Highlights from the Tevatron Experiments

Outline

The Tevatron

Detectors and data

QCD studies

Properties of the top quark

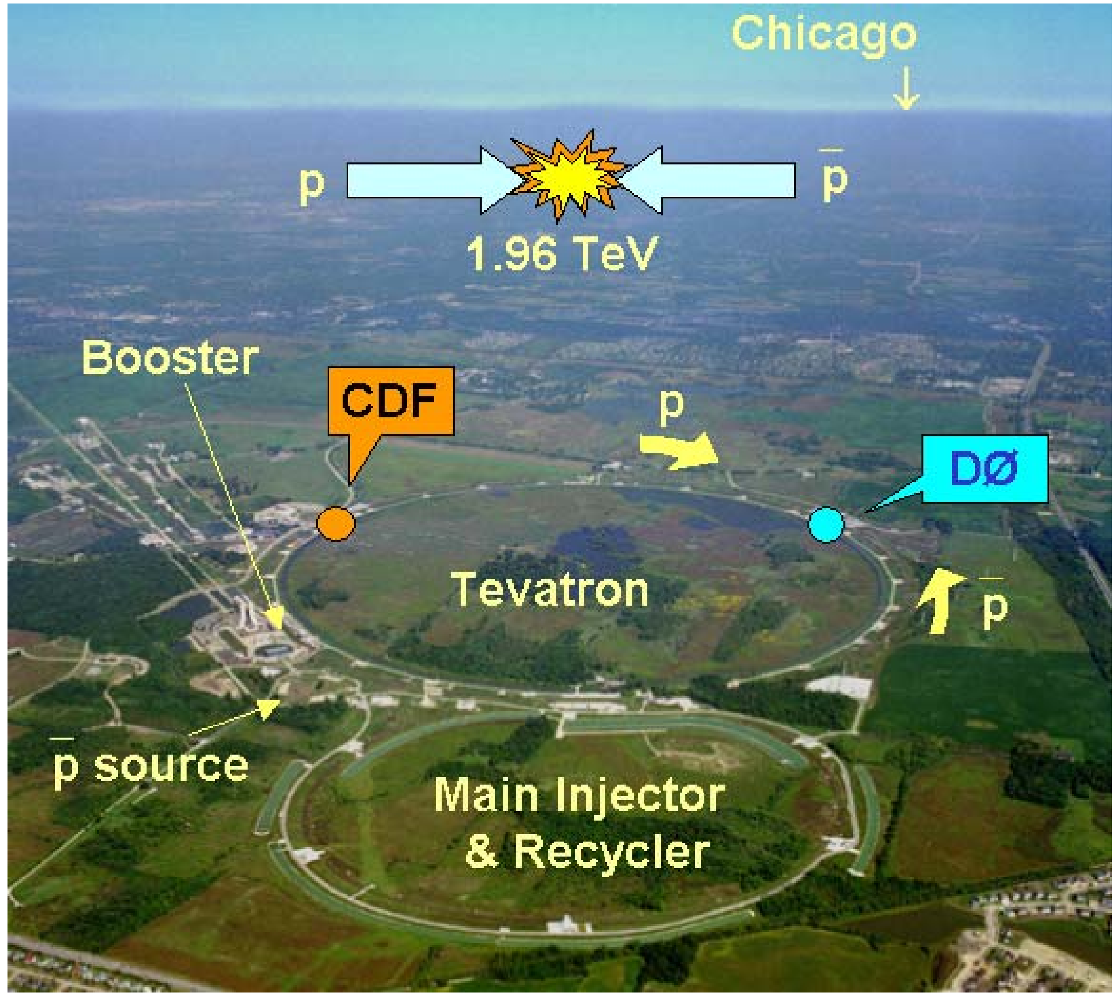
Electroweak studies

B physics

Search for Physics beyond the Standard Model

Higgs searches

Summary



Russian Academy of Sciences Nuclear Physics Session

December 23, 2008

Dmitri Denisov, Fermilab

Disclaimer: DØ is used for majority of the examples, CDF in most cases has similar results

Tevatron: Proton-antiproton Collider

World highest energy collider
1.96 TeV center of mass energy

Substantial upgrades for Run II: 2001-2010

→ 10% energy increase: 30% higher σ_{top}

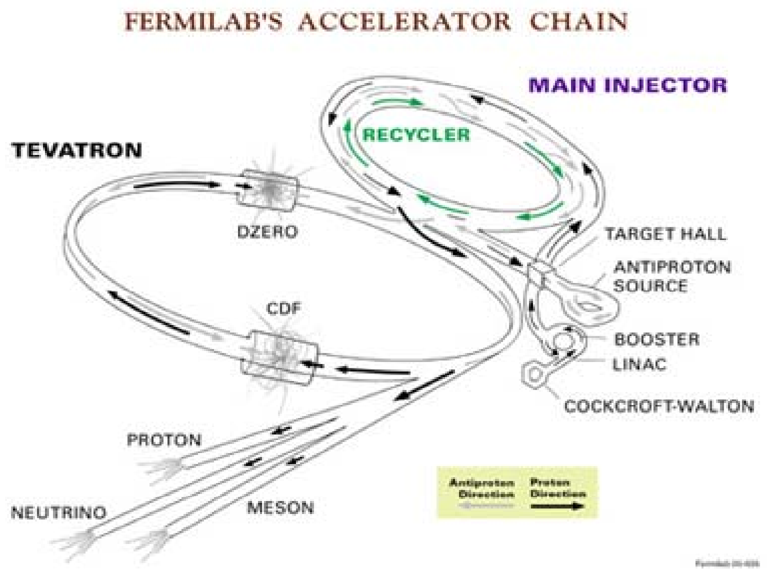
→ integrated luminosity increase: x100

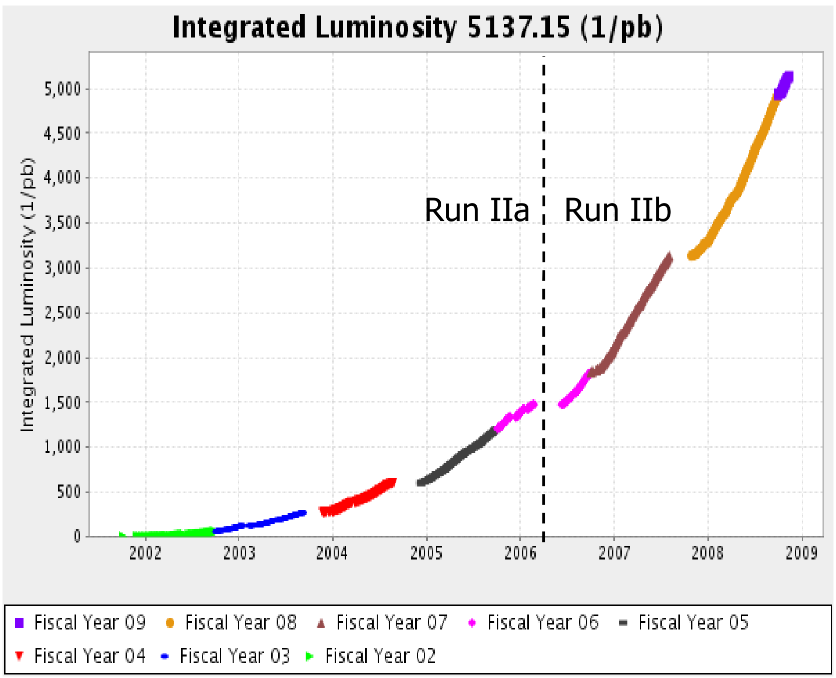
Energy and luminosity

$$N_{events}\,(sec^{-1}) = \sigma(E) \times L$$

	Run I	Run IIa	Run IIb
Bunches in Turn	6 × 6	36 × 36	36 ×36
$\sqrt{s}$ (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	9×10^{31}	3×10^{32}
$\int$ Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/ crossing	2.5	2.3	8

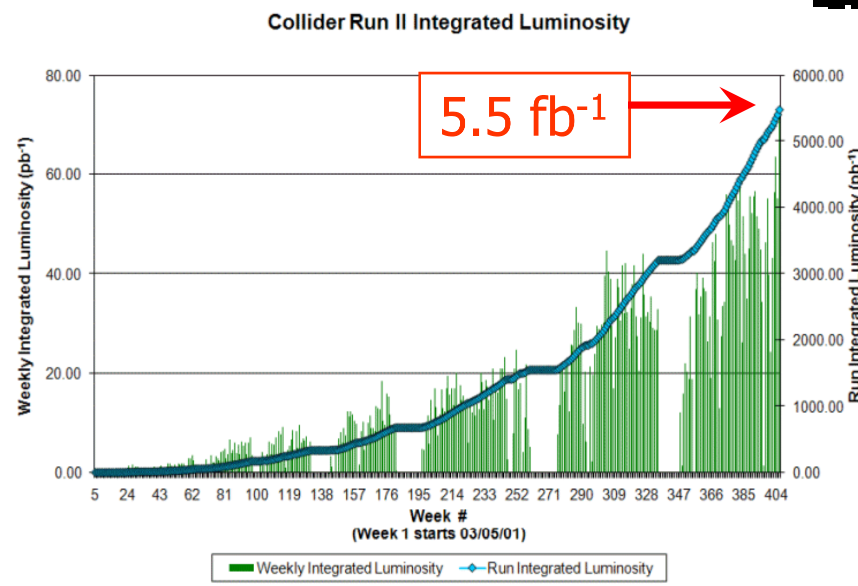
Run I → Run IIa → Run IIb
$0.1\ fb^{-1}$ ~$1 fb^{-1}$ ~$9\ fb^{-1}$

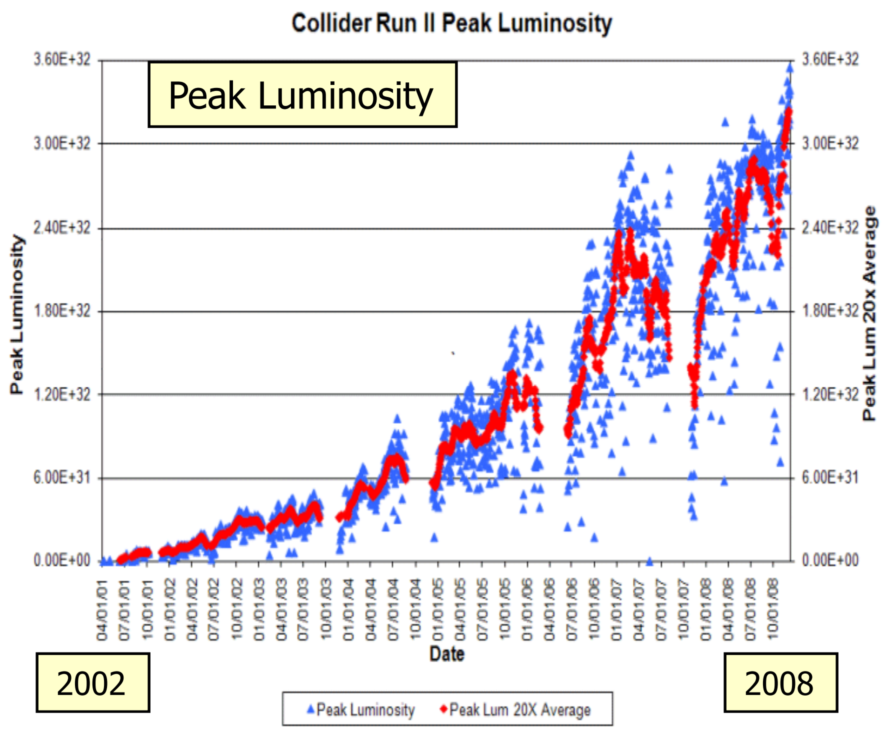


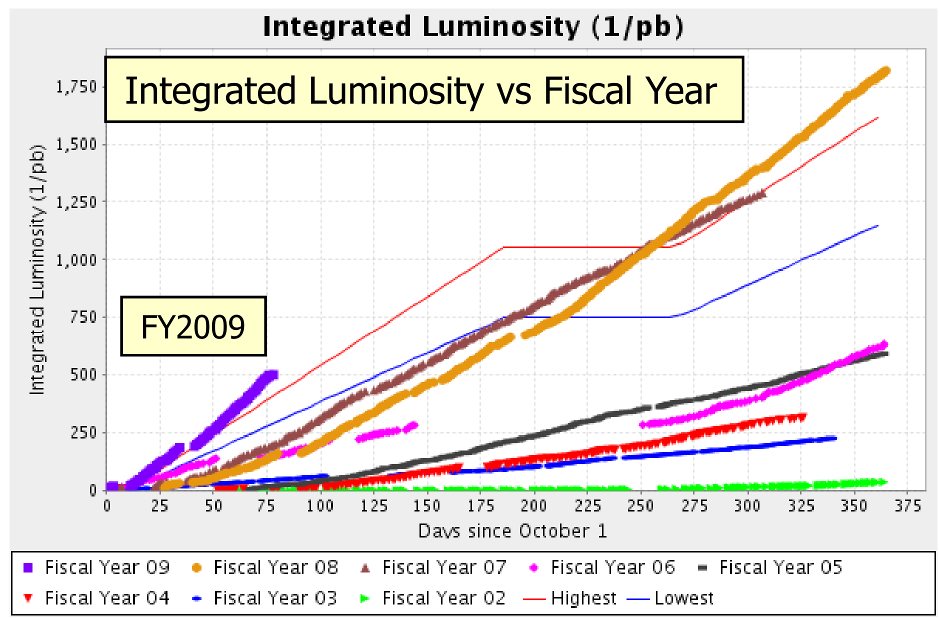


Tevatron Performance

- Peak luminosity is $3.4 \cdot 10^{32}$ $cm^{-2}sec^{-1}$
  - A lot of anti-protons made!
- Reliable operation of very complex accelerators
  - In stores ~120 hours/week
- Total 5.5 fb^{-1} delivered in Run II
  - Better than expected!







Performance continues to improve!

Tevatron Physics Goals

Precision tests of the Standard Model
- **Weak bosons, top quark, QCD, B-physics…**

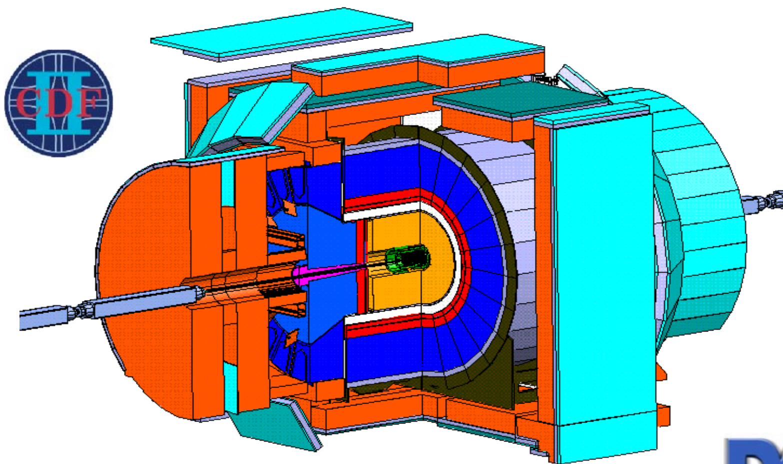
Search for particles and forces beyond those known
- **Higgs, supersymmetry, extra dimensions….**

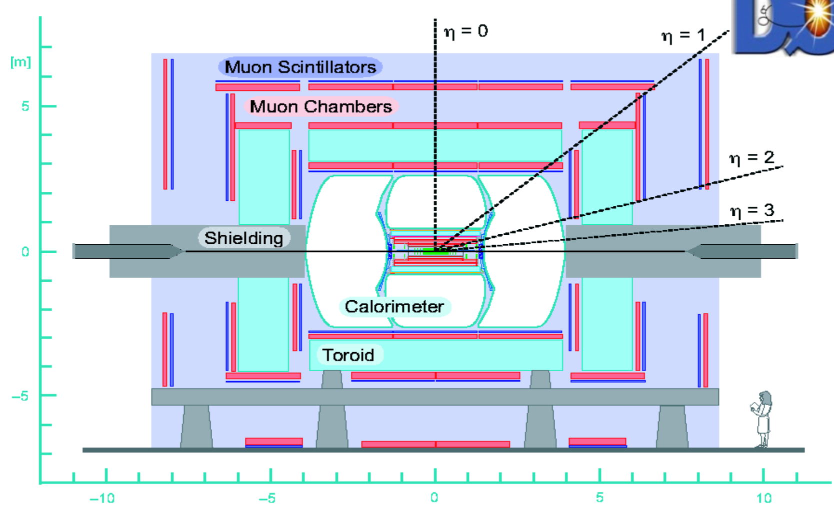
Driven by these goals, the detectors emphasize

Electron, muon and **tau** identification

Jets and **missing transverse energy**

Flavor tagging through **displaced vertices**





Fundamental questions

Quark sub-structure?

Origin of mass?

Matter-antimatter asymmetry?

What is cosmic dark matter? SUSY?

