Top quark studies at the Tevatron

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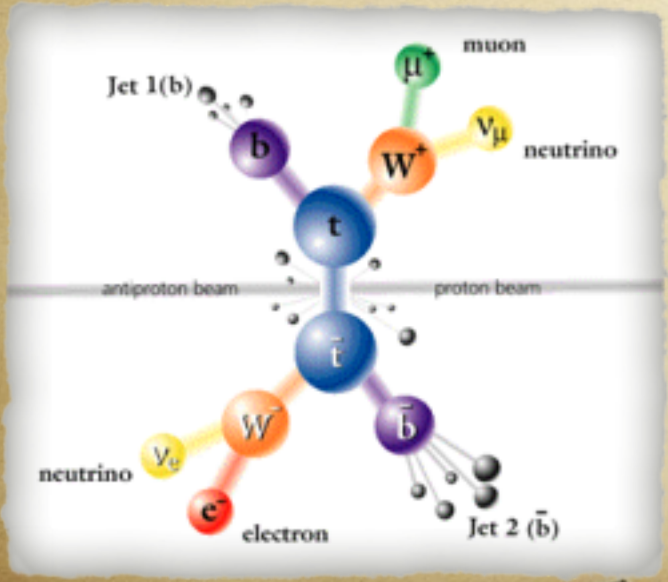
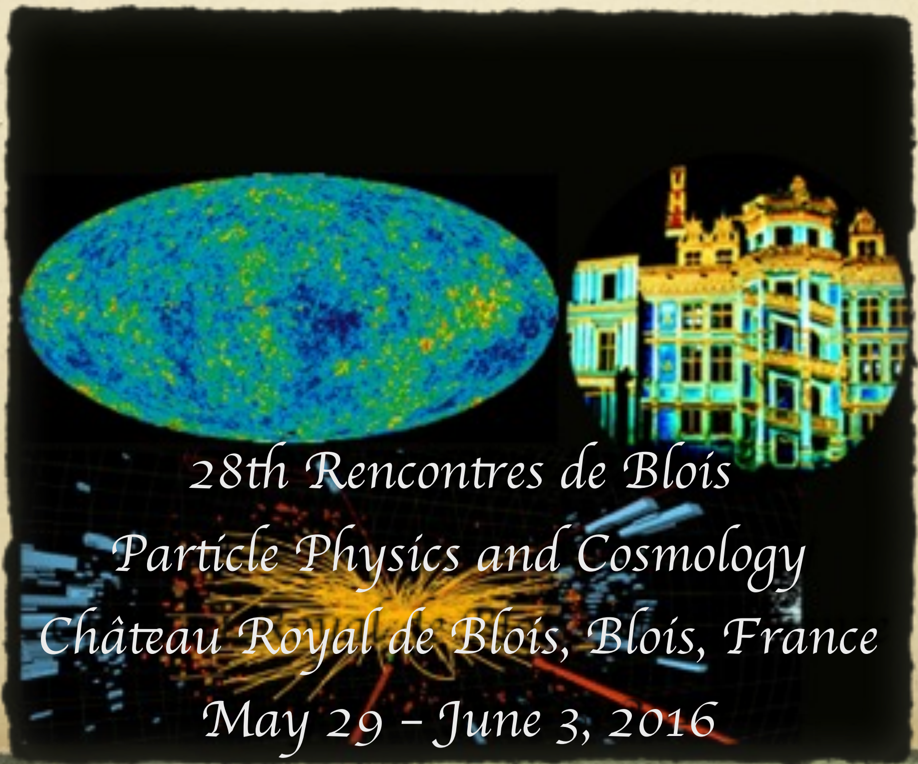
