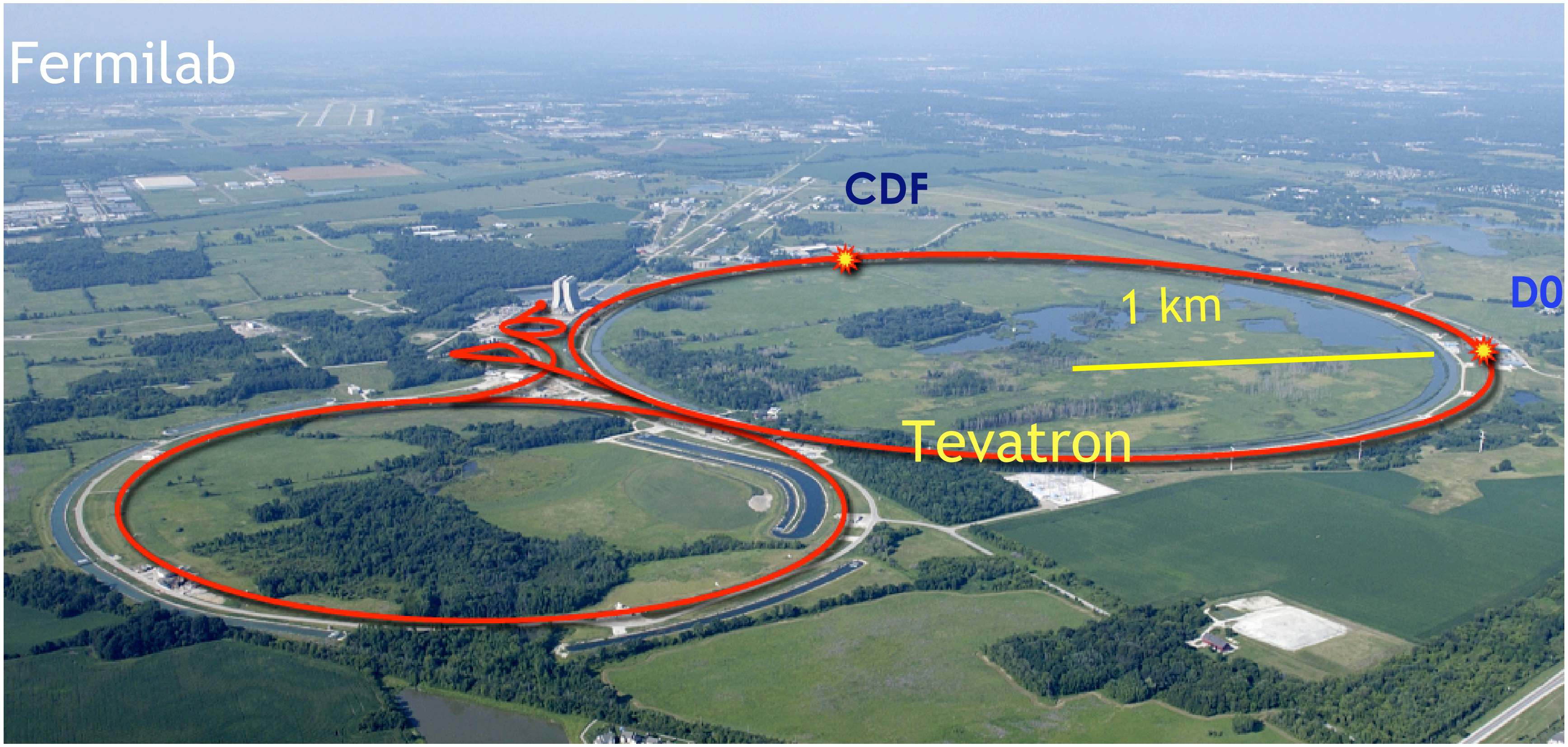
# Top physics and Higgs searches in hadronic signatures at CDF

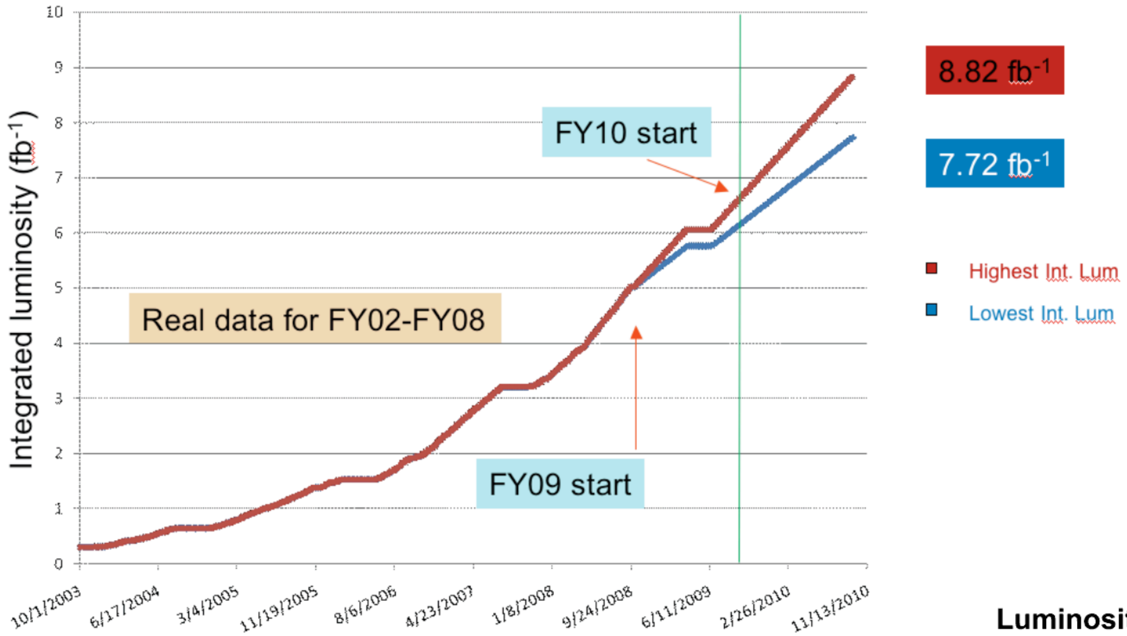
Fabrizio Margaroli
(for the CDF collaboration)

# Tevatron Experiments

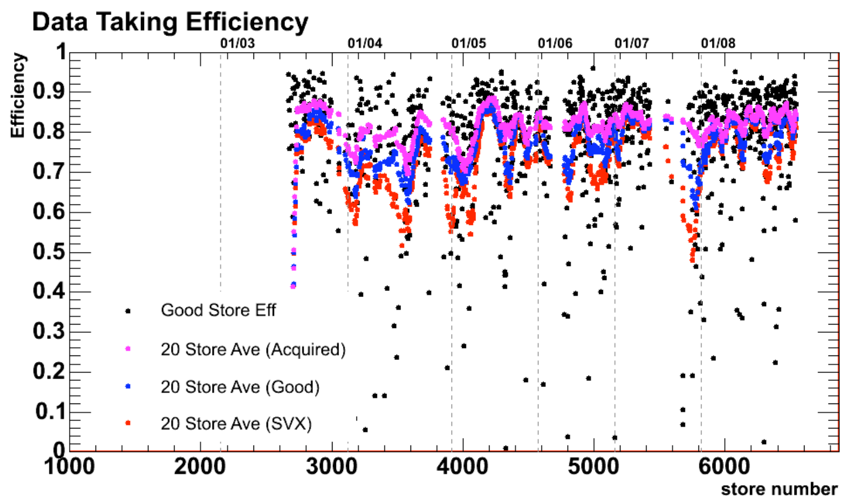
- Fermilab's Tevatron Run II $p\bar{p}$ collider at 1.96 TeV, running since 2001. Currently performing very well:
  - $3.3 \cdot 10^{32}$ $cm^{-2}$ $s^{-1}$ new record! set 2 weeks ago! (November 4th 2008)
- Two multi-purpose detectors (CDF,D0) well-understood

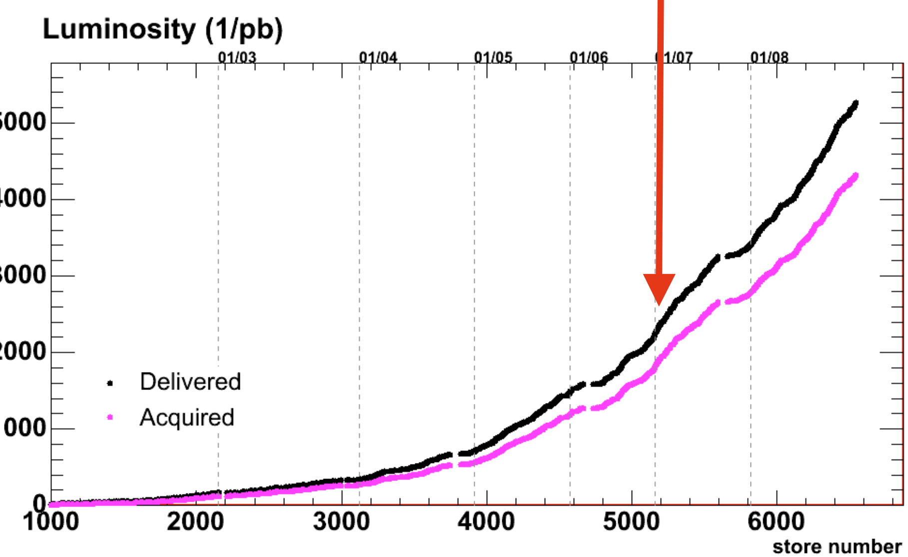


# Integrated luminosity



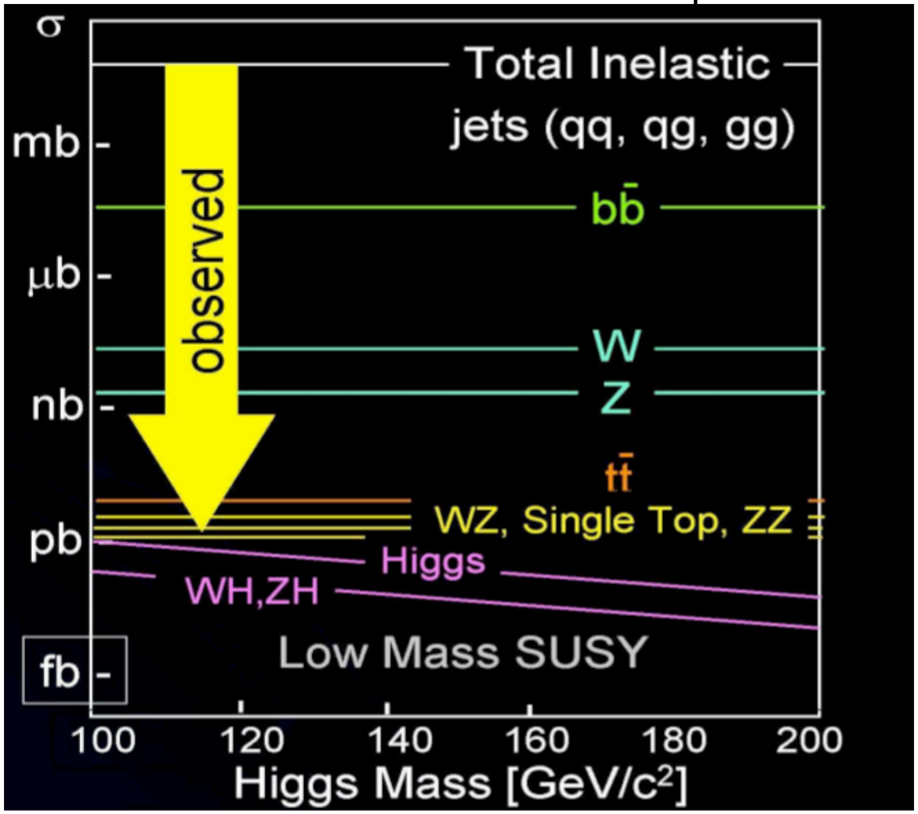

- Expect to have up to almost 9 $fb^{-1}$ at the end of 2010
- More than 4 $fb^{-1}$ available now on tape
- Up to 2.7 $fb^{-1}$ used in the following results



# The rarest SM processes

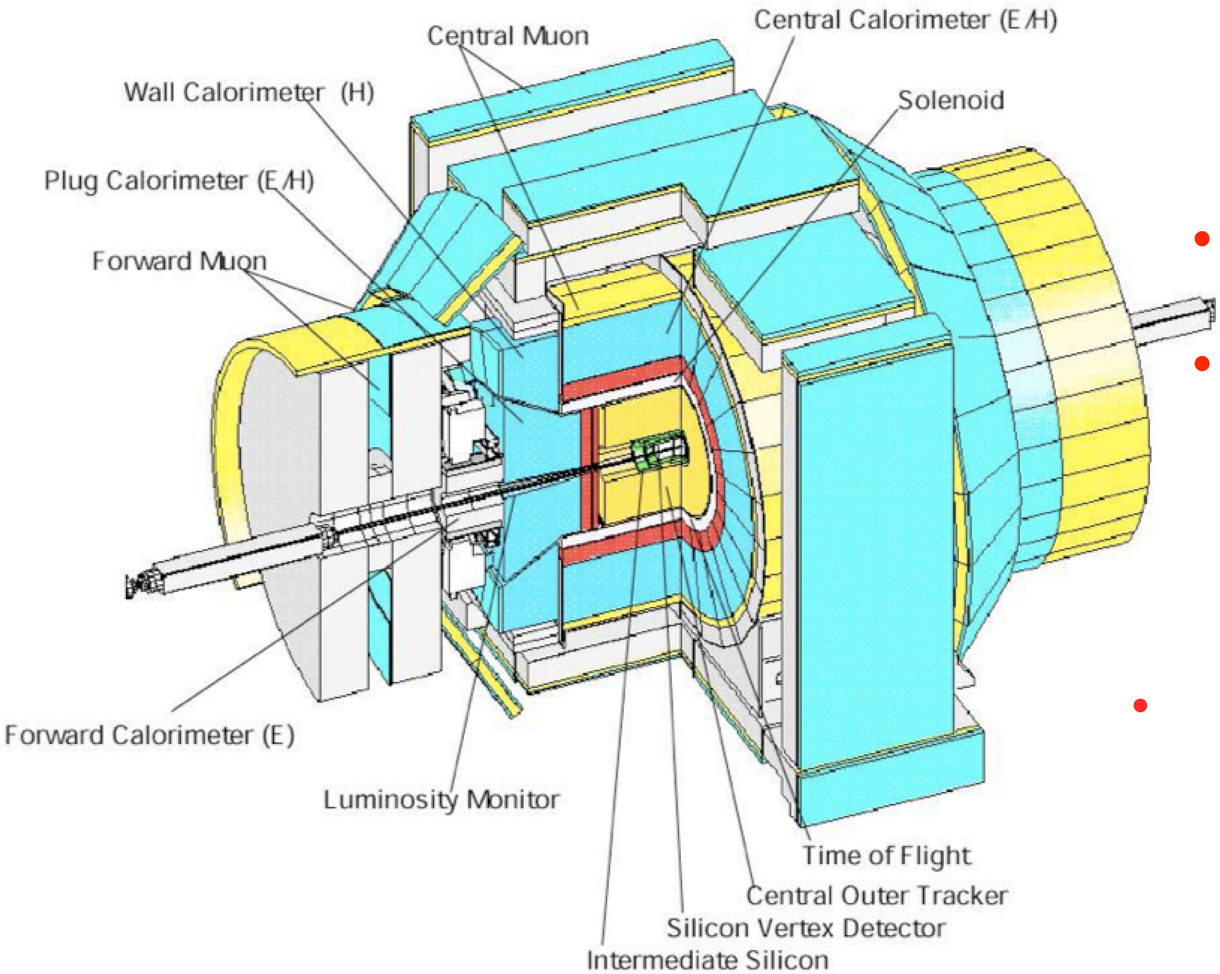
- Tevatron collider has been a discovery machine
  - Top quark in 1995!
- Tevatron collider is also a precision machine
  - $M_W$ known @ 0.05%, $M_{top}$ <1%




Hadronic colliders are QCD factories

- QCD cross sections usually many orders of magnitude (>9) higher than the top and Higgs signal
- Experimentalists prefer to look at signatures with leptons whenever possible!
  - 1(2) lepton → backgrounds at most 4(3) orders of magnitude higher than signals in this talk (W/Z production)
- So why hadronic signatures?
  - Analyzing complementary samples allows to increase precision/sensitivity when looking for small signals!

# The CDF II detector




- Calorimeter split in EM and HAD devices $|\eta|<3.6$
- Shower maximum detector in EM cal

- Tracking:
  - Drift chamber $|\eta|<1$ measures charged particle $P_T$
  - Silicon tracker allows precision vertex detection $|\eta|<2$

- Muon chamber outside calorimeter coverage $|\eta|<1.5$

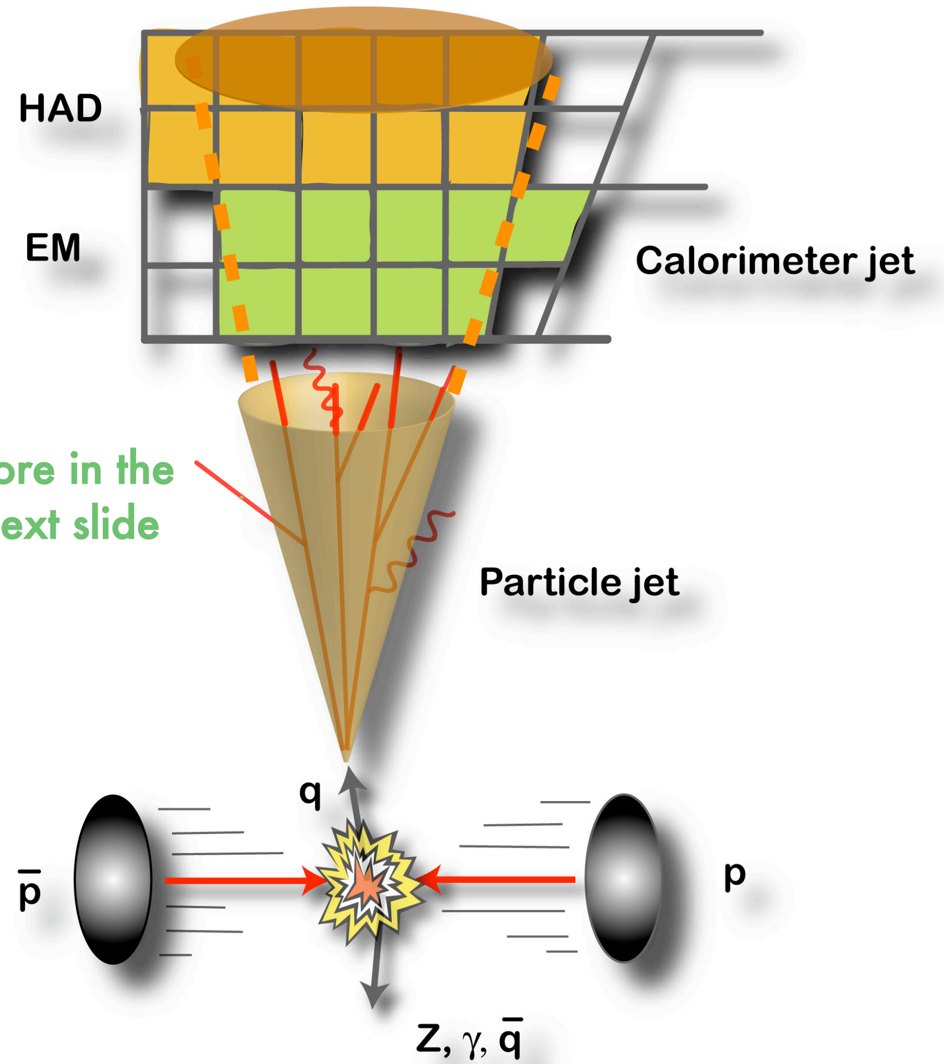
# Quark/gluon ID

- Quark are identified through the hadronic shower, i.e. jets
- Jet reconstruction algorithm at CDF is cone based. Loops over calorimetric towers

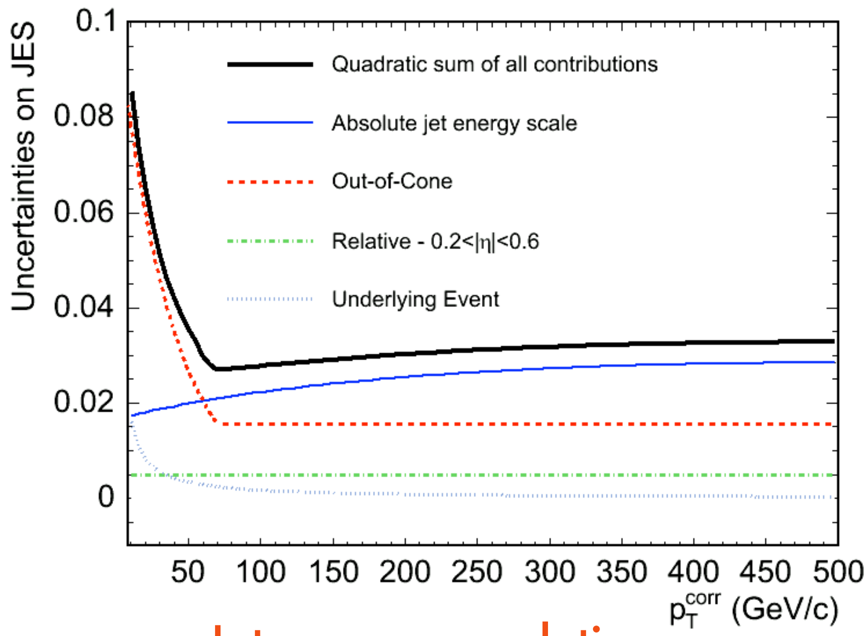
- Disadvantages of jets wrt to leptons:
  - Jet energy resolution driven by had cal resolution 80%/$\sqrt{E_T}$
  - Jet energy scale known@~3%
  - Cracks in the calorimetry lead to underestimate in jet Et → often source of apparent energy imbalance

More in the Next slide

- Advantages of jets wrt to leptons:
  - jet reconstruction efficiency is ~100%
  - Angular acceptance covers almost all solid angle ($|\eta|<2.8$)



# Jets at CDF

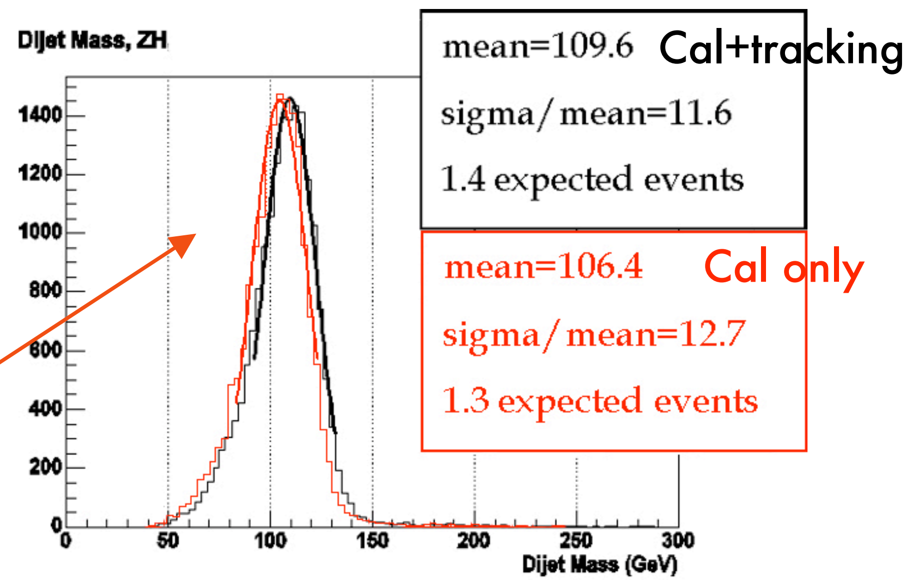



### Jet energy scale uncertainty

- Systematic difference from data and Monte Carlo, convolution of many effects
  - 5% to 3% of the jet energy
- Yields a large systematic uncertainty in many analyses

