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Latest Results and Plans of the Tevatron Experiments

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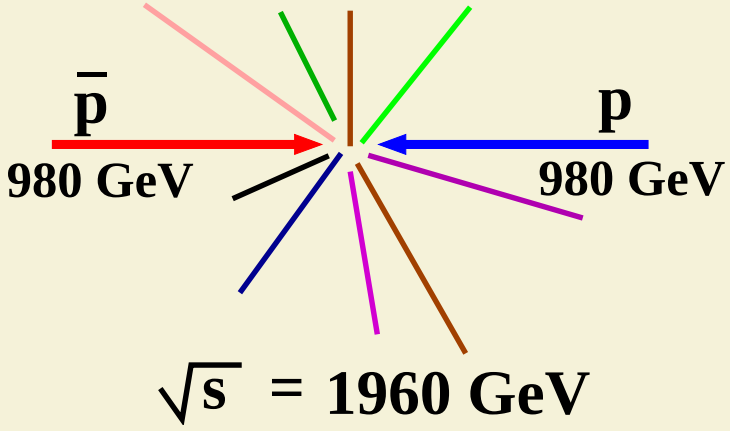
Outline

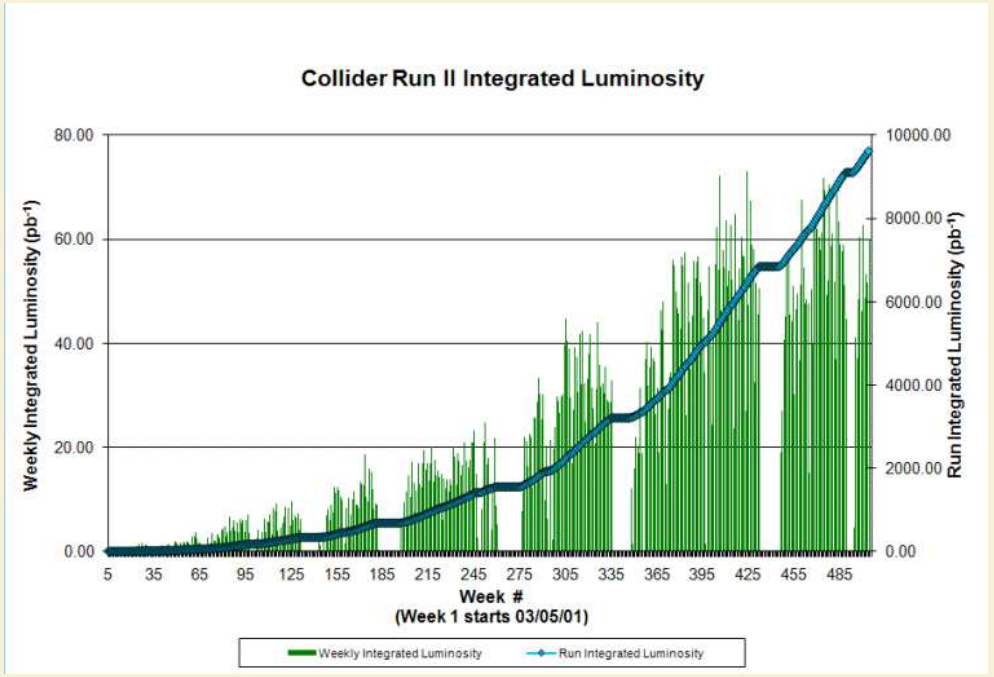
- **Introduction:**
  - $\Rightarrow$ The Tevatron Collider
  - $\Rightarrow$ The CDF and DØ experiments
- **Latest Results**
  - $\Rightarrow$ SM-related analysis (QCD and EWK)
  - $\Rightarrow$ Heavy-flavour Physics
  - $\Rightarrow$ Top Physics
  - $\Rightarrow$ SM Higgs searches
  - $\Rightarrow$ Beyond the Standard Model
- **Plans for the future**

Although covering results from CDF and DØ, I will focus mostly on CDF which is the one with institutional representation from Spain.

The Tevatron Collider: Description

- **Located at Fermilab (USA)**
- **Proton-Antiproton collider with beam energy of 980 GeV.**





⇒ **Beams are collided in two locations, in which the CDF and DØ experiments collect their data.**

⇒ **Bunch Crossing time: 396 ns**

⇒ **Initial Inst. Lum.:** $\sim 375 - 425\ \mu\text{b}^{-1}$**/s (Fall'10)**

⇒ **Currently** $\sim$**10 fb**$^{-1}$ **delivered**

The results shown here do not include all this data sample.

Expecting to have updates soon (use good $\sim 7 - 8$ **fb**$^{-1}$ **for Winter Conf's.)**

The CDF and DØ Experiments

- **Both are multipurpose detectors, with a structure that is the usual for this kind of experiment nowadays.**

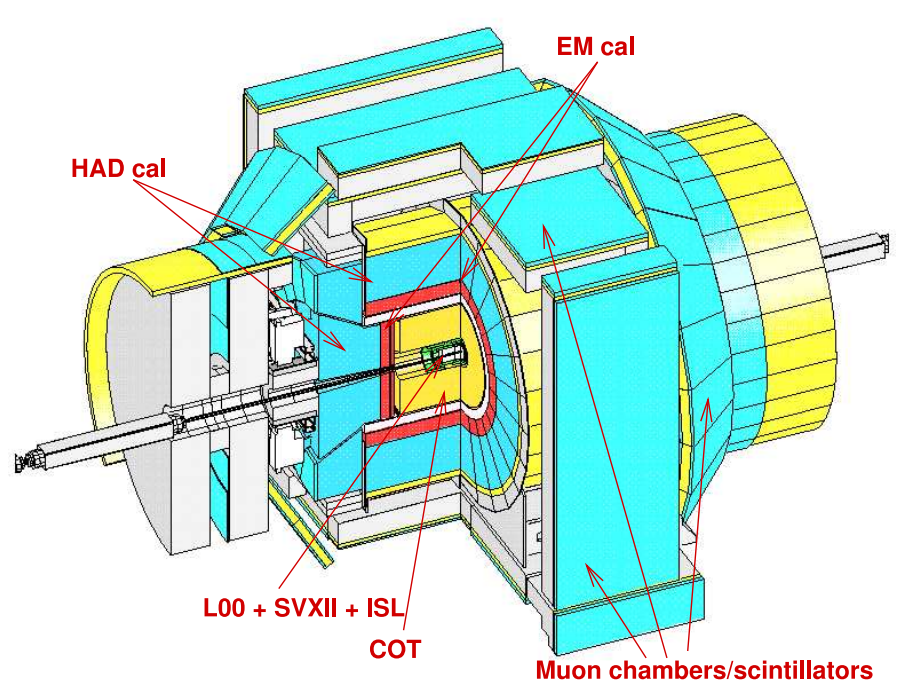
- **Designed to exploit all the information that is needed to do physics at this energy and cover the full program:**

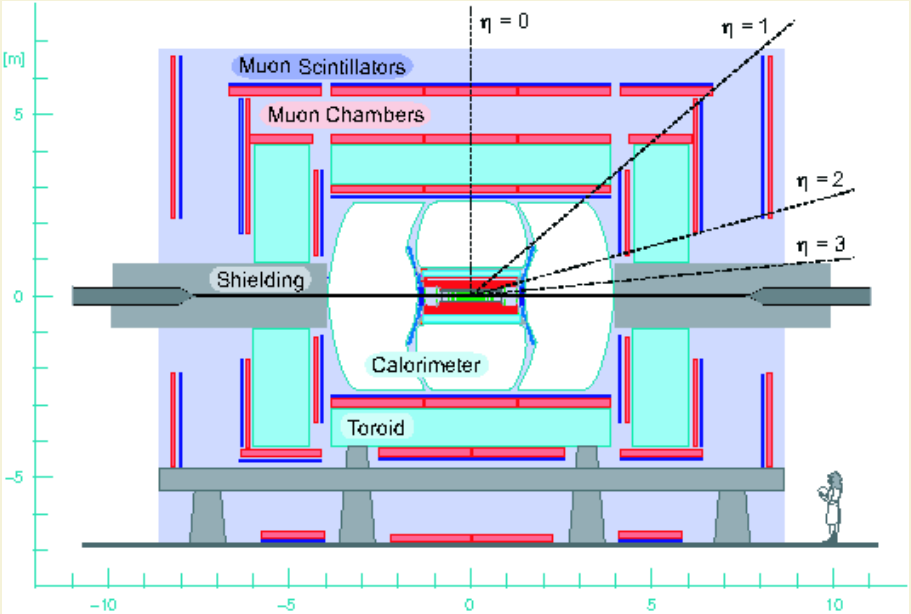
  - ⇒ **Silicon high-precision vertex detectors**
  - ⇒ **Tracking chambers in magnetic field**
  - ⇒ **4π calorimetry with EM preshowers**
  - ⇒ **Calorimetry up to $|\eta| \sim 3/3.5$**

  where the pseudorapidity is a Lorentz longitudinally-invariant alternative of the polar angle and its definition is

  $$\eta = -\ln\left[\tan(\theta/2)\right]$$

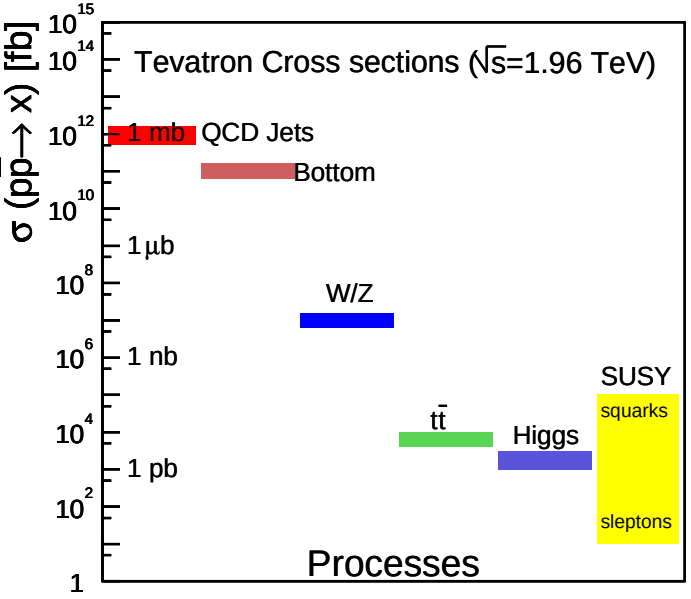
  - ⇒ **Muon detectors (outside)**
  - ⇒ **Axial and forward-backward symmetry**





SM-related analysis at the Tevatron

- **Most of the processes studied at Tevatron are included in the SM.**
- **Hierarchy of cross sections imposing stringent steps for understanding:**



→ **Multijet production**

→ **Heavy-flavour production**

→ **Electroweak boson production**

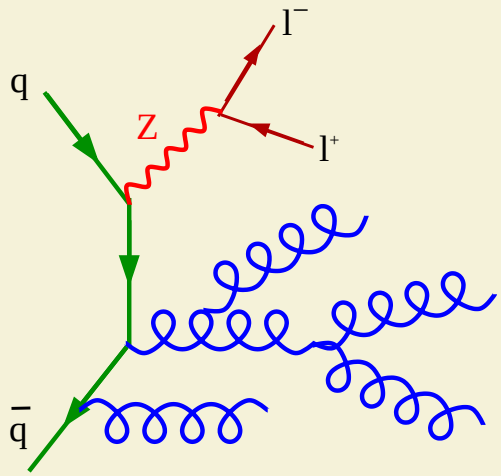
→ **Top production**

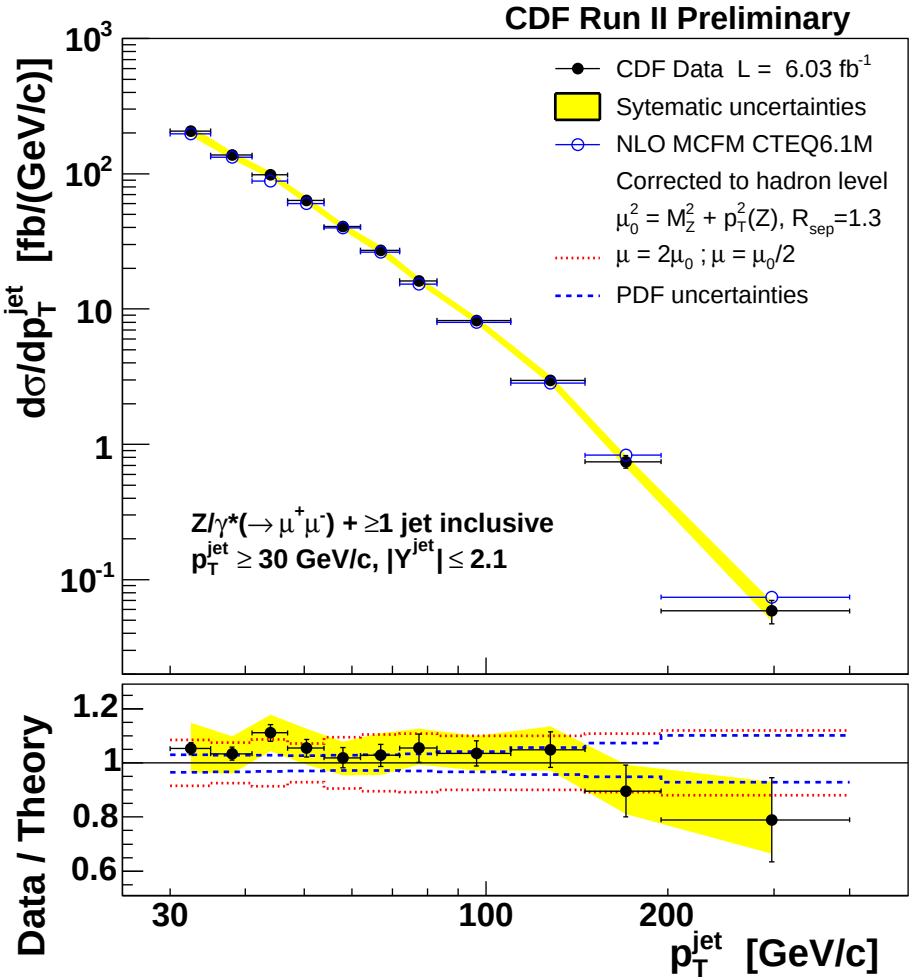
→ **Higgs and New Physics**

- **Clearly the measurements of the SM processes are fundamental to reach sensitivity to possible new processes.**
- **Even today Tevatron experiments keep measuring SM-related properties that are used as benchmark for LHC measurements and Tevatron searches.**

Z+jets Production

Studies of the production of jets in association with a heavy boson are fundamental parts of the Tevatron program:





- **Test of perturbative QCD.**
- **Sensitive to hadronization and underlying event.**
- **Background for lower cross-section SM processes:**

  Top, diboson, . . .
- **Background for New Physics signatures:**

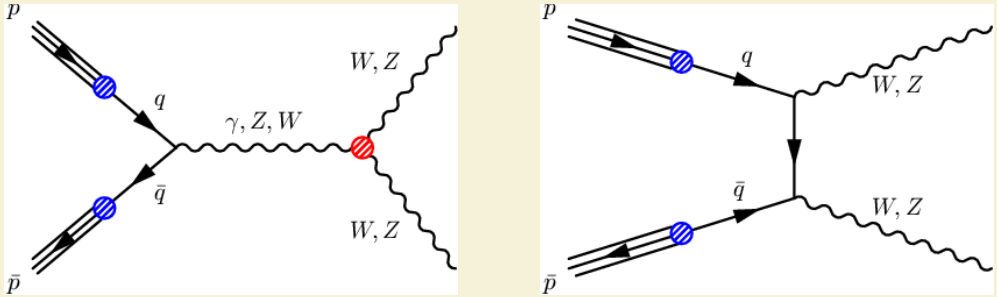
  Higgs, SUSY, . . .

