Higgs and beyond standard model searches at the Tevatron

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Tevatron
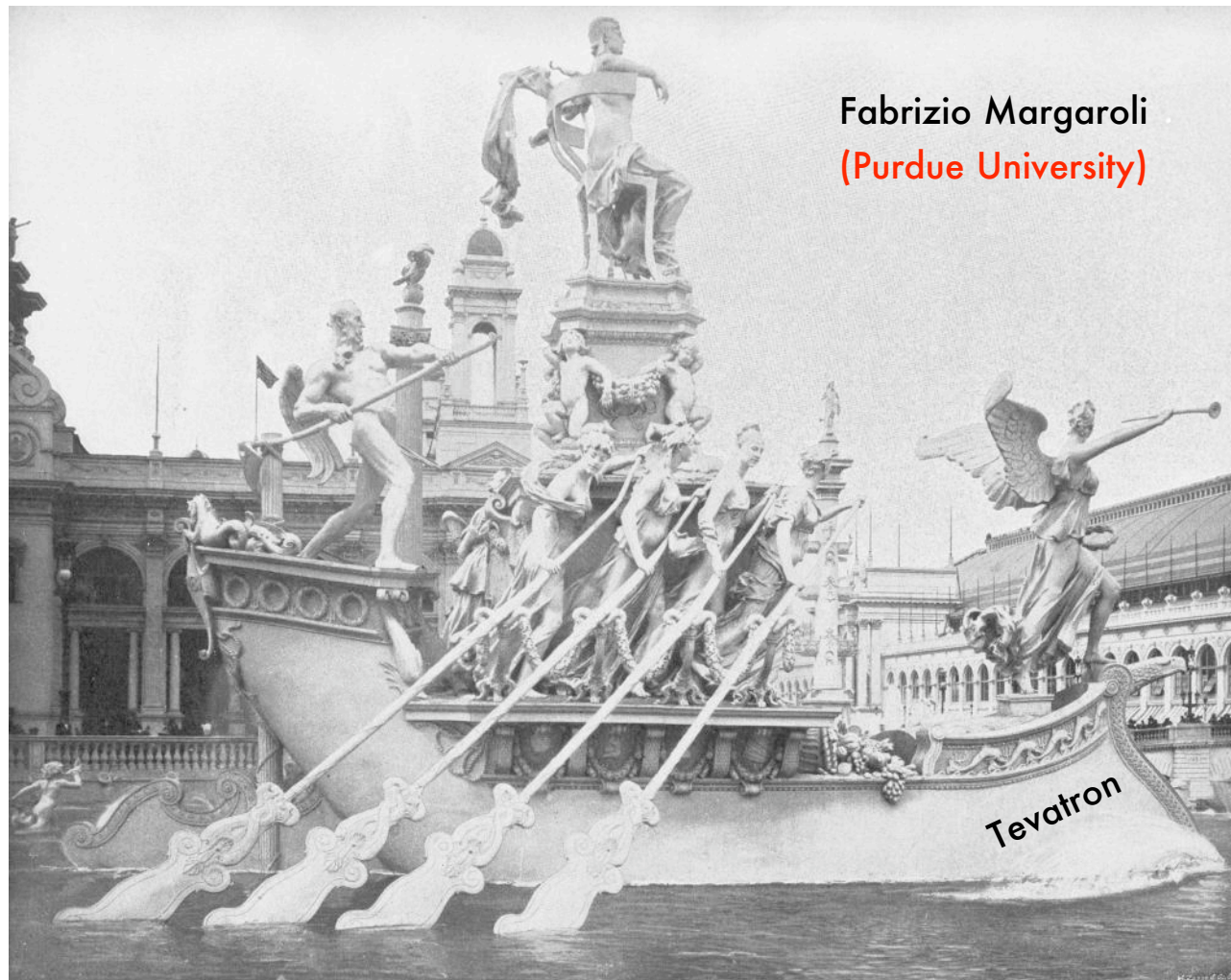
Photograph of the Columbian Fountain at the World's Columbian Exposition in Chicago

Outline

- **The open questions** (from an experimentalist point of view)
- **The roadmap to Higgs - and more!**
- **The tools of the trade**
- **The Higgs search**
- Beyond Standard Model searches
- Conclusions

The open questions

The mass

- In our day-to-day life we would hardly notice if quarks and leptons were massless
  - 99% of mass of things around us is binding energy (QCD): mass of a proton is 1 GeV while mass of three quarks that make it is roughly 10 MeV
- The world (lagrangian) where force carriers are massless is much more elegant than ours from theoretical point of view
- However, all fermions and weak bosons have masses too, ranging from $\sim 10^{-9}$ to 10^2 GeV. Putting masses into Lagrangian the theory breaks: looses gauge invariance and becomes un-renormalizable
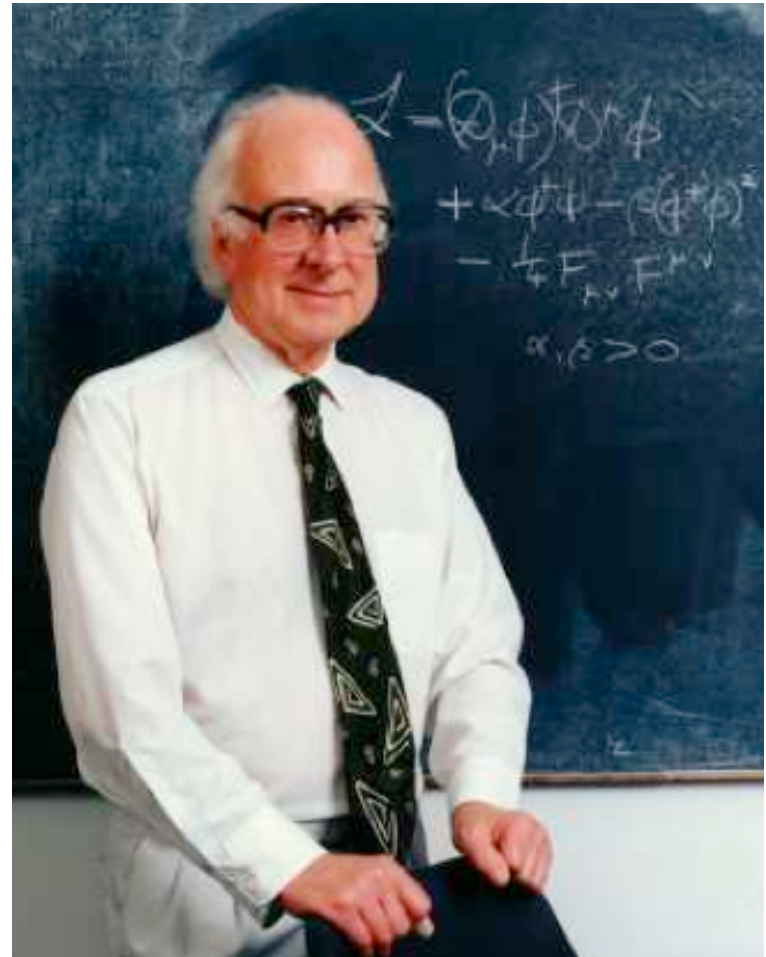
The Higgs mechanism

- Higgs Mechanism
- Separate piece of SM introduced by hand

  - Mass = Rest energy.
  - If we make particle interact with vacuum it will acquire additional energy: MASS
- In the Standard Model the vacuum is not empty: particles get mass from interaction with the Higgs field
- Electroweak symmetry breaking in the SM:
  - 1 complex Higgs scalar doublet (4 d.o.f.)
  - W^+, W^- and Z^0 get mass (three Higgs d.o.f. become longitudinal W/Z components)
  - Fermions get masses through special (Yukawa) coupling to Higgs
- One remaining observable Higgs boson
 - Hasn't been observed yet
  - can not hide much longer!
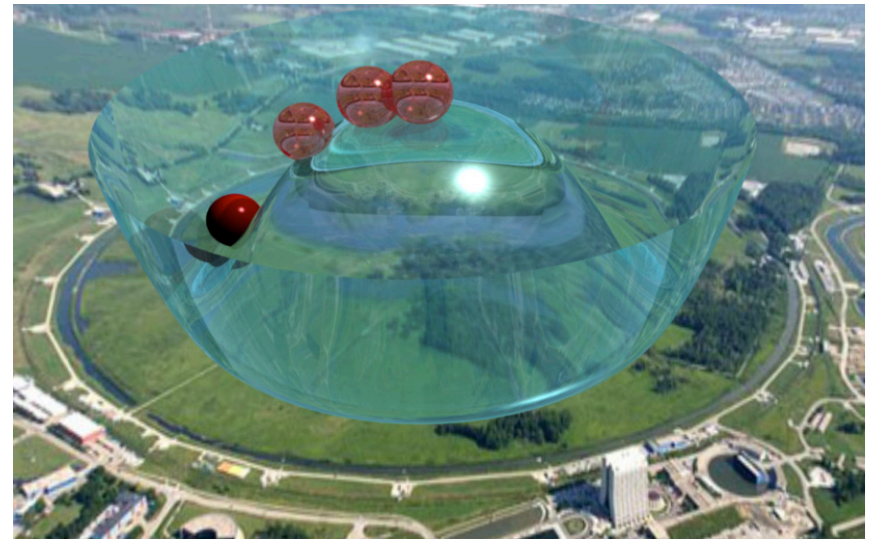
# Limitations of the Standard Model

- During the 80s, the Higgs discovery was thought to put a hat on a beautiful theory, and complete our knowledge.

- Then came dark matter - and dark energy - to tell that we're (possibly) missing much more…roughly 95% of the universe!

- Also, tons of theories predict plenty of new particles

- Experimentalists are guided by

  - Theory driven arguments: SUperSYmmetry (SUSY), technicolor, etc. etc.

  - Intuition/generalization: extra generation of quarks/leptons, heavy W' or Z' bosons

  - Instrumental capability arguments: use best existing machinery (the Tevatron since 2001) and tools, scan all possible range of masses and cross sections

Tevatron Experiments

- Fermilab's Tevatron Run II $p\bar{p}$ collider at 1.96 TeV, running since 2001. Currently performing very well:
  - 3.7·10^{32} cm^{-2} s^{-1} new record in instantaneous luminosity!
  - 1.5fb^{-1} acquired in Y08 - as much recorded by mid-09!
  - Two multi-purpose, well-understood detectors CDF and D0
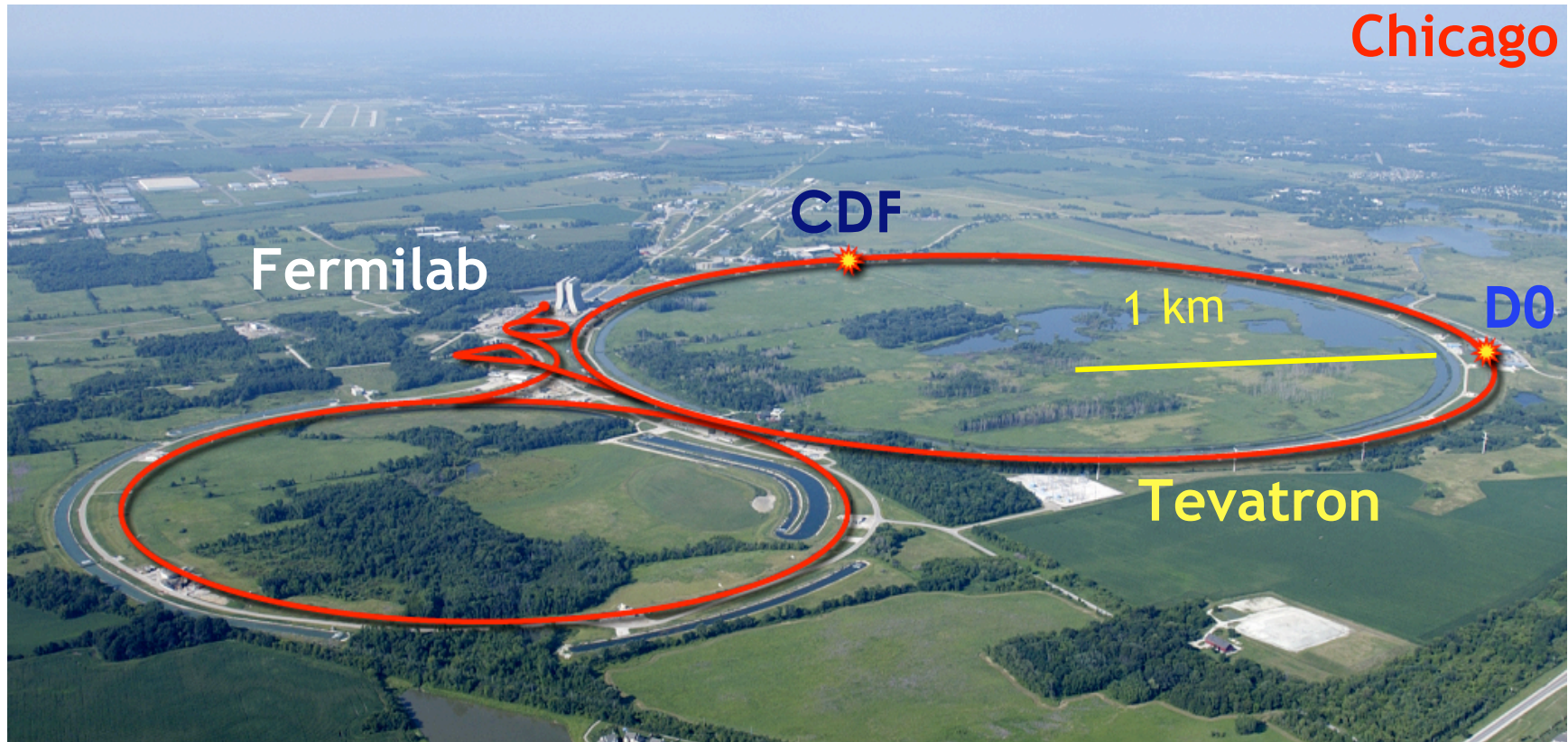
A long way ...
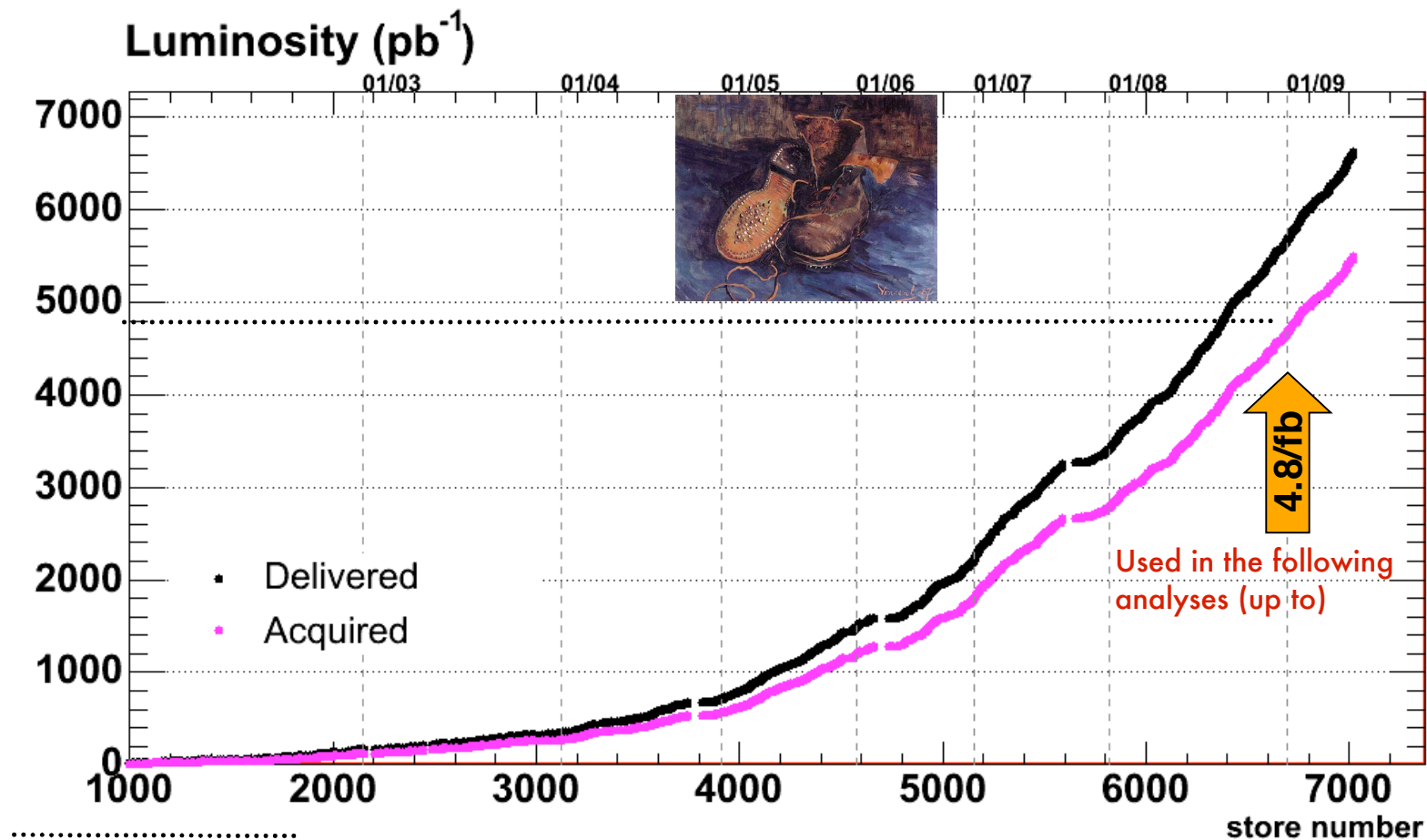
Delivered > 6.8 fb⁻¹
Acquired > 5.6 fb⁻¹ (5.1 fb⁻¹ w/ silicon)
Used here < 4.8 fb⁻¹ (4.2 fb⁻¹ w/silicon)

