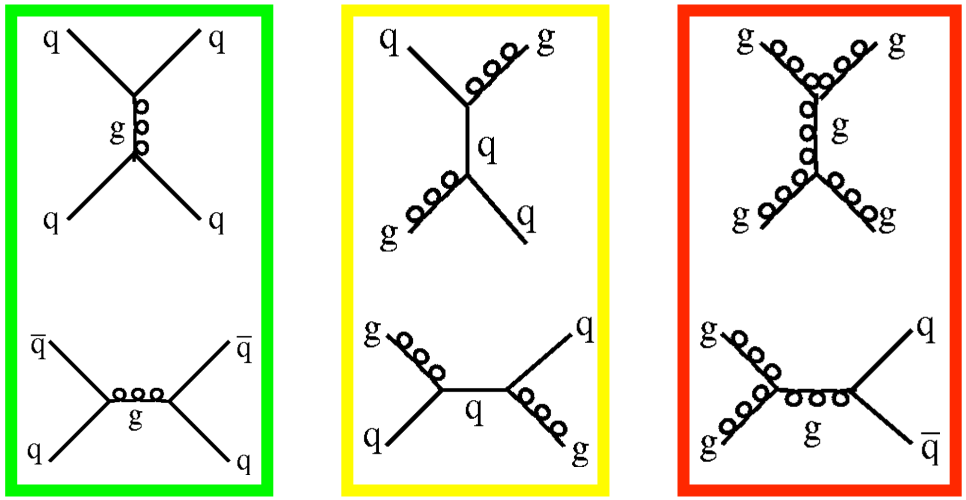


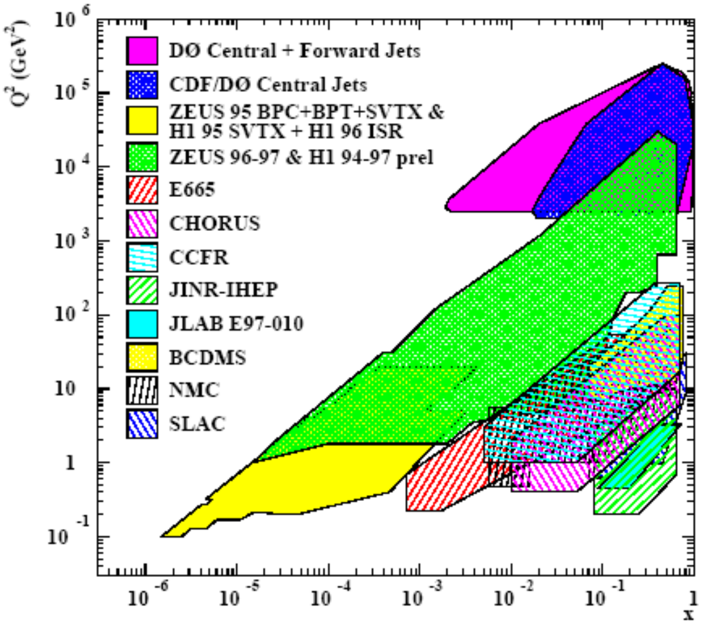
- $\int Ldt = 1\ fb^{-1}$ at LHC competitive with $10\ fb^{-1}$ at Tevatron for high mass processes
- $\int Ldt = 100\ pb^{-1}$ already interesting in some cases

Jet Cross Sections



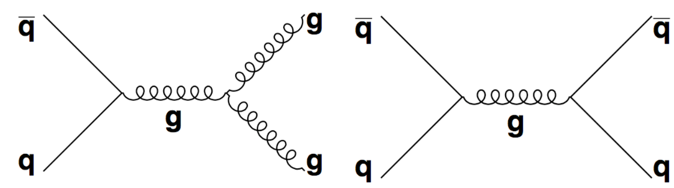
- Inclusive jets: processes qq, qg, gg

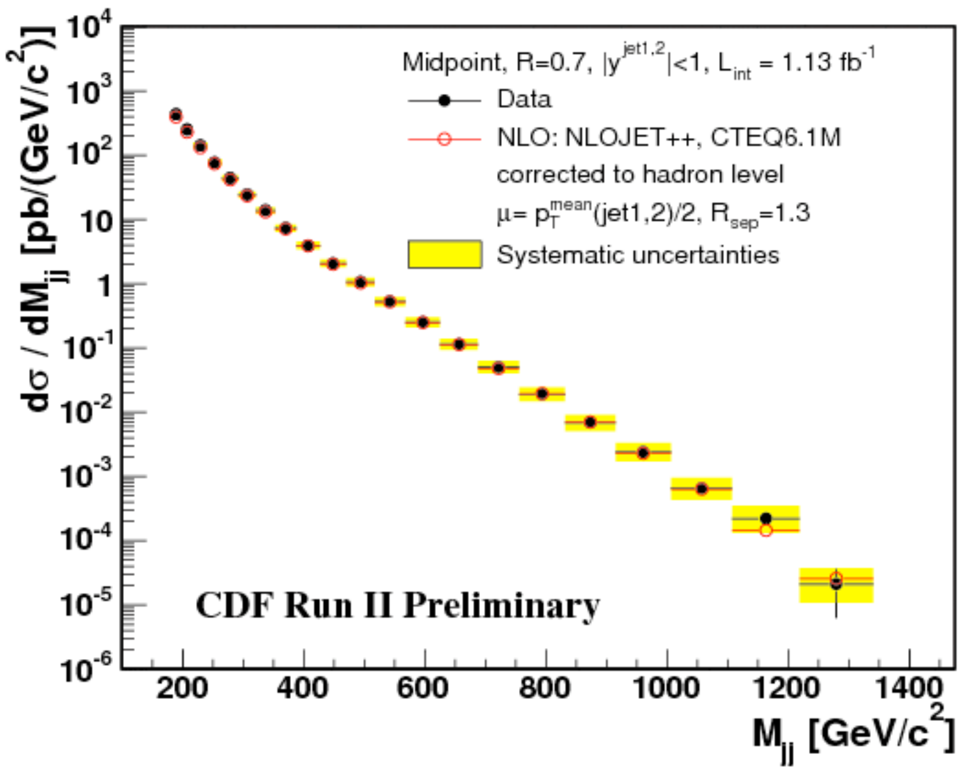


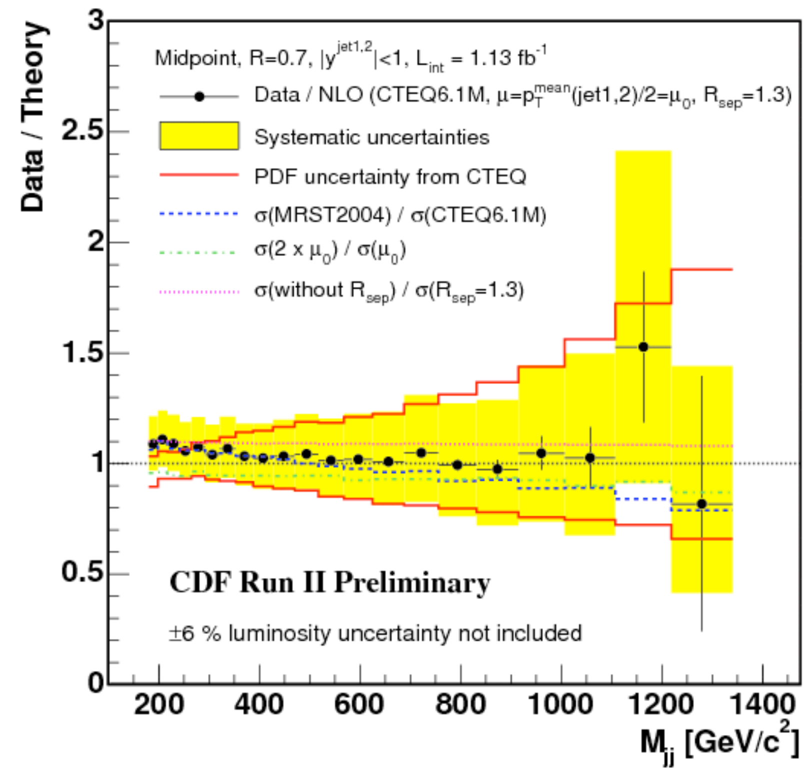


- Highest E_T probes shortest distances
  - Tevatron: $r_q < 10^{-18}$ m
- Tests perturbative QCD at highest energies
- Also sensitive to new physics creating dijet resonance

Jet Cross Sections

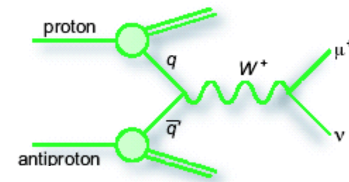


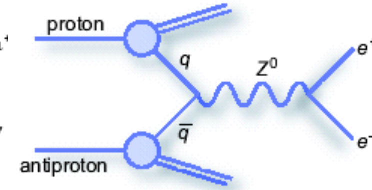




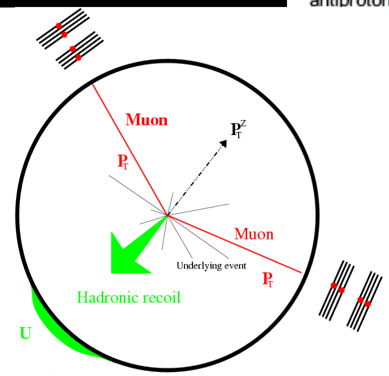
- Cross section measured over 7 orders of magnitude
- Data well described by Standard Model prediction up to masses of 1.3 TeV

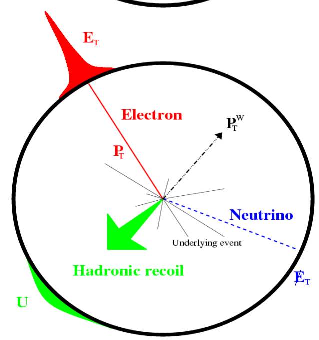
W and Z Bosons

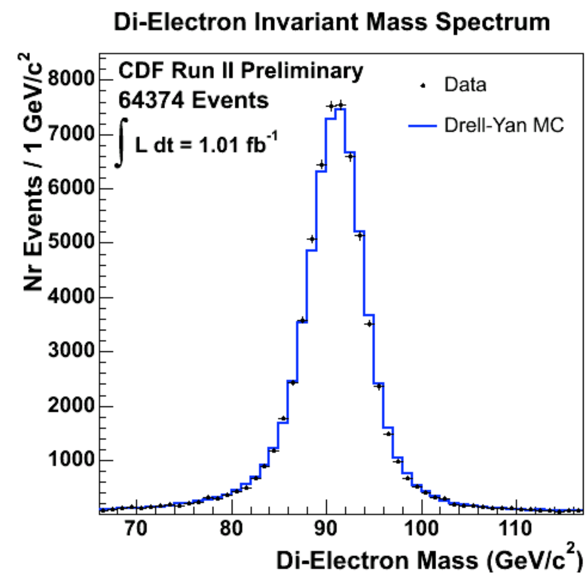


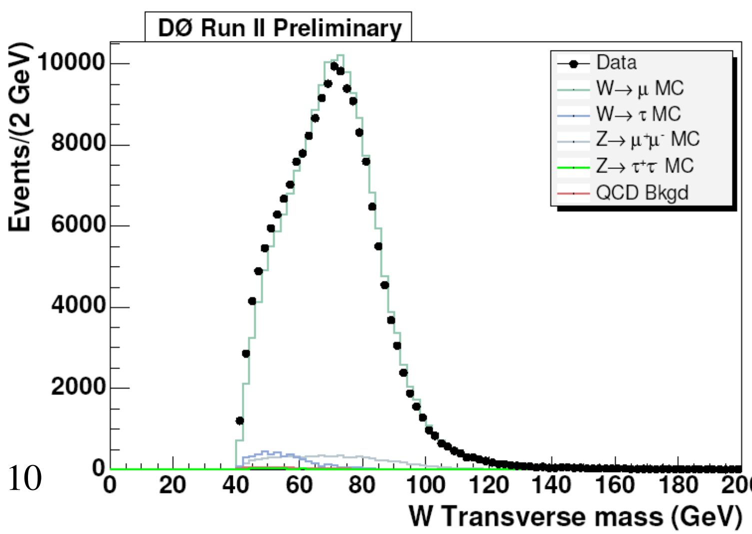


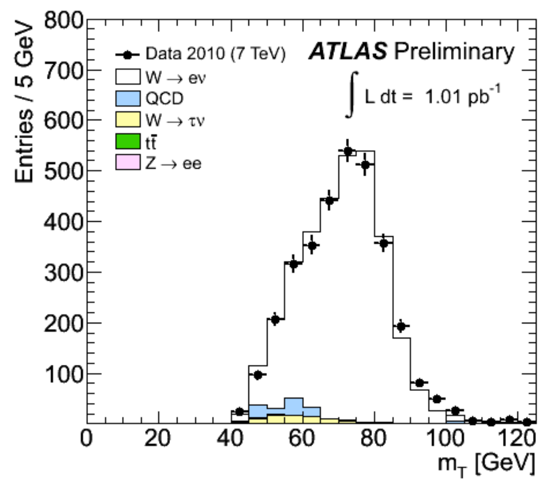
- Selection:
  - **Z:**
    - Two leptons p_T>20 GeV
      - electron, muon, tau
  - **W:**
    - One lepton p_T>20 GeV
    - Large imbalance in transverse momentum
      - Missing E_T>20 GeV
      - Signature of undetected particle (neutrino)

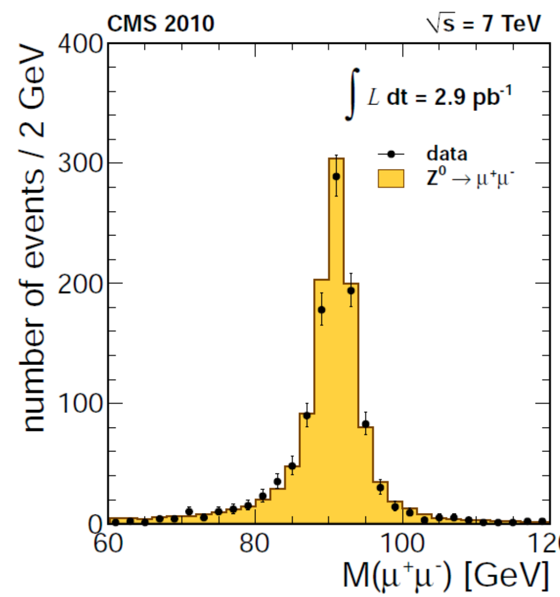






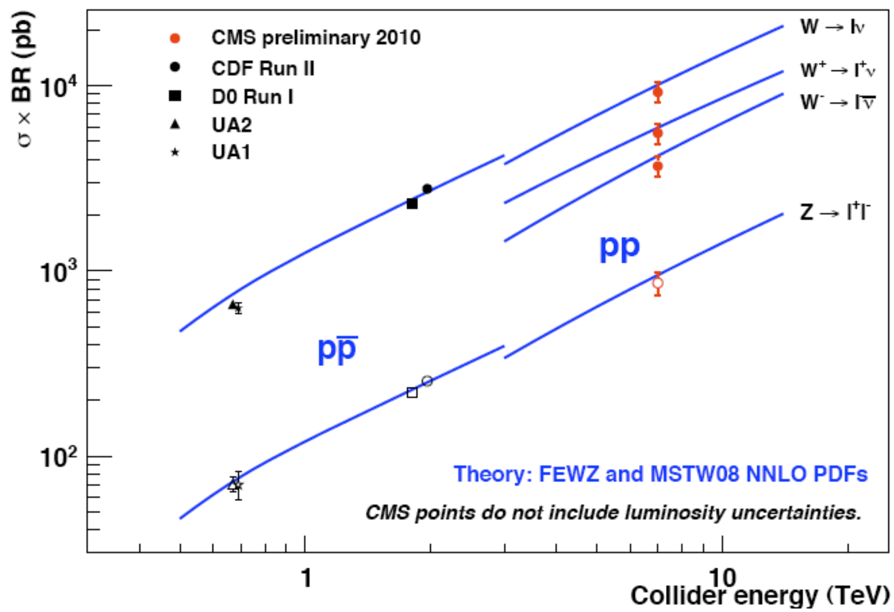


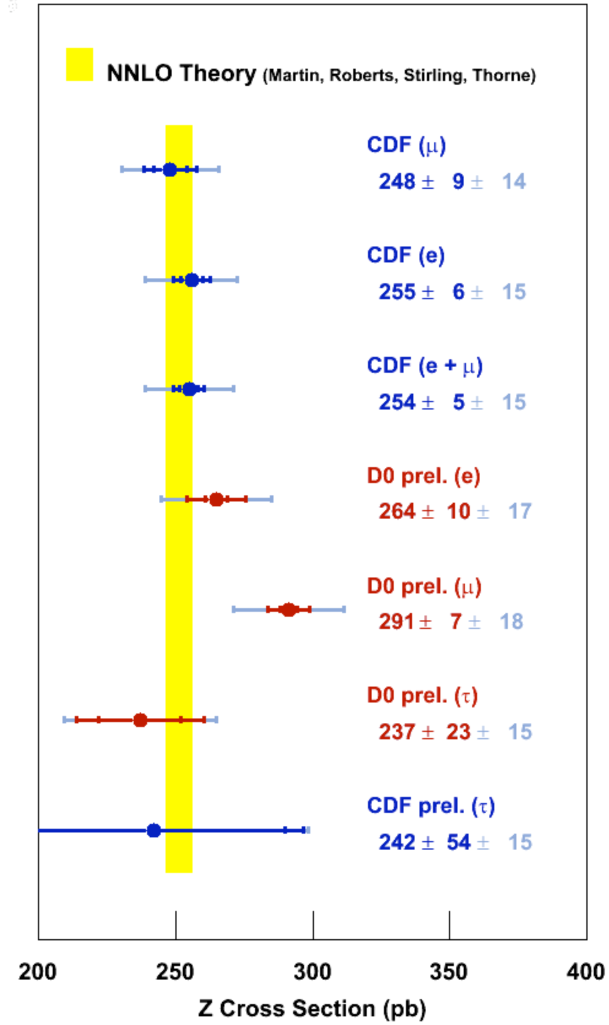




W and Z production

- Tevatron
  - Data precision: 6% (lumi) , 2% (syst.+stat.)
  - Theory precision (NNLO QCD): 2%
- LHC
  - Initial results also agree with theory

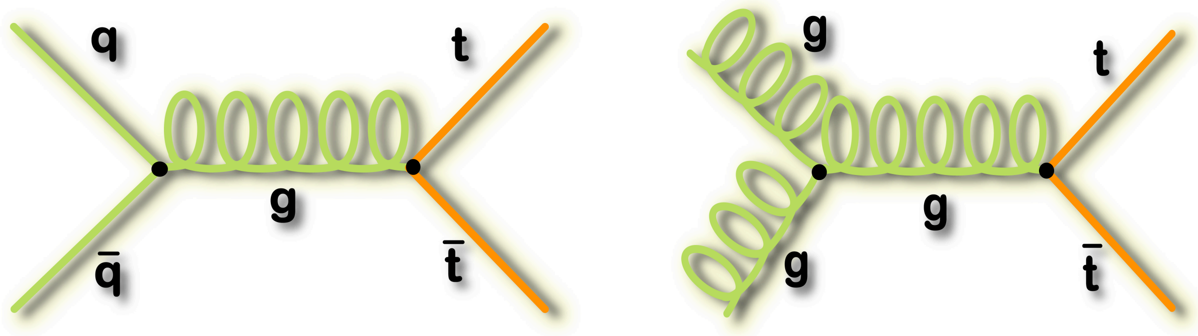




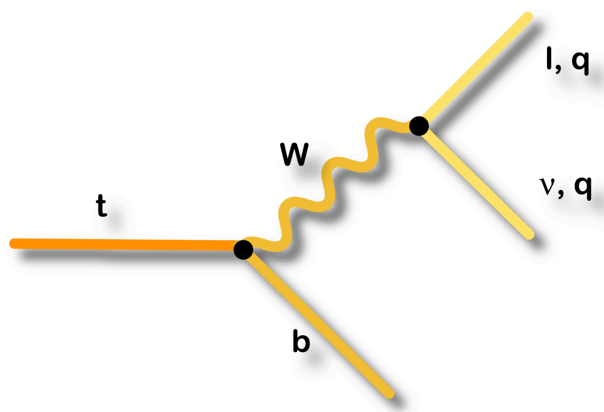
May be able to use this process to normalize luminosity

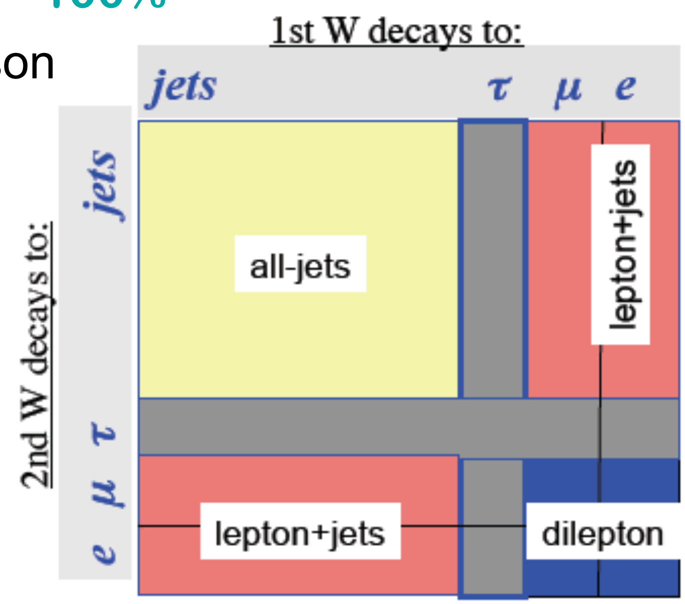
Top Quark Production and Decay

- Mainly produced in pairs via the strong interaction



- Decay via the electroweak interactions **Br(t →Wb) ~ 100%**
  Final state is characterized by the decay of the W boson

