Tevatron Highlights

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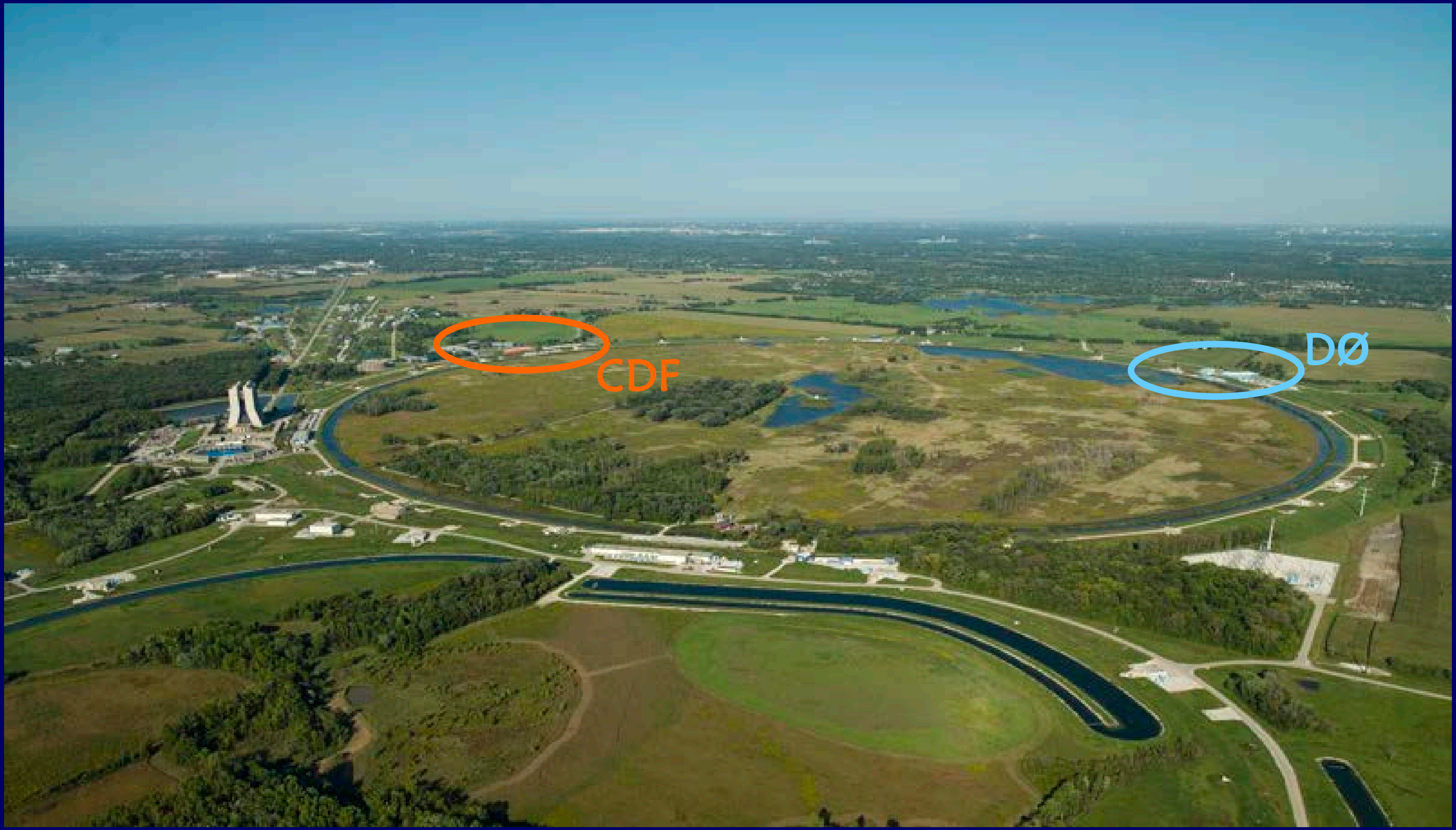

Fermilab Users Meeting
P. Grannis, June 21, 2018
for the CDF and D0 Collaborations

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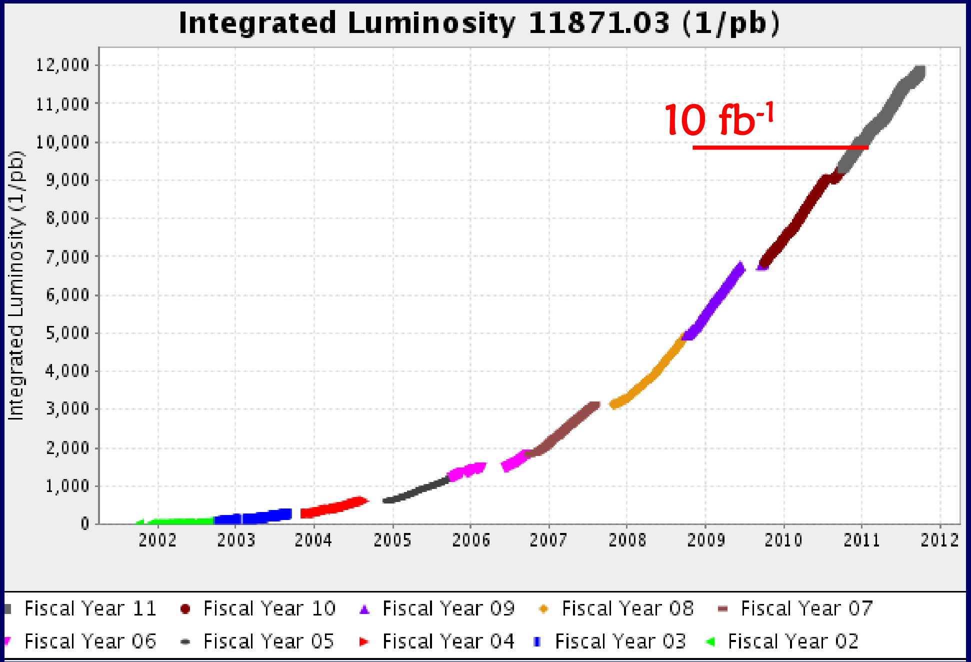
The Tevatron Collider

