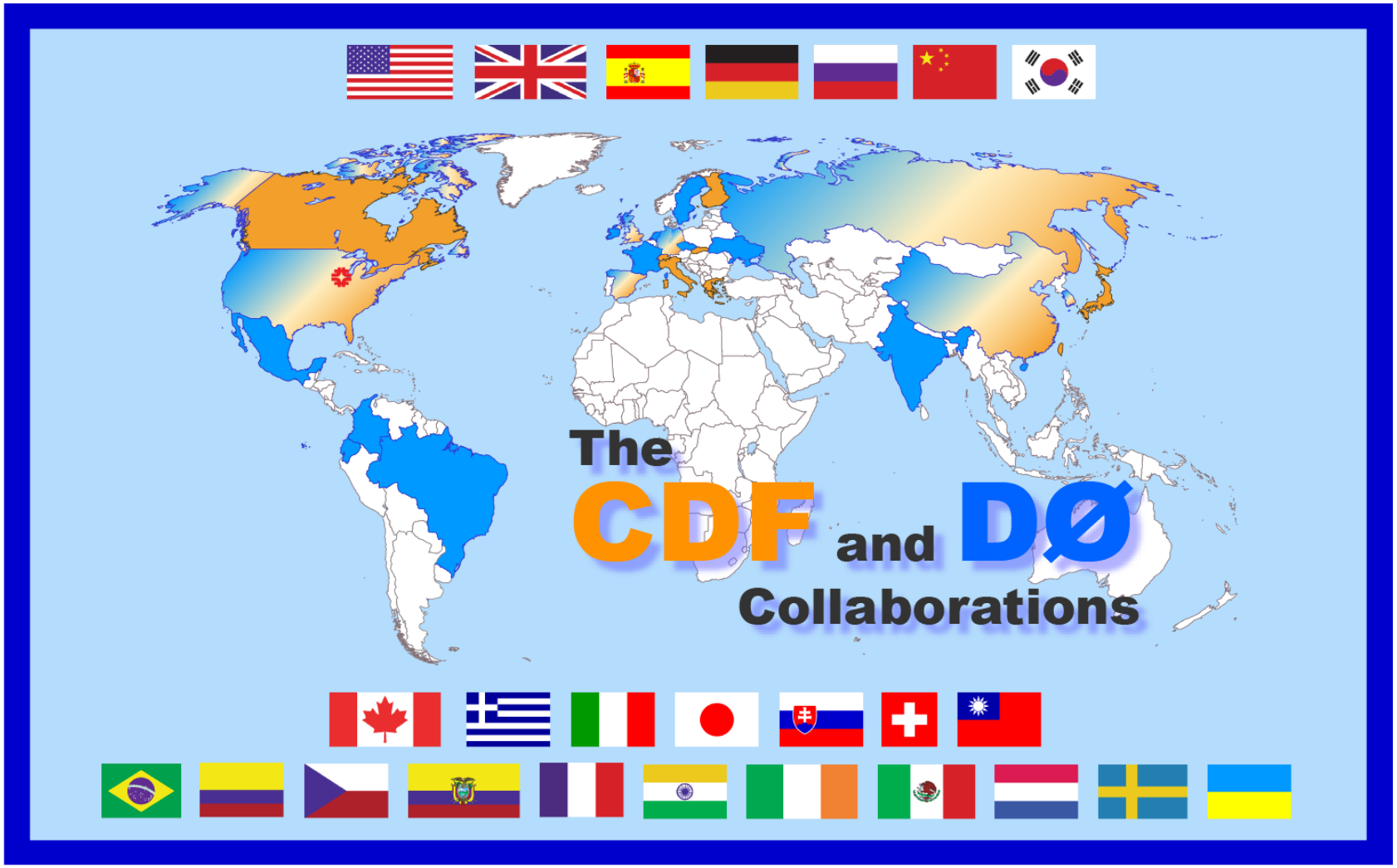
Tevatron Highlights

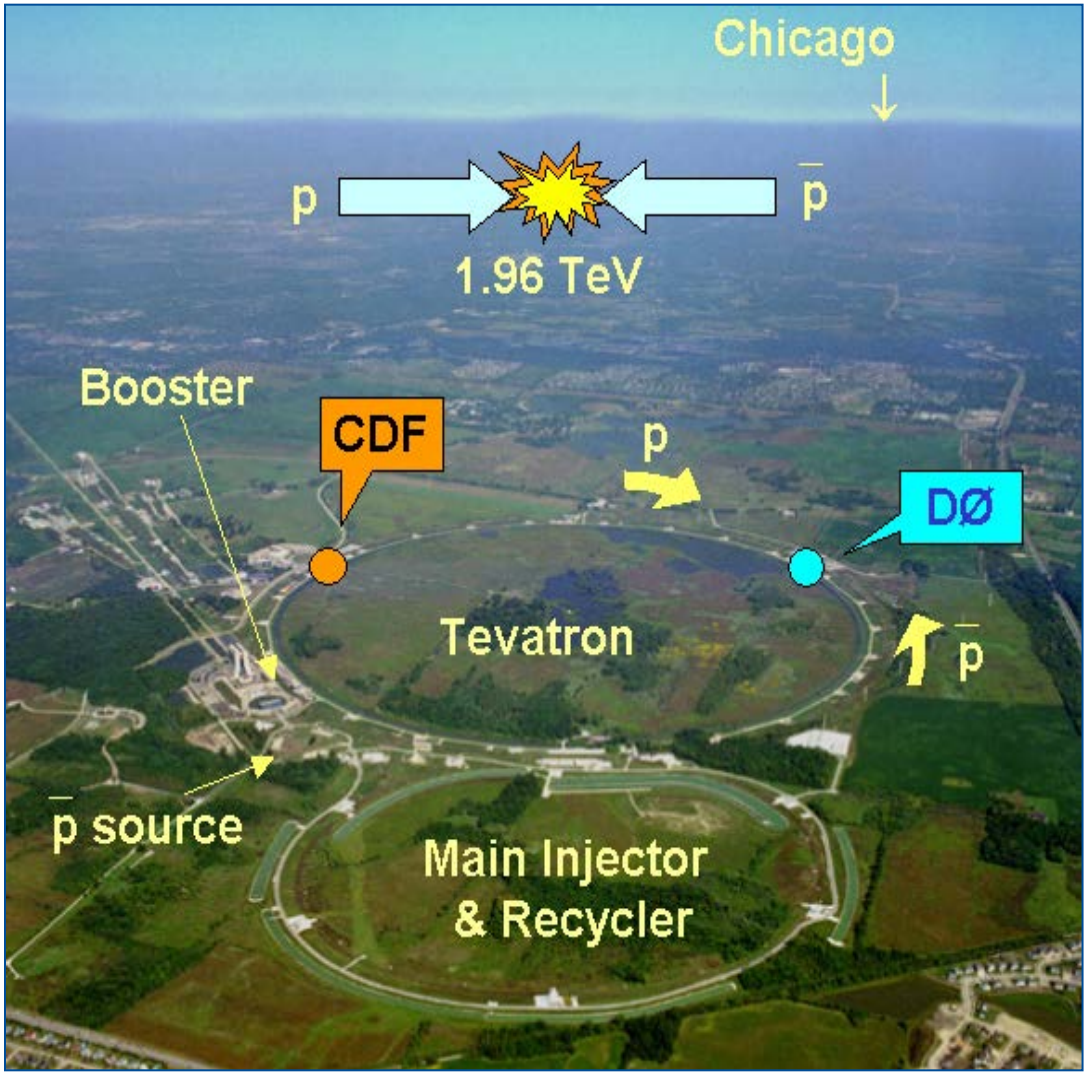


Dmitri Denisov, Fermilab

Higgs Hunting 2015, LAL Orsay

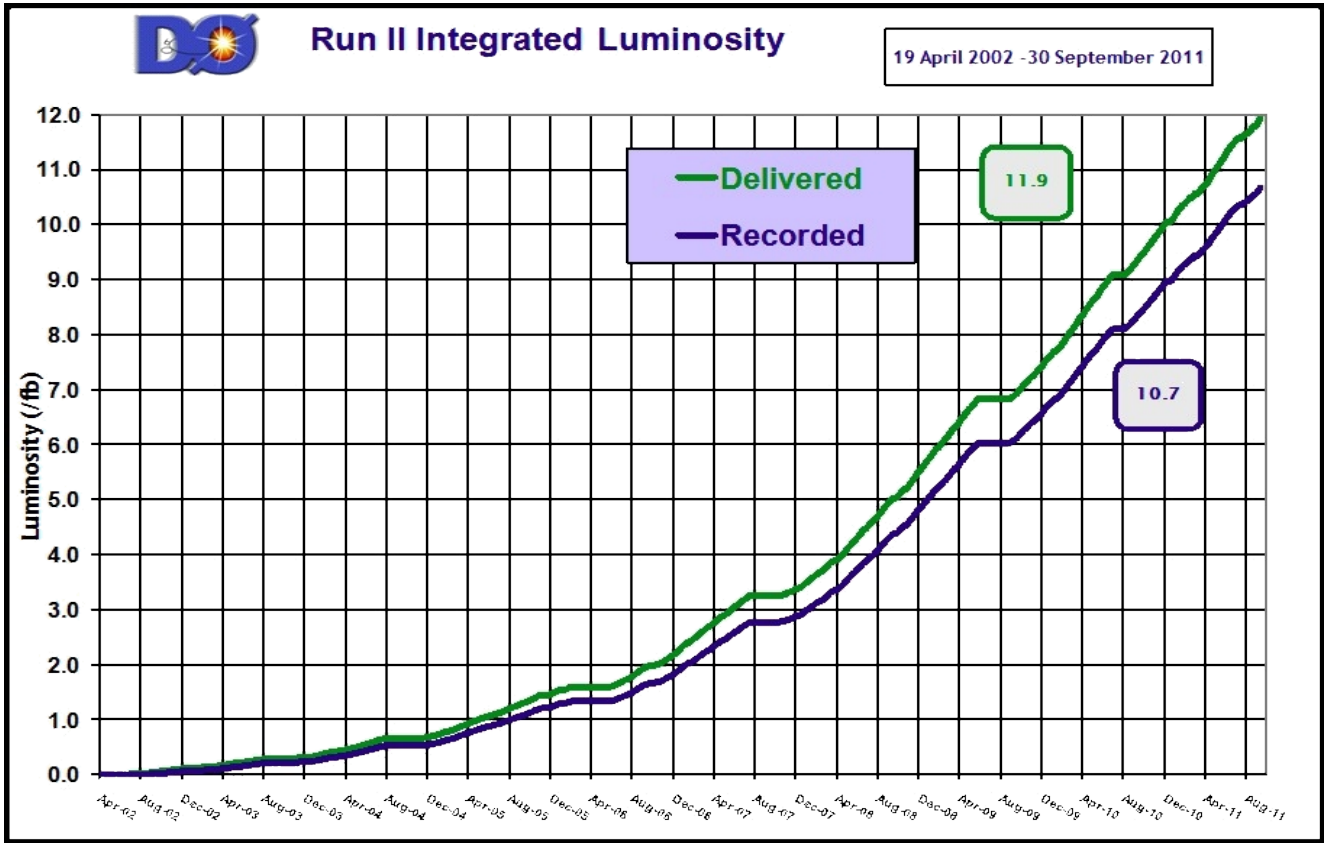
July 31 2015

Tevatron Collider



- Proton-antiproton collisions with 1.96 TeV collision energy
- Peak luminosity 4×10^{32} $cm^{-2}s^{-1}$
  - Up to ~10 interactions per beams crossing at 396 ns crossing time
- Two general purpose experiments: CDF and DØ
- ~ 10 fb^{-1} of luminosity integrated
- Data collection 2001 to 2011

