

The Tevatron Physics Legacy**



25 years of physics in 25 minutes !

Paul Grannis
LHCP 2014
June 2, 2014

The Tevatron Collider

Run I: 1992 – 1996, 1.8 TeV.
120 GeV Main Ring in Tevatron tunnel made pbars.
6 bunches ($\Delta t = 3.5 \mu\text{s}$).

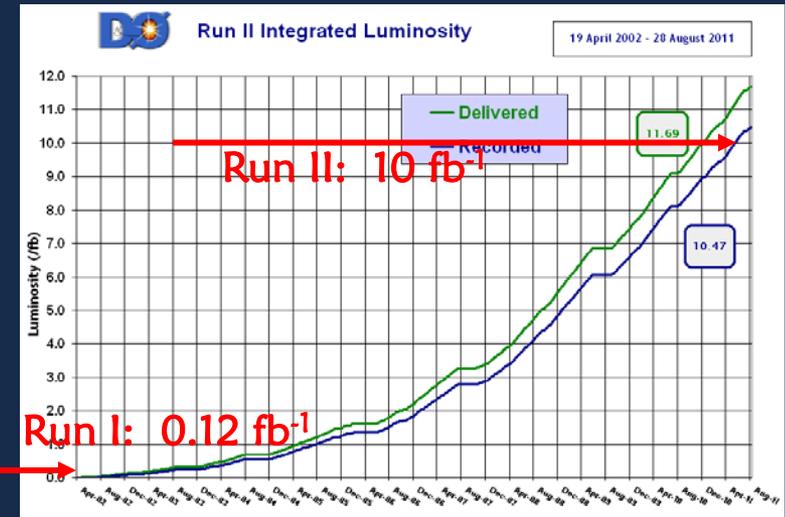
Run II: 2001 – 2011, new 150 GeV Main Injector for pbars.
Recycler ring, e-cooling;
36 bunches ($\Delta t = 396 \text{ ns}$)



Max. Instantaneous $\mathcal{L} \approx 4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

$\sim 12 \text{ fb}^{-1}$ delivered ($\sim 10 \text{ fb}^{-1}$ in analyses)

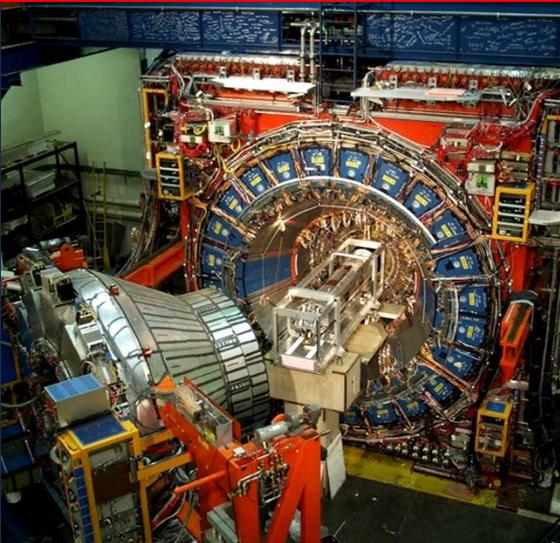
$\sim 3 \times 10^{15}$ pbars ($\sim 500 \mu\text{C}$) died a horrible death in the service of science.



The superb Tevatron performance is the key to the physics accomplishments.

S. Holmes, V. Shiltsev, Ann. Rev. Nuc. Part. Sci. 63, 435 (2013).

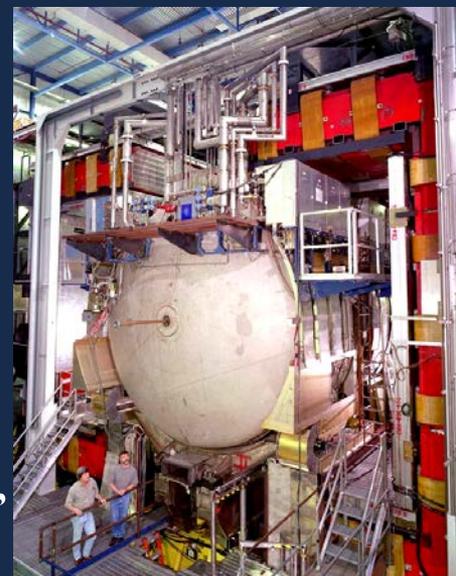
The Experiments



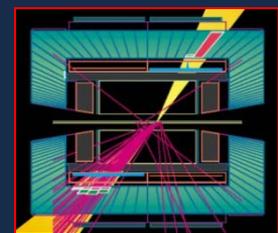
CDF and DØ were quite different in Run I. Both were significantly upgraded for Run II:

CDF: new tracker, new Si vertex detector, upgraded forward cal and muons

DØ: added solenoid, fiber tracker, Si vtx, preshower detectors, new forward muon detectors.



The upgraded experiments looked more alike, but still with complementary strengths. Competition and cross checks with 2 experiments were crucial!



In this talk, I summarize some physics achievements with a selection of results that I particularly like and that I think delineate the Tevatron legacy.



Review of Tevatron physics results through 2012 :

M. Shochet, PG, Ann. Rev. Nuc. Part. Sci. 63, 467 (2013).

Top quark discovery

Chronology

70's: τ , Y discoveries, $b \rightarrow se^+e^-$: top quark exists

80's: $m_t > 23$ GeV (Petra), > 30 GeV (Tristan)

1984: UA1 'discovery' in $W \rightarrow tb$

1990: CDF sets limit $m_t > 91$ GeV (above the W)

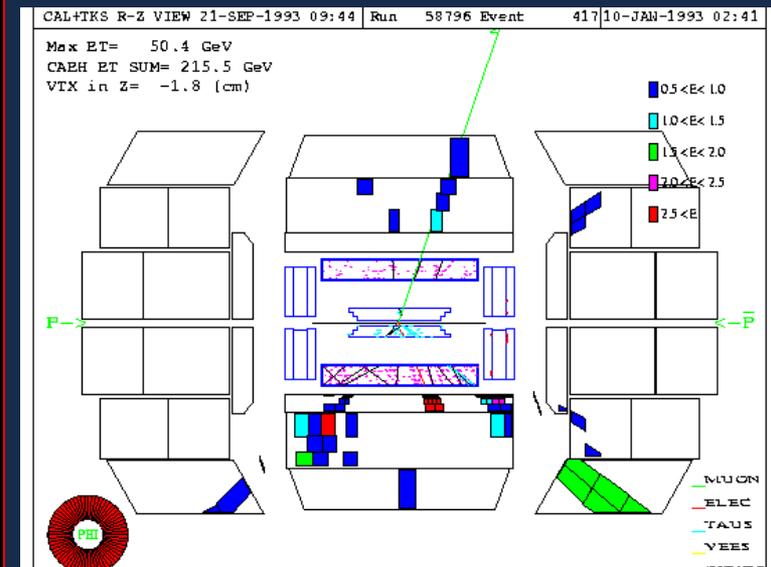
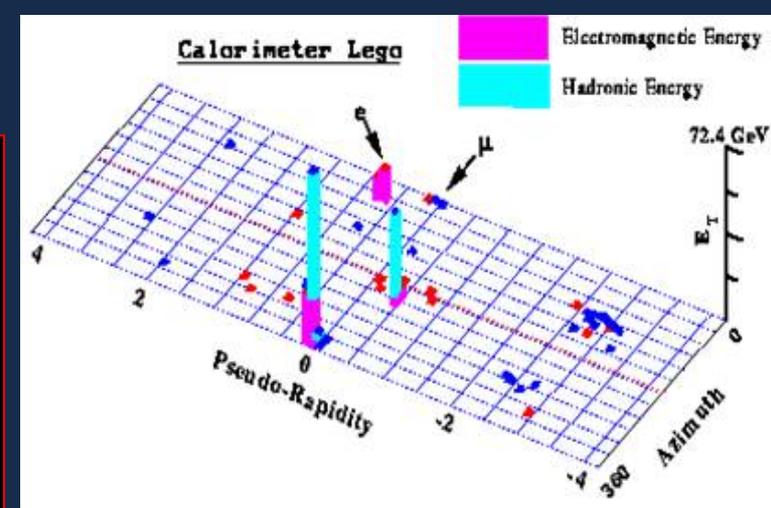
'90's: LEP/SLC precision indirect $m_t \sim 150-200$ GeV

1994: DØ last limit at $m_t > 131$ GeV

Spring 1994: Interesting events seen; CDF evidence at ~ 175 GeV (2.8σ). DØ had similar expected yields, but observed $\sim 2\sigma$

January 1995: With 50 pb^{-1} , CDF/DØ sense discovery is possible; feverish analysis effort.