Run 0 1987 – 1988: 1.8 TeV, CDF only, 4 pb^{-1}

Run I 1992 – 1996: 1.8 TeV, CDF+D0: 120 pb^{-1}

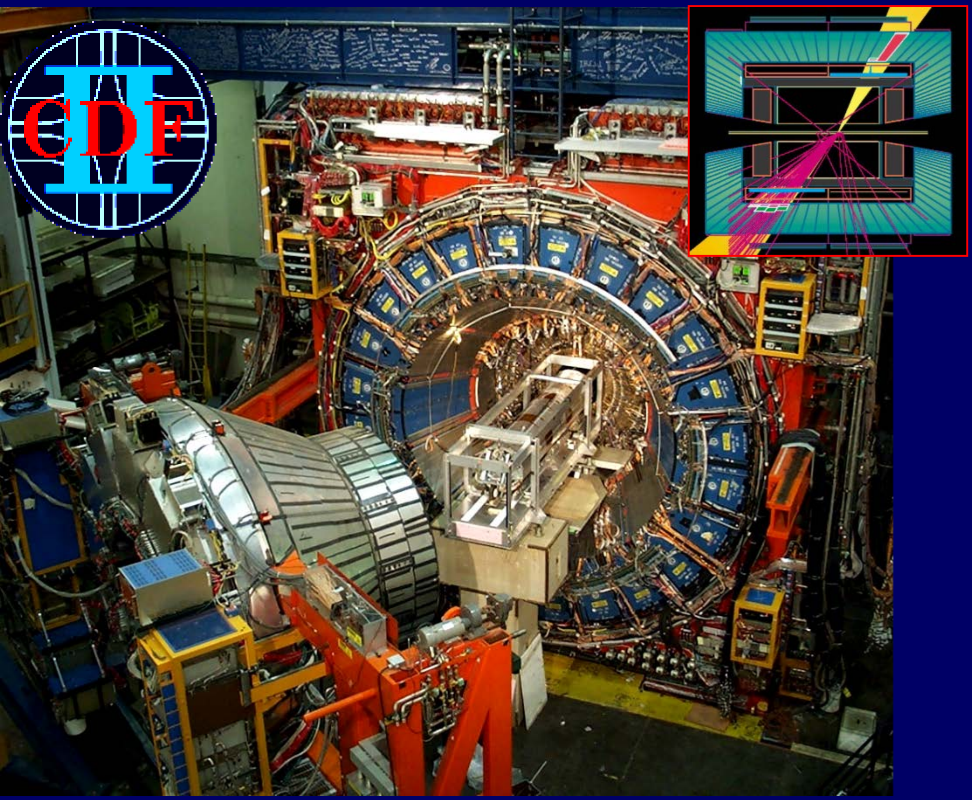
Run II 2001 – 2011: 1.96 TeV, 12 fb^{-1}. Added Main Injector, Recycler, helical orbits, magnet alignment …

Max. Instantaneous L ≈ 4.3×10^{32} $cm^{-2}\ s^{-1}$ (30M collisions/s)



The superb performance of the Tevatron complex was the foundation for the physics accomplishments of CDF and D0. We are indebted to the scientists and engineers of the Accelerator Division.

The experiments



CDF and DØ were quite different in Run I. Major detector upgrades for Run II:

CDF: new tracker, new Si vertex det, upgraded forward calorimeter and muons

DØ: add solenoid, fiber tracker, Si vertex and preshower detectors, new forward muon detectors.

The upgraded experiments looked more like each other, but still with complementary strengths. Cross checks with >1 experiment were crucial!

Publications since Users Meeting 2016

(No report in 2017 due to Fermilab's 50th)

1. Search for fermiophobic Higgs: Phys. Rev. D 93, 112010 (2016) CDF
2. WW and WZ XSs with $\ell^{\pm}$ and heavy flavor jets: Phys. Rev. D **94**, 032008 (2016). CDF
3. Spin correlation between top and antitop: Phys. Lett. B **757**, 199 (2016). D0
4. B_s^0 lifetime in the CP-odd $B_s \rightarrow J/\psi\ f_0(980)$: Phys. Rev. D **94**, 012001 (2016). D0
5. Evidence for a $B_s\ \pi$ state: Phys. Rev. Lett. **117**, 022003 (2016), D0
6. Top mass using matrix element method in dileptons: Phys. Rev. D **94** , 032004 (2016). D0
7. Inclusive ttbar XS and top quark pole mass: Phys. Rev. D **94**, 092004 (2016). D0
8. Top quark polarization in ttbar lepton + jets: Phys. Rev. D **95**, 011101(R) (2017).) D0
9. Direct CPV charge asymmetry in $B^{\pm} \rightarrow \mu^{\pm}\ \nu_{\mu}\ D^0$: Phys. Rev. D **95**, 031101(R) (2017). D0
10. D^+ meson cross section at low p_T : Phys. Rev. D **95**, 092006 (2017). **** CDF pub.# 700**
11. Combination of D0 measurements of top mass: Phys. Rev. D **95**, 112004 (2017). D0
12. Observation of Y(4140) in $B^{\pm} \rightarrow J/\psi\phi\pi$ K decays, Mod. Phys. Lett. **A32**, 1750139 (2017) CDF
13. Inclusive Isolated prompt photon cross section: Phys . Rev. D **96**, 092003 (2017). CDF
14. Combined F-B asymmetry in ttbar production: Phys. Rev. Lett. **120**, 042001 (2018). CDF + D0
15. Search for exotic meson X(5568): Phys. Rev. Lett. **120**, 202006 (2018). CDF
16. Study of X(5568)→Bs π in semileptonic Bs decays: Phys. Rev. D **97**, 092004 (2018). D0
17. Effective weak mixing angle in $Z \rightarrow \ell^+\ell^-$: Phys. Rev. Lett. **120**, 241802 D0
18. Tevatron combination of $\sin^2\theta_{eff}{}^{lept}$: Phys. Rev. D, in press (2018).). CDF + D0

Publications since Users Meeting 2016

The Tevatron results over the past two years still represent 40% of the physics papers based on Fermilab accelerator operations. (The rest are almost all neutrino cross sections and oscillation measurements.)

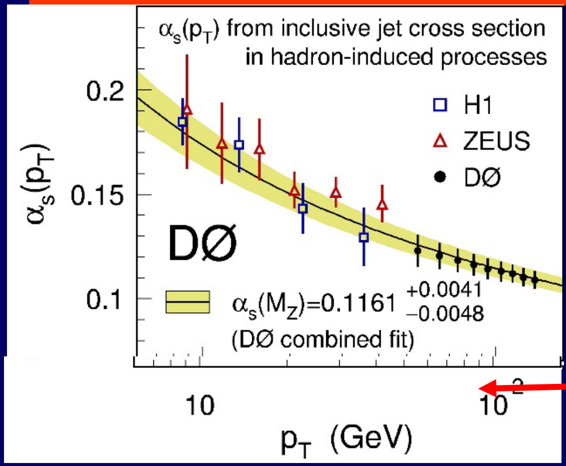
Even during the LHC era, the Tevatron papers have added significantly to our understanding of:

- QCD
- Heavy flavor physics
- Electroweak interactions
- Top quark
- Higgs boson
- (but very little to searches for new phenomena!)

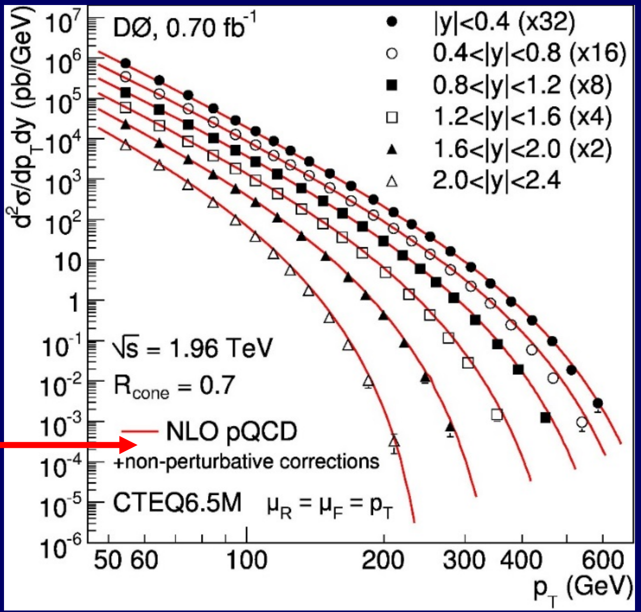
The highlights to follow cover some of the Tevatron legacy results, as well as some since the last Users' meeting report (marked **)

We have benefitted greatly from the Computing Division's support of the CDF and D0 hardware platforms and software systems, particularly in keeping our aging systems going.

