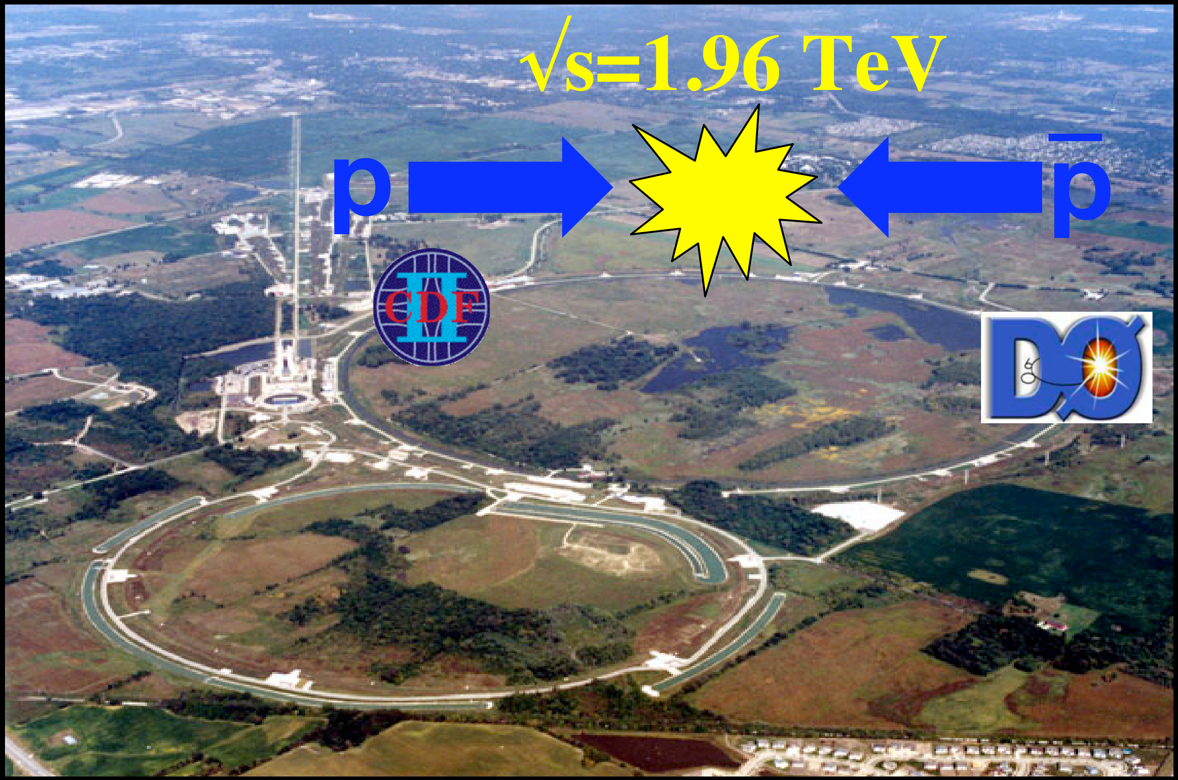
The Tevatron as a Probe of the Fundamental Particles and their Interactions in our Universe



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DESY Seminar, December 2008

The Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\!\!\!/\,\psi$$

$$+ \psi_i\lambda_{ij}\psi_j h + \text{h.c.}$$

$$+ |D_\mu h|^2 - V(h)$$

$$+ \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

gauge sector ✓

flavour sector ✓

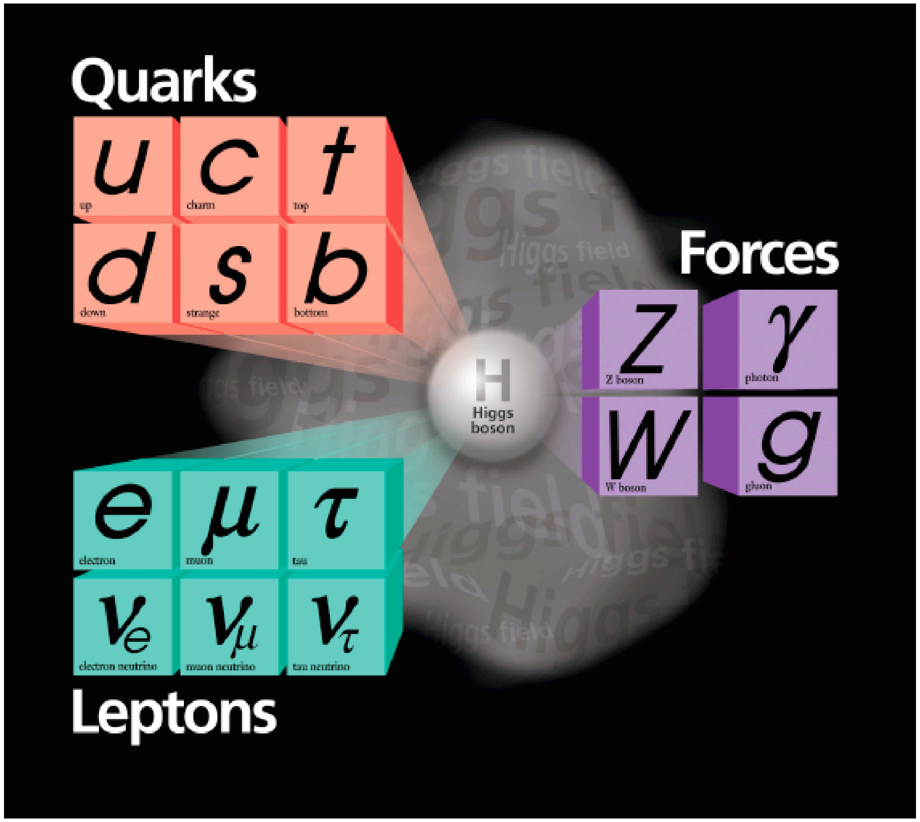
EWSB sector ✓

ν mass sector

… and beyond?

- supersymmetry (many variants)
- extra spacetime dimensions ✓
- compositeness
- strong electroweak symmetry breaking
- …
- something new?!

The Standard Model and it's Problems



- What is the **origin of electroweak symmetry breaking**?
  - Is there a Higgs boson?
  - And WHERE is it?
- What is the **Dark Matter**?
  - Is it produced it at colliders?
- Why is **gravity** so much weaker than the other forces?
- Where did all the **anti-matter** go?
- Do all **forces unify** at high energy?
- …

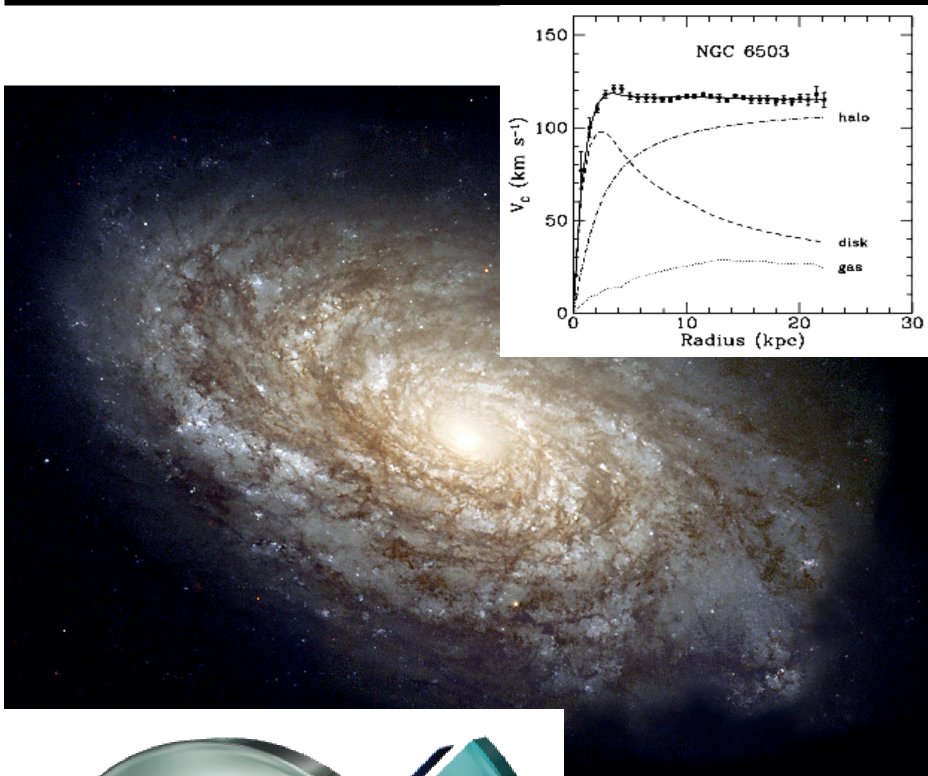
- Tevatron is just touching the TeV scale:

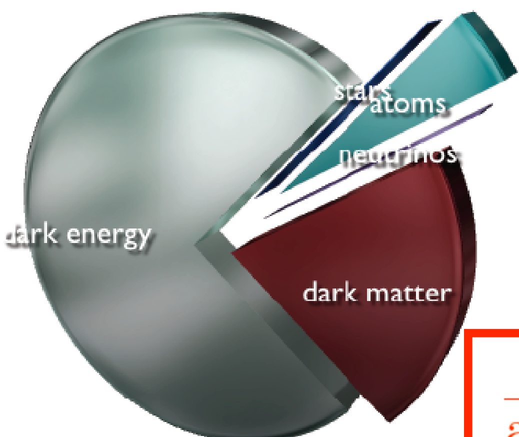
  -Can partially address these questions

  -Can test theoretical and experimental tools

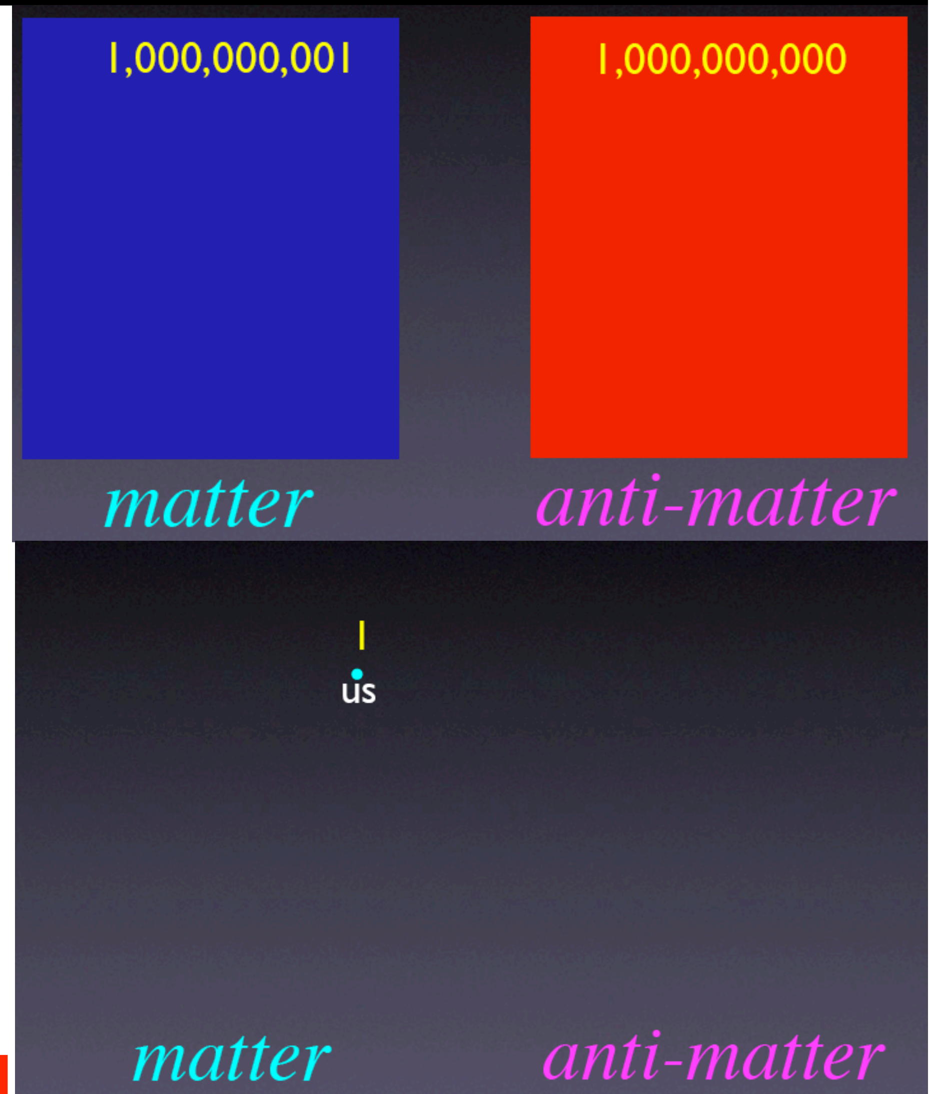
- LHC was build to fully explore the TeV scale

Problems: Dark Matter and Anti-Matter



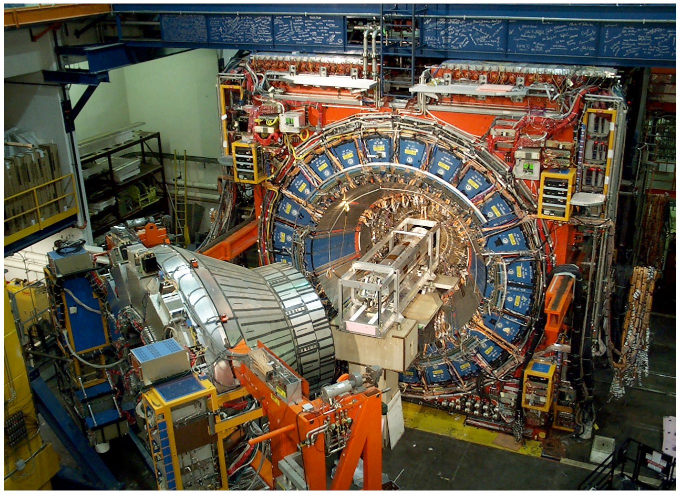


$$\boxed{\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}}$$



Outline

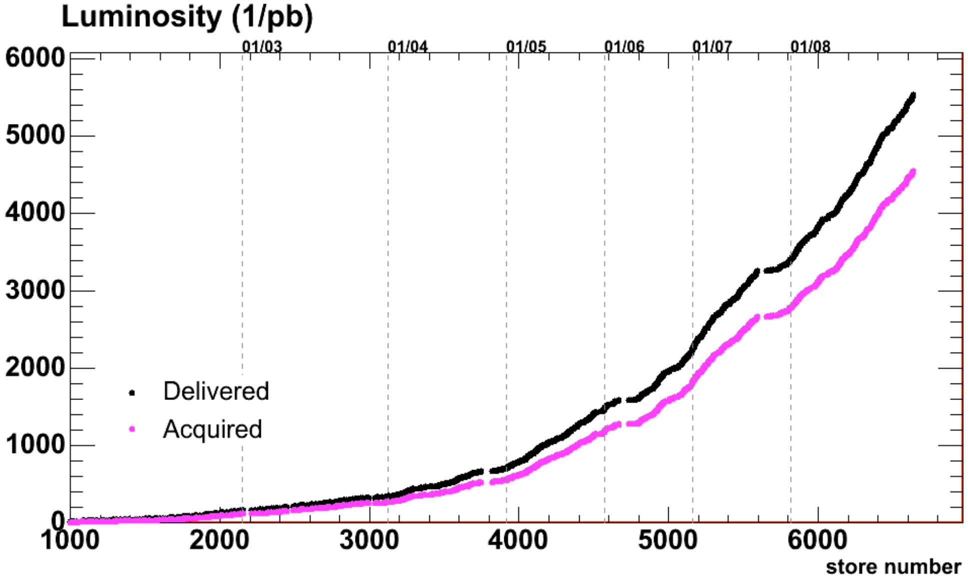
- **Testing Particle Production**
  - Jets, W's and Z's, b-jets, top quarks
    - Builds the basis for searches for Higgs boson and new physics
- **Electroweak Symmetry Breaking**
  - W boson and top quark mass
  - Higgs boson search
- **Beyond the Standard Model**
  - Supersymmetry and beyond
- **Conclusions and Outlook**



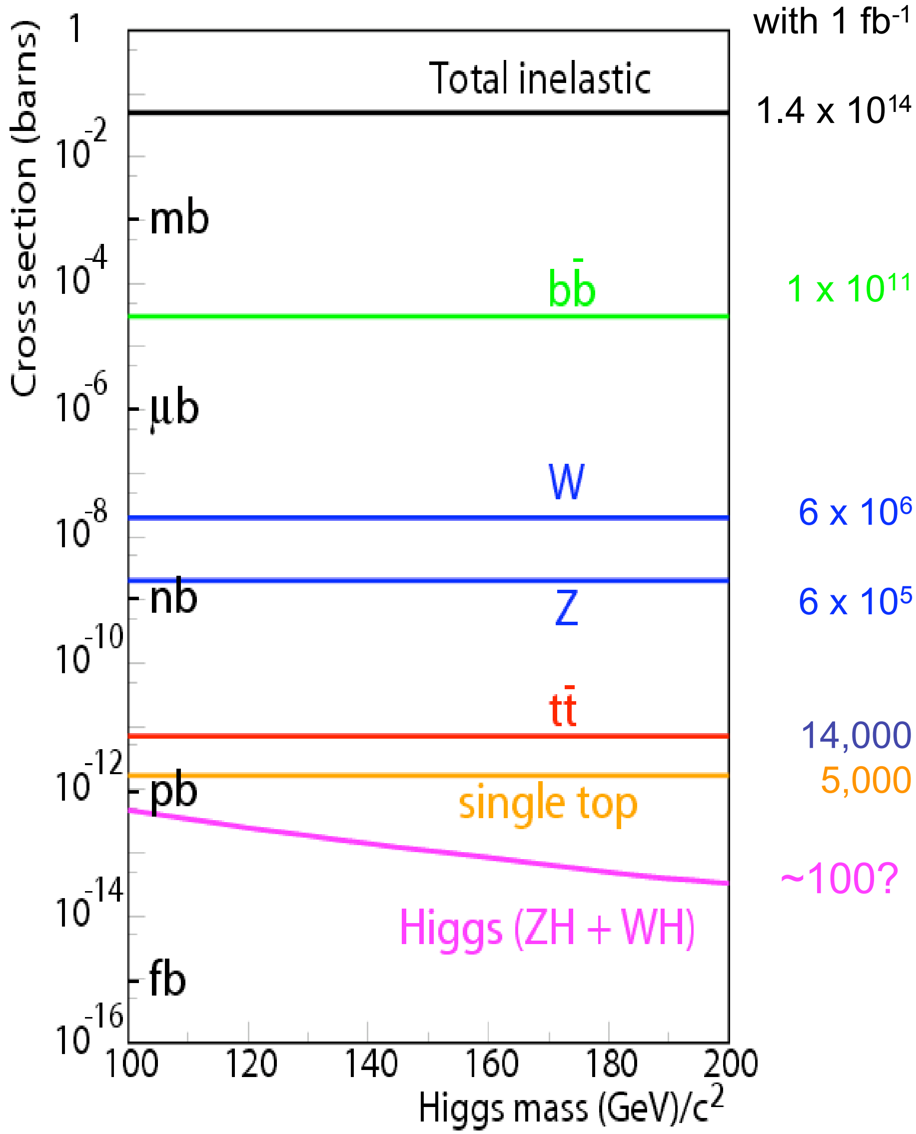
Luminosity and Cross Sections

Delivered: ∫Ldt=5.6 fb^{-1}

Acquired: ∫Ldt= 4.6 fb^{-1}



Excellent data taking:
- **efficiency ~85%:**
- **per week ~50 pb^{-1}**
- **peak lumi: 3.5 x 10^{32} cm^{-2} s^{-1}**



At peak luminosity ~1 W boson per second produced!

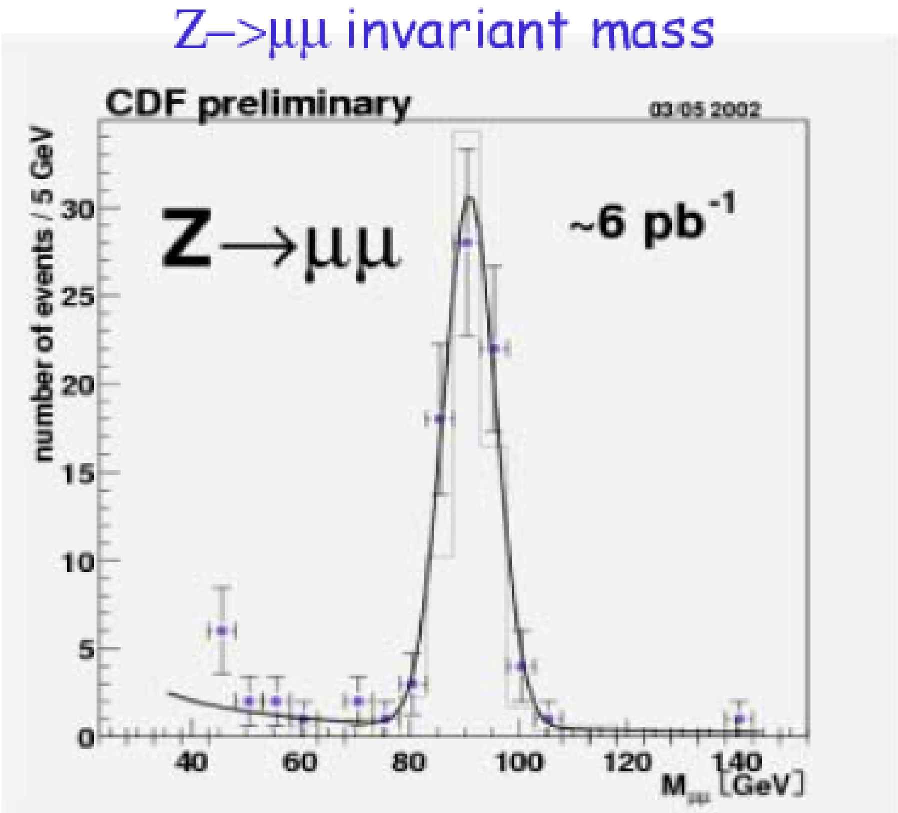
A historic discourse …

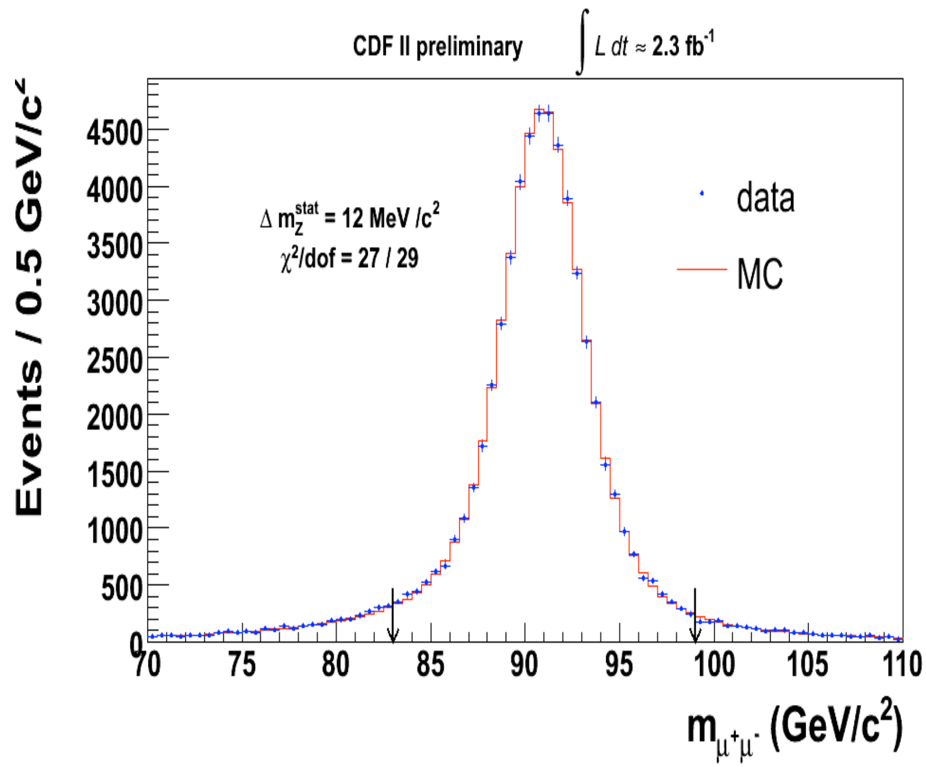
April 2002 (my DESY seminar):

~100 Z bosons ($Z \rightarrow \mu\mu$)

2008 (4.5 fb^{-1}):

~170,000 Z bosons





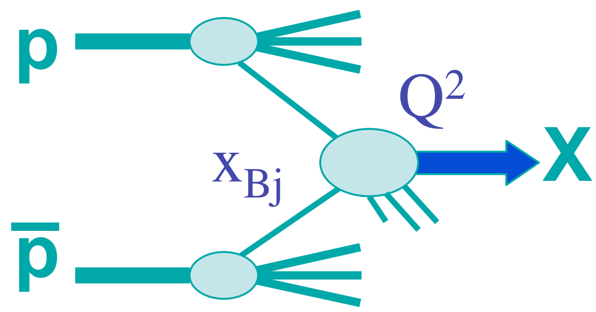
- Amazing how much Tevatron improved in the last 6 years Z's!
  - But the early days (6 pb^{-1}) were also a lot of fun and we learned a lot!