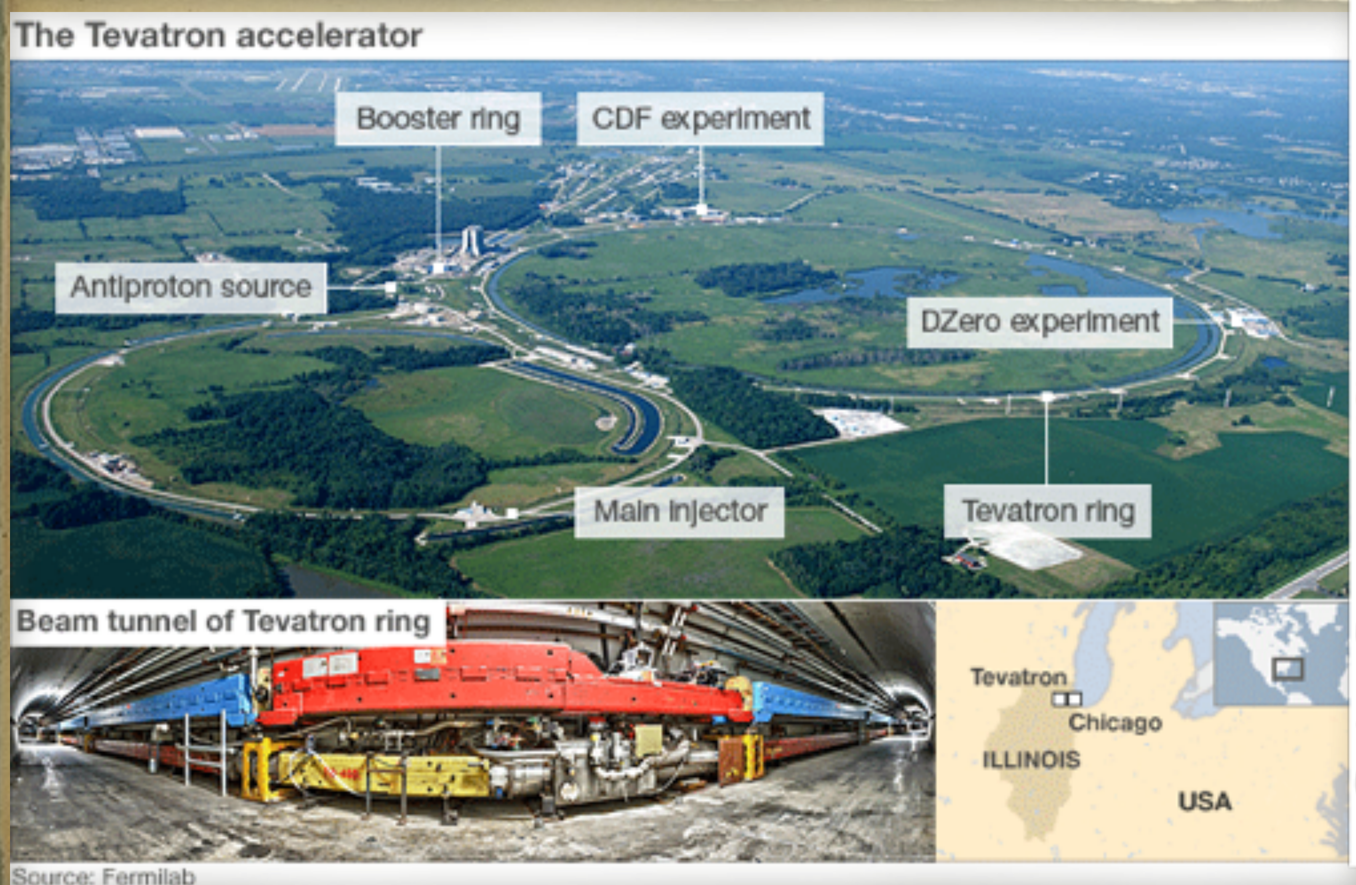
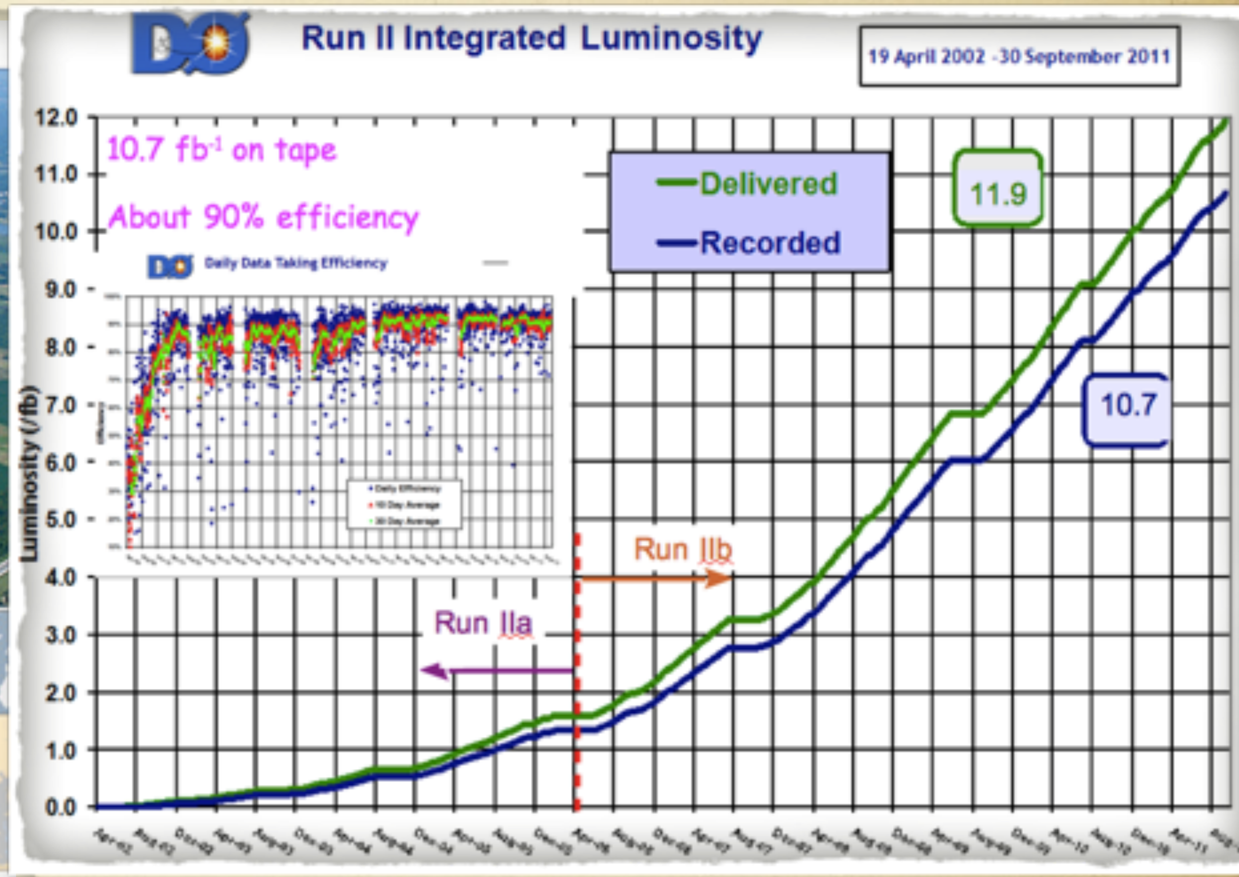
On behalf of CDF *and* DØ *collaborations*