Feb. 24, 1995: Simultaneous CDF and DØ PRL discovery submissions.

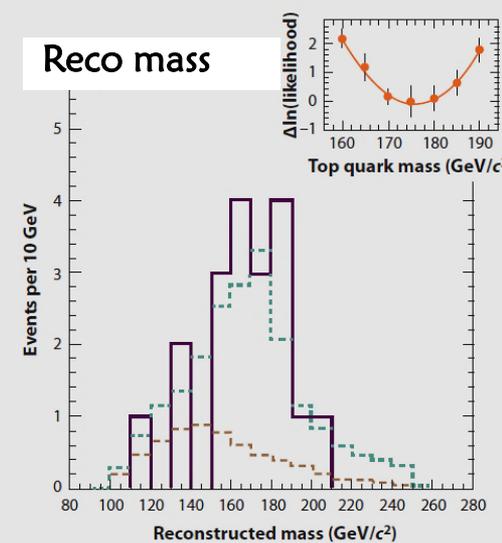
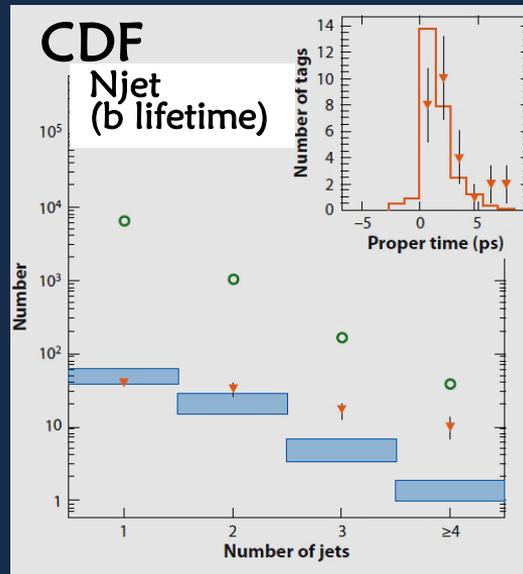


Early top-like $e\mu$ MET +
2 jet events

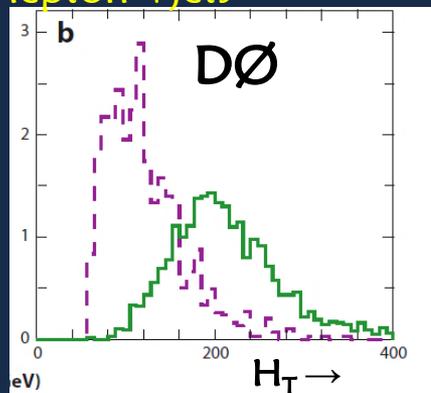
20 years between postulating and discovering top –not quite as long as the Higgs gestation period, but it seemed endless.

Top quark discovery

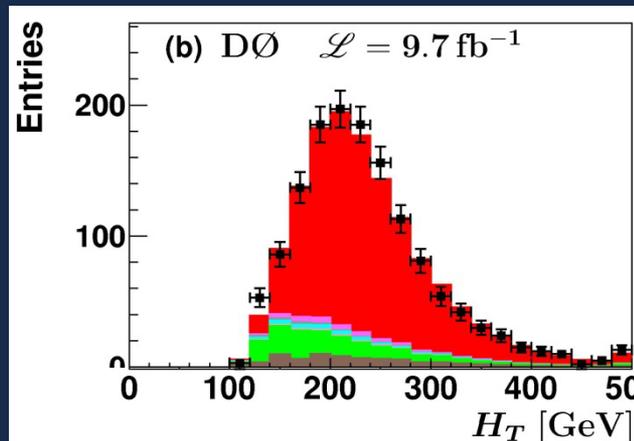
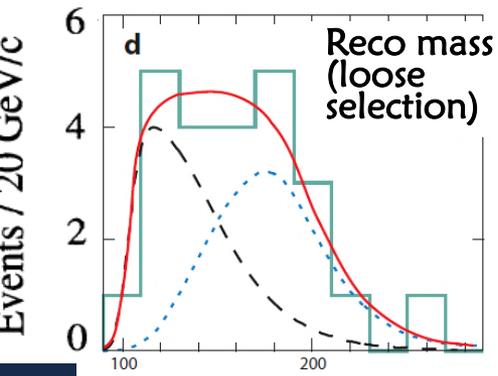
CDF relied heavily on their **Si Vtx detector** to tag b-quarks. Number of single lepton events vs. n_{jet} . Inset shows proper time of ≥ 3 jets for silicon vertex tags, consistent with expectation for b-quarks.



lepton +jets



DØ used **topological variables** Aplanarity and $H_T = \sum E_T^{\text{jets}}$ to distinguish top signal from W +jets and multijet bknds.

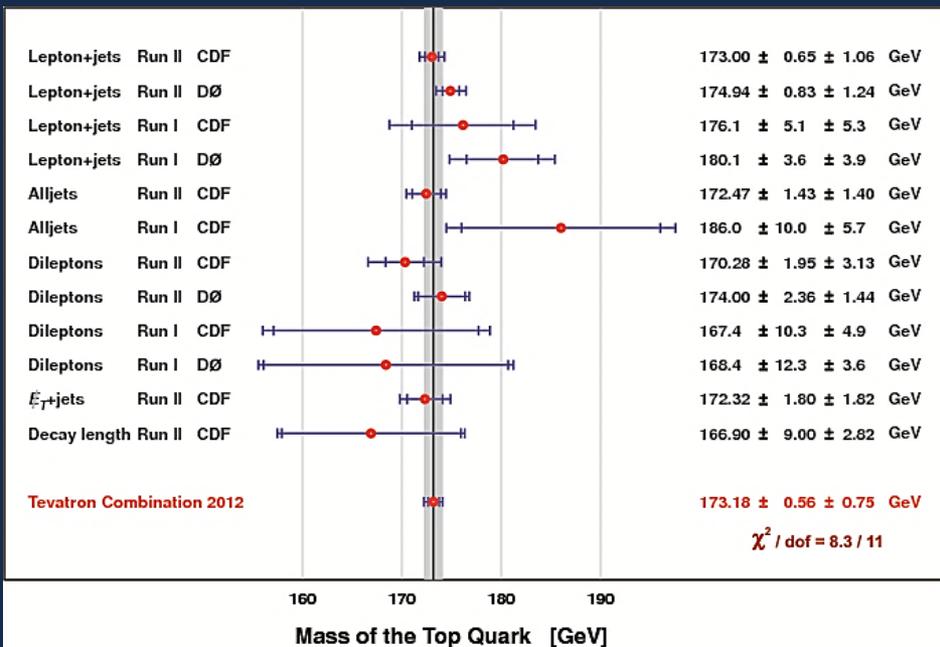
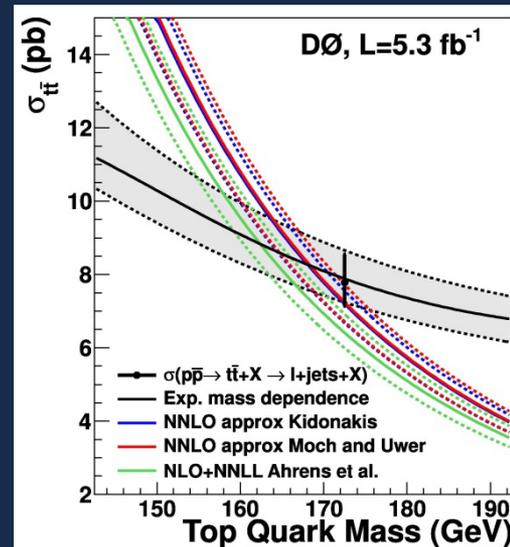


2014 H_T distribution

Just a handful of events at discovery, with relatively simple analyses by today's standards.