Tevatron Integrated Luminosity



- Total luminosity collected by each experiment is ~10 fb^{-1}
  - Luminosity doubled in the last ~1.5 year of data collection
- All results presented in this talk are on the full data set
- Large fraction of luminosity collected with 2-3 interactions per crossing

The CDF and DØ Collaborations

CDF collaboration has 405 scientists in 55 institutions

DØ collaboration has 380 scientists in 71institutions

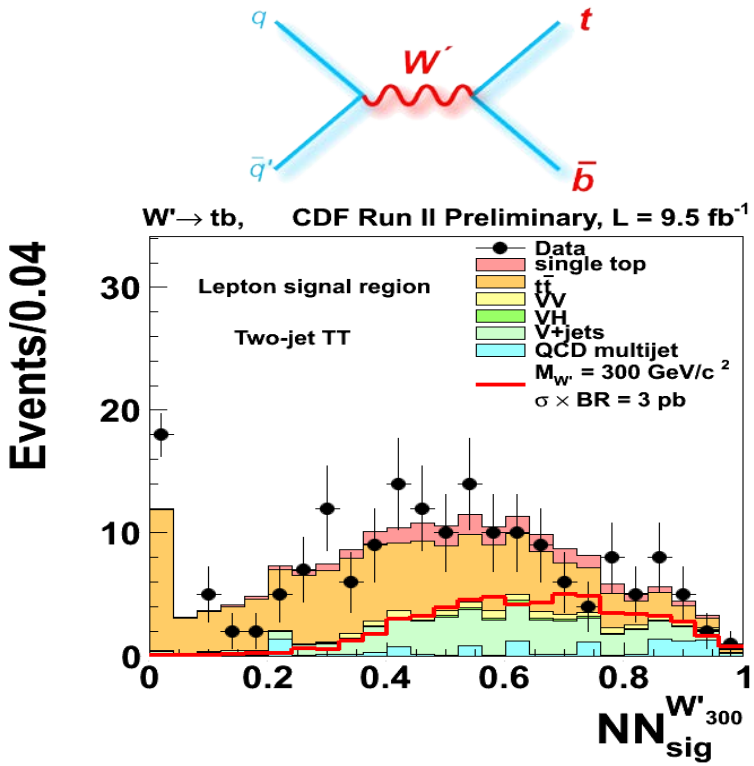
Unique Features of the Tevatron Data

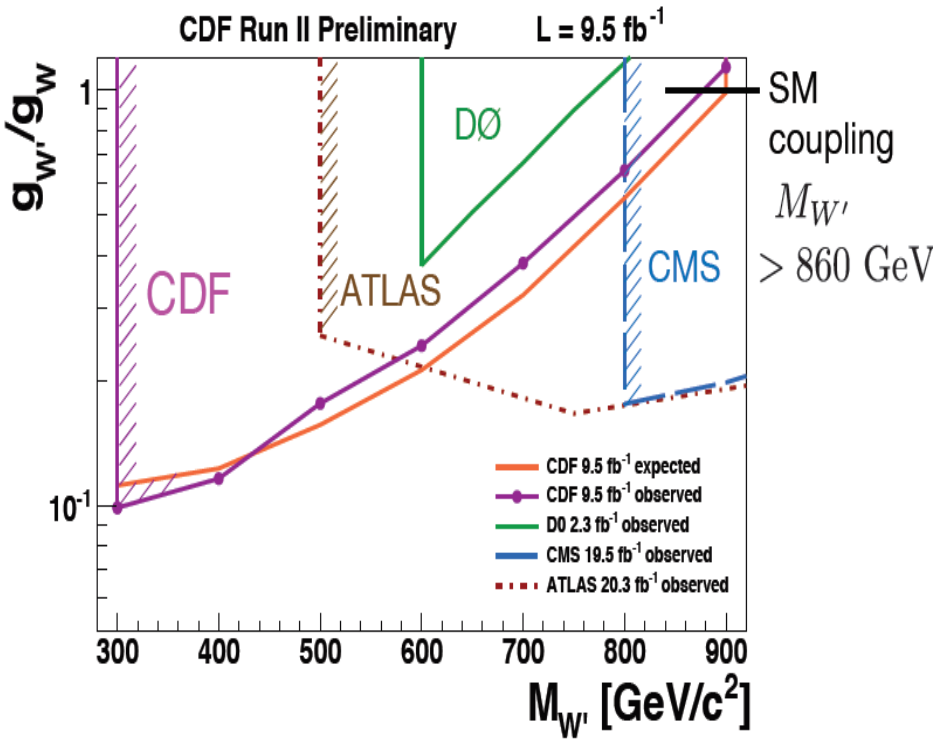
CDF publications summer 2012 to summer 2015

Group	2012	2013	2014	2015	Totals
Higgs	12	6	1	2	21
Top	4	11	9	5	29
EWK	2	3	3	2	10
BSM	2	5	2	—	9
QCD	1	4	2	3	10
Flavor	3	4	4	—	11
Totals	24	33	21	12	90

- Unique features of the Tevatron data set
  - Proton-antirpoton collisions: valence quark-antiquark interactions
  - 2 TeV center of mass energy
  - Well understood detectors/algorithms
  - Unique detector features, including changes in the magnets polarities
- Many combinations between Tevatron experiments
  - More in the last 3 years than in 20 years before
  - Doubling data set, cross checks of methods/uncertainties
- Results highlighted today are from the past 6-12 months, many new for EPS 2015

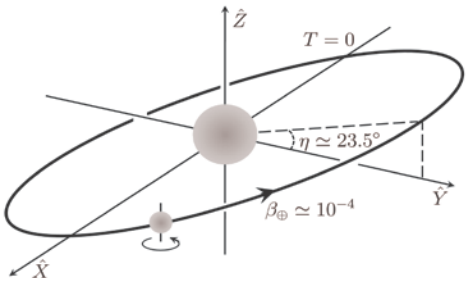
New Phenomena – Search for W'

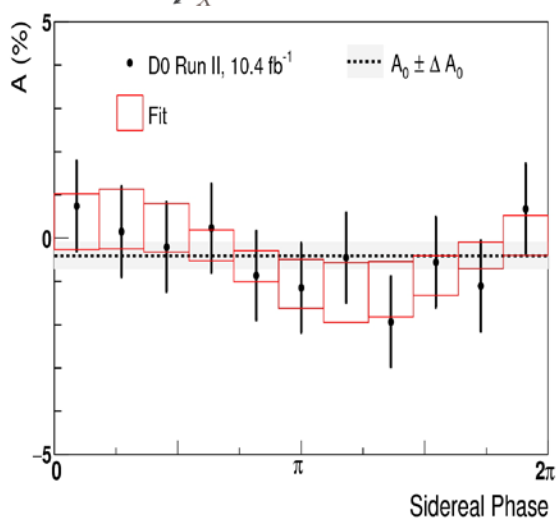




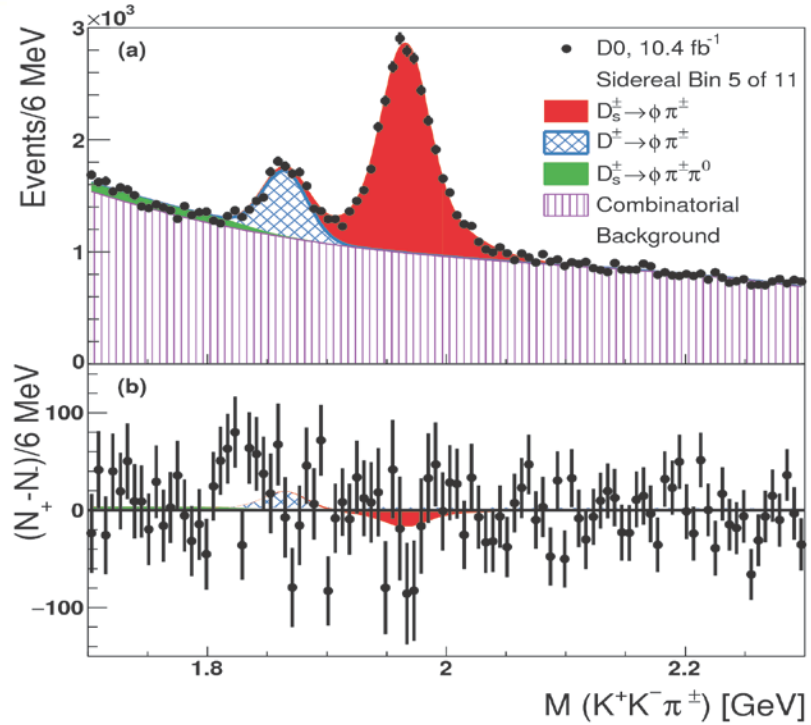
- An example where Tevatron analyses can fill "low mass gaps" in the exclusion space
  - Better signal/background ratio at low masses vs LHC
- Missing energy based triggers
  - Optimized for channels with or without charged lepton
- Examine a benchmark left-right symmetric standard model extension
- Best (only) limits below W' mass of 550 GeV