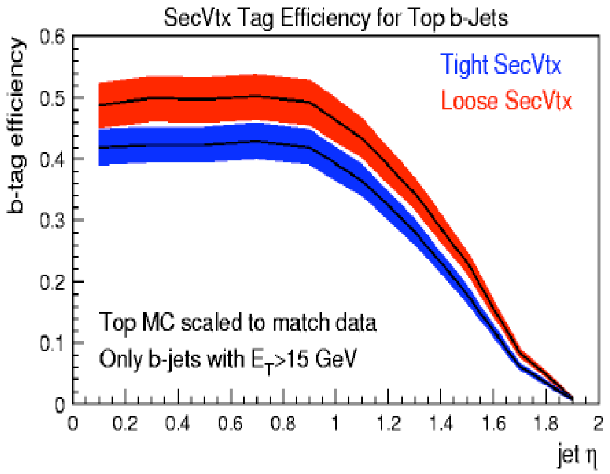
### Jet energy resolution

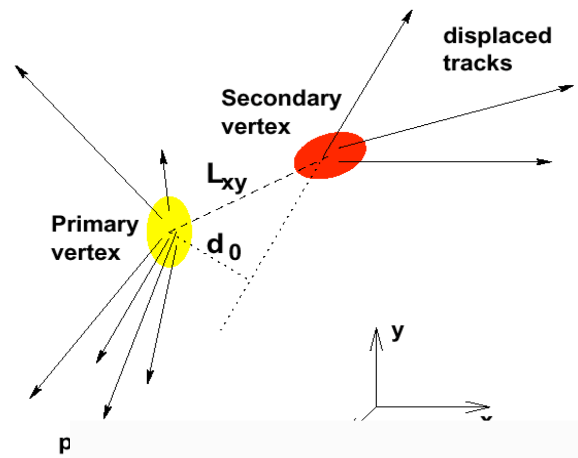
- Tracks resolution is far better than calorimeter resolution for particles with $P_T$<50 GeV
- New jet reconstruction algorithm substitute track $P_T$ with cal $E_T$ whenever possible to improve jet energy resolution (10% improvement)



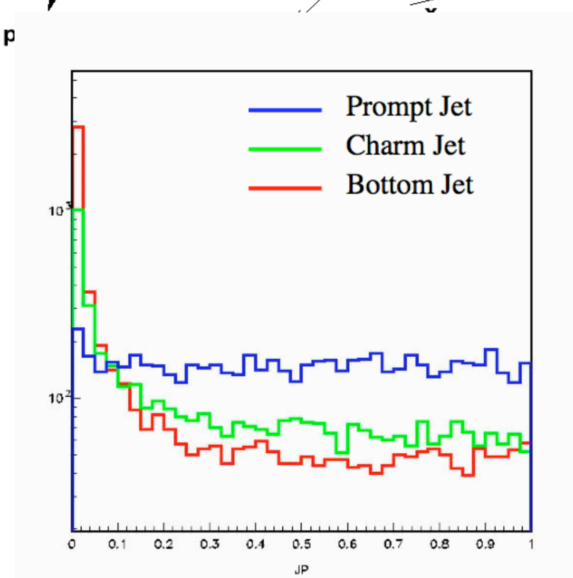
# b-quark ID

- ✓ SecVTX: b-quark can be identified thanks to the long lifetime of the B hadrons they give rise to: identification though search of a secondary vertex within a jet:




- ✓ b-tag eff: ~ 40%
  fake rate ~ 0.5%




- ✓ JetProb: Jet tagging probability algorithm: determines the combined probability that the tracks within a jet are consistent with coming from the primary vertex

- ✓ B-tag eff ~50%
- ✓ Fake rate~5%

# Lepton ID

## The experimentalist point of view:

**Electrons:**

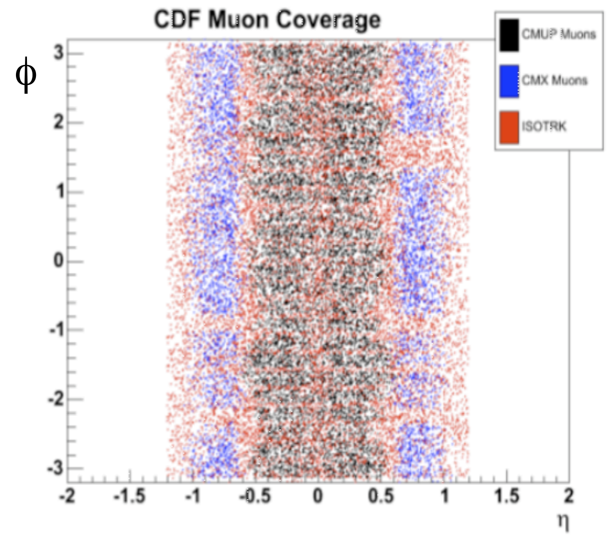
- Pt measurement from central tracking chamber shower max matching (reject $\pi^0$s) isolation (reject showers from quark)

**Muons:**

- matching between track in central tracker and stubs in muon chambers (if $|\eta|<1.3$), isolated track otherwise

**Taus:**

- leptonic taus identified through above bullets, isolated cluster in the calorimeter matched to 1 or 3 tracks




**Neutrinos:**

- appear as <u>*calorimetric*</u> energy flow imbalance in the transverse plane - Missing transverse energy (MET)

Jets fill the gaps!

- Non isolated electrons appear as jets
- Hadronically decaying $\tau$s appear as jets

# Multivariate techniques

- Need for analysis which maximize the discrimination power by looking at global kinematics of signal and backgrounds, i.e. need for multivariate techniques
- CDF and D0 use two different classes of multivariate techniques:

- Physics oriented Use the full dynamics of the event through the knowledge of the matrix element
- Build signal and background probabilities

$$P^{\mathrm{sig}}(\mathbf{x}|M_H) = \frac{1}{N}\int d\Phi |\mathcal{M}_{VH}|^2 \times P(q_1)P(q_2)\times \prod_{i=jets} P(\mathbf{x}_i|p_i)$$

ME PDFs Final state 4-vectors

- Used as a discriminating distribution for signal and background, to measure
  - Top mass
  - Single top cross section measurement
  - Higgs searches

# Machine learning techniques

- Statistics oriented:
  - Likelihood technique Probability density estimators for each variable combined into one (popular in HEP). Returns the likelihood of a sample belonging to a class. Projection ignores correlation between variables.
  - Machine-learning techniques such as boosted decision trees and neural networks (NN) (also evolutionary ones). Exploit correlation among different observables.

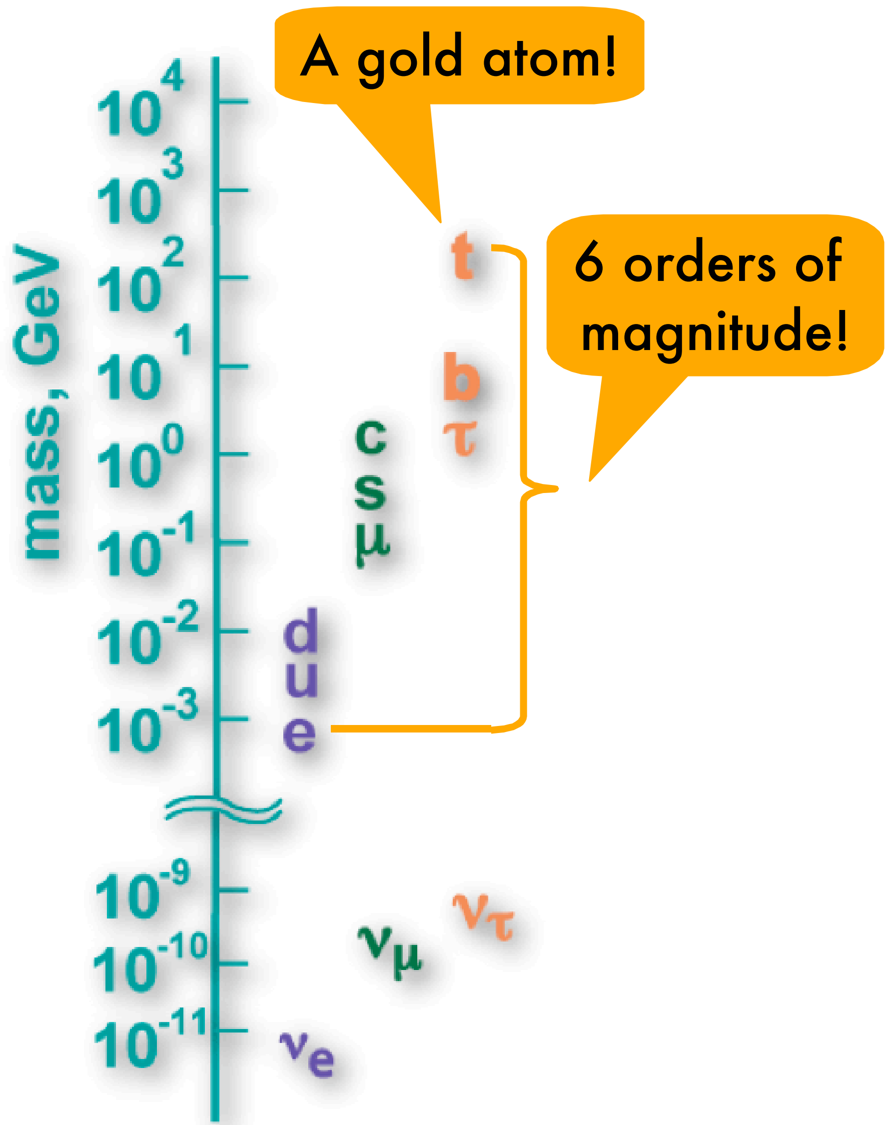
Wikipedia on machine-learning:

## Applications [edit]

Applications for machine learning include natural language processing, syntactic pattern recognition, search engines, medical diagnosis, bioinformatics, brain-machine interfaces and cheminformatics, detecting credit card fraud, stock market analysis, classifying DNA sequences, speech and handwriting recognition, object recognition in computer vision, game playing and robot locomotion.

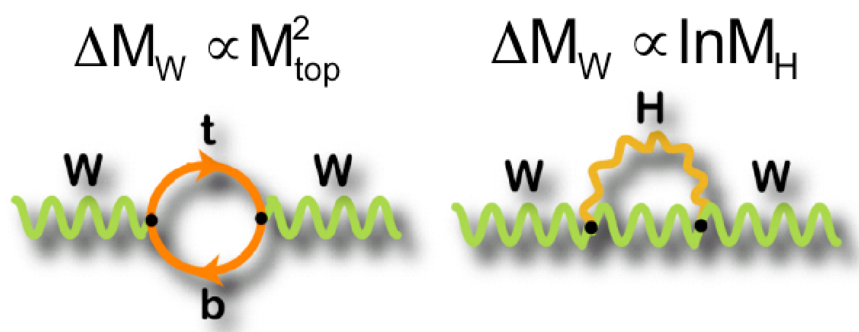
...and particle physics!(yes, sometimes we are slow learners)

# The top quark




Last discovered quark!

- Top mass is a fundamental parameter in the SM
  - Yukawa coupling ~1: hint of special role of the top quark?
  - $M_{top}$ enters in radiative corrections allowing constraint on Higgs mass



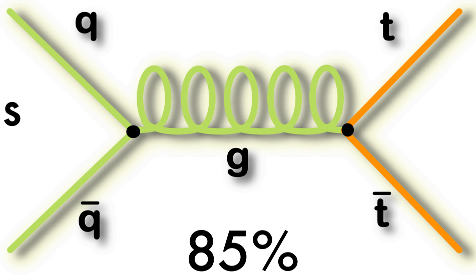

- Top cross section at 1.96TeV is O(pb)

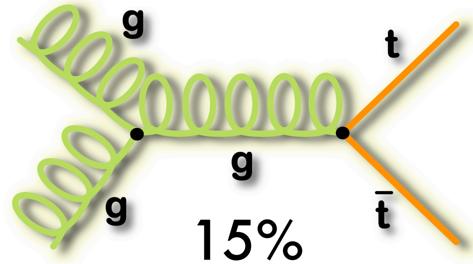
  → tens of thousands produced!
  - Tevatron is a (small) top factory

# Top production at the Tevatron

Top quarks at the Tevatron are produced either through QCD interaction with a cross section of approximately 7pb* and relatively striking final states

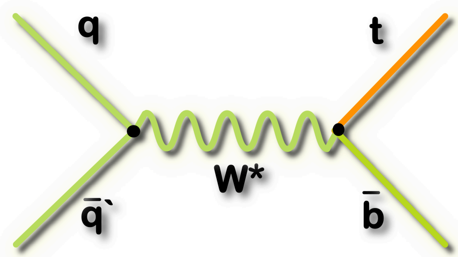
- Discovery mode in 1995
- Measuring the cross section probes QCD computation, constrain new physics

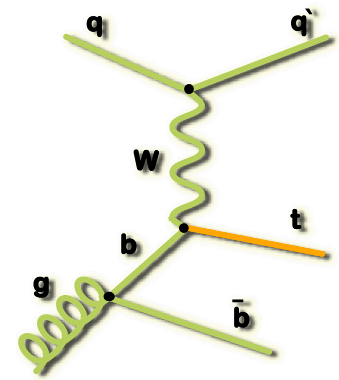



Or through electroweak interaction with a cross section of 2.9pb* but final state similar to many SM processes!

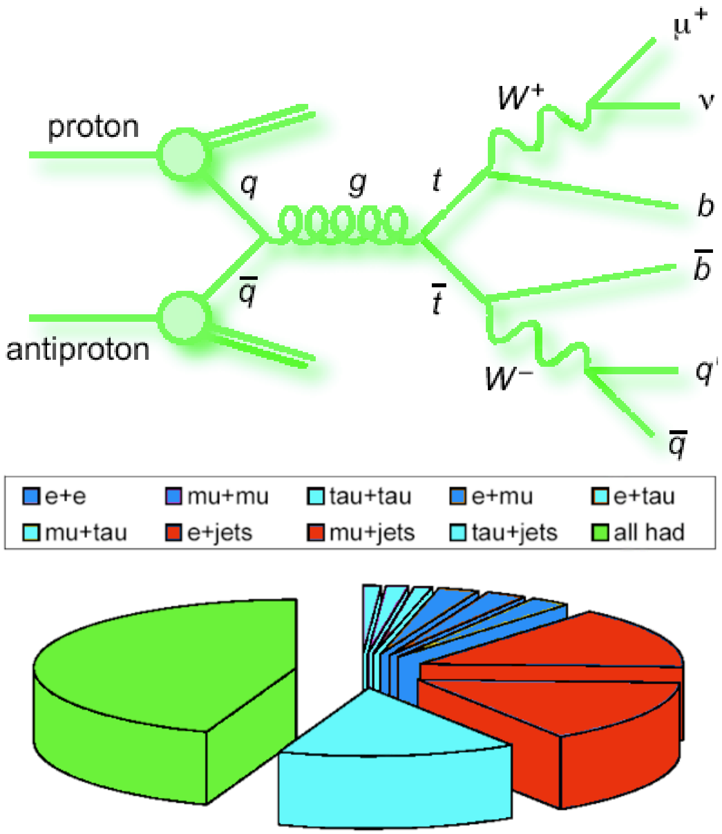
- Typical S/B~1/20
- Evidence difficult but achieved in 2006, discovery hopefully around the corner
- Allows direct measurement of CKM element $V_{tb}$




* Assuming Mtop=175

# ttbar decay signature



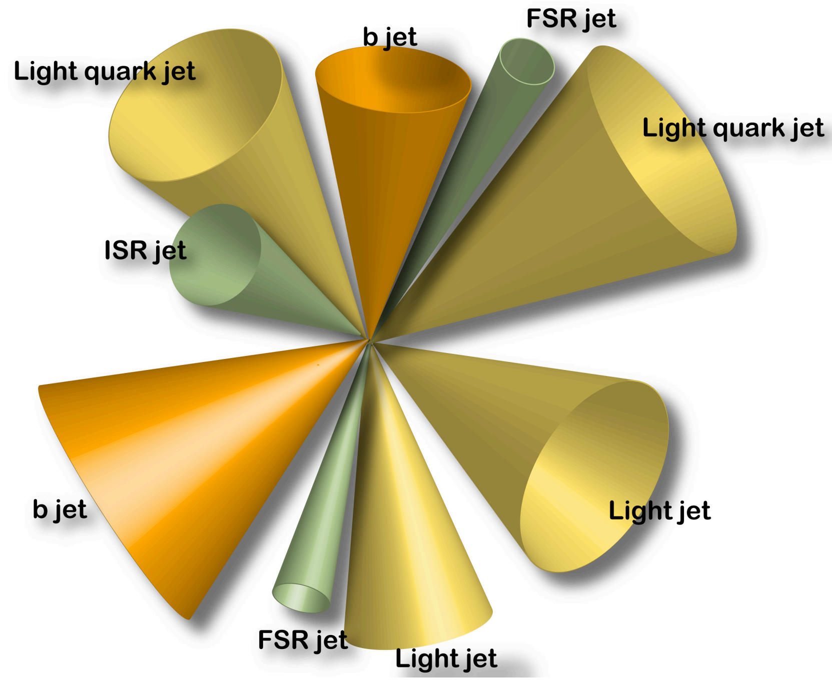

- **Dileptonic**
  cleanest channel - *BUT* lowest BR & neutrinos make event reconstruction difficult
- **Lepton+Jets**
  golden channel: high branching ratio *AND* good S/B ratio.
- **Missing Energy plus jets**
  good S/B ratio, charged lepton not reconstructed
- **All hadronic**
  challenging channel: highest BR *BUT* huge backgrounds

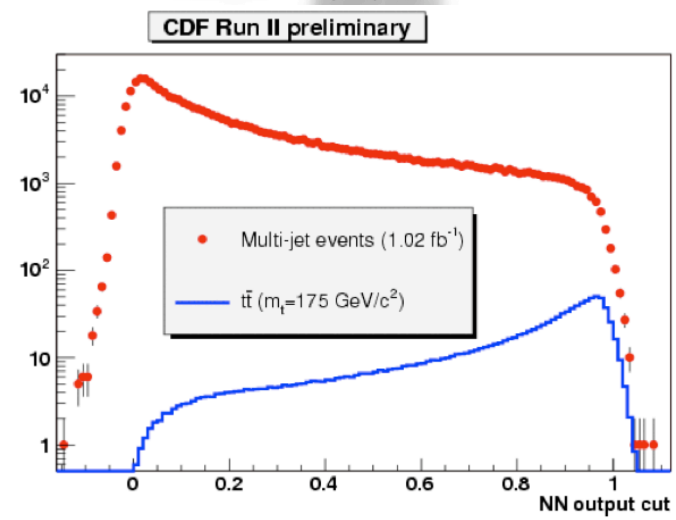
General strategy: perform measurements of top properties in orthogonal samples:

- Consistency check
- Precision through combination
- Discrepancy might hint for new physics!

# All-hadronic channel

- All-hadronic channel suffers from huge QCD: after specific trigger requirement of ≥ 4 jets and $\sum E_T \geq 175$ GeV, signal still overwhelmed by QCD background →S/B~1/1000
  - Discard events with large missing energy - events with real (W+jets) or mismeasured jets
  - Use Neural Network-based event selection to distinguish the features of ttbar signal over QCD background, kills >2 orders of magnitude of QCD
- Ask for identified b-jets to reach reasonable S/B
  - Use data-driven modeling for QCD: parametrize probability to tag a b for generic backgrounds

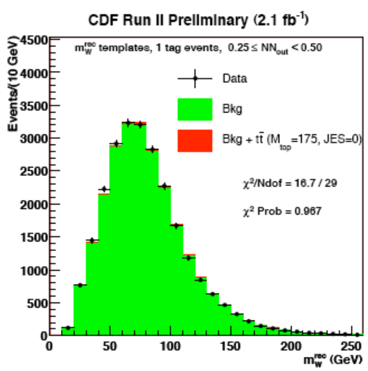


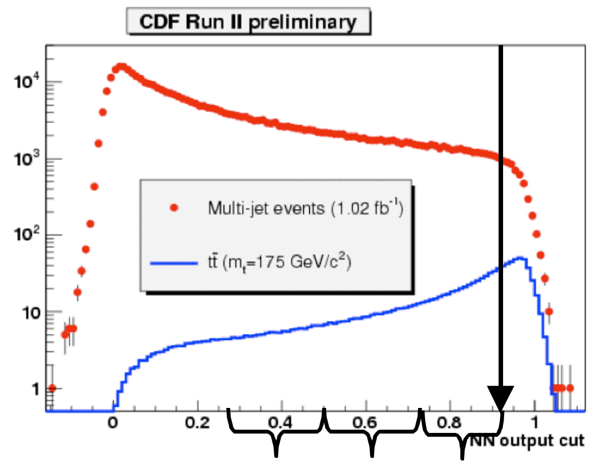



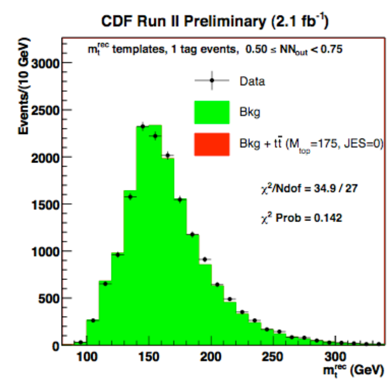
# QCD background modeling

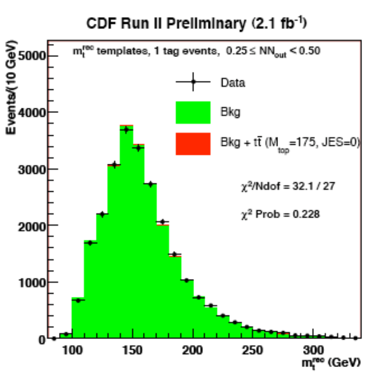
MC modeling suffers of
- poorly known cross-sections
- need generation of huge QCD samples.
- Allows separation of heavy flavour from light flavour quark production

- Sample background dominated → data itself can be used as representation of the background.
- Use properties of jets tagged as b to derive a per-jet probability; pretag data and probs to model data with b-tags

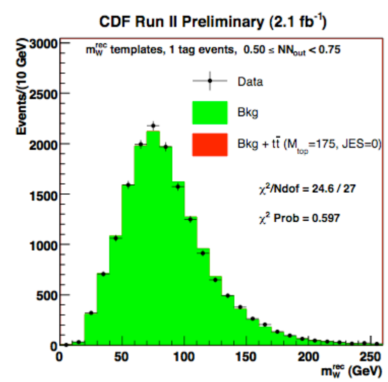


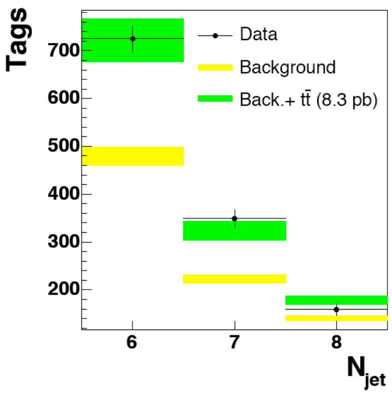

Check modeling in QCD-dominated control regions

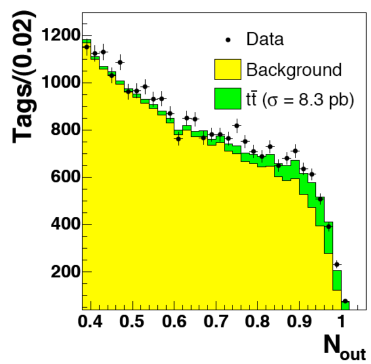


# Previous all-had results

Phys.Rev.D76:072009,2007

- Cross section measurement is first step as it requires thorough understanding of background - done with 1fb$^{-1}$



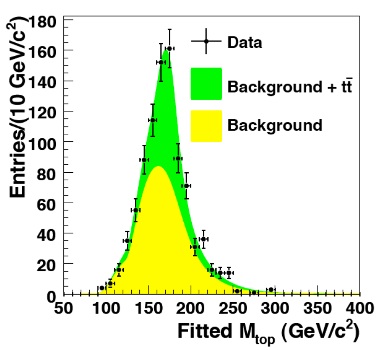




Biggest syst source

| Source | Uncertainty (%) |
|---|---|
| Energy Scale | 16.3 |
| Parton Distribution Functions | 1.4 |
| Initial/Final State Radiation | 2.9 |
| Monte Carlo Modeling | 1.1 |
| Multiple interactions | 2.5 |
| Average number of tags | 7.4 |
| Estimated background | 2.5 |
| Integrated luminosity | 6.0 |

$$\sigma_{t\bar{t}} = 8.3 \pm 1.0(\mathrm{stat.})^{+2.0}_{-1.5}(\mathrm{syst.}) \pm 0.5(\mathrm{lumi.})\ \mathrm{pb}$$