What is space-time structure? Extra dimensions?…

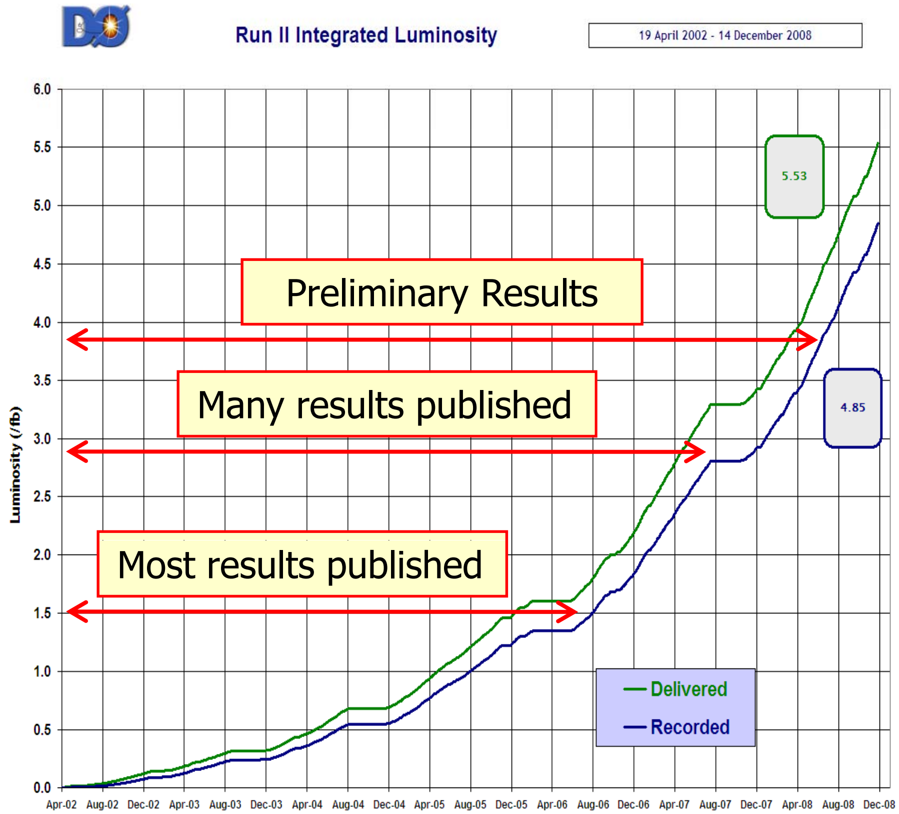
The DØ Collaboration

DØ is an international collaboration of
550 physicists from 18 nations who have designed, built and operate the DØ detector at the Tevatron and perform data analysis

Institutions: 90 total, 39 US, 51 non-US

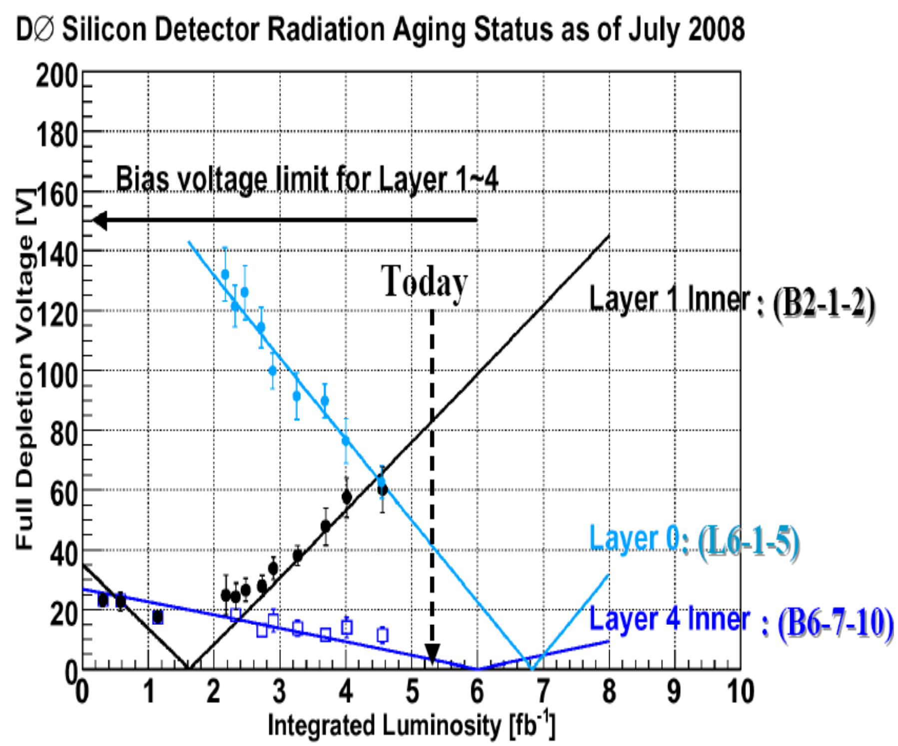
Collaborators:
~ 50% from non-US institutions with strong European involvement
~ 110 postdocs, 120 graduate students

Data Collection



2002 **December 2008**

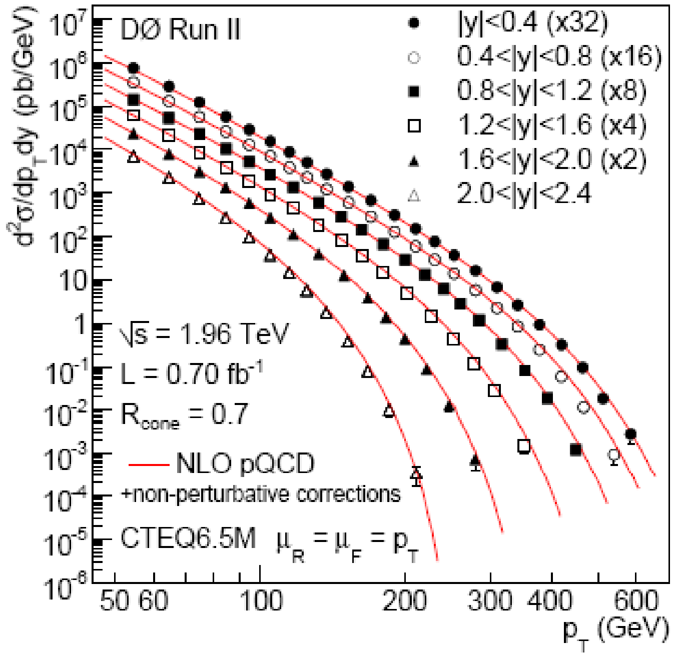
- DØ experiment is smoothly recording high quality physics data
  - Typical week ~50 pb^{-1}
- On average 92% data taking efficiency
- As of today DØ has ~4.9 fb^{-1} on tapes
  - Was ~2.8 fb^{-1} on tapes at 2007 RAS meeting
  - All detectors functioning well



- Radiation doses of the inner silicon layer are reaching Mrads levels
- Carefully monitoring silicone performance
- Layer 1 (one out of 5 layers) will become under depleted after ~8 fb^{-1}
  - All other layers are far from been affected
  - No deterioration of tracking performance is expected for well above 8 fb^{-1}

QCD Studies

Inclusive jet cross sections



Use partons scattering to study proton structure

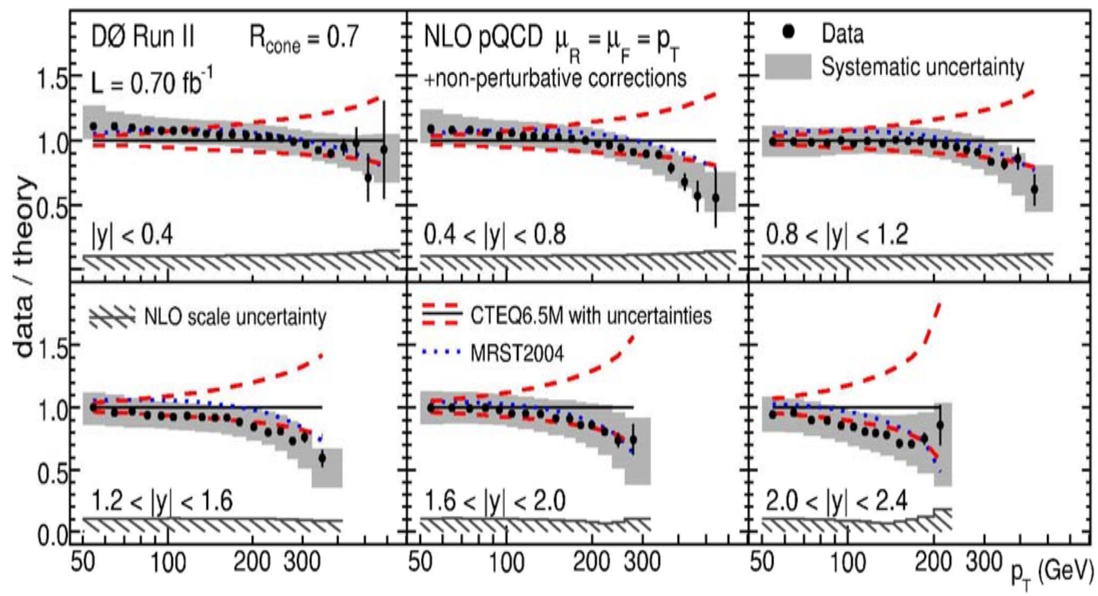
→ Quarks sub-structure? Rutherford style experiment

Measure QCD parameters and structure functions

Determine Jet Energy Scale

→ Critical for top mass and Higgs searches

Understand the backgrounds to physics beyond Standard Model



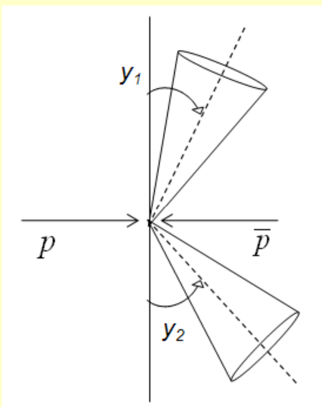
- Inclusive jet cross sections are measured in the widest kinematic region
  - In rapidity and transverse momentum
- Best statistical and systematic errors
  - Excellent jet energy scale is critical
- 8+ orders of magnitude σ changes
- In general agreement with pQCD predictions

- Ratio of data/theory does not demonstrate major deviations
  - Within PDF uncertainties
- Small experimental uncertainties provide opportunity to improve PDFs

Measurement of Angular di-jet Correlations

Angular correlations between jets are not sensitive to precision energy measurements while reflect the dynamics of an interaction
New Physics could manifest itself in these distributions!

- Di-jet angular distributions in bins of di-jet mass



$$\chi_{dijet} = \exp(|y_1 - y_2|) \approx \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

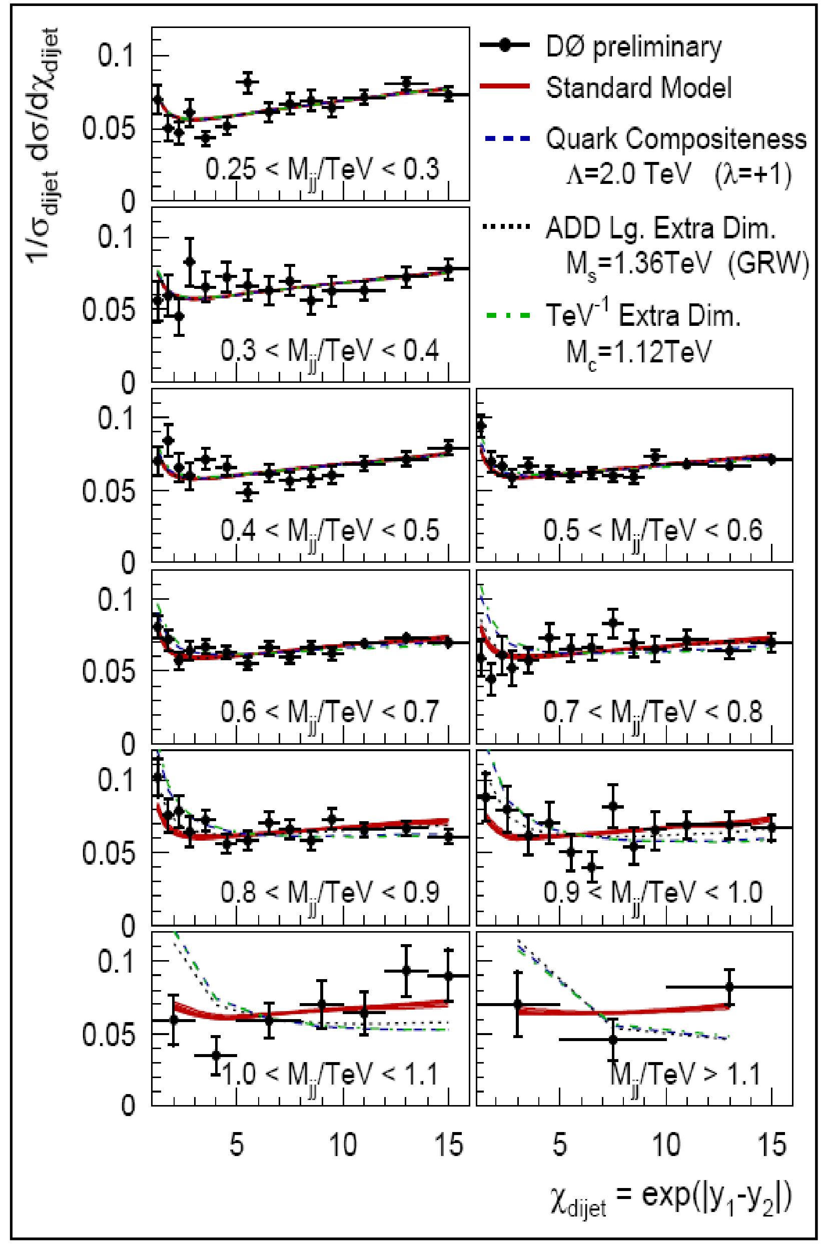
y_i = jet rapidity

- First differential cross section measurement at partonic energies >1 TeV
- Small experimental and theoretical uncertainties
- New Physics 95% CL exclusion limits

Compositeness (λ=+1): Λ>2.6 TeV

ADD extra-dimensions (n=4): M_s>1.6 TeV

TeV^{-1} extra-dimensions: M_c>1.4 TeV

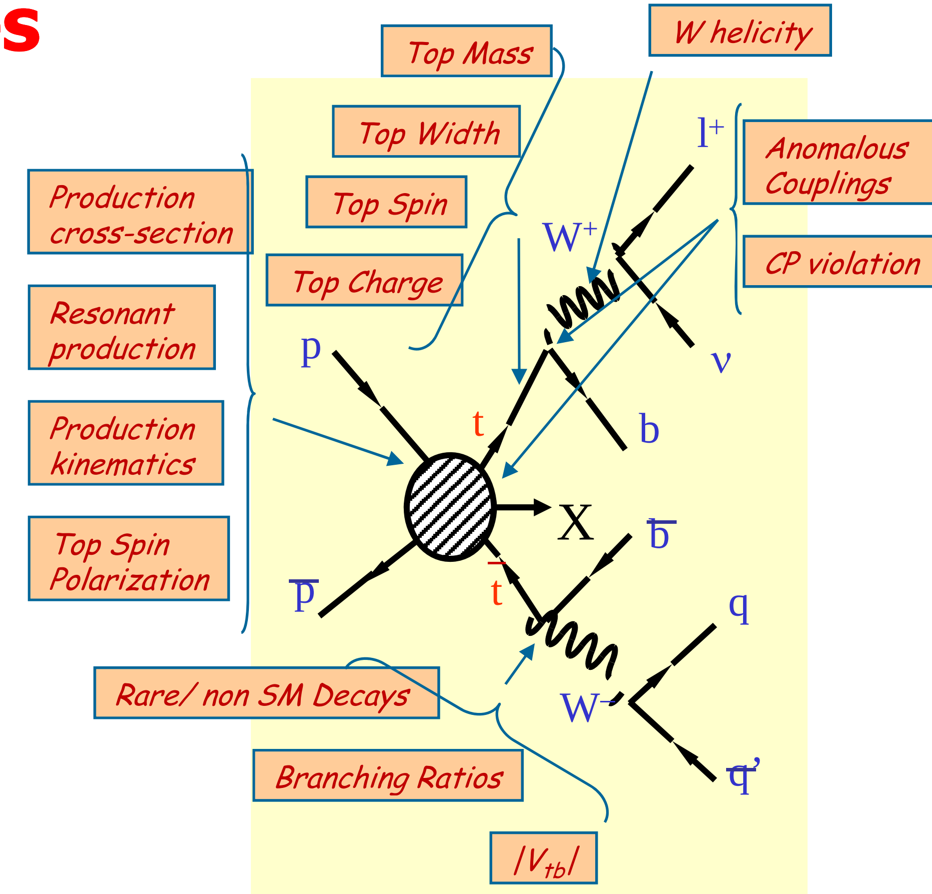


Top Quark Studies

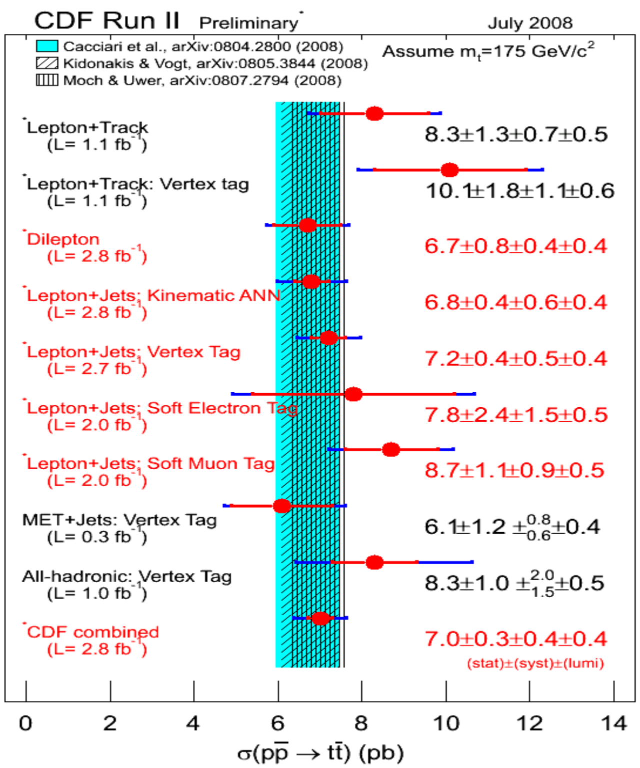
Heaviest known elementary particle: 172 GeV

→measure properties of the least known quark
- → mass, charge, decay modes, etc.
- → data sets of 100's of top quarks exist