Search for CPT violation in $B^0_s \to \mu^{+-} D_s^{-+} X$ Decay



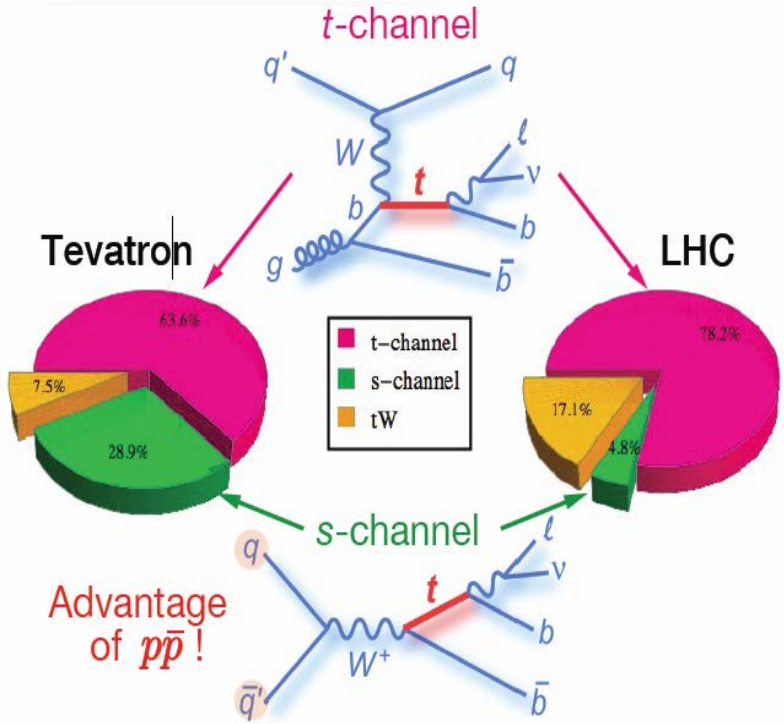


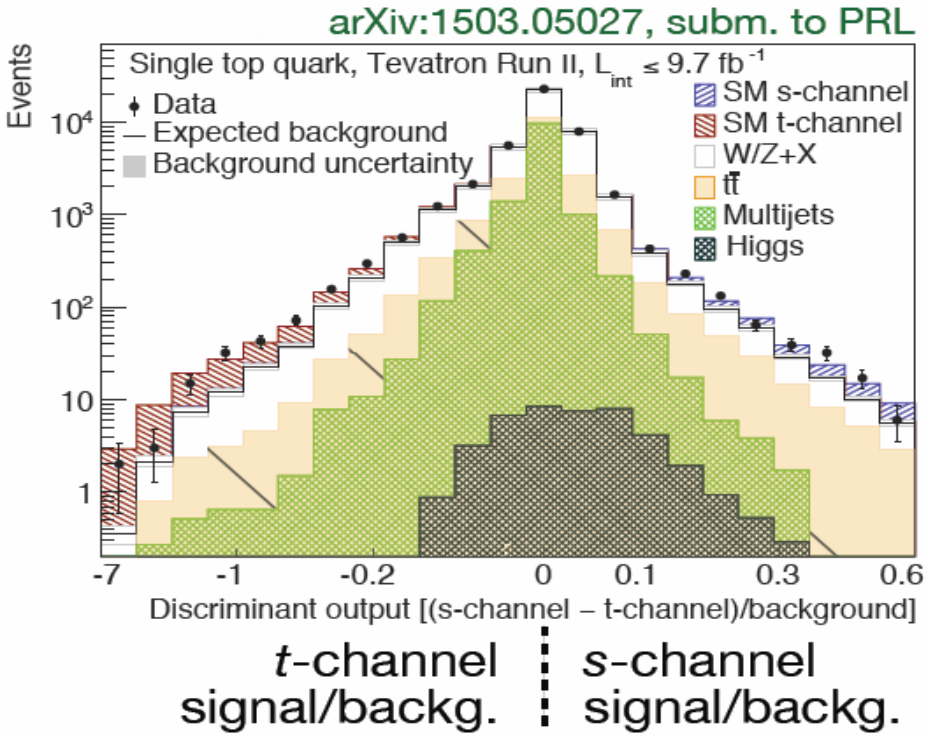
$$A = \frac{N_+ - N_-}{N_+ + N_-}$$



- For B^0_s oscillations the fractional difference between mass eigenvalues is very small (10^{-12}) and the oscillations are sensitive to couplings between quarks and possible Lorentz-invariance violating field
- Search for difference in number of B^0_s vs $\bar{B}^0_s$ using $B^0_s \to \mu^{+-} D_s^{-+} X$ decay
  - With respect to the detector orientation with respect to the Sun
- No asymmetry vs sidereal phase observed and stringent limits on Lorentz violating field set
  - Use of well established B^0_s reconstruction technique and cancellation of detector charge asymmetries by magnetic field changes

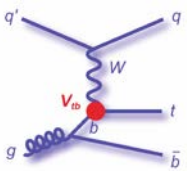
Single Top Quark Tevatron Combinations

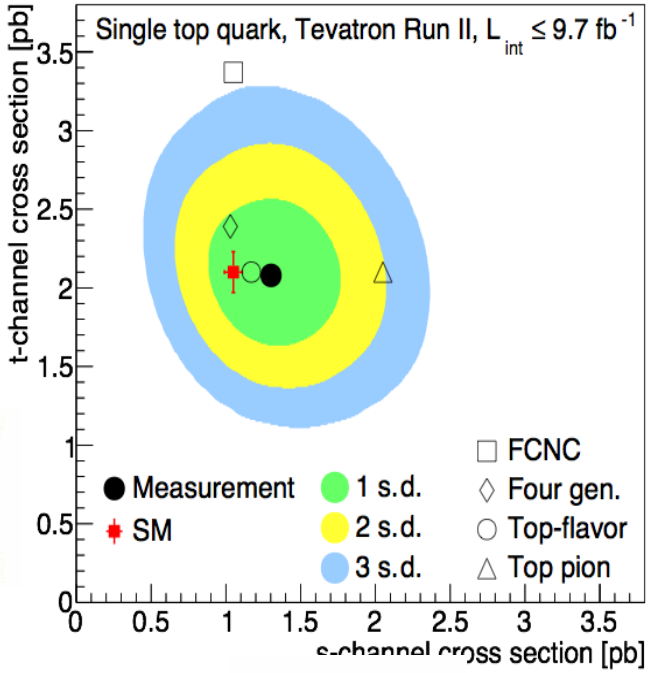


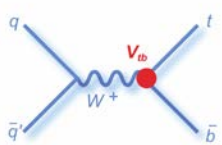


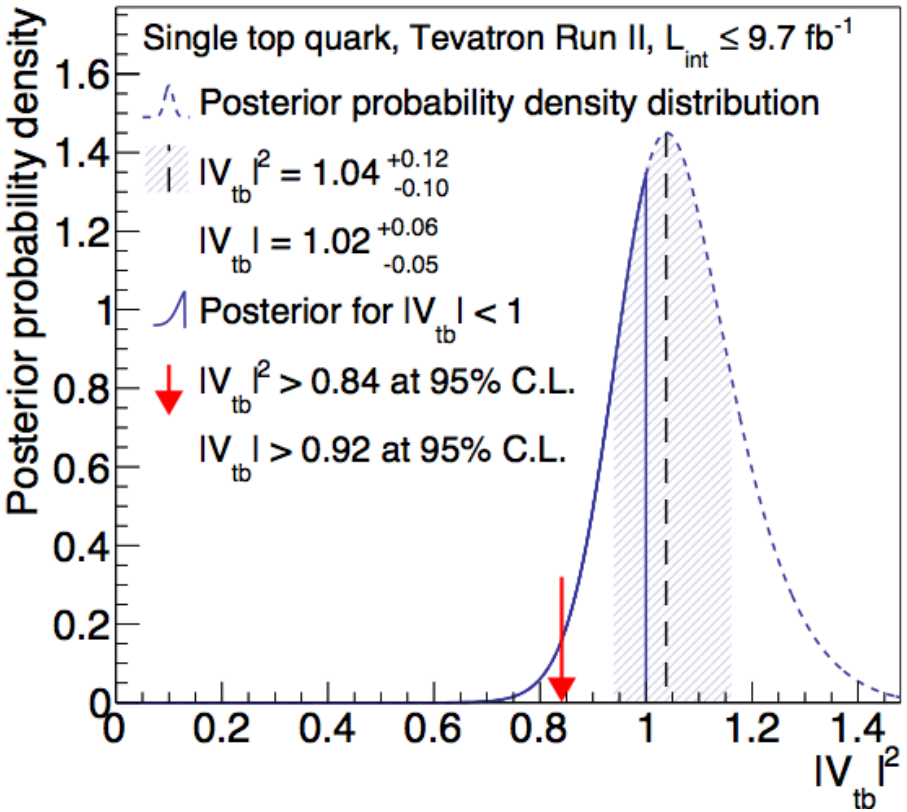
- Single top quark s-channel observed with 6.3σ significance
  - Combining CDF and DØ data
- Finished combination of s- and t-channels independent measurements in l+jets and missing energy + jets channels
  - Many MVAs combined to combat small signals, large backgrounds

Single Top Quark Final Combination



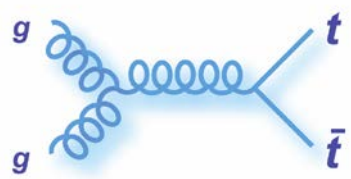


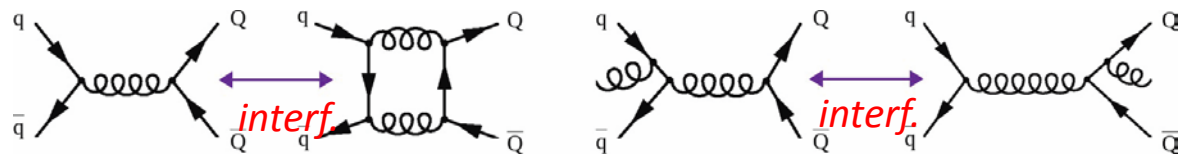




- Independent measurements of s- and t-channels cross sections limits BSM scenarios
- Independent vs number of quark families and unitarity of CKM matrix determination of V_{tb} with ~5% accuracy

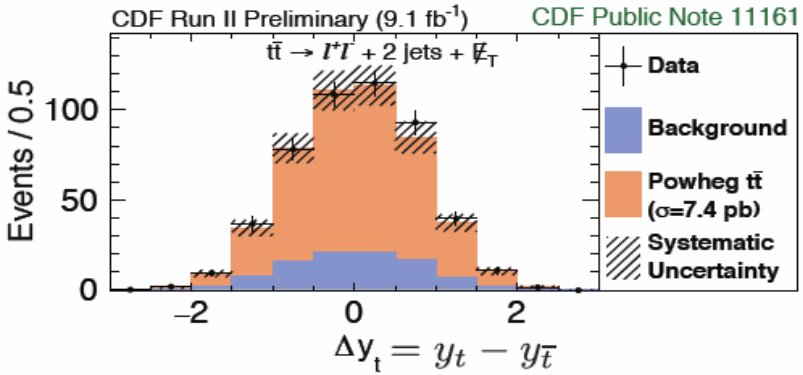
Forward-Backward Quark-Antiquark Asymmetries

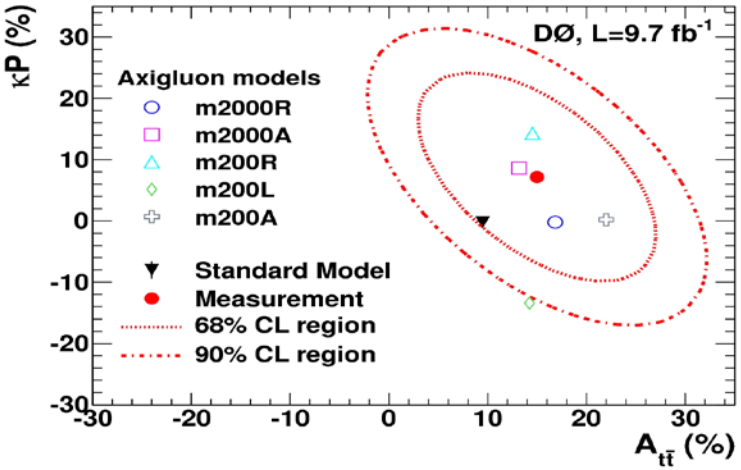




- No forward-backward asymmetry in gg production
- Contributions to asymmetry via interference between qqbar and qg at NLO
- New particles, like axigluons, could change A_{fb} substantially
- New CDF result for A_{fb} in di-lepton channel and DØ result using matrix element method in di-lepton events
  - DØ and CDF combinations of A_{fb} measurements in di-lepton channel and l+jets channel

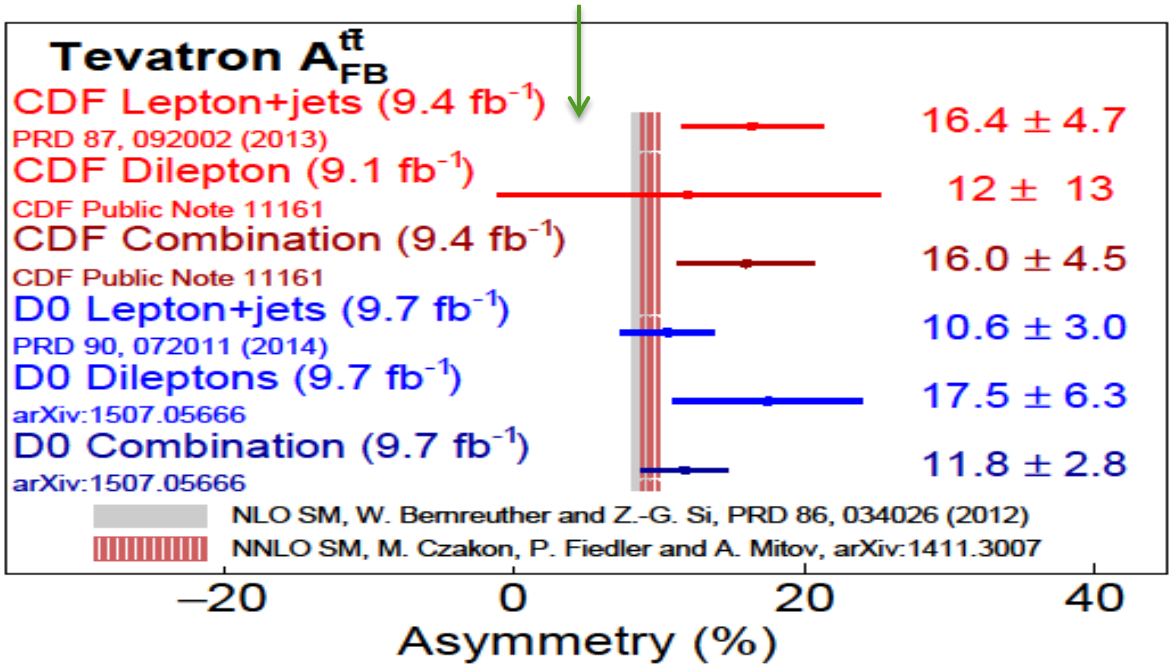
$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N_{\Delta y_t>0} - N_{\Delta y_t<0}}{N_{\Delta y_t>0} + N_{\Delta y_t<0}}$$