Highlights – QCD



Many textbook results on jet production: good agreement with pQCD over 9 orders of magnitude

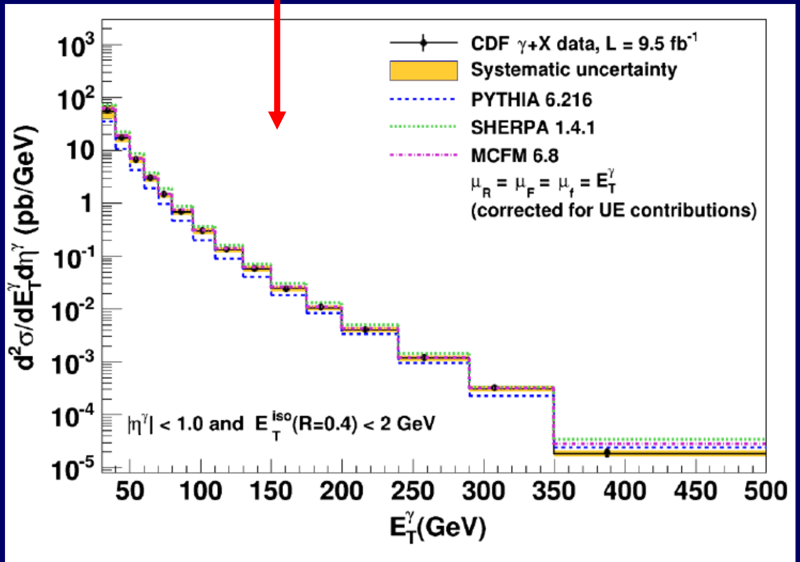


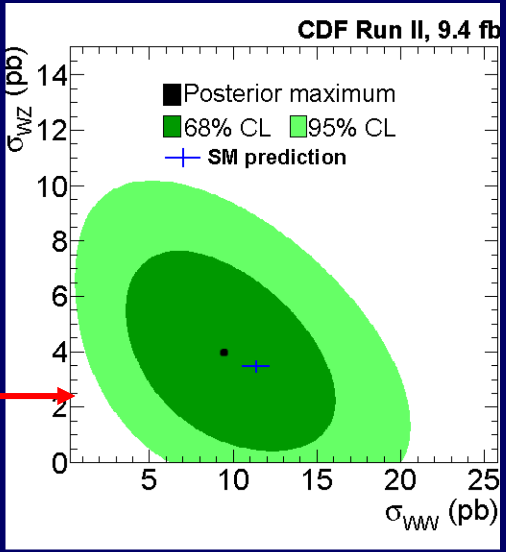
Inclusive jet XS vs p_T

Running of α_s

Many measurements of W/Z + jets vs. p_T^{jet}, η_{jet}, N_{jets}, jet flavor …

** CDF prompt isolated photon XS $p_T^{\gamma}<0.5$ TeV (1/2 E_{beam})



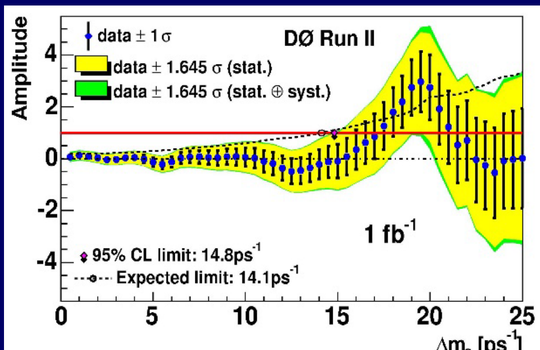


** recent CDF WW/WZ production with decays to $\ell\nu$ + bq/cq

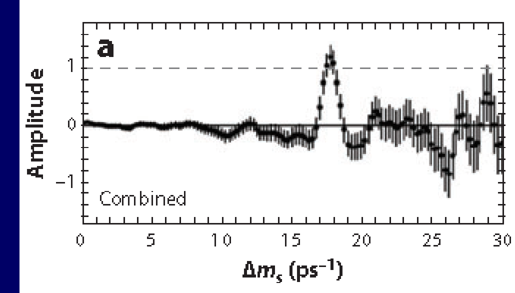
Double parton scattering in single $p\bar{p}$ collision for various processes implies that gluons occupy smaller volume than quarks

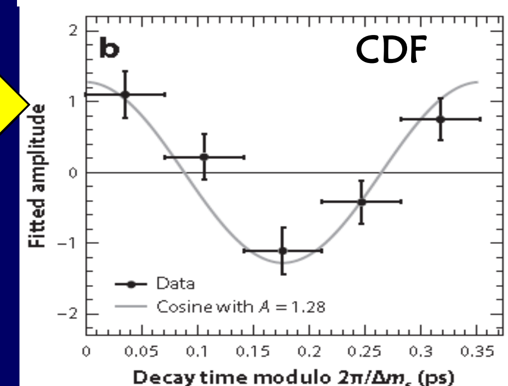
Highlights – Heavy Flavor

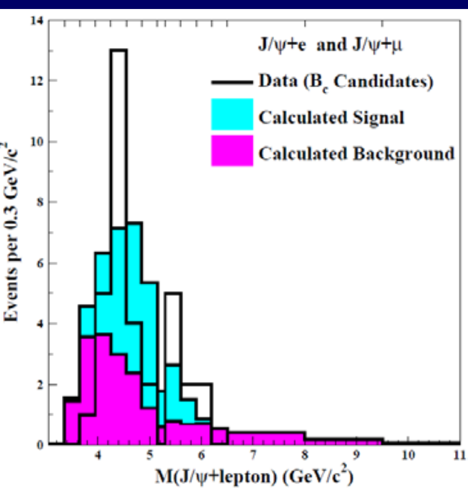
Surprisingly strong Tevatron contributions to heavy flavor.



2006: First evidence and subsequent observation of B_s mixing, consistent with SM prediction, thus constraining sources of new physics.

