Tevatron Overview

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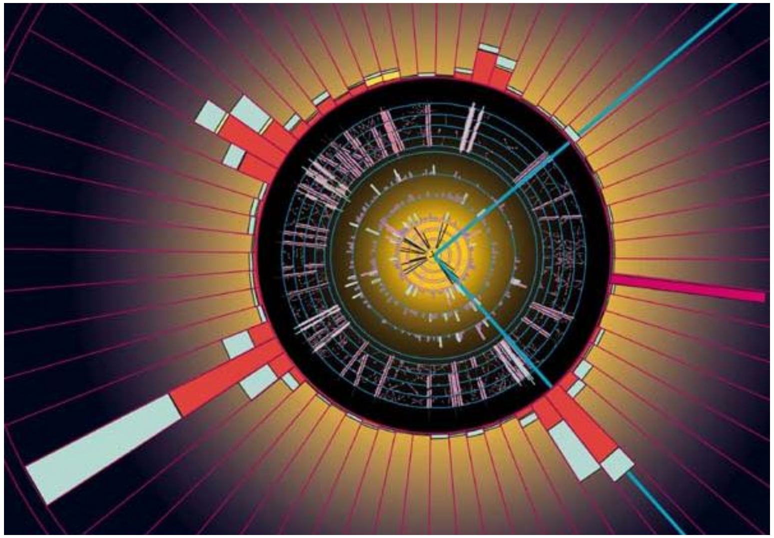
Aspen 2012 – The Hunt for New Particles, from the Alps to the Plains to the Rockies
12-February-2012

Outline

- The accelerators
- The detector
- The people
- The physics
  - Progress & Milestones
  - LHC Complementarity



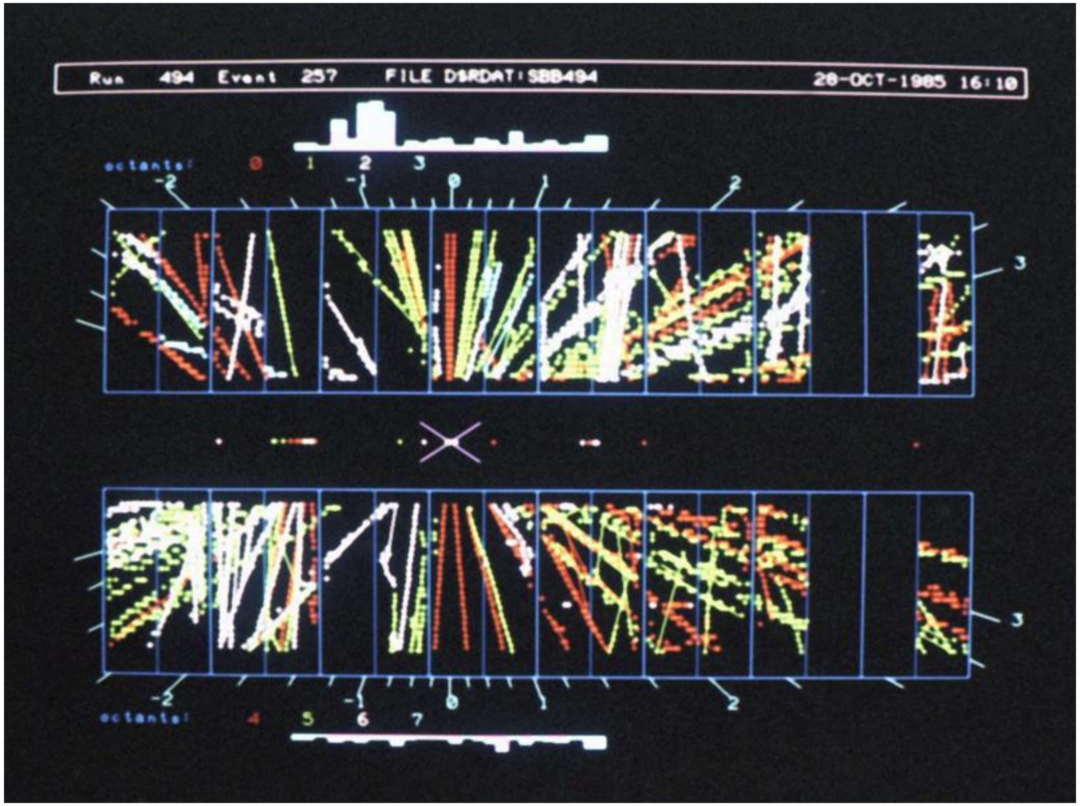
"I come to praise Tevatron, not to bury it."

Thanks to Paul Grannis, Steve Holmes, Emanuela Barberis and Young-Kee Kim for great examples of Tevatron talks

Early History

- July 1979
  - Tevatron construction authorized
- July 1982
  - CDF and Antiproton Source authorized
- July 1983
  - First accelerated beam 512 GeV
- 1984
  - D0 approved by DOE
- October 1985
  - First western hemisphere antiproton-proton collisions

October 13, 1985



Estimated Luminosity: 2×10^{25} cm^{-2}sec^{-1}

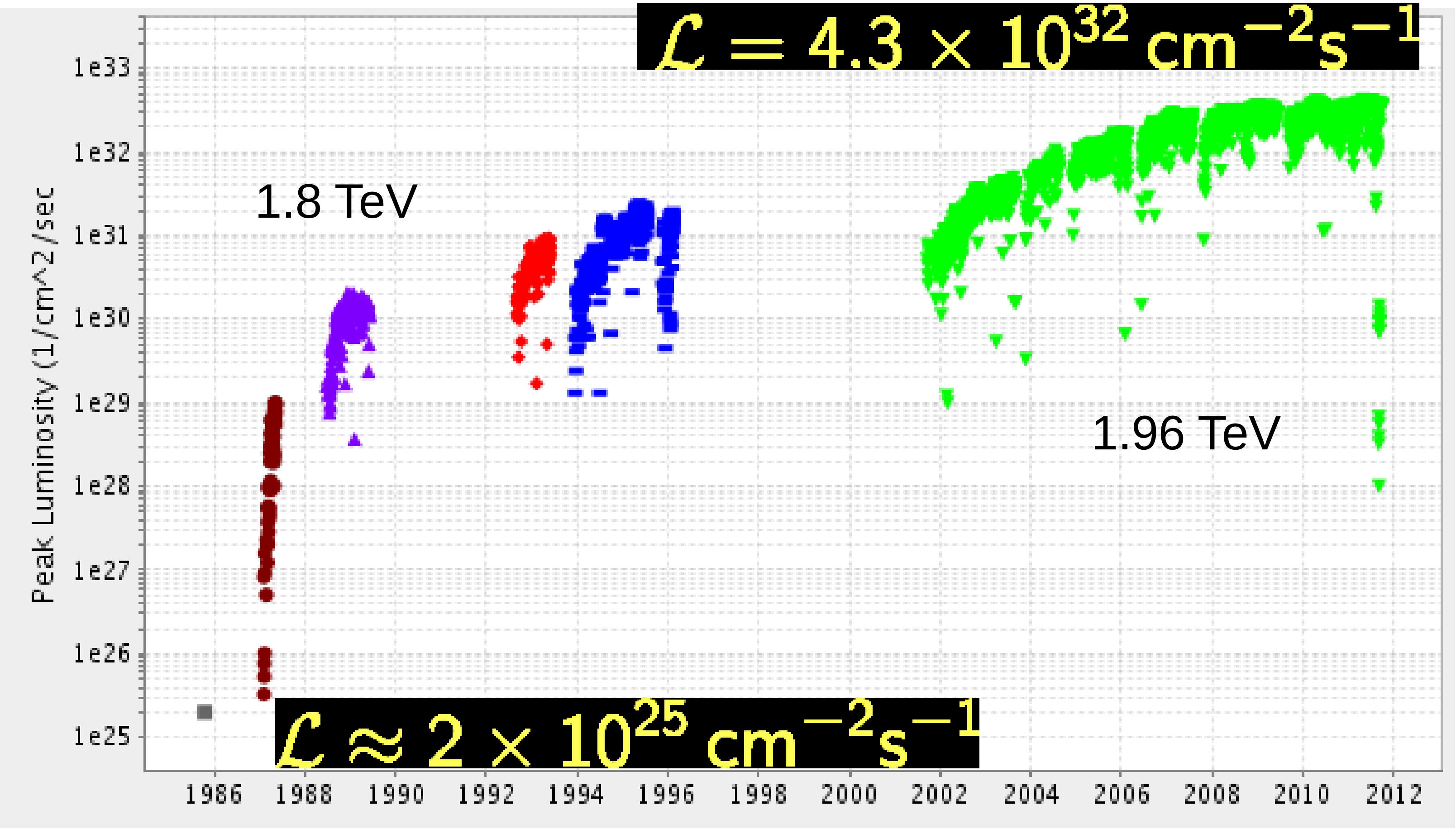
Run II - Main Injector & Recycler

Goals:

- Make antiprotons faster
- Increase antiproton storage capacity
- Deliver more protons to the Tevatron
- Eliminate CDF/DO overpasses
- Support a 120 GeV fixed target program

June, 1999

Tevatron Luminosity



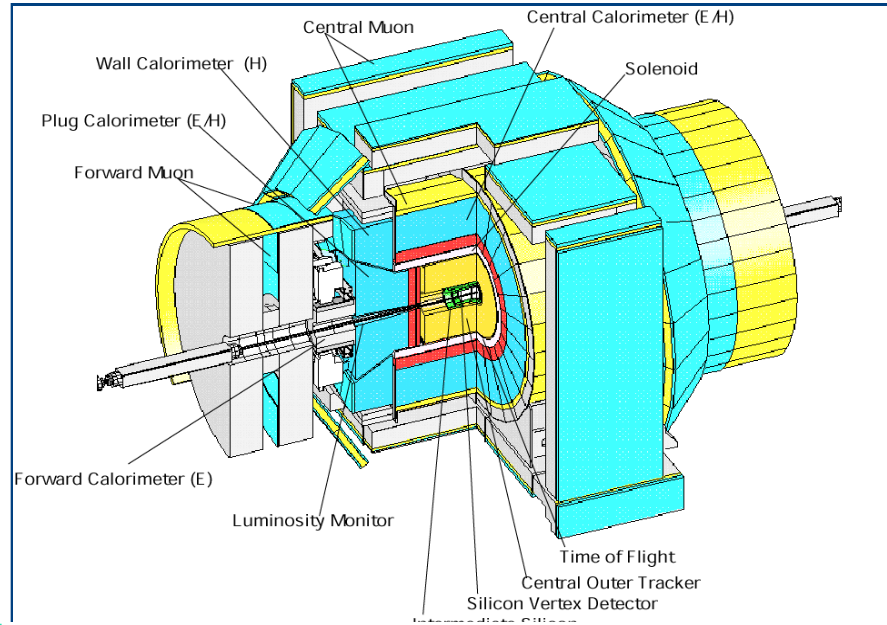
The Accelerator Legacy of the Tevatron

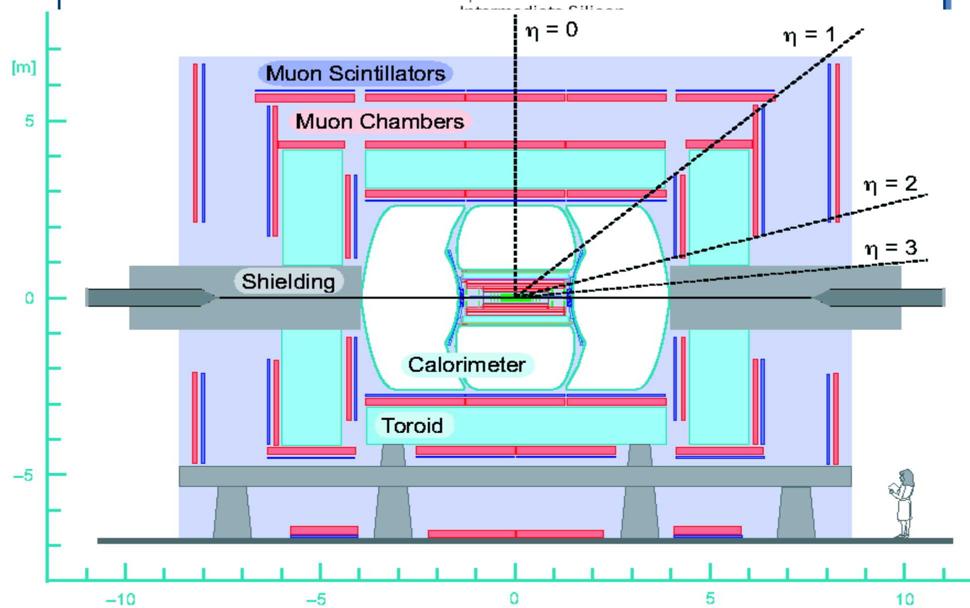
- Ultimate performance exceeded initial goal x400
  - 35% average annual growth over 20 years
- October 4, 2005
  - Tevatron surpassed ISR as highest luminosity hadron collider ever: 1.4×10^{32} cm^{-2}sec^{-1}
- April 22, 2011
  - LHC surpassed the Tevatron as highest luminosity hadron collider: 4.7×10^{32} cm^{-2}sec^{-1}
- The Tevatron remains the highest luminosity proton-antiproton collider ever operated @ 4.3×10^{32} cm^{-2}sec^{-1}