→ short life time: probe bare quark



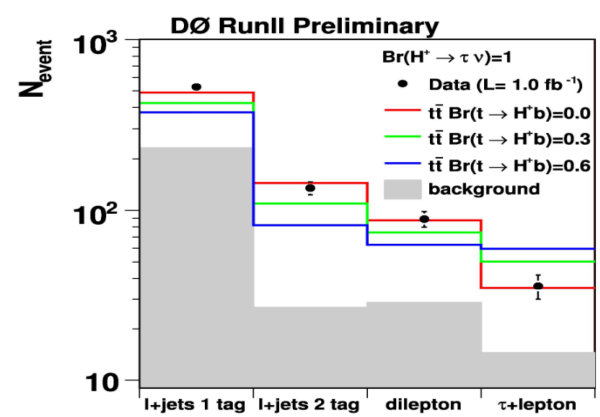
Top quark cross sections in multiple channels



Search for charged H^+ in top decays

$t \to H^+ b$: channels affected differently depending on H^+ decay modes

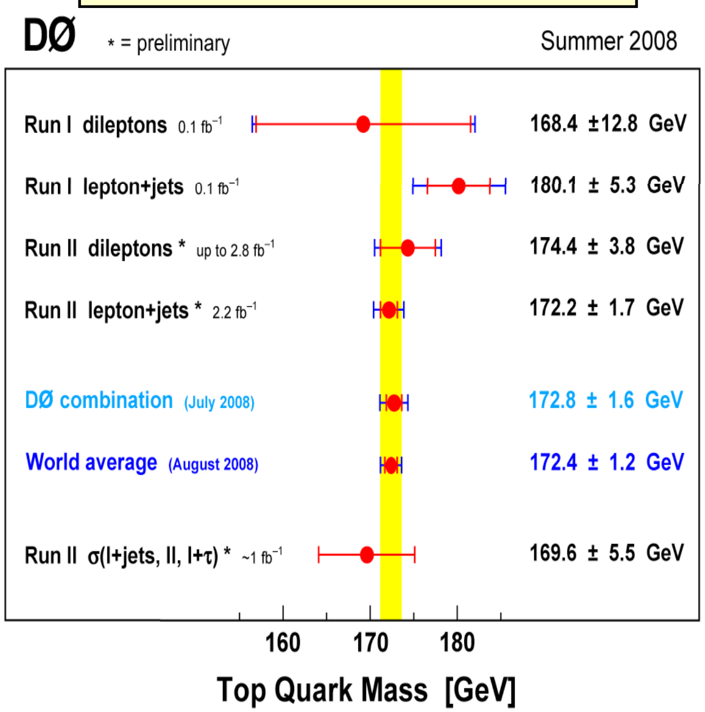
- Tauonic H^+ ?
- Tight limits set

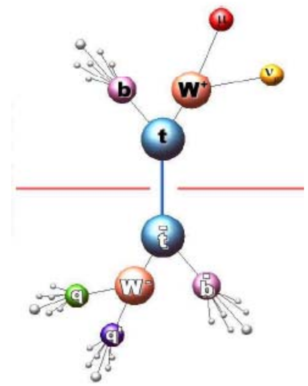


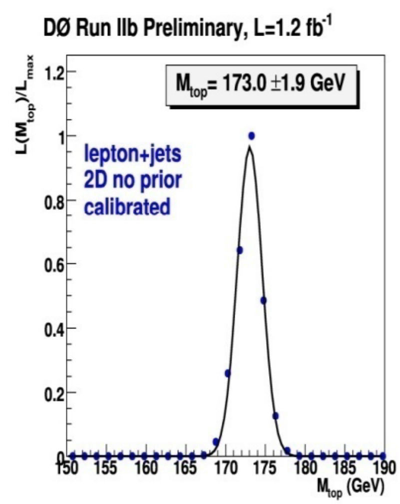
Top Quark Mass Measurement

- Top mass is measured using decay products in many different channels
- Lepton+jets channel with two jets coming from W is the most precise

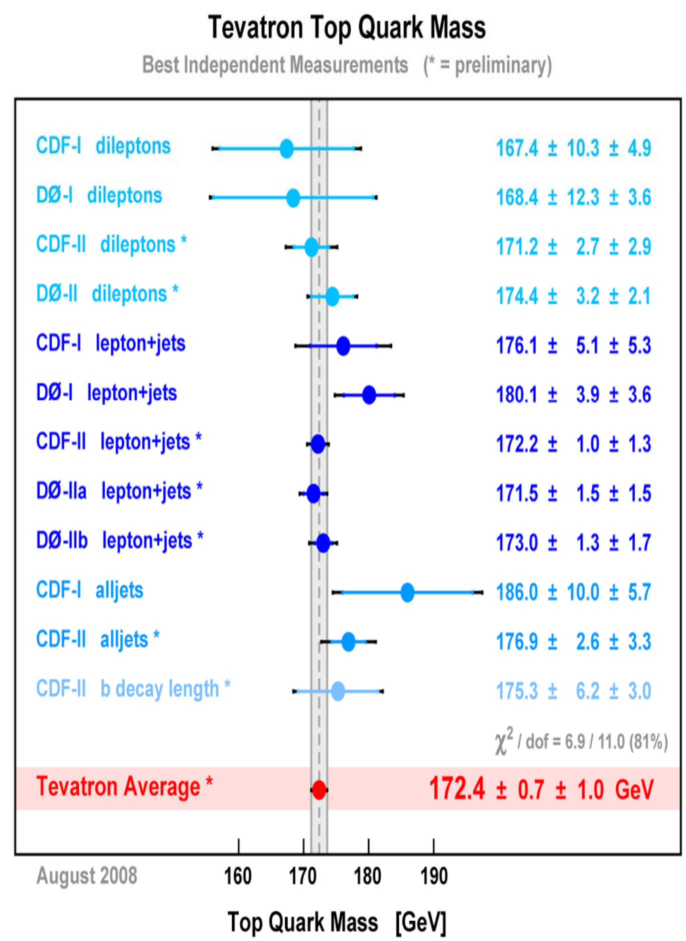
DØ top quark mass results







Systematic error (mainly jet energy scale) is becoming limiting accuracy factor



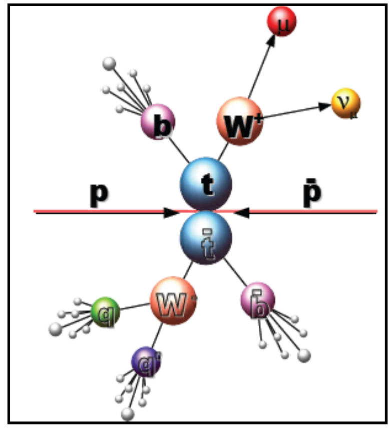
DØ and CDF combined top mass result
m_t = 172.4±1.2 GeV
0.7% accuracy
Best (of any) quark mass measurement!

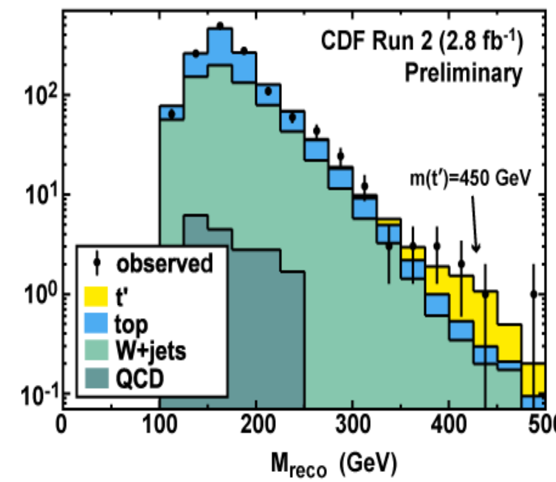
Search for New Physics in Top Quark Sector

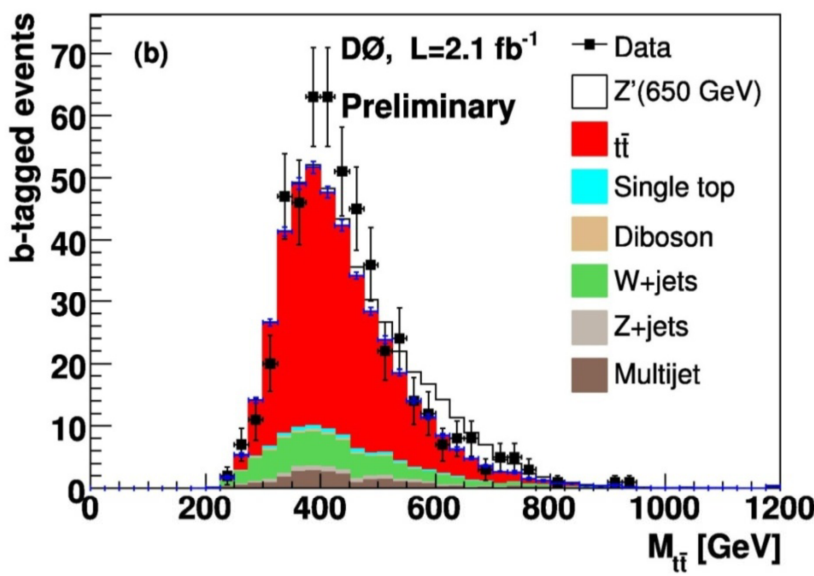
- In the Standard Model top decays before hadronization
- Theories beyond Standard Model predict existence of resonances
  - In top-colour assisted technicolour leptophobic heavy boson couples mainly to 3rd generation
- Search for narrow resonance optimised at high masses
  - Using reconstructed 4-momenta of two top quarks

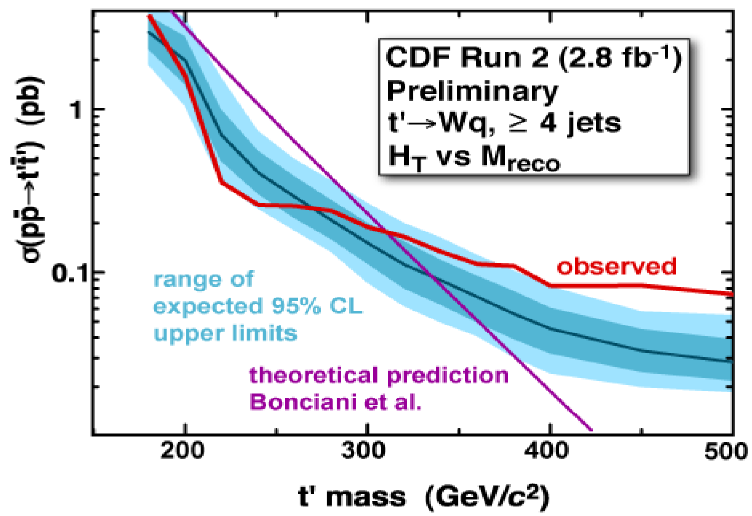
Heavy t′ quark search in the top samples in $t't' \to WqWq$

Lepton + jets









Excess?!

Excess in 400-450 GeV region is not (yet?) significant

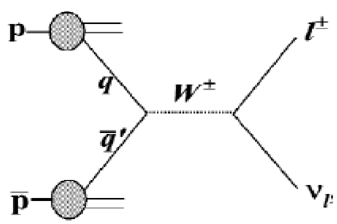
$m_{t'} > 311\, GeV \;@\; 95\%\, CL$

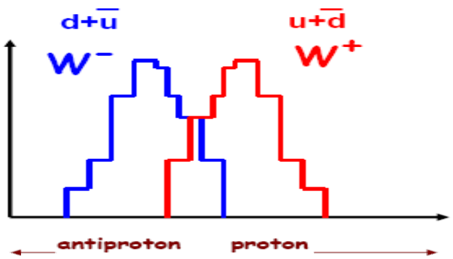
Electroweak Physics

Indirectly constrain new physics through precision measurements of electroweak parameters

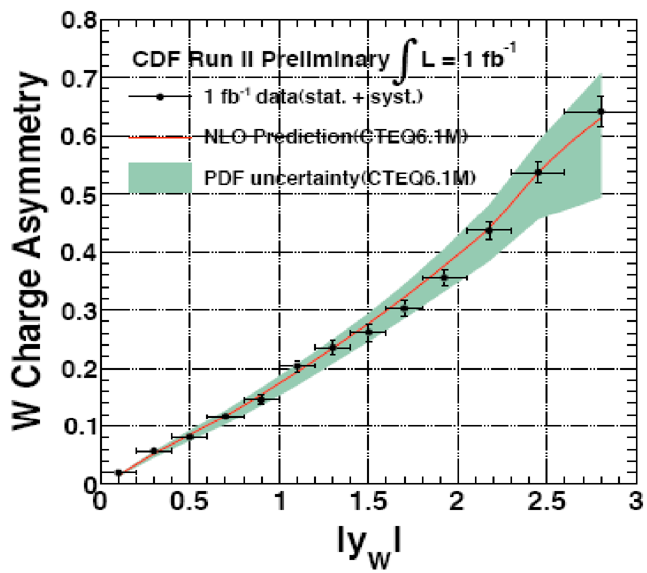
Measure single and multi-boson production, W mass, W production asymmetry, forward-backward asymmetry in Z production, …

Leptonic decay modes of W/Z are used as hadronic modes are overwhelmed by QCD backgrounds

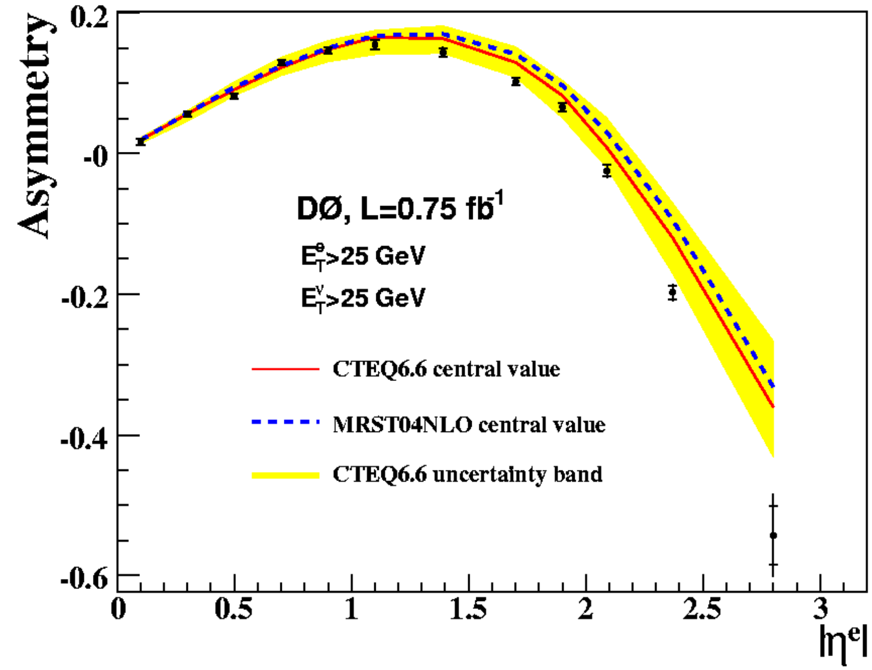




$$A(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$



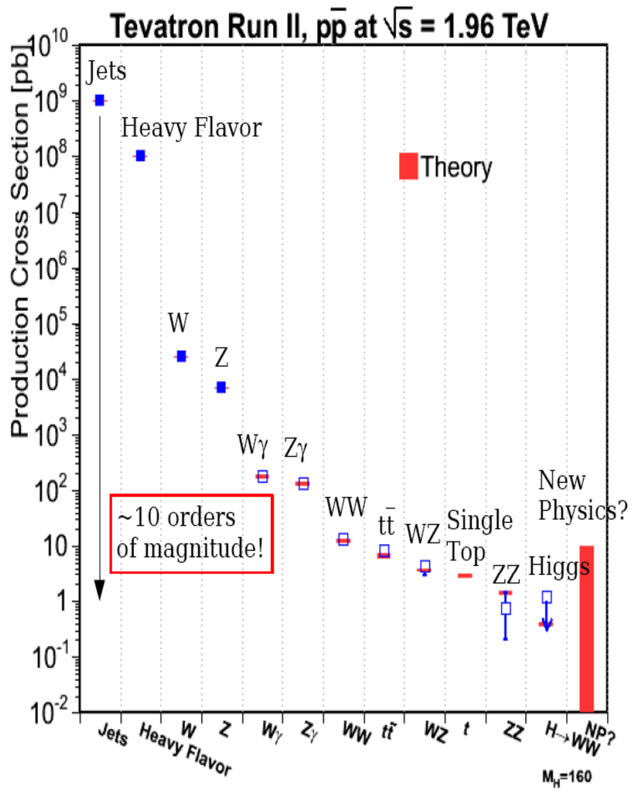
Electrons from W decays asymmetry



- **W charge asymmetry in W → eν decay studied**
- **Errors (mainly statistical) are small and result provides input for PDFs constrains**

Studies of di-boson Production

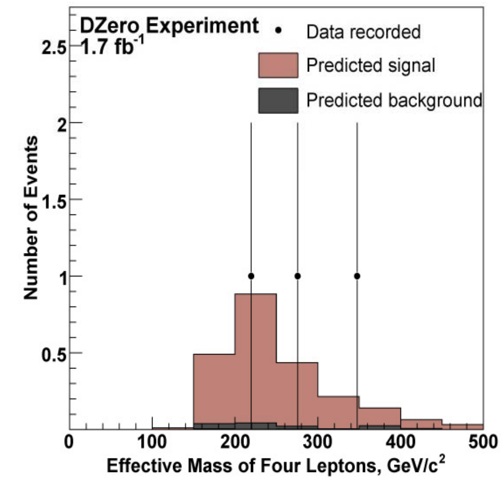
Detect very rare SM processes, search for anomalous vector boson couplings and develop experimental methods for Higgs hunting



Analysis with Z decaying to llνν or four leptons
Events with four charged leptons in final state are rather striking!