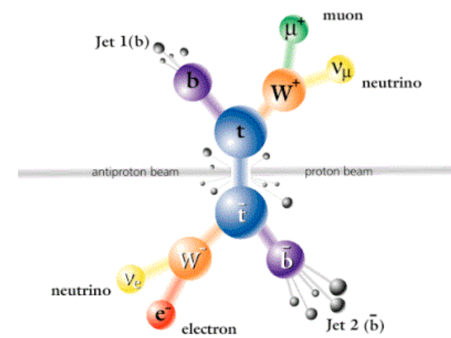


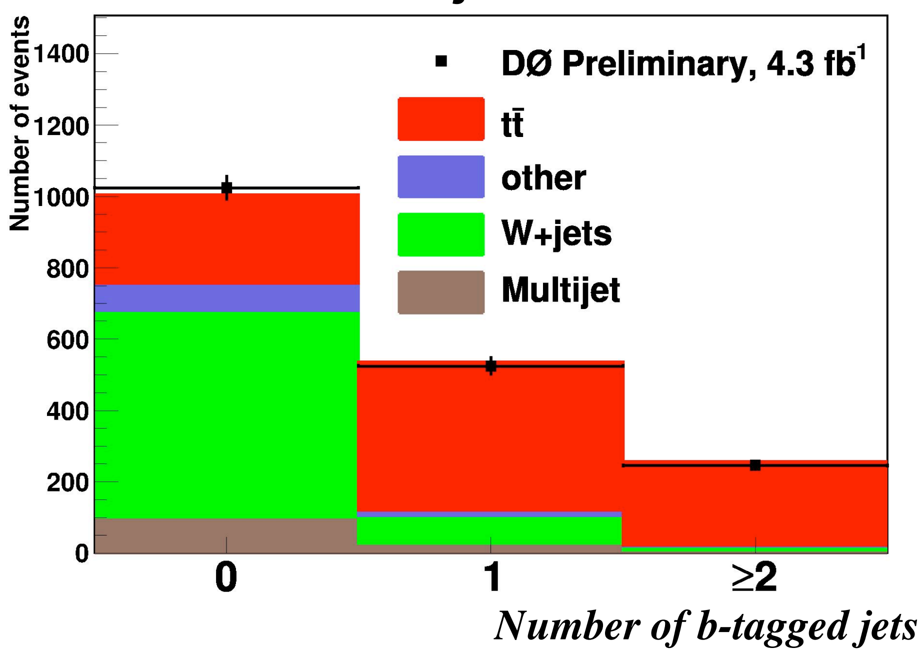


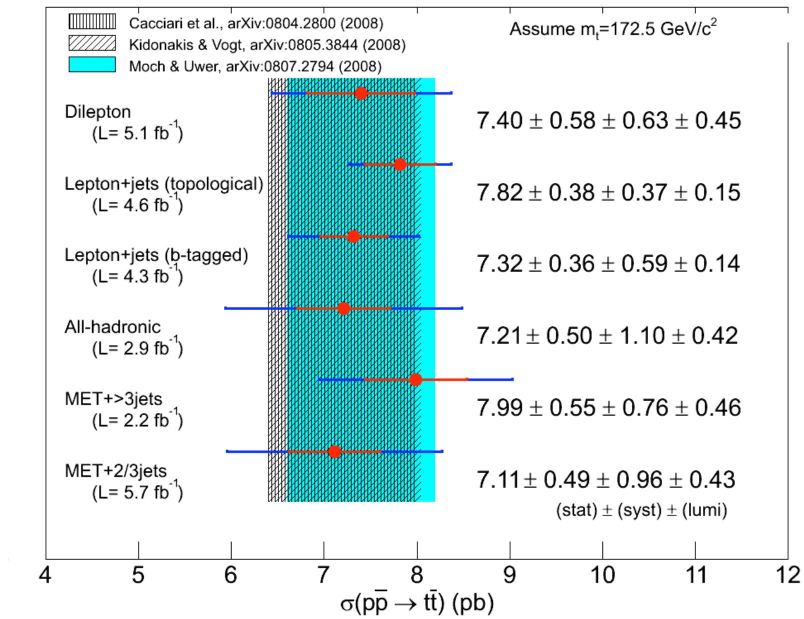
Different sensitivity and challenges in each channel
Lepton+jets is has best sensitivity

The Top Cross Section

- Basic selection:
  - 1 high p_T electron or muon
  - Large missing E_T
  - At least 3 jets

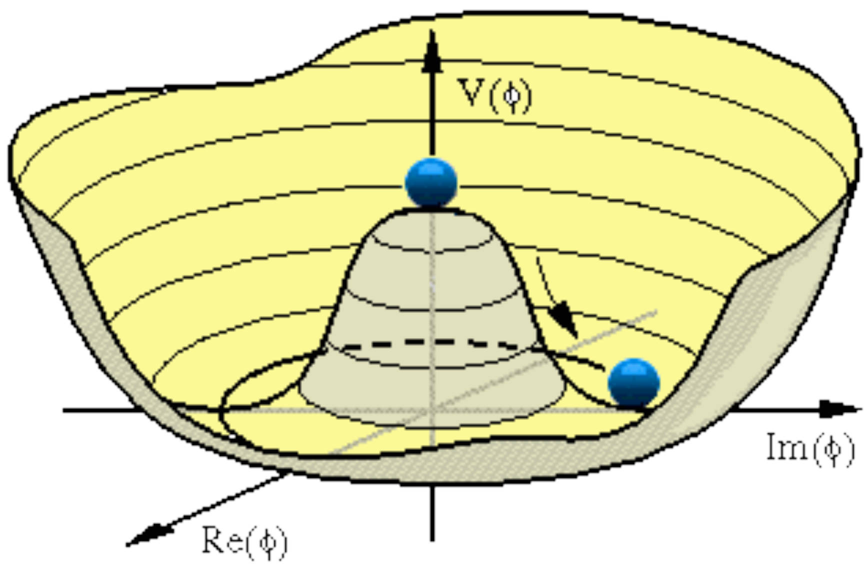






- Good agreement between all measurements (precision 6%) and between data and theory

Electroweak Symmetry Breaking



The Electroweak Precision Data

- **Precision measurements of**
  - muon decay constant and α
  - Z boson properties (LEP,SLD)
  - W boson mass (LEP+Tevatron)
  - Top quark mass (Tevatron)

Measured to 0.015%

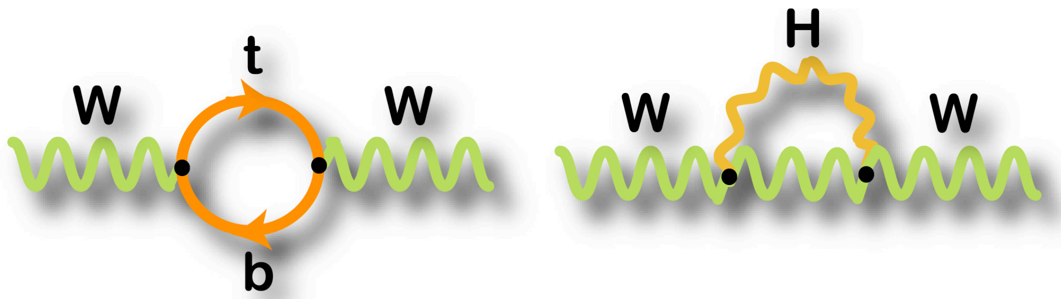
Measured to 0.002%

Measured to 0.036%

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\frac{1}{(1-(M_W^2/M_Z^2))}\frac{1}{(1-\Delta r)}$$

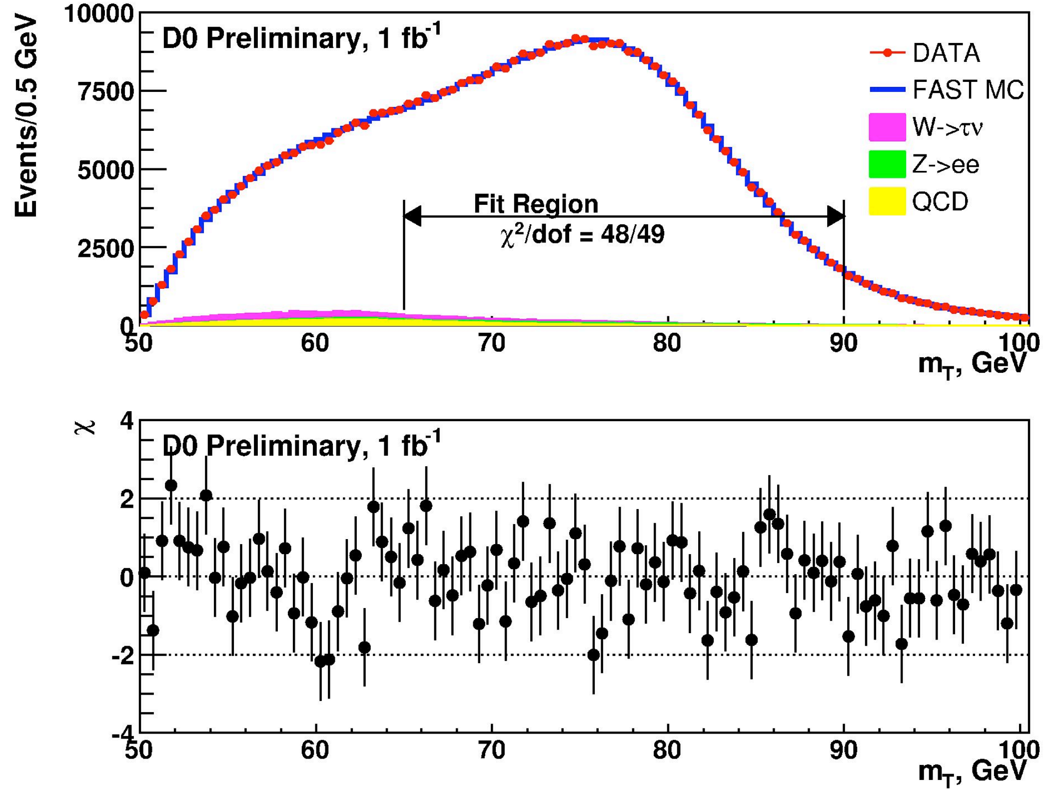
Measured to 0.0009%

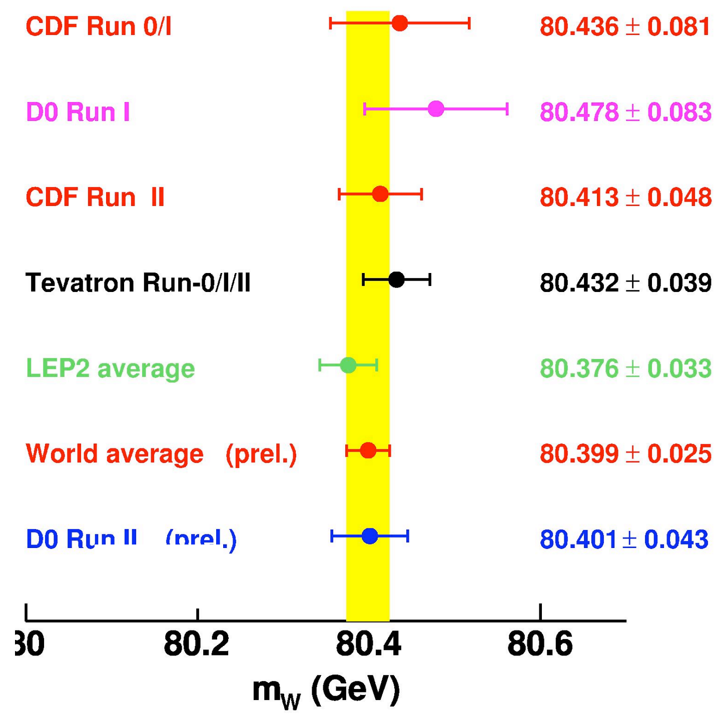
Δr: O(3%) radiative corrections dominated by *tb* and Higgs



$\Delta r_t \sim m_t^2$ $\Delta r_{Higgs} \sim \ln(m_H^2)$

W Boson Mass





World average:

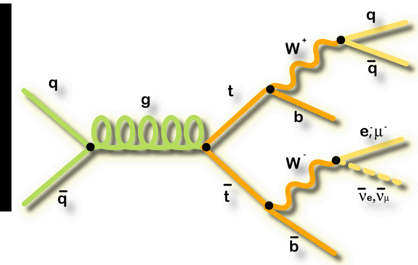
M_W=80399 ± 23 MeV

Ultimate precision:

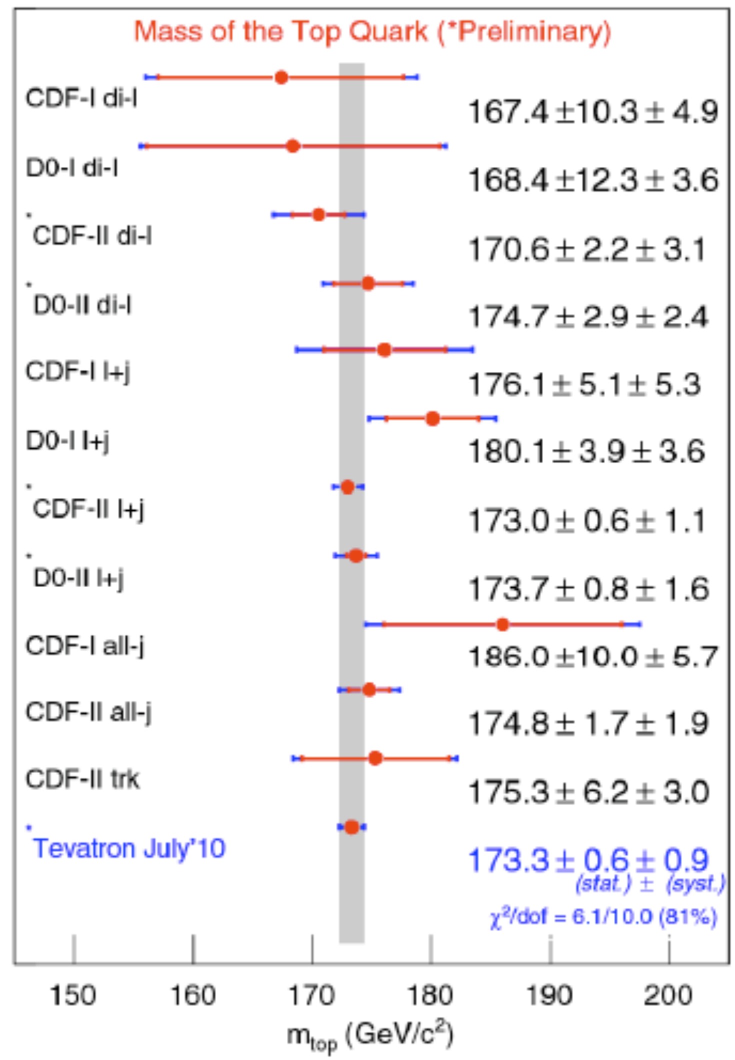
Tevatron: 15-20 MeV

LHC: unclear (5 MeV?)

Top Quark Mass Results



- Many measurements agree
  - CDF and D0
  - Different techniques and decay channels
- Most precise measurement in lepton+jets channel
  - Dominant jet energy scale uncertainty determined within top sample
- **Precision: $\delta m_{top}/m_{top}$=0.6%!**

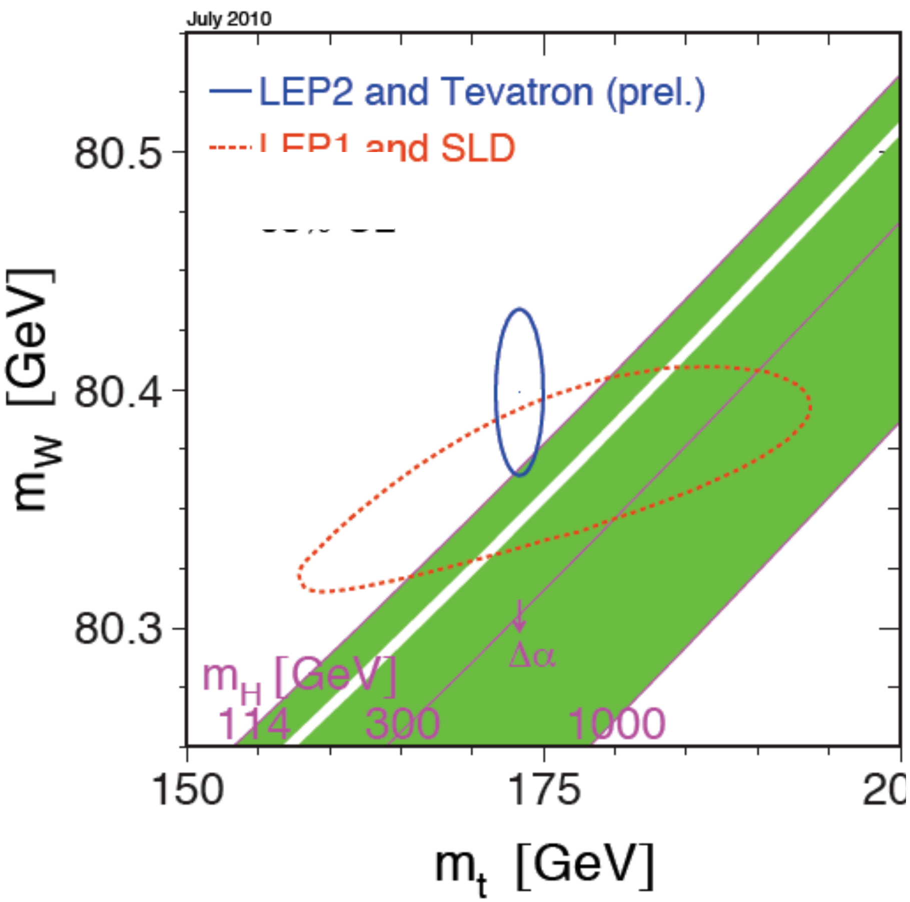


$$\boxed{m_{top}=173.3\pm 1.1\ \mathrm{GeV}/c^2}$$

Prediction from LEP1, SLD, M_W,Γ_W: 178.9 $^{+11.7}_{-8.6}$ GeV/c^2

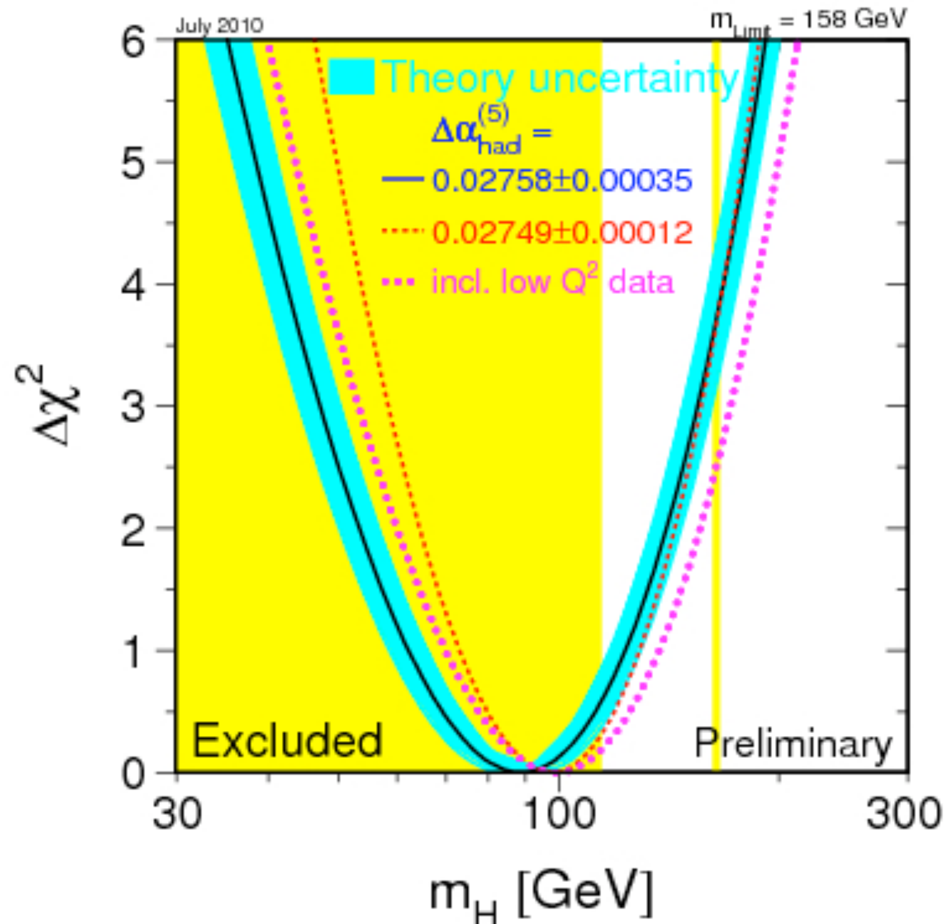
Implications for the Higgs Boson

Relation: M_W vs m_{top} vs M_H



Standard Model still works!