	Tev I Design	Run I	Run II	
Energy	1800	1800	1960	GeV
Protons/bunch	6×10^{10}	23×10^{10}	29×10^{10}	
Antiprotons/bunch	6×10^{10}	5.5×10^{10}	8.1×10^{10}	
Bunches	3	6	36	
Luminosity	1×10^{30}	16×10^{30}	340×10^{30}	cm^{-2}sec^{-1}
Delivered $\int Ldt$		0.18	12.0	fb^{-1}

CDF and DZero Detectors

- Innovations
  - Si vertex detectors (pioneered by CDF)
  - B-tagging
  - 4π LAr calorimeter (D0)
  - Multivariate techniques





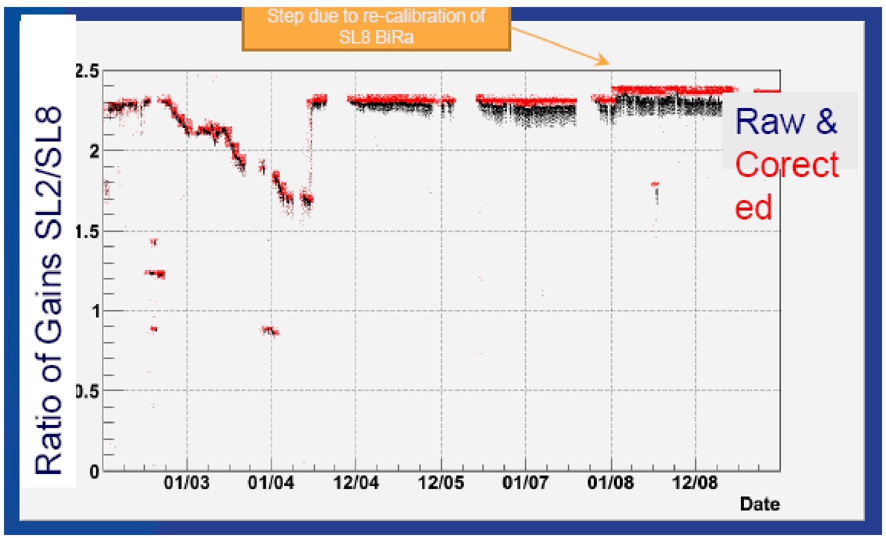
- Major upgrades 1996-2001 (between Run 1 and Run II)
  - Smaller upgrades ~2006

CDF and DZero Detectors

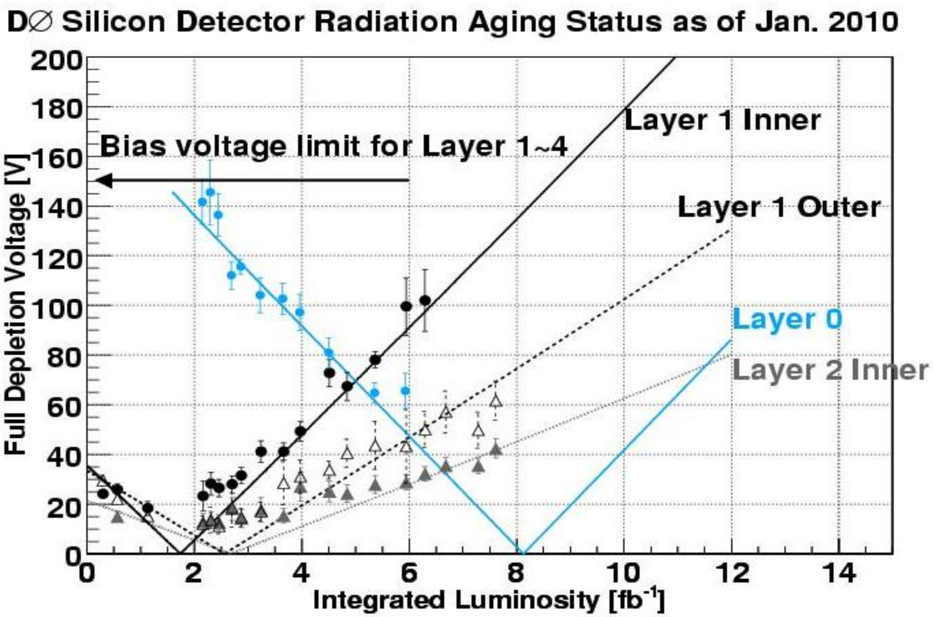
- Detectors operated stably for many years
  - Much longer than they were designed to run
- Faced challenges of extended running
- Important knowledge gained about detector ageing
  - Post-operation studies continue

Example: CDF Central Outer Tracker (drift chamber)

Example: Dzero Silicon Microstrip Detector

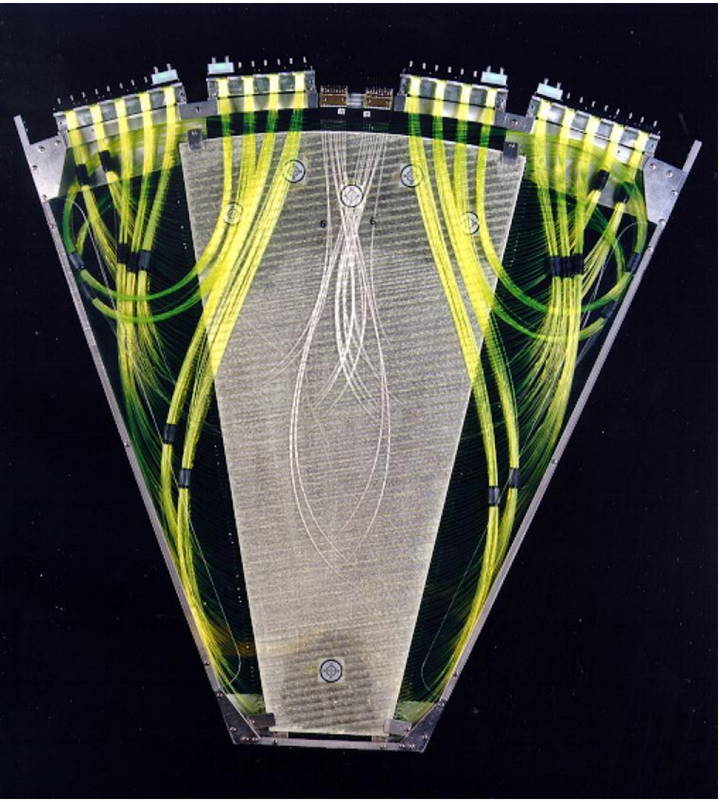


IEEE TNS 52, 2956 (2006)



Detectors as Art

CDF Run I Silicon Vertex Detector at the Smithsonian Museum, Washington



DØ Forward Preshower module at the Museum of Modern Art, New York

People

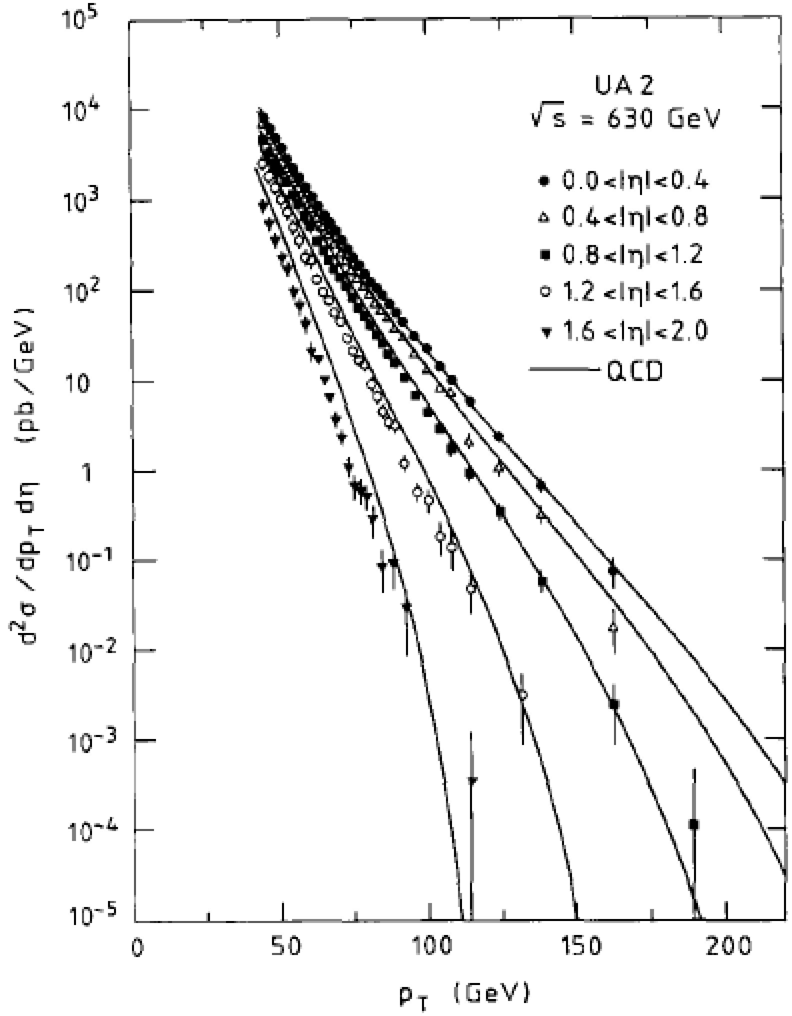
A huge part of the Tevatron impact is its influence the people who work there and who worked there in the past.

100’s of Ph.D. theses

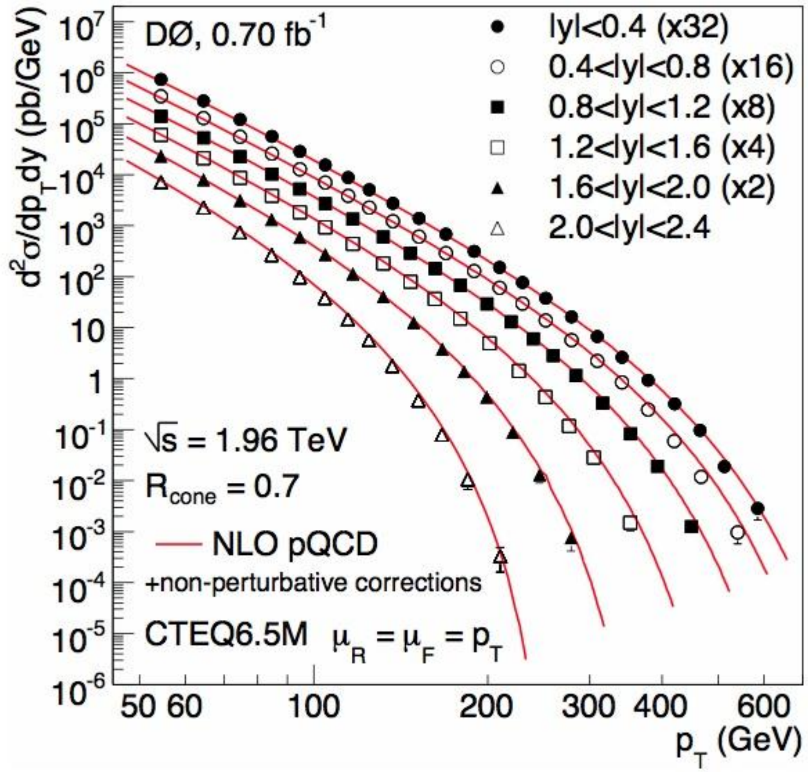
Superb training for a generation (+) of physicists

Many are now leaders in HEP (look at the list of conference chairs) or contributing in other fields (medical physics, finances, etc.)

