The Motivation for two Independent Experiments at a Collider

Hugh Montgomery
Jefferson Lab

Abstract/Outline

It is generally accepted that it is preferable to build two general purpose detectors at any given collider facility. We reinforce this sentiment by discussing a number of aspects and particular instances in which this has been particularly important. The examples are taken mainly, but not exclusively, from experience at the Tevatron collider.

- Introduction
- The Historical Norm
- CDF and DØ
- ATLAS and CMS
- Summary

Acknowledgements

I benefited from suggestions and comments from Paul Grannis and Dima Denisov.

I also leaned heavily on a recent review paper, *Tevatron Greatest Hits* [hep-ex > arXiv:2210.13565] by Dima Denisov and Costas Vellidis.

My apologies for any perceived implications that any one experiment was inferior to another, that was not the thrust of the talk.

I would like to thank the organizers for giving me the opportunity to re-explore this subject.

Introduction

- The Electron Ion Collider is approaching the review (CD2) which will determine the project baseline.
  - Currently the baseline project includes a single intersection region and partial scope of a single detector.

- The Detector Advisory Panel was positive with respect to the need for a second detector.

- Informal statements from DOE, while nominally supporting the concept of a second intersection region and detector, have emphasized the priority that the field should give to the resources needed for the 1st Detector.

- In this talk I will give a personal view of the importance of having more than one detector based on episodes from the past 30 years.

The Historical Norm

- For most of the “fixed target” era of particle physics, an individual experiment did not constitute a significant fraction of the accelerator investment, so individual experiments cross checked and competed with each other. For Colliders, the individual experiments were relatively more costly
- The Convention: More than one general purpose experiment per Collider
  - The SppbarS Experiments UA1, UA2
  - SLC (Mark II/SLD), LEP(Aleph, Delphi, L3, Opal)
    - ALEPH 4 jet peak (mass ~106 GeV) not confirmed, never killed, just quietly dismissed by CERN Courier
  - Tevatron Experiments: CDF, DØ
  - [SSC Experiments: GEM, SDC]
  - HERA Experiments: H1, ZEUS
  - RHIC Experiments: PHENIX, STAR
  - B Factory Experiments: BaBar(PEPII), Belle(KEKB)
  - LHC Experiments: ATLAS, CMS
- Some Exceptions
  - Belle II
  - ALICE
  - LHCb

The Tevatron

- The Tevatron machine
  - FNAL Main Ring, conventional magnets… 400 – 450 GeV
  - Tevatron 900 (980) GeV, p-pbar Collider 1800 GeV (1960 GeV)
- Tevatron was 3rd Hadron Collider after ISR, SppbarS
  - Lessons learned from ISR (in particular 4π detectors needed)
  - Lessons learned at electron colliders, especially PETRA and PEP

- CDF History
  - Thinking started in ~1978
  - Conceived ~1980-82
  - 1st collisions, 1985, 1st physics 1987 – 89
  - Upgrade(s) → 1992
  - Upgrade → 1996 – 2001 Operated to 2011

- DØ History
  - Precursor proposals 1981-83, all rejected
  - DØ Conceived ~ 1983-84 [Grannis invited to pull together a proposal]
  - 1st physics 1992
  - Upgrade → 1996 -2001 Operated to 2011

Initial Tevatron Detector Designs

CDF Initial Design

- Large Solenoid
- Large radius tracking chambers
- Lead Scintillator, Iron Scintillator barrel wedge calorimetry
- Central Detector coverage to η = 1.0
- Muon Detection in multiple partial systems
- Main Ring Beam Overpass made background in top muon detectors

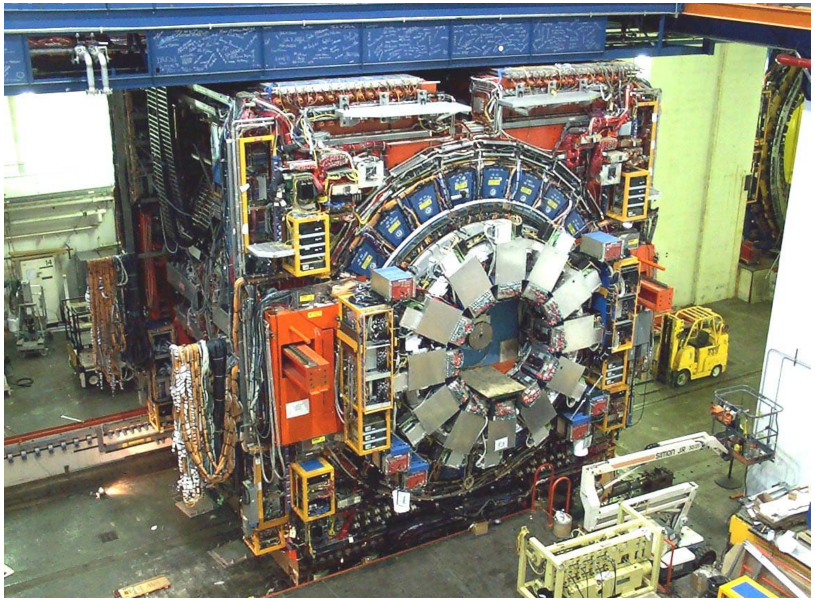
Upgrades "I"

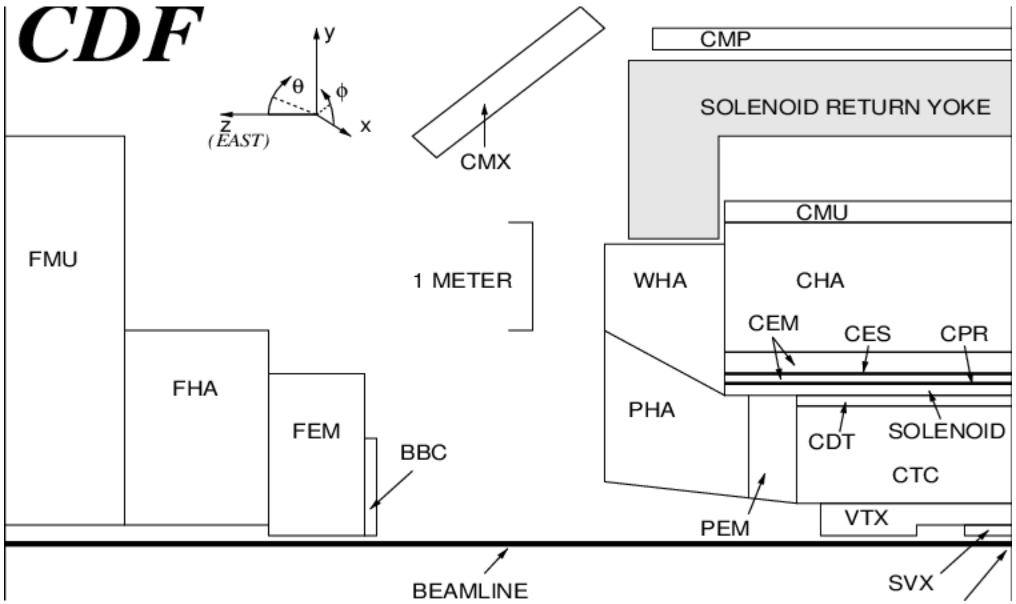
- First and second Silicon Vertex Detectors (3 layer barrels)
- Associative memory track trigger

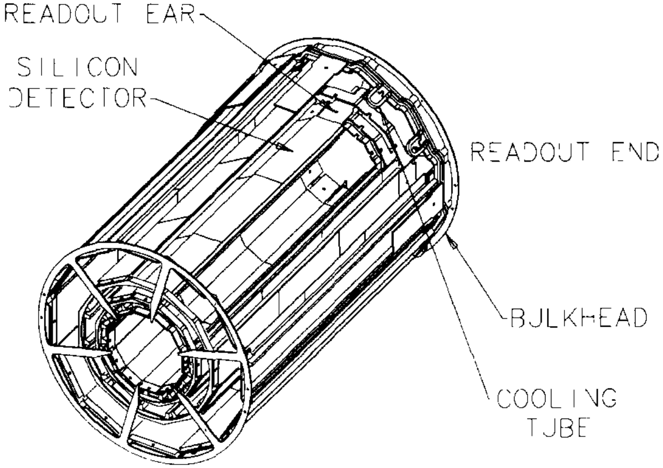
DØ Initial Design

- No central magnetic field
- Modest radius wire-chamber tracking detectors
- Transition Radiation Detector
- Uranium-Liquid Argon Calorimeter, projective geometry, multiple layered readout, barrel and end-caps
- Extensive Muon Detection with iron toroids
- Very Forward Muon detection
- Main Ring Beam overpass went through the hadron calorimeter

CDF Detector







Note Silicon Vertex Detector already installed by early 1990's.

DØ Detector

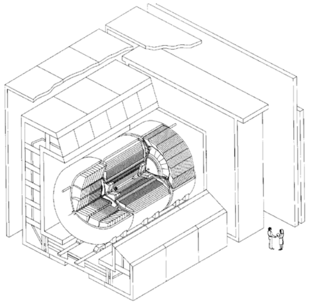
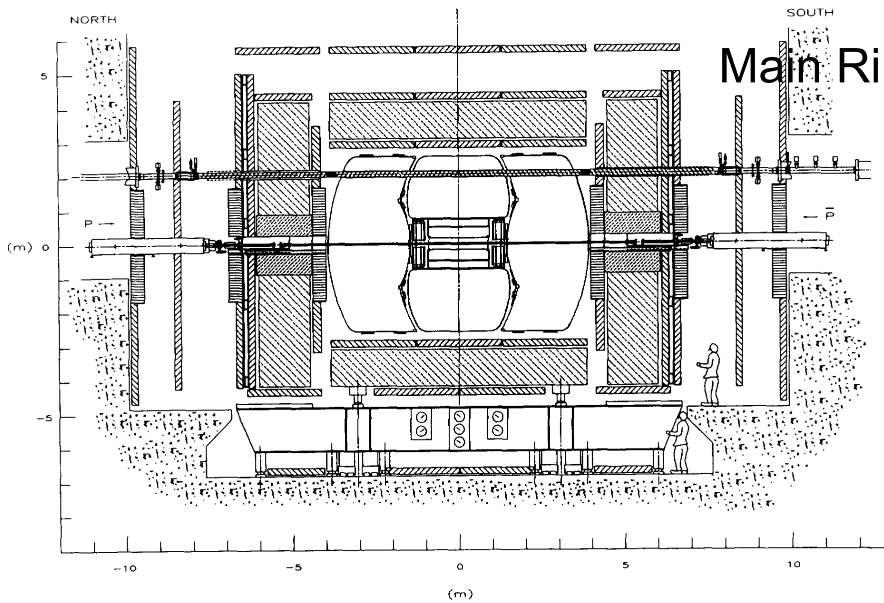
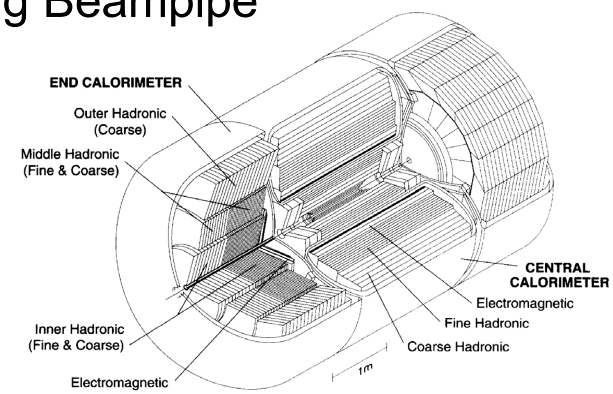