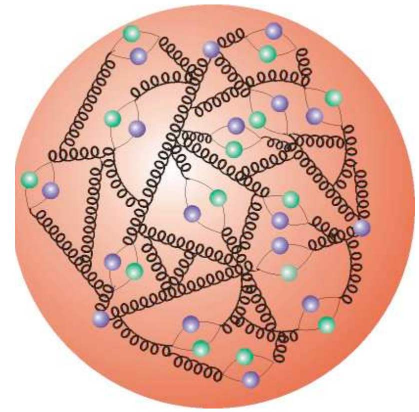
Production of Particles

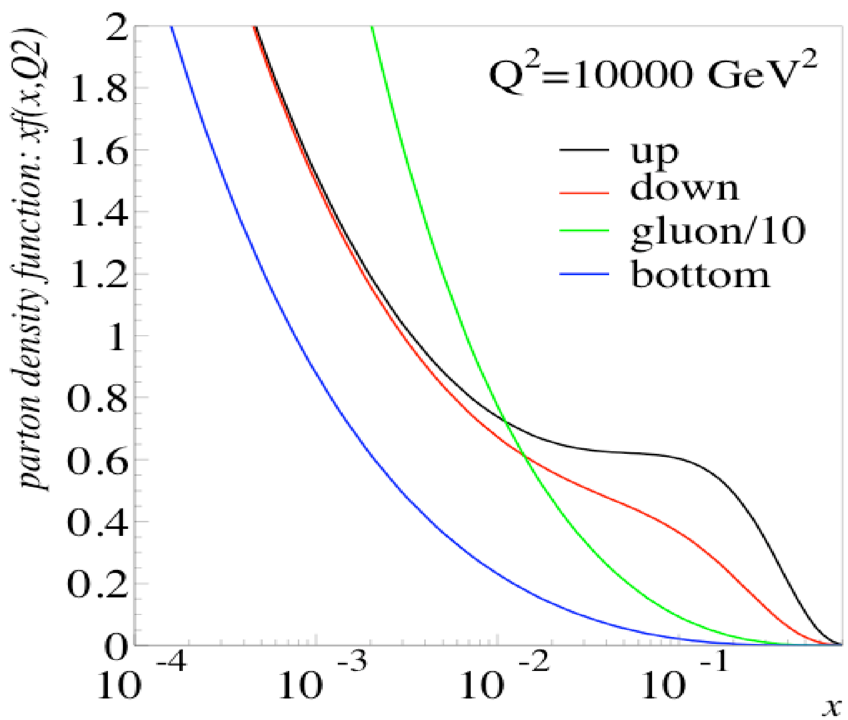
The Proton

- It's complicated:
  - Valence quarks
  - Gluons
  - Sea quarks
- Exact mixture depends on:
  - Q^2: ~$(M^2+p_T^2)$
  - x_{Bj}: fractional momentum carried by parton
- Hard scatter process:

$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

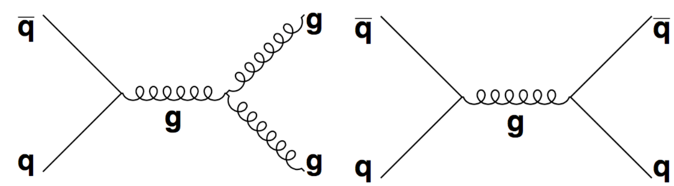


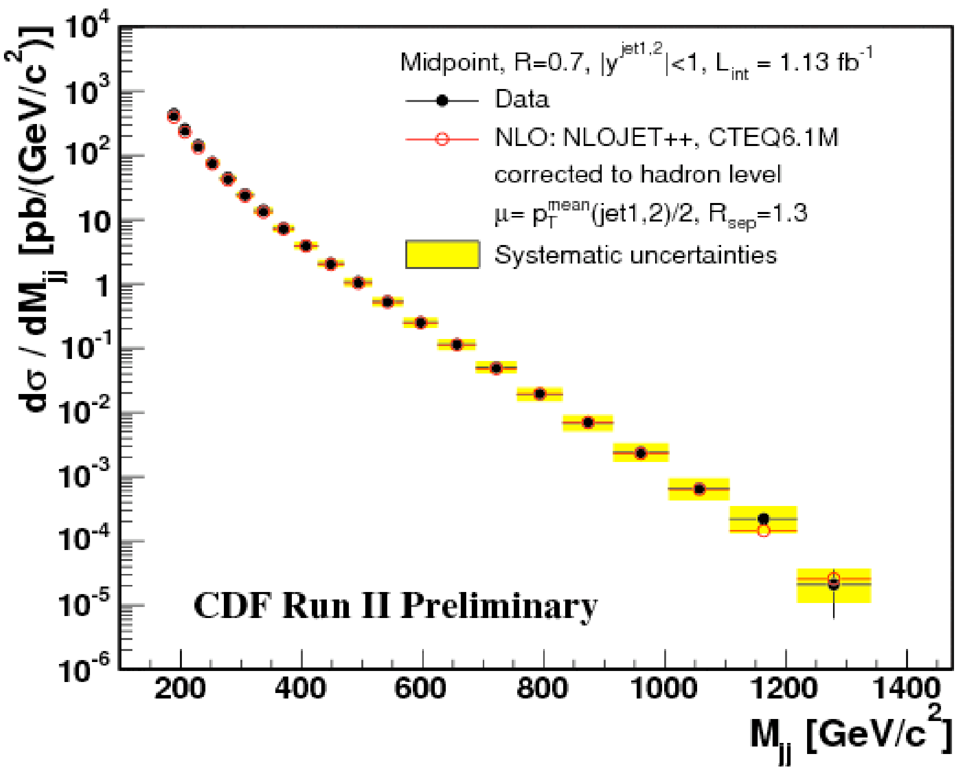


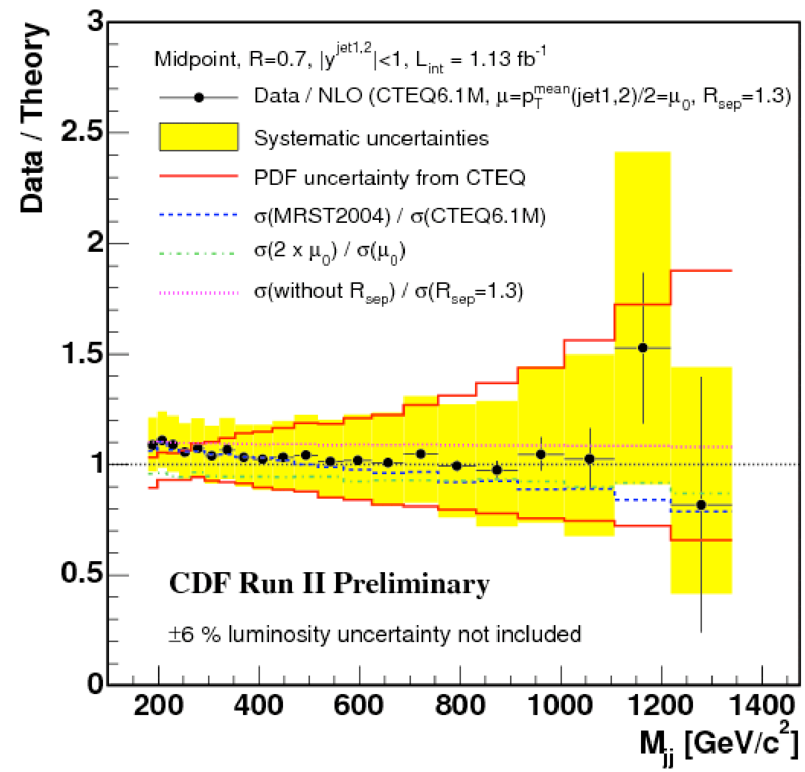


Probed in DIS (HERA!)

Jet Cross Sections

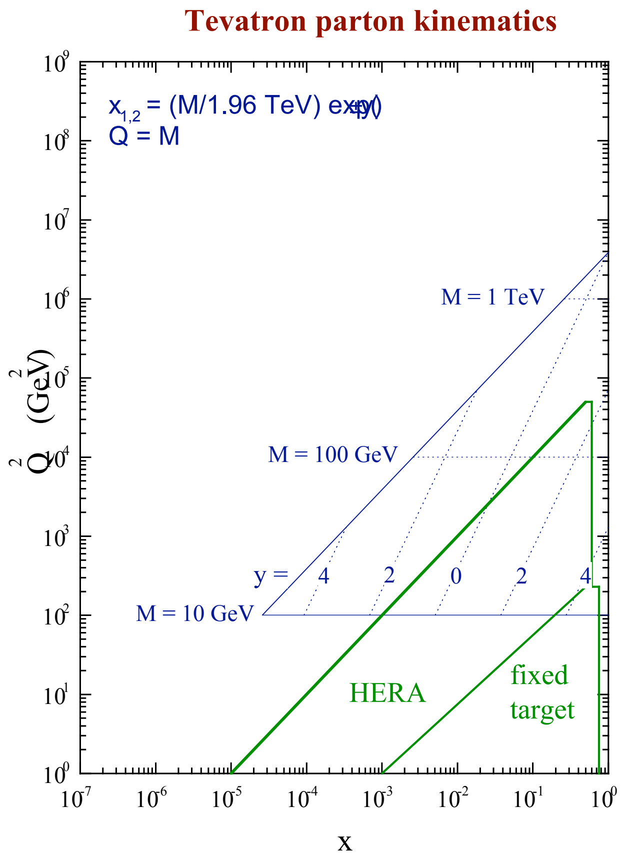


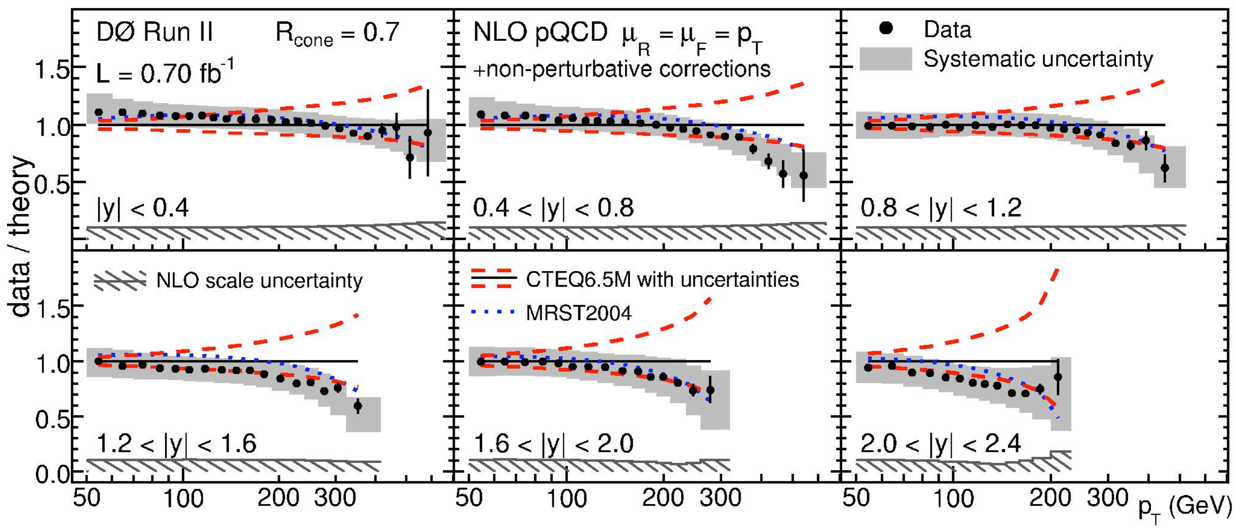




- Cross section measured over 7 orders of magnitude
- Data well described by Standard Model prediction up to masses of 1.2 TeV

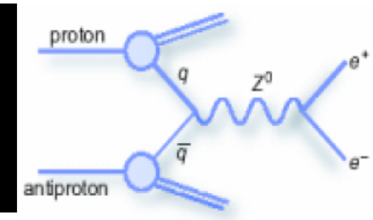
Jet Cross Section: More Differential

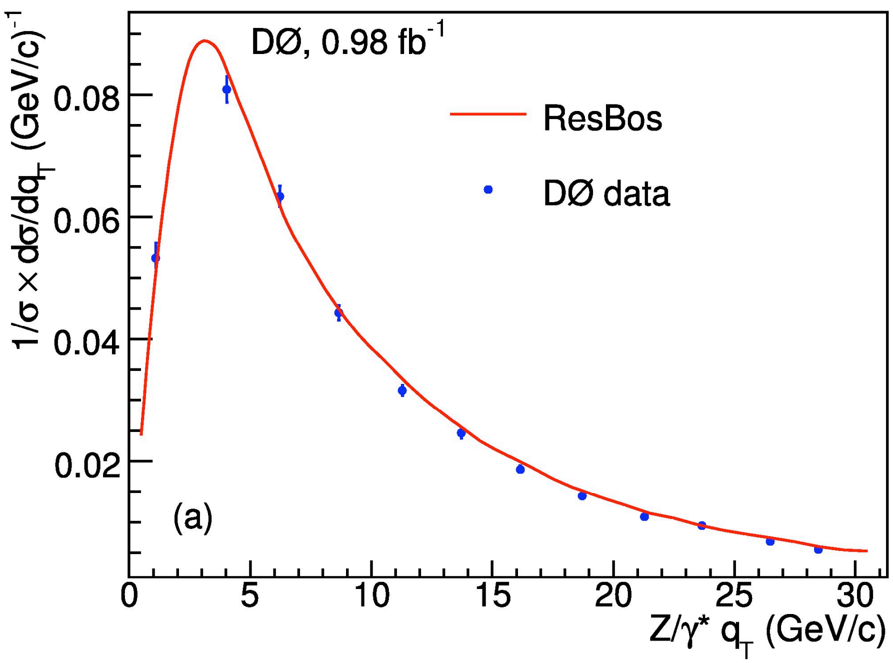


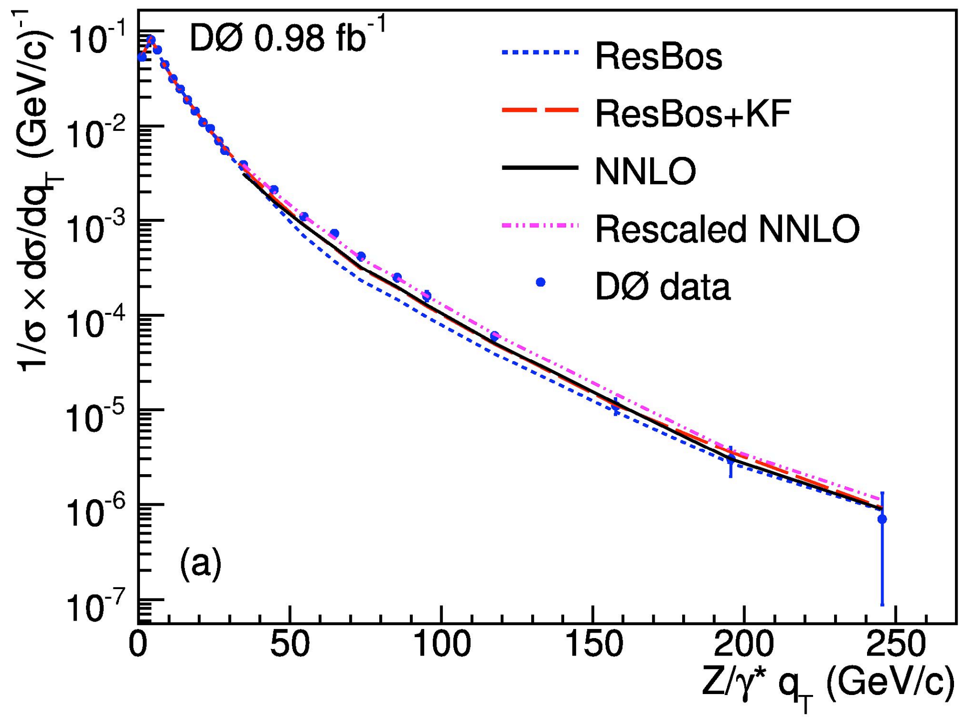


- Double differential measurements in y and p^T map out Q^2-x space
  - High |y|: asymmetric collision
  - Low |y|: symmetric collision
- Data precision better than pdf uncertainties
  - Data constrain the gluon density at high x

Z production

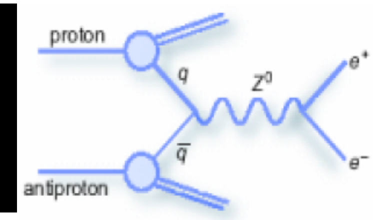




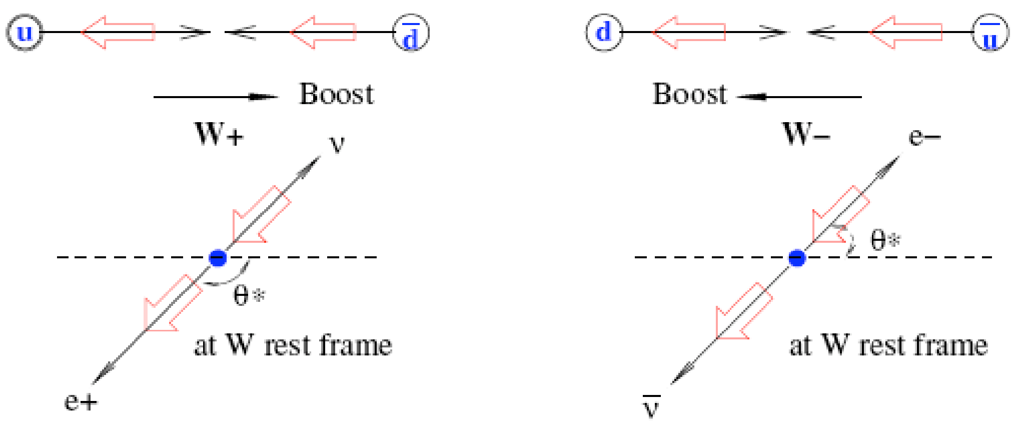


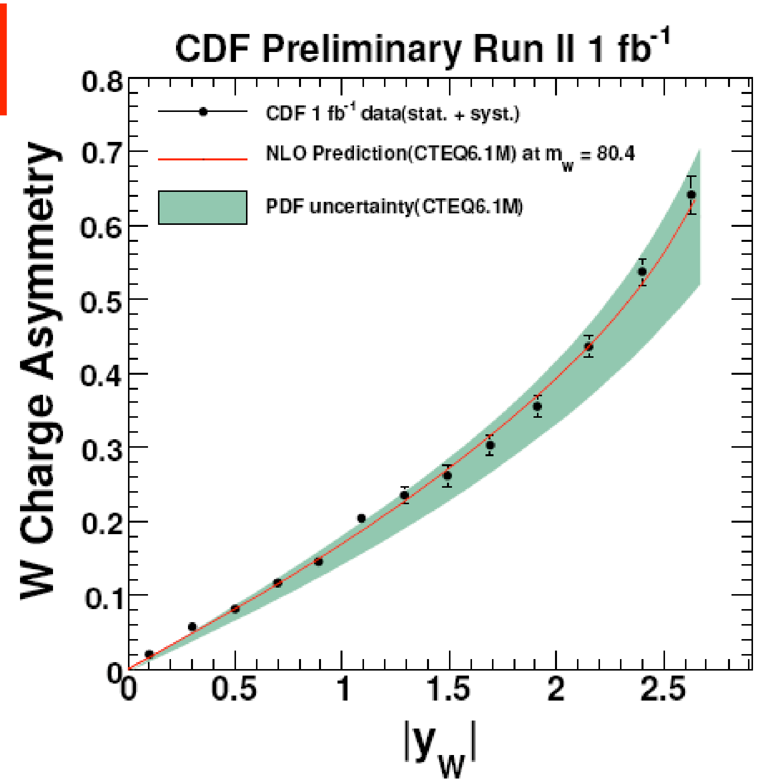
- High precision measurement challenges hard and soft QCD predictions
  - At low $p_T(Z)$: soft non-perturbative effects dominate
    - Important for W boson mass measurement
  - At high $p_T(Z)$: perturbative regime
    - Important for understanding background to new physics searches

W boson charge asymmetry



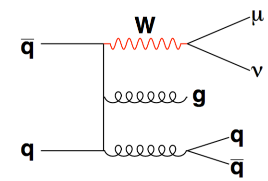
$W^{\pm}$ boost depends on pdf's: $d / \bar{u}$