Physics Progress Example: QCD



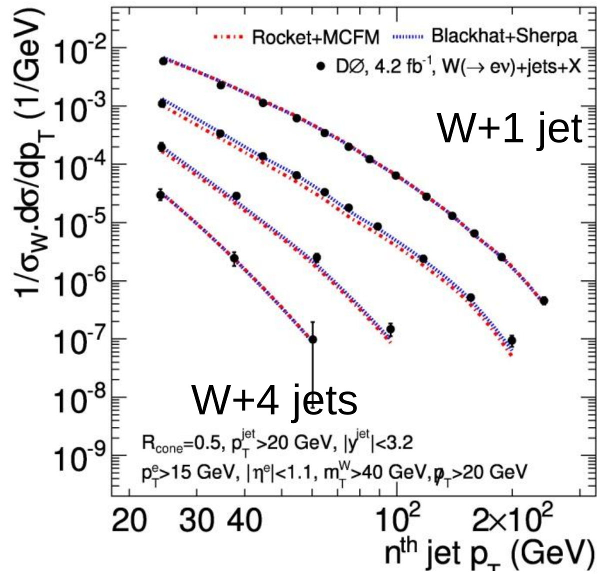
$Sp\bar{p}S$ 1990



Tevatron, 2009

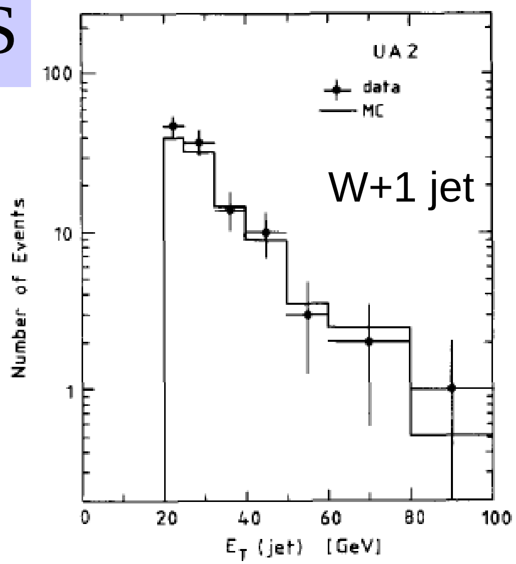
W/Z + jets

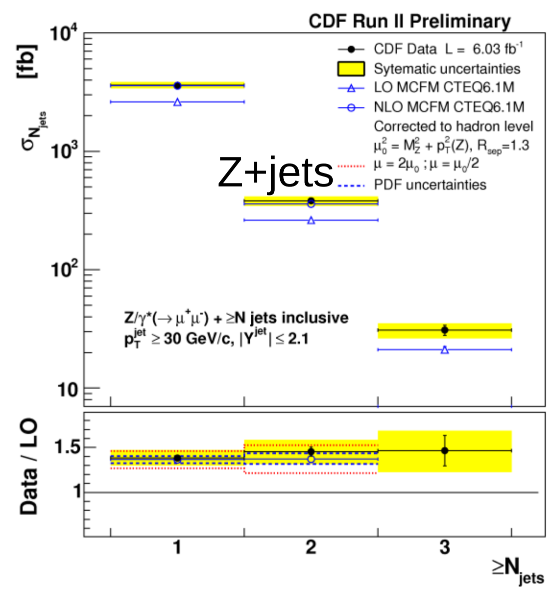
- Fruitful laboratory for studying QCD
- Major background to many important processes
  - Higgs
  - Top
  - LQ
  - …



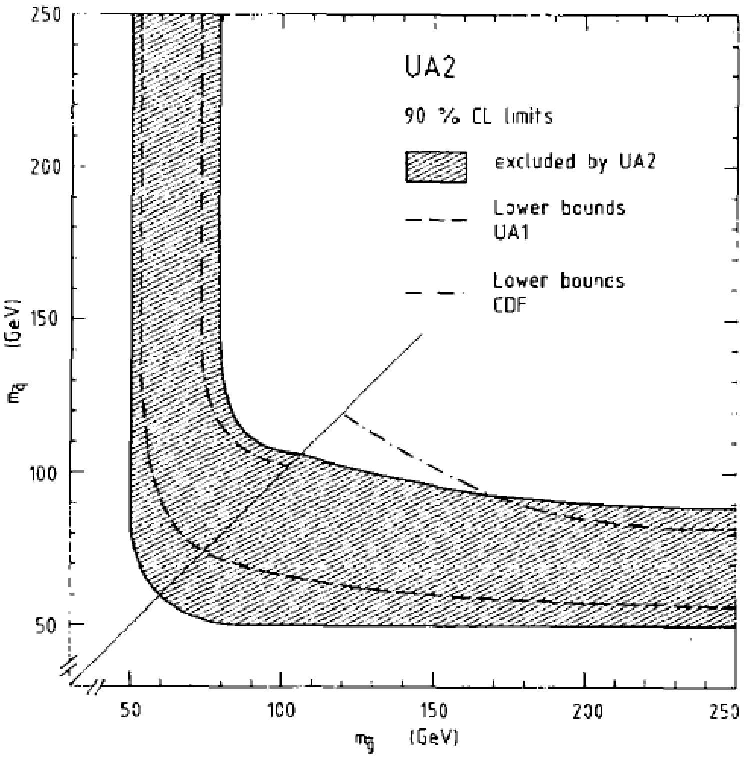
Tevatron

$Sp\bar{p}S$

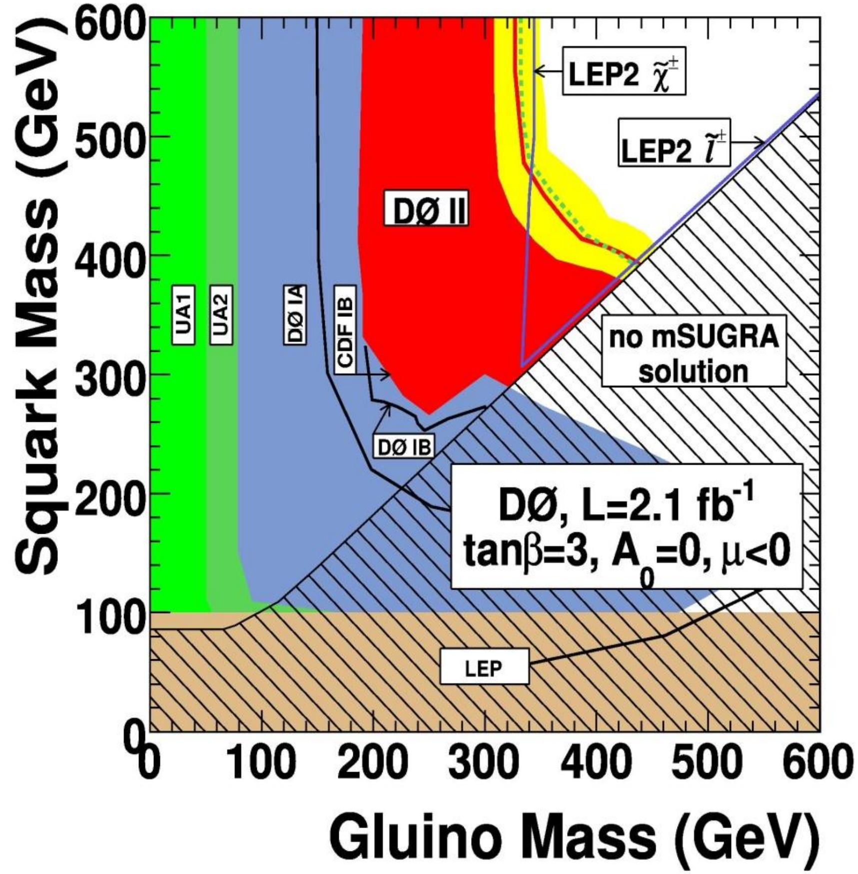




Physics progress example: squarks and gluinos



$Sp\bar{p}S$

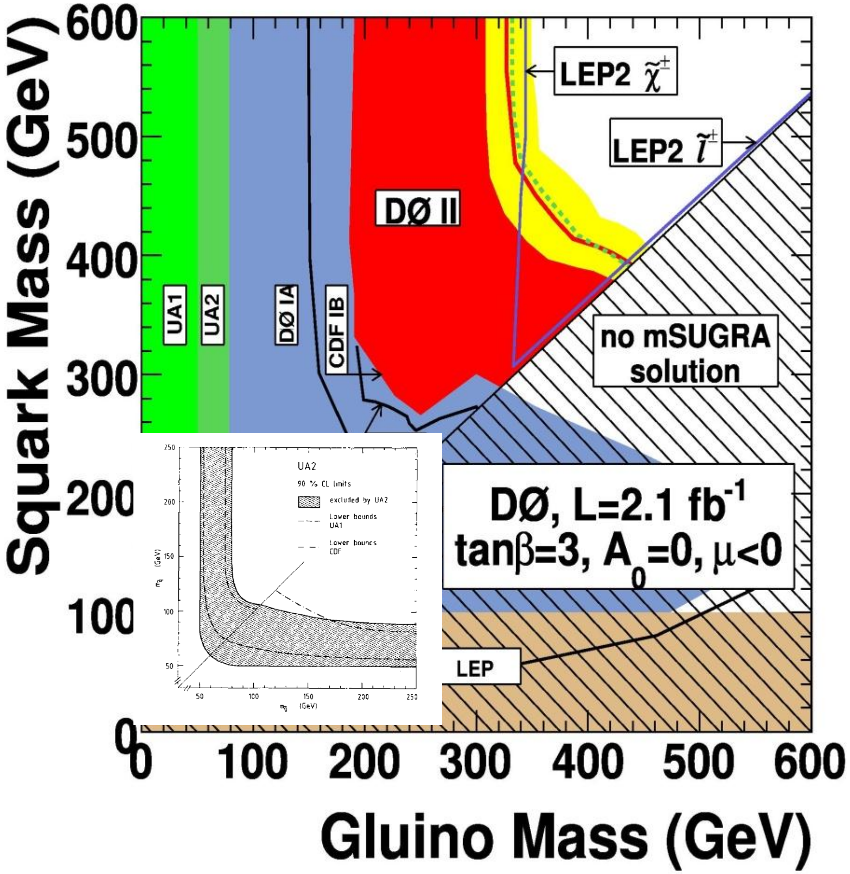


Tevatron

Supersymmetry (MSugra)
squark/ gluino search in
jets+MET

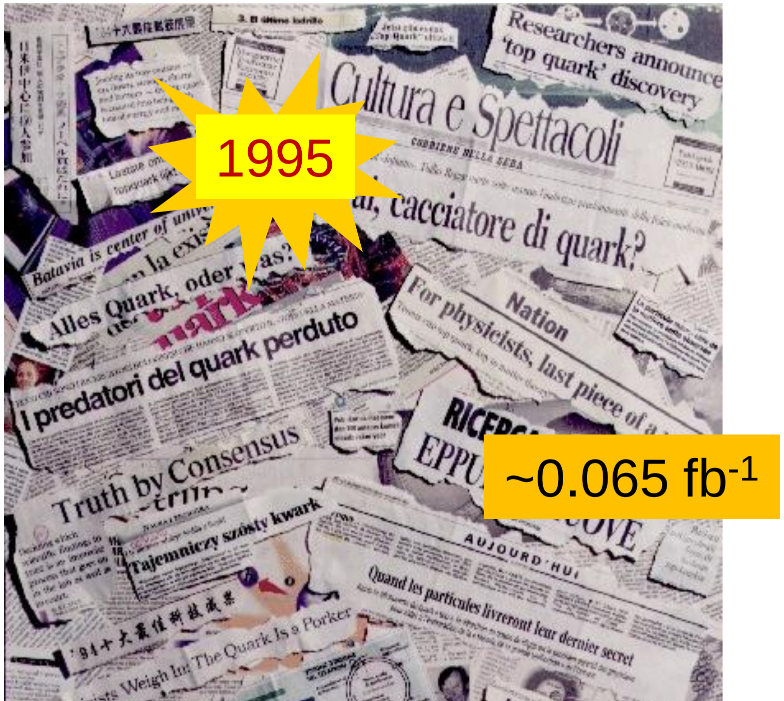
Physics progress : searches for new phenomena

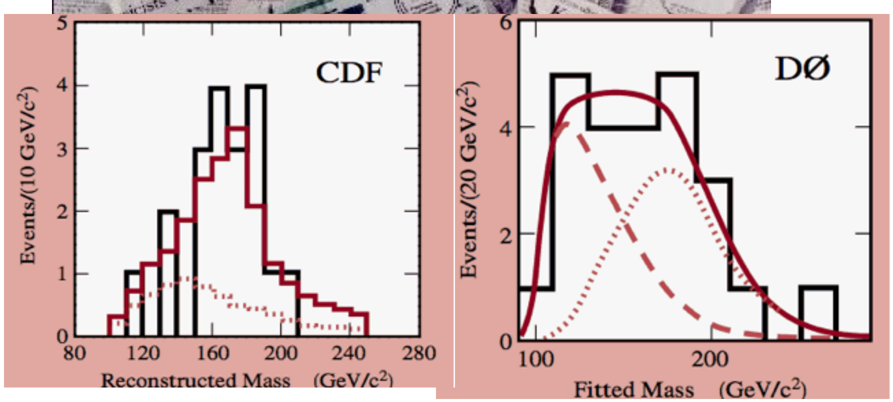
- Enormous variety of beyond the SM physics explored
  - SUSY
    - mSugra
    - Guage mediation
    - R-parity violating
    - …
  - Leptoquarks
  - Technicolor
  - Extra dimensions
  - Hidden Valley
  - Stable charged particles
  - Heavy gauge bosons
  - Excited leptons
  - …