Run IIb

Channel	4e	4μ	2e+2μ	All channels
Signal	0.45	0.60	1.08	2.13
Total background	0.05	0.0003	0.095	0.14
Observed events	2	1	0	3



- ZZ is the smallest SM di-boson cross section: $\sigma(ZZ)=1.6 \pm 0.1$ pb
- On the road to Higgs
- Sensitive to New Physics

	Expected	Observed
P-value:	**1.3×10^{-4}**	**2.9×10^{-8}**
Significance:	**3.6σ**	**5.4σ**

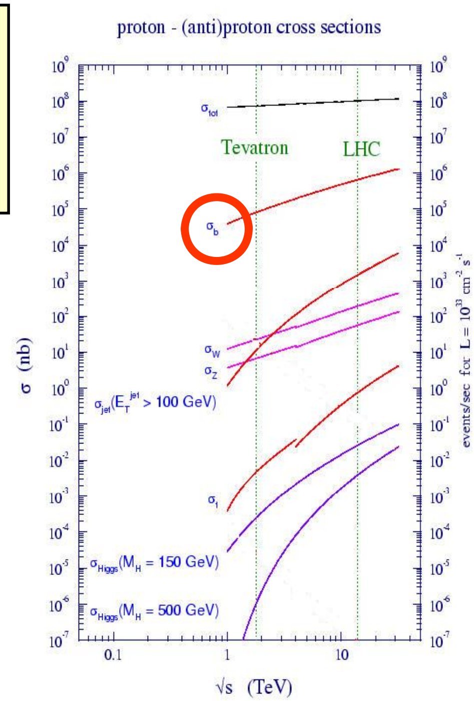
First observation of ZZ production!

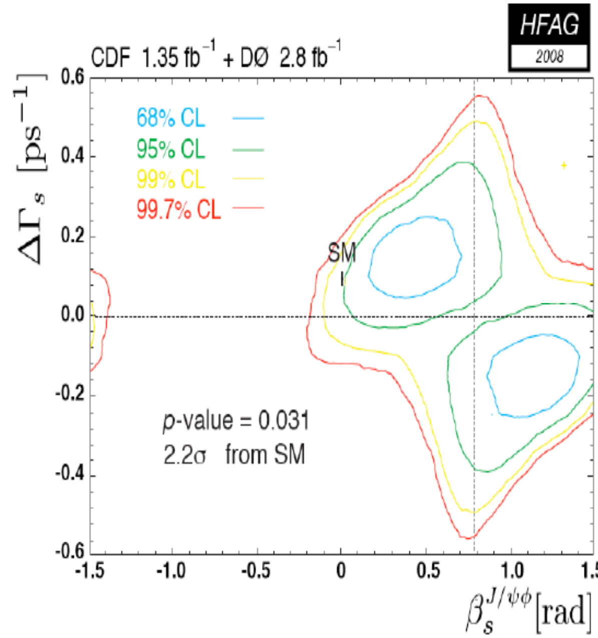
Already published in *Physical Review Letters*. Less than two months from analysis to publication!

Ivan Razumov talk on parallel session Thursday

b Quark Studies

High b quark cross section: ~$10^{-3}\ \sigma_{tot}$
~10^4 b's per second produced!
All b containing species are produced
$B^{\pm}$, B^0, B_s, B_c, Λ_b…



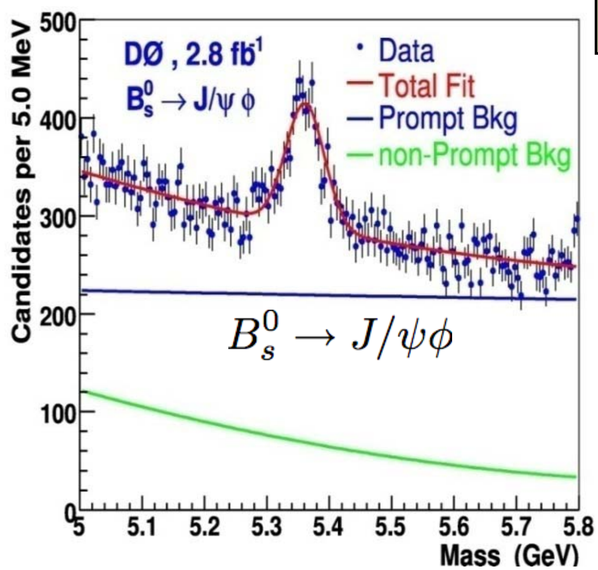


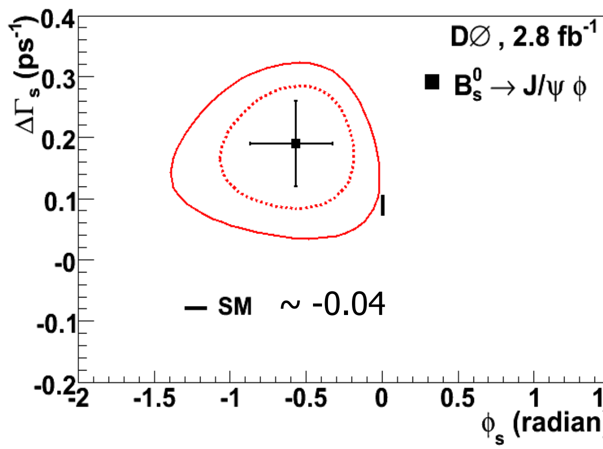
Large b quark data samples provide

- B mesons lifetime studies
- Mass spectroscopy (B_c, etc.)
- Studies of B_s oscillations
- CP violation studies
- Search for new b hadrons
- Search for rear decays

Combination of CDF and DØ measurements
2.2σ deviation from the SM for now…

Studies of CP violation using time-dependent angular analysis in flavor-tagged $B_s \to J/\psi\phi$ decays





B_s meson allows to probe the entire matrix

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

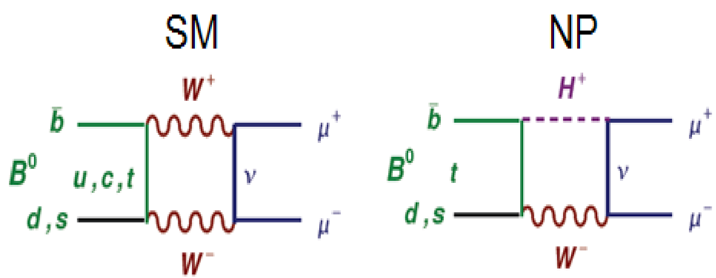
$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$

Rare Decays

- Rare decays are sensitive to New Physics.
  Large b production rate and high luminosity open a window of opportunity at the Tevatron.

- **FCNC $B_{s/d}$ decays:**

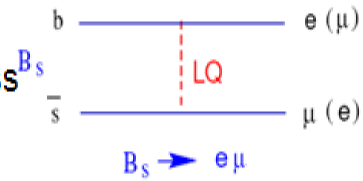


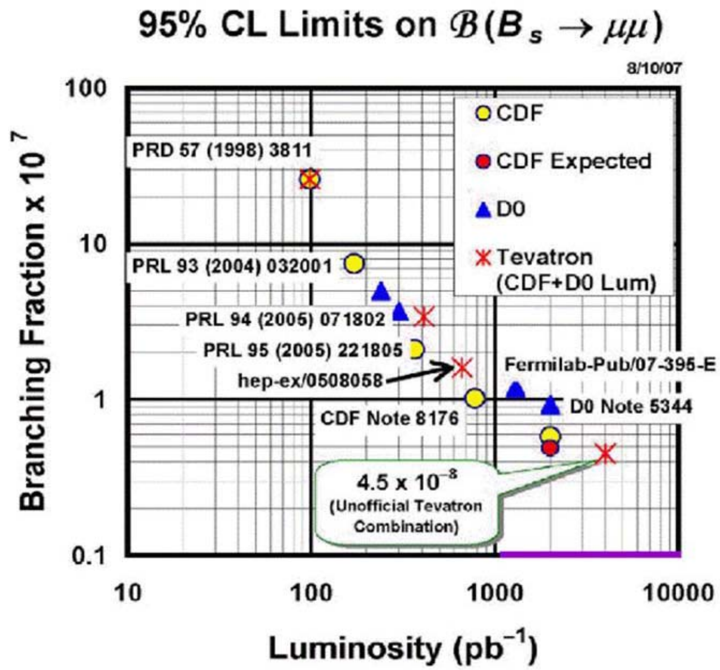
SM: BR($B_s \to \mu\mu$) ~3.8×10^{-9}

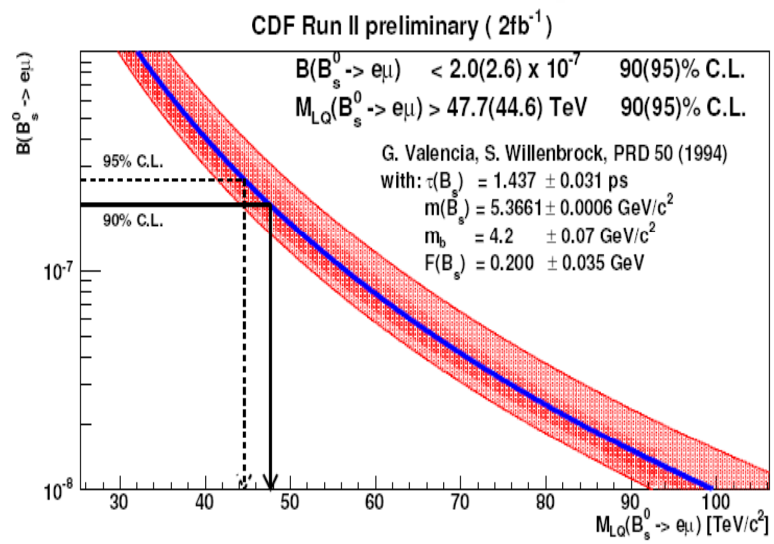
MSSM/2HDM: SM x $\tan^N\beta$ (N=6,4)!

Combined result is only ~10 times above SM

- **Flavor-violating $B_s \to e\mu$ decays:**
  - Forbidden in the SM
  - Sensitivity to very large mass scales







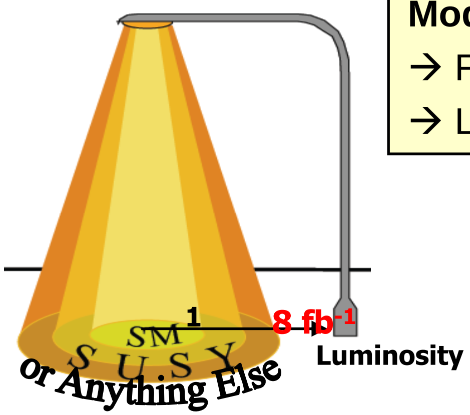
Limits on B_d decays competitive with B factories
Unique limits on B_s decays

Leonid Vertogradov talk on Omega-b baryon discovery

Search for New Phenomena

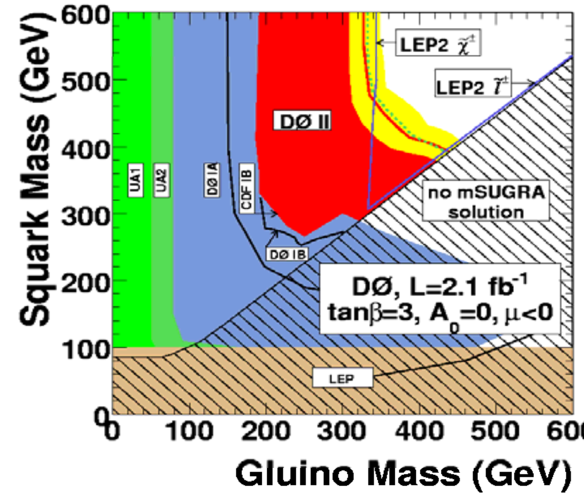
One of the most natural studies is to look for New Phenomena at energy frontier machine: SUSY, leptoquarks, Technicolor, new exotic particles, extra dimensions…

Recipe: search for irregularities in effective mass spectra or other kinematic parameters looking for events not described by the SM

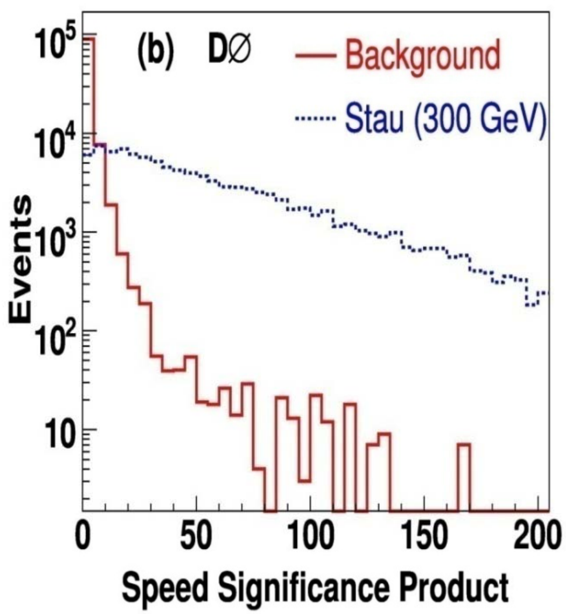


Model or Signature-based searches:
→ Final-state driven
→ Looking for deviations from the SM anywhere

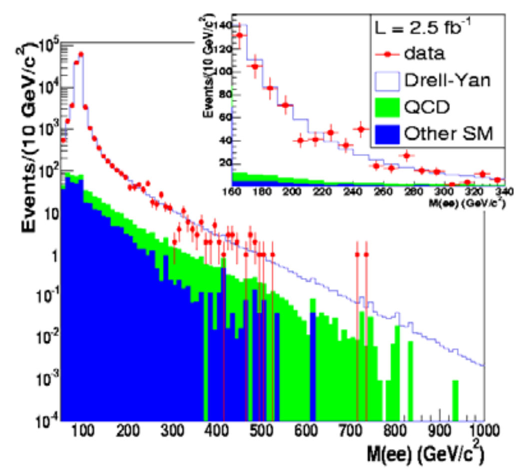
SUSY



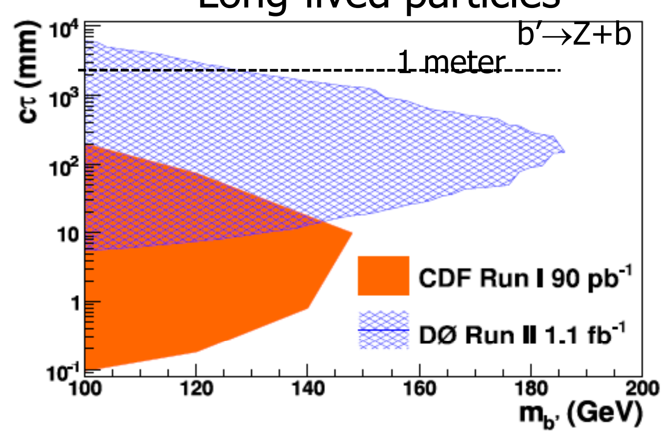
"Stable" particles



Z′ search



Long-lived particles



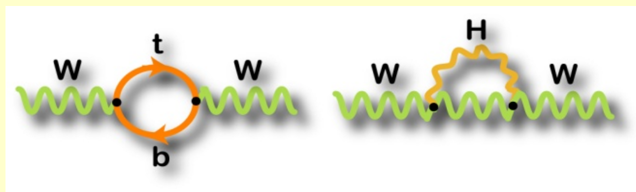
Alexei Popov talk on New Phenomena searches at DØ

Experimental Limits on Higgs Mass

Available experimental limits

→ direct searches at LEP
M_H >114 GeV at 95% C.L.

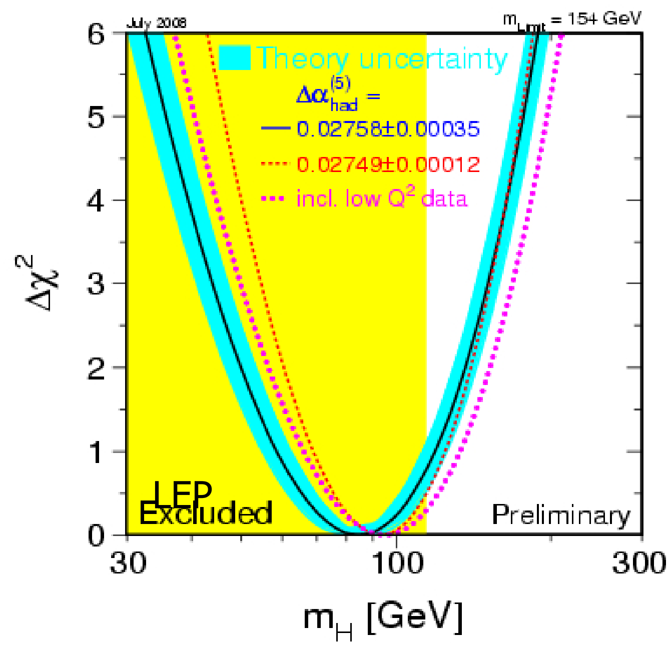
→ precision EW fits



M_H=84 $^{+34}/_{-26}$ GeV

M_H< 154 GeV (95%) or <185 GeV with direct LEP limit

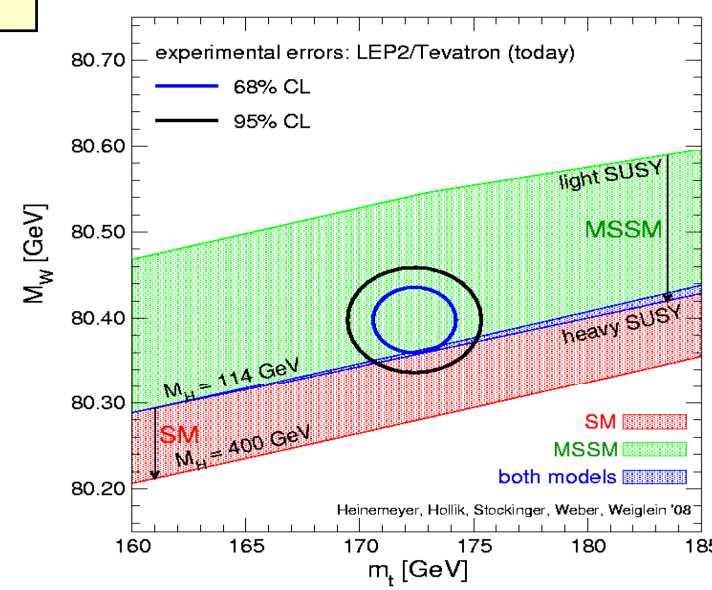
Light Higgs favored!