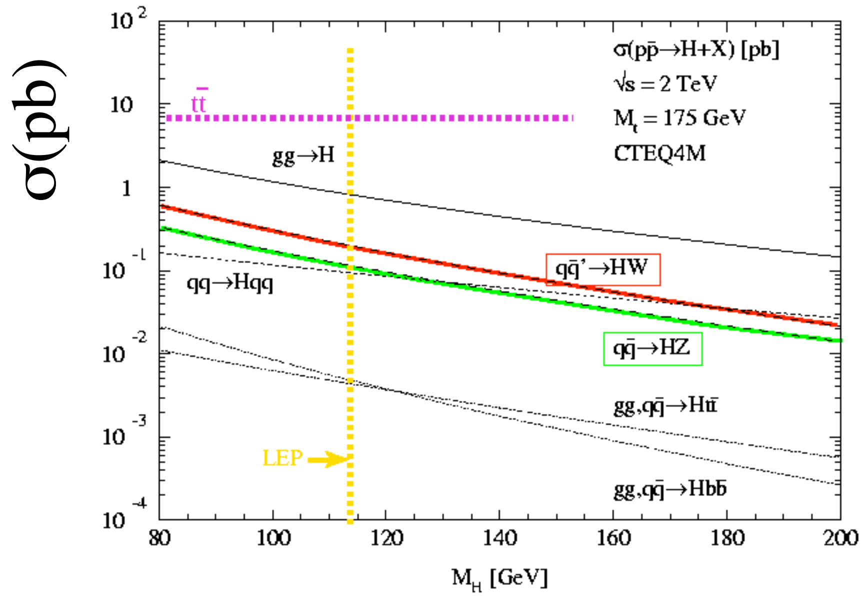
$m_H = 89^{+35}_{-26}$ GeV



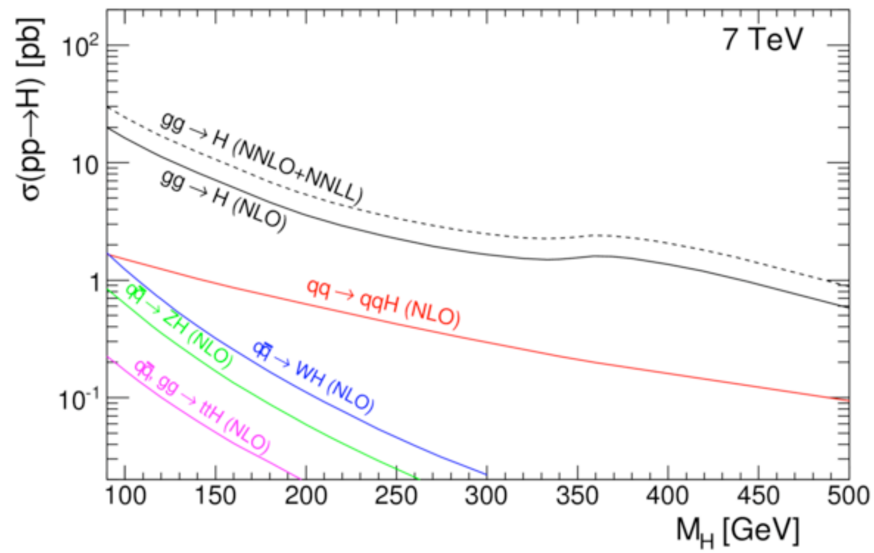
Indirect constraints:
m_H<158 GeV @95%CL

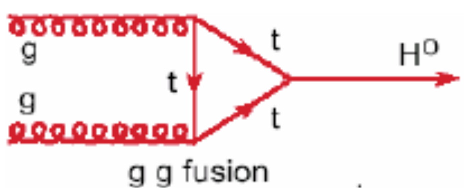
Higgs Production: Tevatron and LHC

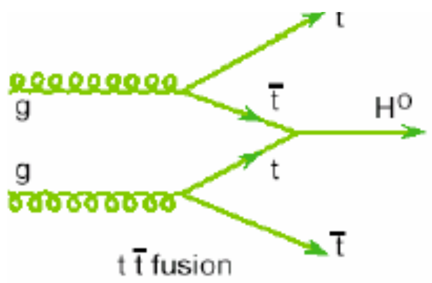
Tevatron

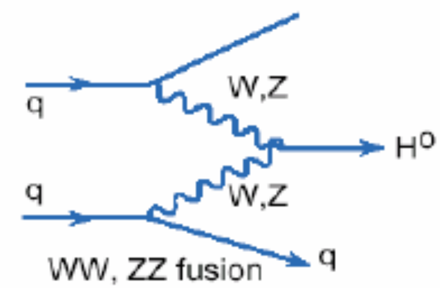


LHC





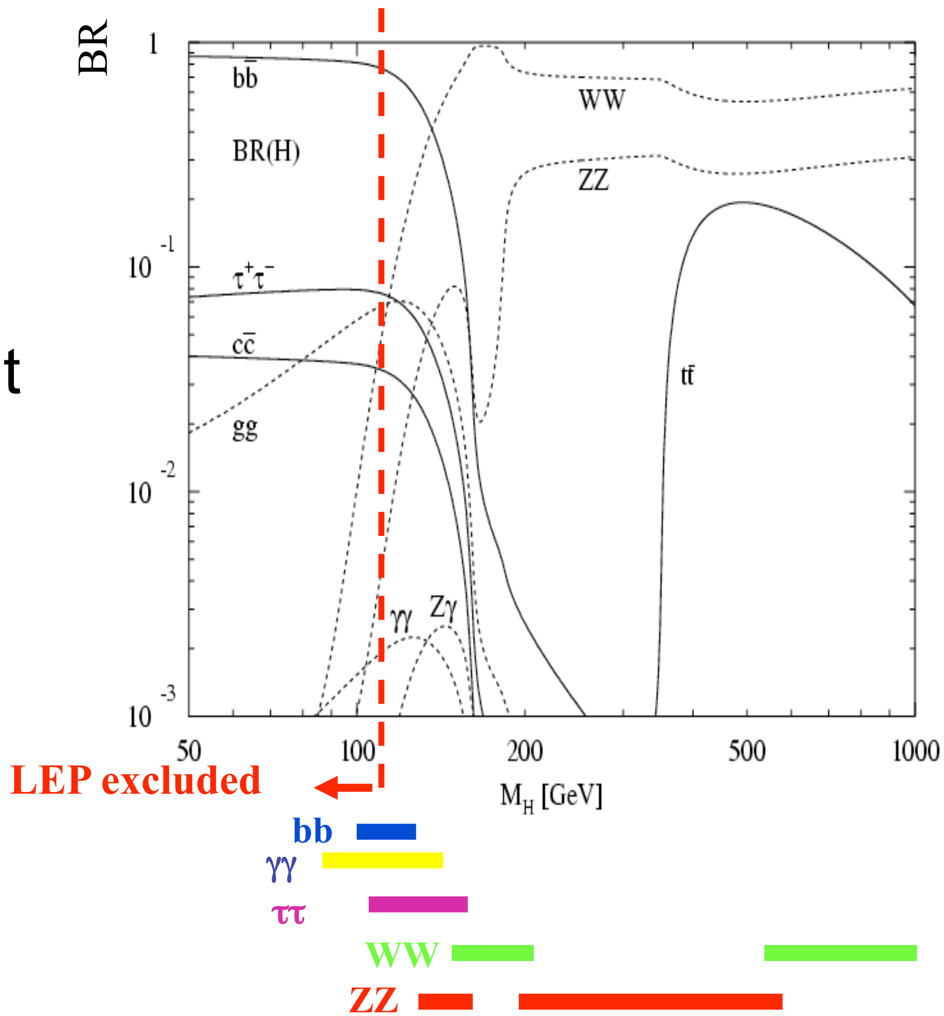




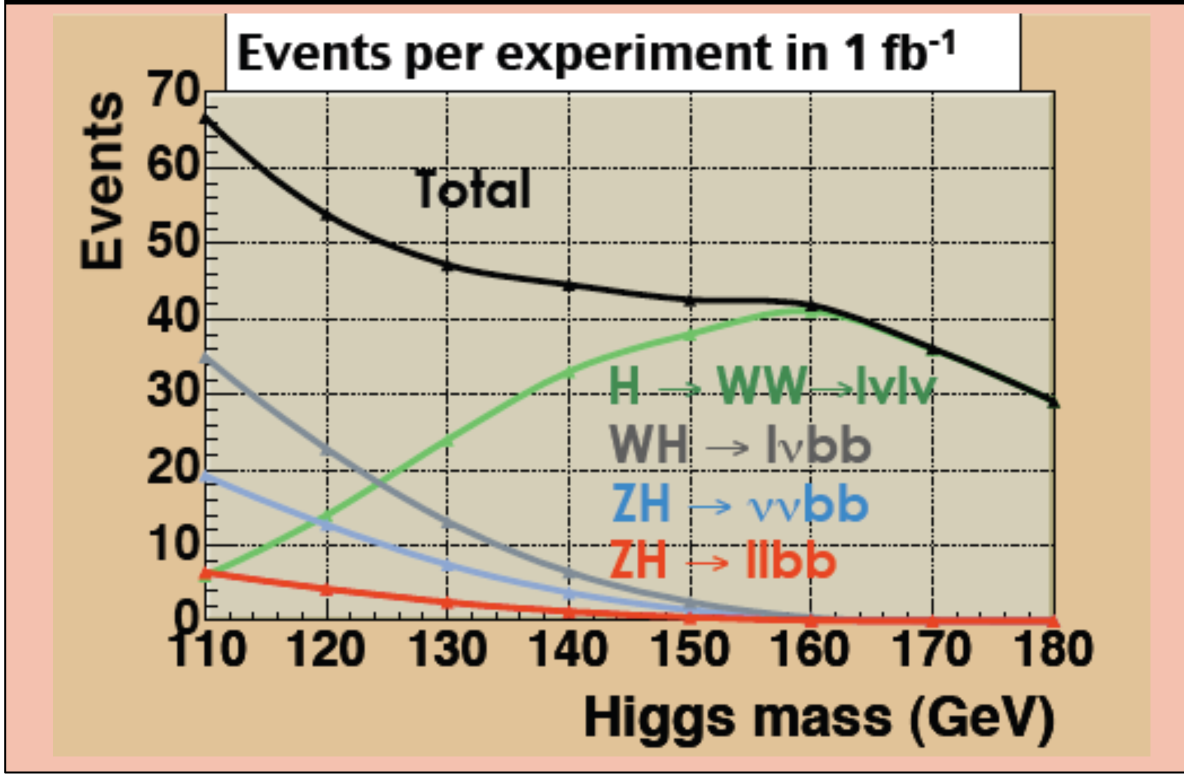
dominant: gg→ H, subdominant: HW, HZ, Hqq

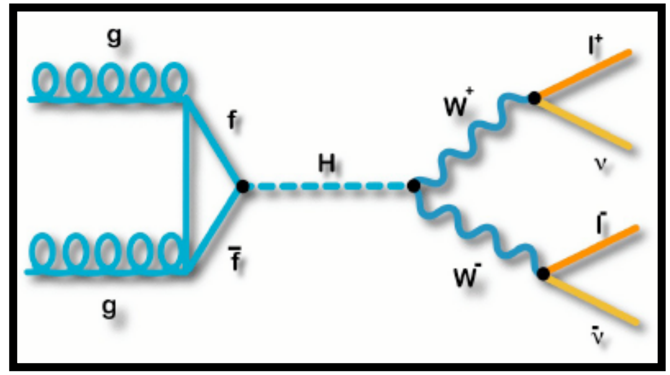
Higgs Boson Decay

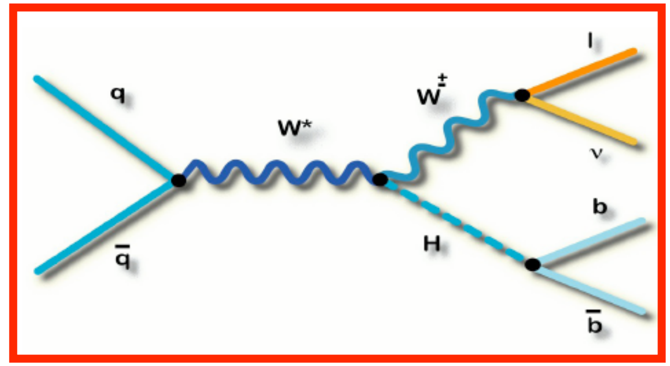
- Depends on Mass
- M_H<130 GeV/c^2:
  - **$b\bar{b}$ dominant**
  - WW* and ττ subdominant
  - γγ small but useful
- M_H>130 GeV/c^2:
  - **WW dominant**
  - ZZ cleanest

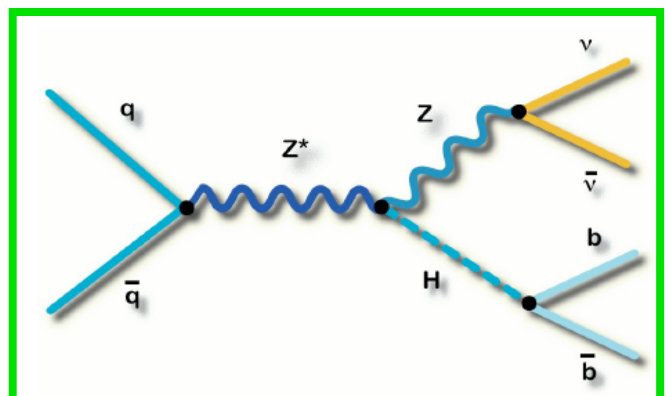


Tevatron Discovery Channels



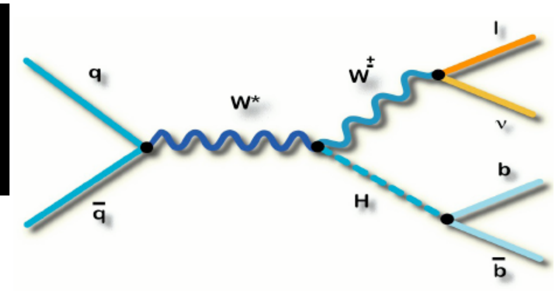


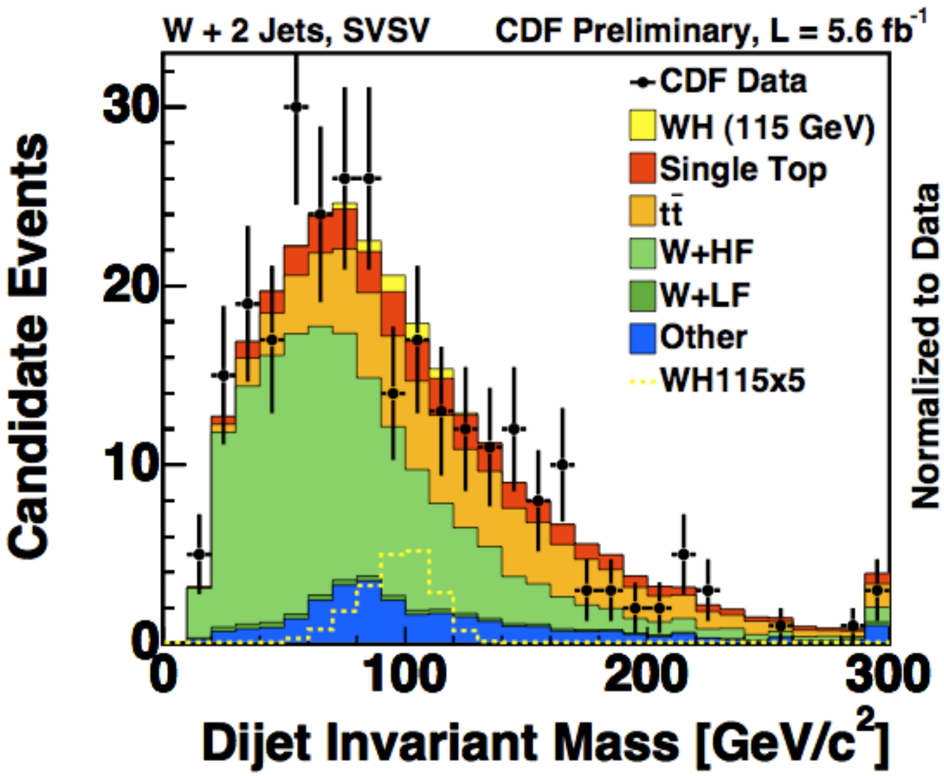


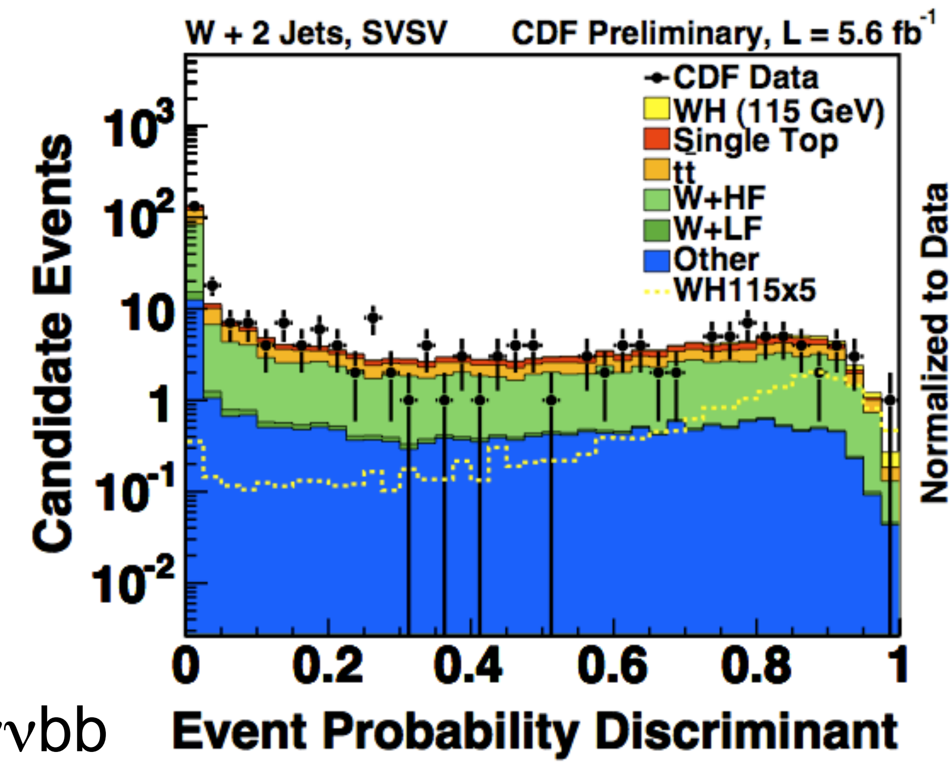


M(H)>125 GeV: WW
M(H)<125 GeV: WH and ZH

W/Z+Higgs with H→bb

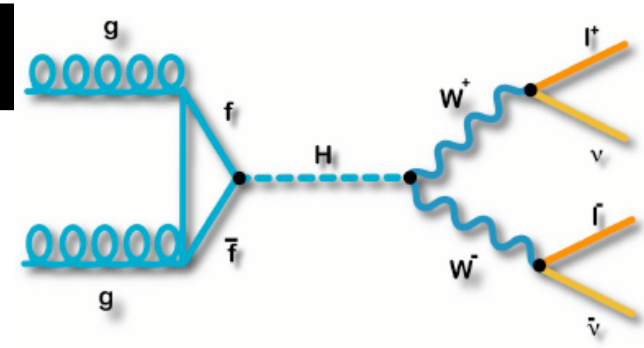




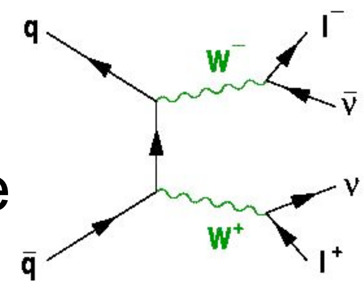


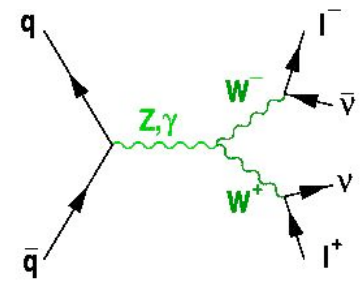
- WH→lνbb, ZH →llbb, ZH →ννbb
- Higgs causes peak in dijet mass
- Analyses make use of full event correlations to improve separation from background
  - *Event Probability Discriminant* (e.g. Neural Network,…)

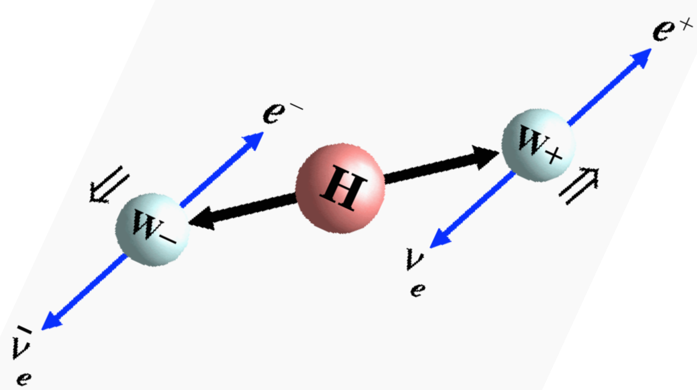
$H \to WW^{(*)} \to l^+l^-\nu\nu$

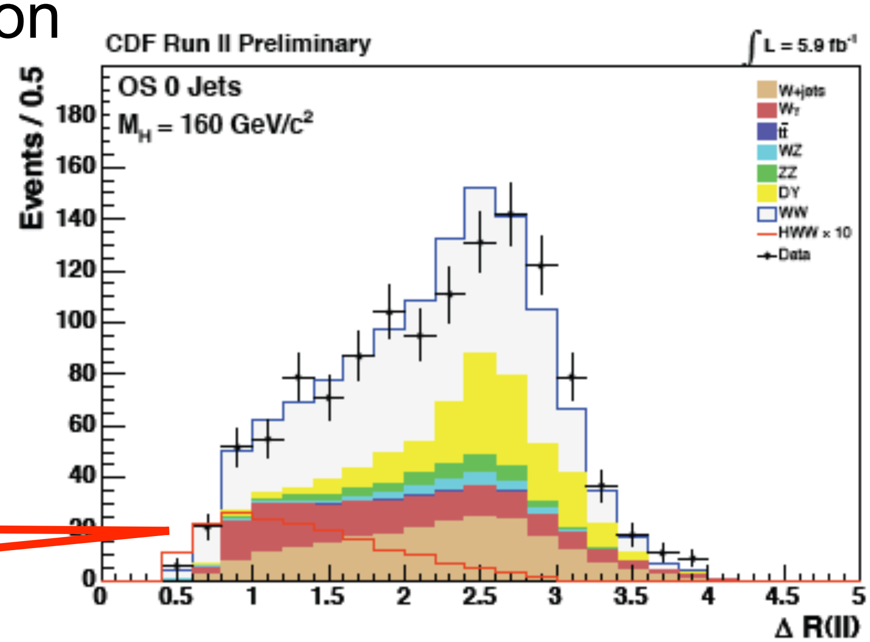


- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs is scalar: spin=0
  - leptons in $H \to WW^{(*)} \to l^+l^-\nu\nu$ are collinear
- Main background: WW production