The Tevatron



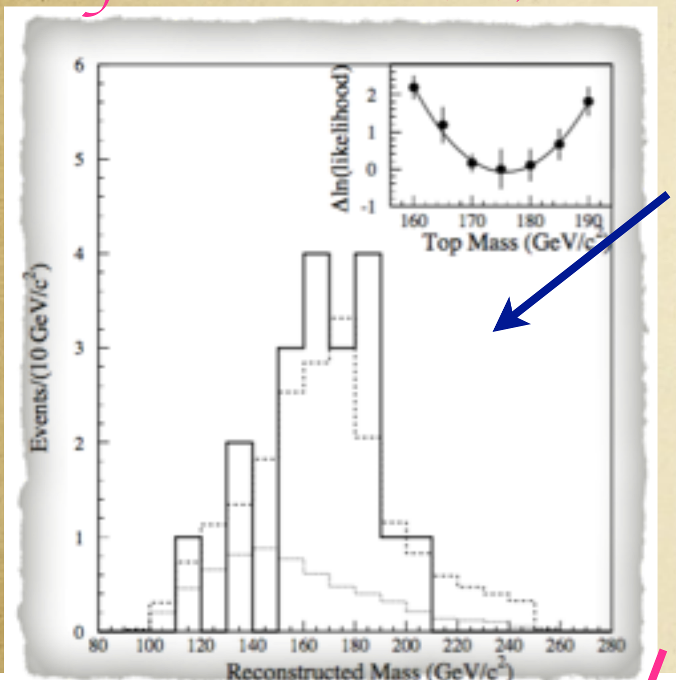


- Ran for 25 years
  - 9 in Run 2 at 1.96 TeV
  - $p\bar{p}$ collider
- Ended operation on 30/9/2011

The Top Quark

Discovered in 1995 at Tevatron, very few events

Phys. Rev. Lett. 74, 2626 (1995)

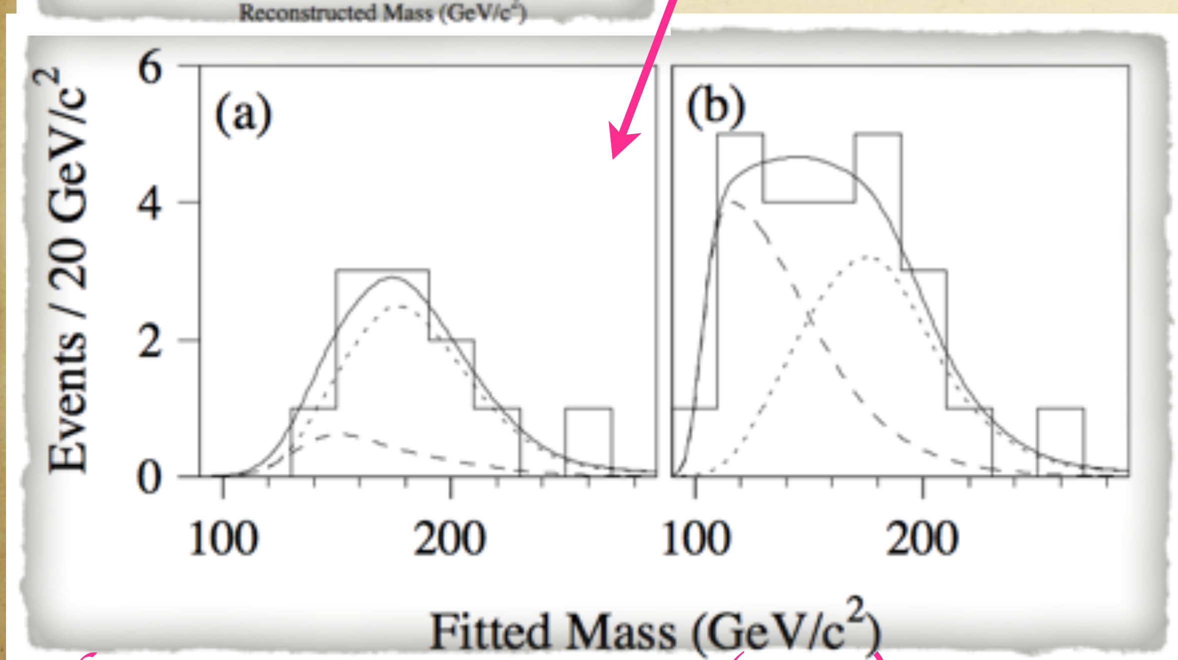


CDF: 4.8σ

m = 176 GeV

D0: 4.6σ

m = 199 GeV



Phys. Rev. Lett. 74, 2632 (1995)