Analysis by Stefano Camarda (IFAE)

- **IFAE also measuring $Z + b$-jet production (by Lorenzo Ortolan)**

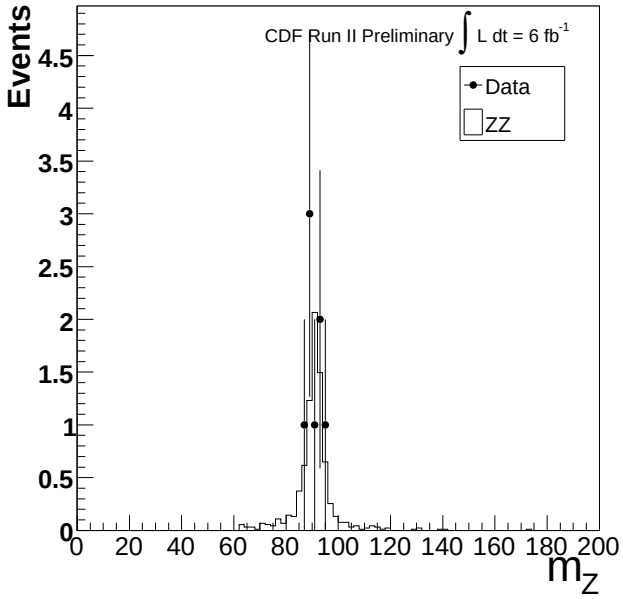
Diboson Production

- **Fundamental test of the electroweak unification: directly sensitivity to boson couplings.**



- **Small cross section, experimentally challenging.**

- **First observed in the clean multilepton signatures.**

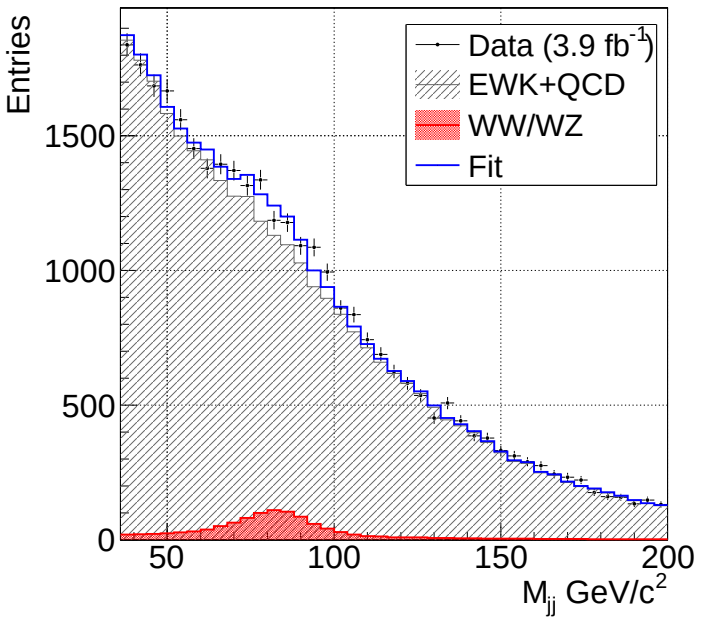


After observation, studies have been completed with signatures including the hadronic (semileptonic) decays:

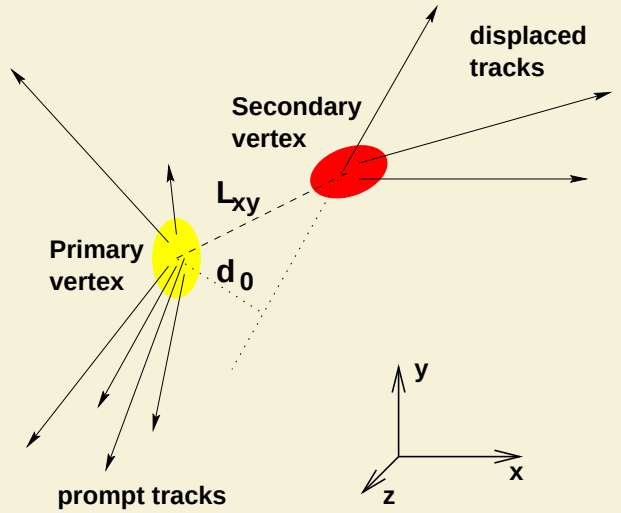
$\Rightarrow$ **Very interesting to study dijet objects.**

$\Rightarrow$ **Benchmark to Higgs in similar signatures.**

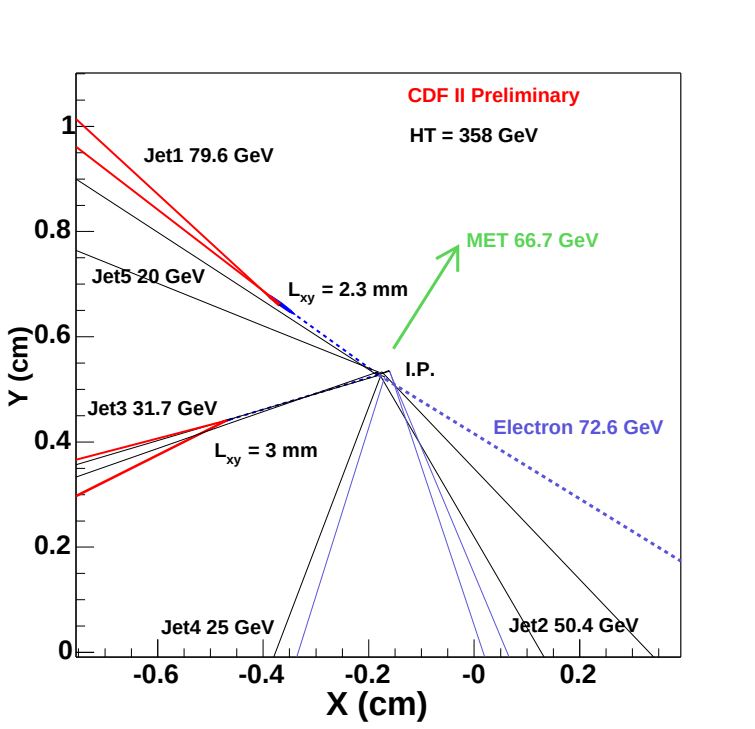
Current goal is the observation of $Z \rightarrow b\bar{b}$ produced in association with a W.



Heavy-flavour Physics at the Tevatron



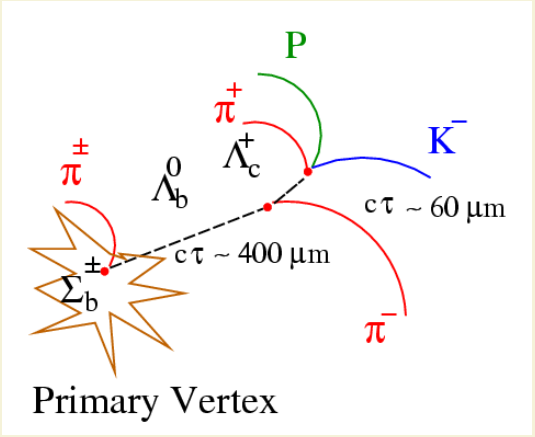
- **Very broad part of the program, relevant to several topics in HEP:**
  - ⇒ **Precise measurement of properties.**
  - ⇒ **Observation of new hadrons.**
  - ⇒ **CP Violation and CKM studies.**
  - ⇒ **Indirect sensitivity to New Physics.**

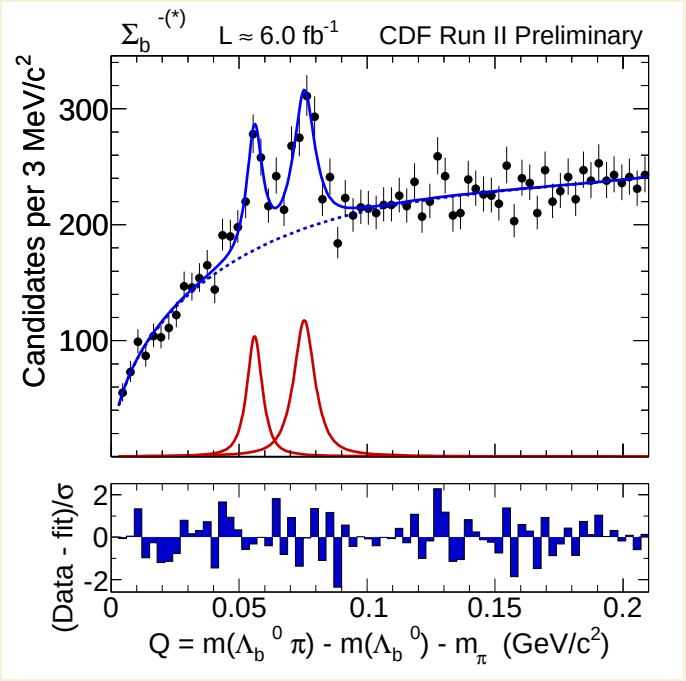


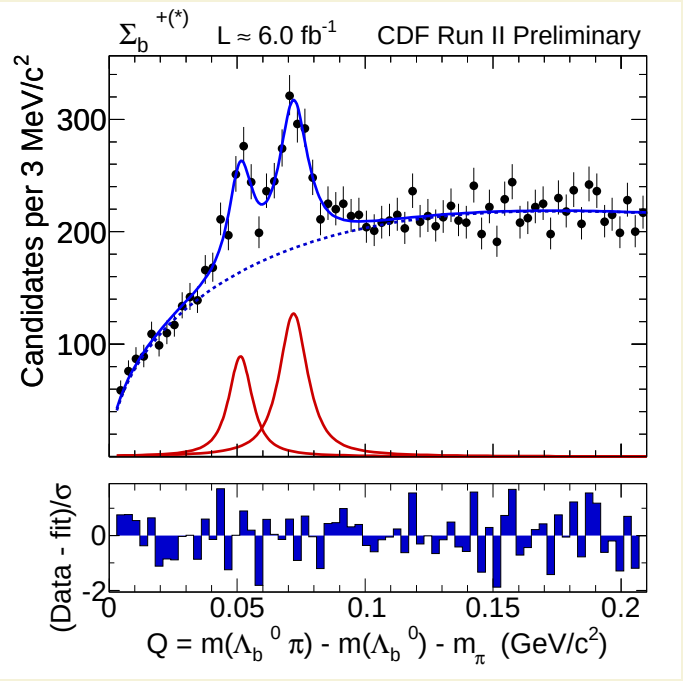
- **Taking advantage of the huge cross section of heavy-flavour quarks at the Tevatron collisions.**
- **Challenging in terms of triggering.**
- **CDF uses a displaced-track trigger (based on the silicon detector) that has provided unique possibilities at a hadron collider.**
- **And with a chapter on its own: studies of the heaviest of all known particles: the top quark.**

Observation of new baryons

- **Several new hadrons have been observed in the large Tevatron datasets.**
- **Recent analysis observed very clearly (7σ) the states of the $\Sigma^{(*)\pm}$ baryon family.**
- **Fully hadronic decay, using CDF displaced-track trigger.**







Analysis by Constantino Calancha (CIEMAT)

- **This analysis also measured the natural widths of these states, in agreement with theoretical predictions.**

CPV measurement in the D^0 system

This asymmetry has been measured in the dipion decay mode:

$$A_{CP} = \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

The initial nature of D^0 is tagged using events from D^*, in which the charge of the slow pion gives the charge of the charm quark.