- After obtaining a relatively clean sample of ttbar events, and background understanding, measure the top quark mass




| Source | Uncertainty (GeV/$c^2$) |
|---|---|
| Jet energy scale | 4.5 |
| Generator | 1.0 |
| b-jet energy scale | 0.5 |
| Parton Distribution Function | 0.5 |
| Background shape | 0.5 |
| Background fraction | 0.5 |
| ISR | 0.5 |
| FSR | 0.5 |
| b-tag | 0.5 |
| MC statistics | 0.1 |
| Template parametrization | 0.1 |
| Total | 4.8 |

Biggest syst source

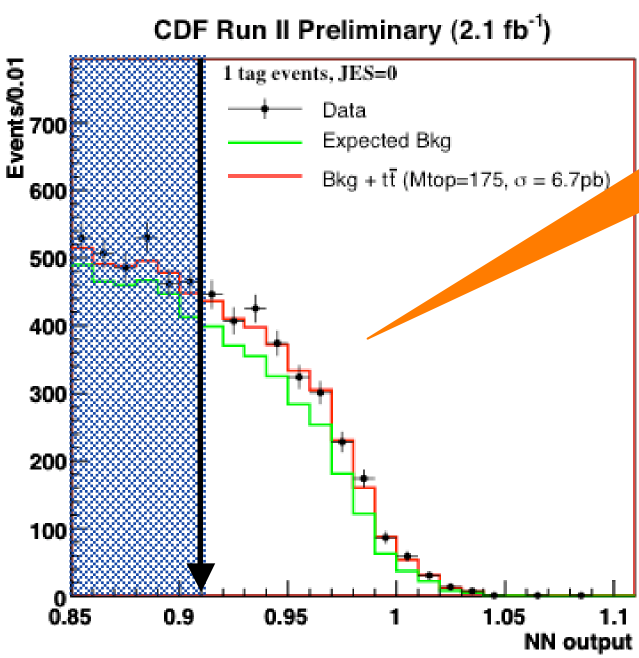
$$M_{\mathrm{top}} = 174.0 \pm 2.2(\mathrm{stat.}) \pm 4.8(\mathrm{syst.})\ \ \mathrm{GeV}/c^2$$

Good statistical power, BUT large uncertainty due to JES

# NN event selection

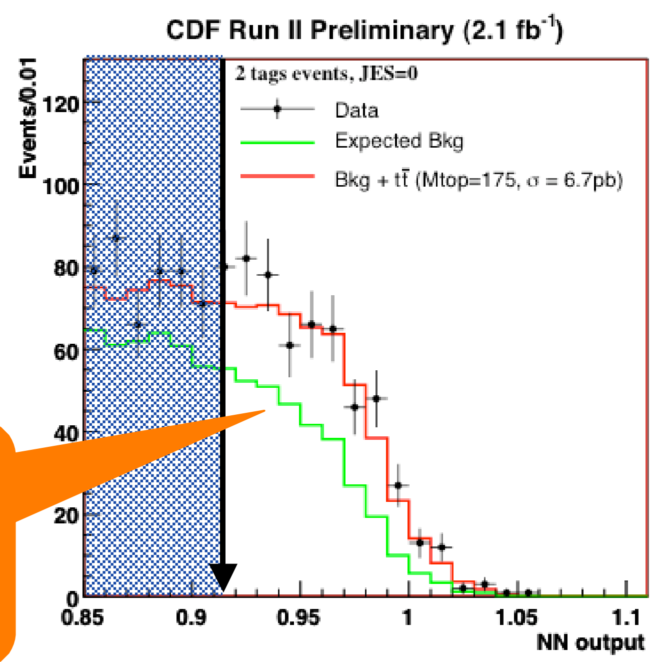
- Improved background modeling allows now separation of events according to number of b-tagged jets → maximize statistical power
  - b-tags also allow reduction in combinatorics when reconstructing the final state

| S/B | Dilepton | Lepton+jets | All-hadronic |
|---|---|---|---|
| 0 b-tag | 1:1 | Not used | |
| 1 b-tag | 20:1 | 4:1 | 1:5 |
| 2 b-tags | | 20:1 | 1:2 |



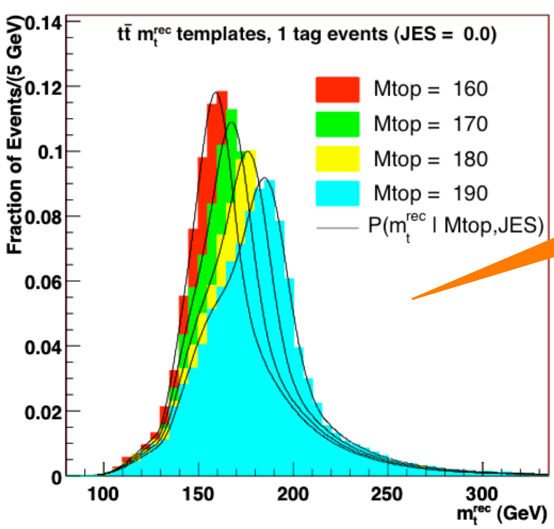

Most signal evts have one b-jet identified

But evts with 2 b-tags have better S/B ratio and smaller combinatorics

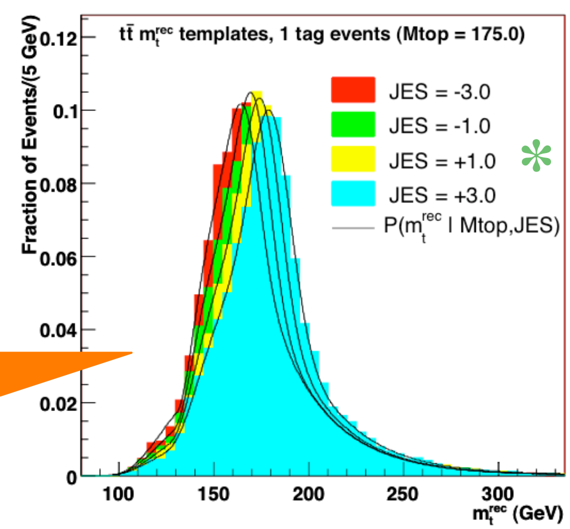


# $M_{top}$ Measurement technique

- Signal kinematics is given by Pythia simulation
- kinematically reconstruct events and pick a variable strongly correlated w. the one under study
  - Reconstruct 3jet invariant mass to measure $M_{top}$
- Compare data to simulated S & B through likelihood.
- Calibrate measured mass with input mass to correct for bias in central value and uncertainty




Clear dependence on the input $M_{top}$



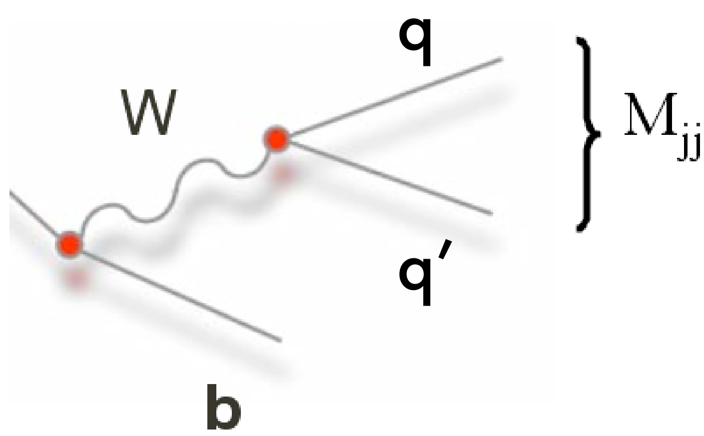

But also on the jet energy scale (JES)!

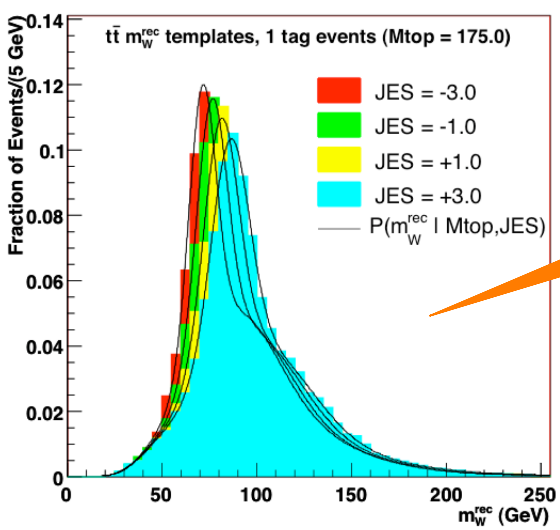
*JES measured in units of nominal uncertainty

# JES measurement technique

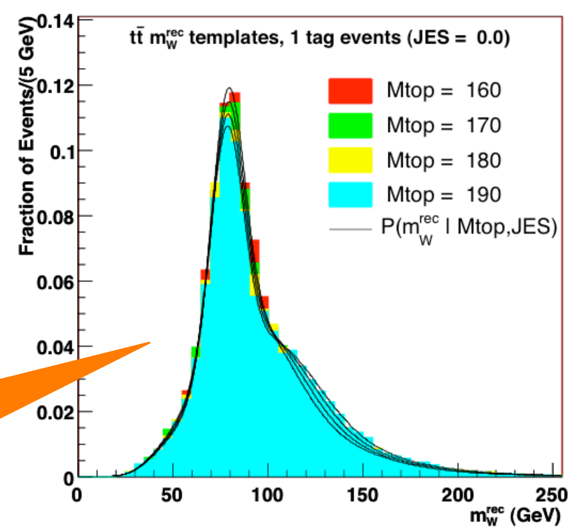
### Jet energy scale uncertainty (JES)

- Systematic from difference in jet $E_T$ between data and Monte Carlo
- Biggest limiting systematic…BUT!
  - We can reconstruct $W \rightarrow qq$ decays and exploit known mass to measure *in situ* the JES



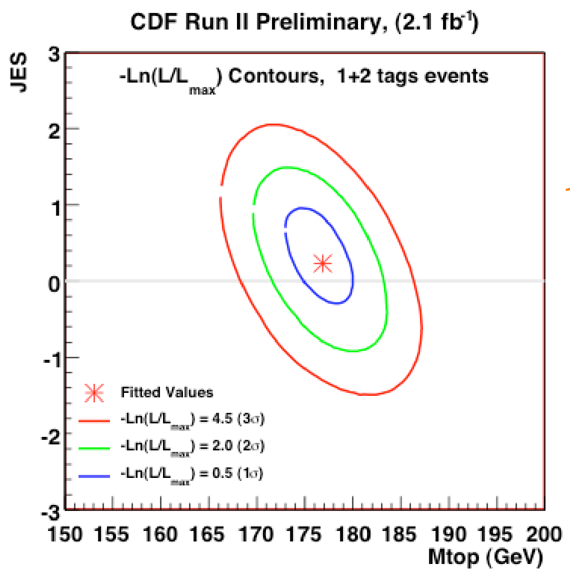

Clear dependence on the input JES




And very small dependence on $M_{top}$

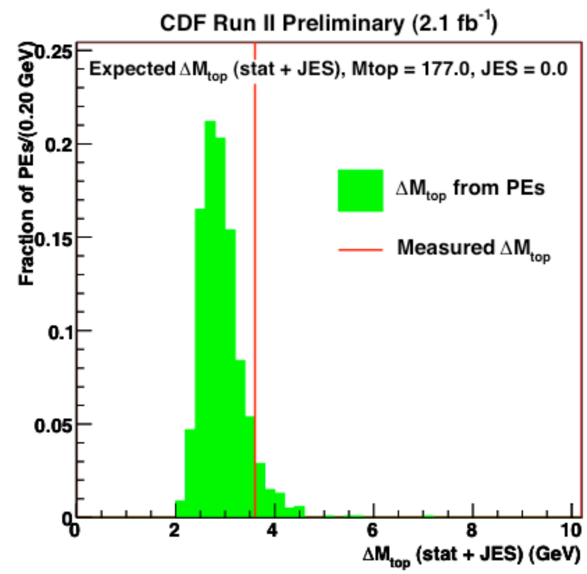
# The top mass measurement

- CDF measures in the all-hadronic channel the following top quark pole mass
  - $M_{top}$ = 176.9 ± 3.8 (stat+JES) ± 1.7 (syst) GeV/$c^2$




2D likelihood contours in $M_{top}$ and JES

Uncertainty from simulation and data



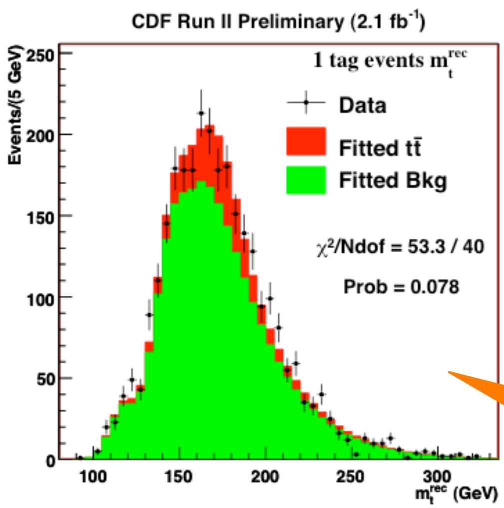

✓ *2% resolution → precision physics in a background dominated sample!*

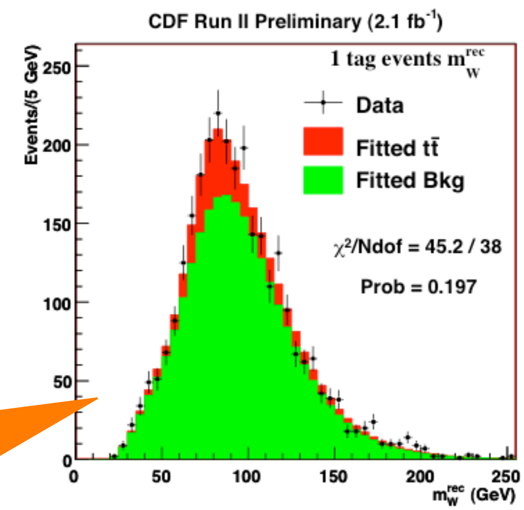
> *Statistically limited (note that JES systematic also scales with $1/\sqrt{L}$)*
>
> *event selection not optimized in this result*

# Output distributions

Reconstructed top mass

Reconstructed W mass

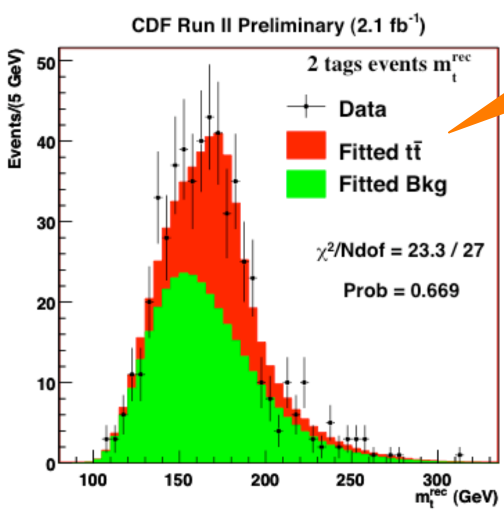


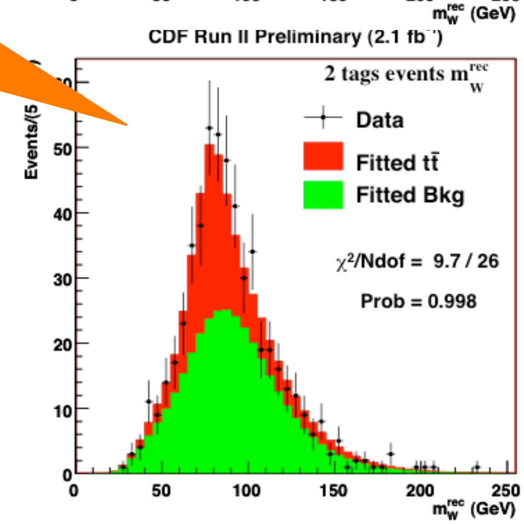




1 tag events

Agreement between expectation and data is good

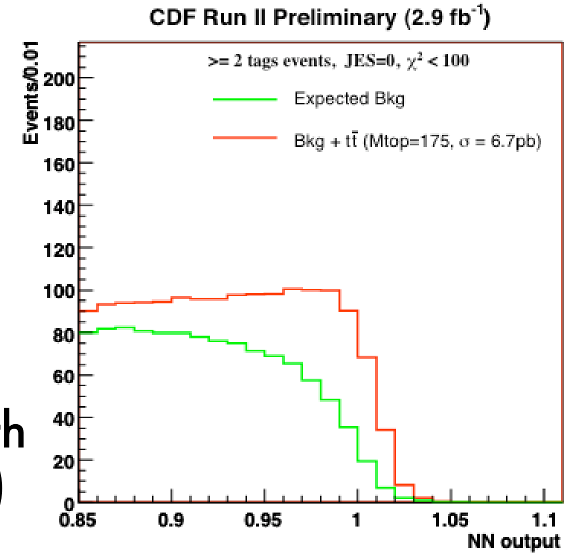
2 tag events

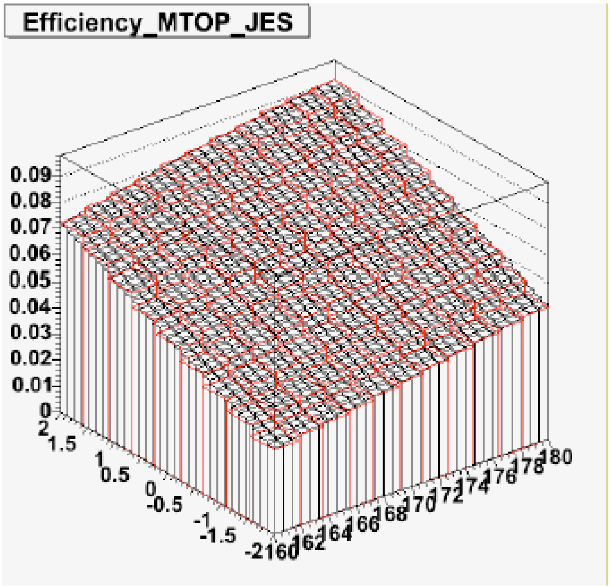


# Improvements in the channel


- Use jet broadness to discriminate quark-jets from gluon-jets
  - Further suppress QCD backgrounds
  - Potential up top x2 improvement in S/B (with roughly same efficiency)

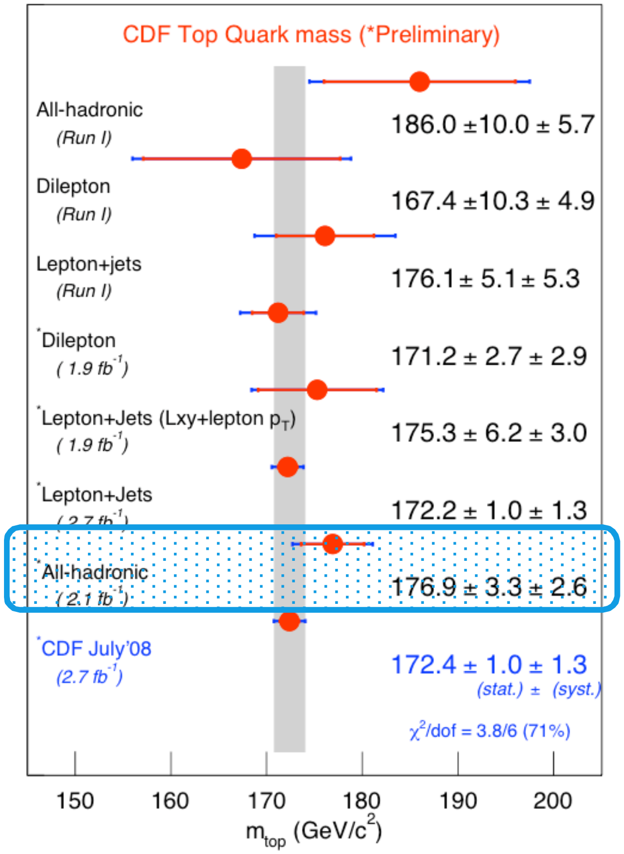


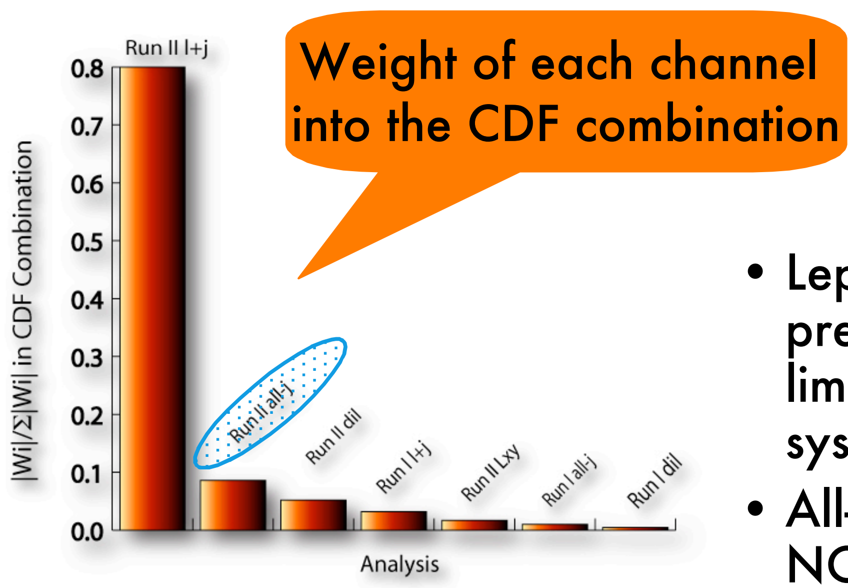

- Better NN improves significance - statistical uncertainty of measurements in this sample
- But $\sigma_{tt}$ is systematically limited by JES
- Use in situ JES calibration to reduce uncertainty on cross section measurement
  - Potential x2 reduction in x-sec systematics with available lumi, and then scaling with $1/\sqrt{L}$!
- For both improvements, more in the back-up!!

# CDF combination

- Performing measurements in orthogonal channels allows us to
  - probe consistency between different channels
  - give confidence in the different modeling/measurement techniques
  - Increase precision by combining them

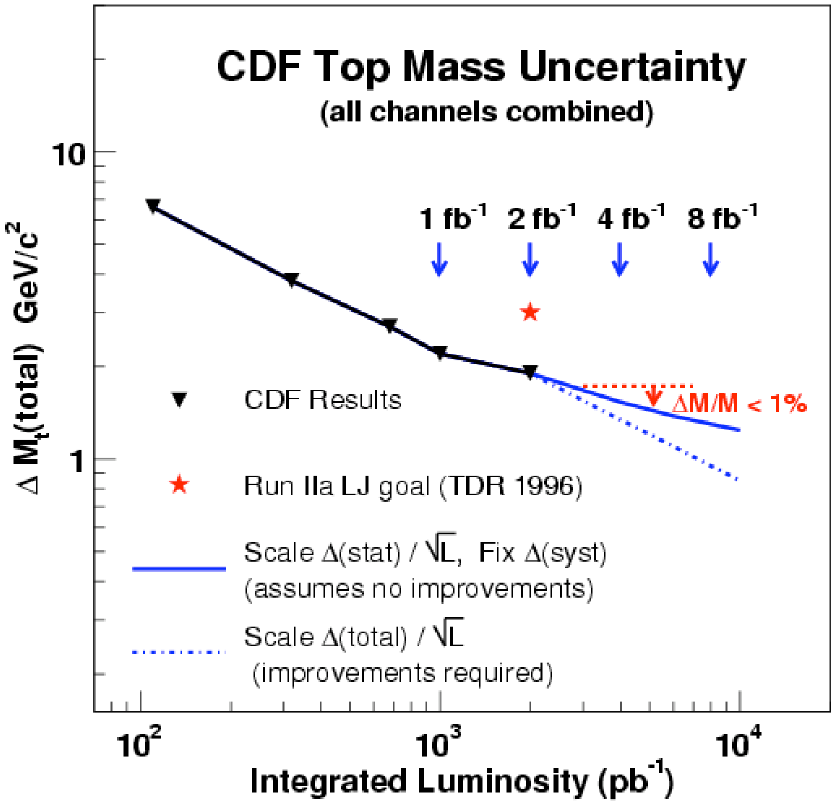



- CDF $M_{top}$=172.4 ± 1.0(stat) ± 1.3(syst) GeV/c$^2$
  =172.4 ± 1.6(stat+syst) GeV/c$^2$
- 0.9% precision (CDF alone)




- Leptonic channels precision now limited by systematics
- All-hadronic is NOT!