Di-lepton A_{fb} and Polarization Measurement

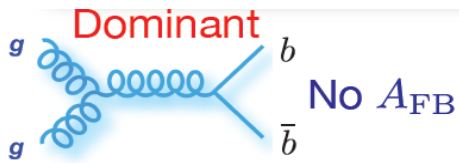
Original Theory Prediction in 2006



- Top quark A_{fb} Tevatron summary
  - Theoretical values increased with higher orders calculations and EW corrections
  - Experimental values decreased (within uncertainties)
- Theoretical predictions are overall in agreement with the experimental results
  - Final Tevatron top quark A_{fb} combination in progress

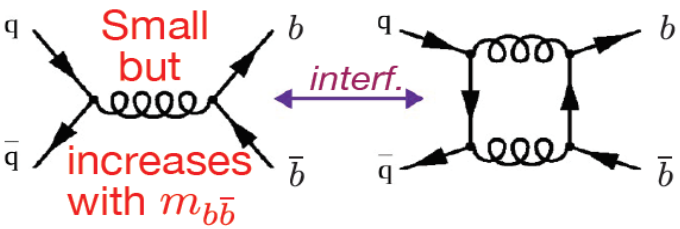
Forward-Backward $b\bar{b}$ Production Asymmetry

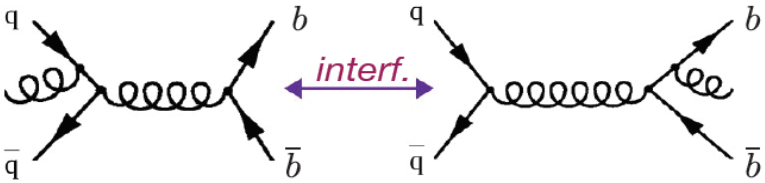
- Studies stimulated by initial anomaly in top quark A_{fb}
  - Similar mechanisms could cause $b\bar{b}$ asymmetry



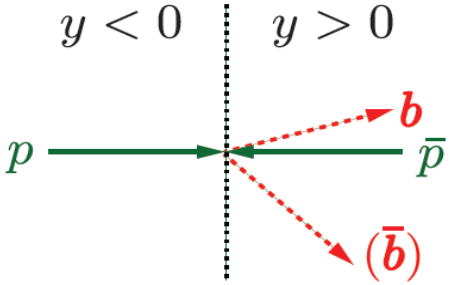
No A_{FB}

- Forward-backward *b* quark asymmetry expected to be small





- Depends upon flavor excitations
- Depends on invariant mass $m_{b\bar{b}}$
- Small contribution from electroweak Drell-Yan $q\bar{q} \to Z/\gamma \to b\bar{b}$



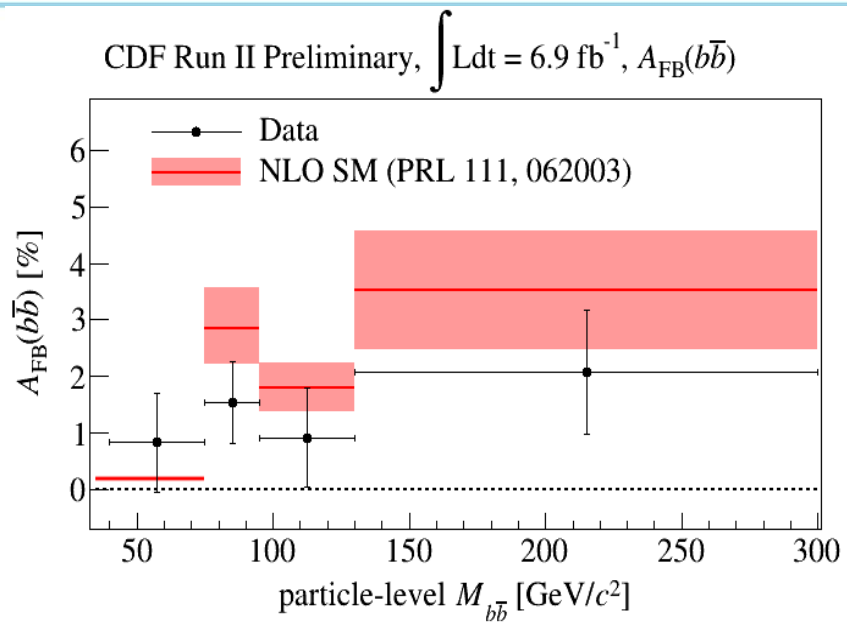
CDF: tagged $b\bar{b}$ jets at low and high $m_{b\bar{b}}$

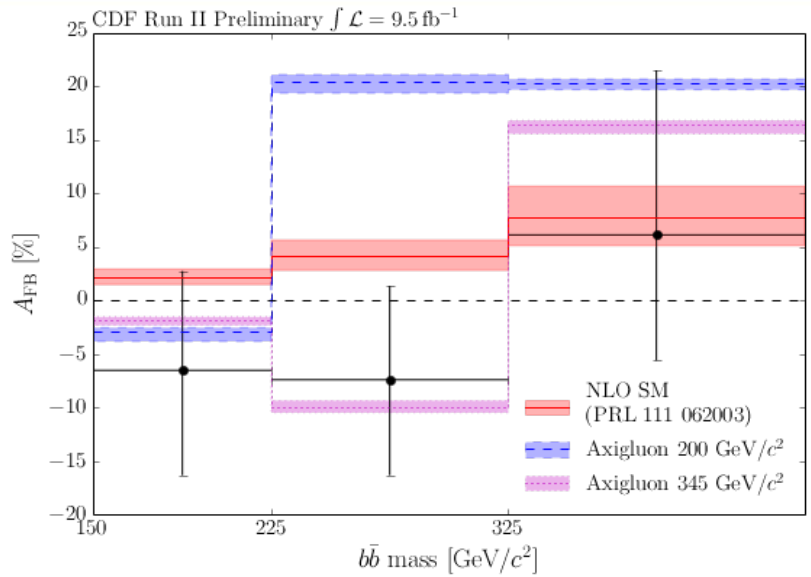
DØ: fully reconstructed B^- $(b\bar{u})$

$$y = y_b - y_{\bar{b}}$$

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}$$

Forward-Backward $b\bar{b}$ Production Asymmetry





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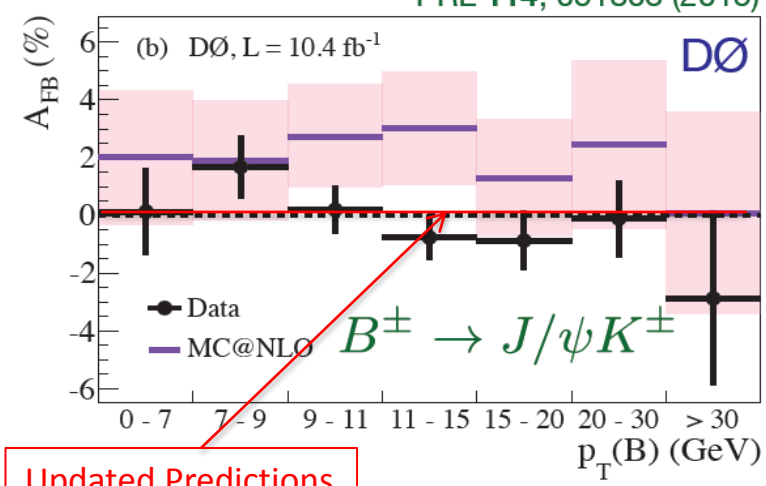
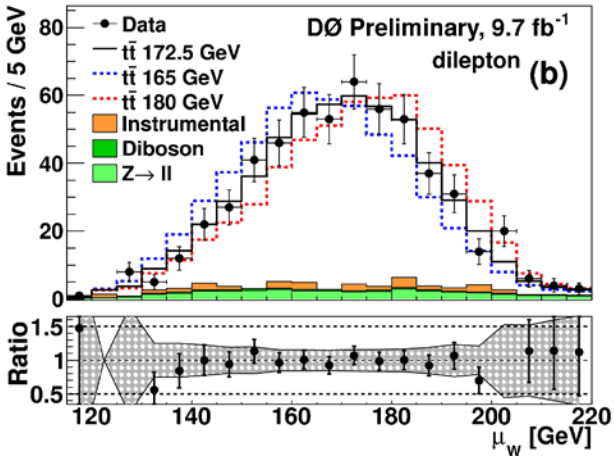


Updated Predictions

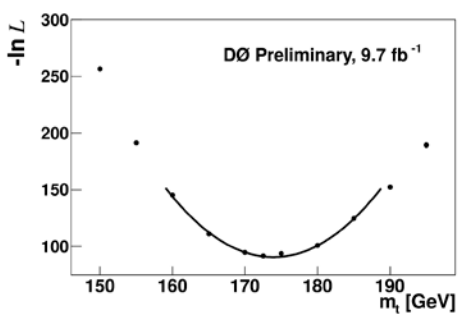
- CDF studies use two methods
  - Soft lepton tagging for low mass m_{bb} jets provided A_{fb} = (1.2 ± 0.7)%
  - Jet charge algorithm for high m_{bb} jets
- DØ used exclusive B decays
  - A_{fb} = [−0.24 ± 0.41 (stat)± 0.19 (syst)]%
- Within experimental uncertainties no deviations from the theoretical predictions observed

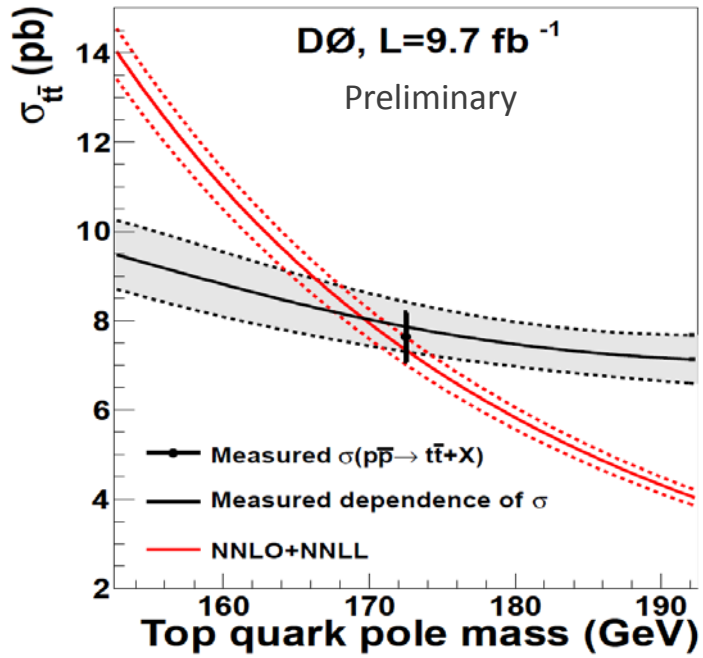
Top Quark Mass and Cross Sections

- New Tevatron analyses on full data set with new ideas to reduce uncertainties in progress
- DØ di-lepton ν-weighting analyses uses jet energy scale from l+jets channel calibration