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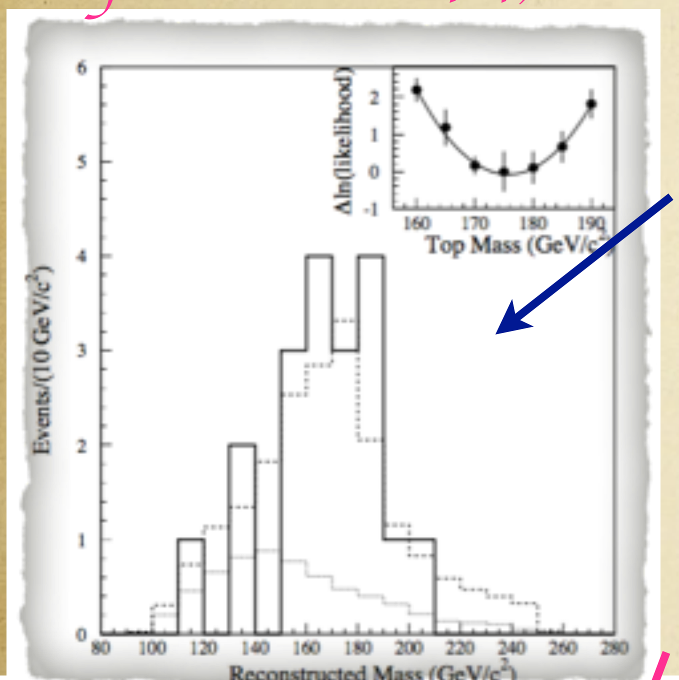

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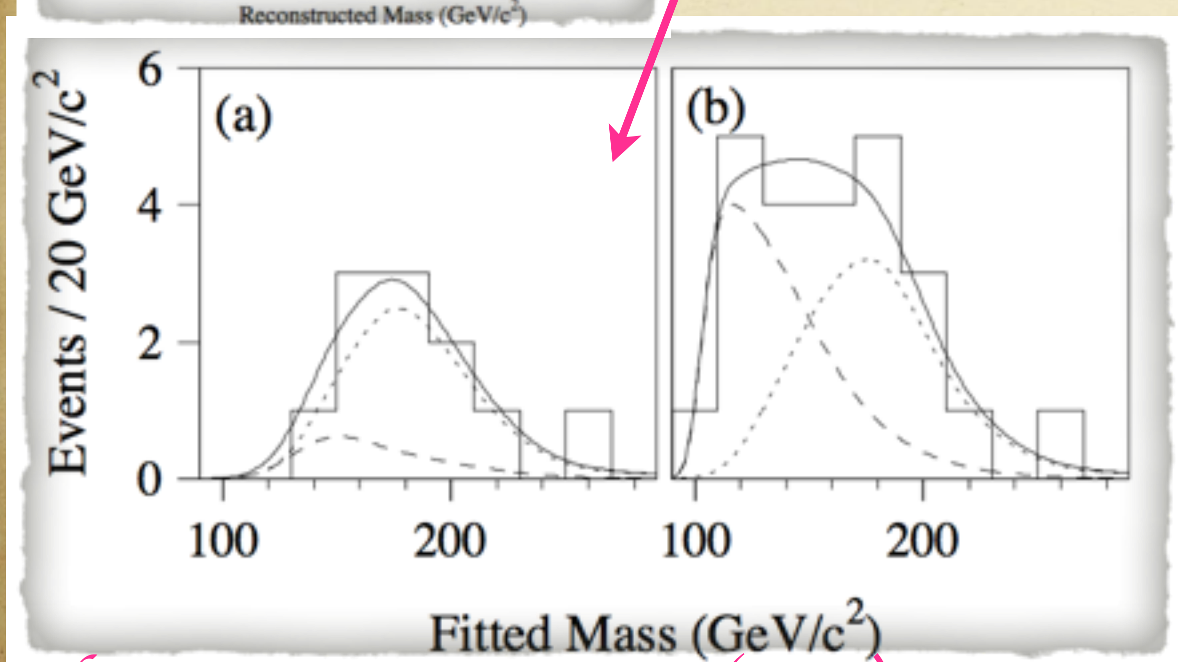
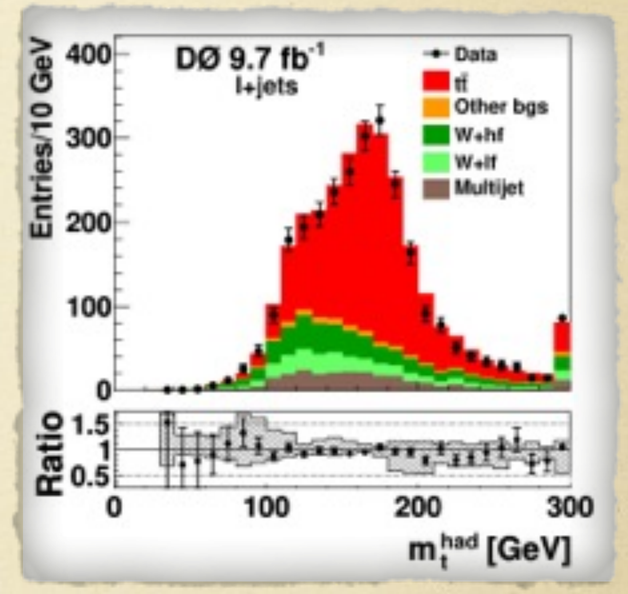
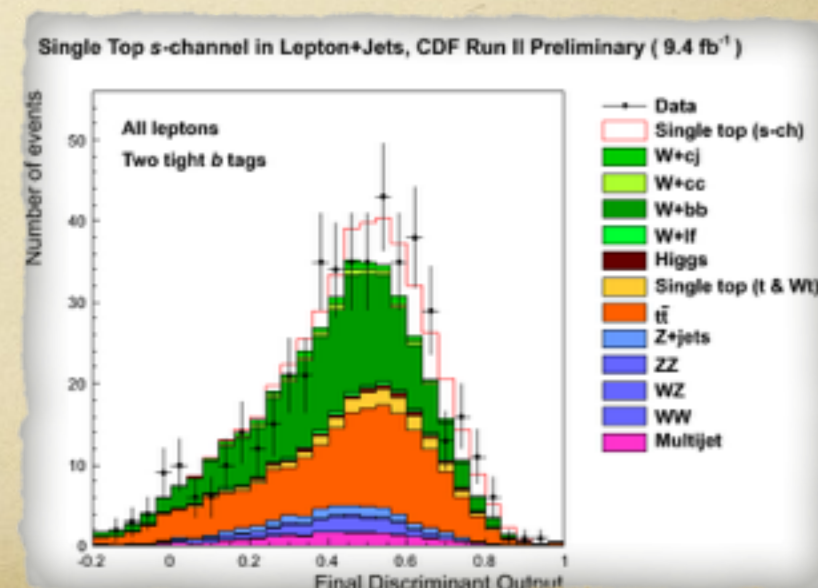