Top quark studies

With the large Run II data sets, several 1000 $t\bar{t}$ pairs are analyzed. The $t\bar{t}$ cross section measured up to 2012, $\sigma \approx 7.5$ pb to $<10\%$, agreed** with approx. NNLO QCD and indicates that we are measuring the pole mass. All decay channels, including all-jets and tau final states have now been analyzed.



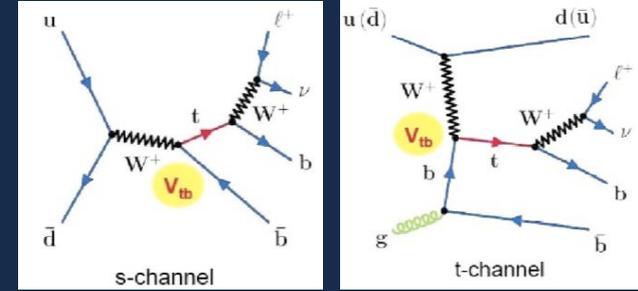
The 2012 CDF+DØ combined top mass measurement** gave 173.2 ± 0.9 GeV (0.55%). Limiting systematics are the light and heavy quark jet energy scales and PDF, ISR/FSR, color recombination. Despite larger LHC data samples, Tevatron still gives better top mass precision – a primary Tevatron legacy

Charge, couplings, lifetime, production properties, spin correlations, lack of 4th generation partner or $t\bar{t}$ resonances all confirm the SM.

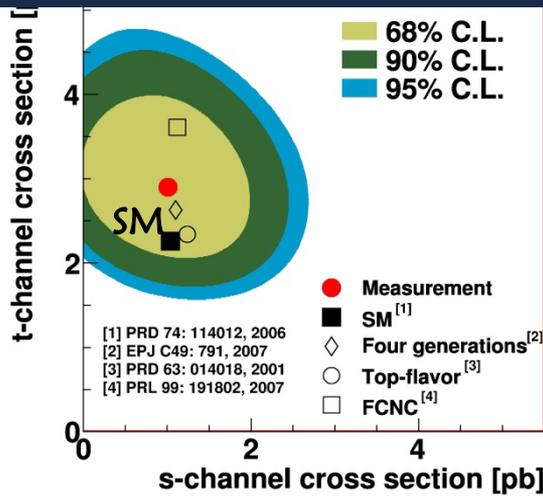
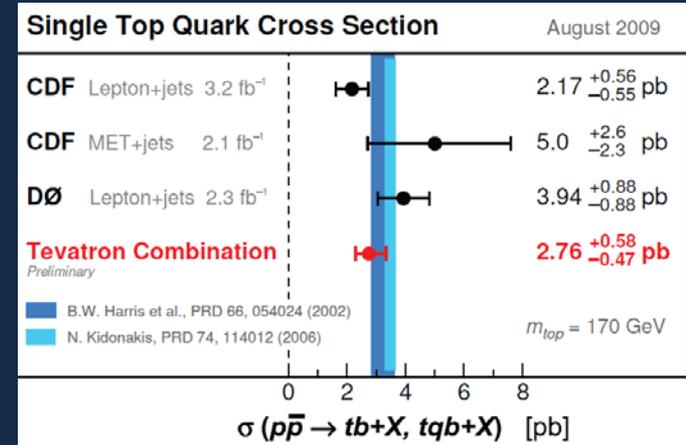
** : recent updates to come in subsequent talks

Single Top

Top quarks are pair-produced by the strong interaction (preserving flavor symmetry). Single top quarks can be produced by EW interaction via s-channel or t-channel W exchange). SM predicts $\sigma \approx 3.2$ pb. $D\bar{O}$ and CDF made first observations in 2009.



By now, analyses became more sophisticated; matrix element methods, use of multivariate (NNs, BDTs) to discriminate signal and background. Single top, with fewer objects and larger backgrounds represents a significant challenge.

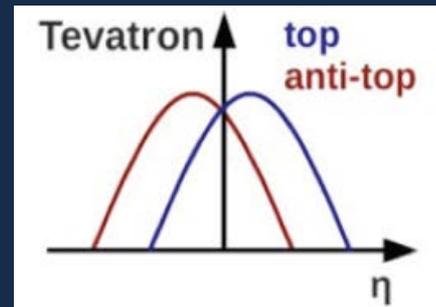


By 2011 the individual t-channel process was observed, with t-channel XS significance of 5.5σ . Measurements begin to rule out some models for new physics. The smaller s-channel XS was not yet unambiguously seen by 2012, but is consistent with the SM **

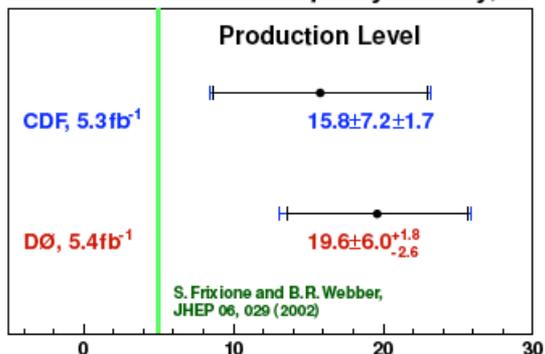
Measure the tbW coupling without 3 generation assumption: $|V_{tb}| = 0.95 \pm 0.02$ (SM = 1) **

Top F-B asymmetry

QCD predicts that top quarks slightly more likely emerge in the proton direction. Define $\Delta y = y_{\text{top}} - y_{\text{antitop}}$ and $A_{\text{FB}} = [N(\Delta y > 0) - N(\Delta y < 0)]/\text{sum}$.

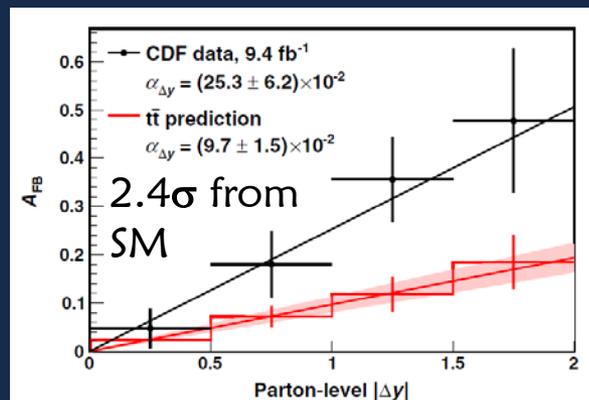
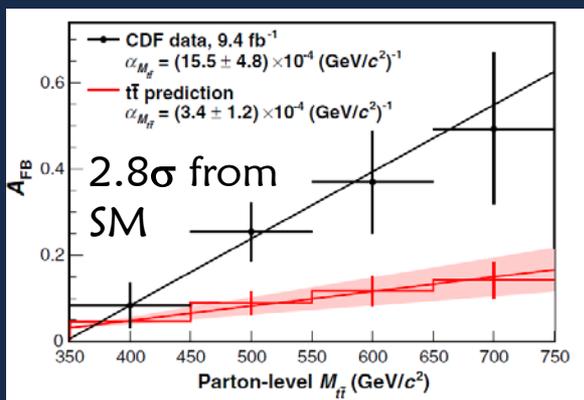


Forward-Backward Top Asymmetry, %



The asymmetry only appears in SM QCD at NLO, so there remain large theory uncertainties, but with half the data set, both CDF and D0 observed a larger A_{FB} than predicted.