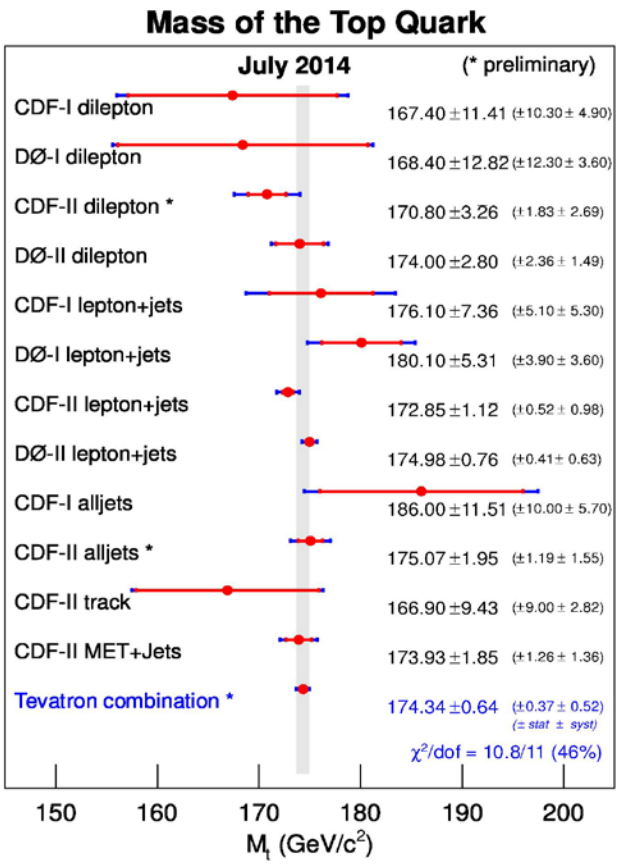
m_t = 173.3±1.4(stat)±0.5(JES)± 0.7(sys) GeV

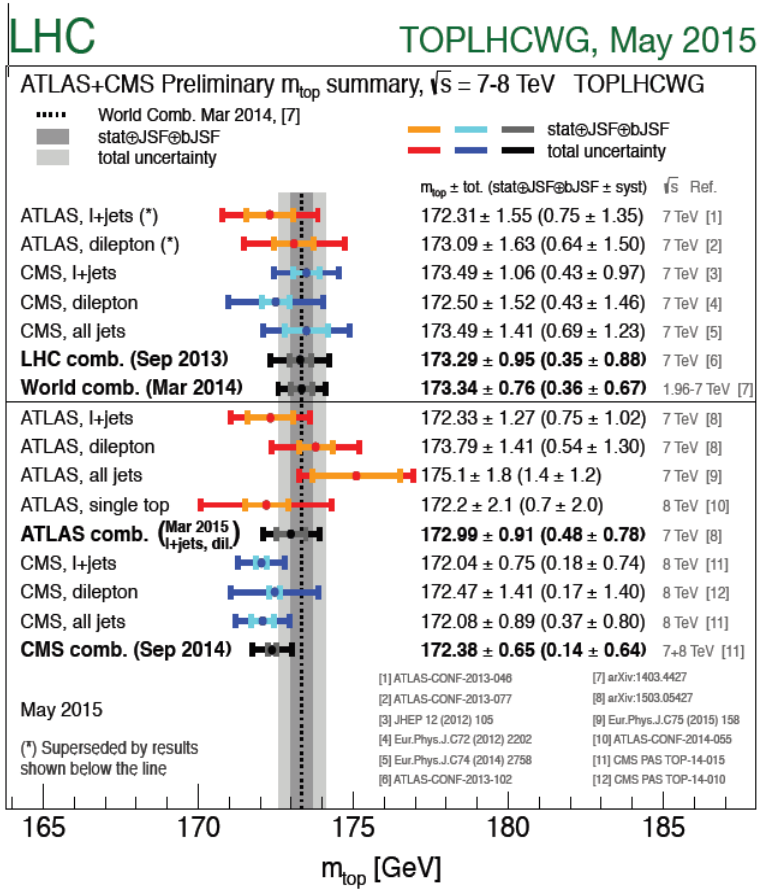




- Using full data set DØ measured σ_{tt} using all final/improved algorithms
  - σ_{tt} = 7.73 ± 0.13 (stat.) ± 0.55 (syst.) pb at m_t = 172.5 GeV
  - 7.3% precision
- Extracted top quark pole mass
  - $169.5^{+3.3}_{-3.4}$ (tot.) GeV
  - 1.9% precision

Top Quark Mass

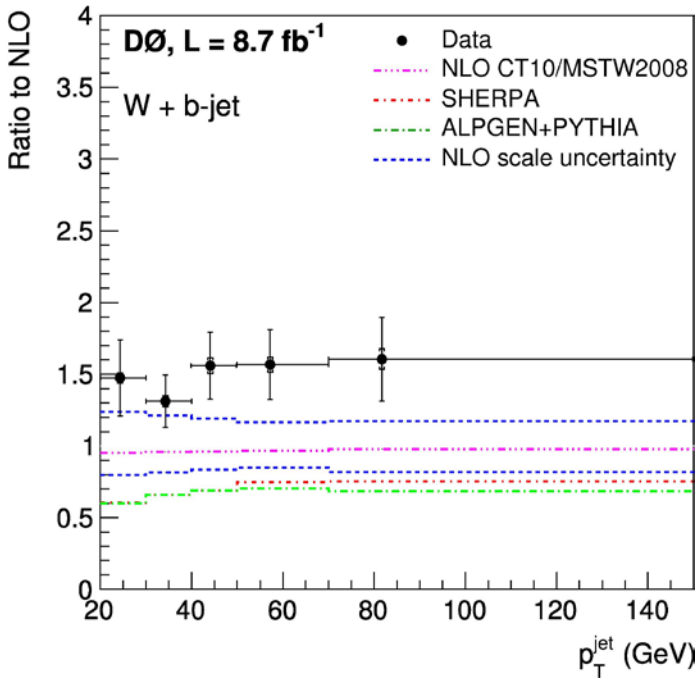


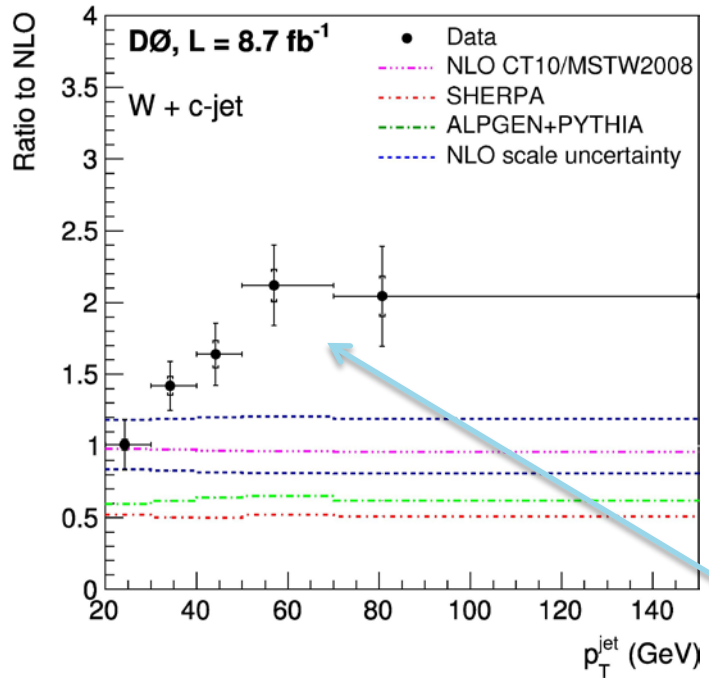


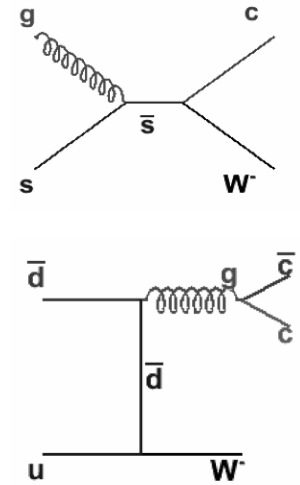
- Tevatron combination and CMS combinations are already more precise than 2014 World Combination
- Expect DØ di-lepton matrix element method and all jets channel measurements and CDF matrix element
  - Then final Tevatron combination
- Combination with LHC is in progress
  - Including to understand/address tension between CMS and DØ most accurate results

W+b-jet and W+c-jet Differential Production

- W+c process is a probe of s-quark PDFs
  - Tevatron W+c proceeds via 85% s-quark initial state
- W+c and W+b are backgrounds to WH(→bb), ttH and beyond the standard model signals
- Measurement based on b/c-jets tagging using secondary vertex tagging algorithms





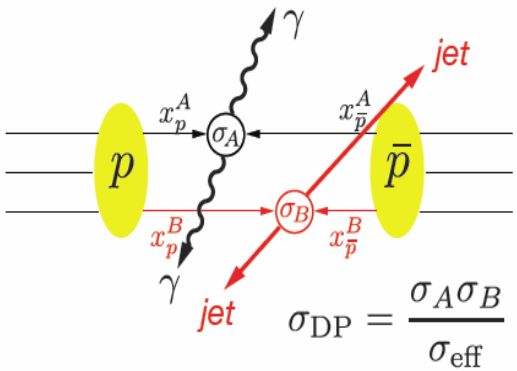


Almost half gluon splitting at high p_T

- First differential measurements of these processes published
- Excess at high P_t for W+c production
  - Missing higher order corrections, enhanced cc splitting, strange sea?

Double Parton Interactions Studies

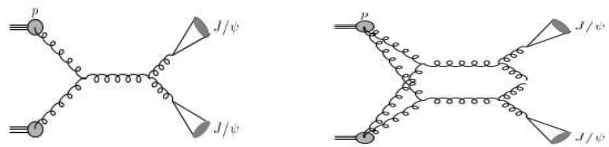
- Use unique features of the Tevatron
  - $p\bar{p}$ collisions, large data set and low number of interactions per beam crossing
- Double parton interactions studies provide information about both structure of the proton as well as backgrounds to high P_t new physics searches

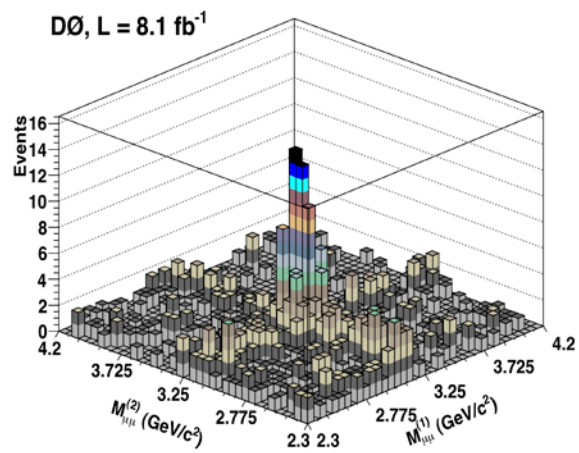


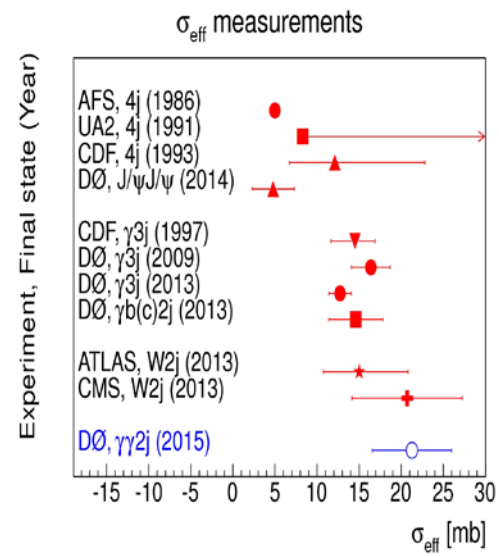
$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

