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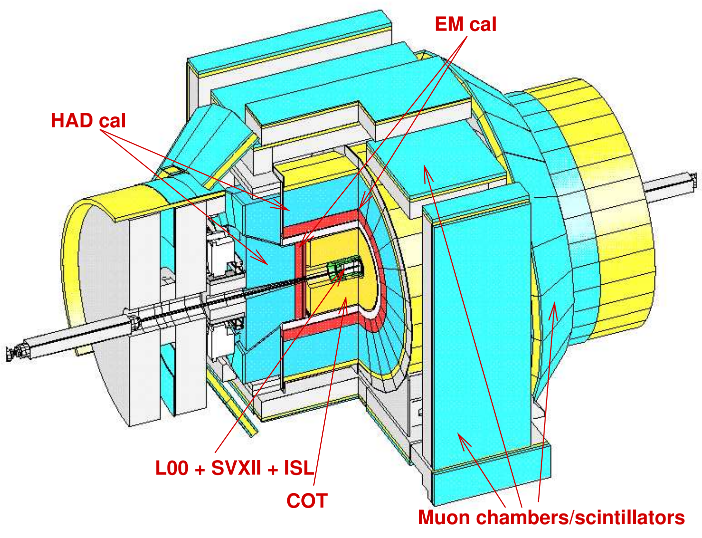
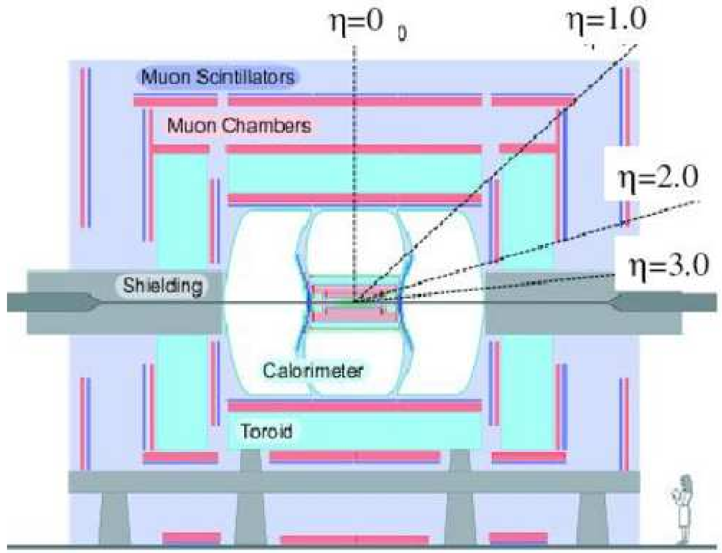
New Physics Searches at Tevatron





Tevatron and the experiments

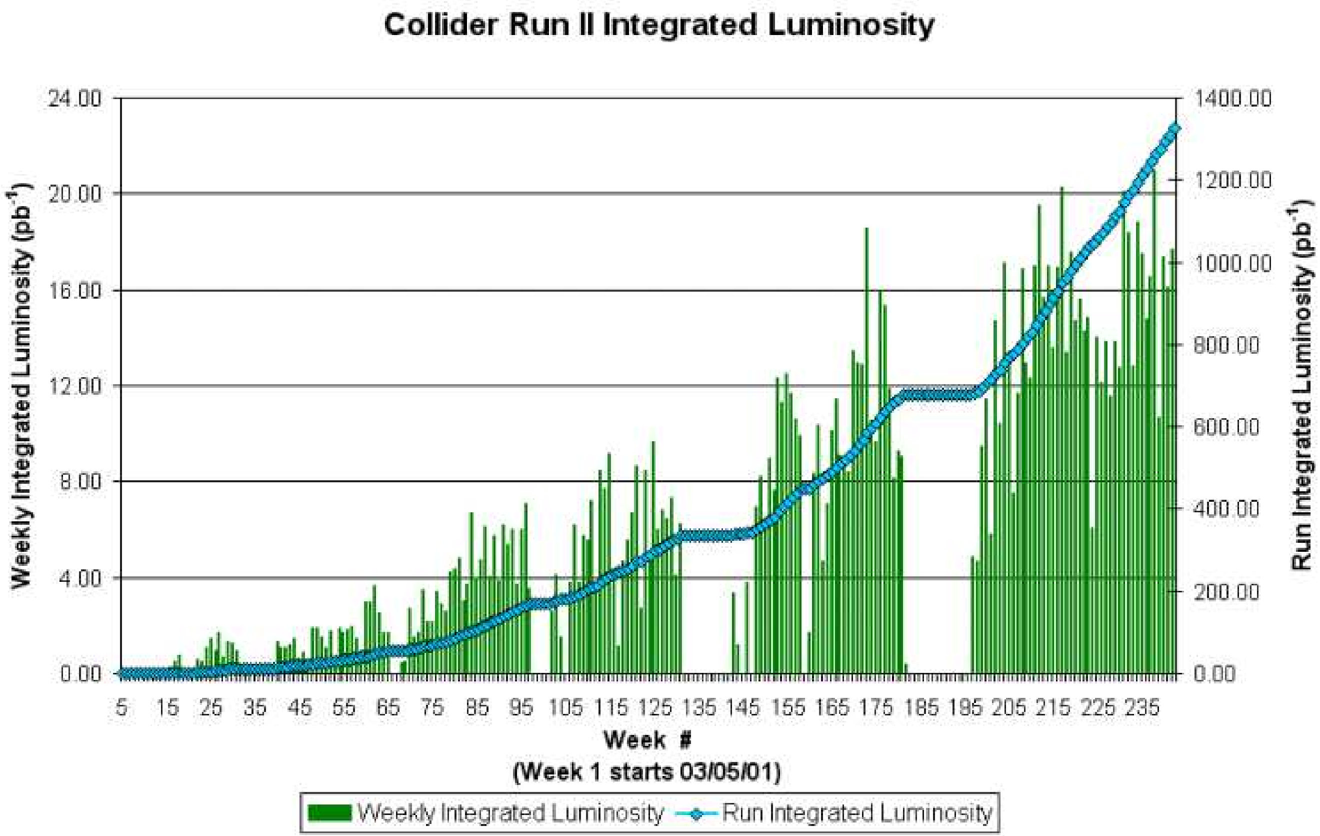
Proton-antiproton Collider located at Fermilab (cms energy: 1.96 GeV).

Tevatron is performing very well and achieving records of peak luminosity every few days now.

Total delivered luminosity rapidly growing: experiments close to have 1 fb^{-1} of useful data for analysis.

Plan for total Run 2: among 4 and 8 fb^{-1} of integrated luminosity.

Experiments are working fine and producing interesting results



- **Detectors well understood: time to get the most of them.**
- **Getting ready for the large amount of data to come.**

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
- Three generations
- Composition of Dark matter
- Gravity at the particle (quantum) level
- . . .

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

- Mass hierarchy problem
- Possible unification (=simplication) of forces
- Explain Universe from first principles: e.g. how did antimatter disappear?
- . . .

All this introduces a need for new physics to exist. . . at the TeV scale.

Theoretical Models

Several models have been proposed to explain the structure of the Standard Model and solve the different problems.

- **Supersymmetric models (SUSY)**

  Introduce a new symmetry between bosons and fermions

  It is broken: models differ in breaking mechanism.

  New quantum number: R-parity (1 for SM, -1 for superpartners)

  If conserved: Dark Matter Candidate, pair-produced superpartners.

- **Extradimensions**

  Requirement for string theories to "work"

  Some new dimensions may be observable at TeV scales

- **Extended gauge theories**

  Predicting new gauge bosons (more massive than EWK bosons)

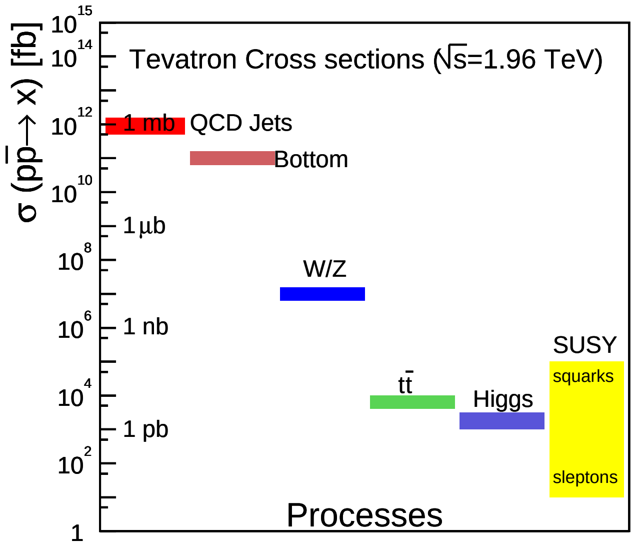
- **Compositeness**

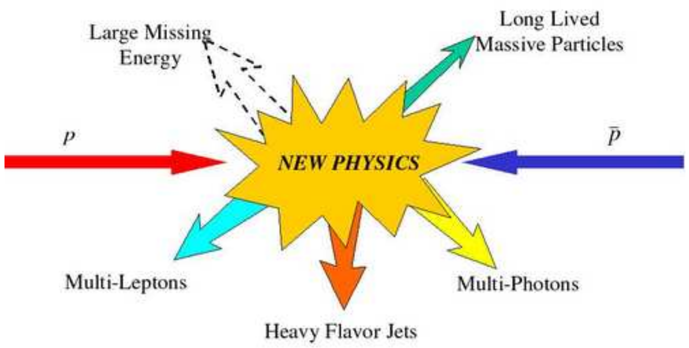
  To explain multiplicity of generations: internal structure.

- **and others. . .**

Experimental Searches at Tevatron

From the point of view of the experiment, the main limitation is the small cross section of the processes involving *New Physics*.





Experimentally, the theoretical models are used as references for getting possible signatures allowing the distinction between signal and background from Standard Model processes.

$\Rightarrow$ Enhanced cross sections on high-p_T tails

$\Rightarrow$ Production of new particles (observed as resonances or through "exotic" decays)

$\Rightarrow$ Observation of $\not{E}_T$ (transverse momentum not conserved) due to weakly-interacting particles escaping detection.

In addition, we are always looking for striking signatures even with no explicit models supporting them.

Looking for Supersymmetry

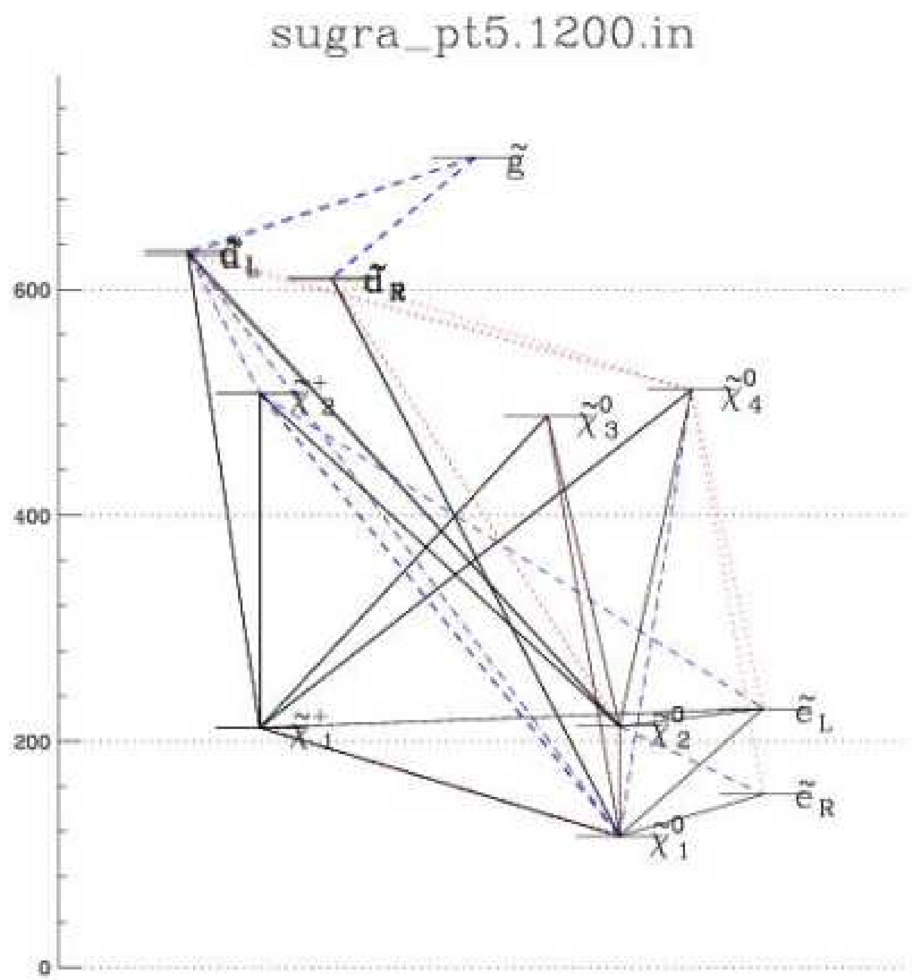
SUSY is very attractive for theory and experiment due to the possibilities to solve the SM "problems" and to the addition of "easy" signatures.