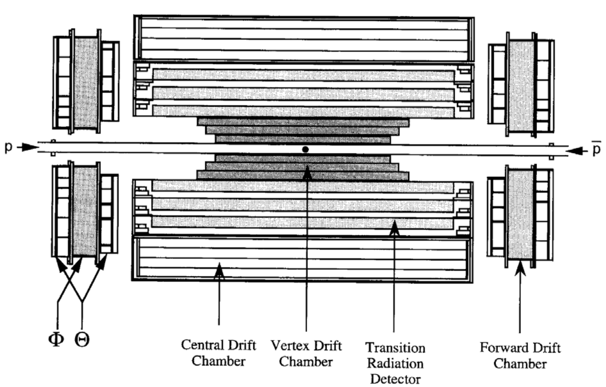
Fig. 1. Isometric view of the DØ detector.



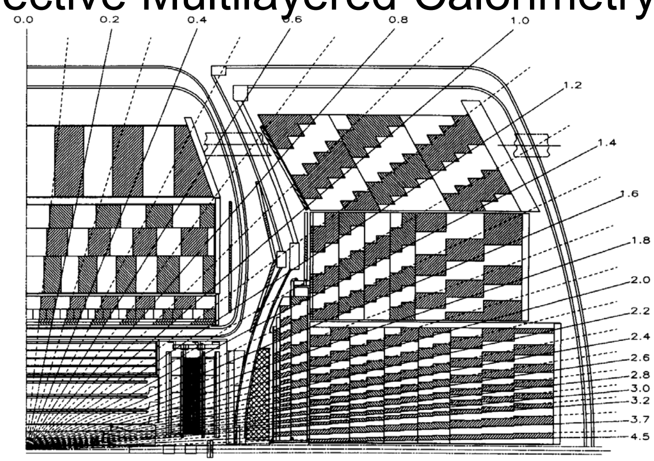
Main Ring Beampipe



Tracking and Transition Radiation



Projective Multilayered Calorimetry



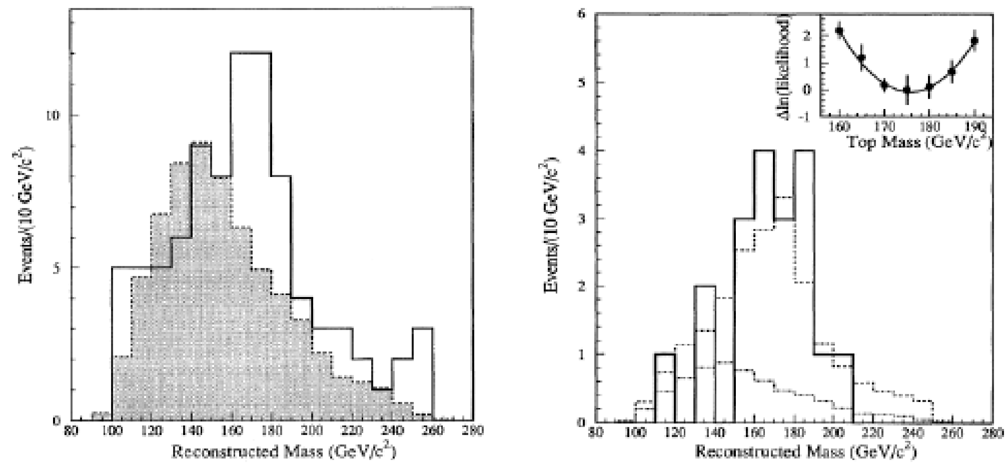
The Top Quark

- Evidence circa March 1994
  - CDF had a 3σ evidence,
  - DØ had no significant signal, despite similar sensitivity, although some argued for a particularly spectacular single event.
- Observation, Spring 1995, enabled by increased luminosity.
  - Both experiments had signal
  - However,
    - Production cross section: CDF ~12 pb, DØ ~6 pb
      - Current Value at 1800 GeV: 5.7 +- 1.6 pb (DØ)
    - Top Quark Mass: CDF~175 GeV, DØ ~199 GeV
      - Current Value: 174.3 GeV

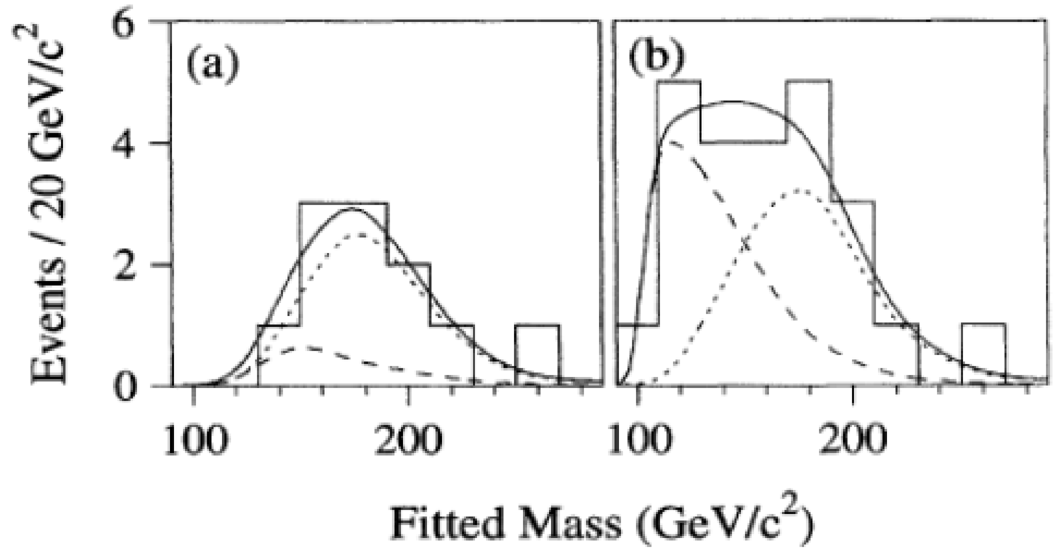
Competition! Complementarity

The Top Quark Observation

- CDF mass distributions from the observation paper 1995
- Signal enhanced by vertex tagging



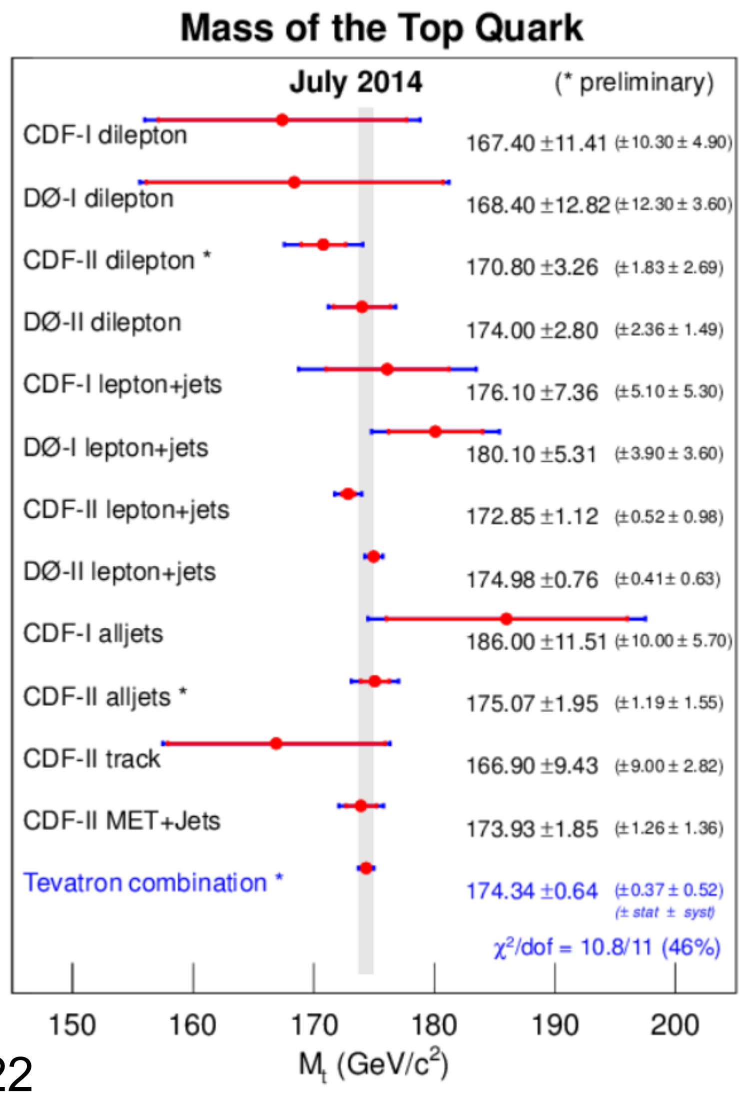
- DØ mass distributions from the observation paper, 1995
- Signal enhanced by lepton tagging and topological variables.