- σ_{eff} : a factor characterizing the size of the effective interacting region, contains info on spatial distribution of partons inside proton
  (large if uniform; small if "clumpy")

Single parton Double parton



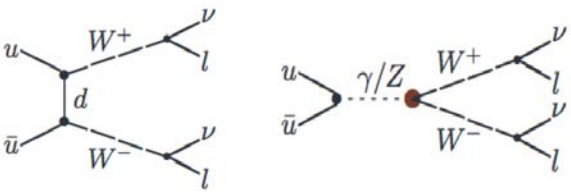




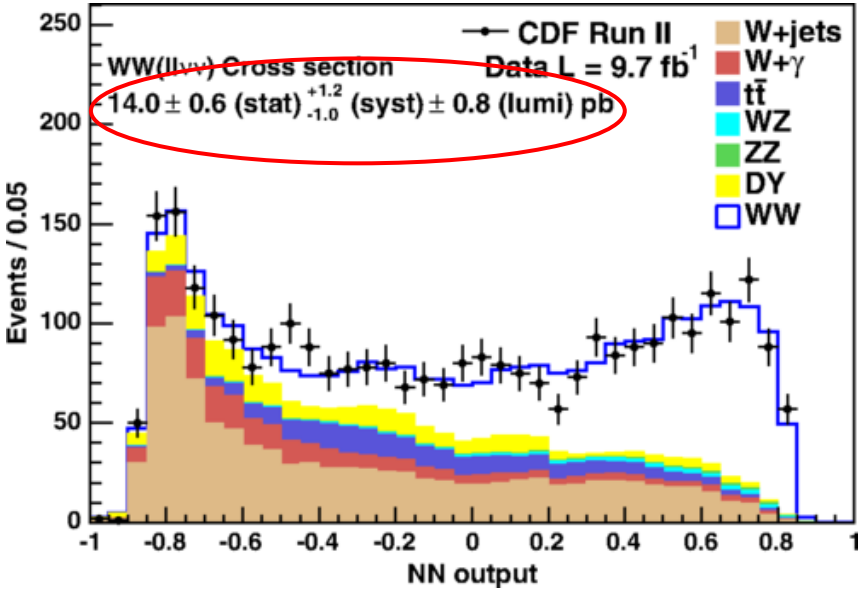
- Double J/ψ production observed with ~50% from double parton interactions
- Studies of large number of processes helps understanding double parton production
  - Smaller σ_{eff} for gg initial state processes suggests smaller volume for gluons vs quarks?

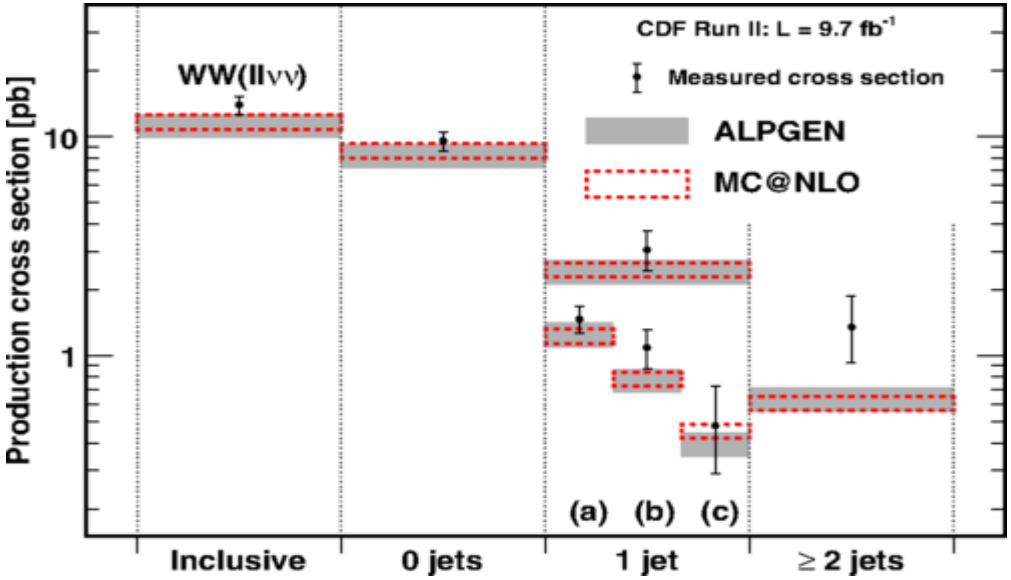
W^+W^- + jets Cross Sections Measurements

- WW+jets production is an interesting process in the gauge sector being produced both by radiation from quarks and multiple gauge boson coupling
  - Important background for WH production
  - Use methods similar to H to WW searches at the Tevatron



Combined discriminant for inclusive WW measurement

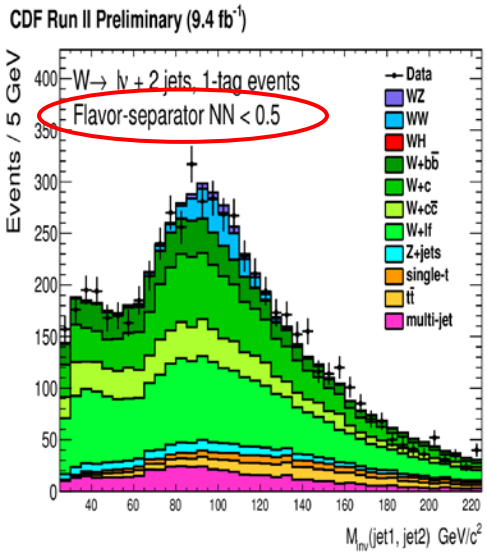


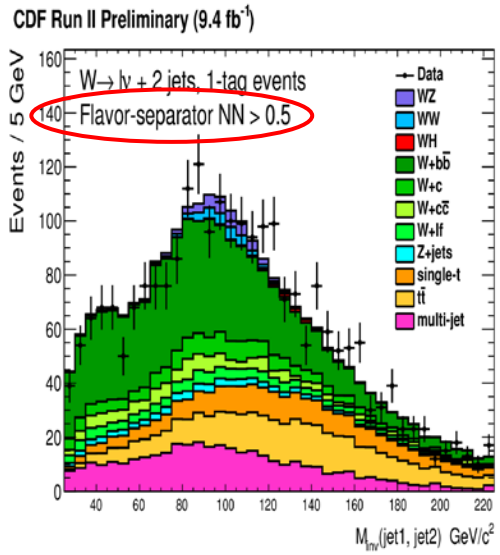


- First differential cross section measurement in a massive di-boson state
  - Somewhat higher than, but consistent with predictions

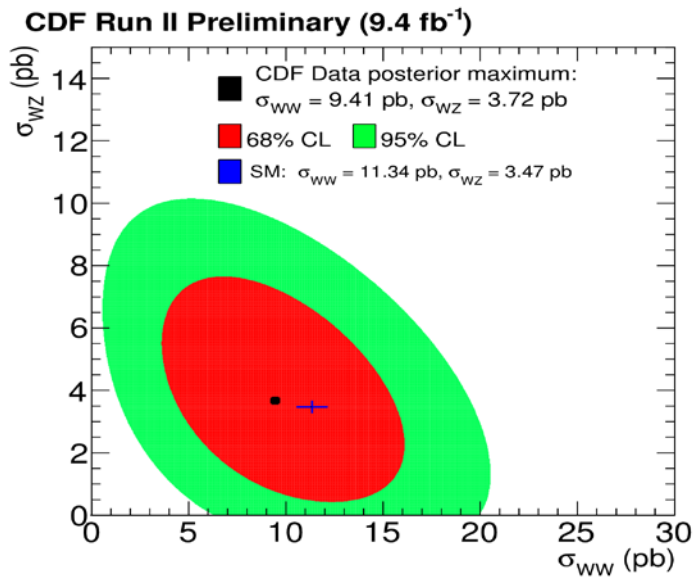
WW and WZ Decays in Heavy Flavor States

- Di-boson WW and WZ production with semi-leptonic W decay plus heavy flavor quarks for second W/Z decay
  - W→cs, Z→ bb, cc





Independent WW and WZ measurement



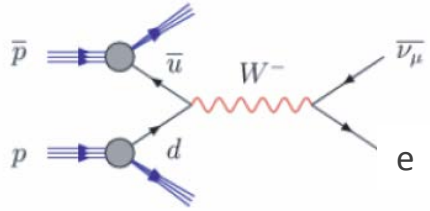
Analysis of the di-jet invariant mass spectrum
3.7σ evidence of WW+WZ in HF final states

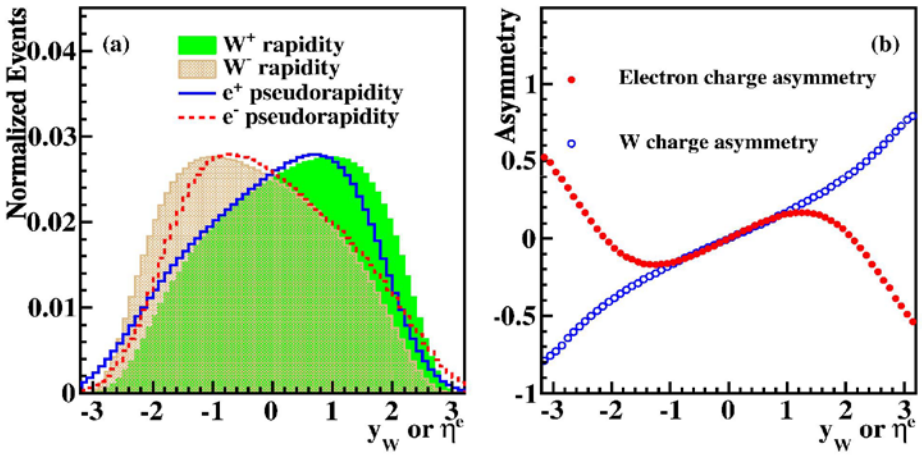
Cross section measurement
σ_{WW+WZ} = 13.7 +/- 3.9 pb

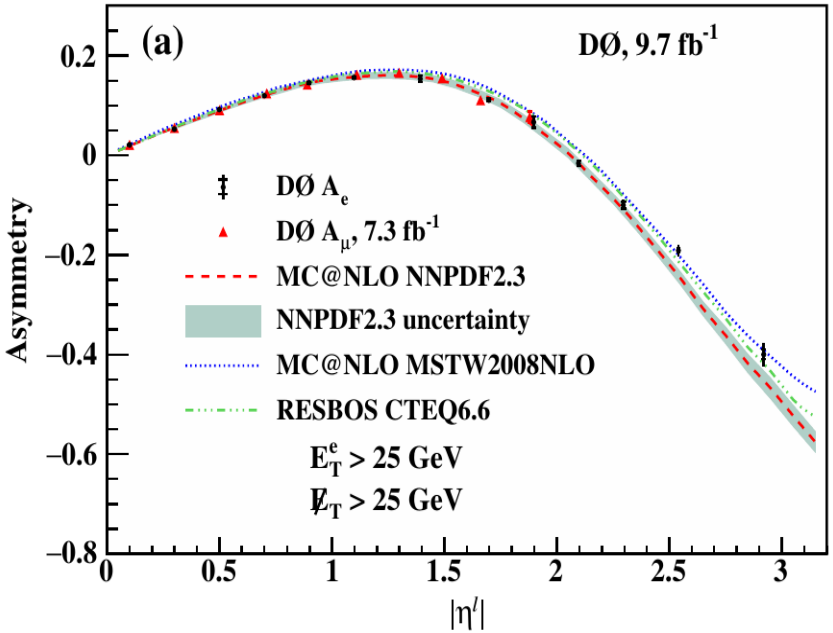
- Use different HF decay pattern of the W and Z
  - Via analysis of the secondary-decay vertex
- Independently measure the WW and WZ production cross section in a hadronic final state
  - For the first time at hadron colliders
  - 2.1σ for WZ and 2.9σ for WW production