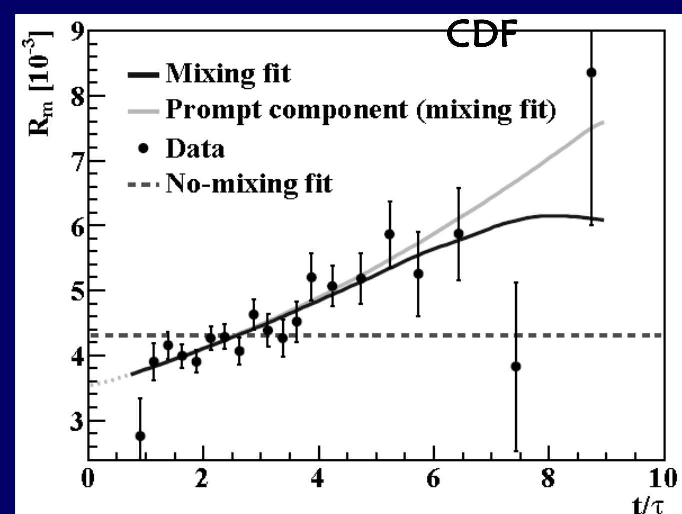






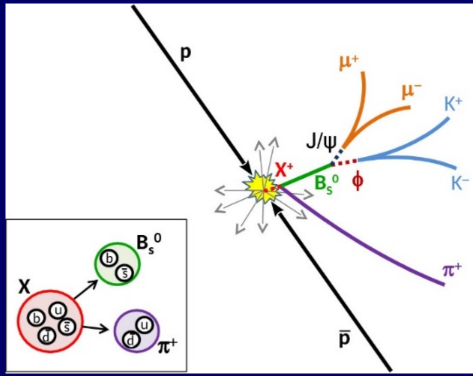
Discovery of B_c (& Σ_b, Ξ_b, Ω_b), charmless B_s decay, evidence for CP violation in $\mu^+\mu^+/\mu^-\mu^-$ asymmetry …

The mixing of D and $\bar{D}$ was difficult to observe since the mixing period >> decay time. The 2013 CDF measurement found 6.1σ significance for mixing.



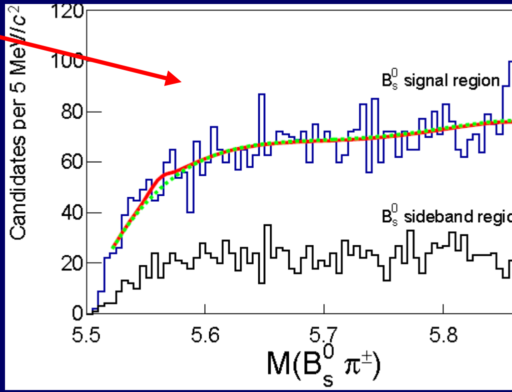
Highlights – Heavy Flavor

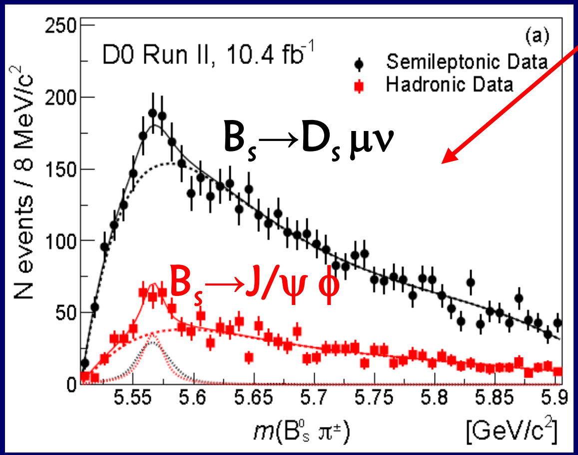
Exotic hadrons with additional $q\bar{q}$ pairs to the usual $q\bar{q}$ (meson) or qqq (baryon) have long been predicted but only recently seen, both in e^+e^- and hadron collisions. Those with heavy flavor are easier to identify than purely light quark exotics due to distinctive decays and lower backgrounds. CDF and D0 have added important new information on exotics' production mechanisms (e.g. **prompt vs. in decay products).



** In 2016 D0 published strong evidence for a new state $X(5568)^+ \rightarrow B_s^0\,\pi^+$ with $B_s^0 \rightarrow J/\psi\,\phi$. The minimal quark content is $b\bar{s}u\bar{d}$ – the first exotic state with 4 quark flavors. LHC experiments did not see it in pp collisions.

** In 2018, CDF did not observe X(5568) in $B_s^0 \rightarrow J/\psi\,\phi$ but ** D0 did see it in $B_s^0 \rightarrow D_s^+\,\mu^-\,\nu$. A combined fit of the two channels gives significance=6.7σ.

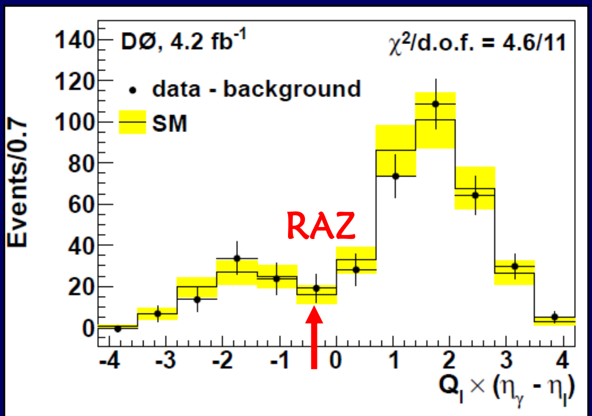




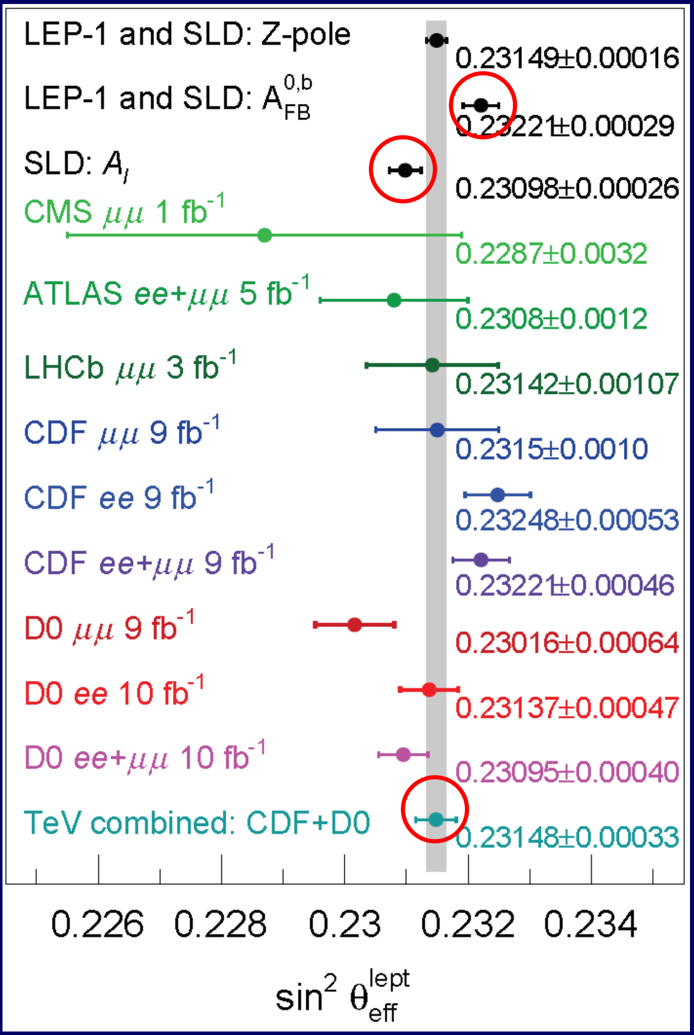
A puzzling situation: D0 signal comes primarily when at least one μ from J/ψ is outside CDF coverage.