The Top Quark Mass

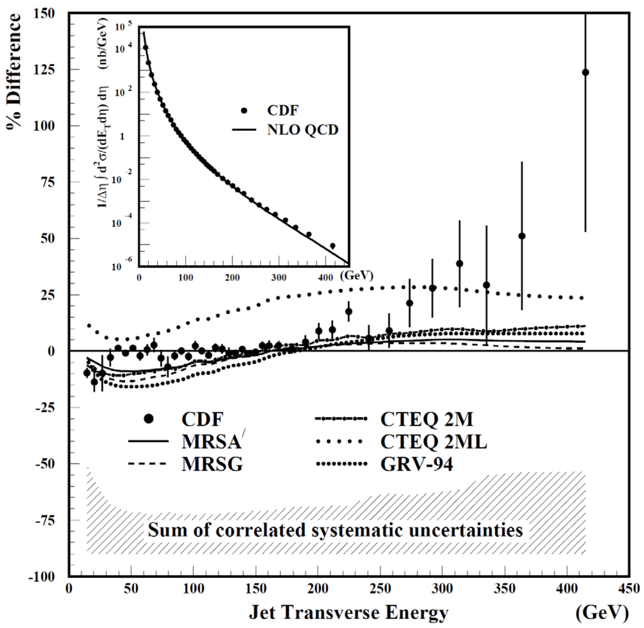
- Ultimately, a multiplicity of measurements from the two experiments using a variety of techniques led to a combined measurement of the top quark mass which is:
  - Consistent between the two experiments
  - Unexpected precision of <0.4%

Cross Checks followed by Combination

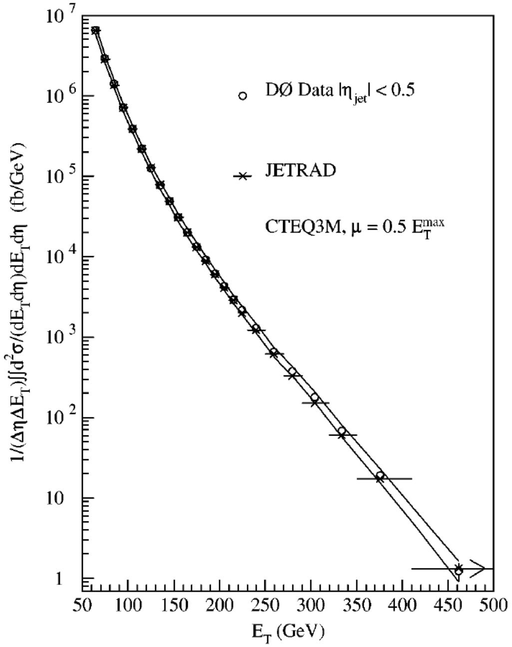


Dmitri Denisov, Costas Vellidis 2022

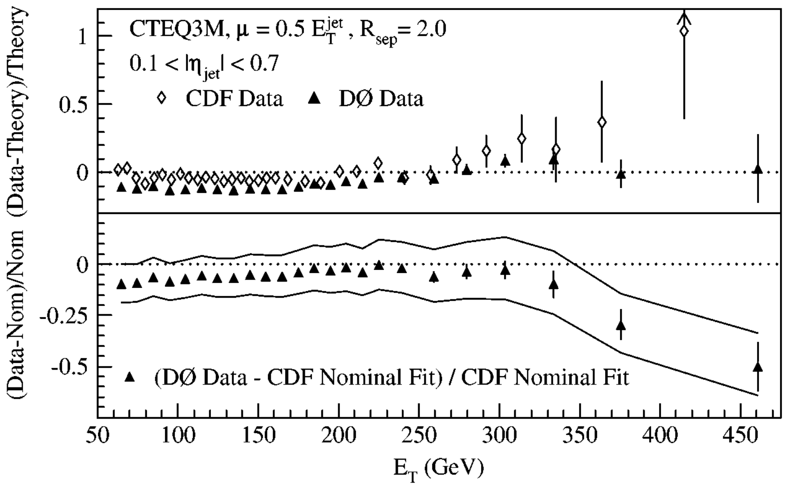
Jet Excess at high p_T in CDF…. But not in DØ



- CDF High p_T excess wrt expectations
- DØ data match expectations
- Direct comparison
  - Data to Data
- Difference
  - DØ - CDF



Competition and Cross-check



Leptoquarks at HERA …………

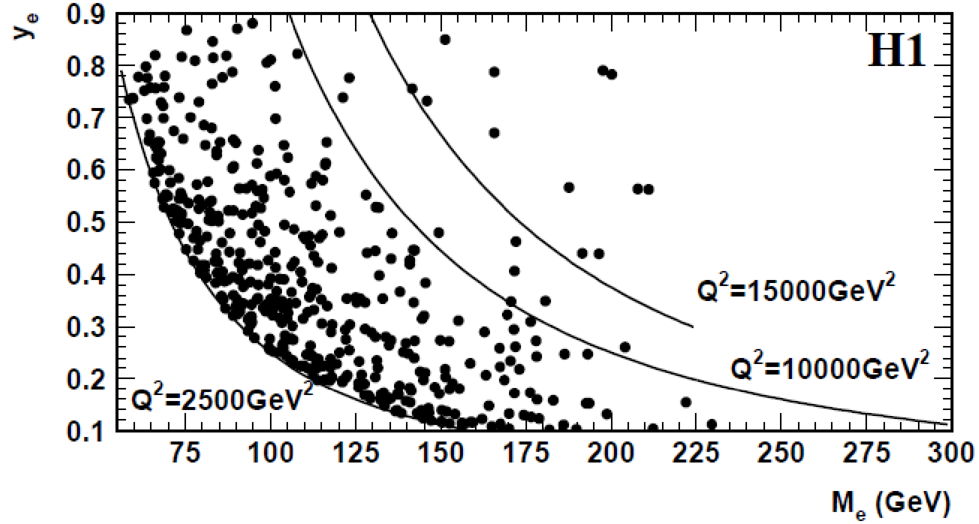
H1

- For $Q^2 > 15000$ GeV^2,
- $N_{obs} = 12$ neutral current candidate events, expectation is $N_{DIS} = 4.71 \pm 0.76$ events.
- $N_{obs} = 4$ charged current candidates are observed expectation is $N_{DIS} = 1.77 \pm 0.87$ events.
- The probability $P(N \geq N_{obs})$ that signal N fluctuates to $N \geq N_{obs}$ is $6 \times 10-3$ for neutral current and 0.14 for charged current.
- Difference is mostly at large masses $M = \sqrt{x\, s}$, positron is backscattered at large $y = Q^2/M^2$.

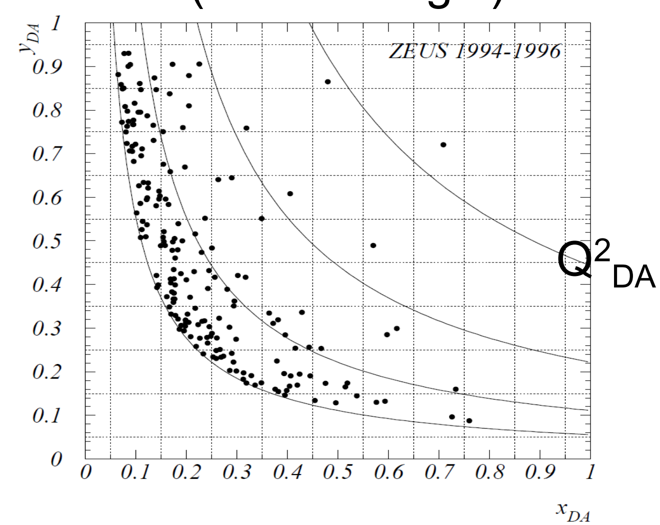
ZEUS

- A stat analysis of simulated Standard Model experiments.. with probability 6.0%, an excess at least as unlikely as that observed would occur above some Q^2 cut.
- For $x > 0.55$ and $y > 0.25$, four events are observed where 0.91 ± 0.08 events are expected.
- Probability of 0.72% for the region $x > 0.55$ and $y > 0.25$ and a probability of 7.8% for the entire $Q^2 > 5000$ GeV^2 data sample.
- The observed excess above Standard Model expectations is particularly interesting because it occurs in a previously unexplored kinematic region.

e(positron) kinematics

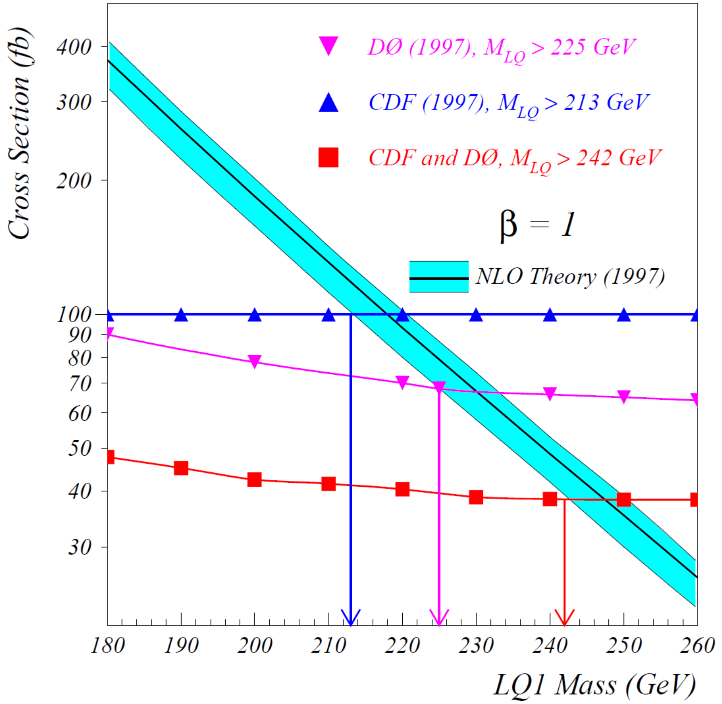


DA(Double Angle) kinematics



…………but not at the Tevatron

- 95% CL lower limits on the first generation scalar leptoquark mass of 213 GeV (CDF) and 225 GeV (DØ), respectively, under assumption of 100% branching fraction of the leptoquark decay into the eq channel.
- Ruled out an interpretation of the HERA high-Q^2 event excess reported by the H1 and ZEUS Collaborations [3, 4] as an s-channel production of leptoquarks with 100% branching fraction to the charged lepton channel (eq).
- Combined limit from the two experiments is 242 GeV.
- Most stringent limit on the first generation scalar leptoquark mass to date.