Electron Production Asymmetry in W to eν Decay

- Electron asymmetry in $pp \rightarrow W + X \rightarrow e\nu + X$ process probes valence quark parton distributions PDFs
  - Convolves W production asymmetry and V-A decay



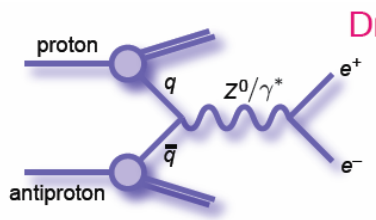




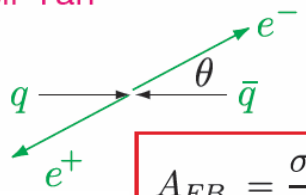
- Most precise measurement, benefits all hadronic measurements via PDFs improvements
- Extended kinematic range to η_e= 3.2
- Improvement of PDF models in the region of interest for W mass at the Tevatron
  - Estimated to reduce the PDF uncertainty in the M_W measurement by approximately 30% (2-3 MeV)

Effective Weak Mixing Angle in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events

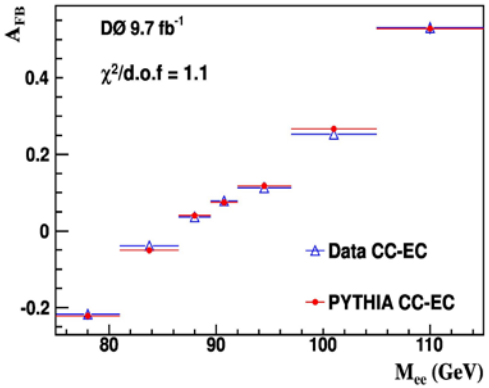
- Weak mixing angle measured using forward-backward asymmetry of lepton polar angle distribution
  - Sensitive to $\sin^2\theta_W$ through interference of vector and axial vector couplings of Z boson
- Measure A_{FB} vs di-lepton pair invariant mass

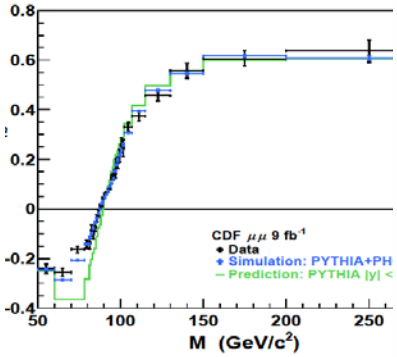


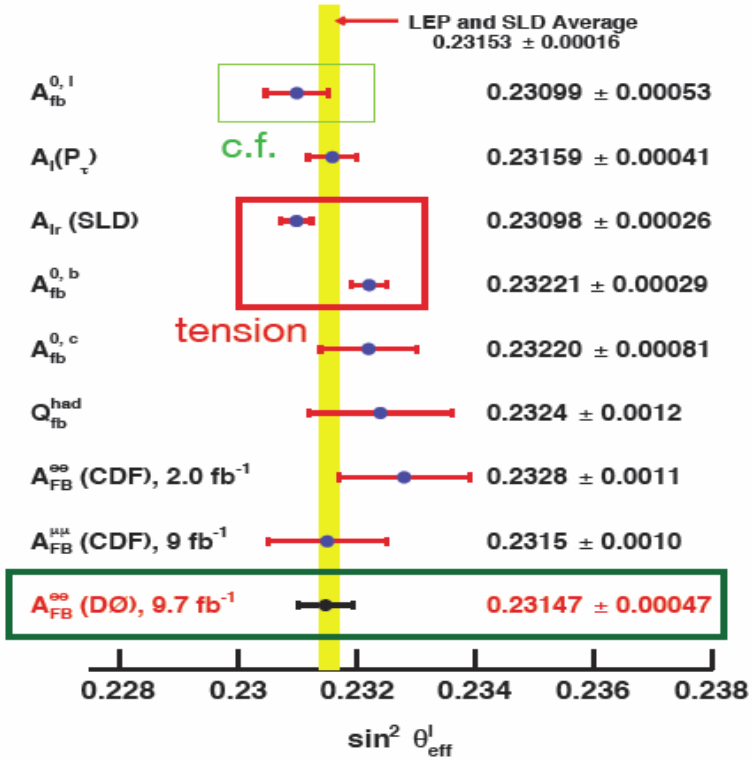
Drell-Yan



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



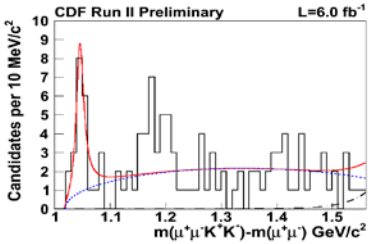


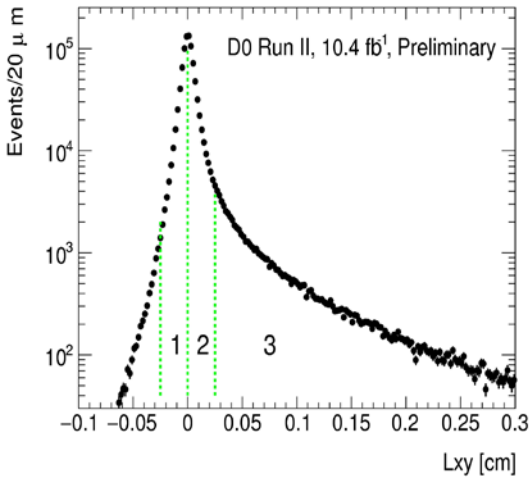


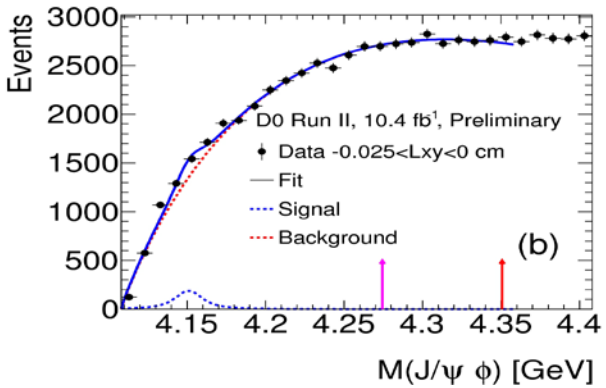
- Weak mixing angle measured from forward-backward asymmetry of lepton polar angle
  - $\sin^2\theta^l_{eff} = 0.23147 \pm 0.00047$ – world best from a hadron collider
  - Periodic magnet polarities changes important
- Helps to understand long standing tension in $\sin^2\theta^l_{eff}$ measurements

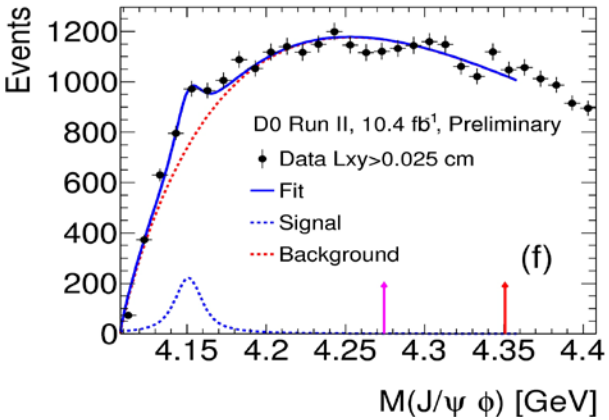
Studies of Production of X(4140)

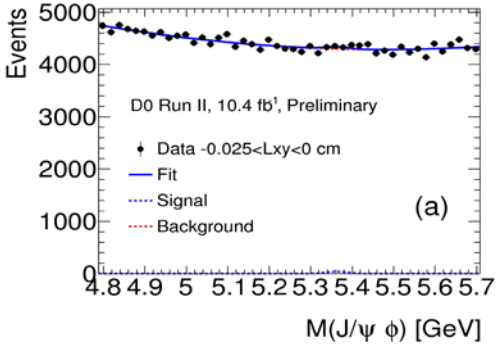
- X(4140) narrow stay was observed by CDF in 2009 in the decay $B^+ \to J/\psi\varphi K^+$ in the $J/\psi\varphi$ effective mass spectrum
  - Confirmed by CMS, not confirmed by LHCb
  - Confirmed in 2014 by DØ
- Nature of this state is still puzzling, so DØ studied inclusive production to separate prompt and non-prompt production channels

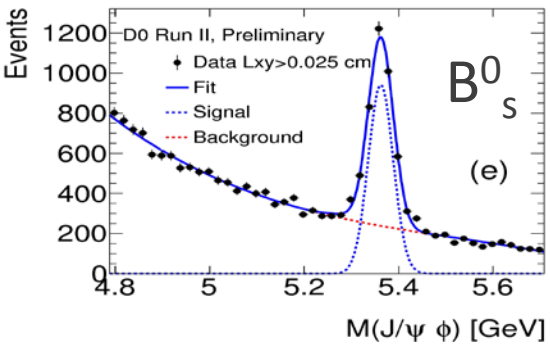








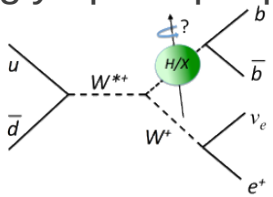


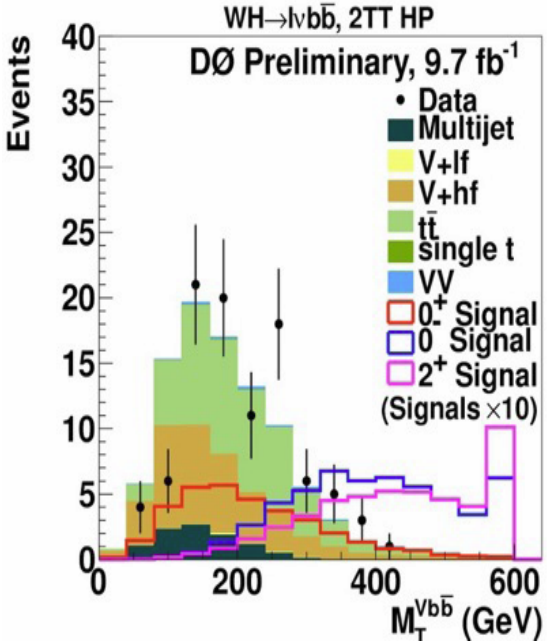


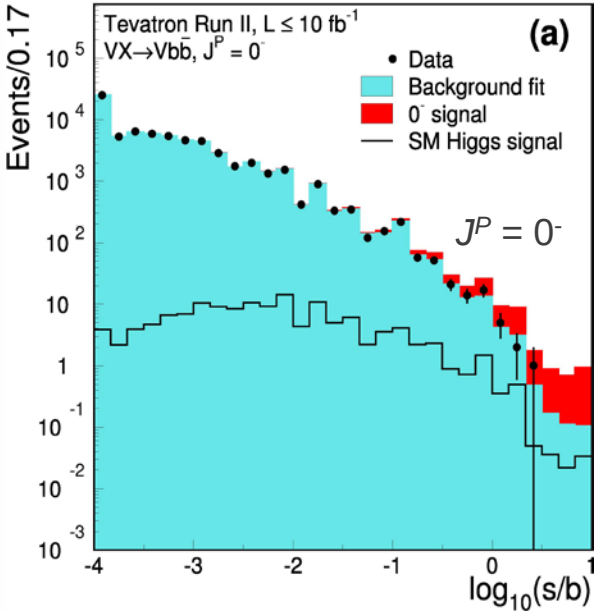
- Observed prompt production of X(4140) with 4.7σ significance
  - Non-prompt rate relative to B^0_s is 0.19+-0.09