With the full data set, CDF found A_{FB} , after correcting to the parton level, increasing with both $M_{t\bar{t}}$ and Δy . At reconstruction level, the measurements disagree with SM (POWHEG) at $\sim 2.5\sigma$.



The Tevatron, with $q\bar{q}$ collisions, is more favorable for this study than LHC. Work continues to illuminate this Tevatron legacy**.

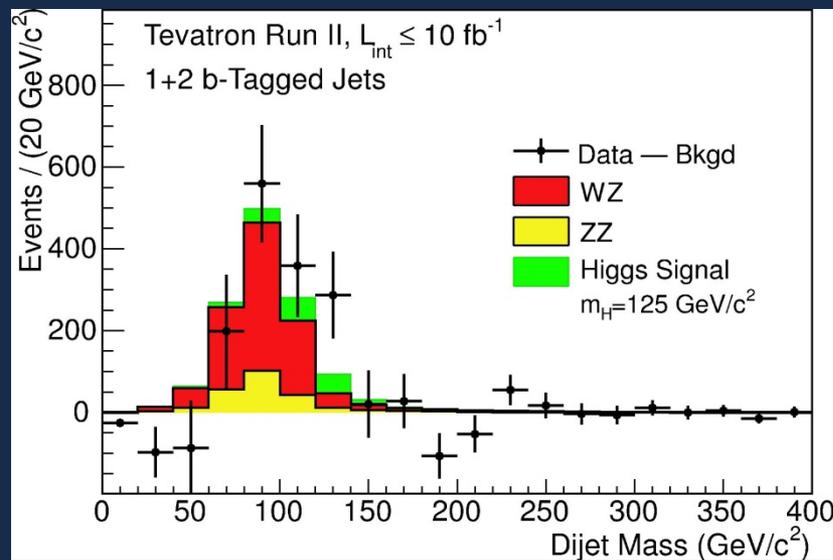
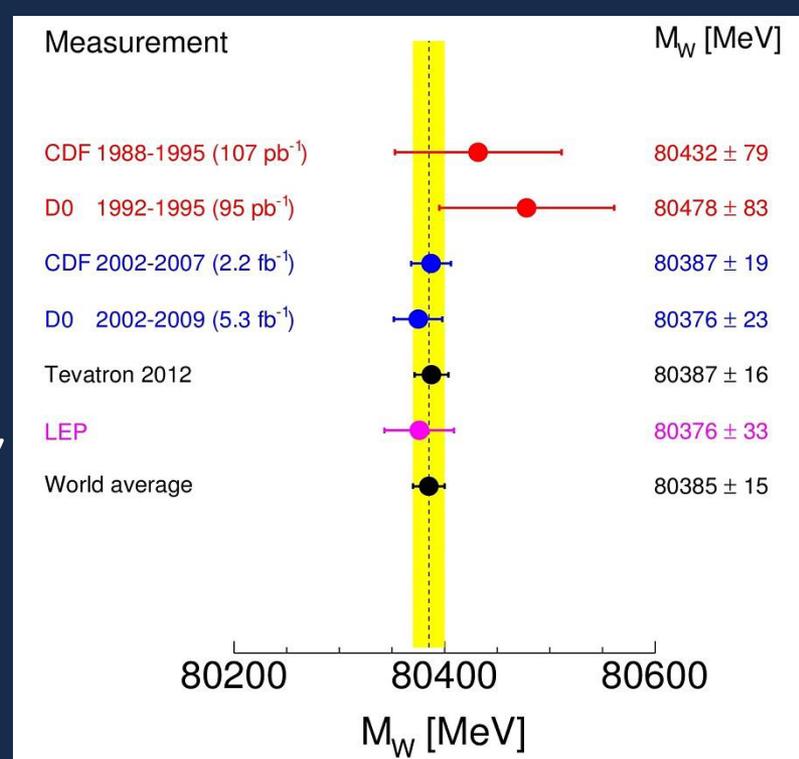
Electroweak measurements

The Poster Child measurement is the **W boson mass**. New World Average (LEP, Tevatron):

$$M_W = 80,385 \pm 15 \text{ MeV}$$

With full Run II statistics and extended rapidity coverage, hope for 10 MeV.

Tevatron precision will be hard to top at LHC.



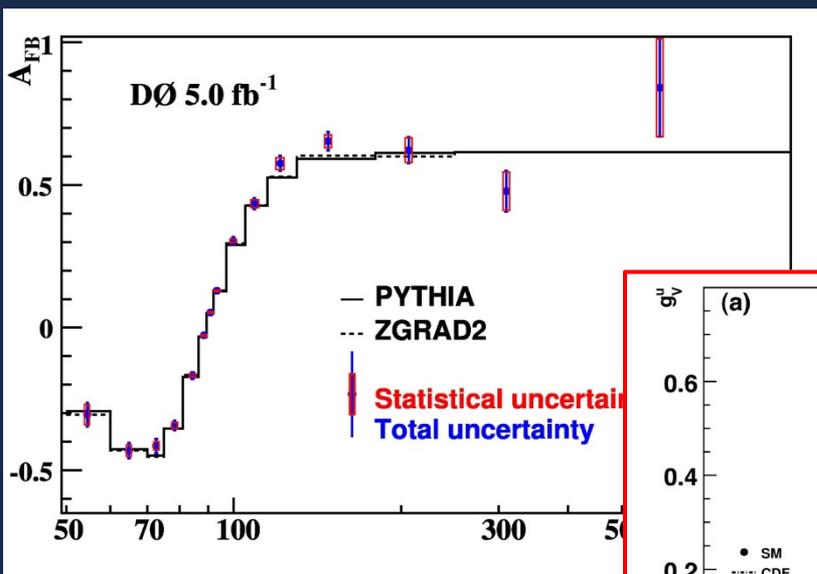
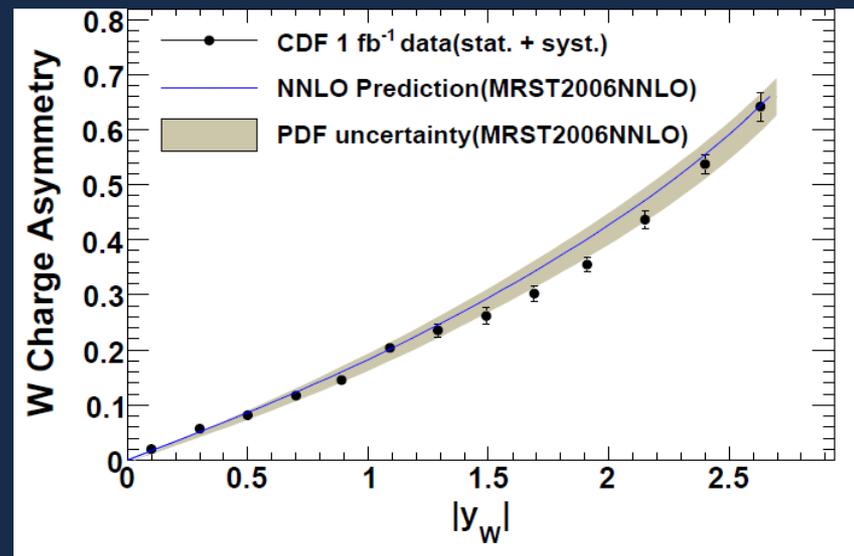
W/Z peak in $\ell\nu b\bar{b}$ – same channel as WH Higgs search

Diboson cross sections all measured – including $Z(\nu\nu)Z(ee)$ and $Z(bb)W(\ell\nu)$. These XSs are only a few times larger than Higgs XS, so measurements serve as validation of the Higgs studies. All agree well with SM.

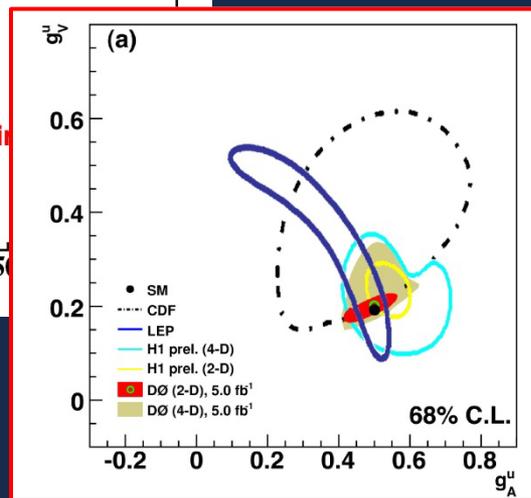
Anomalous TGCs now superseded by LHC.

