XXXVII International Meeting on Fundamental Physics
Benasque, Huesca (Spain)
February, 9-13 2009

Searches at the Tevatron

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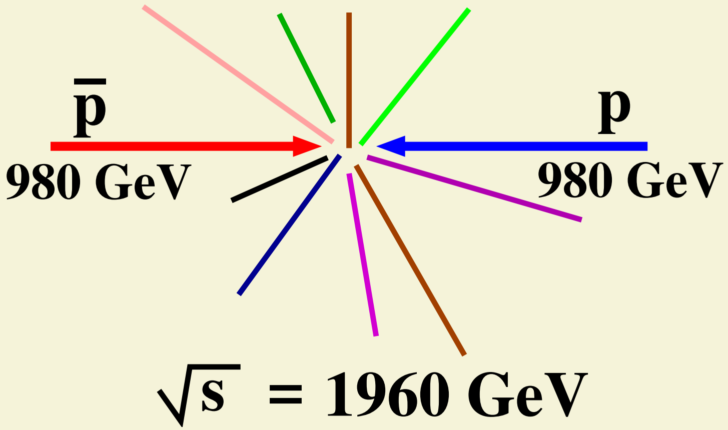
Outline

- Introduction:
  - ⇒ The Tevatron Collider
  - ⇒ Searches at the Tevatron
- Basic techniques used in searches
- The CDF and DØ Experiments
- Results of the analyses:
  - ⇒ SM-related searches
  - ⇒ SM Higgs searches
  - ⇒ Beyond the Standard Model
- Summary and future prospects

The Tevatron Collider: Description

- Tevatron is an accelerator colliding protons and antiprotons.
- Located at Fermilab (USA)
- The beam energy is 980 GeV, which provides the most energetic collisions in the world (for now).



$\Rightarrow$ Beams are collided in two locations, in which the CDF and DØ experiments collect their data.

$\Rightarrow$ Crossing time: 396 ns

$\Rightarrow$ Initial Inst. Lum.: $\sim 350\ \mu$b^{-1}/s (Jan'09)

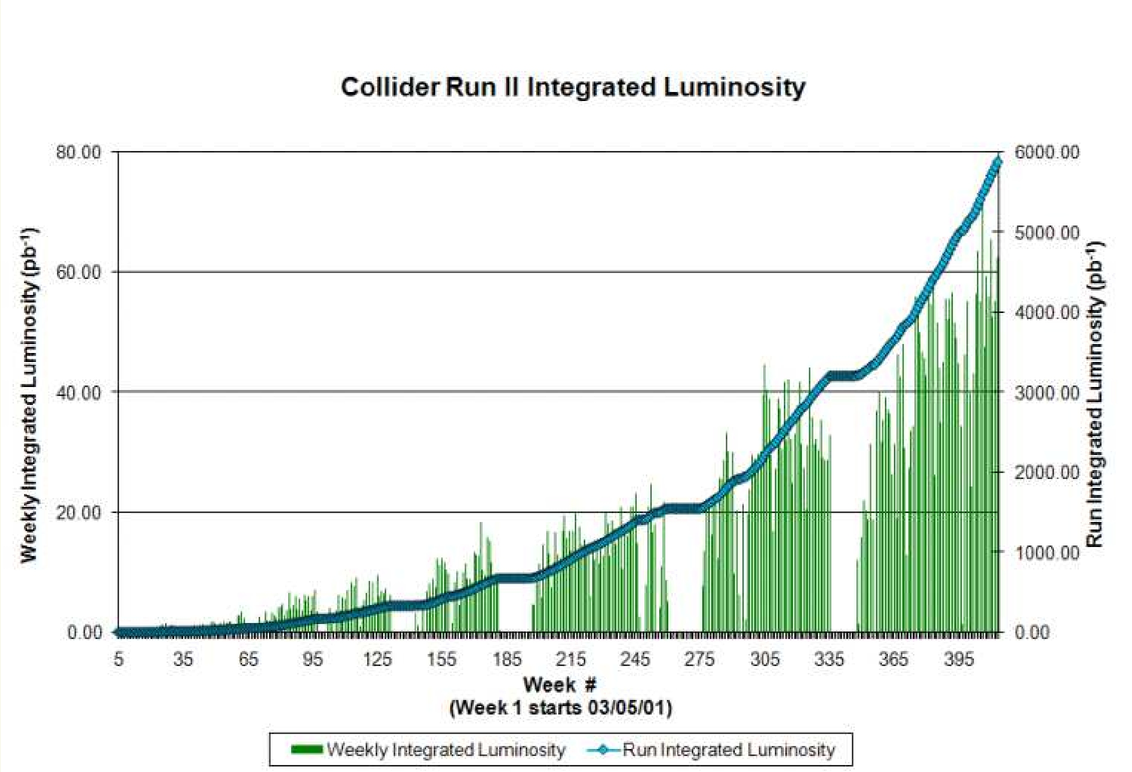
$\Rightarrow$ 5-6 pile-up collisions on average

The Tevatron Collider: Performance

Although the beginning of the Run II was rather disappointing, the machine is performing really well for the "Run IIb" (after the April'06 shutdown).

The luminosity (L) is the reference variable to quantify performance since it allows to compute the expected number of events coming from a process with a known (or predicted) cross section (σ)

$$\boxed{N = \sigma \cdot L}$$



⇒ Integrating ~ 250 pb^{-1}/month

⇒ Currently 6 fb^{-1} delivered

⇒ New luminosity-based records very often.

The results shown here do not include all this data sample.
Expecting to have updates soon (Experiments will use ~ 4 fb^{-1} for Winter Conf's.)

Searches in HEP

What do we actually mean by "search"?

It means to look for events/properties not explained by already-known processes

In practice (i.e. in this talk) means that based on some kind of knowledge:

⇒ Look for what we expect to be there (e.g. diboson production, single-top)

Depending on the context, this may be considered a "confirmation check" or an actual search for something we never observed/measured before

⇒ Look for what we hope/suspect it is there (e.g. Higgs boson)

In this kind of search signature and predictions are typically known, which sometimes does not simplify the analysis

Distinction with previous one may be controversial

⇒ Look for what we do not know whether it is there (exotics)

More freedom of what to require to the events since the idea is to find events that are hardly explainable by our established knowledge.

In some limit, it may be consider as a "tough test" of the theoretical predictions as it checks the expectations in strange corners of the phase space.

Searches at the Tevatron: The problem

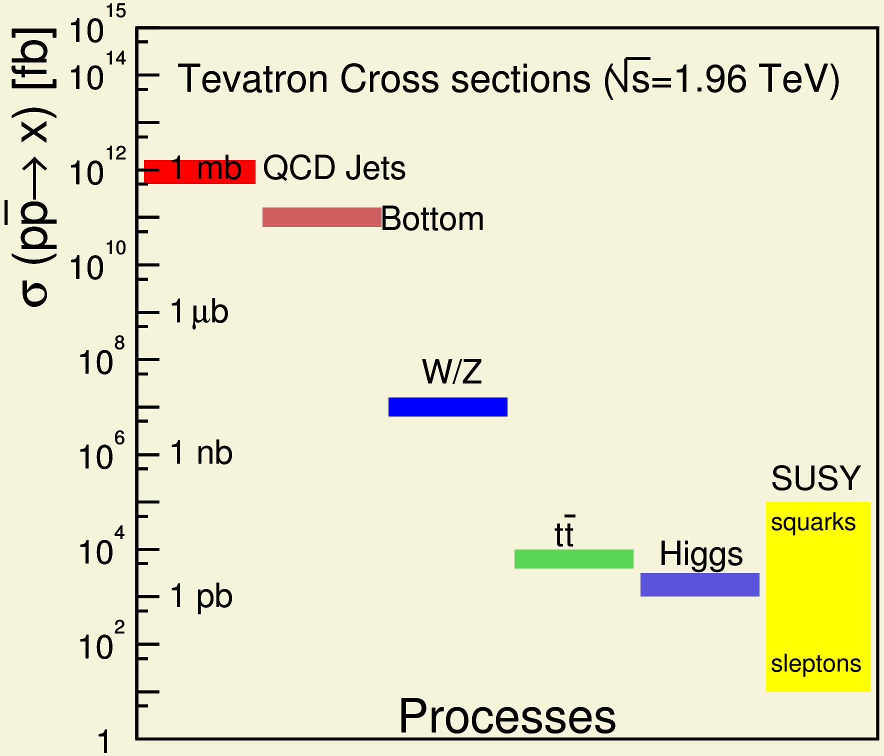
- Tevatron, having been the frontier-energy collider for a long time, is an ideal place to perform searches.

- Searches at a collider are generally hard since the interesting processes are swamped by the known processes.

- In the case of a hadron collider the main problem is QCD jet production that is really hard to deal with because:

→ It has a huge cross section when compared to other processes.

→ Detector effects or misreconstructions compete with a physics explanation of an hypothetical signal.



- Additionally in a hadron collider the initial state is neither determined nor simple.

- This complicates the understanding of the backgrounds (even the signal-like) and reduces the sensitivity.

Reducing the background

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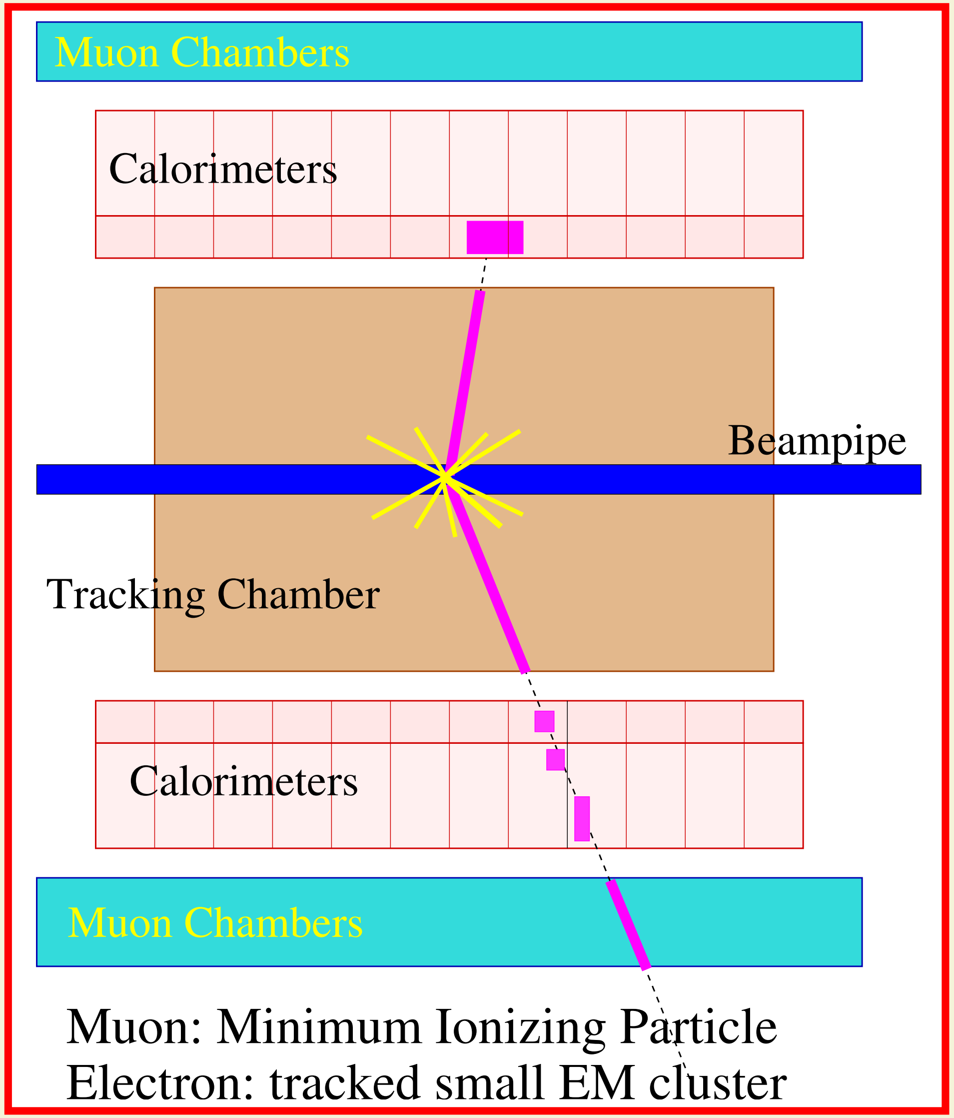

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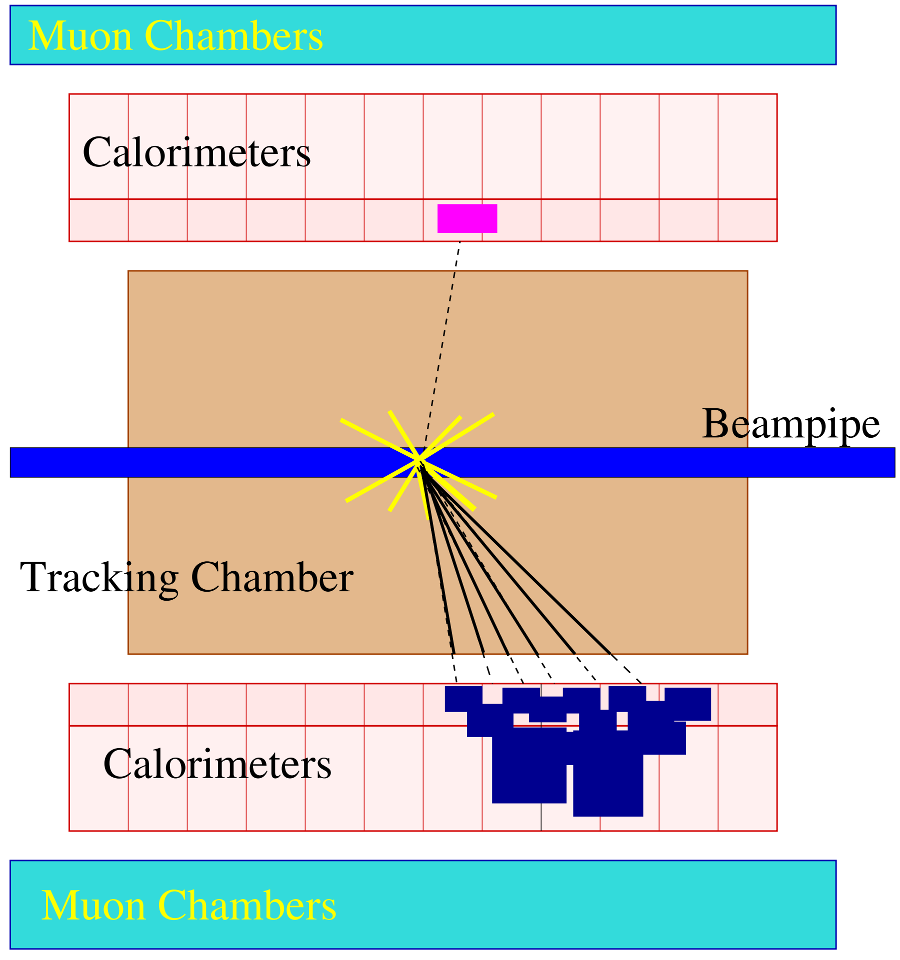

Photon: small EM cluster

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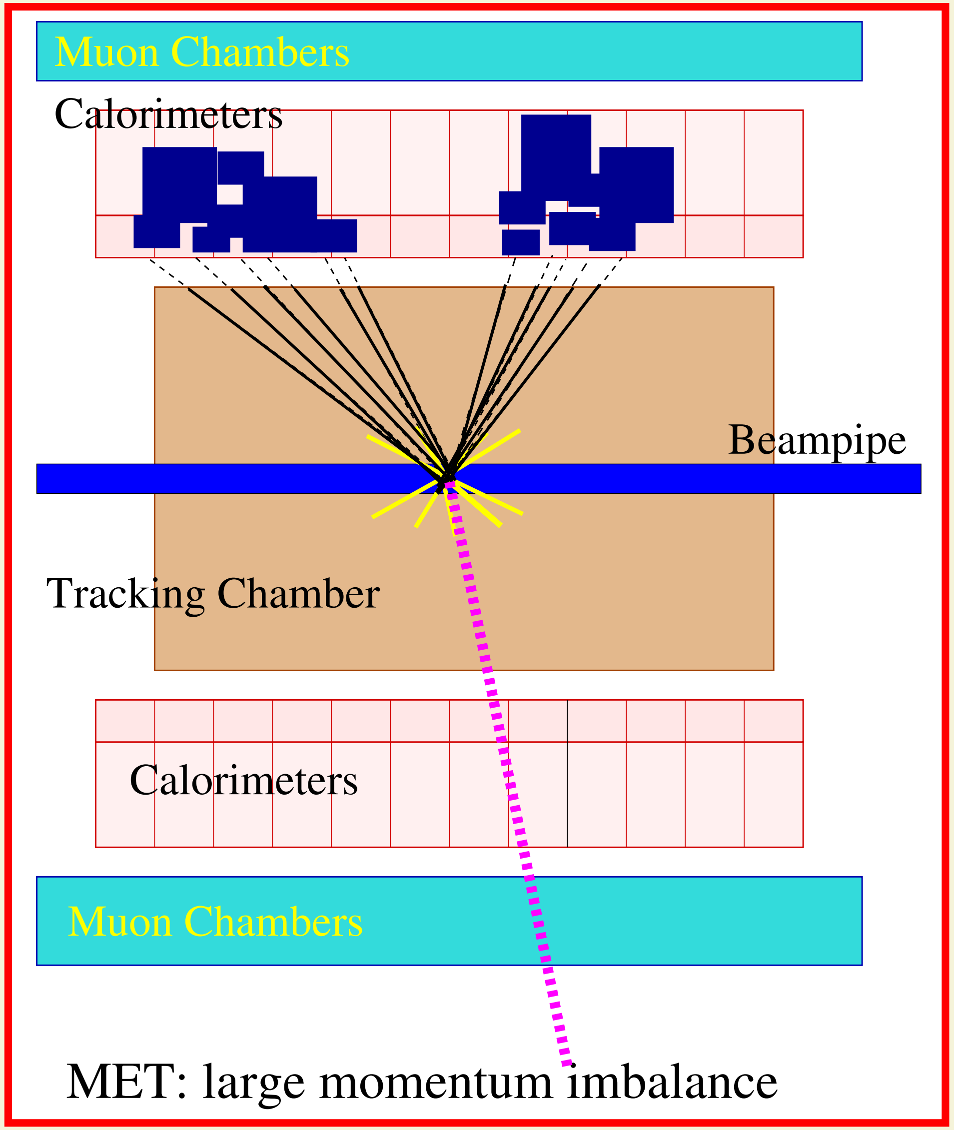

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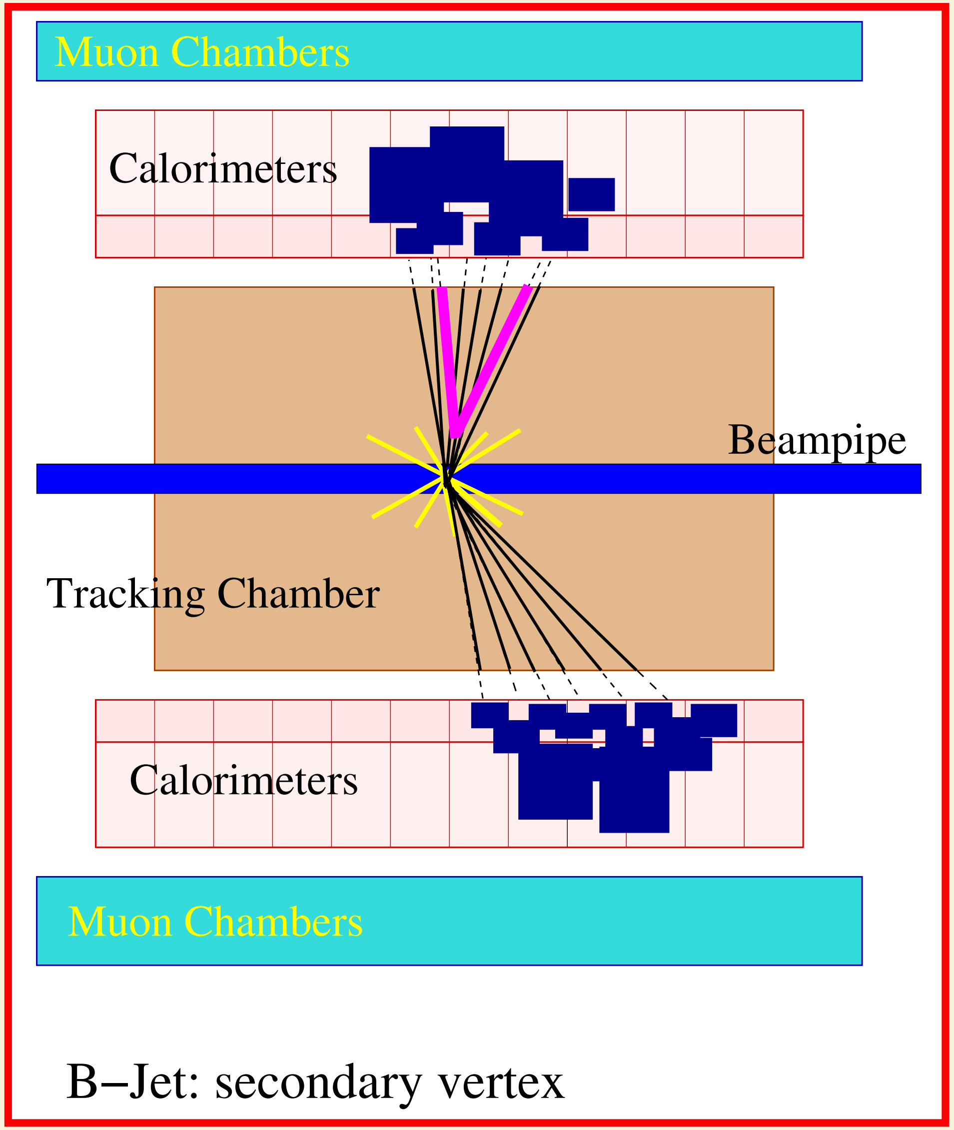