At Tevatron, SUSY provides a rich program for searches (second in importance, after SM Higgs) which several topics

- **Enhanced sensitivity to the Higgs sector for large $\tan\beta$**
- **Leptonic final states: Trilepton as the Golden Channel!!!**
- **Squarks and gluinos produced with (relatively) high cross sections.**

Especially for sbottoms and stops, which may be the lightest colored particles.

- **Indirect observation of SUSY: $B_s \to \mu\mu$**



MSSM Higgs in $A \rightarrow \tau\tau$

- In the MSSM we expect 5 Higgs bosons: h, H, A and $H^{\pm}$

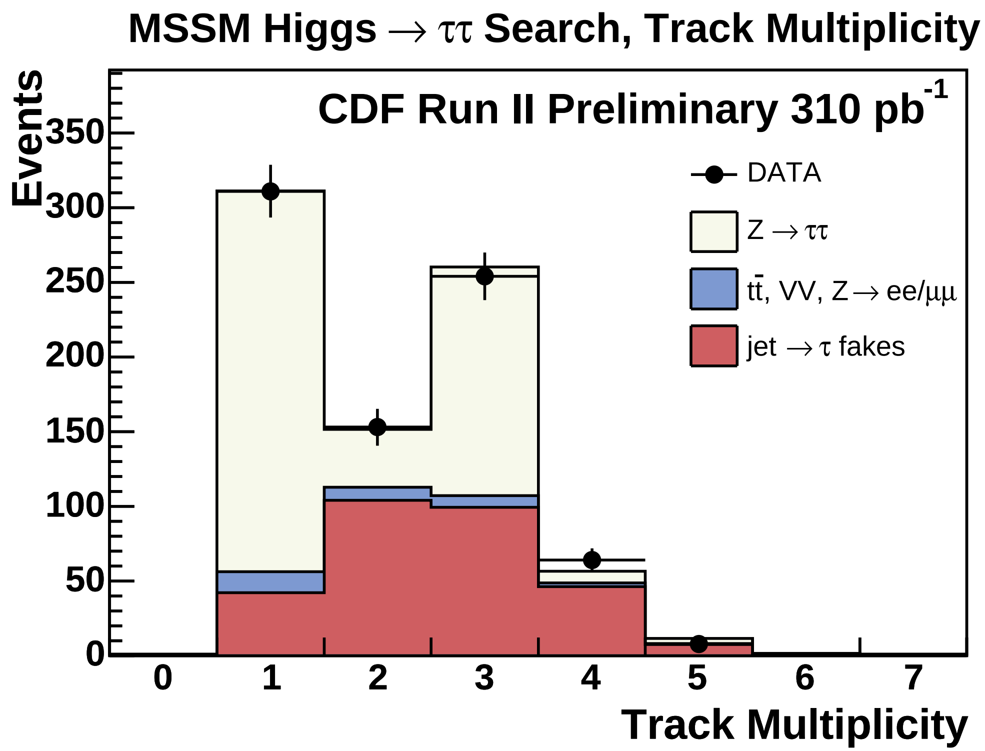
- For high $\tan\beta$: A is degenerated in mass with h or H and the cross section is enhanced (coupling to down-type quarks).

- Decay into $\tau\tau$ (10%) and bb (90%)

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

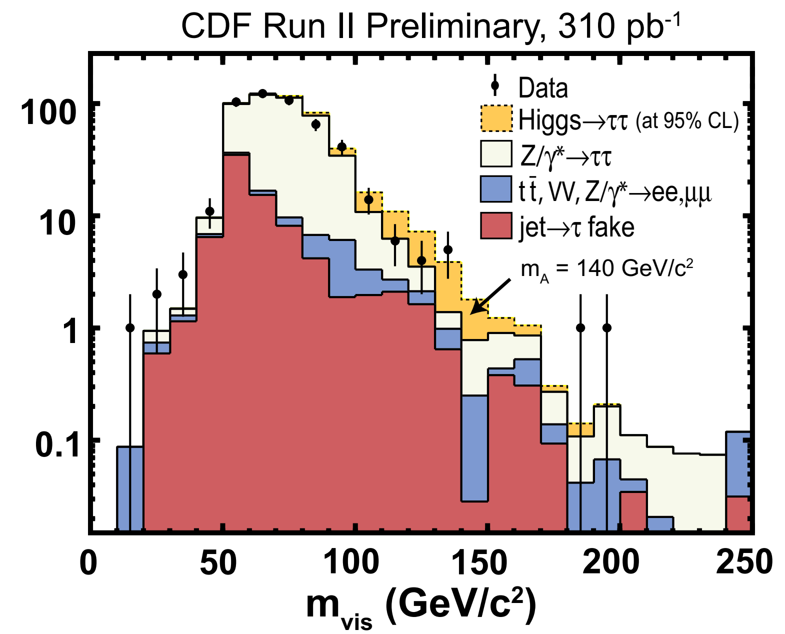
Big effort performed to understand hadronic tau's at Tevatron to avoid missing events in hadronic-tau decays.

Using $Z \rightarrow \tau\tau$ as a control sample to understand the hadronic tau selection.

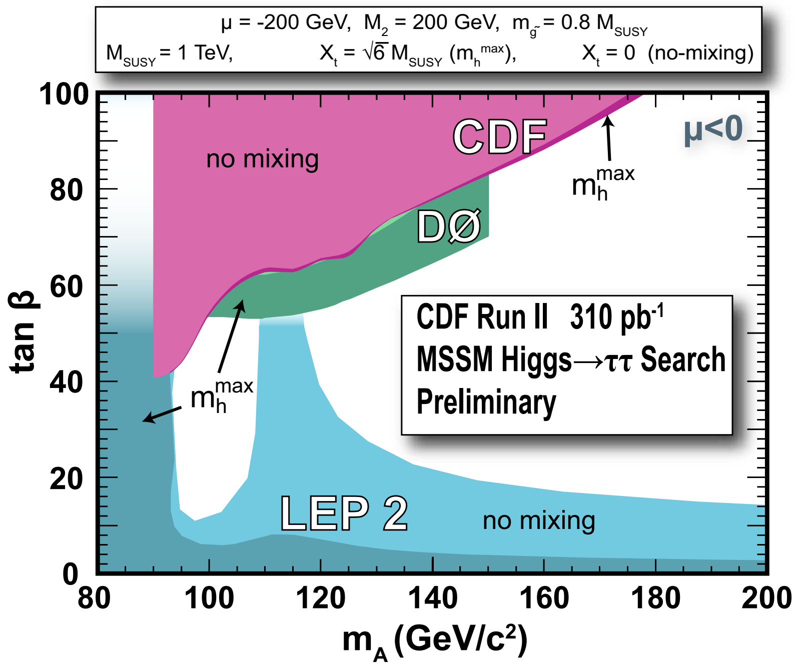


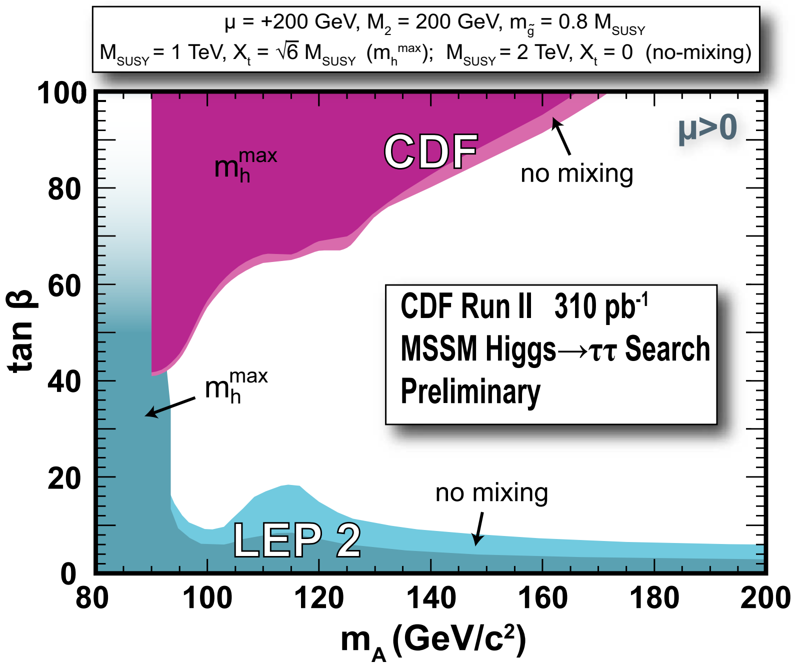
MSSM Higgs in $A \to \tau\tau$ (II)

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.





Higgs in $bbbb$ events

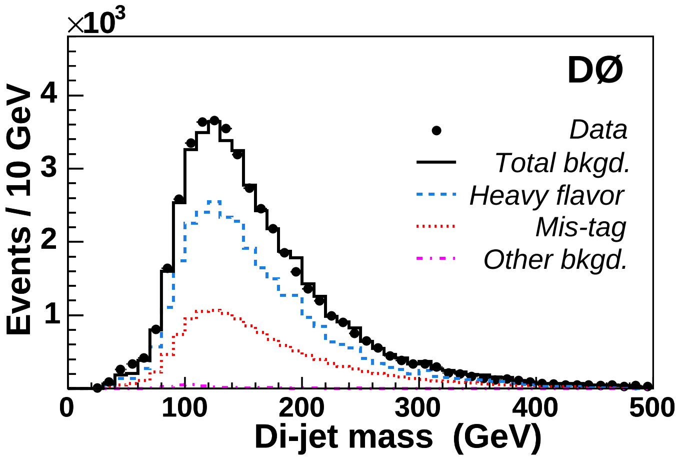
Production of Higgs in association with b-quarks is enhanced in extensions of the SM such as MSSM with large $\tan\beta$.

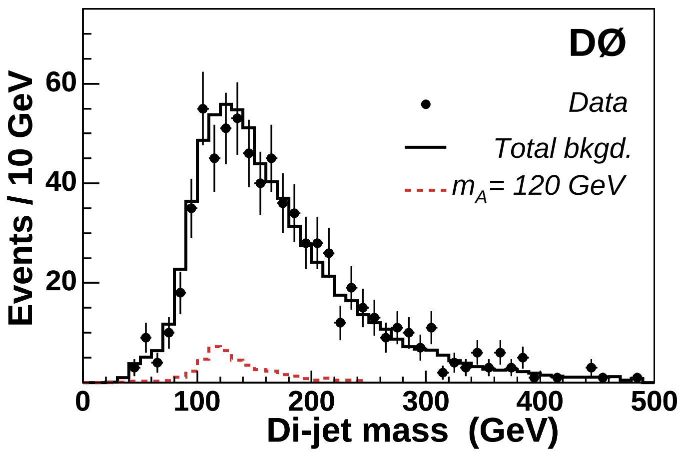
Selecting events with at least two and three b-tagged jets

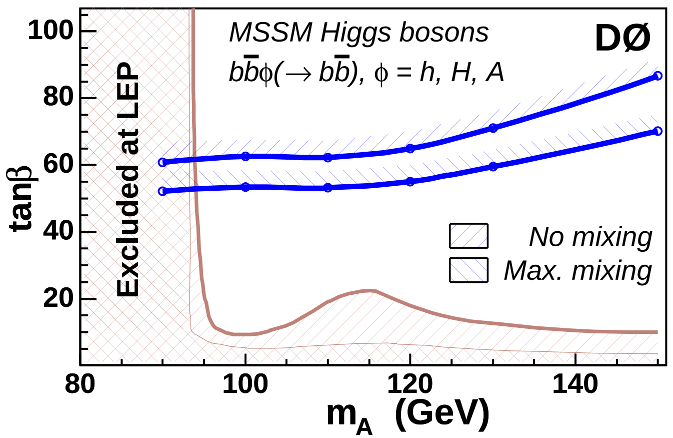
⇒ For the three-tag selection, taking shape from the 2 b-jets and 1 mistag sample.

⇒ 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.





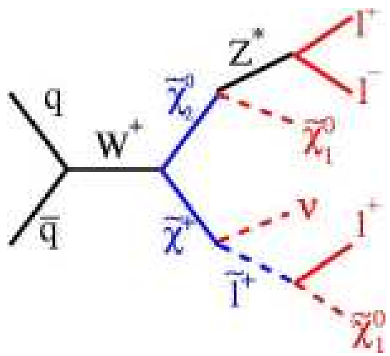


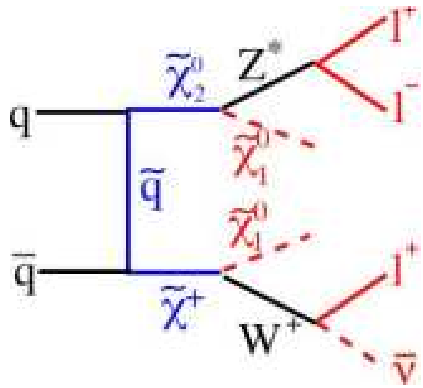
The results are complementary to the ditau search: different sensitivity to radiative corrections.

