# Recent Results from the Tevatron

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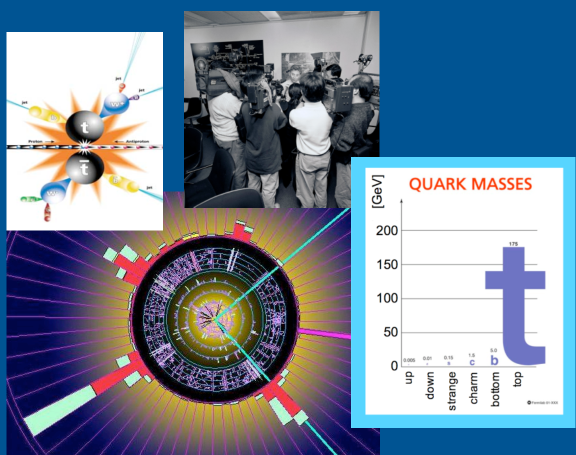
# Outline

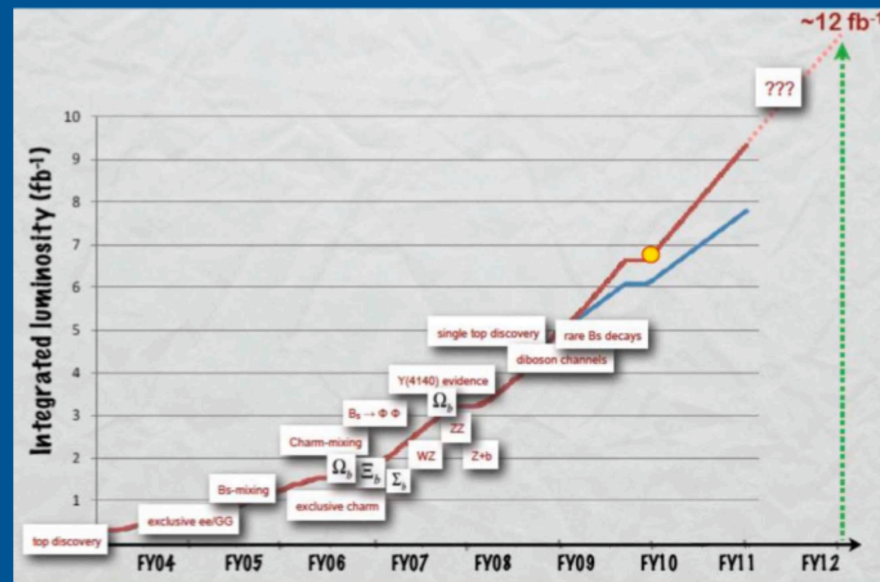
- The Tevatron
  - Status and records
- Standard Model precision measurements
  - From QCD physics to the top mass precision measurement
    - And a window to new physics….
- Higgs boson search
  - Current high mass exclusion limits and the physics case for running beyond 2011
- Searches for BMS
  - Signature-based searches
  - Evidence for anomalous like-sign dimuon charge asymmetry
- Conclusions

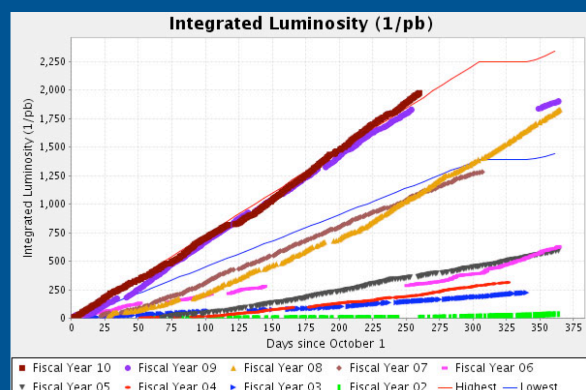
# The Fermilab Tevatron

## The Fermilab Tevatron is …
## …a Discovery Machine!

Top Quark Discovery (1995)




Today the collider experiments have collected 125 times more data than what we used to discover the top quark

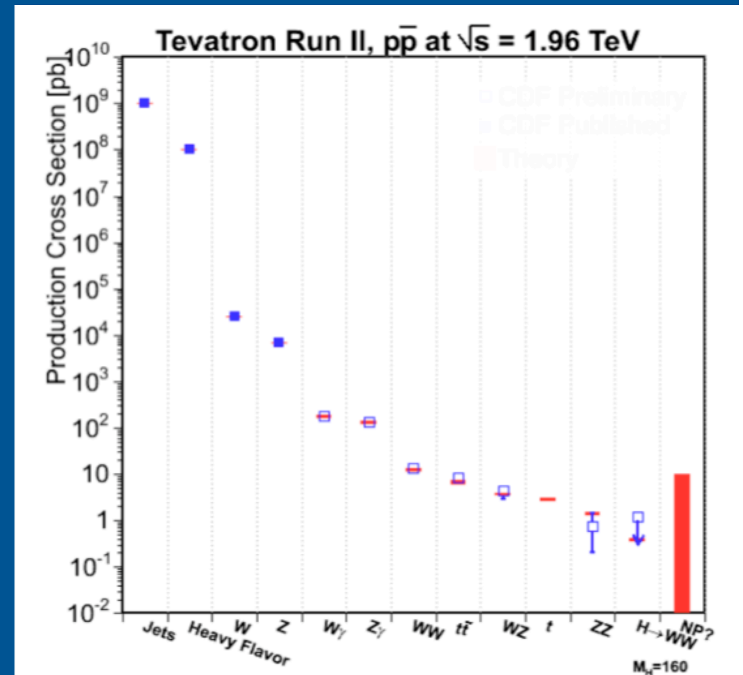
Many new luminosity records set!

# The Tevatron Research Program

Precision Mesurements & New Discoveries

- Mixing, CKM constraints and CP violation
- Heavy flavor spectroscopy
- New Heavy barions states
- Tests of Quantum Chromodynamics
- Precise Mesurements of the Top quark and W boson mass
- Top Quark Properties
- Diboson production and SM gauge couplings
- New Exclusive/difractive processes
- …..

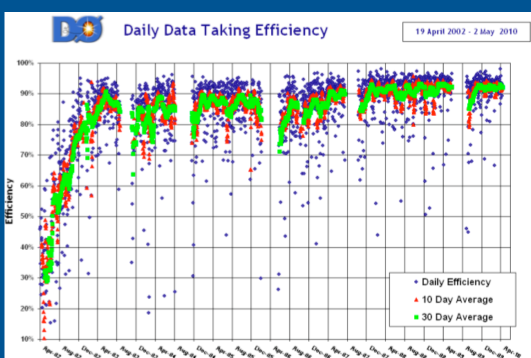
Harder to Produce




Harder to Observe

We are still probing the Terascale, as the integrated luminosity of our datasets increases

Are we on the verge of a new discovery?

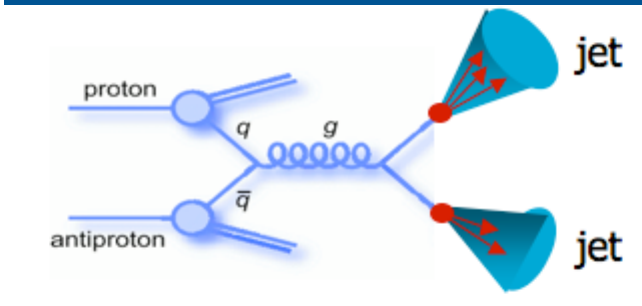



CDF and D0 are running at ~90% efficiency

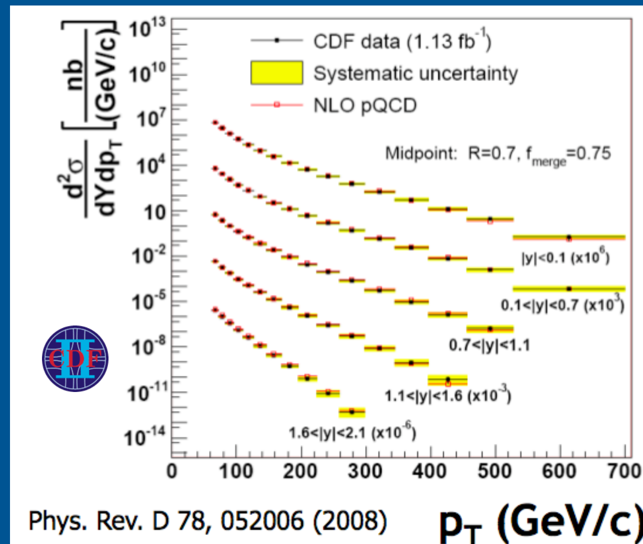
# Precision Measurements and windows to new physics

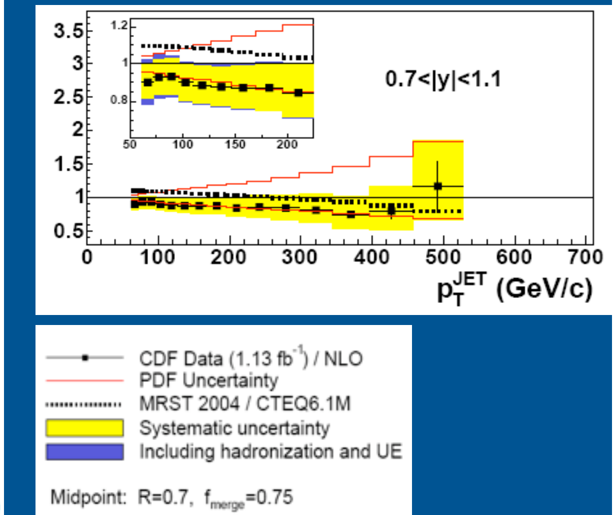
- Test of QCD
  - Inclusive Jets production
    - PDF's constraint and measurement of the strong coupling constant
    - Dijet angular distribution and mass
- Top Quark
  - Top Mass Measurement
  - Anomalies in top sample
- Electroweak Physics
  - W mass measurements
  - Multiboson production

# Inclusive Jet Production



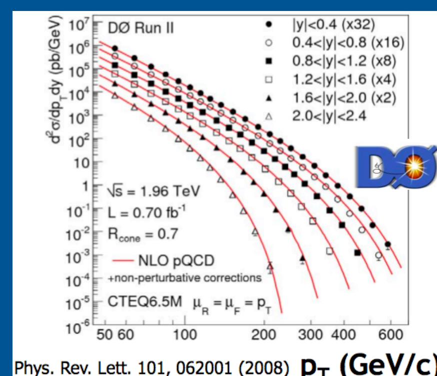

Collimated sprays of particles originating from quark and gluon fragmentation




**Sensitive to:**

- Hard partonic scattering
- strong coupling constant
- proton's parton content
  - → unique sensitivity to high-x gluon
- dynamics of interaction
  - validity of approximations (NLO, LLA, …)
  - QCD vs. new physical phenomena

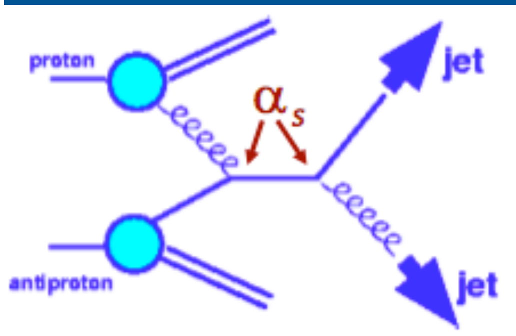



Experimental precision now exceeds the PDF theoretical uncertainty

data are used in PDF fits:

- included in MSTW2008 PDFs
- at work: forthcoming CTEQ PDFs

# Strong Coupling Constant




Measurement uses the $P_T$ dependence of the jet x-section

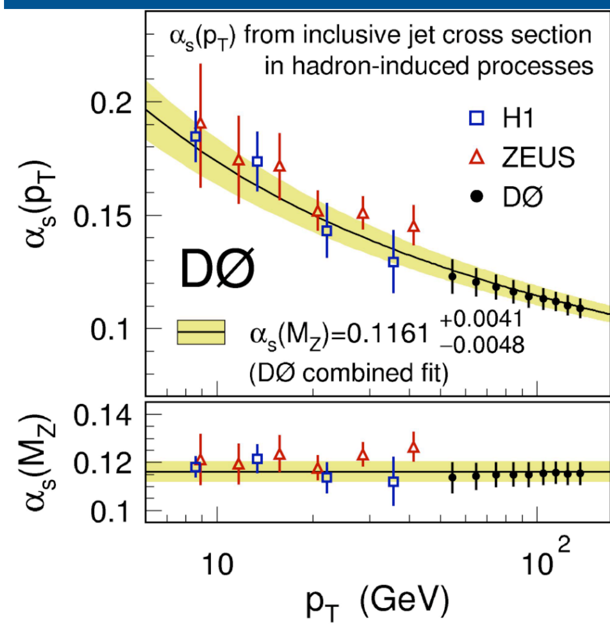
-$\chi^2$ minimization of data/theory points