Phys. Rev. Lett. 74, 2632 (1995)

By the end: thousands of events



Rediscovered in a single production



So why do we still study it?

- Top is the heaviest known fundamental particle
  m ~ 173 GeV
- A quark with a charge 2/3e and spin 1/2
- Decays almost exclusively to Wb
- Produced by strong and weak interactions

- We can study the properties of a bare quark
  - Lifetime < hadronisation
- Due to its high mass strongly influences Higgs mass in SM
- New physics can be found in deviation from the SM predictions
- Top is a background to many other searches

Top quark studies

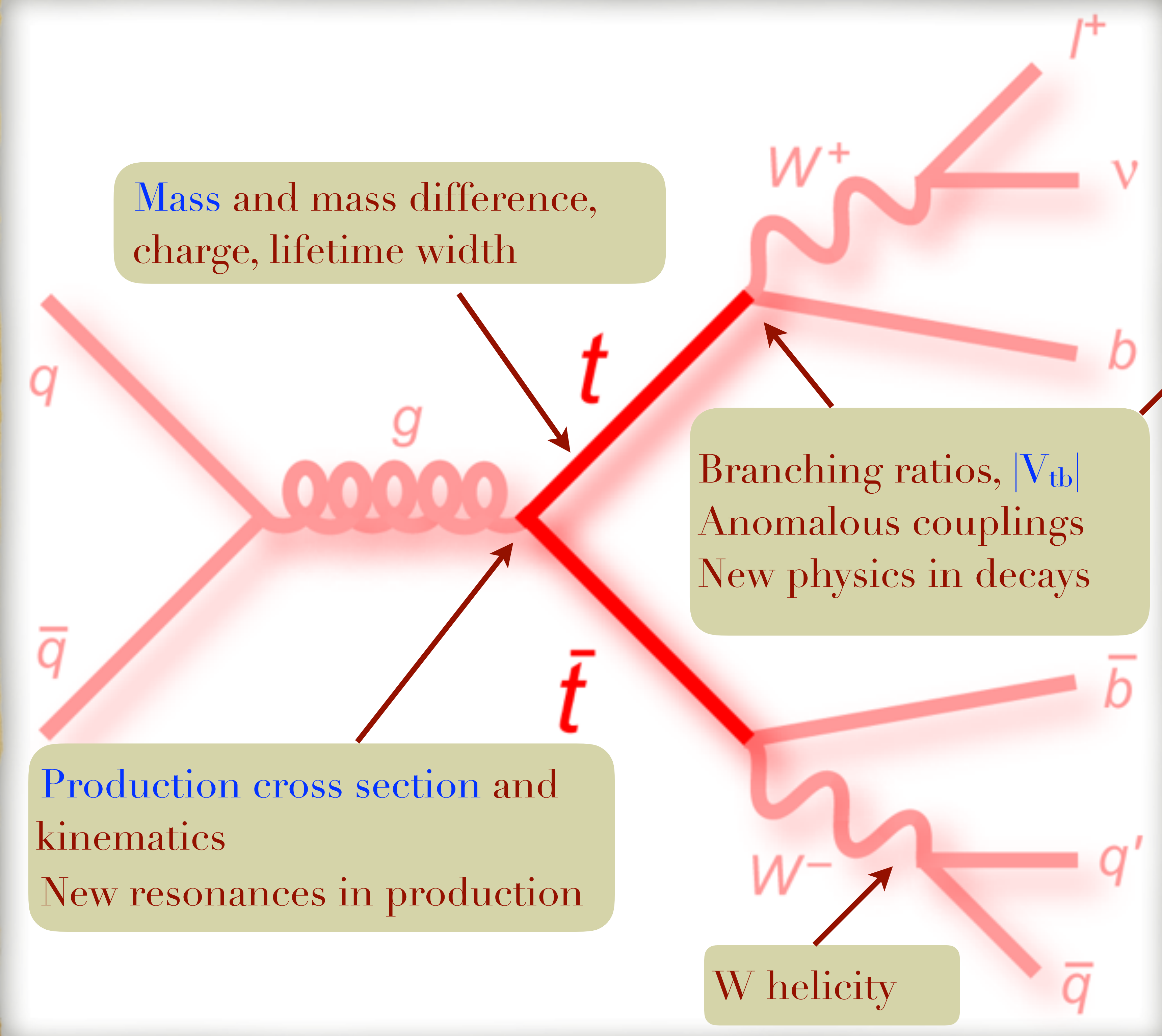
Spin correlation
Charge asymmetry
Color flow