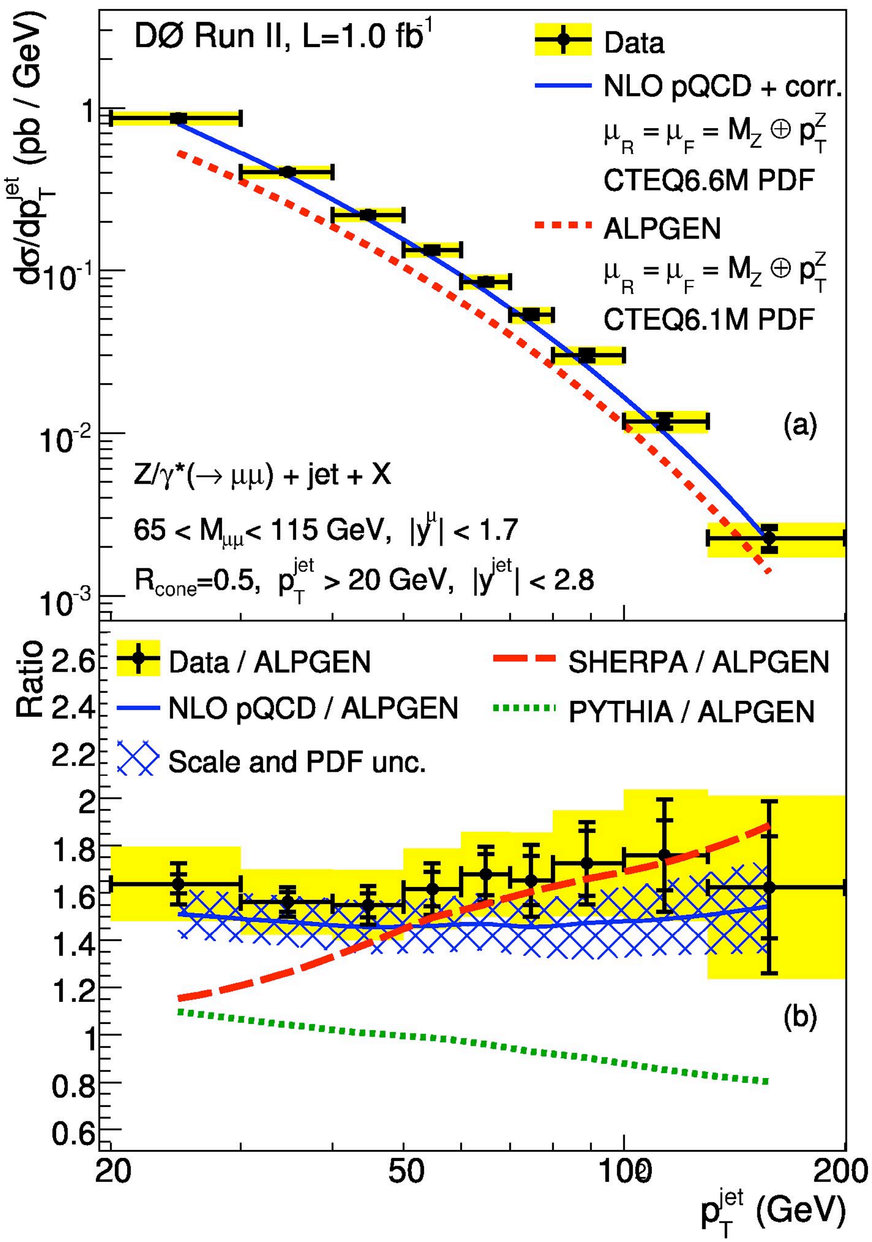


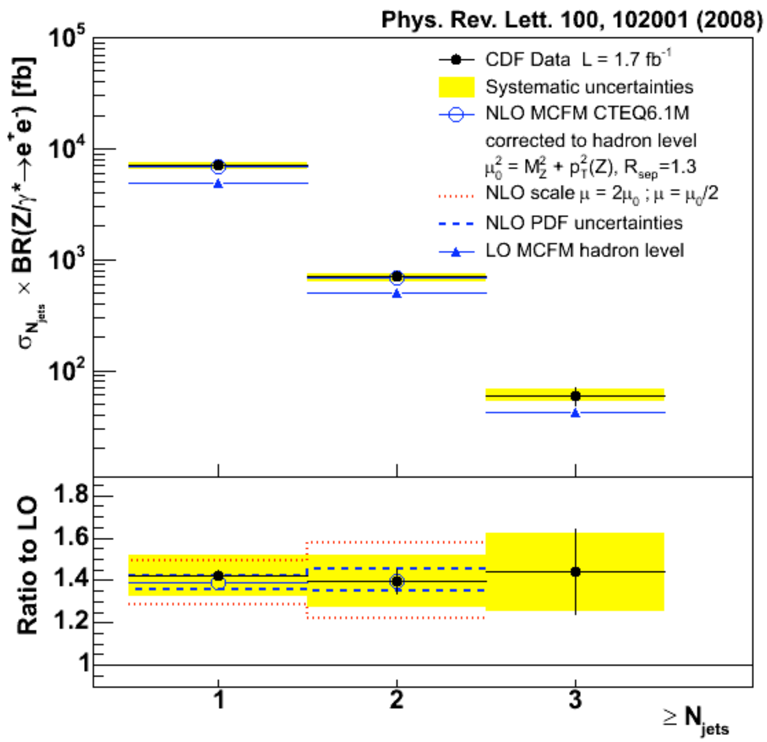


- High precision measurement
  - Constrains parton distribution functions: $d/\bar{u}$
  - Important for measurement of W boson mass

Z + Jets Production

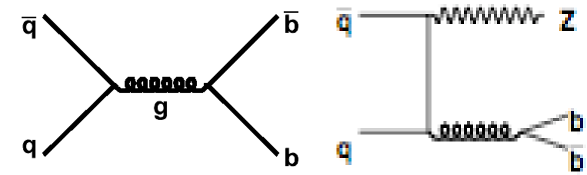


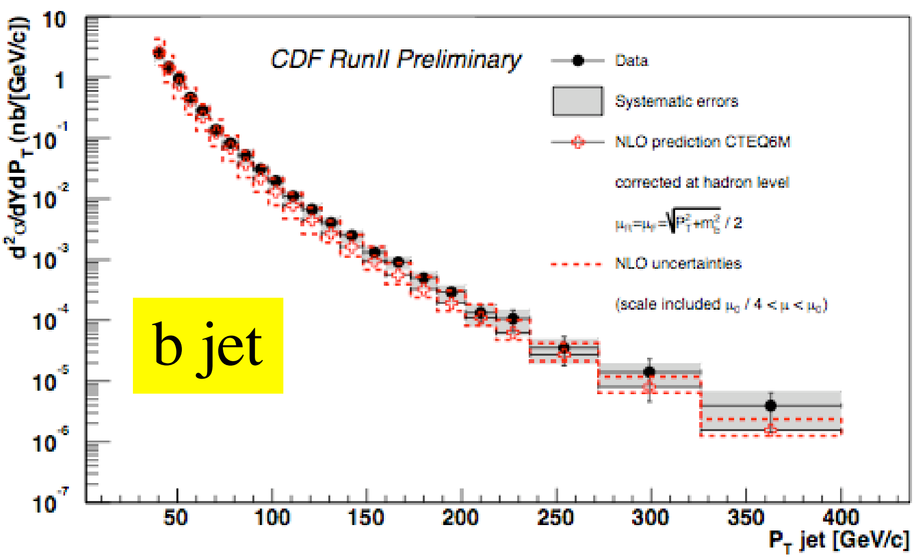


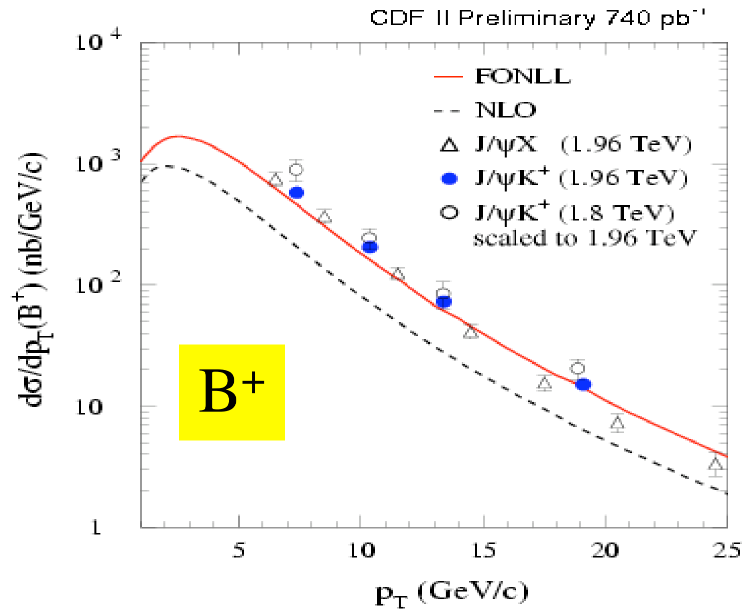


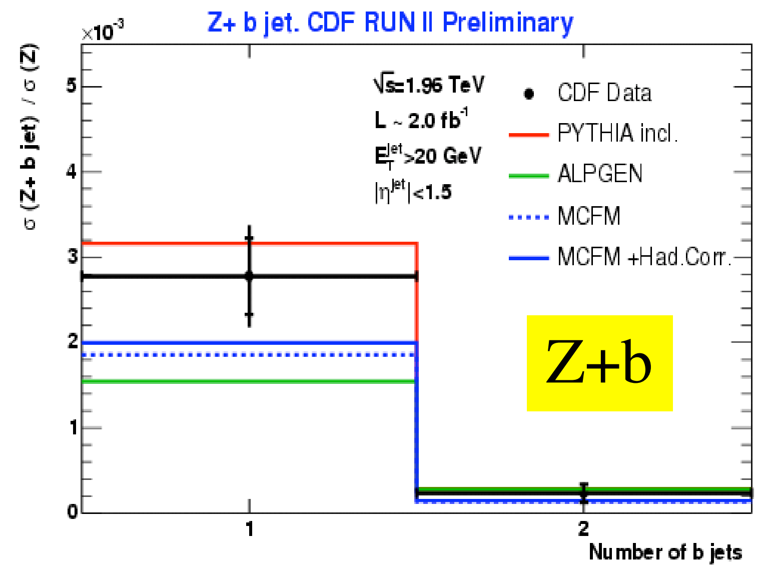
- W/Z+jets are important backgrounds:
  - Top production
  - SUSY
  - Higgs boson
- Data agree with NLO within ~15%
  - MC models more or less successful

b-quark Production



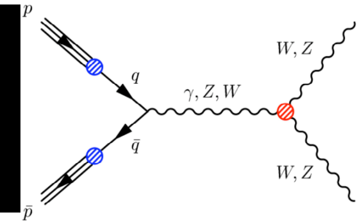


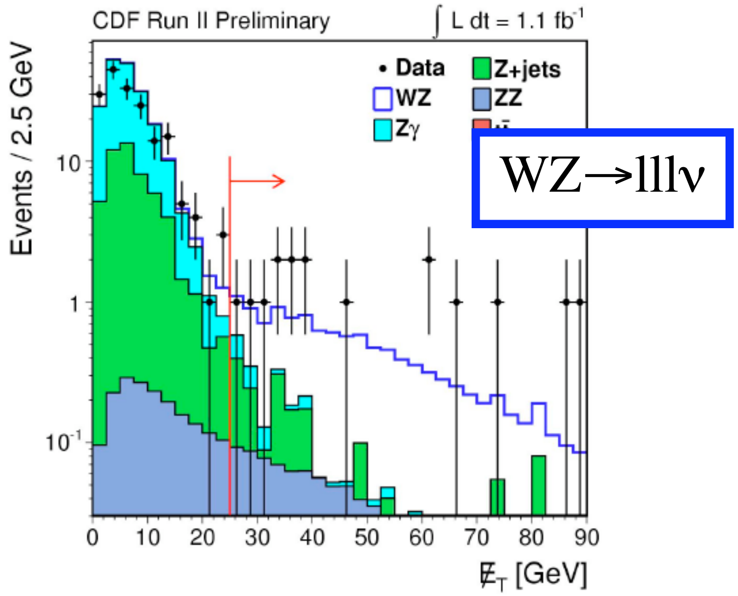


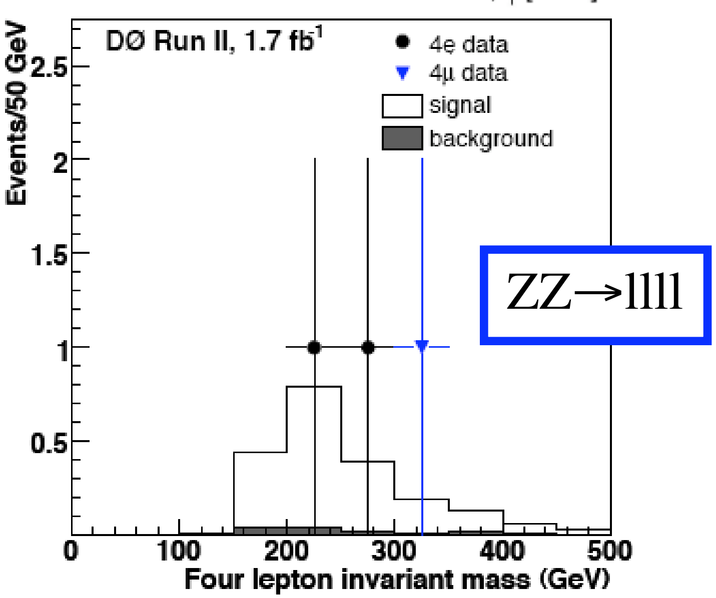


- Measurements of b-jet production in variety of processes
  - Data agree with theoretical predictions within large uncertainties
  - Typical theoretical uncertainties are ~50%

Diboson Production: WZ,ZZ

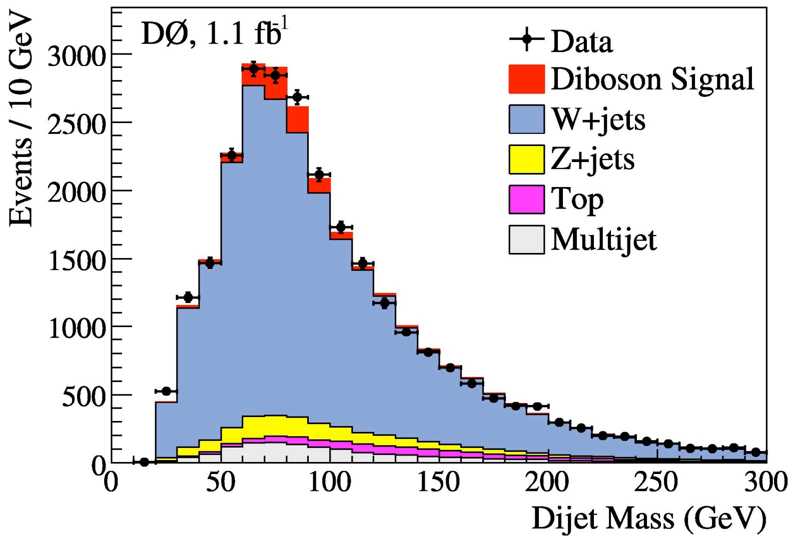


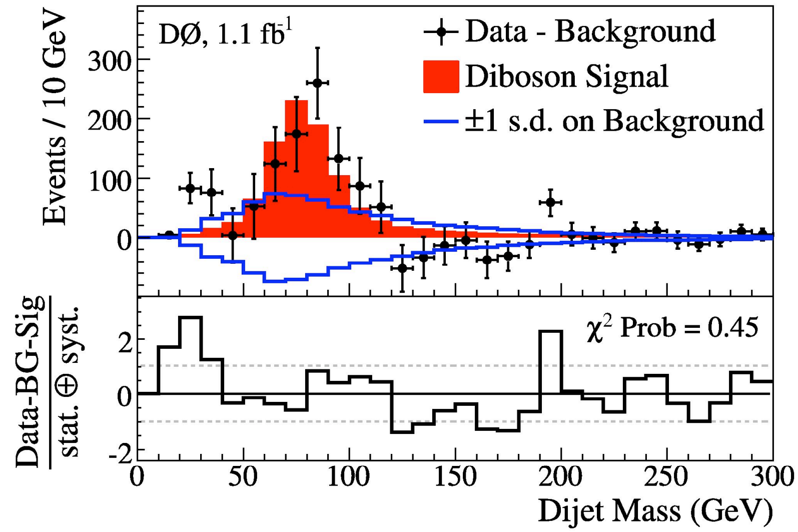




- Diboson production
  - Sensitive to trilinear couplings among gauge bosons
  - Direct consequence of SU(2)xU(1) gauge group
- Recent highlights:
  - WZ:
    - 5.9σ observation
    - Cross section: $5.0^{+1.8}_{-1.6}$ pb
  - ZZ:
    - 5.7σ observations
    - Cross section: 1.60±0.65 pb
- All diboson measurements in agreement with SM prediction

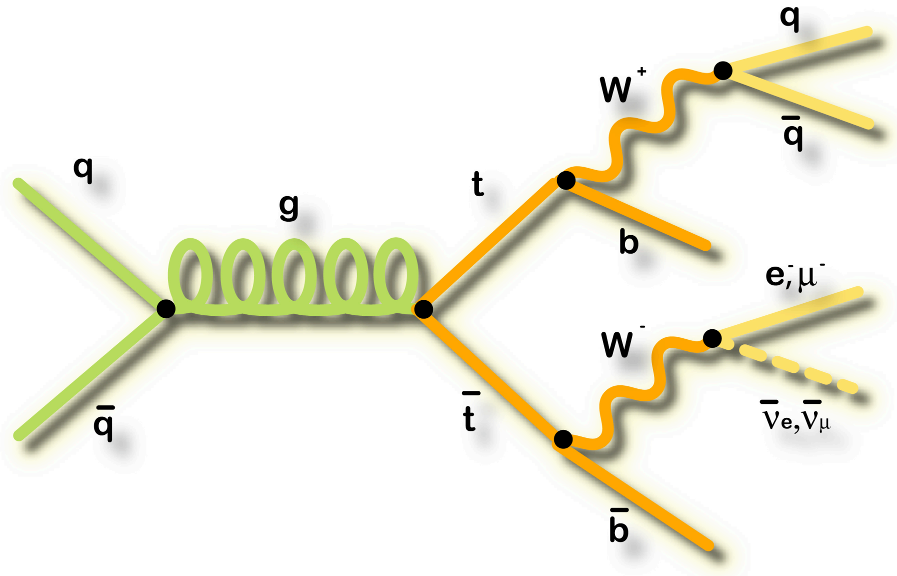
Evidence at 4.4σ for WW+WZ →lvjj

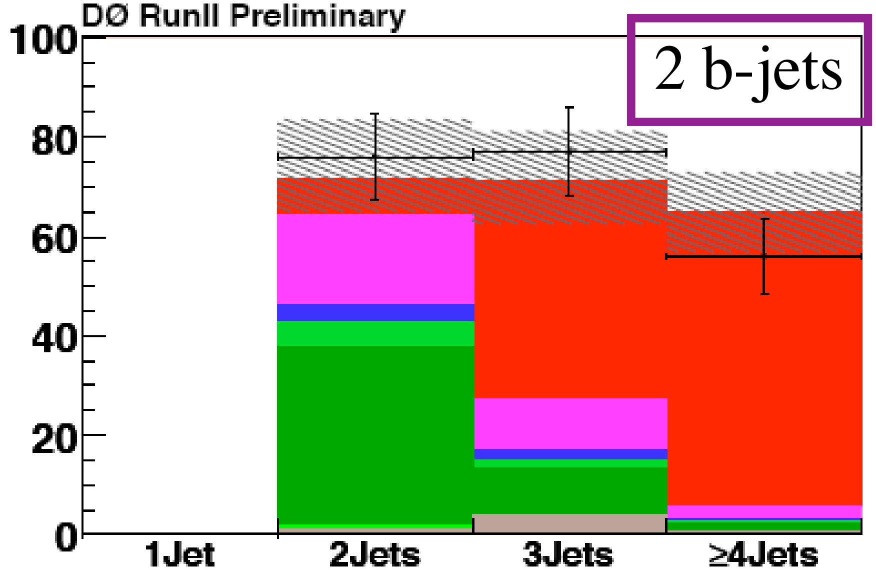


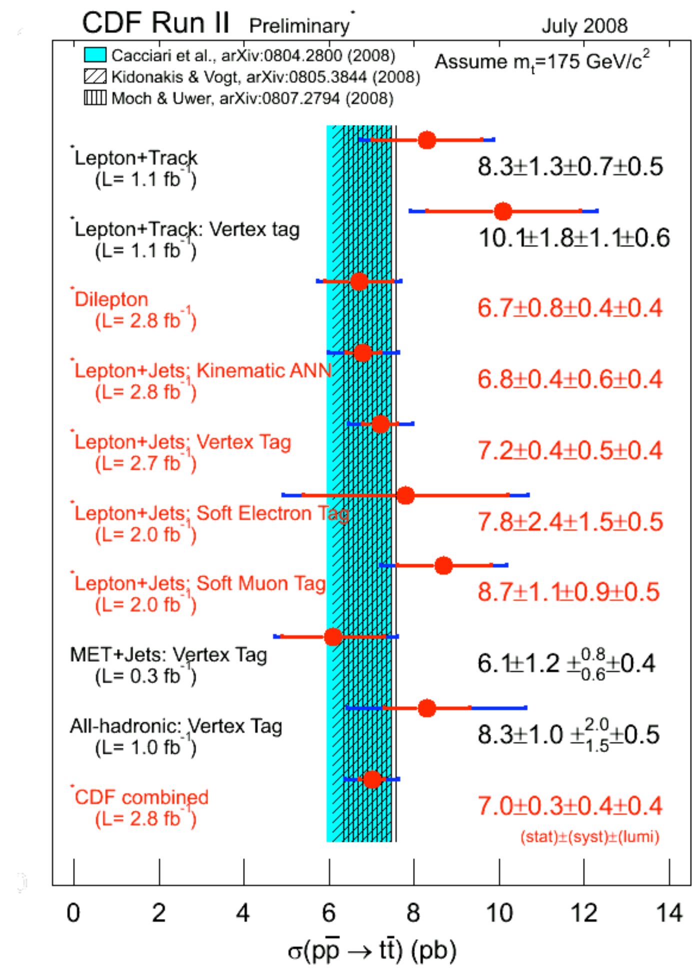


- Very similar analysis to Higgs search (see later)
  - Also needs to find a peak on a huge (sculpted) background
    - Great that this has now succeeded
  - Cross section: 20.2 +/- 4.5 pb (in agreement with theory)
- Being done also for WZ/ZZ with Z→bb
  - Evidence needs to be achieved before the Higgs since rate is 3 time higher