Final value (corrected for detector asymmetry for reconstructing +/- tracks):

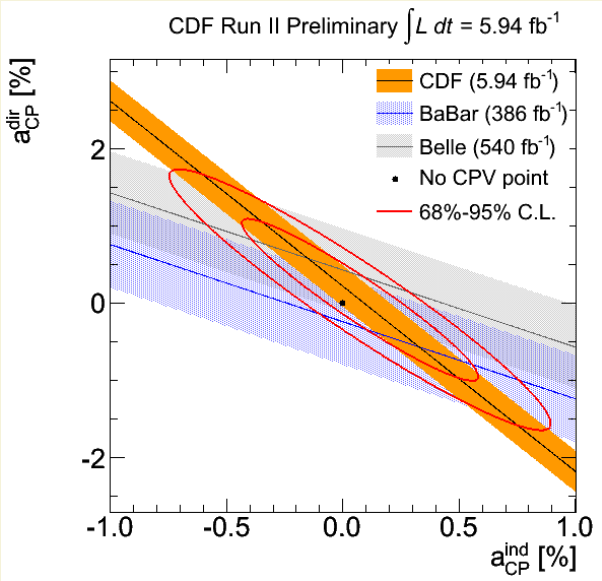
$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24(\text{stat}) \pm 0.11(\text{syst})]\%$$

- **This correction is performed using data to reduce uncertainty.**
- **Measurement is simplified at Tevatron due to CP-symmetric initial state.**

Both direct and mixing-induced CP violation contribute to the asymmetry, with a time-dependence for the latter. For the slow mixing rate for charm, we obtain:

$$A_{CP} = a_{CP}^{\text{dir}} + \frac{\langle t \rangle}{\tau} a_{CP}^{\text{ind}}$$

This makes a difference in interpretation for CDF and the B factories because of the CDF bias on $\langle t \rangle$ from the displaced-track trigger.



CPV in Like-Sign Dimuons

DØ measured the asymmetry in dimuon production:

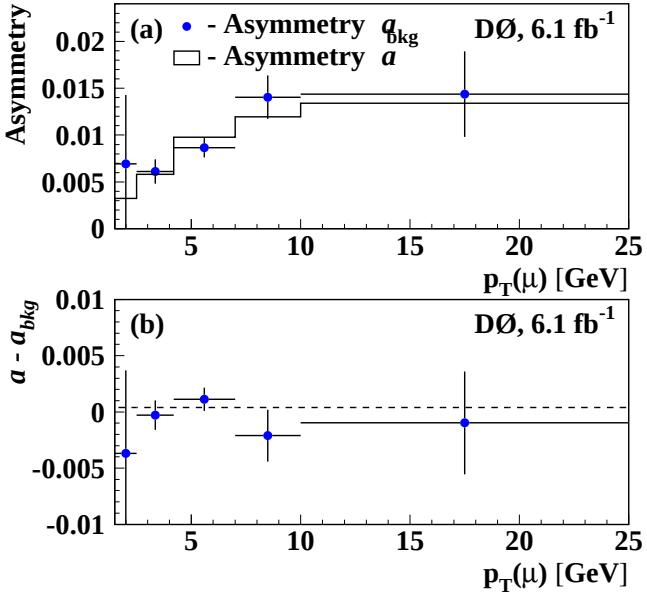
$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

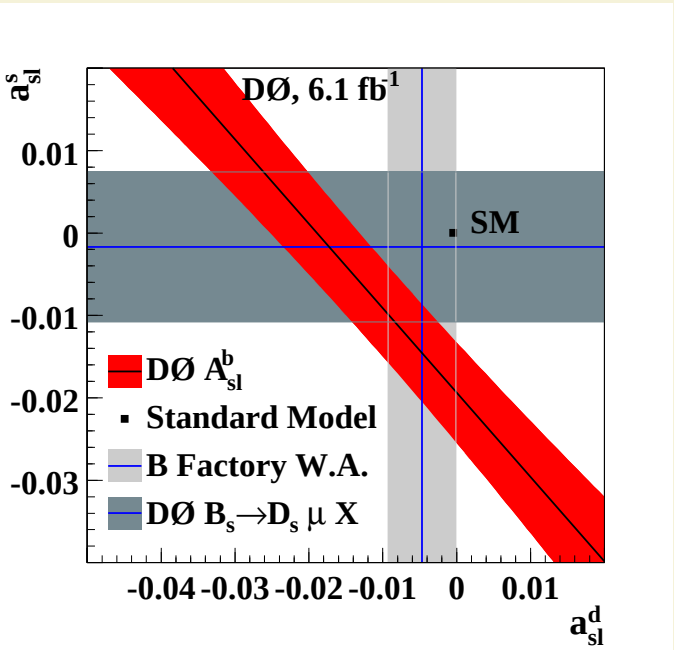
which is interpreted as purely coming from CP-violation in mixing of neutral B mesons (A^b_{sl}).

- **The possibility of reversing the magnetic field allows to reduce detector effects due to asymmetric efficiencies for positive and negative muons.**
- **Need to correct for misidentified muons (from kaons or others), which is done using data.**
- **Single-muon event sample used as control sample, although also sensitive to the underlying asymmetry, after correction from the background components.**
- **Final measurement (evidence for a non-zero value) comes from the combination of the two measurements with weights that minimize the uncertainty:**

$$A^b_{sl} = [-0.957 \pm 0.251(\text{stat}) \pm 0.146(\text{syst})]\%$$

- **Result was interpreted in terms of B^0_d and B^0_s contributions.**
- **CDF is working to reproduce the analysis.**





Top-quark physics

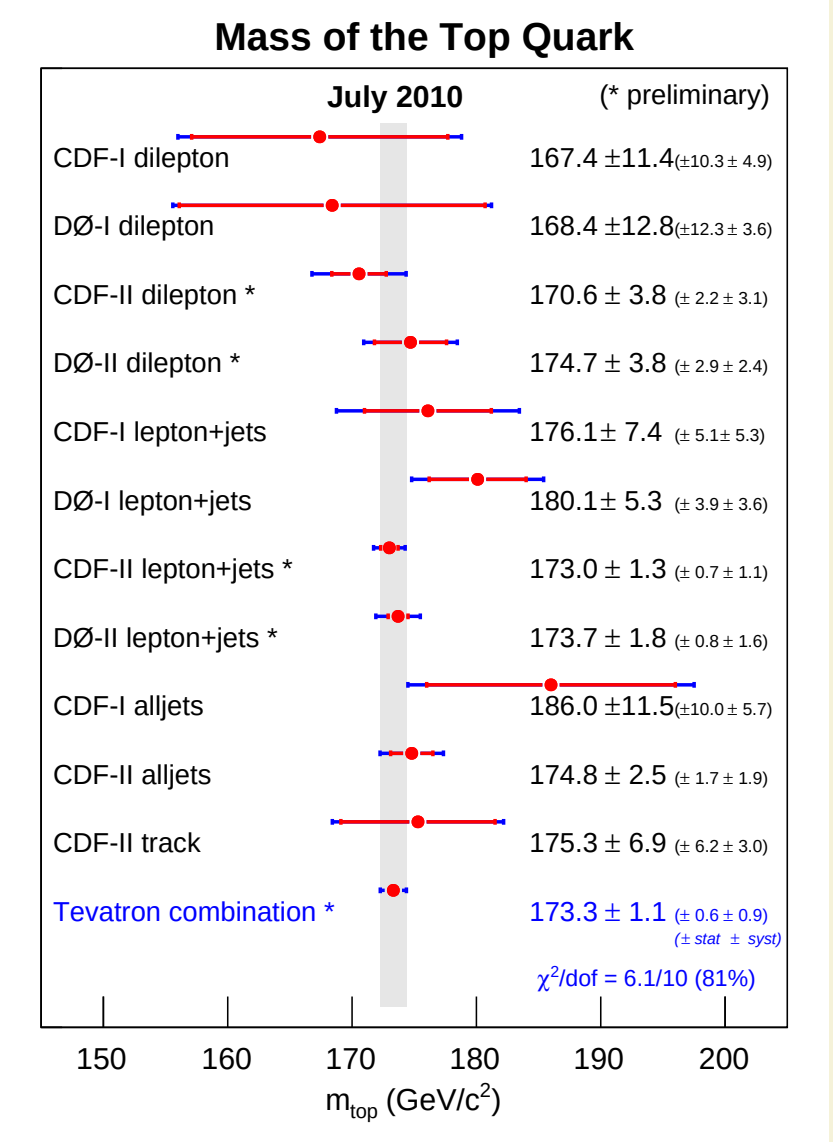
- **Since the discovery of the top quark, a lot of progress has been done at Tevatron to study its properties.**

- **Very good precision in measurements of the mass and the production cross section at 2 TeV.**

- **Very broad program and studies: lots of final states considered.**

- **Hard to improve in the near future at Tevatron.**

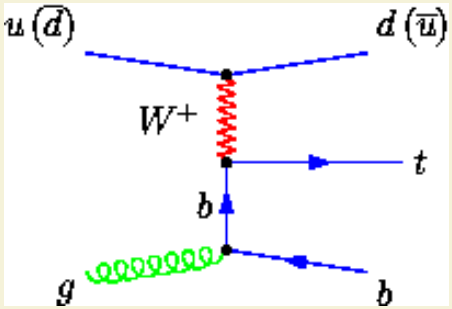
- **Currently Tevatron is planning to start using the $t\bar{t}$ events as control samples for studies (b-tagging, jet resolution, ...), oriented to improve Higgs searches.**

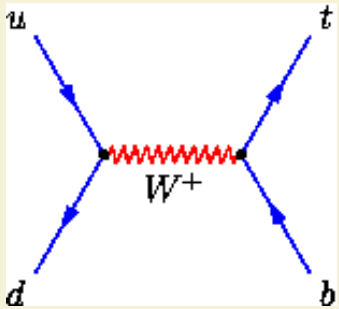


- **Looking forward to have ATLAS and CMS numbers in the tables!**

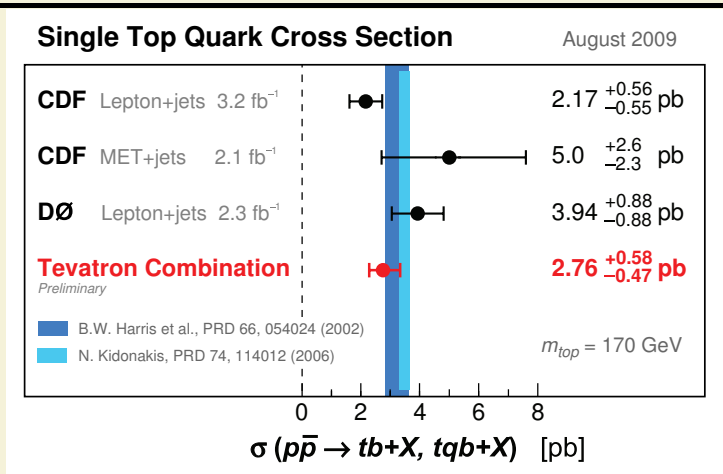
Observation of Single-top Production

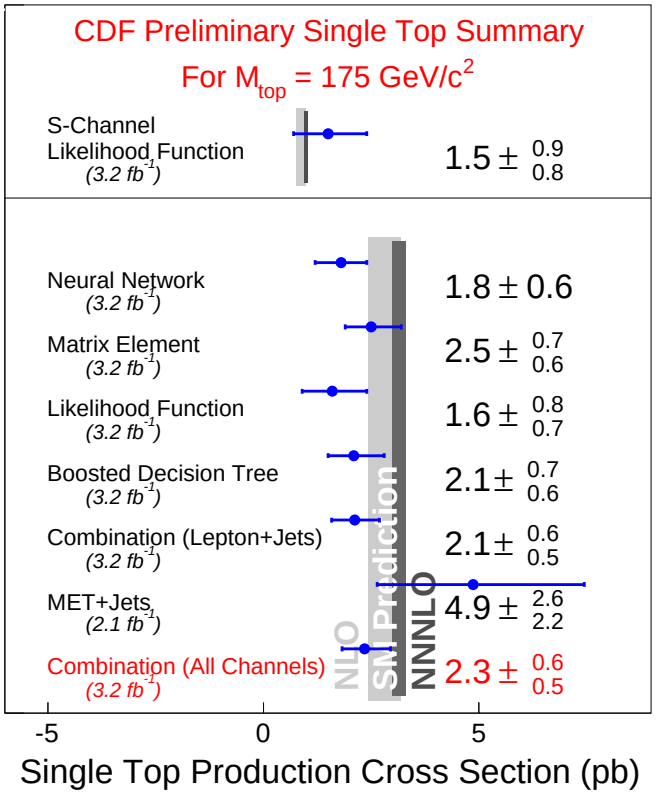
- The last big step toward understanding the top quark has been the observation of single-top production.
- Fundamental process as it is directly proving the EWK couplings of the top quark.
- Direct test of the V_{tb} element of the CKM matrix.





- The observation was achieved with the combination of several signatures and channels.
- Intense use of high-level optimization techniques.
- Test bed for the strategy in Higgs analyses.
- Measured cross sections by both collaborations in agreement with expectations from the SM.





PhD Thesis by Bruno Casal (IFCA)

Measuring Top-quark properties

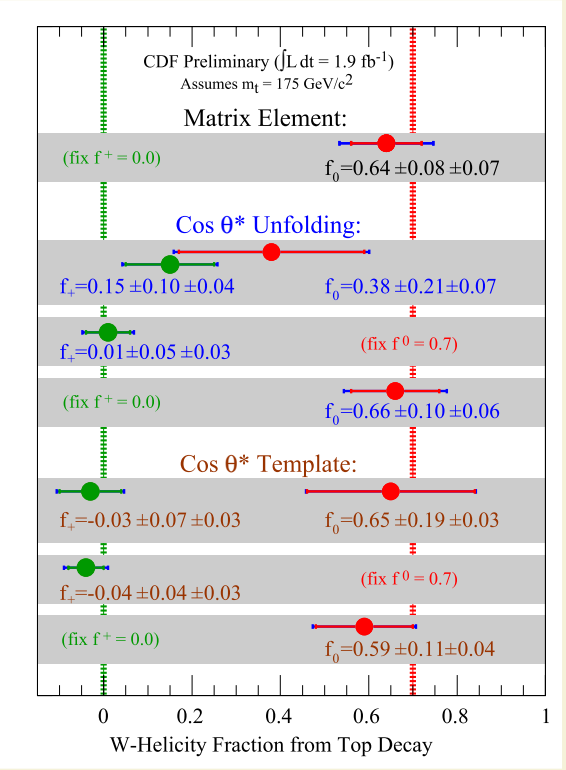
Tevatron is using the currently available samples to increase the knowledge about the top, e.g.