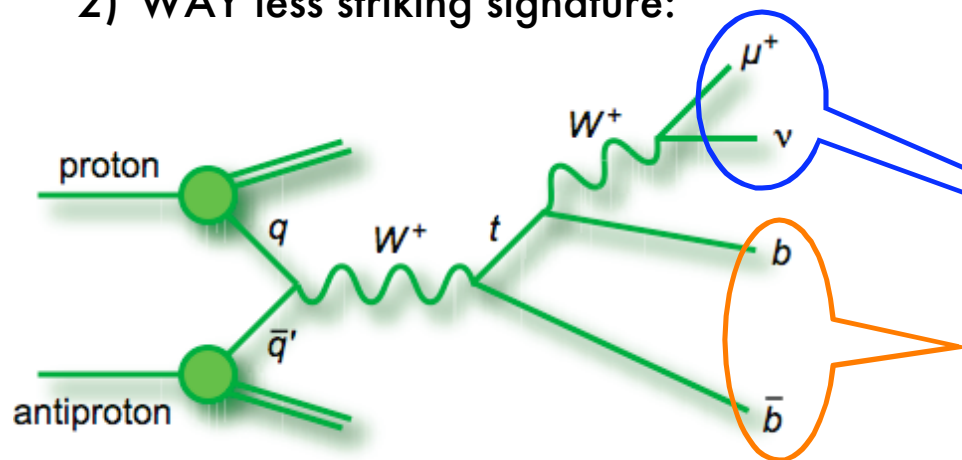# The roadmap to Higgs - and more!

The rarest SM processes: ttbar

- Tevatron collider is a discovery machine
  - Top quark discovered in ttbar events
  - All decay modes observed in RunI. In-depth understanding in RunII
  - ...
- Tevatron collider is also a precision machine
  - $\sigma_{t\bar{t}}$ known to 9%
  - M_{top} known to 0.75% (hep-ex/0903.2503)
- Striking signature → "easy" to reject backgrounds

$\sigma_{t\bar{t}} = 6.7\text{pb}^*$

*for $M_{top} = 175\text{GeV}$
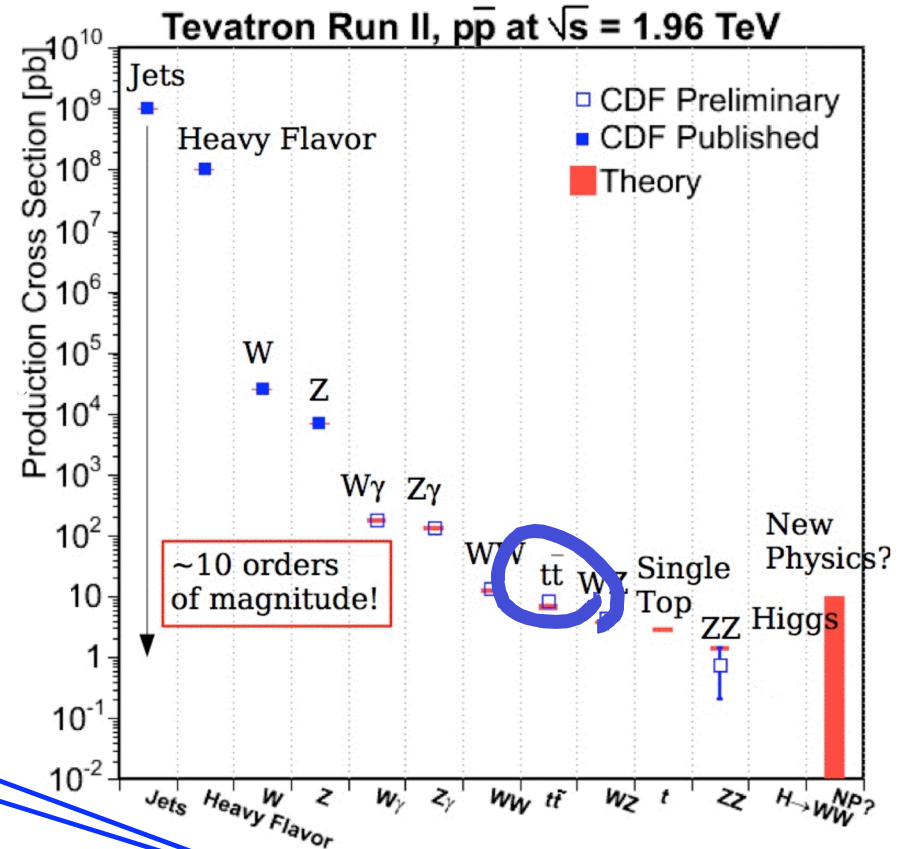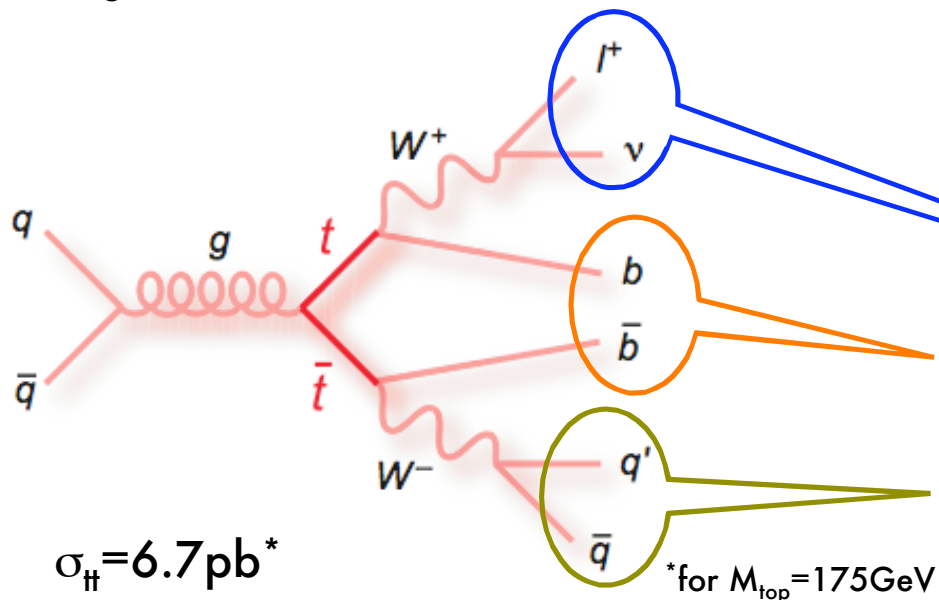
- b-jets and/or leptons ID reduces bck by many orders of magnitude
- High multipl. of objects in final state reduces W+jets/QCD bckd

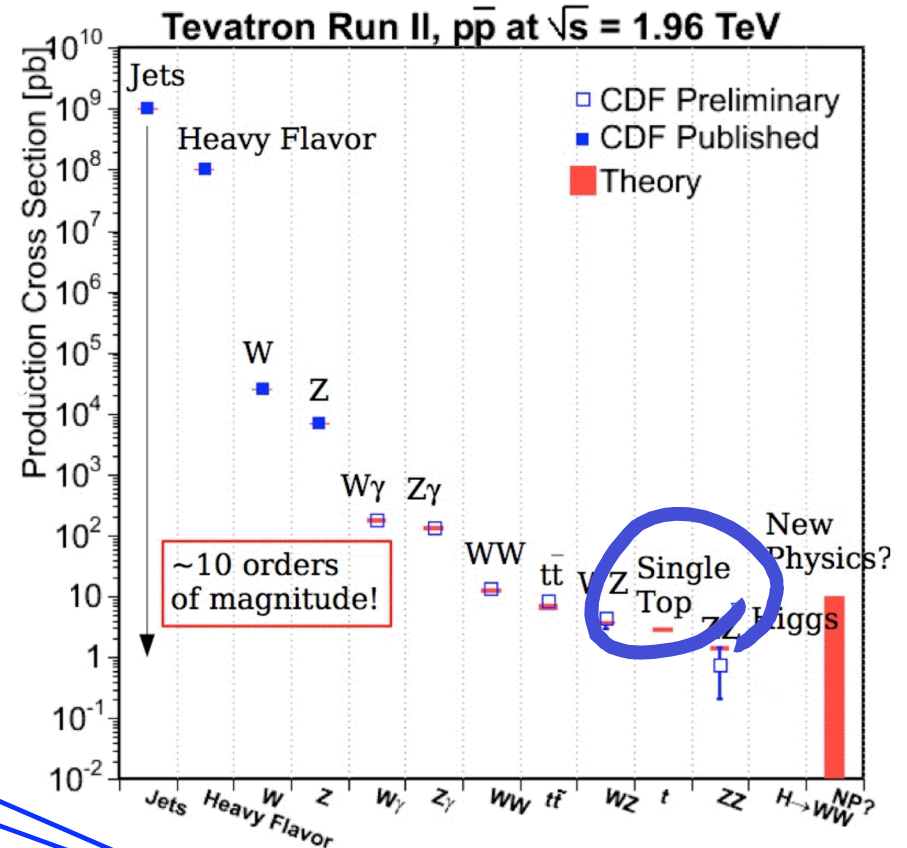# Then single top production

- Tevatron collider is a discovery machine
  - Top quark discovered in ttbar events
  - All decay modes observed in RunI. In-depth understanding in RunII
  - Discovery of single top quark production!
- Tevatron collider is also a precision machine
  - σ_{tt} known to 9%
  - M_{top} known to 0.75% (hep-ex/0903.2503)
- Why it took so long?
  1) Smaller cross section, and most of all
  2) WAY less striking signature:

Tevatron Run II, $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV

~10 orders of magnitude!
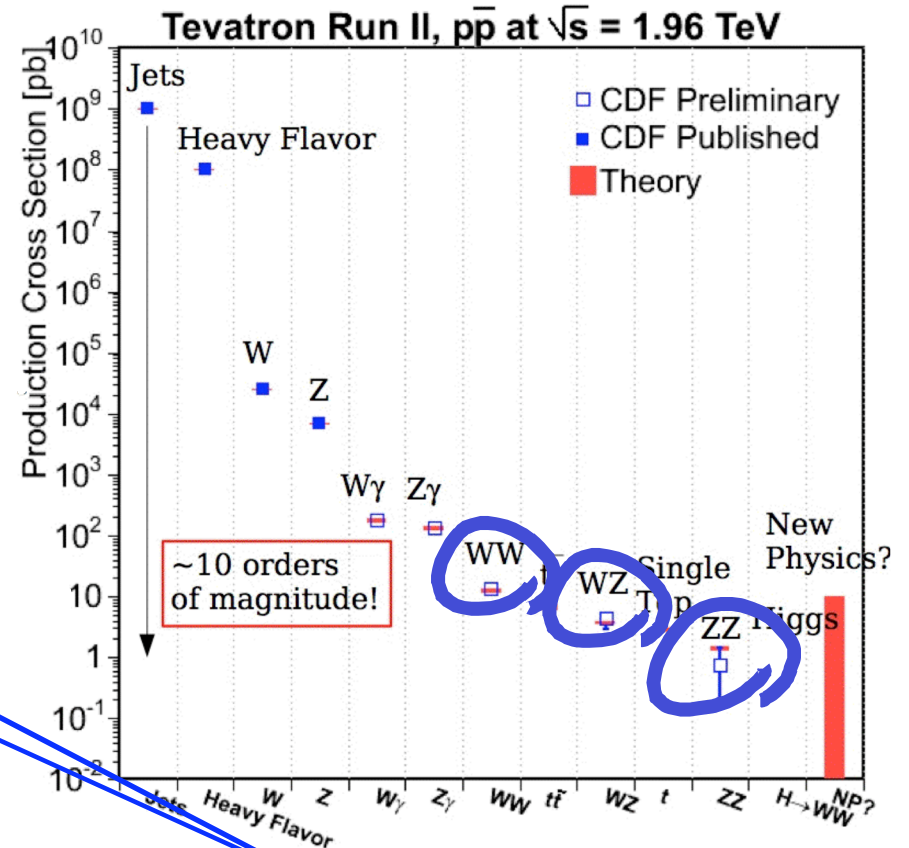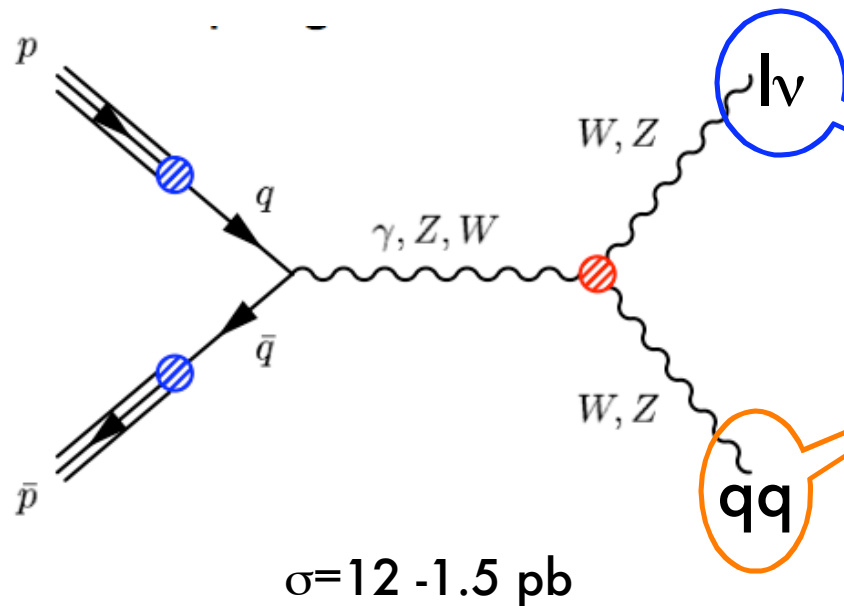
s-channel, σ=0.88pb*, t-channel, σ=1.98pb*
*for M_{top}=175GeV

- b-jets and/or leptons ID reduces bck by many orders of magnitude
- But W/Z+2 jets (and QCD) still high!