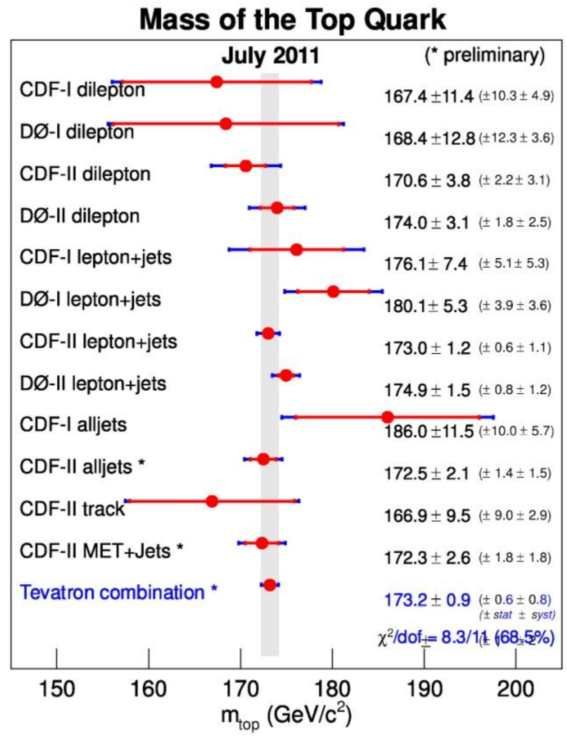


Supersymmetry (MSugra) squark/ gluino search in jets+MET

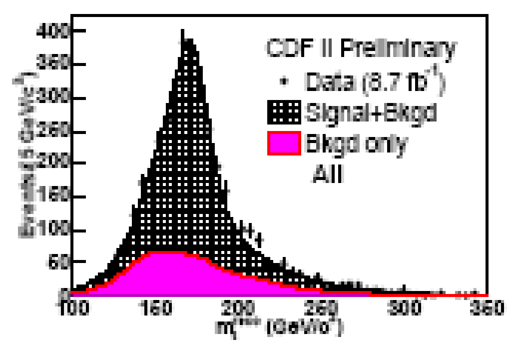
Top quark: discovery and progress



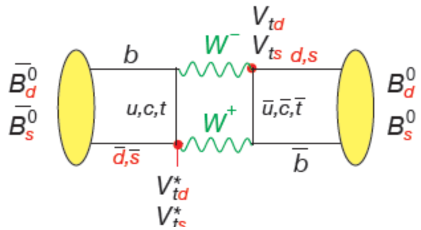




Current

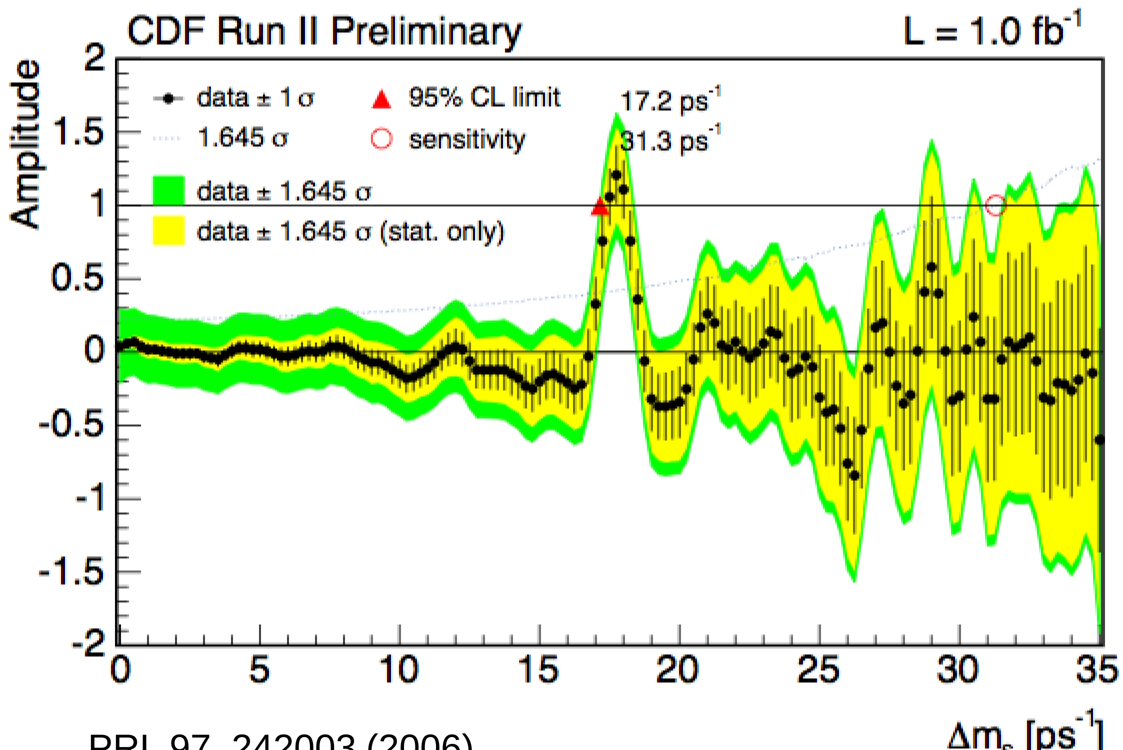


Heavy flavor physics – B_s oscillations



$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

$$\text{Prob}[\bar{B}^0](t) = \frac{1}{4}\left[\exp(-\Gamma_1 t) + \exp(-\Gamma_2 t) - 2\exp(-\Gamma t)\cos(\Delta m t)\right]$$

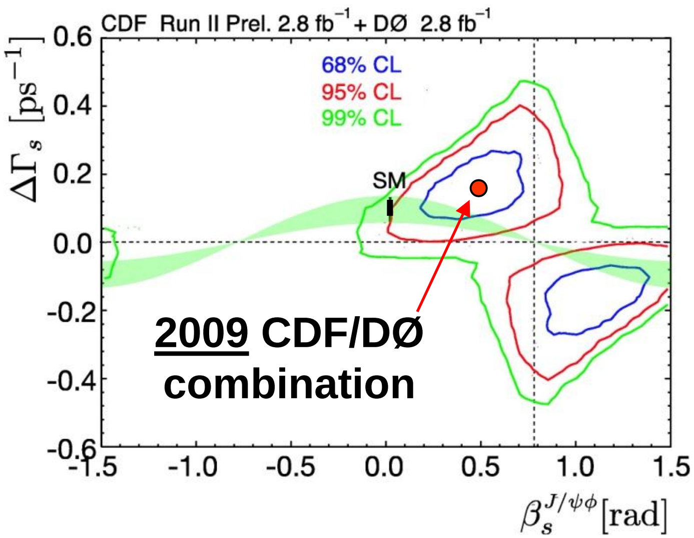


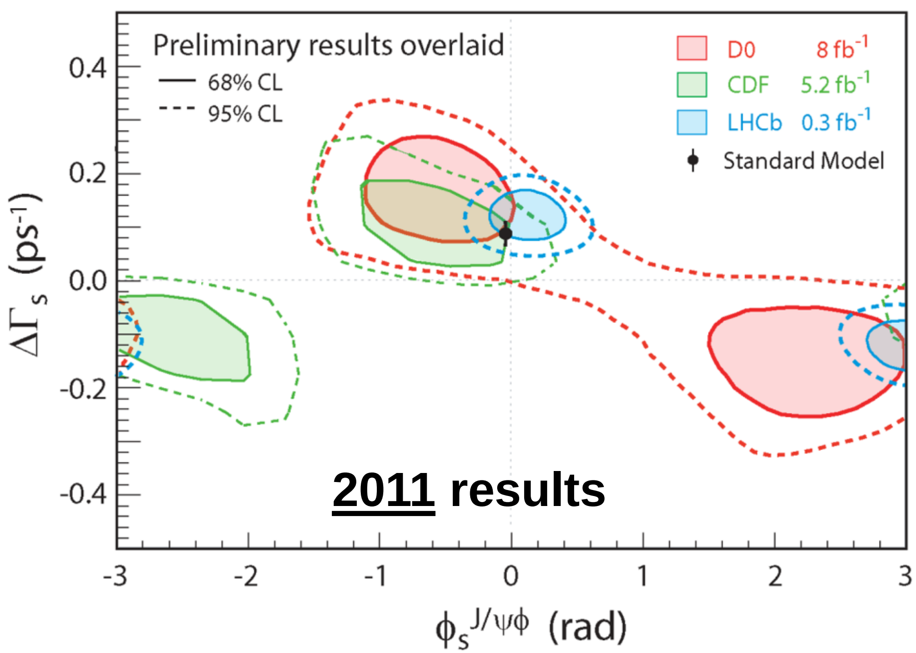
PRL 97, 242003 (2006)

2006

Heavy Flavor: CP violation in B_s decay

$$B_s^0(\bar{B}_s^0) \rightarrow J/\psi\phi$$

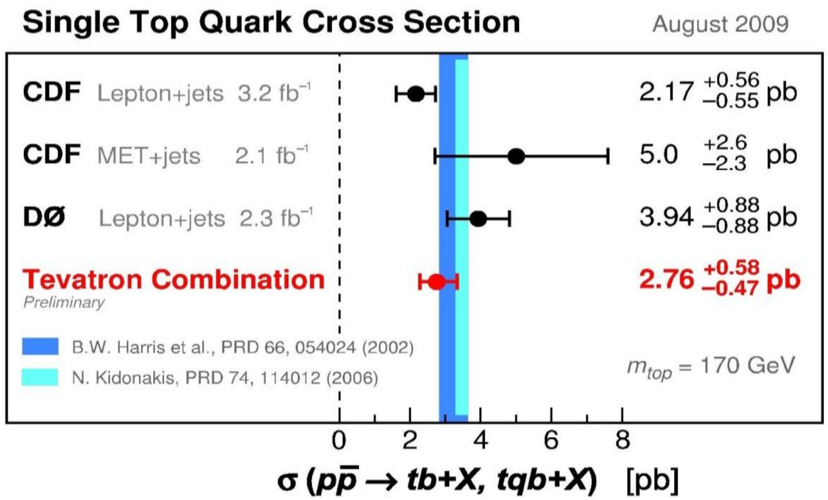


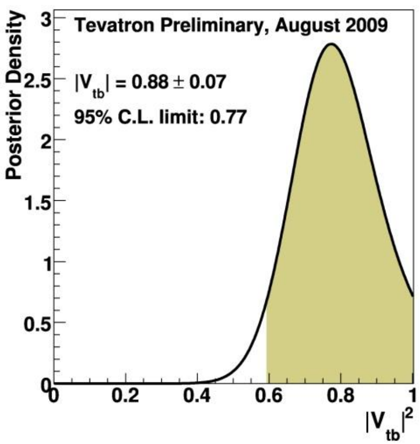


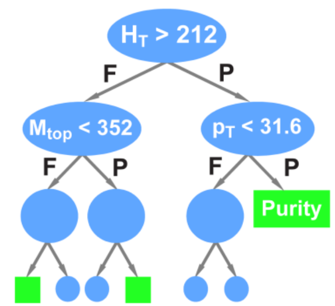
$(\phi_s^{J/\psi} = -2\beta_s^{SM} + \phi_s^{NP})$