Cross-check of HERA experiments; Check then Combination by Tevatron Experiments

The CDF and DØ Upgrades (const 1997-2001)

CDF Upgrades – Major Features

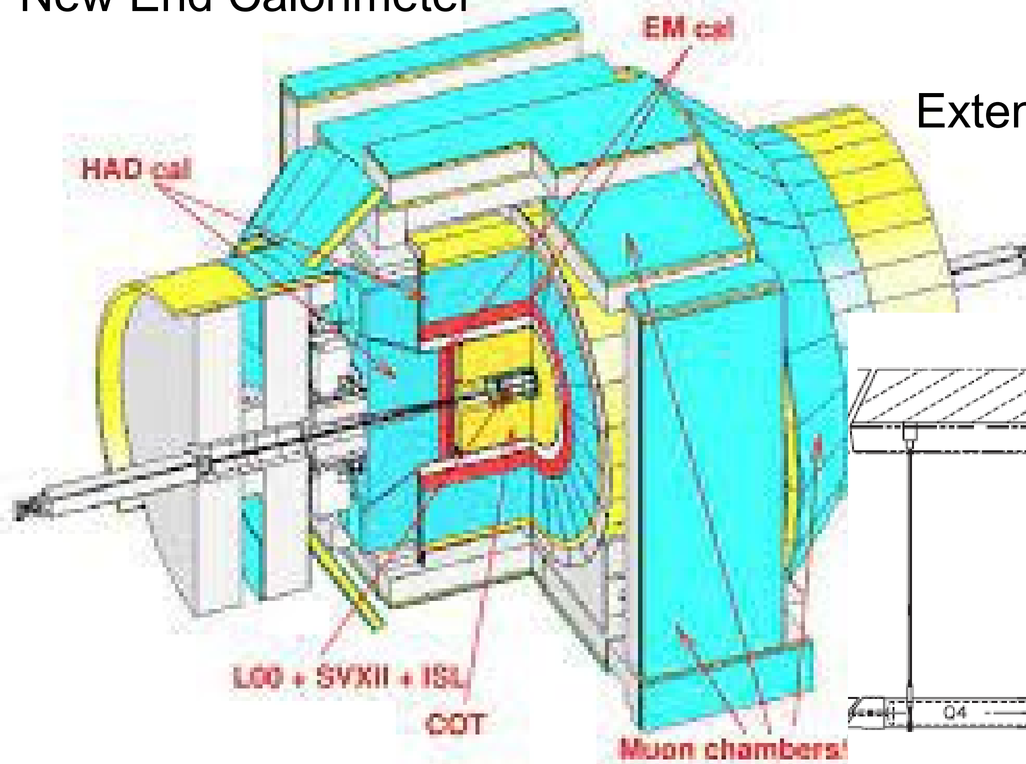
- Complete replacement of the central tracking system including:
  - 3 separate silicon strip detector systems
  - New drift chamber.
- scintillating tile-fiber calorimeter 1.1 < $|\eta|$ < 3.6
- Muon detection extended both in the central and forward directions.
- A new time-of-flight system
- electronics data acquisition and trigger system to accommodate 132 nsec bunch spacing.

DØ Upgrades - Major Features

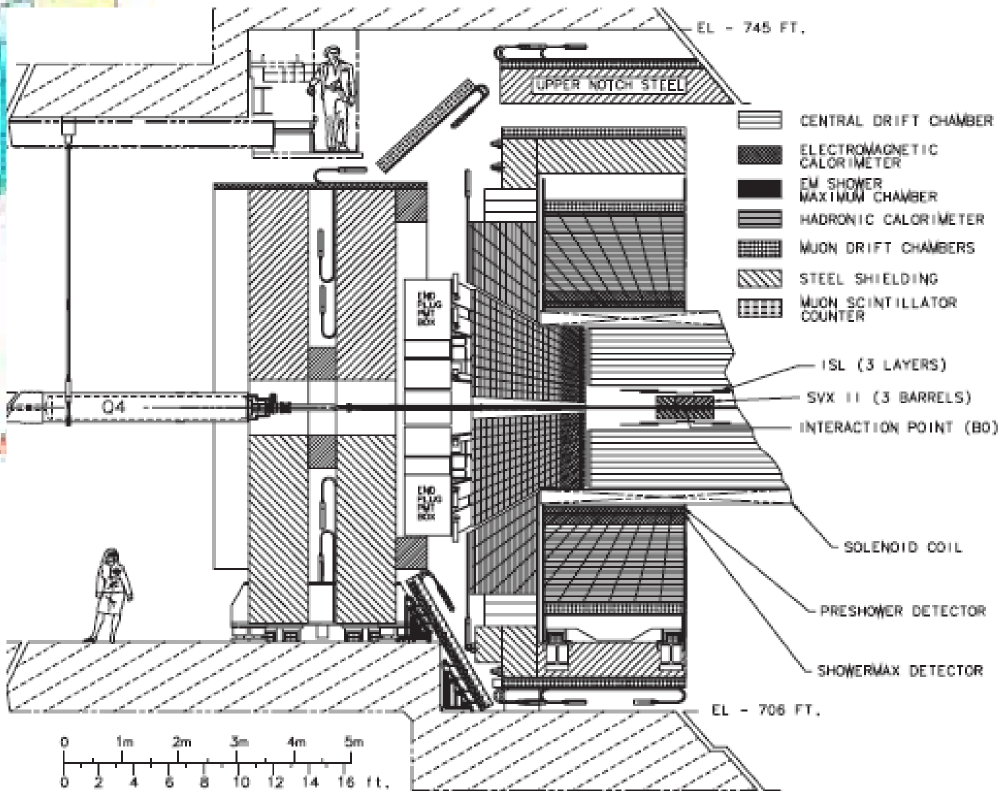
- New, small radius, 2T solenoid
- New tracking system to η = 3.0
  - Silicon vertex detector including barrels, interleaved radial discs
  - Scintillator Fiber Tracker
- Preshower detectors in barrel and End cap regions
- Calorimeter electronics upgrade
- Complete replacement of end muon chambers with both scintillator and drift tubes
- electronics data acquisition and trigger system to accommodate 132 nsec bunch spacing.

Collider Detector Facility ~2001

New End Calorimeter



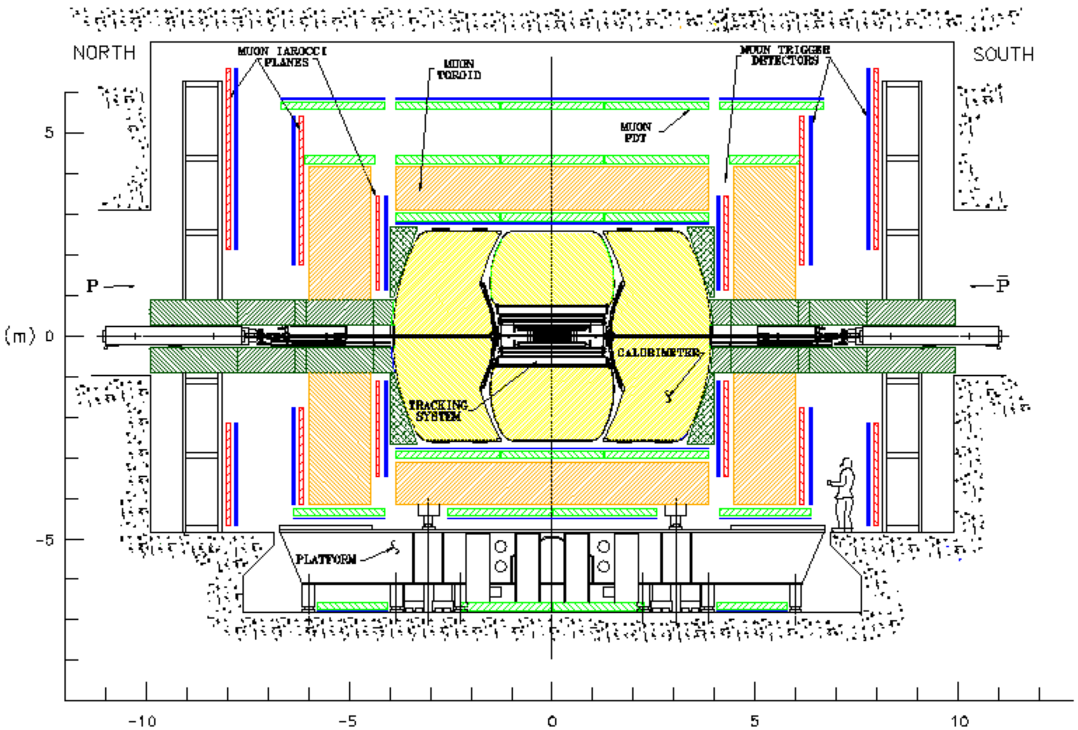
Extended Muon Detectors



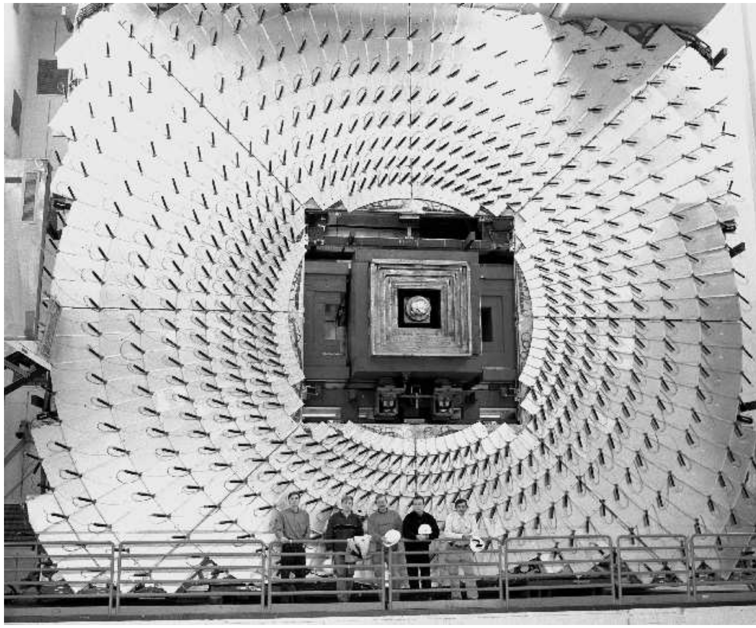
New Silicon Tracking
New Central Outer Tracker,

DØ Detector ~2001

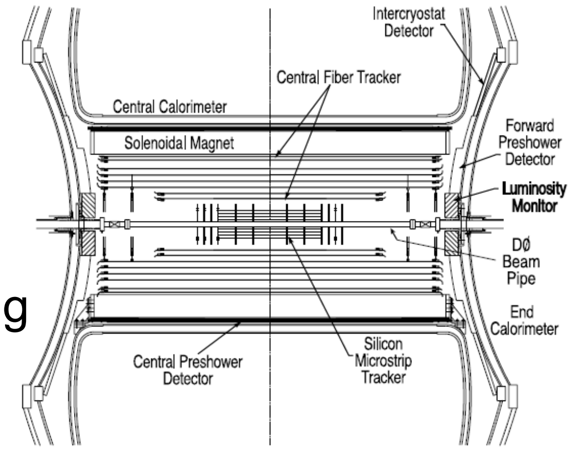
No Main Ring!