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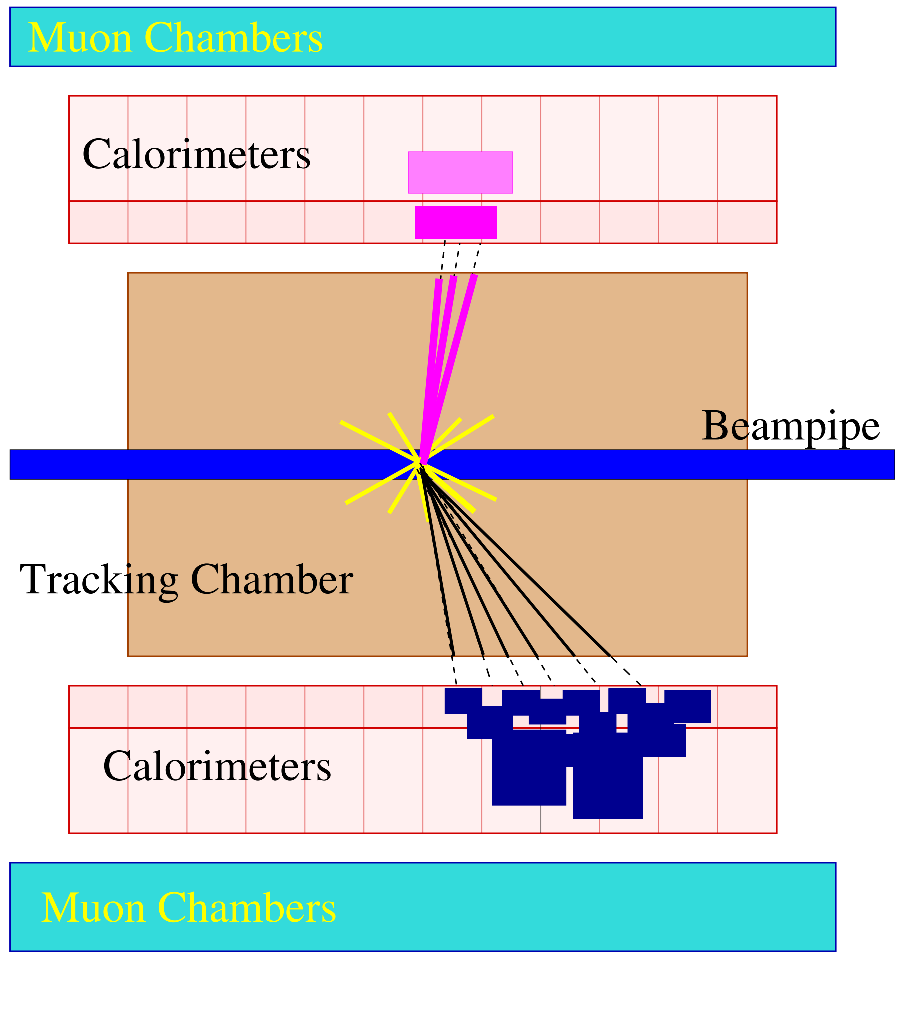
- **Tau leptons**
  - ⇒ Hard to reconstruct, and low resolution
  - ⇒ Very hard to trigger on



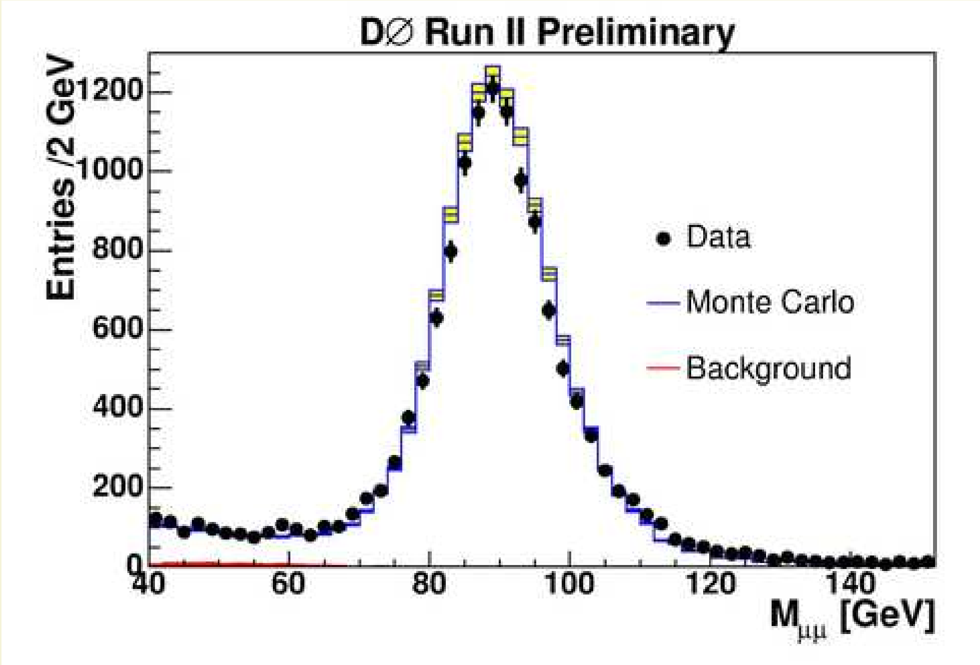
Tau: 1(3) tracks(s) and reduced cluster

Using leptons for searches

ELECTRONS are identified as small and short-depth shower ("EM cluster") in the calorimetry. If fiducial to the tracking, an associated track is usually required.

MUONS are identified as low-ionizing particle (MIP) crossing through the calorimeters and being detected in the muon chambers (located in the outside part of the detector).

- Good resolution using tracking for angular variables and tracking for muon p_T and calorimetry for electron energy.
- This is very useful to allow calibration of objects
- They are so distinctive (from jets) that are easy to identify and to use to select events online.



- They are so rarely produced that events with high-p_T leptons are always interesting and stored for analysis or calibrations.

Most of the Tevatron high-p_T program relies on lepton-based events and selection, and this also applies to searches.

Photons for searches

- Photons are reconstructed as EM Clusters without associated track.
- Veto the presence of track to reduce background.
- More difficult than electrons due to less detector information:

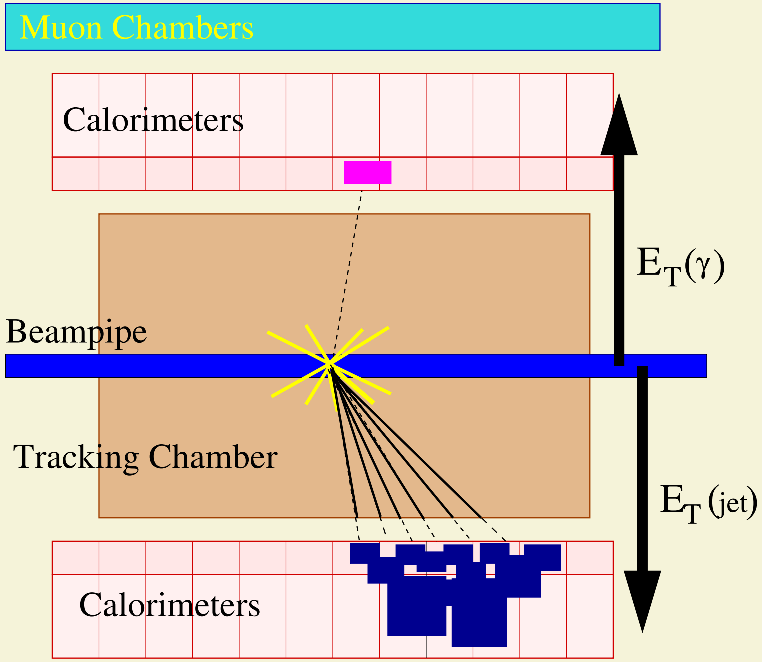
  ⇒ Higher backgrounds on event selection (even non-physics ones)

  ⇒ Harder to trigger on them

- Very important in searches to identify rare signatures (or diphoton resonances)
- On the other hand, photons are fundamental pieces of the jet energy calibration using γ+jet events and the relation

$$E_{T,\text{jet}} = E_{T,\gamma}$$

- These events allow (together with $Z \rightarrow ee$) to set the energy scale and reduce the jet-energy scale uncertainty, needed for analysis based on jets:



  ⇒ Main systematic uncertainty for signal acceptance (typically).

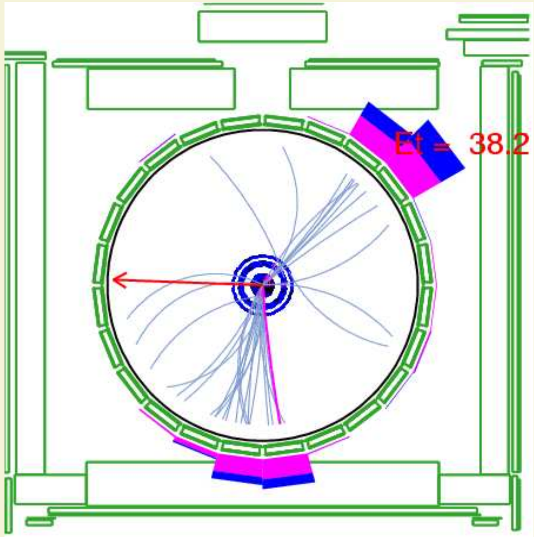
  ⇒ Large uncertainty to calibrate/normalize backgrounds.

  ⇒ Absolutely needed for sensitivity of the Higgs searches at low masses.

$\not{E}_T$ in searches

- The missing transverse energy (in fact a momentum) is defined as

$$\vec{\not{E}}_T = -\sum_{\text{observed}} \vec{p}_T$$



and provides information about the presence/production of particles that do not interact with the detectors (neutrinos).

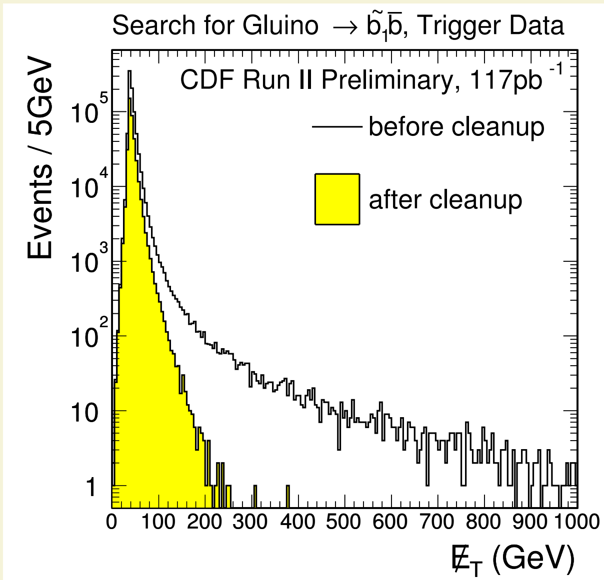
- Reconstructed summing over the calorimeter units and corrected for identified muons in the event.
- Therefore ideally requires 4π coverage
- However, the $\not{E}_T$ is a difficult quantity to work with, as expected for something that "detects invisible particles":

⇒ Very sensitive to beam-related effects

⇒ Very sensitive to the energy scale

⇒ Sensitive to pile-up collisions

⇒ Hard reconstruction and trigger

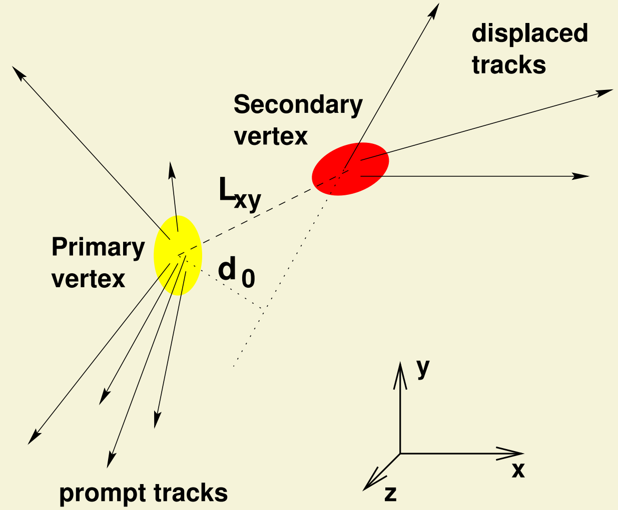


When leptons are not present, events with large $\not{E}_T$ need to be identified using triggers based on $\not{E}_T$ reconstruction.

Tagging Heavy-flavoured jets

- **With high-resolution vertex detectors it is possible to identify the presence of heavy-flavoured hadrons inside jets by reconstructing the decay vertices.**

- **This provides a currently standard way of identifying (tagging) jets in the final state as originating from a heavy quark (c or b): final states with b-jets.**

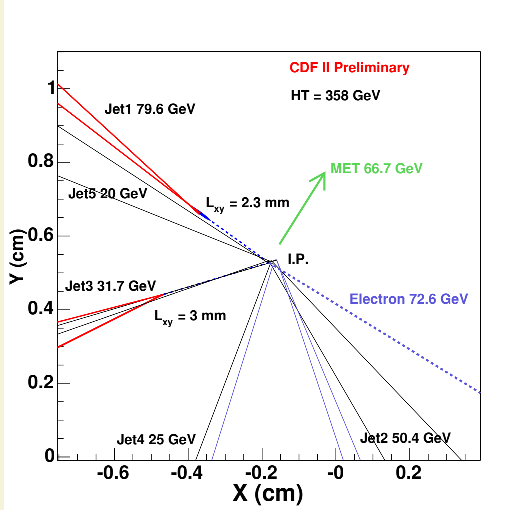


- **Common algorithms:**

  ⇒ **Reconstructing significantly displaced vertices**

  ⇒ **Studying displaced tracks within jets**

  ⇒ **Multivariate techniques combining properties of the heavy-flavoured quarks**



- **Heavy-flavour jets are enhanced requiring the presence of leptons due to semileptonic decays**

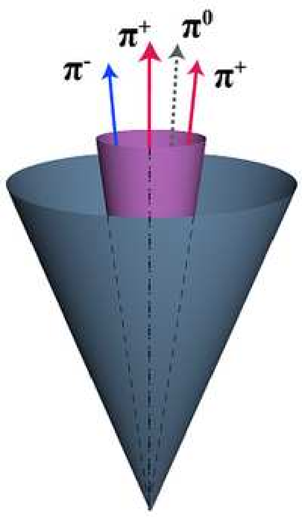
  It has the advantage of not requiring high-resolution tracking, but leptons within jets are not simple to identify/reconstruct (e.g. low p_T).

- **It should be noted that all these techniques yield samples that are enhanced in heavy-flavour jets, but still an important fraction of mistagged jets is present.**

Tau identification

Big effort performed to understand hadronic τ at Tevatron to avoid losing sensitivity due to hadronic decays.

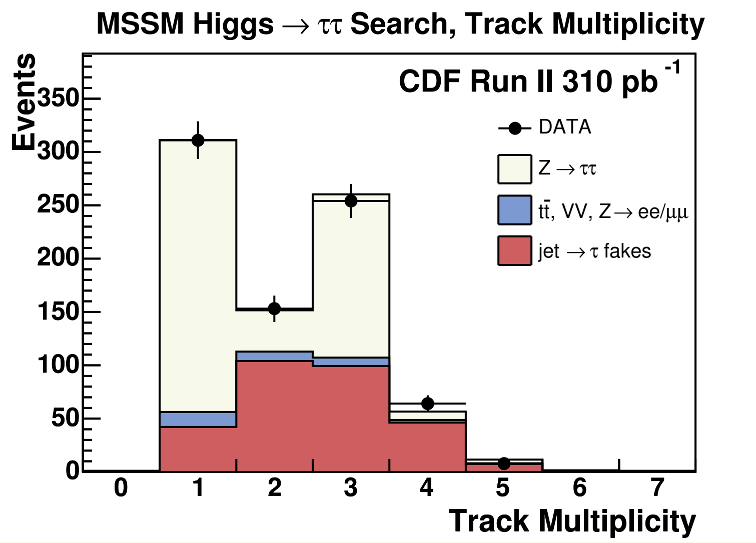
The program based on τ's is very important and interesting, especially in searches (as Higgs and SUSY).



Similarity of hadronic τ with jets makes life very hard. Algorithm are focusing on exploting the differences:

- $\Rightarrow$ **Lower tracking activity**
- $\Rightarrow$ **Narrower calorimetry depositions**
- $\Rightarrow$ **Higher EM activity (from π^0)**

Good understanding of isolated hadronic τ at both experiments



- **$Z \rightarrow \tau\tau$ is a typical control sample, but sometimes $W \rightarrow \tau\nu$ is preferred to avoid biases in signals similar to the Z.**
- **Trigger is the main limitation.**

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 tools that are needed to do physics, especially suitable for searches:

  ⇒ Silicon high-precision vertex detectors

  ⇒ Tracking chambers in magnetic field

  ⇒ 4π calorimetry with EM preshowers

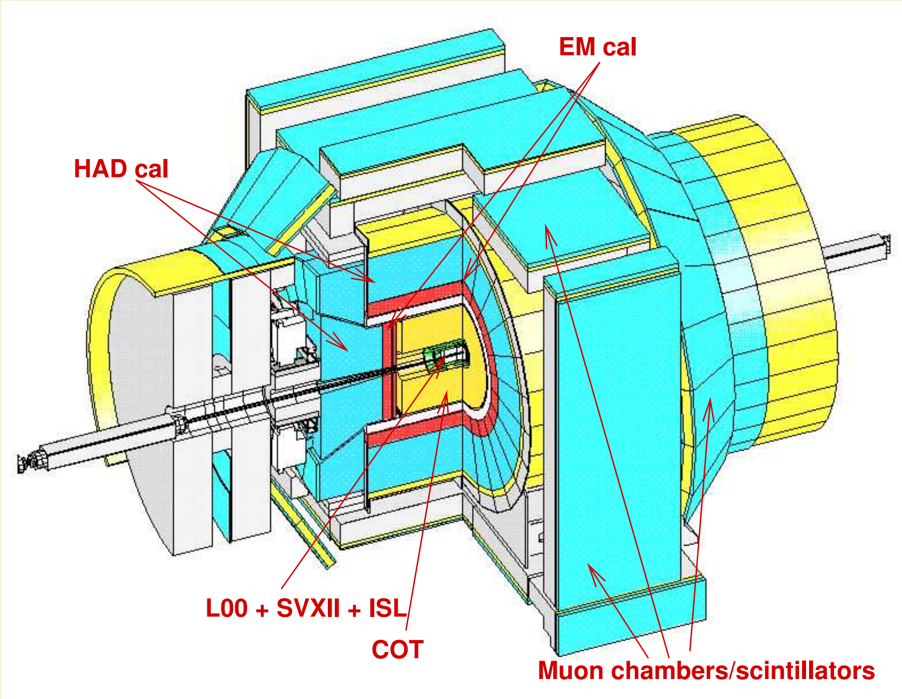
  ⇒ Calorimetry up to $|\eta| \sim 3/3.5$

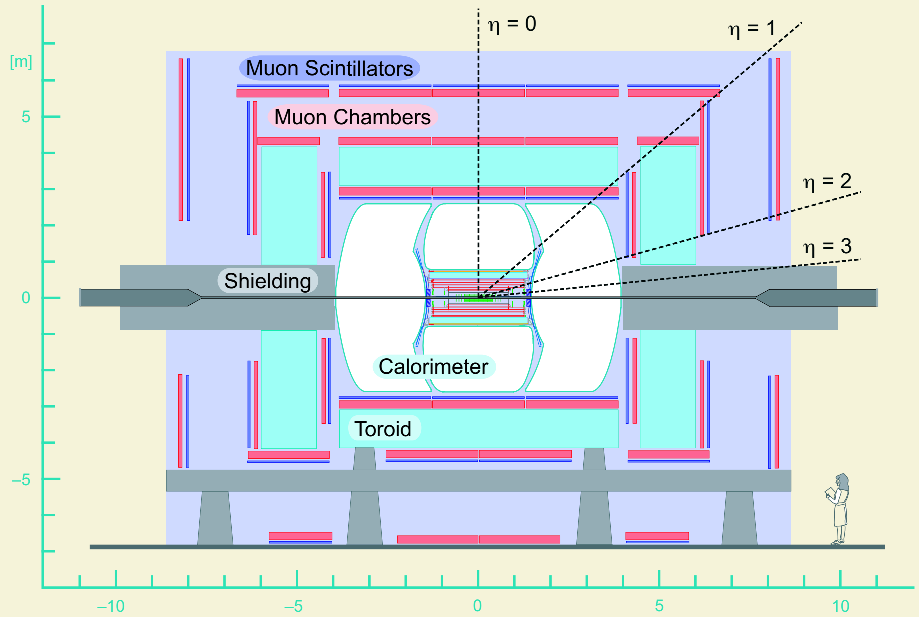
  where the pseudorapidity is a Lorentz longitudinally-invariant alternative of the polar angle and its definition is

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

  ⇒ Muon detectors (outside)

  ⇒ Axial and forward-backward symmetry





(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)

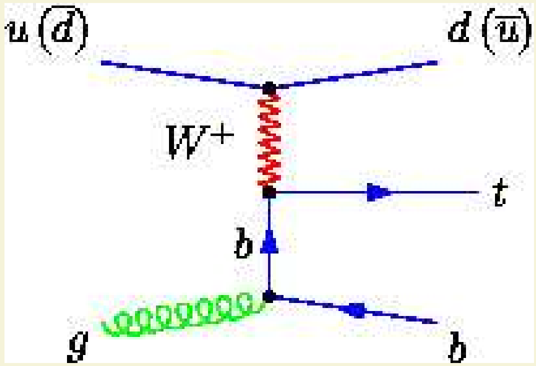
Competitive/better results in b-tagging and τ-based analyses.

SEARCHES TO

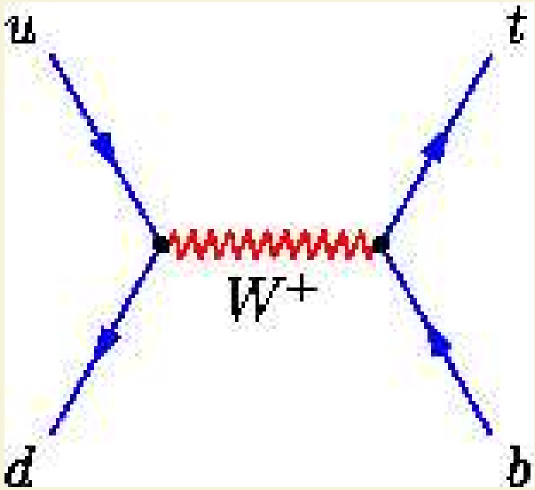
COMPLETE THE STANDARD MODEL

Search for single top production

- The top quark and its basic properties have been studied in detail during Run II via pair-production.
- However, several of its properties are not completely known and require further study.



- Single top production is a fundamental process since production is mediated by the electroweak forces.
- Sensitive to EWK couplings of the top and the $|V_{tb}|$ CKM element.



- May be sensitive to new physics (top mass is a real puzzle)
- Signature and topology is slightly different for the two main processes.
- Theoretical cross sections:

  s-channel (2 b-jets): 0.88 pb
  t-channel (1 b-jet): 1.98 pb

- W-associated production has very small cross section and it is not reachable at Tevatron.

Search for single top production (II)

- At CDF, common basic selection based on the principle of increasing acceptance, with a selection of W+jet(s) (with at least one b-tagged jet).

- Same selection for top and Higgs searches (see later).

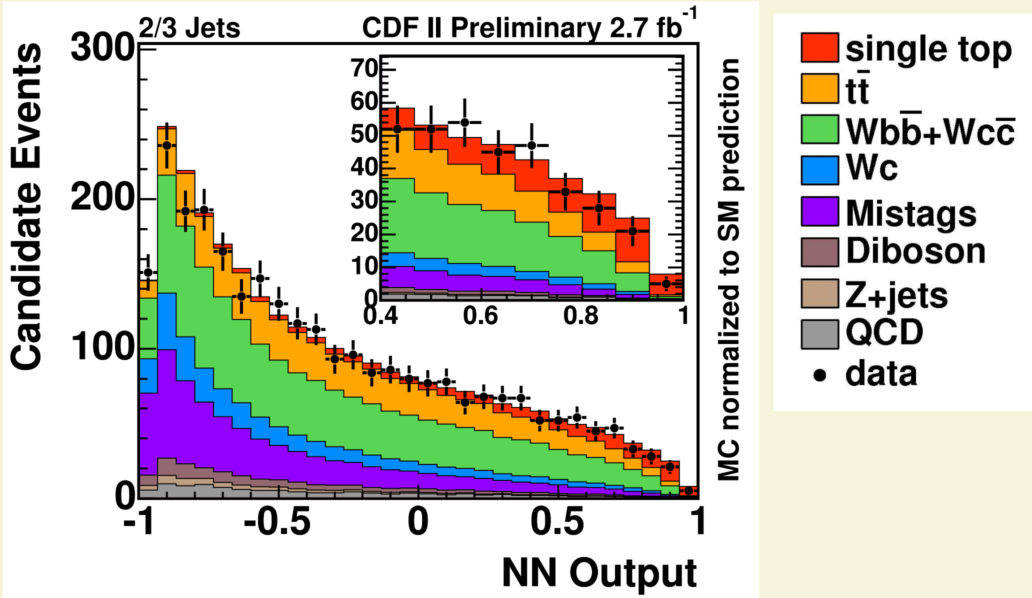
- Optimization done with several advanced techniques:

  Neural Network

  Multivariate Likelihood Function

  Boosted Decision Trees

  Matrix Element Discriminant



In addition, further sensitivity is achieved by separating the signal region in pieces depending on the number of final-state and b-tagged jets.