- -22/110 points in the inclusive jet cross section used
  - -50 < $P_T$ < 145 GeV/c,
  - - high points excluded to minimize PDF uncertainty correlations

- NLO+2 loop thresholds corrections
- MSTW2008NNLO PDF's

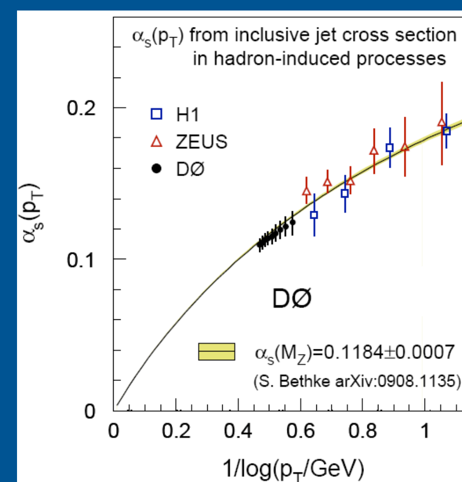
$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

Phys. Rev. D 80, 111107 (2009)



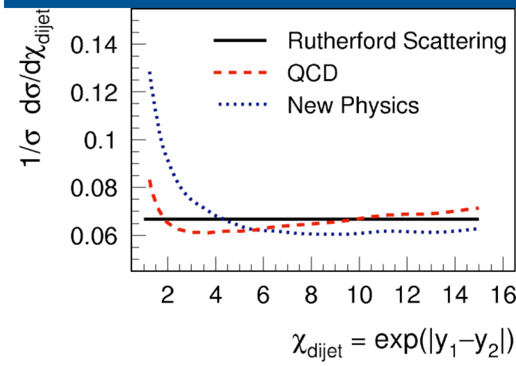

HERA results extended to high $P_T$

**Most precise result at hadron-hadron collider !**



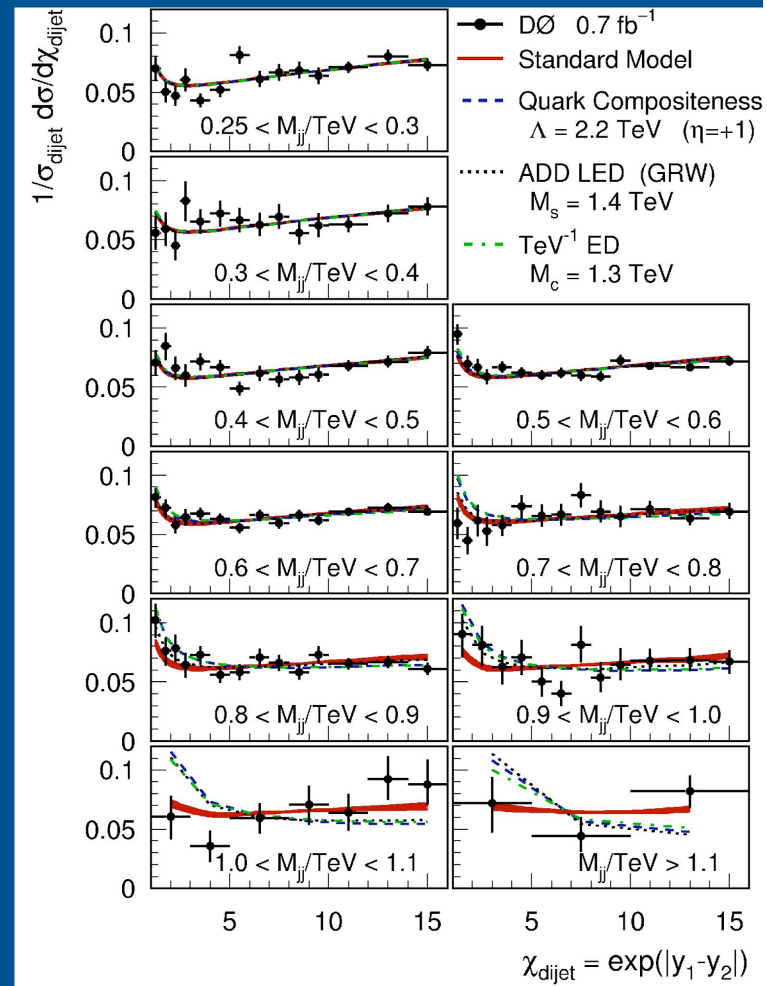
# Dijet angular and mass distributions

Dijet angular distributions is measured in bins of dijet mass

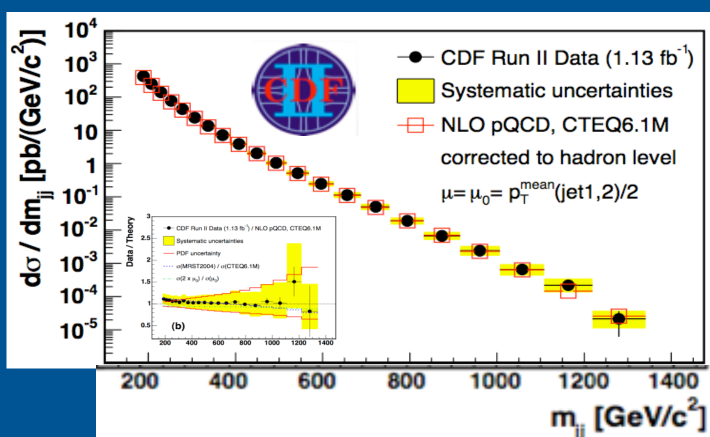



**Limits on Compositeness & LED**

- Quark Compositeness Λ > 2.9TeV
- ADD LED (GRW) Ms > 1.6 TeV
- TeV-1 ED Mc > 1.6 TeV




Dijet mass distributions is scanned for mass bumps!




Excludes (at 95% CL) excited quarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV

# Top Quark Physics

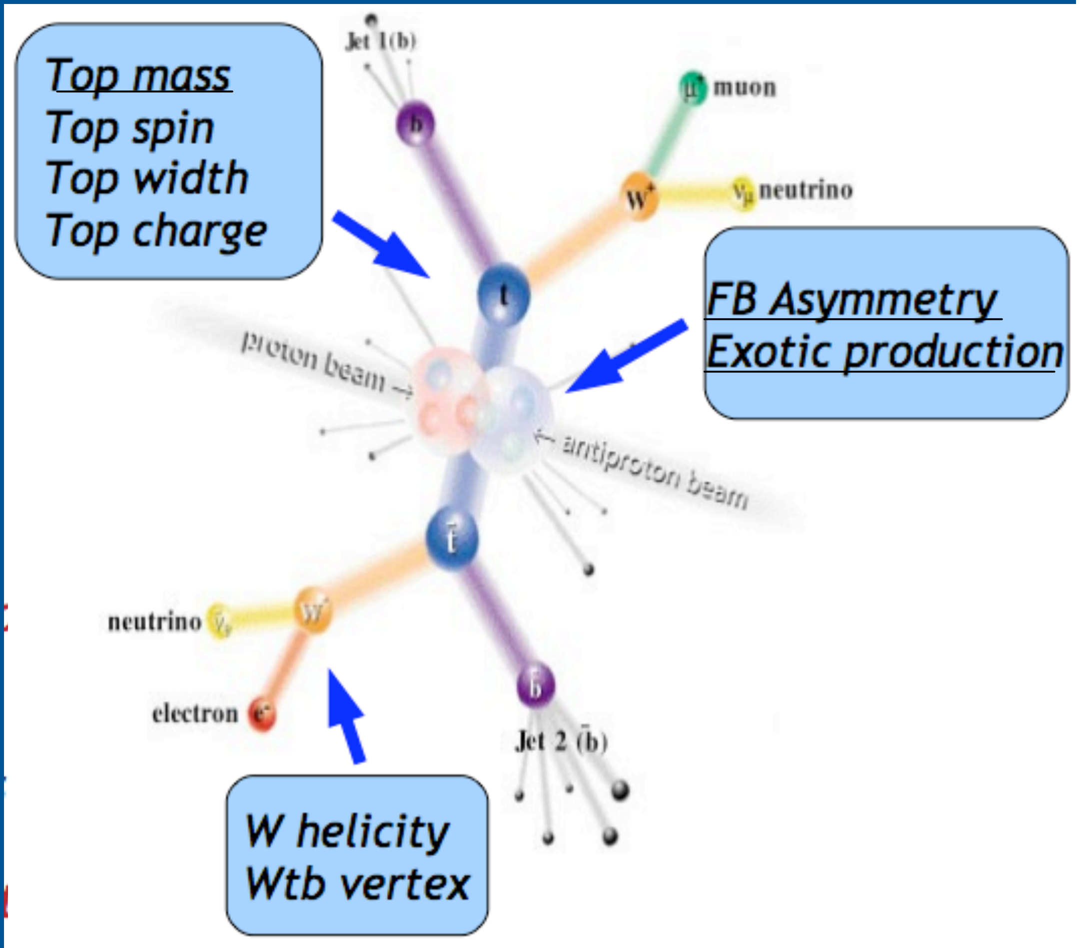
The Tevatron program explores all top properties as well as sources of new physics

*top quark* ***production***
- *top pair production*
- *Single top production*

*top quark* ***properties***
- *Mass, spin, width, charge*

*top quark* ***decay***
- *W boson helicity in top decays*
- *Probe the W-t-b vertex*

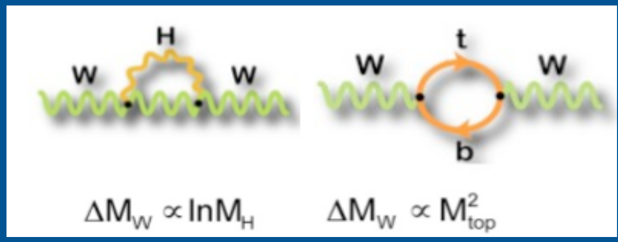
***Exotic sources*** *of top quarks*
- *Non SM top*
- *Forward-backward asymmetries*



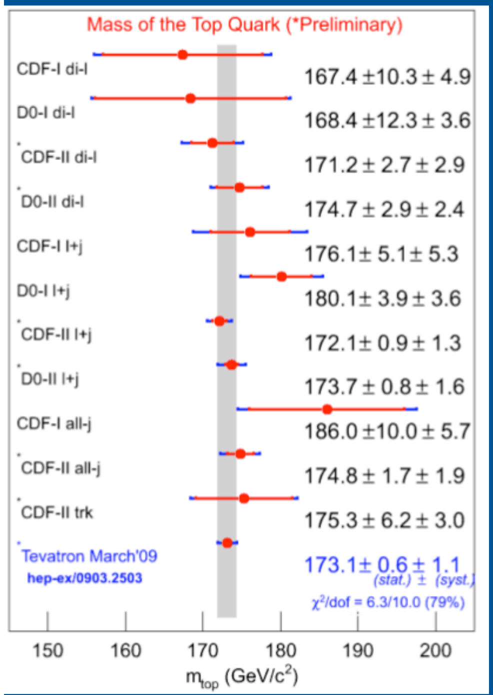
# Top Quark Mass

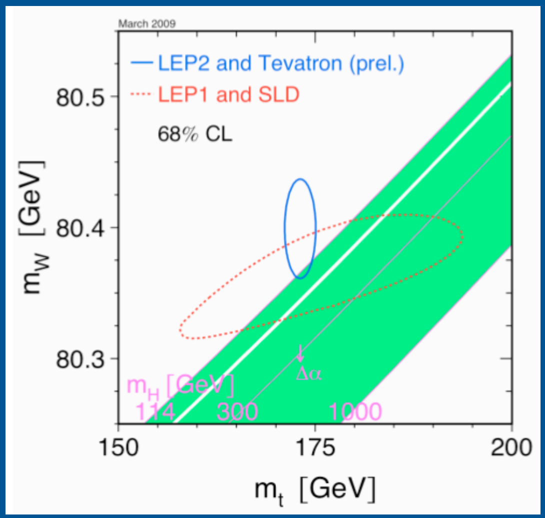
## Top Mass is a fundamental parameter of the Standard Model