Helicity measurements:

⇒ **Top spin information is transmitted to decay products (due to lack of hadronization).**

⇒ **Spin correlation is sensitive to production mechanism, and therefore sensitive to new physics (Z', KK g).**

⇒ **Good agreement with SM predictions.**



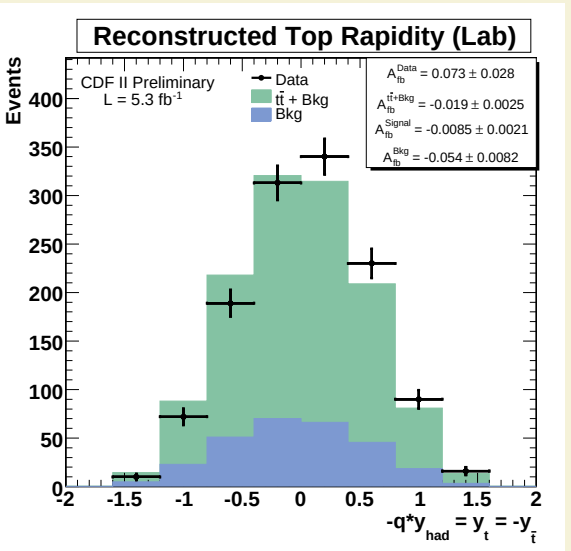
Forward-Backward asymmetry:

⇒ **Expected to be small in the SM (null at LO).**

⇒ **Very sensitive to new production mechanisms and new physics**

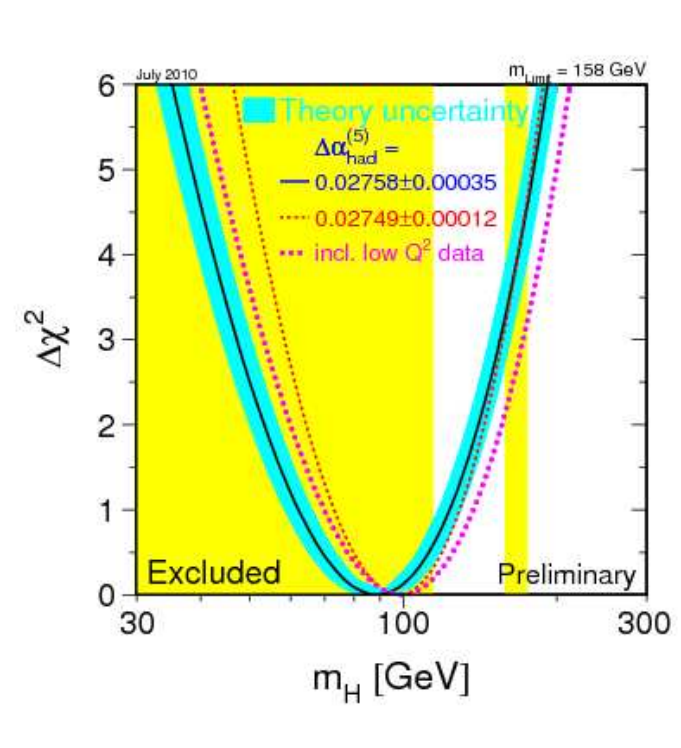
⇒ **CDF measures a significant ($\sim 2\sigma$) asymmetry when compared to SM prediction at NLO (MCFM).**

⇒ **DØ also observes (4.3 fb^{-1}) a much larger asymmetry than the expectation (but measurements are not directly comparable yet).**



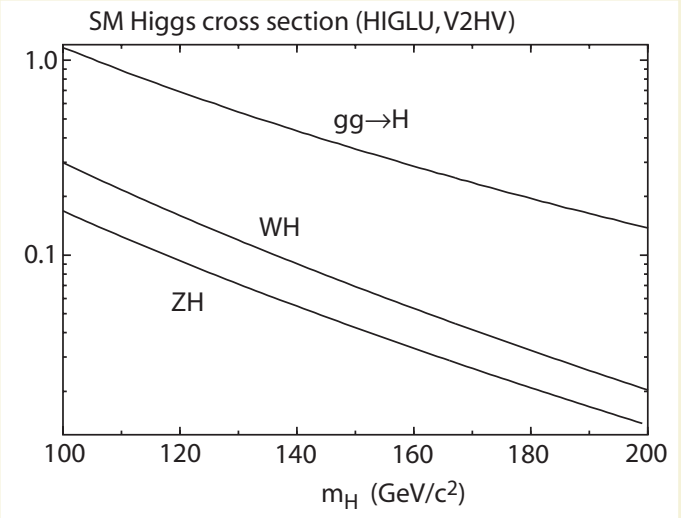
SM Higgs searches at Tevatron (I)

Since the Higgs is the keystone of the SM, this search is the HEP priority.



We know all its properties except the mass, for which we have the constraints.

- **Production is dominated by the inclusive process (basically gluon-gluon fusion via a top-quark loop).**
- **Reasonable contributions from associated production (with a W or Z boson)**
- **Little dependence on mass of the qualitative picture (but big dependence on cross section).**

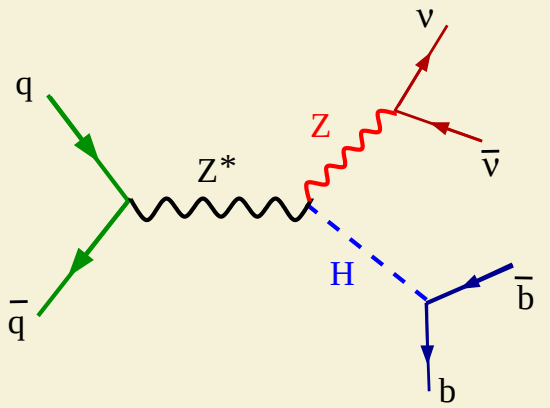


- **Branching ratios depends strongly on the mass**
- **Low mass (motivated by fits): $b\bar{b}$ (some $\tau\tau$)**
- **High mass (up-to 180-200 GeV): WW**
- **Higher masses are unreachable at Tevatron.**

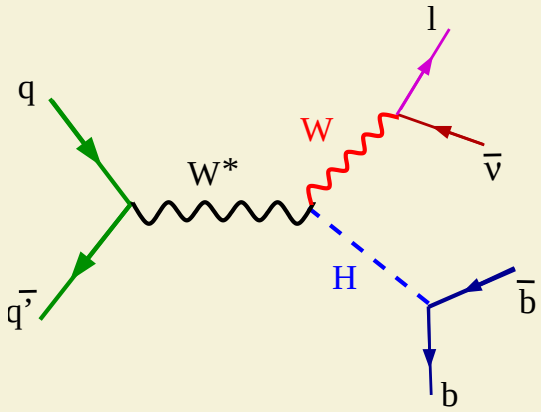
SM Higgs searches at Tevatron (II)

Considering the production cross section and branching ratios, the strategy at Tevatron is as follows:

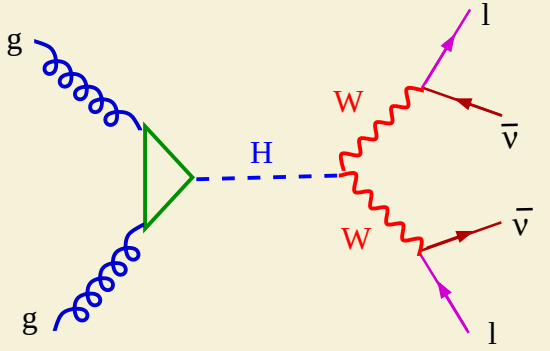
- **Low mass ($m_H < 130$ GeV/c^2) decay dominated by $H \rightarrow b\bar{b}$**
  - $\Rightarrow$ **Impossible to observe in inclusive production**
  - $\Rightarrow$ **Using ZH and WH production requiring a b-jet and leptonic decays**



- **High mass ($m_H > 150$ GeV/c^2) decay dominated by $H \rightarrow WW$**
  - $\Rightarrow$ **Leptons from the Higgs reduce background**
  - $\Rightarrow$ **Inclusive production is dominant channel (although associated production is not negligible, e.g. $WH \rightarrow W(WW)$)**



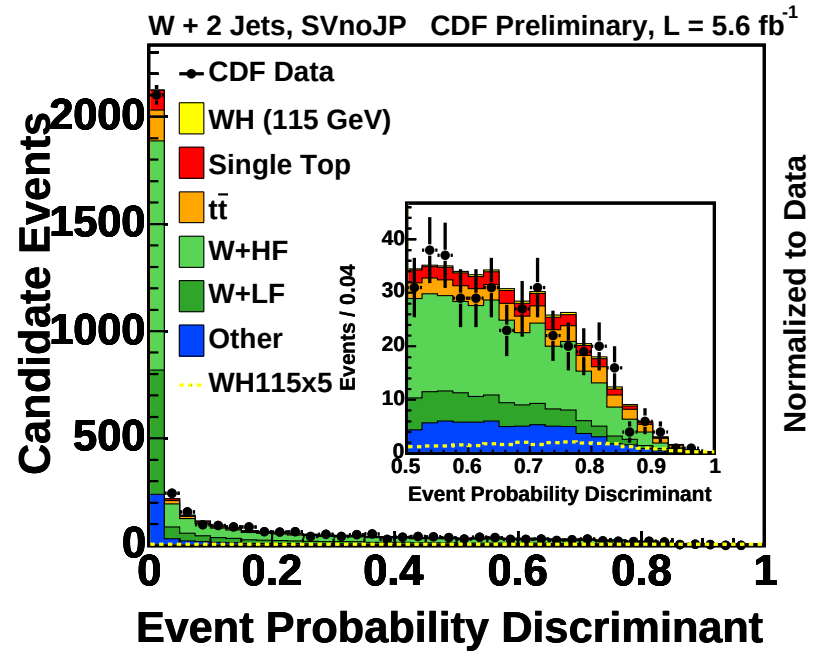
- **Intermediate region**
  - $\Rightarrow$ **Sensitivity from previous modes**

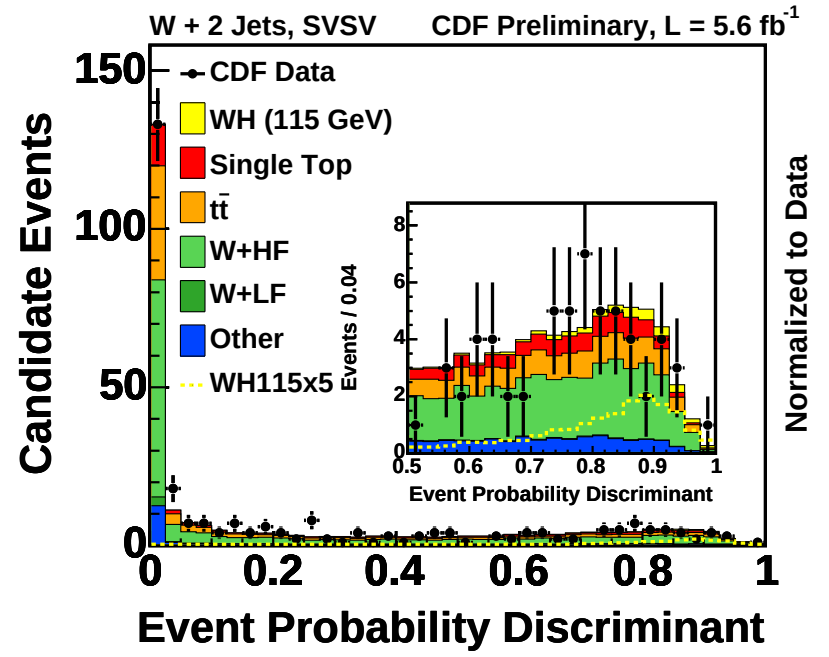


We need good lepton identification, $\not\!\!E_T$ reconstruction and b-jet tagging to perform the search.