Electroweak asymmetries

Forward-backward asymmetry of W bosons probes the u/d ratio in the proton (needed for modelling W mass). First measurements were decay lepton asymmetry. Now unfold to get W production asymmetry directly. **
 Unique to Tevatron ($p\bar{p}$).



F-B asymmetry in $Z\gamma^*$ vs. $m(ee)$ measures $\sin^2\theta_W$ for light quarks, and constrains non-SM couplings (here g_V^u vs. g_A^u) **.



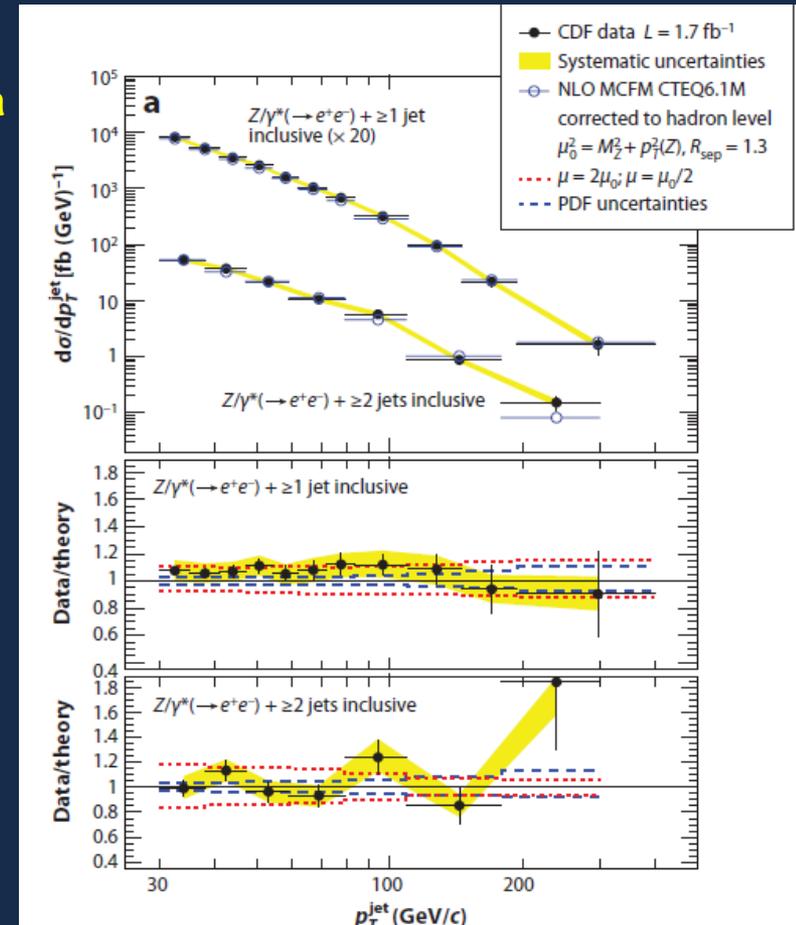
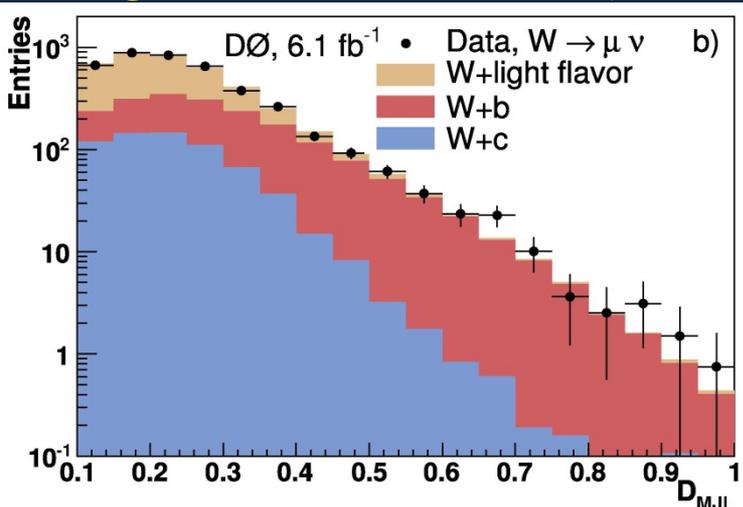
Also unique to Tevatron and more precise than LEP.

QCD production of EW bosons with jets

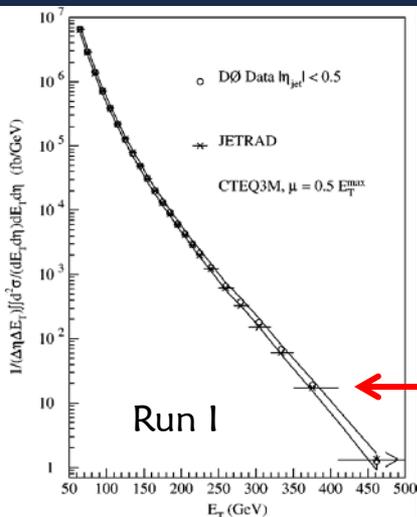
Measurements of γ , W , Z jets is in principle a test of QCD. However, QCD calculations and MC generators are generally not good enough to predict the V +jets cross sections as a function of p_T , γ , n_{jet} well enough to use for background estimation in rare processes (Higgs, VBS etc). CDF/DØ have made numerous γ, V +jets measurements.

W/Z + jet distributions have been measured as a function of M_{jj} , p_T^j, p_T^V , γ , $\Delta\gamma$, etc. for $n_{jet} \leq 4$

Measurements of $\gamma/W/Z$ + (c,b) jets** have been made. These processes are dominant backgrounds for many rare processes.



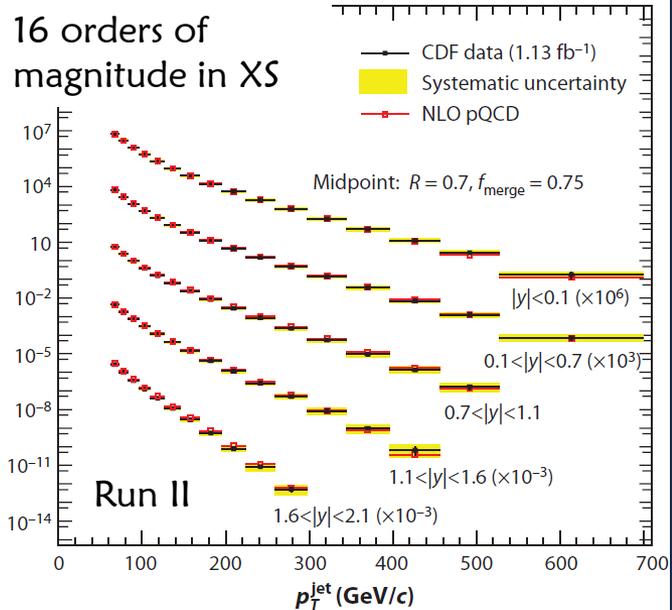
QCD studies with jets



QCD production of jets allows tests of the underlying theory, provides information on PDFs, and is sensitive to new physics. Initial results for $E_T \leq 450$ GeV evolved to cover $E_T \leq 700$ GeV, $|y| \leq 2$.