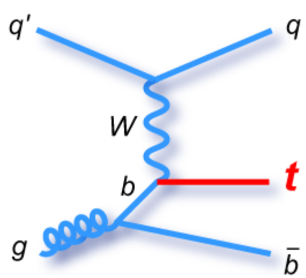
Single top and V_{tb}

2009

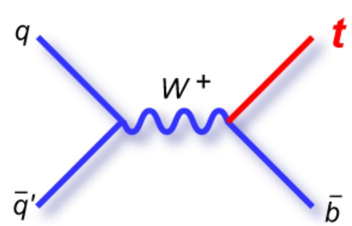




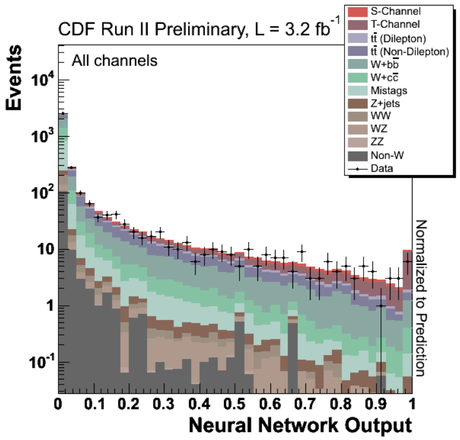




t-channel

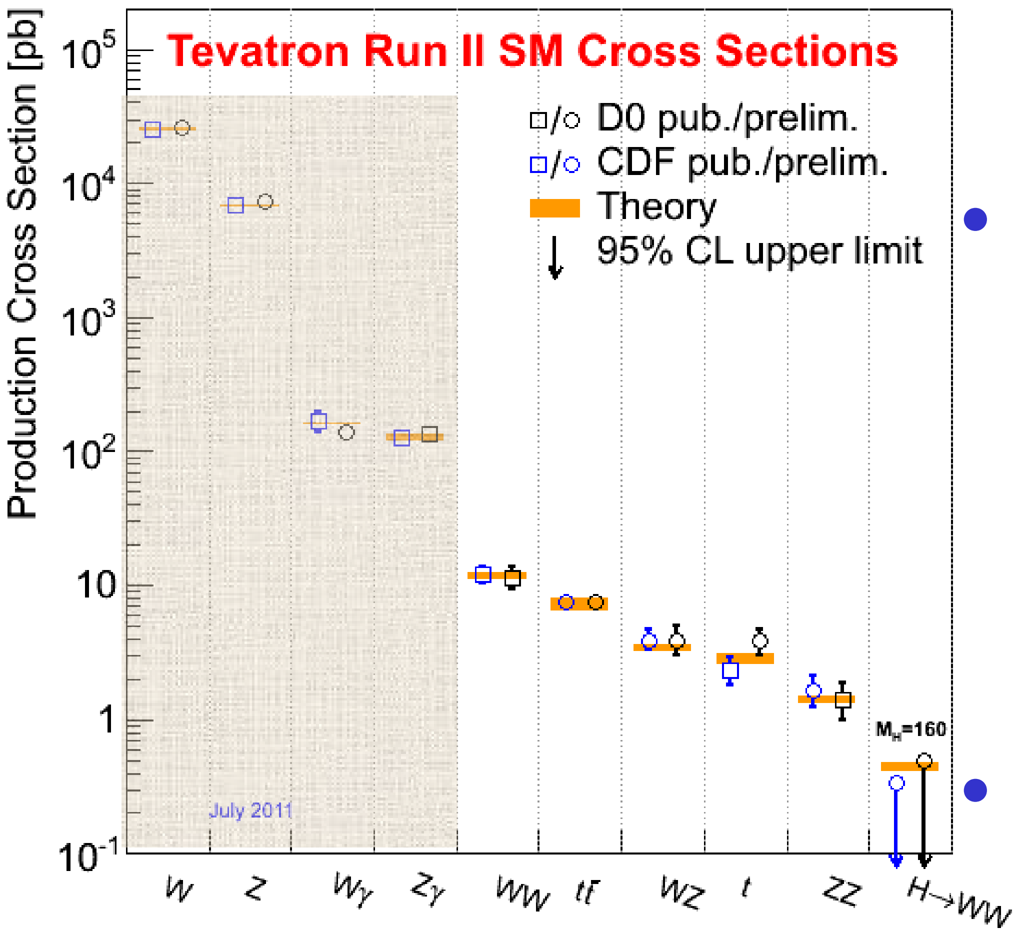


s-channel



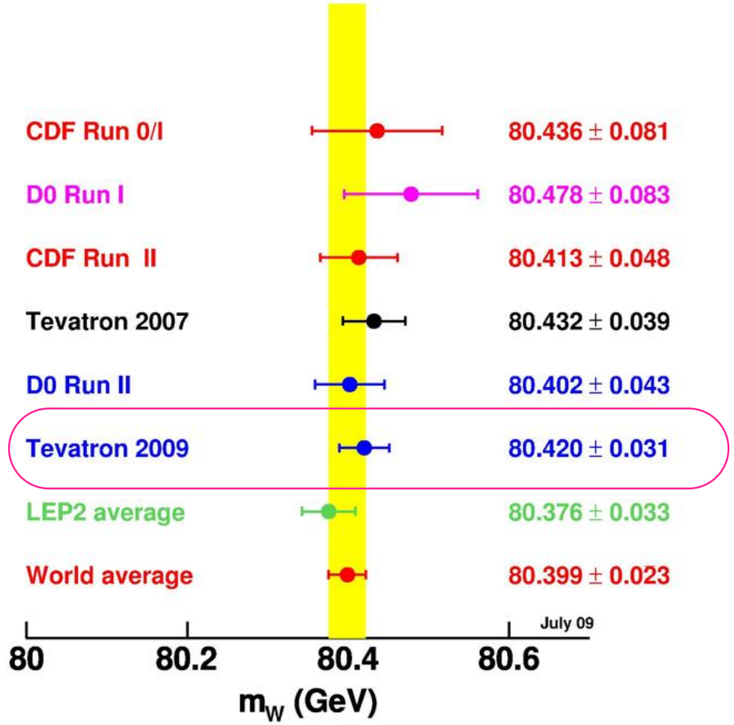
- Observation of EW production of single top quarks was one of the major goal of Run II
  - Achieved by CDF and D0 in 2009
  - Allows measurement of CKM element $|V_{tb}|$
  - Pioneering use of multivariate techniques

Electroweak Physics: Diboson production

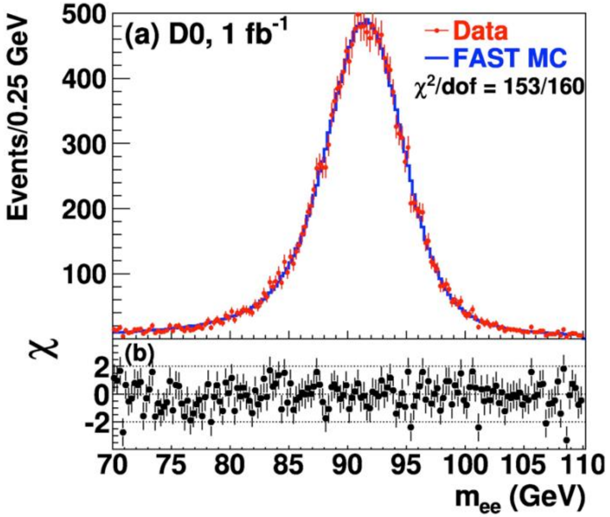


- Previously observed at the $S p\bar{p} S$:
  - W, Z, Wγ, Zγ (in leptonic modes)
- First observed at the Tevatron
  - WW, WZ, ZZ
  - Modes with jets: WW/WZ→ℓνjj
  - Modes with neutrinos: Zγ→ν ν γ
- Necessary predecessor to Higgs exclusion or discovery

Future Legacy: W mass

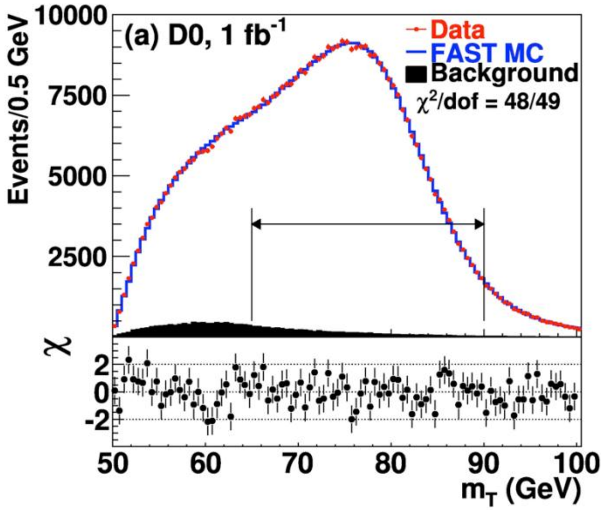


calibration



~18k events in 1 fb^{-1}

signal



~485k events in 1 fb^{-1}

PRL 103, 141801 (2009)

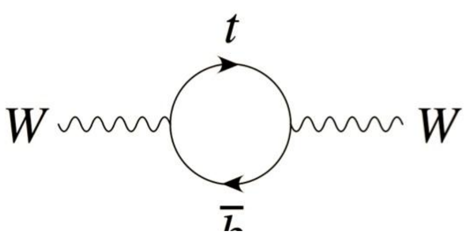
current Tevatron precision: 0.04%

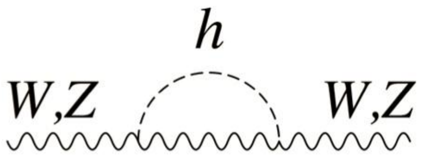
-Slightly better than LEP2

- Expect new results with larger data sets soon from both CDF and D0

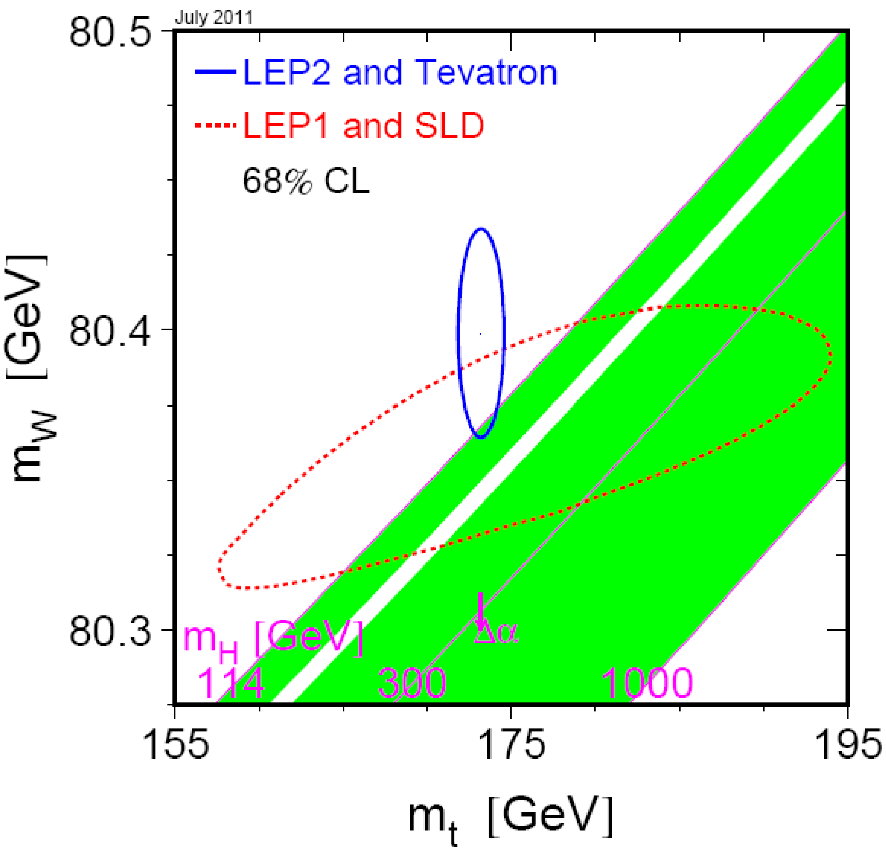
- Will probably stand as most precise W mass for some time to come