- Combination is done considering the correlations between the several analyses.

Search for single top production (III)

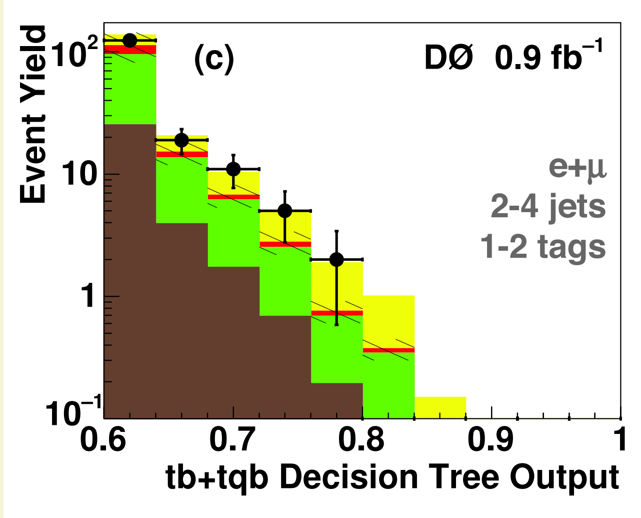
- DØ set the first evidence for single top production and measured $|V_{tb}|$ with 900 pb^{-1} of data.

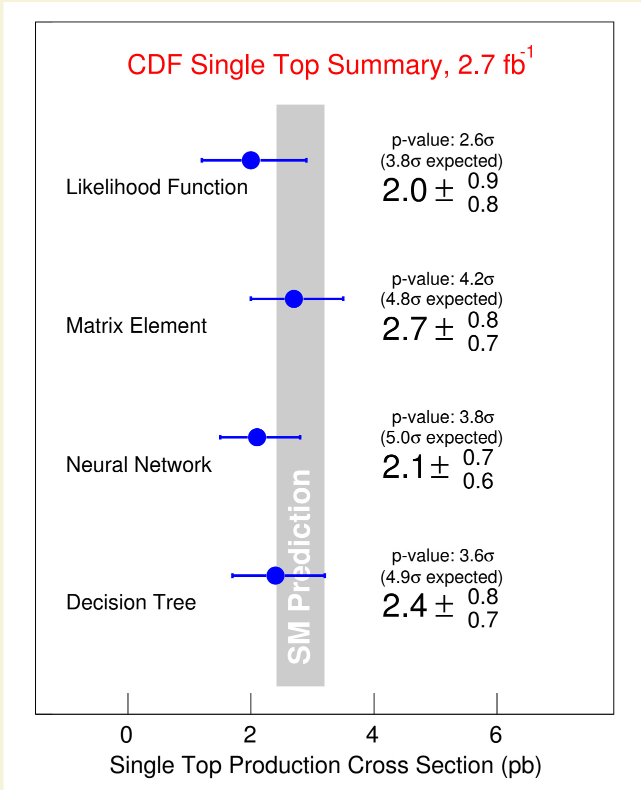
- CDF reached the observation sensitivity last year and measured the cross section. Measured sensitivity ($\sim 4\sigma$) was lower than expected.

- σ is compatible with the expectation from the SM (on the low side, that is why observed sensitivity is lower than expected).

- Hard work to observe the process and decrease uncertainties in the measured properties.

- Plan to have updated results from both experiments for Winter Conferences.

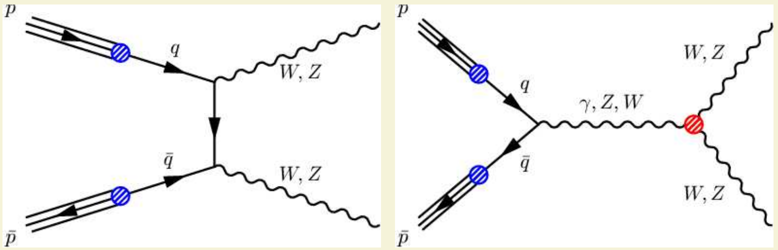


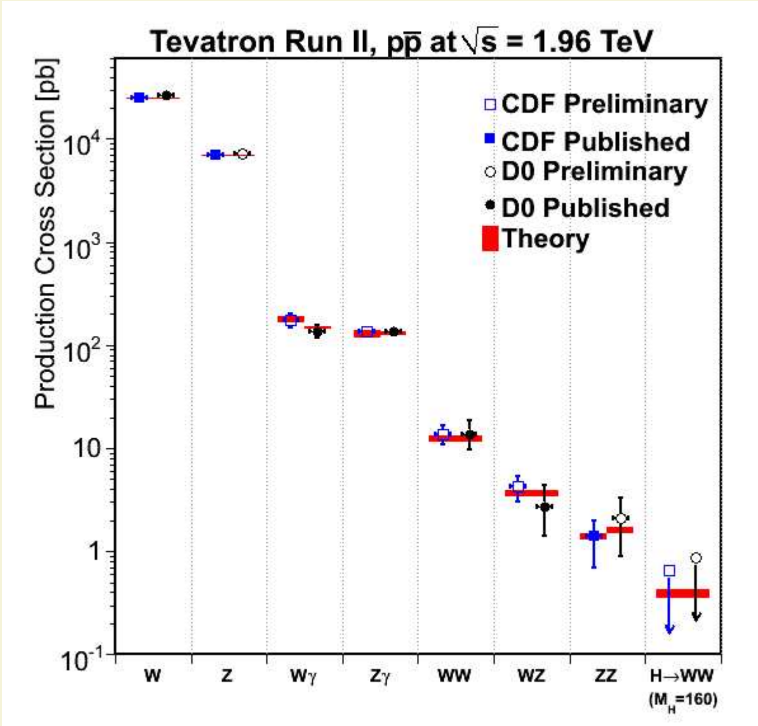


Diboson production at the Tevatron

Diboson production is a very important test of the SM structure

⇒ Sensitive to couplings between EWK bosons.





⇒ Final states are **sensitive to new physics (i.e. divergences to the SM predictions)** due to the small cross sections.

⇒ Big effort over Run II to measure cross sections

Impressive agreement with the SM predictions for boson production

⇒ Last one is *ZZ* production with large significances:

CDF: 1.4 ± 0.7 (stat)± 0.6 (sys) pb (4.4σ)

DØ: $1.75^{+1.27}_{-0.86}$ (stat)± 0.08 (sys)± 0.10 (lumi) pb (5.3σ)

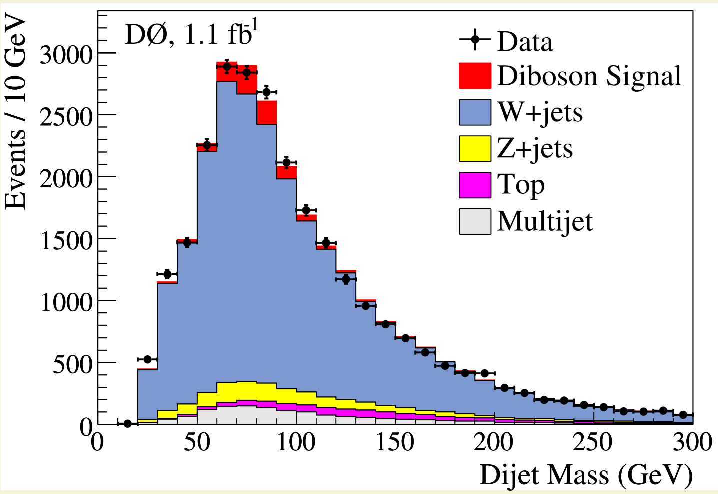
⇒ Necessary steps **towards the discovery of the Higgs!**

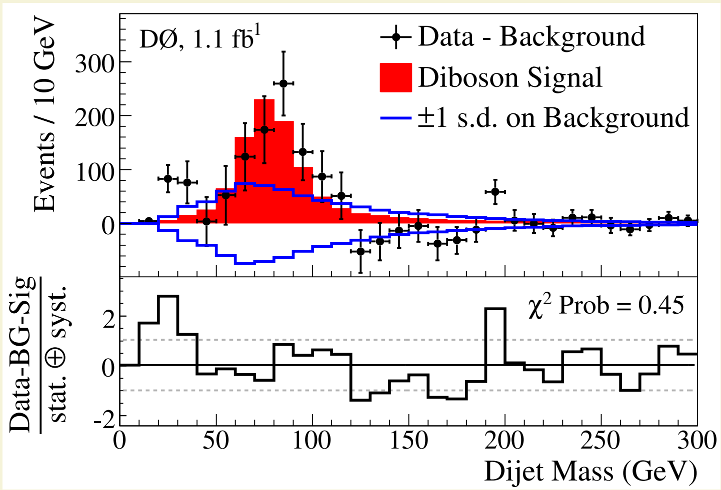
Diboson production and hadronic decays

There is a current interest to observe the hadronic decays, as

$$WW/WZ \rightarrow l\nu q\bar{q} \text{ (or } l\nu b\bar{b}\text{)}$$

- Several motivation for this search:
  - $\Rightarrow$ Resonant production will help to calibrate jets
  - $\Rightarrow$ Similar tools as for low-mass Higgs searches
  - $\Rightarrow$ Needed step towards the low-mass Higgs
- DØ published an analysis for $WW/WZ \rightarrow l\nu q\bar{q}$ with a big effort to have background under control.
- Both signals are indistinguishable (and WZ represents 1/7 contribution).





Sensitivity increased using "Random Forest" technique (based on the use of many Boosted Decision Trees).

SEARCHES OF

THE STANDARD-MODEL HIGGS BOSON

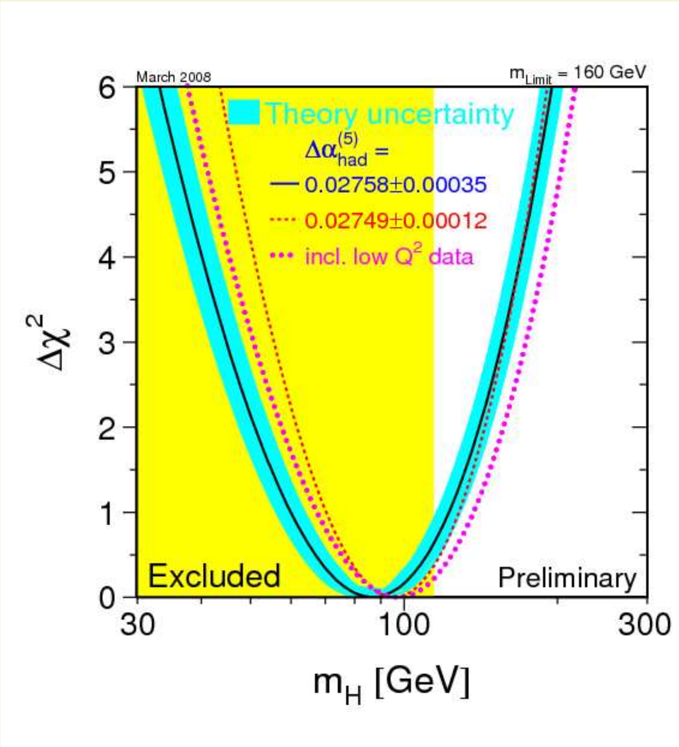
Higgs constraints from previous measurements

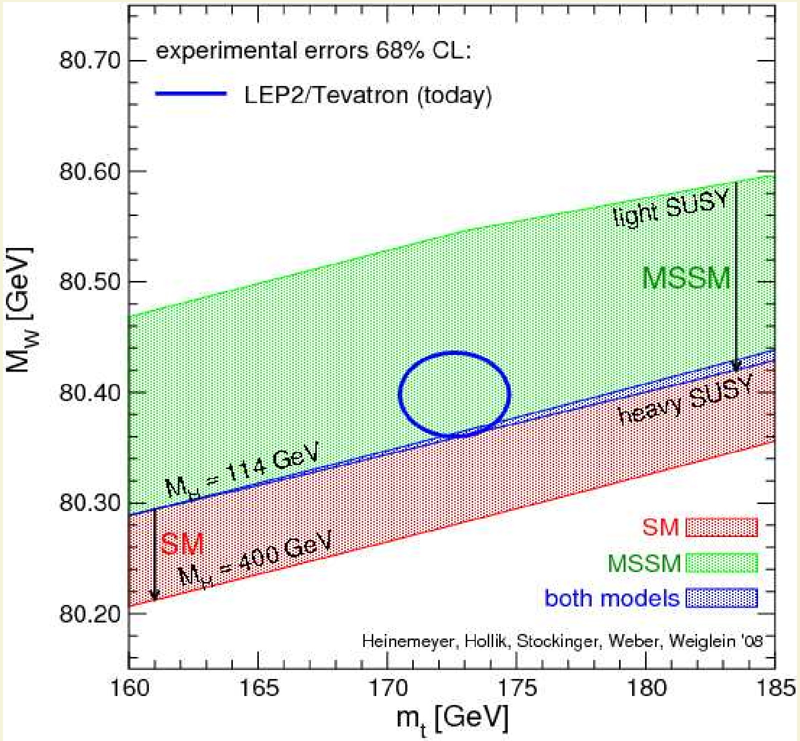
The only particle of the SM that has not been observed is the Higgs boson.

Precision data prefer a light SM (MSSM??) Higgs

$$m_H = 87^{+36}_{-27}\ \text{GeV}/c^2$$

$$m_H < 160\ \text{GeV}/c^2 \text{ at 95\% CL}$$



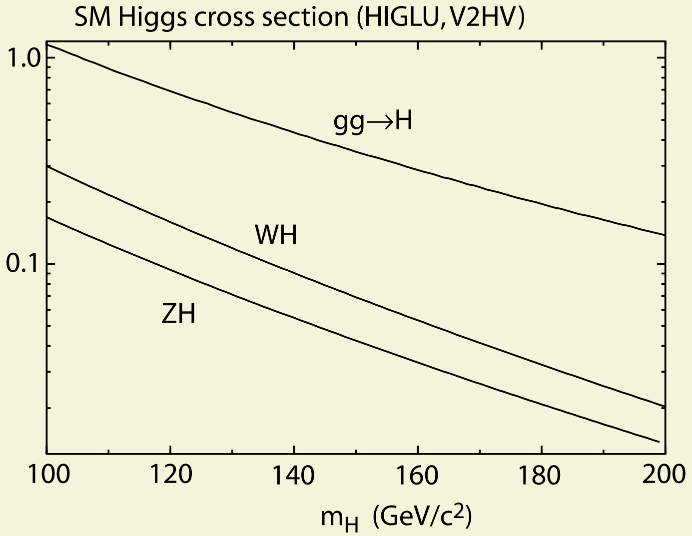


- **Direct searches at LEP excluded a Higgs with $m_H < 114.4$ GeV/c^2 (at 95% CL)**

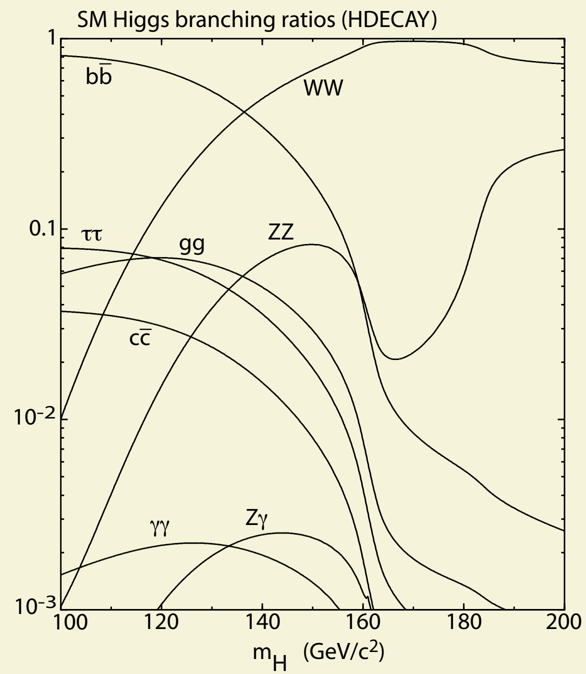
Higgs at the Tevatron

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 $\tau\tau$ contribution)**
- **High mass (up-to 180-200 GeV): WW**
- **Higher masses are hopeless for Tevatron.**

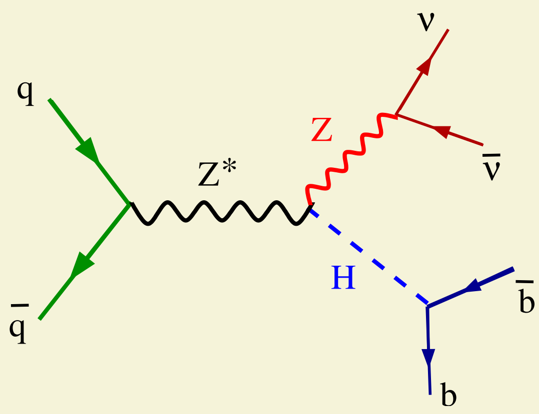
Tevatron and the SM Higgs: Strategy

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 $H \to b\bar{b}$

  $\Rightarrow$ Impossible to observe in inclusive production

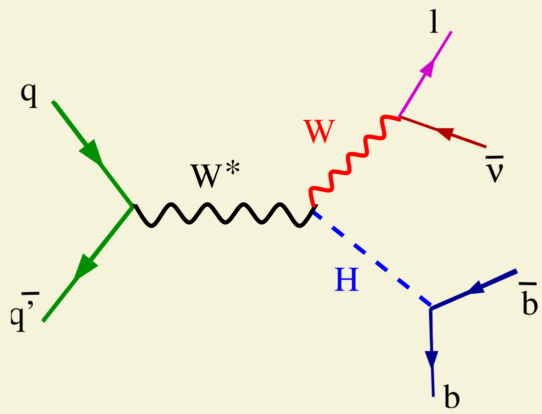
  $\Rightarrow$ Using ZH and WH production requiring a b-jet and leptonic decays



- High mass ($m_H > 150$ GeV/c^2) decay dominated by $H \to WW$

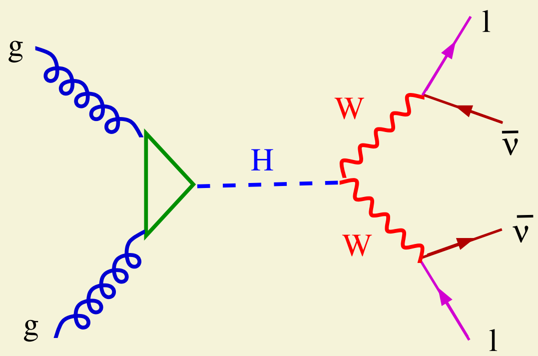
  $\Rightarrow$ Leptons from the Higgs reduce background

  $\Rightarrow$ Inclusive production is dominant channel (although associated production is not negligible, e.g. $WH \to W(WW)$)



- Intermediate region

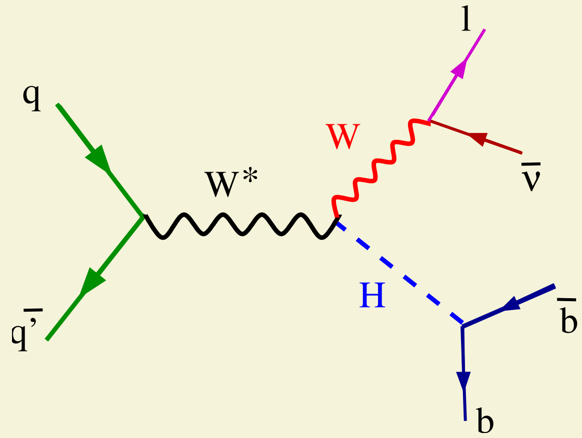
  $\Rightarrow$ Sensitivity from previous modes

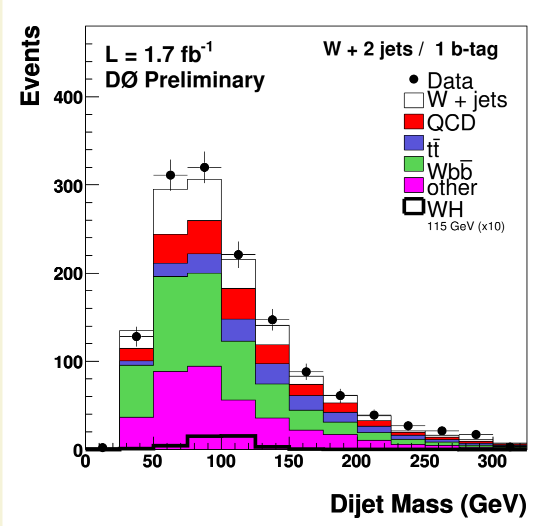


We need good lepton identification, $\not{E}_T$ reconstruction and b-jet tagging to perform the search.

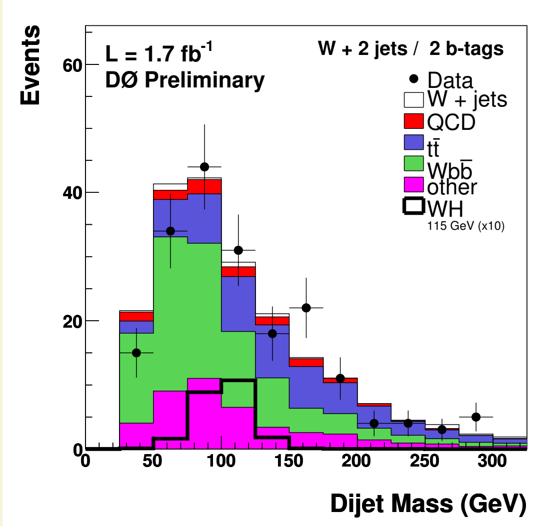
Low mass Higgs: WH search (I)

- This is the reference channel for masses right above the LEP limit, in which **the Higgs preferably decays into a $b\bar{b}$ pair.**





- Characteristic is narrow resonance in the dijet mass.
- Discrimination done using multivariate analysis techniques (NN, BDT,. . .)
- Hard work to **increase acceptance for signal, which is the main limitation in this search.**
- Increase in discriminating power by the **ability to improve the dijet mass resolution (specifically for b-jets).**

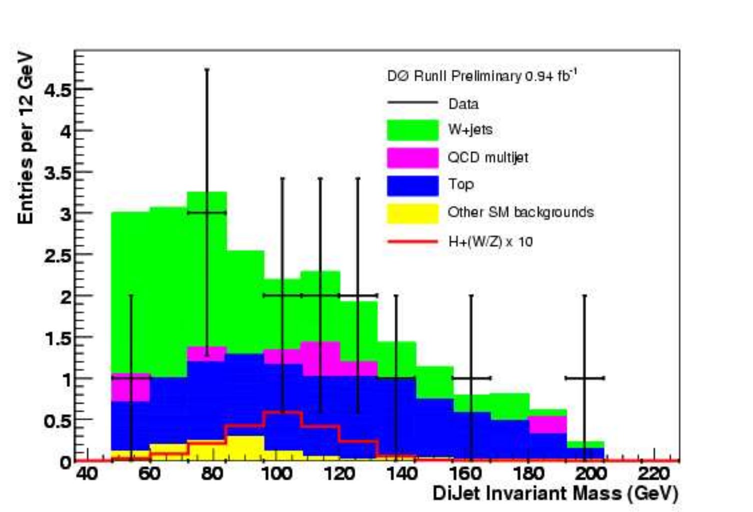


- At CDF the analysis is done in a similar way as the single-top search, but optimizing the selection for the WH signal.