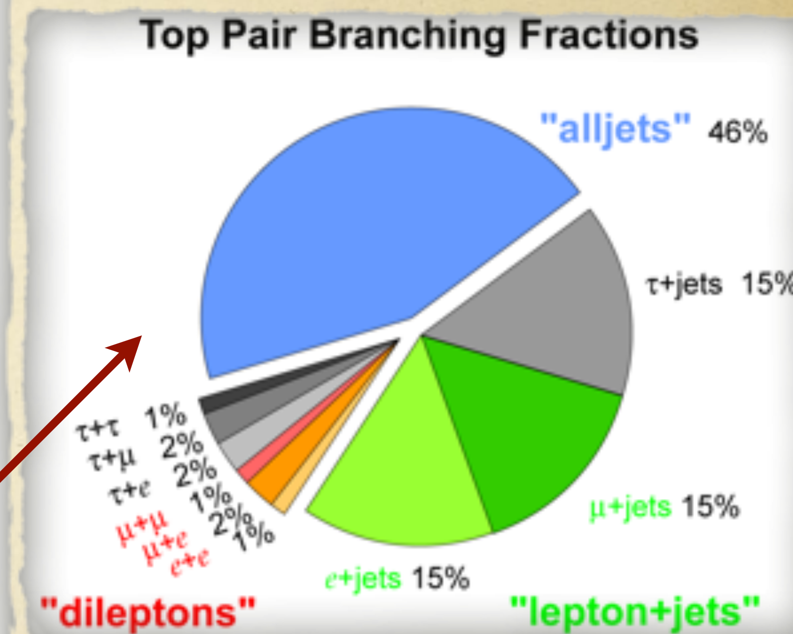
Mass and mass difference, charge, lifetime width

Branching ratios, $|V_{tb}|$
Anomalous couplings
New physics in decays

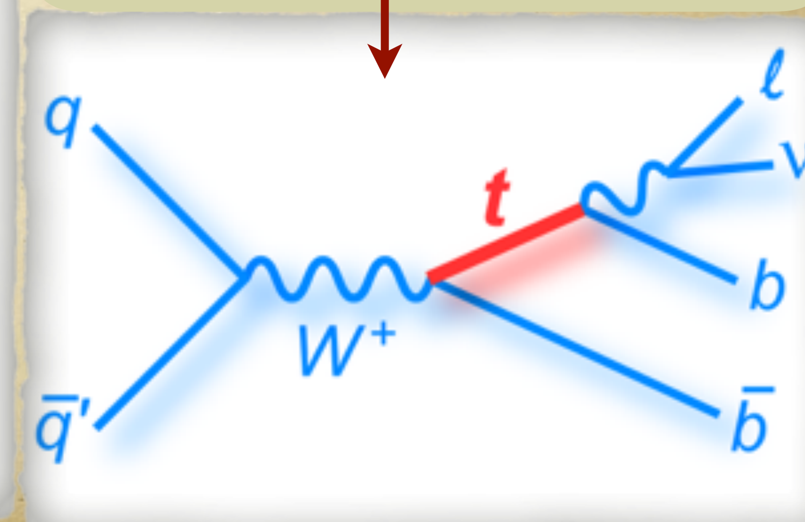
Production cross section and kinematics
New resonances in production

W helicity



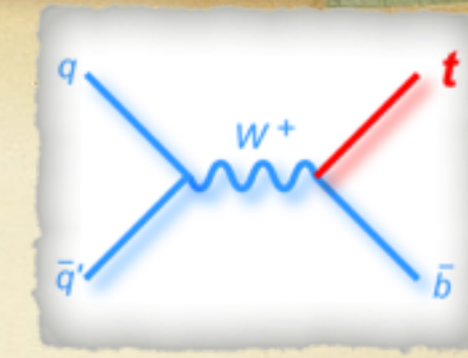


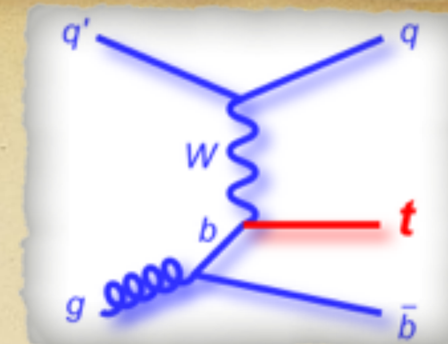
Single top - s and t channel production, properties, new physics