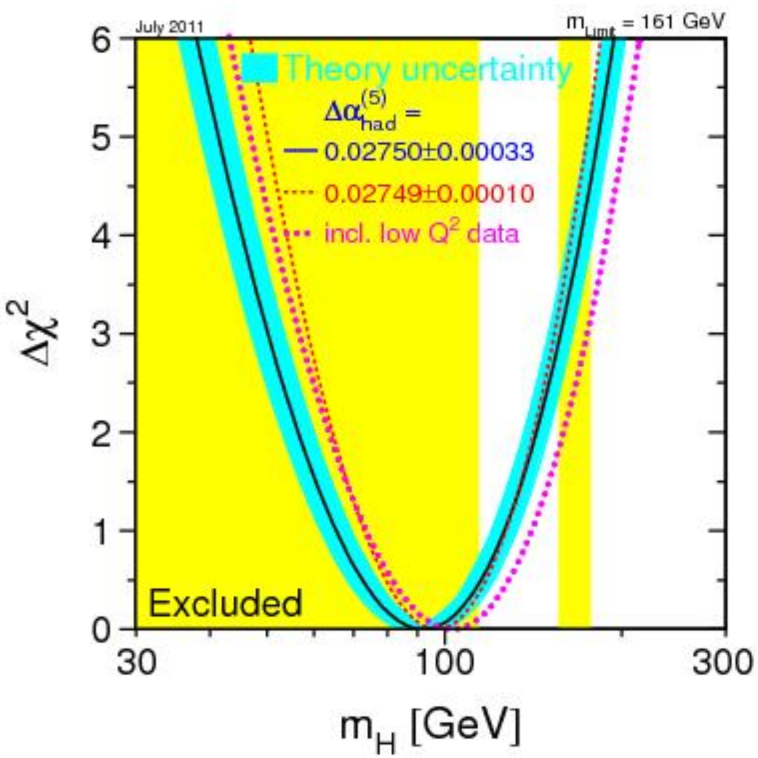
Self-consistency of the SM





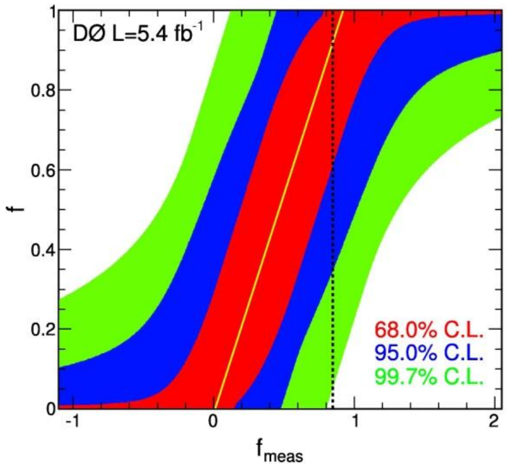
Current





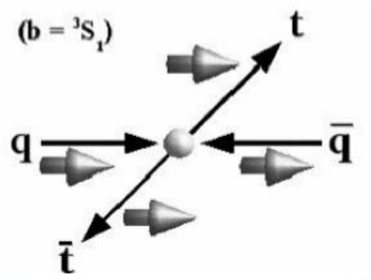
Complementary: Tevatron is a proton-antiproton collider

Example: spin correlations in t-tbar production

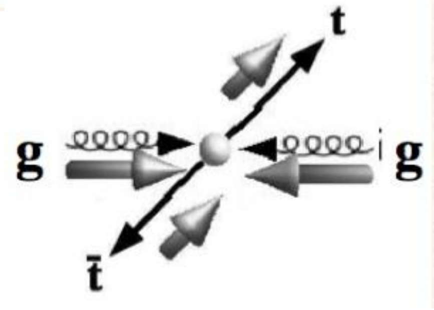


PRL 108, 032004 (2012)

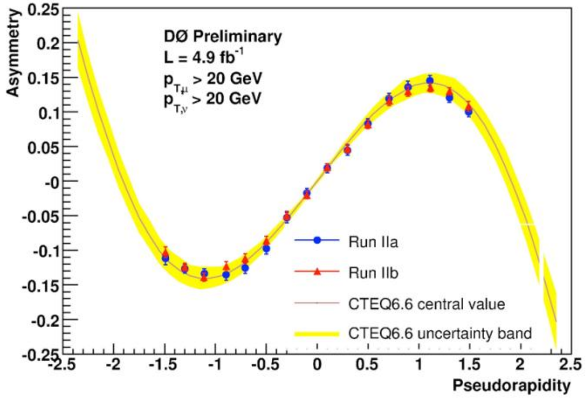
Tevatron

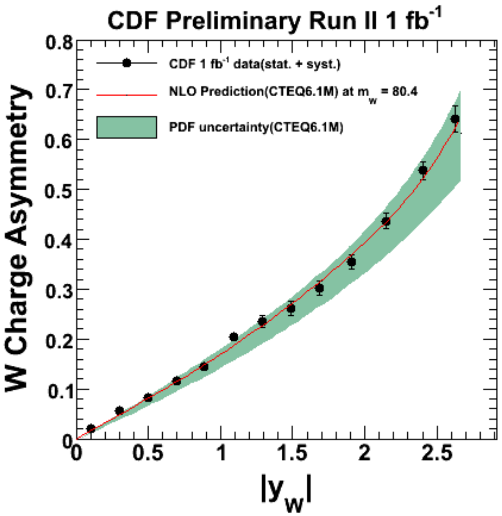


LHC



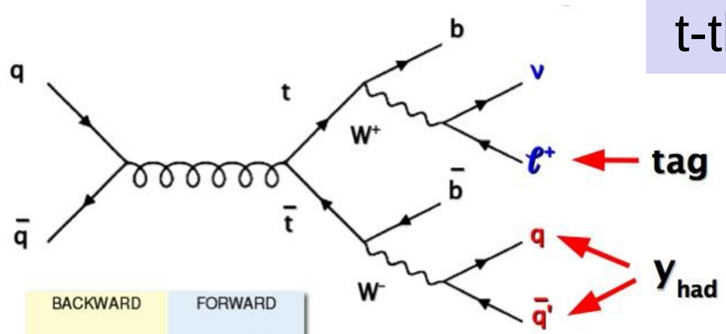
Example: W→ℓν asymmetry:

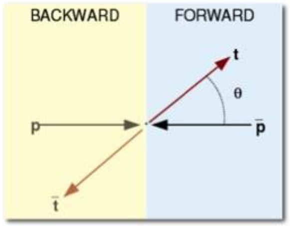




More proton-antiproton features

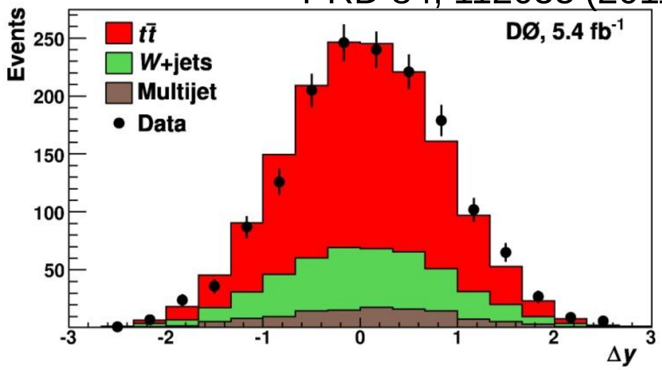
t-tbar asymmetry:

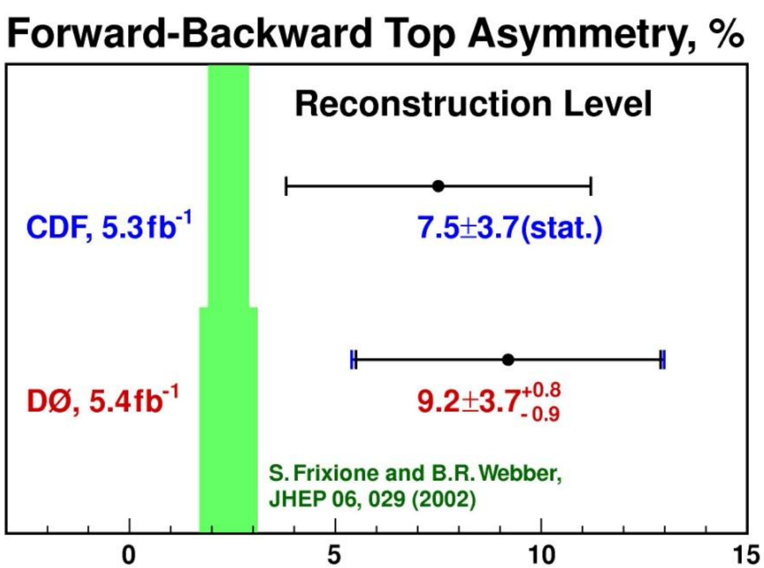




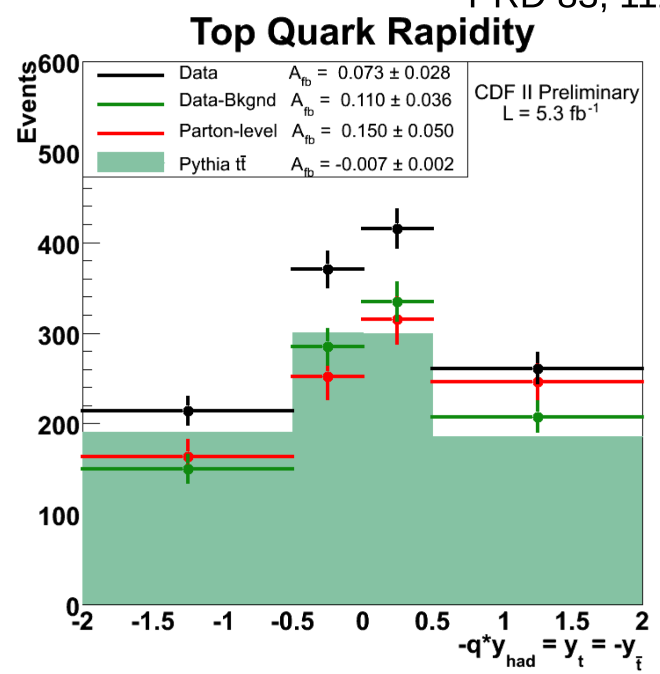
$$A_{fb} = \frac{F - B}{F + B}$$

PRD 84, 112055 (2011)

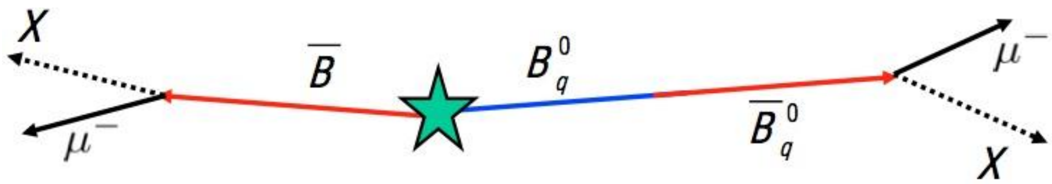




PRD 83, 112003 (2011)



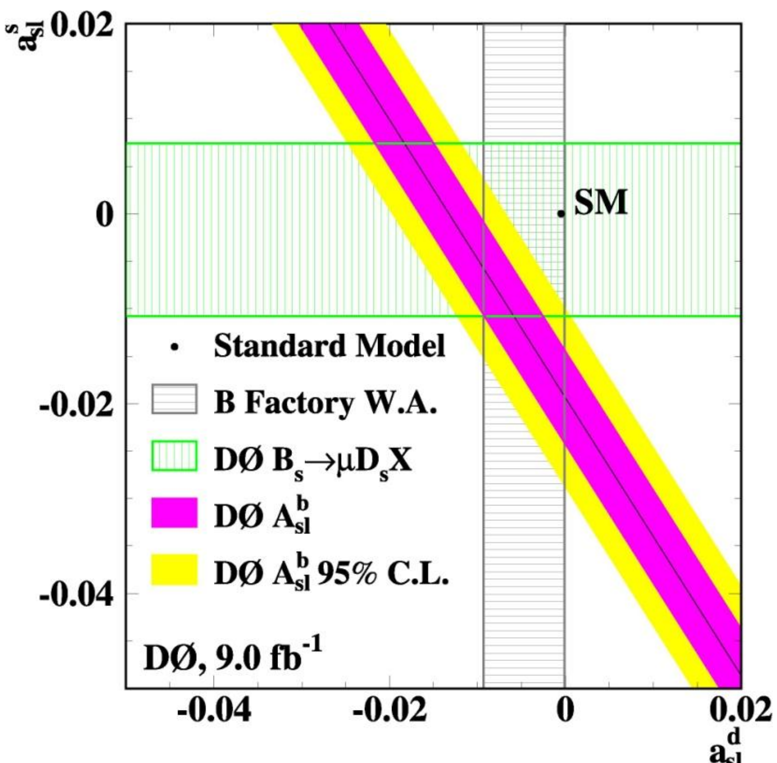
Complementary: Di-muon Asymmetry



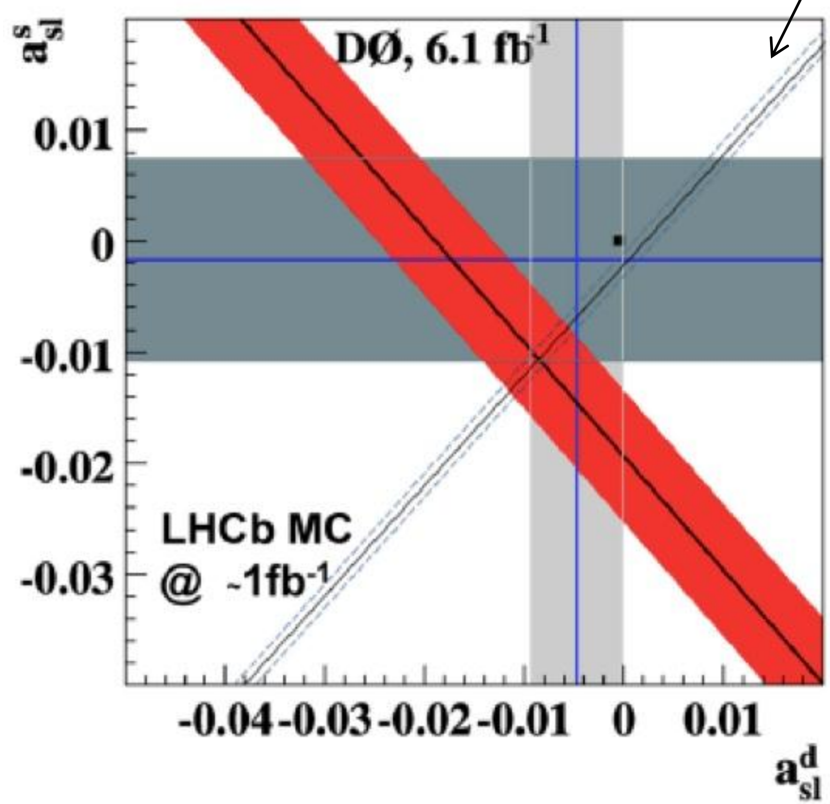
$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