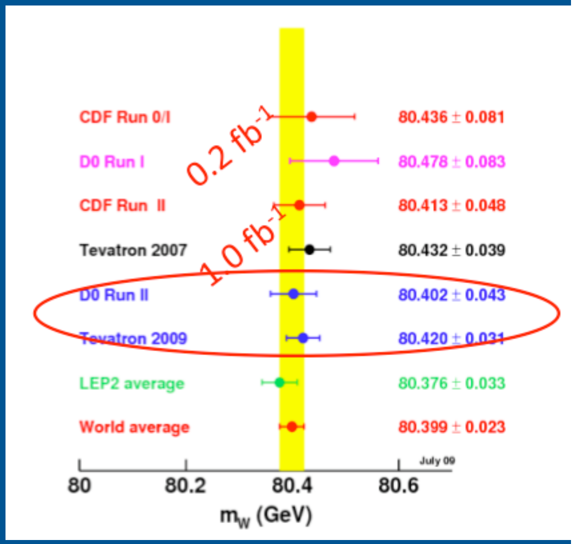
Due to the large M(top), quantum loops involving top quarks are important when calculating the theoretical value of precision observables




Measuring the W boson mass and the top quark mass precisely allows for prediction of the mass of the Higgs boson and constraint to new physics




Precision is now limited mainly by systematic uncertainty - joint effort on improving its understanding

# Top Quark Mass Measurements

The most advanced measurements are using complete Matrix element information as well as multivariate techniques to distinguish signal from background

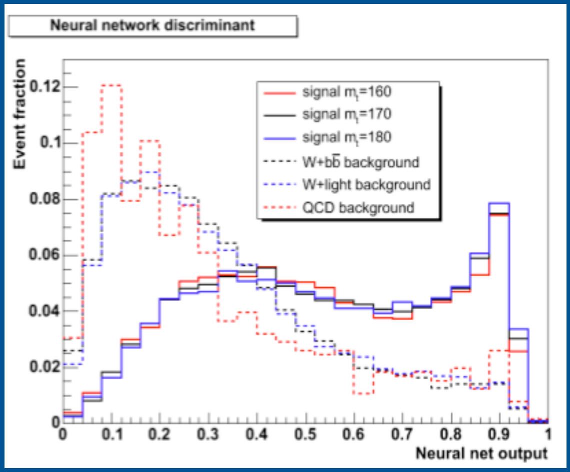
**ME Method:**
Define the probability $P_{evt}$ that the *observed* kinematics arise from possible signal or bkg kinematics at parton level, then maximize $L = \Pi Pevt(M_{top}, JES, f_{top}(M_{top}, JES))$

$$P_{evt}(\vec{x}) = f_{top} \cdot P_{sig}(\vec{x}, m_t, JES) + (1 - f_{top}) P_{bkg}(\vec{x}, JES)$$

$$P_{sig}(\vec{x}) = \frac{1}{\sigma(m_t, JES)} \int f(q_1)dq_1 f(q_2)dq_2 \times |M(\vec{y})|^2 \phi(\vec{y}) dy \times W(\vec{x}, \vec{y}; JES)$$

Parton distribution functions | Differential cross section (LO ME) | Transfer Function: maps parton level (y) to reconstructed variables (x)

**D0 (3.6 fb$^{-1}$) Lepton + Jets Matrix Element Technique**
**$M_{top}$ = 173.7 ± 0.8(stat) ± 0.8(JES) ± 1.4(syst) GeV/c$^2$**

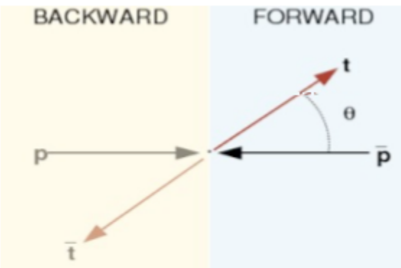



More precise than world average!

**CDF (4.8 fb$^{-1}$) Lepton+Jets, Multivariate:**
**$M_{top}$ = 172.8 ± 0.7 (stat) ± 0.6 (JES) ± 0.8 (syst) GeV/c$^2$ = 172.8 ± 1.3 (total) GeV/c$^2$**

# Anomalies in Top Sample

## - Forward-backward asymmetry

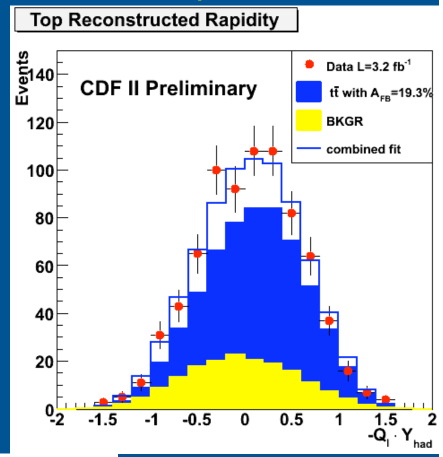



$$A_{fb} = \frac{F - B}{F + B}$$

New physics could give rise to asymmetry (Z', axigluons etc)
Standard Model predicts: $A_{FB}$ = 0.05±0.015 (NLO QCD)

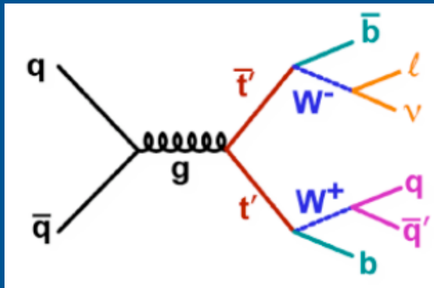
**CDF (3.2 $fb^{-1}$):**
Afb = 0.19 ± 0.07 (stat) ± 0.02 (syst)

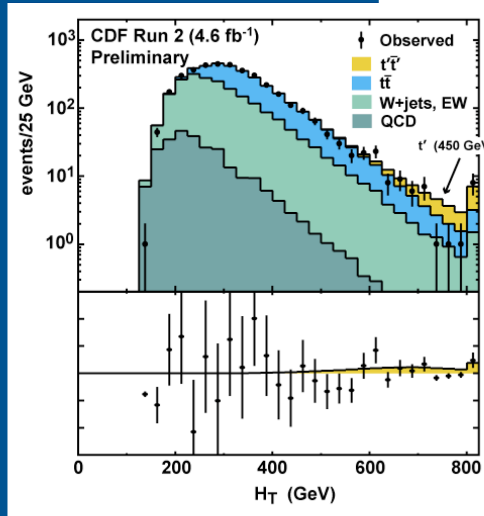
**D0 (1.0 $fb^{-1}$):**
Afb det = 0.12 ± 0.08 (stat) ± 0.01 (syst)




## - Apparent heavy top quark events

Search for a heavy t-like quark, decaying to Wb in the same way as top



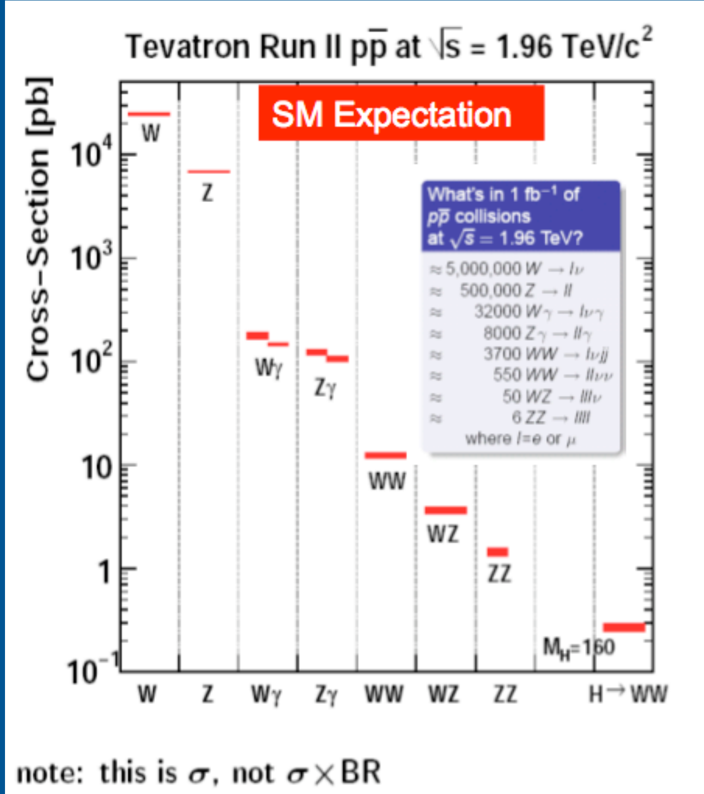

Less than 2σ significance

# Diboson Production

•Diboson production is one of the least tested areas of the SM

•The triple gauge vertices are sensitive to physics beyond the SM

•SM diboson production share many characteristics and represent background to Higgs and SUSY searches




- WW+WZ

  D0: σ (WW+WZ) = 20.2  4.5 pb evidence at 4.4σ

  CDF: σ (WW+WZ) = 16.5 $^{+3.3}_{-3.0}$ observation at 5.4σ

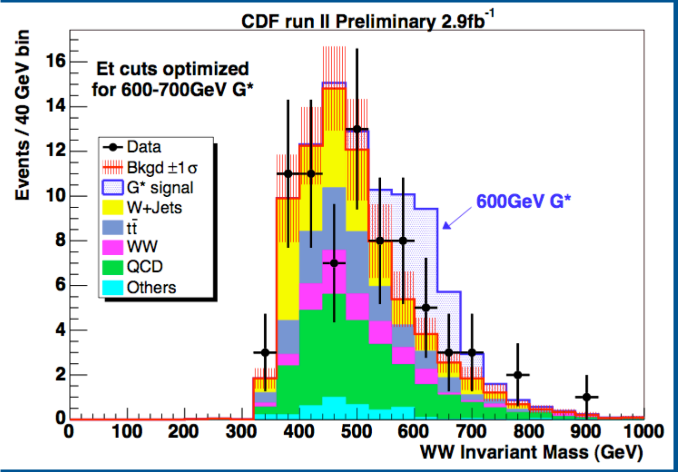
- WW+WZ+ZZ

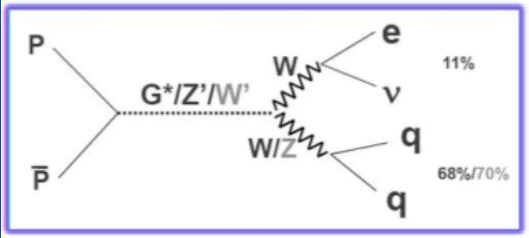
  CDF: σ (WW + WZ+ ZZ) = 18.± 2.8(stat) ±2.4(sys) ±1.1(lum)pb

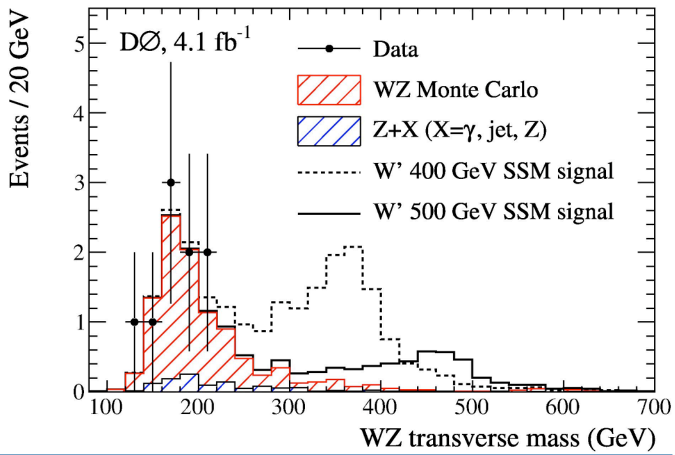
  SM prediction = 16.8 ± 0.5 pb (MCFM+CTEQ6M)

  observation at 5.3σ significance

# Search for new physics in dibosons



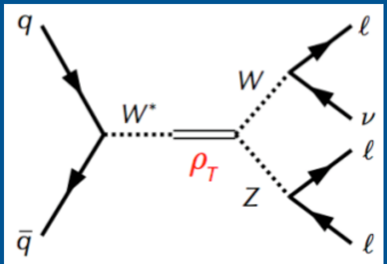



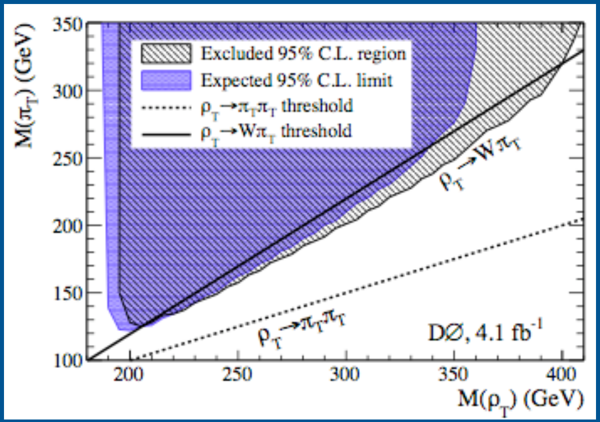

$M_G$ > 607 GeV ($k/M_p$ = 0.1)