SUSY in trilepton events

Production of chargino and neutralino in R-parity conserved models provide a golden mode for observation of SUSY at hadron colliders in the leptonic decay.

- **Trileptons are clean signature at hadron colliders**
- **Cross section may be “large” (however, branching ratio typically small)**
- **Large amounts of integrated luminosity for reaching beyond LEP limits.**





Due to small backgrounds from SM processes for trilepton selection, both experiments tried to gain acceptance relaxing condition on third lepton:

At D0:

- **2l+isolated track (l= e, μ or τ)**
- **2 same-sign muon (i.e. third lepton implicitly selected)**

At CDF:

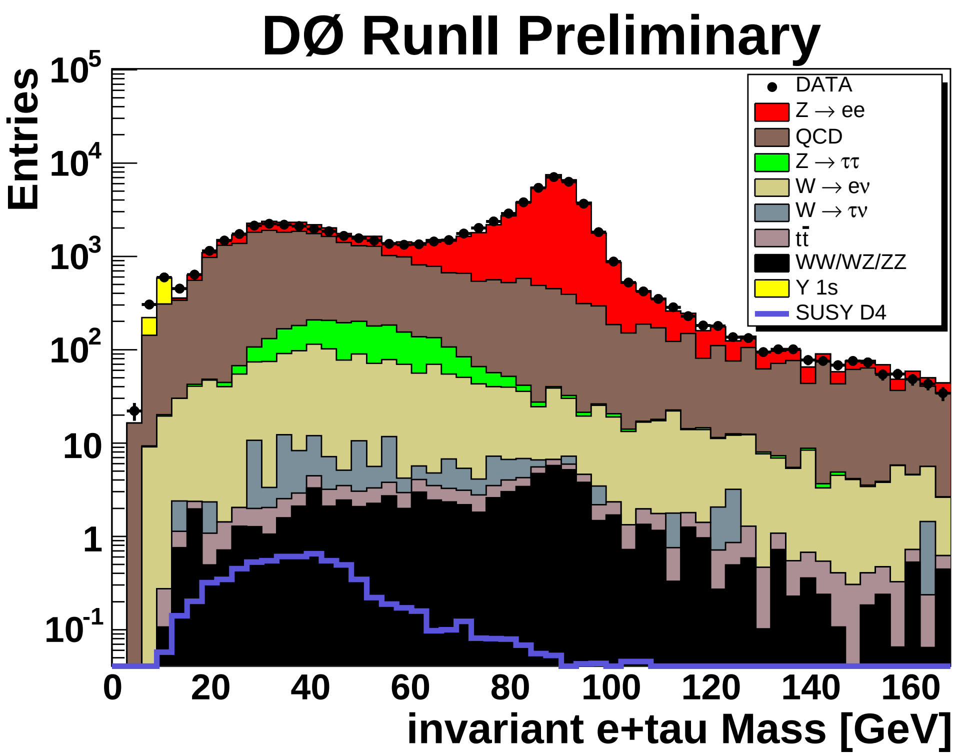
- **2l+third object (isolated track or “loose” lepton)**

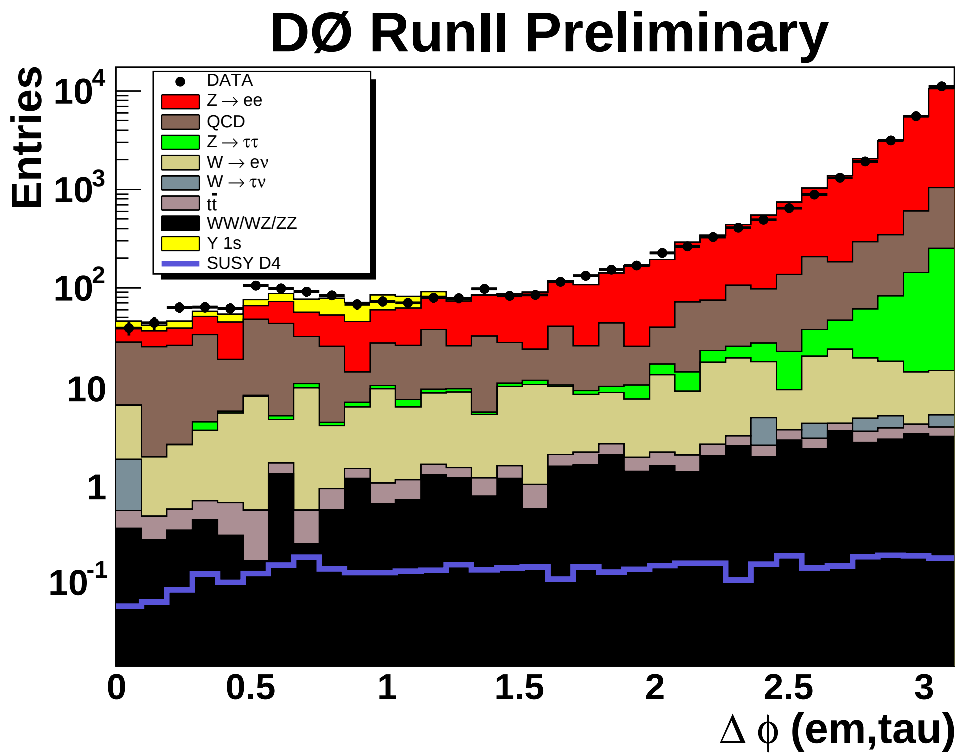
SUSY in trilepton events (II)

Due to the limitation in the small BR, more channels are included to gain sensitivity.

Especially interesting are selection of trilepton events including hadronic tau's:

- **Increased acceptance (especially when decays mediated by stau are present).**
- **Harder to understand: not as clean as the "actual trilepton".**





SUSY in trilepton events (III)

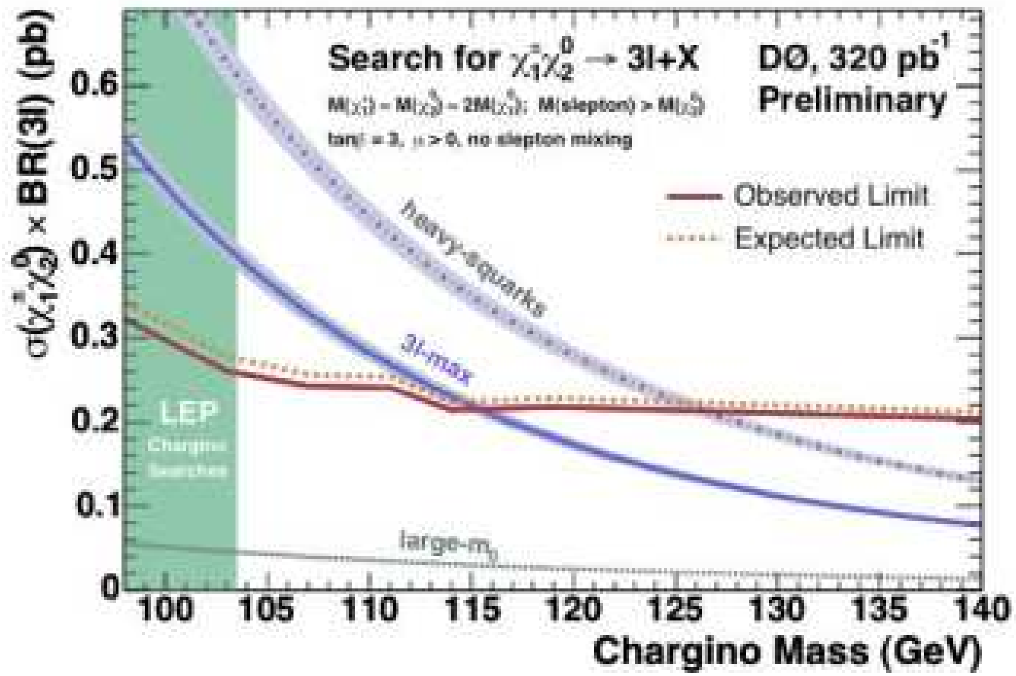
The main backgrounds are di-boson production (including Drell-Yan+γ) and the misidentication of the third lepton.

At CDF:

Channel	Expected (SM)	Observed
$ee+l$	0.17 ± 0.07	0
ee+track	0.36 ± 0.27	2
$\mu\mu+l$	0.09 ± 0.03	0

At D0:

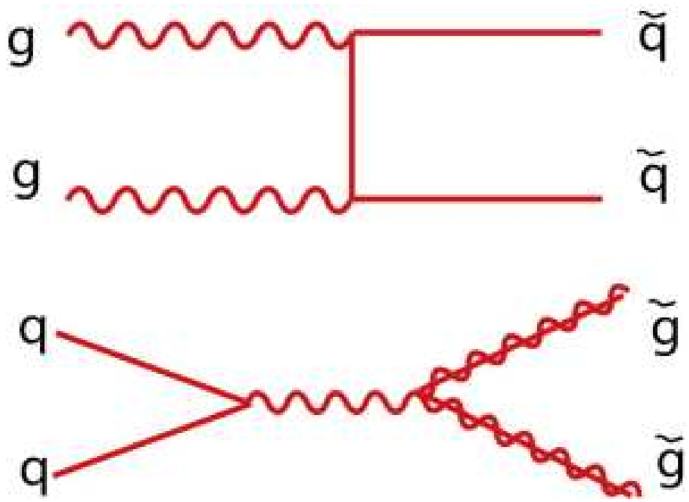
Channel	Expected (SM)	Observed
ee+track	0.21 ± 0.12	0
$e\mu$+track	0.31 ± 0.13	0
$\mu\mu$+track	1.75 ± 0.57	2
LS $\mu\mu$	0.64 ± 0.38	1
$e\tau_h$+track	0.58 ± 0.14	0
$\mu\tau_h$+track	0.36 ± 0.13	1
Total	3.85 ± 0.75	4



Search of squark and gluino production

Production of squarks and gluinos is attractive at Tevatron:

- **Large cross section (via strong interaction)**

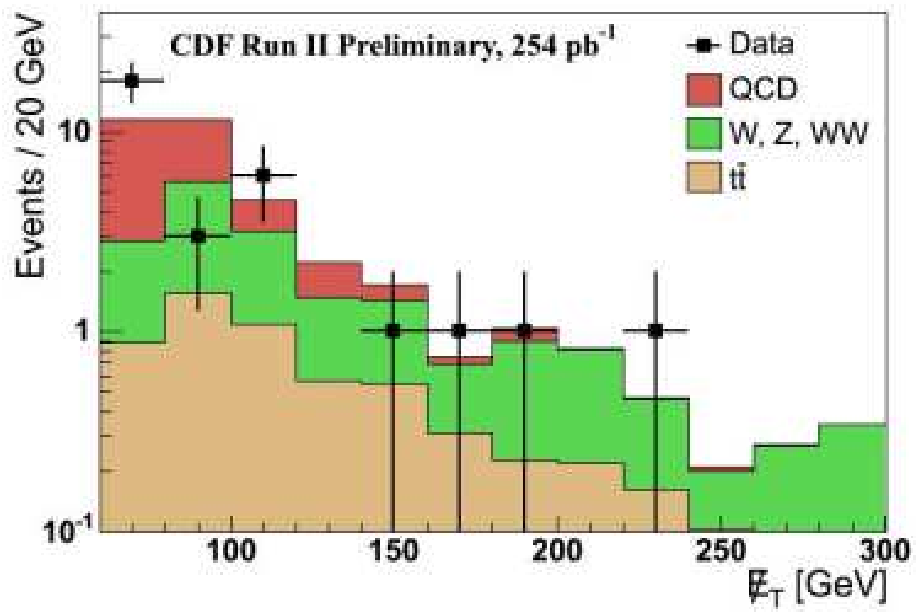


The large QCD background is suppressed by selecting events where the $\not{E}_T$ is unlikely to be "generated" by detector effects (i.e. not aligned with jets).

EWK background estimated from simulation and used for optimization.

At CDF, remaining QCD contribution is estimated with the simulation which is cross-checked in the control regions.

Data in good agreement with expectations (for 3 jets and $\not{E}_T$).