Low Mass Higgs (l): $WH \rightarrow l\nu bb$

- Reference channel due to the presence of a lepton: high sensitivity.
- Signature extended with “loose” (i.e. non-trigger) leptons to increase acceptance.
- Several channel used: 3-jet, tagging categories,...
- Several optimizations: Neural-network, ME-based discriminants,...
- IFCA/U. Oviedo involved in the analysis





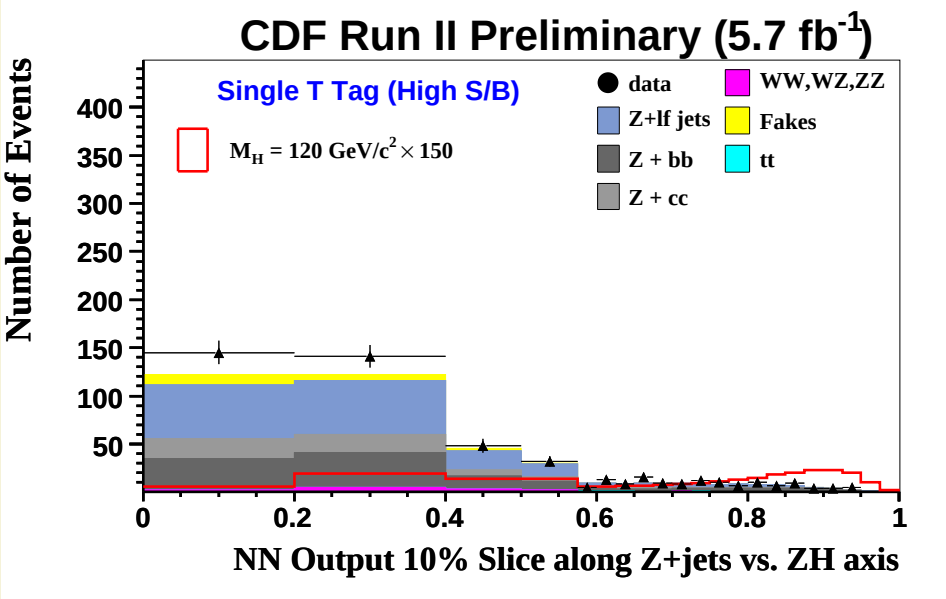
PhD Thesis by Bárbara Álvarez (U. Oviedo)

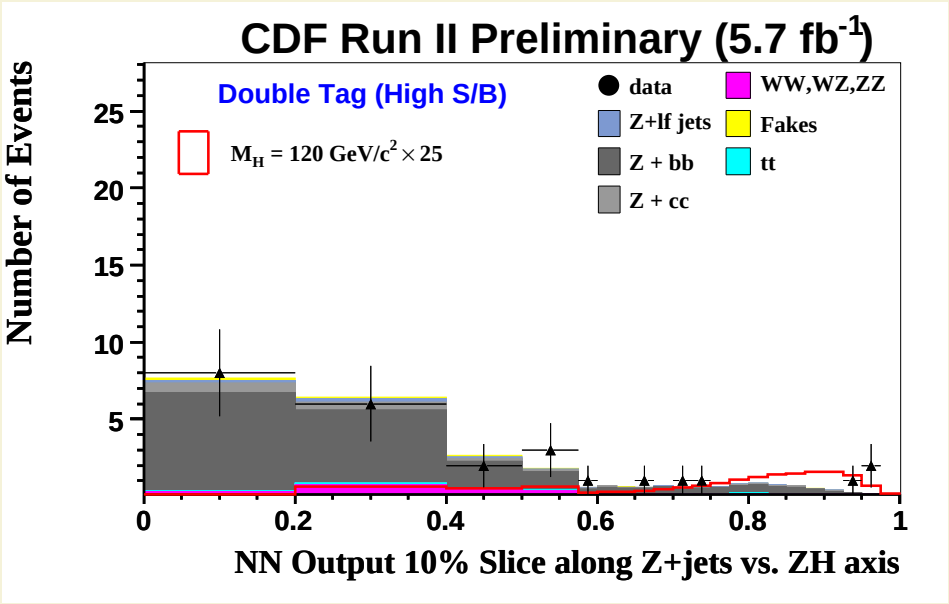
The 95% C.L. observed (expected) limit over the SM obtained in this signature:

3.6 (3.5) for a Higgs mass of 115 GeV/c^2

Low Mass Higgs (ll): $ZH \rightarrow llbb$

- Very clean signature even with “loose” leptons due to Z constraint.
- Sensitivity is reduced by the branching ratio (but still good!)
- But topology is used to improve dijet-mass resolution (by assuming total transferve momentum is zero).
- Also using several parallel channels and optimizations.
- IFAE involved in the analysis



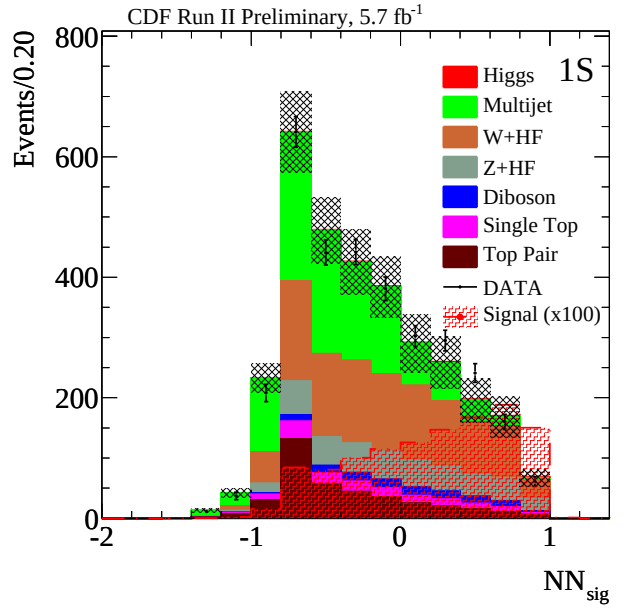


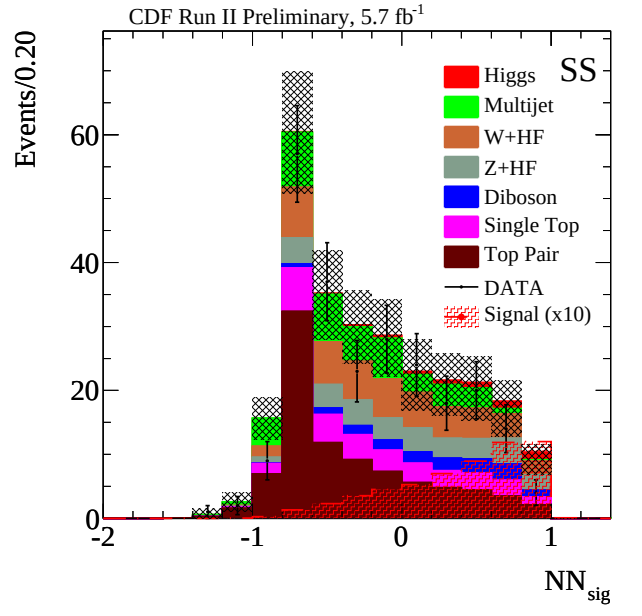
The 95% C.L. observed (expected) limit over the SM obtained in this signature:

5.99 (5.48) for a Higgs mass of 115 GeV/c^2

Low Mass Higgs (III): $ZH \rightarrow \nu\nu bb$

- Very sensitive final state due to large branching ratio.
- Signature is not clean due to lack of charged leptons.
- But topology used to reduce backgrounds, especially fake Missing-ET due to mismeasured jets.
- Also using several parallel channels and optimizations.
- CIEMAT involved in the analysis



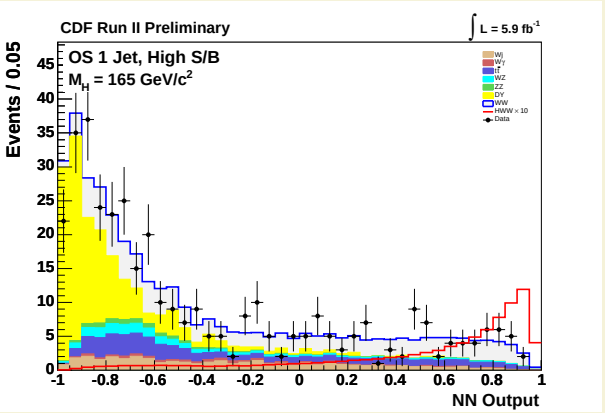


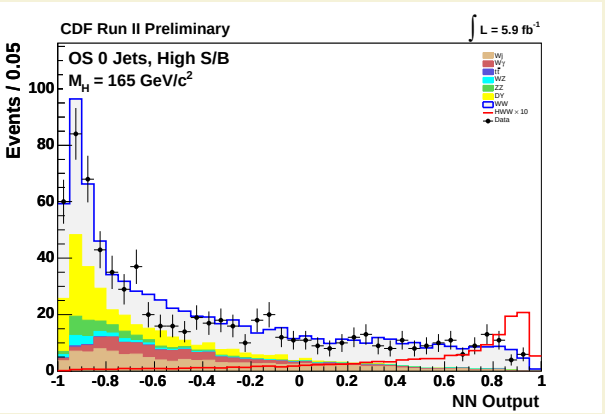
The 95% C.L. observed (expected) limit over the SM obtained in this signature:

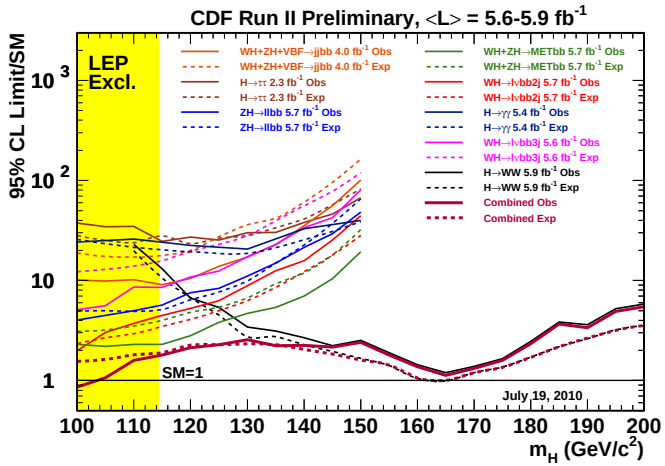
2.3 ($4.0^{+1.6}_{-1.2}$) for a Higgs mass of 115 GeV/c^2

High Mass Higgs: $H \rightarrow WW$

- Search of the gluon-gluon fusion in dilepton channel.
  - → High cross section (reaching high mass)
  - → Clean signature (high sensitivity)
- Additional channels allows to increase acceptance.
- Already at exclusion of SM Higgs.
- The current plan (for Winter Conferences?) is to exclude regions with data from single experiment.





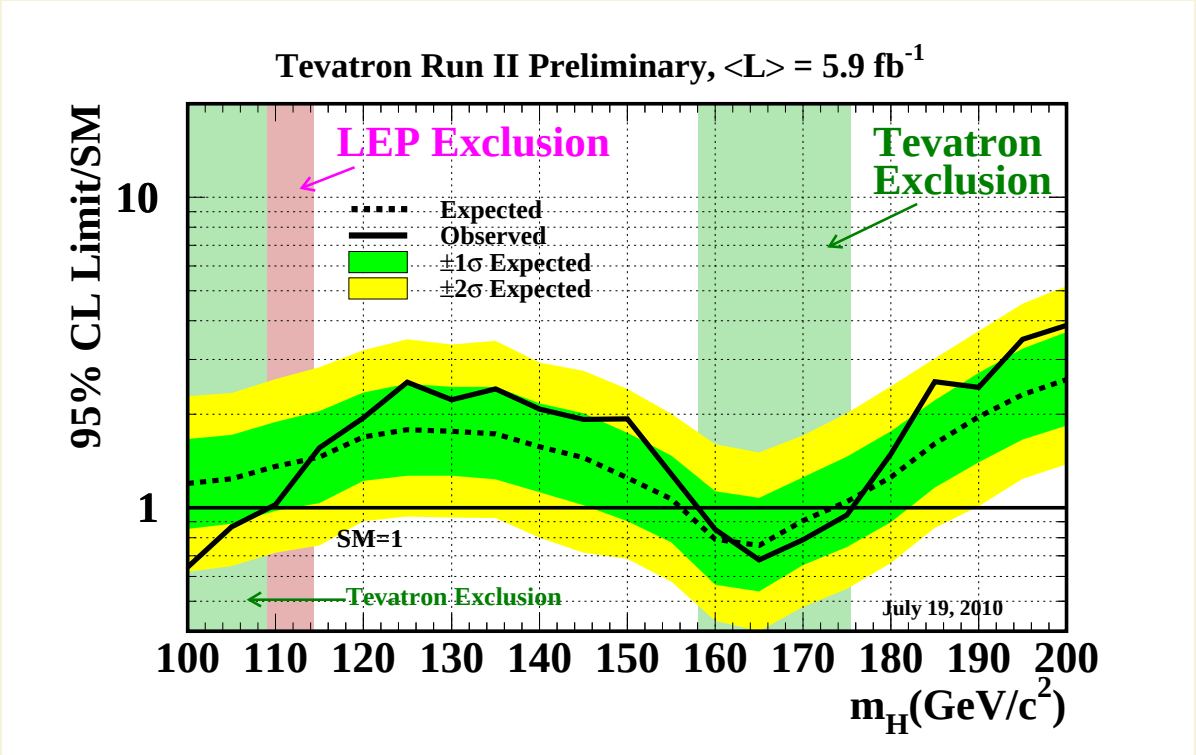


- The results at high masses is encouraging the collaborations to look everywhere for the Higgs.
- Several main signatures
- Several channels in each signature
- This makes the combination a complete nightmare

but it really pays back in terms of scientific output.

Tevatron Combination

. . . and the final exclusion plot (as in Summer 2010) is:



- **The allowed regions are getting tight:**

Soon there will be no place to hide!!!

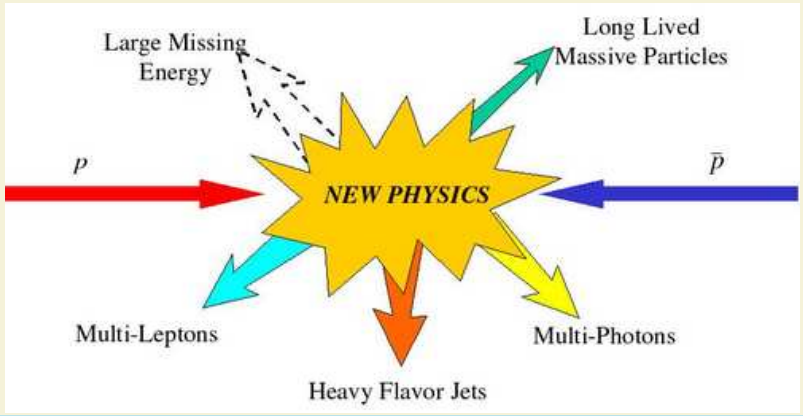
- **Combining this result with the electroweak fits the contraints on Higgs are becoming seriously tight:**

⇒ **High-mass Higgs is becoming more and more unlikely (again, assuming just SM).**

⇒ **Finding low-mass Higgs is becoming reachable at Tevatron (purely SM-Higgs).**

Beyond the Standard Model

- **Despite of its sucess, we know the SM cannot be complete.**
- **It does not explain all observations:**
  - $\Rightarrow$ **Gravity not yet included at quantum level.**
  - $\Rightarrow$ **Neutrino masses and oscillations.**
  - $\Rightarrow$ **Dark matter and dark energy.**
- **And it has (theoretical) problems with unaswered questions:**
  - $\Rightarrow$ **Three generations?**
  - $\Rightarrow$ **Hierarchy problem.**
  - $\Rightarrow$ **. . .**
- **The SM requires to be extended to include all these.**



The large amount of energy available at the Tevatron collider makes it a very good place to look for Physics beyond the SM

Searches for Supersymmetry

- This is the most popular extension to the SM (with several models containing it)
- Very rich spectra of new particles.
- Well-motivated theoretically.
- Provide stable and neutral candidate to Dark Matter (if R-parity is conserved).