End Muon
Scintillator Detectors



New Magnet and Tracking



B_S Mixing

Previous lower limits on B_S mixing $\Delta m_s > 16.6\ ps^{-1}$

It was generally accepted that for this measurement DØ was substantially inferior to CDF, data rates, silicon detector …

Method for B_s mixing analysis;

Identify and measure decay length for each type of B^0

Determine flavor at creation by tagging, opposite side or same side

Express a signal probability as:

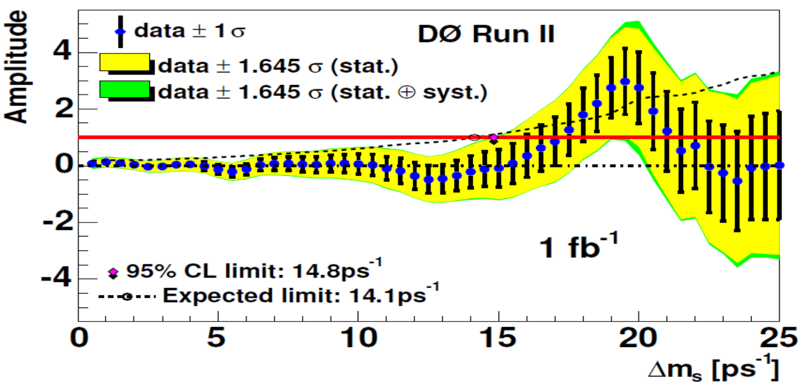
$$p^{nos/osc}(l, K, d_{tag}) = K/(c\tau_{B0})\exp(-Klc\tau_{B0})[1 \pm D(d_{tag})\, A \cos(\Delta m_s \cdot Kl/c)]/2$$

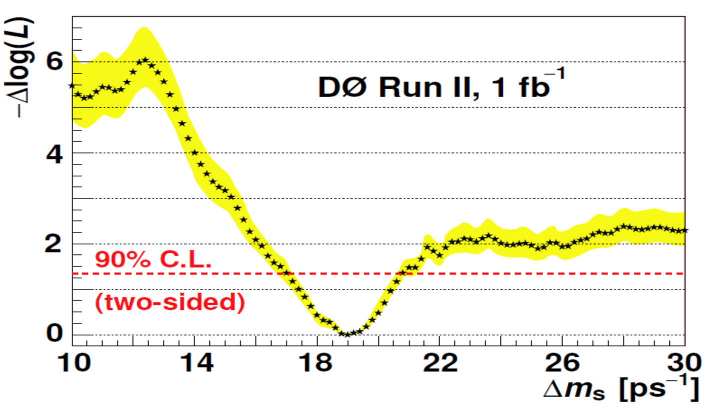
1. Fit with amplitude $A=1$ and get a Likelihood dist as function of Δm_s

2. Fit amplitude A for each Δm_s; $A=1$ for signal : $A=0$ within errors otherwise

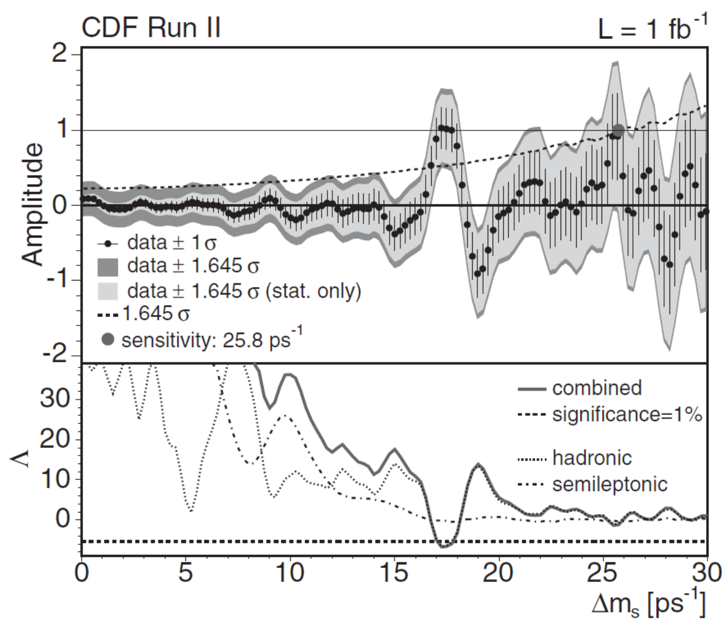
B_S Mixing

- DØ : dated March 15, 2006
- 27k B_S> D_S candidates
- 17 < Δm_s < 21 ps^{-1} at the 90% C.L.



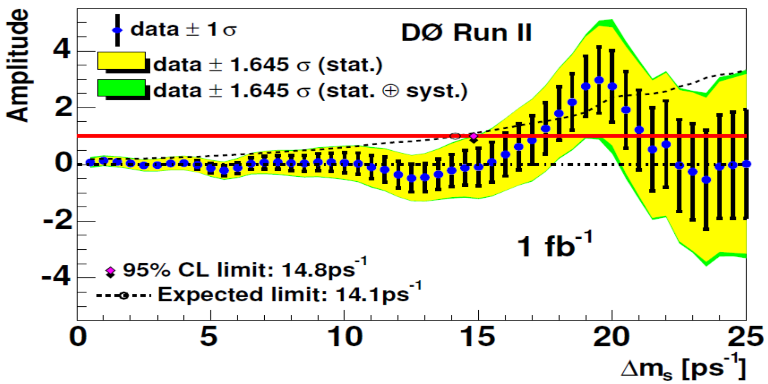


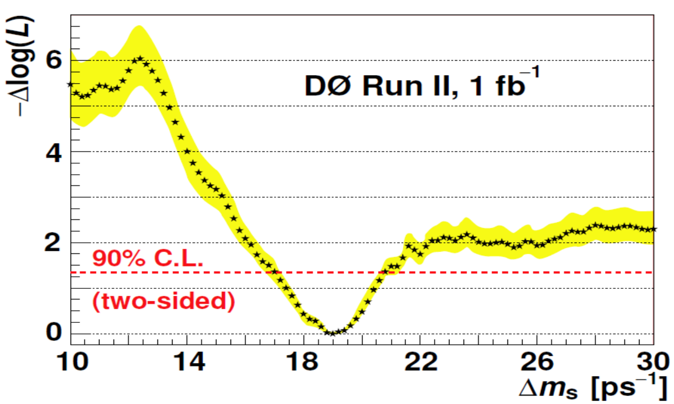
- CDF: submitted 13 June2006
- 41k B_S candidates including 3600 hadronic decays
- Δm_s $17.31^{+0.33}_{-0.18}$ stat +-0:07 syst ps-



B_S Mixing

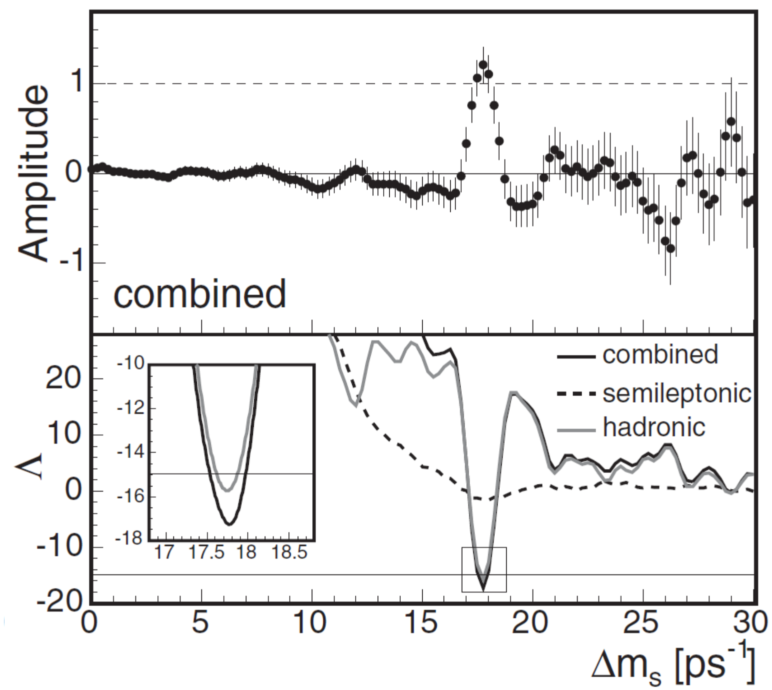
- DØ : dated March 15, 2006
- 27k B_S> D_S candidates
- 17 < Δm_s < 21 ps^{-1} at the 90% C.L.





- CDF: submitted 18 Sept 2006
- 70k B_S candidates incl 5600 fully recons

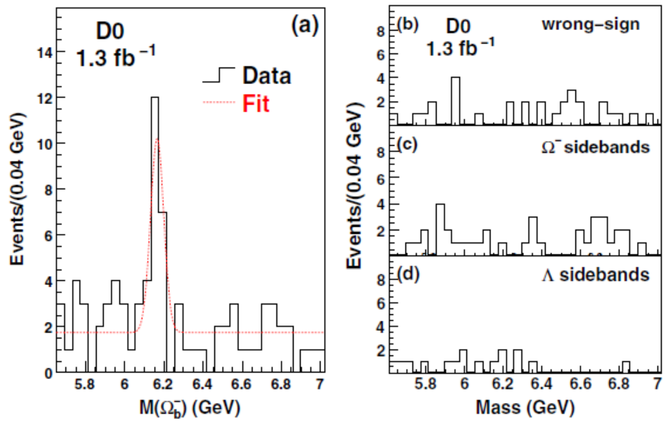
□ Δm_s 17:77 0.10 stat 0.07 syst ps-



Same Sample,
improved analysis: competition!

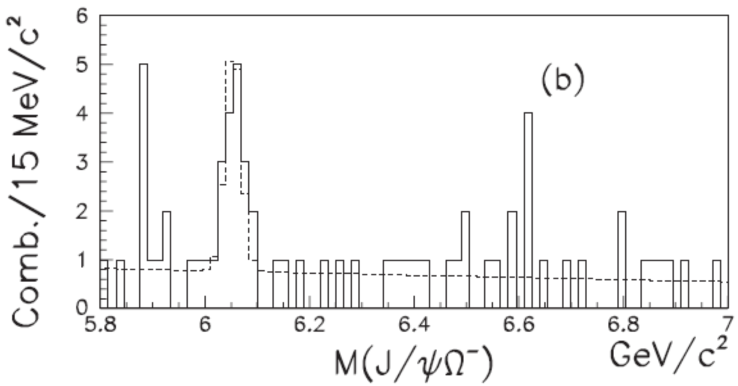
Mass of the Ω_b Baryon?

DØ "Observation" December 2008



DØ sig: 5.4σ (bkgd p = 6.7 10^{-8})
$M_{\Omega b}$= 6.165 +/- 0.010 +/- 0.013 GeV

CDF Observation October 2009



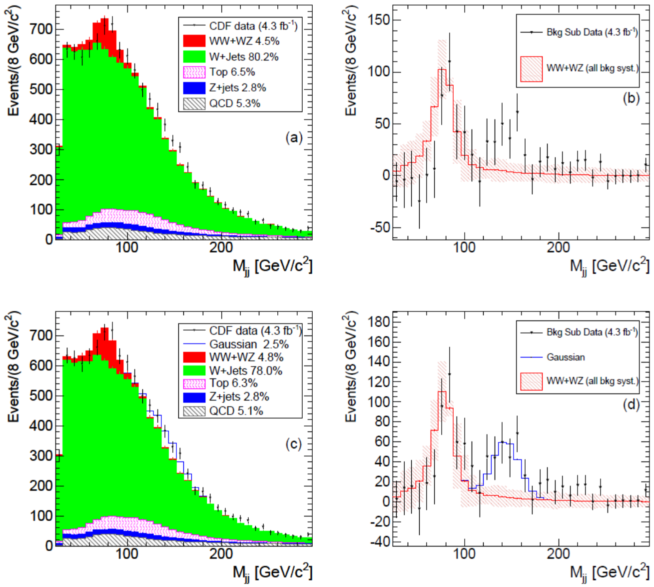
CDF sig: 5.4σ
$M_{\Omega b}$= 6.054 +/- 0.007 +/- 0.001 GeV

Crosscheck!!