Diboson production
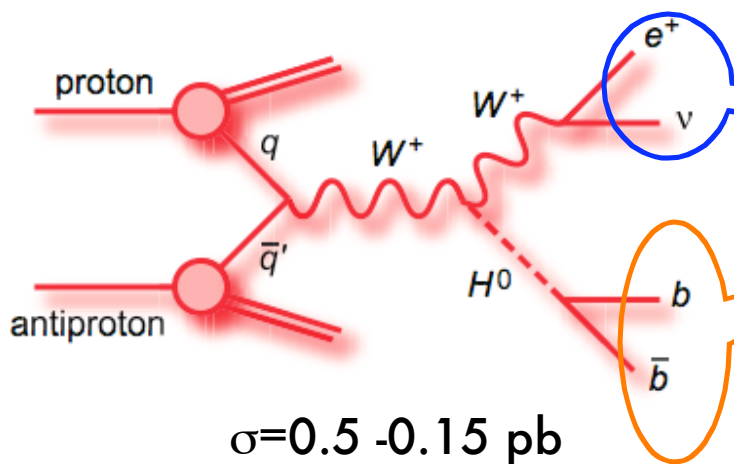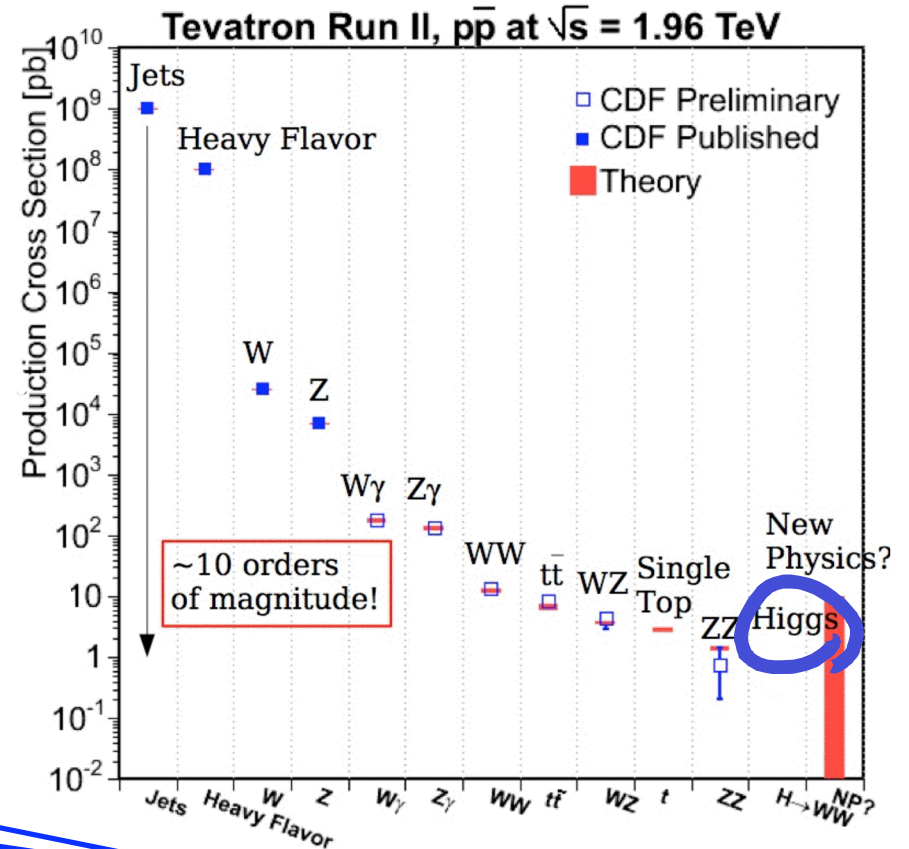
- Tevatron collider is a discovery machine
  - Top quark discovered in ttbar events
  - All decay modes observed in RunI. In-depth understanding in RunII
  - Discovery of single top quark production!
- Higgs is next goal; HW/HZ most likely production process
  - All dibosons WW/WZ/ZZ observed in all possible channels (b decays are comparable to Higgs though)

Tevatron Run II, $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

σ=12 -1.5 pb

- jets and/or leptons ID reduces bck by many orders of magnitude
- But W/Z+2 jets and QCD still high!

The Higgs search

- Tevatron collider is a discovery machine
  - Top quark discovered in ttbar events
  - All decay modes observed in RunI. In-depth understanding in RunII
  - Discovery of single top quark production
  - Observation of WW/WZ/ZZ
- Higgs mechanism gives mass to fundamental particles. Long sought by earlier experiments, latest limits from LEP and now Tevatron too

σ=0.5 -0.15 pb

- jets and/or leptons ID reduces bck by many orders of magnitude
- But W/Z+2 jets and QCD still high!
- And $\sigma_{HW} \sim 1/10 \ \sigma_{Singletop} \sim 1/10 \ \sigma_{Diboson}$

The beyond standard model search

- Tevatron collider is a discovery machine
  - Top quark discovered in ttbar events
  - All decay modes observed in RunI. In-depth understanding in RunII
  - Discovery of single top quark production
  - Observation of WW/WZ/ZZ
- Higgs mechanism gives mass to fundamental particles. Long sought by earlier experiments, latest limits from LEP and now Tevatron too
- And whatever else we can discover!
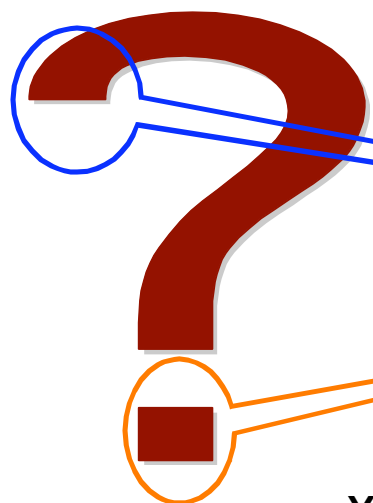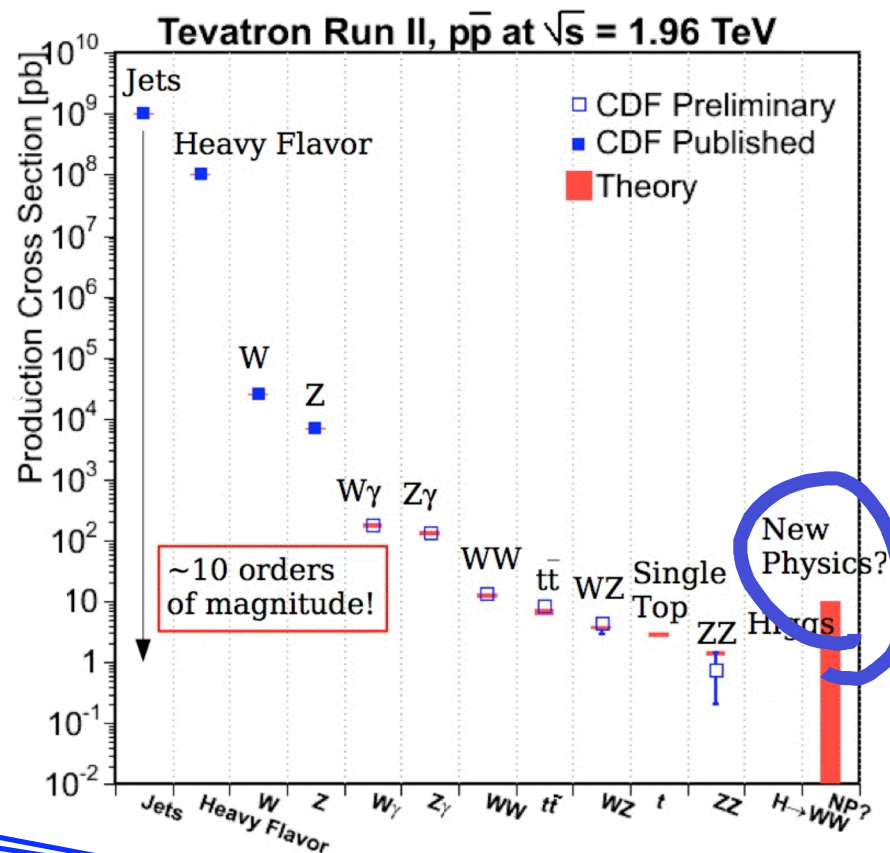
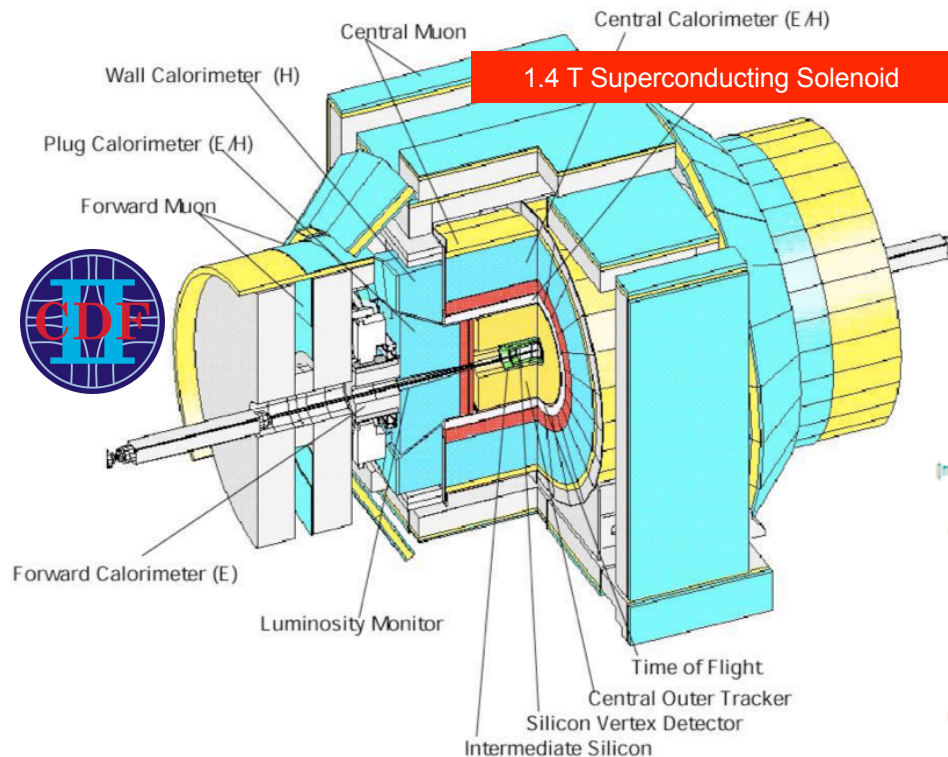$\sigma=$X.XX pb

- How often is it produced? Together with what? What does it decay to?
- So many theories on the market.....

Tevatron Run II, $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV

- □ CDF Preliminary
- ■ CDF Published
- ■ Theory

~10 orders of magnitude!

New Physics?

The tools of the trade

The detectors

Central Muon
Central Calorimeter (E/H)
1.4 T Superconducting Solenoid
Wall Calorimeter (H)
Plug Calorimeter (E/H)
Forward Muon
CDF
Forward Calorimeter (E)
Luminosity Monitor
Time of Flight
Central Outer Tracker
Silicon Vertex Detector
Intermediate Silicon

✓ Calorimeter split in EM and HAD devices. Shower maximum detector in EM cal

- coverage: $|\eta|<3.6$ CDF
  $|\eta|<4.2$ D0

2.0 T Superconducting Solenoid

Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
$\eta = 0$
$\eta = 1$
$\eta = 2$
$\eta = 3$

✓ Tracking: silicon tracker allows precision vertex detection $|\eta|<2$ (2.5) for CDF (D0) and spectrometer up to $|\eta|<1.5$ (3) for CDF (D0)

✓ Muon chamber outside calorimeter coverage $|\eta|<1.5$ (2.0) for CDF (D0)
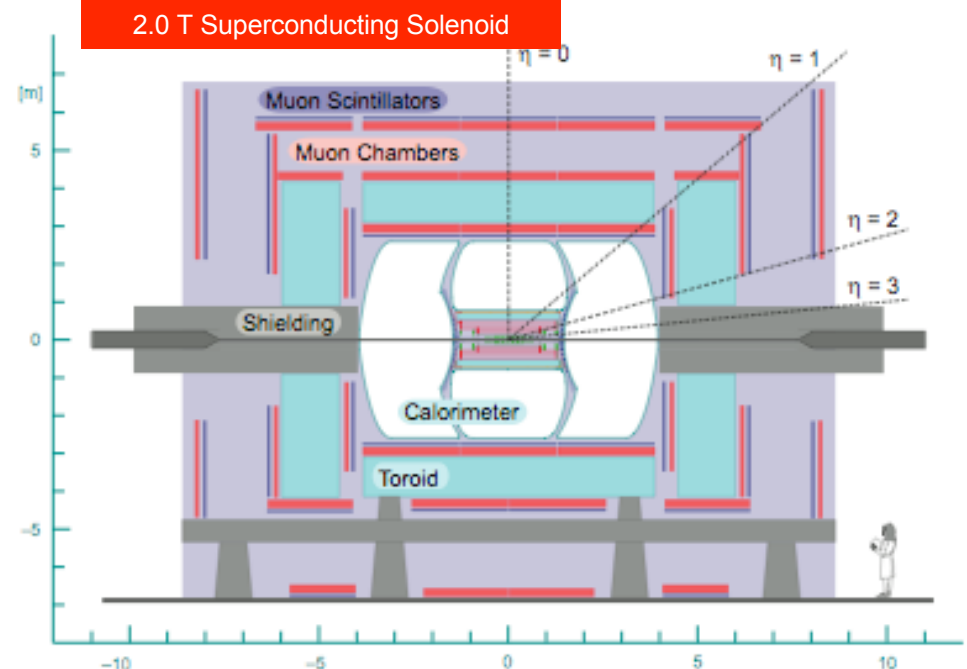
Quark/gluon ID

- Quark hadronize and produce particle jets
- Both exp. use cone based jet reconstruction algorithm. Loops over <u>calorimetric towers</u>
- Pros:
    - jet reconstruction efficiency is nearly 100%
    - Angular acceptance covers almost all solid angle
- Cons:
    - Jet energy resolution driven by had cal resolution $80\%/\sqrt{E_T}$
    - Jet energy scale known@~3%
    - Non-instrumented regions in calorimetry lead to underestimation of jet $E_T \rightarrow$ often source of energy imbalance in transverse plane

HAD

EM

Calorimeter jet

Particle jet

q

$\bar{p}$

p

Z, γ, $\bar{q}$
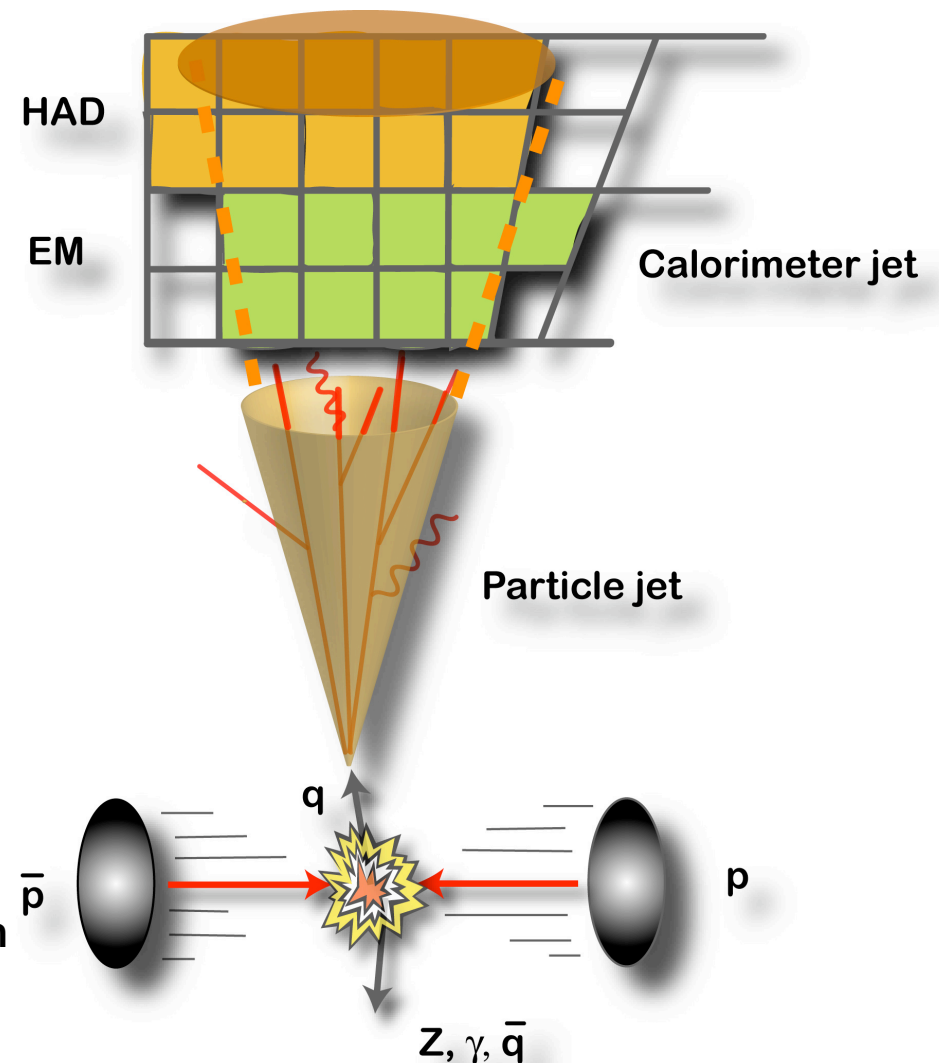
b-quark ID

✓ **SecVTX:** b-quark id'ed w long lifetime of the B mesons they form: identification through search of a secondary vertex within a jet:
 - b-tag eff: ~ 40%
  - fake rate ~ 0.5%
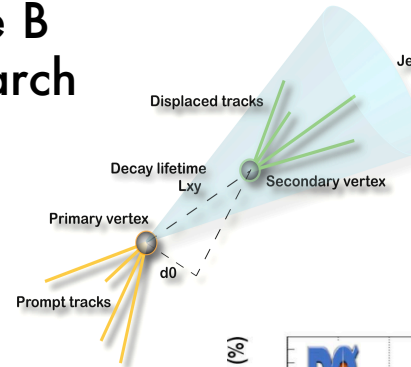
✓ **Neural Network** for flavor separation

  - L_{xy}, vertex mass, track multiplicity, impact parameter, semi-leptonic decay information