Top Quark Production

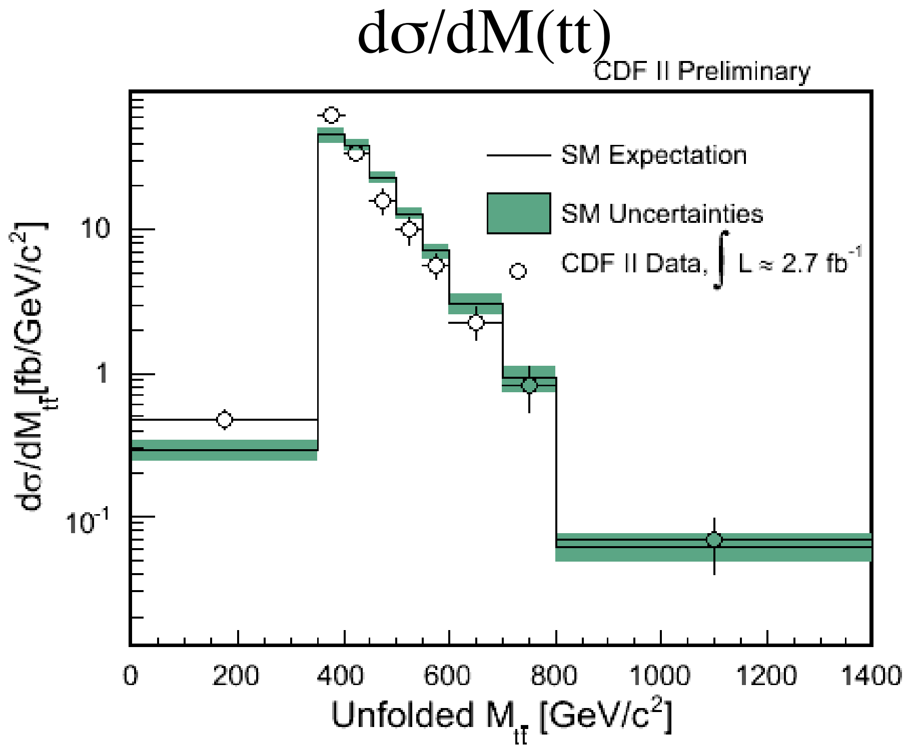


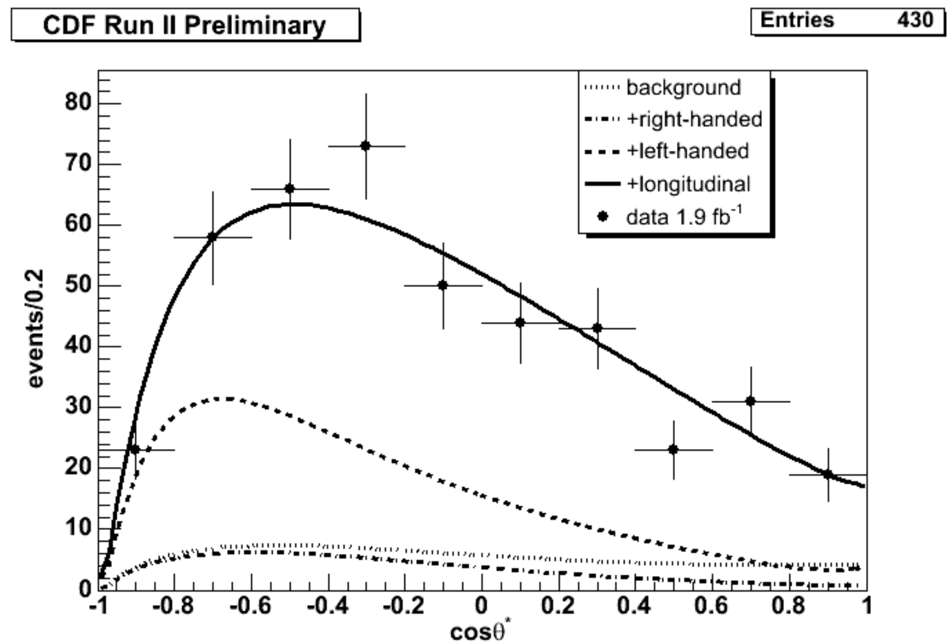


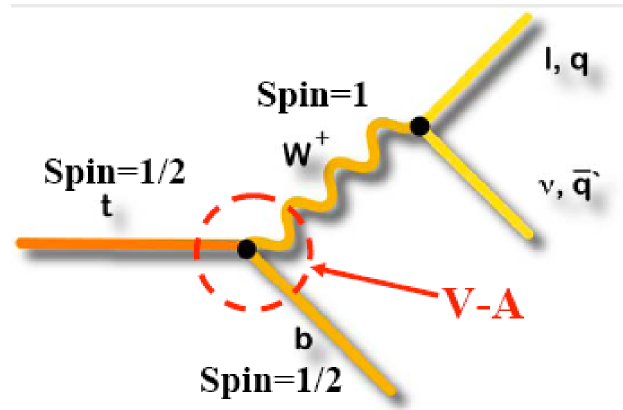


- **Measured cross section consistent with theory**
  - **Precision ~8%**

Top Quark: Kinematics+Properties

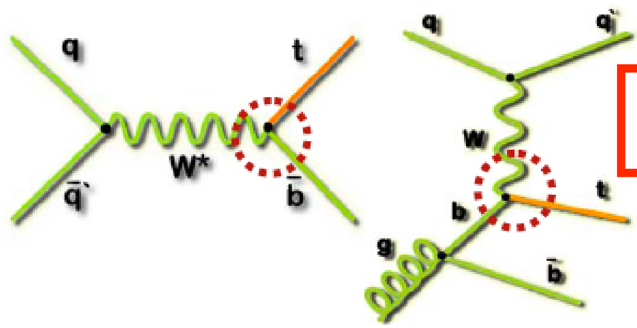






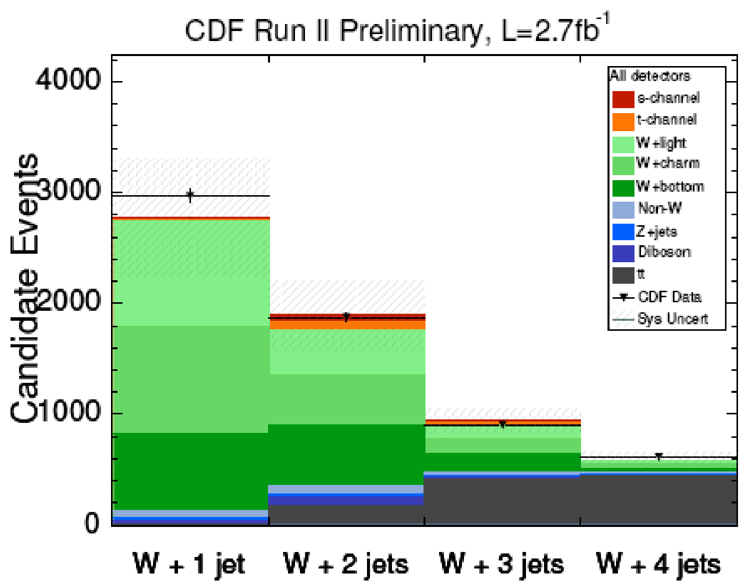
- Kinematic properties, couplings and charge consistent with Standard Model top production so far
  - Precision typically 10%

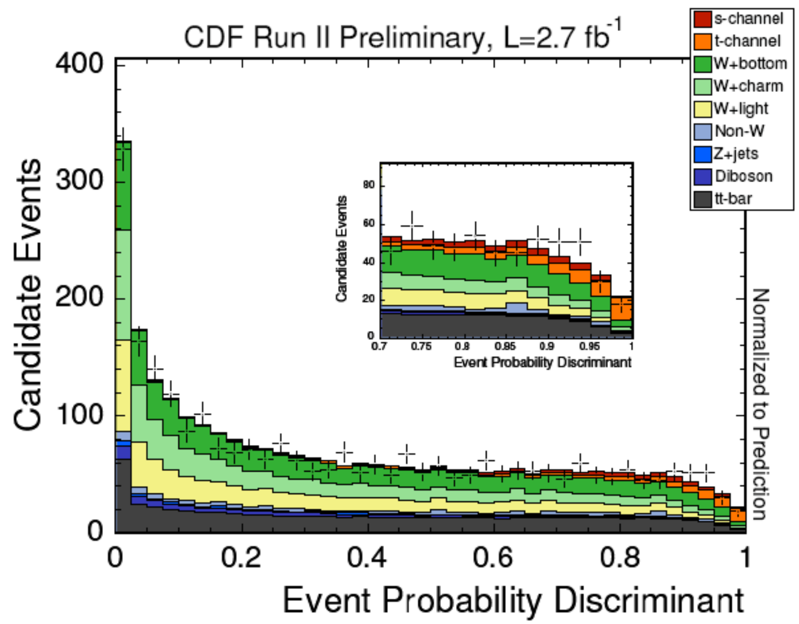
Single Top Production



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

- Evidence for single top established by CDF and DØ:
  - CDF: 2.2 ± 0.7 pb
  - DØ: 4.7 ± 1.3 pb
  - Theory: 2.86 ± 0.36 pb





- Very difficult analysis
  - Signal / background small and backgrounds uncertain
  - Important “practice” for Higgs boson: σ(single top) / σ(WH)~10

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%

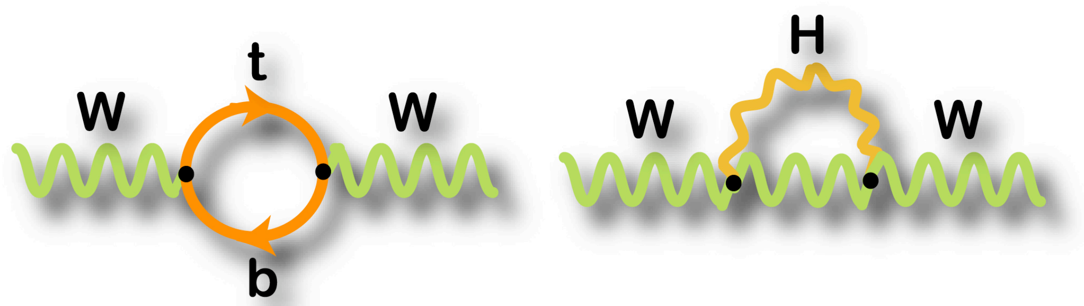
Measured to 0.002%

Measured to 0.036%

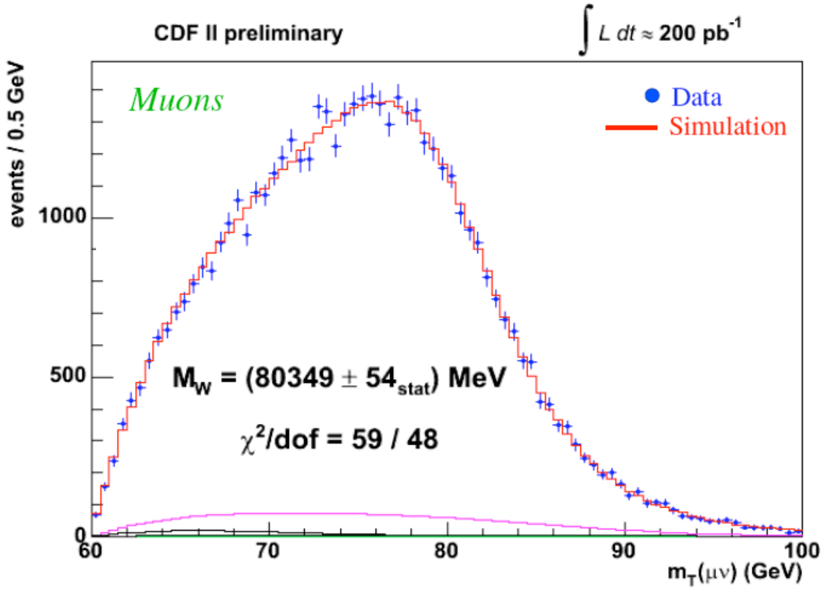
$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\,\frac{1}{(1-(M_W^2/M_Z^2))}\,\frac{1}{(1-\Delta r)}$$

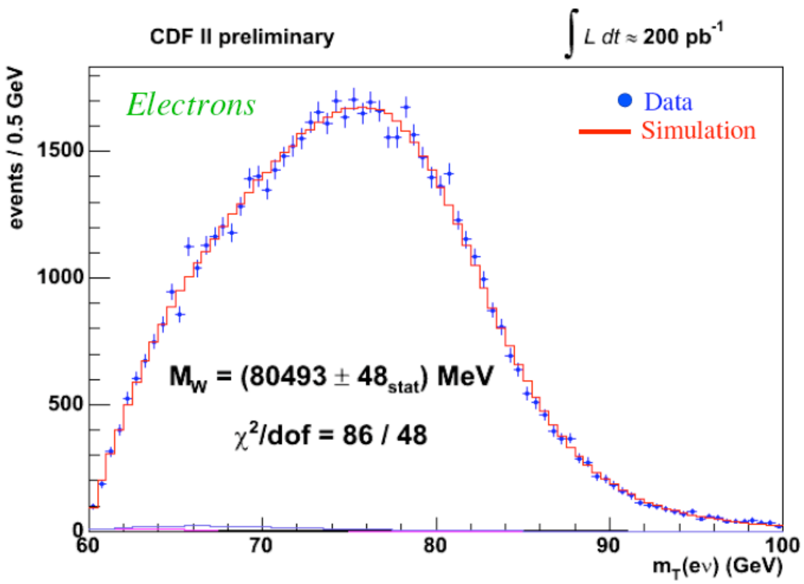
Measured to 0.0009%

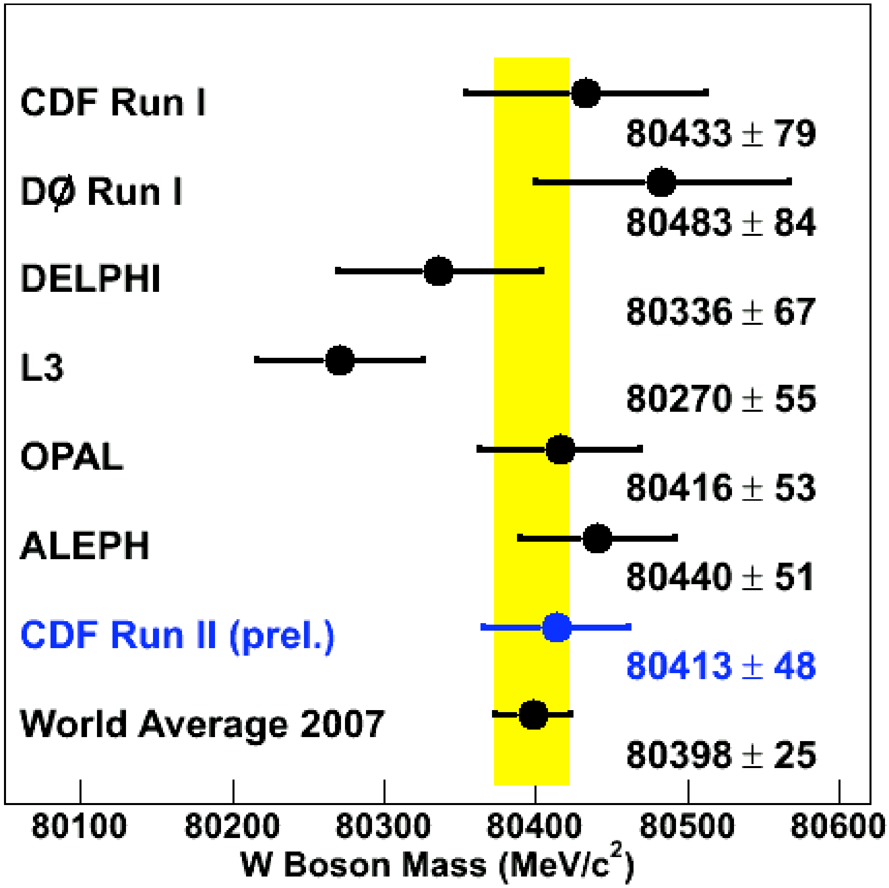
Δr: O(3%) radiative corrections dominated by *tb* and Higgs



W Boson Mass







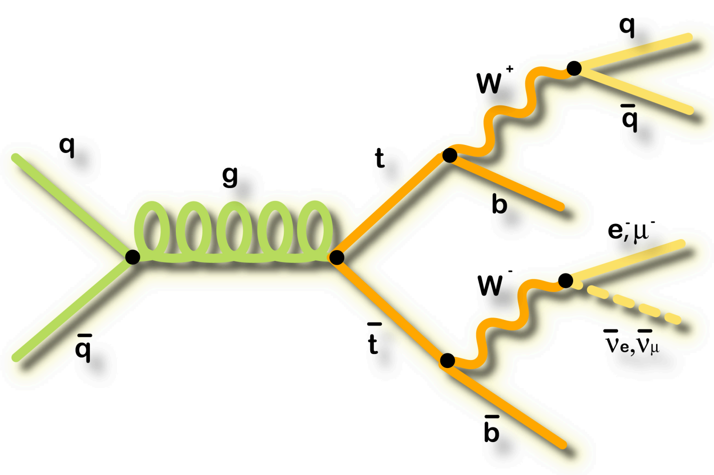
- New world average:

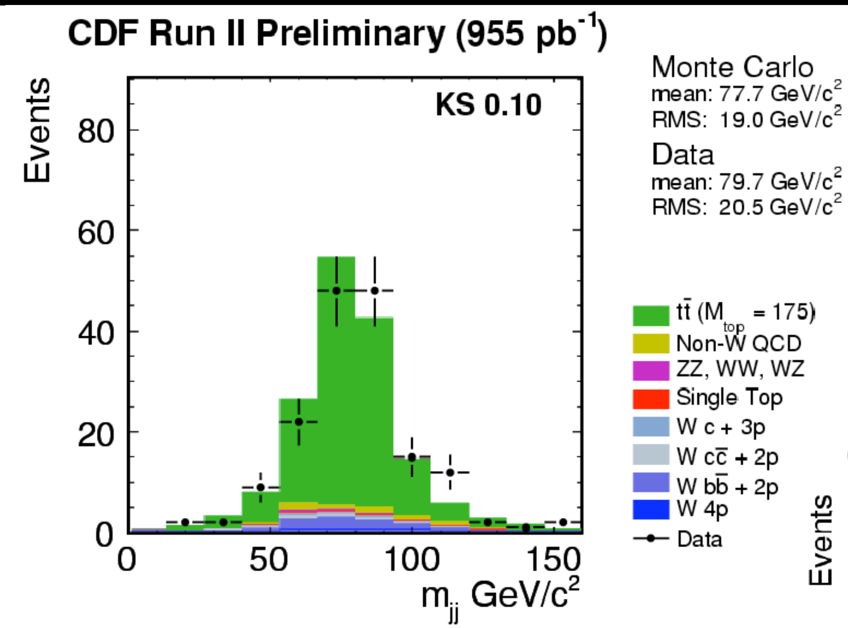
  M_W=80398 ± 25 MeV

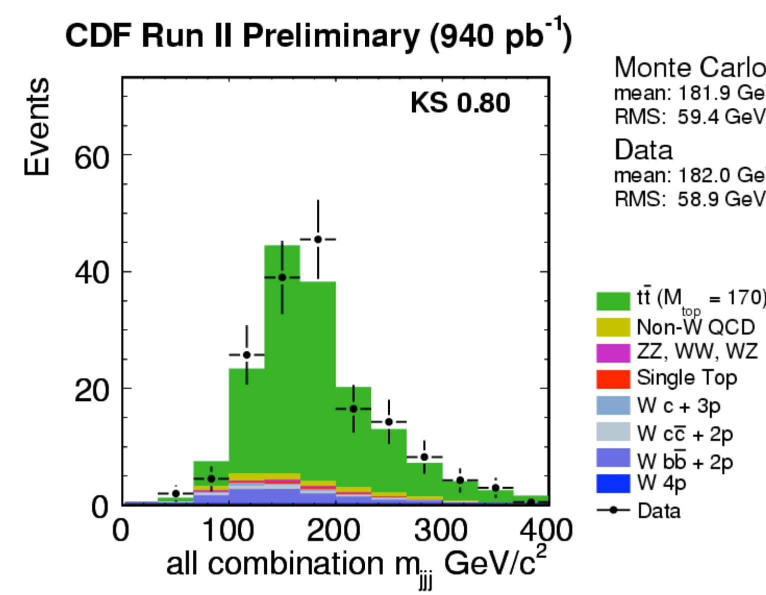
- Ultimate Run 2 precision:

  ~15 MeV

Top Quark Mass

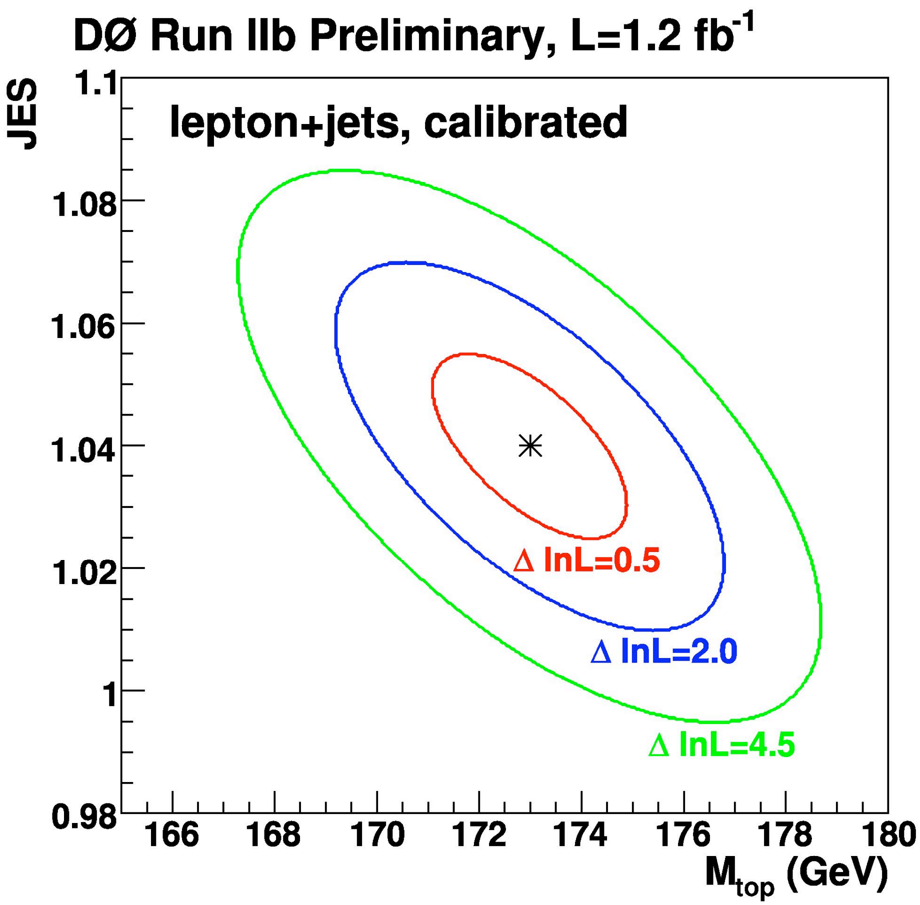


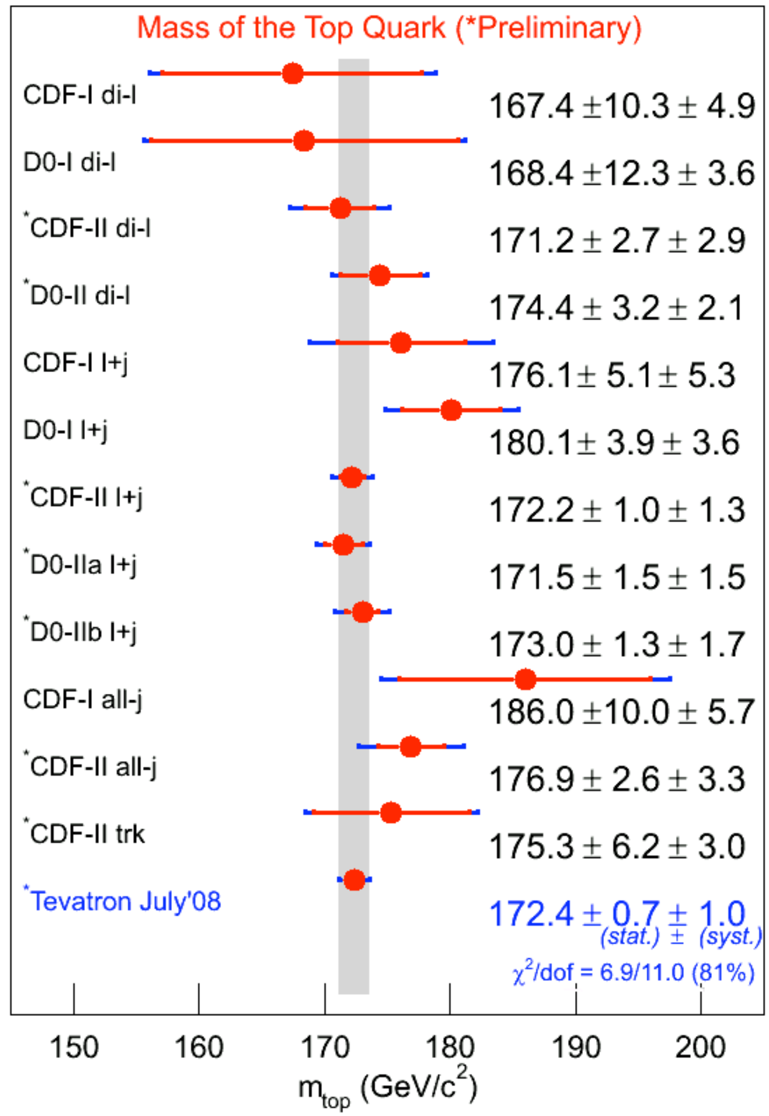




- Rather large pure samples available:
  - 166 events: S/B=4/1
- Perform simultaneous fit for
  - Top quark mass
  - Jet energy scale (M_W=M_{jj})
    - dominant systematic uncertainty