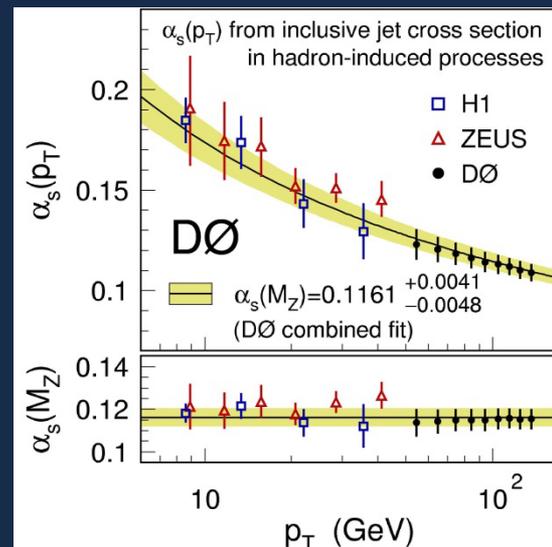
16 orders of magnitude in XS

$$\left[\frac{d^2\sigma}{dY dp_T} \right] \left[\frac{nb}{GeV} \right]$$



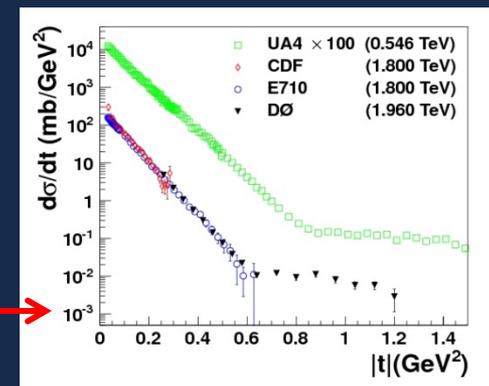
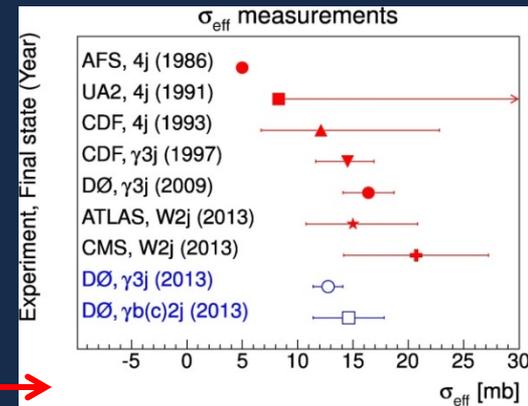
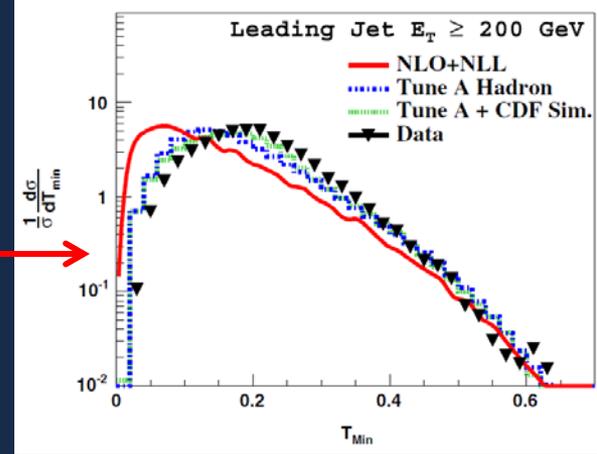
pQCD jet studies include dijet masses, angular distributions and excited quarks, multijet production, dijet correlations, quark/gluon discrimination, etc. These have led to refinements in event generators, PDFs, treatment of higher order QCD.

Running of α_s has been established out to $Q^2 = 2 \times 10^4 \text{ GeV}^2$



Non-perturbative QCD

- ❖ Event shape analyses (thrust etc.) allow tunes to MC generators for hadronization and underlying event.
- ❖ Momentum correlations among particles show that the fragmentation process preserves the underlying partonic correlations.
- ❖ Color flow/interference pattern between jets seen
- ❖ Growth of XS with Δy_{jet} at fixed x_1, x_2, Q^2 shows BFKL-like behavior
- ❖ Double parton scattering within colliding protons measures the spatial distribution of partons within the proton. **
- ❖ Hard diffraction production of high mass states ($jj, ll, \gamma\gamma, W/Z, J/\psi$) with color singlet t-channel exchange favors color-singlet two gluon structure for Pomeron.
- ❖ Elastic scattering XS shows larger slope in $|t|$ and decrease in t value of kink, relative to $SppS$.



Searches for BSM physics

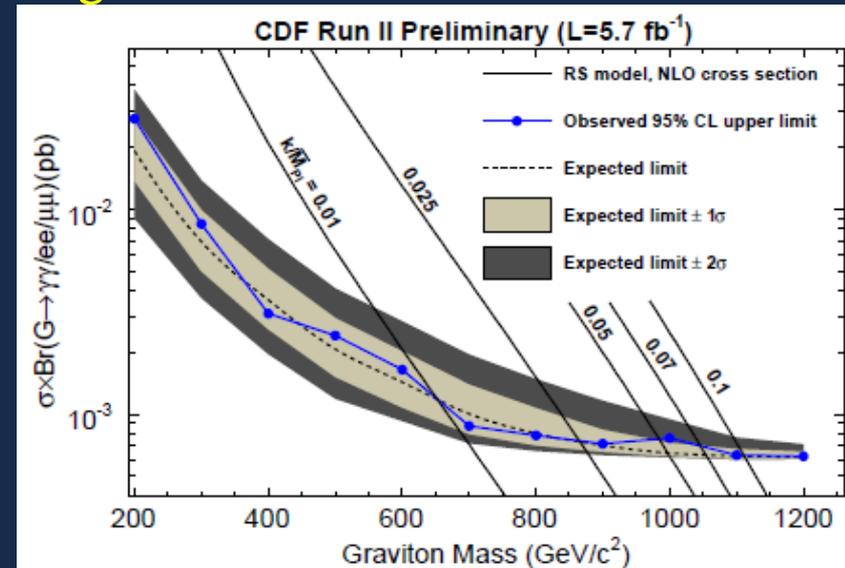
The New York Times

“400 Physicists Fail to Find Supersymmetry” (1992)

As well as ...

- ❖ Leptoquarks
- ❖ Randall Sundrum gravitons
- ❖ Scalar quarks
- ❖ 4th generation quarks
- ❖ Dark photons
- ❖ Long-lived quarks
- ❖ Excited quarks, leptons, vector bosons
- ❖ Kaluza Klein bosons
- ❖ Cannonballs
- ❖ Axiguons
- ❖ Quirks
- ❖ Anomalous couplings of W/Z/top
- ❖ Magnetic monopoles
- ❖ Signature based searches, etc.

e.g.



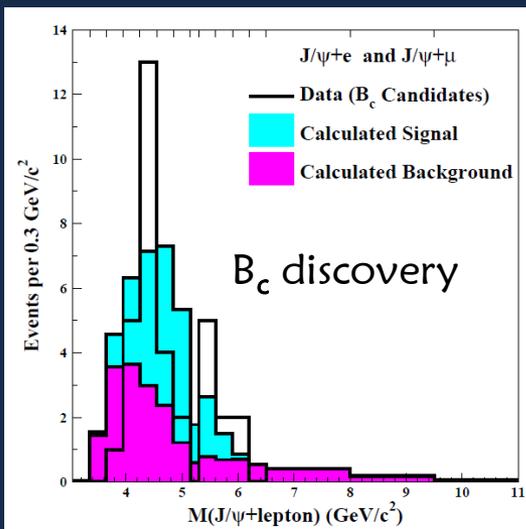
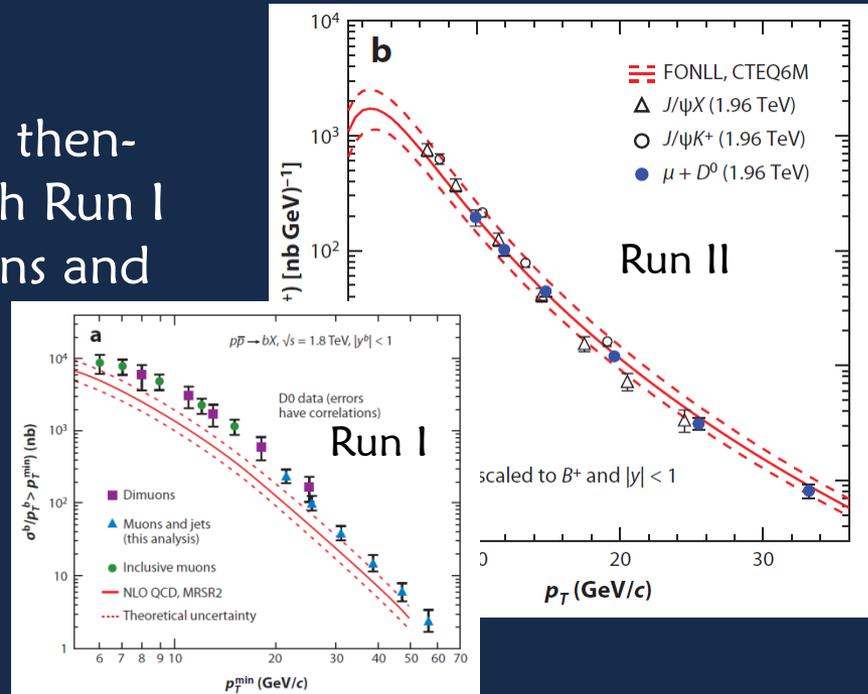
Nearly half of the Tevatron publications reported null searches for new phenomena.