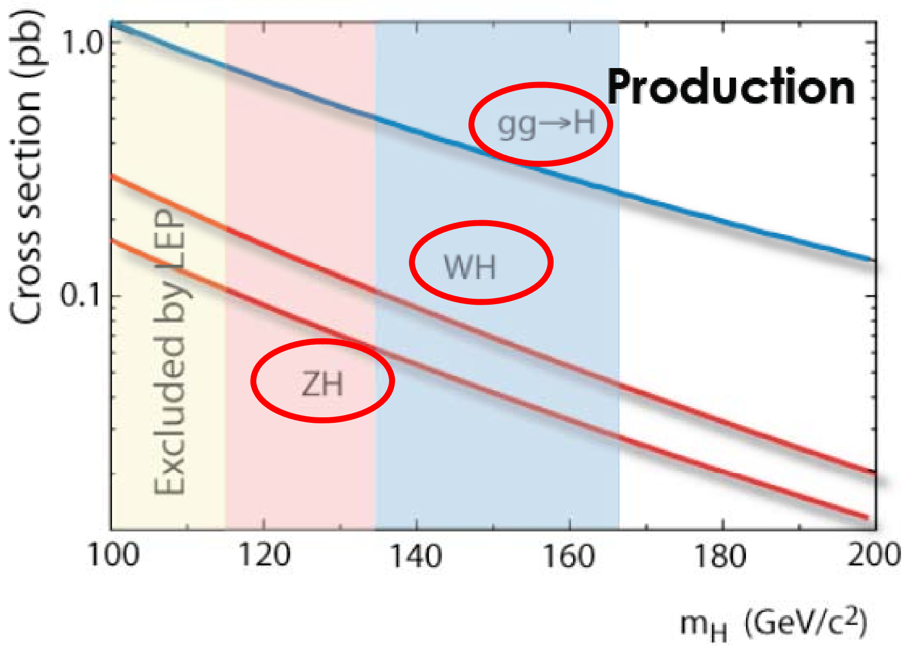
Tevatron provides:

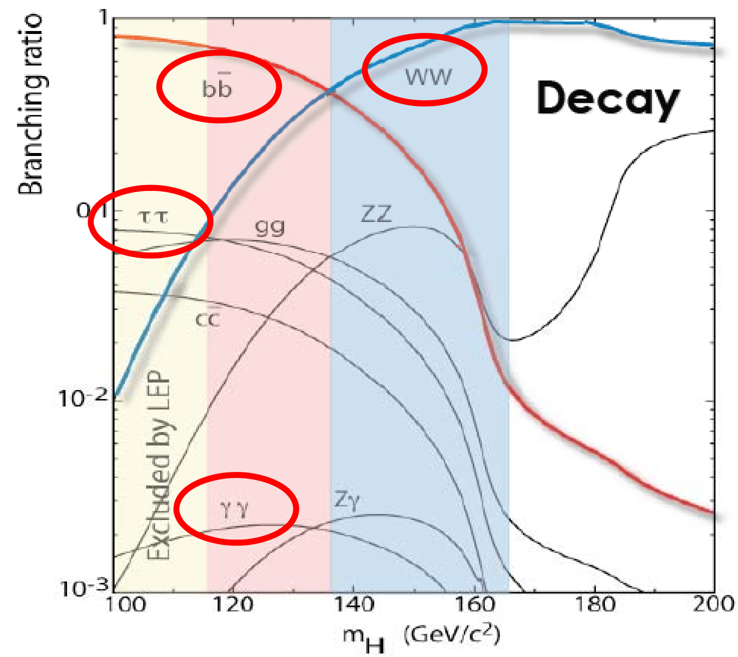
Precision m_{top} and M_w measurements

Direct searches!



SM Higgs Production and Decays at Tevatron





Production cross sections
→ in the 1 pb range for gg → H
→ in the 0.1 pb range for associated vector boson production

Decays
→ bb for M_H < 130 GeV
→ WW for M_H > 130 GeV

Search strategy:

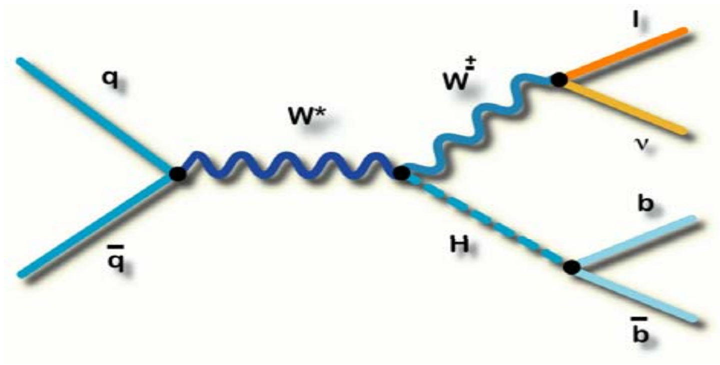
M_H <130 GeV associated production and bb decay W(Z)H → lν(ll/νν) bb

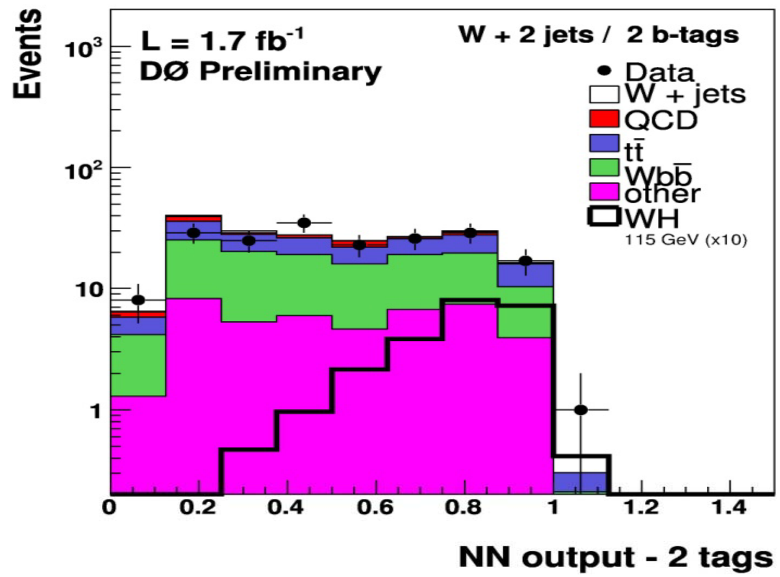
Backgrounds: top, Wbb, Zbb…

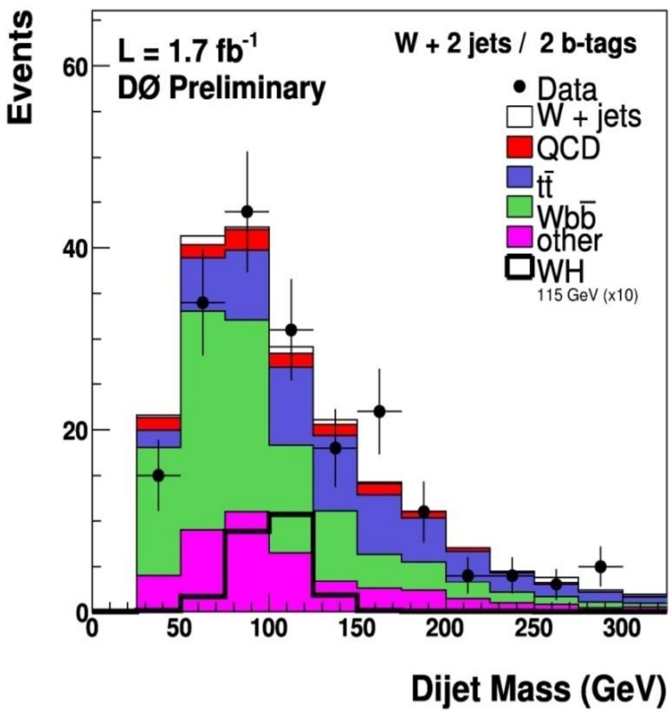
M_H >130 GeV gg → H production with decay to WW

Backgrounds: electroweak WW production…

SM Higgs Search: WH → lνbb (M_H<130 GeV)



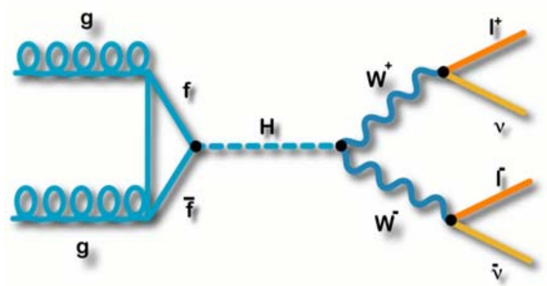




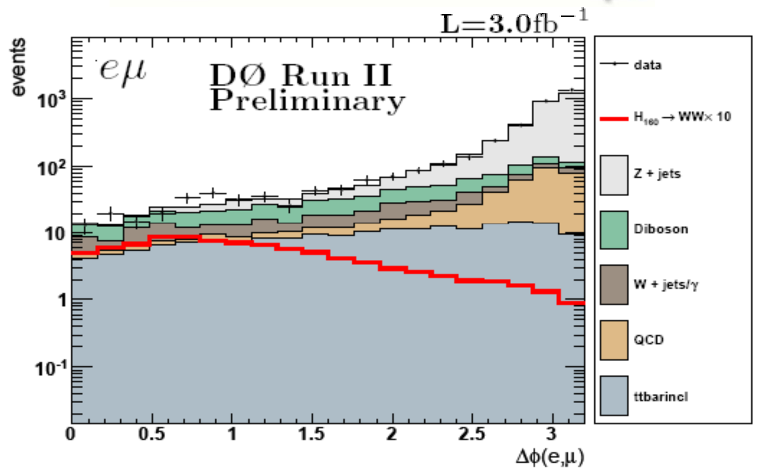
- One of the most sensitive channels in the ~110-130 GeV mass range
- Consider 8 independent channels
  - e+jets, μ+jets
  - 2, 3 jets
  - 1, 2 b-tags (NN-based)
- Main background: W+b/c jets, tt
- Dijet mass → multivariate discriminant

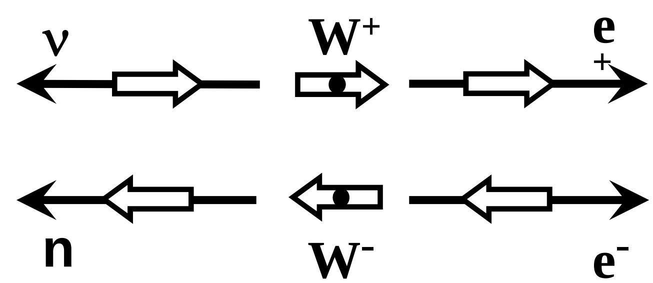
Limits are used for DØ combination

SM Higgs Search: H → WW → lνlν (M_H >130 GeV)

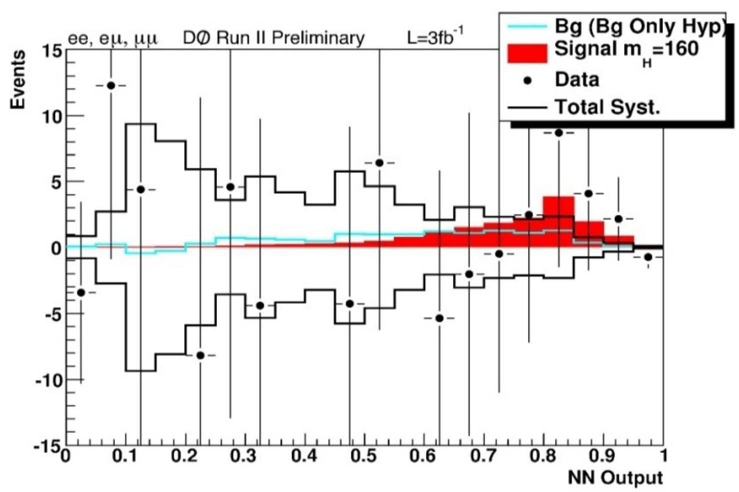


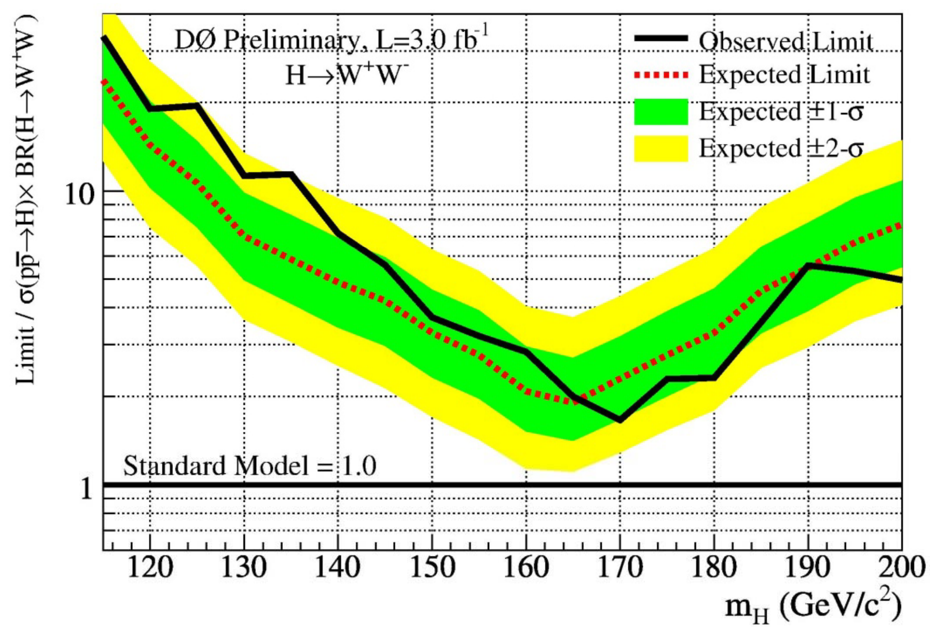
Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction





Observed and expected limits



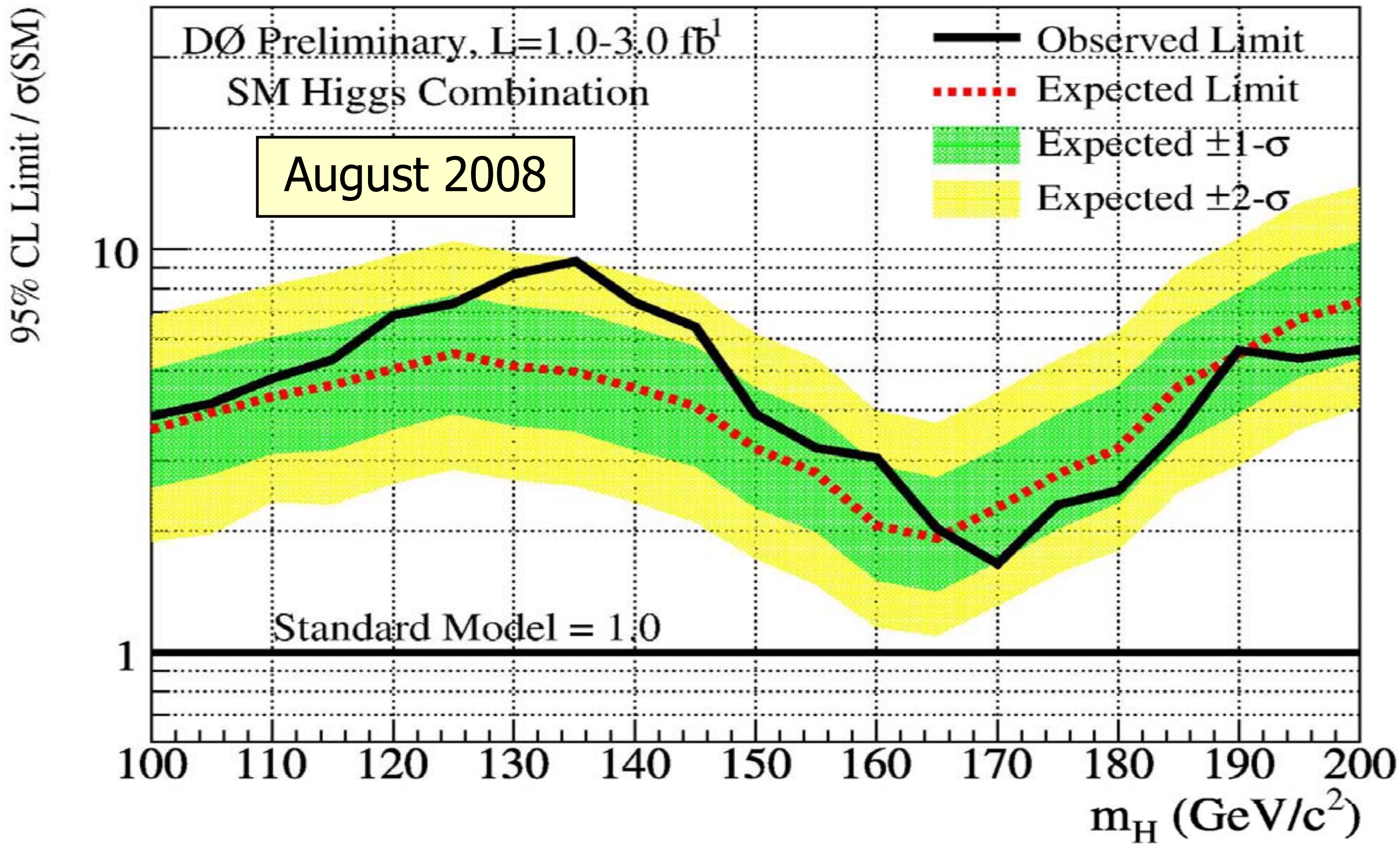


Dmitri Denisov, RAS, December 2008

Standard Model Higgs Search

Combining **multiple** search channels DØ sets Standard Model Higgs limits

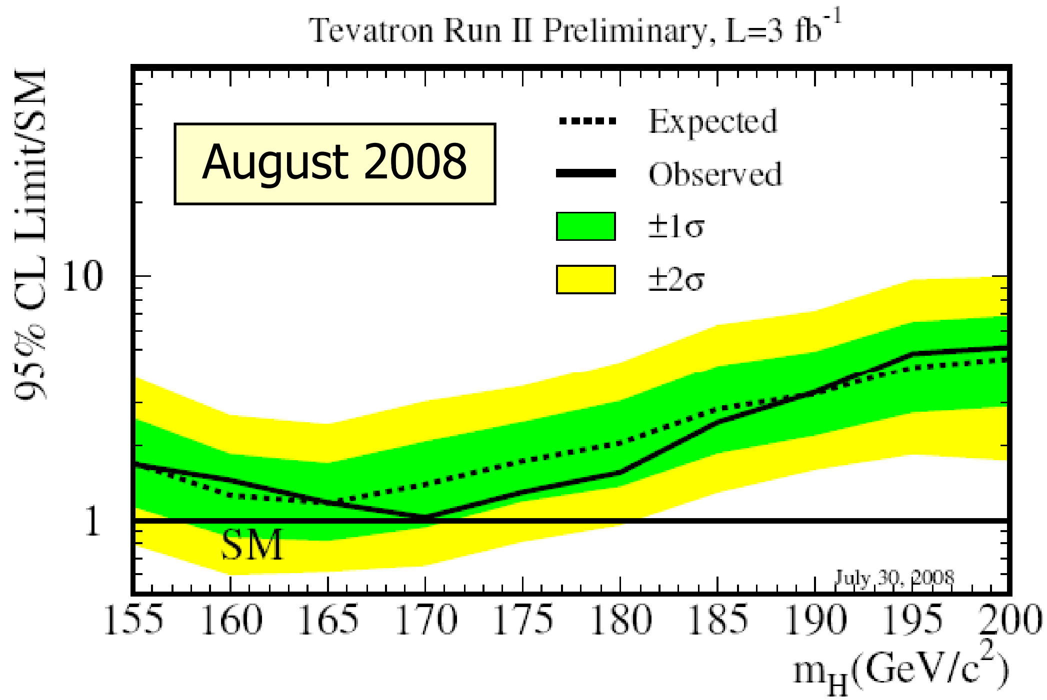
DØ ratios to SM, observed(expected)
5.3 (4.6) @ 115 GeV
1.7 (2.3) @ 170 GeV



When ratio becomes equal to one – specific Higgs mass is excluded at 95% CL

DØ and CDF SM Higgs Combined Limits

Excluded m_H = 170 GeV @ 95% CL !

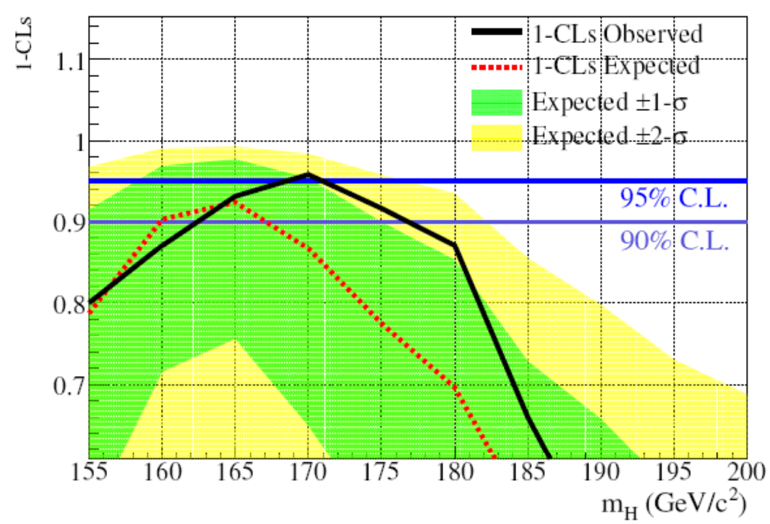


- First direct exclusion since LEP II
- Limits continued to scale ~linearly with luminosity between Moriond 2008 and ICHEP 2008
  - Analysis improvements
- Expect to improve limits by Moriond 2009

Different combination methods

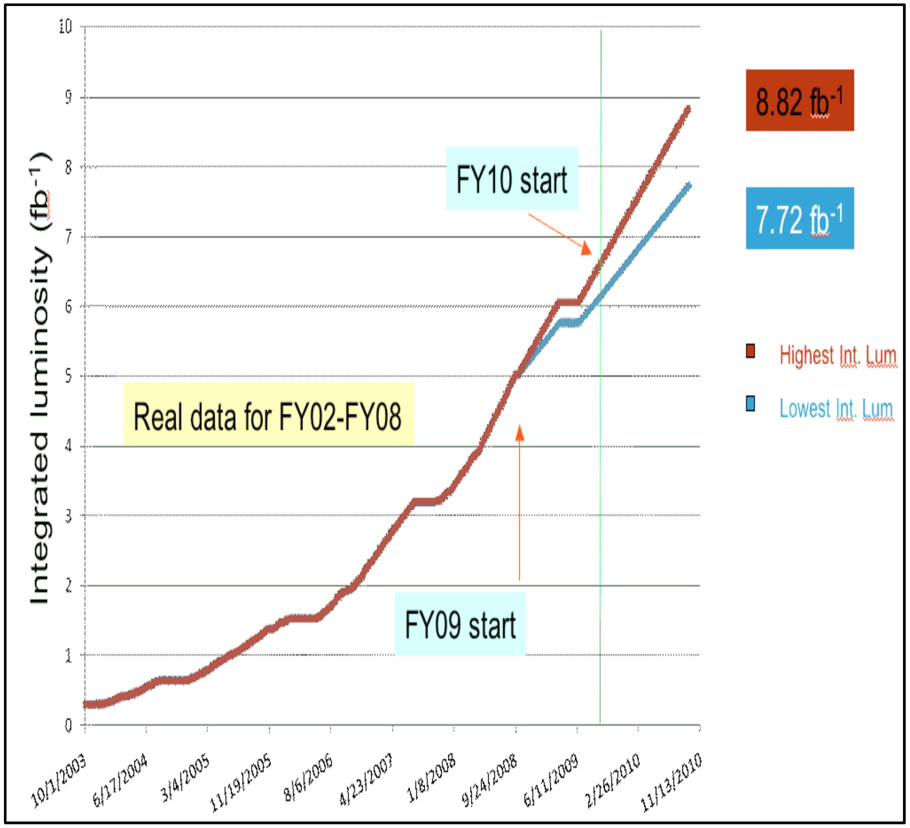
95%CL Limits/SM

M_Higgs(GeV)	160	165	170	175
Method 1: Exp	1.3	1.2	1.4	1.7
Method 1: Obs	1.4	1.2	1.0	1.3
Method 2: Exp	1.2	1.1	1.3	1.7
Method 2: Obs	1.3	1.1	0.95	1.2



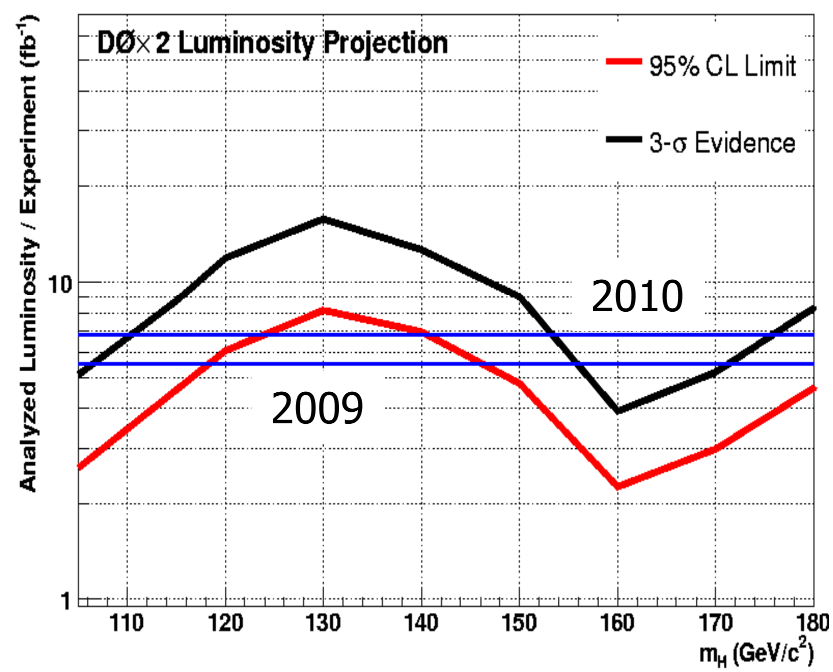
Tevatron demonstrated sensitivity to Higgs and from now will increase exclusion region or… find the Higgs

Tevatron Luminosity Projections



- Projections are based on extrapolations of the current performance
  - Improvements, like shorter shot setup time, are still coming
- We expect ~9 fb^{-1} delivered by the end of 2010
- Excellent physics program
  - Many studies are statistically limited

SM Higgs Projections



SM Higgs Projections

- With data accumulated by the end of 2010 we expect
- 95% exclusion possible over almost entire allowed mass range
- 3σ evidence possible at low and high ends of range

Tevatron Physics Highlights: Summary

Tevatron is performing extremely well

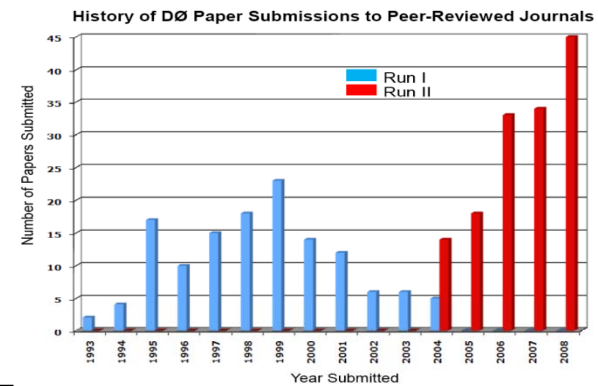
Experiments are collecting and analyzing data from the energy frontier collider
→ Many discoveries and precision measurements recently
→~200+ studies in progress publishing 2 papers every week!

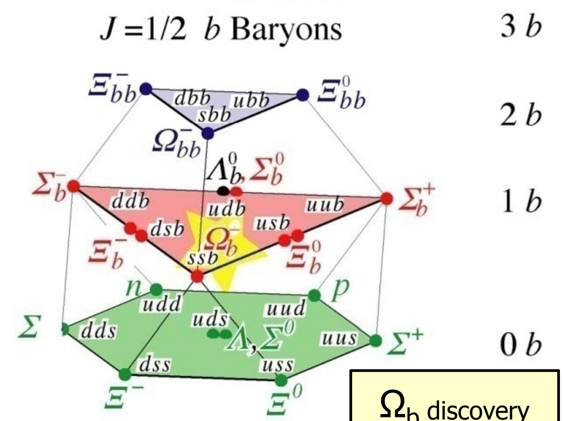
No significant deviations from the Standard Model observed yet
→ Although there are "~2 sigma" discrepancies…
→ Data samples analyzed are to increase by 5-7 times

SM Higgs search is in a very active stage
→ Excluded at 95% CL Higgs with mass of 170 GeV
→ Proceeding to exclude wider mass range or… to see the Higgs!

Major contributions from Russian groups to the Tevatron
→ 10% of the DØ and CDF collaborations
→ IHEP, JINR, PNPI, ITEP and Moscow State University
→ Detectors, algorithms, major physics results

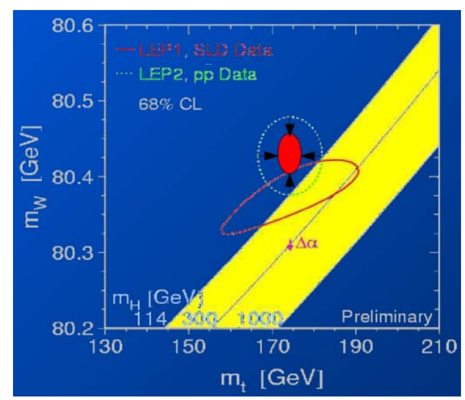
Looking with excitement forward for continuing excellent physics results from the Tevatron experiments!





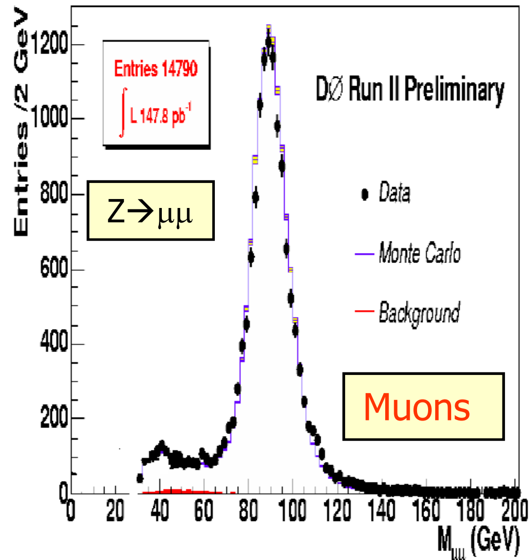
Ω_b discovery

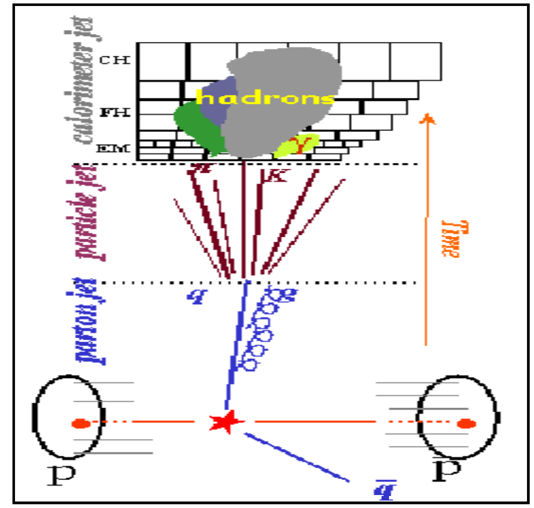
Among top ten 2008 Physics Results!

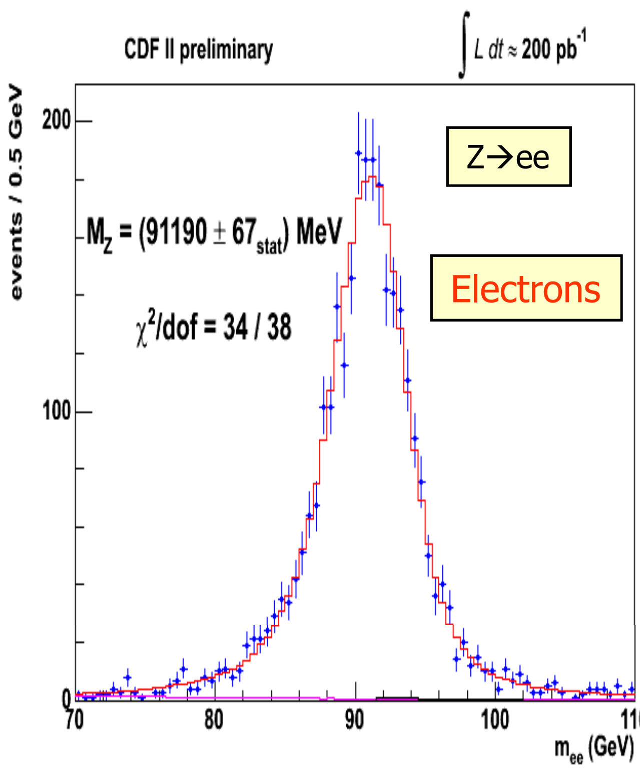


Detectable Objects – Particle Identification

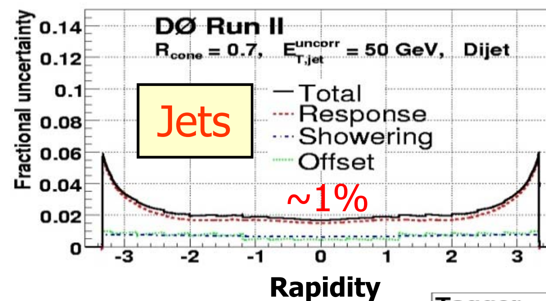
- Excellent understanding of the detector and algorithms achieved
  - Took many years…
- Certification of additional data for identification methods within a few weeks
  - Automated software