# Future prospects




Some remarks:

- Results by far surpass initial expectations (3 GeV)
- After in situ calibration, all-hadronic result is still limited by statistics ( JES scales with 1/√Lum )
- CDF and D0 lepton+jets results nearly identical
- Combined measurement is limited by systematics (see next slide)

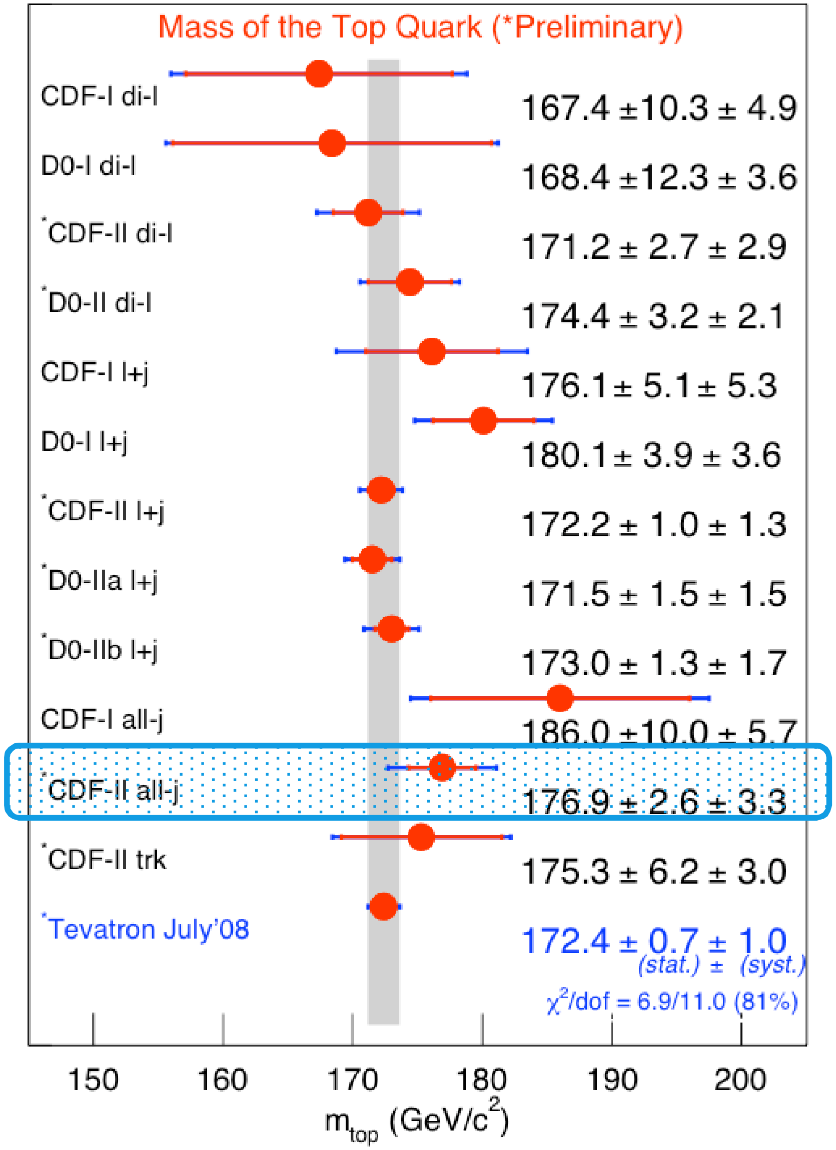
# Tevatron combination

- D0 measures the top quark mass in dileptonic and lepton+jets channel
- CDF and D0 combined measurement in July 2008 to give:

  $M_{top}$=172.4±0.7(stat)±1.0(syst) GeV/c$^2$

**Top quark mass measurement is precision physics → 0.7%!!**

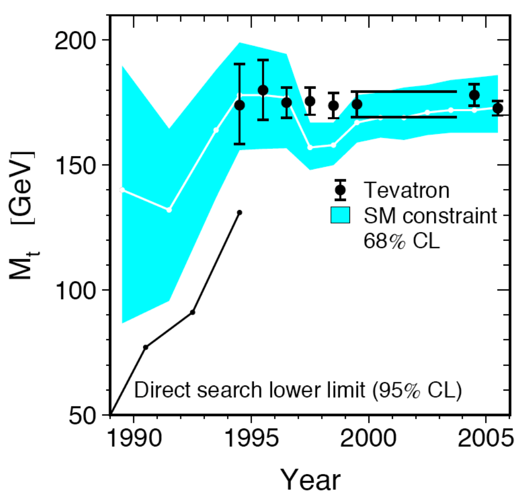
- Need now to probe the magnitude of systematic sources neglected before:
  - Higher order diagrams (NLO)
  - Color reconnection effects between final state particles
- Hope to understand these systematic effects by winter conferences



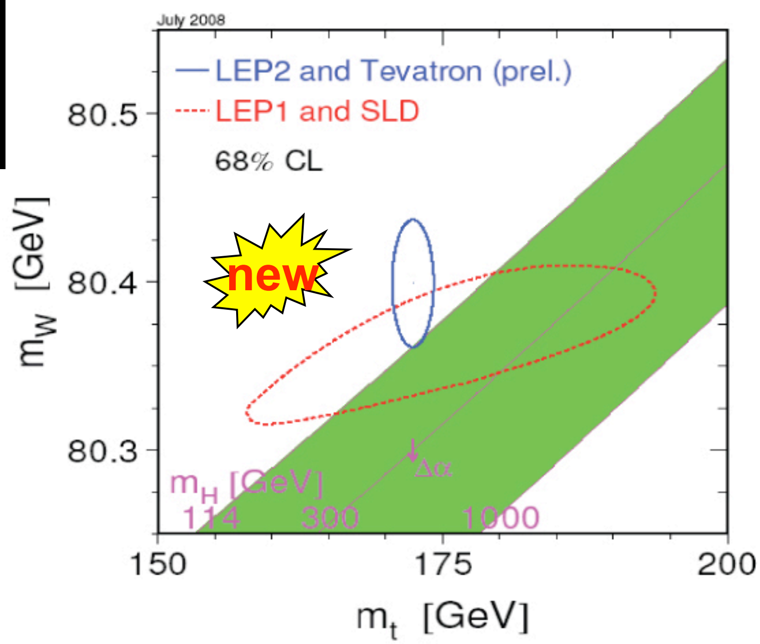
# How it fits in the big picture (SM)

| Date | Direct | SM constraints | | Indirect |
|---|---|---|---|---|
| | H mass from LEP II (GeV) | Mtop (GeV) | δMW (MeV) | EWK fit (GeV) |
| 1998 | >89 | 173.5±5.2 | 90,90 | 74,<250 |
| 2000 | >108 | 174.3±5.1 | 49.62 | 76,<188 |
| 2004 | >114.4 | 178.2±4.3 | 42,59 | 114,<260 |
| 2006 | >114.4 | 171.4±2.4 | 33,59 | 85,<166 |
| 2008 | >114.4 | 172.4±1.2 | 33,39 | 84,<154 |

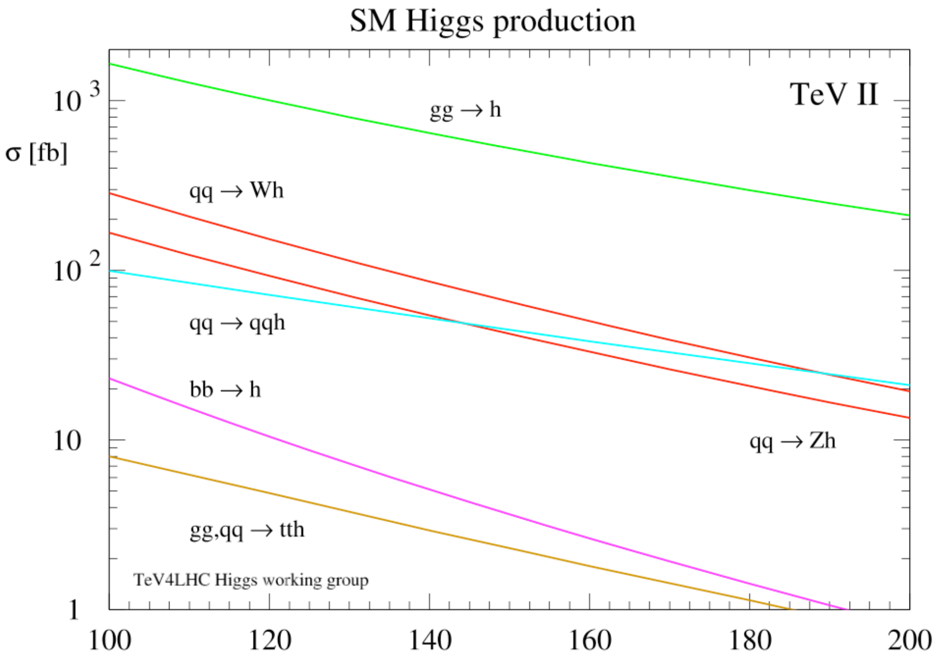
- Running traditional LEP EWK fits, updated using latest Tevatron W boson (2007) and top quark mass (ICHEP 2008)




- EWK predicitons were verified in the top quark mass - good agreement with SM
  - Will it happen for the Higgs (if it exists)?

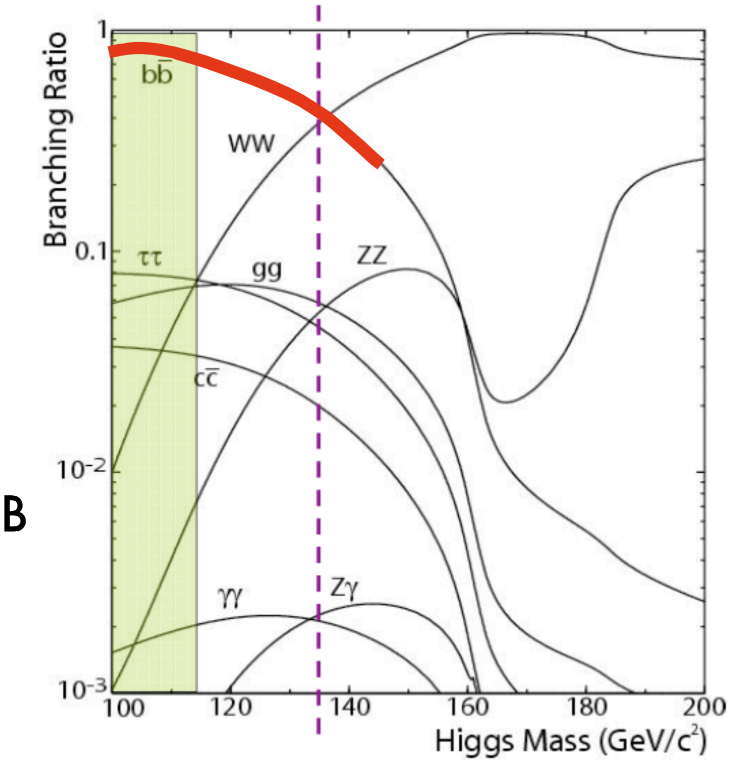


# Higgs strategy at the Tevatron




Higgs production cross secton at the Tevatron:

- gg→H highest production x-sec
- W/Z+H about a order of magnitude smaller

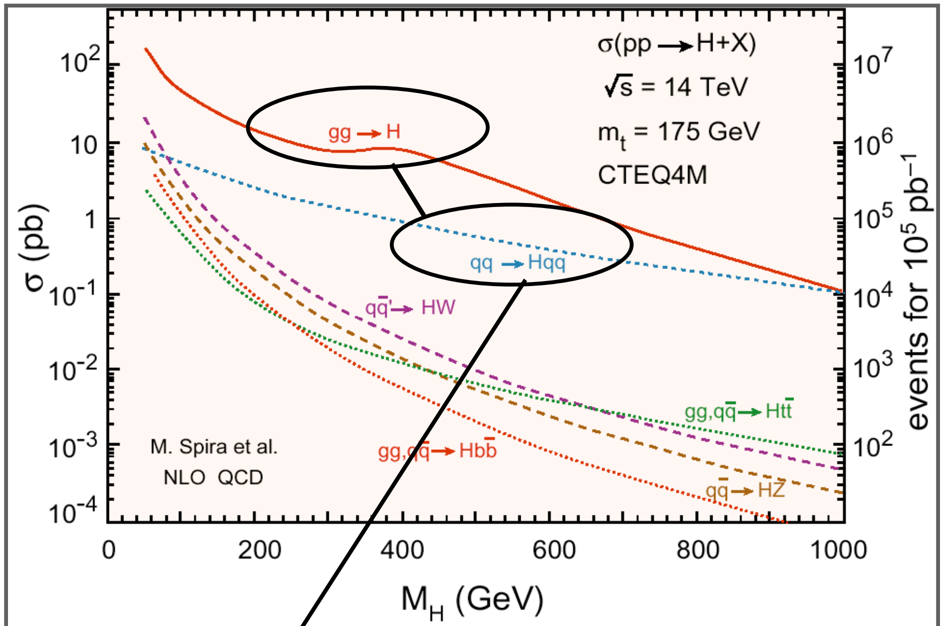



Low mass $m_H < 135$GeV:
BR(H→bb̄) dominates:
gg → H → bb̄ too challenging! QCD irreducible
Look at HV evts, use W/Z signatures to increase S/B

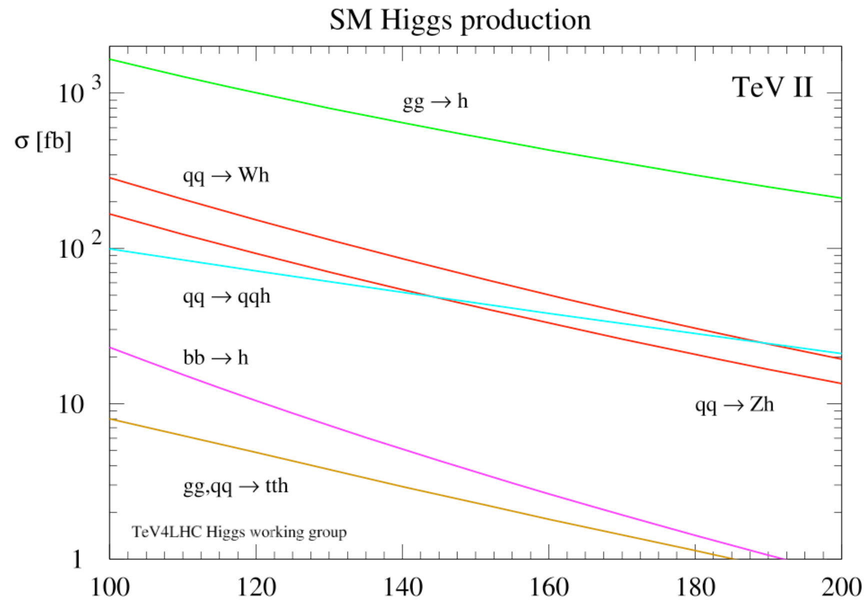
High mass $135 < m_H < 200$GeV:
gg → H → WW with leptonic W decays

# Higgs @ LHC/Tevatron

LHC




Tevatron




- Plan is to use rare decays to improve S/B
  - will need high luminosity

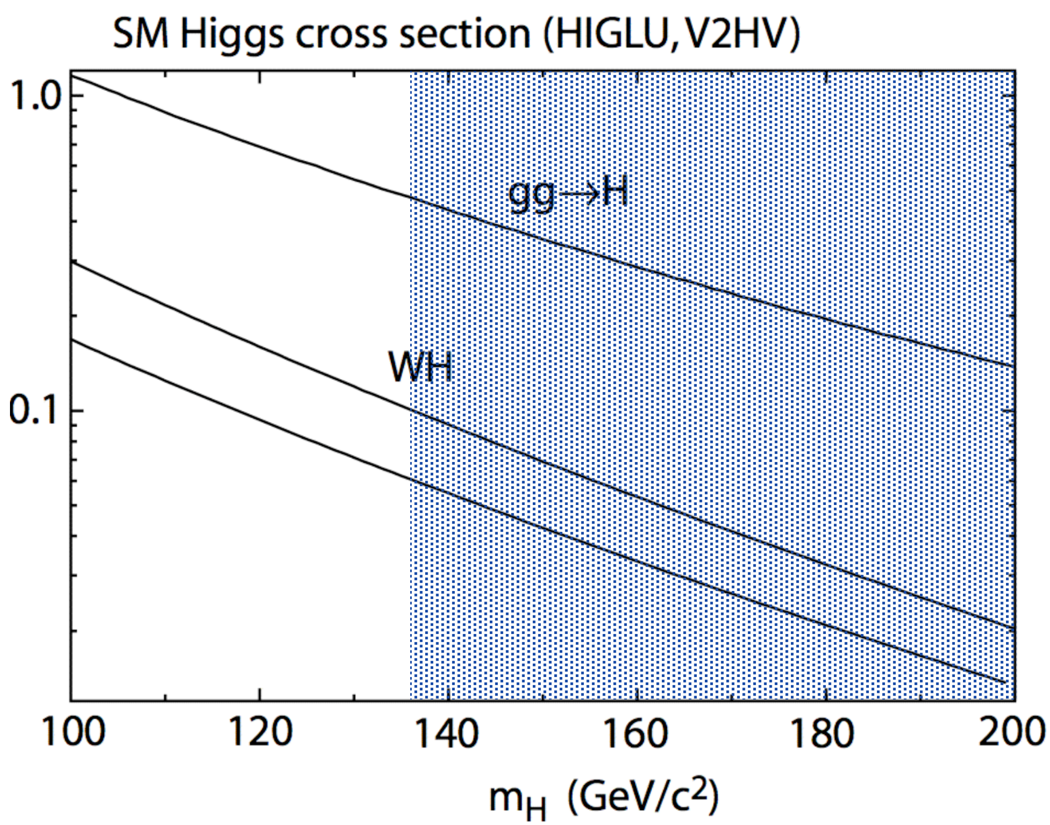
$\sigma$(LHC)/$\sigma$(Tevatron)
~70 (gg→H)
~60 (qq→qqH)
~10 (qq→WH/ZH)
~100 (gg→ttH)
for $m_H$<200 GeV

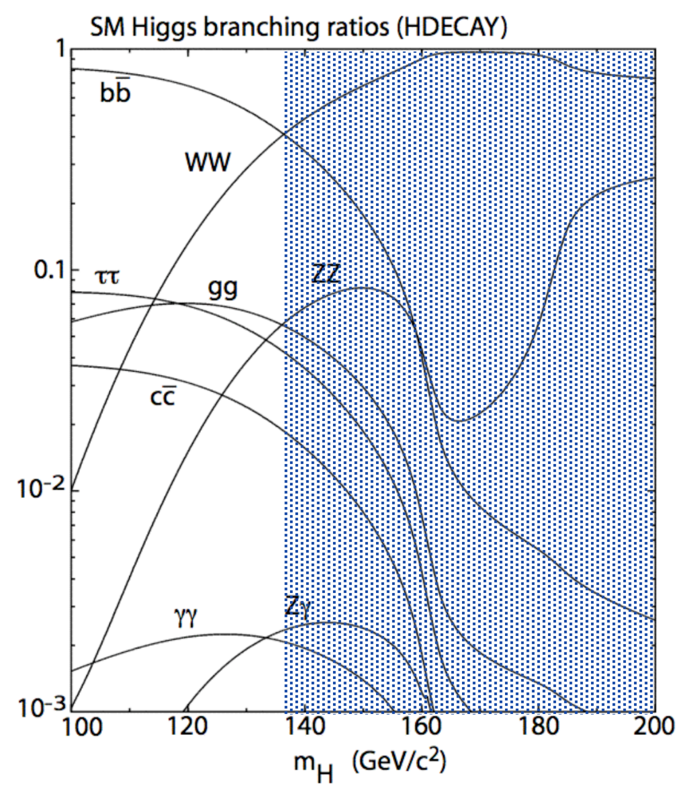
- Rare decays are a luxury here
  - available statistics is limited
- Tevatron experiments cannot afford this strategy

# Why not high mass in this talk

High mass searches (135 GeV ≤ MH ≤ 200 GeV) are not covered in this talk; let's look at hadronic signatures

- $gg \to H \to WW \to qqqq$ : "low" jet multiplicity, no b-jets in the final state
- $WH \to WWW \to qqqqqq$ : lower x-sec and no b-jets in the final state
- $ZH \to ZWW \to b\bar{b}/\nu\nu\ qqqq$ : x-sec X BR even lower



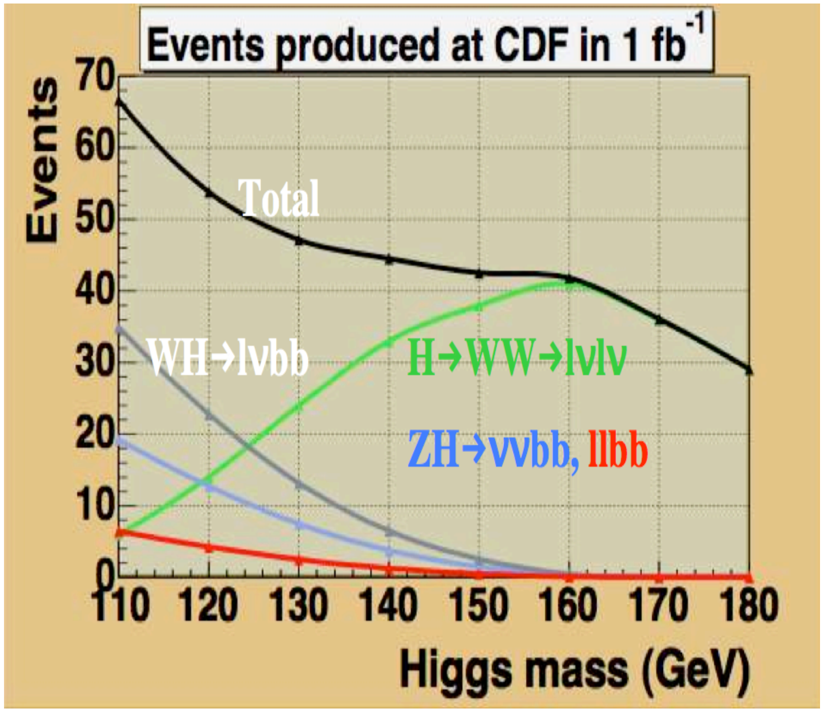



# General low mass Higgs strategy

- Only a handful of Higgs events in each channel
- Backgrounds orders of magnitude higher

- **$H \to b\bar{b}$ is a resonance, but a broad one due to calorimeter resolution!**
  - **Dijet mass resolution ~13%**

- Single channels not sensitive to Higgs
  - Exclusion can be achieved by combination of DEDICATED analysis for EACH channels from BOTH experiments!




And (if it exists) with 7-9 fb$^{-1}$ we expect to integrate, we produce quite a few of them!