We devoutly wish for better success at the LHC!

Heavy Flavor Studies

Run I B production data disagreed with then-current theory. Run II data agreed with Run I but improved collinear gluon calculations and treatment of fragmentation brought theory into agreement.

The large cross sections and available energy opened the way for observation of new HF states:

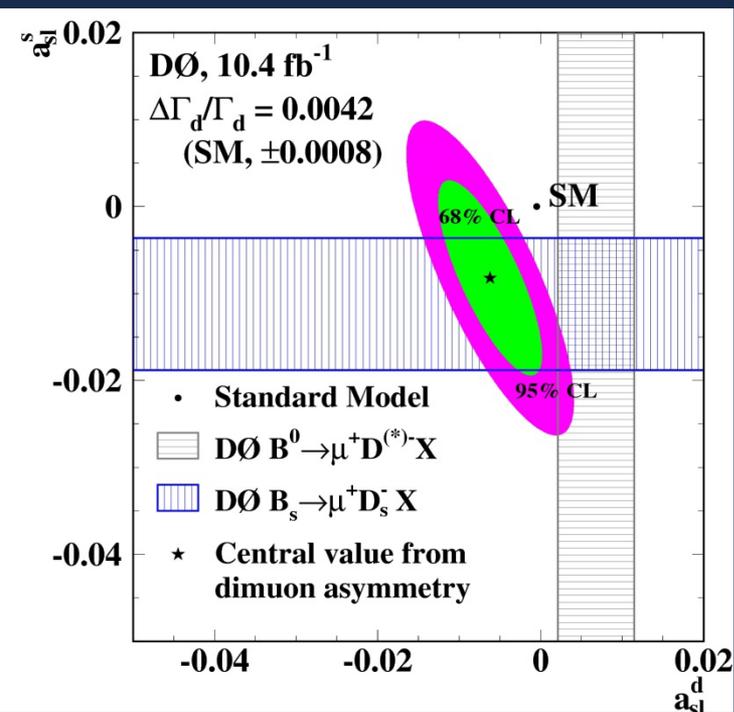
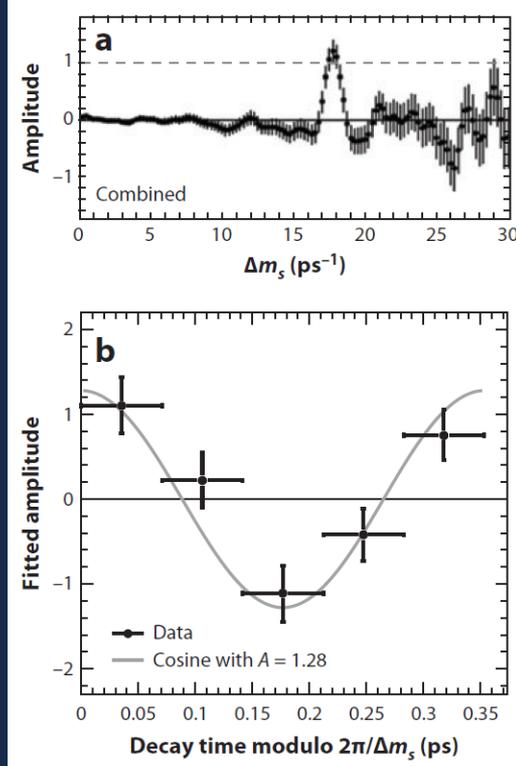


Also: $\Sigma_b^\pm, \Xi_b^-, \Omega_b$ and 1st completely reconstructed B_s .
 Observations of $X(3872), Y(1S)+\gamma$ states, orbital excitations of B_s . Evidence for $Y(4140)$,

Many world-leading HF lifetimes allow precise tests of HQET: $B_u, B_d, CP\text{-odd } B_s, \Lambda_b, \Xi_b, \Omega_b \dots$

Heavy Flavor Studies

First observations of the very rapid ($\sim 1/3$ ps) B_s oscillations yielded $\Delta m_s = 17.77 \pm 0.12$ ps $^{-1}$. The ratio $\Delta m_s/\Delta m_d$ cancels hadronic uncertainties in calculating $V_{ts}^*V_{td}$.



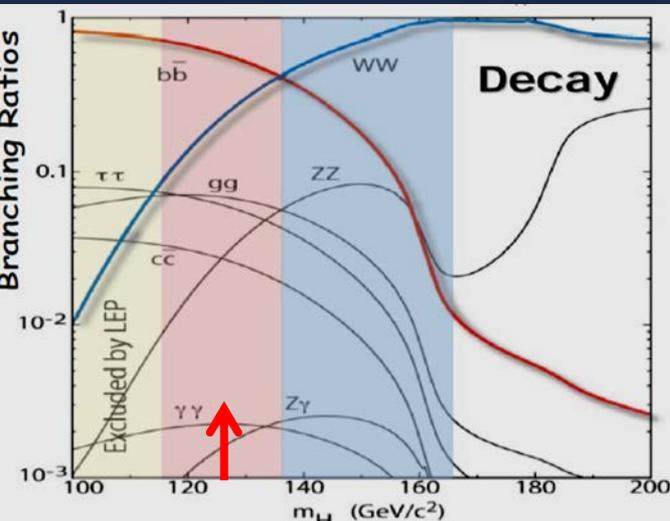
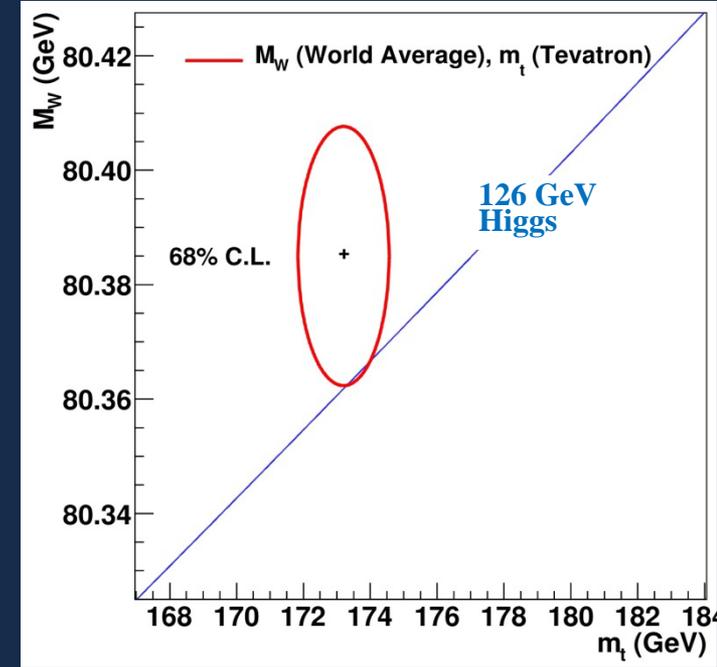
CP violation searches in B_s decays: Measured asymmetries in $B_q \rightarrow \bar{B}_q \rightarrow \mu^+ X$ and its conjugate ($q=d$ or s). The dimuon like sign asymmetry ($\mu^+\mu^+$ vs. $\mu^-\mu^-$) is sensitive to both B_s and B_d . The $D\emptyset$ measurements used the capability to reverse magnet polarities, thus cancelling detector asymmetries. Like-sign dimuon asymmetry is 3.6σ from SM.**

Higgs boson

What Tevatron legacy?? The Higgs was discovered at LHC and its properties are being measured there!