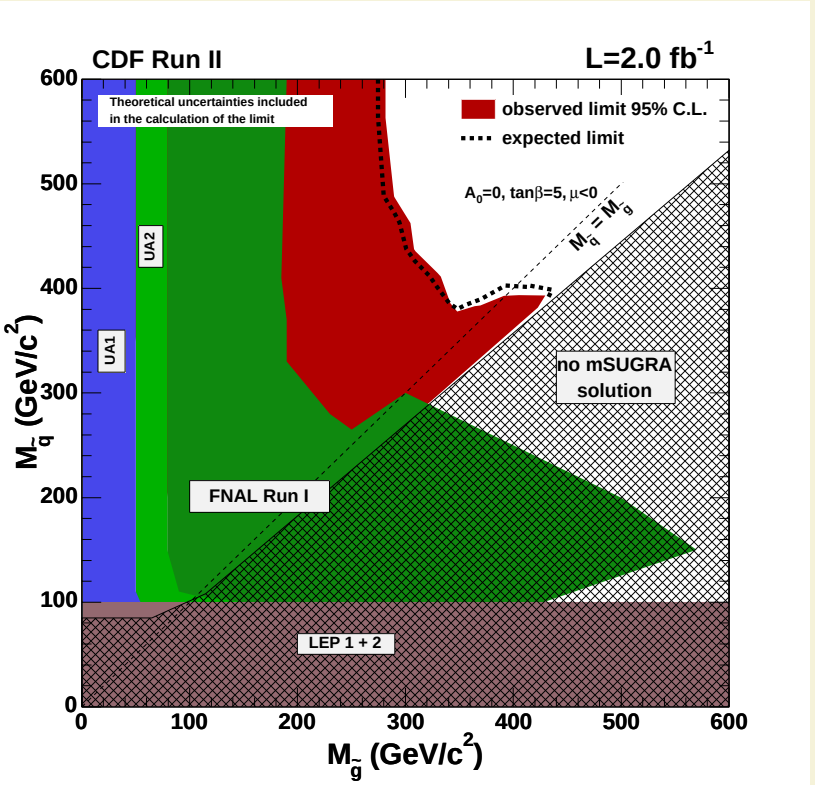
- The most important channels at a hadron collider (squarks, gluinos, gaugino-pair production) did not report hints of New Physics.

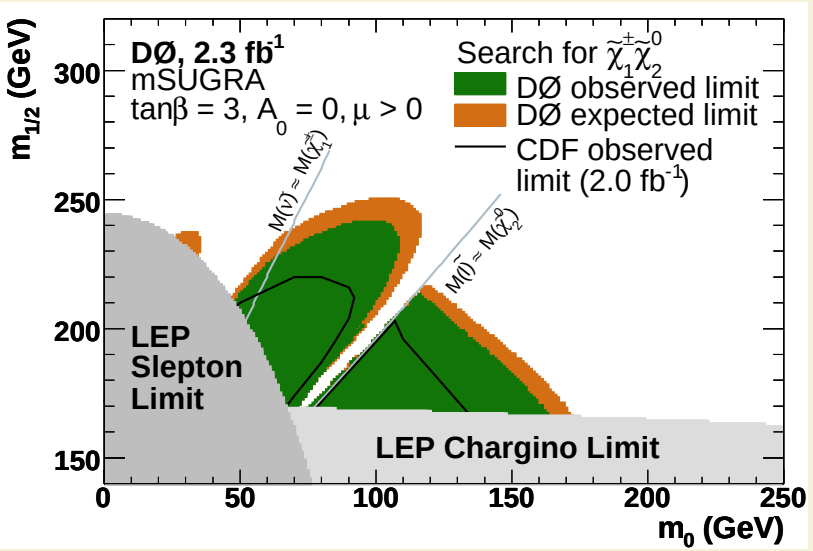
- In the last years focused on more specific final states that may escape main channels:

  $\Rightarrow$ Use of b-tagging, photons (GMSB).

  $\Rightarrow$ Still motivated theoretically.

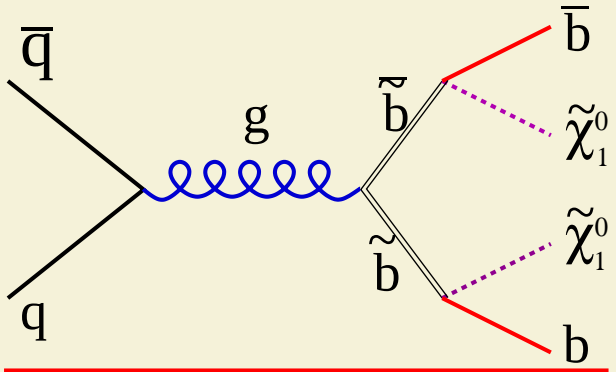
- We expect LHC will soon take over on SUSY.





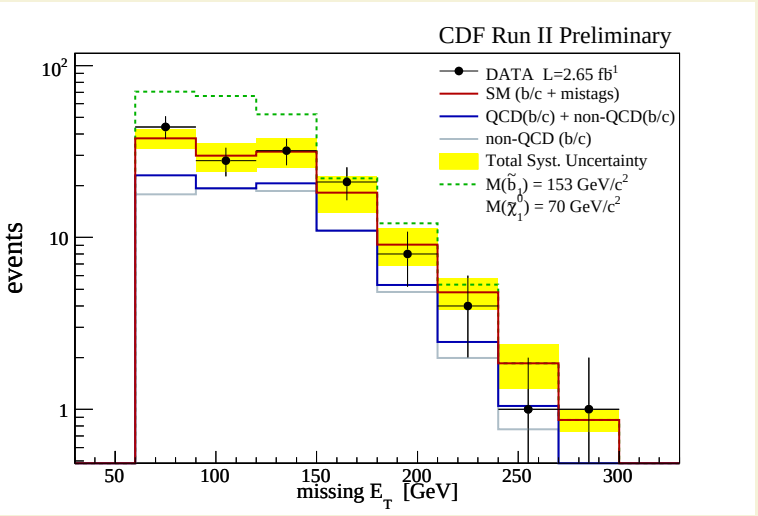
Direct Sbottom Production

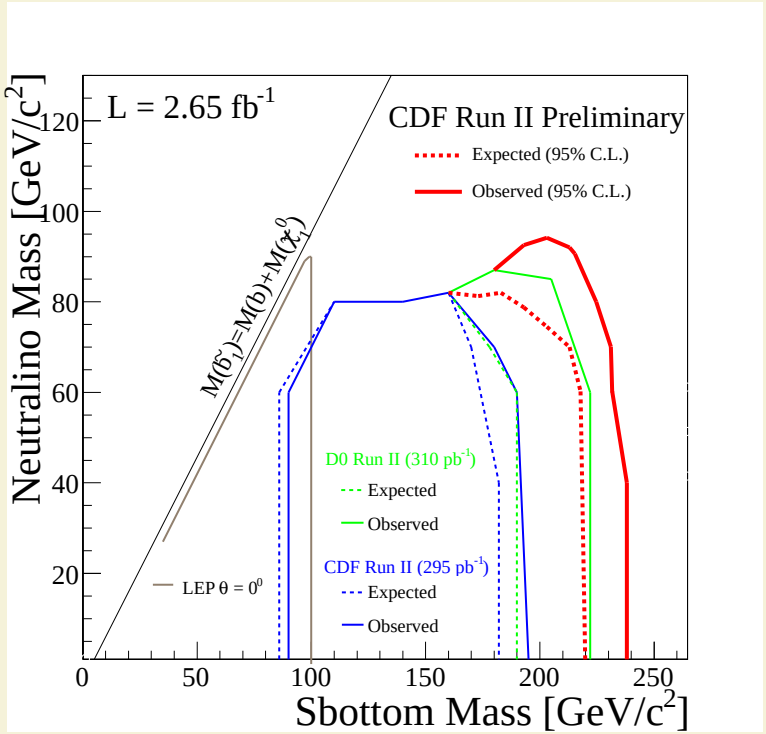
- **The decay is 100% to bottom and neutralino.**



$\not\!\!E_T$+2 b-jets

- **Background dominated by multijet and mistags.**
- **Others are estimated with MC.**
- **Optimization based on**
  - ⇒ **Kinematics: $\not\!\!E_T$, $\sum E_T$ (jets)**
  - ⇒ **b-tagging of jets (secondary vertices)**
- **Good agreement with the SM expectations.**

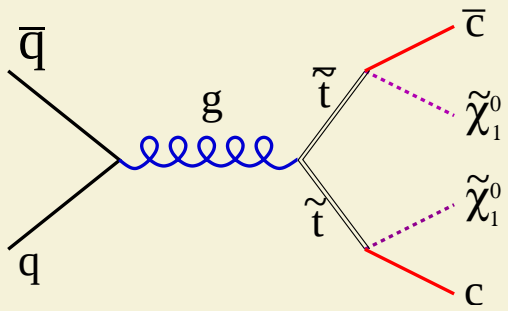


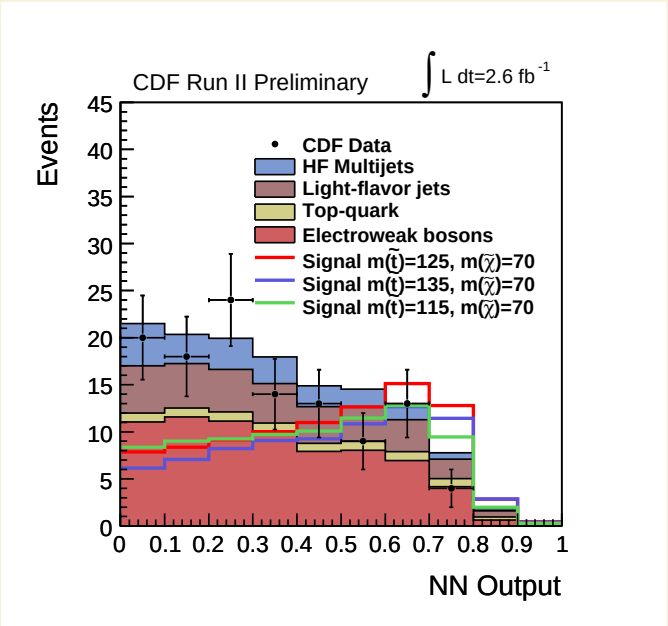


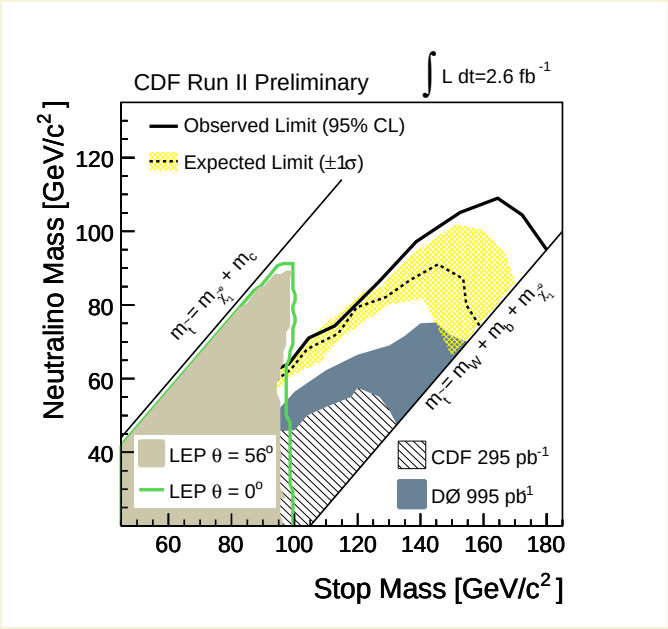
PhD Thesis by Gianluca De Lorenzo (IFAE)

Direct Stop Production

- Due to the specifics of the third generation, there are motivations that the SUSY partners may also have specific properties.
- Having a large mixing of chirality states, the lightest mass eigenstate could be much lighter to “normal” sfermions.
- In fact there is strong motivation to set the scalar top as the next-to-LSP particle (due to large top mass) and its decay into charm and LSP.