$M_{Z'} \notin (247,545)$ GeV

$M_{W'} \notin (284,515)$ GeV

Technicolor scenario with $m(\rho_T) < m(\pi_T) + M(W)$ Excluded mass 208-408 GeV/c$^2$ @ 95% CL



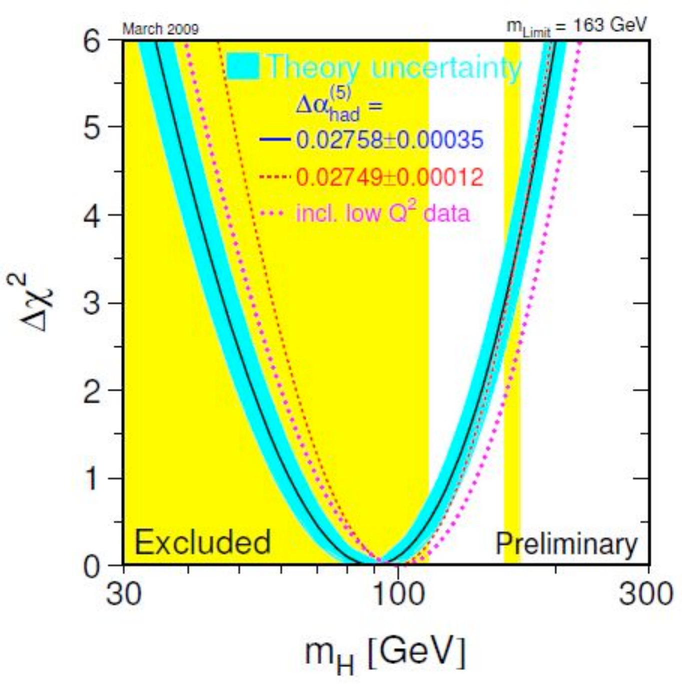



# The Higgs Boson

The Higgs mechanism generates the masses of particles…

…yet, ironically, it reveals no hint of what its mass would be

If the Higgs boson exists, its mass must be determined experimentally
Here's what we've learned so far:



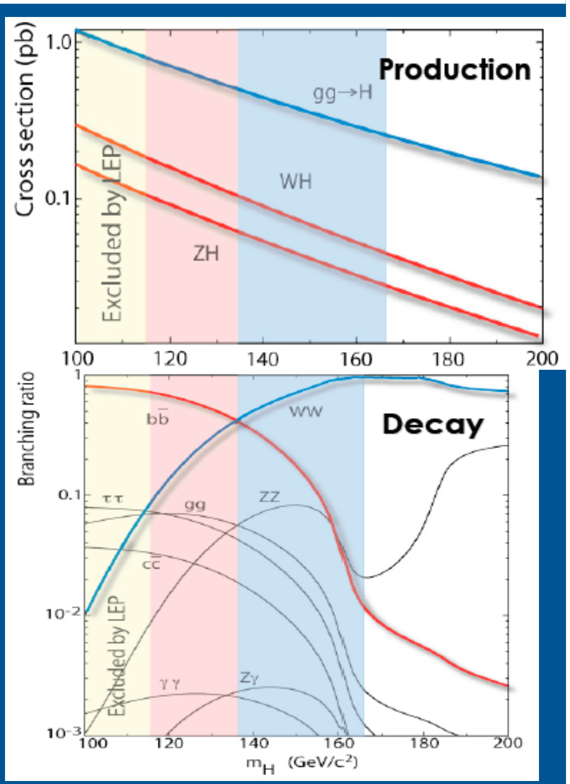

- Based on a direct search at LEPII
  - $m_H > 114$ GeV/c$^2$ @ 95%CL
- According to precision electroweak measurements
  - $m_H < 186$ GeV/c$^2$ @ 95%CL

Probing the mass range
$100 < m_H < 200$ GeV/c$^2$
is crucial !

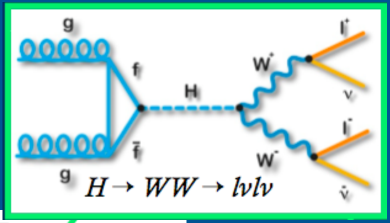
This is exactly the range where the Tevatron is sensitive!

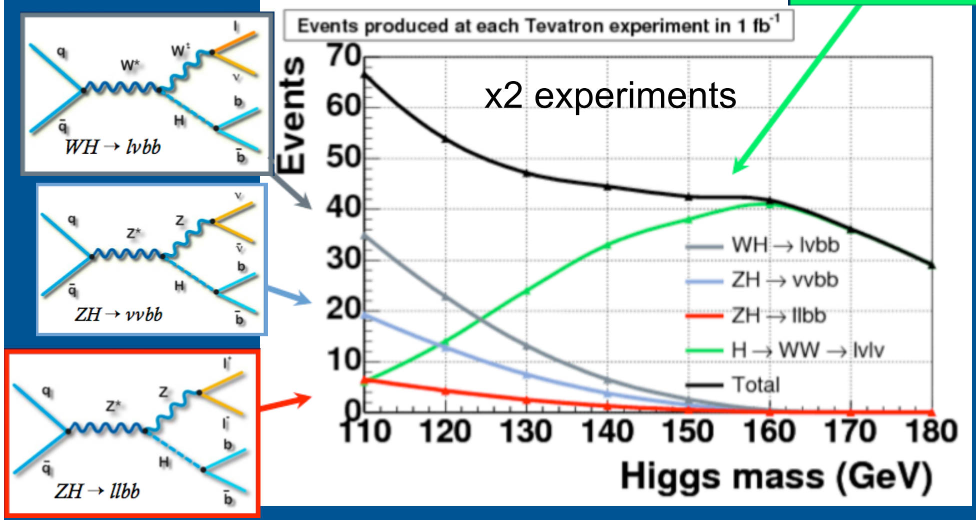
# Higgs Production and Decay

- <u>Low Mass Higgs</u>
  - H→bb, QCD bb background overwhelming
  - Use associated production to reduce background
- <u>High Mass Higgs</u>
  - H→WW→lνlν decay available
  - Take advantage of large gg→H production cross section



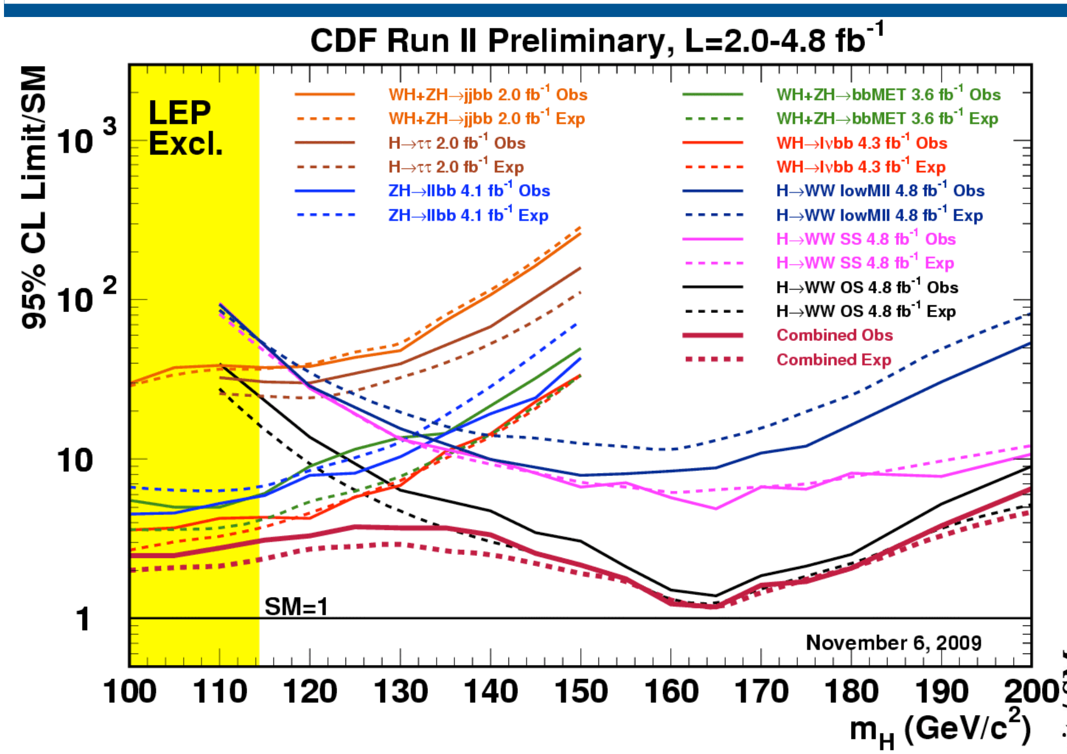

Major Tevatron channels
Part of a larger comprehensive search program



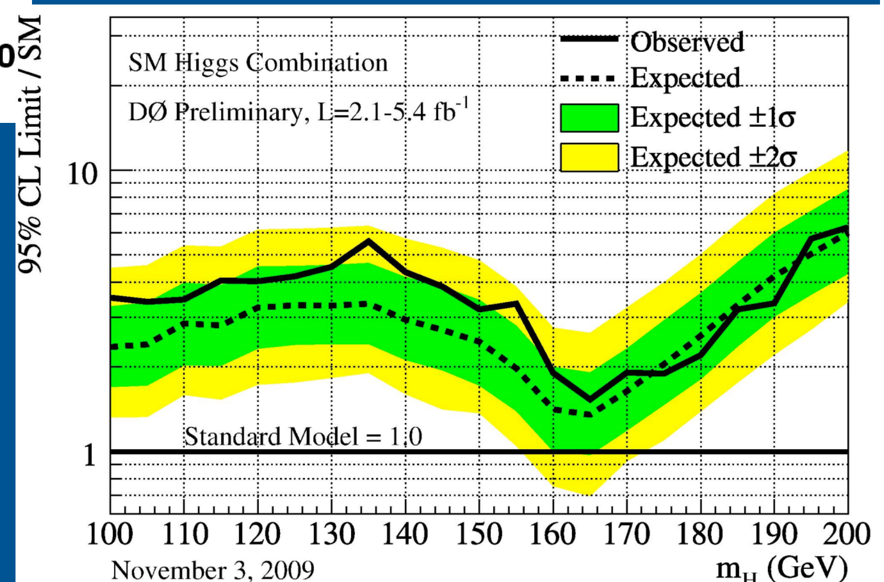




**Threefold strategy**
- Maximize signal acceptance
- Reduce background
- Employ multivariate techniques

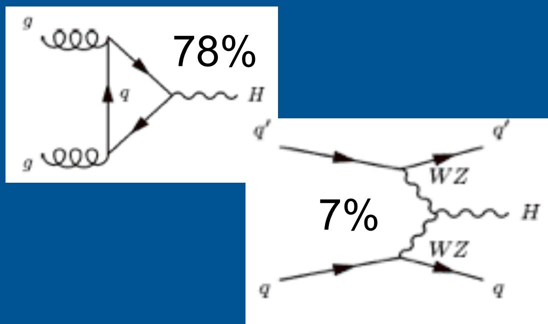
# Many Analysis

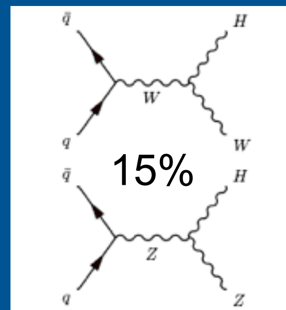



Both Tevatron experiments are extremely active!