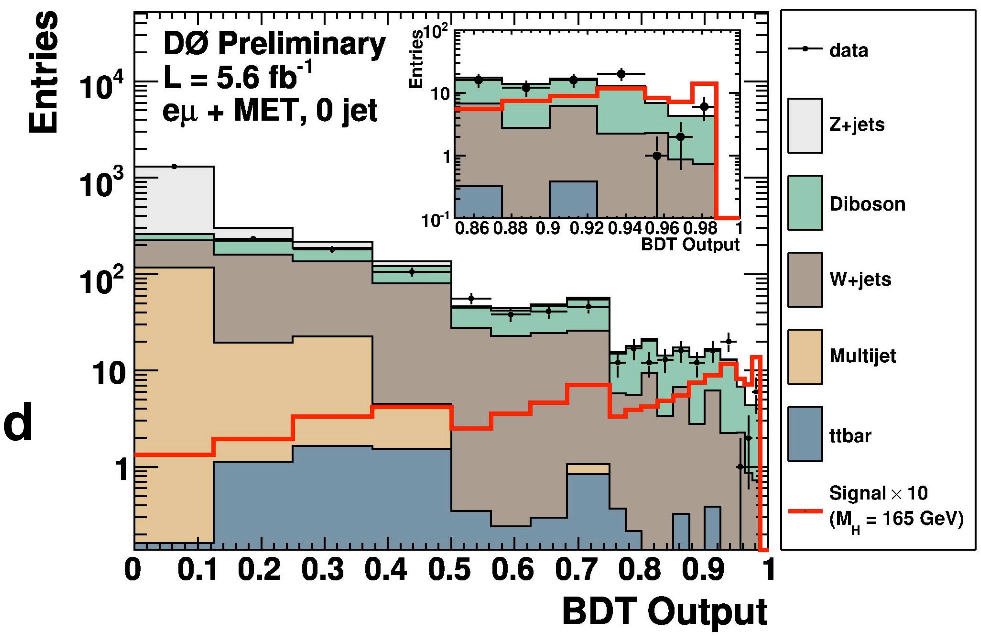




10x Higgs Signal

$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ ($l=e,\mu$)

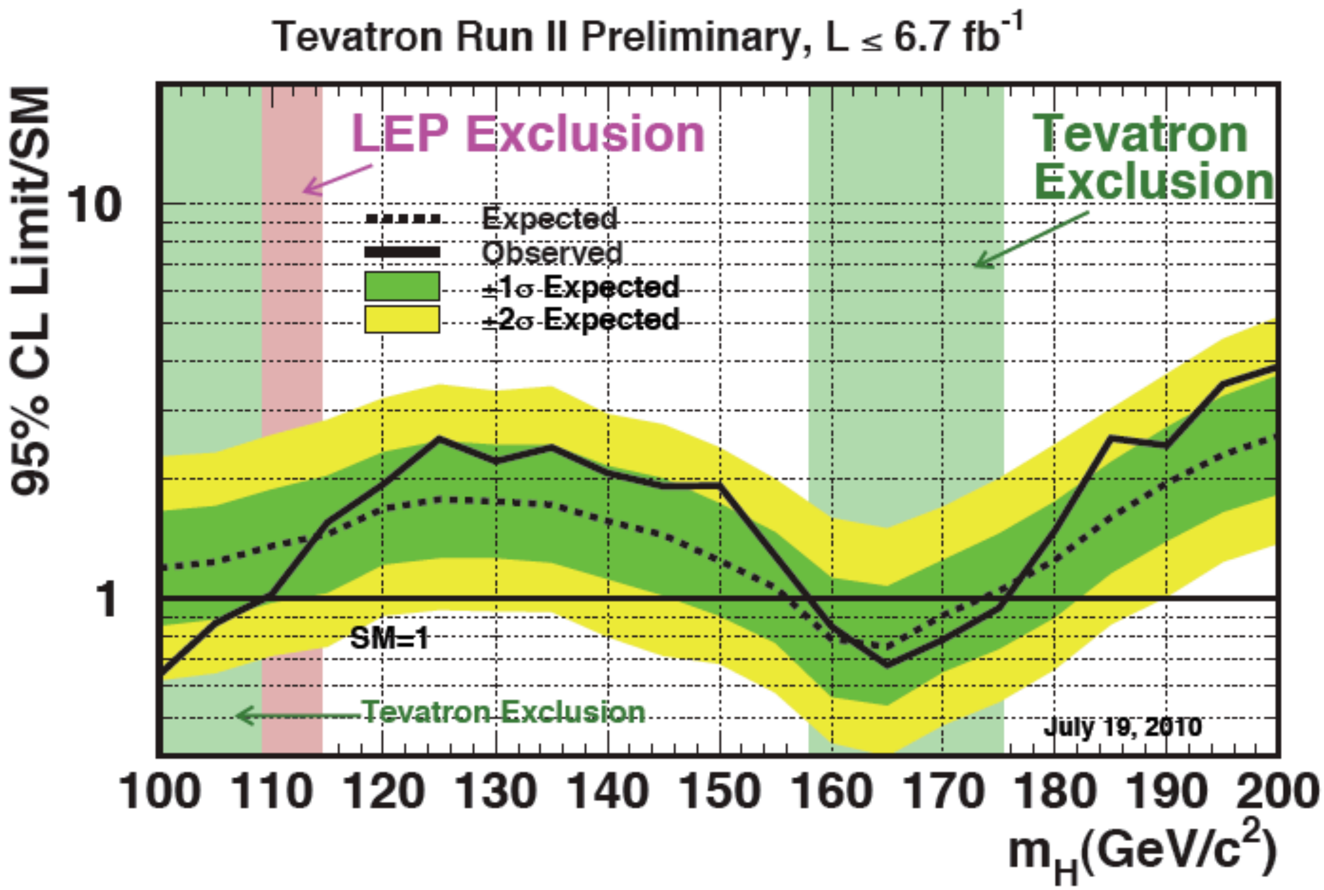
- **Event selection:**
  - 2 isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets (against top)



- **Separate signal from background**
  - Use discriminant to enhance sensitivity
  - Many varieties:
    - “Neural Network”, “Boosted Decision Tree”, “Likelihood”,… (see literature)
  - Basically combine many variables into one to exploit as much information as possible

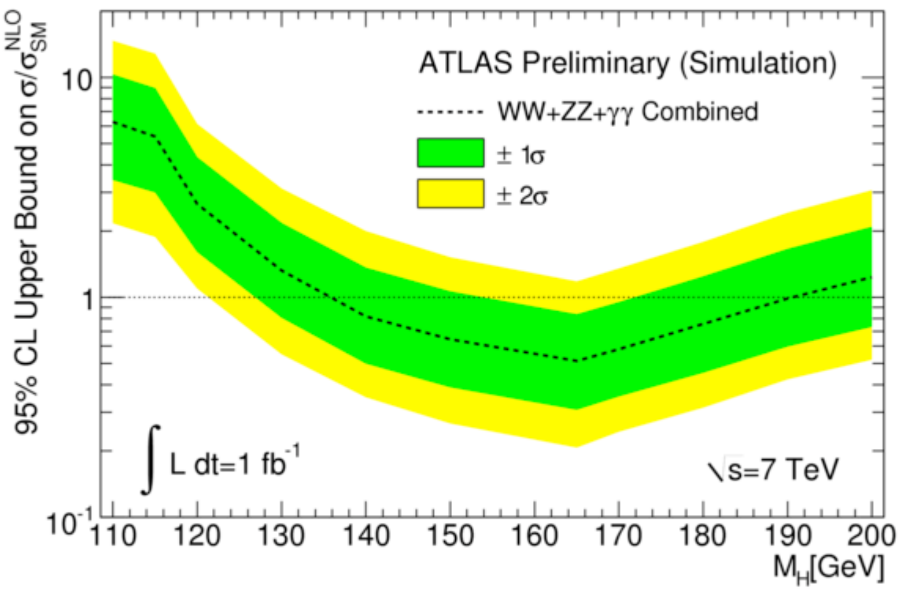
No Higgs Signal found
⇒Set limits on cross section

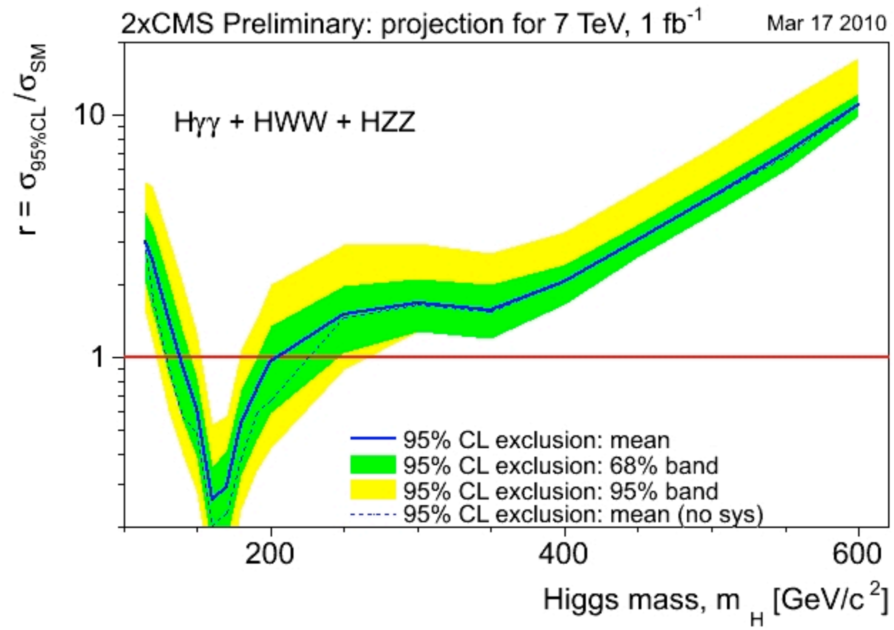
Tevatron Higgs Limit



- Combine CDF and DØ analyses from all channels at low and high mass
  - Exclude m_H=158-175 GeV/c^2 at 95% C.L.
  - m_H=120 GeV/c^2: limit/SM ≈ 1.5

LHC Higgs Prospects with 1 fb^{-1}

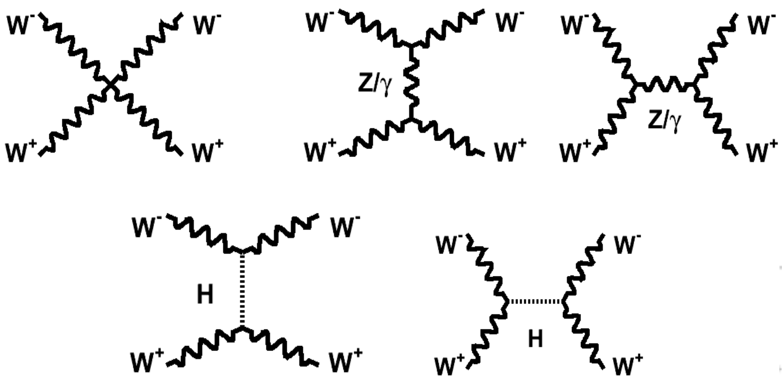




- ATLAS and CMS can jointly exclude the mass range 140-200 GeV with 1 fb^{-1}
  - Using WW, ZZ and diphoton decay
  - Competitive with Tevatron at ~7 fb^{-1} at high mass
  - May be better if more sophisticated analyses techniques deployed (like at Tevatron)

What if there is no Higgs?

- In the SM the Higgs boson prevents *unitarity violation* of WW cross section
- Without the Higgs: $\sigma(pp \rightarrow WW) > \sigma(pp \rightarrow \text{anything})$
  - => illegal!
  - At $\sqrt{s}$=1.2 TeV!



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires M_H < 800 GeV

⇒Something has to be found at the LHC: Higgs boson or something else

Beyond the Standard Model

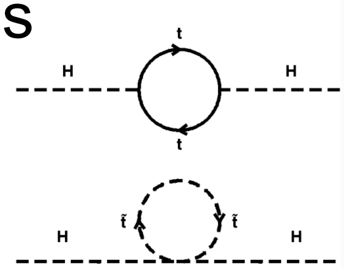
New Physics beyond the SM

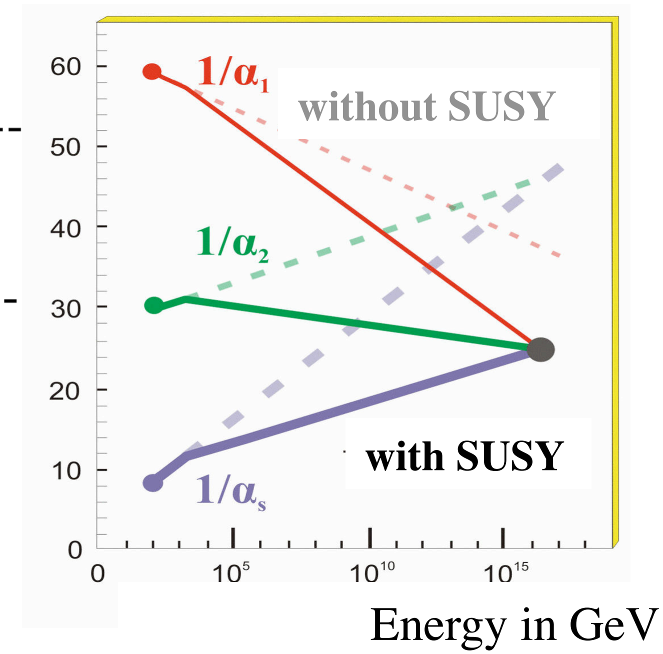
- **Supersymmetry**
  - Strong theoretical prejudices for SUSY being true
  - However, we need to keep our eyes open

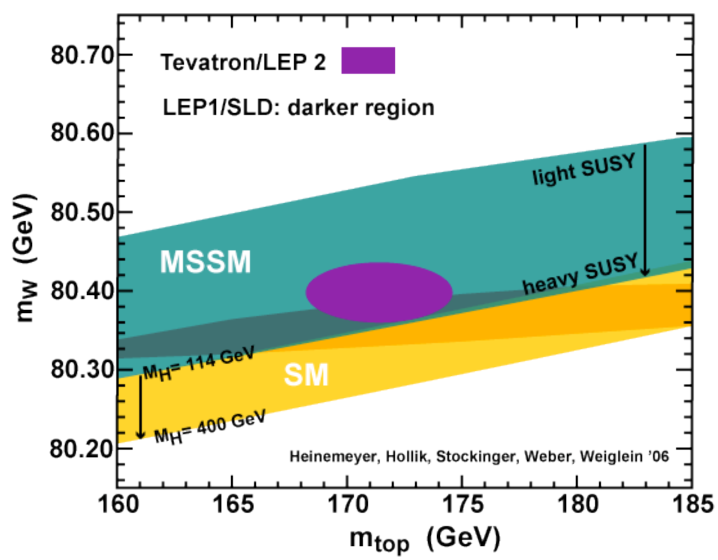
- **Other theories**
  - Extra spatial dimensions:
    - "Solve" hierarchy problem by making gravity strong at TeV scale
  - Extra gauge groups: Z', W'
    - Occur naturally in GUT scale theories
  - Leptoquarks:
    - Would combine naturally the quark and lepton sector
  - ????

What's Nice about SUSY?

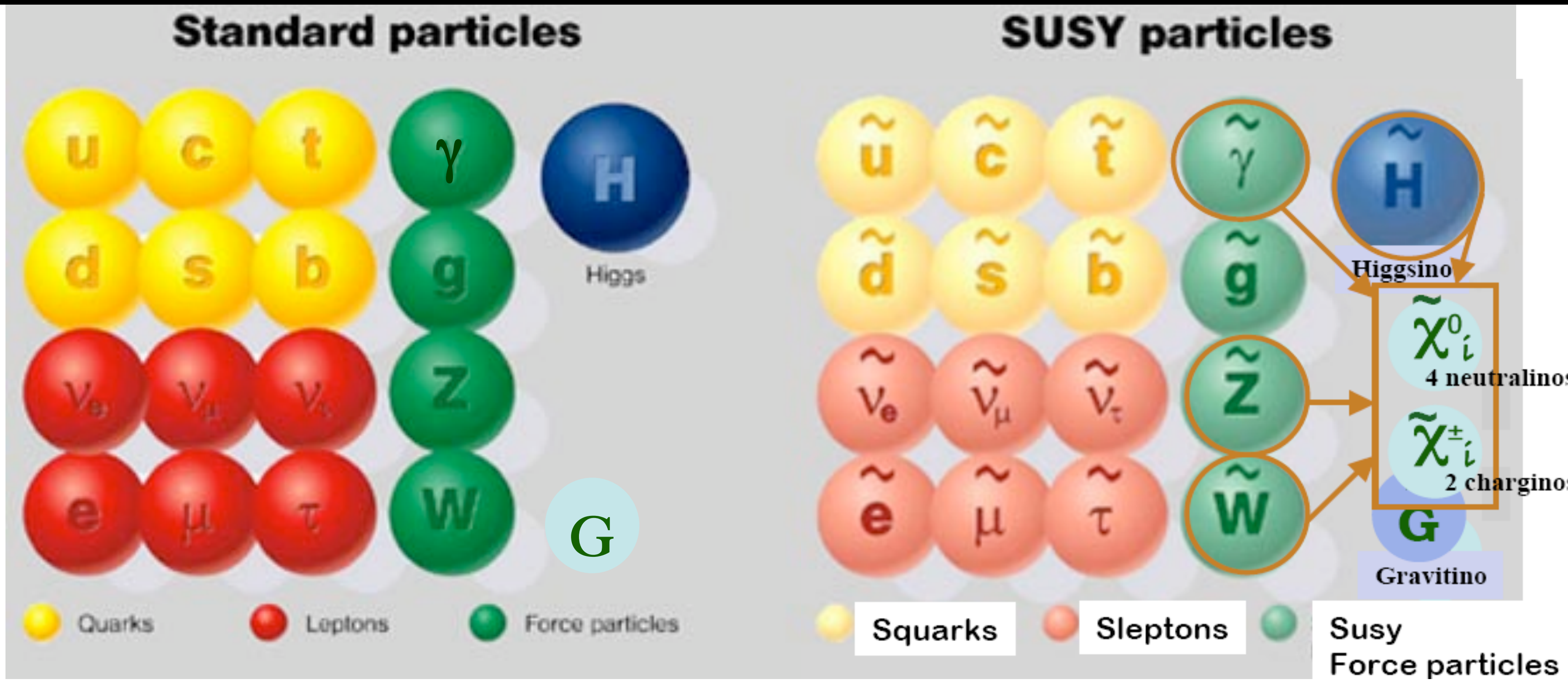
- Radiative corrections to Higgs acquire SUSY corrections:
  - No/little fine-tuning required
- Unification of forces possible
- Dark matter candidate exists:
  - lightest neutral gaugino
- Changes relationship between m_W, m_{top} and m_H:
  - Also consistent with precision measurements of M_W and m_{top}
- **SUSY particles must be near EWK scale (~TeV) to actually solve these problems**







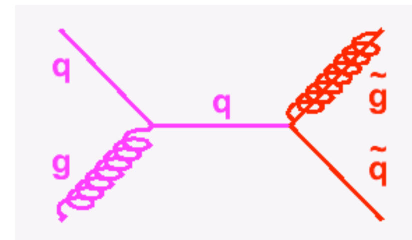
Supersymmetry (SUSY)

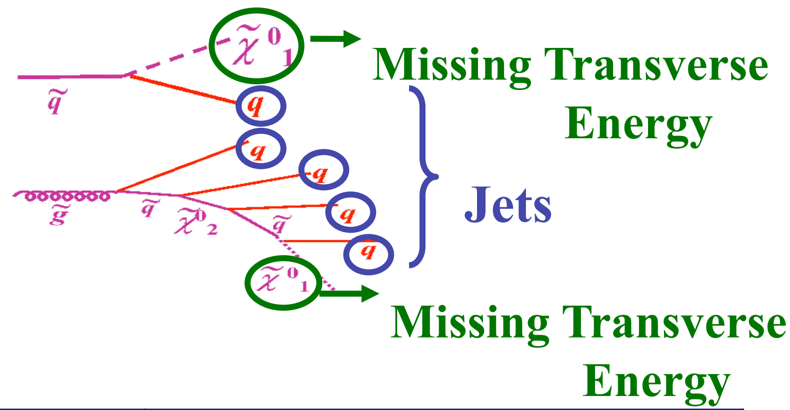


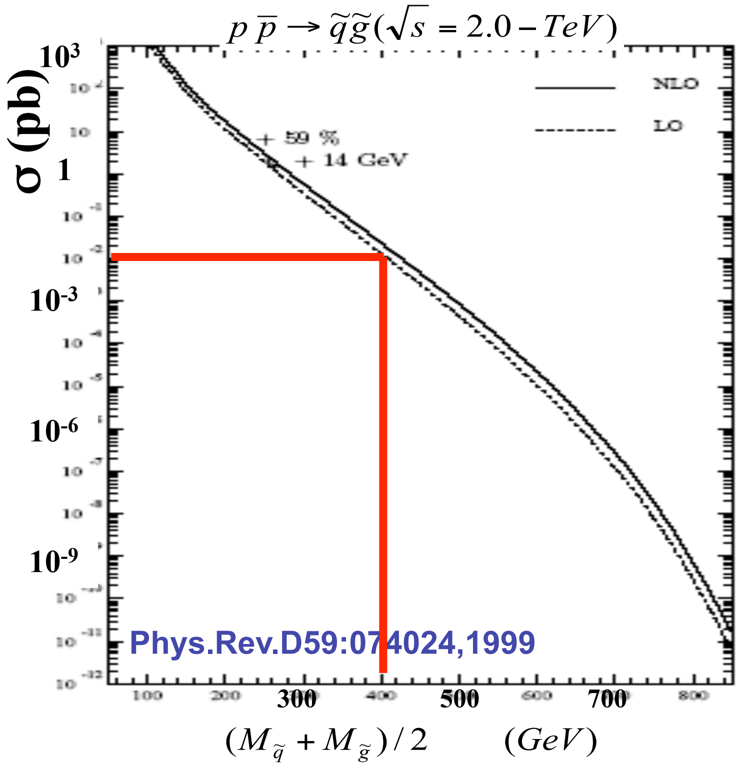
- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squark, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology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