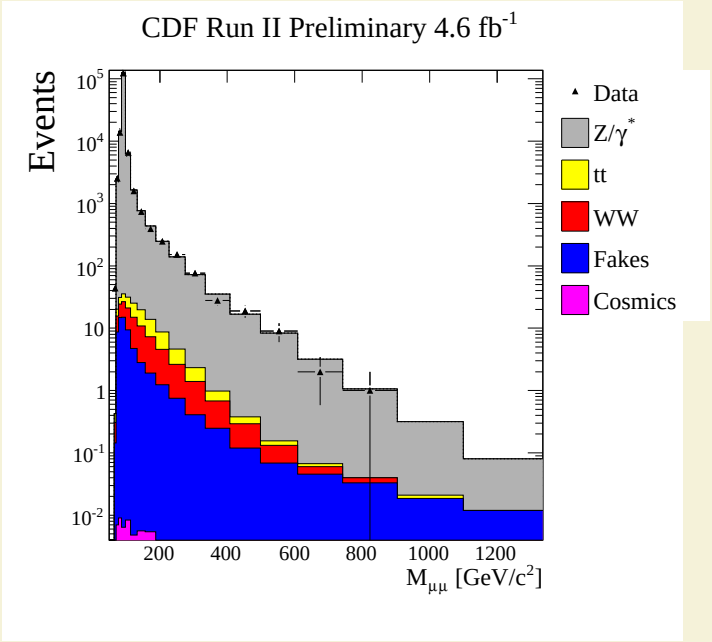


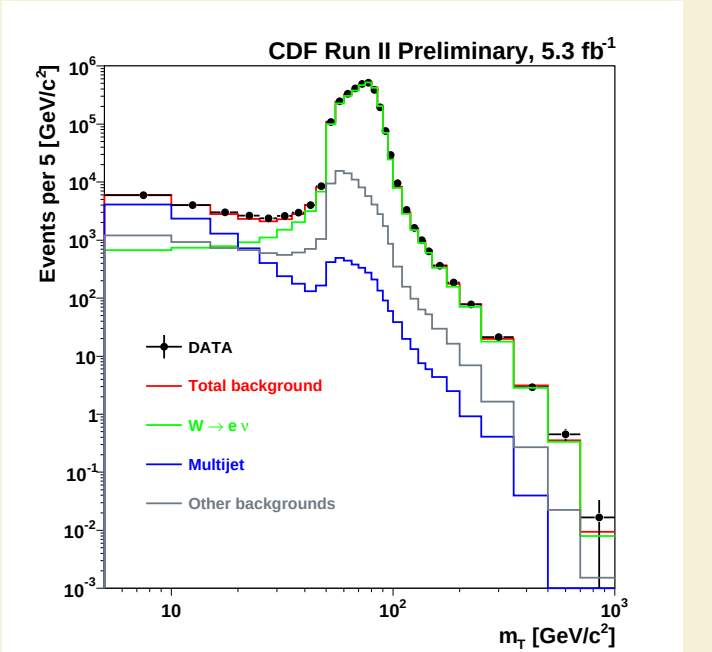


PhD Thesis by Miguel Vidal (CIEMAT)

- New CDF analysis exploited properties for charm-tagging of jets to reduce background.
- Kinematic Neural-Network output used as discriminating variable (using tools and experience from Higgs searches).

Z' and W' searches





- **Expected resonances in several extensions of the SM, especially in those with additional gauge groups.**

- **Searches sensitive to resonances decaying to dileptons (either ll or $l\nu$), very model independent.**

- **Very recent effort to get the best possible result before LHC takes over.**

- **Good agreement with SM predictions.**

- **Results at the kinematic limit:**

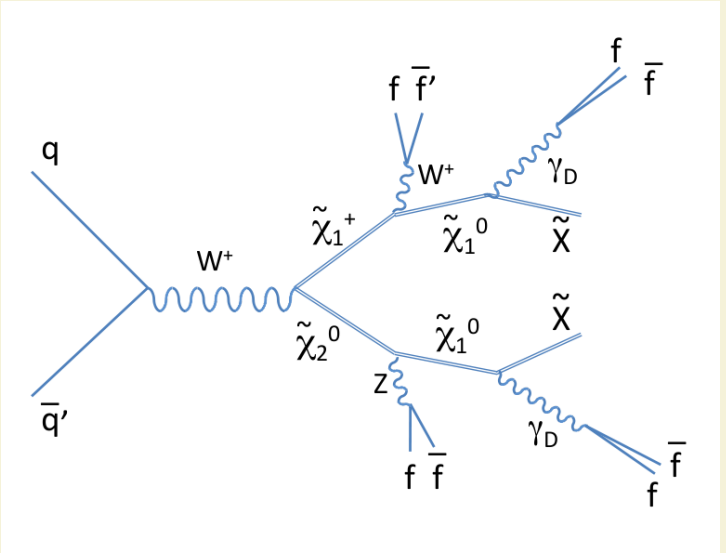
$$m(Z') > 1.07\ \text{TeV}/c^2 \quad \textbf{(SM couplings)}$$

$$m(W') > 1.1\ \text{TeV}/c^2 \quad \textbf{(Manifest LR symmetric)}$$

(Limits at 95% C.L.)

Moving towards more exotic signatures

With the reduced chances of fastly increasing statistics and the LHC taking over, the Tevatron searches are moving towards more exotic or rare signatures.

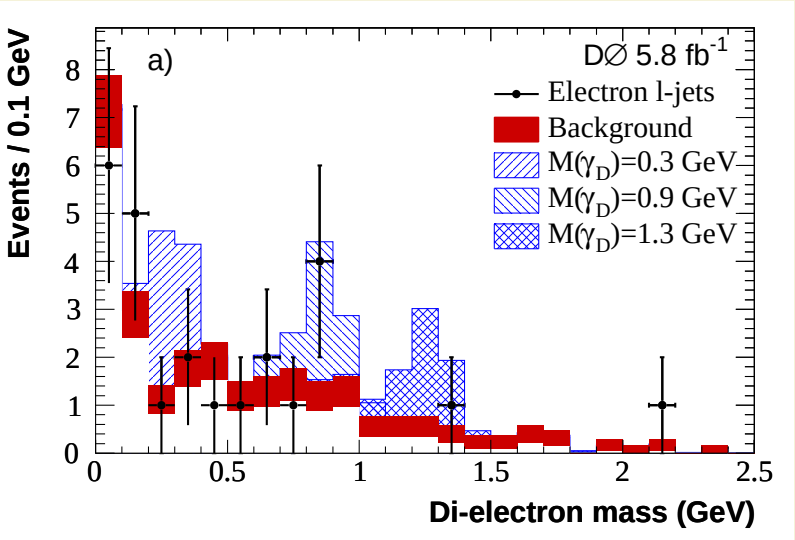


- **Interest in Hidden-valley models with hard to reconstruct signatures:**

  ⇒ Near-by dileptons from boosted low-mass objects.

  ⇒ "Leptonic" jets.

- **Motivated by the positron excess in cosmics rays (observed by PAMELA).**

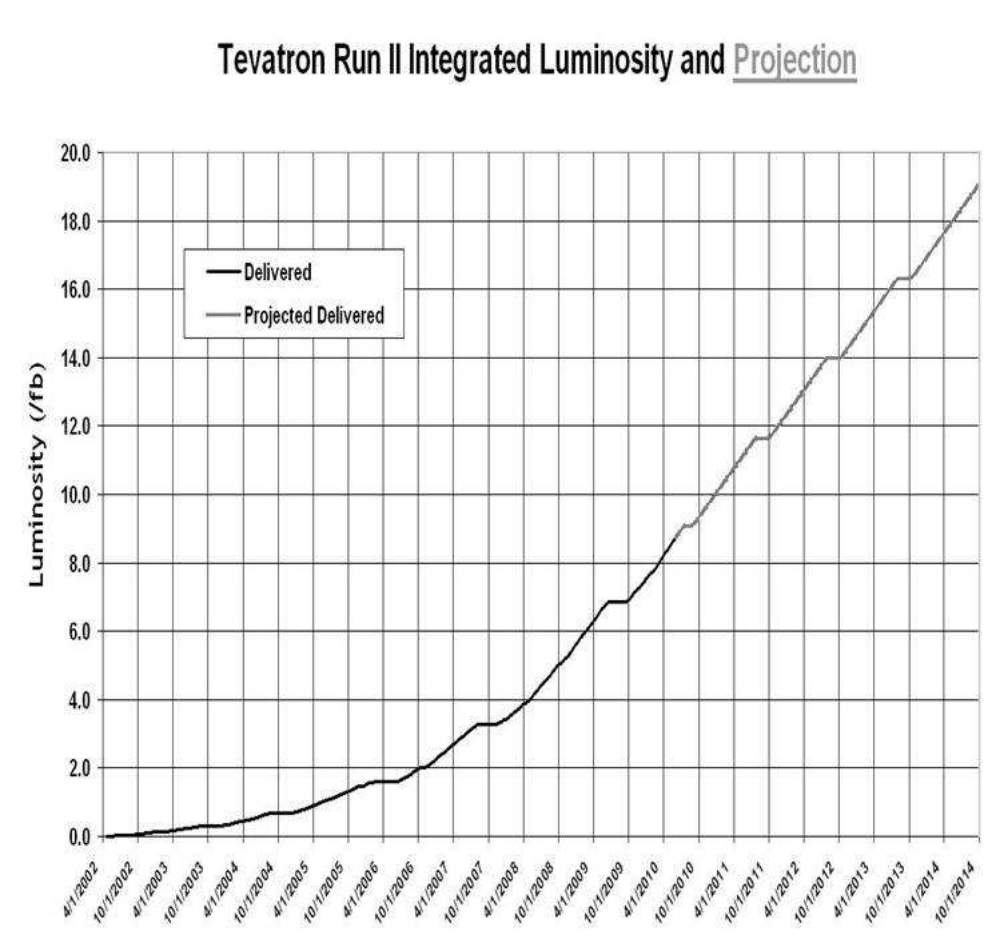


- **Perhaps missed in unoptimized analyses.**
- **Several analysis by DØ very recently.**
- **Results in good agreement with expectations.**
- **First limits in this kind of topologies.**
- **More statistics would improve sensitivity.**

We still expect hints of New Physics in the Tevatron datasets

Plans for the future: extending the Tevatron run

- **Current plan is to run the Tevatron up to September 2011.**
- **Main reason to stop is for Fermilab to focus on NOνA and the intensity frontier.**
- **On the other hand, Tevatron is still the most productive experimental program at Fermilab and it is performing very well.**
- **There is a proposal to extend the Tevatron run for 3 more years (up to Sep 2014)**



For this to happen:

$\Rightarrow$ **Additional funds ($35M per year) should be provided to the field in the USA budget.**

$\Rightarrow$ **Effort to minimize impact on NOνA and other projects.**

(However, it is known that some impact cannot be avoided).

The general case for the extension

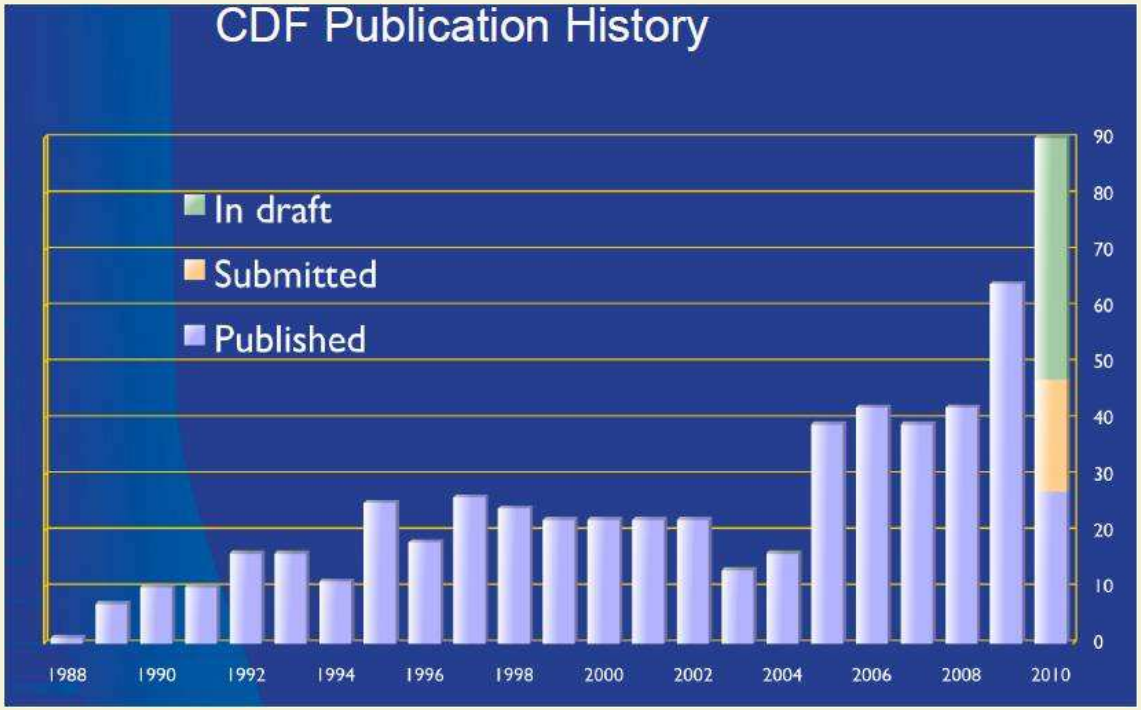
Tevatron is unique as a $p\bar{p}$ collider, giving complementarity in some topics to the LHC measurements.