# High Mass Higgs (H→WW)




Several orthogonal samples used to maximize acceptance/sensitivity:

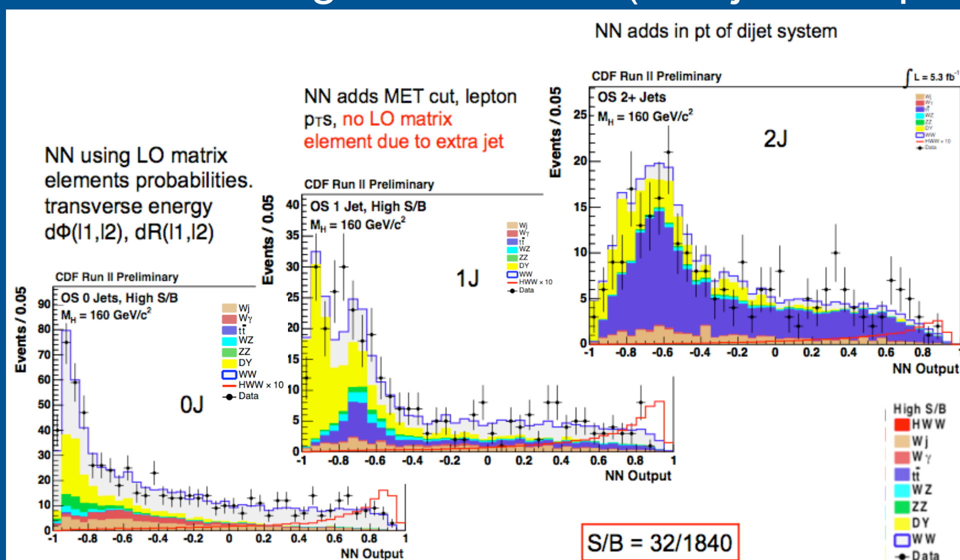
All production modes

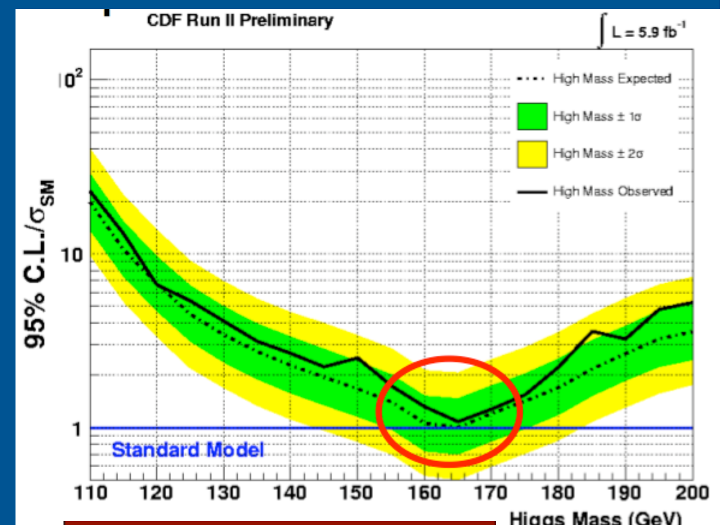
Various decay signatures

- Low/High dilepton inv mass
- Same-sign dileptons
- Trileptons

The power of discriminating variables combined in Neural Networks

Trained independently for each Higgs mass point hypothesis and orthogonal channel (and jet multiplicity bin)



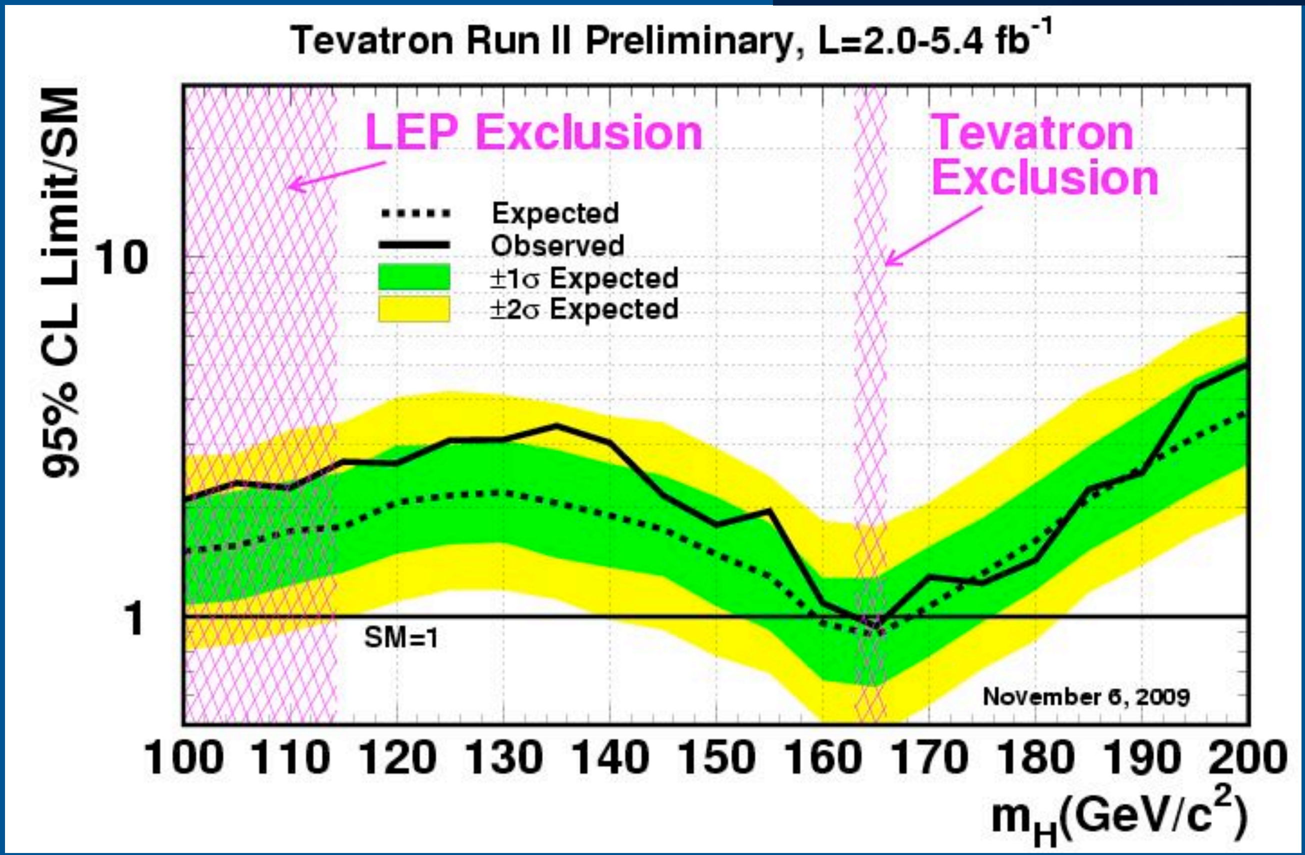

**Observed (Expected) Limits at**
**160: 1.32 (1.05)**
**165: 1.08 (1.00)**
**170: 1.28 (1.20)**

# Current Exclusion Limits

Although no single experiment can currently exclude the Higgs

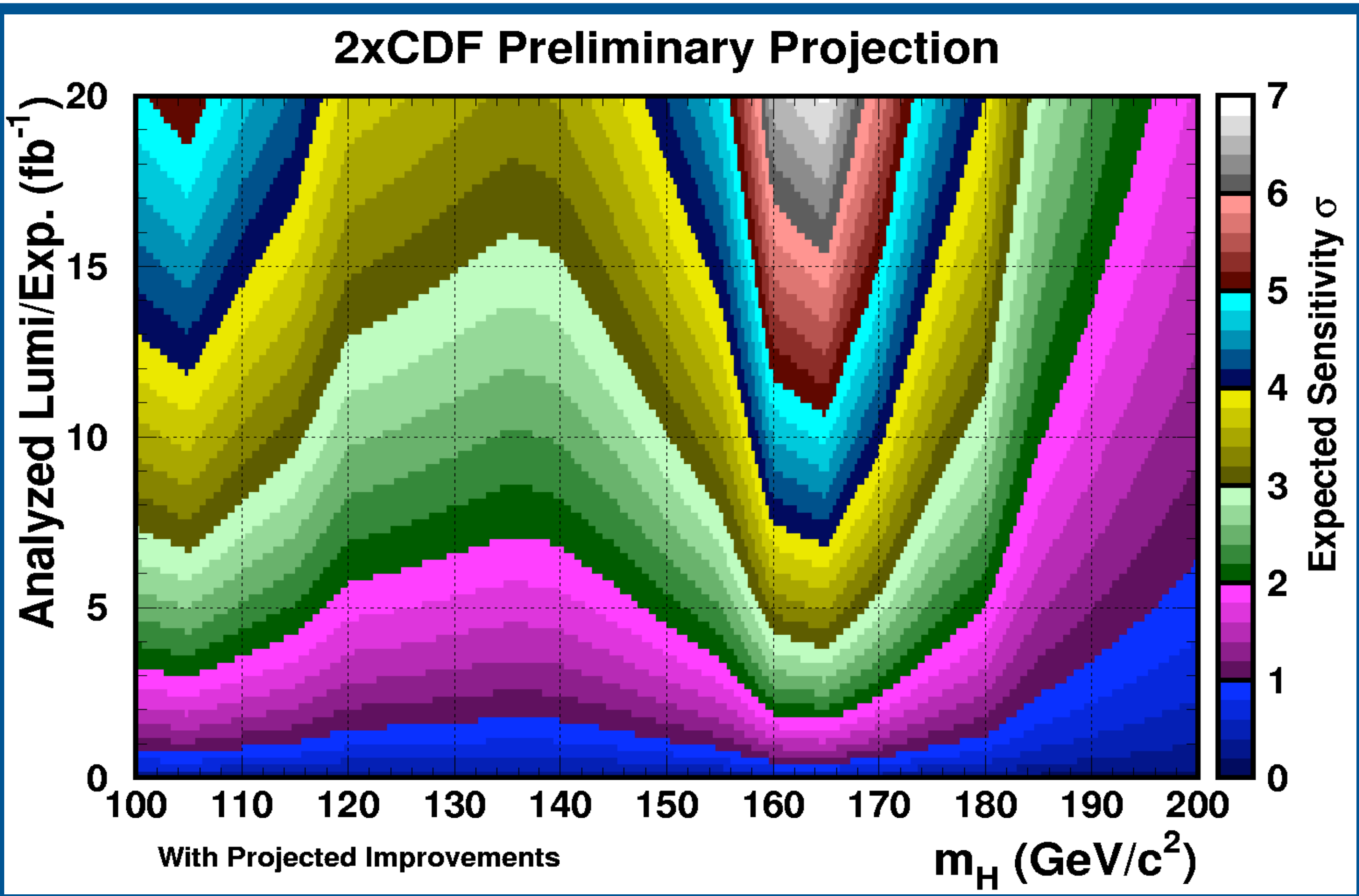
CDF & D0 combined

PRL 104, 061802 (2010)




The Standard Model Higgs is excluded in the range 163-166 GeV/$c^2$ at 95% CL

# Outlook for the future..




Terrific motivation to collect data beyond 2011!!!

# Search for New Physics

- Signature-based searches
  - Dilepton
  - Diphotons
  - Complex final states (MET, jets, h.f.)
    - Leptoquarks
    - SUSY
- Excitement in Flavor Physics
  - Anomalous like-sign dimuon asymmetry

# Dilepton final states

## Old-fashioned mass bump hunt..

CDF: 2.5$fb^{-1}$
D0: 3.6$fb^{-1}$

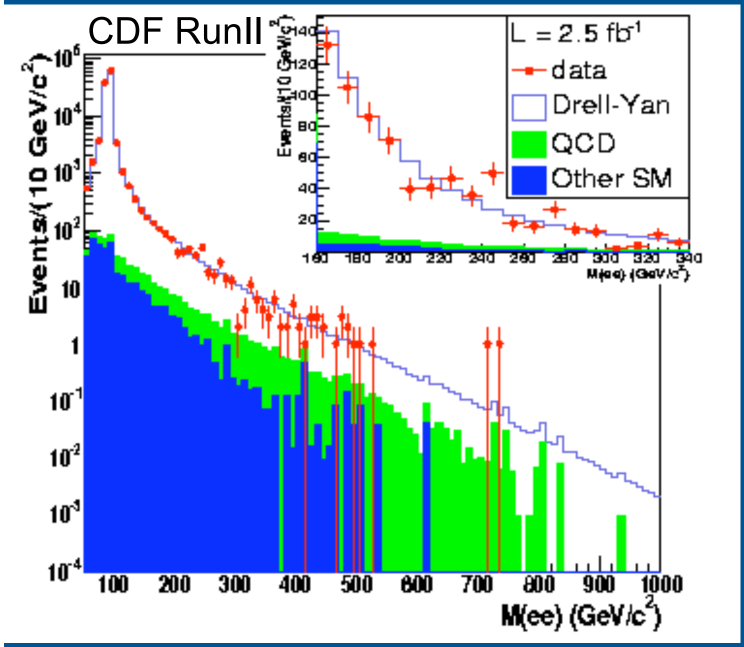
-Z production and decay into ee/$\mu\mu$ precisely measured
-Lepton ID/Reco and Trigger efficiencies high and very well understood
-Background low and easily determined (QCD fakes)
-Clean events