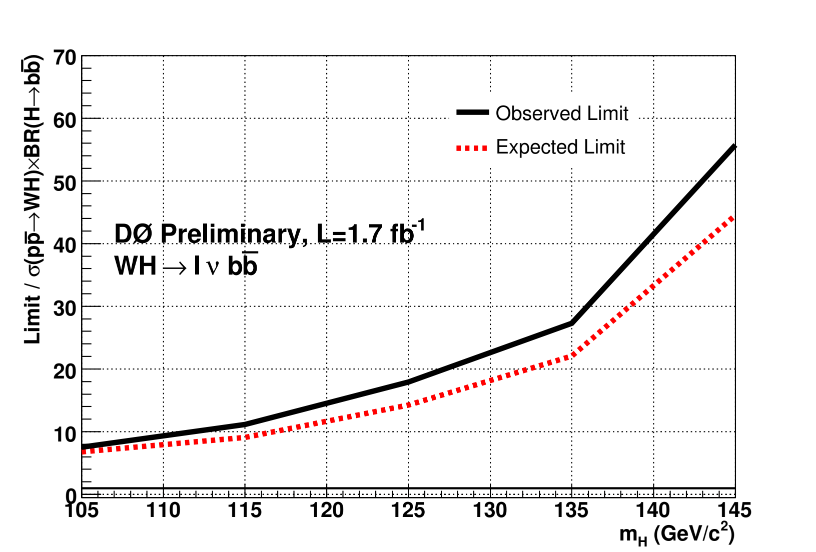
Low mass Higgs: WH search (II)

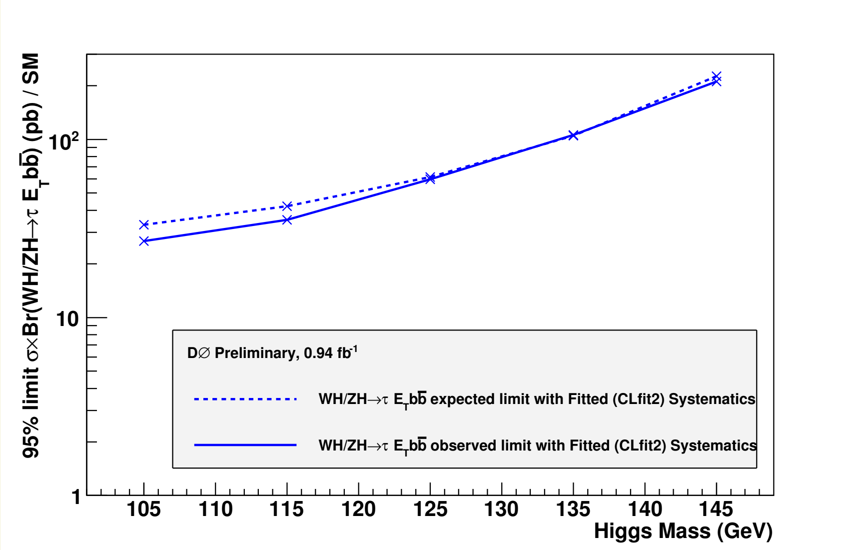
Increase acceptance getting all the charged leptons, including the hadronic τ decays (big challenge)

- **Using a trigger for medium $\not\!\!E_T$ and jets**
- **Background from multijets estimated from data using loose τ selection.**
- **Normalized in a preselection stage of signal region**
- **3 types of τ: $\tau \rightarrow \pi^+\nu$, $\tau \rightarrow \pi^+\pi^0\nu$, and 3-prongs**



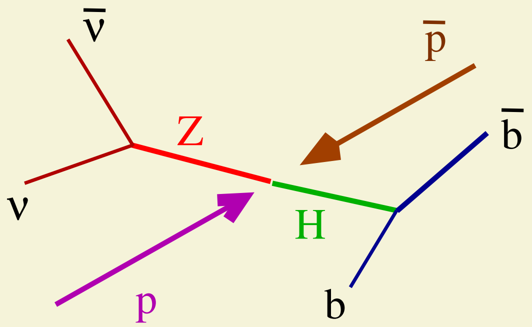
Sensitivity is ~ 4 times worse than the main e/μ analysis (with half of the data).

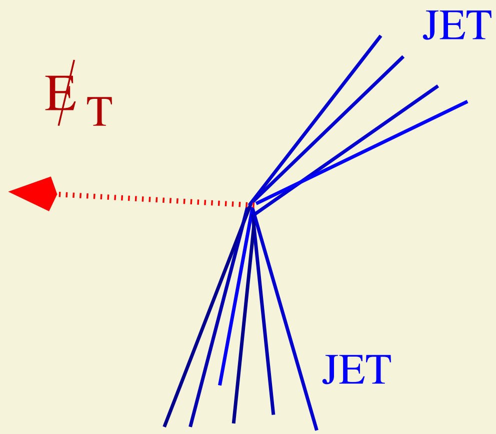


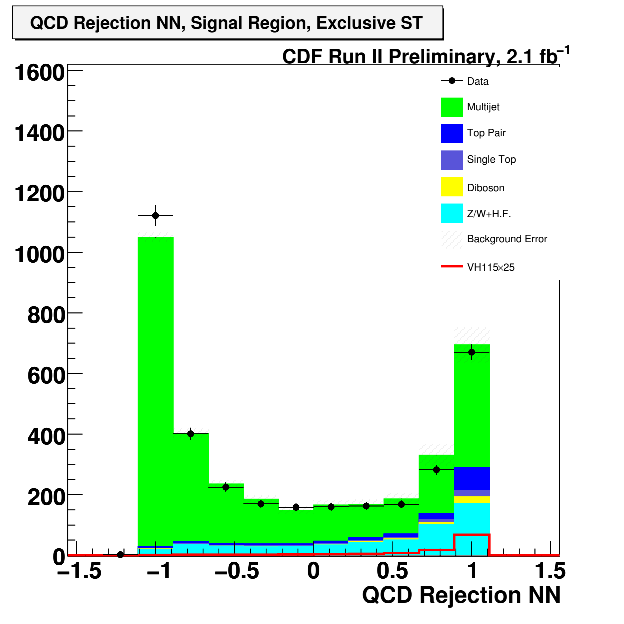


Low mass Higgs: ZH search ($\not\!\!E_T bb$)

This channel, exclusive to the previous one, has the advantage of the large branching ratio of $Z \to \nu\bar{\nu}$



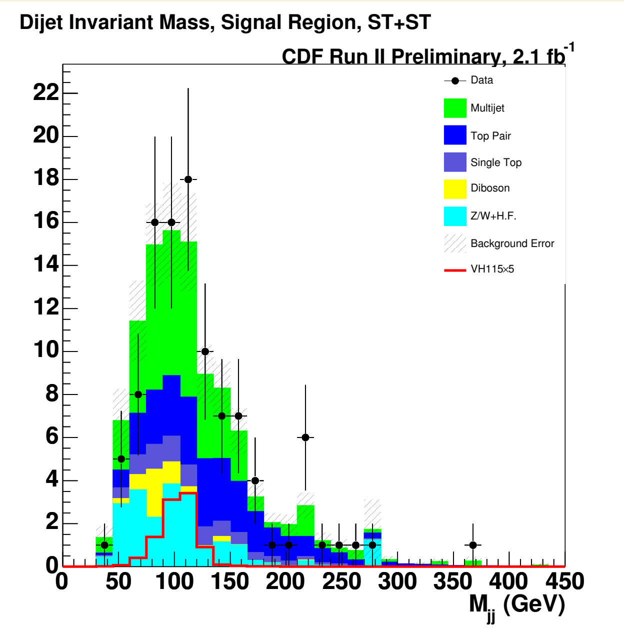




⇒ We also expect a resonance in the dijet mass.

⇒ Huge QCD background that has been estimated using data, validated in Control regions and suppressed in signal Region (in this case with a specific Neural Network).

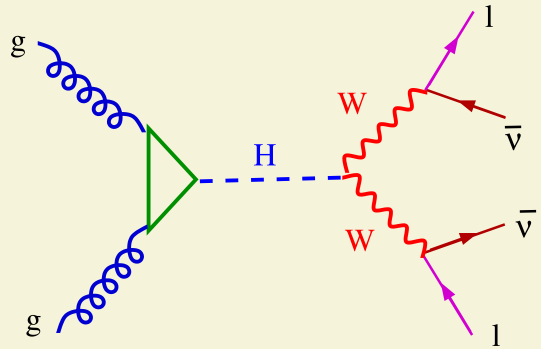
⇒ QCD and mistagged light-flavour jets goes together



Achieved sensitivity is similar to the $WH \to l\nu bb$ search: combination of the two strategies will be fundamental to find/exclude a low-mass Higgs.

High mass Higgs

At higher masses ($m_H > 150$ GeV/c^2) the dominant decay channel is to WW^*



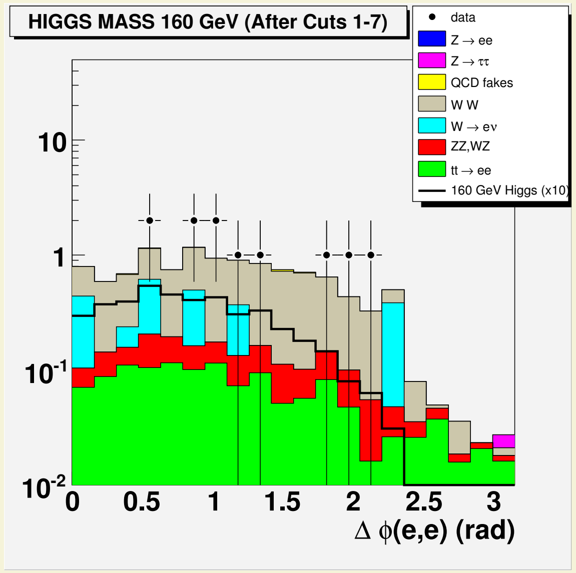
- **Selection cuts:**

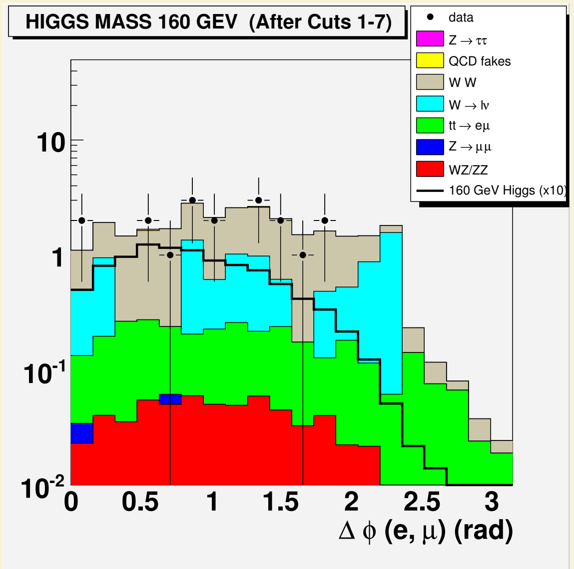
  Two opposite-charged leptons

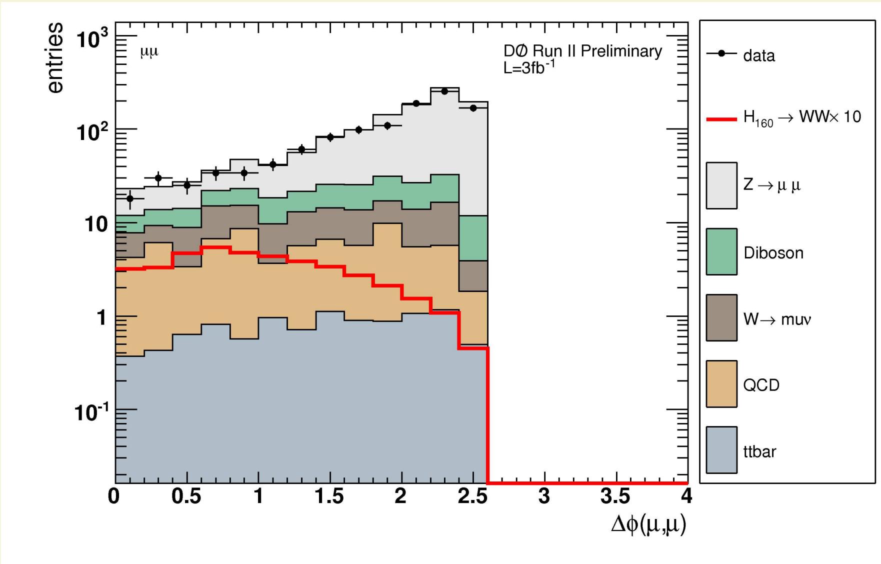
  $\not{E}_T$ in the event

- **Due to the scalar nature of the Higgs Boson, the angular correlation between the W (and the charged leptons) is different than the dominant background (WW production)**

- **Amount of background depends on the selection cuts (which depends on m_H)**





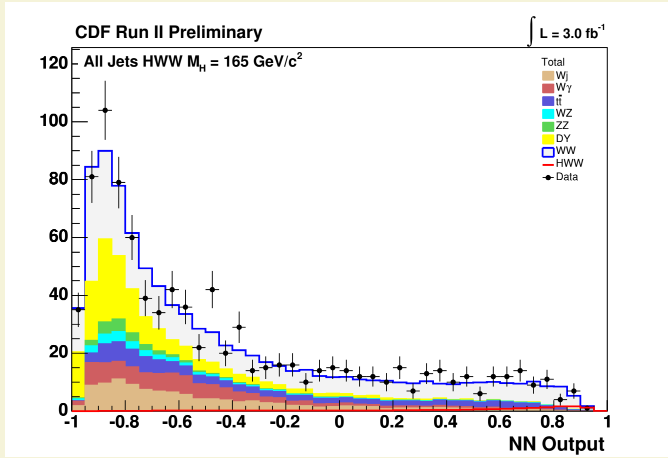


High mass Higgs and Tevatron limits

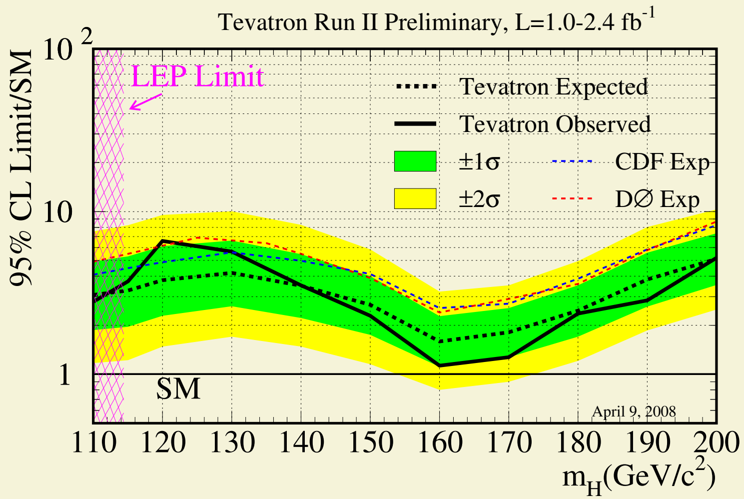
⇒ Sensitivity is enhanced using multivariate techniques exploiting kinematics differences between signal and background.

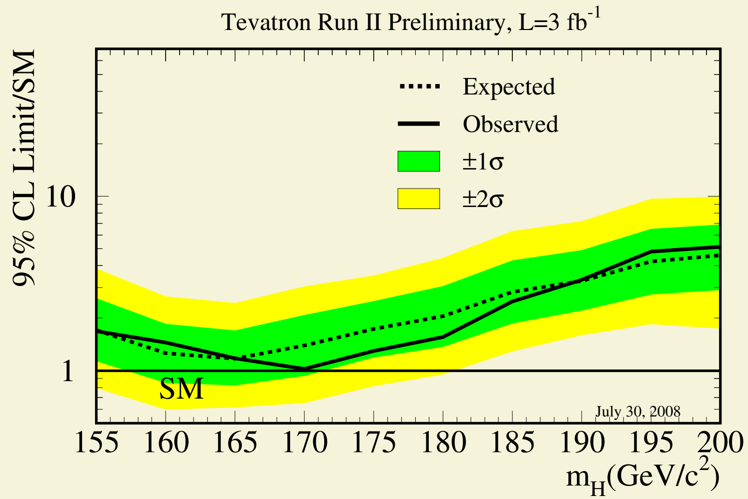
⇒ Increase of the acceptance including events with jets, as separated channels to maintain sensitivity.

⇒ Coordination of the two experiments is key point.



The big effort to increase lepton and process acceptance paid back and Tevatron already reached sensitivity to the SM cross section at high masses.





- The plan is to have an improved Tevatron combination for Winter Conferences.
- More data and work to come and be included in the analyses.

SEARCHES OF PHYSICS

BEYOND THE STANDARD MODEL

(Mostly Supersymmetry)

Motivation for new physics

Standard Model (SM): big success during the last 30 years to explain the experimental results in collider physics.

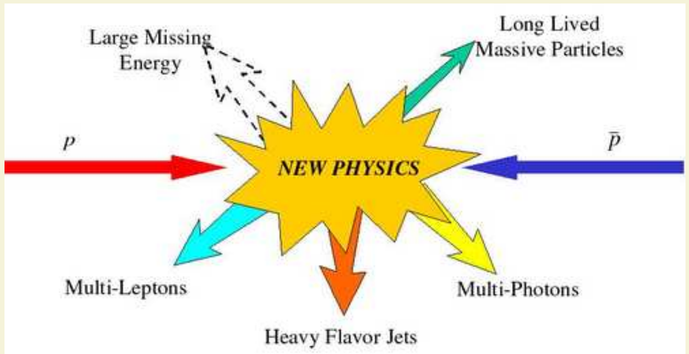
However, still some **open questions about Nature:**

- The origin of mass
- Why three generations?
- Composition of Dark Matter and Energy
- Gravity at the particle (quantum) level
- ...

and some motivations from theory to "justify" the success of the Standard Model:

- Mass hierarchy problem (low Higgs mass)
- Possible unification (=simplication) of forces
- Explain Universe from first principles: e.g. matter/antimatter asymmetry
- ...

All this introduces a need for new physics to exist... at the TeV scale that may be produced at Tevatron



Supersymmetry: summary

- The most promising extensions of the SM are based on the introduction of a new symmetry between bosons and fermions in Nature.
- This Supersymmetry (SUSY) makes Nature invariant under the transformation:

$$\boxed{\text{bosons} \Leftrightarrow \text{fermions}}$$

- For this to be satisfied we require a supersymmetric partner for each known (or to be known) particle.
- This symmetry is broken at currently reached energies, since no superpartner is found. On the other hand, masses of superpartners should be $\lesssim 1$ TeV if SUSY would help to resolve the difficulties of the SM.
- The quantum number

$$R_p = (-1)^{2S+3B+L}$$

is therefore 1 for "common" particles and -1 for the superpartners.

- Most models (and everything in this talk) assume that this quantity is conserved by interactions, yielding:

$\Rightarrow$ The lightest supersymmetric particle (LSP) is stable (Dark Matter? $\not{E}_T$!!!)
$\Rightarrow$ Supersymmetric particles are produced in pairs.

SUSY at the Tevatron

SUSY can be produced at the Tevatron in very different ways and is one of the most active and richest parts of the program.

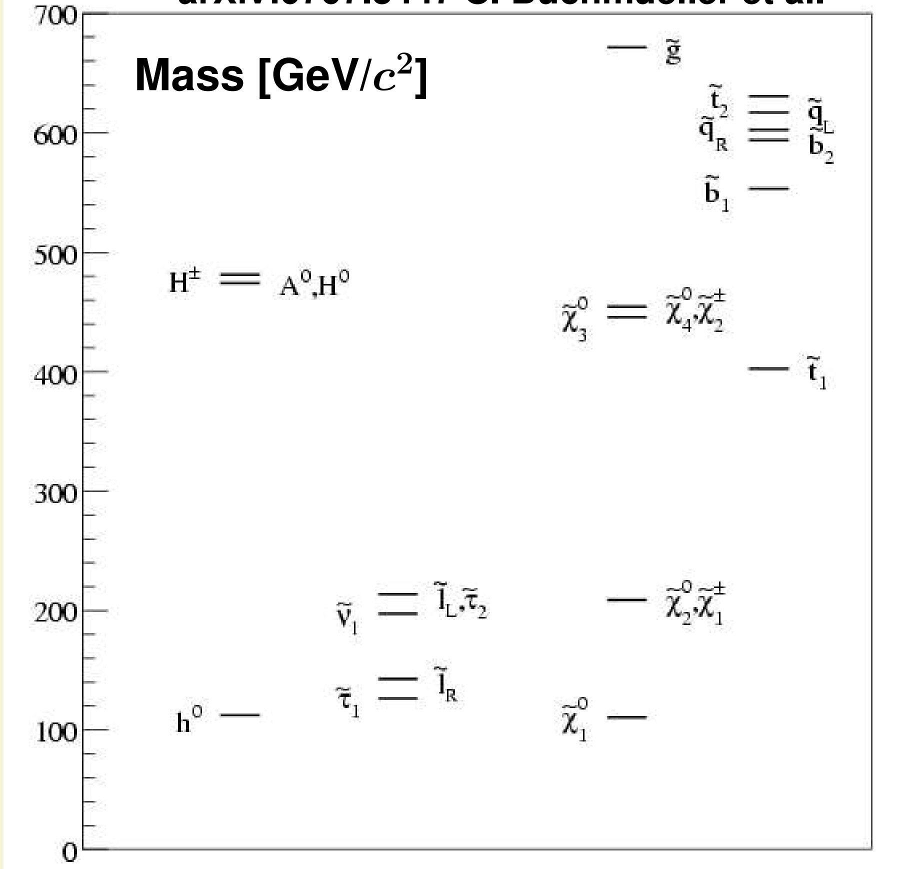
Usually working in the cMSSM/mSUGRA model since it simplify interpretation of different search analyses.

It usually motivates an attractive spectrum for Tevatron searches in the commonly discussed fronts:

- squarks and gluinos:
  - $\Rightarrow$ Produced via strong interaction
  - $\Rightarrow$ High masses accessible
  - $\Rightarrow$ Signature: $\not{E}_T$+jets
- gauginos (and sleptons):
  - $\Rightarrow$ Produced via electroweak interaction
  - $\Rightarrow$ Low masses with leptonic signatures
  - $\Rightarrow$ Need to understand low-p_T leptons
- Higgses are at Tevatron's reach

Using the third-generation objects.

arXiv:0707.3447 O. Buchmueller et al.



SUSY and search analyses at the Tevatron (II)

Searches for Physics Beyond the Standard Model performed at Tevatron present a large variety (as models to extend the SM).