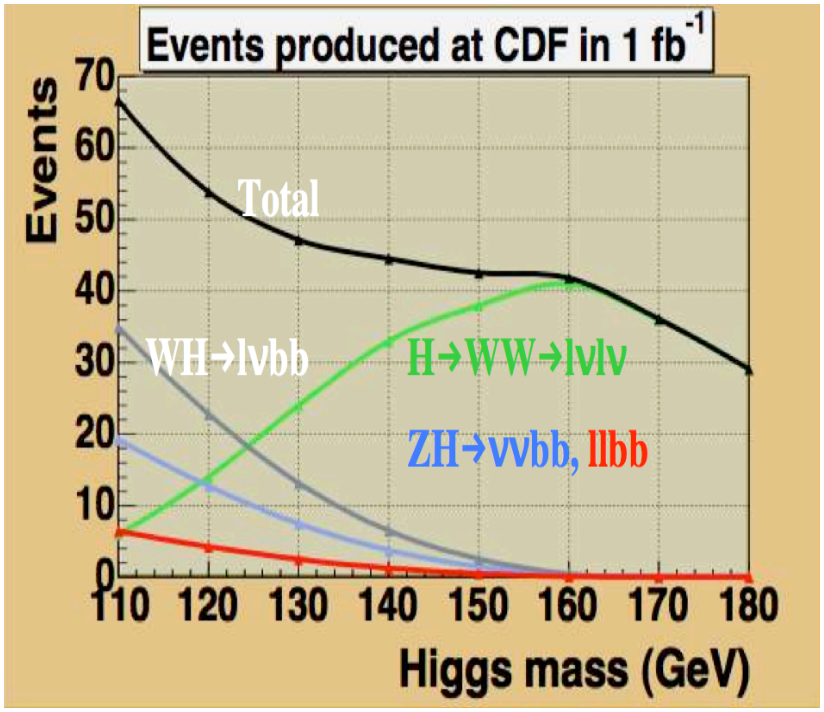
# Low mass Higgs

- Dileptonic ZH → ll $b\bar{b}$
  cleanest channel and fully reconstructed final state - *BUT* lowest σXBR

- Lepton+Jets WH → lν $b\bar{b}$
  good S/B ratio, limited lepton coverage

- All hadronic WH/ZH → qq $b\bar{b}$
  challenging channel: highest BR *BUT* huge QCD *physics* backgrounds (hard to reduce)

- Missing Energy plus jets WH/ZH → l ν/νν/ll $b\bar{b}$
  have acceptance to different Higgs processes, BUT huge QCD *instrumental* background

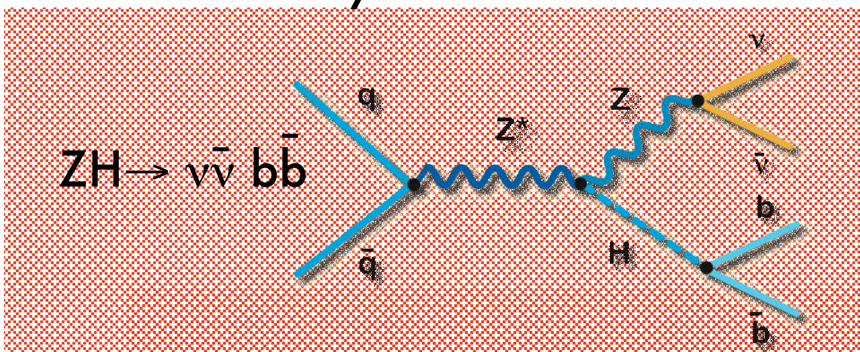


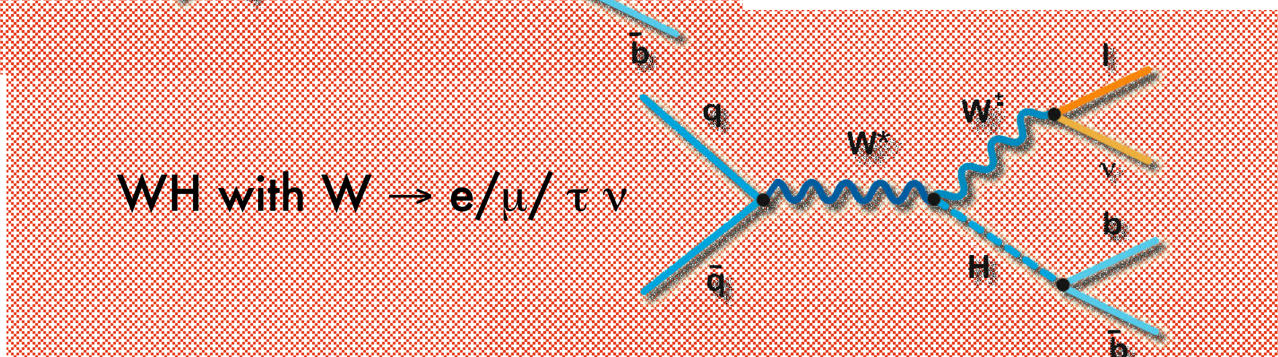

And (if it exists) with 7-9 fb$^{-1}$ we expect to integrate, we produce quite a few of them!

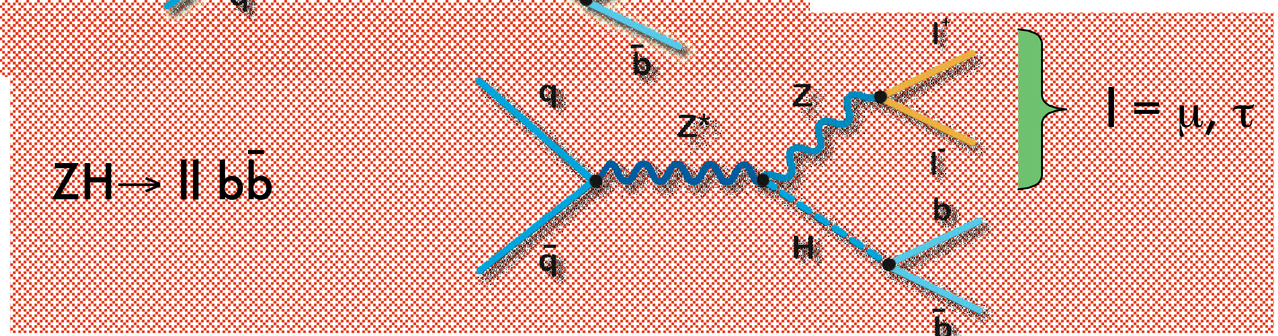
# ZH/WH→ missing $E_T$ +jets

Acceptance to HV production through $H \rightarrow b\bar{b}$ decay and many different vector boson decay modes

Not-identified $\mu$ = MET
Non-isolated e = jet
Hadronic $\tau$ = jet



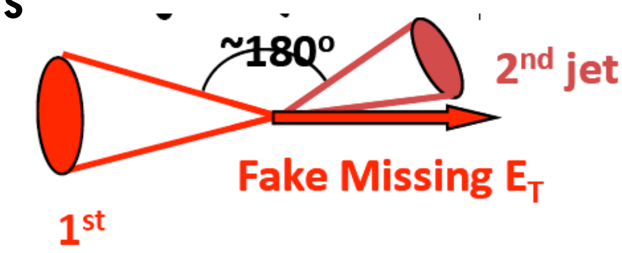



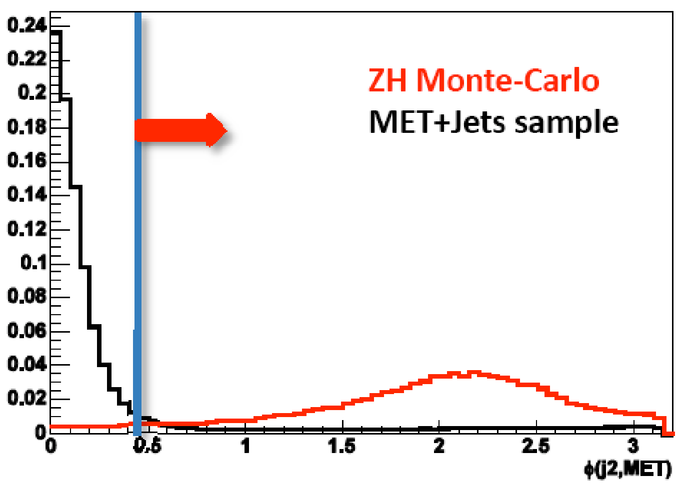

👎 no identified leptons→QCD instrumental contribution huge!(mismeasured jets=MET)
👍 generic signature →large number of signal events!

# Rejecting QCD (1)

- Main background source even after trigger reqs is instrumental
  - –QCD events with mismeasured jets will appear as events with high MET




- Requiring MET and jets to be misaligned is very effective in removing the QCD backgrodunds:

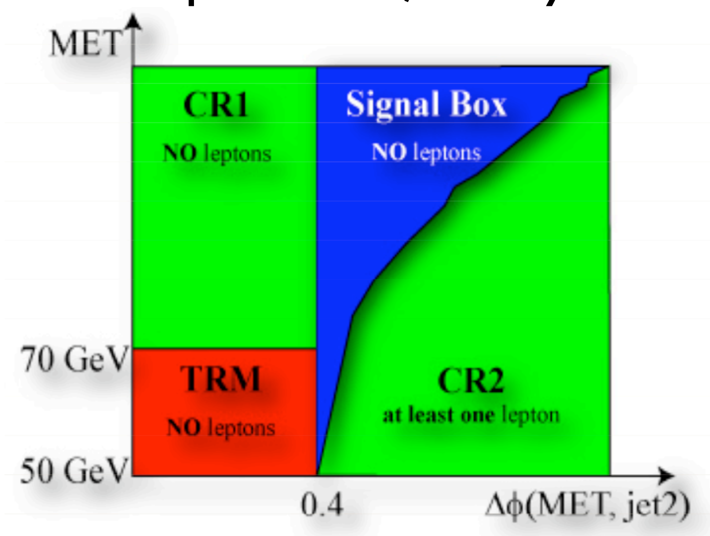



  - rejects 1 order of magnitude of backgrounds, while causing loss of only about few % of signal
  - Can use discarded QCD events to build a data-driven model of b-tagged multijet production (analogous to the one showed earlier)

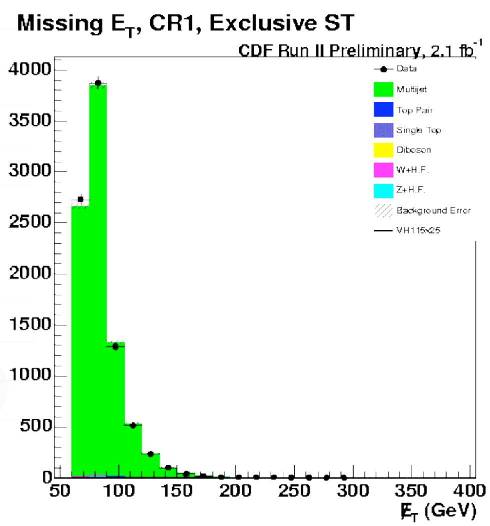
- Require b-tagging to reject QCD production of light flavour jets (reduces 1-2 orders of magnitude)

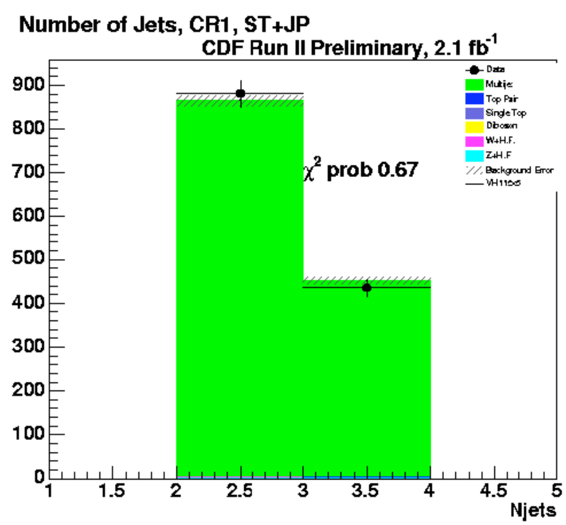
# Baseline requirements

- Require orthogonality in lepton cuts to channels with identified leptons
- Low jet multiplicity: 2 jets from Higgs, additional jet from
  - Initial/final state radiation
  - e or $\tau$ leptons reconstructed as jets
- Analysis with identified leptons usually have a "reasonable" S/B ratio after minimal requirements. Here S/B ~ 1/20,000 after trigger on Met and jets requirements, mostly QCD




Use sidebands to check background modeling - prediction

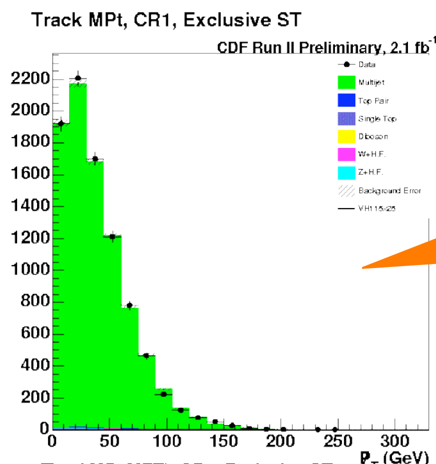


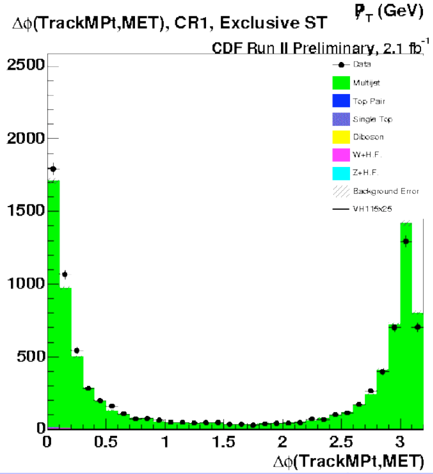
# QCD rejection using tracks

Other key elements to reduce QCD:

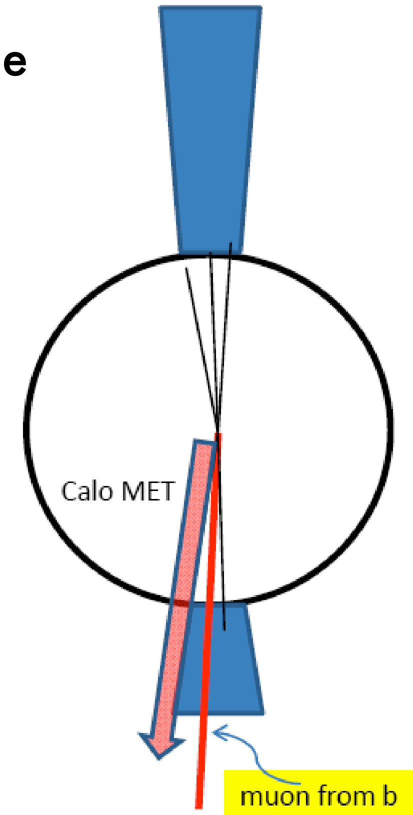
- compute the track Pt imbalance (MPT) in the transverse plane
  - Complementary information to the transverse energy imbalance in the calorimetry (MET)




Absolute amount of Track Pt imbalance is small for events with mismeasured jets




MET/MPT correlation is different for QCD and signal

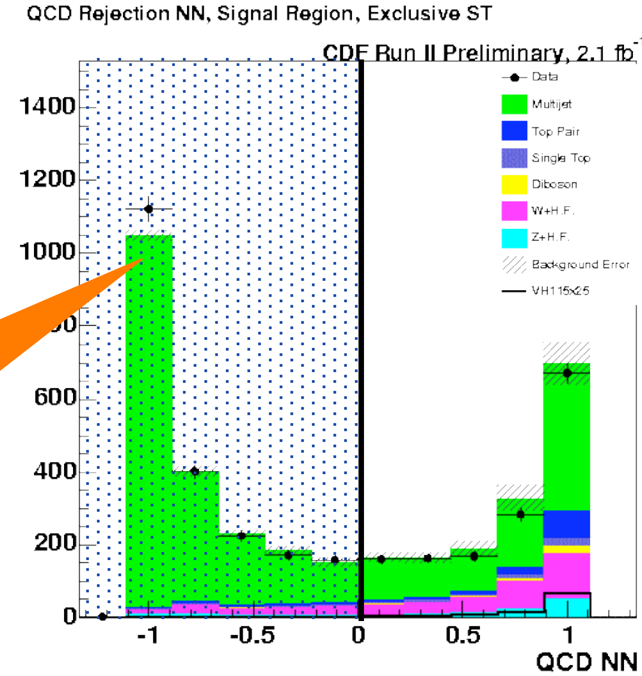



- Use both MET and MPT infos into multivariate technique to reduce QCD! Advantages:
  - increase the signal significance and purity
  - use QCD-rich region of NN to set a normalization for QCD

# Final event selection

Use all possible informations to reduce the instrumental QCD background

- Most of multijet events (the ones due to instrumental effects) are separable with this technique, with minimal loss of signal and large increase in sensitivity




Showing NN output on events with 1 identified b-jet (b-tag)

Average over the three b-tagged subsamples

| Qt.y | Preselection | After QCD cut | Difference |
|---|---|---|---|
| S | 7.6 | 7.5 | - 0.5% |
| B | 4010 | 1800 | - 50% |
| S/B | ~1/500 | 1/240 | times 2! |
| $S/\sqrt{S+B}$ | 0.12 | 0.18 | + 50% |

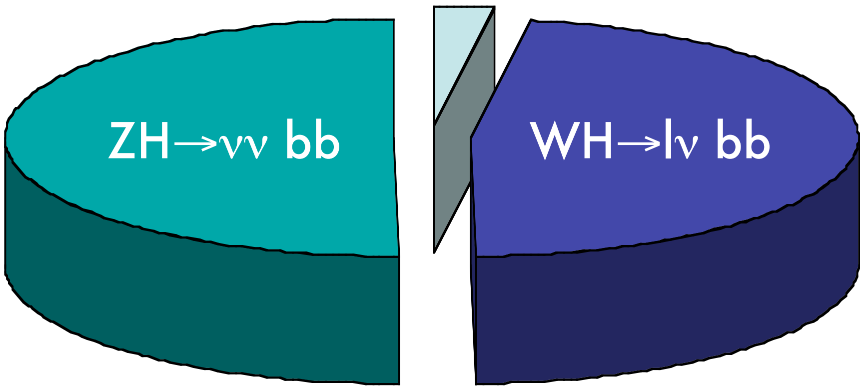
Now the S/B ratio is as good as in events with 1 identified lepton, and acceptance is larger!

# Subdivide the sample

After all cuts, we maximized acceptance to Higgs in signal region!

Almost 4 evts/fb-1

ZH → ll bb (leptons are mostly μs or τs)




WH events are

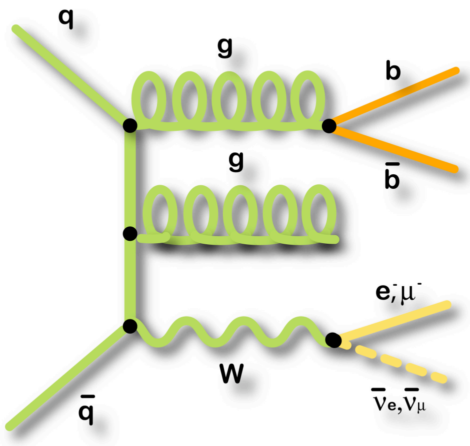
- Around 50% WH→e/μν bb
- Around 50% WH→τ ν bb, where half of the times the τ is reconstructed as a jet

Using as figure of merit S/√B we expect roughly

- 40% improvement by splitting in high and low S/√B regions
- 10% improvement by including the worst S/√B region (1 b-tagged jet)

| b-tags | N Higgs evts (@115GeV) | N bck evts | S/√B |
|---|---|---|---|
| All | 7.5 | 1802 | 0.18 |
| 1 SecVTX | 4.0 | 1548 | 0.10 |
| 1 SecVTX +1 JetProb | 1.5 | 149 | 0.12 |
| 2 SecVTX | 2.0 | 105 | 0.20 |
| Quadrature sum of three categories | | | 0.25 |

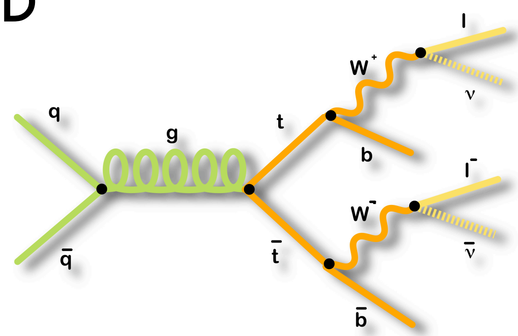
# Other SM backgrounds



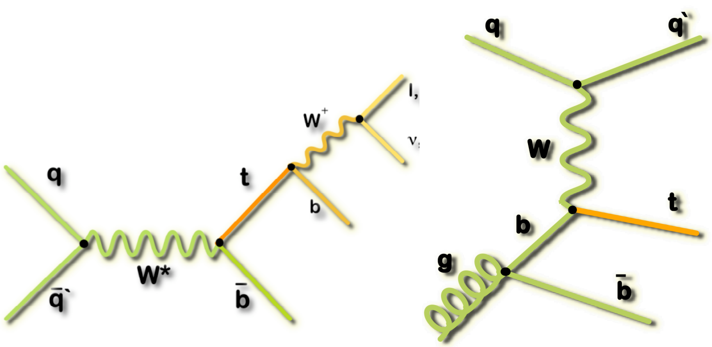

W/Z production in association with jets

Largest background after QCD

Top pair production

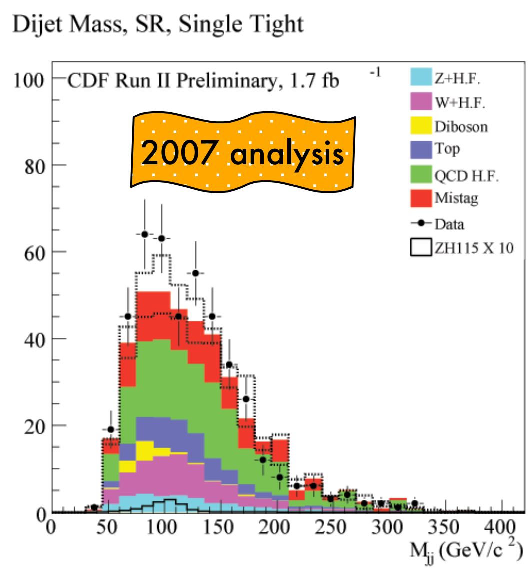



Single top s- and t-channel




Dibosons  WW/WZ/ZZ

Most similar to signal, but also smallest cross section



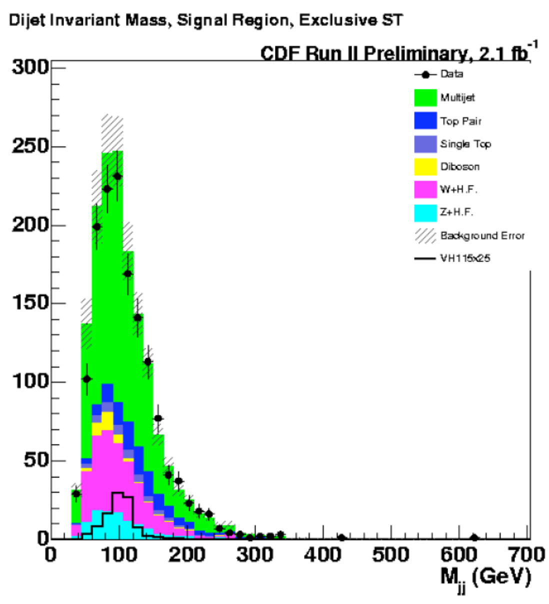

- $M_{jj}$ most peculiar feature of Higgs signal
- But resonance is broad, and all bcks peak in the same place!