PRL 102, 031801 (2009)

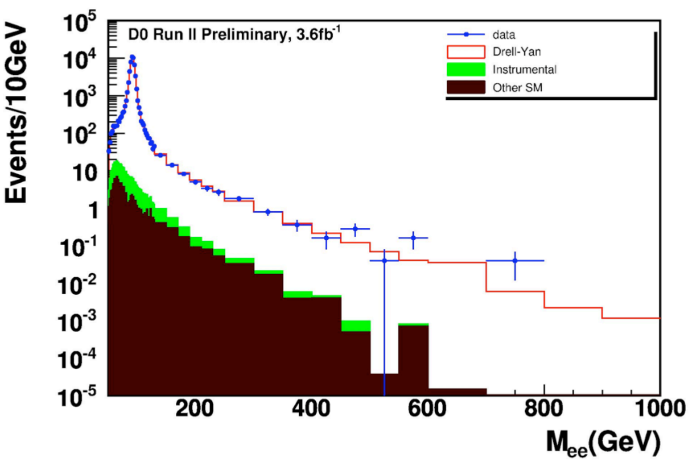
The most significant region of excess for an $e^+e^-$ invariant mass window of 240 GeV/$c^2$ (CDF)

2.5 standard deviations above the SM prediction

D0 does not see any deviation from SM in ee channel



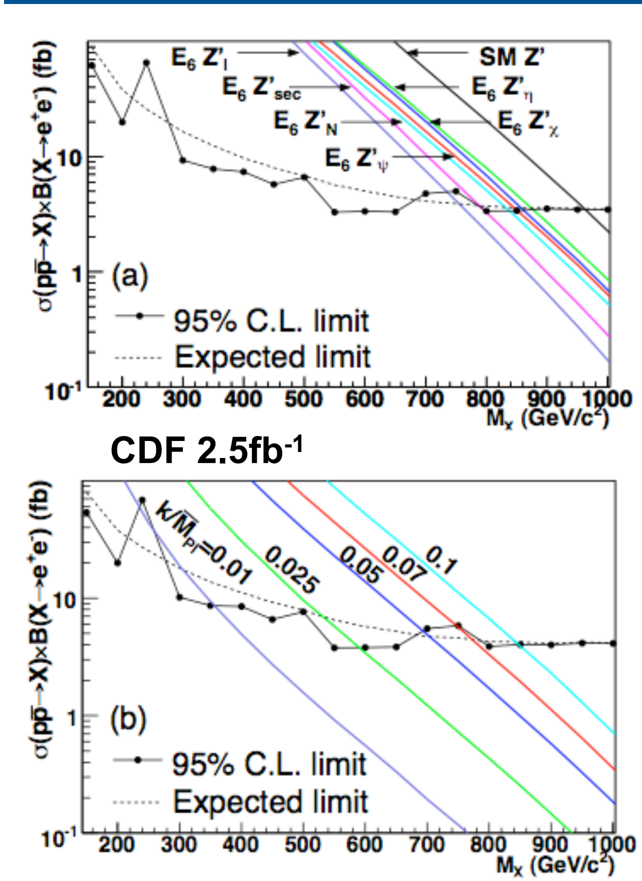

Conference Note 5923-CONF



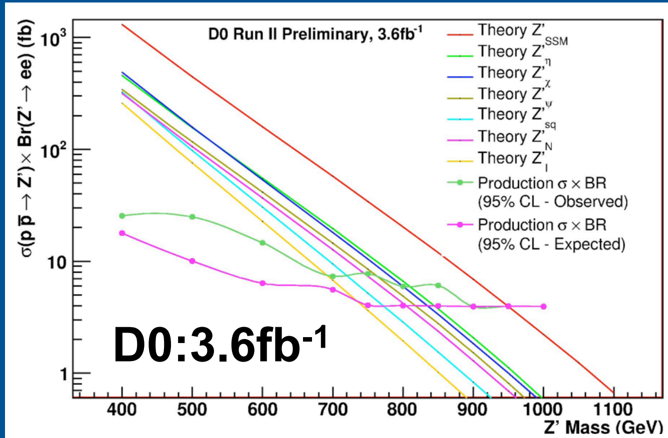
# Testing different models

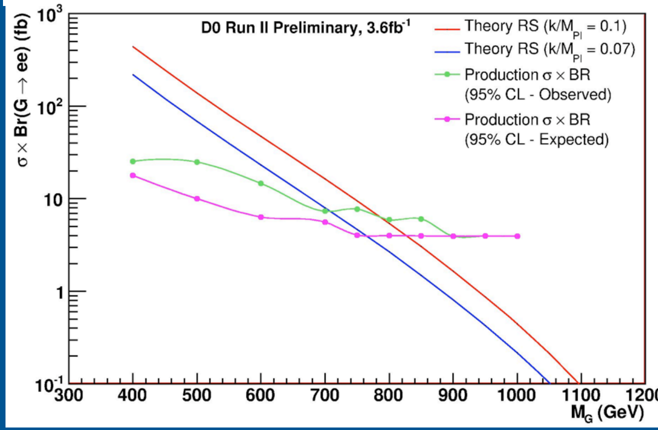
Once the data spectrum is well understood in terms of SM background, from MC, the acceptances for resonant states for different spin particles are derived (Z', RS Graviton) and the expected number of BSM events is calculated.

In the absence of an excess of data, 95% CL limits on production cross-sections and mass of the particles are set.




$m_{Z'}$ > 966 GeV (SM couplings)
$m_{RSG}$ > 850 GeV ($k/M_{Pl}$ = 0.1)

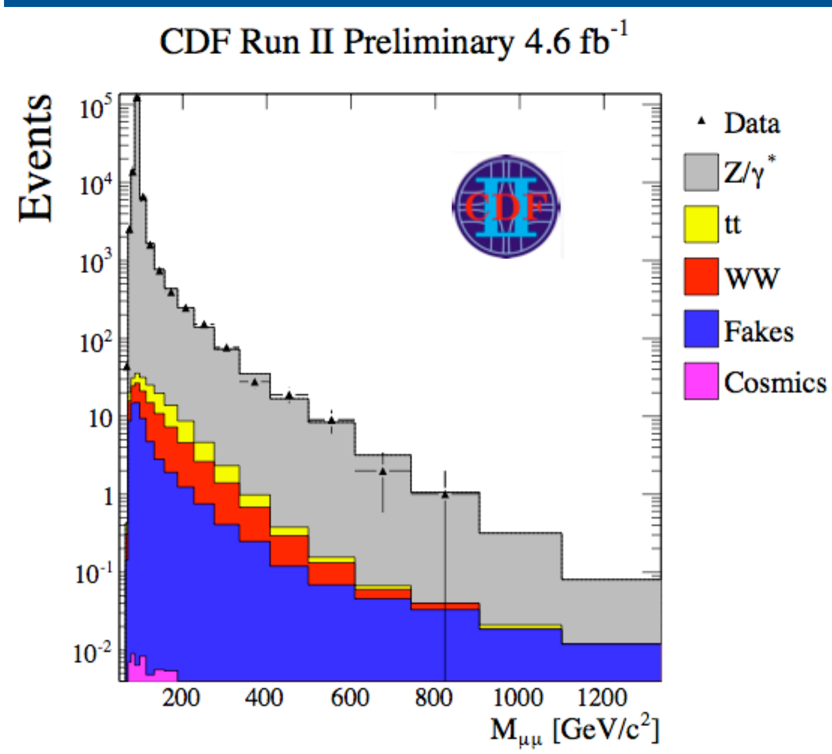



$m_{Z'}$ > 950 GeV (SM couplings)
$m_{RSG}$ > 786 GeV ($k/M_{Pl}$ = 0.1)

# Dimuons final state

CDF has looked for bumps in the $X \to \mu\mu$ final state: no excess is observed.




CDF:4.6fb$^{-1}$

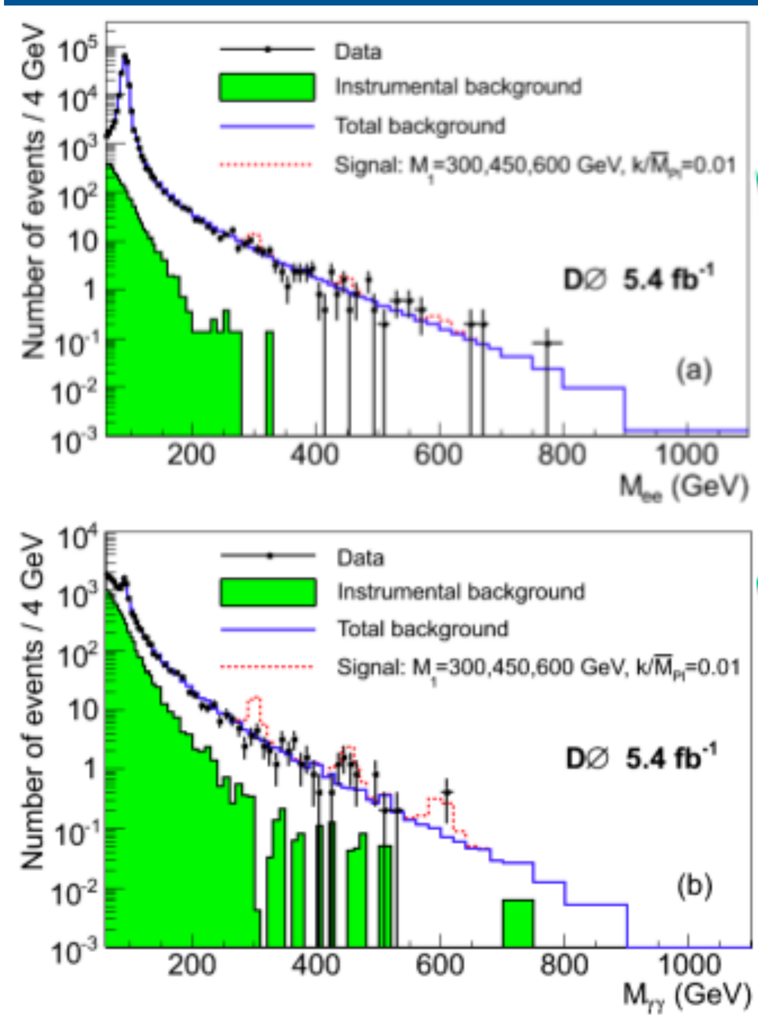
| Model | Mass Limit (GeV/$c^2$) |
|---|---|
| $Z'_I$ | 817 |
| $Z'_{sec}$ | 858 |
| $Z'_N$ | 900 |
| $Z'_\psi$ | 917 |
| $Z'_\chi$ | 930 |
| $Z'_\eta$ | 938 |
| $Z'_{SM}$ | 1071 |

Limits are derived for other scenarios (2.3fb$^{-1}$)

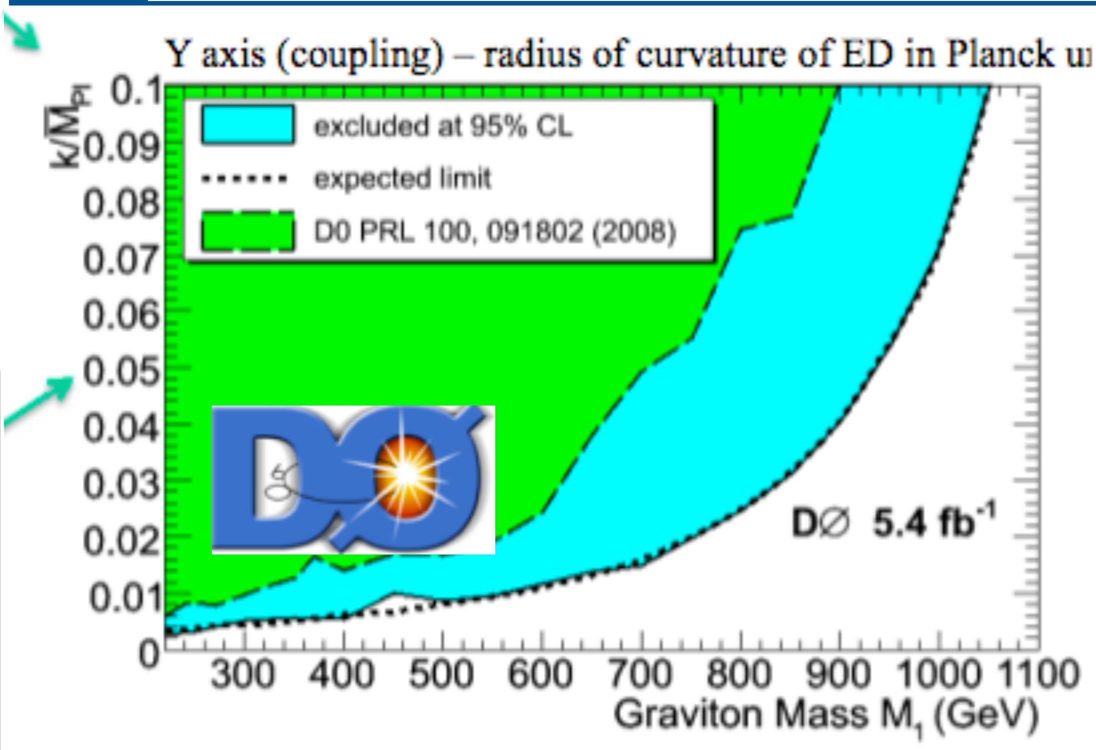
Sneutrino: up to 866 GeV/c$^2$ ($\lambda^2$BR = 0.01),