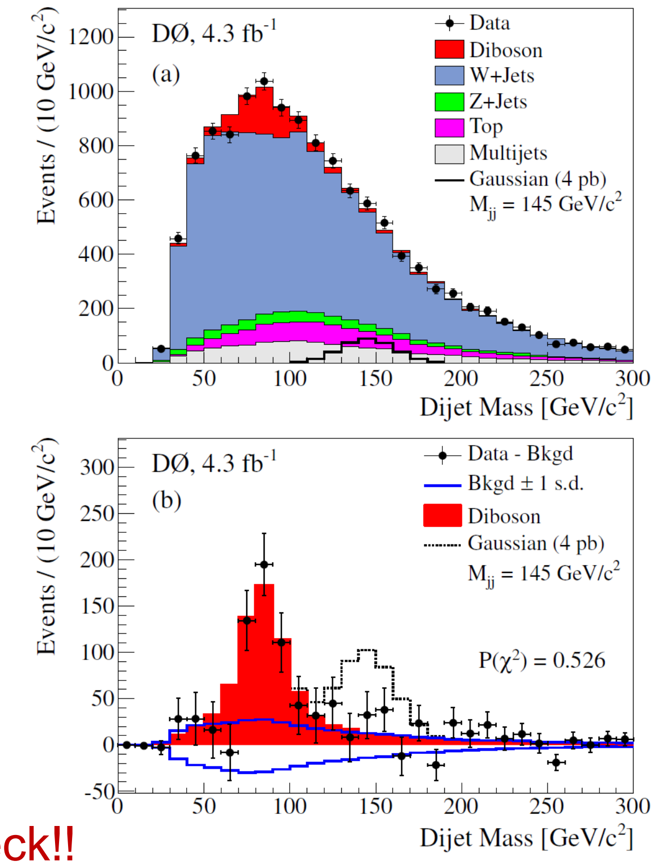
CDF Measurement April 2014
$M_{\Omega b}$= 6047.5 +/- 3.8 +/- 0.6 MeV

DØ note (2015): The re-evaluated lower statistical significance of the Ω_b signal, and the mass disagreement of the 2008 result with other experiments, lead us to conclude that the 2008 result was likely not due to the presence of an Ω_b signal but rather due to a background fluctuation and/or other unidentified effects, and thus should be disregarded as an observation of the Ω_b baryon.

144 GeV Resonance? No!



- 2011 CDF study of dijet mass distributions in W + jets measurement.
- Statistically significant (p-value 7.6 10^{-4}, 3.2 σ) excess
- Fit to extra Gaussian with width scaled to dijet resolution→ mass 144+- 5 GeV, σ.BR = 4 pb.

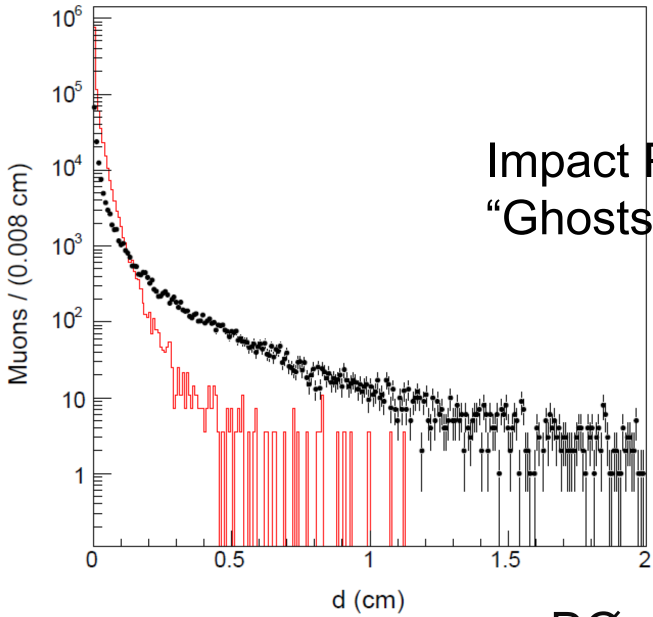


Crosscheck!!

- 2011 DØ study gives no excess, with likelihood of 145 GeV resonance of σ.BR= 4 pb of 8. 10^{-6} Rejection 4.3 σ, 95% CL UL 1.9 pb

Ghost Muons

- Observation by CDF of “excess”, ghost muons (~12%) apparently originating outside the 1.5 cm beam pipe.
- Impact parameters of these muons are distributed differently from those of QCD events.



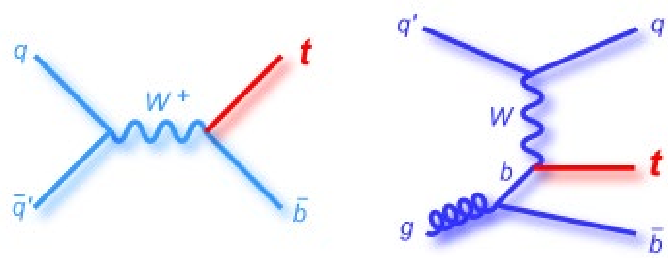
Impact Parameter Distribution
“Ghosts” in black, “QCD” in red.

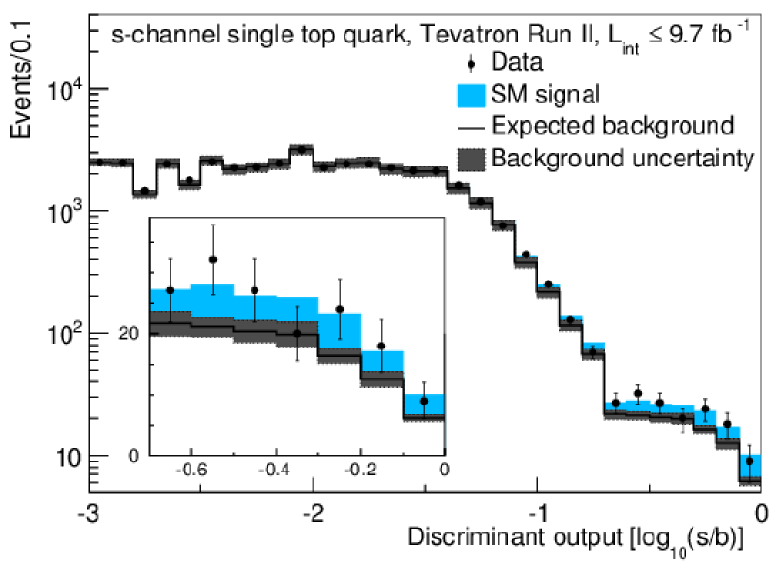
Crosscheck!!

- DØ replicated CDF analysis of di-muons with at least one of muons with vertex distance 1.6< R<10 cm found

null “excess” (0.4 +/- 0.26 +/- 0.53)%.

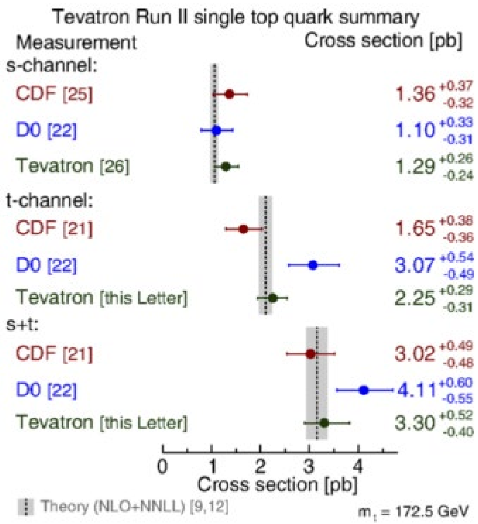
Single Top Production



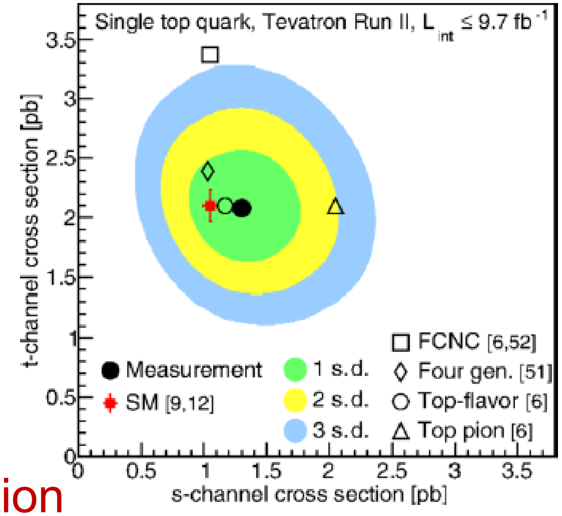


- Single top involves W exchange diagrams to get flavor change.
  - s channel
  - t channel
  - associated production negligible
- Cross sections similar to ttbar production because the ttbar has to produce two top quarks. (Weak interaction versus kinematics)
- However, backgrounds and uncertainties high with respect to signal
- Multiple multi-variate analyses mandatory feeding "super-discriminant.
- Signal observed for t-channel, and evidence in s-channel.
- Therefore, combined the two experiments.