Some measurements are unique/easier with a CP-symmetric initial state

- **Although Tevatron is no longer the energy frontier, its physics output will be fundamental during the first LHC years.**

- **Very large datasamples and well understood detectors.**

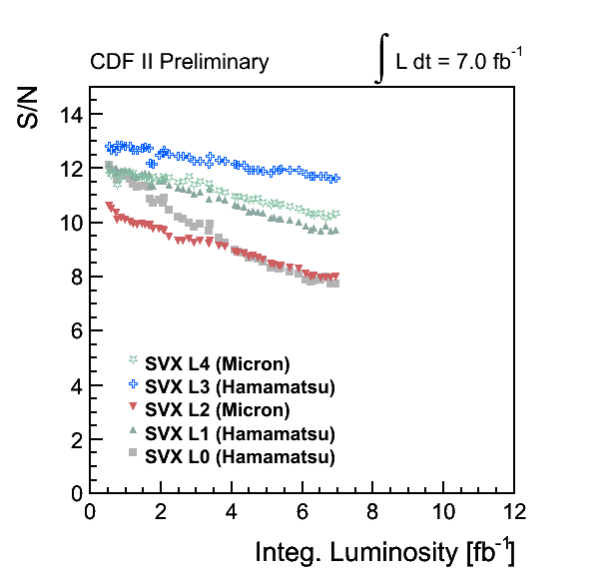
- **Also the experiments are perfoming very well and are still at their top of physics production.**

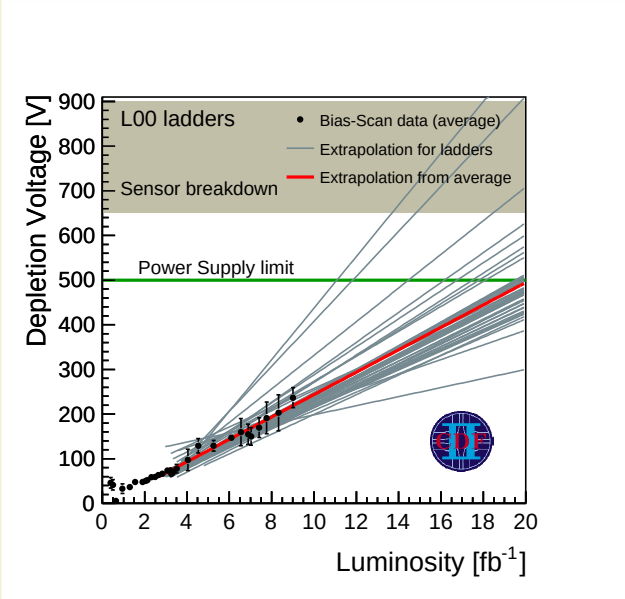


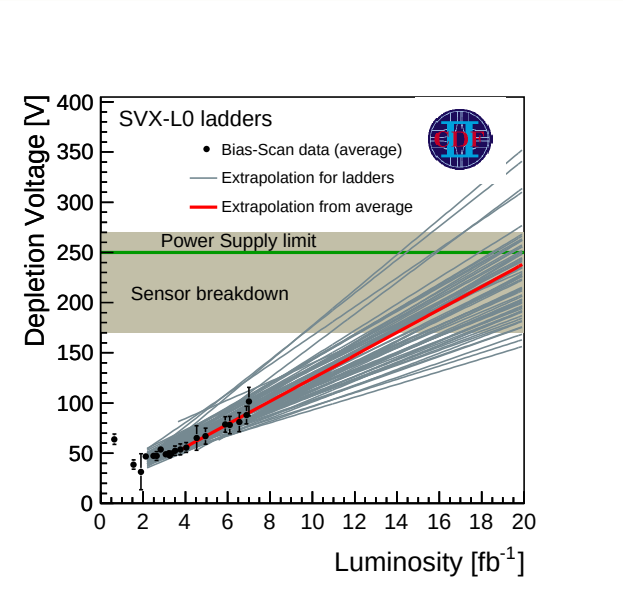
- **The three Spanish institutions at CDF have expressed interest in staying beyond 2011 if the run is extended.**

Will the detectors survive?

- One of the main questions is whether the detectors will be able to make it for 3 more years.
- Detailed studies to assess longevity, especially for the ageing in the inner tracking detectors.
- e.g. Silicon detectors at CDF **(CIEMAT is the main player here)**







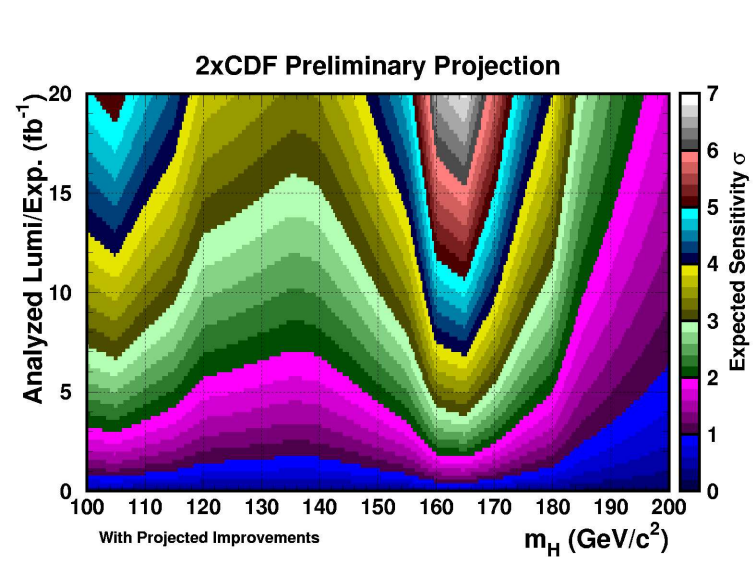
PhD Thesis by Roberto Martínez Ballarín (CIEMAT)

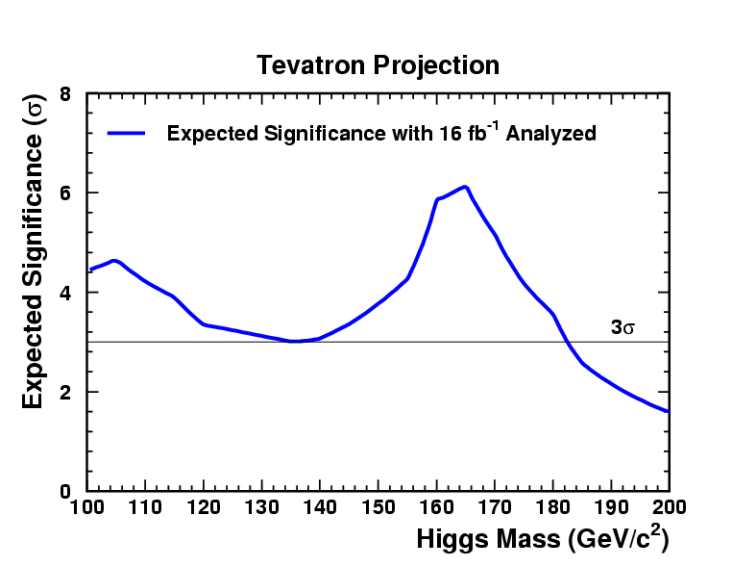
- Situation will not be ideal, but perspectives are very good.
- Degradation in performance will be compensated by improving reconstruction.
- Other concerns: electronics, spare situation, . . . (ok if extension is warranted).

Physics motivations: Low-mass Higgs

- As have been advertised the main motivation is the possibility of learning something about the presence of a low mass Higgs.

- With the expected datasets at the end of the extended run, sensitivity is enough to exclude or see first hints of the Higgs for all masses reachable at Tevatron.





- Especially interesting is the possibility of detecting $H \longrightarrow b\bar{b}$ that will be hard to measure in the first LHC years.

The Tevatron extension should be seen as a collaborative CERN-FNAL effort and a scientific opportunity for the HEP community

http://www.fnal.gov/pub/today/archive_2010/today10-09-17.html
http://cdsweb.cern.ch/journal/CERNBulletin/2010/38/News%20Articles/1291610?ln=en

Summary

- **Presented the status and latest results from the Tevatron experiments:**
  - $\Rightarrow$ **Accelerator and detectors are performing very well.**
  - $\Rightarrow$ **Physics output at its best.**
- **Improving SM measurements and precision with every fb^{-1}.**
- **Still lots to do on Higgs and New Physics Searches.**
- **Only a small fraction of topics covered: for more, check web pages:**
  - **CDF: http://www-cdf.fnal.gov/physics/physics.html**
  - **DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results.htm**
- **Optimism to extend the run up to September 2014 (18-20 fb^{-1})**
  - $\Rightarrow$ **Complementarity to LHC is SM and "low-energy" measurements.**
  - $\Rightarrow$ **Good chances for low-mass Higgs.**
- **The importance and reach of the Tevatron data is still to be seen.**

BACK-UP SLIDES

(Qualitative) Comparison between CDF and DØ

CDF Characteristics

- Wire drift chamber in 1.4 T

⇑ Silicon detector with very inner layer (mounted directly on the beampipe)

⇓ Muon coverage $|\eta| < 1.5$

⇓ Simple muon reconstruction

⇑ Better tracking (specially in trigger)

DØ Characteristics

- Scintillating fiber chamber in 2 T

⇑ Weekly reversed polarity

⇓ Inner layer added for Run IIb

⇑ Muon coverage $|\eta| < 2.0$

⇑ Cleaner muon reconstruction

⇑ Better calorimetry and muons

CDF limited coverage for muons is compensated by the use of isolated tracks as muon candidates:

⇒ Lower purity and no dedicated triggers (using $\not\!\!E_T$)

⇒ Calorimetry helps in identification (as MIP signatures)

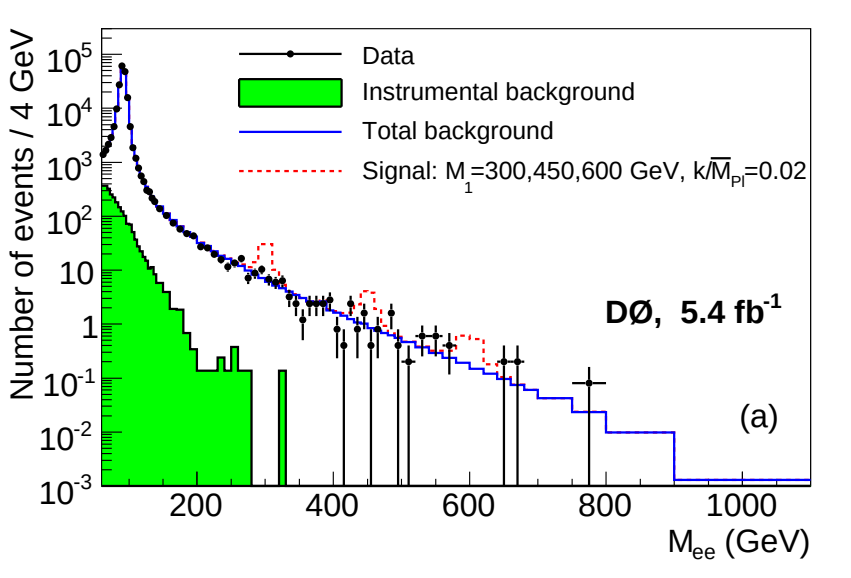
⇒ Useful in analyses where acceptance is an issue (e.g. Higgs)

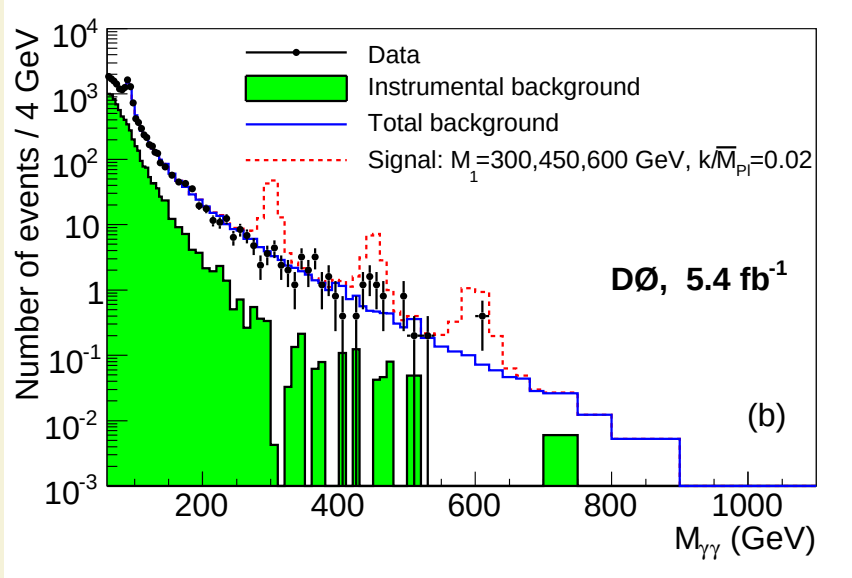
DØ has really been able to compensate his limitation in tracking for high-p_T (which is not actually the case for b-physics)

Competitive/better results in b-tagging and τ-based analyses.

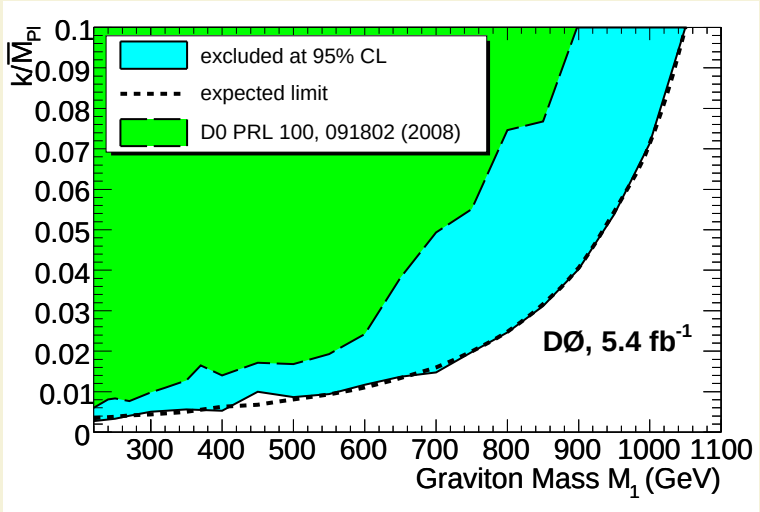
Graviton searches

- **Searching for general diphoton resonances.**
- **Motivated by Kaluza-Klein tower of graviton states, appearing in Randall-Sundrum models for warped multidimensional geometry.**





- **Since the branching ratio to ee is half of that for diphotons, DØ increased the sensitivity by adding this signature.**
- **For large couplings results reached the kinematic limit.**
- **For small couplings Tevatron will be competitive for some time.**



Tevatron Combination: setup

- **Combination of all the results of Higgs searches from both experiments.**
- **Using discriminant distributions, not counting experiments, so several "bins" per channel.**
- **Plots are produced with entries in each "bin", ordered by sensitivity power (i.e. signal to background ratio).**
- **But limits are obtained by following a rigorous statistical analysis of the distributions and their correlations.**
- **A good way to test significance is the Log-Likelihood ratio which allows to compare with the Background-only and Background+Signal significance.**