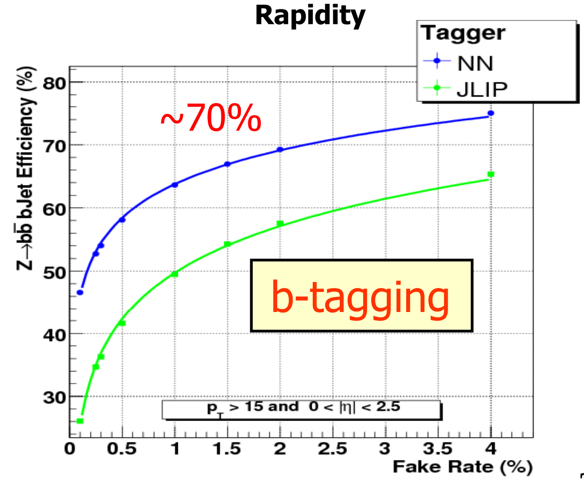


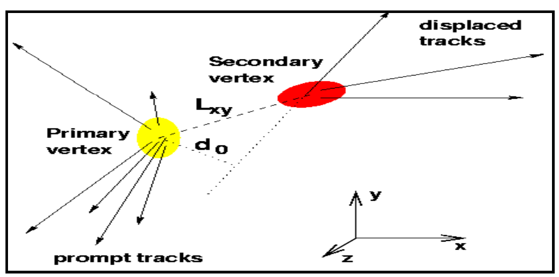




Final decay products
→ electrons
→ muons
→ charged tracks
→ jets (b)
→ missing E_t (ν)
Detection and MC optimization using well known objects

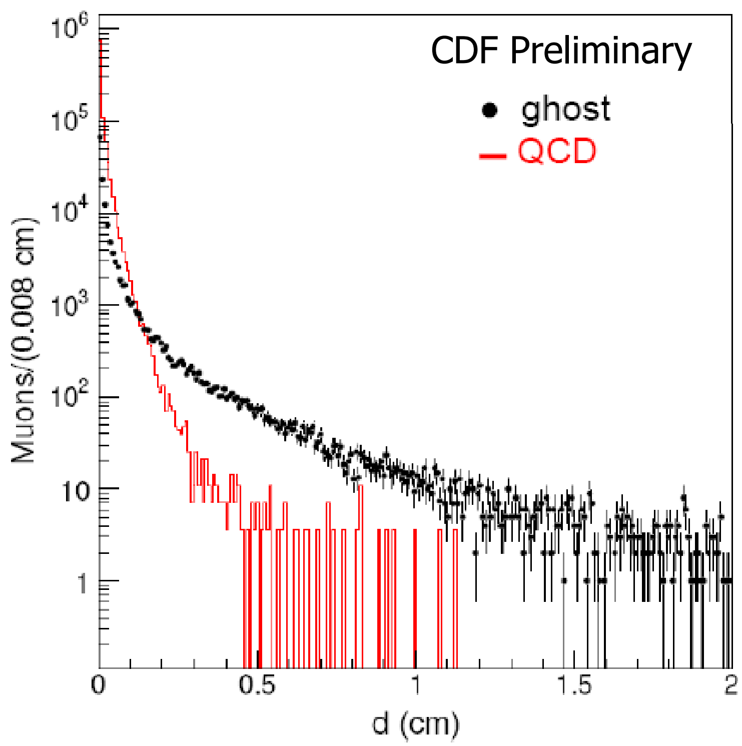






"Ghost" Muons

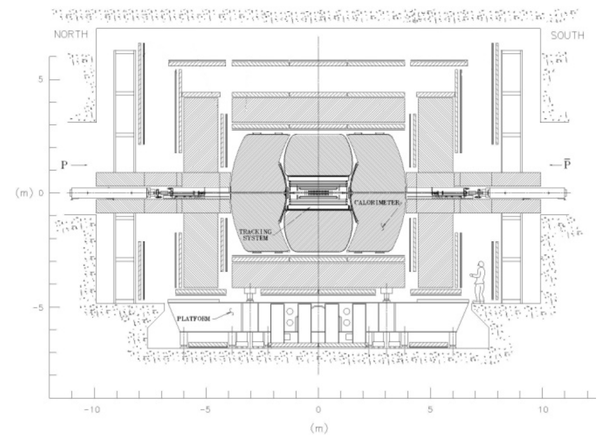
Recently CDF reported observation of excess of muons with large decay distances



For better or for worse excitement has been created – New Physics?!

While we have a healthy skepticism about this result DØ has major advantages to address this issue

- Substantially thicker muon system and magnetized iron toroid
  - Punchthrough is much less than in CDF's case
- Excellent time resolution of trigger counters in all layers of the muon system
  - Rejection of muons in cosmic showers



- Do we have data?
  - Yes, di-muon triggers are part of the trigger menu since early Run II
- Could DØ reconstruct displaced vertices with large distances?
  - Yes, tracking impact parameter cut is 2.5cm and could be increased
- A team of experts is analyzing DØ data

Russian Groups Participation in CDF

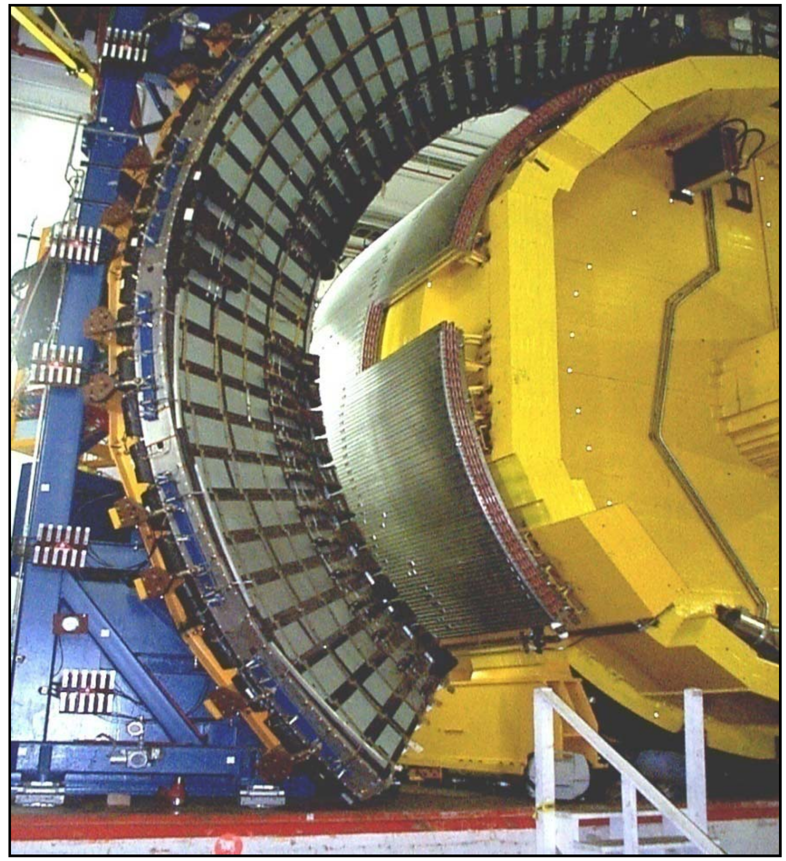
JINR and ITEP

JINR CDF's team

A.Artikov, J.Budagov, I.Chirikov-Zorin, G.Chlachidze, D.Chokheli, N.Giokaris, V.Glagolev, F.Prokoshyn, O.Pukhov, A.Semenov, A.Sissakian, I.Suslov

Major JINR's contributions

- **Creation and maintenance of the scintillation complex for CDF μ-trigger for c,b,t – physics study**
- **Creation and maintenance of the Silicon Vertex Trigger for secondary vertex detection**
- **Top mass analysis**
- **Search for the Very High Multiplicity processes using CDF data**



Excellent contributions!

Russian Groups Participation in DØ

JINR, IHEP, ITEP, MSU, PNPI – 10% of the Collaboration

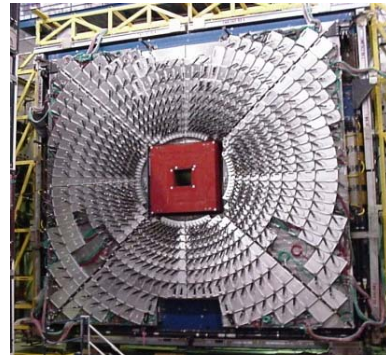
V.M. Abazov, G.D. Alexeev, G. Golovanov, Y.M. Kharzheev, E.V. Komissarov, D. Korablev, V.L. Malyshev, Y.P. Merekov, G. Panov, S.Y. Porokhovoi, V. Rodionov, A. Rozhdestvenski, N.A. Russakovich, N.B. Skachkov, V.V. Tokmenin, L.S. Vertogradov, Y. Vertogradova, Y.A. Yatsunenko
Joint Institute for Nuclear Research, Dubna, Russia

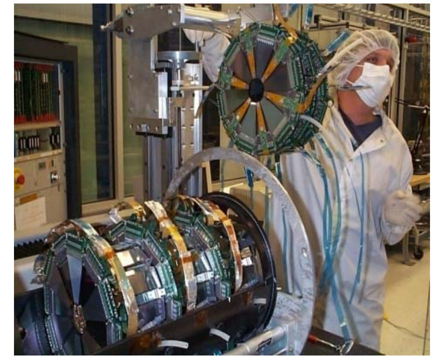
V. Gavrilov, P. Polozov, G. Safronov, V. Stolin, V.I. Turtikov
Institute for Theoretical and Experimental Physics, Moscow, Russia

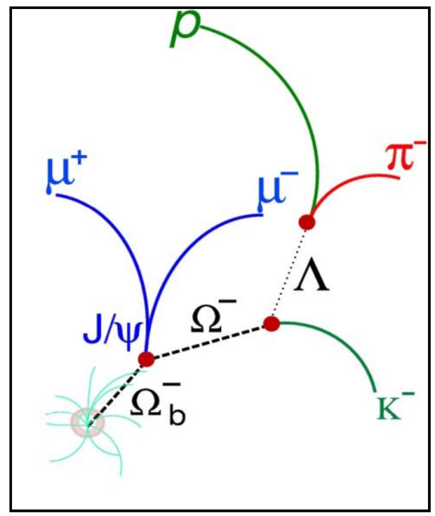
E.E. Boos, V. Bunichev, L.V. Dudko, P. Ermolov, D. Karmanov, V.A. Kuzmin, A. Leflat, M. Merkin, M. Perfilov, A. Uzbyakova, E.G. Zverev
Moscow State University, Moscow, Russia

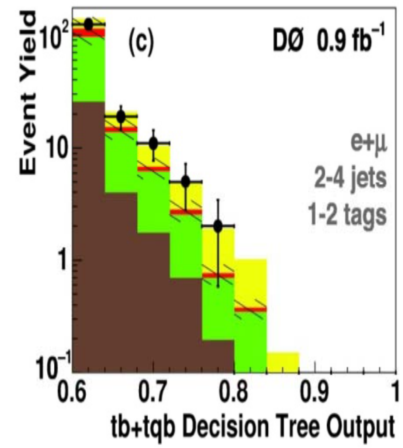
V.A. Bezzubov, S.P. Denisov, V.N. Evdokimov, V.I. Koreshev, M. Kostin, A.V. Kozelov, E.A. Kozlovsky, S. Kulikov, V.V. Lipaev, L. Mikhalev, A.V. Popov, N. Prokopenko, A.A. Shchukin, D.A. Stoyanova, I.A. Vasilyev, S.A. Zvyagintsev
Institute for High Energy Physics, Protvino, Russia

G. Alkhazov, S. Evstyukhin, V. Kim, A. Lobodenko, P. Neustroev, G. Obrant, V. Oreshkin, S. Oganesyan, Y. Scheglov, L. Uvarov, S. Uvarov
Petersburg Nuclear Physics Institute, St. Petersburg, Russia









- Muon system design, construction and operation: IHEP, JINR, PNPI, ITEP
- Silicon detector: MSU
- Key contributions to physics analysis in
  - B-physics
  - Single top observation
  - New Phenomena searches

Talks later today!

Without contributions from Russian groups none(!) of the results presented in this talk would be possible

MSSM Higgs Search

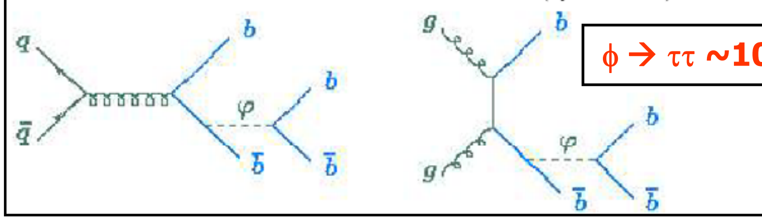
MSSM predicts larger Higgs cross sections for some values of parameter space than SM

Using NLO cross section calculations and assuming no difference between A and h/H search for MSSM Higgs is performed

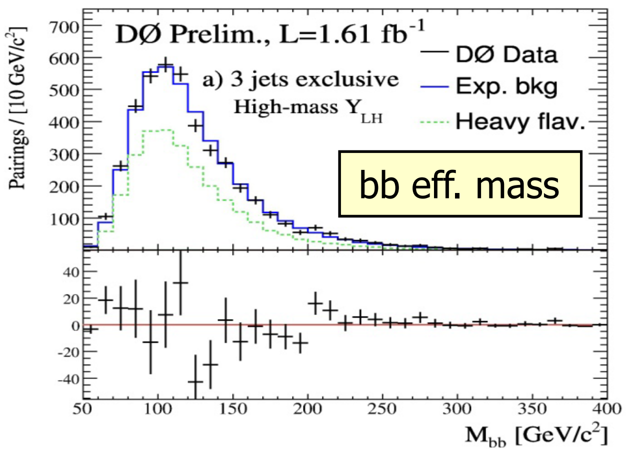
- **→multi b-jets**
- **→ di-τ events (inclusive) or with two extra b-jets**

Two Higgs Doublets $\mathcal{H}_1, \mathcal{H}_2$ and 5 physical states

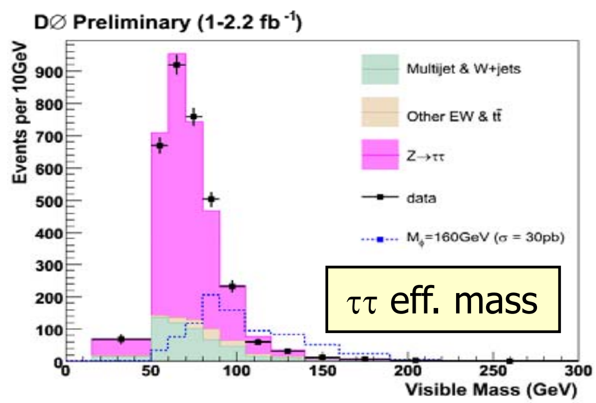
2 CP-even neutral Higgses	h^0, H^0	$m_h < m_H$
1 CP-odd neutral Higgs	A^0	
2 charged Higgses	$H^\pm$	
Free parameters:	$\tan\beta = v_2/v_1$	(VEV ratio)
	α	(mixing angle of h, H)
	μ	Higgs mass parameter
	A_0	common trilinear Higgs-sfermion coupling
tree level:	$m_h < m_Z < m_H$	
rad.corrected:	$m_h <$ 130 GeV	$Br(\phi \to b\bar{b}) \sim 90\%$



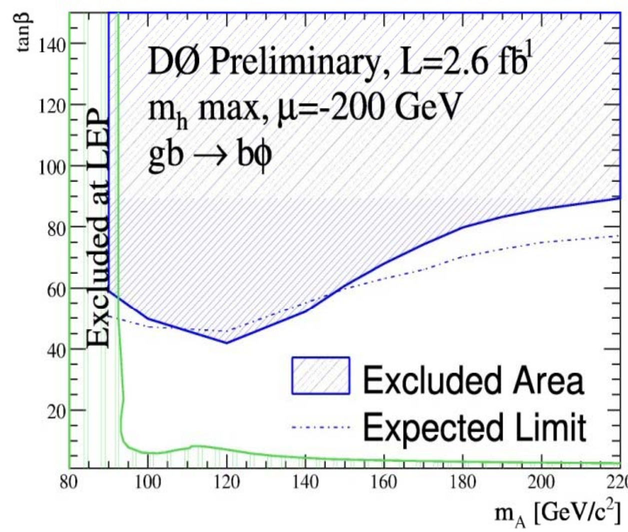
$\phi \to \tau\tau$ ~10%

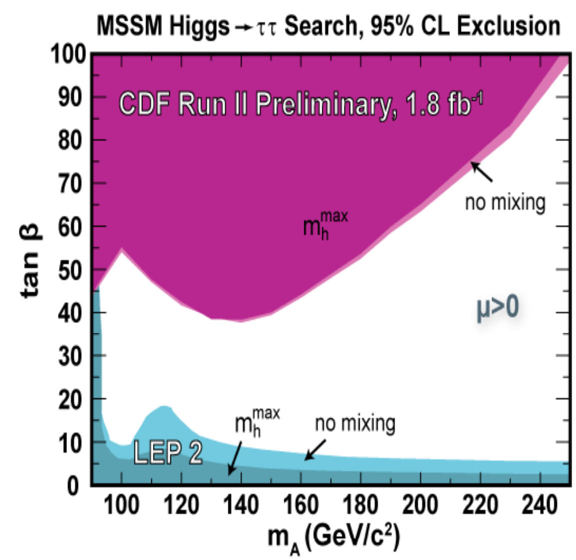


bb eff. mass



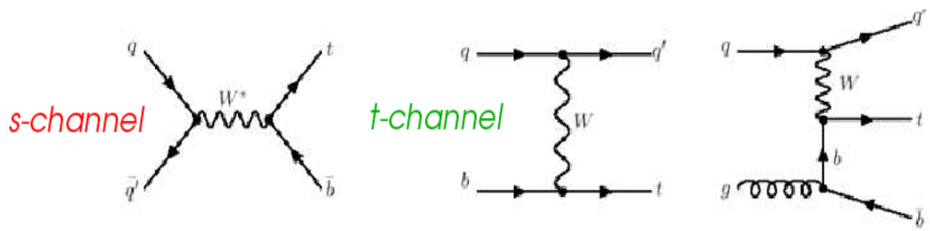
$\tau\tau$ eff. mass





Large region in the MSSM parameter space
Combination of all three channels ($\tau\tau$, $b\tau\tau$, bbb) in progress