RS graviton: up to 921 GeV/c$^2$ ($K/M_{PL}$ = 0.1)

# Diphotons final states

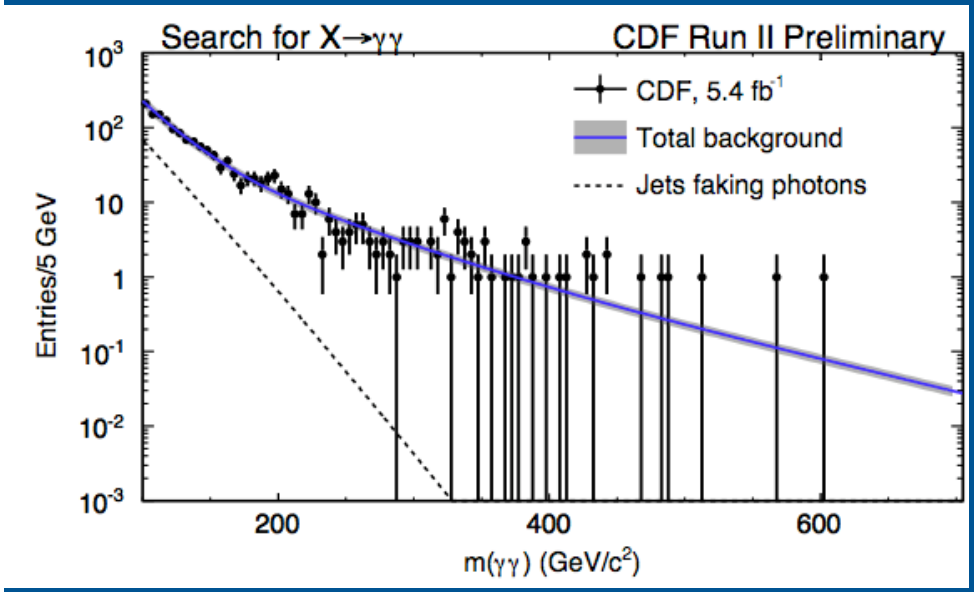



**Graviton KK excitation mass limits: 560 - 1040 GeV for $0.01 \leq k/MPl \leq 0.1$**



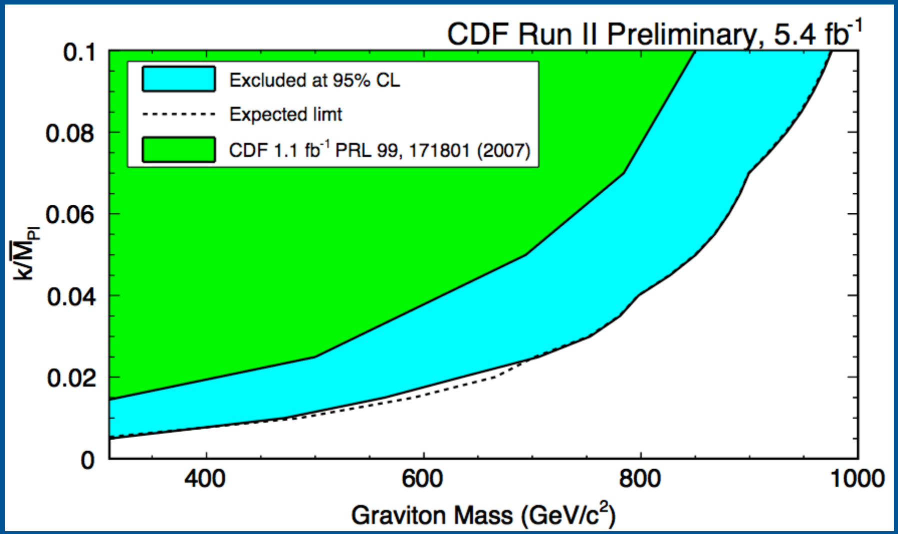

Small excess at 450 GeV/$c^2$ (diphoton)
2.3$\sigma$ significance - CDF does not observe it..

# Diphotons

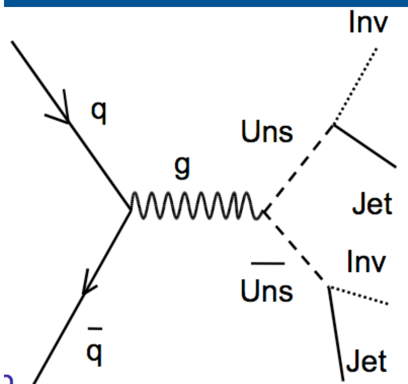



CDF:5.4fb$^{-1}$

Largest excess at 200 GeV/c$^2$
< 2$\sigma$ significance - D0 does not observe it..

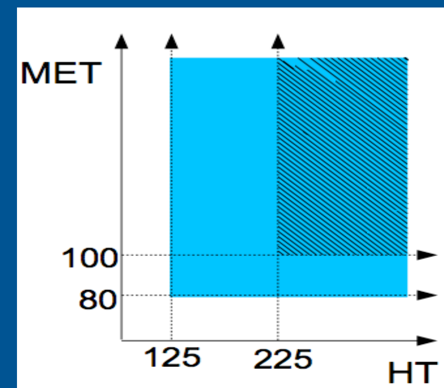


# Jets+MET final state:Leptoquarks




The analysis is a counting experiment examining two different kinematic regions (each region being more sensitive to different models) defined by HT and MET cuts.

Cuts are not optimized for a specific model.

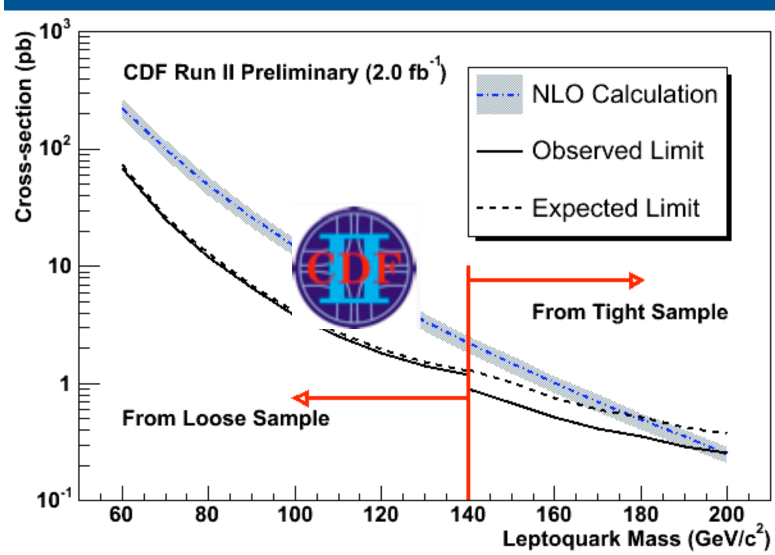



Main backgrounds:

- Z → ν ν + jets (irreducible background)
- W → *l* ν + jets (with charged lepton lost)
- Residual QCD and non-collision backgrounds.

Data driven prediction

arXiv:0912.4691



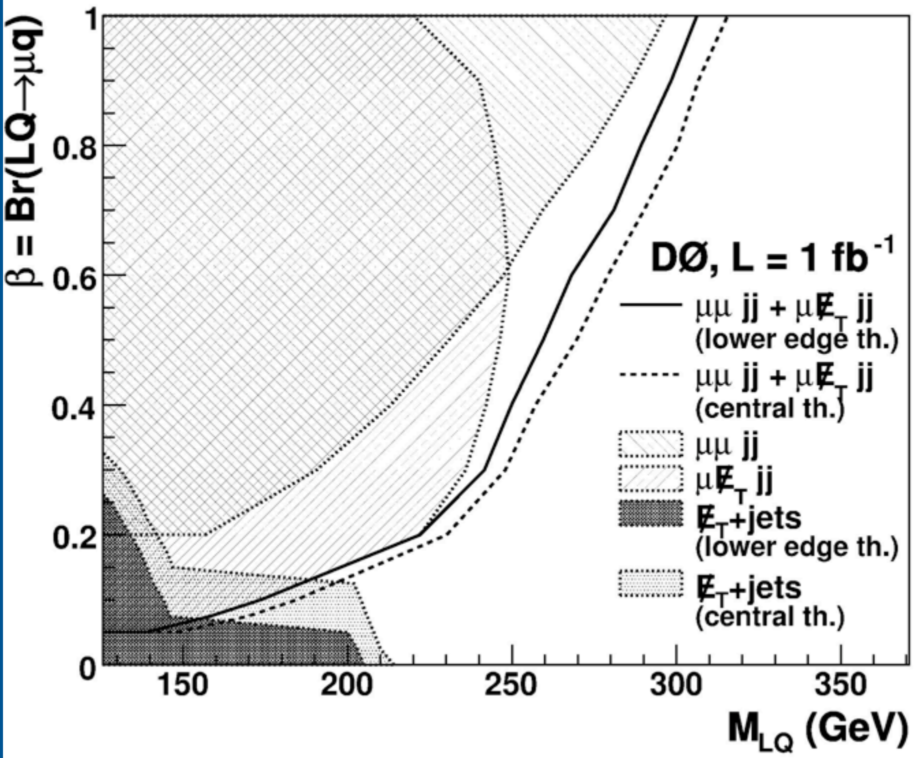

| Background | Number of Events |
|---|---|
| Z -> ν ν | 888 +/- 54 |
| W -> τ ν | 669 +/- 42 |
| W -> μ ν | 399 +/- 25 |
| W -> e ν | 256 +/- 16 |
| Z -> l l | 29 +/- 4 |
| Top Production | 74 +/- 9 |
| Diboson Production | 90 +/- 7 |
| QCD | 49 +/- 30 |
| Gamma plus Jet | 75 +/- 11 |
| Non-Collision | 4 +/- 4 |
| Total Predicted | 2533 +/- 151 |
| Data Observed | 2506 |

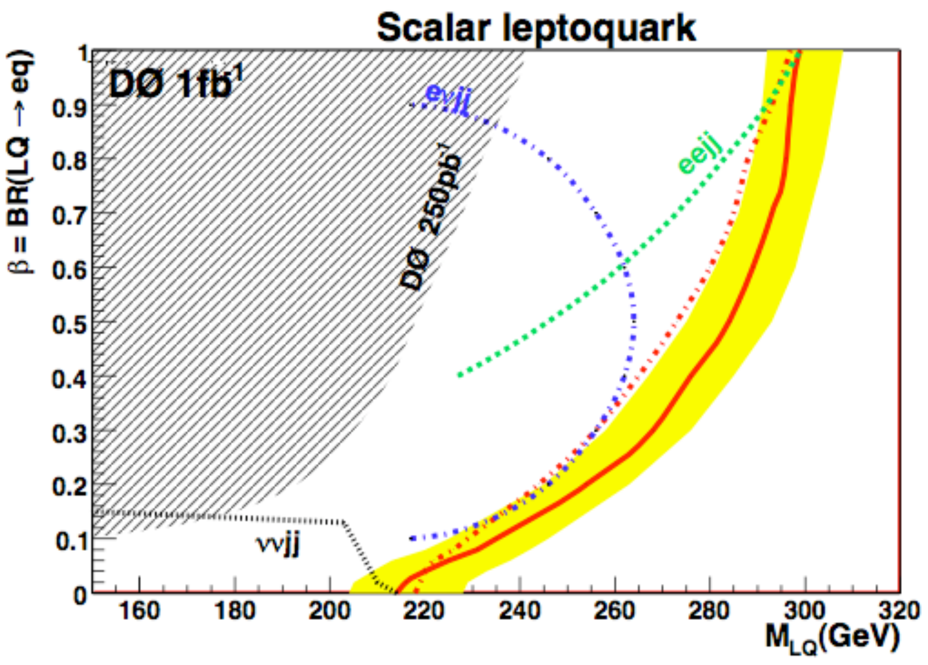
| Background | Number of Events |
|---|---|
| Z -> ν ν | 86.4 +/- 12.7 |
| W -> τ ν | 50.6 +/- 8.0 |
| W -> μ ν | 32.9 +/- 5.2 |
| W -> e ν | 14.0 +/- 2.2 |
| Z -> l l | 1.7 +/- 0.2 |
| Top Production | 10.8 +/- 1.7 |
| Diboson Production | 4.9 +/- 0.4 |
| QCD | 9.0 +/- 9.0 |
| Gamma plus Jet | 4.8 +/- 1.1 |
| Non-Collision | 1.0 +/- 1.0 |
| Total Predicted | 216.1 +/- 29.8 |
| Data Observed | 186 |