The combination of the precise measurements of top and W masses at Tevatron, with LHC Higgs mass give a stringent test of SM consistency.

And, does it decay dominantly to bb ?



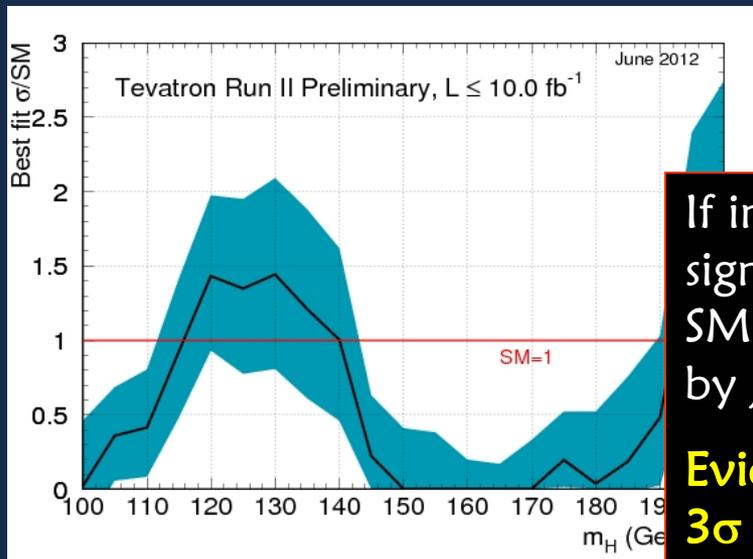
At Tevatron, dominant gg fusion production is inaccessible (QCD backgrounds) until the $H \rightarrow WW^*$ channel opens at higher Higgs mass. At low mass where $H \rightarrow bb$ dominates, rely on VH production with $V \rightarrow$ leptons.

The observed Higgs is near the boundary of these two regimes. Tevatron measurements use VH , gg , VBF production and decays to WW , ZZ , bb , $\tau\tau$, $\gamma\gamma$.

Higgs boson

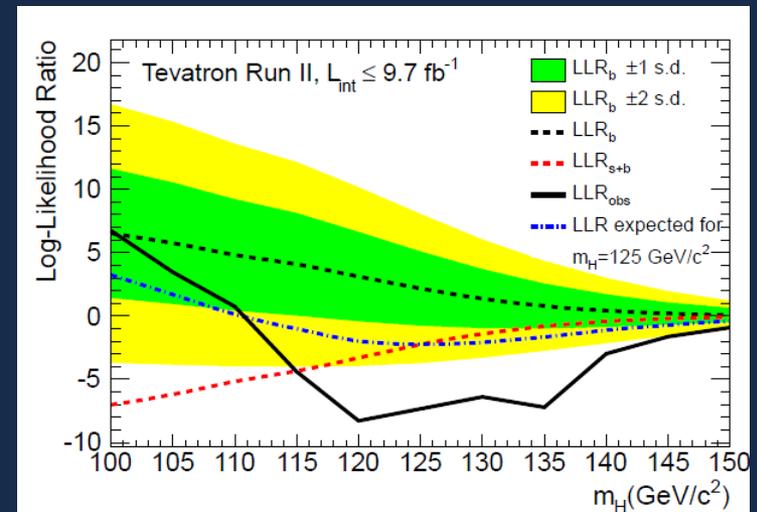
~100 individual production/decay channels searched by CDF and DØ, making extensive use of multivariate (NN, BDT, ...) methods to distinguish signal and backgrounds. The shapes of the MVA distributions in the background dominated regions are used to constrain systematic uncertainties. Bayesian (CDF) and modified frequentist (DØ) limit setting methodologies agree to <5%.

In July 2012, published combined CDF/DØ analyses of $W/Z H$ in final states $bb + (\ell\ell \text{ or } \ell\nu \text{ or } \nu\nu)$.



If interpreted as $H \rightarrow bb$ signal, XS agrees with SM. Width controlled by jet resolution.

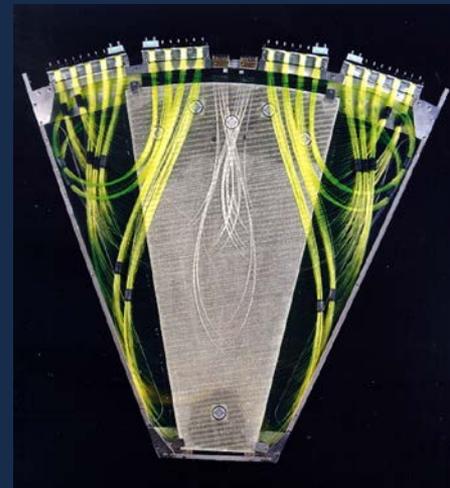
Evidence for $H \rightarrow bb$ at 3σ level, including LEE.



Subsequent updates include all channel combinations, boson/fermion couplings, J^P in bb^{**}

Other legacies

- ❖ A large number of physicists with experience in hadron collider physics for the LHC experiments
- ❖ New collider detector techniques introduced:
 - 4π silicon vertex detectors
 - highly granular calorimetry
 - multi-stage trigger architectures
 - multivariate techniques for object ID, background suppression, etc.



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



We have seen the progression of our knowledge of the particle universe, and of new experimental techniques, from ISR to SpS to Tevatron to LHC.

Each new step builds on what went before.

P. Jenni, PG, Phys. Today, 66(6), 38 (2013)

Recent results

Many new important results from the Tevatron since 2012 – to be covered in subsequent talks.

Top:

- top mass combination and new individual measurements
- tt cross section
- s-channel single top
- FB asymmetry
- Top width

EW:

- W and $W \rightarrow \ell$ FB asymmetries
- Z decay asymmetry & $\sin^2\theta_{\text{W}}(ud)$
- AQGC limits
- Diboson cross sections

Higgs:

- Full Tevatron combination, $\kappa_{\text{V}}/\kappa_{\text{f}}$
- Final specific Higgs channels
- J^{P} in $H \rightarrow b\bar{b}$

QCD:

- 3jet/2jet ratio
- γ +jets, γ +c/b jets
- W/Z + b/c
- $W+n_{\text{jets}}$
- $\gamma\gamma$ production
- Double parton interactions
- Dijet azimuthal decorrelations

HF:

- Like sign dimuon CP asymmetry
- Semileptonic CP asymmetries
- CPV in $B_s \rightarrow J/\psi K$
- CPV in $D_s \rightarrow \phi\pi$
- $\bar{D}D$ mixing
- Evidence for X(4140)
- Orbitally excited B mesons
- $B_s \rightarrow \mu\mu$

The Tevatron Physics Legacy

- ❖ Top quark discovery and its properties
- ❖ Single top production (s and t channel processes)
- ❖ Precision W boson mass measurement
- ❖ Higgs to $b\bar{b} \rightarrow$ SM-like Higgs boson
- ❖ B_s mixing
- ❖ New heavy flavor hadrons
- ❖ Wide range of measurements of QCD processes involving jets, γ , W , Z

The SM emerged nearly unscathed from the Tevatron campaign despite the fact that it has no business doing so well ($>3\sigma$ CP asymmetry in B_s decays remains but other hints disappeared).

We wish the LHC luck in cracking the SM façade!