This talk will not attempt to cover them, but just the most interesting/attractive from the experimental or theoretical point-of-view:

- Searches for SUSY particles:
  - $\Rightarrow$ Inclusive squark and gluino searches
  - $\Rightarrow$ Scalar bottom production
  - $\Rightarrow$ Scalar top production
  - $\Rightarrow$ Trilepton signature for gauginos
- Higgs searches beyond the SM:
  - $\Rightarrow$ b-jet and τ-based analyses
  - $\Rightarrow$ Search for charged Higgses (in the back-up)
- Searches with photons:
  - $\Rightarrow$ Large Extradimensions
  - $\Rightarrow$ Gauge-Mediated Supersymmetry Breaking Models

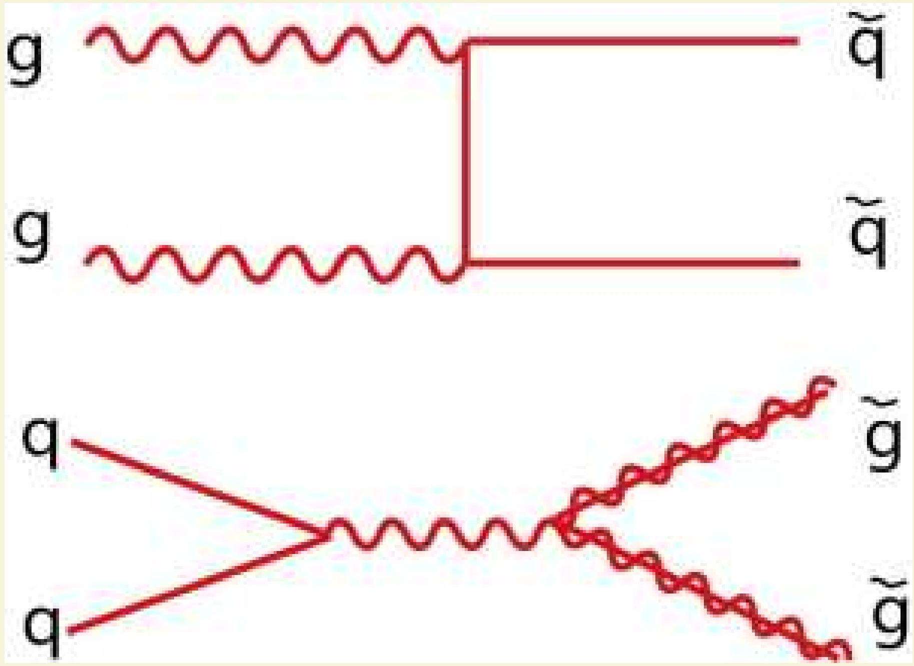
Inclusive squarks and gluinos

- If coloured superpartners are light enough their production cross sections will be large since they are strongly produced.

- Those events will populate the sample with jets and $\not{E}_T$ due to their cascade decays leading to:

$$p\bar{p} \rightarrow \tilde{q}\tilde{q}X \rightarrow q\tilde{\chi}^0 q\tilde{\chi}^0 X$$
$$p\bar{p} \rightarrow \tilde{g}\tilde{q}X \rightarrow q\tilde{\chi}^0 q\tilde{\chi}^0 X$$
$$p\bar{p} \rightarrow \tilde{g}\tilde{g}X \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0 X$$

and neutralino is assumed to be stable (R_p conserved) and weakly-interacting particle, therefore escaping detection.



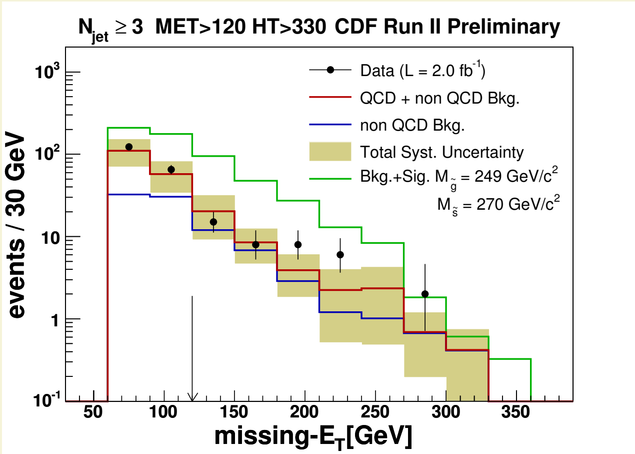
- Final event topology strongly depends on the phenomenology
- Basically the relationship between the squark and gluino masses
- Flavour-blind analysis: search is performed without investigating the nature of the jets in the final state.

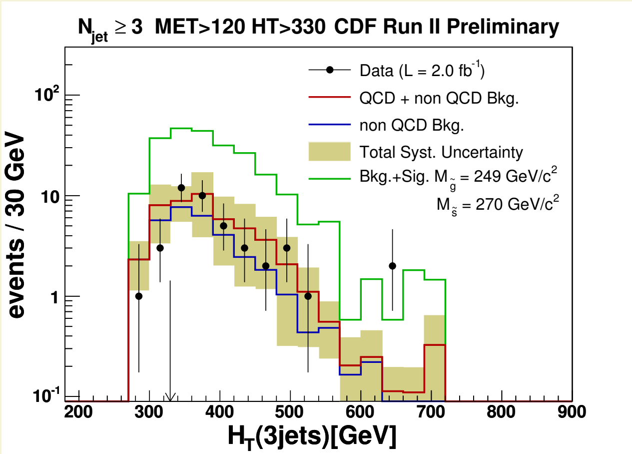
Inclusive squarks and gluinos (II)

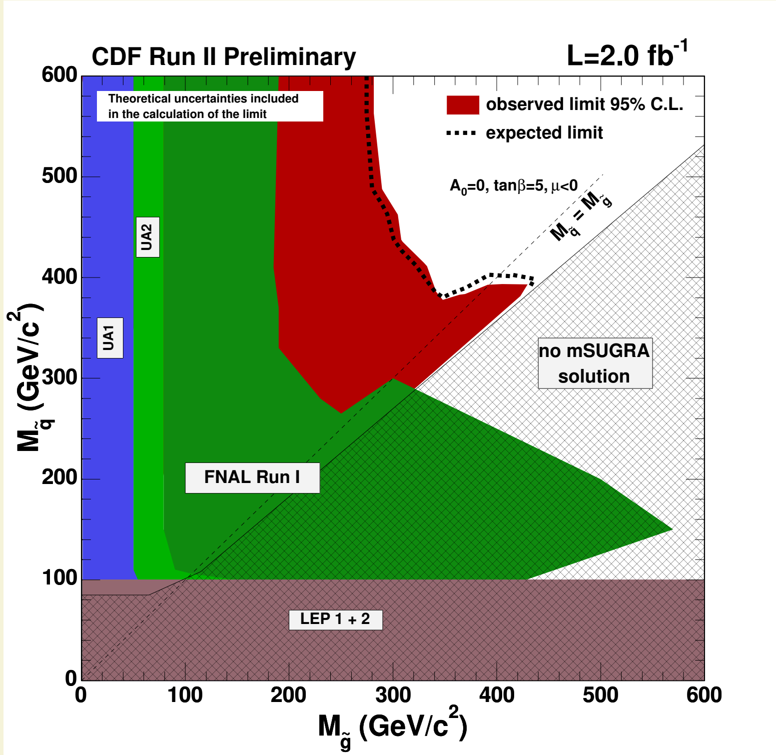
Analysis optimized in different regions to account for different jet-multiplicities topologies:

- $\Rightarrow$ $\not\!\!E_T$+2 jets for squark pair production
- $\Rightarrow$ $\not\!\!E_T$+3 jets for squark+gluino production
- $\Rightarrow$ $\not\!\!E_T$+4 jets for gluino pair production

The key variables are $\not\!\!E_T$ and the sum of the E_T of all the jets in the event.



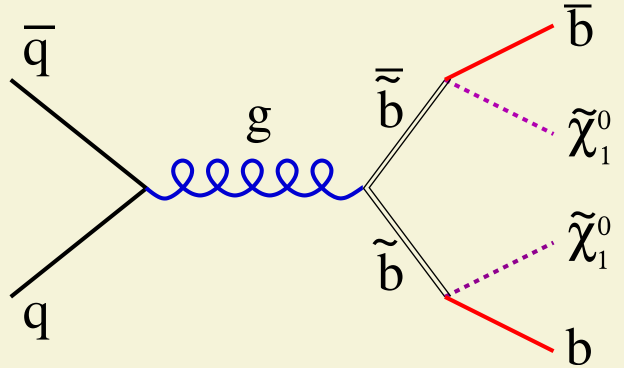


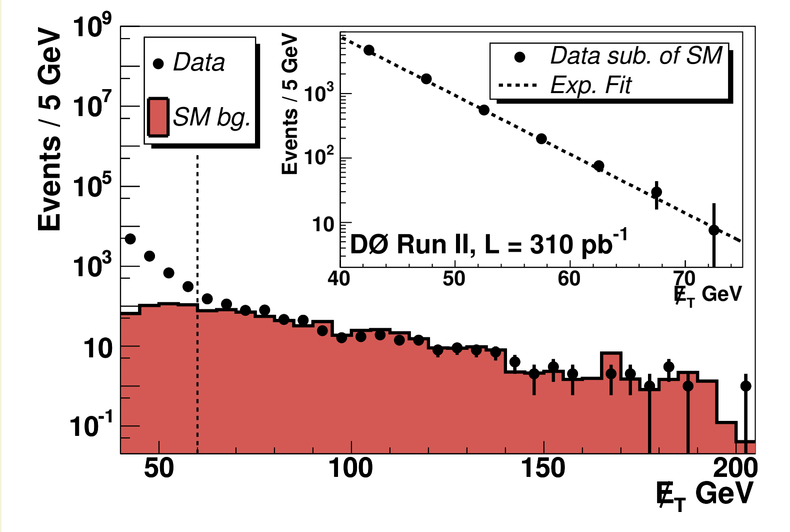


- **Gluinos with less than 280 GeV/c^2 are excluded**
- **For $M(\tilde{g}) \sim M(\tilde{q})$, exclusion up-to 390 GeV/c^2**
- **In the mSUGRA interpretation, excluding regions not accessed by LEP**

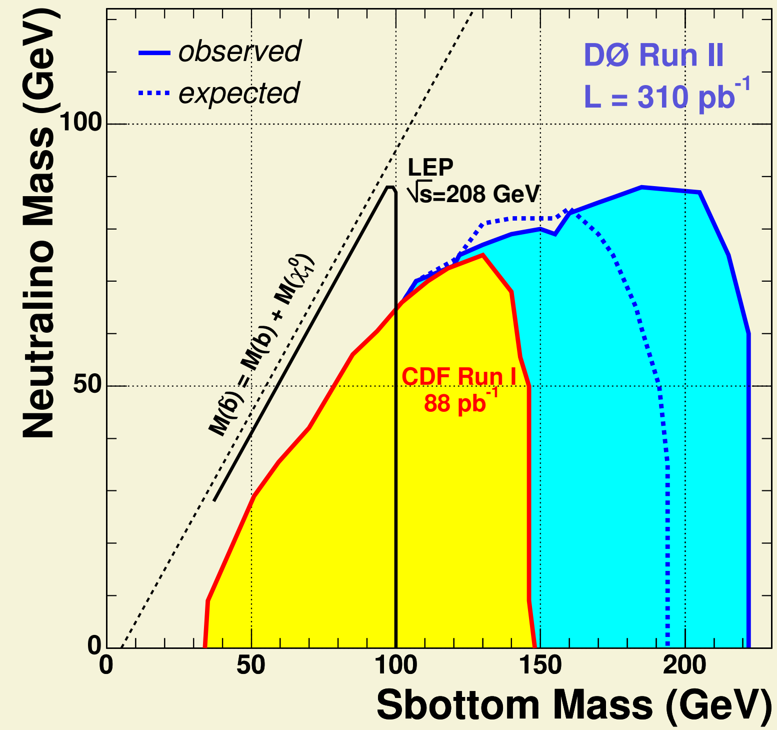
Search for sbottom direct production

- The simplest addition to the squark inclusive search is to require b-jets in the final state, in addition to the $\not{E}_T$.
- This nicely fits the search for the scalar partner of the bottom quark, in a model for which that is the Next-to-lightest SUSY particle.





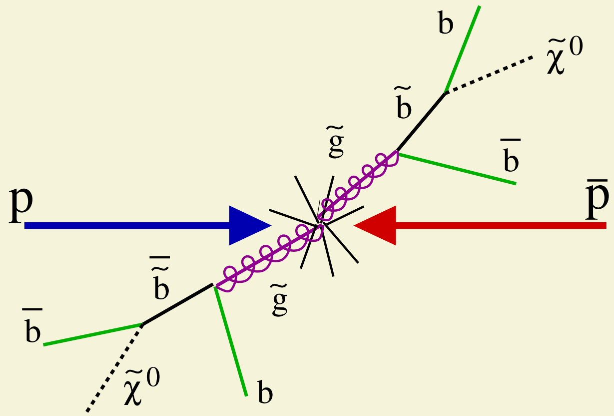
- Again, the $\not{E}_T$ is the main variable to reduce the background.
- The addition of b-tagging reduces inclusiveness (i.e. bigger dependence with the model).
- But it enhances the sensitivity to events containing sbottoms.



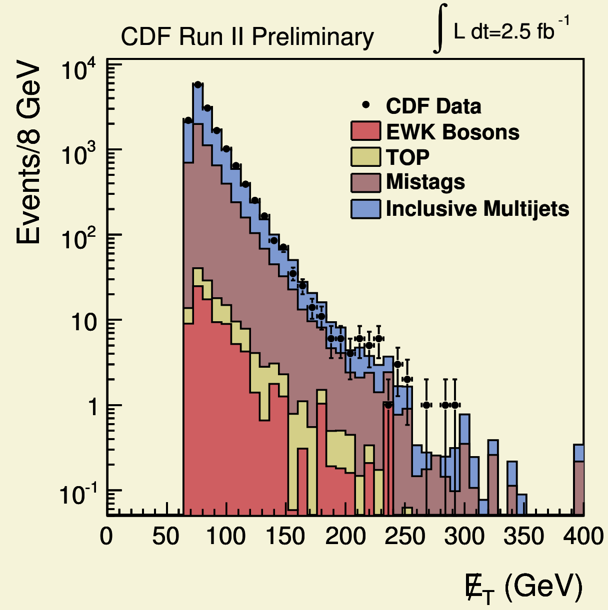
sbottom from gluinos

Since sbottom may be light, if may be produced in the decay of gluinos produced in the interaction.

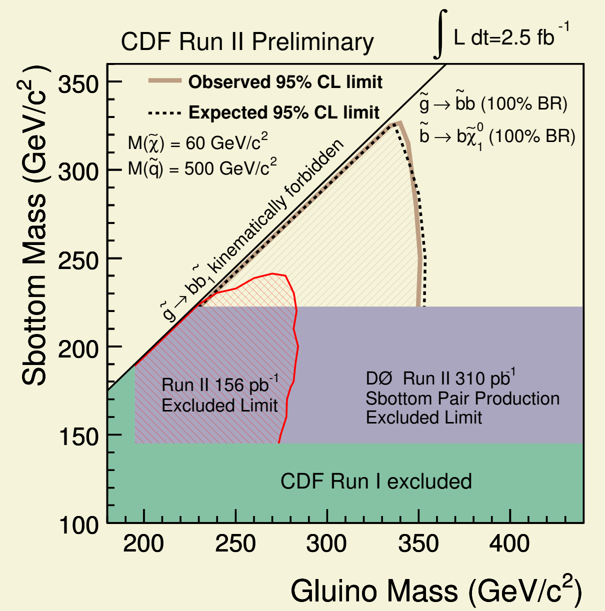
For similar masses, gluino cross section is much larger



MET + 4 b-jets

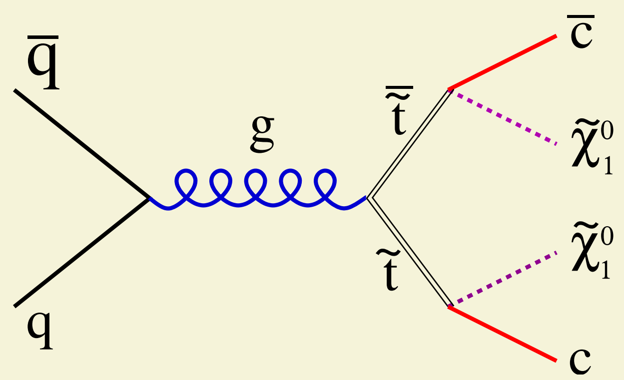


- **Lots of (not really motivated) assumptions.**
- **But signature is interesting enough to motivate the search of this kind of events**
- **Good agreement with Standard Model prediction (in a tough corner of the phase-space)**
- **Note complementarity with previous search: Better performance when masses are similar.**



stop decaying to charm and neutralino

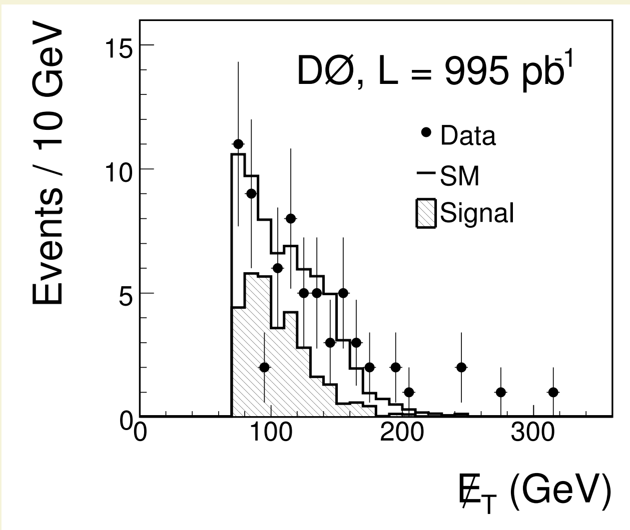
- **When the scalar partner of the top is the next-to-lightest SUSY particle, the main decay channel is to charm and neutralino (if W channels are closed).**

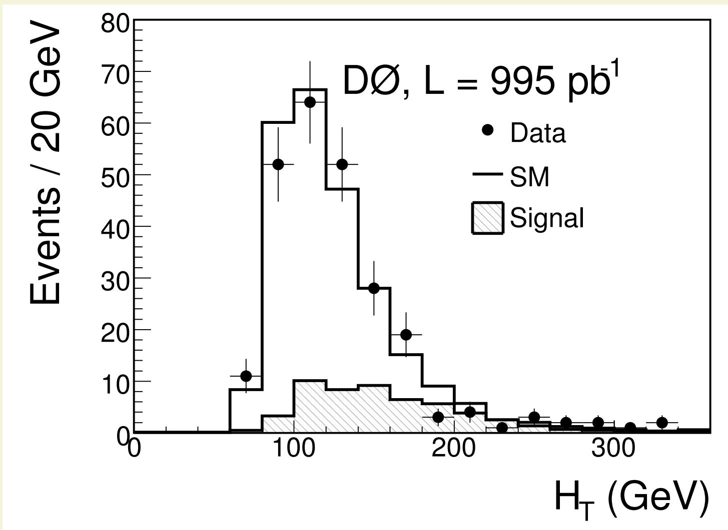


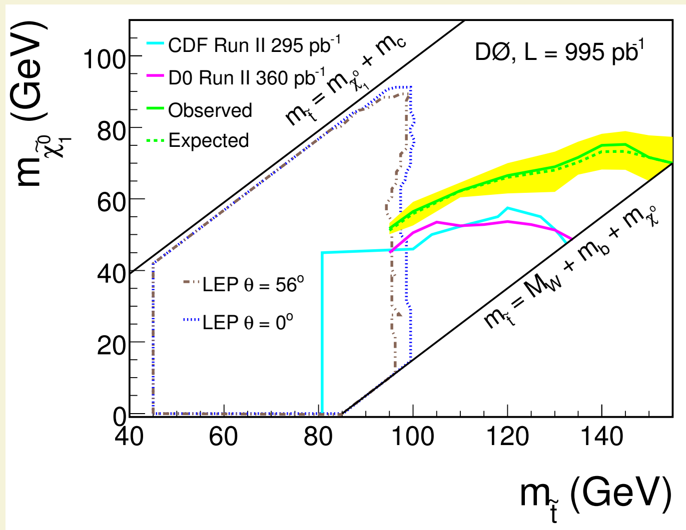
- **Strongly motivated by MSSM with a light scalar top.**
- **One of the leading channels to find SUSY at Tevatron.**
- **Experimentally very challenging due to the need to identify charmed jets:**

  $\Rightarrow$ **Looser heavy-flavour tagging (more mistagged jets).**

  $\Rightarrow$ **Large background with b-jets (higher acceptance).**





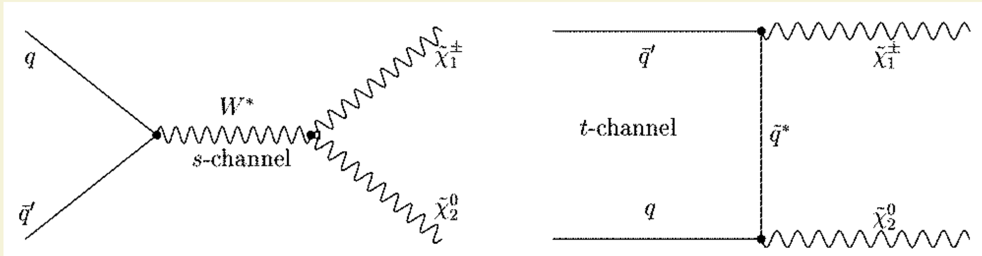


- **LEP limits still very competitive (dependent of electroweak parameters)**

Trilepton searches

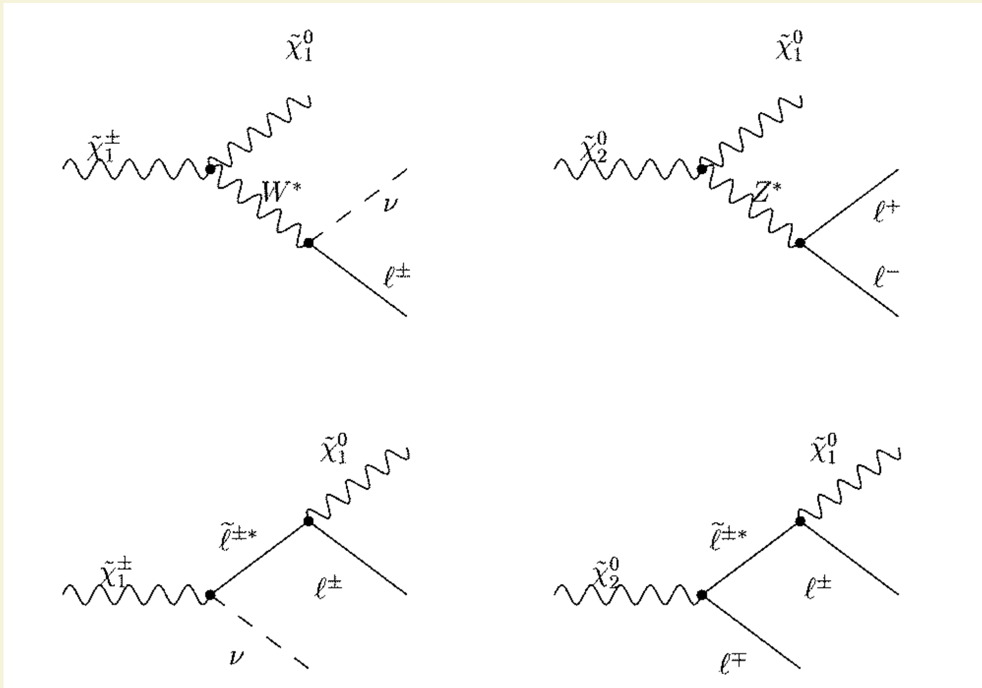
One of the “golden modes” to detect Supersymmetry at Tevatron is the detection of neutralino and chargino production in the trilepton channel.