N_b^{++} (N_b^{--}) – number of same-sign $\mu^+\mu^+$ ($\mu^-\mu^-$) events from $B \to \mu X$ decay

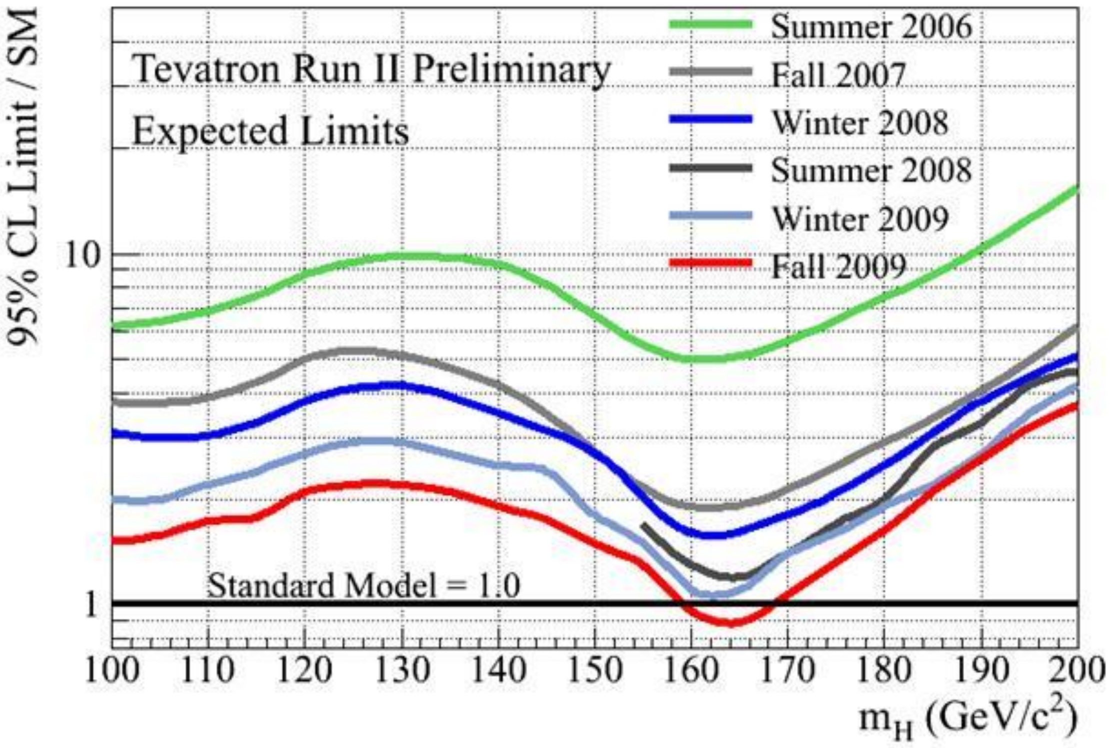
Sensitivity studies from LHCb semileptonic decays:
$B_{s,d} \to D\mu\nu$



PRD **84**, 052007 (2011)



SM Higgs Search: Historic Progress

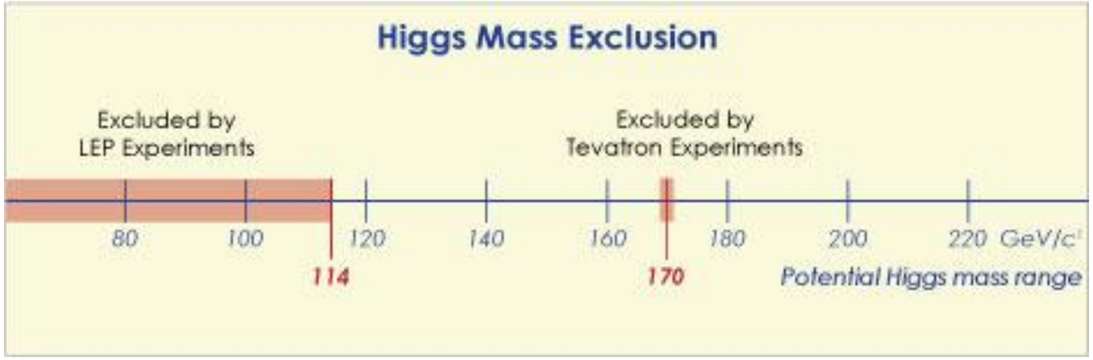


- Expected limits are the measure of experimental sensitivity

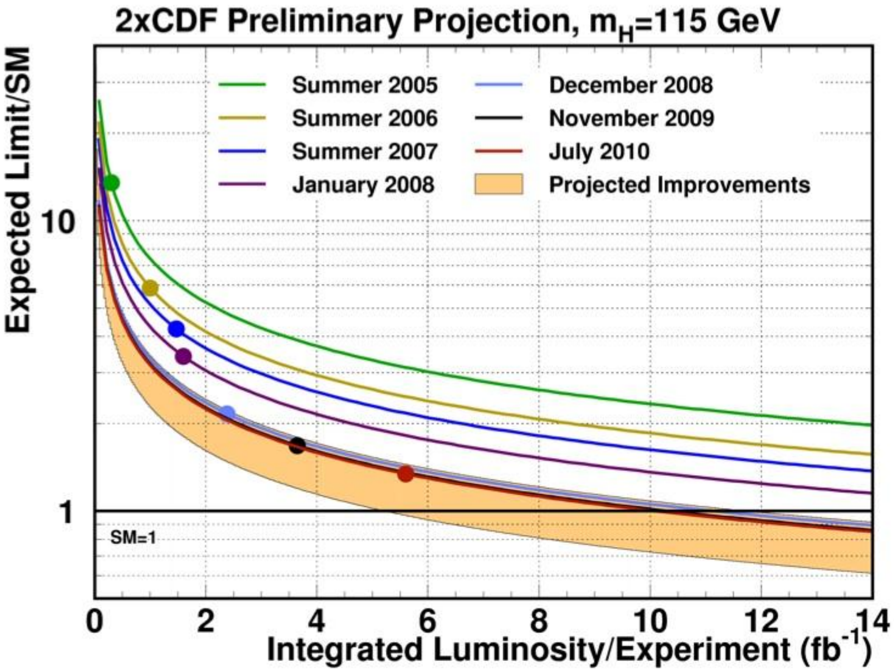
-– See talks from T. Yasuda and A. Safonov for current limits