  - Replaces Yes-No tag decision by a continuous variable *(0<b<1)* (CDF) but

  - Can also decide working points (D0)
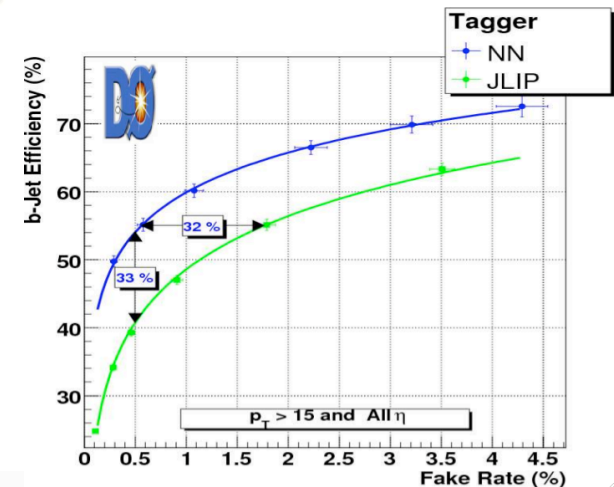
✓ **JetProb**: Jet probability algorithm: determines prob that the tracks within a jet are consistent with coming from the primary vertex
  - b-tag eff ~50%
  - fake rate~5%
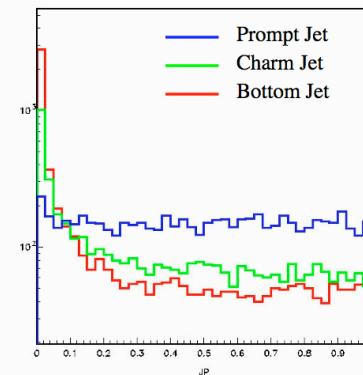
Charged lepton ID
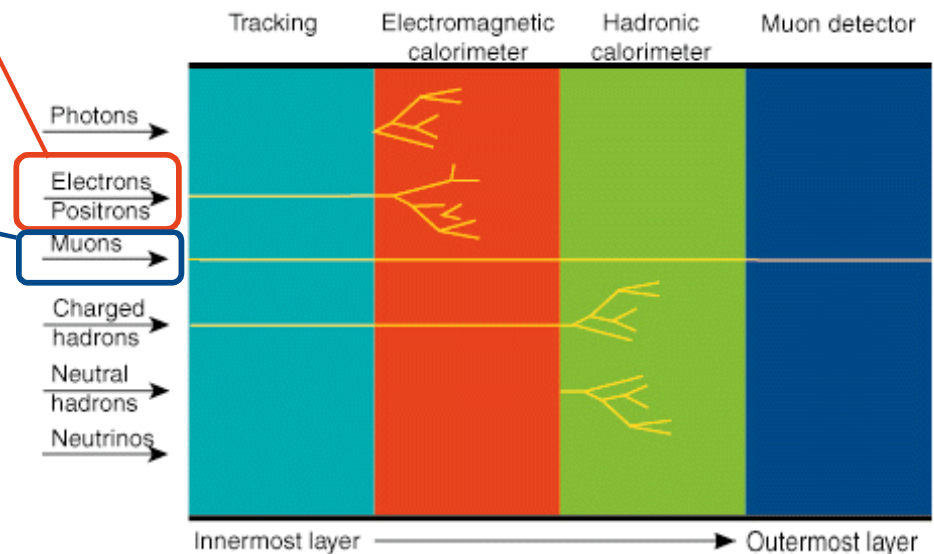
Electrons(positrons):

- matching between track and EM calo
- shower compatibility (reject π^0s)
- isolation (reject showers from quark)

Muons:

- matching track to muon chambers,
- isolated tracks otherwise

Taus:

- D0 uses <u>explicit</u> τ ID
- CDF (and sometime D0 too) accepts
    - $\tau \rightarrow$ *leptons* through μ,e and
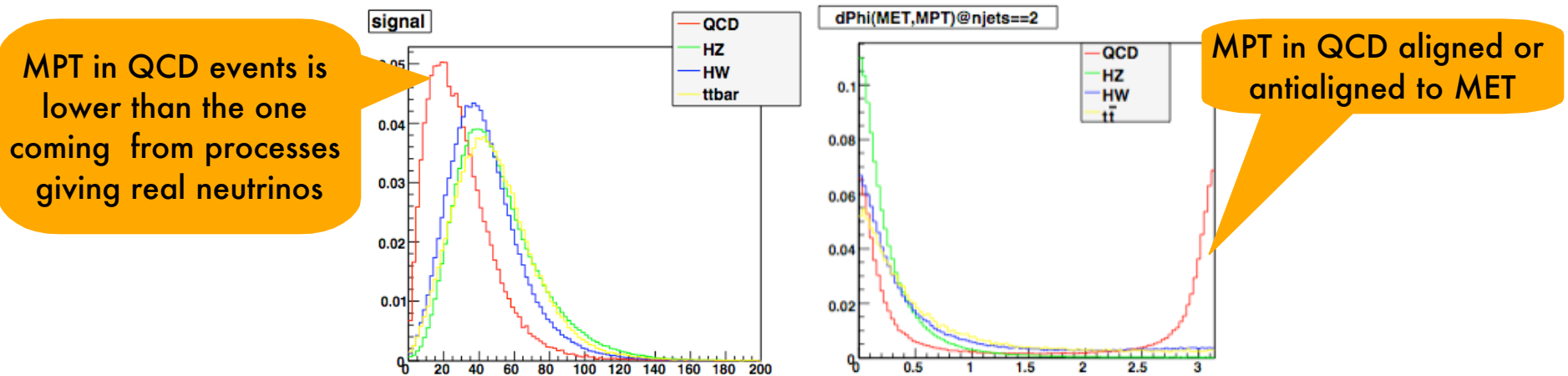   - $\tau \rightarrow$ *hadrons* through jets

Neutrino ID

Neutrinos:

- appear as energy flow imbalance in the transverse plane; measured using the missing transverse energy (MET) from calorimeter.

- Now using also the *momentum flow imbalance in the transverse plane* as measured from the *spectrometer*: the missing transverse momentum (MPT) *New!*
    - In presence of a neutrino MPT largely correlated to true neutrino energy/direction
    - For QCD events, MPT originates from fluctuations in the charged-to-neutral fraction of a jet energy flow

- -

Example: events triggered with MET>50 GeV, 2 high P_T jets

MPT in QCD events is lower than the one coming from processes giving real neutrinos

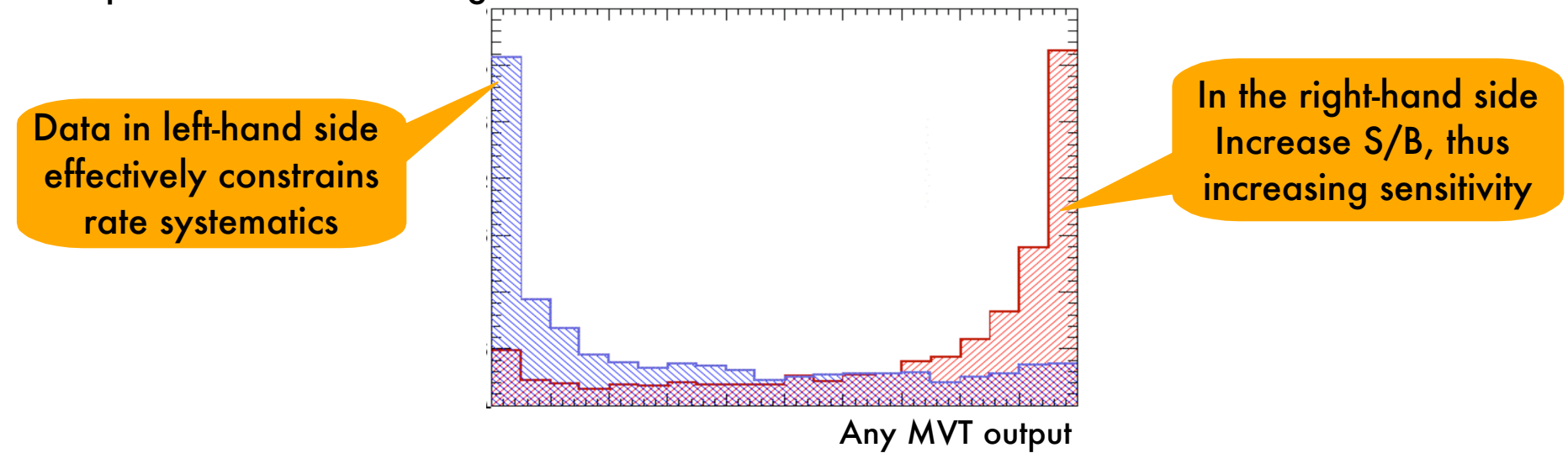MPT in QCD aligned or antialigned to MET

Multivariate techniques

- Small signal and large backgrounds with large background uncertainties: need to maximize the discrimination power

CDF and D0 use different classes of multivariate techniques (MVT):

- Physics oriented Use the full dynamics of the event through the knowledge of the *matrix element* of the process. Need to match final state observable particles to partons;

- 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). Exploit correlation among different observables.

Data in left-hand side effectively constrains rate systematics

In the right-hand side Increase S/B, thus increasing sensitivity

Any MVT output

Estabilished tt̄ from high to low S/B

Let's look at ttbar cross section measurements in different *samples*, with different *techniques*

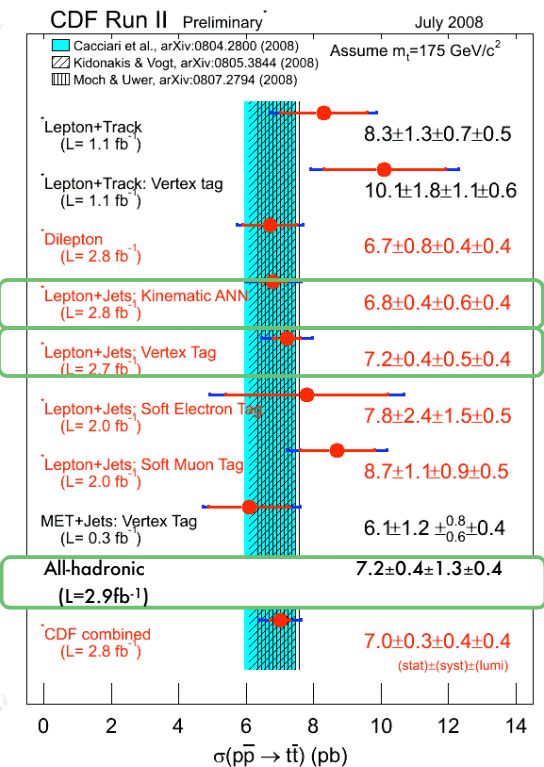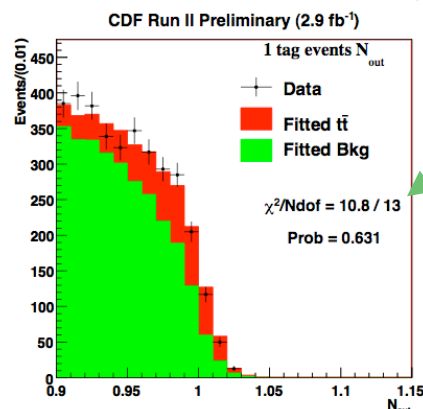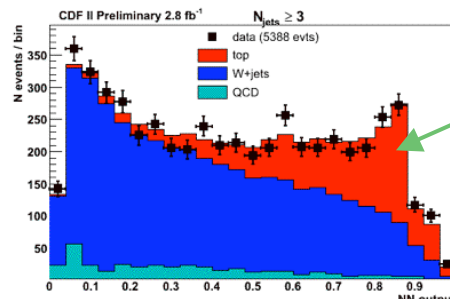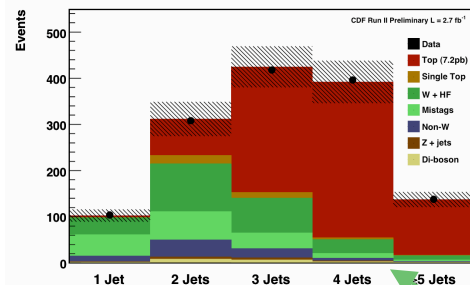**Semileptonic decays**, ID'ed final state particles, do counting experiment
- S/B~3/1

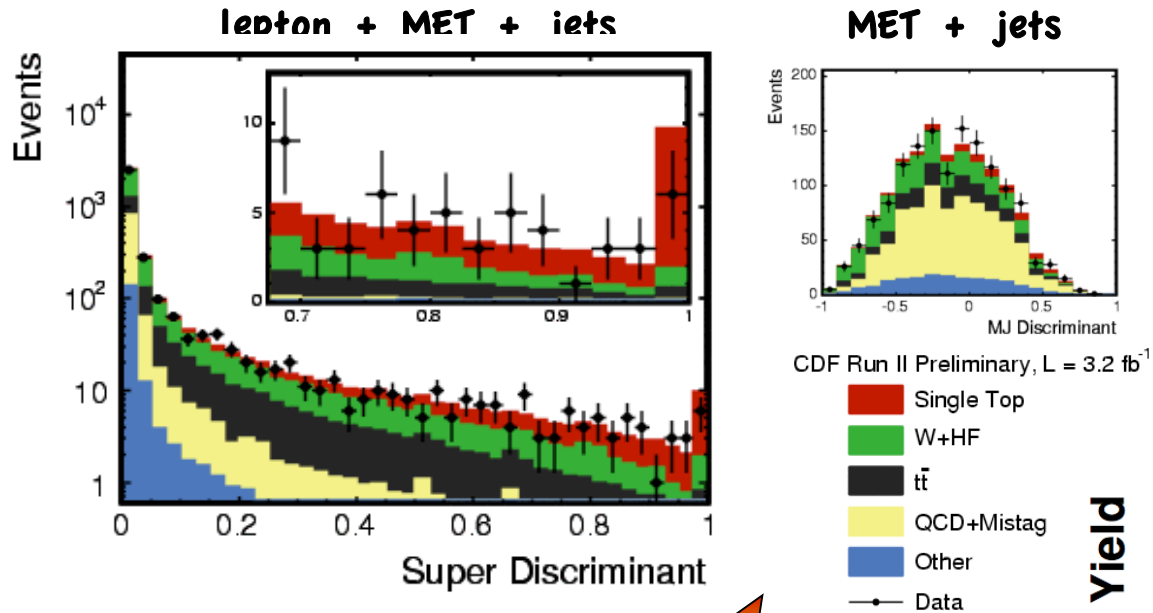**Semileptonic decays**, no b-tag, Likelihood fit to NN output
- S/B~1/5

All-hadronic, counting experiment after NN ev selection
- S/B ~1/100 before NN cut

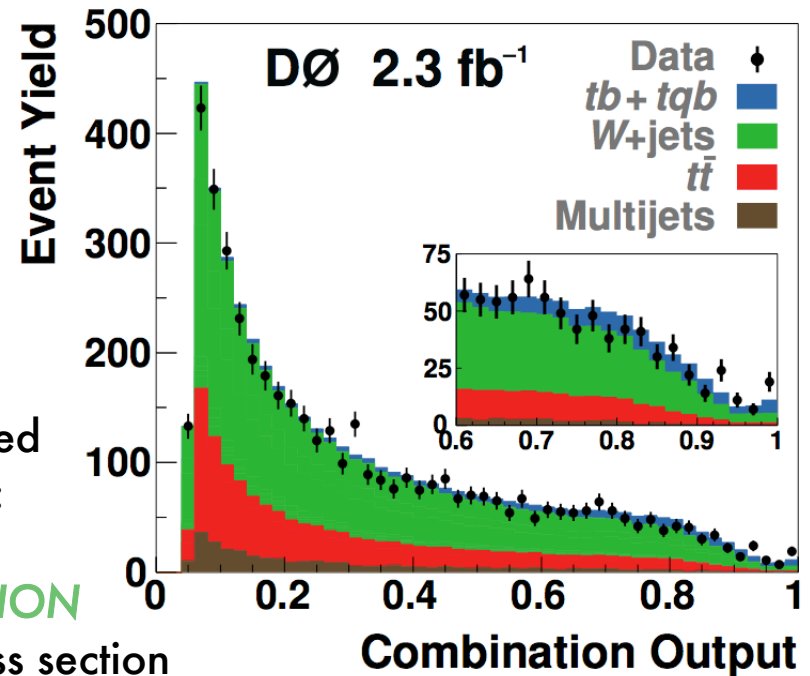They all agree with each other and SM prediction: bad S/B ratio can be handled

And top with even lower S/B!

lepton + MET + jets

MET + jets

Average S/B around 1/20, still….

5σ Observation!

CDF Run II Preliminary, L = 3.2 fb⁻¹

- Single Top
- W+HF
- tt̄
- QCD+Mistag
- Other
- Data

5σ Observation!