In this case, the second less-massive neutralino ($\tilde{\chi}_2^0$) and the less-massive chargino ($\tilde{\chi}_1^\pm$) are produced. They may decay leptonically, as shown in the figures.



The production of the neutralino-chargino is higher than other SUSY processes in mSUGRA scenarios.

The signature (3 leptons and $\not{E}_T$) is very clean for a hadron collider. Jets faking lepton (+boson production or Drell-Yan) is the background to reduce.



The disadvantage is the small branching ratio for the chargino-neutralino into leptons. Large samples are needed for competitive results.

Trilepton searches (II)

Although the signature is very clean, the analysis is far from trivial because:

⇒ Require increasing lepton acceptance to the last corner

Commonly analysis based on Dilepton+track selections

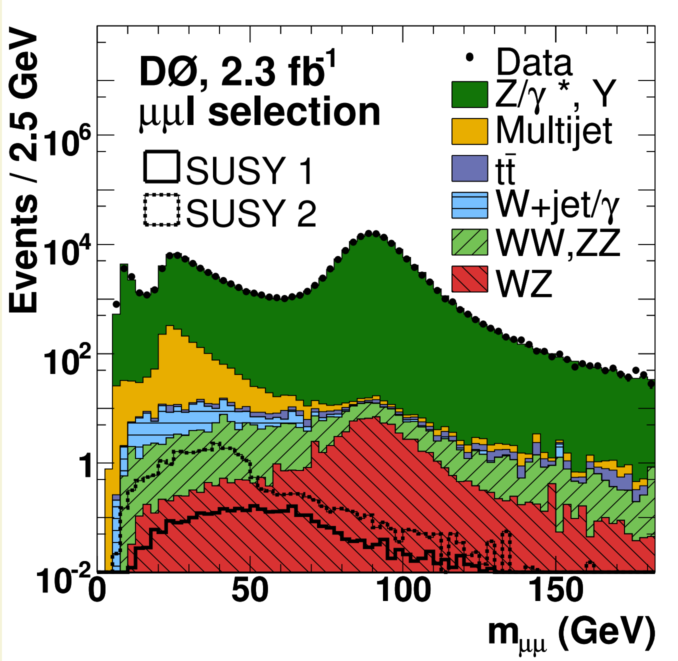
⇒ Need to understand low-p_T leptons

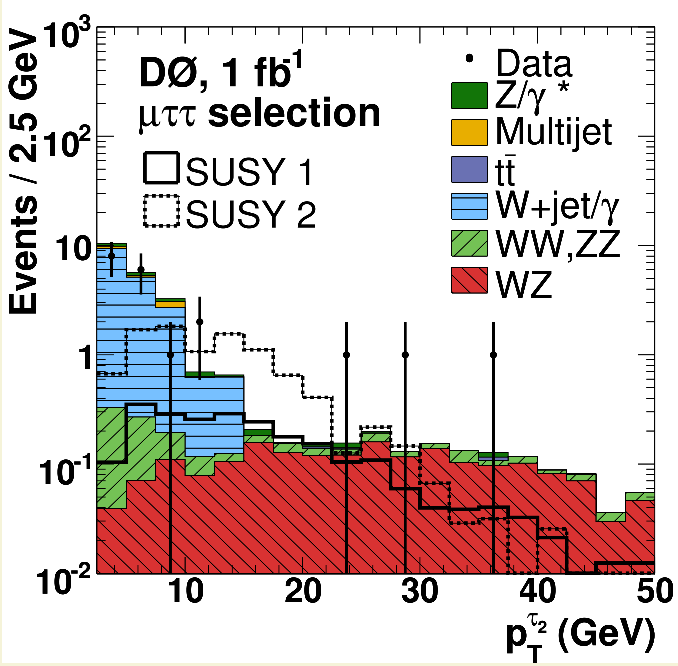
Also same-sign dileptons are very important since third lepton is usually very soft.

⇒ Use of the Dilepton samples to check background estimations.

In the final selection, the fight for sensitivity is translated into the understanding of processes with small-cross sections or hard to estimate:

Dibosons, fake-leptons, conversions,...





Trilepton searches (III)

⇒ **The analysis is also complicated when interpreting the results.**

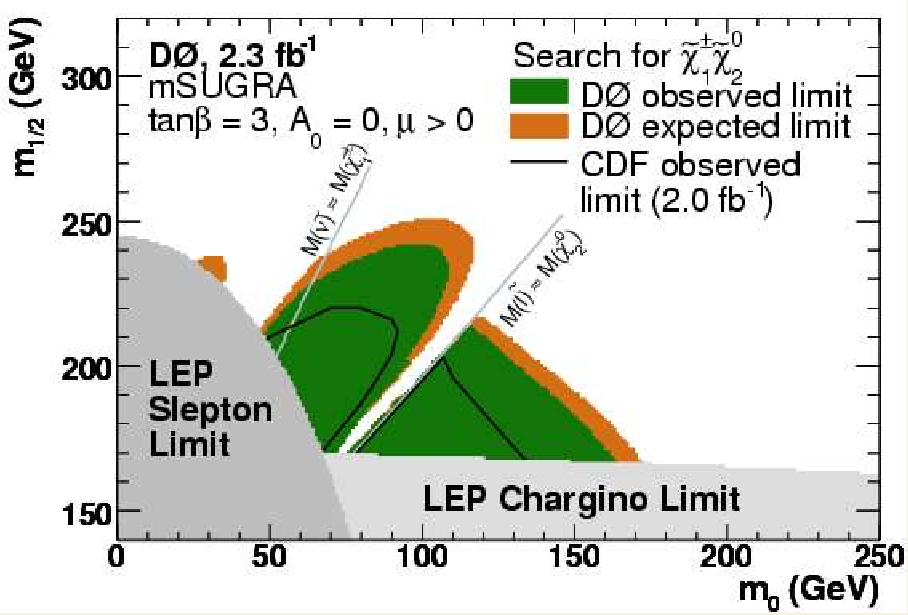
As a difference with the squark/gluino final states, phenomenology of the trilepton search is very complicated:

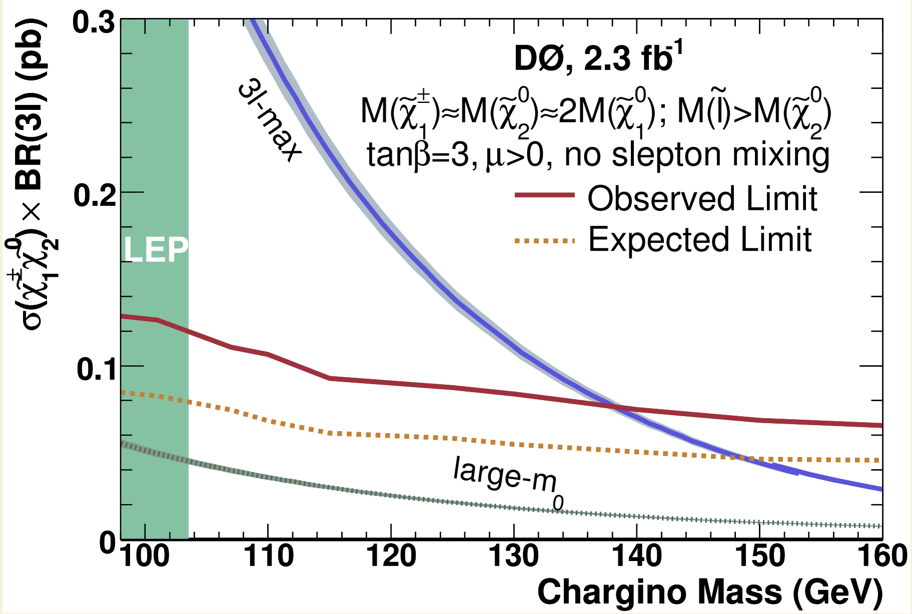
⇒ **Depending on spectrum and electroweak properties of the superpartners, leptons may be produced with very different kind of processes**

e.g. relations of masses of sleptons, squarks and gauginos determine acceptance

⇒ **Relation of the masses of the superpartners with W and Z also relevant.**

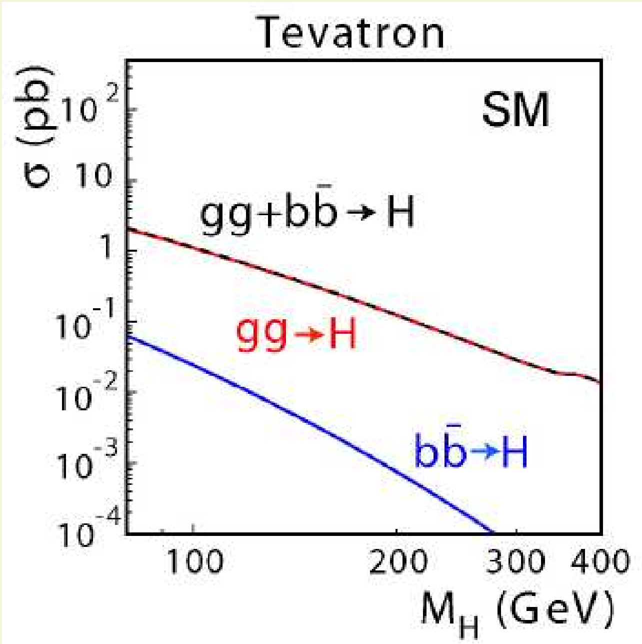
Normally working on mSUGRA framework and several asumptions

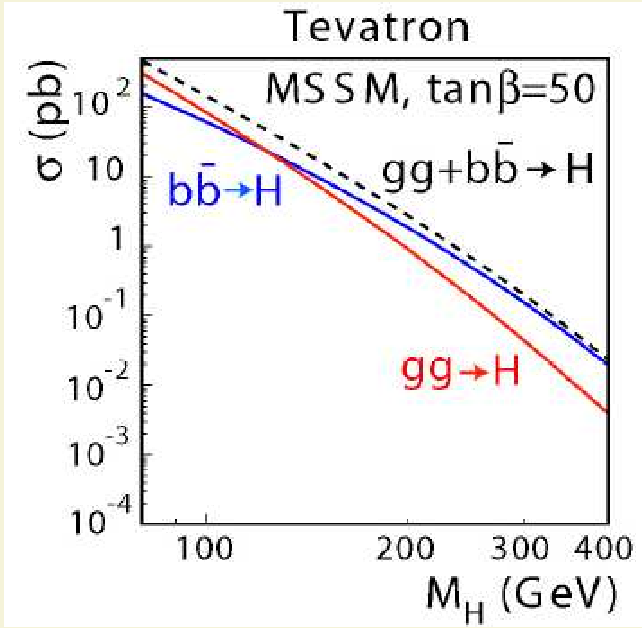




The MSSM Higgses

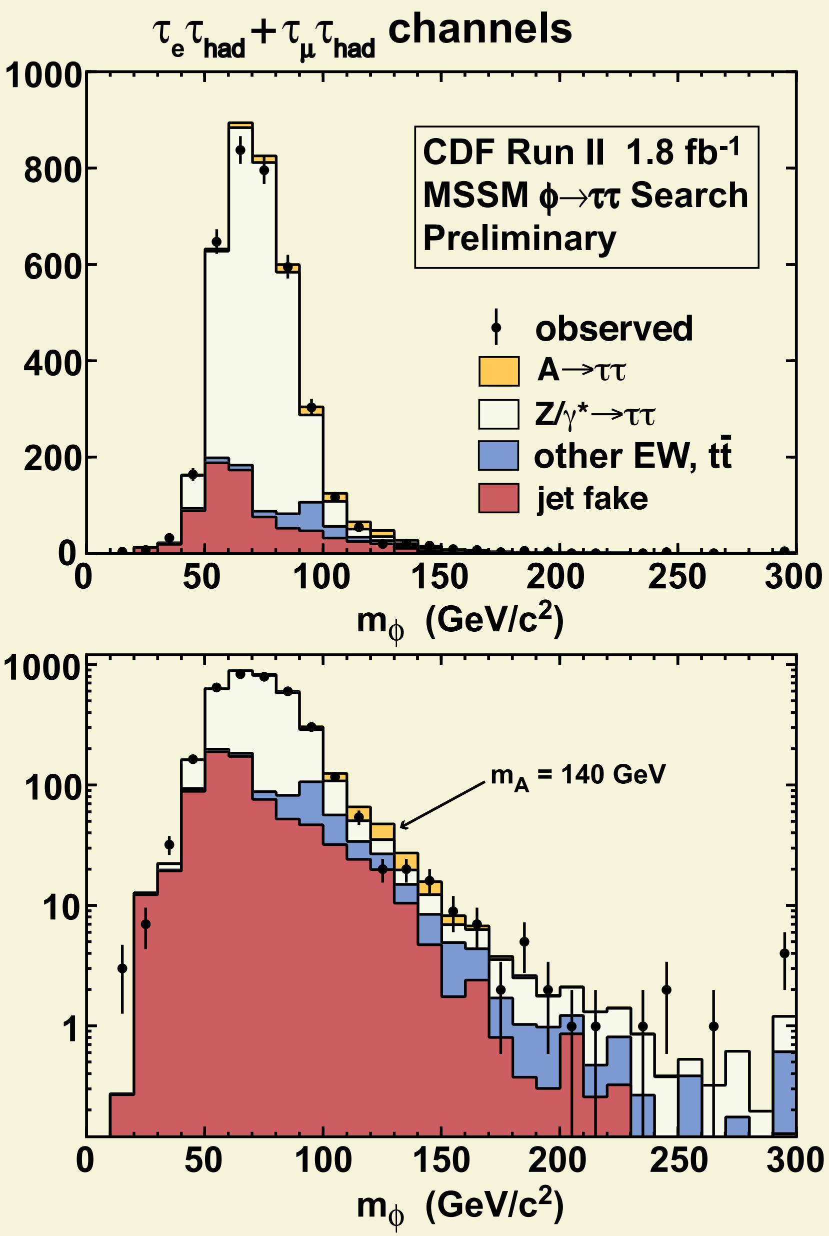
- In the MSSM we expect 5 Higgs bosons: h, H, A and $H^{\pm}$
- For high $\tan\beta$: A is degenerated in mass with h or H and the cross section is enhanced (coupling to down-type quarks and leptons).
- bottom-quark loop enters in the production diagrams, and associated production (Hbb) has a very relevant contribution.
- The degenerated state (ϕ) decays into $\tau\tau$ (10%) and bb (90%)





Although the tau channel has smaller branching ratio, it is much cleaner and allow observation of inclusive production.

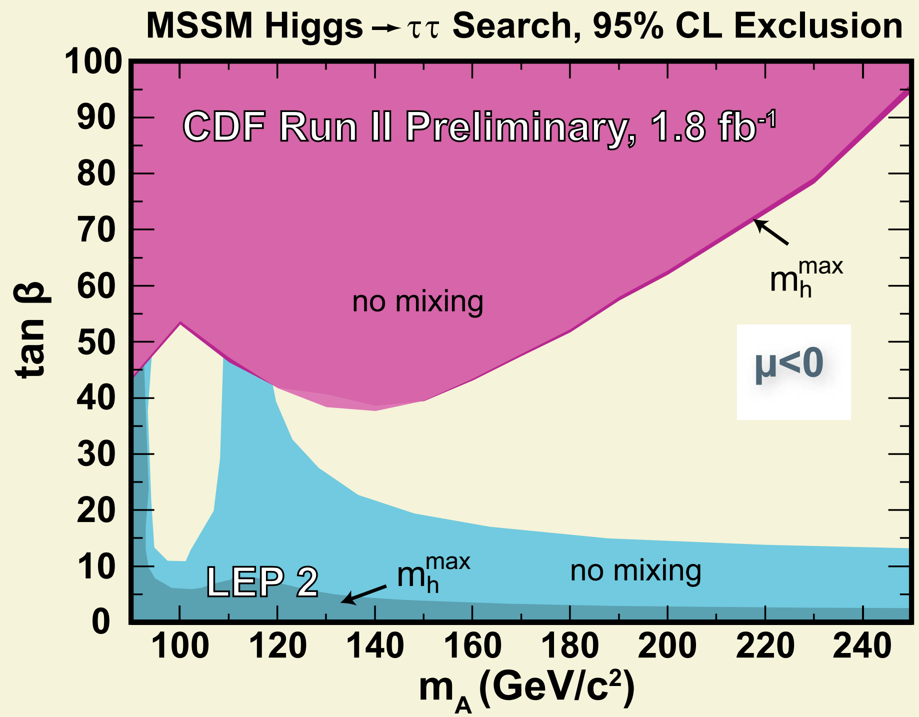
MSSM using taus



The analysis is performed with one leptonic tau and one hadronic tau, in order to get the largest acceptance (in the BR), simple trigger selection and reduce the QCD background.

Main background is Drell Yan production of tau-pairs.

Observed events in agreement with SM predictions: we set limits on the MSSM parameter space.



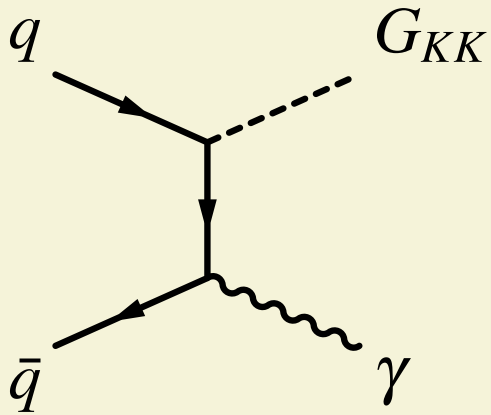
Searches with Photons

- Photons provide also an useful tool for exotic final-state signatures
- The most popular one is the search of the "Monophoton" that **appears in Large Extradimension (LED) Models.**

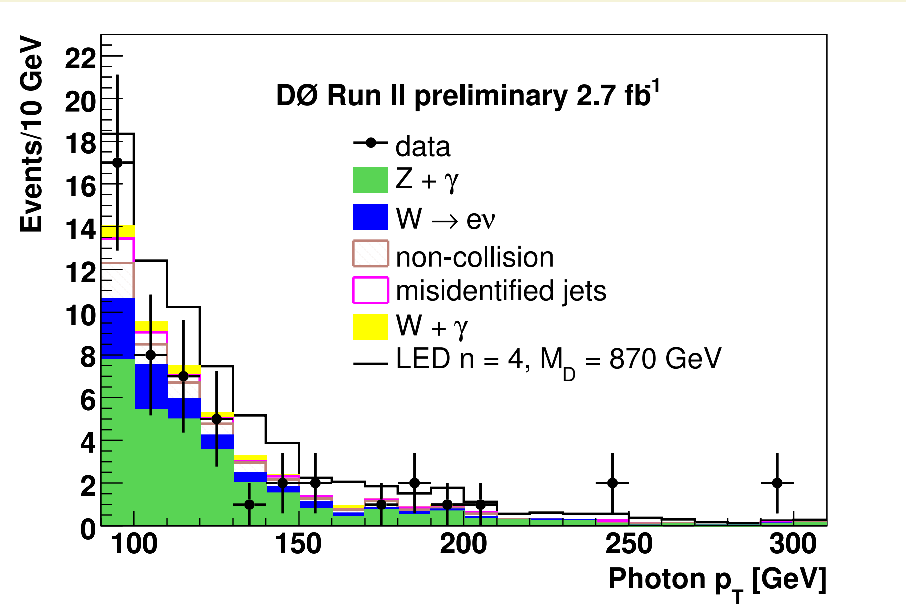
⇒ This analysis searchs for the production of a photon and a Kaluza-Klein graviton (that is not detected).

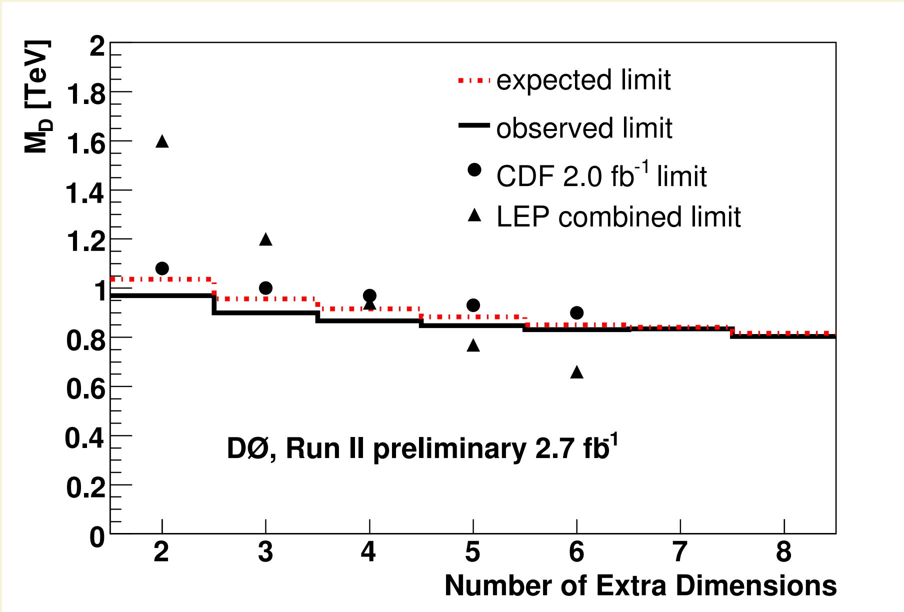
⇒ Irreducible background: $Z\gamma$ ($Z \rightarrow \nu\overline{\nu}$).

⇒ Data in good agreement with SM expectation.