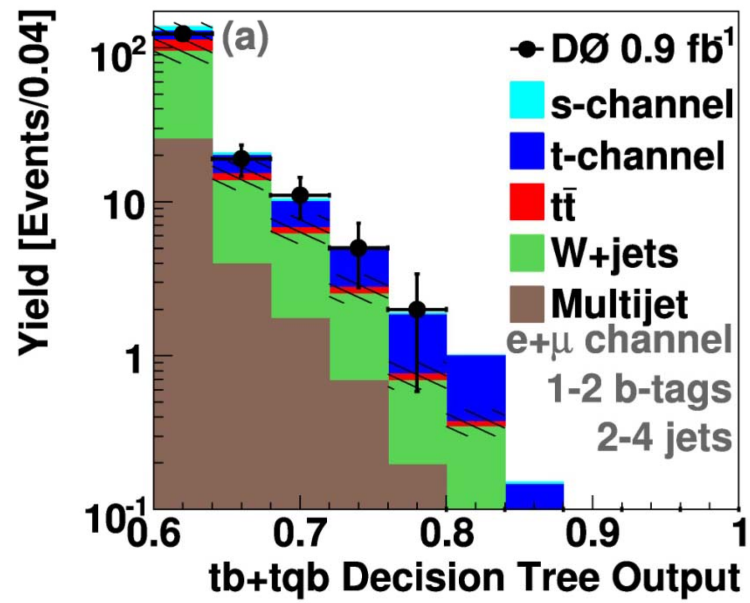
Single Top Quark Production



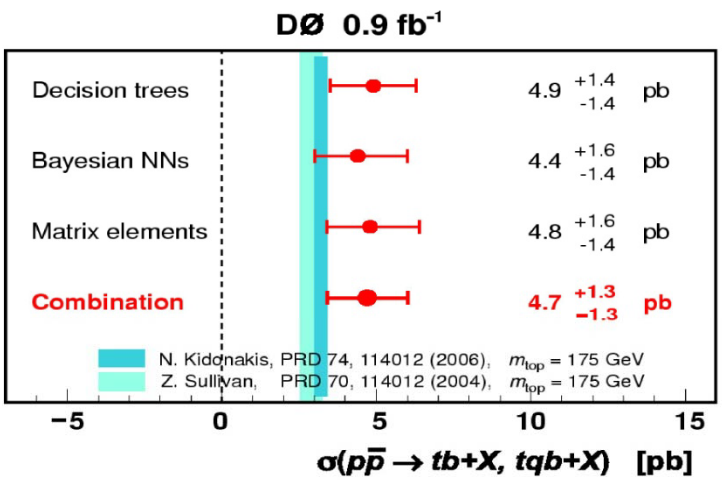
σ_s=0.88±0.07 pb σ_t=1.98±0.21 pb

EW production of top quark
→ direct probe of |V_{tb}|
→similar to hunt for Higgs: (Wb)b
→ High backgrounds

- **Consistent results obtained from three techniques**
  - **boosted decision trees, matrix elements, Bayesian NN**
- **Combined result:**
  - **4.7 ± 1.3 pb (3.6 σ significance)**
  - **Consistent with SM expectations**
- **First direct determination of |V_{tb}|**
  - **0.68 < |V_{tb}| < 1 at 95% CL**
  - **|$V_{tb} f_1^L$| = 1.3 ± 0.2 no |V_{tb}| < 1 limit**



Blue - single top signal

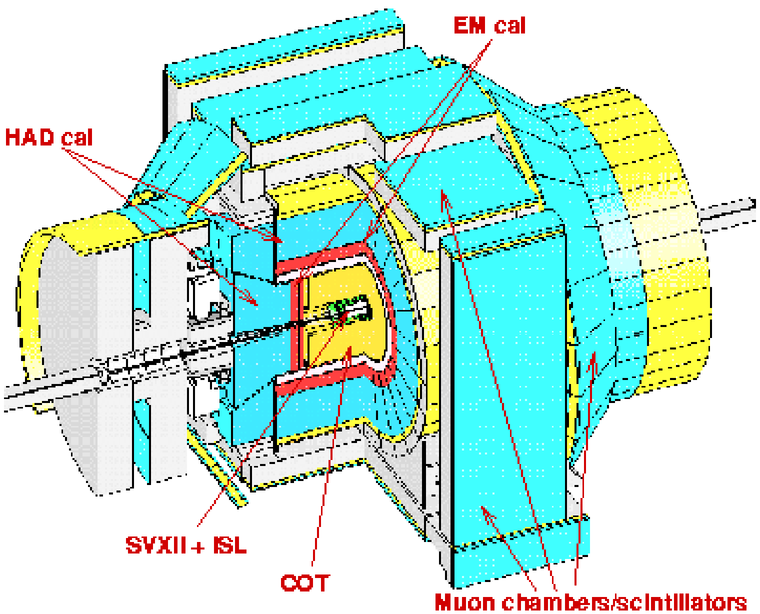


Developed and used advanced methods
to separate signal
events from substantial backgrounds

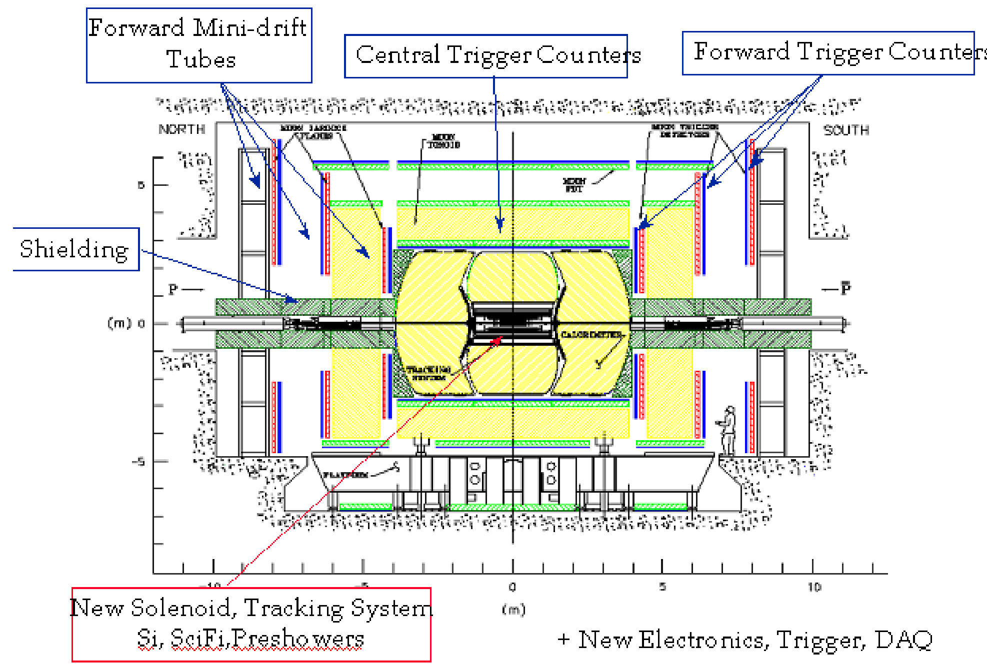
Finalizing result on based on 3 fb^{-1} of data

CDF and DØ Experiments in Run II

CDF



DØ



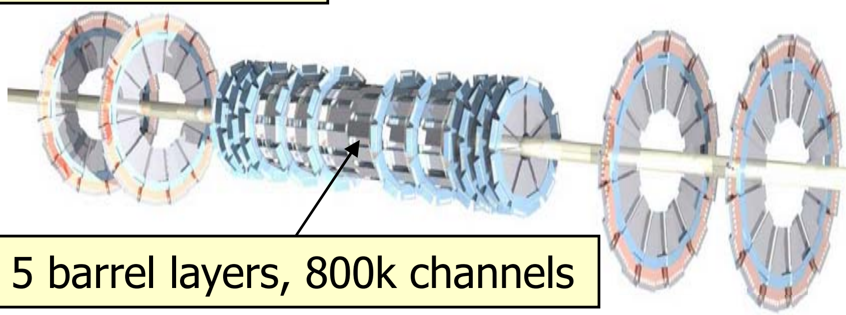
New Silicon Detector
New Central Drift Chamber
New End Plug Calorimetry
Extended muon coverage
New electronics

Silicon Detector
2 T solenoid and central fiber tracker
Substantially upgraded muon system
New electronics

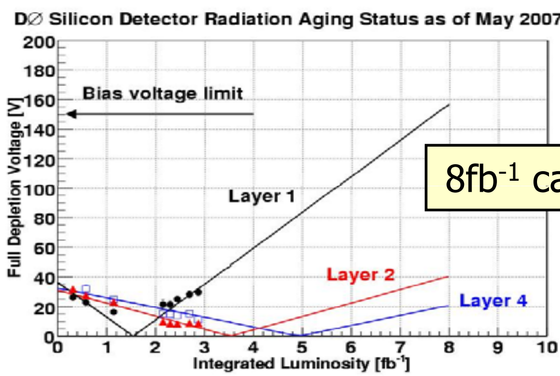
Driven by physics goals detectors are becoming “similar”:
silicon, central magnetic field, hermetic calorimetry and muon systems

DØ Detector

Silicon Detector

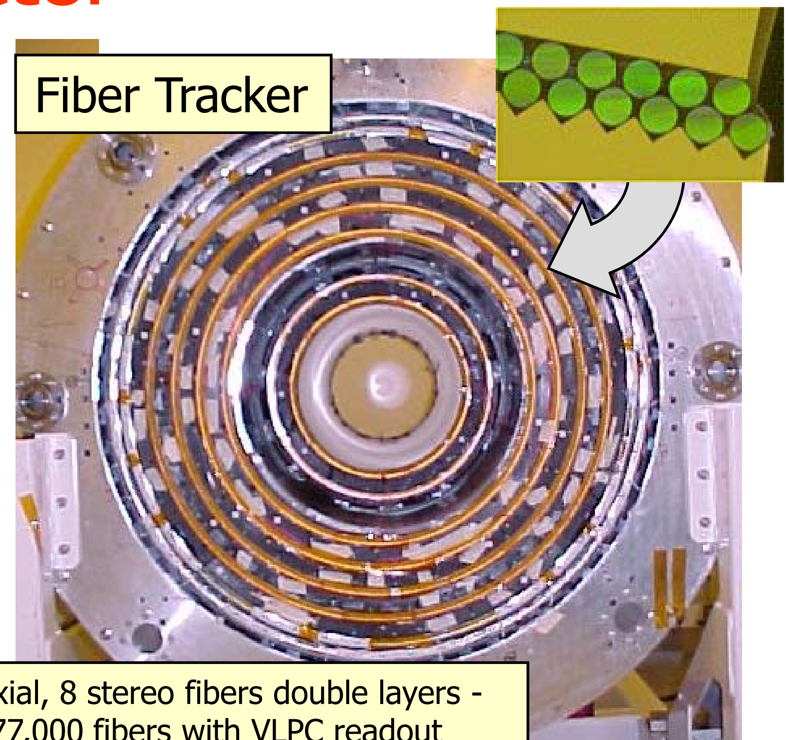


5 barrel layers, 800k channels



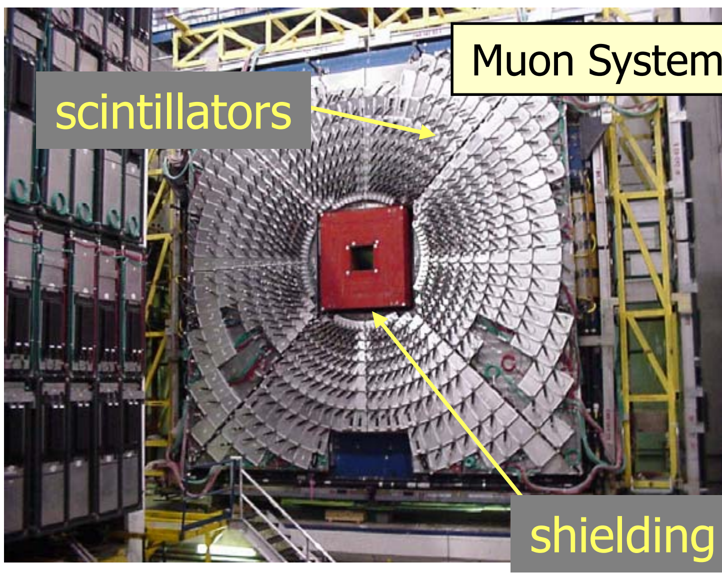
$8fb^{-1}$ capable!

Fiber Tracker



8 axial, 8 stereo fibers double layers - 77,000 fibers with VLPC readout

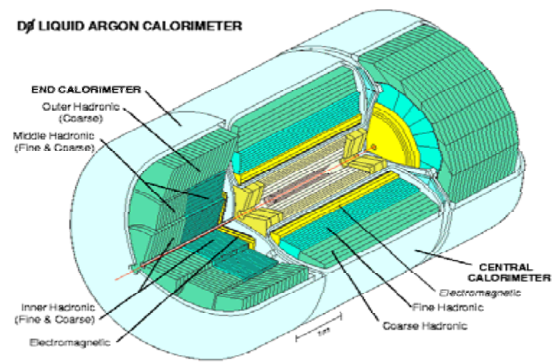
Muon System



scintillators

shielding

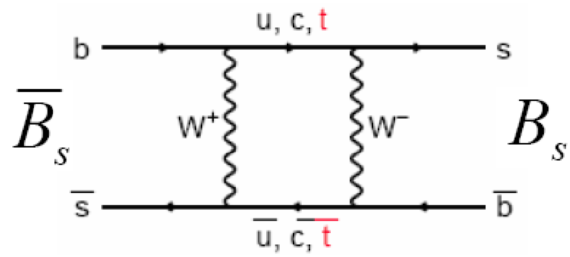
Uranium Liquid Ar Calorimeter



All detectors are running very well!

B_s Mixing Observation

In SM B-mixing is explained by box diagrams
→ Constrains V_{td} and V_{ts} elements of CKM matrix
→ New physics → new particles in the box

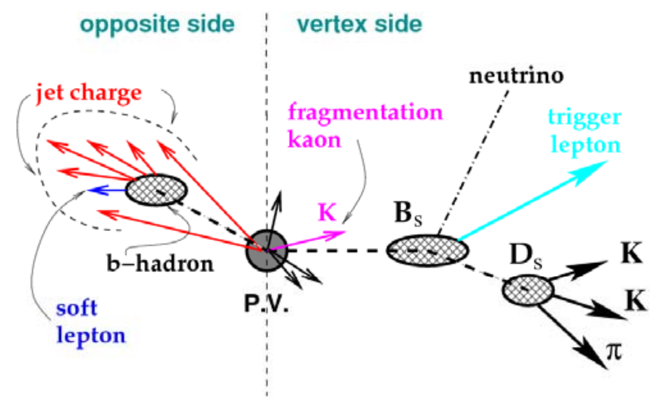


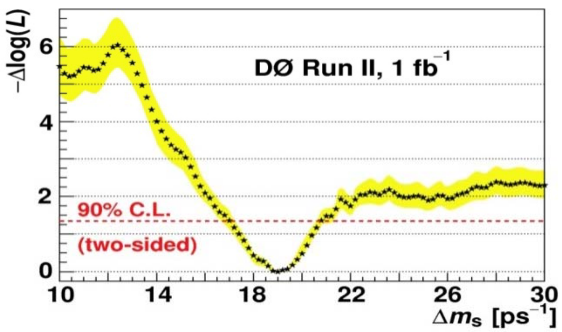
First evidence by DØ: used semileptonic data sample μD_s

Decay mode $D_s \to \Phi\pi$, $\Phi \to K^+K^-$

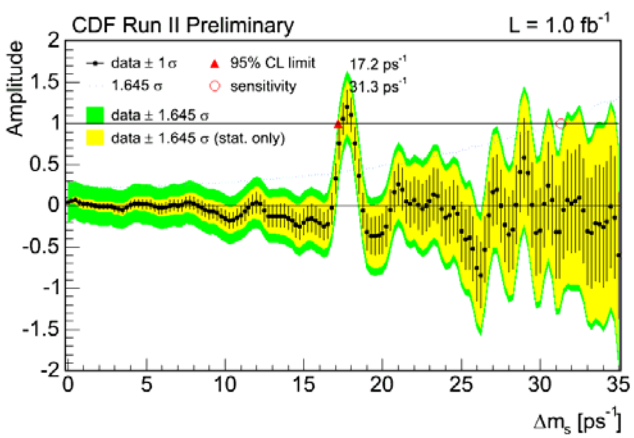
Charge of the muon provides Final State Tag

90% CL limit: $17 < \Delta m_s < 21$ ps^{-1}, statistically limited

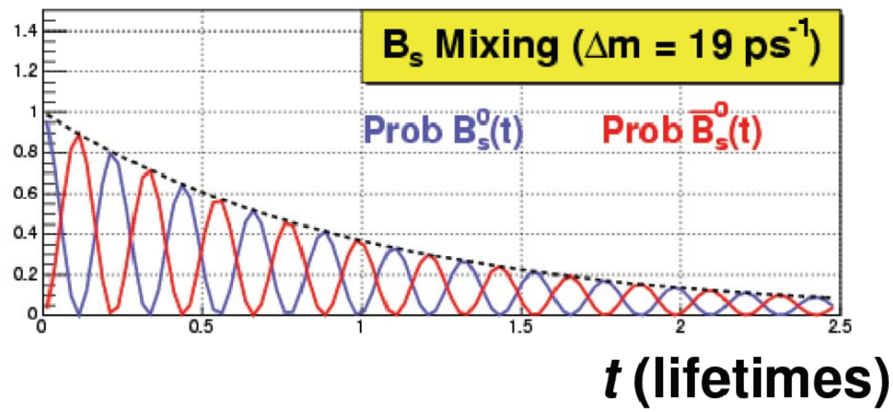




CDF nailed down B_s oscillations with >5 sigma significance



$$\Delta m_s = 17.77 \pm 0.10\ (\mathrm{stat}) \pm 0.07\ (\mathrm{syst})\ \mathrm{ps}^{-1}$$



No luck for new physics in this case, but keep looking…