DØ 2.3 fb⁻¹
- Data
- tb + tqb
- W+jets
- tt̄
- Multijets

Few words about standards: excess of signal quantified in how likely a bckd fluctuation can mimick the signal:

3sigma → low prob O(10⁻³)   → *EVIDENCE*

5sigma → extremely low prob O(10⁻⁷) → *OBSERVATION*

Otherwise set 95%C.L. upper limit on production cross section

The Higgs search

Where to look

Constrains computed using fits to EWK parameters guided us toward the top quark discovery.

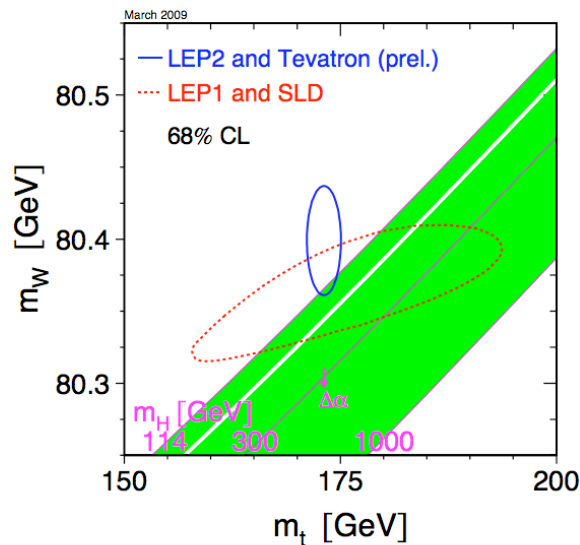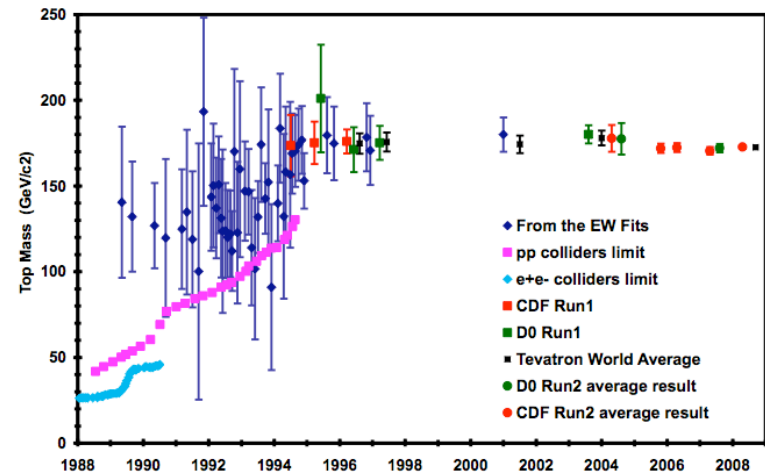We can now use in the same way the top quark mass and other parameters to point us to the Higgs! Tevatron's gave some very precise measurements:

m_{top} = 173.1 ± 1.3 GeV (arXiv:hep-ex/0903.2503v1)

m_W = 80.399 ± 0.025 GeV

which in the EWK fit give the following predictions
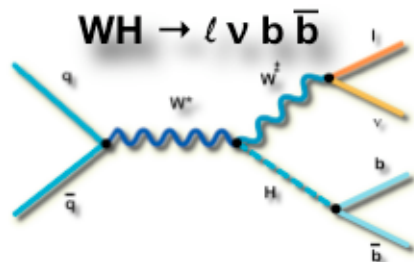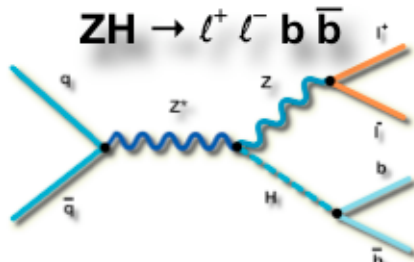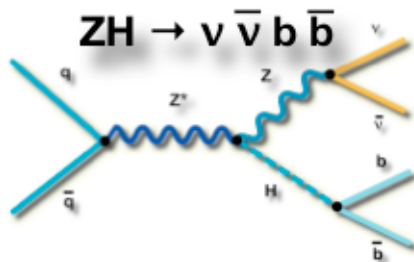
- m_H = 90+36-27 GeV   @ 68 % CL
- m_H < 163 GeV   @ 95 % CL

LEP directly searched the existence of the Higgs boson and found:

m_H > 114.4 GeV @ 95% CL
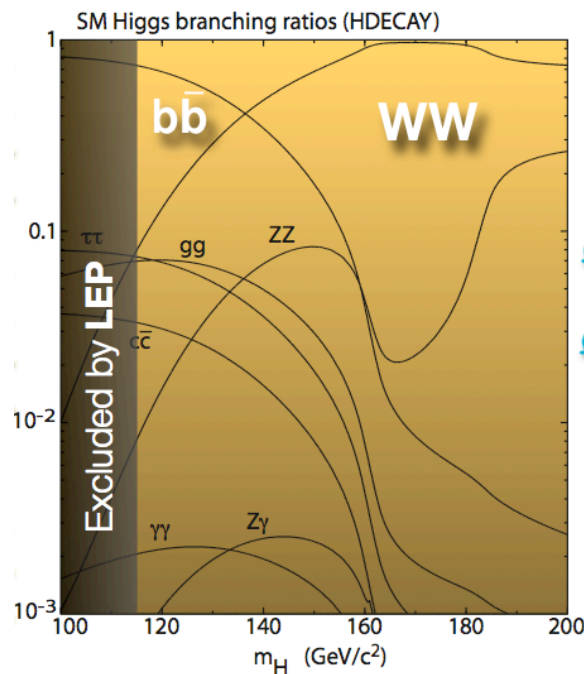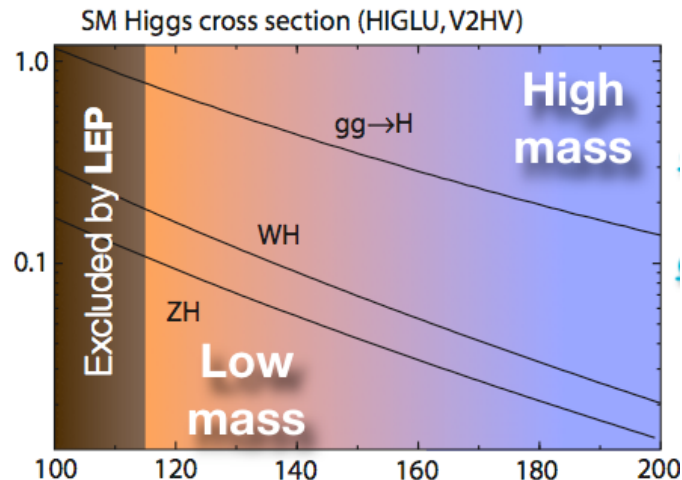
Mass is fundamental not only because it's a free parameter, but also because cross section and branching ratios depend on it!
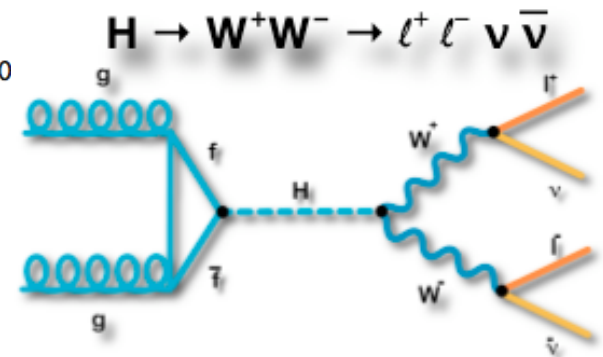
Where to look

ZH → ν ν̄ b b̄

ZH → ℓ⁺ ℓ⁻ b b̄

WH → ℓ ν b b̄

SM Higgs cross section (HIGLU, V2HV)

High mass

gg→H

WH

ZH

Excluded by LEP

Low mass

SM Higgs branching ratios (HDECAY)

bb̄   WW

ττ

gg   ZZ

cc̄

γγ   Zγ

Excluded by LEP

m_H (GeV/c²)

- $\sigma(H) \times BR(H \to bb) \sim 0.5\,pb$ at low mass
- But bbar final state overwhelmed by QCD

H → W⁺W⁻ → ℓ⁺ ℓ⁻ ν ν̄
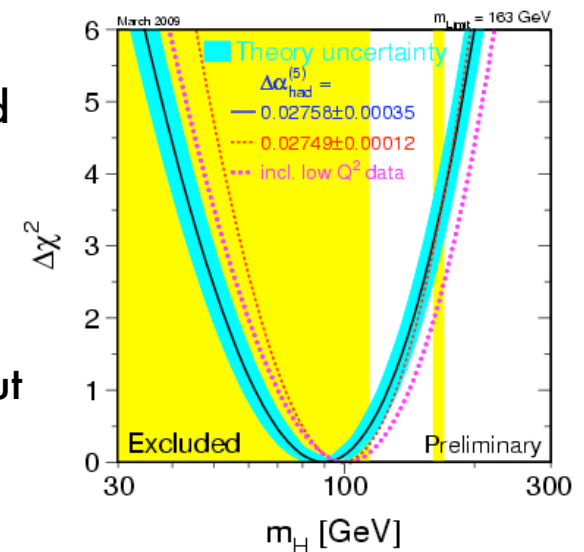
- $\sigma(VH) \times BR(H \to bb) \sim 0.1\,pb$ at low mass
- Presence of extra vector boson decays helps to reduce backgrounds

- $\sigma(H) \times BR(H \to WW) \sim 0.3\,pb$ at high mass
- But presence of charged and neutral leptons allows cleaner signature

Higgs search strategy

- Separate channels according to production mode, final state signature
- Analyze each channel separately to increase sensitivity
- Efficient triggers to keep most of potential Higgs candidates
  - **Dilepton + jets** Z→ll (**e** or μ); jets from H→bbar
  - **L + MET + jets**: **e** or μ to select leptonic decays of the W/Z, jets from H→bbar
  - **MET+Jets**: to select Z→νν decays, recover not identified μ; jets from H→bbar
  - **Dilepton + MET + X**: H → WW, HW → WWW

Caveat: if Higgs exist and is SM-like!

Events/fb^{-1}/exp	ZH → llbb (M$_H$=115)	WH→ lnubb (M$_H$=115)	VH→MET+bb (M$_H$=115)	ll +MET+X (M$_H$=165)
Signal produced	10	40	35	30
Signal accepted	2.5	4	3.5	5
Signal/Background	1/150	1/75	1/60	1/30

- The statistical significance of single channels **is not enough**
  - Combine **all the channels** within CDF and D0, and combine **CDF and D0 together!**
- <u>With 10fb^{-1}</u> the Tevatron will record **hundreds** of Higgs events, whatever the mass (<200GeV)

Dileptons+jets

$$ZH \to \ell^+\ell^- b\bar{b}, \ell = e, \mu$$

- Small acceptance but clean signature
- 2 high P_T (b-)jets, 2 high P_T leptons
- Fully reconstructed final state
- Dominant backgrounds:
  - Z+jets (irreducible Z+bb), top, dibosons
- Correct jet energies for MET from mismeasurement
  - Improve dijet mass resolution
- Likelihood scan of 2D ME+NN (HZ vs Z+jets, HZ vs ttbar) for CDF and 1D BDT for D0
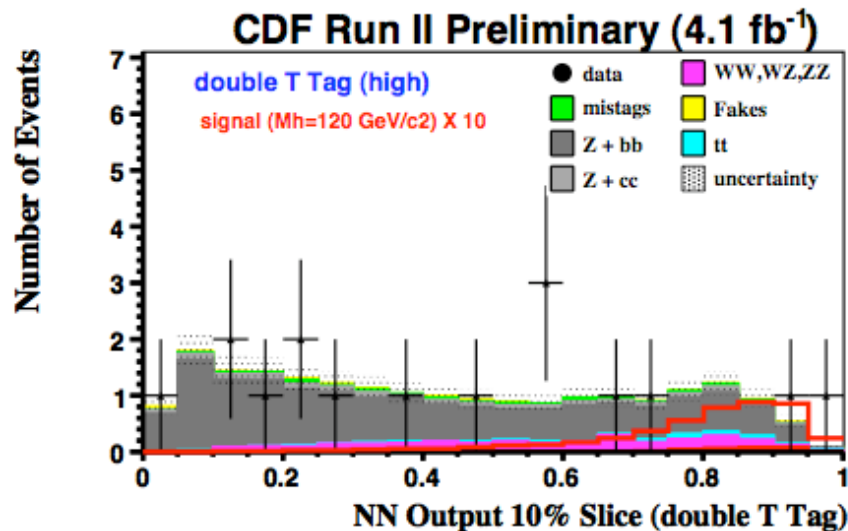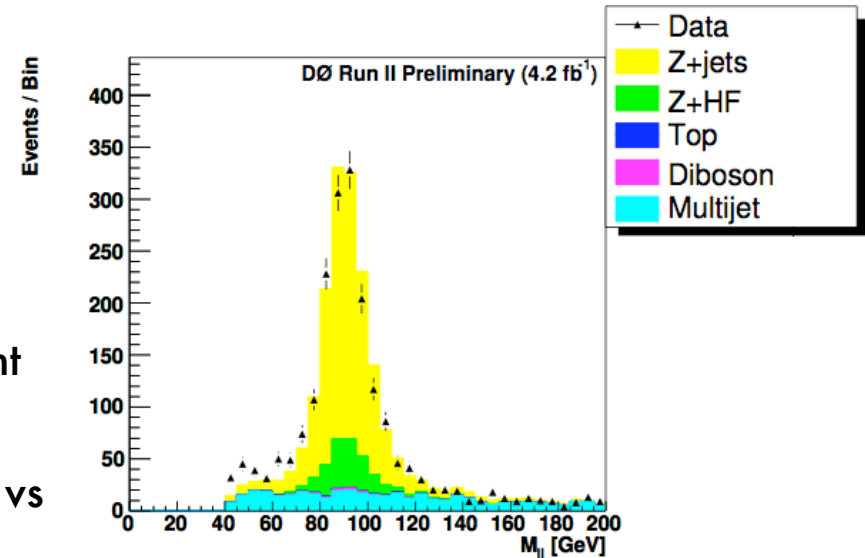
Exp	Lum (fb^{-1})	Higgs Events (@115)	Exp. Limit	Obs. Limit
CDF	4.1	2.1	6.8	5.9
DØ	4.2	3.1	8.0	9.1

Lepton+MET+jets $WH \to \ell \nu b\bar{b}, \ell = e, \mu$

- *"Large"* σ x Br, clean signature
  - Acceptance to about **3-4 events/fb^{-1}**
  - High P$_T$ leptons, MET and 2 high P$_T$ jets
- Dominant backgrounds:
  - **W+bb**, top, diboson, QCD multi-jet
- D0 uses NN, CDF uses ME and NN and combines the 2 different analyses using NN to enhance sensitivity ~15% better
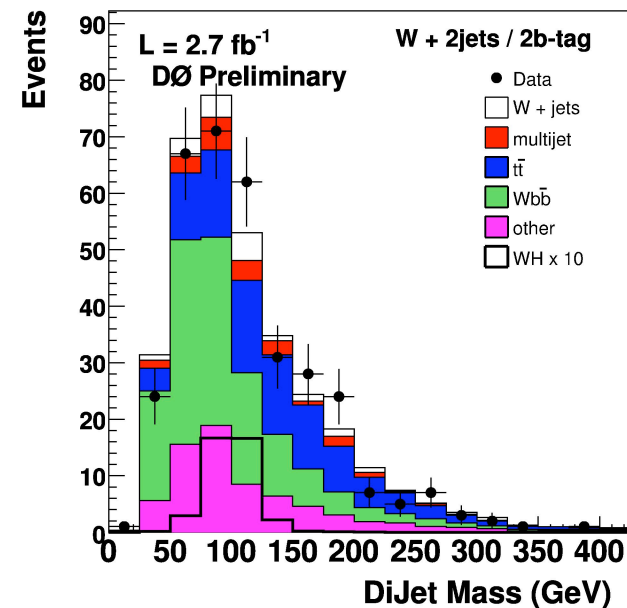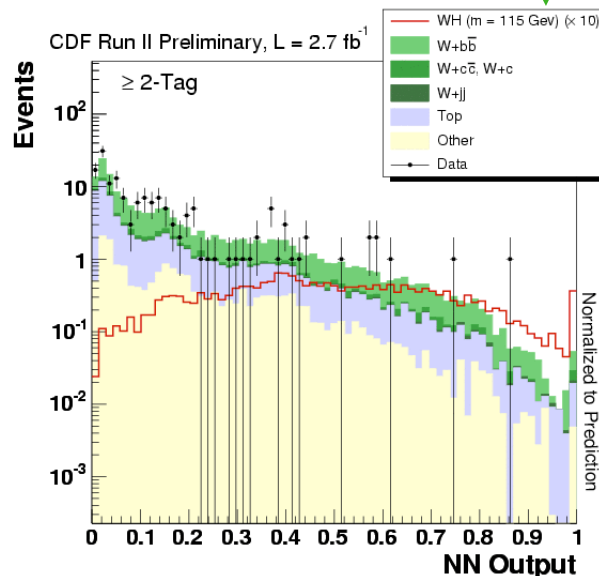
Same techniques used for single top observation