Search of squark and gluino production (II)

At D0, three different strategies have been developed in order to cover the different possibilities in the final states

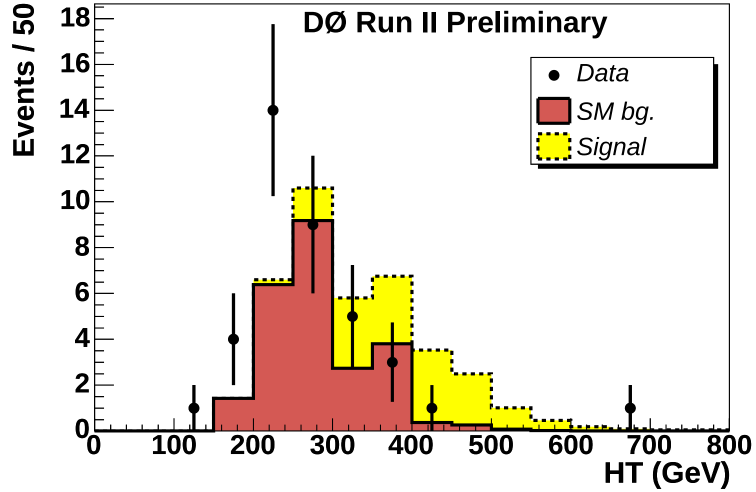
- **Dijet: motivated for squark-pair production**

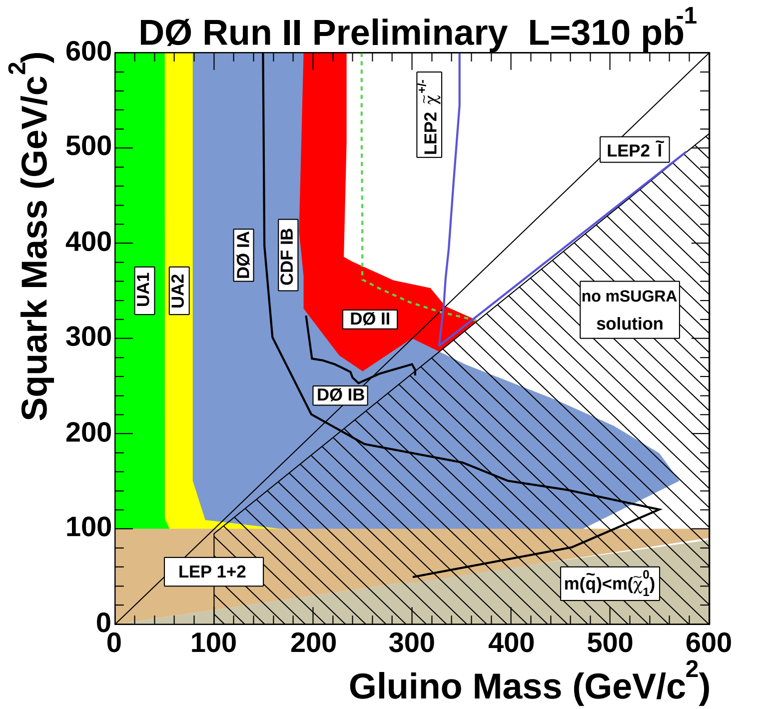
- **Gluino: motivated for gluino-pair production.** Requires at least 4 jets in the events.

- **Three-jet events: for regions where gluinos are produced in assotiation with squarks.**

QCD background is estimated from data: computed in a region were new physics is small and extrapolated to signal regions.

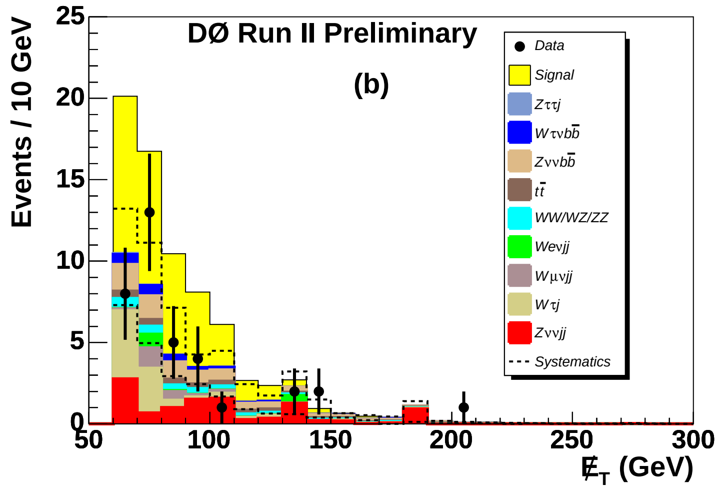
Limits from D0 due to no evidence for squark or gluino events. CDF limits to be calculated.





Sbottom production

In SUSY it is expected that the third generation behaves in a slightly different way with respect to the mass eigenstates.



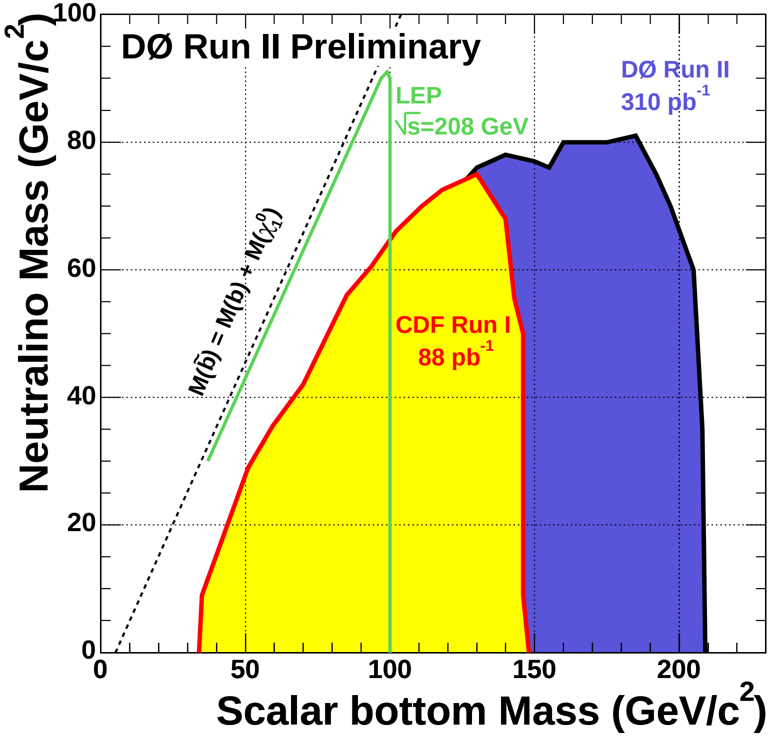
Concretely, the stop, sbottom and stau are expected to have different states for chirality and for mass due to mixing of states.

As a consecuence: the lightest squark could be the lightest stop or sbottom (depending on parameters of the SUSY model)

Large production cross section → good for first hint of SUSY

In mSUGRA-motivated searches, the sbottom will be observed as $\tilde{b}_1 \rightarrow b + \tilde{\chi}$, or with the following signature

- **2 b-jets and $\not\!\!E_T$**
- **Cuts on $\not\!\!E_T$ and $E_{T,jet}$ optimized for different masses**

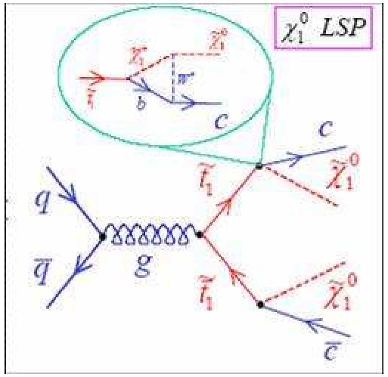


Stop production in RPC SUSY (I)

In the case of the stop, one typically assumes that the decay to top is forbidden

(otherwise those events are observed as excess on the top production containing events with anomalous kinematics, due to the neutralinos).

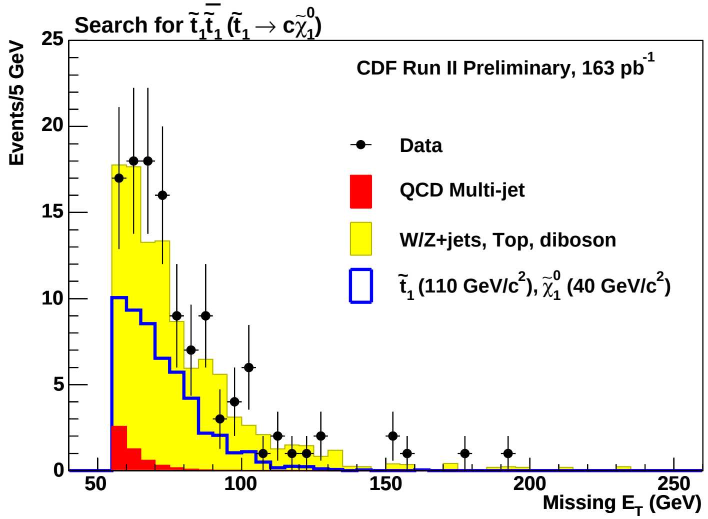
Within mSUGRA-based models, a preferred decay is into a charm quark and LSP (which is loop-suppresed in absence of FCNC).

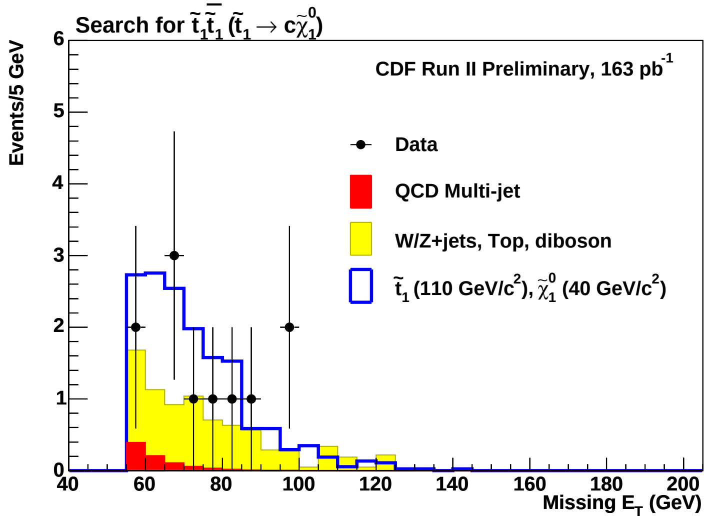


Analysis requiring jets from heavy-flavour quarks

Expected from SM: $8.3^{+2.3}_{-1.7}$

Observed: 11 events





With the current performance it is not possible to set a limit (better than those obtained in Run I, ~ 120 GeV/c^2).

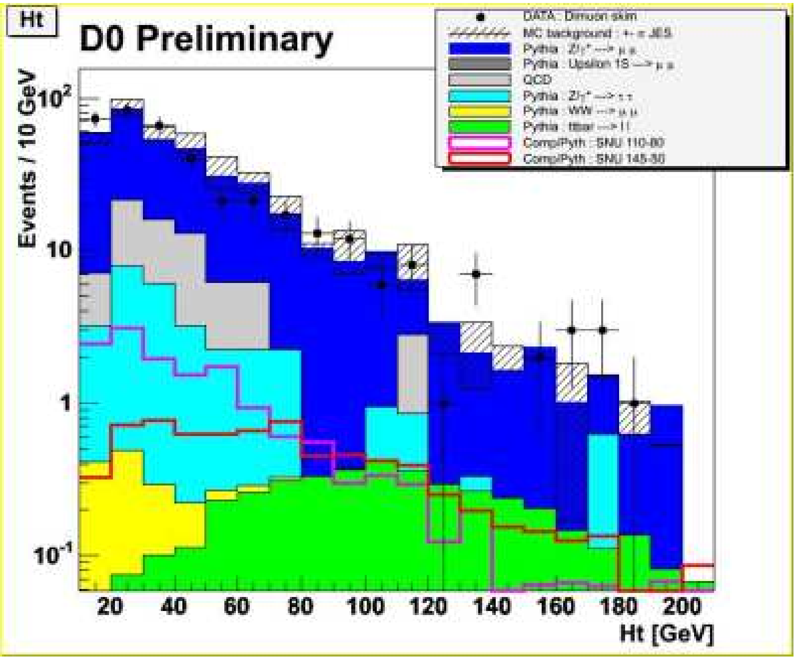
Stop production in RPC SUSY (II)

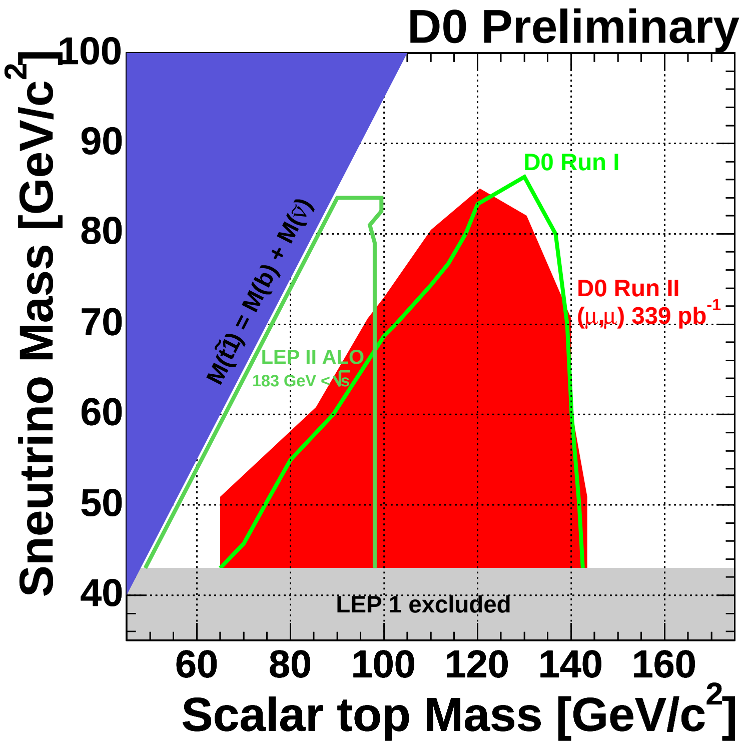
Another possible decay for the stop is $\tilde{t} \to l b \tilde{\nu}$

providing a very attractive signature:

2 leptons+ b-jets + $\not{E}_T$

Study has been performed at D0 using dimuon+b-jet events, and a limit was set.