Highlights – Electroweak

W boson mass (CDF+D0) measured 16 MeV (0.02%) uncertainty – one of the most powerful tests of the EW sector of the Standard Model.

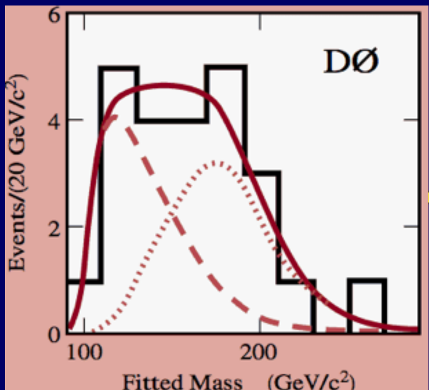


Many measurements of vector boson trilinear couplings. Here, the first observation of **Radiation Amplitude Zero in WWγ** coupling due to interference of s- and t-channel processes.



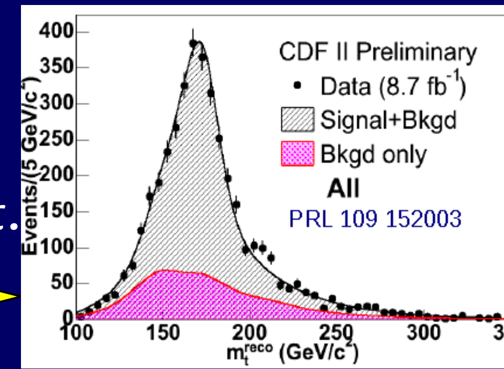
** (2018, PRD in press): Measure the **weak mixing angle** that governs EWSB using the $Z\rightarrow\ell^+\ell^-$ F-B asymmetry. Combined Tevatron result ($\delta\sin^2\theta_{eff}$=0.00033) rivals the precision of 20-year old LEP-1 and SLD measurements (δ=0.00029 and δ=0.00026) and is midway between them, and also in excellent agreement with world average.

Highlights – Top Quark



1995 at discovery
(13 D0 tt events)

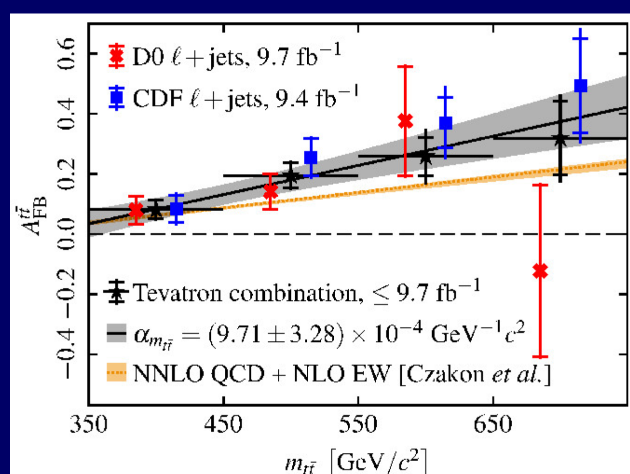
1995 top quark discovery by CDF and D0 was the most notable Tevatron result.

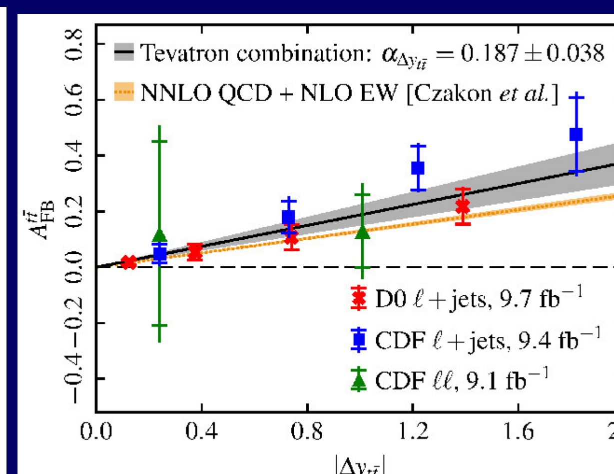


2013 near final ∫ℒdt
(~3000 CDF tt events)

Early measurements of forward-backward $t\bar{t}$ asymmetries showed excess over SM prediction both vs. m_{tt} and y_{tt}, suggesting possible non-SM physics.

** Recent combination of final CDF and D0 measurements agree with new Standard Model NNLO(QCD) +NLO(EW) theory.

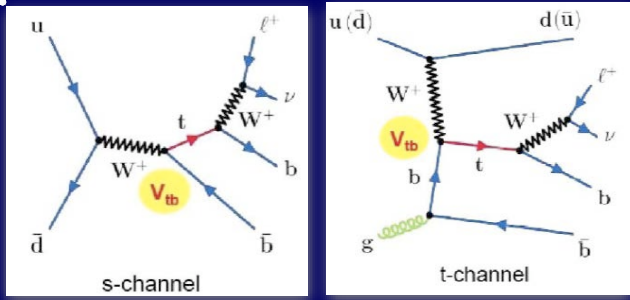




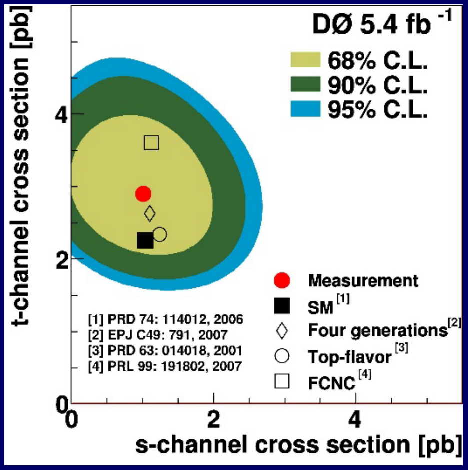
Highlights – Top Quark

The fact that top decays before hadronizing allows measurements of top charge, polarization, spin correlations, lifetime, CPT violation, decay W helicity, and searches for FCNC, resonances, anomalous couplings etc.

** D0 combination of top mass using comparison to MC templates (based on the matrix element method) for all channels: m_t = 174.95 ± 0.75 GeV (0.4%) (CDF analysis is in progress).
Also measure theoretically well-defined top pole mass by comparing measured σ_{tot} with m_t-dependent QCD NNLO/NLL calculations.



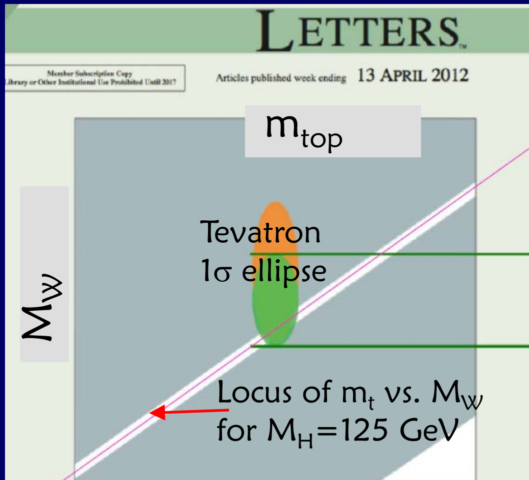
Single top quark production via EW reactions was first discovered in 2009. Both s- and t-channel W exchange processes were observed.