# Multivariate discriminant

Higgs (and single top) typical search challenges: small significance of a possible excess, and large systematics, (up to 40%) which easily cover the signal

- Need for a multivariate analysis

Convolution of many track-related observables, discriminate residual instrumental QCD

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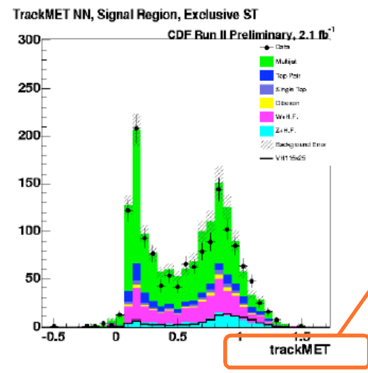


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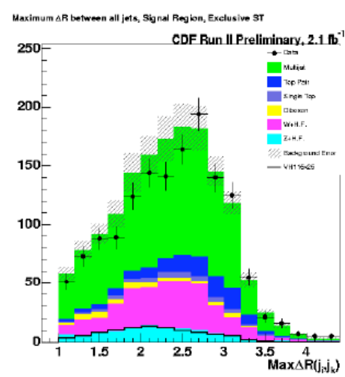


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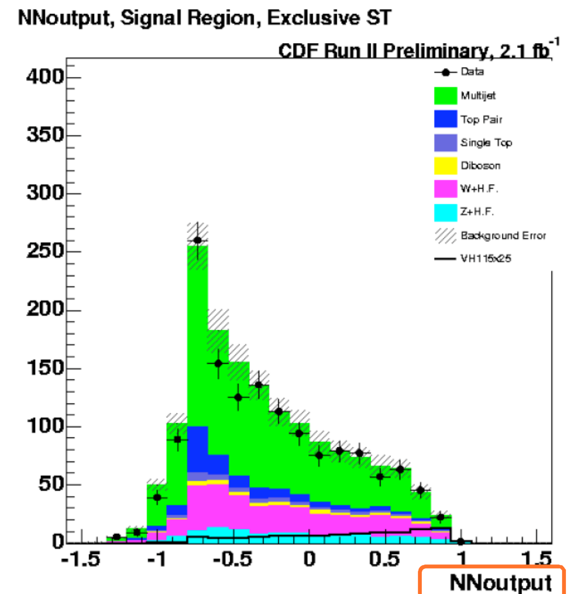
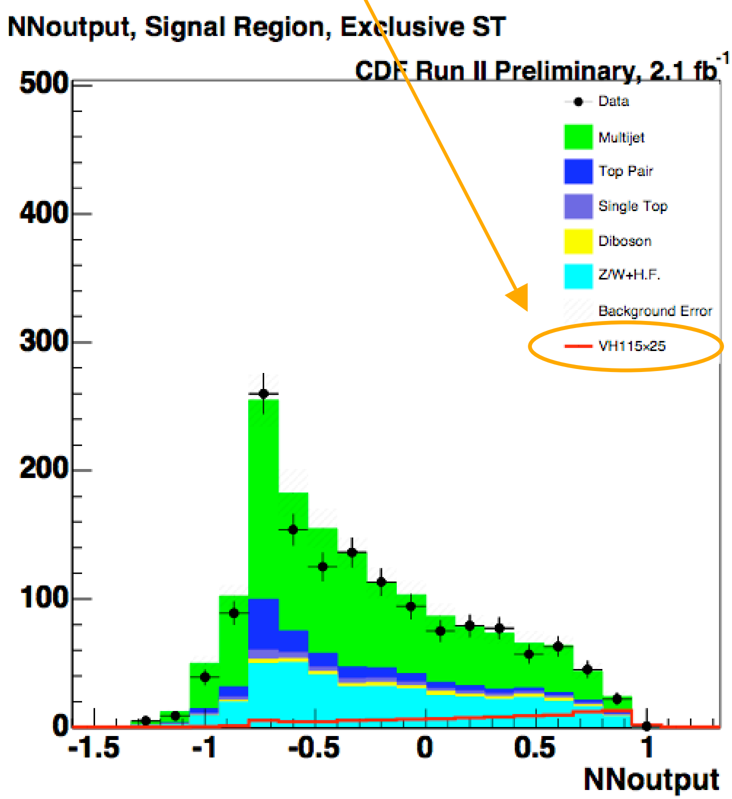



+ more

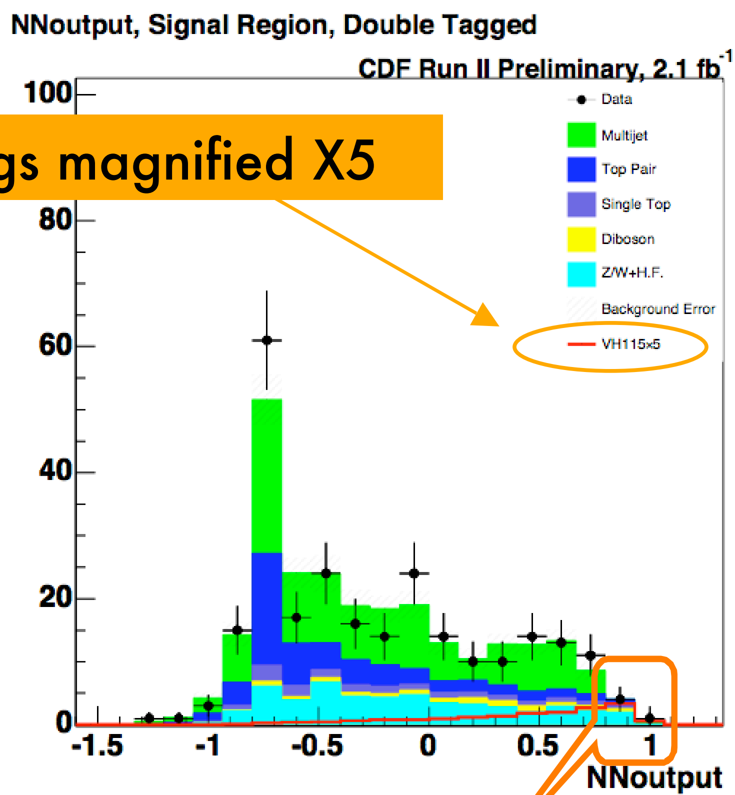
Final discriminant

# A look at the discriminant

Higgs magnified X 25




Higgs magnified X5



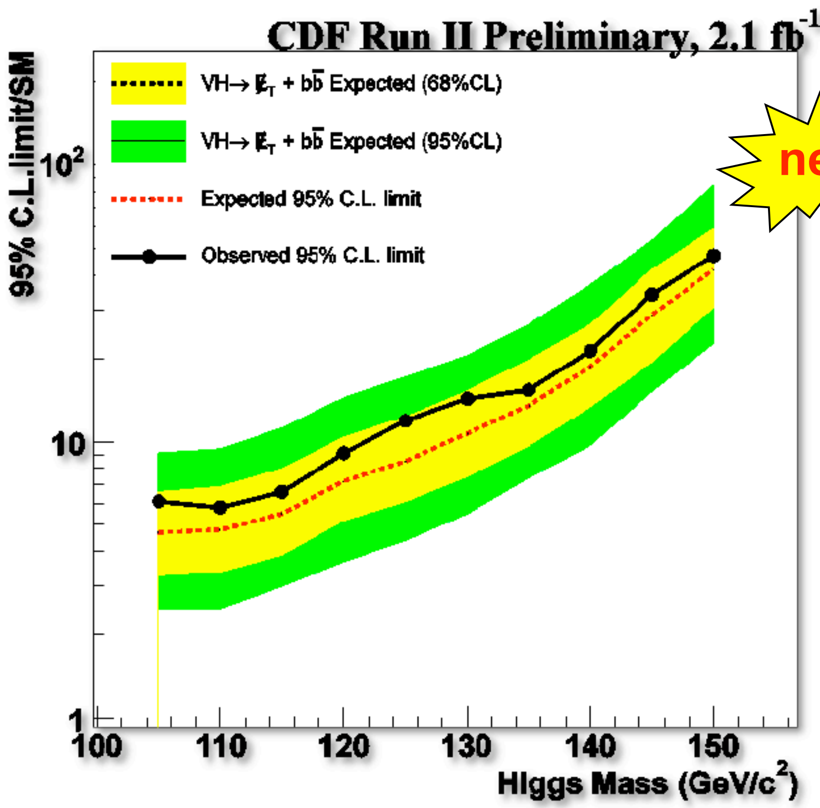

S/B ratio 1/5 in most sensitive bin

We expect 0.4 Higgs events here

– (assuming $M_H$=115)

# Final results

- Analysis updated since ICHEP. Changes since then:
  - Discriminant optimization separated for 2- and 3-jets events (6% improvement)
  - Wider use of track-based variables in discrimination (6% improvement)
  - Included the acceptance from ZH → ll bb (3% more signal)



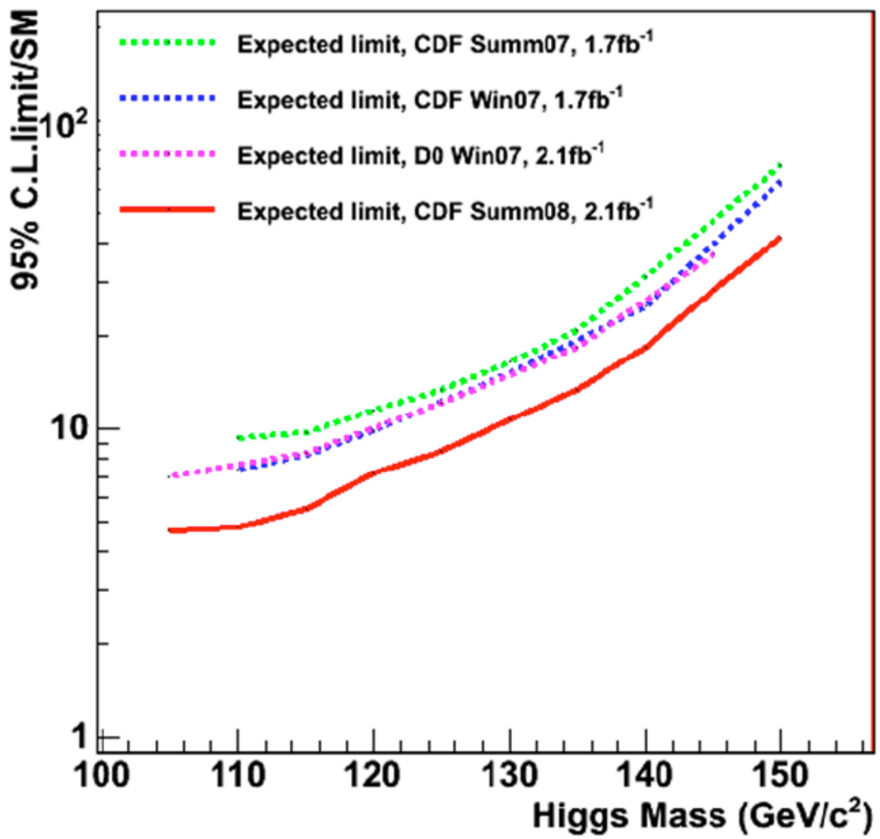


Result approved by the CDF collaboration last week, heading toward a publication!

| Higgs mass (GeV) | 105 | 115 | 125 | 135 |
|---|---|---|---|---|
| Exp | 4.7 | 5.5 | 8.5 | 13.5 |
| Obs | 6.1 | 6.6 | 11.9 | 15.4 |

# Key components of the analysis

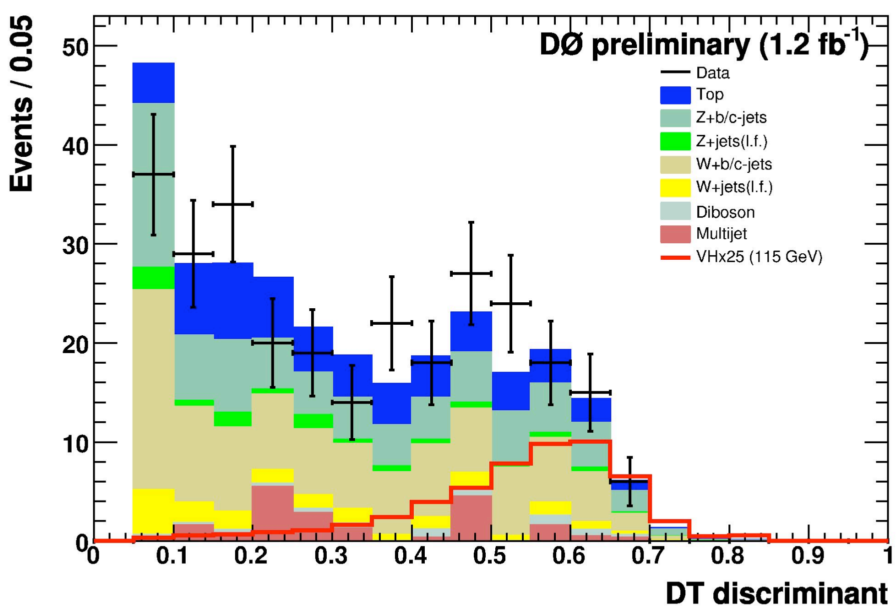
- Lowered MET cut and accepting 3 jet events
  - Doubled the acceptance
- But backgrounds increase much faster! Use track MPT and more in a NN to select events
  - Increased significance
- Data-driven background modeling
  - Control systematics
- track+cal jet energy measurement to improve $M_{jj}$ resolution
- Multivariate discriminant
  - enhance sensitivity




**Improvement of almost factor of 2 since summer 2007!**
**With only 20% more integrated luminosity!!**

# What about D0’s met+jets?

- D0 looks in the same channel using similar techniques; not really an apple-to-apple comparison though:
  - D0 has a dedicated HW → $\tau\nu$ bb channel
  - D0 has larger e/mu angular coverage
- Main differences in the strategy
  - D0 does not use events with 1 tag - CDF gets 10% sensitivity here
  - D0 does not have a NN event selection - CDF gets additional 10% here




| Analysis | Lum (fb$^{-1}$) | Higgs Events (@115) | Exp. Limit | Obs. Limit |
|---|---|---|---|---|
| CDF | 2.1 | 7.5 | 5.5 | 6.6 |
| DØ | 2.1 | 3.7 | 8.4 | 7.5 |

Remember! At low mass, we need combination of many channels from both experiments to have a chance to exclude/have a hint of Higgs

# How to further improve

- Improving the background rejection
  - Already have ideas on how to improve the QCD NN selection
  - Work ongoing to relate MET to jet energy through jet energy resolution
- Acceptance gain
  - Improve trigger understanding to use the low MET tail and gain acceptance
  - Improve MET resolution at trigger level
  - Use additonal trigger to recover events (MET>45 GeV)
- b-tagging improvements
  - NN b-tagger at work,  increase tagging efficiency keeping same fake rate - work in progress

# Benchmarking

- Want to benchmark with larger cross-section processes, using the same tools used for the Higgs analysis

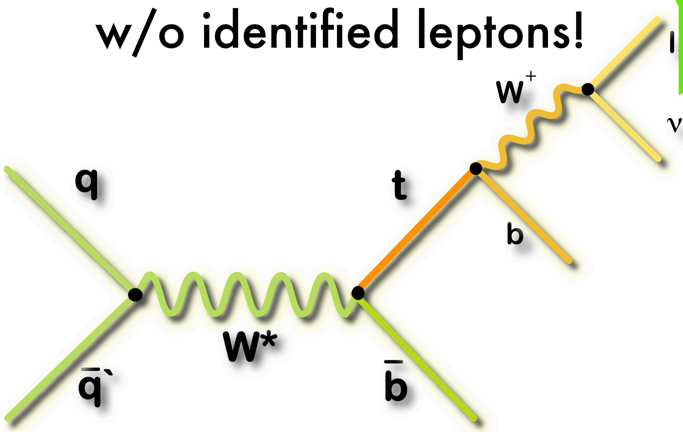
| Process | Exclusive 1Tag | ST+ST | ST+JP |
|---|---|---|---|
| QCD + Mistags | $941 \pm 44$ | $42.1 \pm 8.7$ | $78 \pm 12$ |
| Single Top | $43.2 \pm 7.9$ | $8.5 \pm 1.7$ | $7.2 \pm 1.5$ |
| Top Pair | $125 \pm 17$ | $27.4 \pm 4.3$ | $27.1 \pm 4.6$ |
| Di-boson | $35.6 \pm 6.8$ | $4.9 \pm 1.2$ | $4.3 \pm 1.1$ |
| W + h.f. | $297 \pm 130$ | $11.0 \pm 6.5$ | $21 \pm 11$ |
| Z + h.f. | $107 \pm 46$ | $10.8 \pm 5.0$ | $11.3 \pm 5.2$ |
| Total Exp | $1548 \pm 146$ | $105 \pm 13$ | $149 \pm 17$ |
| Observed | 1443 | 105 | 148 |
| $ZH \to \nu\nu bb$ (MH115GeV) | 2.1 | 1.0 | 0.8 |
| $WH \to (l)\nu bb$ (MH115GeV) | 1.8 | 0.9 | 0.7 |
| $ZH \to (ll)bb$ (MH115GeV) | 0.09 | 0.04 | 0.03 |

- Diboson production well known thanks to LEP
- Acceptance here to WZ and ZZ to bbar and missed charged leptons/neutrinos S=45 events
- Similar to WH/ZH thanks to the Z reconstructed mass

Diboson are natural benchmark, but…see next slide

# Single top

- Single top discovery ($5\sigma$) not achieved yet
  - will integrate more luminosity
- Can we use orthogonal datasets to increase precision?
  - No efficient trigger for all-had decays
- But we can use events w/o identified leptons!

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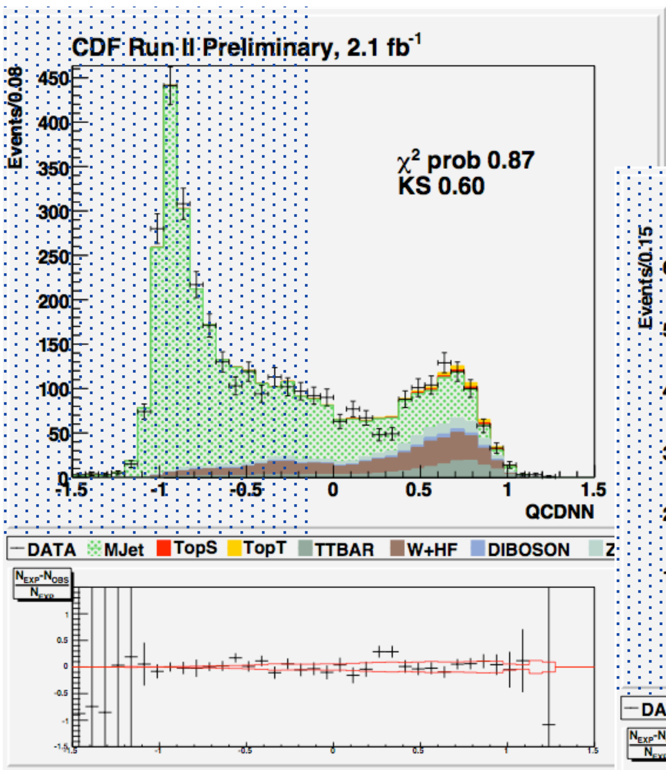
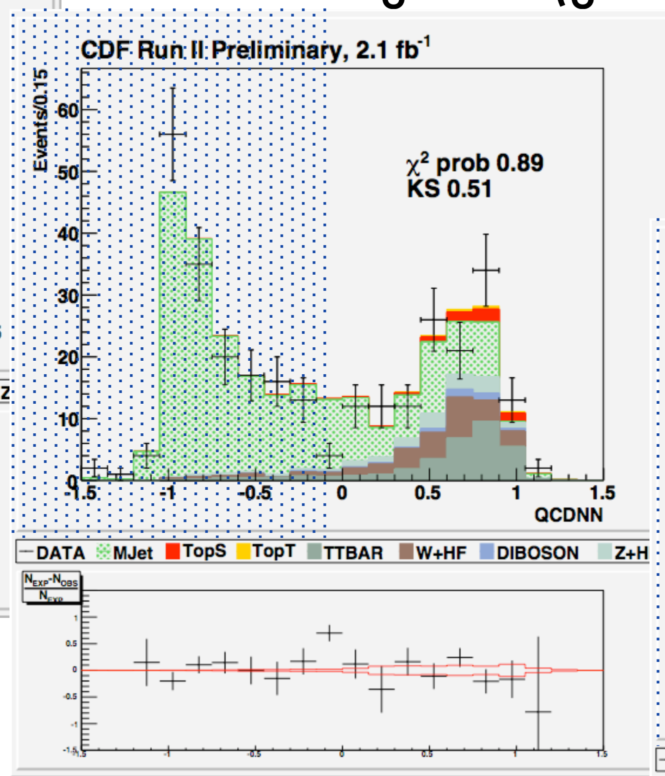
| Observed | 1443 | 105 | 148 |
| $ZH \rightarrow \nu\nu bb$ (MH115GeV) | 2.1 | 1.0 | 0.8 |
| $WH \rightarrow (l)\nu bb$ (MH115GeV) | 1.8 | 0.9 | 0.7 |
| $ZH \rightarrow (ll)bb$ (MH115GeV) | 0.09 | 0.04 | 0.03 |

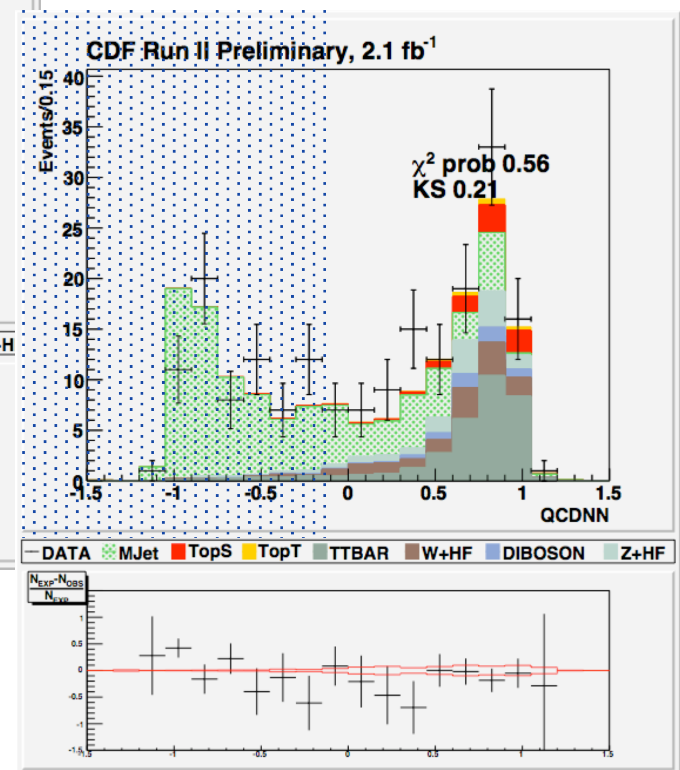
- Acceptance here to events with escaping e/$\mu$, hadronic $\tau$ → 70 signal events!
- S/B ratio ranging from 1/10 to 1/30, similar to leptonic channel!
- Extremely challenging to discriminate
  - Top four momentum cannot be reconstructed here due to the W boson being not identified

# Single top in MET+jets

- Single top is yellow and red
  - Use shaded area to normalize multijet background (green)



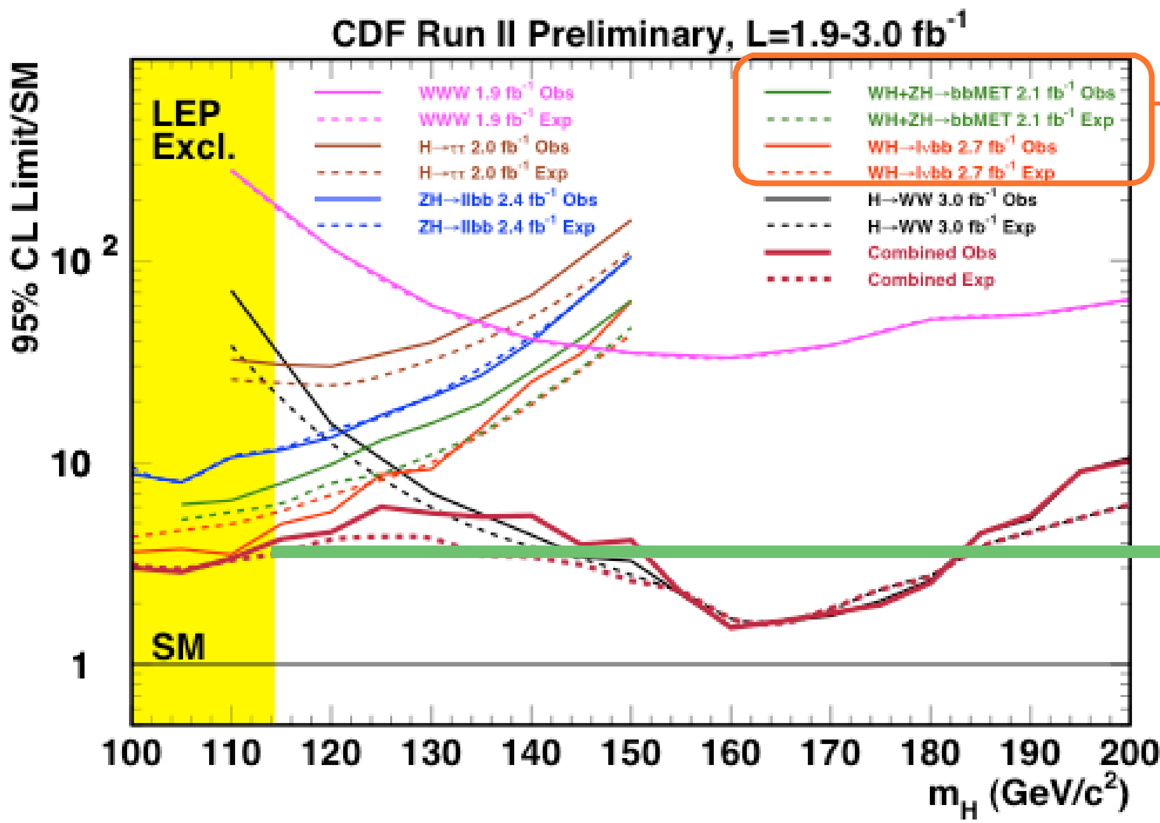




Improved event selection wrt Higgs search, studies ongoing

- sample orthogonal to the published analysis - will be combined to increase precision on $V_{tb}$
- hope to finish for winter conference