Generic Squarks and Gluinos

- Squark and Gluino production:
  - Signature: jets and E_T^{miss}
- Strong production
  - Large cross section, depending on mass of gluino and squarks

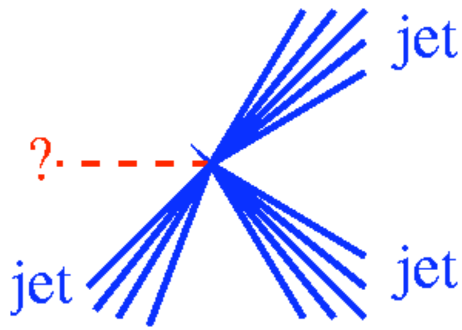


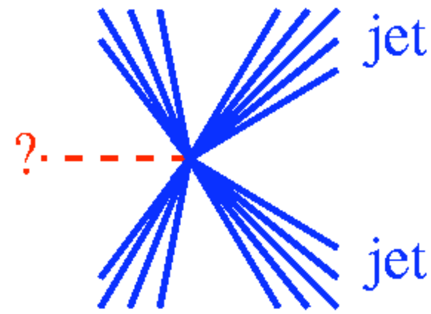


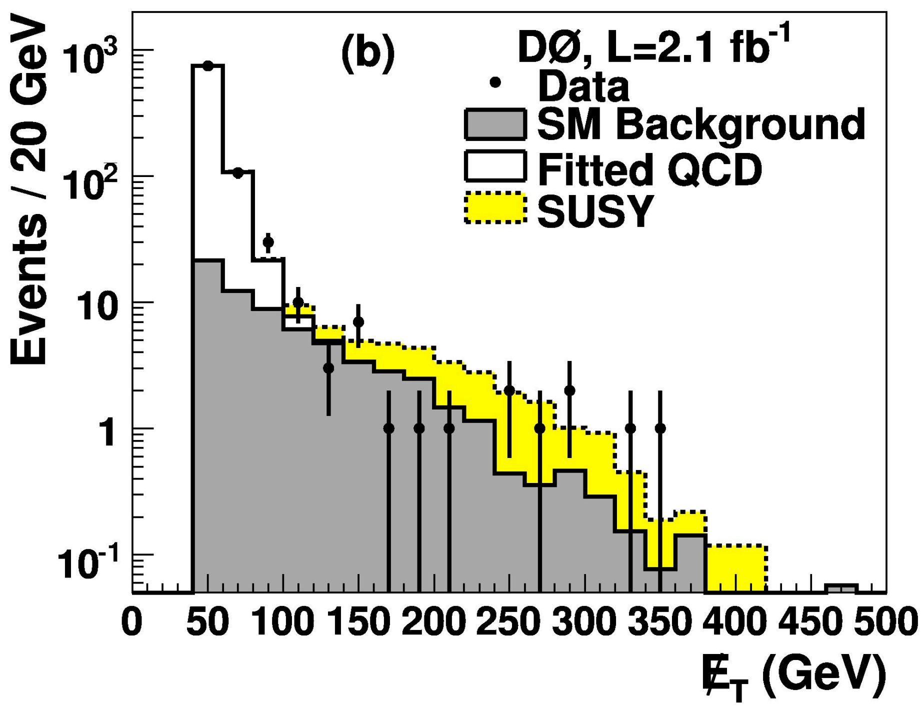


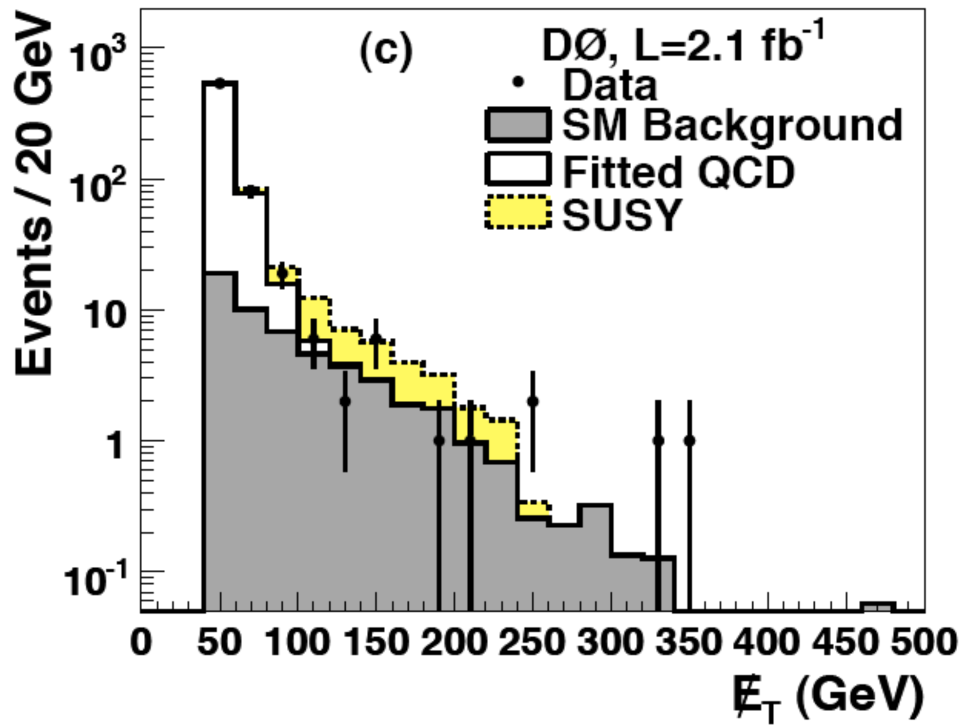
M(gluino)	Events per fb^{-1} Tevatron	LHC
300	1000	250000
400	10	50000
1000	0	100

Missing E_T for multi-jet events

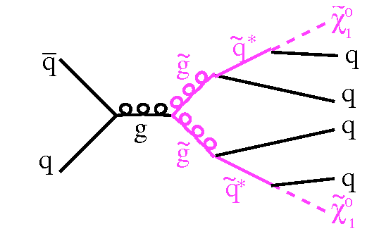


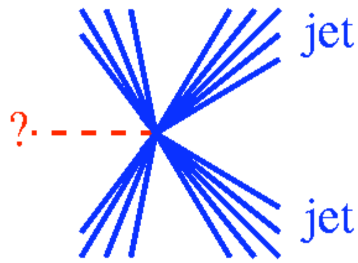


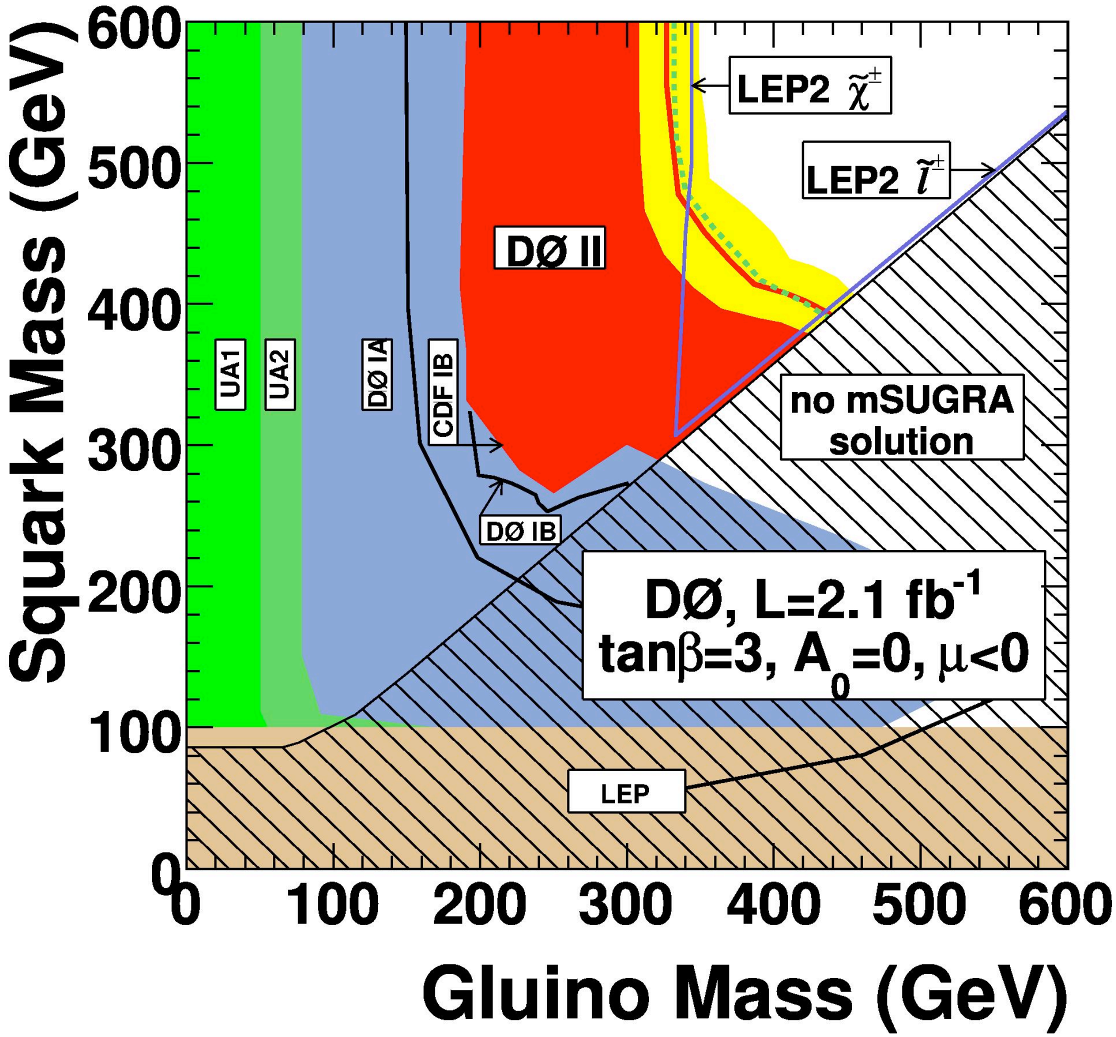


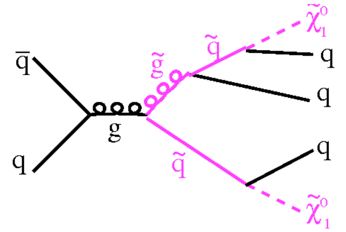


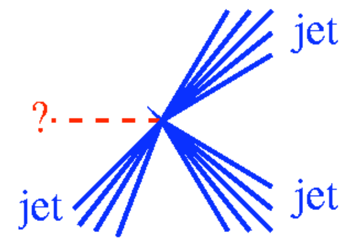
Supersymmetry Parameter Space

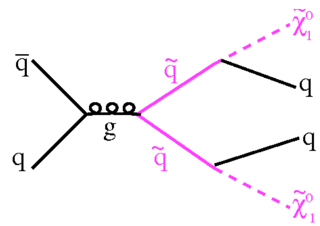


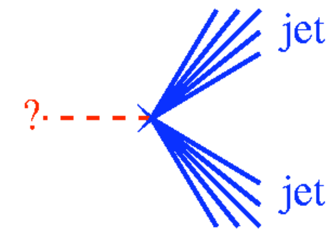






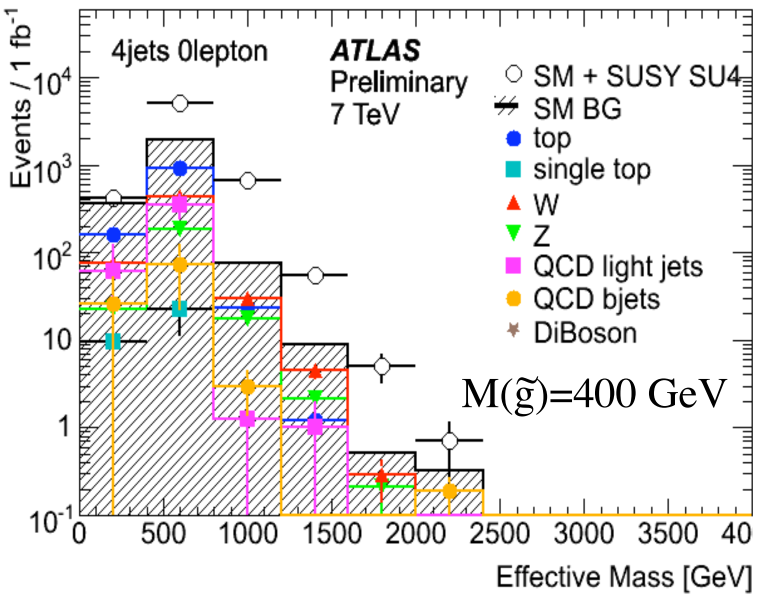


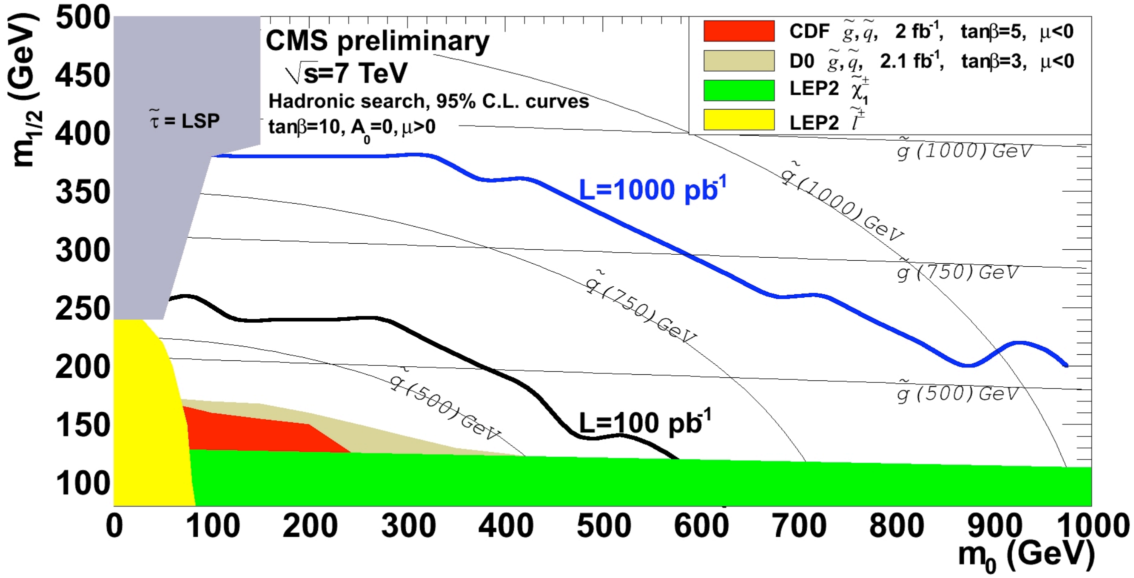


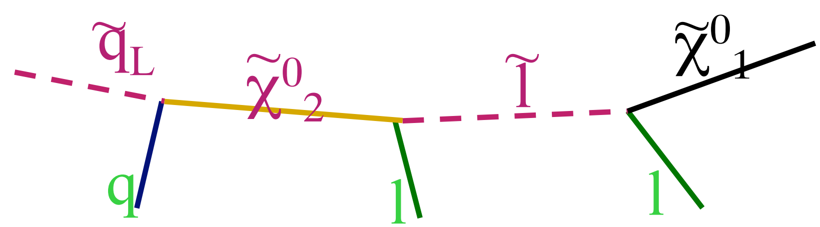


$M(\tilde{g}) > 308$ GeV and $M(\tilde{q}) > 379$ GeV

LHC SUSY Searches and Reach



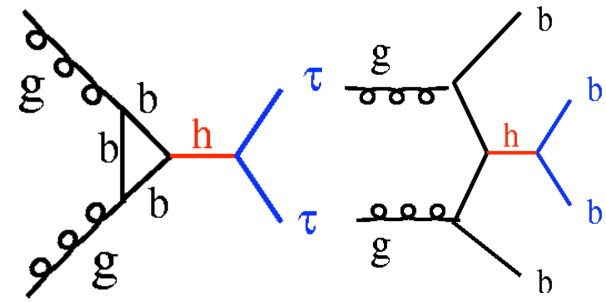




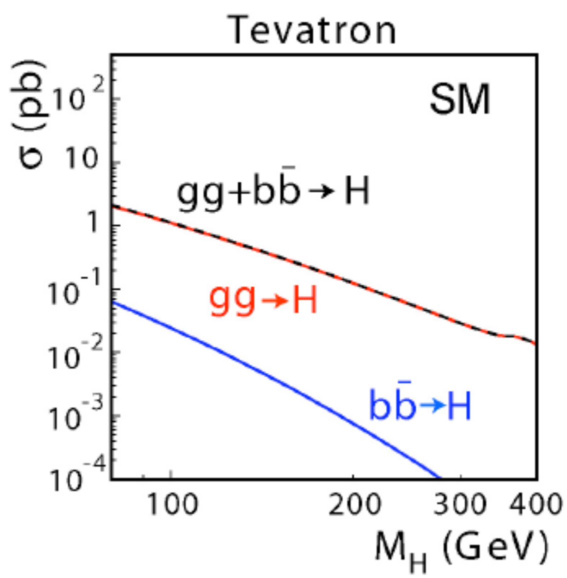
- **Searches in many modes**
  - 1, 2, 3, 4 jets with 0, 1, 2 leptons
  - Specific searches with b-jets
  - Completely different SUSY scenarios…
- **Sensitivity beyond Tevatron with 100 pb^{-1}**
  - Will probe masses of ~800 GeV with 1 fb^{-1}

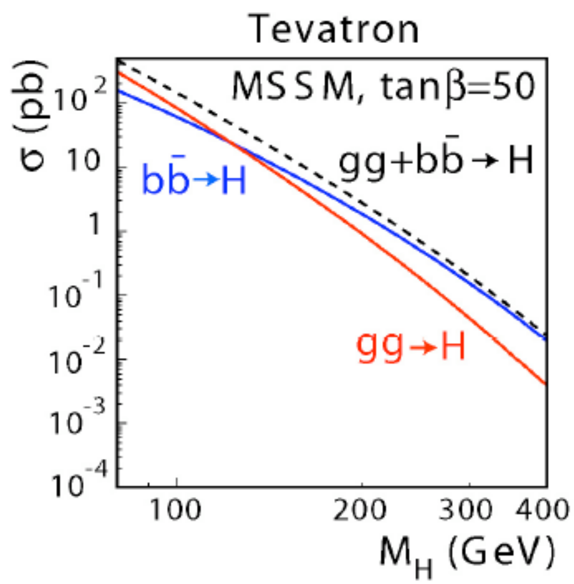
Higgs in Supersymmetry (MSSM)

- 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
    - A is degenerate in mass with either h or H
  - Decays always into either two τ's or two b's



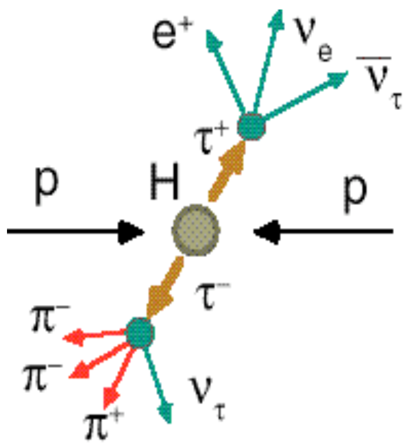
$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