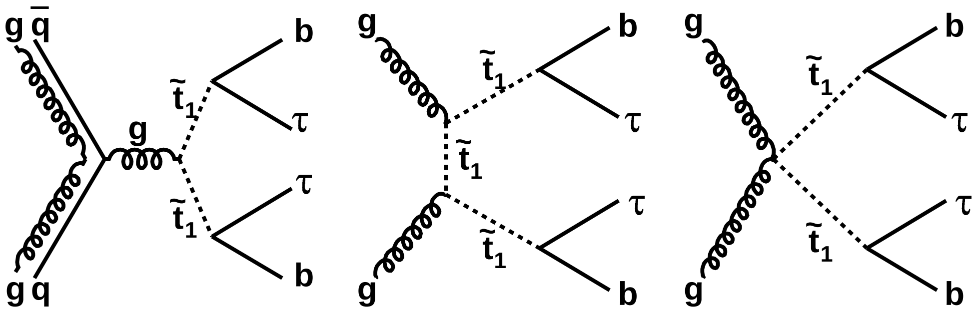


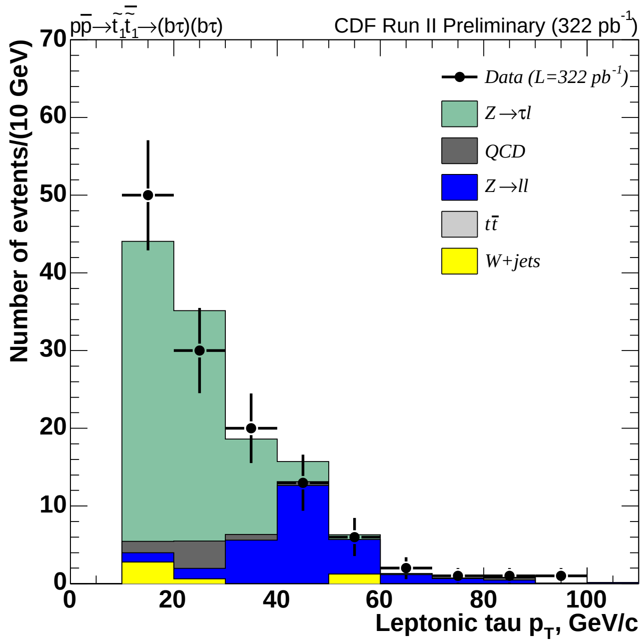


Observed 1 event (for $2.88 \pm 0.43^{+0.10}_{-0.04}$ expected)

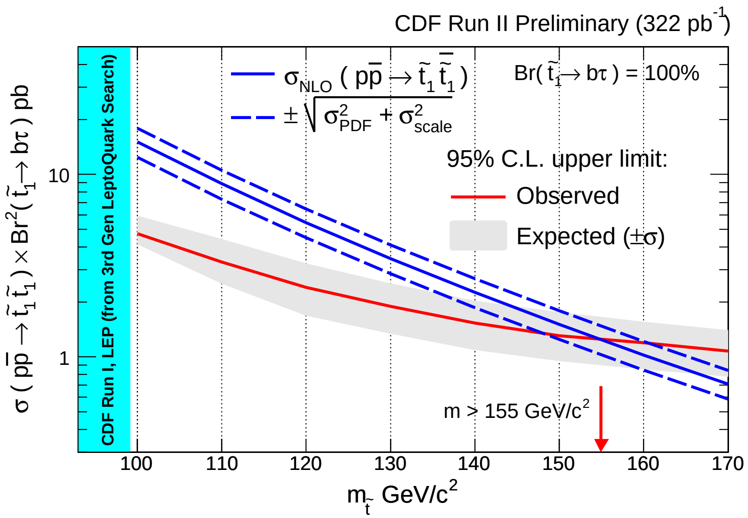
Stop production in RPV SUSY

- In models for which R_p is not conserved, a possible decay of the s-top is into a b quark and a τ lepton:





- The signature is (in principle) very clean since production of τ with jets has a "reasonable" cross section.



- The complication comes from the identification of the hadronic decay of the τ, which represents most of the branching ratio:

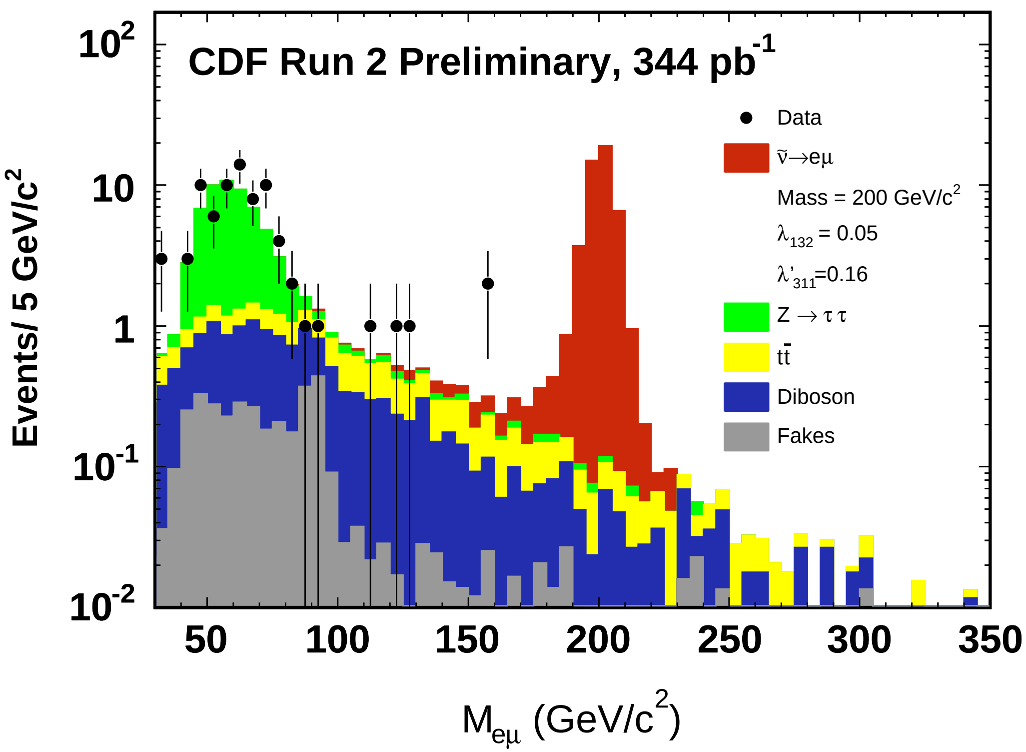
In the signal regions, 2 events are observed for $2.26^{+0.46}_{-0.22}$ expected.

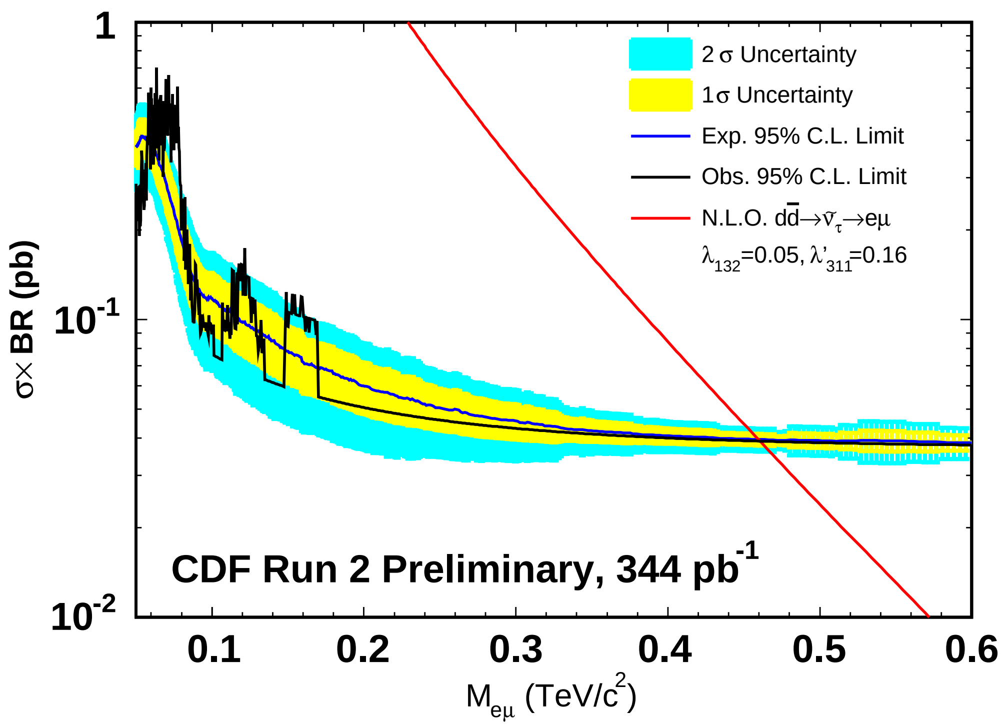
Sneutrinos in RPV SUSY

CDF has searched for the production of events with one electron and one muon from the decay of a resonance.

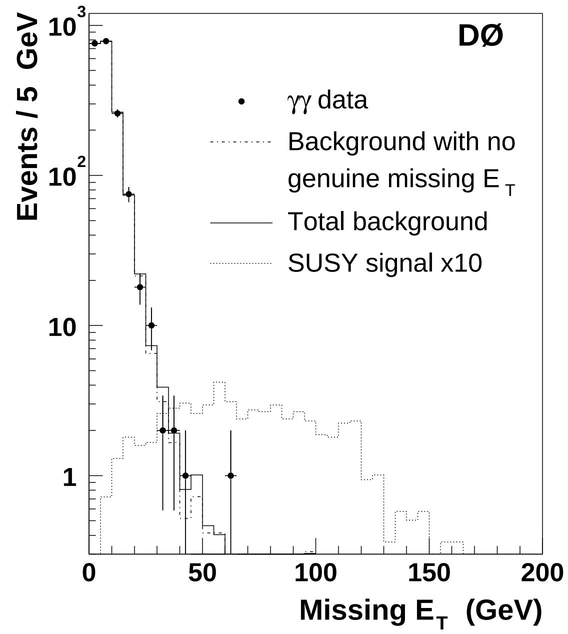
⇒ **High p_T leptons (large sneutrino mass)**

⇒ **No evidence of excess over background: limits were set!**





GMSB SUSY in $\gamma\gamma \not\!\!E_T$ at Tevatron



In this model, SUSY is broken via gauge interactions.