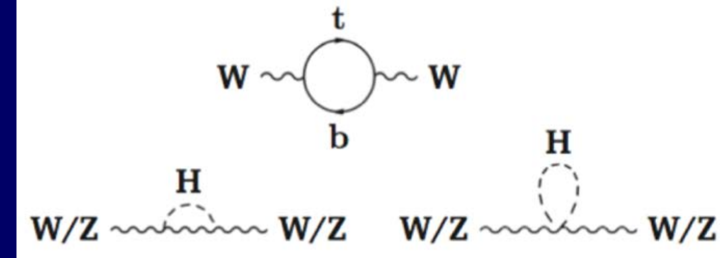


Although single top cross section is about ½ of pair production, fewer final particles and higher backgrounds make this an exquisitely difficult measurement. Multivariate methods to separate signal and background were essential.

Comparison of s- and t-channel XS constrain new physics.

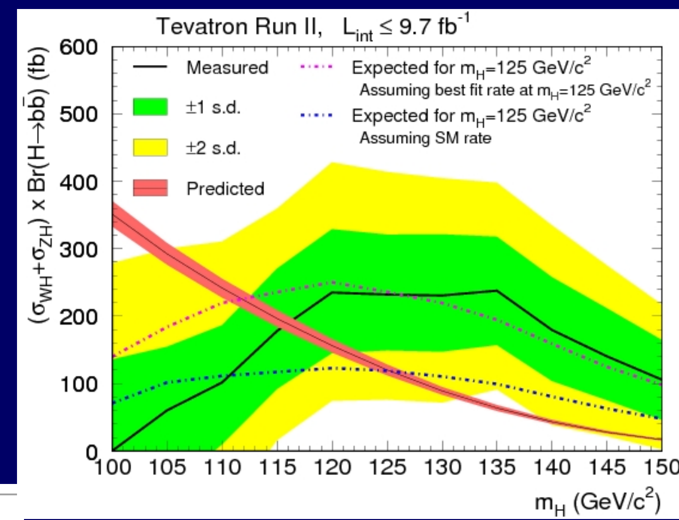
Highlights – Higgs boson

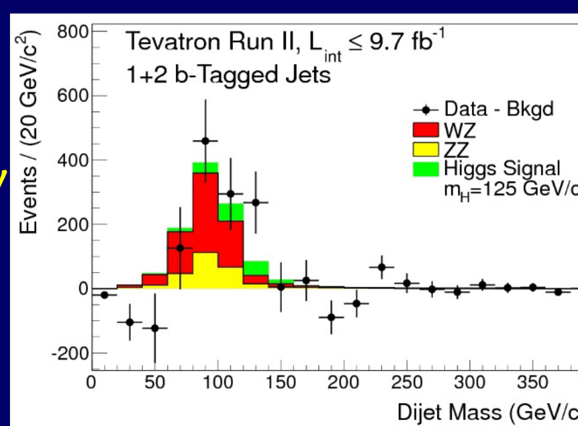




The top and W masses measured in the Tevatron are modified in the SM by loop corrections involving the Higgs, and thus told us where to look for the Higgs. CDF & D0 combined to exclude $149 < M_H < 182$ GeV in direct searches.

The Higgs was discovered in 2012 at LHC in the γγ & ZZ decays. Simultaneously, CDF & D0 obtained the first 3σ evidence for H→bb using the combined W(ℓν)H, Z(ℓℓ)H and Z(νν)H channels. This preceded the LHC evidence for fermionic Higgs decays by 4 years and was the first direct evidence for the Higgs Yukawa coupling.





Higgs analyses validated by observing W(ℓν)Z(bb) & Z(ℓℓ)Z(bb) at the SM level in the same final states.

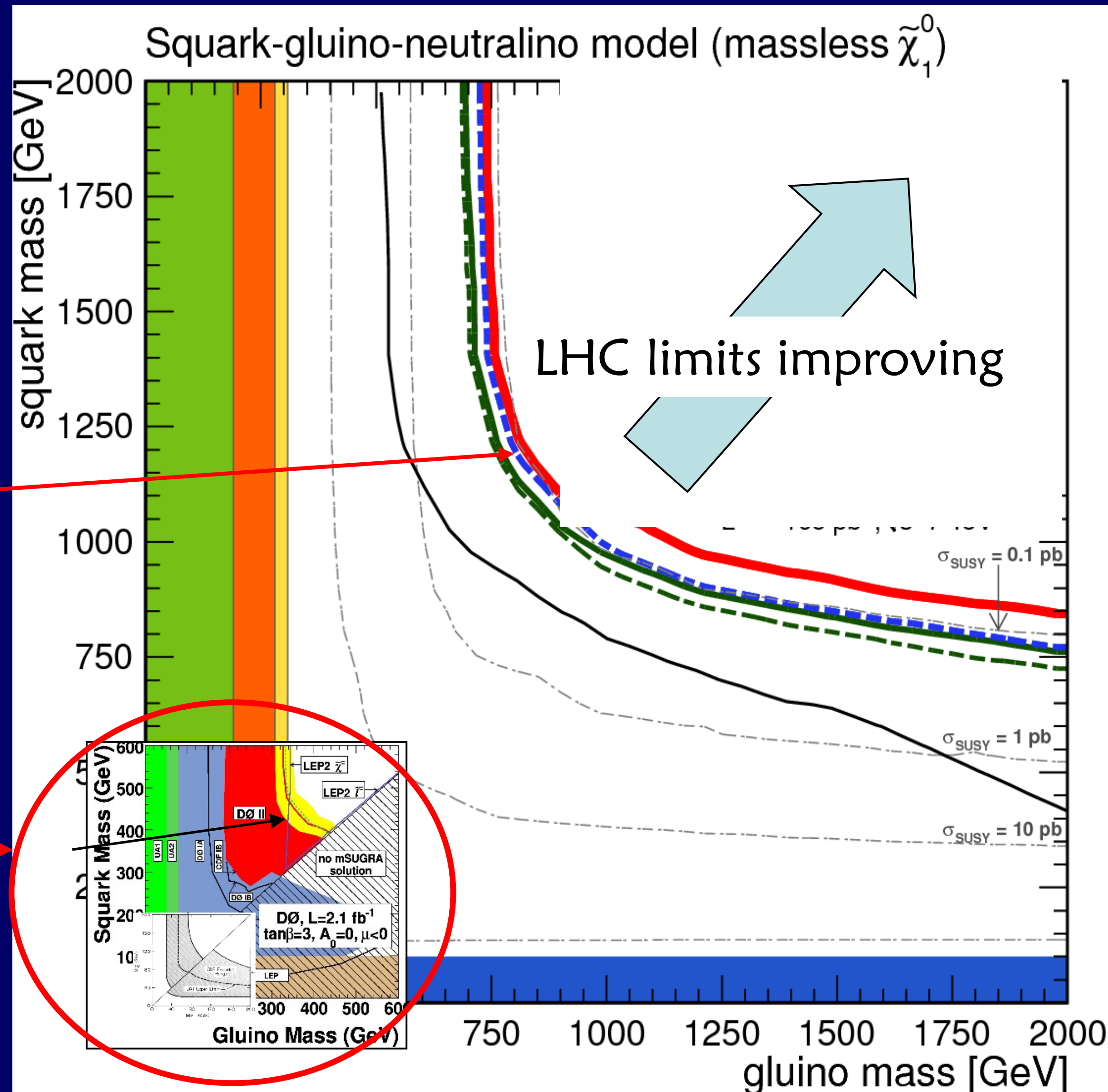
** CDF rules out fermi-ophobic Higgs partner for $10 < M_h < 100$ GeV