Single top

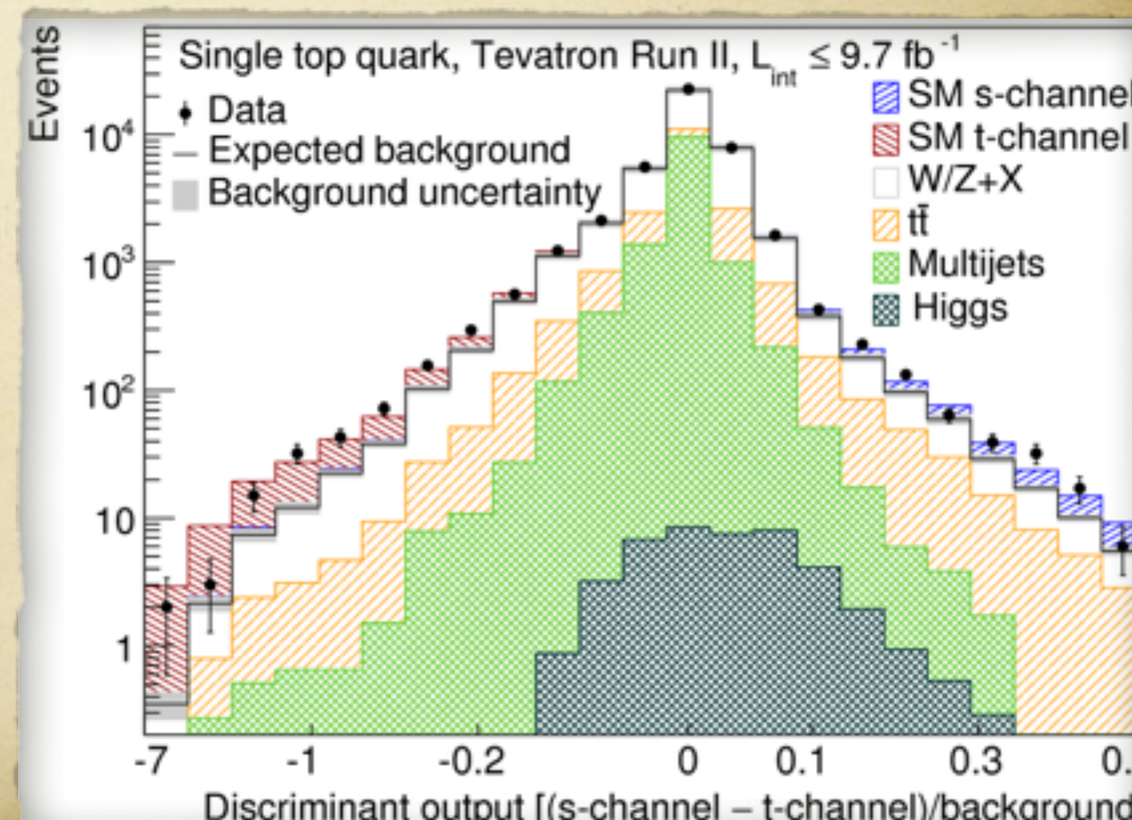
Phys. Rev. Lett. 115, 152003 (2015)



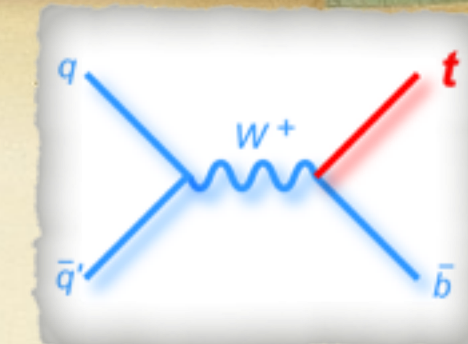


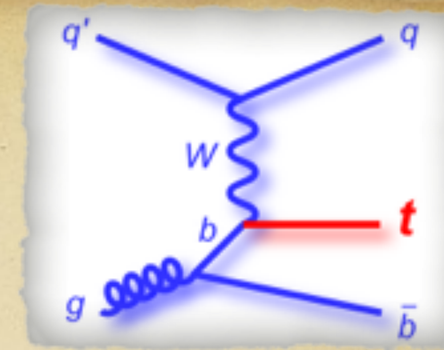
- Electroweak production in: s, t and Wt channel (Wt negligible @Tevatron)
- Selected events with
  - l+jets - 1 high p_T lepton
  - MET+jets - high MET
  - 2 and 3 jets with 1 or 2 b-tagged
- Main background from V+jets
- Shape from MC, normalization from data
- Final selection with Multivariate discriminant

	s - channel (σ_{tb})	t - channel (σ_{tqb})
Tevatron $p\bar{p}$ @1.96 TeV	1.04 pb	2.26 pb
LHC pp @7 TeV	4.6 pb	64.6 pb