Using $\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ production we may obtain events with the rare signature:

2 photons and $\not\!\!E_T$

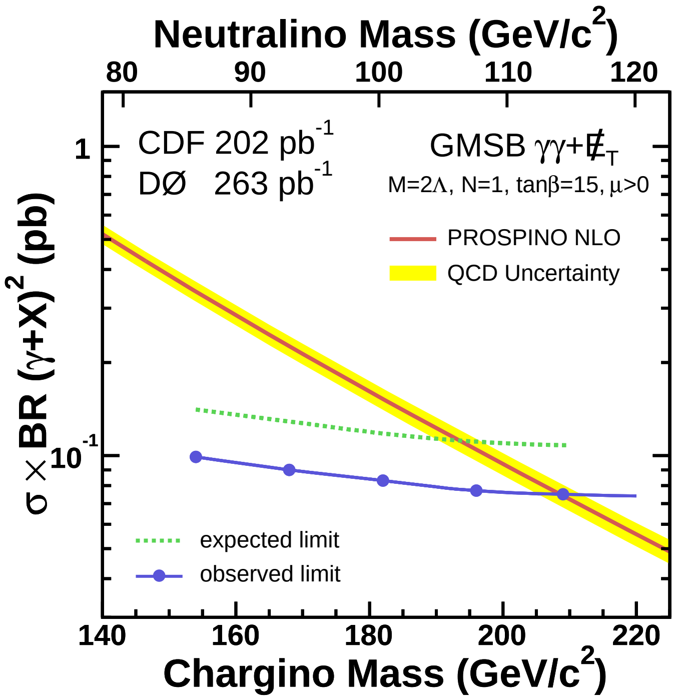
Slightly different strategies from both experiments:

CDF: 2 photons with $E_T > 13$ GeV and $\not\!\!E_T > 45$ GeV

D0: 2 photons with $E_T > 20$ GeV and $\not\!\!E_T > 40$ GeV

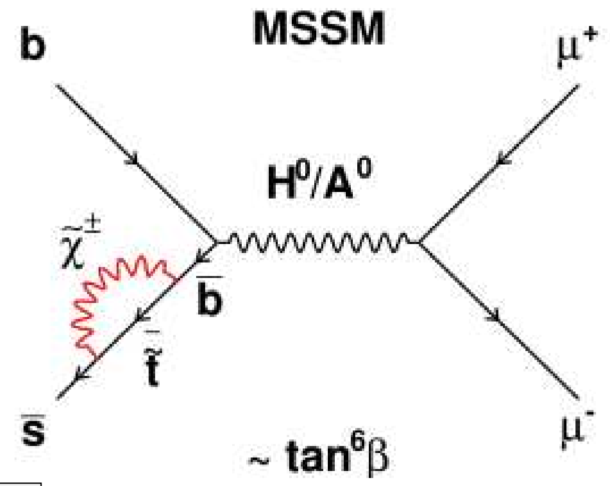
Results have been merged to get a combined limit

	Expected (SM)	Observed	Limit ($\tilde{\chi}^{\pm}$ mass)
D0	3.7 ± 0.6	2	195 GeV/c^2
CDF	0.3 ± 0.1	0	167 GeV/c^2
Combined			209 GeV/c^2



Looking for $B_s \to \mu\mu$

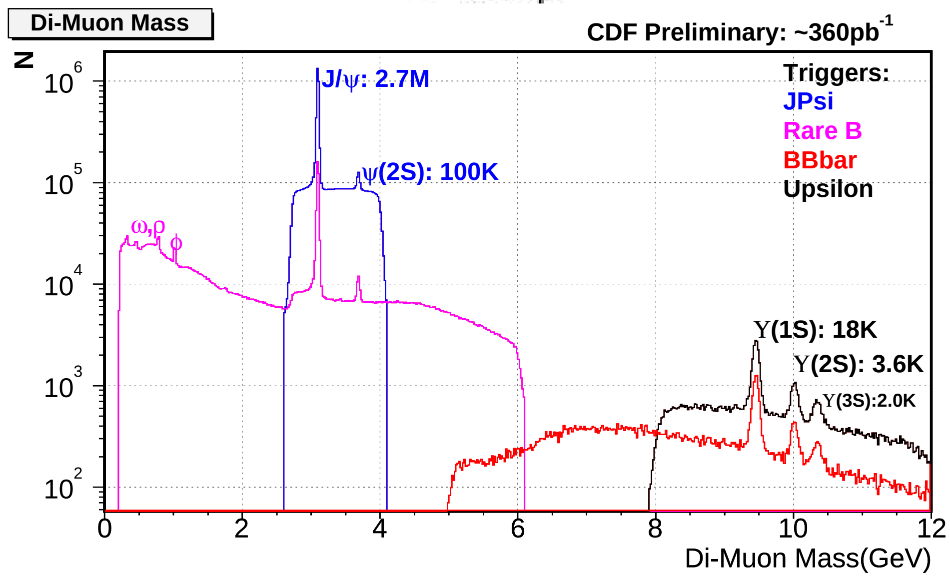
Tevatron is not sensitive to the process as predicted within the SM due to small predicted Branching Ratio.



$\Rightarrow$ Clean (indirect) observation of new physics enhancing this decay.

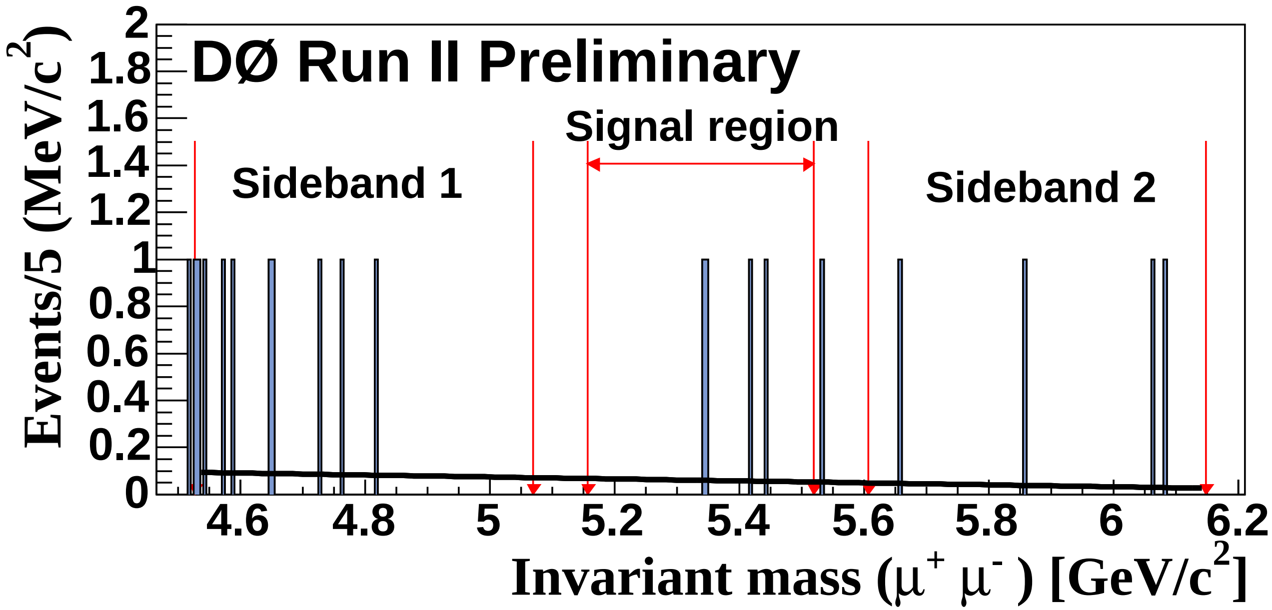
$\Rightarrow$ Recently gained a lot of attention when interpreting WMAP data due to relationship with Dark Matter properties.

The challenge is to have correct muon identification even at the trigger level for selecting low-p_T dimuon events.



Looking for $B_s \to \mu\mu$ (II)

After selection, both experiments reports no anomalous events observed and set limits on the Branching Ratios



CDF: BR ($B_s \to \mu\mu$)$< 1.6 \cdot 10^{-7}$ (at 90% C.L., 364 pb^{-1})

D0: BR ($B_s \to \mu\mu$)$< 3.0 \cdot 10^{-7}$ (at 90% C.L., 300 pb^{-1})

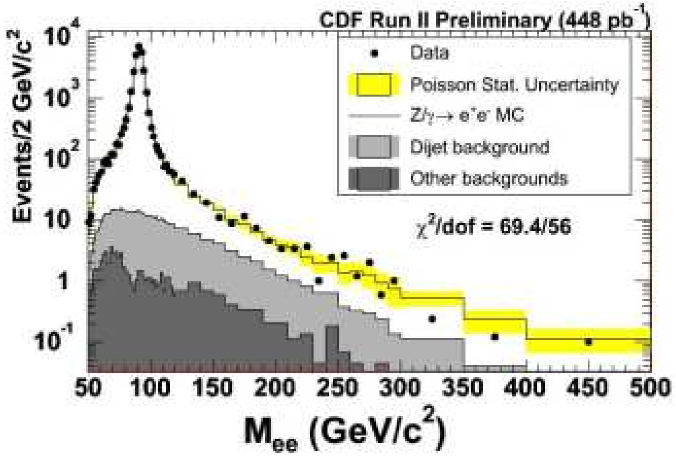
Results from both experiments have been combined to achieve higher sensitivity:

BR ($B_s \to \mu\mu$)$< 1.2 \cdot 10^{-7}$ (at 90% C.L.)

High Dilepton Mass Searches (resonances and tails)

Observation of new physics is simple in leptonic channels in the partonic-dominated environment at Tevatron.

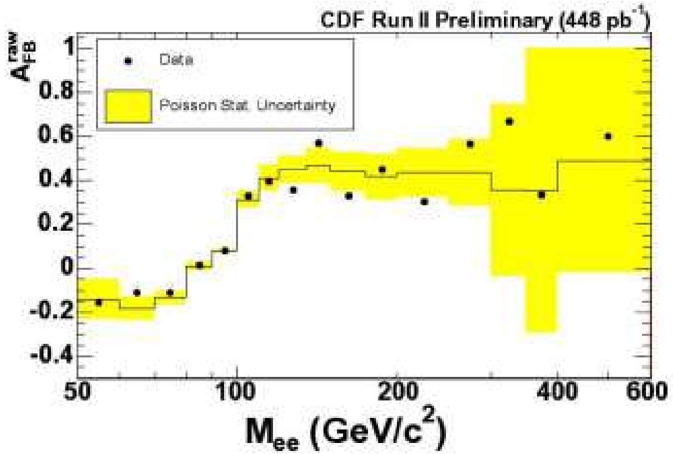
Studies on dilepton pairs at high masses is very attractive due to different possible contributions:



$\Rightarrow$ **New particles decaying into dileptons:**

NEW RESONANCES!!!

This is strongly motivated by theoretical models adding new kind of interactions containing bosons which couple to leptons: Z', W'.



$\Rightarrow$ **Contributions of new physics may increase (or decrease) cross section of high-mass dilepton pairs.**

New analysis by CDF looks at the forward-backward asymmetry which is sensitive to the interference between γ, Z and possible new Z'.

Allow to get evidence of a Z' below the pole.

For $M > 200$ GeV/c^2, expected 125 ± 11, observed 120.

Limit $M > 700 - 845$ GeV/c^2 (depending on model)

Search of $W' \to e\nu$

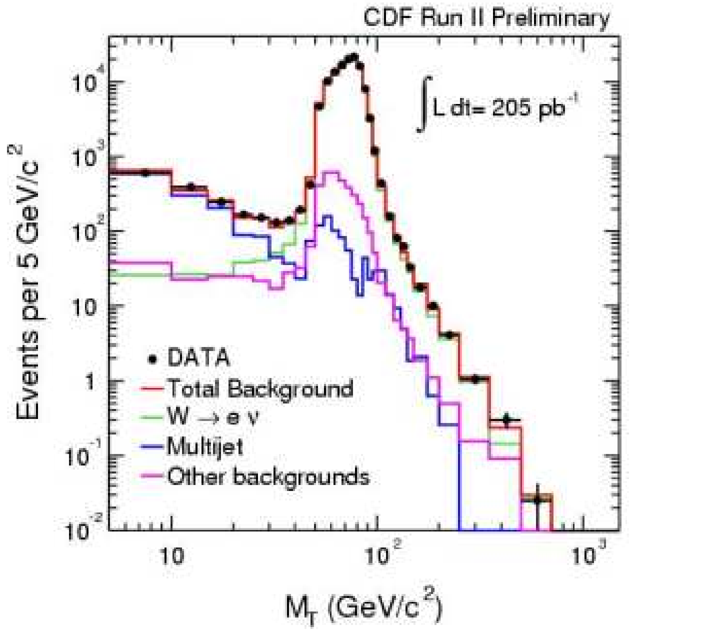
As the Z', W' is related to new physics in extended gauge theories, especially those containing Left-Right symmetry: heavy right-handed W'.

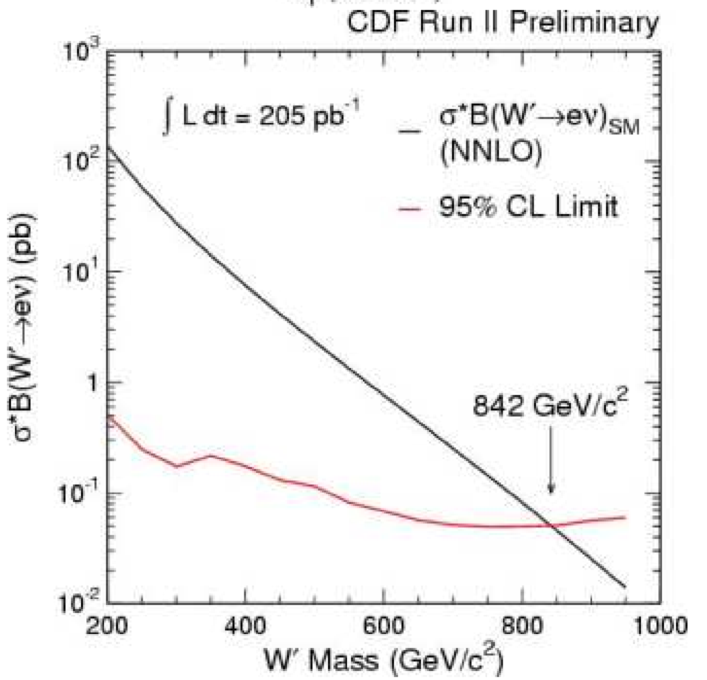
The signature is one high-p_T lepton and large $\not{E}_T$.