Top Quark Mass Results

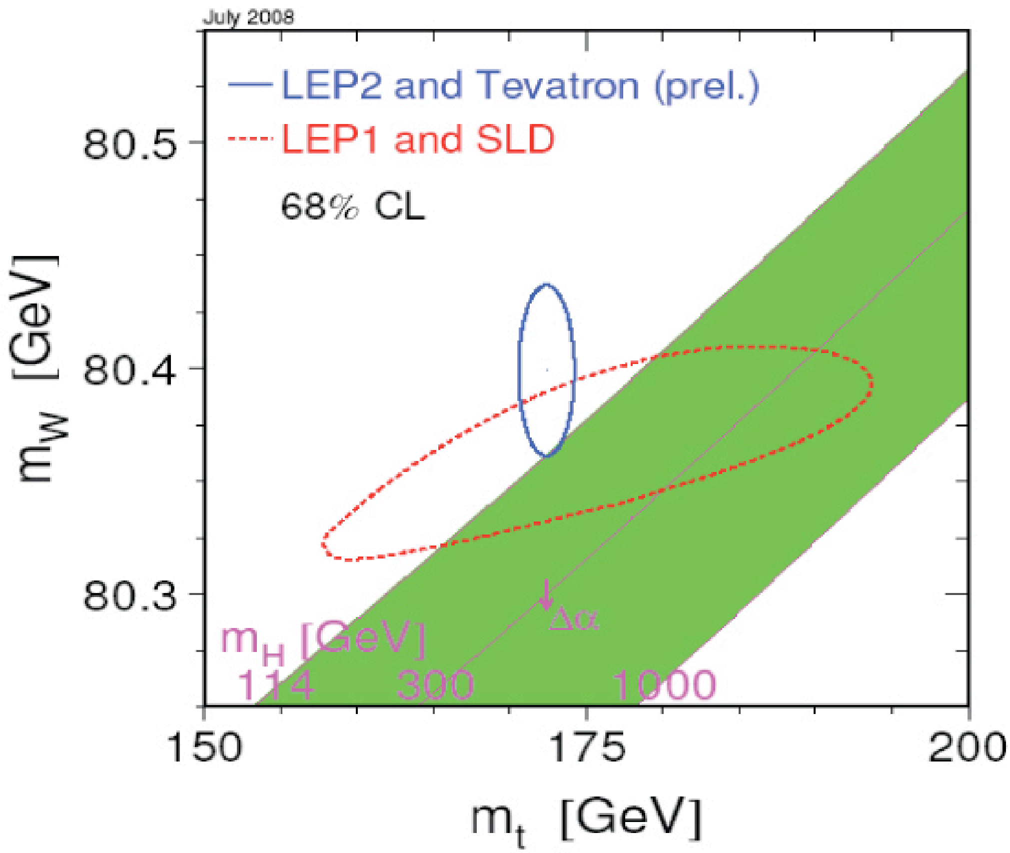


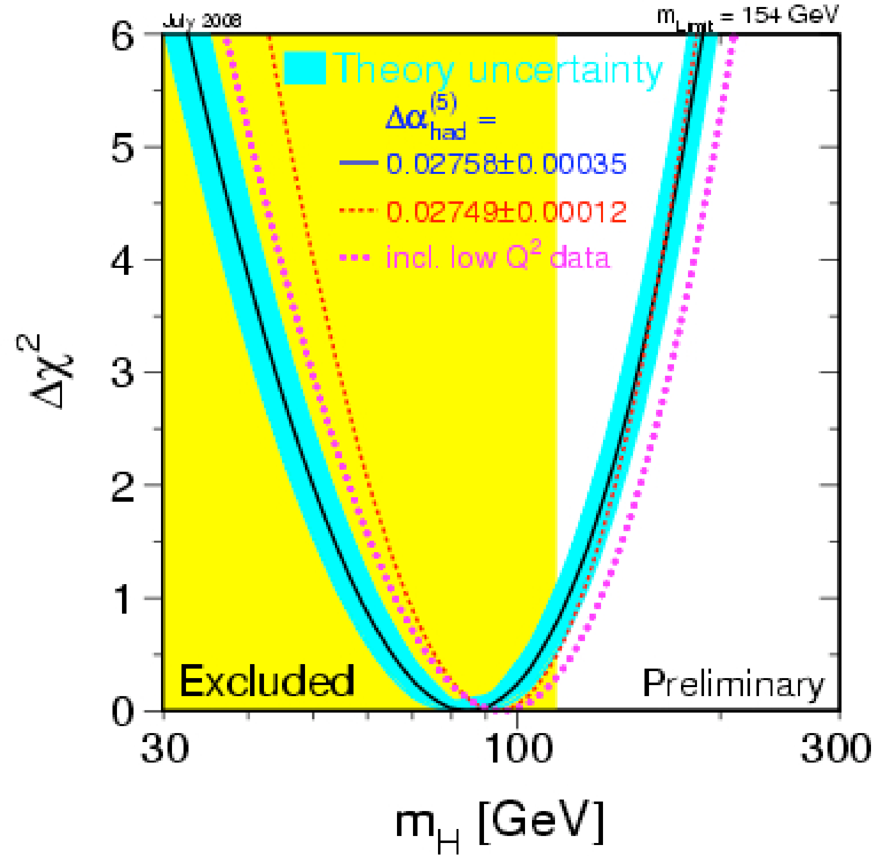


m_{top}=172.4± 1.2 GeV/c^2

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

M_W, m_{top} and m_{Higgs}

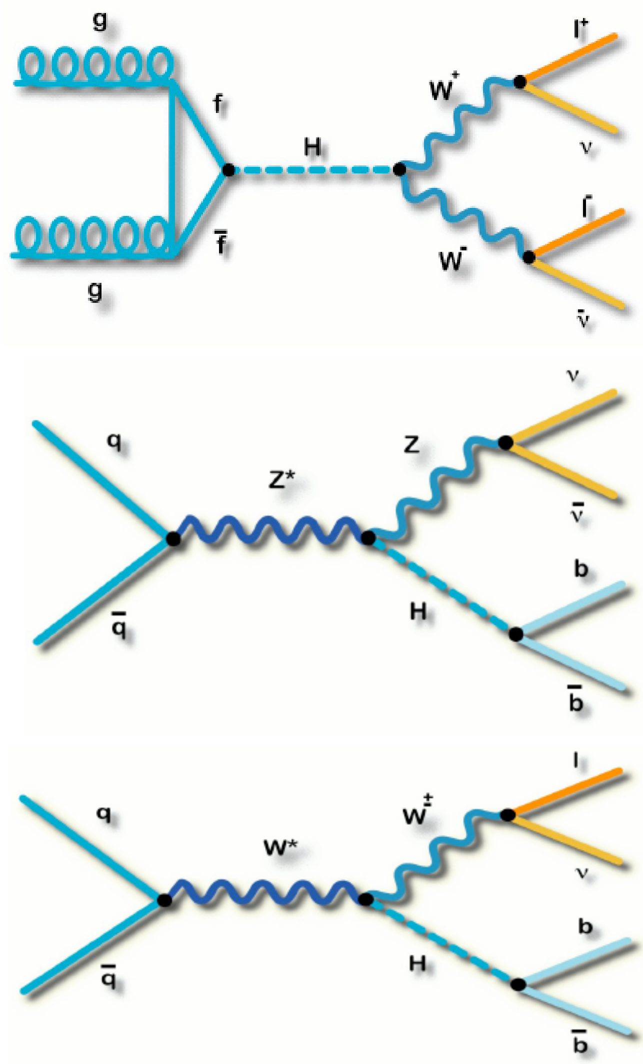


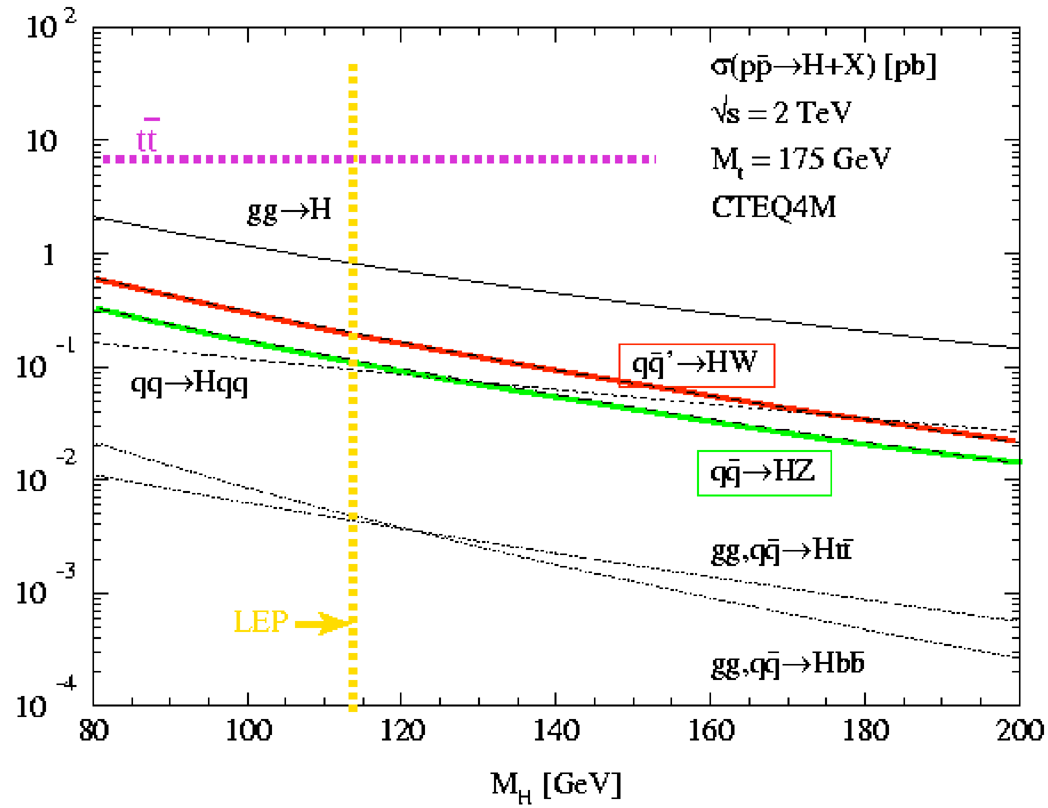


- **Indirectly: m_H<154 GeV@95%CL**
- **Directly (LEP): m_H>114 GeV@95%CL**

(caveat: is the measured top mass the pole mass?)

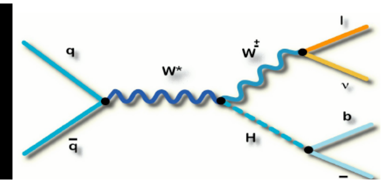
Higgs Production at the Tevatron

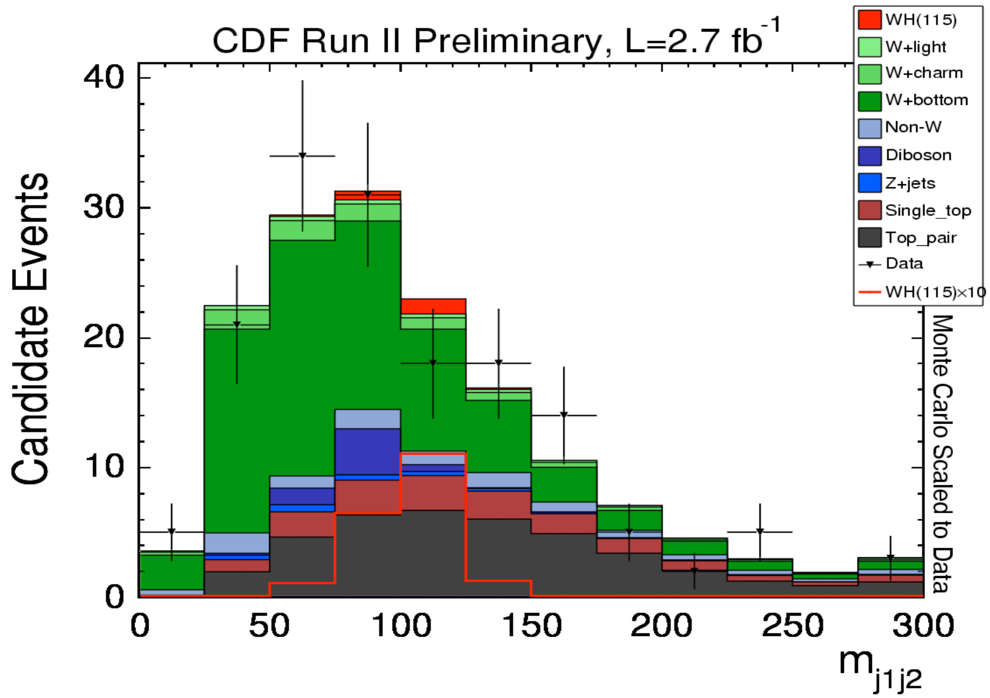


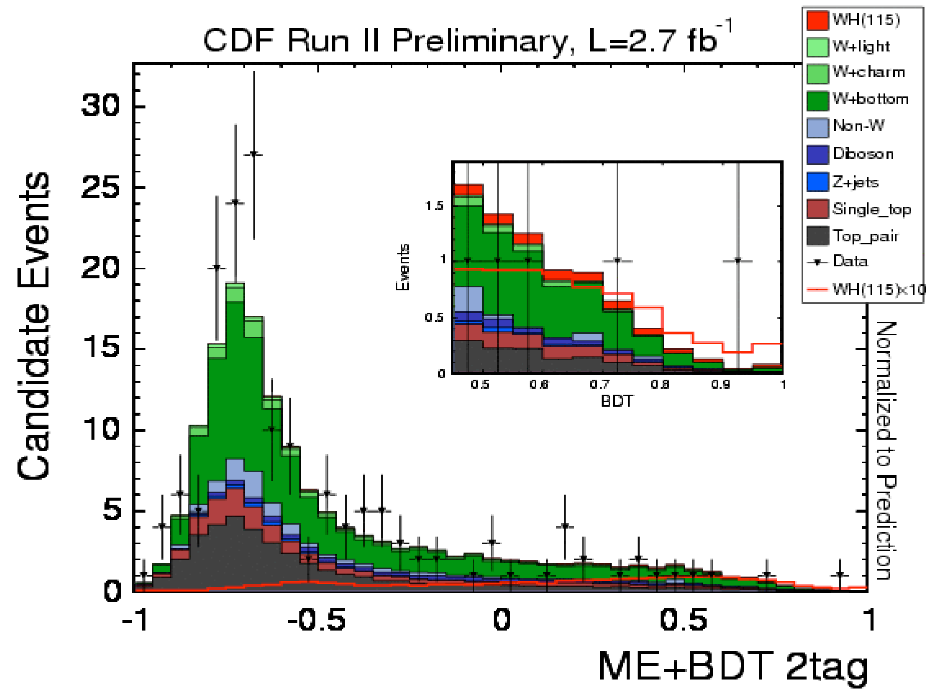


- Dominant **gg->H**
- Subdominant **WH**, ZH

W+Higgs with H→bb



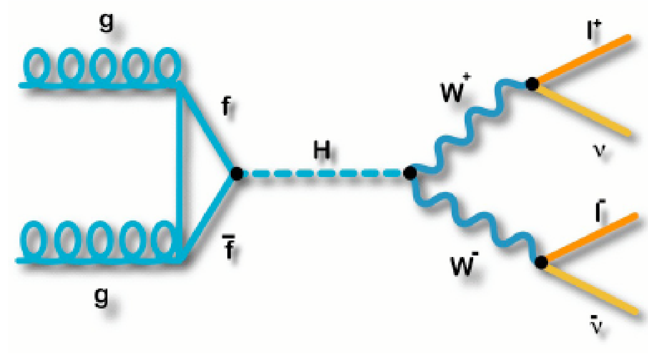


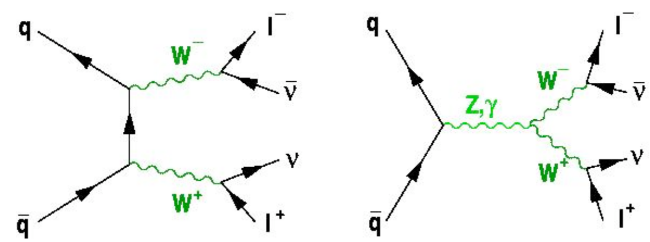


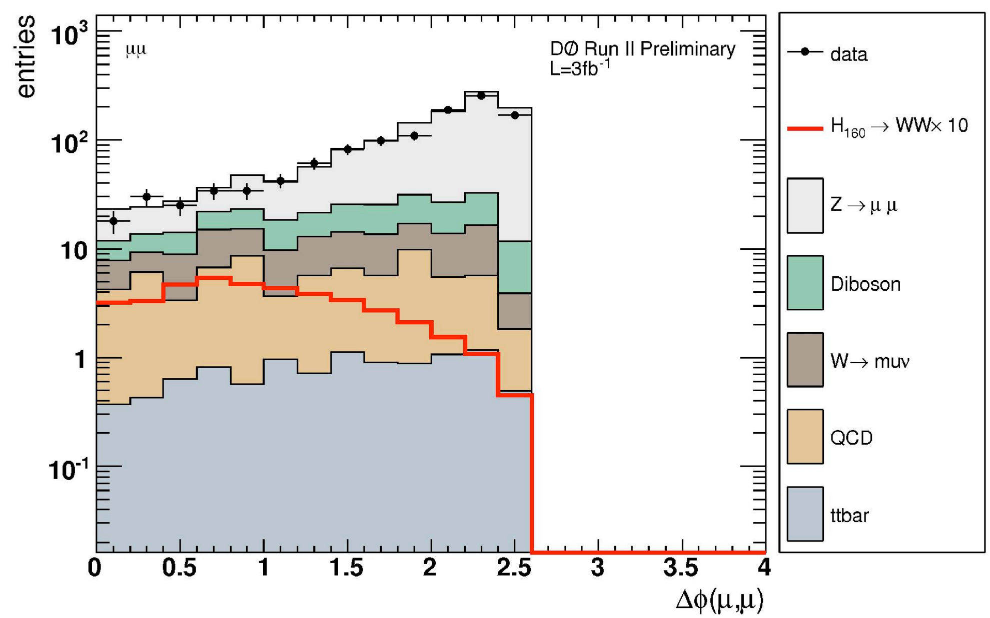
- For m_H<135 GeV/c^2:
  - WH→lνbb, ZH →llbb, ZH →ννbb
- Both collaborations have analyzed nearly 3 fb^{-1} in for all three modes:
  - Analyses based on advanced analysis techniques
    - Neural Networks, Boosted Decision trees, etc.

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

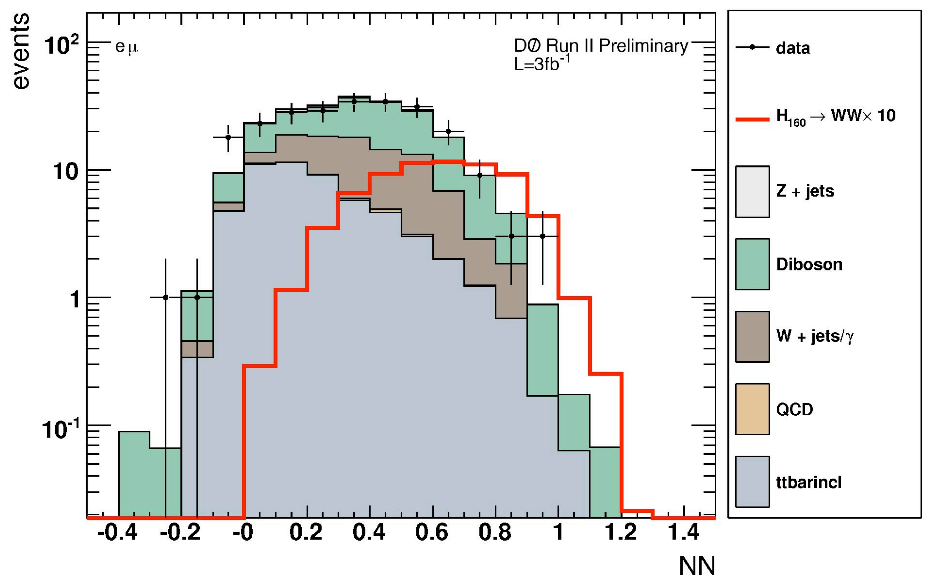
- Main background:
  - WW production
- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Use advanced techniques (NN etc.) to gain further separation power