Highlights – New phenomena

LHC has overtaken Tevatron in almost all aspects of searches

LHC squark gluino limits (already in 2011)

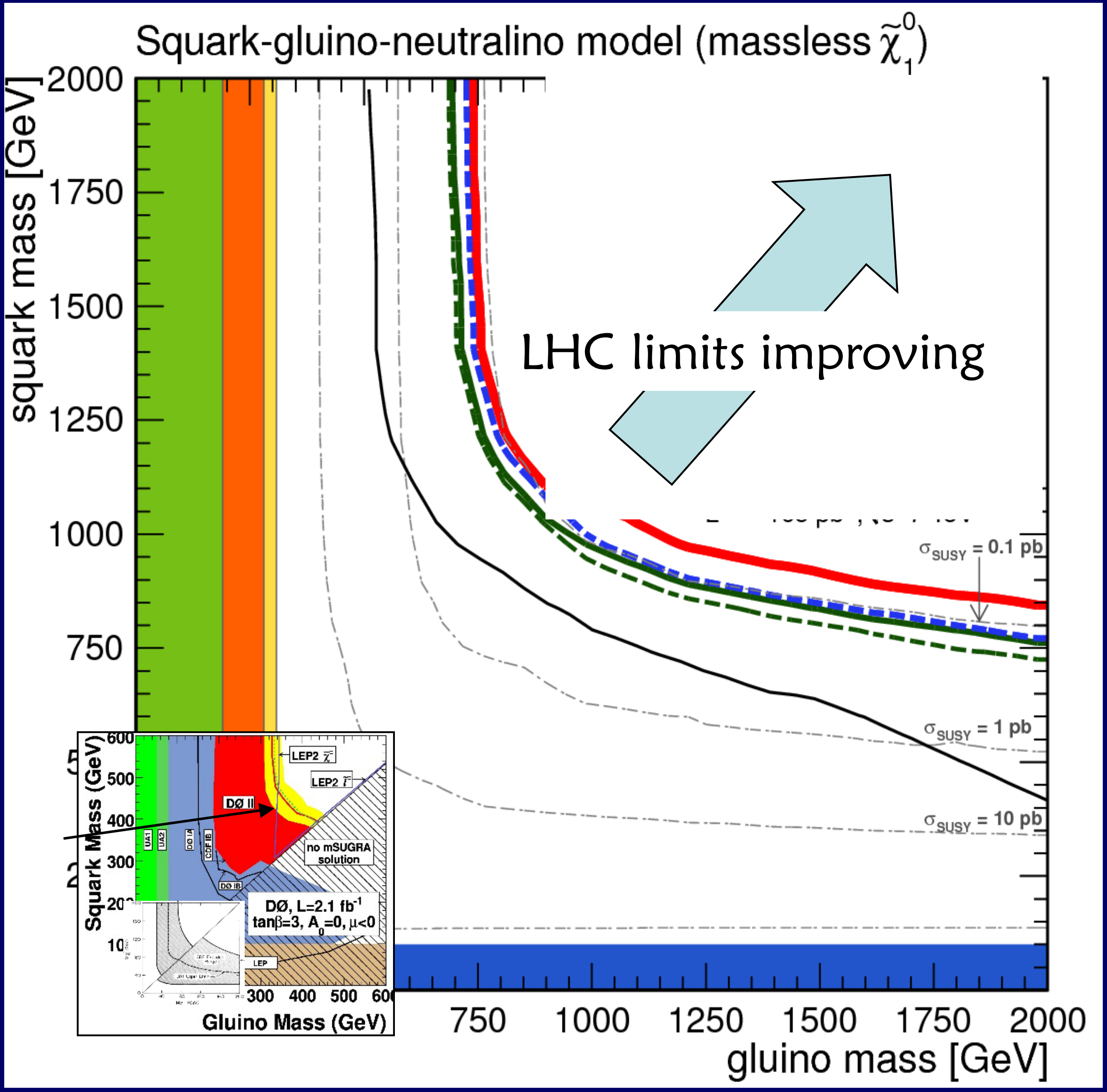
Tevatron squark gluino limits



Highlights – New phenomena

LHC has overtaken Tevatron **in more ways than one**

“400 Physicists Fail to Find Supersymmetry”
(NYTimes, ca 1992)