Expected to observe and excess in the transverse mass distribution.

No evidence for the presence of a new W'

$\Longrightarrow$ limits are set.





(Large) Extra dimensions

Presence of dimensions (addition from the 3+1 we all know) motivated in several theories.

The extra dimensions could be observable at current energies (i.e. size of the extradimensions of order ~ 1 TeV^{-1} in natural units).

$\Rightarrow$ Direct production of particles (gravitons/excitations) escaping in the other dimensions.

Striking signatures: searches for jet$+\not{E}_T$ or $\gamma + \not{E}_T$ events.

$\Rightarrow$ Production of particles mediated by processes sensitive to the LED. Observed as modifications of spectra or cross sections.

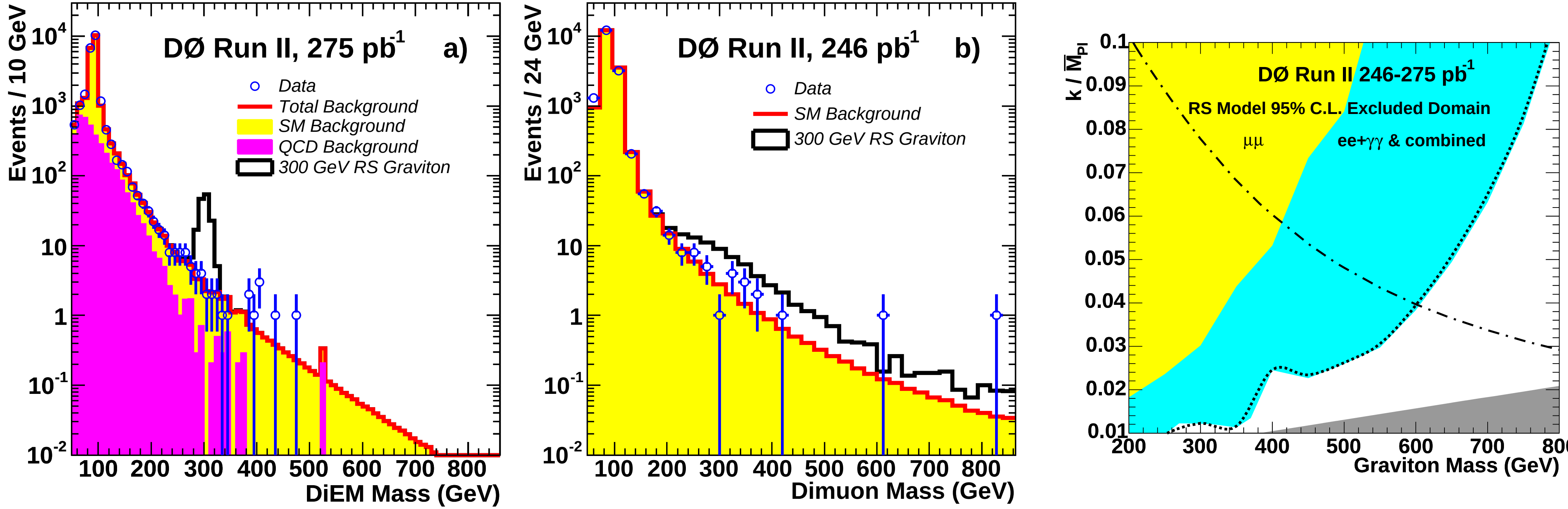
Searches for anomalous tails in ee, $\mu\mu$ and $\gamma\gamma$ production at Tevatron may be interpreted in LED and in RS models.

More on LED searches at Tevatron in talk by O. Saltó (here just an overview).

Randall-Sundrum gravitons

D0 has performed a search for the Kaluza-Klein modes of Randall-Sundrum gravitons using dielectron, dimuon and diphoton events.

Expected to observe excess in the invariant mass (resonances)



Lower limits on the mass of the first mode were set between 250 and 785 GeV/c^2 depending on its coupling the SM particles.

Limits set by performing a counting experiment in a mass window depending on the corresponding graviton mass.

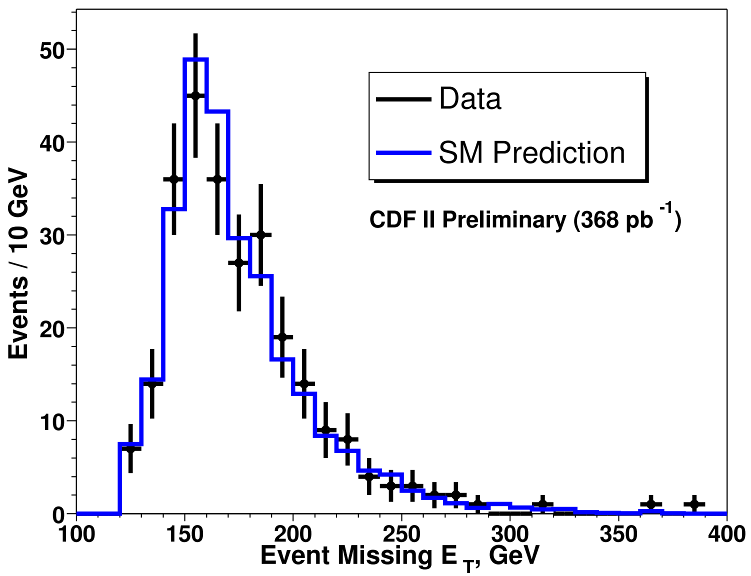
Searches for LED in the jet+$\not{E}_T$ topology

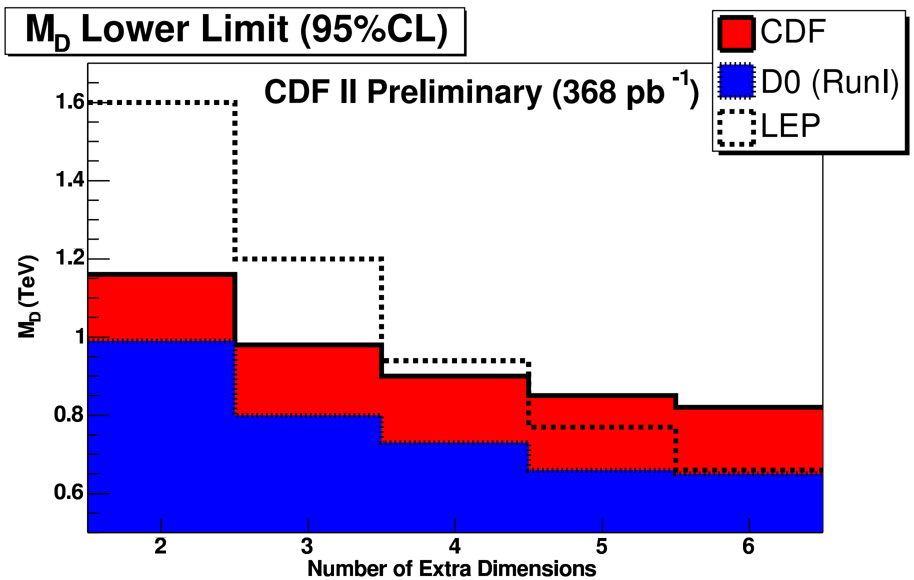
- **Events selected with a high-E_T jet and no additional jets (i.e. monojet selection) with $E_T > 60$ GeV.**
- **Background estimated using data-driven estimators**

QCD contributes when the non-leading jets are lost. It is estimated by extrapolating in the region where the second jet is lost due to low E_T.

The EWK background is estimated combining MC and data.

- **With the final selection we observe 263 events for 265 ± 30 pb^{-1}**





Limits for the effective Planck scales as a function of the number of LEDs.

Other searches: CHAMPs

Charged particles with large mass, long lifetime and weakly interacting are observed in the detector as

$\longrightarrow$ Charged but low ionizing particles

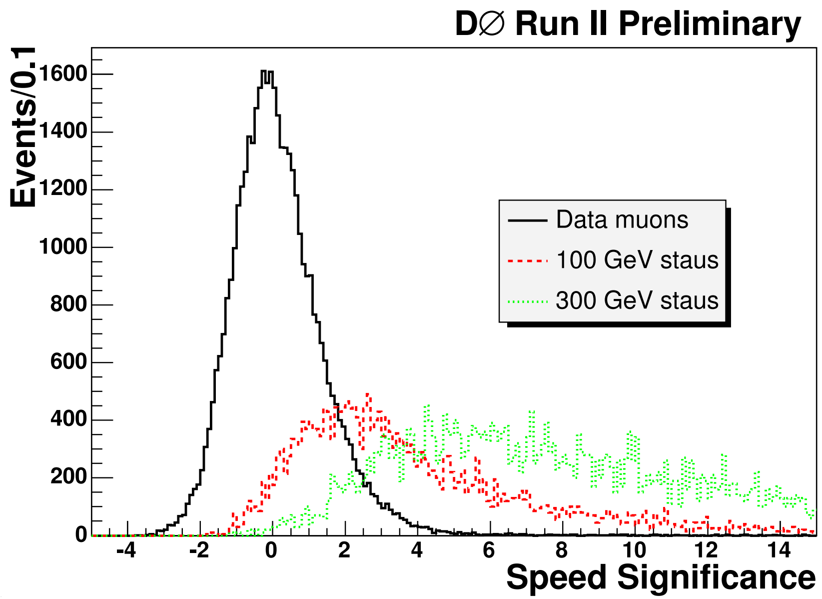
$\longrightarrow$ Slow-moving particles (speed< 1 in natural units).

They look like slow-moving muons

In the analysis, two of these objects are produced and detected. Events are required to have two particles with speed significance satisfying

$$\frac{1-\text{speed}}{\sigma_{\text{speed}}} > 0$$

for each particle. Additional cut on the mass-speed significance plane removes SM dimuon events.



Selection	Data events	SM Background	Signal acceptance
Preselection	18,985	–	0.19
speed significance > 0	6,410	$6,279 \pm 127 \pm 44$	0.17
final	0	$0.66 \pm 0.06 \pm 0.02$	0.06

Limis are interpreted in different ways:

Cross section for stable stau: 0.06 - 0.62 pb

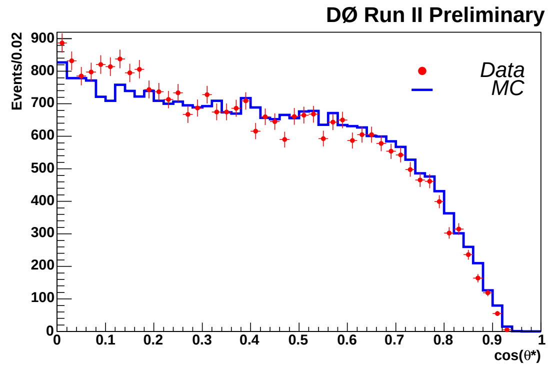
Mass limits for stable charginos: 140 GeV/c^2 (higgsino-like) to 174 GeV/c^2 (gaugino-like)

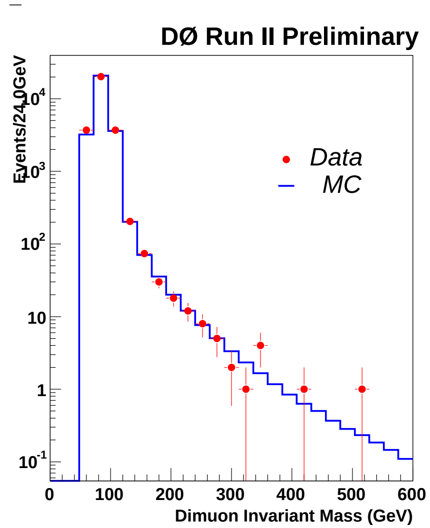
Other searches: excited leptons and compositeness

New lepton/quarks states appear in different models and they are observed as excess in high-p_T tails.

Compositeness in the dimuon channel

$M_{\mu\mu}$ and $\cos\theta^*$ are sensitive to new physics.





Model-dependent limits are set for constructive and destructive interference between Drell-Yan and new possible contact interactions.

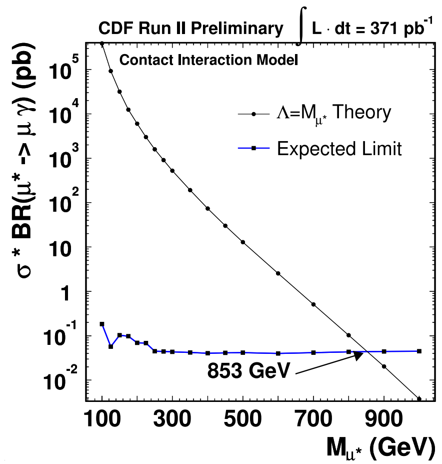
Compositeness scale limit 4.2-9.8 TeV

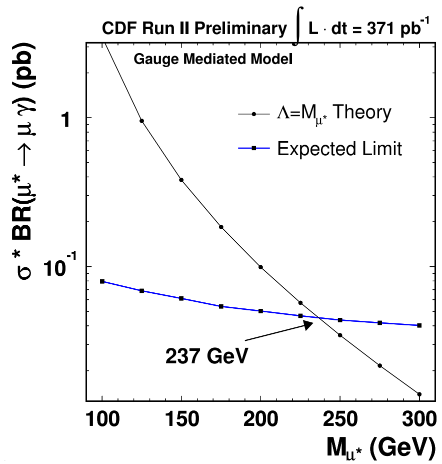
Analysis also sensitive to new resonances or gauge interaction (Z').