# Other Leptoquarks Results

| 1st Generation | 2nd Generation |
| --- | --- |
| $LQ\,\overline{LQ} \rightarrow e^- e^+ q\bar{q}$ | $LQ\,\overline{LQ} \rightarrow \mu^+ \mu^- q\bar{q}$ |
| $LQ\,\overline{LQ} \rightarrow e^{\pm} \nu_e q_i q_j$ | $LQ\,\overline{LQ} \rightarrow \mu^{\pm} \nu_\mu q_i q_j$ |
| $LQ\,\overline{LQ} \rightarrow \nu_e \nu_e q\bar{q}$ | $LQ\,\overline{LQ} \rightarrow \nu_\mu \nu_\mu q\bar{q}$ |

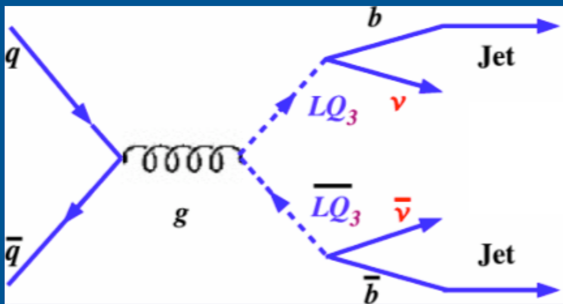
Phys. Lett. B **671**, 224 (2009)

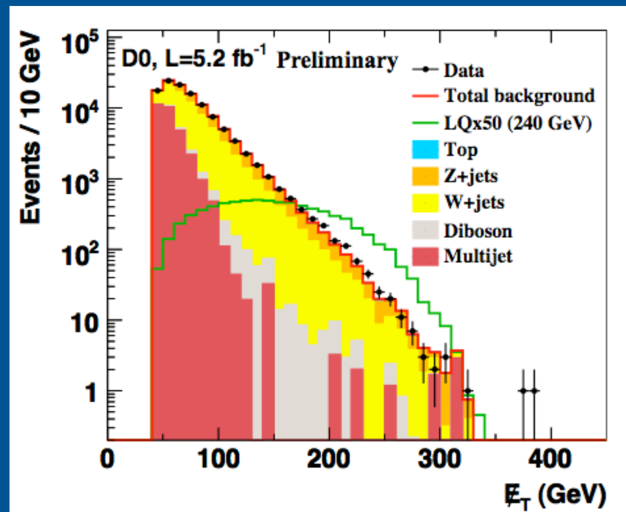


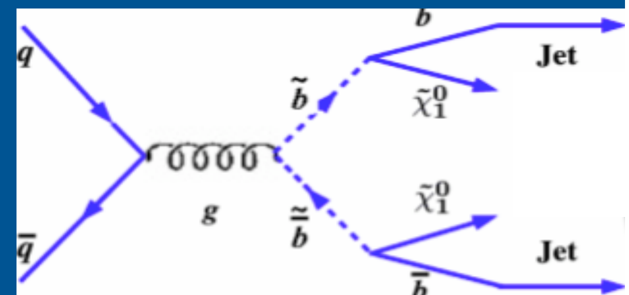




Phys. Lett. B **681**, 224 (2009)

# MET + b-jets: LQ and SUSY

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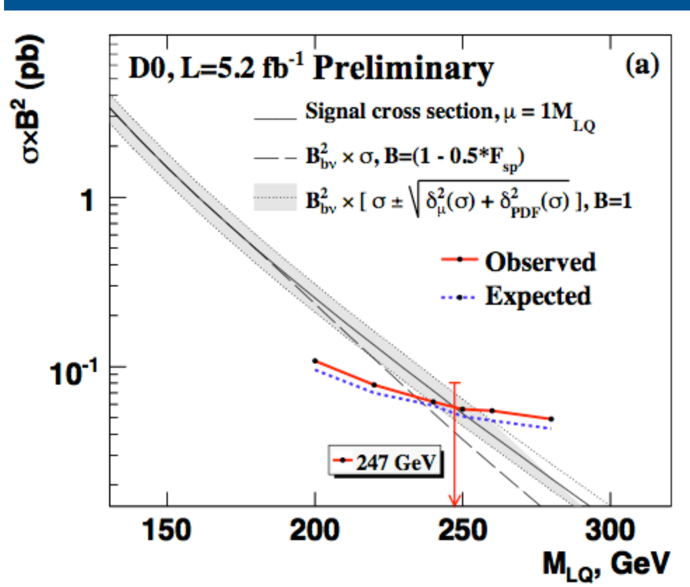
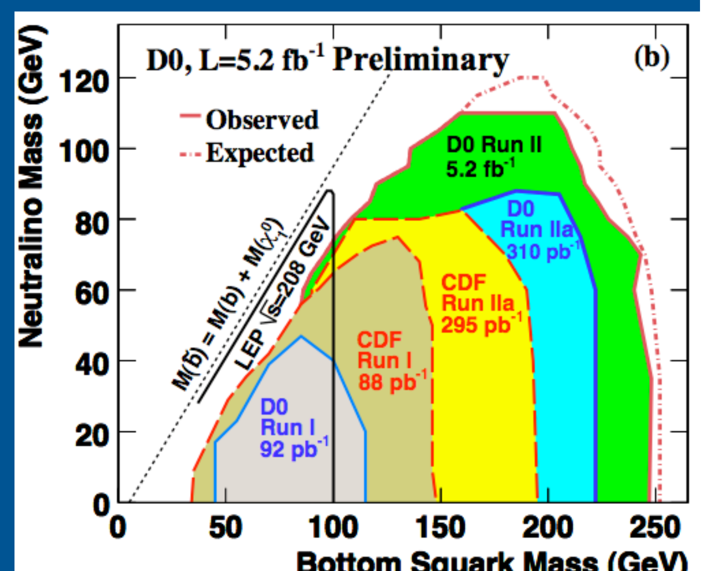
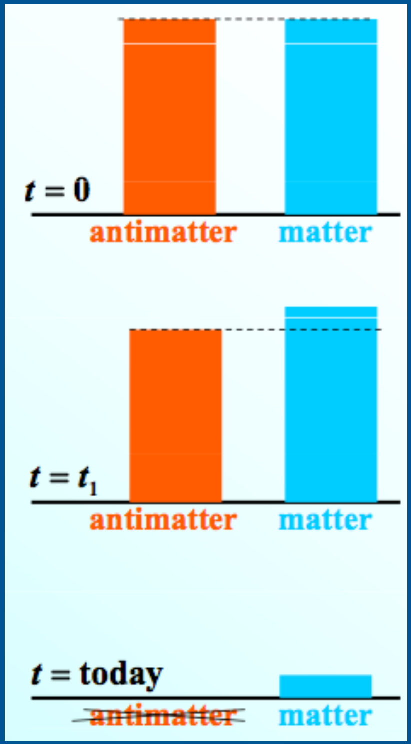



5.2fb$^{-1}$



# Like-sign dimuon asymmetry

Matter-AntiMatter asymmetry
At the beginning of time matter and anti-matter were in equilibrium
Then something happened…
Antimatter completely annihilated..




**One of conditions (A. Sakharov) required to explain this process – properties of particles and antiparticles must be different (*CP* violation)**

CP-violation is naturally included in the SM via the CKM matrix
Many different measurements of CP-violation are in excellent agreement with the SM
However the SM source of CP-violation is not enough to explain the imbalance between matter and antimatter
New sources of CP-violation are required to explain the matter dominance

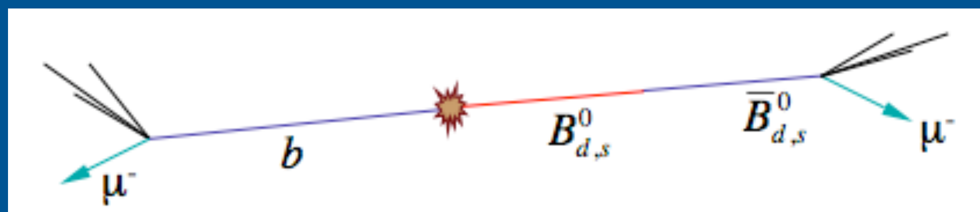
# Like-sign dimuon asymmetry: Analysis

Goal of this measurement is to study CP violation in the mixing of the $B_d$ and $B_s$ systems

The magnitude of CP-violation predicted by the SM is negligible

$$A^b_{sl} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

Contribution of new physics sources can significantly alter the SM prediction




CP-violation in mixing is measured using the dimuon charge asymmetry of semileptonic b-decays

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

and the inclusive muon charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

- $N_b^{++}$, $N_b^{--}$ – number of events with two $b$ hadrons decaying semileptonically and producing two muons of the same charge
- One muon comes from direct semileptonic decay $b \to \mu^- X$
- Second muon comes from direct semileptonic decay after neutral $B$ meson mixing: $B^0 \to \bar{B}^0 \to \mu^- X$

Semileptonic B decays contribute to both A and a.

$$a = k\, A^b_{sl} + a_{bkg}$$
$$A = K\, A^b_{sl} + A_{bkg}$$

The correlations in their background uncertainties allow for a very precise measurement

# Like-sign dimuon asymmetry: Results

Advantage is taken of the correlated background contributions and obtain $A_{sl}^{b}$ from their linear combination

$$A' \equiv A - \alpha\, a$$

The coefficient $\alpha$ is chosen as to minimize the uncertainty of $A_{sl}^{b}$

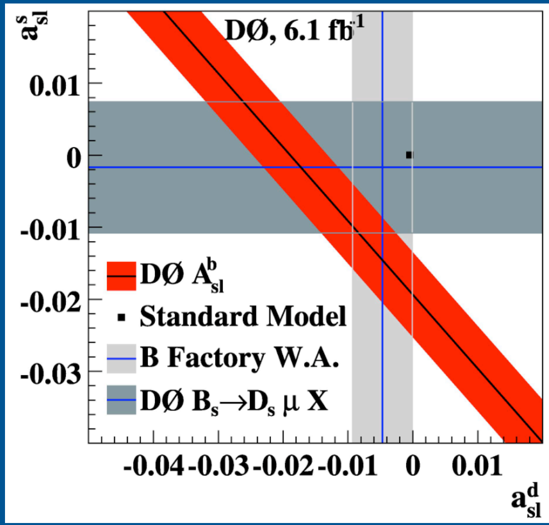
$$A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

**3.2σ (99.8% C.L.) disagreement with SM**

This analysis measures $A^{b}_{sl}$ as a linear combination of $a^{d}_{sl}$ & $a^{s}_{sl}$

$$A_{sl}^{b} = 0.506\, a_{sl}^{d} + 0.494\, a_{sl}^{s}$$

Which are in agreement with other measurements



# Conclusions

- The Tevatron is a Discovery Machine.
  - Despite its age, it keeps performing very well and with increased luminosity records
- A wide range of physics processes are studied:
  - Precision measurements in QCD jet physics
    - The most precised hadron colliders measurement of $\alpha_s$
  - Precision measurement of the top quark and W masses
    - Known now at < 1% experimental precision
    - Critical input to EW theory fit for Higgs boson mass
  - Searches for new physics
    - Small cross-section phenomena now accessible due to large luminosity
    - Evidence for new physics in $B_s$ mixing
  - CDF and D0 are working very hard to discover the Higgs
    - Evidence for it in the mass range favored by current theoretical fits of EW data is within reach at the Tevatron especially if the machine will continue to run past 2011