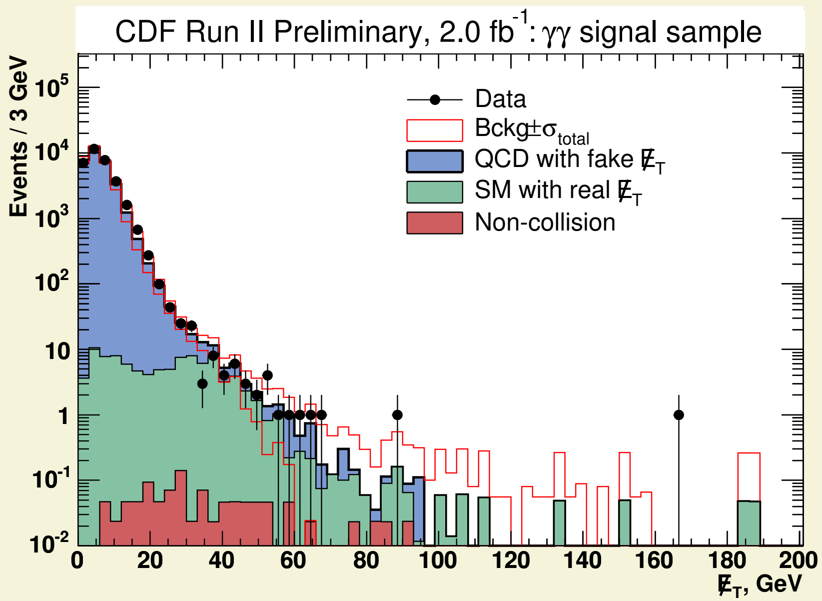
- There is no evidence of the presence of LED: **competitive limits are set.**

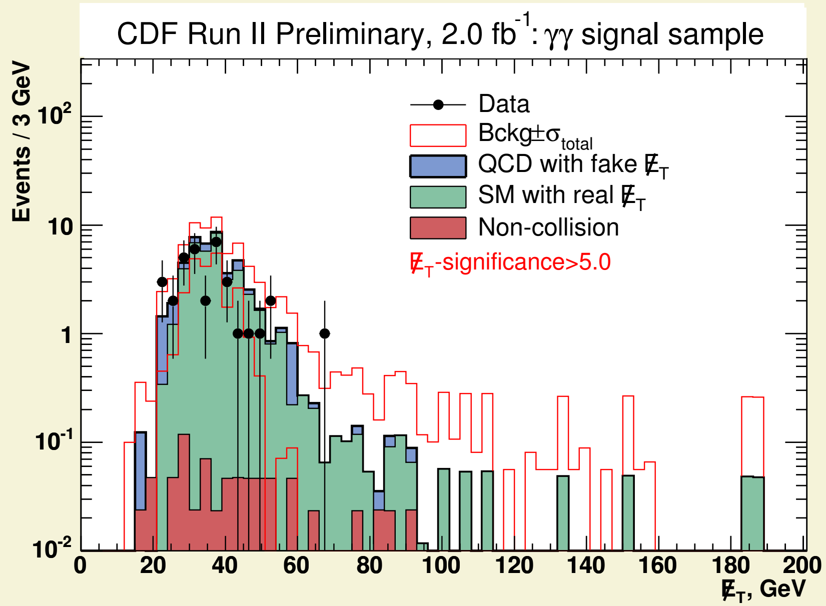




GMSB signatures: $\gamma\gamma\,\not{E}_T$

- SUSY is broken with a mechanism that is mediated by "messengers" which couple to the SUSY particles (and to the actual source of the symmetry breaking).
- LSP is gravitino and Next-to-LSP is neutralino or slepton
- In the first case the signature is given by: $\tilde{\chi}^0 \rightarrow \gamma\tilde{G}$
- In R-parity conserved models, the expected final state would be $\gamma\gamma\,\not{E}_T$





- Good agreement in the $\not{E}_T$ distribution of diphoton events, after applying cuts on the significance of the observed $\not{E}_T$
- This significance is a probability-based variable which takes into account the kinematic properties of the event and the observed objects.

Outlook

- Tevatron experiments are performing well and collecting data steadily.

- The search program is completely up to speed and continuously producing new results (and improving limits)

Tevatron is already where nobody has been before

- New tools under development to increase sensitivity:

  ⇒ Improved lepton reconstruction (for acceptance)

  ⇒ Improved triggers (get smarter)

  ⇒ Jet resolution, new b-tagggers,…

- Current efforts are lead by the Higgs searches

but can be applied anywhere (or everywhere).

The covered topics are a biased representation of the search program performed at Tevatron.

Please check the Public pages of the experiments for more details and other important results:

http://www-d0.fnal.gov/results/index.html

http://www-cdf.fnal.gov/physics/physics.html

But Man does not know what the future may bring…

End of Tevatron Run II Running?

Due to the excellent performance of the Tevatron and the Physics outcome, there has been proposals to extend the Run II beyond the expected date.

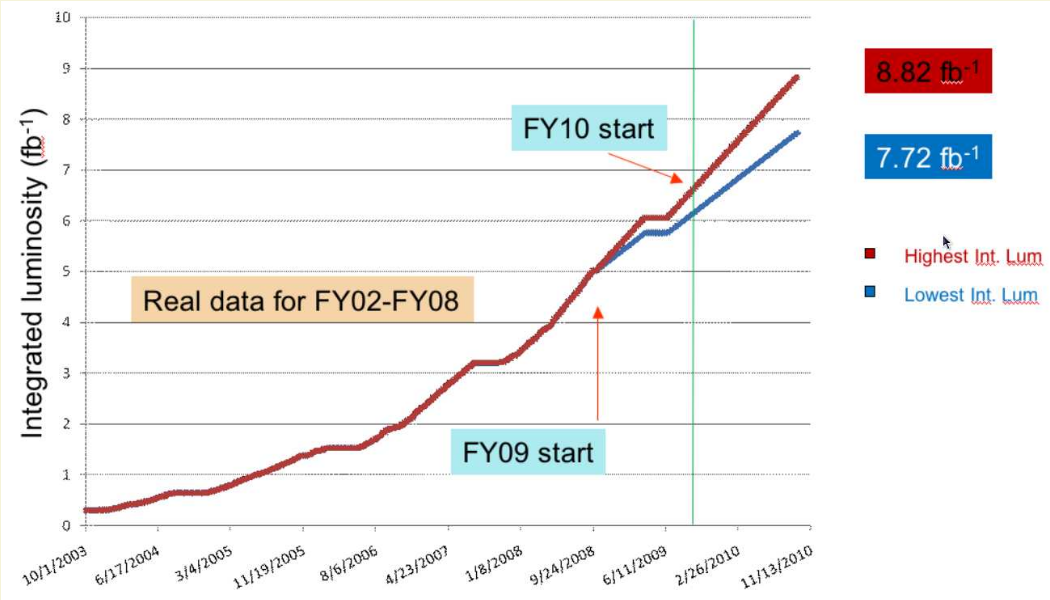
Currently expect to have ~ 6 fb^{-1} GOOD-FOR-PHYSICS datasample by Fall 2009.

We would integrate 2 fb^{-1} more if running in 2010

Motivation is mostly that we expect Tevatron to be competitive beyond the starting point of the LHC since:

$\Rightarrow$ Some interesting areas are hard for "Early LHC" (as low mass Higgs/Gauginos)

$\Rightarrow$ Detectors/Datasets are understood and in "physics mode" (as opposed to "Commisioning mode").



With these motivations, there is also some work to extend the Run II to double the 2009 dataset, i.e.running up to 2012/2013.

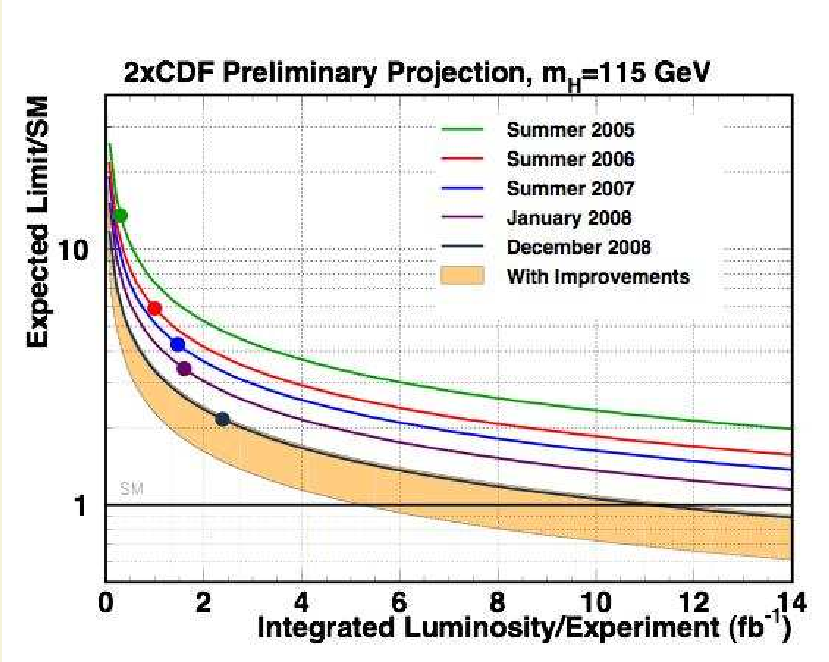
With datasets of 10-12 fb^{-1}, reach of $q\bar{q}$ processes at the 100-GeV scale (not easy at "Early LHC") is really compelling.

Possibilities and Opportunities

Several topics motivate the extension of the Run II beyond the start of the LHC:

- **Competitive results for hard analysis at LHC:**

  Hints for low mass Higgs



- **Complementarity for measurements**

e.g. mSUGRA motivated:

$\tilde{q}/\tilde{g}$ **at "Early LHC" (e.g. 500 GeV)**

$\tilde{\chi}^0/\tilde{\chi}^{\pm}$ **at Tevatron (e.g. 150-200 GeV)**

- **If nothing at reach is found, LHC folks will focus on the higher masses, forgetting about the tough "soft production".**

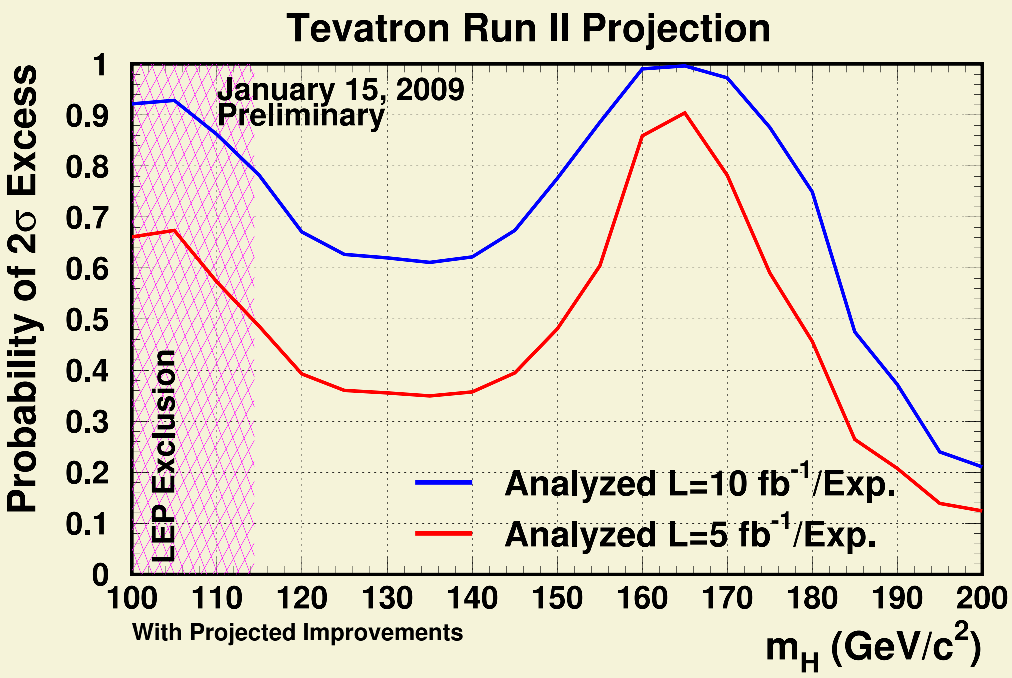
Motivation mainly comes from searches and measurements that are not expected to be easy at the beginning of the LHC experiments.

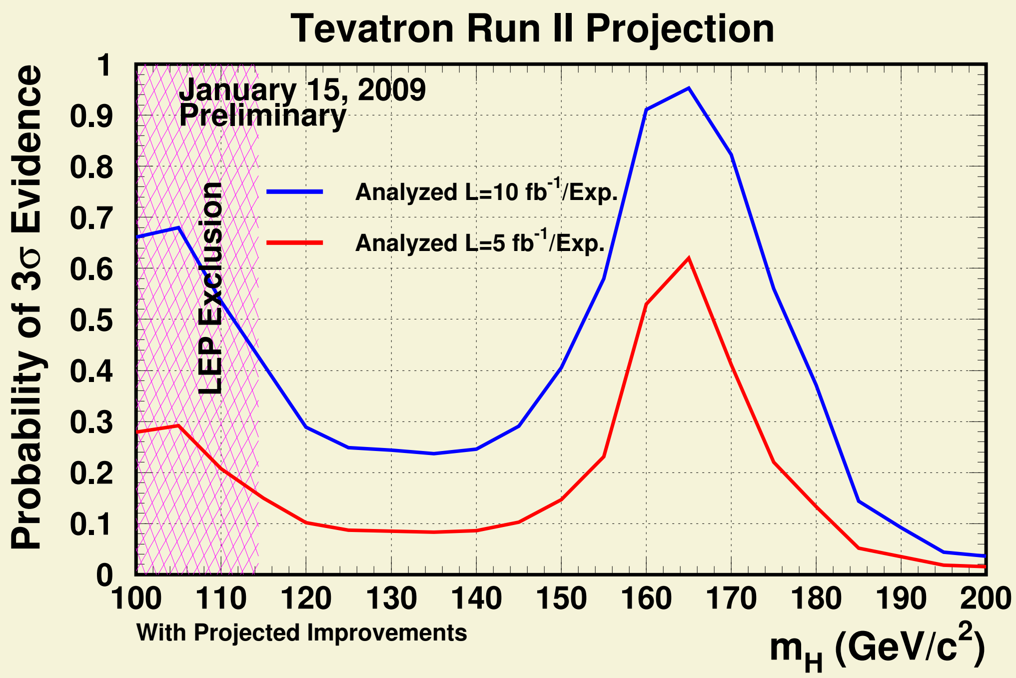
Tevatron experiments won't easily give supremacy to LHC...

stay tuned!

BACK-UP SLIDES

More expectation plots for the SM Higgs search





The third generation and new physics

- The third generation is very interesting due to their properties that suggest they "are closer" to the new physics.
- Even in the SM: the Higgs has a preference for the third generation of fermions due to the coupling to mass.
- Furthermore: third generation objects are harder to produce in the collisions so they provide more unique signatures.
- In the MSSM the third generation particles present mixing of the chirality states in the mass matrix, e.g. for the $\tilde{t}$:

$$m^2(\tilde{t}_{1,2}) = \frac{1}{2}\left[m^2(\tilde{t}_L) + m^2(\tilde{t}_R) \pm \sqrt{\left[m^2(\tilde{t}_L) - m^2(\tilde{t}_R)\right]^2 + 4m^2(\tilde{t})\left[A_t - \mu\cot\beta\right]^2}\right]$$

- This leads to typical signatures with light mass states for $\tilde{t}$ (due to large $m(t)$), $\tilde{b}$ and $\tilde{\tau}$ (large $\tan\beta$).
- From the experimental point of view, the third-generation objects are typically hard to reconstruct/idenfify...

but they are worth the effort to reduce backgrounds and to enhance these third-generation based signal.

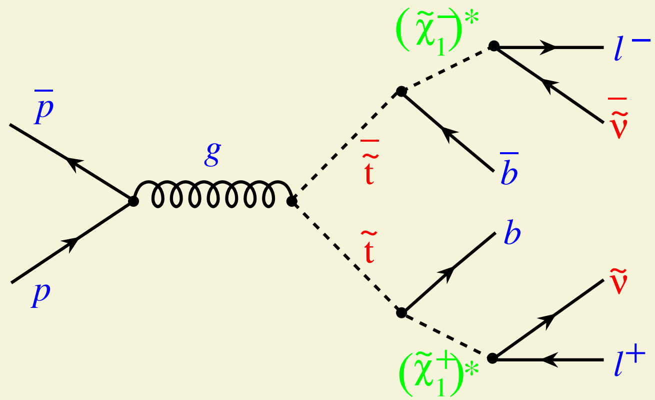
stop in the dilepton signature

Motivated by MSSM with a light scalar top, if sneutrinos are also light: the dominant decay channel contains charged leptons.

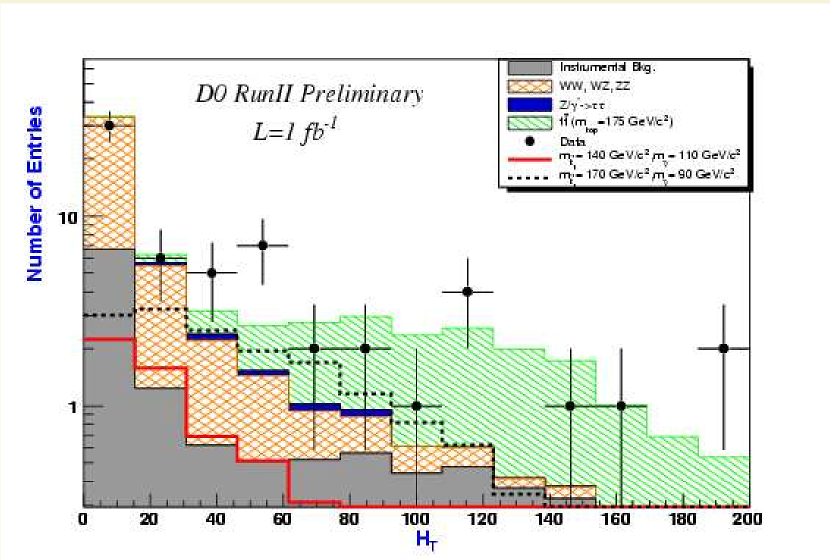
Signature is similar to the typical top pair production in the dilepton channel, but here leptons are expected to be softer.

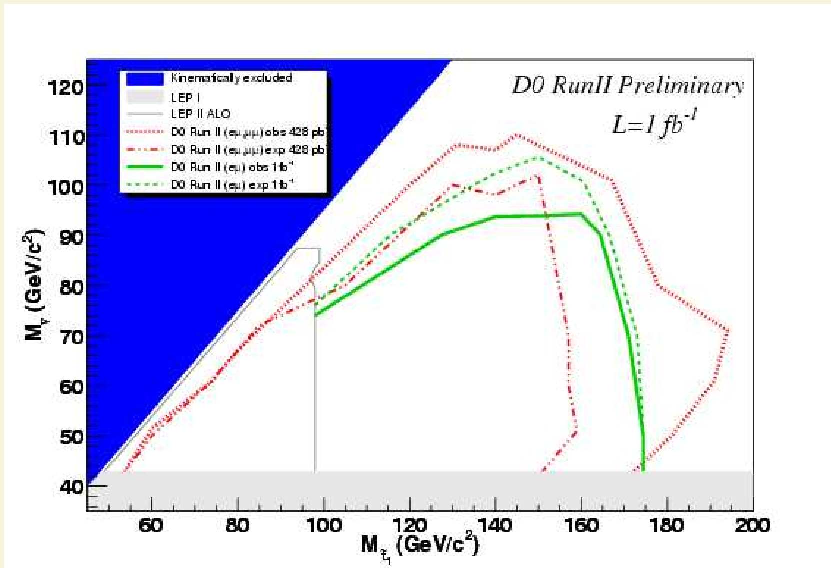
Kinematics also different because of the large mass of the sneutrinos.

The most sensitive channel is the $e\mu$ final state, since main background (Drell-Yan) is very reduced while containing half of the signal.



The H_T variable (scalar sum of the jet E_T) is a very good variable, but distribution for signal is very dependent on the mass difference.



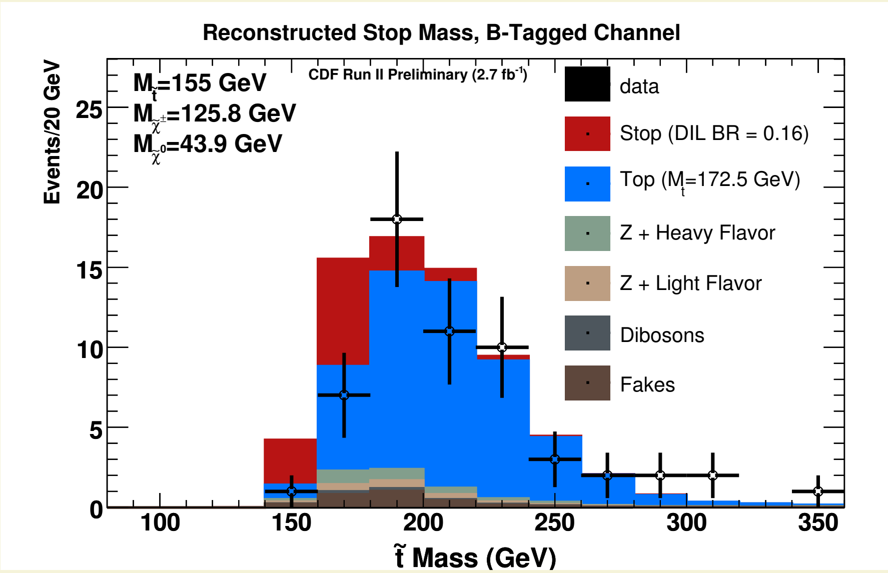


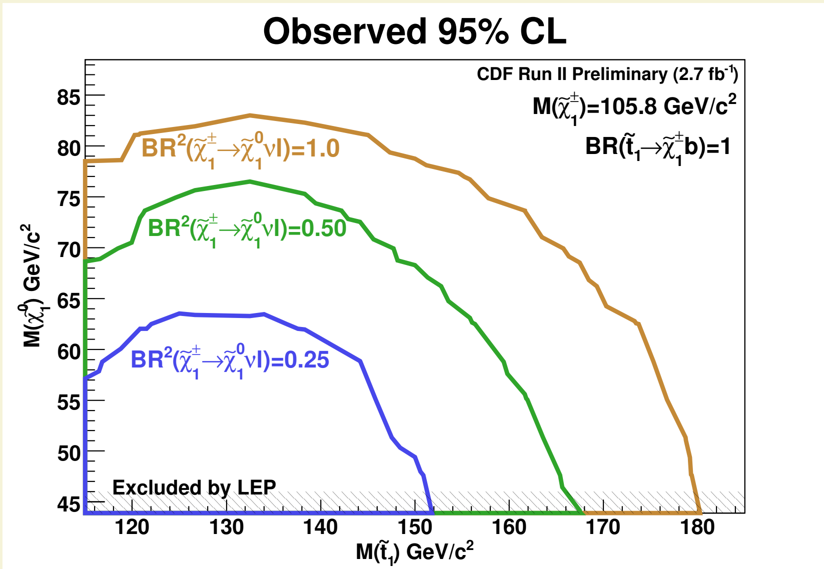
stop in top-like events

- However, if scalar top is more massive than the lightest chargino, the decay is very similar to the top quark

$$\tilde{t} \to b\tilde{\chi}^+ \to bl\nu\tilde{\chi}^0$$

- Small kinematic differences due to the final neutralino.
- Otherwise identical: scalar top pair production will appear in the top sample.
- The mass of the scalar top is the key variable to separate the signal from $t\bar{t}$





- Very good agreement. . . with the top-production hypothesis.
- Sensitivity depends on how much the chargino decay enhances the dilepton final state (i.e. SUSY phenomenology)

MSSM Higgs using b-jets

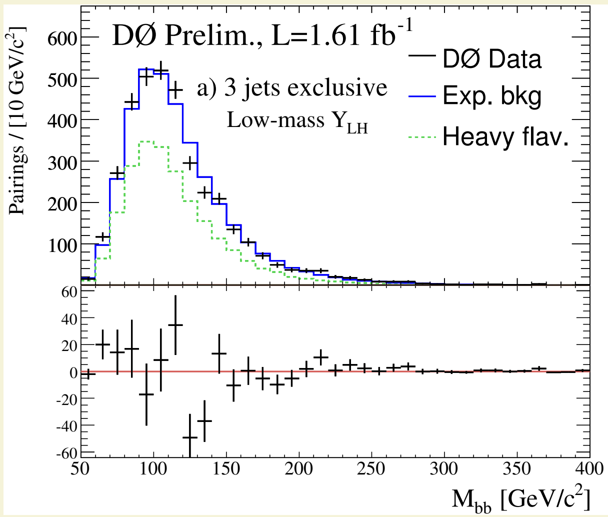
Production of Higgs in association with b-quarks is enhanced in extensions of the SM such as MSSM with large $\tan\beta$.