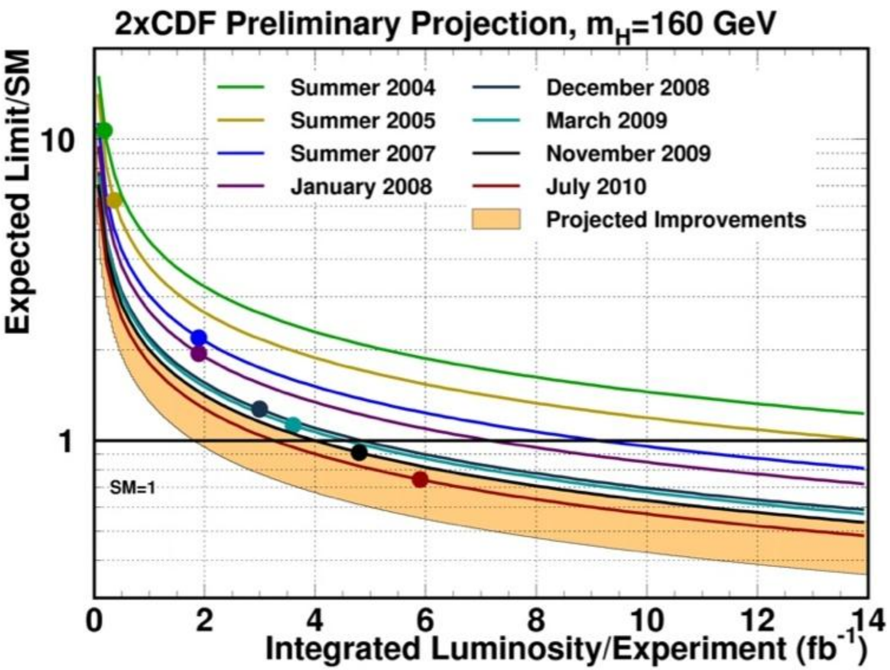
-Milestone: 2008

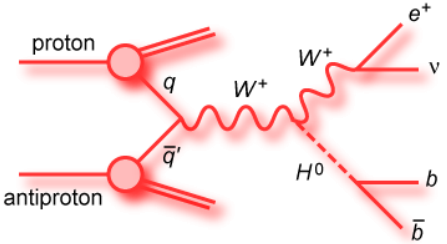
-First direct mass exclusion since LEP

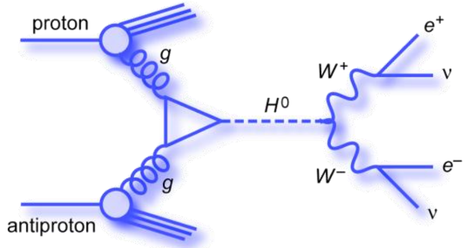


Improvements



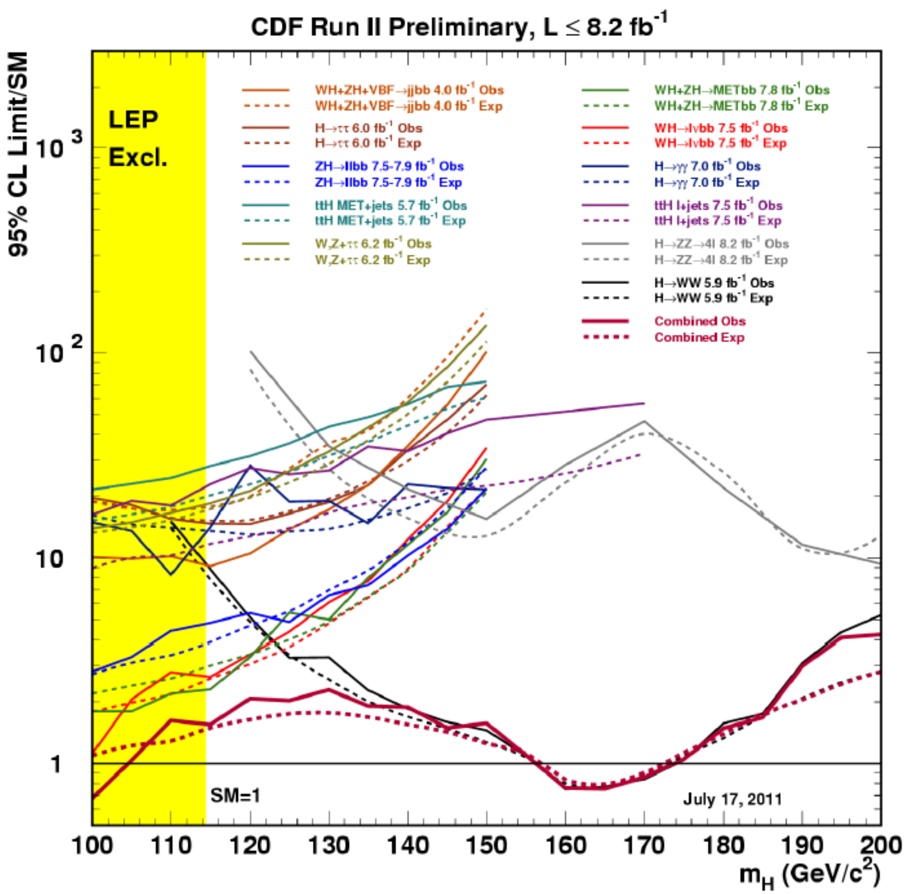


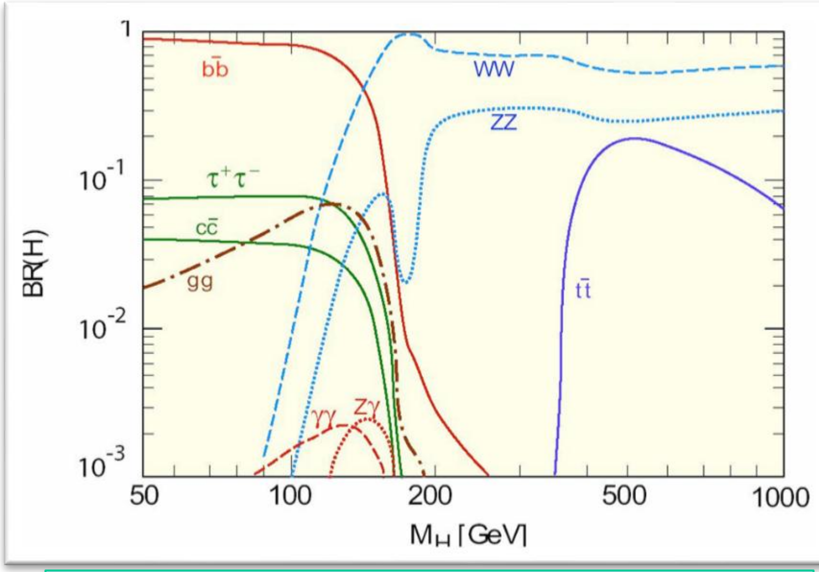




Beyond discovery: probing the Nature of the SM Higgs

Low mass Higgs search at the Tevatron relies on WH→ℓνbb, ZH→ννbb and H→WW





Low mass Higgs search at the LHC relies on H→γγ, H→ZZ and H→ττ

To understand EWSB, one wants direct evidence of Higgs decays into b jets

Complementary

Conclusion

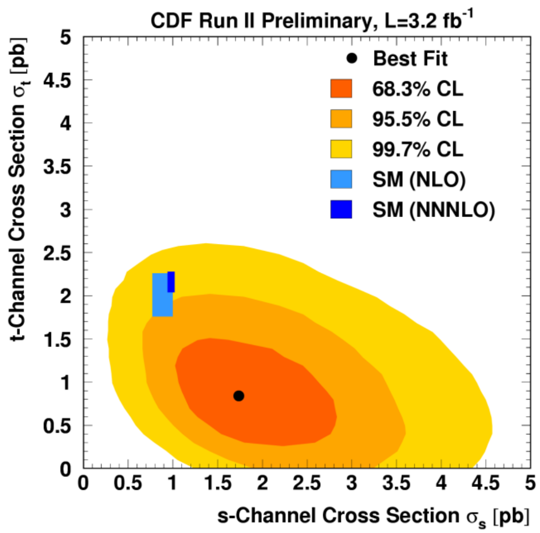
- The Tevatron operations ended in September, which inspires some reflection
  - Incredible 28-year history
  - In intensity the machine exceeded its original design goals by a factor of 400
  - Predecessor to both Hera proton ring and the LHC
- Amazing physics journey
  - Discovery of the top quark at a surprisingly large mass
  - Bs mixing and many b results
    - Previous conventional wisdom was that this was province of e+e- colliders
  - Tour-de-force of jets and W/Z + jets measurements
  - Exclusion of high-mass Higgs
    - Again defying conventional wisdom
- Detectors lasted much longer than anticipated
  - People too

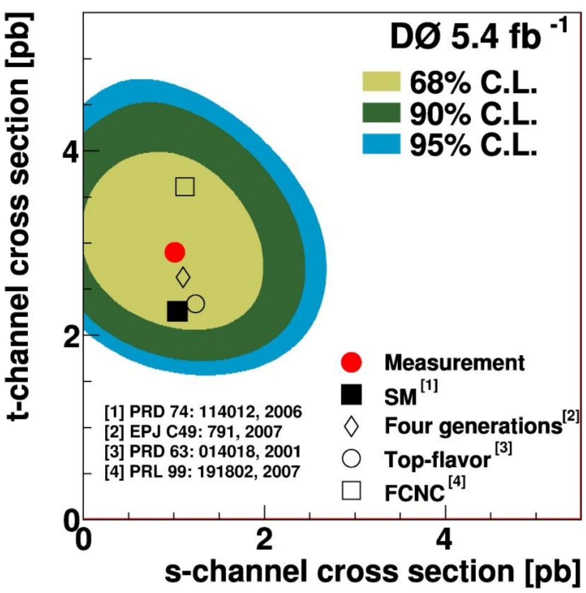
More to come

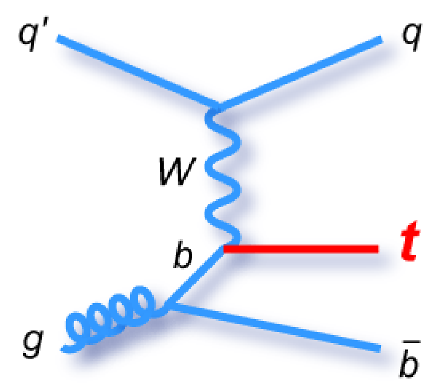
- The Tevatron Legacy is still being written as the last data are analyzed
- Tevatron talks this week
  - Today
    - Top Cross sections – Q. Liu
    - Top Properties – E. Varnes
    - Electroweak – B. Quinn
  - Monday
    - Heavy Flavor – M. Rescigno
  - Tuesday
    - QCD – A. Mazzacane
    - Higgs (CDF) – A. Safonov
    - Higgs (D0) – T. Yasuda
  - Wednesday
    - BSM searches – I. Katsanos

BACKUP SLIDES

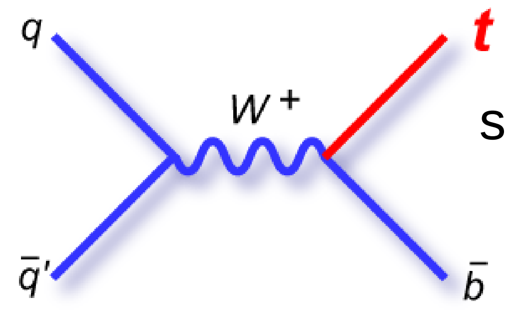
Complementary/Legacy: Single top (s-channel)







t-channel



s-channel

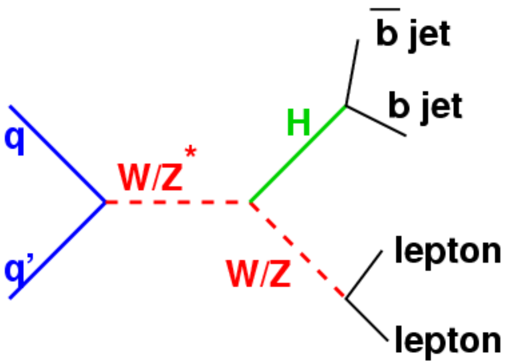
LHC estimation: 10-30 fb-1 at $\sqrt{s}$=14 TeV for 3-sigma excess in s-channel

SM Higgs search at the Tevatron

Low mass (m_H <~135 GeV):
dominant decay:

$$H \rightarrow b\bar{b}$$

Use associated production modes to get better signal/background



$$q\bar{q}' \rightarrow WH \rightarrow \ell \nu b\bar{b}$$

$$q\bar{q} \rightarrow ZH \rightarrow \ell^+\ell^- b\bar{b}$$

$$q\bar{q} \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}$$

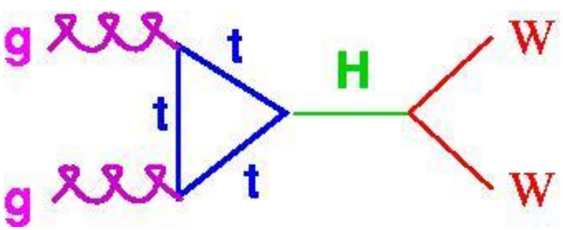
Intermediate mass:

$$q\bar{q} \rightarrow WH \rightarrow WWW^{(*)}$$

$$gg \rightarrow H \rightarrow \gamma\gamma$$

High mass (m_H>~135 GeV):
dominant decay:

$$H \rightarrow WW^{(*)}$$

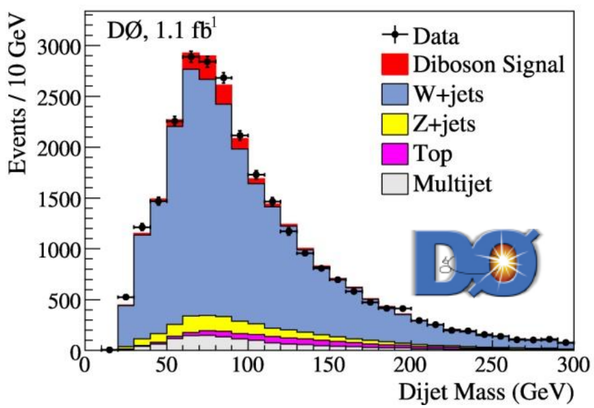


$$gg \rightarrow H \rightarrow WW \rightarrow \ell \nu \ell' \nu'$$

WW/WZ(→lνjj) production

Evidence for WW/WZ→lνjj (at 4.2σ)

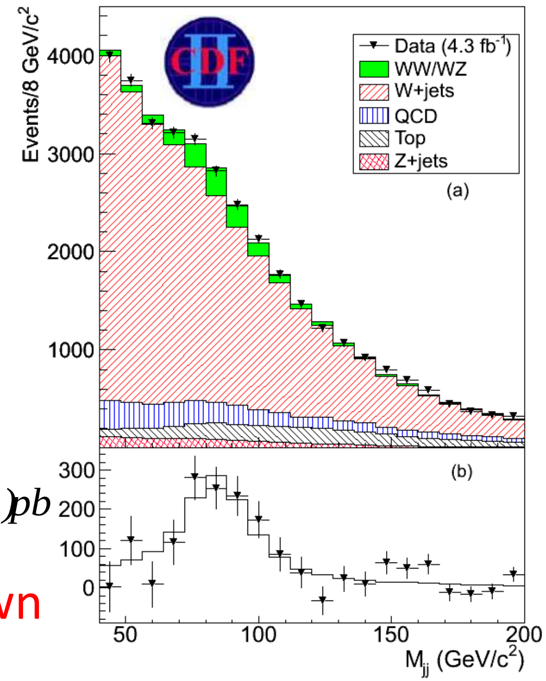
$\sigma(WV) = 20.2 \pm 4.5$ pb ***Phys. Rev. Lett. 102 (2009)***



Measurement of WW/WZ→lνjj (at 5.2σ)

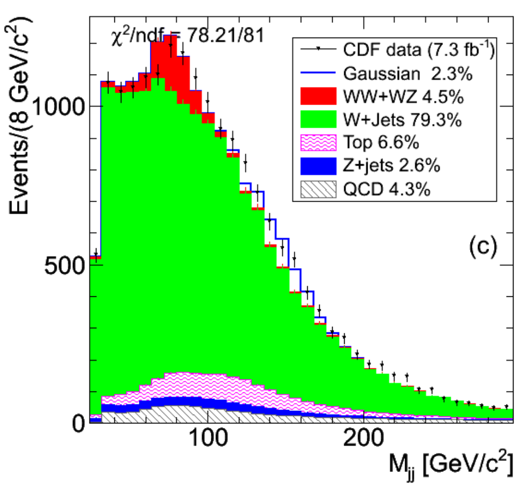
Phys. Rev. Lett. 104 (2010)

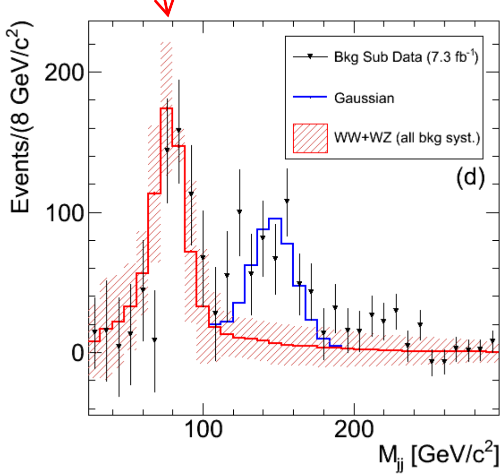
$\sigma(WV) = 18.1 \pm 3.3(stat.) \pm 2.5(syst.)$ pb



CDF measures an excess in the di-jet mass, shown here for 7.3 fb^{-1} (at 4.1s), not observed by DØ

Phys. Rev. Lett. 106 (2011)





Phys. Rev. Lett. 107 (2011)