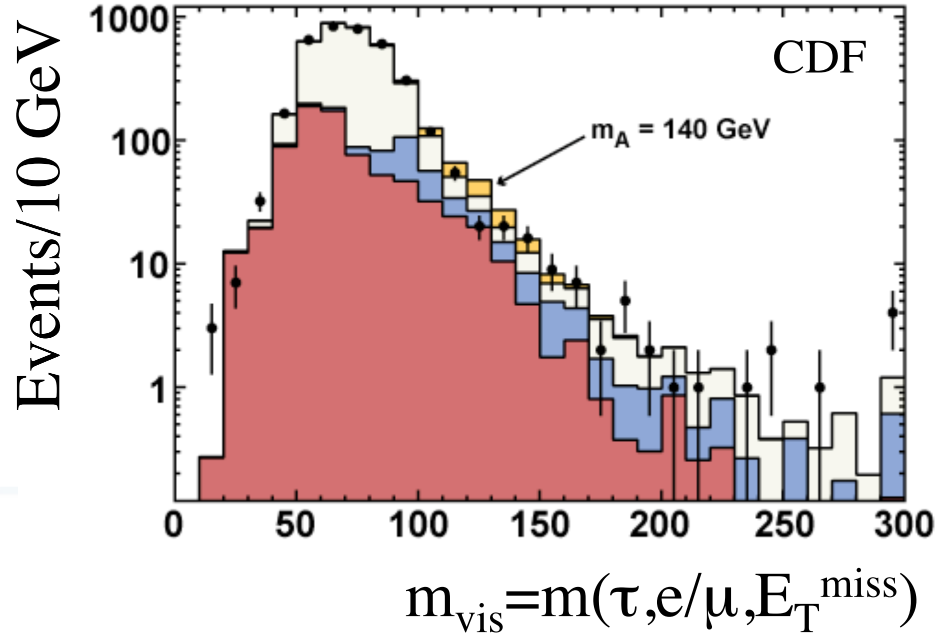


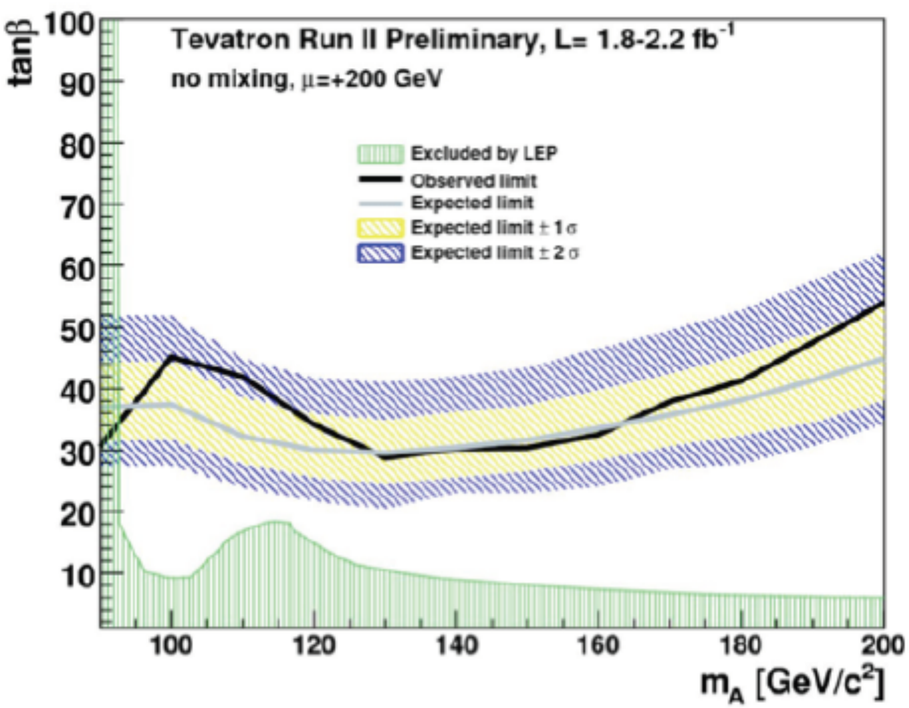


C. Balazs, J.L. Diaz-Cruz, H.J. He, T.Tait and C.P. Yuan, PRD 59, 055016 (1999)

MSSM Higgs Boson Search: di-tau signature

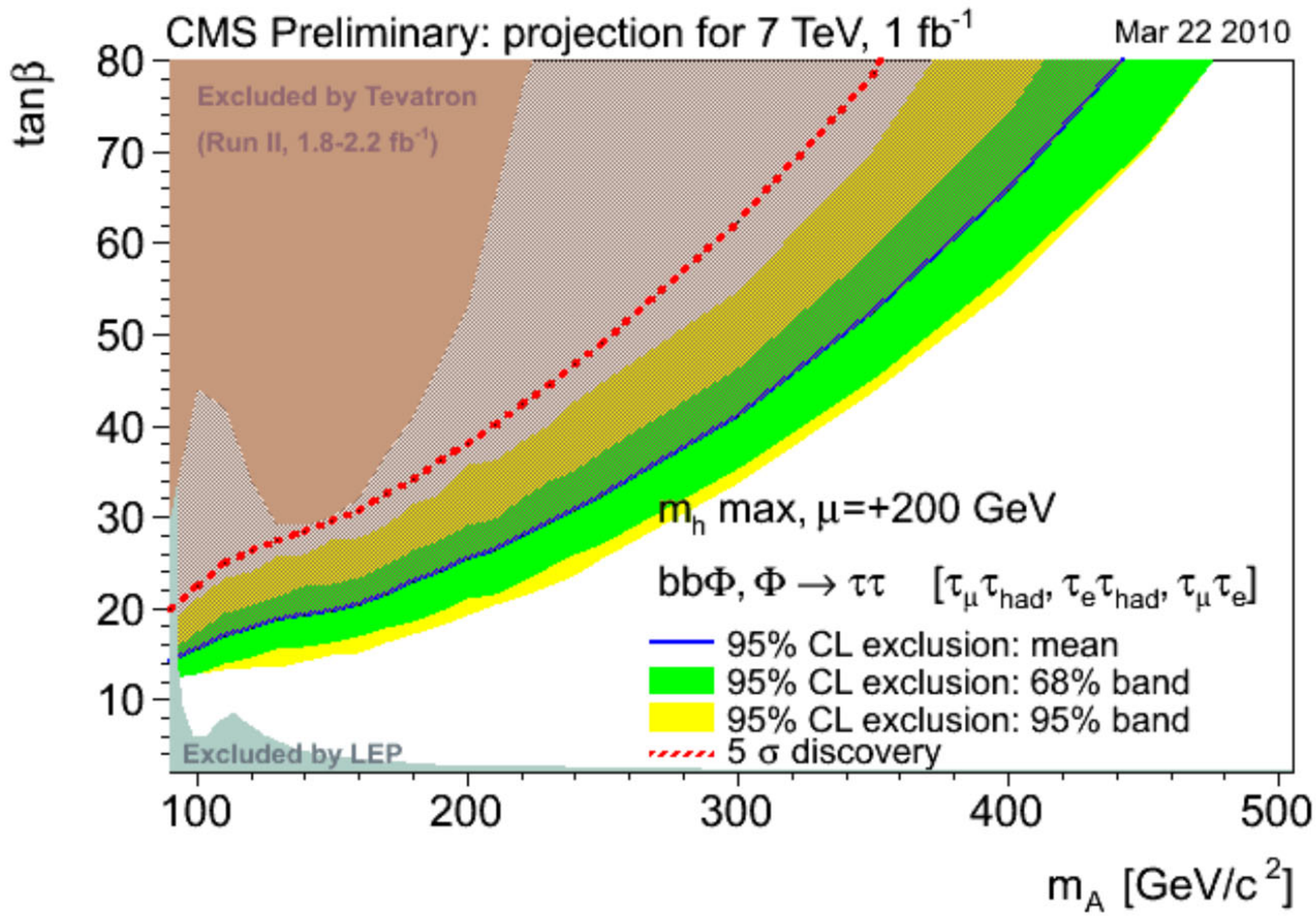






- Data agree with SM backgrounds
- Limits on supersymmetric Higgs bosons
  - Exclude tanβ>30-40 for m_A<200 GeV

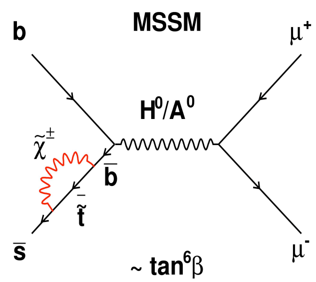
LHC Prospects for MSSM Higgs



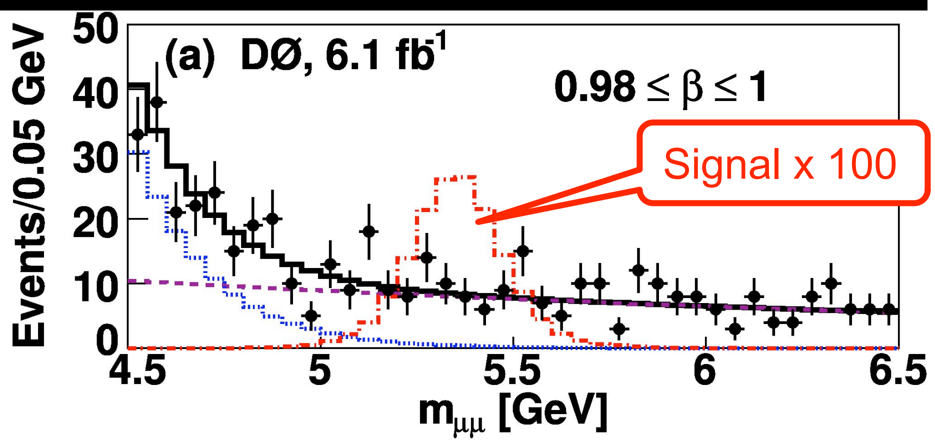
- Sensitivity up to m_A=300 GeV for tanβ=40 with 1 fb^{-1}
- Improves current Tevatron sensitivity

$B_s \to \mu^+\mu^-$ Branching Ratio

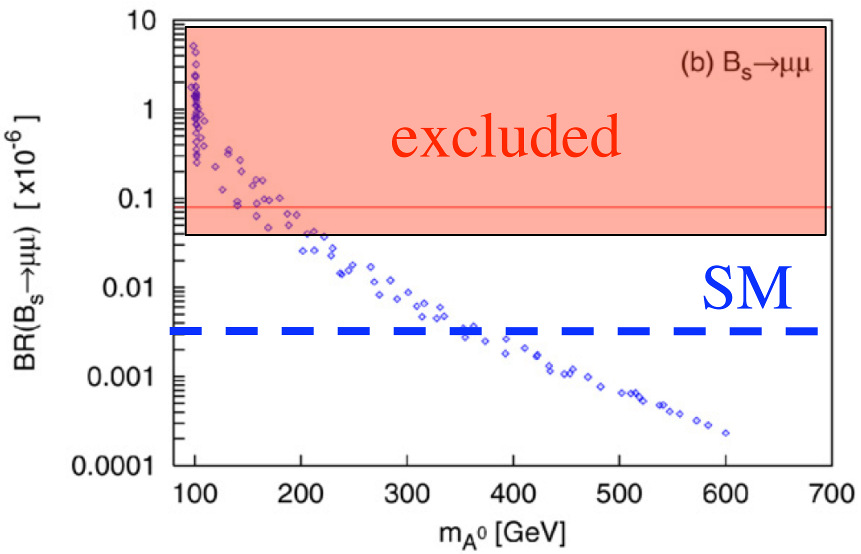
- Standard Model prediction:
  BR=(3.6±0.3) x 10^{-9}
  A.J. Buras Phys.Lett.B 566, 115 (2003)
- Large enhancements e.g. in Supersymmetry possible



$\sim \tan^6\beta / m_A^4$



J.K. Parry, Nucl. Phys. B 760, 38 (2007)

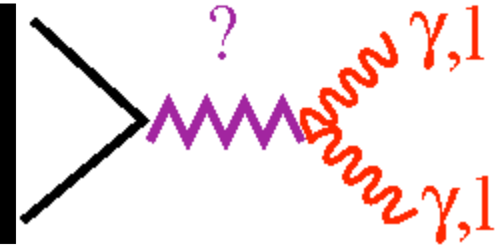


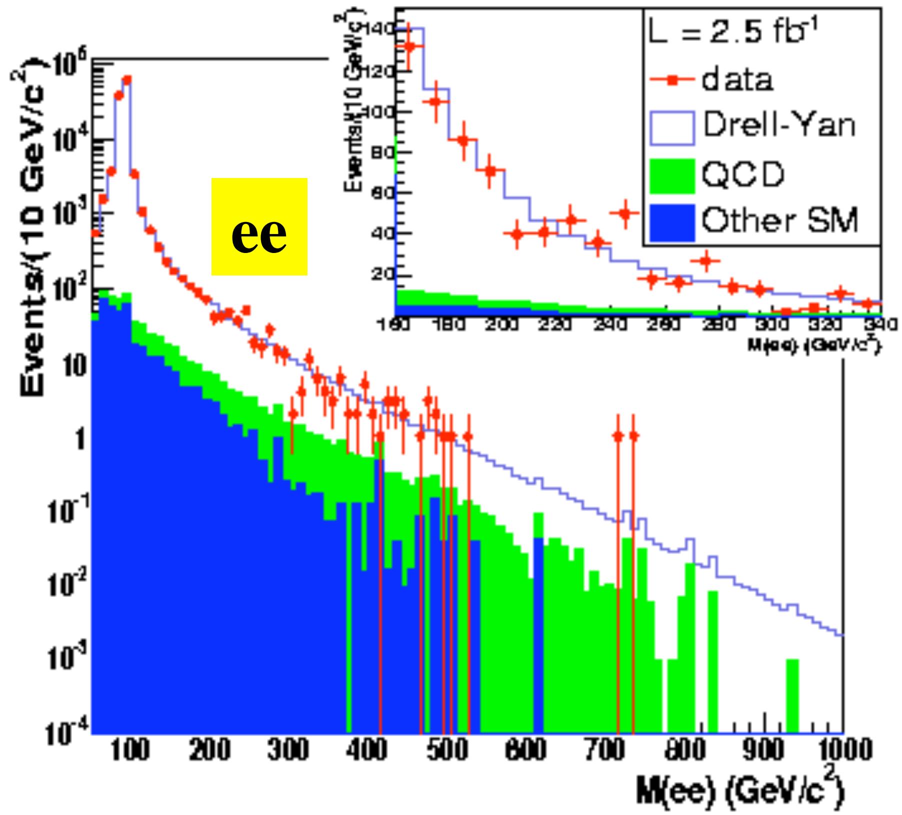
	CDF L=3.7 fb^{-1}	DØ L=6.1 fb^{-1}
Limit at 95%CL	**<4.3 x 10^{-8}**	**<5.1 x 10^{-8}**

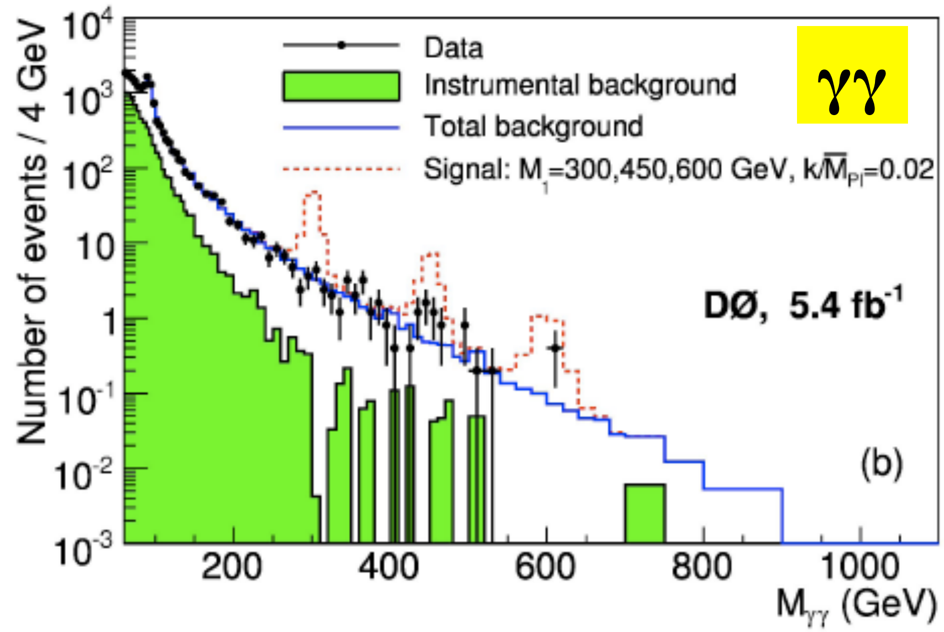
LHCb will supersede Tevatron with 200 pb^{-1}

Beyond SUSY

ee and γγ Mass Spectra



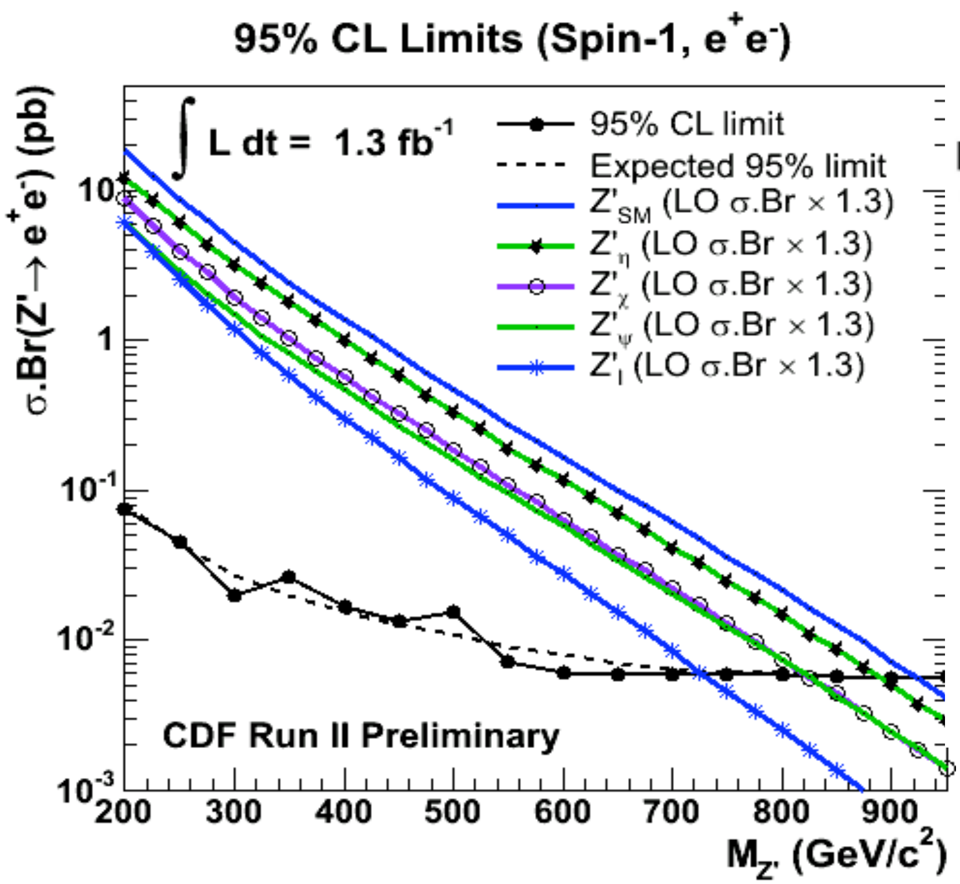


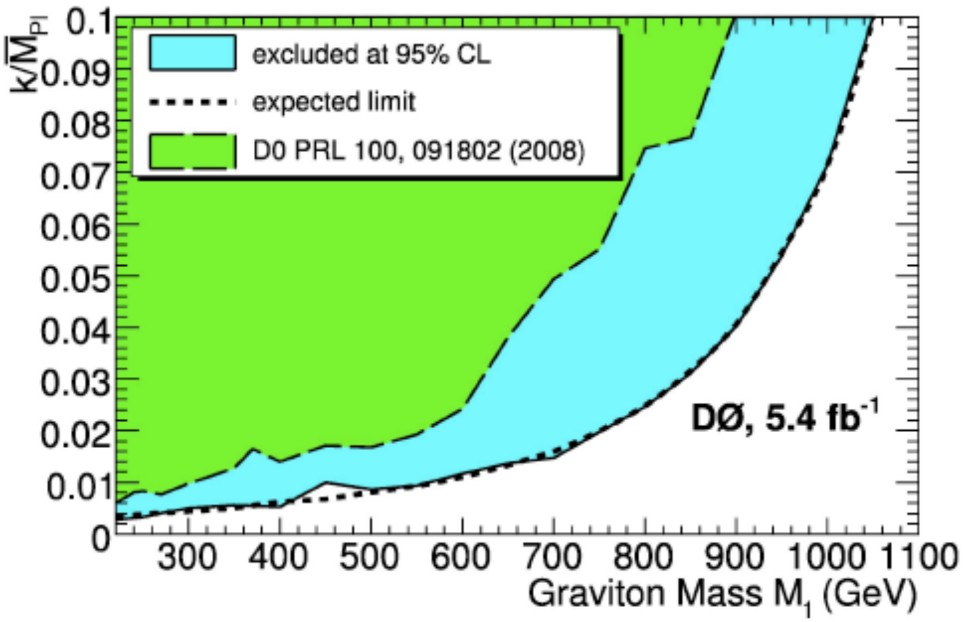


- **Dielectron and diphoton mass distributions**
  - Data agree well with Standard Model spectrum
  - Slight excesses at 450 GeV (D0 γγ) and 250 GeV (CDF ee)

Excluding Z' and Graviton

- Resonance in diphoton or dielectron mass spectrum predicted in
  - Z' models (ee only): Spin 1
  - Randall-Sundrum graviton (ee and γγ): Spin 2