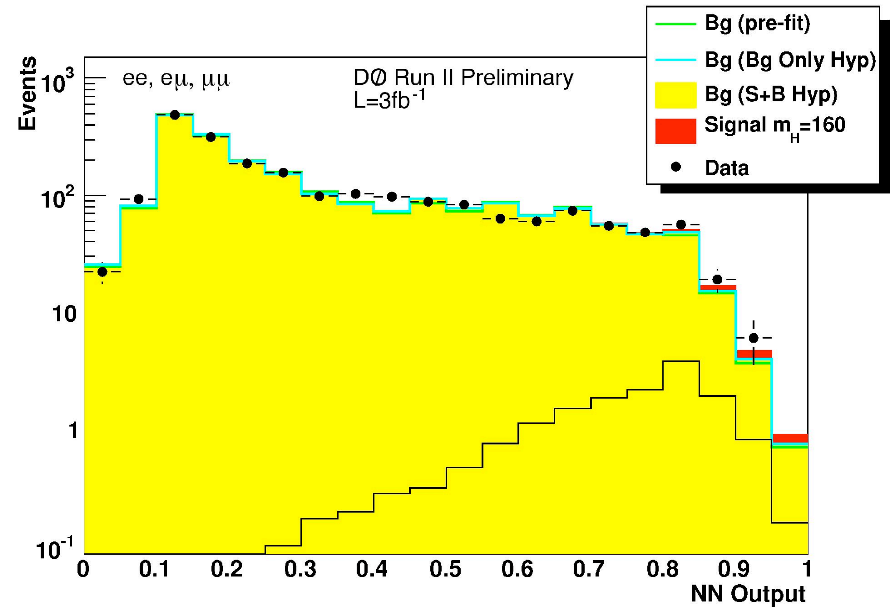




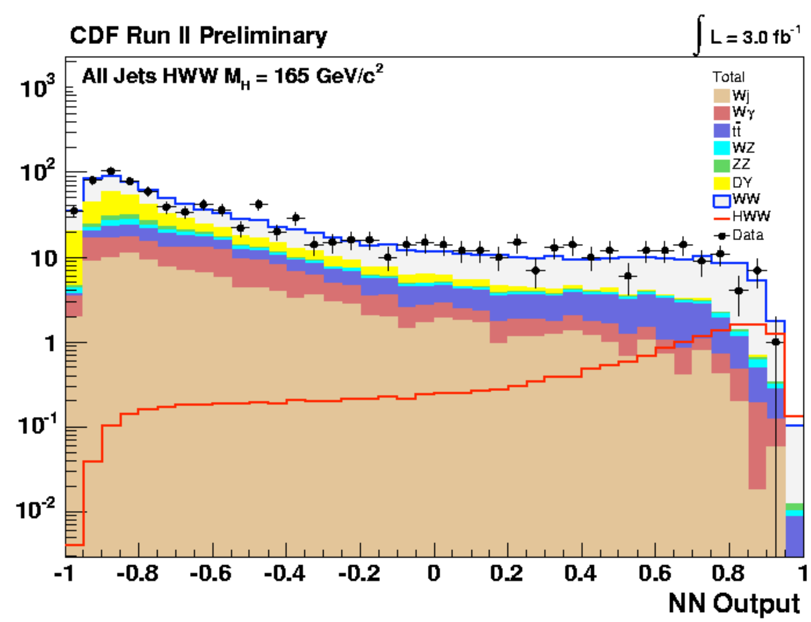


$H \to WW^{(*)} \to l^+l^-\nu\nu$

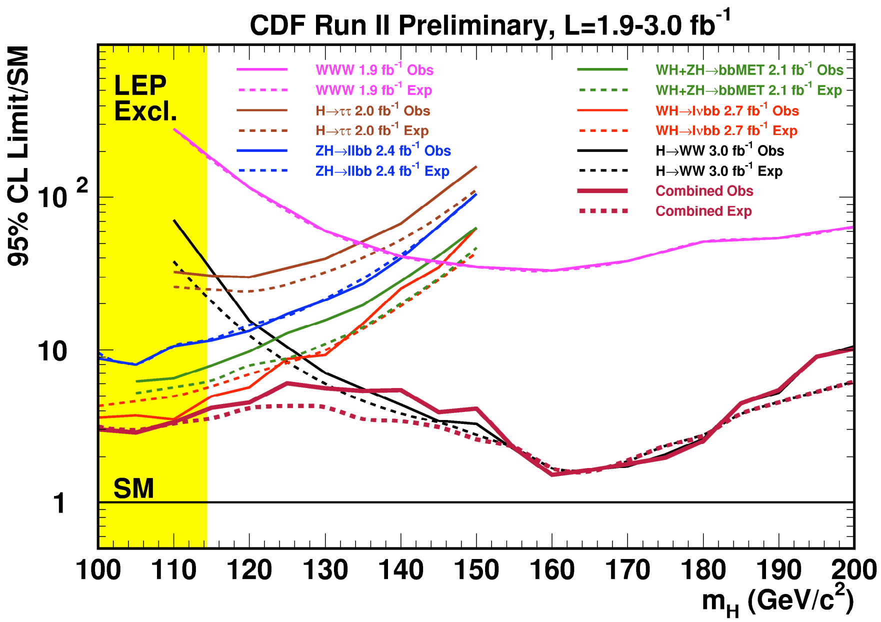


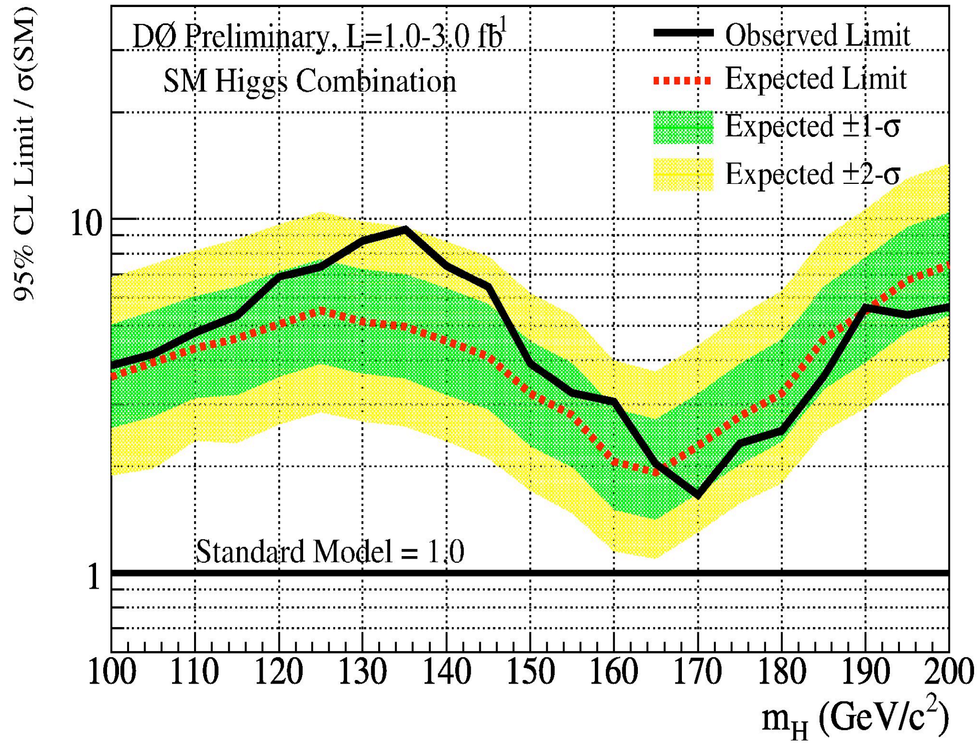


- Neural Network separates signal from background rather well
  - Data well described in background dominated region
  - no sign of excess in the data
- Data used to set limits on Higgs boson cross section



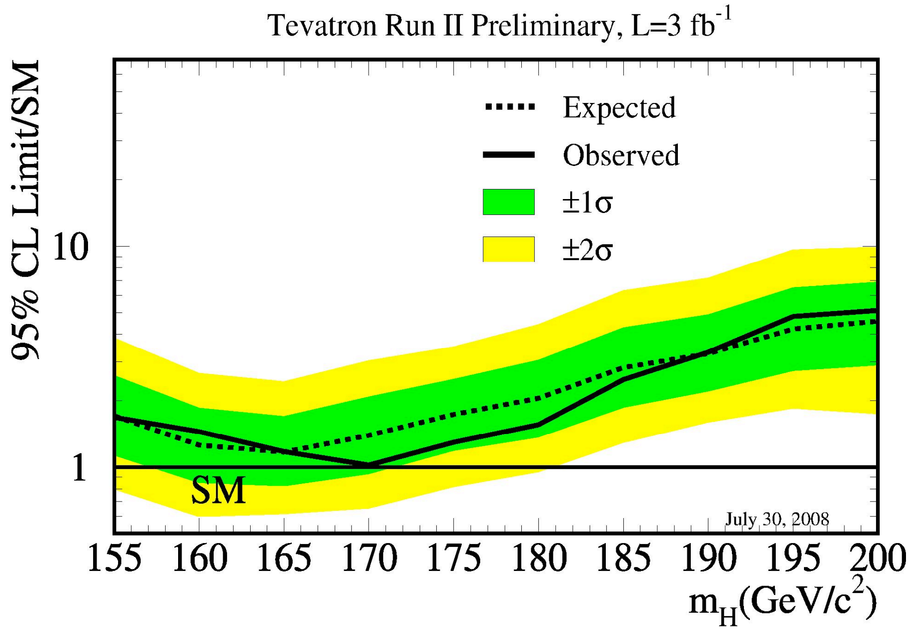
Higgs Cross Section Limit per Experiment

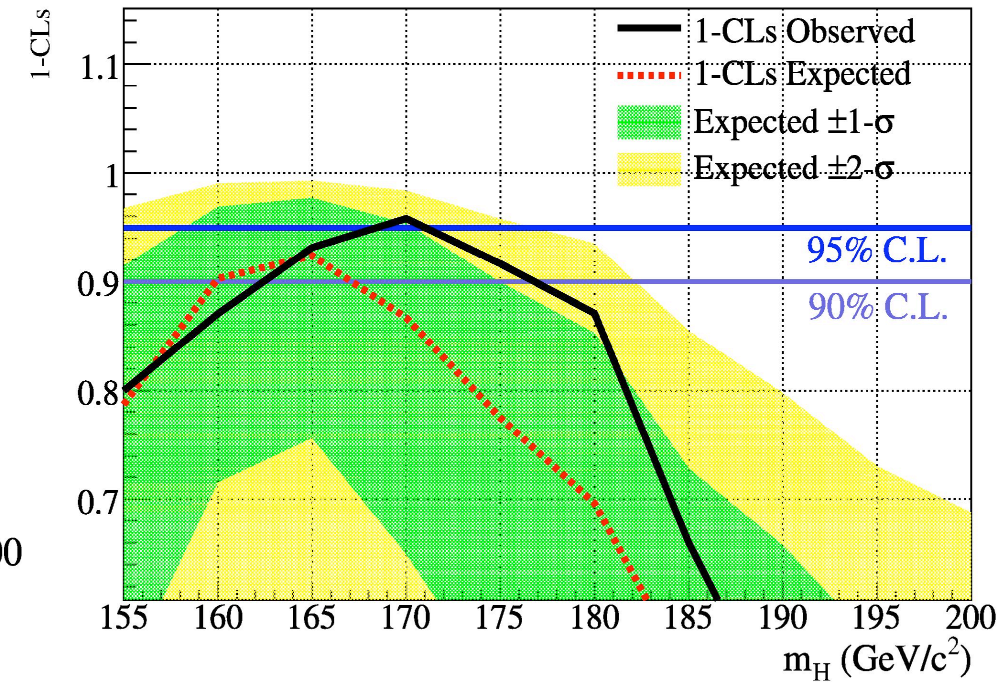




- Cross Section limits from each experiment
  - MH=115 GeV: σ_{limit} factor 4.2 (CDF)-5.3 (D0) above the SM
  - MH=165 GeV: σ_{limit} factor 1.8 (CDF)-1.7 (D0) above the SM
    - Note the 1σ downward fluctuation by D0 at 170 GeV

High Mass Higgs Combination

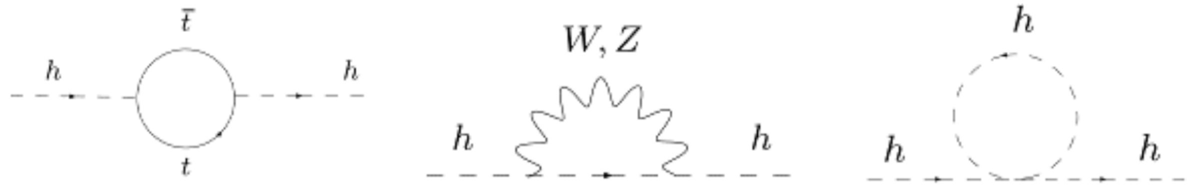




- Higgs excluded at 95% CL at 170 GeV
  - Still debates ongoing about the theoretical cross section value
  - Most likely theoretical cross section will increase
    - That would increase the exclusion range

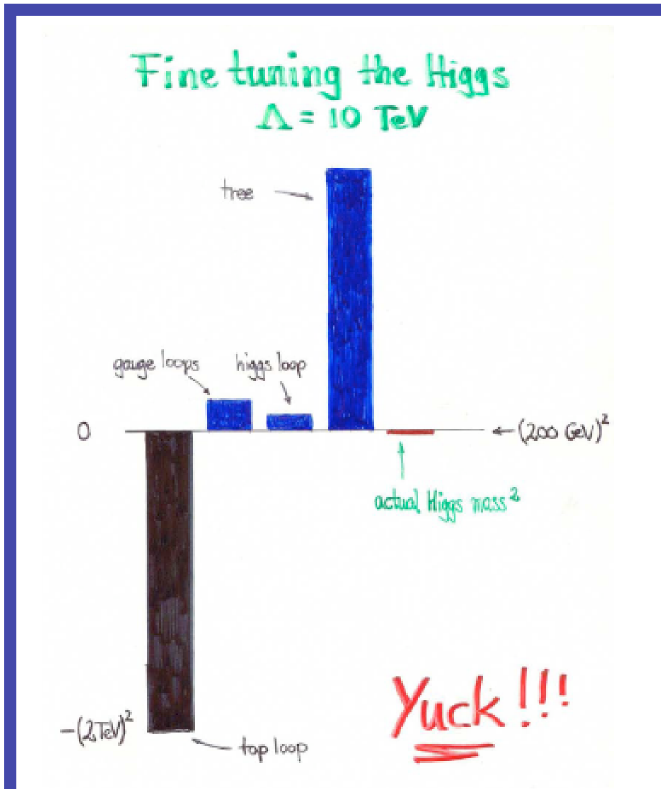
Beyond the Standard Model

Problems of the Standard Model



$$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{\text{tree}} + \delta\, m^2_H{}^{\text{top}} + \delta\, m^2_H{}^{\text{gauge}} + \delta\, m^2_H{}^{\text{higgs}}$$

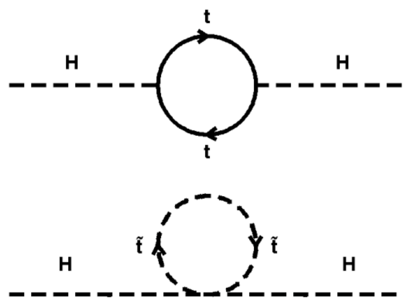
- Large fine-tuning required:
  - $m_H << m_{Pl}$
- Accounts for just 4% of the Universe
  - No dark matter candidate
  - Cosmological constant problem
- No prediction for
  - fundamental constants, unification of forces, number of generations, mass values and hierarchy of SM particles, anything to do with gravity

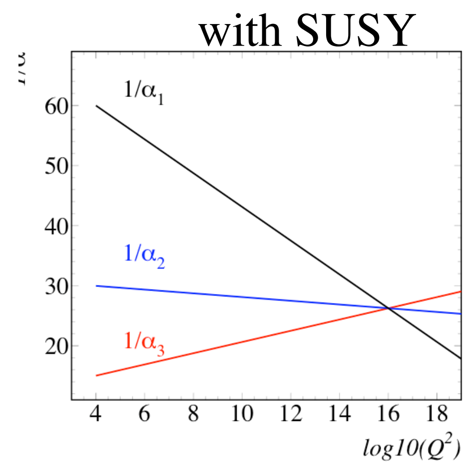


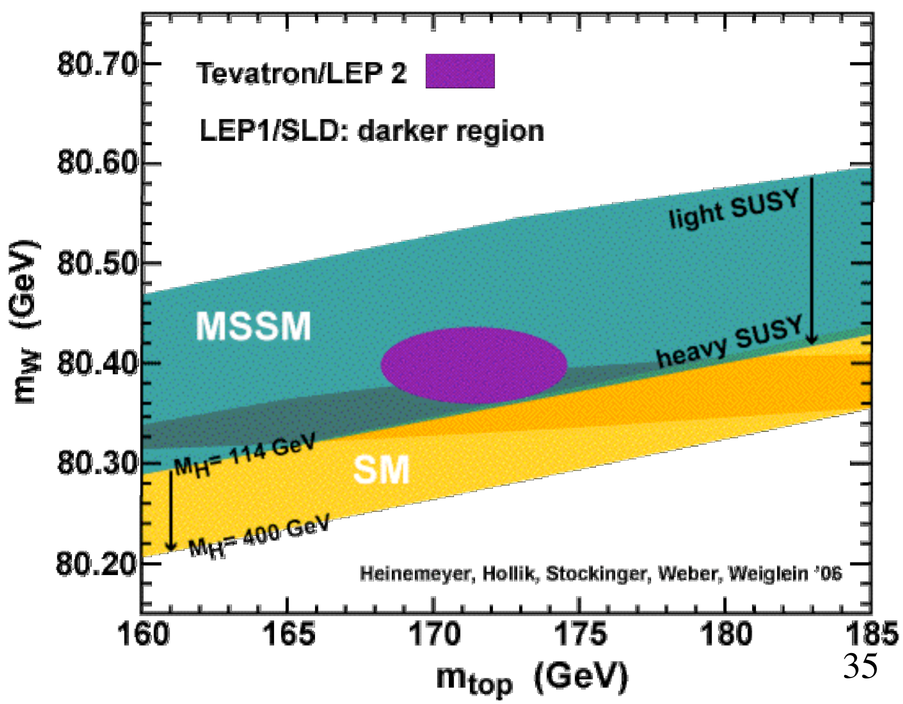
M. Schmaltz, ICHEP 02

What's Nice about SUSY?

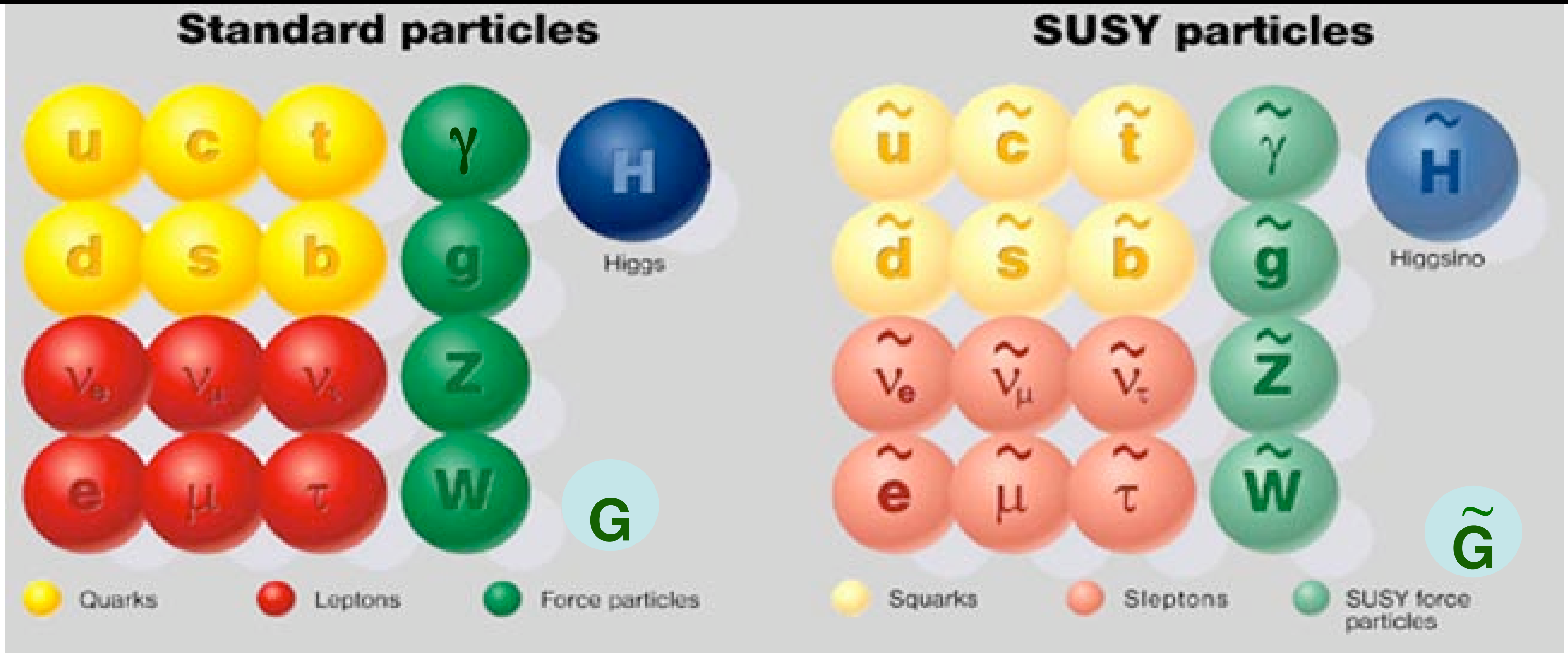
- Radiative corrections to Higgs acquire SUSY corrections:
  - No/little fine-tuning required
  - Particles masses must be near EWK scale
- Unification of forces possible
- Dark matter candidate exists:
  - lightest neutral gaugino
- Changes relationship between m_W, m_{top} and m_H:
  - Also consistent with precision measurements of M_W and m_{top}





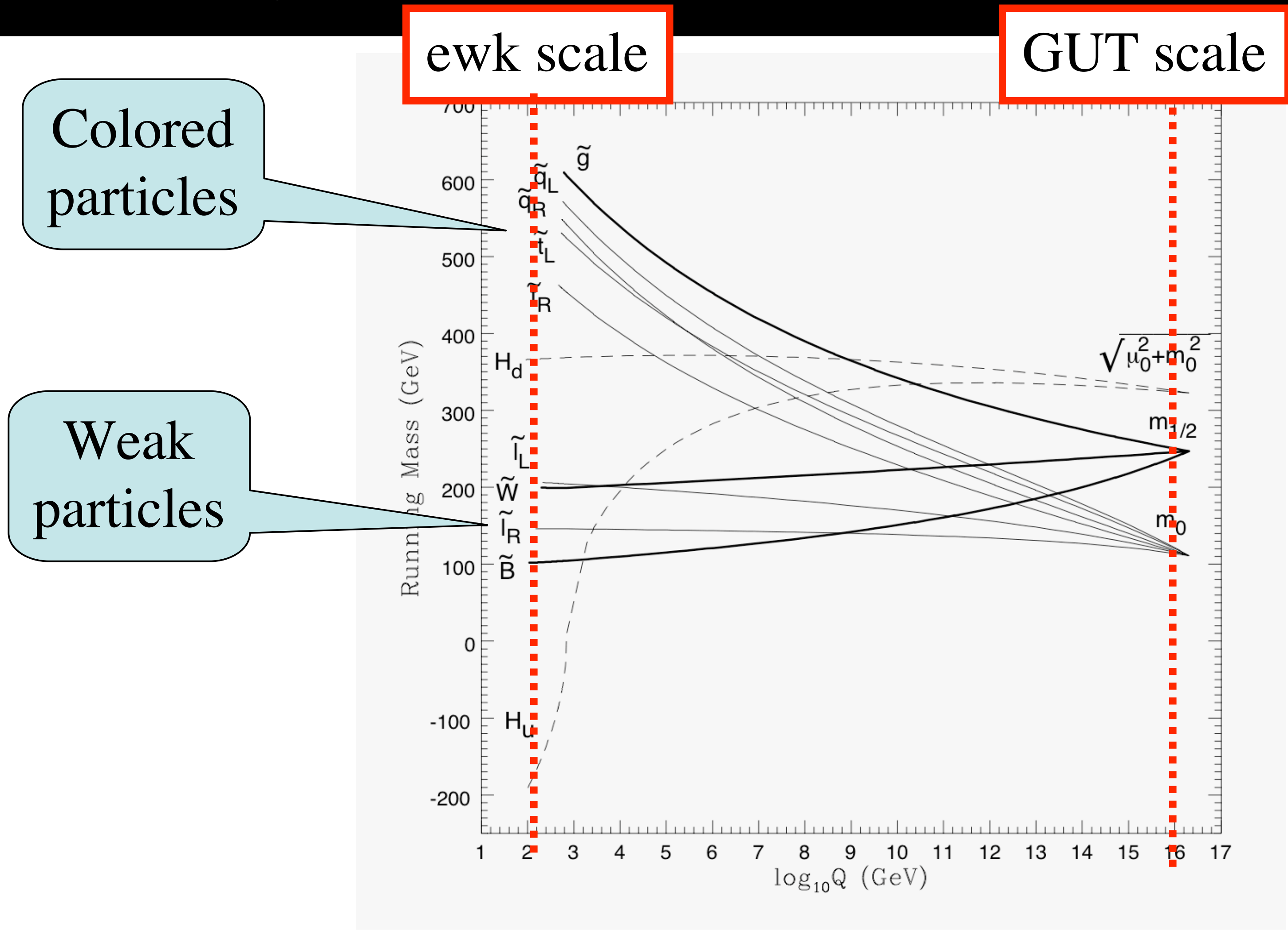


Supersymmetry (SUSY)