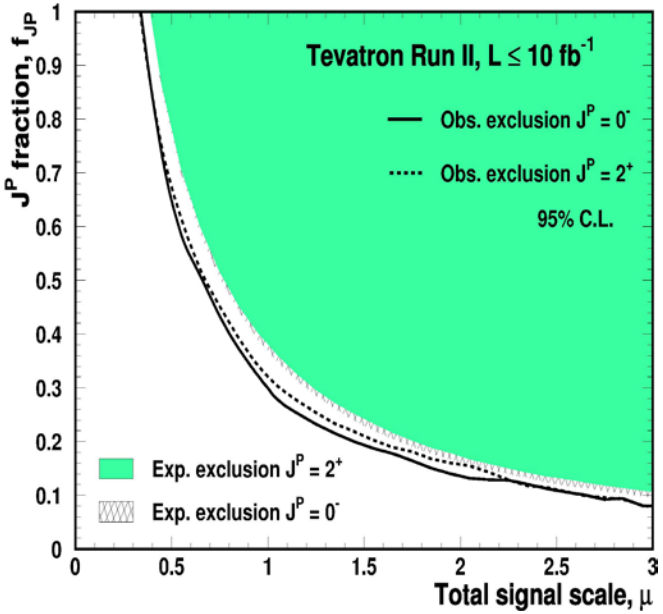
Higgs Studies

- In early 2013 ~20 publications summarized Tevatron Higgs searches and studies program
- Theorists predicted that effective mass of Vbb (V = W or Z) depends strongly upon spin/parity of the Higgs boson
  - Discriminate Higgs J^P based on *production* vs *decay*
- No theoretical predictions for cross section of exotic J^P production
  - Assume standard model cross sections and provide fractional exclusion vs signal strength









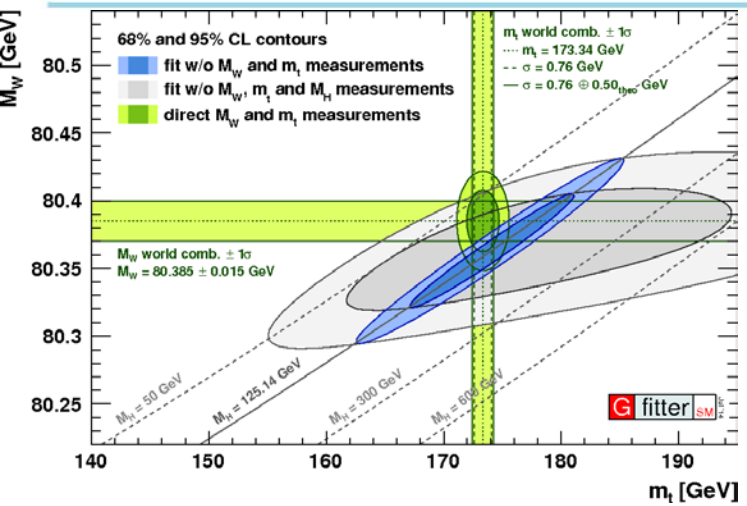
- $J^P = 0^-$ is excluded at 4.9σ and $J^P = 2^+$ is excluded at 5.0σ
- This interesting Higgs study complimentary to LHC concludes Tevatron Higgs program

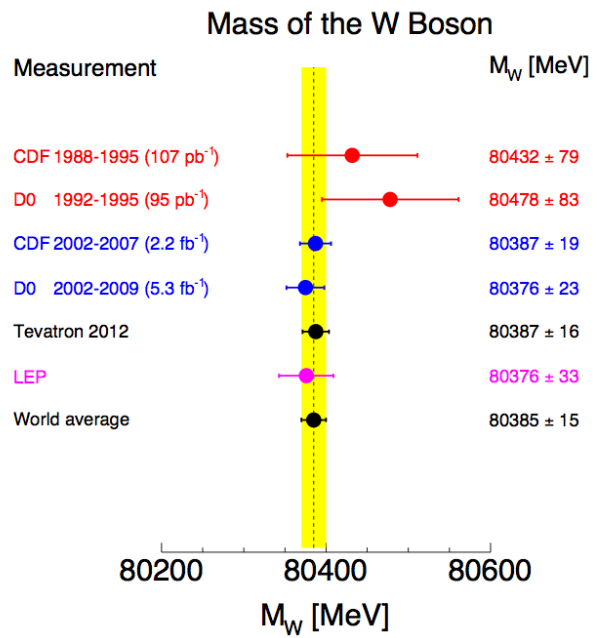
Tevatron Analysis Plans

- Concentrating on the physics potential of the unique Tevatron data set
  - $p\bar{p}$ collisions: valence quark-antiquark interactions
  - 2 TeV center of mass energy: all standard model particles produced
  - Well understood detectors/algorithms
  - Low number of interactions per beam crossing
  - Unique detector features, including changes in magnet polarities

- Highlights of the coming results (~40 analyses in progress)
  - Top quark: top mass in di-lepton channel using matrix elements method, in all hadronic decay channel and l+jets with matrix element method, top quark mass Tevatron combination, top mass combination with LHC, A_{fb} Tevatron combination
  - Electroweak: W boson mass – both experiments and the combination, A_{fb} for di-lepton production ($\sin^2\theta_W$) and Tevatron combination, W production asymmetry
  - Heavy flavor: D^+ and D^0 cross section, Upsilon cross sections, B_s lifetime, A_{fb} in Omega and Lambda production
  - QCD: photon+jets cross sections, central exclusive meson production, double parton interactions, $J/\psi+$ Upsilon pair production

W Boson Mass





Projections for CDF

Source	0.2/fb (MeV)	2.2/fb (MeV)	10/fb (MeV)
Lepton energy scale	23	7	3
Lepton energy resolution	4	2	1
Recoil energy scale	8	4	2
Lepton removal	6	2	1
Backgrounds	6	3	2
pT(W) model	4	5	2
PDFs	11	10	5
QED radiation	10	4	4
Total systematics	**34**	**15**	**8**
W statistics	34	12	6
Total	**48**	**19**	**10**

Assume 50% reduction in BC-NBC and QED/energy loss uncertainties

Assume the same scaling as 0.2/fb → 2.2/fb

Assume 1/ √L scaling

Assume 50% reduction in PDF uncertainty

Assume the same QED

Assume 1/ √L scaling

Limiting factors:
1). PDFs (and QED)
2). BC-NBC difference
3). QED/energy loss modeling

- W boson mass is a fundamental parameter of the standard model
  - Input for the standard model self-consistency check
- With newer PDFs (W asymmetry measurements) ~5 MeV PDF uncertainty (leading systematic) could be reached
- Projections demonstrate ~10-12 MeV uncertainty per experiment with 10 fb^{-1} data set
  - Both experiments are working on the analysis

Tevatron Highlights Summary

- Tevatron analyses are concentrating on unique features of the data set and detectors
  - High center of mass energy, initial $p\bar{p}$ state, magnets polarities changes, low number of interactions per crossing
  - Very high precision measurements of standard model parameters such as top quark and W boson masses, $\sin^2\theta_W$ and many others obtained recently and more to come

- 50 results published by the collaborations over last year
  - Expect another ~40 papers based on the Tevatron data

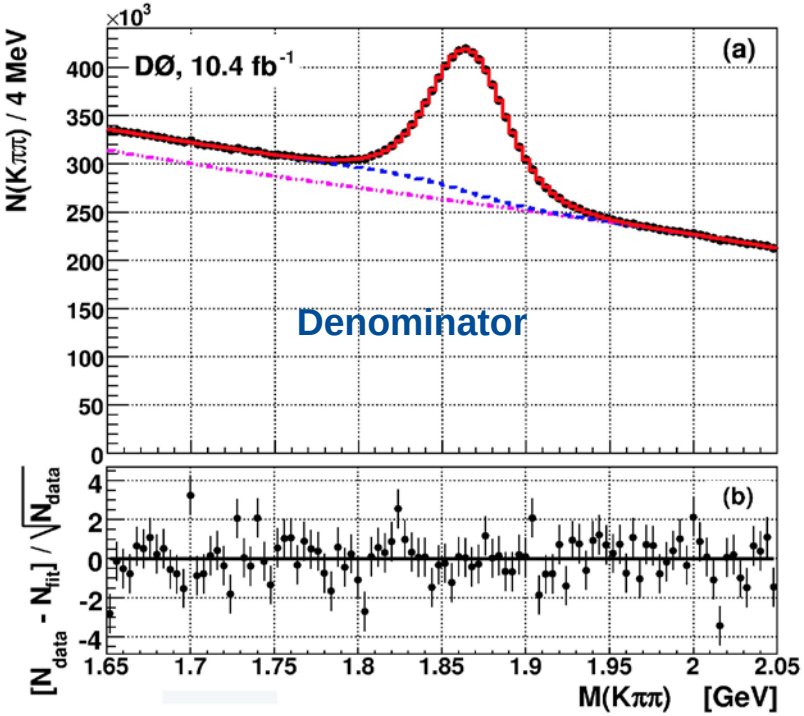
- Tevatron data are preserved
  - Data on new tapes, software made compatible with long term supported operating system
  - ~20,000 CDF and DØ Notes are in Inspire (most recent are protected)
  - Agenda servers with ~100,000 talks migrated to Indico

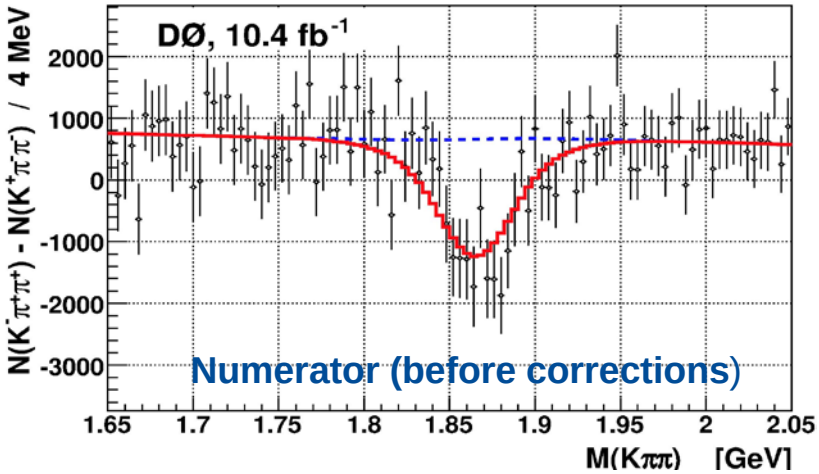
Very productive Tevatron program with over 1,000 publications and over 1,000 PhDs defended is successfully converging

Measurement of the Direct CP-violating Parameter $A_{CP}(D^+ \to K^-\pi^+\pi^+)$

- Large data set and charge symmetry of the detector due to magnetic polarities changes makes high accuracy charge asymmetry studies possible
- Measurement of CP violating parameters in Cabibbo-favored decays are crucial to establish experimental basis for CP violation searches in decays proceeding via box or penguin diagrams

$$A_{\rm CP}(D^+ \to K^-\pi^+\pi^+) = \frac{\Gamma(D^+ \to K^-\pi^+\pi^+) - \Gamma(D^- \to K^+\pi^-\pi^-)}{\Gamma(D^+ \to K^-\pi^+\pi^+) + \Gamma(D^- \to K^+\pi^-\pi^-)}$$





$$A_{\rm CP}(D^+ \to K^-\pi^+\pi^+) = [-0.16 \pm 0.15\,({\rm stat.}) \pm 0.09\,({\rm syst.})]\%$$

Improved previous accuracy on A_{CP} in this decay by a factor of 2.5