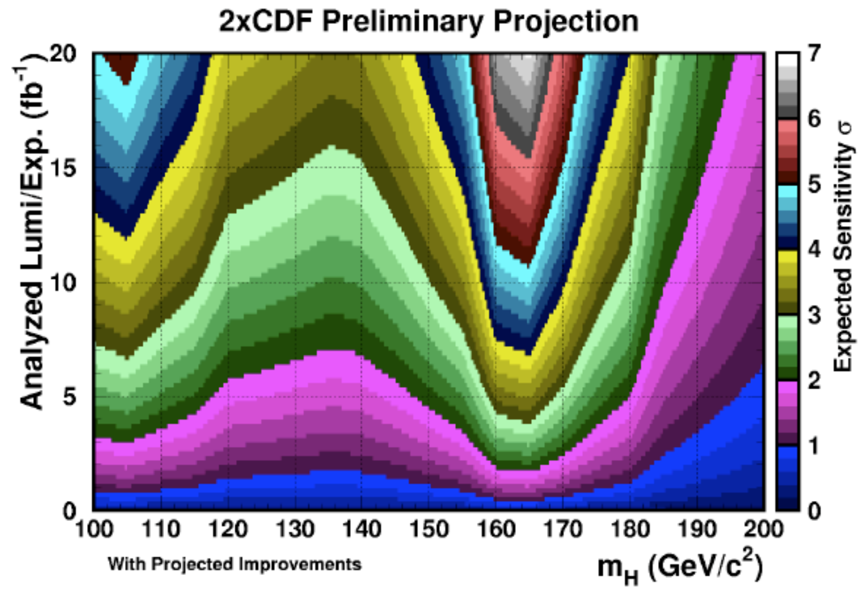


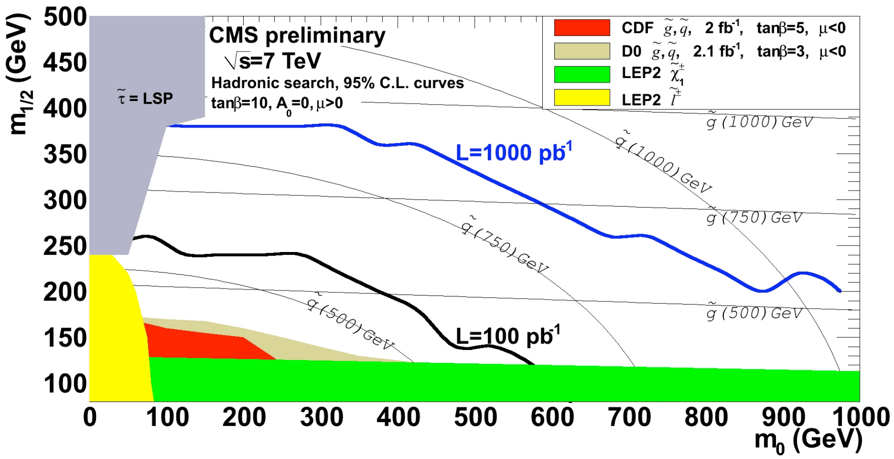
M_G>1050 GeV for k/M_{Pl}=0.1

$M_{Z'}$>923 GeV for SM-like Z'

Summary

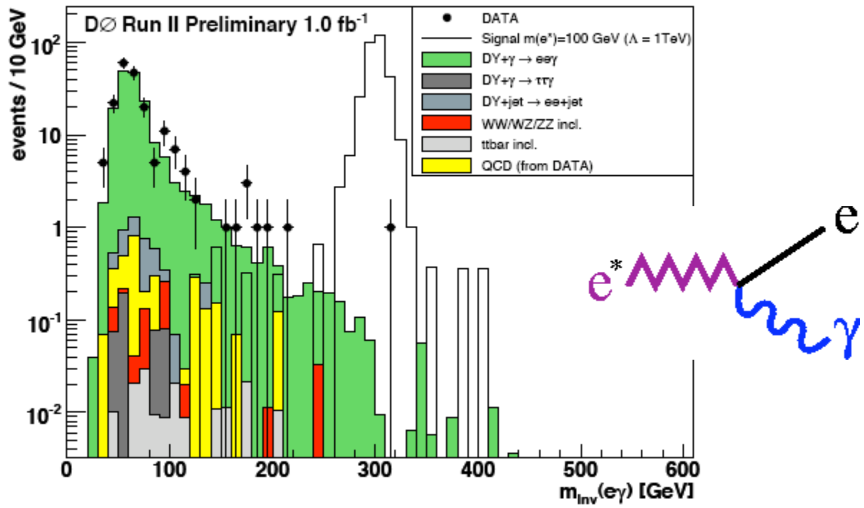
- **We will find new particles at the electroweak scale at Tevatron and/ or LHC**
  - Either "only" the **Higgs-boson**
  - Or **possibly a lot more**
- **Hadron colliders probe fundamental forces and particles in earnest:**
  - **QCD** thoroughly being tested:
    - Exp. precision challenges theory
  - **Electroweak** sector:
    - Indirect : exclude m_H>158 GeV
    - Direct: exclude 158<m_H<175 GeV
  - **Searches** beyond the Standard Model
    - Many direct searches ongoing probing many theoretical possibilities
    - Flavor measurements probe new physics indirectly
- **Great times ahead!**
  - **This was merely a glimpse of the physics we can do now/soon!**

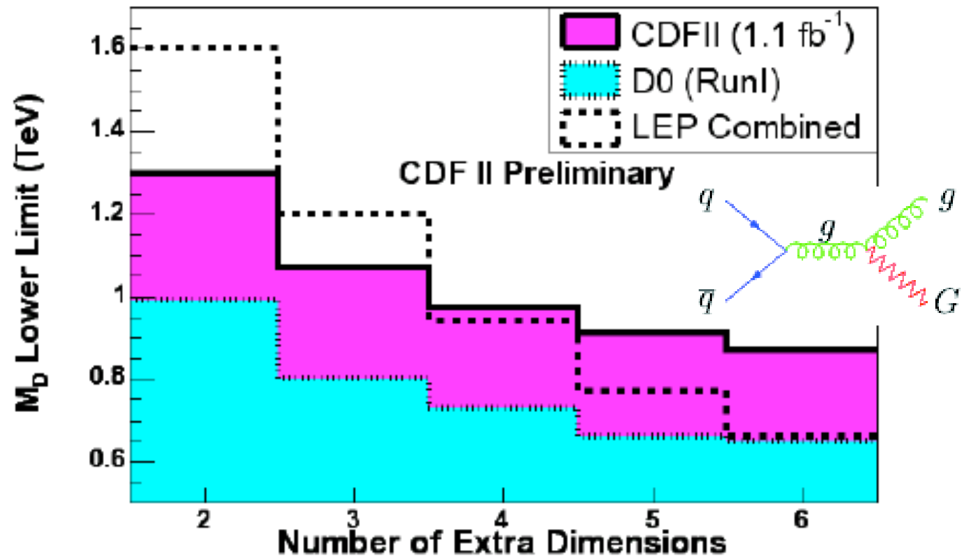


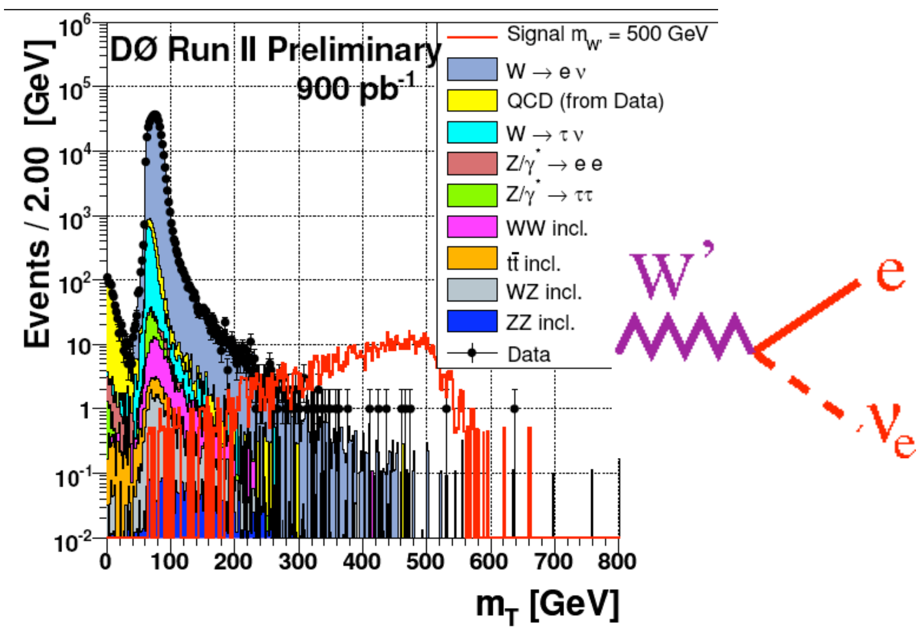


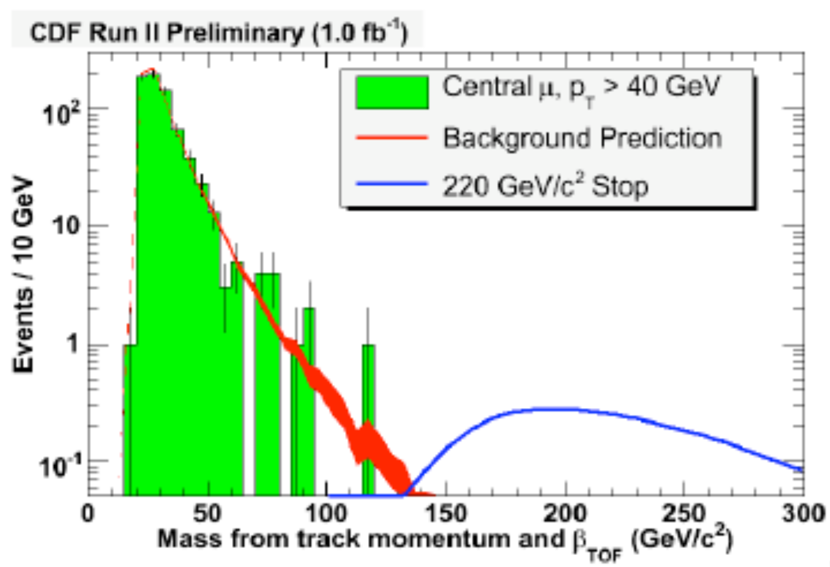
Backup

Many More Searches

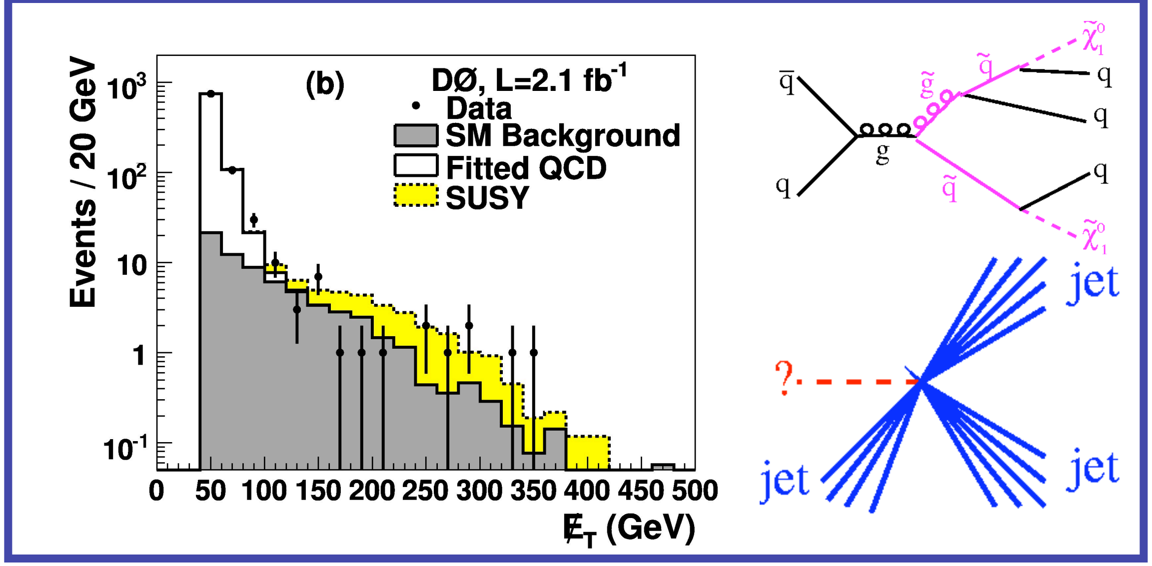


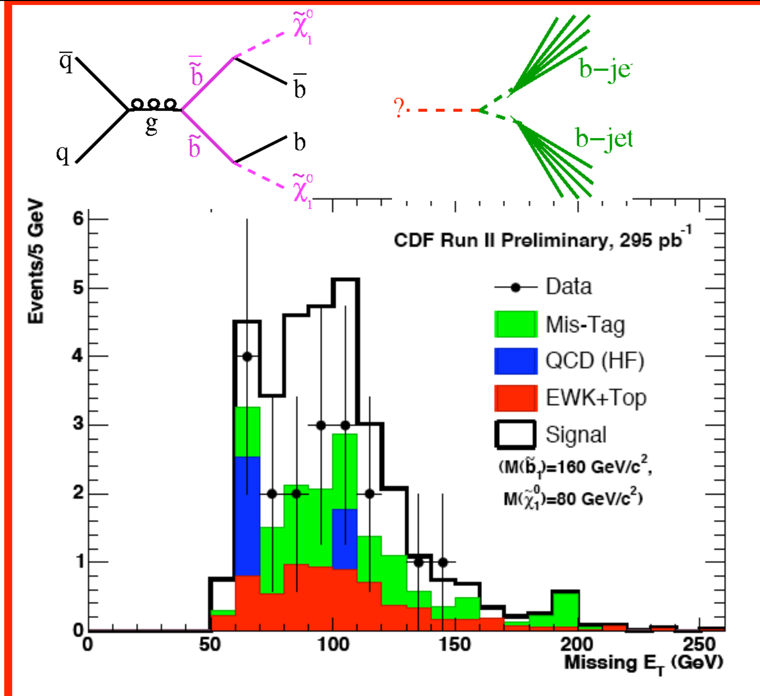


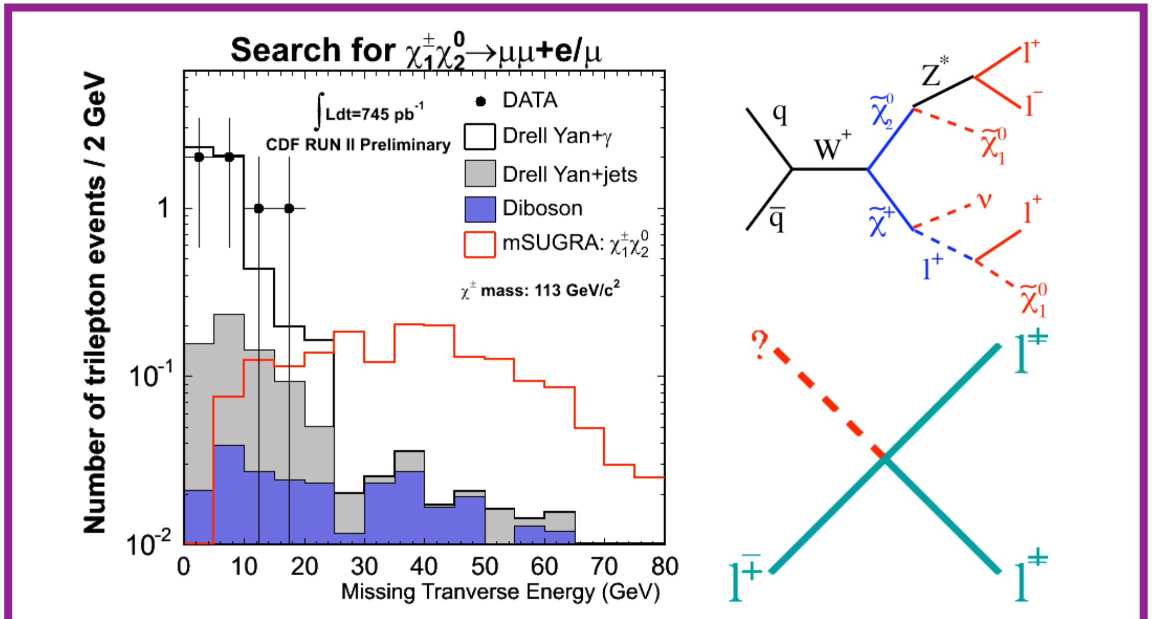


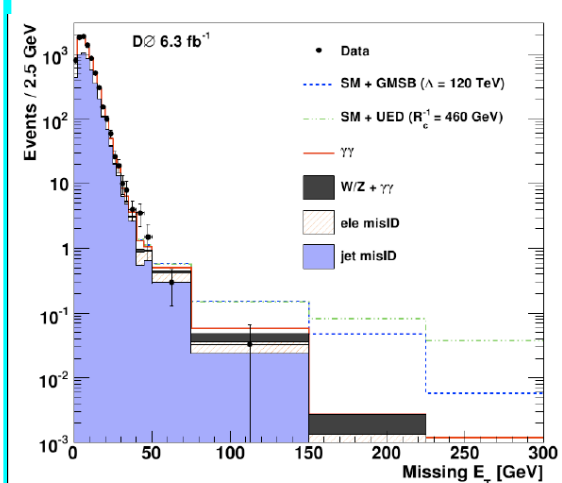


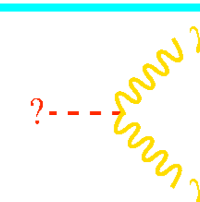
More Supersymmetry Searches



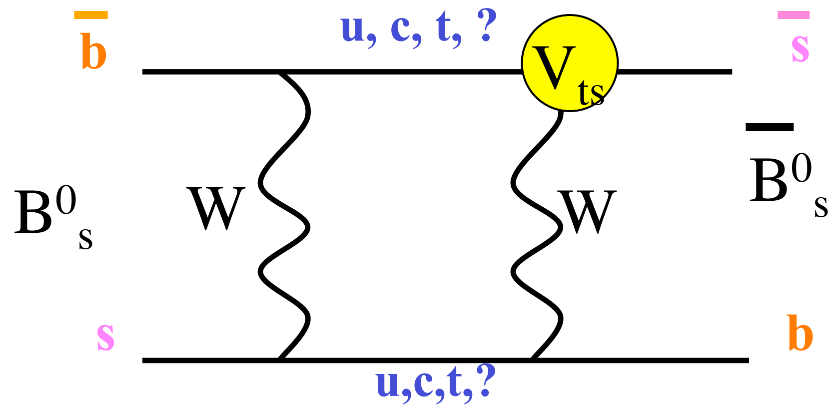








B_s - $\overline{B}_s$ Oscillation Frequency



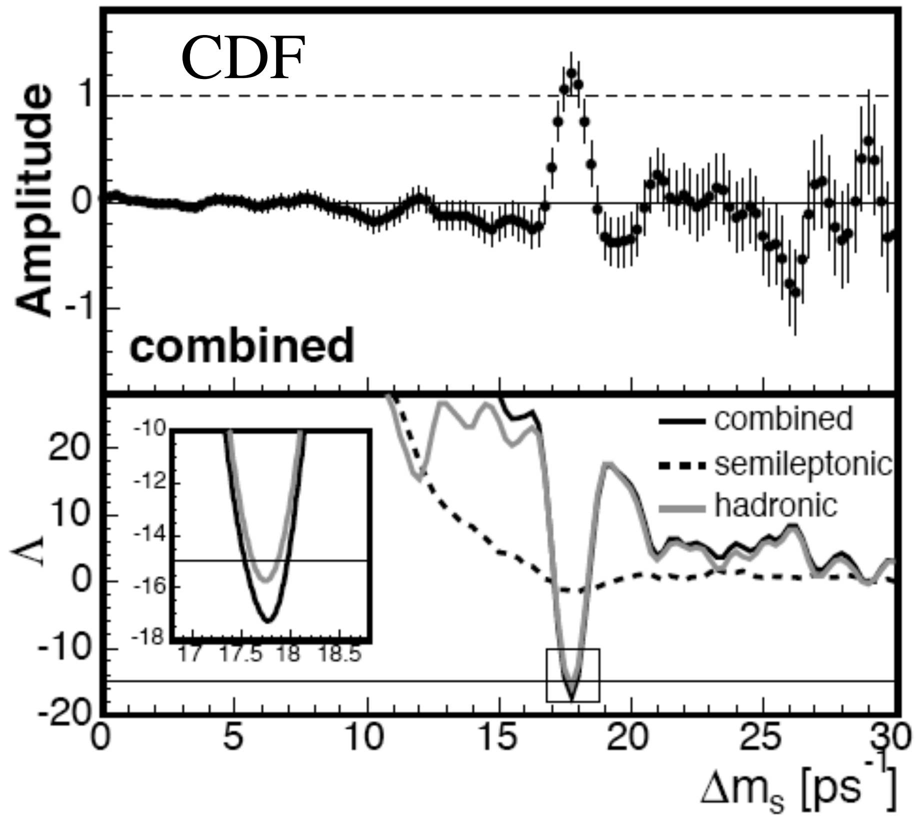
CP-odd: $B_H = pB + q\overline{B}$
CP-even: $B_L = pB - q\overline{B}$
with $|p|^2 + |q|^2 = 1$

$$P^{B_s}_{unmix} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}\left(1 + A\cos\Delta m_s t\right)$$

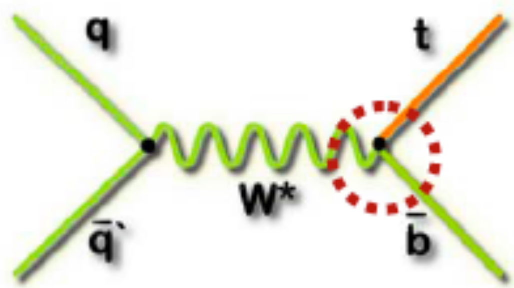
$$P^{B_s}_{mix} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}\left(1 - A\cos\Delta m_s t\right)$$

H. G. Moser, A. Roussarie, NIM **A384** (1997)

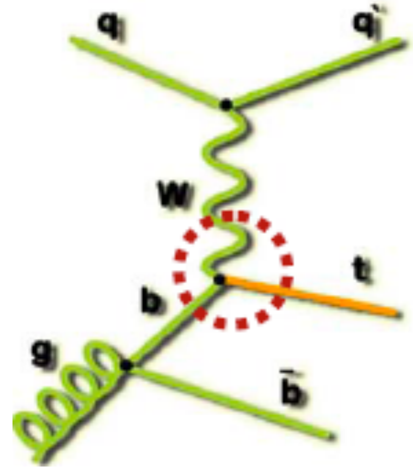
- **CDF Measurement:**
  - Prob. of stat. fluctuation: 8×10^{-8}
  - $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}
  - $|V_{td}/V_{ts}| = 0.2060 \pm 0.0007 {}^{+0.008}_{-0.006}$ (th.)
- **DØ:** $17 < \Delta m_s < 21$ ps^{-1}