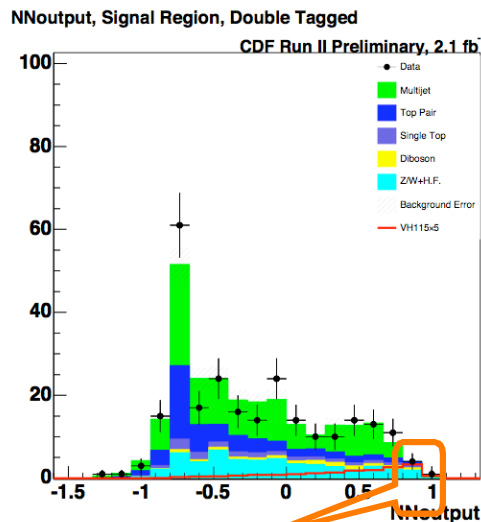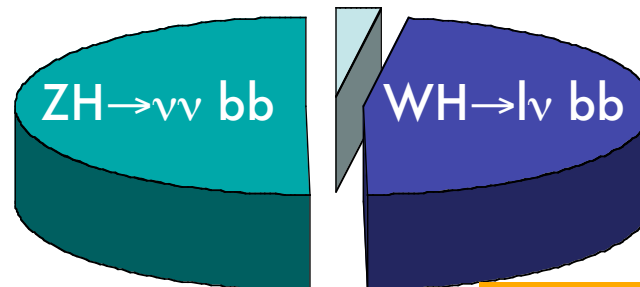| Exp.	Lum (fb^{-1})	Higgs Events (@115)	Exp. Limit	Obs. Limit
CDF	2.7	8.3	4.8	5.6
DØ	2.7	13.3	6.4	6.7

MET+jets

$$VH \rightarrow \not{E}_T b\bar{b}$$

- Large signal acceptance:
  - Large MET and 2 or 3 high P_T jets
  - NN-based event selection to reject QCD with jet Et mismeasurement giving large MET
- Dominant backgrounds:
  - QCD with fake MET due to calo resolution (eliminated)
 - W/Z+jets, top, diboson
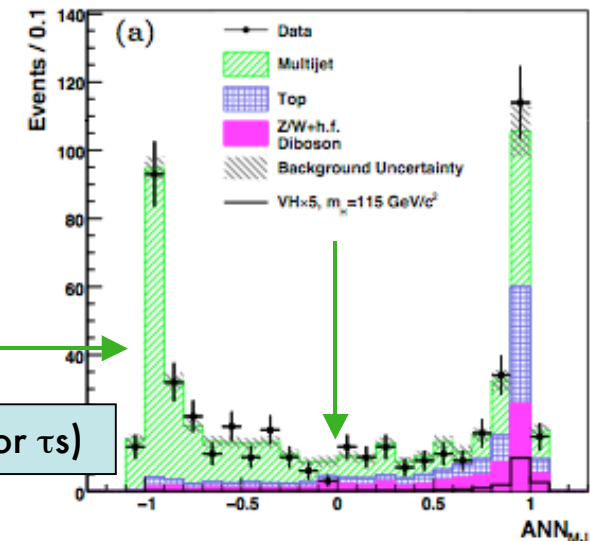
ZH → ll bb (leptons are mostly μs or τs)

ZH→νν bb   WH→lν bb

NNoutput, Signal Region, Double Tagged

S/B ratio 1/5 where we expect 0.4 Higgs evts @115

(CDF) Same techniques used for single top

Exp.	Lum (fb⁻¹)	H evts (@115)	Exp. Limit	Obs. Limit
CDF	2.1	7.5	5.5	6.6
DØ	2.1	3.7	8.4	7.5

The high mass Higgs

- The "easiest" channel at the Tevatron and LHC. The reason? Look at final state with 2 high pt leptons and main background is WW production O(10pb)

- Interest: reaching standard model exclusion level
  - Which means sensitive to observation too!

- Also sensitive to BSM physics: production cross section greatly enhanced if a fourth generation exist! Might end up with 2 discoveries in one shot (or zero??)

$$H \to W^+W^- \to \ell^+ \ell^- \nu \bar{\nu}$$
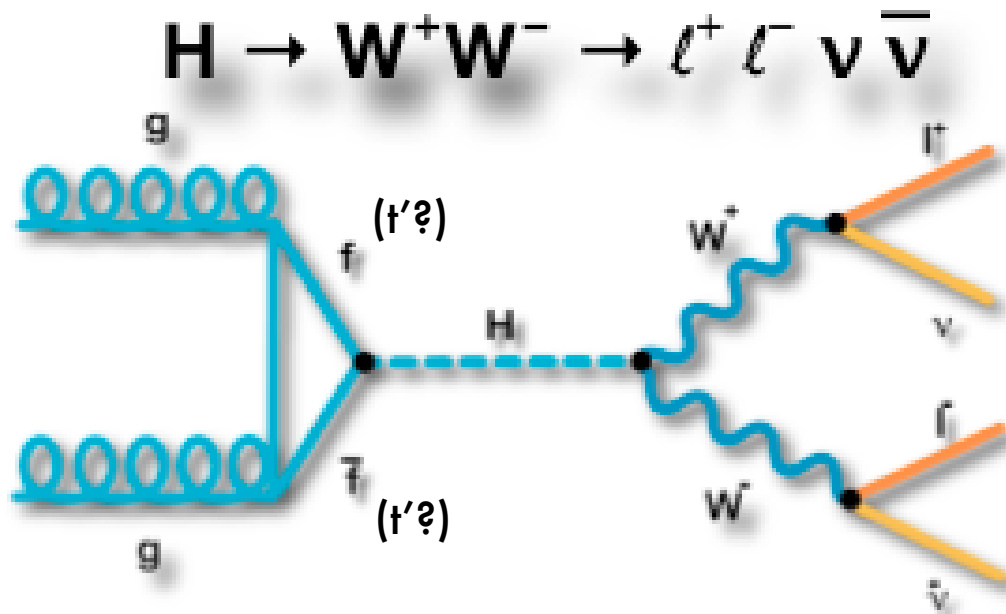
Other processes contribute too
- HW → WWW → ll(l) MET + X
- HZ → ll MET + X
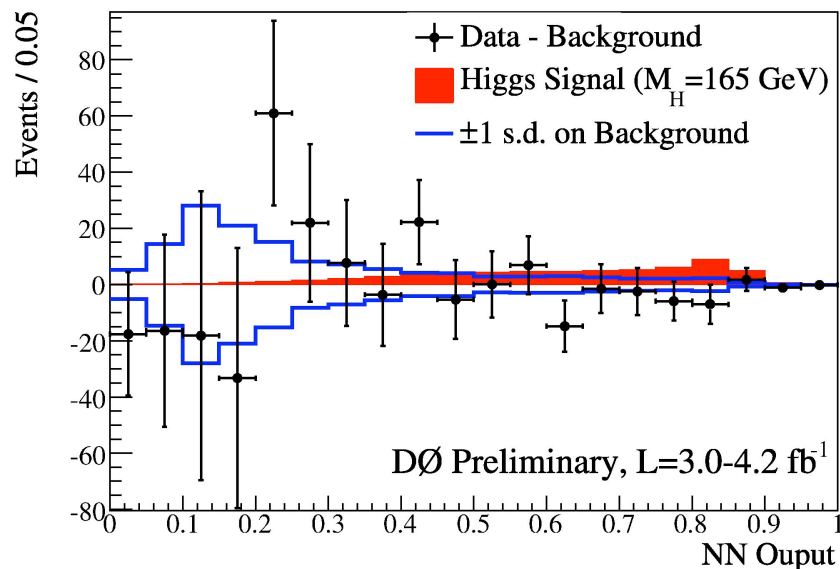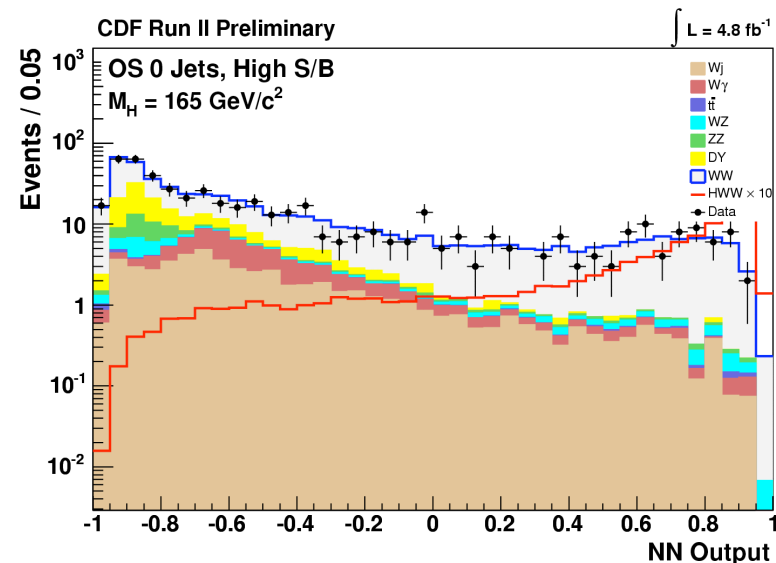- Hqq → ll + MET +X

Dilepton + MET + X

Most sensitive channel at high mass

Basic selection

- 2 high pT lepton large MET
- (CDF only) Events with extra jets sensitive to different Higgs production modes

Same sign leptons also included to catch associate production WH → WWW
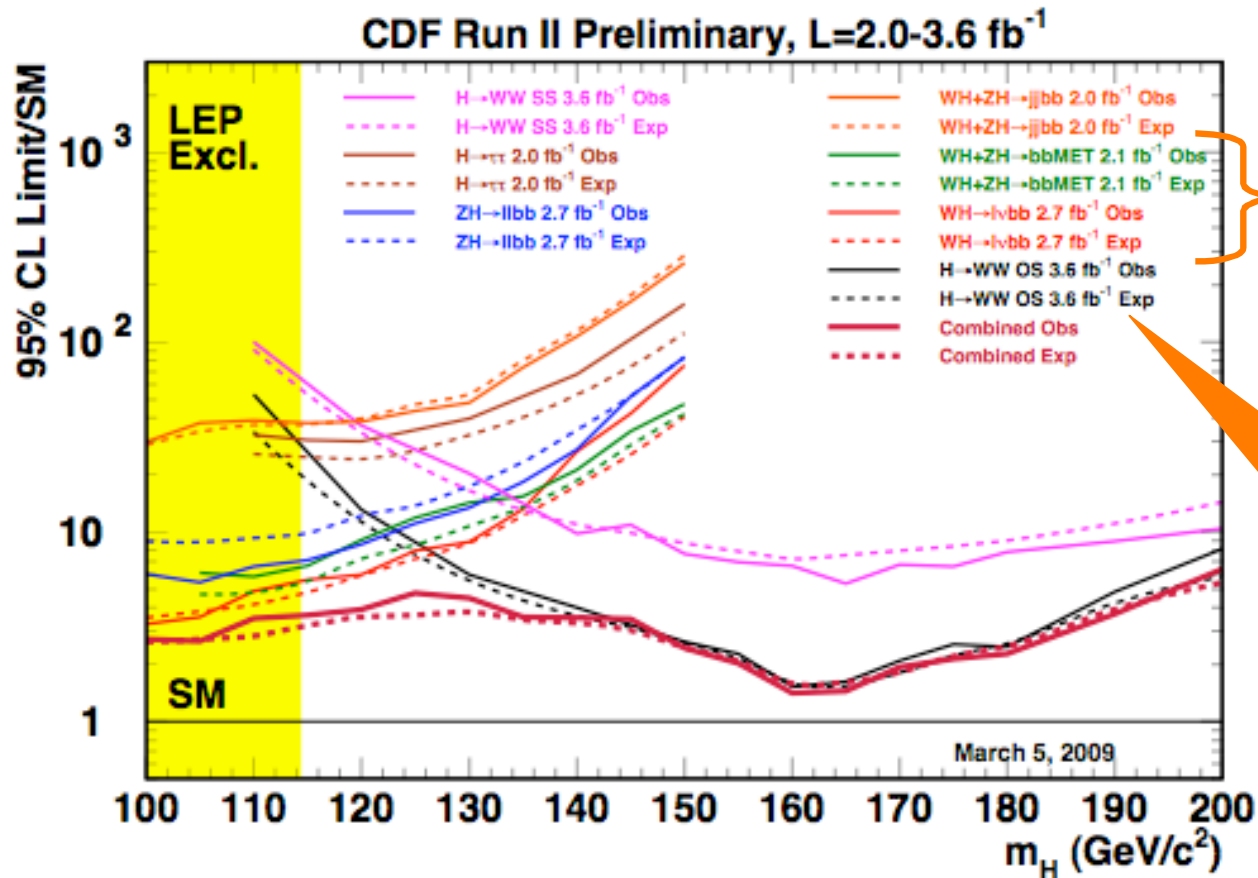
- LLR based on ME as input variable
- Fit on NN output

→ Ratio plot. No excess! Set limits

Exp.	Lum (fb⁻¹)	H evts (@165)	Exp. Limit	Obs. Limit
CDF	4.8	27	1.3	1.3
DØ	3.6	23	1.7	1.3

Channels relative importance

CDF example

Preferred region (low mass) also most difficult. There you have contribution of many channels in similar proportions. Most accessible spectrum dominated by the ll+MET+X search
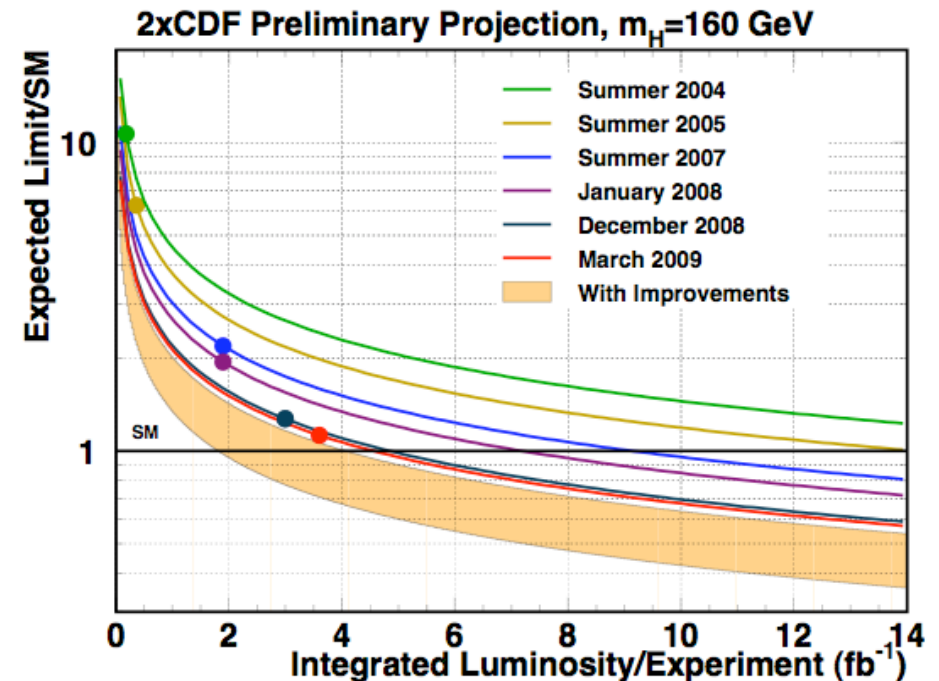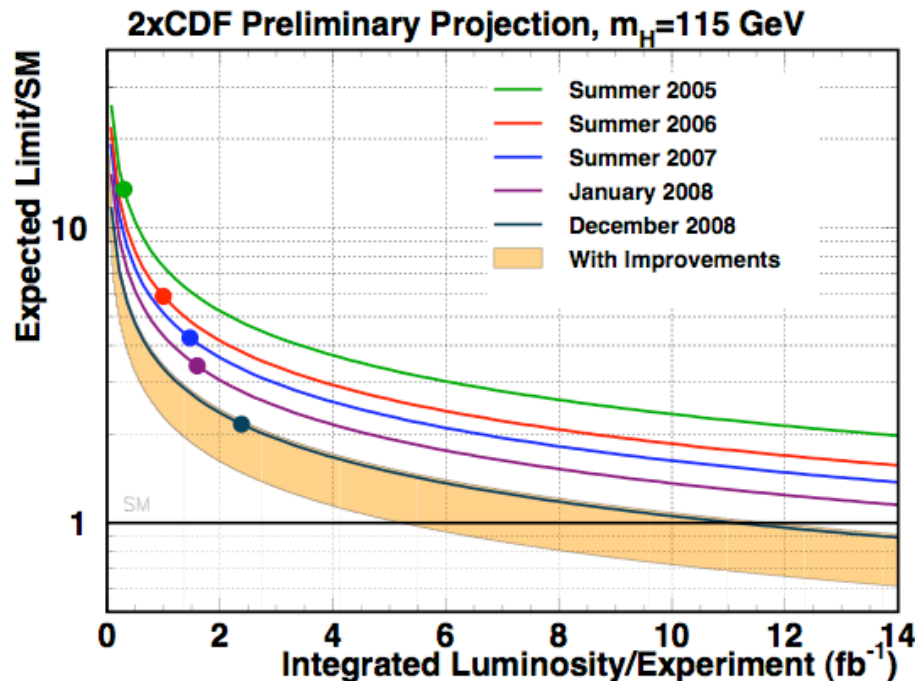
Tevatron combined limits