- **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!**

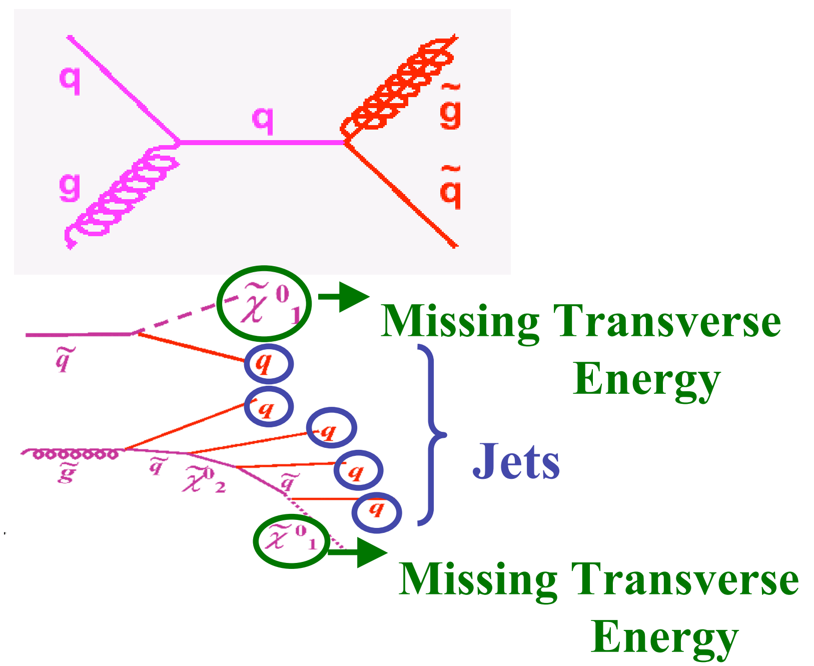
Mass Spectrum and Unification

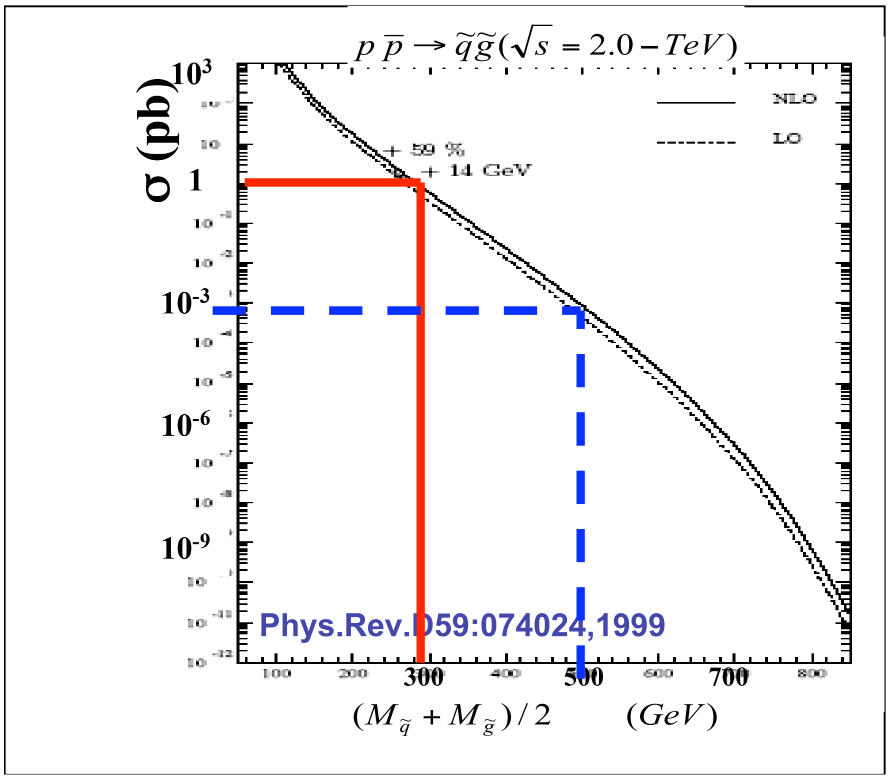


- Lightest SUSY particle (χ_1^0) is Dark Matter candidate (if stable)
- Models predict mass relations: $M(g) \approx 3M(\chi_1^{\pm}) \approx 6M(\chi_1^0)$

Generic Squarks and Gluinos

- **Squark and Gluino production:**
  – Signature: jets and E_T^{miss}

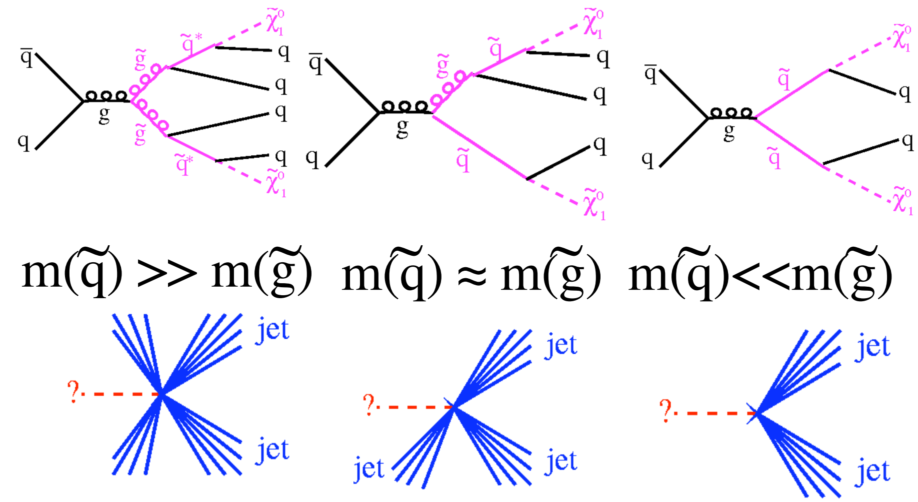


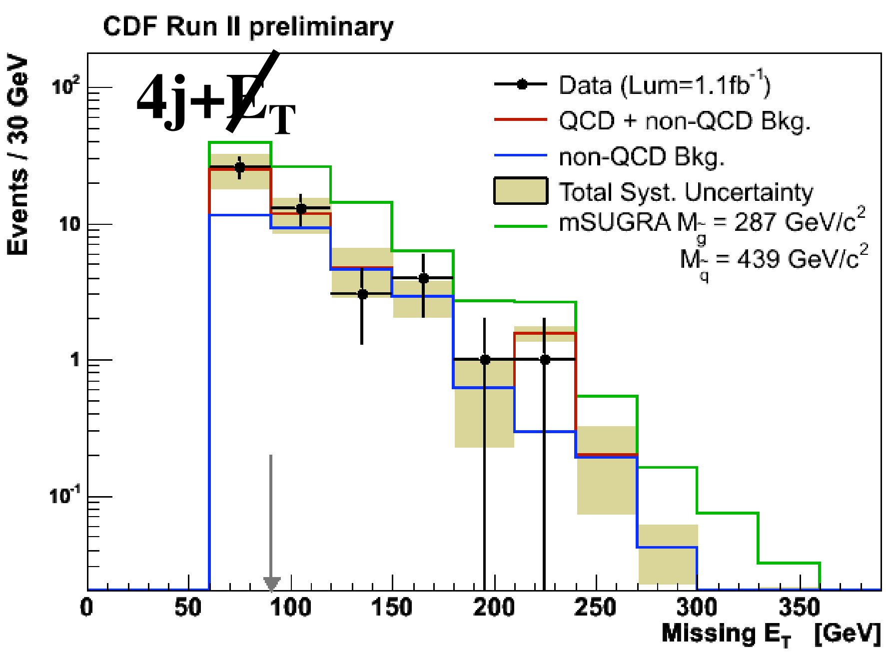


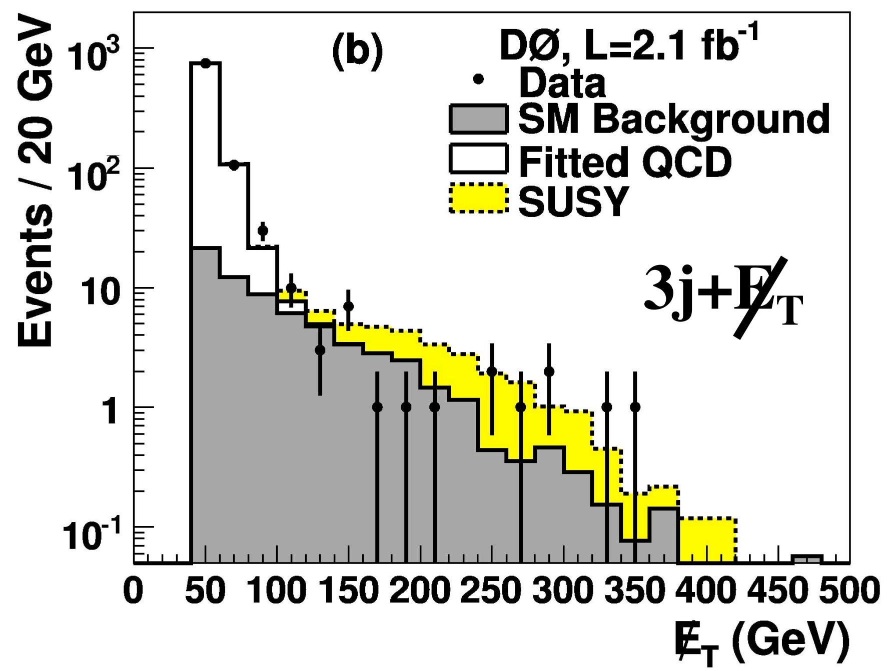
- **Strong interaction => large production cross section**
  – for M(g̃) ≈ 300 GeV/c^2:
    • 1000 event produced/ fb^{-1}
  – for M(g̃) ≈ 500 GeV/c^2:
    • 1 event produced/ fb^{-1}

Squarks and Gluinos

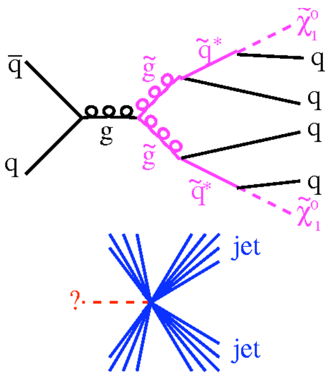
- Squark and Gluino production:
  - Signature: jets and E_T^{miss}
  - At Tevatron no long cascades to leptons expected:
    - Lepton veto applied
- Analysis optimized depending on mass hierarchy

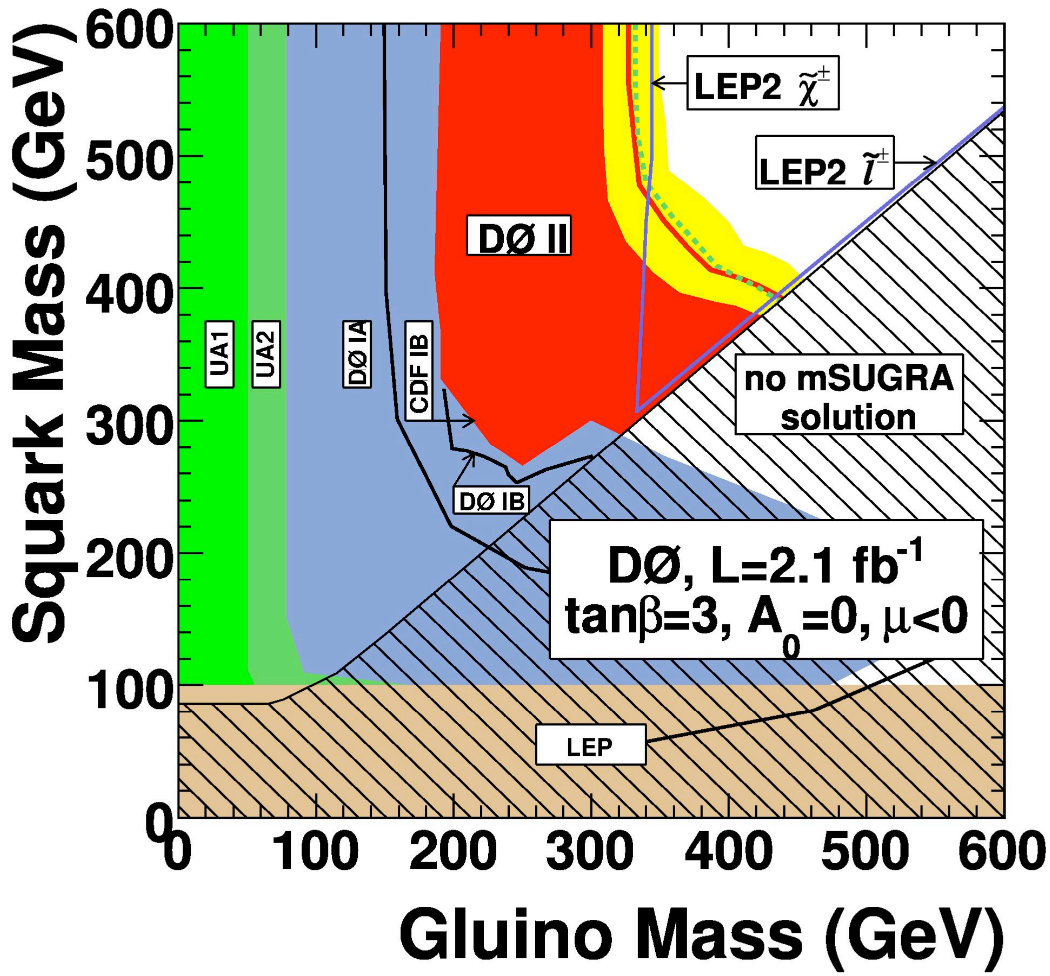


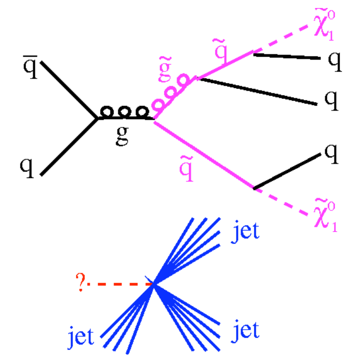


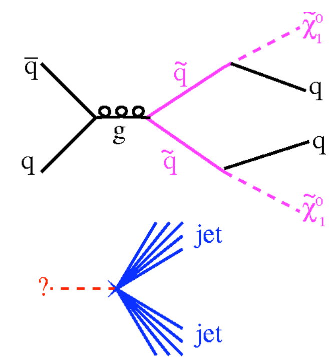


Supersymmetry Parameter Space





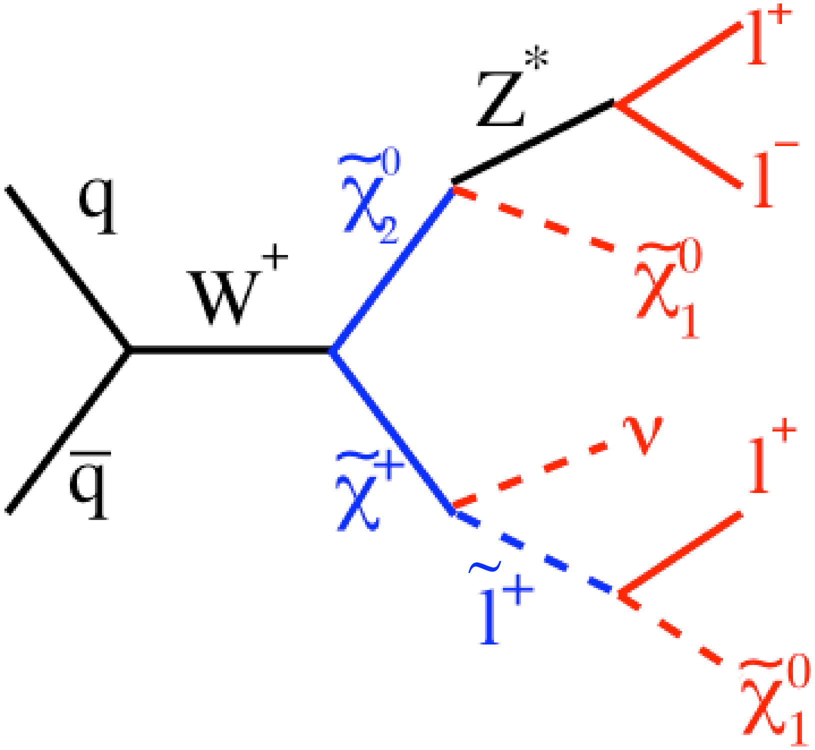




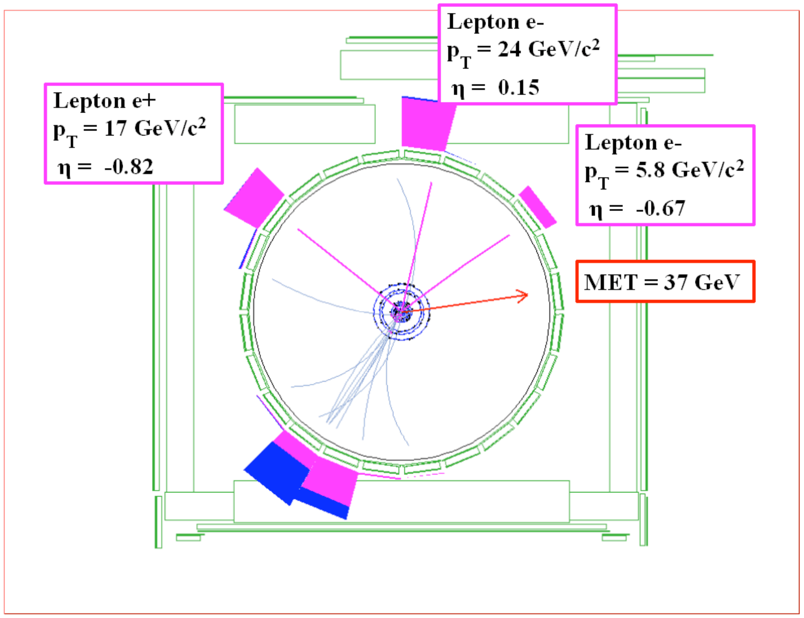
$M(\tilde{g})>308$ GeV, $M(\tilde{q})>379$ GeV

NB: up to 10 GeV differences depending on treatment of theoretical cross section uncertainties

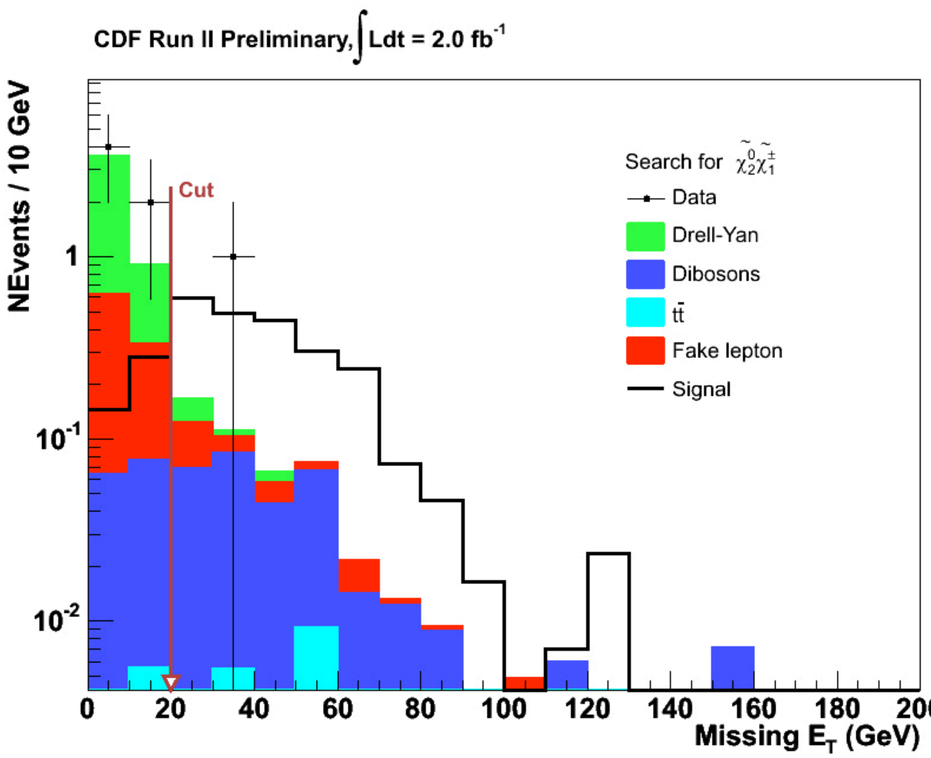
Trileptons: Another Look for SUSY

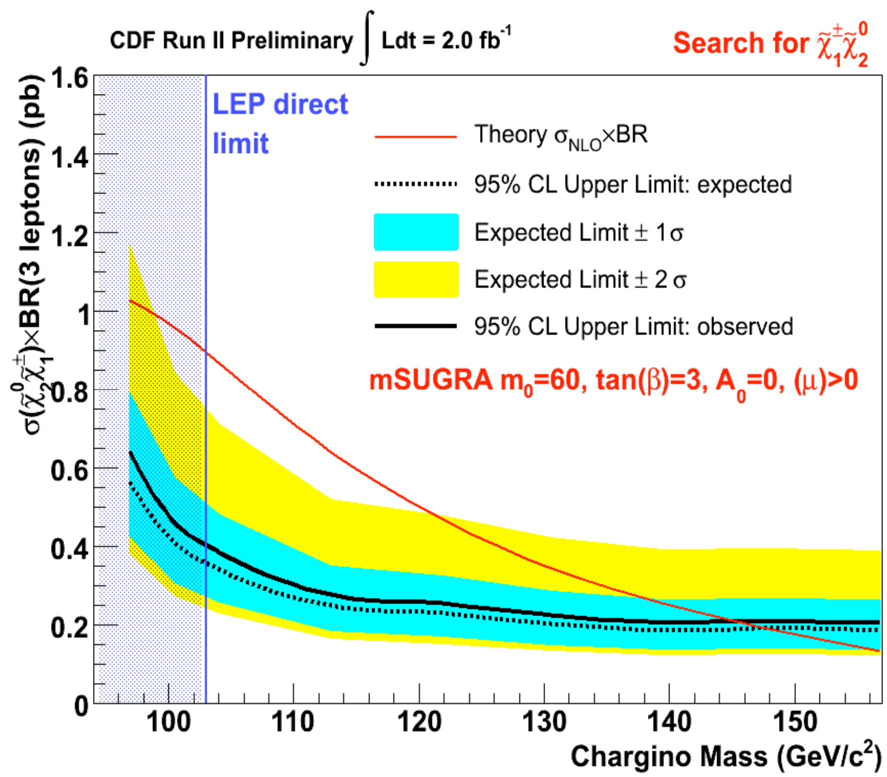


- Search for partners of W and Z boson
  - Decaying via leptons
- Signal:
  - 3 leptons and missing E_T



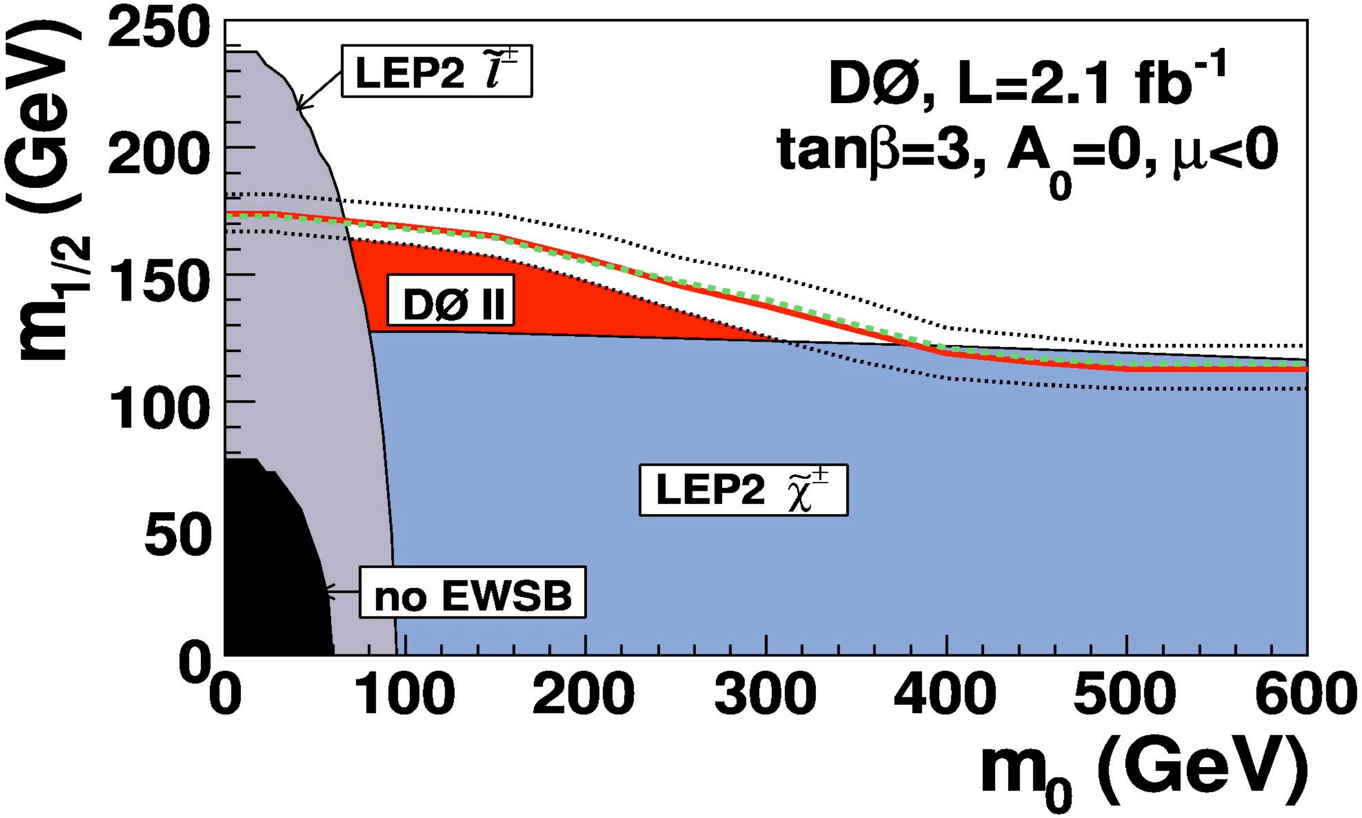
The Trilepton Data





- Also consistent with background expectations
  - M(chargino)>140 GeV/c^2 at 95% confidence level
  - rather model-dependent though

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

Beyond SUSY

Confusion among Theorists?