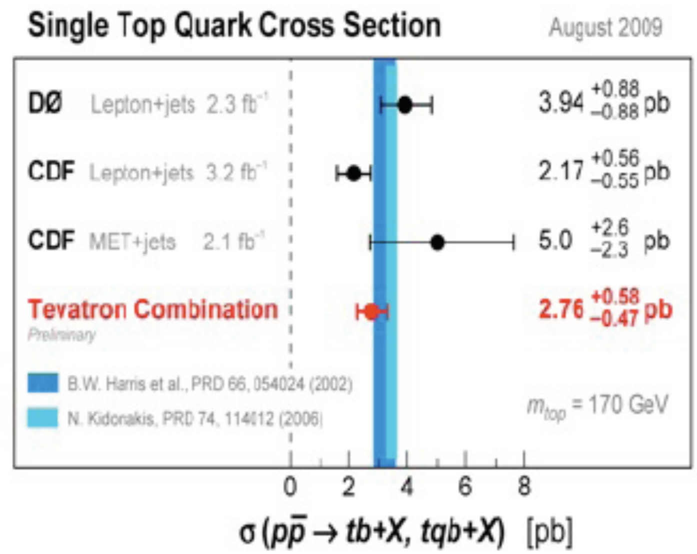


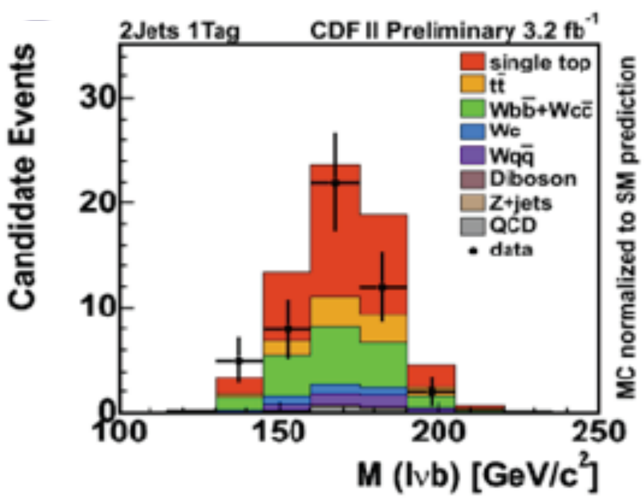
Single Top Production

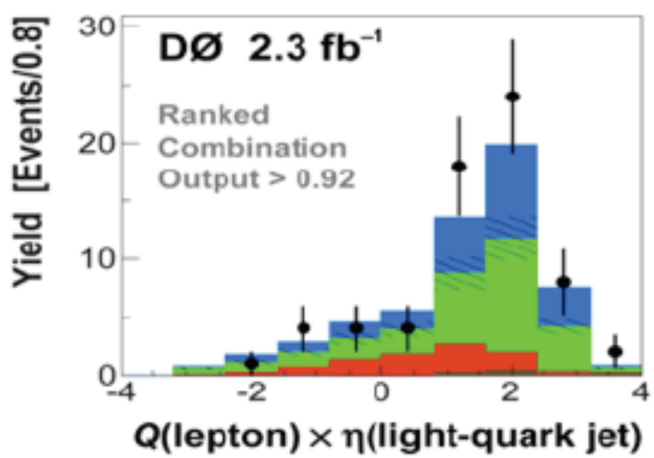


$\sigma \propto V_{tb}^{2}$





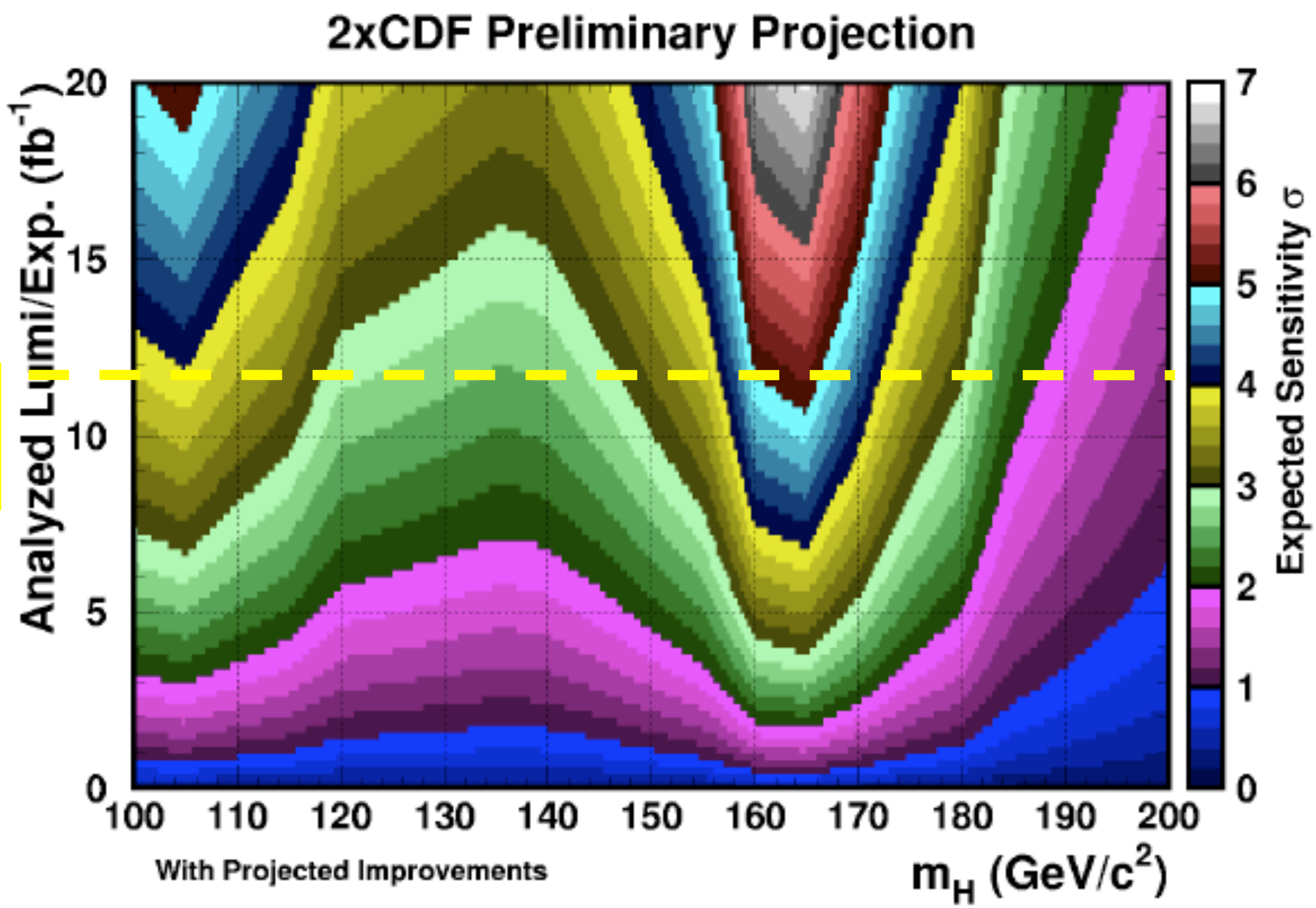




$V_{tb}=0.91 \pm 0.08$

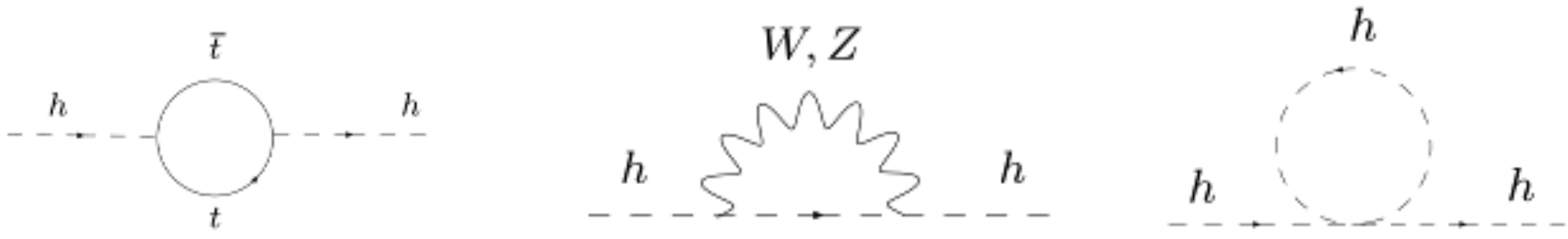
- 4.8σ observation of single-top production
- Uses elaborate techniques also needed for Higgs search

Prospects for Tevatron Higgs Search



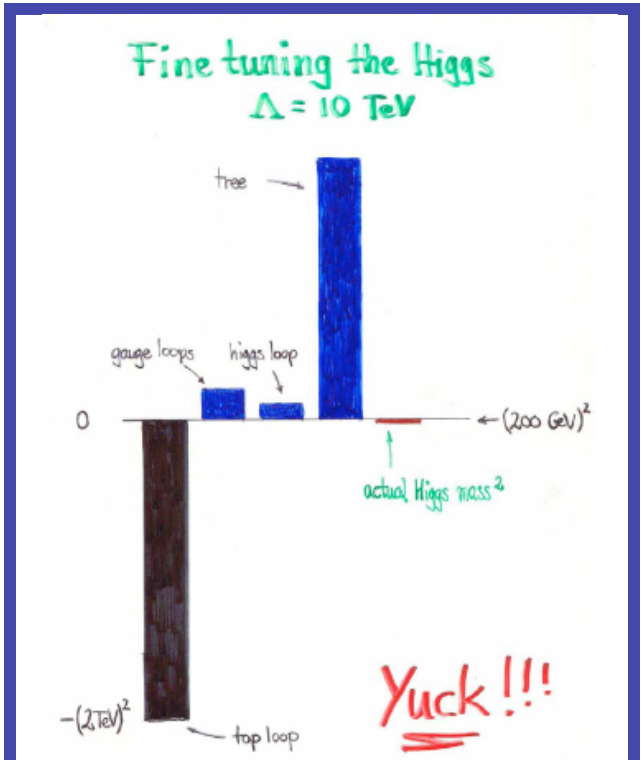
End of 2011
2.4-5.2 σ

Problems of the Standard Model



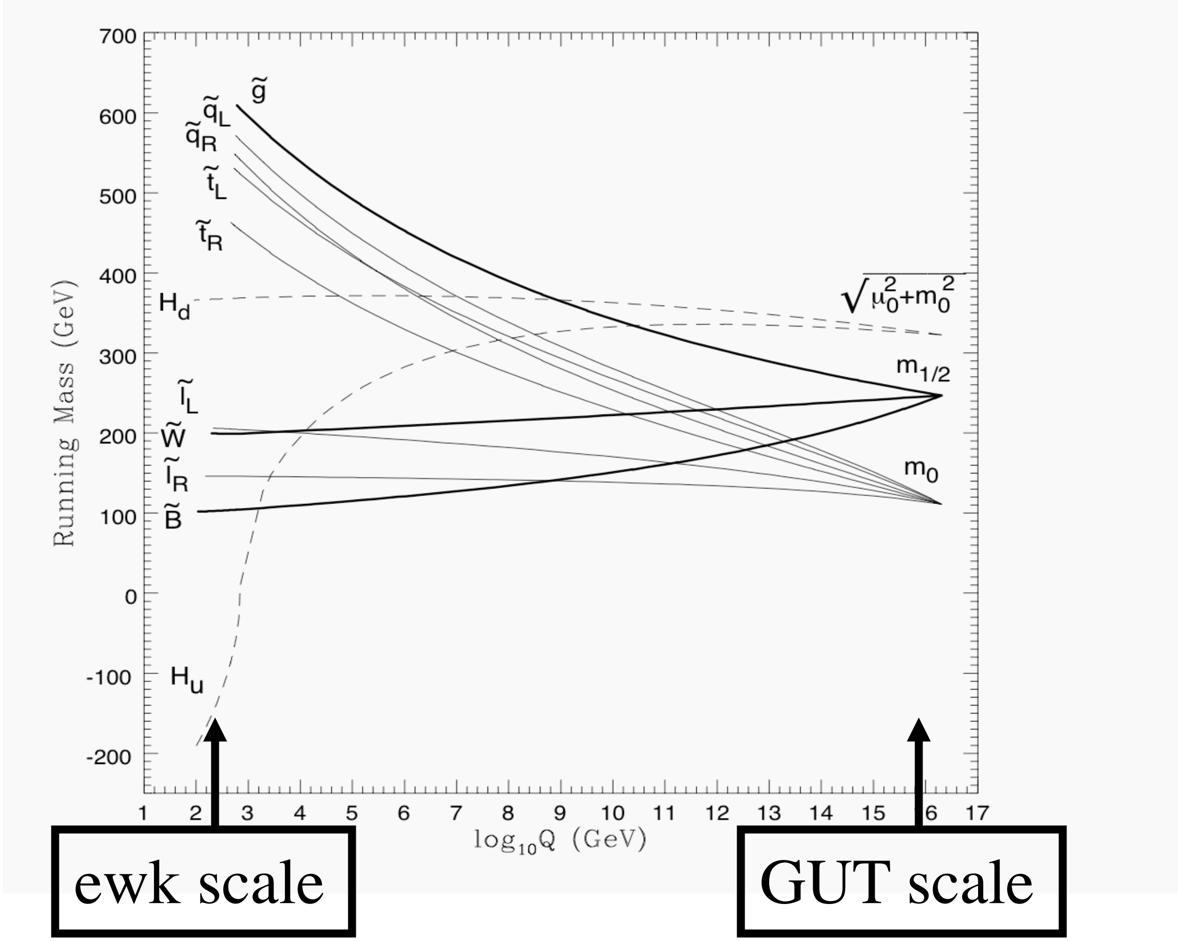
$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2}\,\frac{3}{2}\,\frac{\Lambda^2}{m_W^2}\left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right] + \cdots$$

- Large fine-tuning required:
  - m_H naturally similar to cut-off Λ
- Accounts only for **$17.5^{+2.1}_{-1.1}$%** of the matter on the Universe
  - No dark matter candidate
- No prediction for
  - fundamental constants, unification of forces, number of generations, mass values and hierarchy of SM particles, anything to do with gravity



M. Schmaltz, ICHEP 02

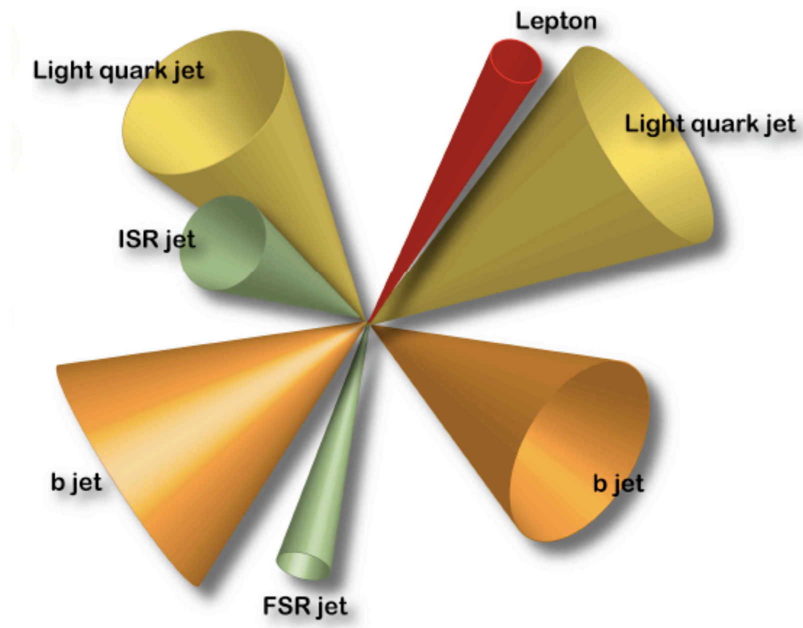
Mass Unification in mSUGRA

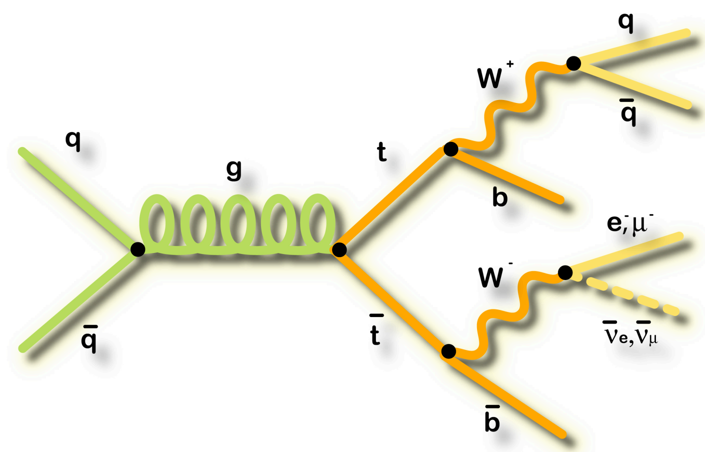


- Common masses at GUT scale: m_0 and $m_{1/2}$
  - Evolved via renormalization group equations to lower scales
  - Weakly coupling particles (sleptons, charginos, neutralions) are lightest
  - Strongly coupled particles (squarks, gluino) are heaviest

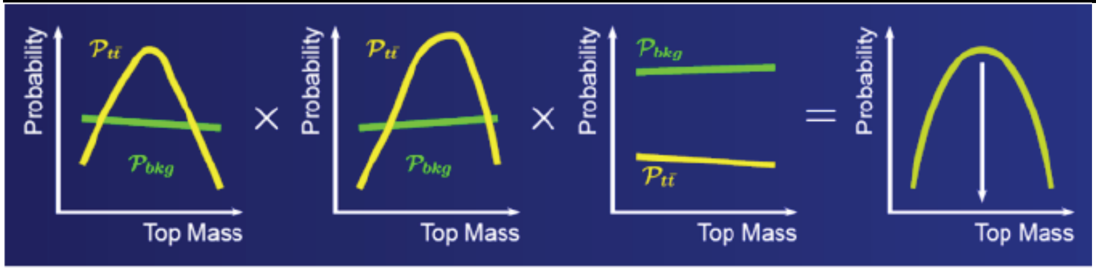
Top Mass in tt→(blν)(bqq)

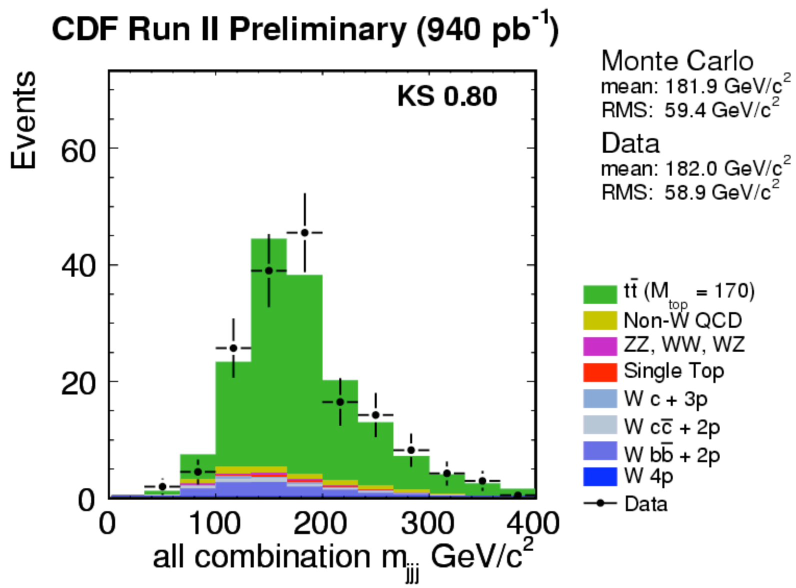
- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires $m(t)=m(\bar{t})$
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top

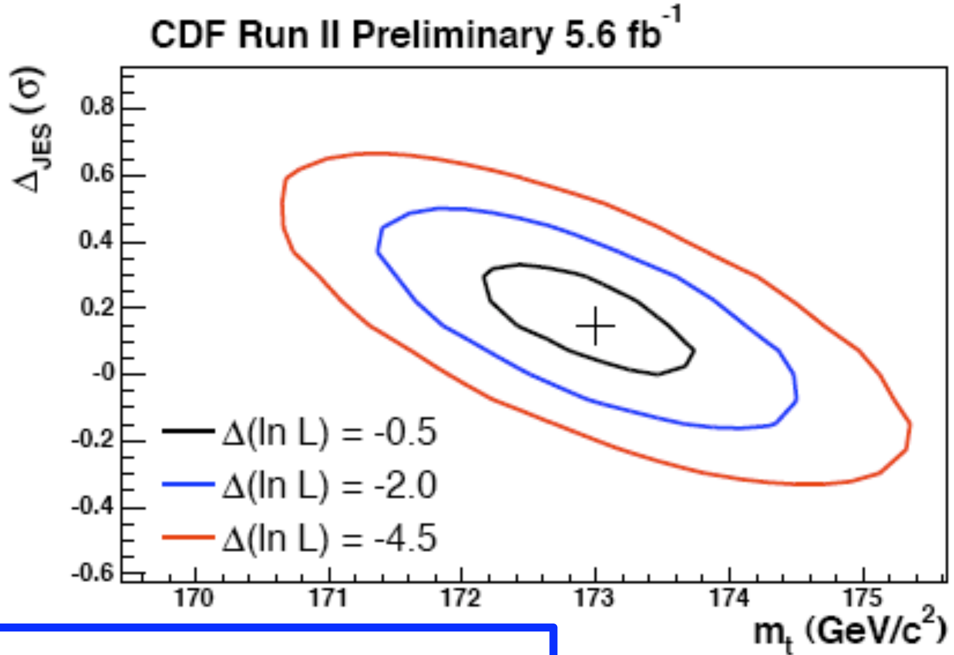




Precision Measurement of m_{top}







m_{top}=173.7±0.8±1.6 GeV (L=2.6 fb^{-1})

m_{top}=173.0±0.6±1.1 GeV (L=5.6 fb^{-1})