Excited Muons

Looking for the process: $p\bar{p} \to \mu^*\mu \to \mu\gamma\mu$

Results show no evidence of excess.





Limits are set for different models predicting excited muons.

Other searches: Magnetic Monopoles

- Monopoles predicted at very high masses (10^{17} GeV/c^2) in Grand-Unification theories.

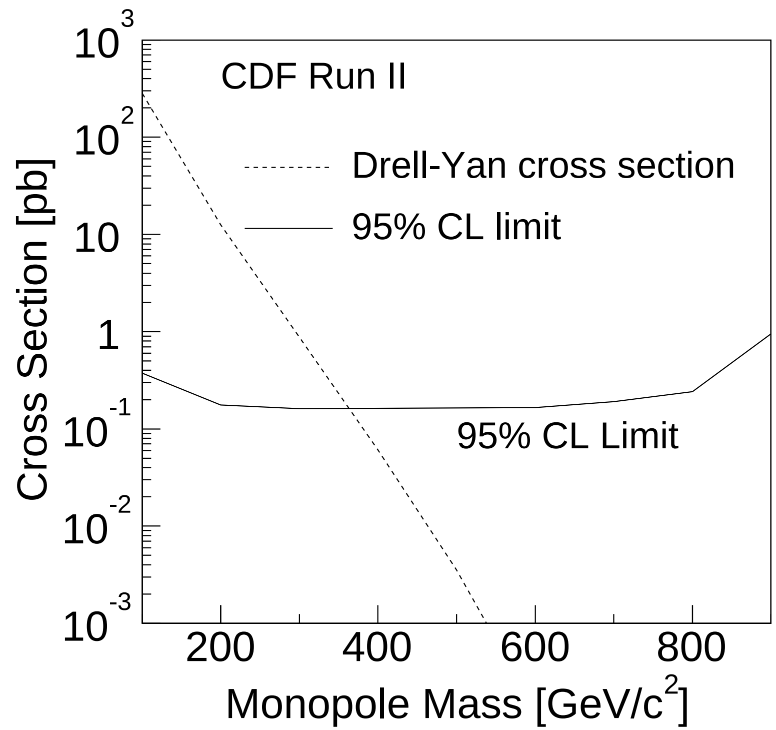
- 37.5 pb^{-1} of data with a specific trigger (Time-Of-Flight detector) exploiting the large ionizating (and delta ray generation) power of magnetic monopoles.

- In addition, specialized resconstruction from the central tracker was needed in order to take into account the expected properties from a monopole moving inside a magnetic field:

  ⇒ Large ionization in hits

  ⇒ Track consistent with a straight line in the plane perpendicular to the magnetic field (transverse plane).

  ⇒ Monopole may be slow particle, so effect is considered when checking the timing of the tracker hits.



No events passed the monopole selection (out of 13,000 accepted by the trigger), and limits were set.

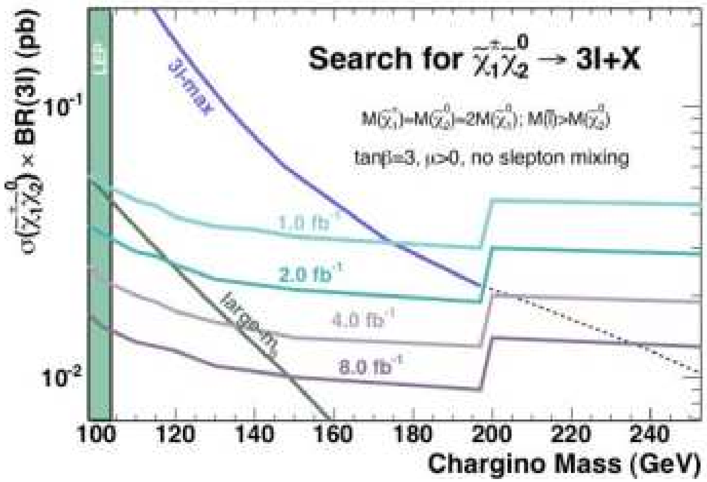
Summary and perspectives

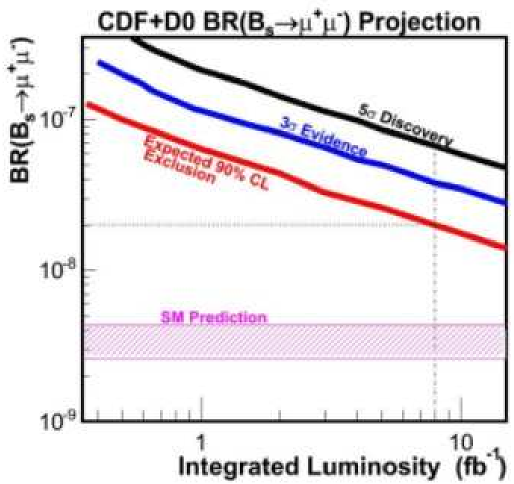
- We presented an overview of searches of new physics performed at the Tevatron
- A LOT not convered: Leptoquarks, technicolor, $\gamma + \not{E}_T$,...

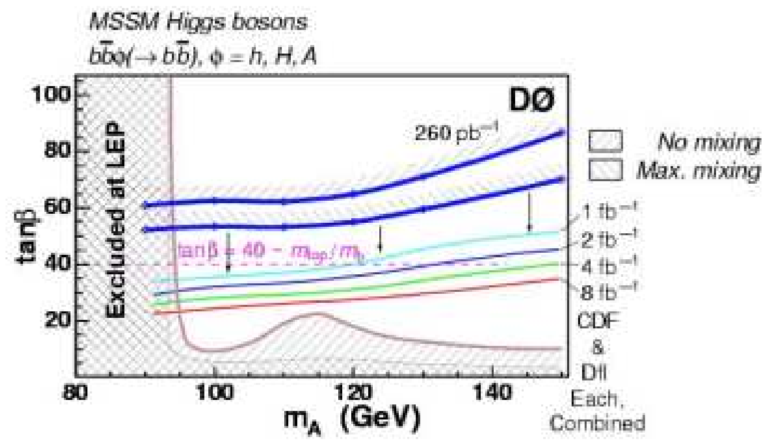
Do not forget to check the CDF and D0 web pages!

- No news yet, but we are optimist for the near future:
  - $\Rightarrow$ Tevatron (and the experiments) are performing well
  - $\Rightarrow$ Most of the current analyses are exploring new regions
  - $\Rightarrow$ Much more data to be analyzed: results with 1 fb^{-1} for next Winter.

The best from Run 2 is yet to come!







- New physics hints may be observed before LHC starts.

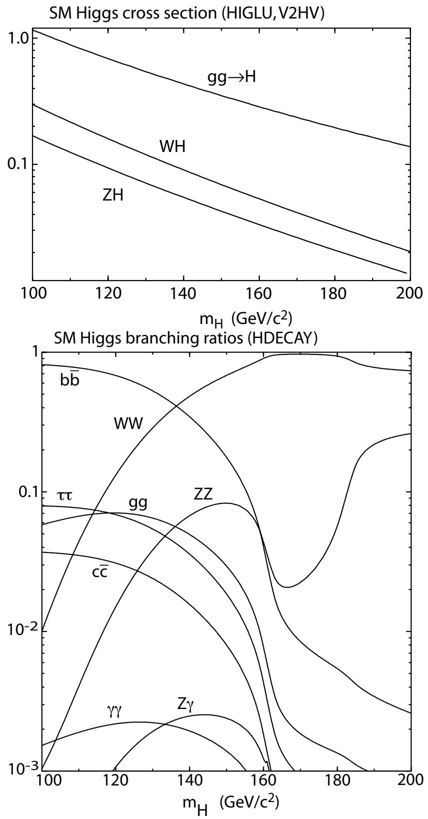
Search of the SM Higgs (I)

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

Precision data prefer a light SM Higgs:

$$m_H = 91^{+45}_{-32}\ \text{GeV}/c^2$$

However, the error is so large that the search is performed in different regimes:



- **Low masses (110-135 GeV/c^2): dominant decay is $H \to bb$ which makes impossible to observe the Higgs in inclusive production.**

Need for associated production (WH or ZH) which have a reduced cross section but more distinctive signature.

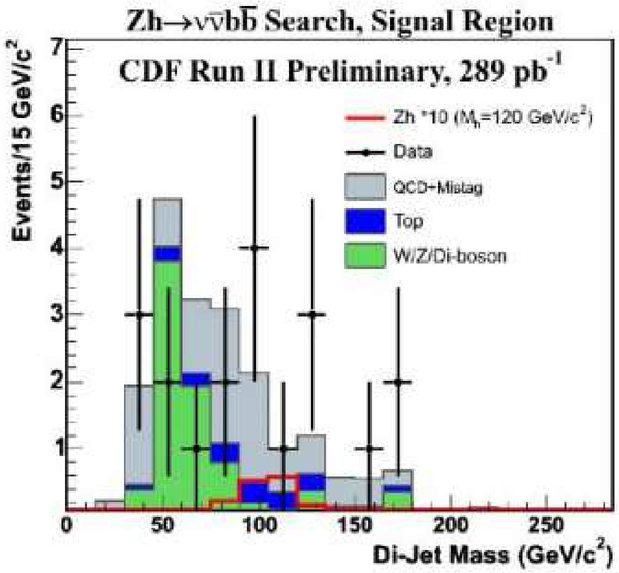
- **High masses (130-180 GeV/c^2): dominant decay is $H \to WW^*$ which may be observed cleanly in the dilepton channel (in Higgs inclusive production).**

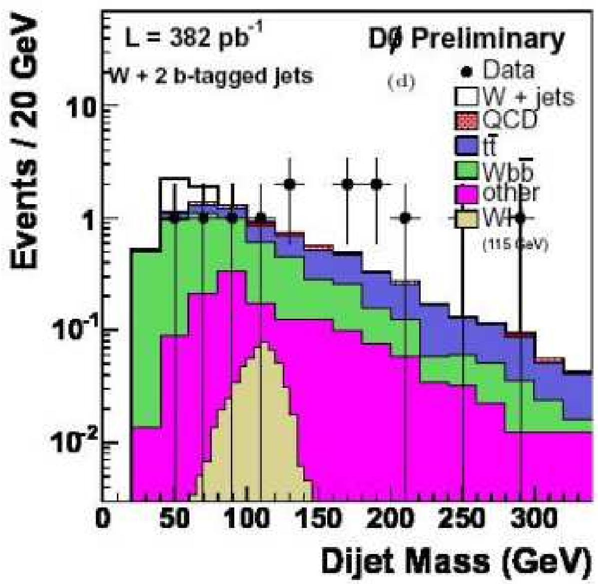
For higher masses, cross section is too small for being observed at Tevatron.

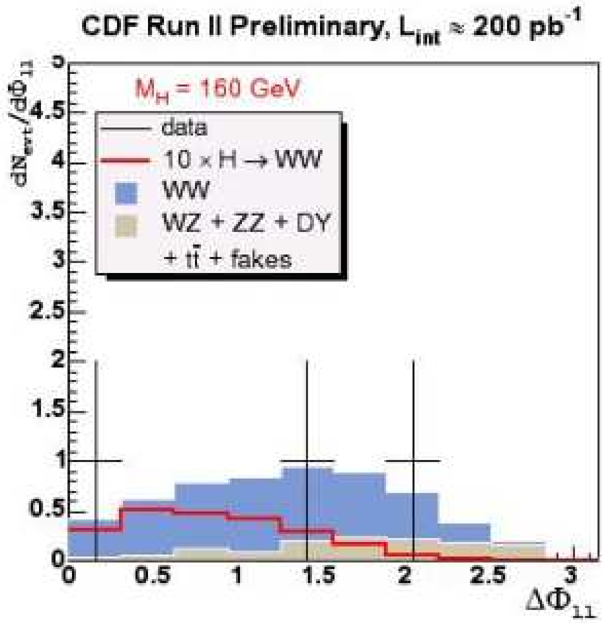
Other channels (e.g. $HW \to WW^*W$ with same-sign leptons) are also considered due to their clean signature.

Search of the SM Higgs (II)

Good agreement with SM expectations for all the channels:







With the different searches, we have several limits which are far from the SM predictions but which are helpful to know where we are and how we should proceed:

- **More luminosity is needed**
- **Improvements to increase sensitivity:**

  Dijet mass resolution, Neural-Network approach, increase acceptance,. . .