Increase the Tevatron reach: statistically combine all search channels

- Effectively double the analyzed luminosity by combining D0 with CDF
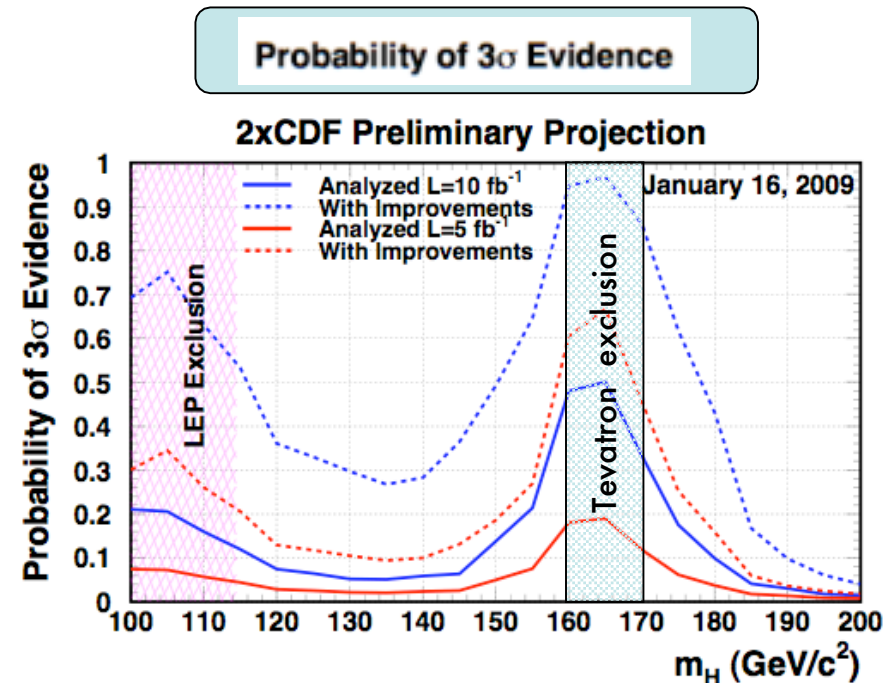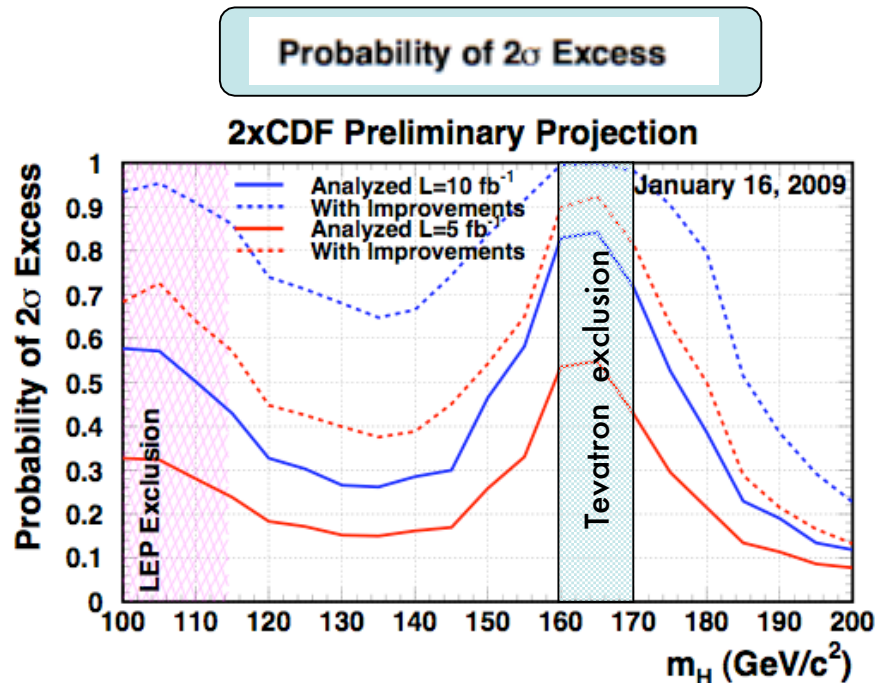- Set 95% C.L. upper limits on the Higgs boson production cross-section

Tevatron Run II Preliminary, L=0.9-4.2 fb^{-1}
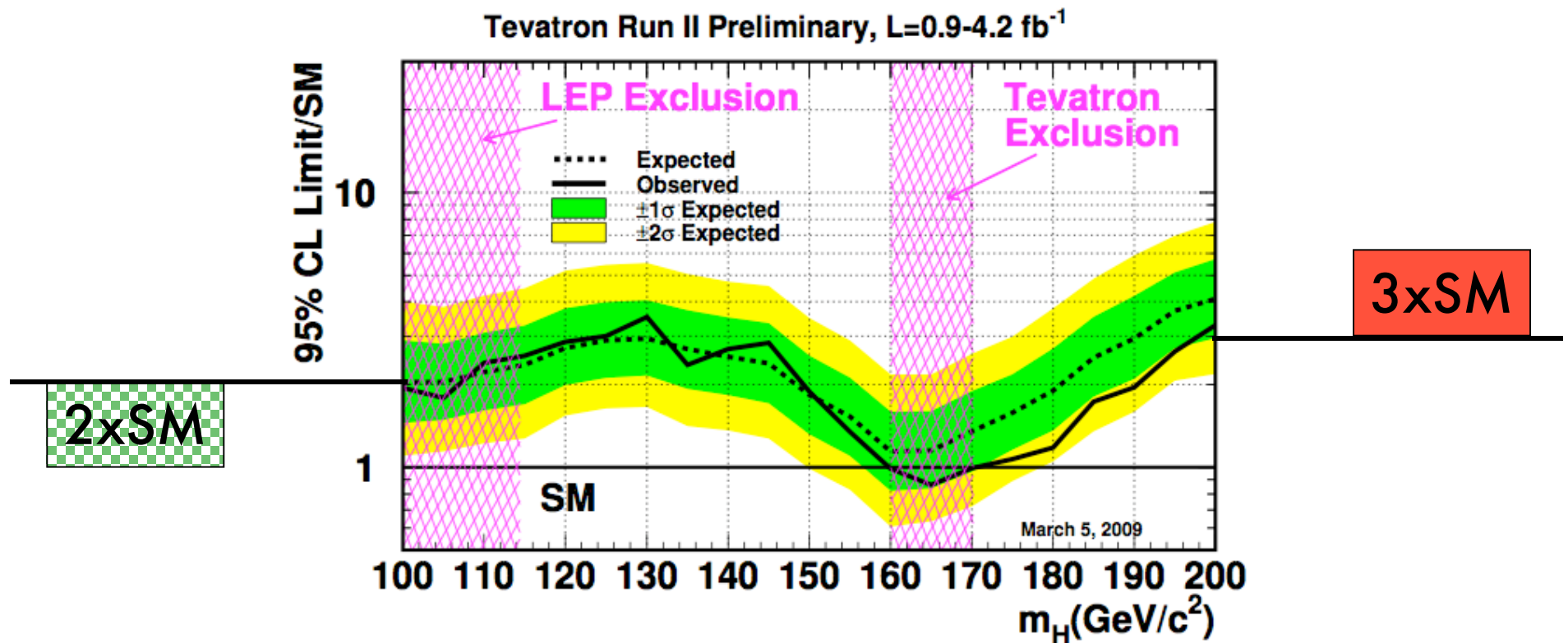
Tevatron set the first direct limit on Higgs since LEP era!

Tevatron in the (near) future

2xCDF Preliminary Projection, m_H=115 GeV

2xCDF Preliminary Projection, m_H=160 GeV

- Experiments are continuously improving analysis technique:
  - Summer 07 projection expect a improvements between 1.5 to 2.25 to existing sensitivity
  - increased indeed by a factor of 1.5 last year: equivalent of using more than double luminosity
  - More/new ideas currently being tested to increase further

If Higgs exist, will we see it?

Probability of 2σ Excess — 2xCDF Preliminary Projection

Probability of 3σ Evidence — 2xCDF Preliminary Projection

- Experiments are continuously improving analysis technique:
  - Summer 07 projection expect a improvements between 1.5 to 2.25 to existing sensitivity
  - increased indeed by a factor of 1.5 last year: equivalent of using more than double luminosity
  - More/new ideas currently being tested to increase further
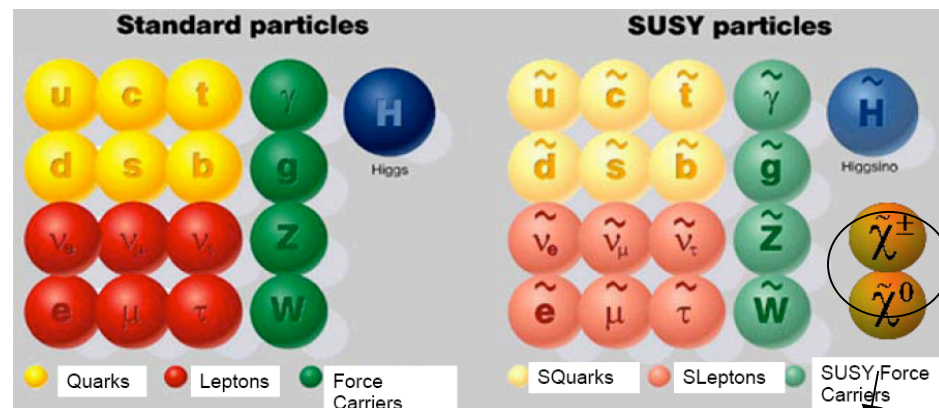
Beyond Standard Model

Supersymmetry

- The Standard Model is theoretically incomplete
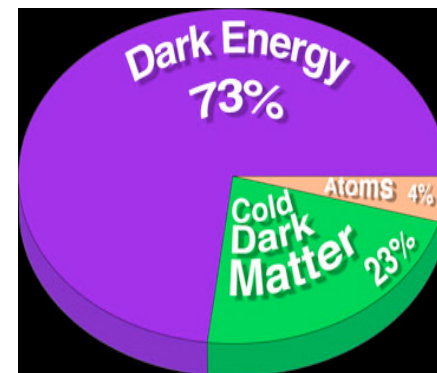 - account only for 4% of energy in Universe
  - Requires fine tuning

- SUSY: New spin-based symmetry relating fermions and bosons:

  Q | Boson> = Fermion

  Q | Fermion> = Boson

→ *Naturally solves the hierarchy problem*

- Define R-parity = $(-1)^{3(B-L)+2s}$
  - R = 1 for SM particles
  - R = -1 for MSSM partners

If conserved, provides Dark Matter Candidate
(Lightest Supersymmetric Particle)

- If SUSY were an exact symmetry, m(particle) = m(sparticle)
  - SUSY must be a broken symmetry
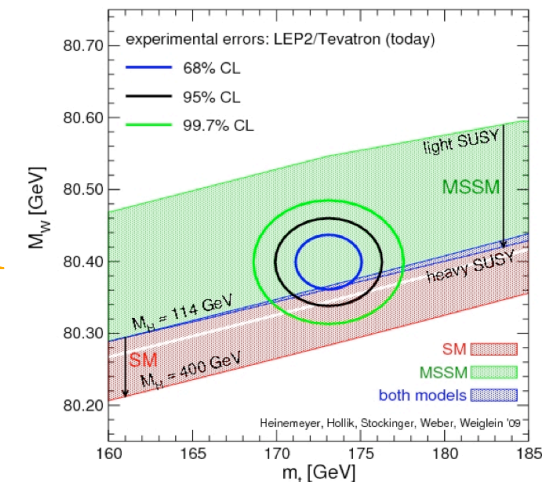 - > 100 parameters even in "minimal" models

gaugino/higgsino mixing

If Higgs exists, is it SM?

- In Minimal SUSY SM (MSSM) two Higgs doublet fields result in 5 Higgs's ($H^{\pm}$, h, H, A) after Symmetry Breaking.
- M(A) and tanβ typically chosen to describe the MSSM sector.
  - tanβ = ratio of VEVs of the two doublets

The MSSM sector seems to be getting more favourable

- Coupling of A to down type quarks and leptons (e.g. b's, τs) enhanced by tanβ (cross sections enhanced by tan²β).
- For low MA, and high tanβ the Tevatron can set strong limits within a number of benchmark scenarios that complement the searches carried out by the LEP.
- So, even though the channels gg → φ → τ τ,bb do not provide significant sensitivity to SM Higgs searches, they do in some MSSM scenarios
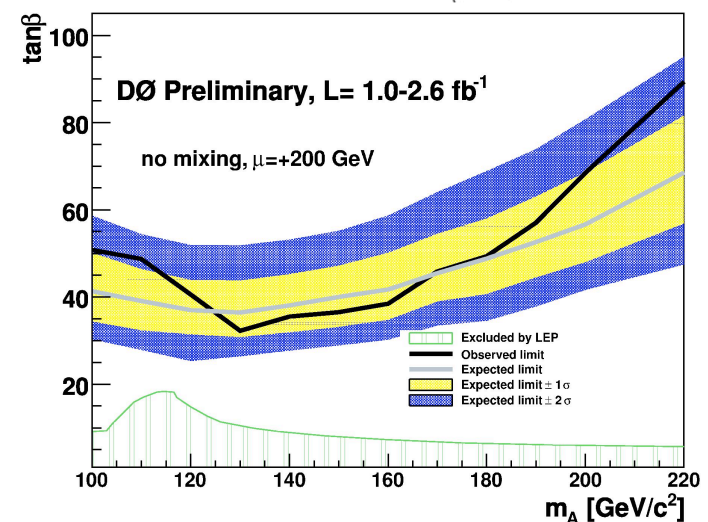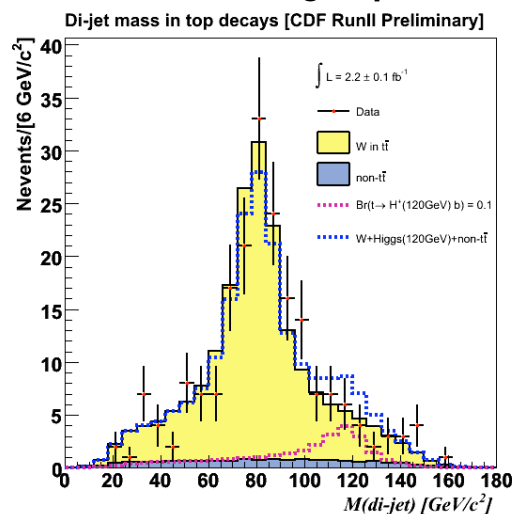
Search for charged Higgs

Finding a charged Higgs would <u>unambiguously</u> mark the discovery of new physics
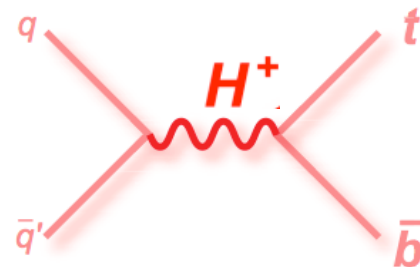
$H^{\pm}$ in ttbar decay ($m_H < m_{top}$)
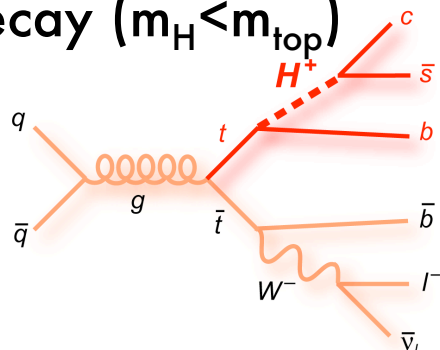
$H^+ \to c\,s$ decay when $\tan\beta \sim 1$ and for low mass charged Higgs (≤ 130 GeV). H^+ would appear as a second peak in an invariant mass of two light jets in top quark decays.
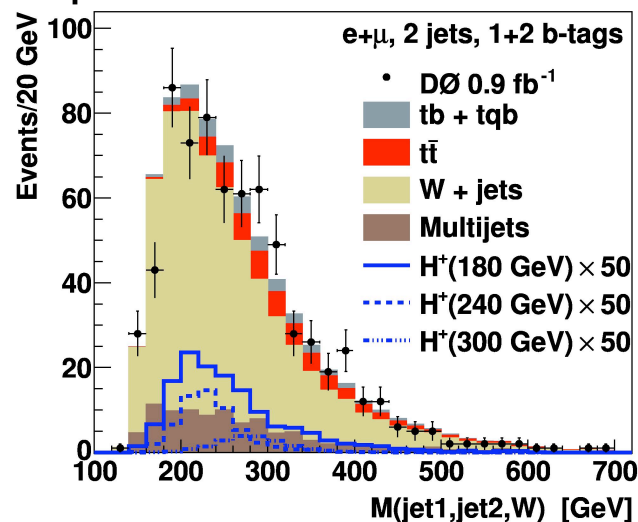