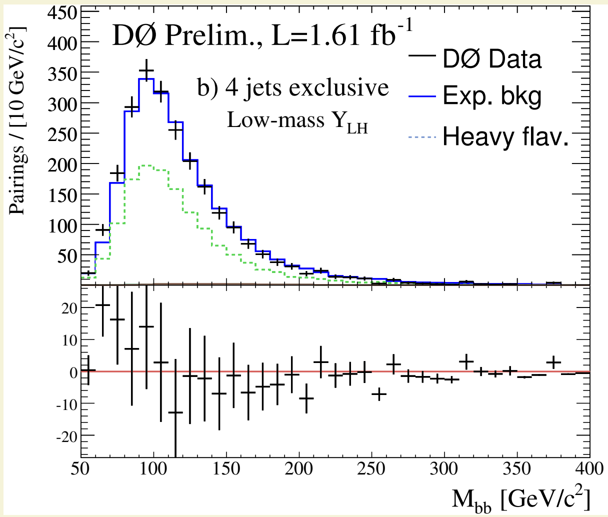
Separating in exclusive regions depending on jet multiplicity

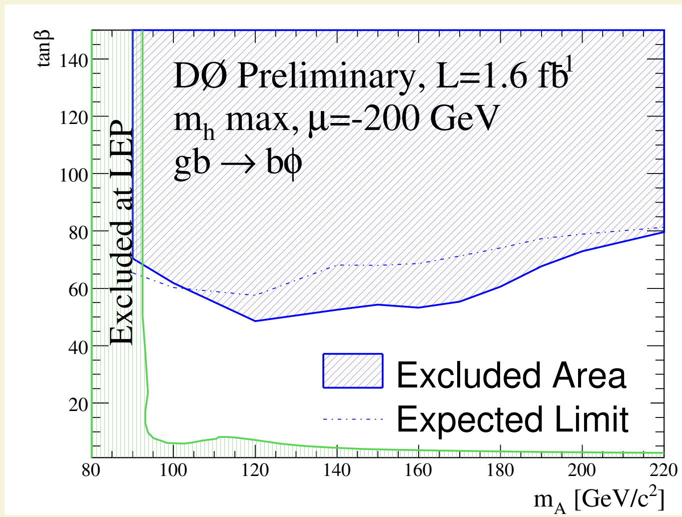
$\Rightarrow$ Heavy-flavour Multijets (QCD) shape obtained from data in control regions

$\Rightarrow$ Normalization obtained from data (i.e. real three b-jet backgrounds assumed to have the same shape) outside the mass window populated by the Higgs.

No excess observed over the predicted background.







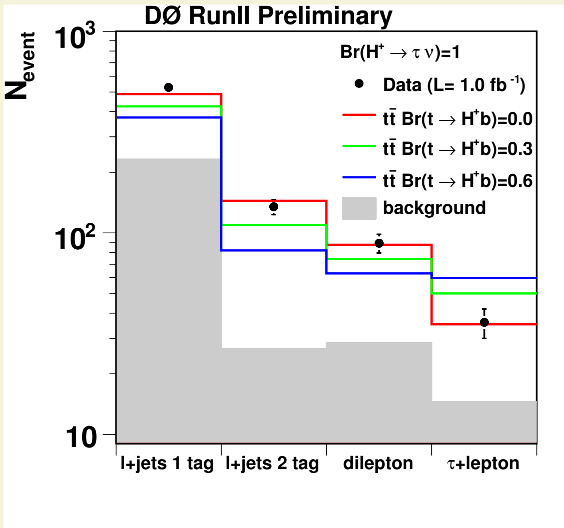
Complementary to the ditau search: different sensitivity to radiative corrections.

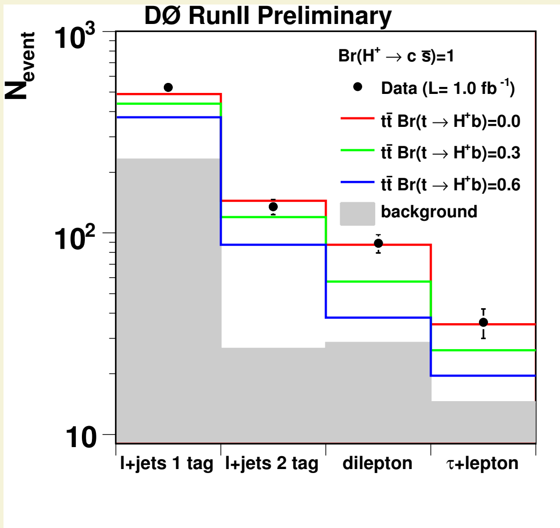
Charged Higgs in top decays ($t \rightarrow H^+ b$)

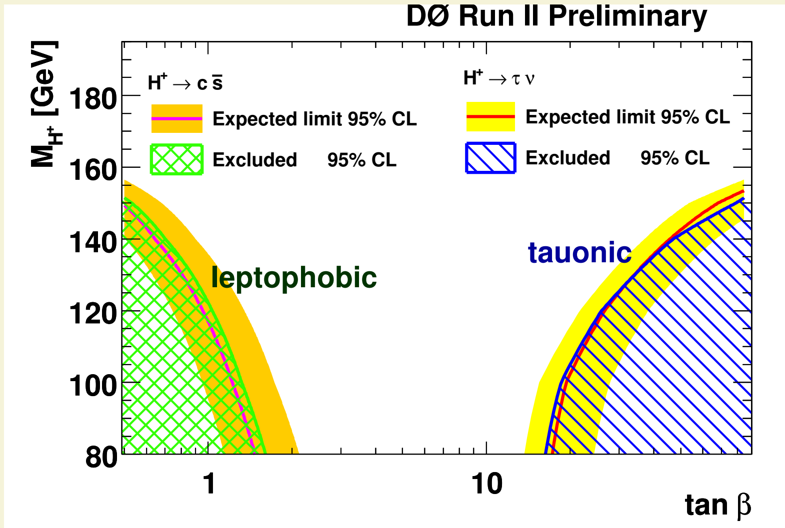
- Searches are also performed to look for the charged Higgs within the MSSM.
- This kind of Higgses also appears in other models and their observation would provide unambiguous discovery of new physics.
- Direct production is complicated by reduced sensitivity in the dominant decays.
- For that reason, analysis are searching for the presence of this Higgs using the couples to the top quark:

  ⇒ Decay to top (for $m(H^+) > m(t)$) using single-top signature
  ⇒ Production via top decays: $t \rightarrow H^+ b$

The last one may be observed as an anomalous branching-ratio decays of the W coming from the top quark.

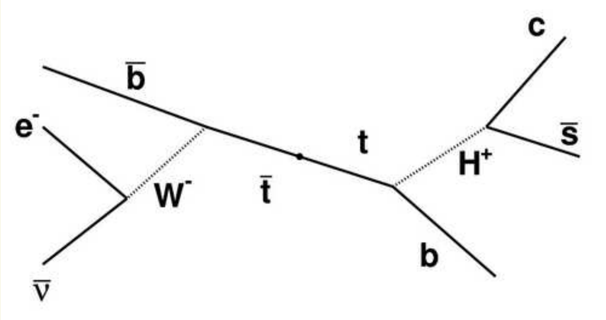




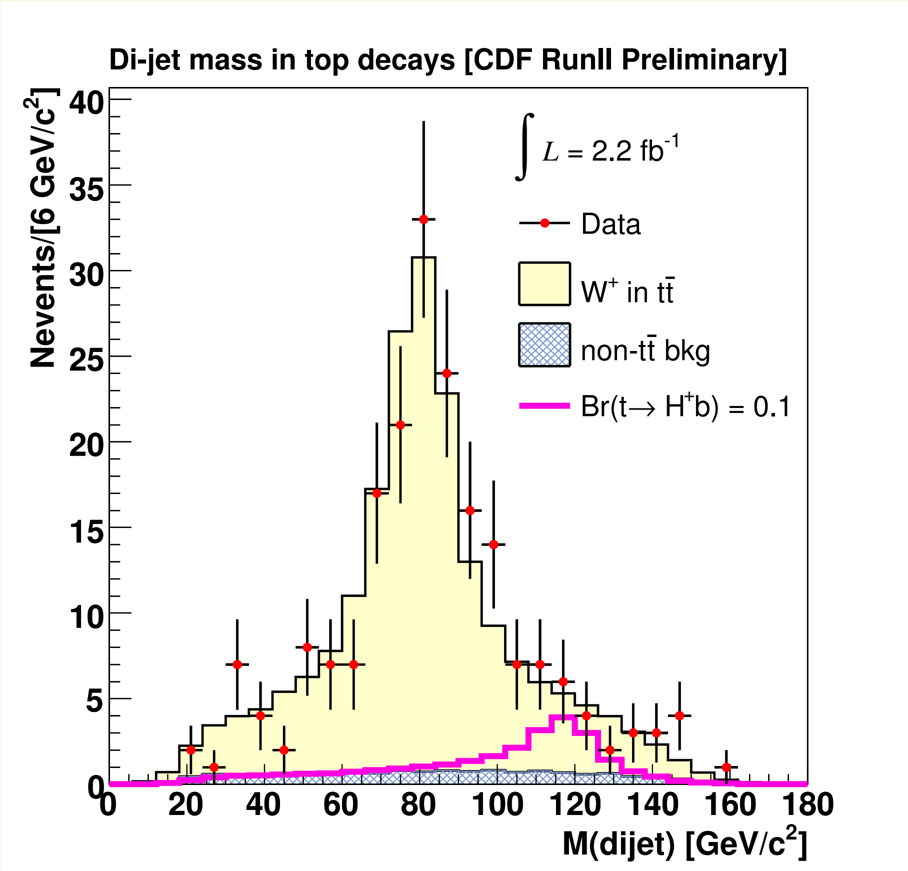


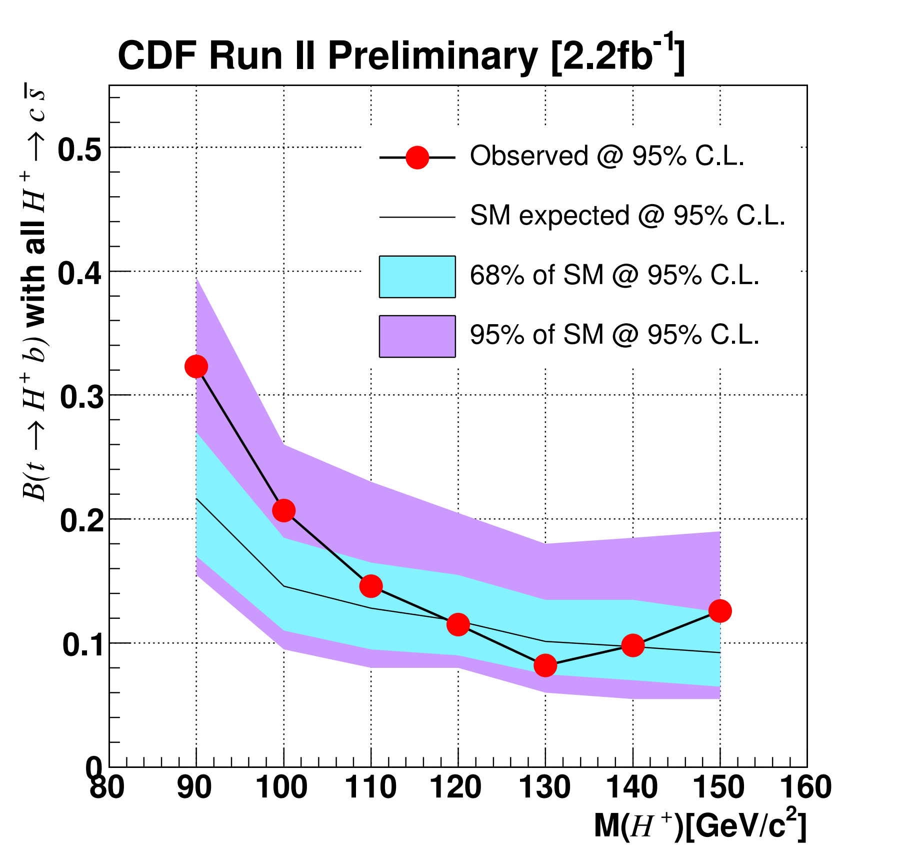
$t \to H^+ b$: Results

- At high $\tan\beta$, the dominant decay is into $\tau\bar{\nu}_\tau$.
- The decay $H^+ \to c\bar{s}$ is dominant for low $\tan\beta$ (leptophobic Higgs).



- The anomalous decays of the top quark could also be observed as a dijet resonance located in a different position of the W mass.



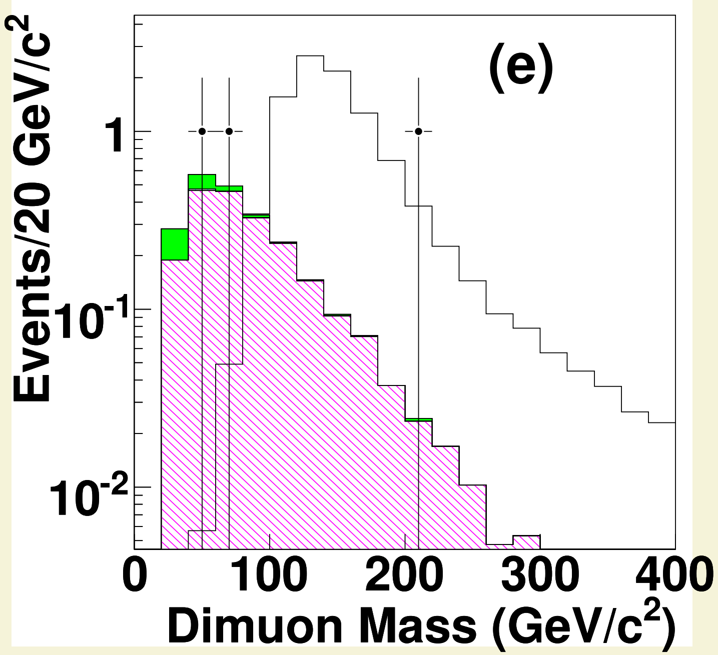


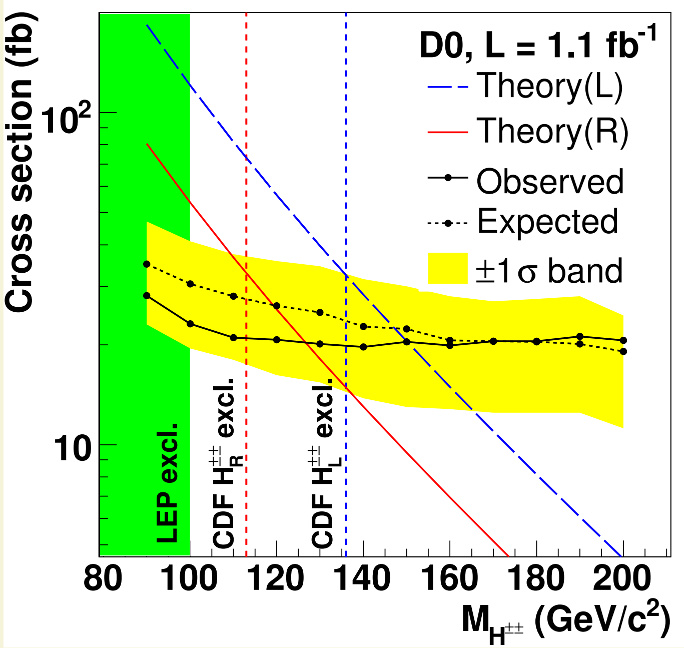
Doubly charged Higgs

- Looking for Drell-Yan production of two Higgses.
- This kind of particle appears in Left/Right symmetric models, Higgs triplets and Little Higgs.
- The analysis searches for multimuon final states (using good detector coverage)

$$p\bar{p} \rightarrow H^{--}H^{++}X \rightarrow \mu^-\mu^-\mu^+\mu^+X$$

- Selection:
  - $\Rightarrow$ Two same-sign high-p_T muons
  - $\Rightarrow$ Third muon is required to reduce background
  - $\Rightarrow$ $\Delta\phi$ cut to suppress $Z \rightarrow \mu\mu$
- Very high signal acceptance ($\sim 30\%$) very independent of mass.
- Good agrement with expectation. Limits are set for the mass depending on Left/Right Higgs couplings.





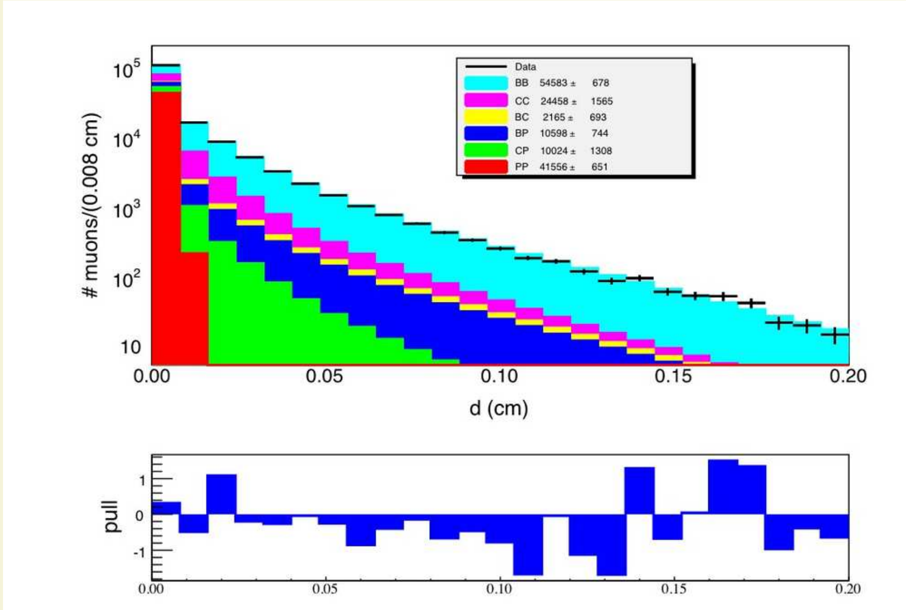
Displaced multimuon events at CDF (I)

From measurements at hadron colliders there has been the suspicion that b production or decay was somewhat different in hadron and lepton colliders.

The puzzle (with low statistics) indicates an excess of the b-production cross section when measured with semileptonic decays.

However, there is good agreement with LEP with the measurement done using dispaced secondary vertices.

A recent measurement with high statistics done by CDF using low-p_T dimuon events shows a very good agreement with expectation.



From a preliminary view it seems that the inconsistency is solved using the Run II selection and Run I measurement was "not correct".

What are the differences?

Displaced multimuon events at CDF (II)

The main difference is that in the Run II measurement is based on much tighter cuts on the silicon side, taking advantage of the improved detectors.

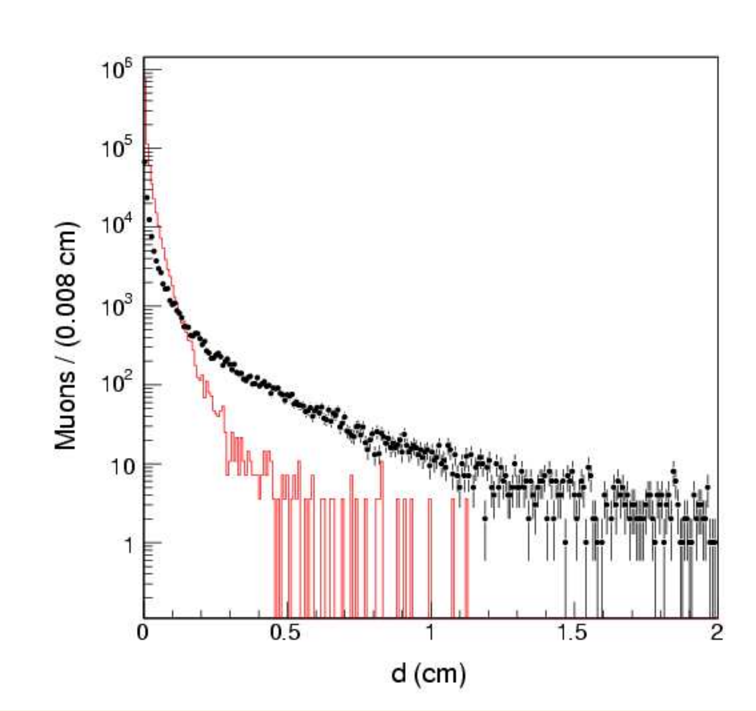
A check doing the analysis using cuts similar to those of the Run I selection yielded a big surprise that may be summarized as:

$\longrightarrow$ Computing the efficiency (ϵ) of the tighter cuts for muons using J/ψ allows to extrapolate from the "tight" to the "loose" selection.

$\longrightarrow$ The observed number of events with the loose selection is not N/ϵ, being N the number of events passing the "tight" (and understood) selection.

$\longrightarrow$ The excess, 20% of the events, is VERY significant.

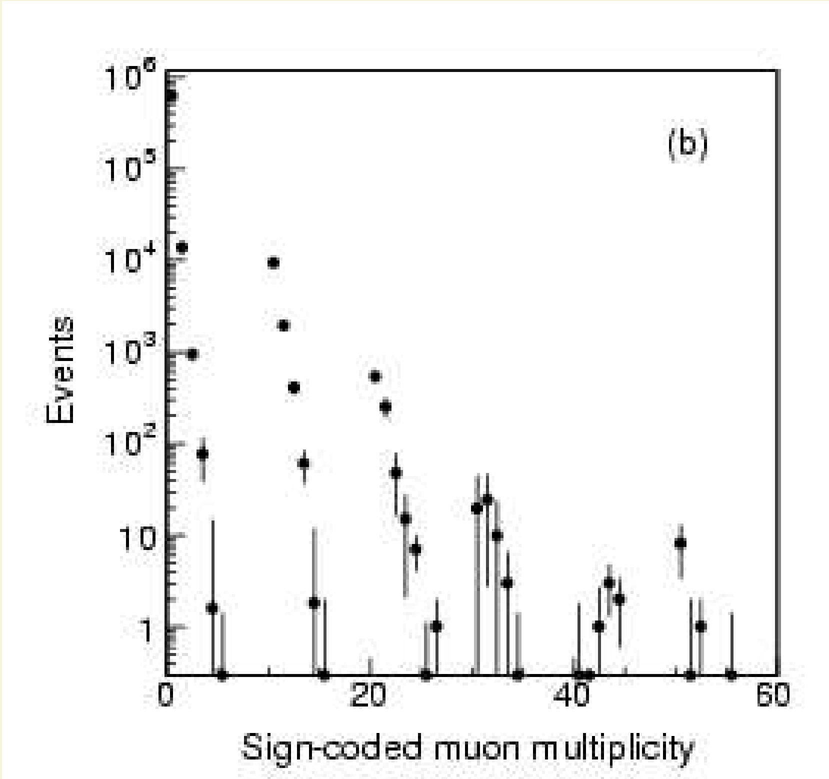
Studies of the two samples lead to the conclusion that the "additional events" fail to pass the tighter cuts because the muons are very displaced, as produced far from the interaction point.



These "additional events" does not only present displaced muons, but also a larger content of multimuonic jets (i.e. several muons that are close in space).

Displaced multimuon events at CDF (III)

The distribution of the number of muons in the "muonic jets" is very interesting, especially due to the charge symmetry.



Enhancement of multimuon is correlated in both sides of the event (i.e. two b candidates).

To summarize:

- Large-d_0 dimuon production not understood.
- Excess of displaced multimuonic events is not explainable by SM processes.
- Uncertainties in how well under control is the reconstruction of these muons.

- CDF is working on the sample to investigate the source of the strange events, which biased the b-production studies in the past, and may be a hint of new physics.
- DØ has neither confirmed nor excluded yet the presence of these events in the data.

Hard analysis for DØ due to the way the data is processed…very displaced tracks are not reconstructed by default.