Single Top Production

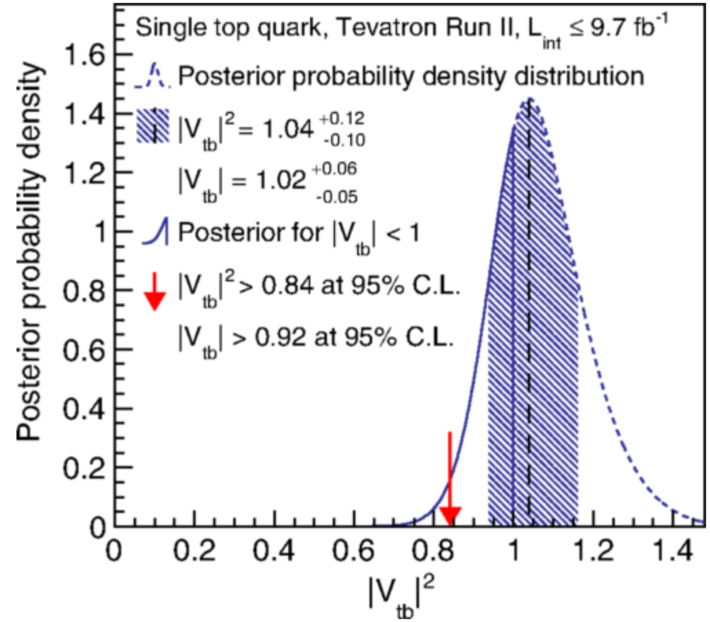


Cross Checks
followed by Combination

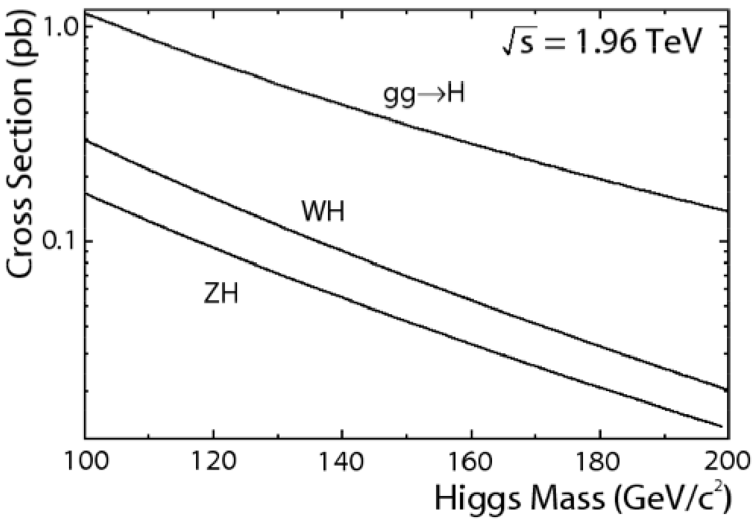


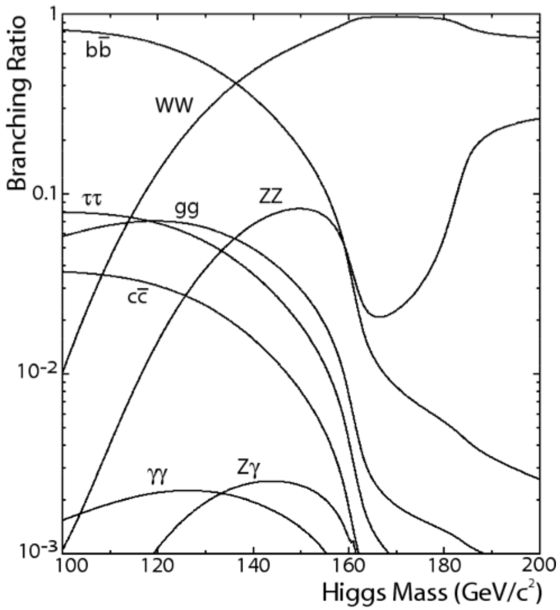
- Results from combined effort!
  - s-channel σ_s = 1.29+-0.25 pb with 6.3σ significance.
  - t-channel σ_t = 1.29+-0.3 pb
  - s+t channels σ_{s+t} = 3.30+0.52-0.40 pb

  - Agreement with Standard Model
  - CKM $|V_{tb}|$ > 0.92 with 95% cl

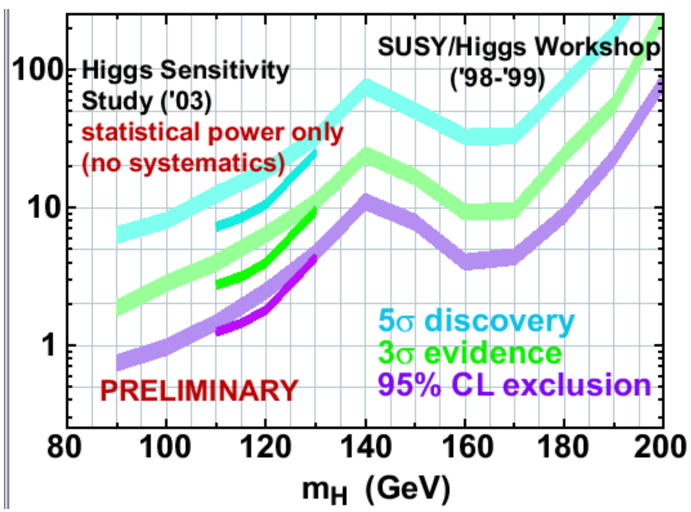


The Higgs Boson at theTevatron

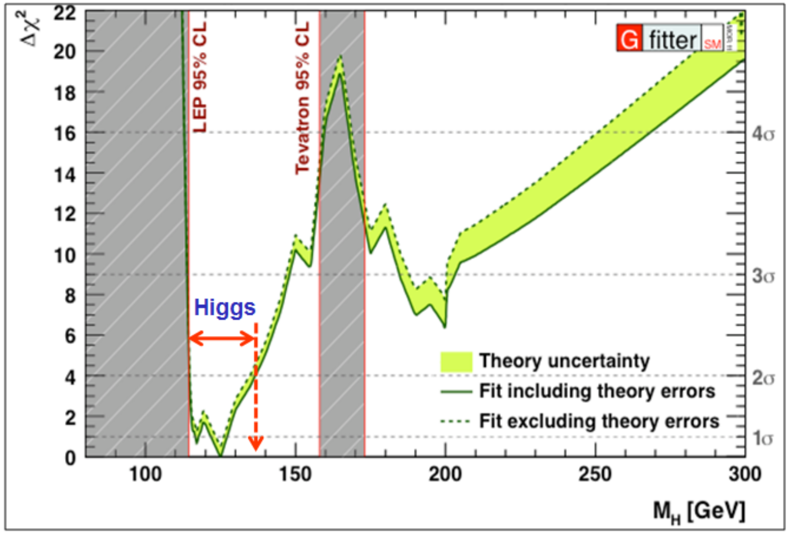




- Higgs Production cross-sections at Tevatron
  - 10 fb → 10000 events
- Higgs Branching Ratios as a function of mass
- Predicted Sensitivities, 95% cl exclusion, 3σ and 5σ; vertical scale is integrated luminosity in fb^{-1} per experiment and assumes combination of CDF and DØ.



The Higgs Boson at theTevatron



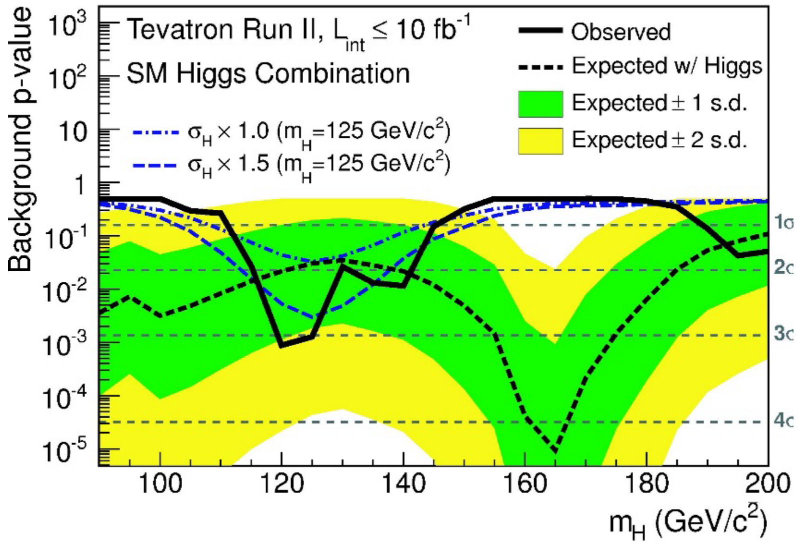
- Intermediate results with ~ 5fb^{-1} for each experiment but results combined.
  - Exclusion above 160 GeV

- 15 channels included by CDF
- 13 channels included by DØ

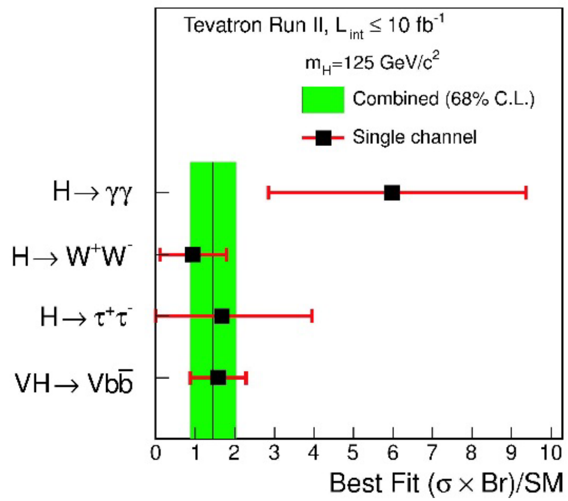
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
CDF		
$WH \to \ell\nu bb$ (2-jet channels)	9.45	90-150
$WH \to \ell\nu b\bar{b}$ (3-jet channels)	9.45	90-150
$ZH \to \nu\bar{\nu}b\bar{b}$	9.45	90-150
$ZH \to \ell^+\ell^- b\bar{b}$ (2-jet channels)	9.45	90-150
$ZH \to \ell^+\ell^- b\bar{b}$ (3-jet channels)	9.45	90-150
$WH + ZH \to jjb\bar{b}$	9.45	100-150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$		
(4 jets)+(5 jets)+(≥6 jets)	9.45	100-150
$H \to W^+W^-$		
(0 jets)+(1 jet)+(≥2 jets)		
+(low $m_{\ell\ell}$)	9.7	110-200
$H \to W^+W^-$ (e-$\tau_{\rm had}$)+(μ-$\tau_{\rm had}$)	9.7	130-200
$WH \to WW^+W^-$		
(same-sign leptons)+(3 leptons)	9.7	110-200
$WH \to WW^+W^-$		
(3 leptons with 1 $\tau_{\rm had}$)	9.7	130-200
$ZH \to ZW^+W^-$		
(3 leptons with 1 jet, ≥2 jets)	9.7	110-200
$H \to \tau^+\tau^-$ (1 jet)+(≥2 jets)	6.0	100-150
$H \to \gamma\gamma$ (0 jets)+(≥1 jet)	10.0	100-150
$H \to ZZ$ (4 leptons)	9.7	120-200
D0		
$WH \to \ell\nu bb$ (2-jet channels)	9.7	90-150
$WH \to \ell\nu b\bar{b}$ (3-jet channels)	9.7	90-150
$ZH \to \nu\bar{\nu}b\bar{b}$	9.5	100-150
$ZH \to \ell^+\ell^- b\bar{b}$		
(2-jet channels)+(4 leptons)	9.7	90-150
$H \to W^+W^- \to \ell^{\pm\nu}\ell^{\mp\nu}$		
(0 jets)+(1 jet)+(≥2 jets)	9.7	115-200
$H + X \to W^+W^- \to \mu^{\mp}\nu\tau^{\pm}_{\rm had}\nu$	7.3	115-200
$H \to W^+W^- \to \ell\bar{\nu}jj$		
(2 jets)+(3 jets)	9.7	100-200
$VH \to e^{\pm}\mu^{\pm} + X$	9.7	100-200
$VH \to \ell\ell\ell + X$ ($\mu\mu e$)+($e\mu\mu$)	9.7	100-200
$VH \to \ell\bar{\nu}jjjj$	9.7	100-200
$VH \to \tau_{\rm had}\tau_{\rm had}\mu + X$	8.6	100-150
$H + X \to \ell^{\pm}\tau^{\mp}_{\rm had}jj$	9.7	105-150
$H \to \gamma\gamma$	9.6	100-150