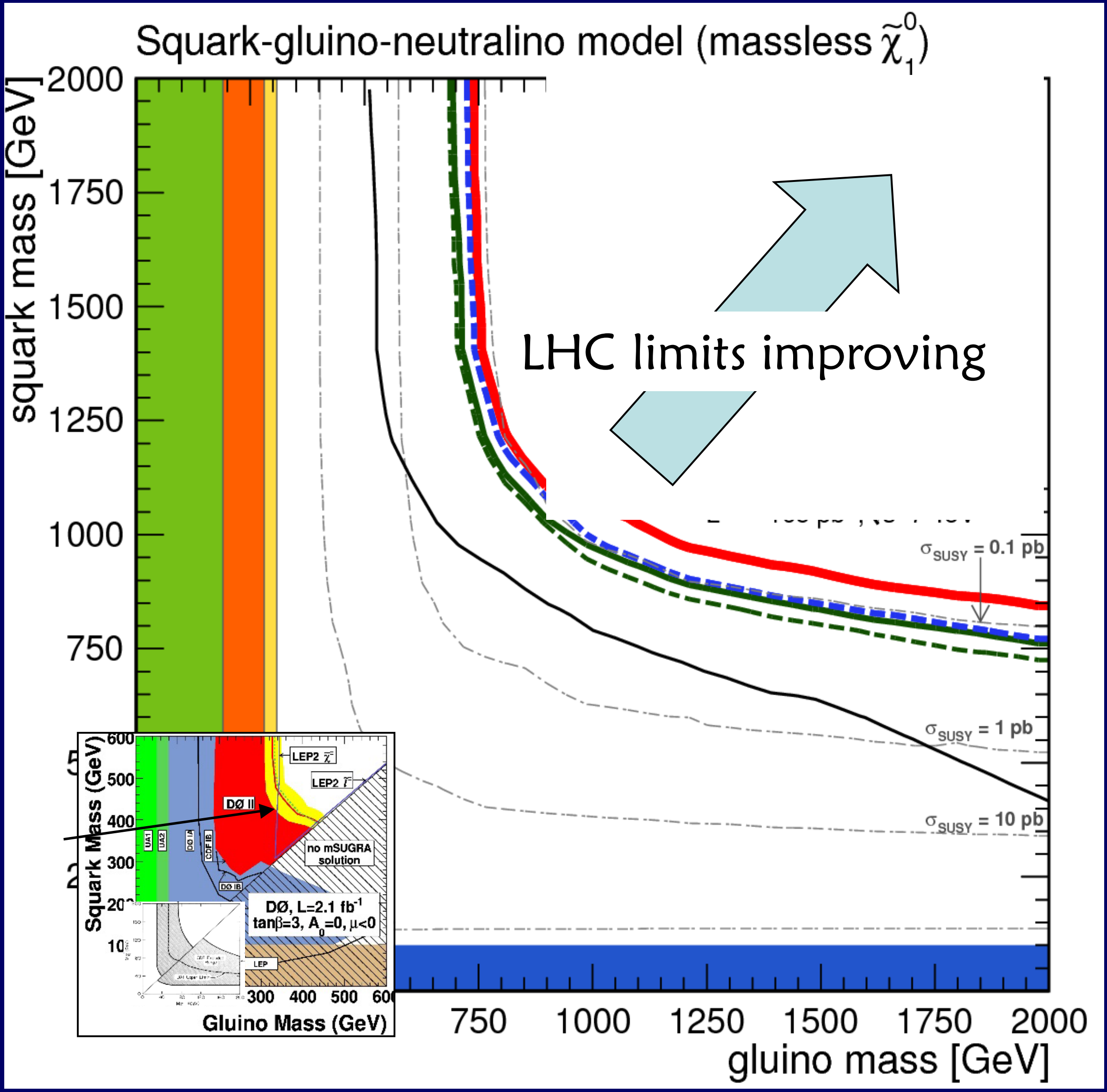


Highlights – New phenomena

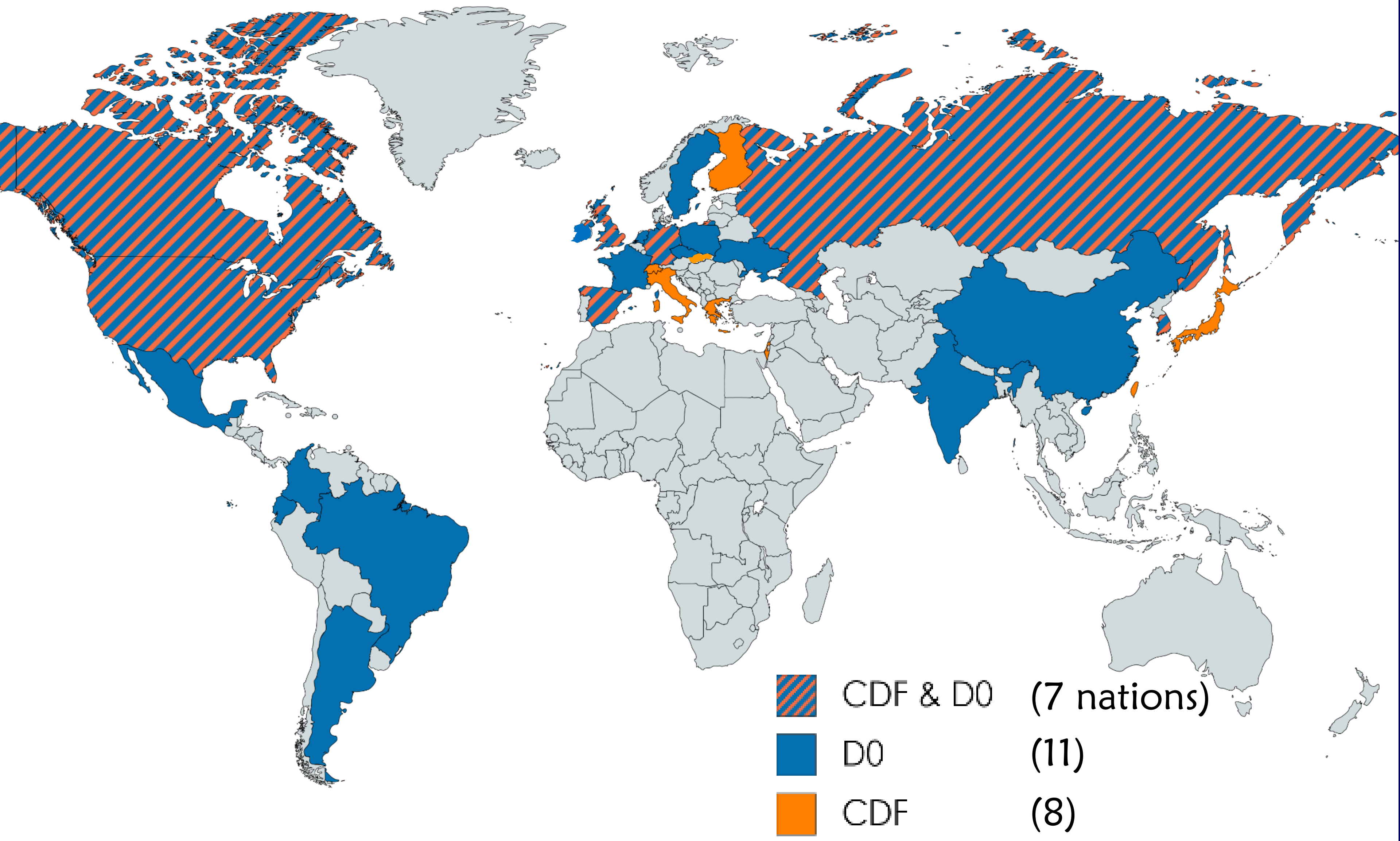
LHC has overtaken Tevatron **in more ways than one**

"400 Physicists Fail to Find Supersymmetry"
(NYTimes, ca 1992)

"6000 Physicists Fail to Find Supersymmetry"
(Tribune de Geneve, 2018)



The World of CDF and D0



The Tevatron by the Numbers

- 40 years since inception of the Tevatron program (and still counting)
- 35 experiment-years of colliding beams delivered
- Almost 12 fb^{-1} delivered to CDF and D0 (about 10 fb^{-1} in analyses)
- 7 Accelerator Division Heads during the Tevatron era
- ~1200 CDF and D0 publications; including 6 joint PRLs and 8 joint PRDs.
- Almost 600 total Physical Review Letters
- About 3000 collaborators over the lifetimes of the two experiments
- 1128 PhD theses
- 26 nations collaborated in CDF and D0 (including 7 in both)
- 26 people served as spokespersons (3 did so twice)
- About $2\text{x}10^{15}$ antiprotons (300 μC) died a horrible death at BØ and DØ

Summary

The Tevatron experiments have provided a significant legacy in validating the Standard Model and dramatically increasing our knowledge of its particles and forces.

Their contributions still continue.

Thanks to all those in CDF and D0, and the Fermilab staff, who made it possible.

Thanks