# CDF Low mass Higgs combination

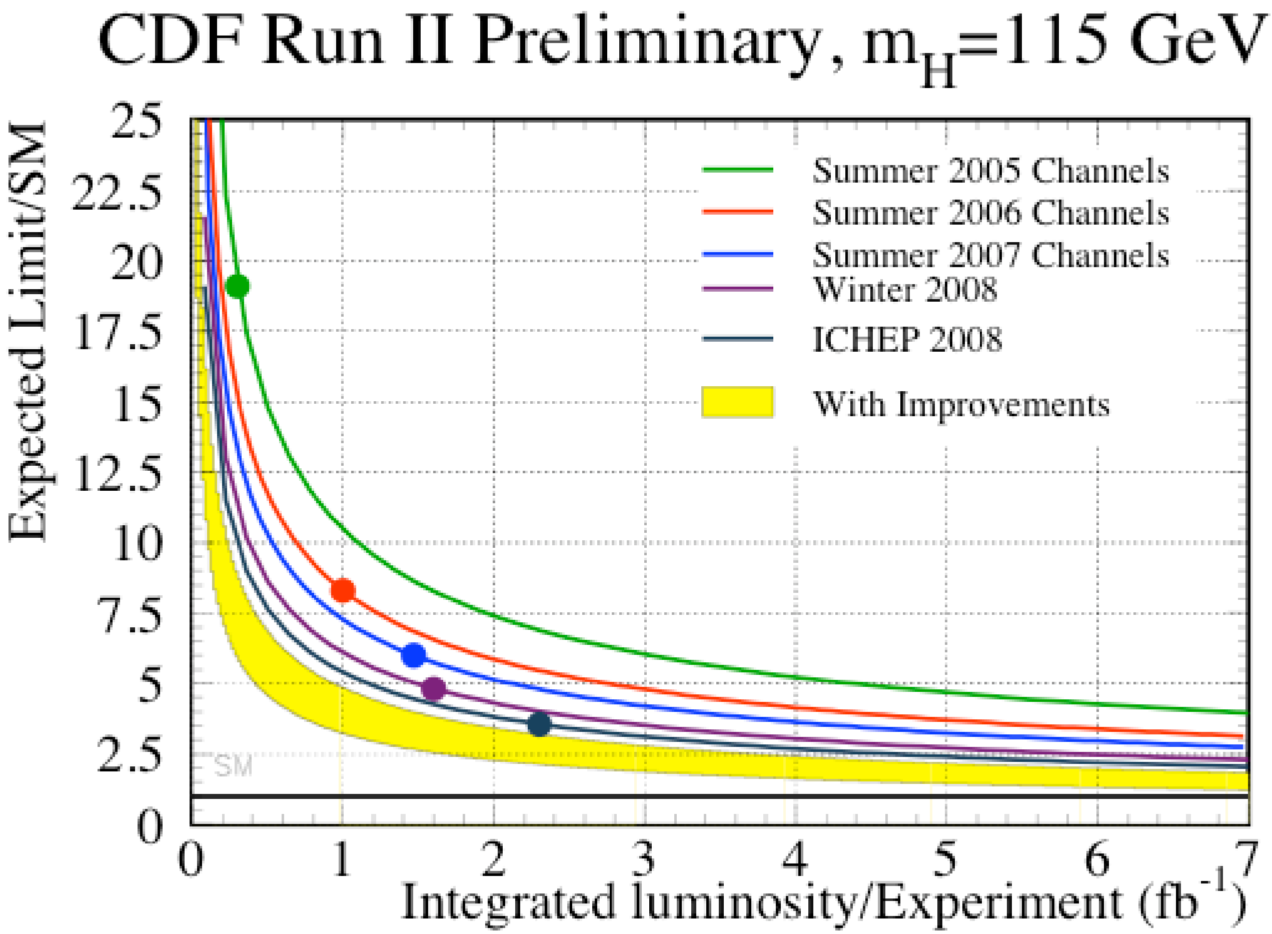



Both results are very new and each provides up to 15% improvement wrt what is shown here

Was 3.3 times the SM expectation. Now likely below 3

- No single analysis at low mass sensitive to Higgs
- BUT!Combination provides a <u>x2 improvement</u> wrt to the single analysis

# Improving w luminosity and ideas!



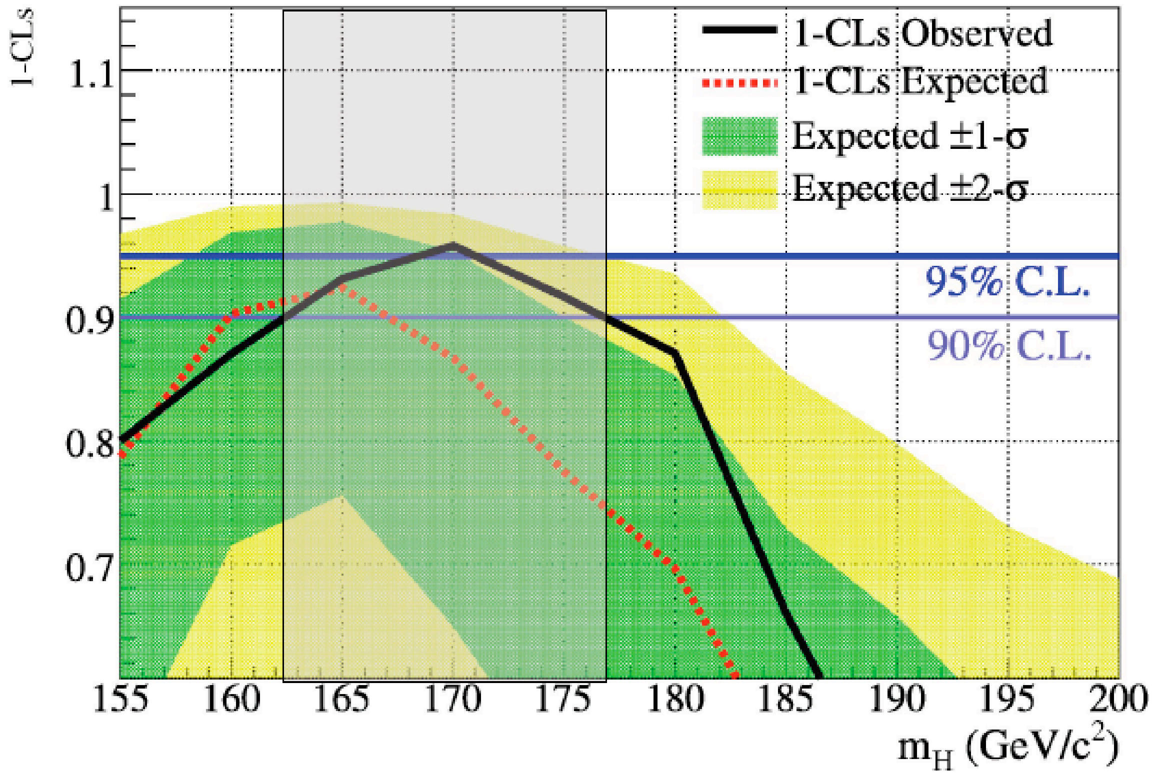

- All analysis are improving faster than $1/\sqrt{L}$ !
- Latest MET+jets and lepton+jets searches not shown here
  - 15% improvement in both channels with same luminosity
- Yellow band means exclusion level once combined with D0
  - Getting close to the yellow band!

# Tevatron Low mass Higgs

| Channel | CDF 95% C.L. Limits $\sigma\cdot BR/SM$ obs (exp) | DØ 95% C.L. Limits $\sigma\cdot BR/SM$ obs (exp) |
|---|---|---|
| $VH\rightarrow \nu\nu/(l)bb$ | 6.6 (5.5) 2.1fb$^{-1}$ | 7.5 (8.4) 2.1fb$^{-1}$ |
| $WH\rightarrow l\nu bb$ | 5.6 (4.8) 2.7fb$^{-1}$ | 9.3 (8.5) 1.7fb$^{-1}$ |
| $WH\rightarrow \tau\nu bb$ | - | 35.4 (42.1) 0.9fb$^{-1}$ |
| $VH\rightarrow qqbb$ | 37.0 (36.6) 2.0fb$^{-1}$ | - |
| $ZH\rightarrow llbb$ | 11.6 (11.8) 2.4fb$^{-1}$ | 11.0 (12.3) 2.3fb$^{-1}$ |
| $ZH\rightarrow llbb$ | 14.2 (15.0) 2.0fb$^{-1}$ | |
| $ttH\rightarrow l\nu bbbbqq$ | - | 63.9 (45.3) 2.1fb$^{-1}$ |
| $H\rightarrow \gamma\gamma$ | - | 30.8 (23.2) 2.7fb$^{-1}$ |
| $H\rightarrow \tau\tau$ | 30.5 (24.8) 2.2fb$^{-1}$ | - |
| Combined | In progress | In progress |

# Tevatron combination

- As you know, CDF+D0 started excluding SM Higgs boson in the mass range of 170 GeV



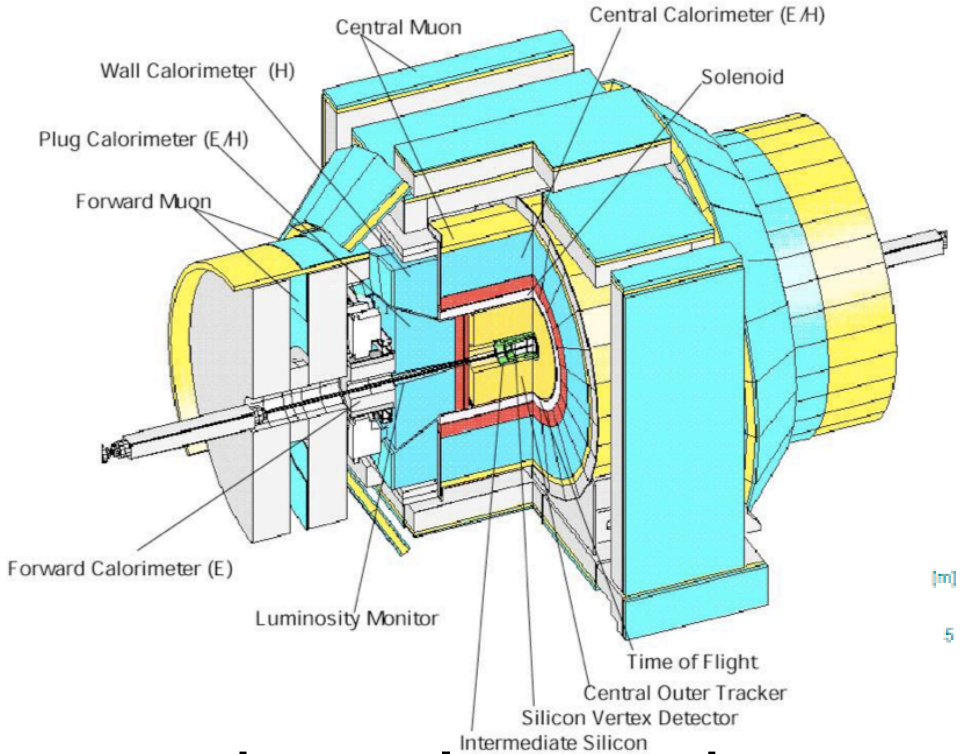

- **First Tevatron direct limit!**
- Plot show ICHEP result, mass range rapidly expanding
- Combination @ low mass much more complicated, require combining tens of different channels, with additional subsamples - work in progress
  - Expect to see something at the winter conferences

# Conclusions

- When looking for small signals, do not throw anything away!
  - Hadronic signatures have acceptance to large variety of decays (leptonic as well)
  - Enhance sensitivity of measurements and searches through combination of different decay modes (additional statistical power, different systematic sources)
- Top mass will be a long-standing Tevatron legacy!
  - 0.7% precision, and improving
- Hope to be able to exclude a wide Higgs mass range
  - Starting to carve around 170 GeV - need more (and fresh) brains at low mass, but we are on the good track
  - Exclude SM Higgs, or discover it!

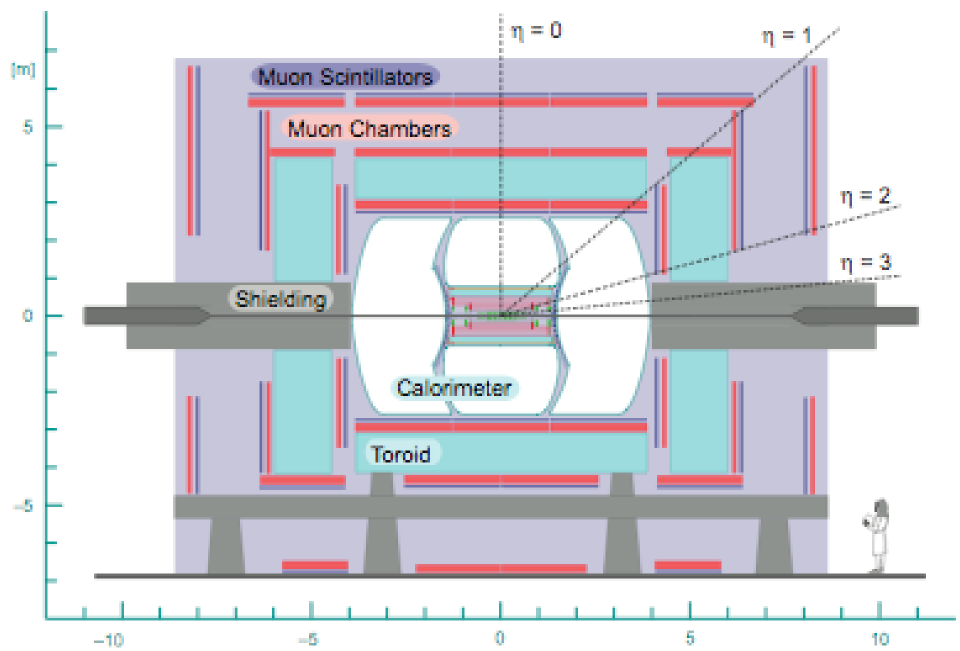
# BACK UP SLIDES

# The detectors



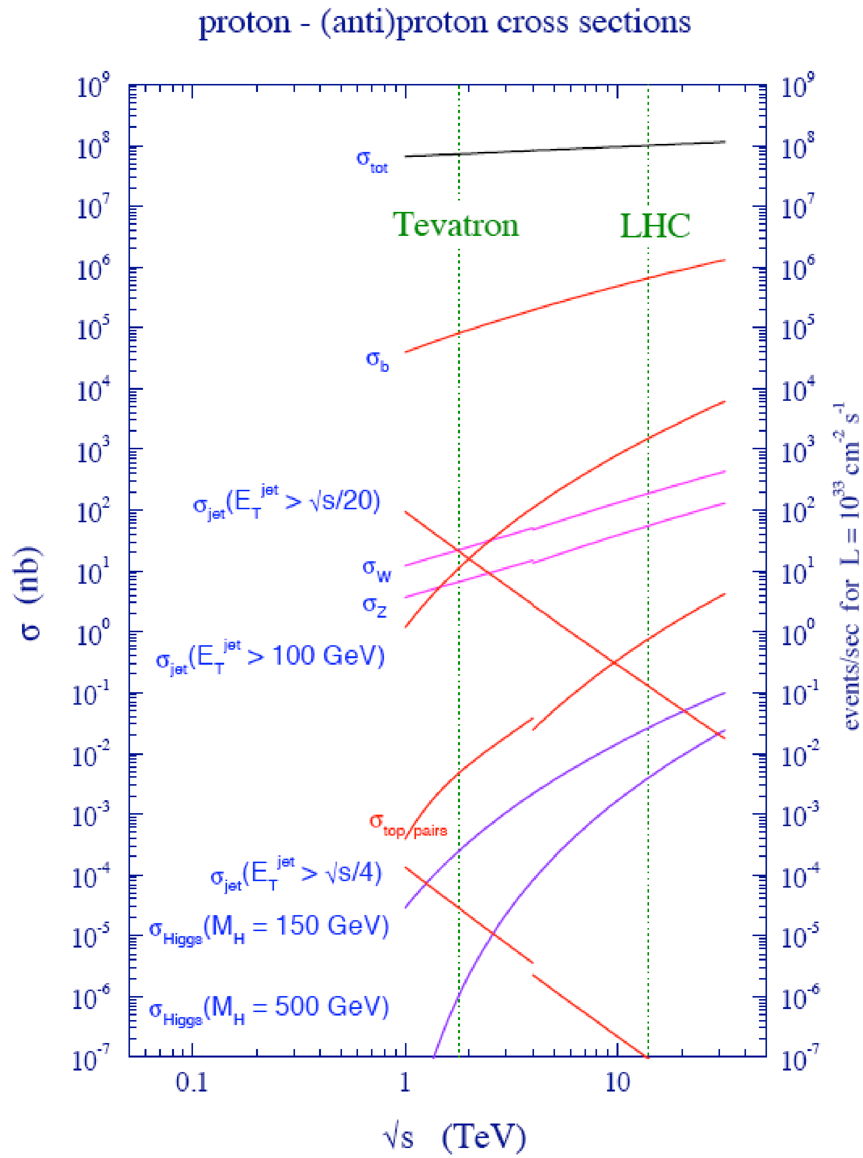

✓ Calorimeters:
central, wall, plug
coverage: $|\eta|<3.6$ CDF
$|\eta|<4.2$ D0

✓ Tracking: silicon tracker + drift chamber (CDF) $|\eta|<2$
scint(D0) $|\eta|<3$



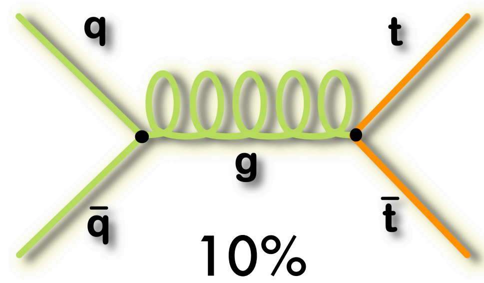

✓ Muon coverage $|\eta|<2$

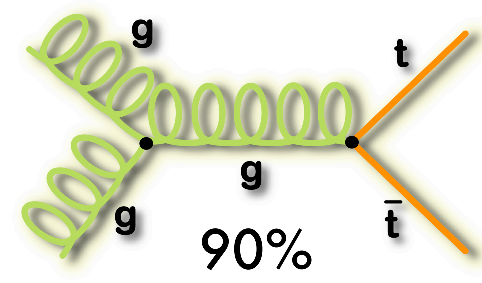
# Production cross-sections



# Top production at the Tevatron

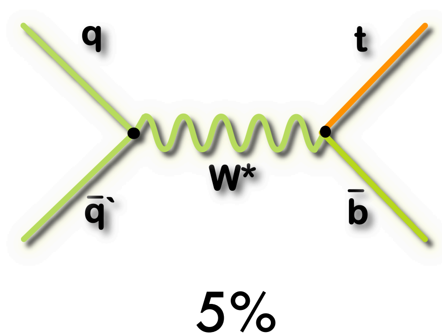
Top quarks at the LHC are produced either through QCD interaction with a cross section of approximately 800pb* and relatively striking final states

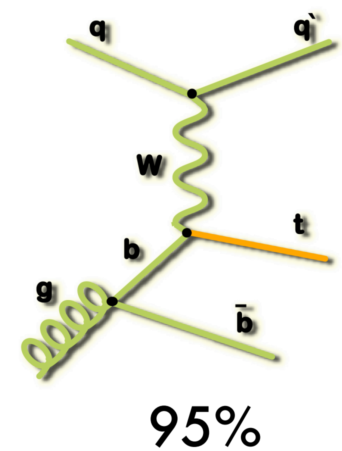



* Assuming Mtop=175

Or through electroweak interaction with a cross section of ~100 pb* but final state similar to many SM processes!



# The Mtop/JES measurement

Step 1: Kinematically reconstruct the events to build the observbles most sensitive to Mtop and JES

$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \frac{\left(m_{jjb}^{(2)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2}$$

Step 2: parametrize Mtop templates (varying top masses) with a smooth function

Step 3: feed an unbinned, extended likelihood to be maximize as a function of Mtop, JES, number of signal and background events

$$\mathcal{L} = \mathcal{L}_{1\,tag} \times \mathcal{L}_{2\,tags} \times \mathcal{L}_{\mathrm{JES}_{constr}}$$

$$\mathcal{L}_{M_{top}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_t^{rec}}(m_{t,\,i}\,|\,M_{top}, \mathrm{JES}) + n_b \cdot P_{bkd}^{m_t^{rec}}(m_{t,\,i})}{n_s + n_b}$$

$$\mathcal{L}_{1,2\,tags} = \mathcal{L}_{M_{top}} \times \mathcal{L}_{\mathrm{JES}} \times \mathcal{L}_{poiss} \times \mathcal{L}_{N_{constr}^{bkg}}$$

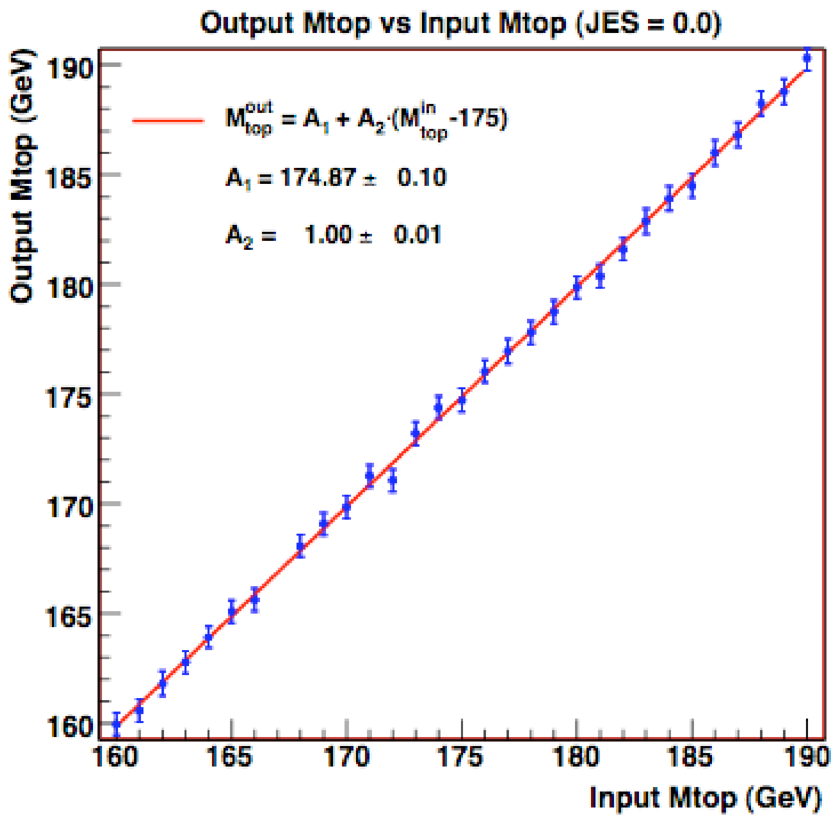
$$\mathcal{L}_{\mathrm{JES}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_W^{rec}}(m_{W,\,i}\,|\,M_{top}, \mathrm{JES}) + n_b \cdot P_{bkd}^{m_W^{rec}}(m_{W,\,i})}{n_s + n_b}$$