The Higgs Boson at theTevatron

- Final results, Solid Black Line indicates background p-value for data.
  - Excess in mass region 110 – 140 Gev
  - 3σ at 125 GeV. (Expected 2σ)



- Observed σ.BR/Standard Model
  - Consistent with standard model
  - VH-> V bbbar is evidence for H-> fermions

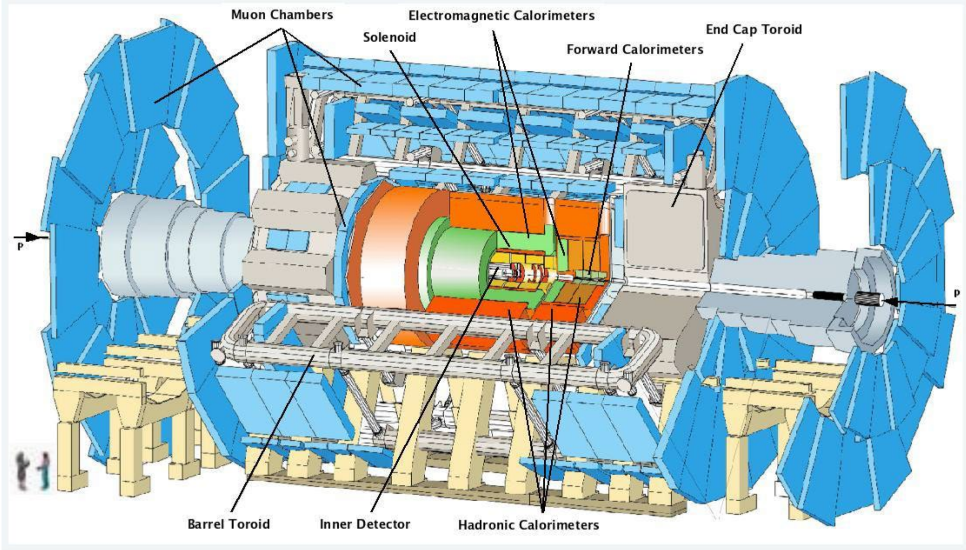


- Result only possible because BOTH experiments existed, milked their data to the maximum, and combined the efforts.

Combination, absolutely necessary

The Large Hadron Collider – ATLAS

- **ATLAS**
  - Conceived in the face of a worry that particle tracking will not work at LHC
  - Space dominated by enormous external air core toroids giving muon momentum and direction, protected from hadrons
  - Liquid Argon Electromagnetic Calorimetry with high longitudinal and transverse segmentation
  - Deep scintillator tile hadron calorimetry
  - Thin superconducting solenoid inside EM calorimeter cryostat
  - Central tracking using Transition Radiation Tracker (further safety net vs tracking difficulties) and Silicon strips and pixels

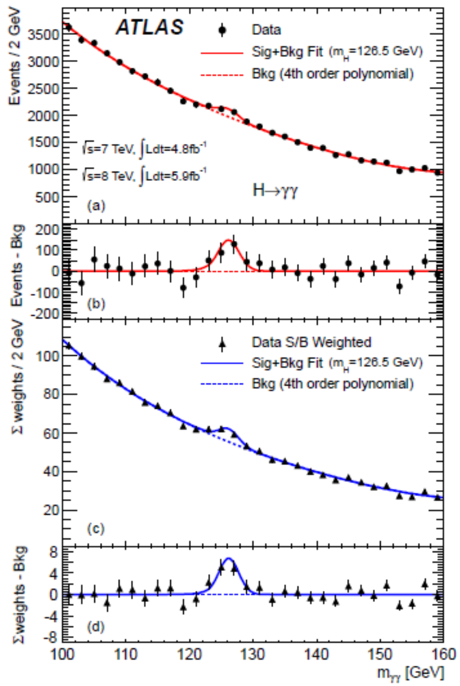


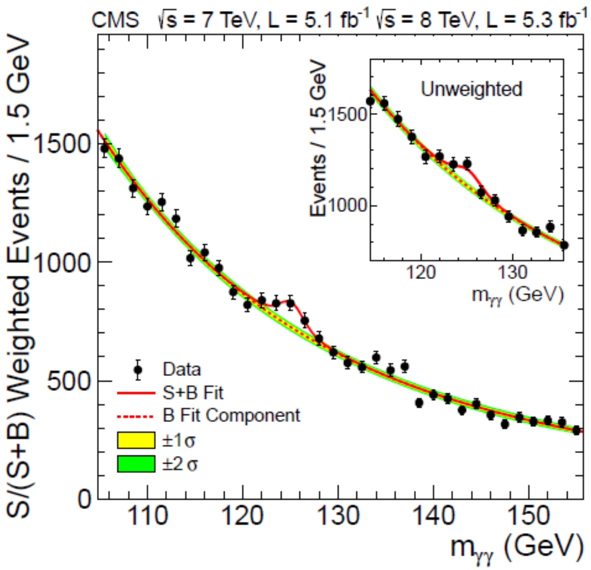
The Large Hadron Collider - CMS

- **Compact Muon Solenoid**
  - Very Large, High Field Central Solenoid
  - 100% silicon tracker
  - Crystal electromagnetic calorimeter
  - Brass-scintillator hadron calorimeter
  - Superconducting 5T Solenoid
  - Outer Iron Toroidal Muon Detector
  - Note the sub-detector by sub-detector complementarity with ATLAS

Higgs at the LHC

- Discovery Channel at LHC always perceived to be H→ γγ
- Performance of the detectors remarkably similar despite the orthogonal approaches to the em calorimeter

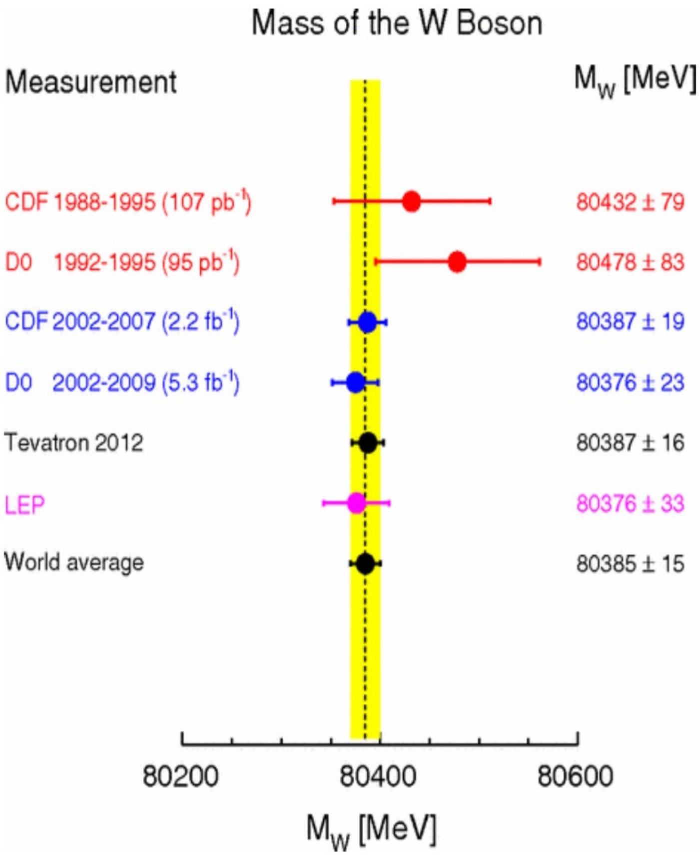




- Results reinforced each other but it was important that each saw the signal for July 4.

Crosscheck!!

The W-Boson Mass I



ΔM_W

- ~ 500 MeV UA2
- ~ 100 MeV CDF, DØ Run I
- ~ 50 MeV LEP Experiments
-
- ~ 20 MeV CDF, DØ
- ~ 15 MeV Tevatron 2012

Crosscheck and Combination

The W-Boson Mass II

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

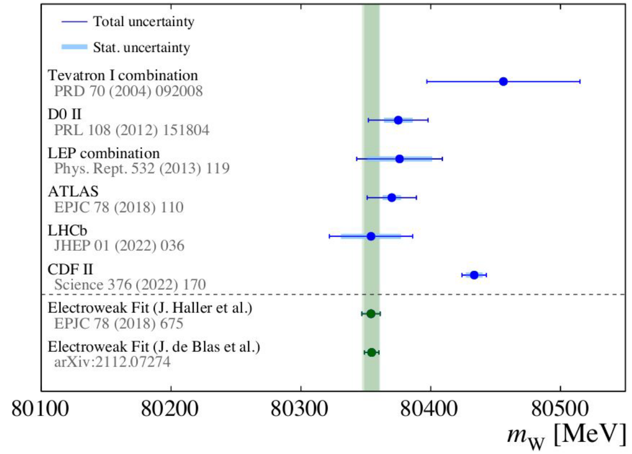
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

ATLAS (4.6 fb^{-1}) [*Eur. Phys. J.* ***C78*** *(2018) 110*]

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

LHCb (1.7 fb^{-1}) [*JHEP* ***01*** *(2022) 036*]

m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV



New and Highest precision Tevatron measurement (CDF 2022) appears to be inconsistent with other measurements!!!

Of the two General Purpose detectors at LHC, only one has produced a measurement.

The LHCb Measurement has a different η acceptance; this means pdf dependences are anti-correlated

Another motivation for diversity!!!

Back to Crosschecks!!

Summary

- We have presented some examples which illustrate the experience with two detectors at collider facilities.
- As we expected there are desirable technical results of implementing two detectors at a collider:
  - Complementary designs with complementary technology choices mitigate risk and enhance the physics potential
  - Physics progresses and having two detectors facilitates upgrade paths, again with different emphases.
  - Different designs can broaden the overall physics program
- In a situation when a new result appears, it is mandatory that there be independent confirmation.
- The presence of competition is an important motivator and accelerator of new results.
- When signal is weak, two measurements can be combined.
- The case for two detectors at the Electron Ion Collider is irrefutable, and the sooner the better.