BR($t \to H^+ b$) < 0.2-0.1
for 90 < M(H^+) < 150

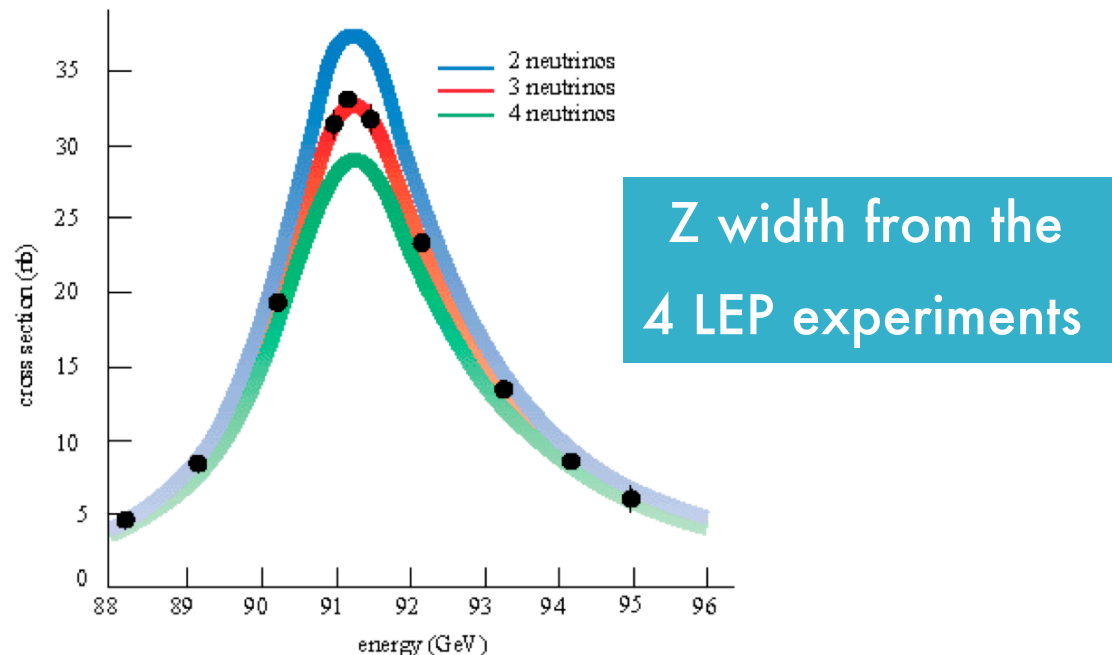## $H^{\pm}$ decaying to tb ($m_H > m_{top}$)

Scan the invariant mass of the top daughters and b to find a resonance. No significative peak found, set limits in the $\tan\beta$, M(H^+) parameter space

Fourth generation

- LEP set direct limits on 4th gen charged and neutral leptons to be M(l,ν,t',b')>100GeV

- LEP set indirect limit on number of light neutrinos to be 3; M(ν_4)>45GeV

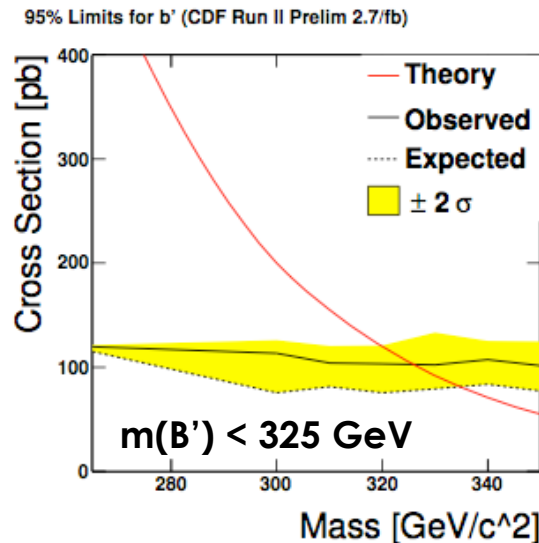Z width from the

4 LEP experiments

- Tevatron has sensitivity to higher mass range, ideally up to the TeV range

- Search for `*fourth generation*' or `*4th generation*' on Spires gives >250 results, mostly phenomenology papers

  - Many possible scenarios still compatible with direct and indirect constraints!
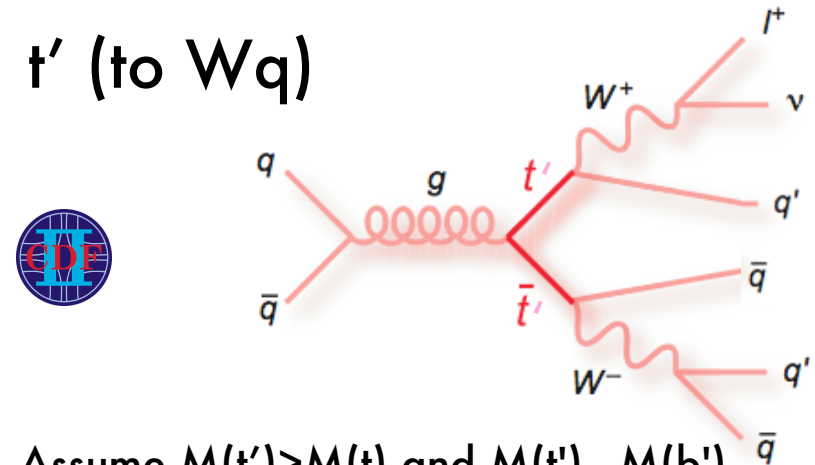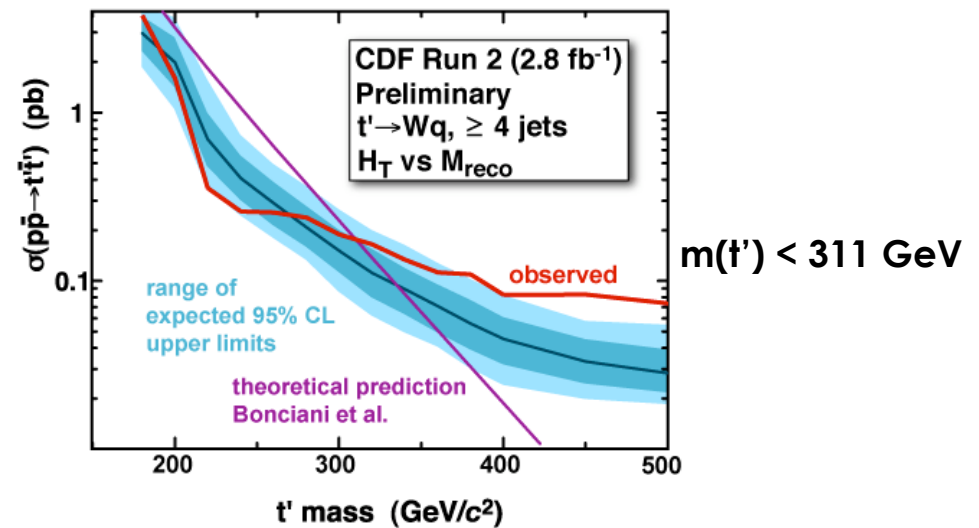
Fourth generation of quarks

b' (to tW)
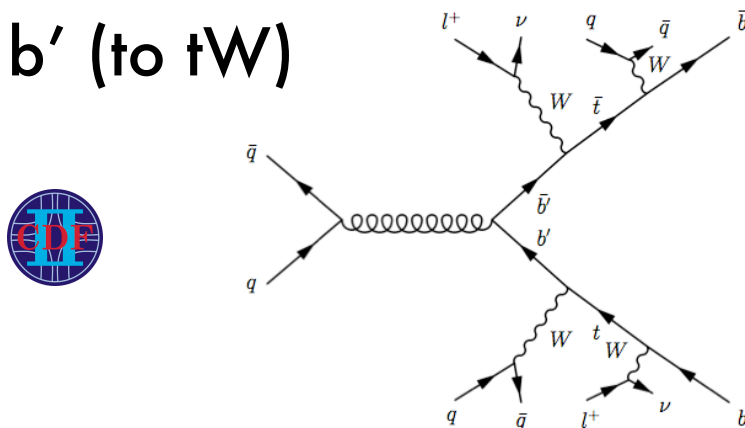
Assumes M(b')>M(t)+M(W)
Look at same-sign dilepton, MET, b-jets
Scan for an excess in Njets distribution

95% Limits for b' (CDF Run II Prelim 2.7/fb)

— Theory
— Observed
···· Expected
■ ± 2 σ

m(B') < 325 GeV

Cross Section [pb] / Mass [GeV/c^2]

t' (to Wq)

Assume M(t')>M(t) and M(t') - M(b')
< M(W) then decay t't'→qqWW. Similar to
ttbar but do not require b-identification

CDF Run 2 (2.8 fb^{-1})
Preliminary
t'→Wq, ≥ 4 jets
H_T vs M_{reco}

range of
expected 95% CL
upper limits

observed

theoretical prediction
Bonciani et al.

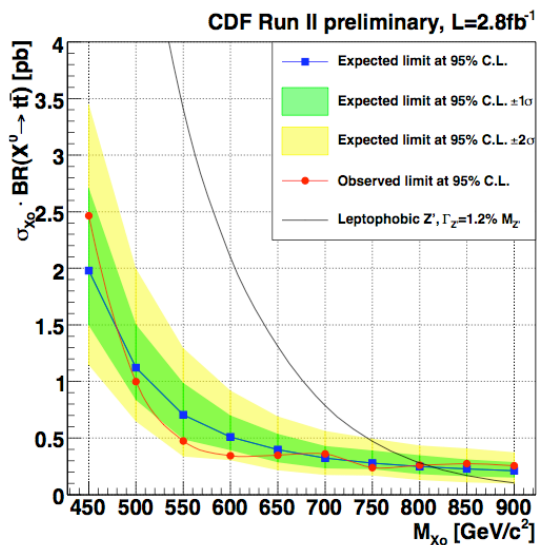$\sigma(p\bar{p}\to t'\bar{t}')$ (pb) / t' mass (GeV/c^2)

m(t') < 311 GeV

New Z' vector bosons

Z' (to quarks)

Search for resonant ttbar production from the decays of massive Z-like bosons. Many theories predict the Z' to be leptophobic: Z' decays to ttbar. Very striking signature of energetic Resonance decaying to high P_T multijets

Z' (to leptons)

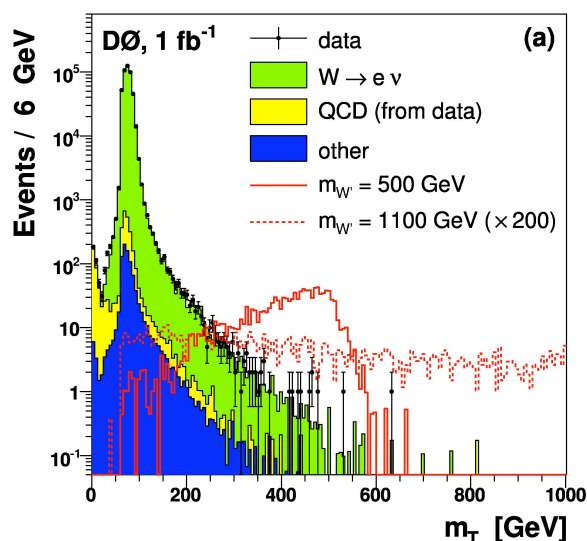Search for Z' to e+e-: electron P_T measured with calorimeter, resolution improves at higher energies
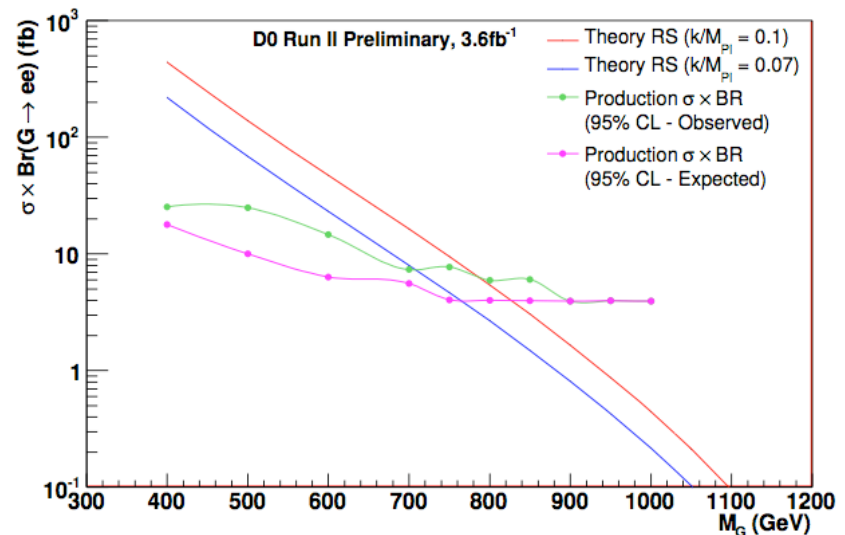
Tevatron reaching sensitivity to resonances in the TeV range!

New W' vector bosons

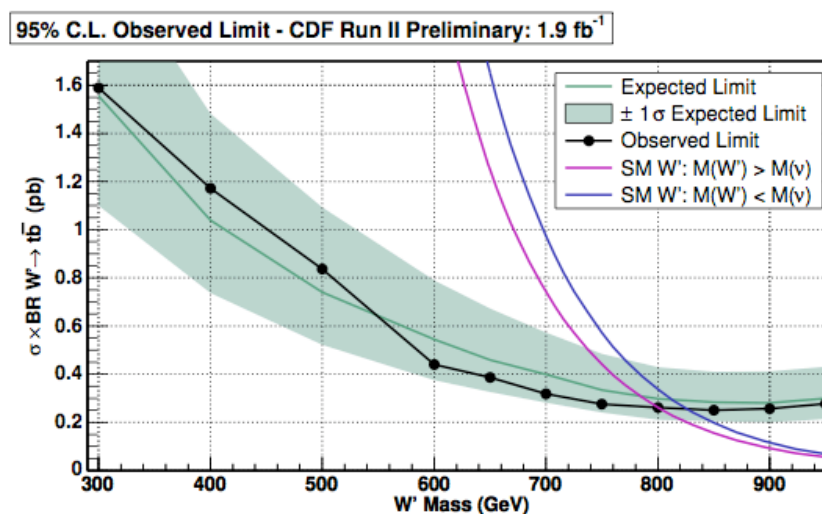## W' (to eν)

W' with the same fermion couplings as the W. Postulated by some exotic models (SUSY-GUT) Exclude SM-like new vector boson with mass up to 1TeV!

W' (to tb)

W' with the same fermion couplings as the W. We assume a model without interference with W boson and associated single top production.

Tevatron reaching sensitivity to resonances in the TeV range!

Conclusions

Conclusions

There has been no hint of a Higgs (SM or otherwise) so far

Still the Tevatron will integrate 10-12fb^{-1} by 2011 which gives **exciting opportunities**:

- if no Higgs with MH less than 190 GeV, the Tevatron will exclude all masses up to this by 2011

- if there is a SM-like Higgs in this range, the Tevatron have a chance to see **evidence** for it by 2011

- In the meanwhile, testing many theories (SUSY,4th gen, etc.) and investigating our data at 360°

The LHC will open up a new era of discovery potential.

- If nothing is found at the Tevatron, it will be up to the LHC to discover new physics.

- If the Tevatron does see hints of something it will be likely up to the LHC esperiments to figure out what it is See thu/fri Joe Incandela talk

If this wasn't enough for you..

I made here only a (sometime personal) overview of the searches ongoing at the Tevatron. To see more, please go to the CDF and D0 collaborations public webpages, and enjoy the reading!

- http://www-cdf.fnal.gov/physics/physics.html
  - CDF updating Higgs analysis with twice the data in all the most relevant channels. Some results shown here already, some others coming in ~1/2 week
  - Check out the latest Higgs combined limits, coming up in ~1/2 weeks!!
  - BSM results constantly updated with more data, original searches ongoing

- http://www-d0.fnal.gov/Run2Physics/WWW/results.html
  - D0 too updating Higgs analysis with twice the data in all the most relevant channels.
  - Some new channels sensitive to SM and BSM coming too!