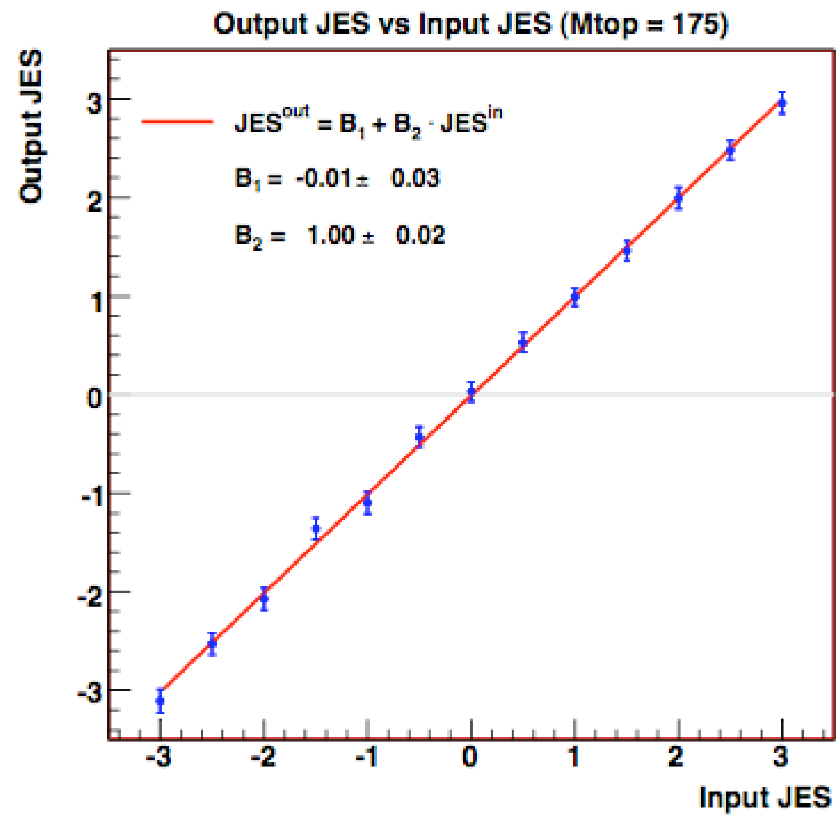
$$\mathcal{L}_{\mathrm{JES}_{constr}} = e^{-\frac{(\mathrm{JES} - \mathrm{JES}_{constr})^2}{2\sigma^2_{\mathrm{JES}_{constr}}}}$$

$$\mathcal{L}_{poiss} = \frac{e^{-(n_s+n_b)} \cdot (n_s+n_b)^{N_{obs}}}{N_{obs}!}$$

$$\mathcal{L}_{N_{constr}^{bkg}} = e^{-\frac{(n_b - n_{(b,\,exp)})^2}{2\sigma^2_{n(b,\,exp)}}}$$

# Calibration



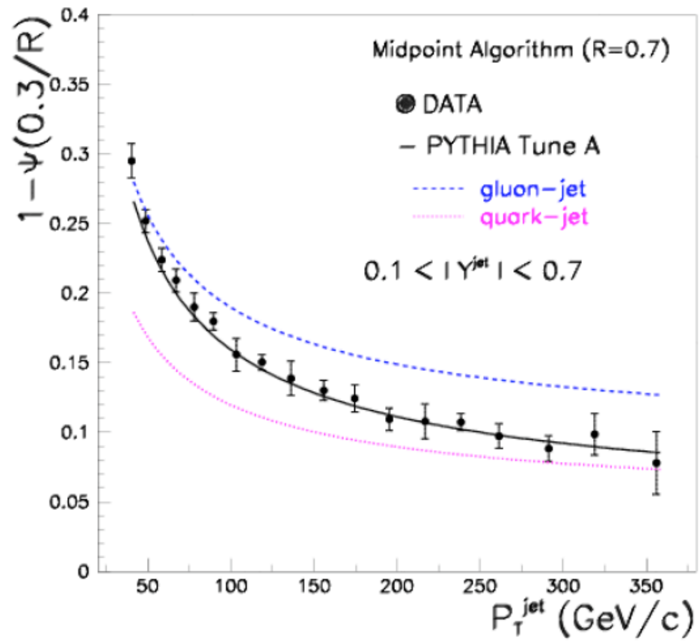



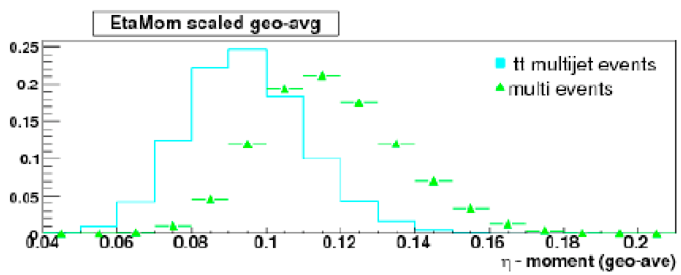
# $M_{top}$ Systematics

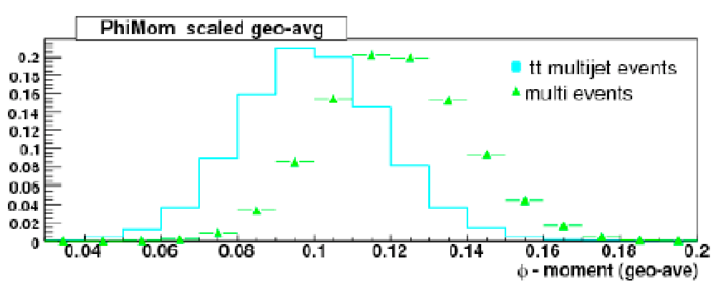
| Source | $\delta M_{top}^{syst}$ (GeV/$c^2$) | $\delta JES^{syst}$ | |
|---|---|---|---|
| Residual bias | 0.32 | 0.06 | |
| 2D calibration | 0.03 | 0.01 | |
| Generator | 0.48 | 0.26 | |
| ISR/FSR | 0.31 | 0.10 | |
| Background templates | 1.03 | 0.16 | Will scale w 1/√L |
| Signal templates | 0.26 | 0.05 | |
| $b$-jets energy scale | 0.55 | 0.09 | |
| SF $E_T$ dependence | 0.35 | 0.05 | |
| Residual JES | 0.80 | – | |
| PDF | 0.41 | 0.11 | |
| $m_t^{rec}/m_W^{rec}$ correlations | 0.21 | 0.00 | |
| Pileup | 0.28 | 0.03 | |
| Total | 1.70 | 0.36 | |

# Using jet shapes

- After using NN with 11 variables and b-tag S/B still < 1
- Need unused variables
- Quark-jets are known to be (on average) narrower than gluon-jets
  - Both get narrower as Et increases



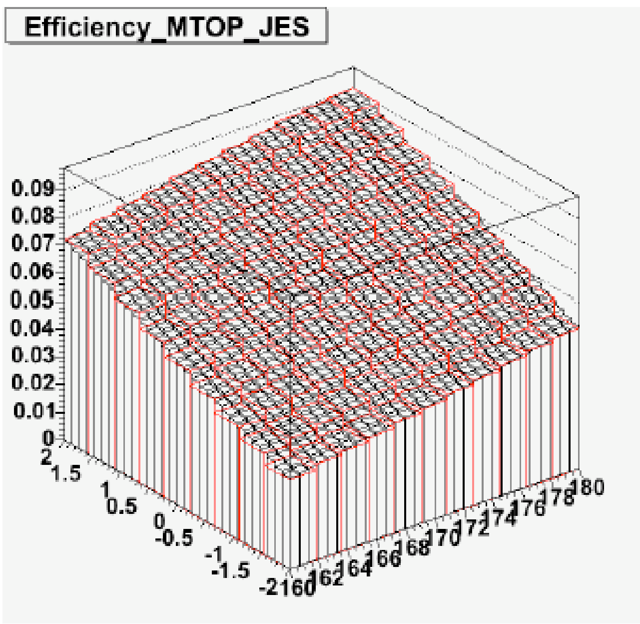




- Jet shapes orthogonal information to the ones in the NN
- Feed the NN with this additional variables
- Potential up top x2 improvement in S/B (with roughly same efficiency)

# Using in situ JES calibration for $\sigma_{tt}$

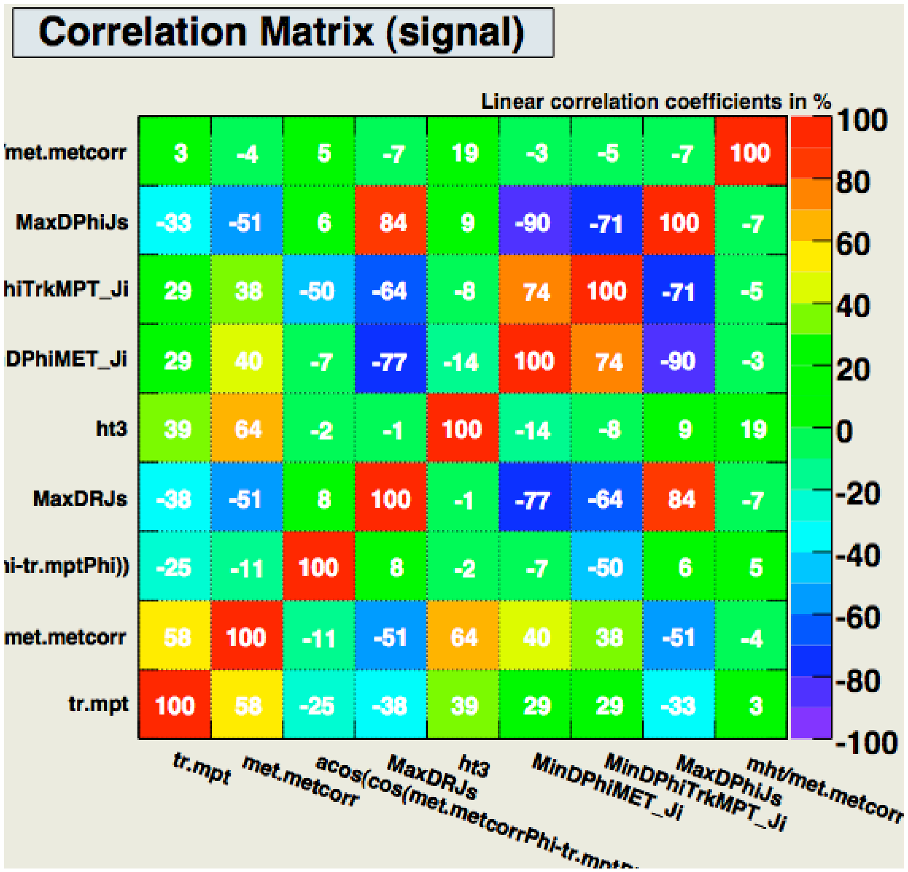
- Problem: Previous cross section measurement of $\sigma_{tt}$ in the all-hadronic channel was limited by JES
- Solution: use in situ JES calibration to reduce systematics!

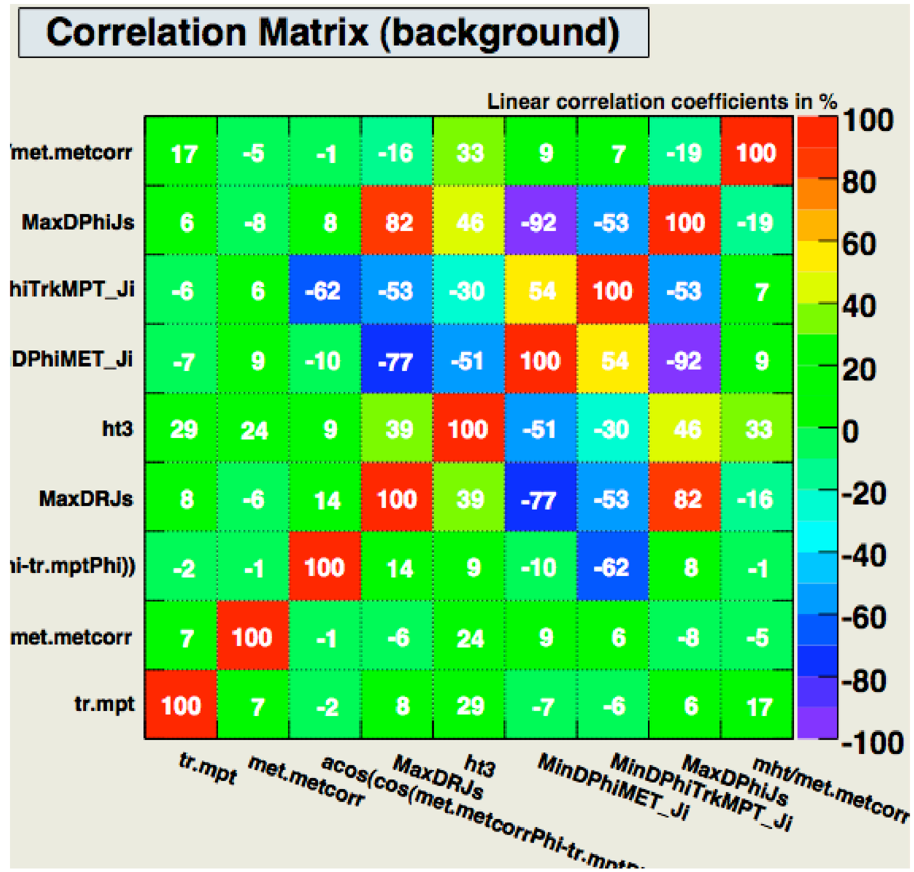
$$L_{sample} = e^{-\frac{(n_b - N_b)^2}{2\sigma^2_{N_b}}} \cdot e^{-\frac{(n_b + n_s - N)^2}{2\sigma^2_N}} \cdot \prod_{i=1}^{N} \frac{n_b P_b(m_i^{jjj}) + n_s P_s(m_i^{jjj}|M_{top}.JES)}{n_b + n_s} \cdot \prod_{i=1}^{N} \frac{n_b P_b^W(m_i^{jj}) + n_s P_s^W(m_i^{jj}|M_{top}, JES)}{n_b + n_s}$$




- Parametrize the efficiency as a function of $M_{top}$ and JES
- Write $n_s = \sigma$ x L x $\epsilon(M_{top}, JES)$
- Measure simultaneously $M_{top}$ JES and $\sigma_{tt}$ (allow correlations)

# Correlation for QCDNN

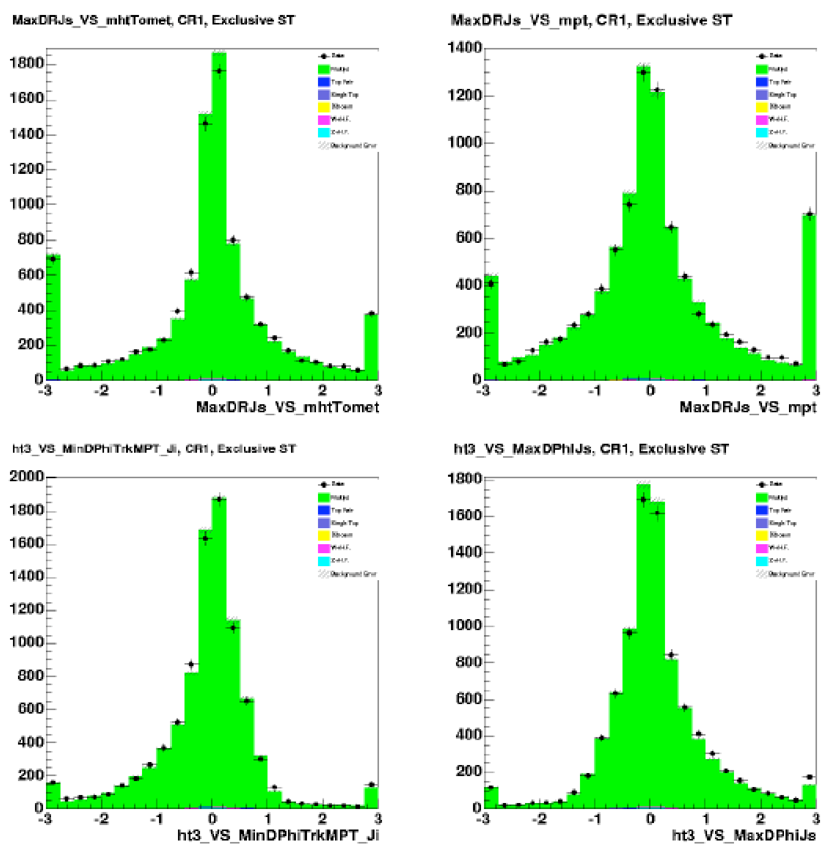


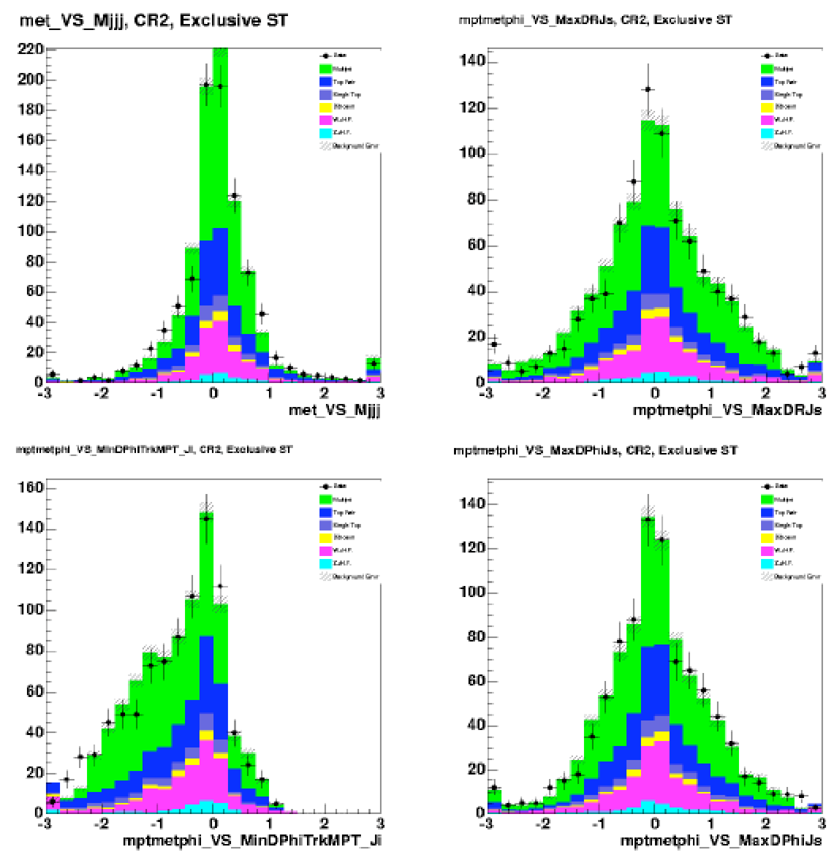

- Neural networks allow easy exploitation of the different correlations in S/B between input variables
- Correlation pattern is indeed pretty different

# Correlations for QCDNN (2)

Check modeling of correlations $r_{XY} = \frac{(X_i - \overline{X})(Y_i - \overline{Y})}{\sigma_X \cdot \sigma_Y}$ between different observables

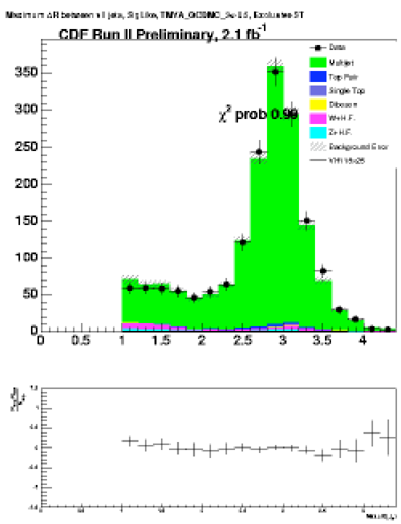


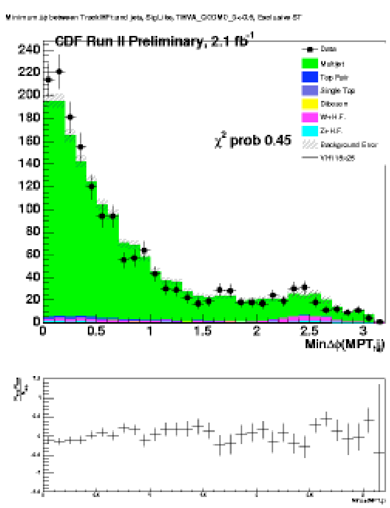

Data-driven QCD modeling



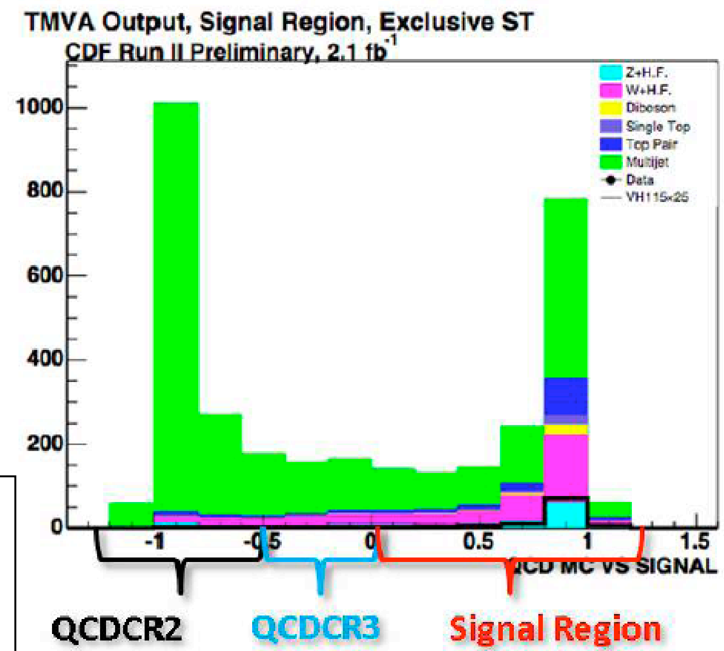

Monte Carlo modeling

# More on data-driven multijet model




Check QCD shapes, Extract normalization




Check QCD shapes AND normalization

**Look for signal!**

# Higher/lower sig samples

| Top | N signal evts | N bck events | S/√(S+B) |
|---|---|---|---|
| All | 608 | 2748 | 10.5 |
| 1Tag | 408 | 2410 | 7.7 |
| TT | 200 | 338 | 8.6 |
| Quadrature sum of three categories | | | 11.5 |

~10% improvement by splitting,
~20% improvement by including the low S/B region (1Tag)

~40% improvement by splitting,
~10% improvement by including the low S/B region (1Tag)

| Higgs | N signal evts | N bck events | S/√(S+B) |
|---|---|---|---|
| All | 7.7 | 1805 | 0.18 |
| 1Tag | 4.0 | 1550 | 0.10 |
| T+JEtProb | 1.8 | 150 | 0.15 |
| TT | 1.9 | 105 | 0.19 |
| Quadrature sum of three categories | | | 0.26 |

# Higgs MET+jets: 2/3 jets

| 2 jets | S | B | S/√(S+B) |
|---|---|---|---|
| All | 5.2 | 1160 | 0.15 |
| 1Tag | 2.6 | 1000 | 0.08 |
| TJ | 1.2 | 94 | 0.12 |
| TT | 1.4 | 66 | 0.17 |
| Quadrature sum of three categories | | | 0.23 |

| 3 jets | S | B | S/√(S+B) |
|---|---|---|---|
| All | 2.2 | 635 | 0.09 |
| 1Tag | 1.3 | 544 | 0.06 |
| TJ | 0.4 | 55 | 0.05 |
| TT | 0.5 | 37 | 0.08 |
| Quadrature sum of three categories | | | 0.11 |

$0.23^2+0.11^2=0.255$ vs $0.25$

i.e. negligible gain

| 2+3 jets | N signal evts | N bck events | S/√(S+B) |
|---|---|---|---|
| All | 7.7 | 1805 | 0.18 |
| 1Tag | 4.0 | 1550 | 0.10 |
| TJ | 1.8 | 150 | 0.15 |
| TT | 1.9 | 105 | 0.19 |
| Quadrature sum of three categories | | | 0.25 |

# Setting the limit

- Use Bayesian approach:
  - Bayesian $$L(R,\vec{s},\vec{b}|\vec{n},\vec{\theta})=\prod_{i=1}^{Nc}\prod_{j=1}^{Nbins}\mu_{ij}^{n_{ij}}e^{-\mu_{ij}}/n_{ij}!\times\prod_{k=1}^{n}e^{-\theta_k^2/2}$$

- If the excess is significant after combination, do more checks to make sure not statistic fluctuation.
- If no excess, set 95% CL upper limit vs mH

# CDF and D0

| Final state signature | | CDF | D0 |
|---|---|---|---|
| 115 GeV | $WH \to l\nu bb$ | 5.6 | 8.5 |
| | $VH \to$ Met + bb | 5.5 | 8.4 |
| | $ZH \to ll\ bb$ | 10 | 12 |
| | CDF gg, VBH, $VH \to \tau\tau jj$<br>D0 $H \to \gamma\gamma$ | 25 | 23 |
| | $VH \to qqbb$ | | |
| 160 Gev | $H \to WW^* \to l\nu l\nu$, | 1.6 | 1.9 |

# D0 Higgs combination