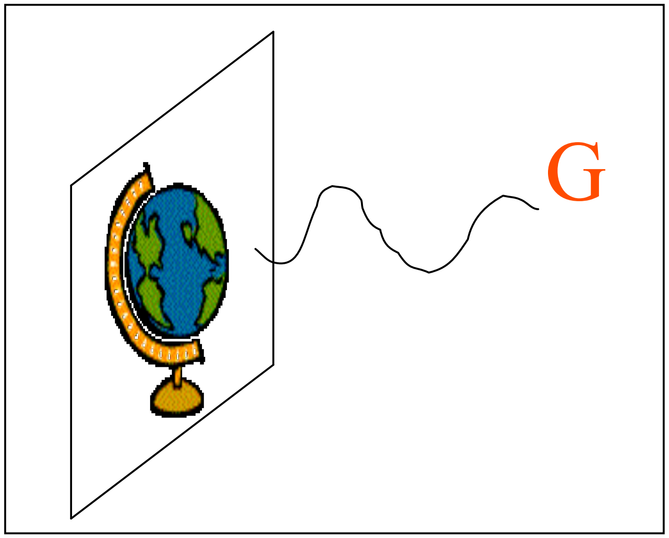
[Hitoshi Murayama] 45

Solving the Hierarchy Problem with Extra Dimensions

- String theory:
  - There are more than 3 spatial dimensions
- Large Extra Dimensions
  (Arkhani-Hamed, Dimopoulos, Dvali)
  - Electroweak and strong interaction live in our dimensions
  - Gravity lives also in extra dimensions

$$M_{Pl}^{2} \sim R^{n} M_{Pl(4+n)}^{(2+n)}$$

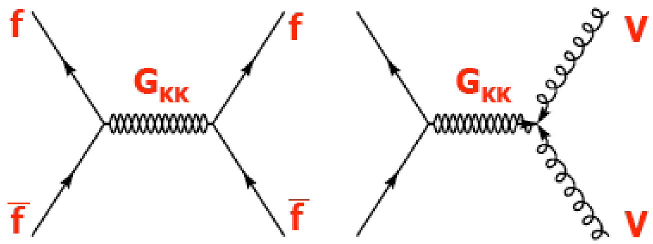
  - R=radius of extra dimensions
    - R=100 μm - 1 fm for n=2-7

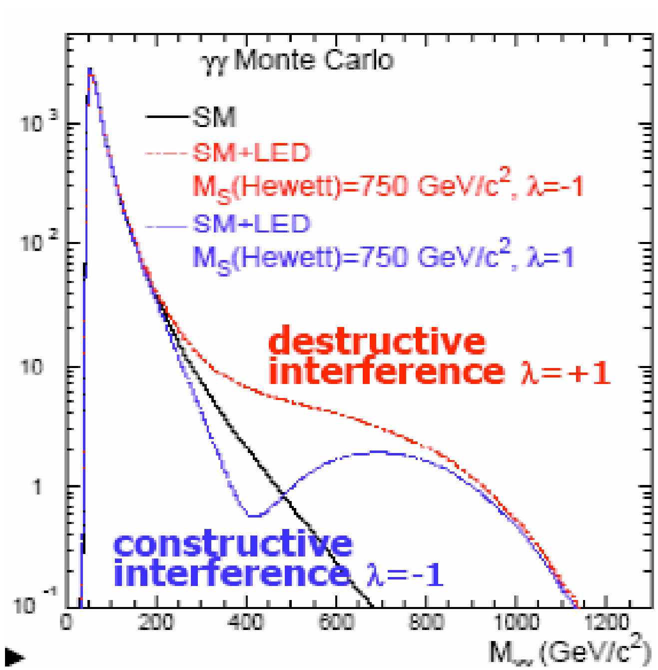


Other models:
e.g. Randall-Sundrum

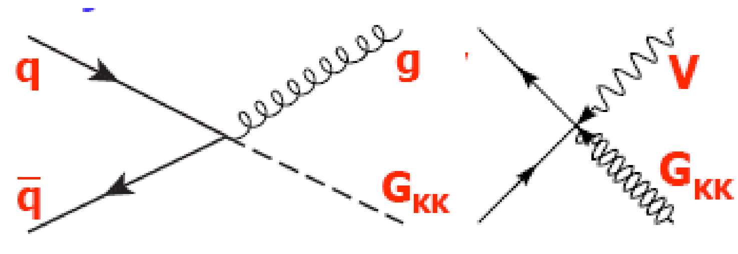
Possible Experimental Signatures

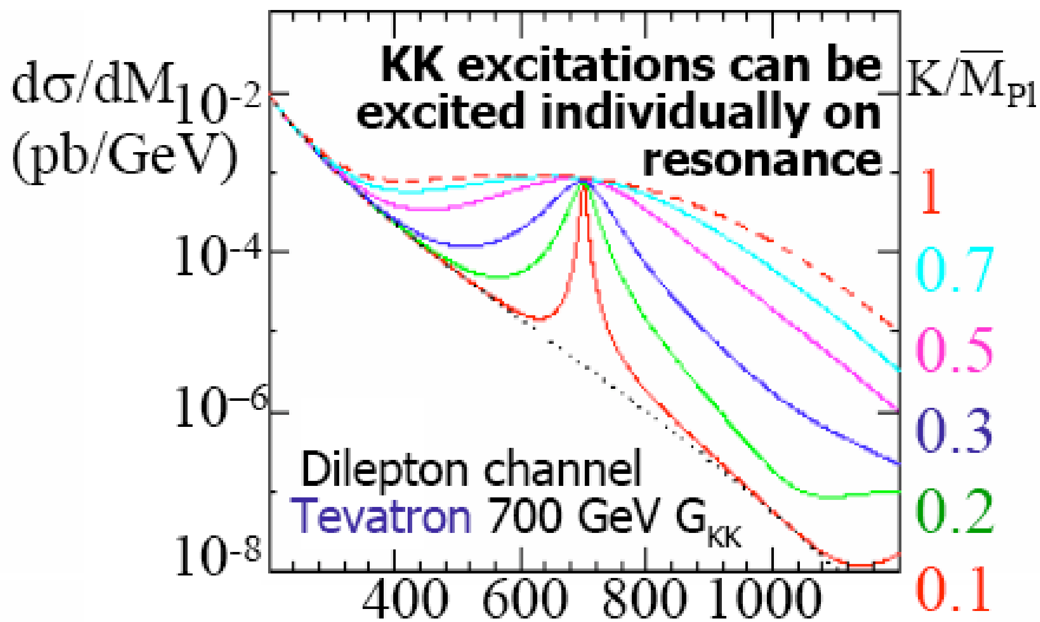
Virtual exchange





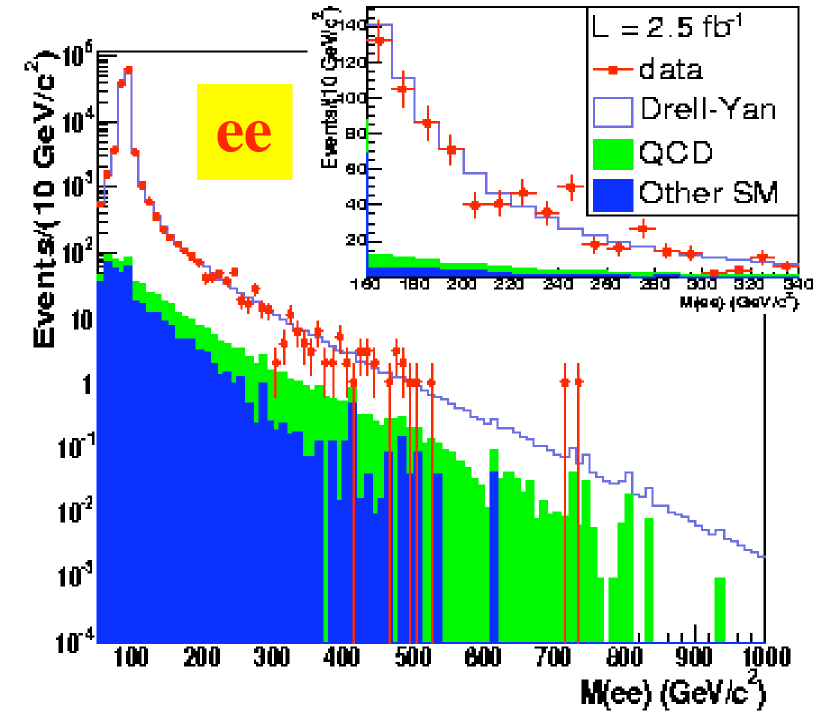
Direct emission

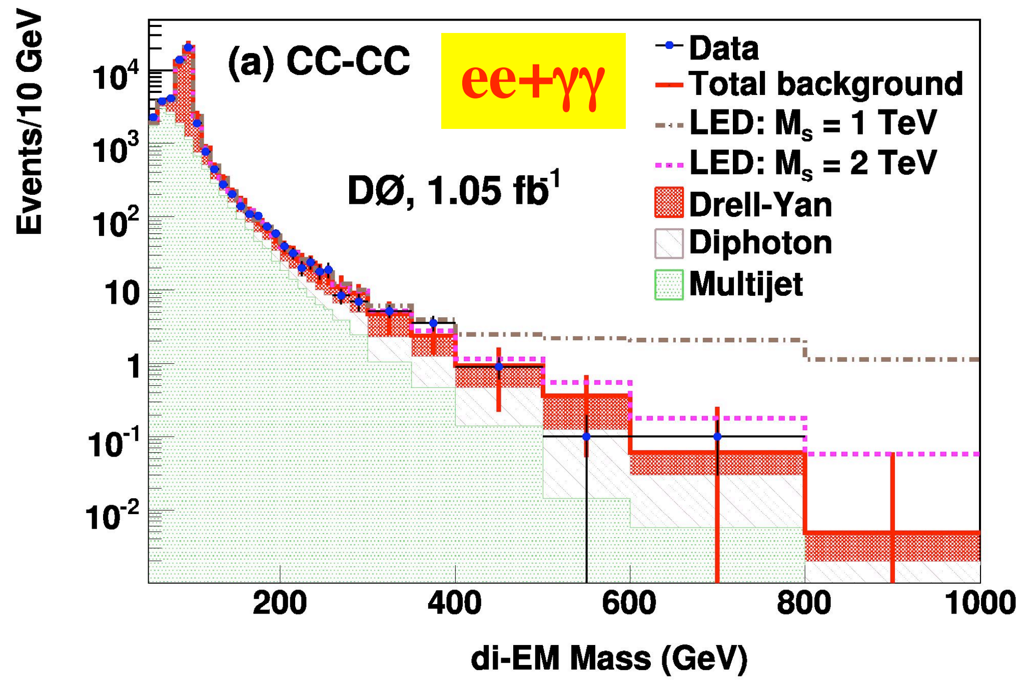




Dielectron and Diphoton Mass Spectra

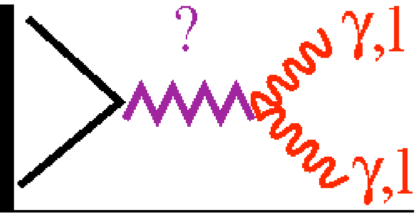
CDF Run II Preliminary



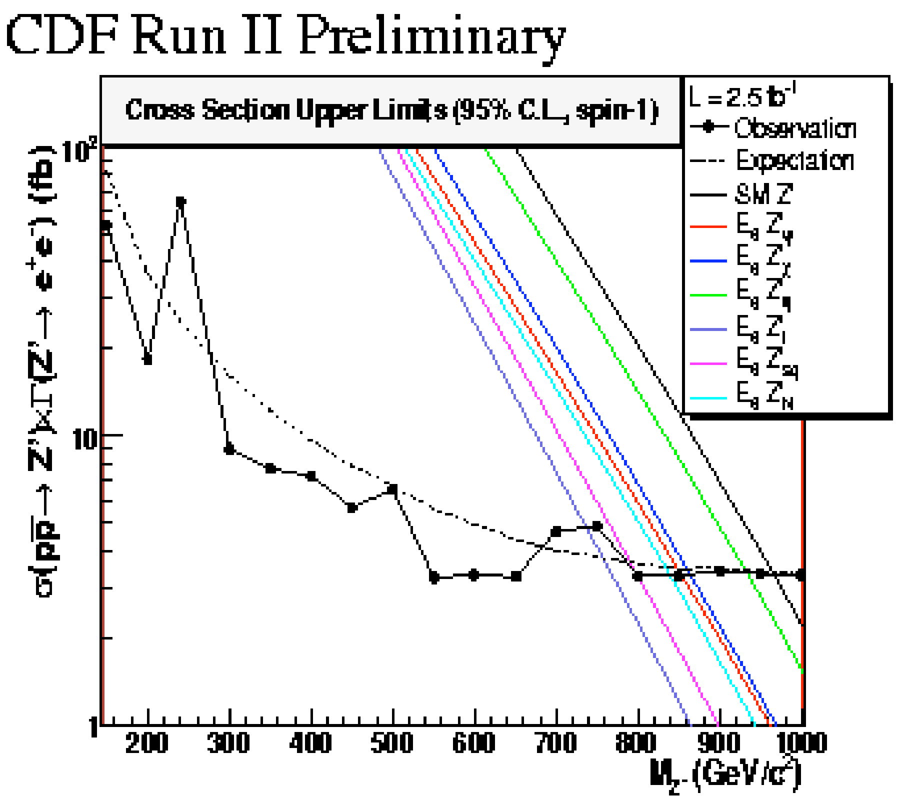


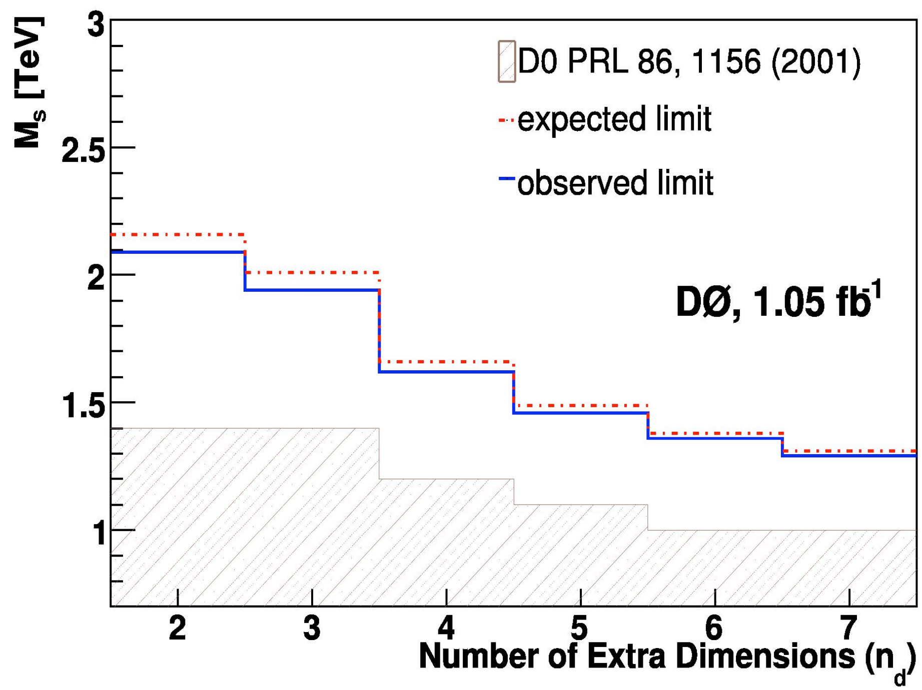
- Data agree with background prediction
  - Slight excess in CDF ee spectrum at 240 GeV (prob.~0.6%)
    - 50 events on a background of 27
  - Not clear if observed by D0 also

High Mass ee and $\gamma\gamma$



- Anomalous in diphoton or dielectron mass spectrum predicted in
  - Resonance: Z' models (spin 1) and Randall-Sundrum Graviton (spin 2)
  - Hard tail: large ED model (ADD)



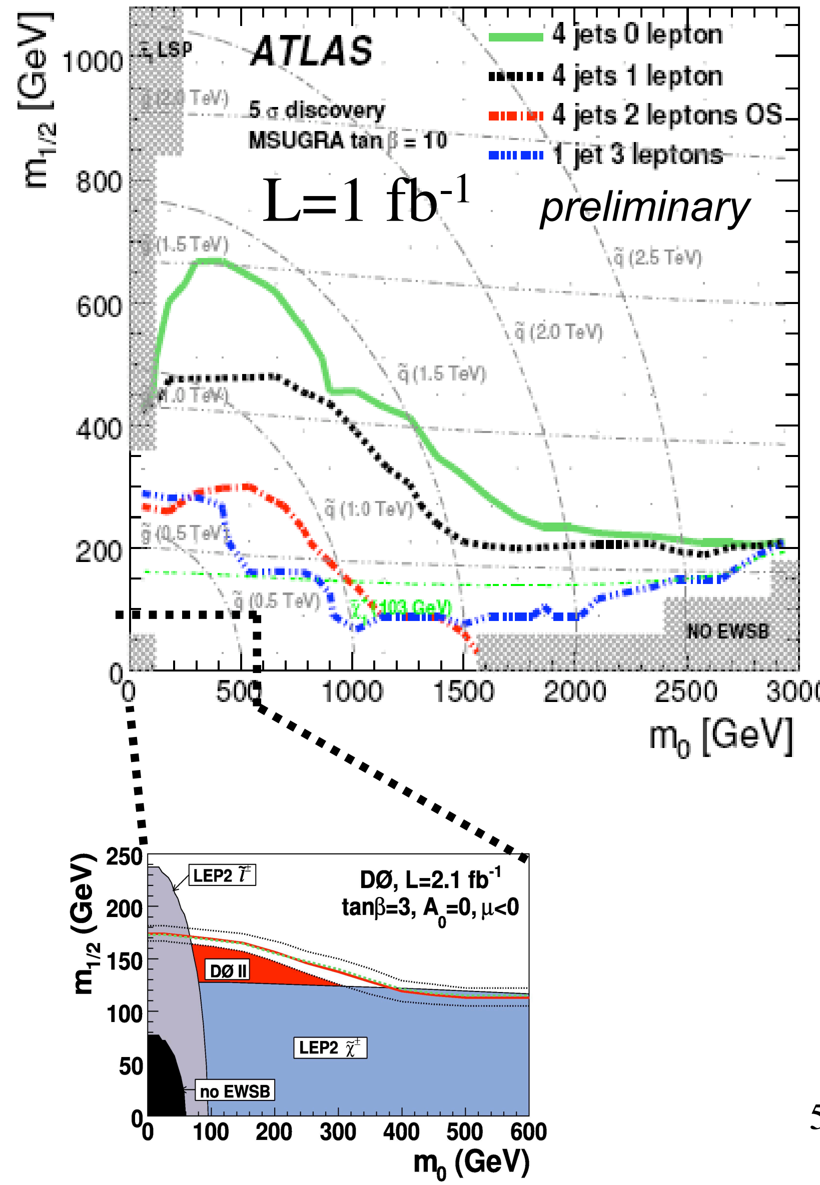


$M_{Z'}$>966 GeV for SM-like Z'

M_s>2.1-1.3 TeV for N_{dim}=1-7

Conclusions and Outlook

- **Tevatron + experiments operating well**
  - Analyses based on up to 3 fb^{-1}
  - Already >4.5 fb^{-1} on tape
- **Physics result cover broad range:**
  - **QCD** thoroughly being tested:
    - works very well even in complicated final states!
    - Precision between 2 and 50%
  - **Higgs boson constraints at 95% CL**:
    - Indirect (m_W and m_{top}): m_H<154 GeV/c^2
    - Direct searches: $m_H \neq 170$ GeV/c^2
  - **Searches** beyond the Standard Model
    - Many searches but no sign of new physics yet
- **Valuable input for the LHC**
  - **Testing background predictions for new physics searches**
    - Higher order QCD calculations
    - MC programs
  - **Develop search strategies**
    - Although may be lot easier at the LHC



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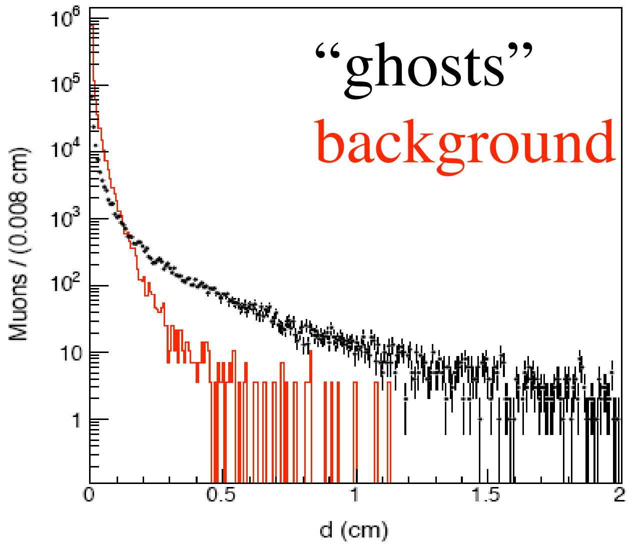
Process (mass)	σ(Tevatron) / σ(LHC)
$W^{\pm}$ (80 GeV)	~10
tt (2x172 GeV)	~100
gg->H (120 GeV)	~40
$\chi^{+}_{1}\chi^{0}_{2}$ (2x150 GeV)	~10
qq (2x400 GeV)	~1000
gg (2x400 GeV)	~20000
Z' (1 TeV)	~300

Hopefully we are at the verge of making a striking discovery!

Backup Slides

CDF Multi-Muon Study aka “Ghosts”



	Data	Background
N(extra μ)≥0	1.42 x 10^6	1.13 x 10^6
N(extra μ)≥1	1.41 x 10^5	0.94 x 10^5
N(extra μ)≥2	1.02 x 10^4	0.39 x 10^4

- Recent preprint (0810.5357) discusses excess of muons
  - Muons have anomalously high impact parameters:
    - Lifetime: $\tau \approx 20$ ps
  - There are extras muons in these events
  - Considered backgrounds due to b-decays, punch-through, decay-in-flight
- Unclear if this is due to a signal or a miscalculated background
  - Would be interesting to see if HERA experiments see this
  - Warning: very difficult analysis (e.g. hadronic interactions, punch-through,…)