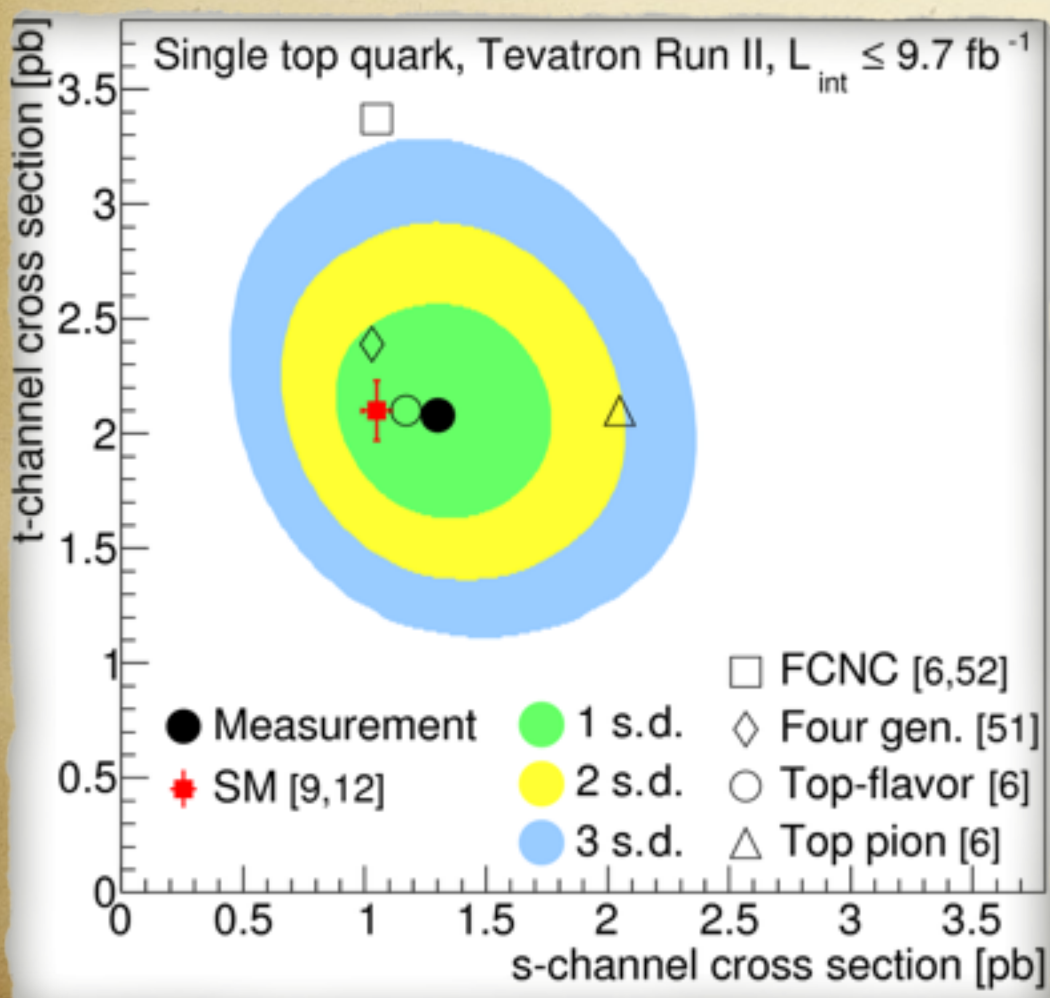
Single top

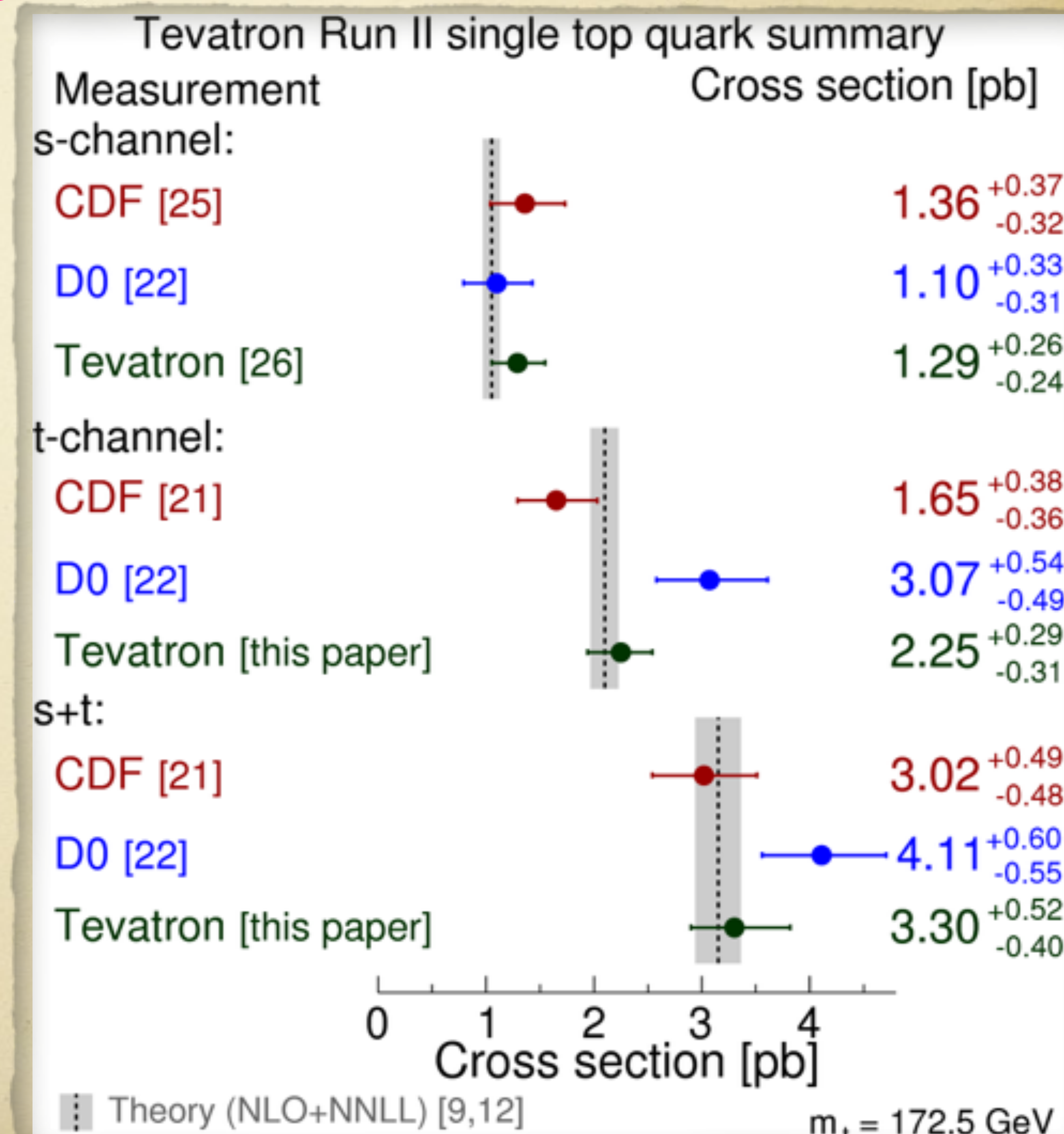




- Electroweak production in s and t channels
- It is directly sensitive to the $|V_{tb}|^2$
  - $|V_{tb}| > 0.92$ @ 95% C.L.
- Final result from Tevatron

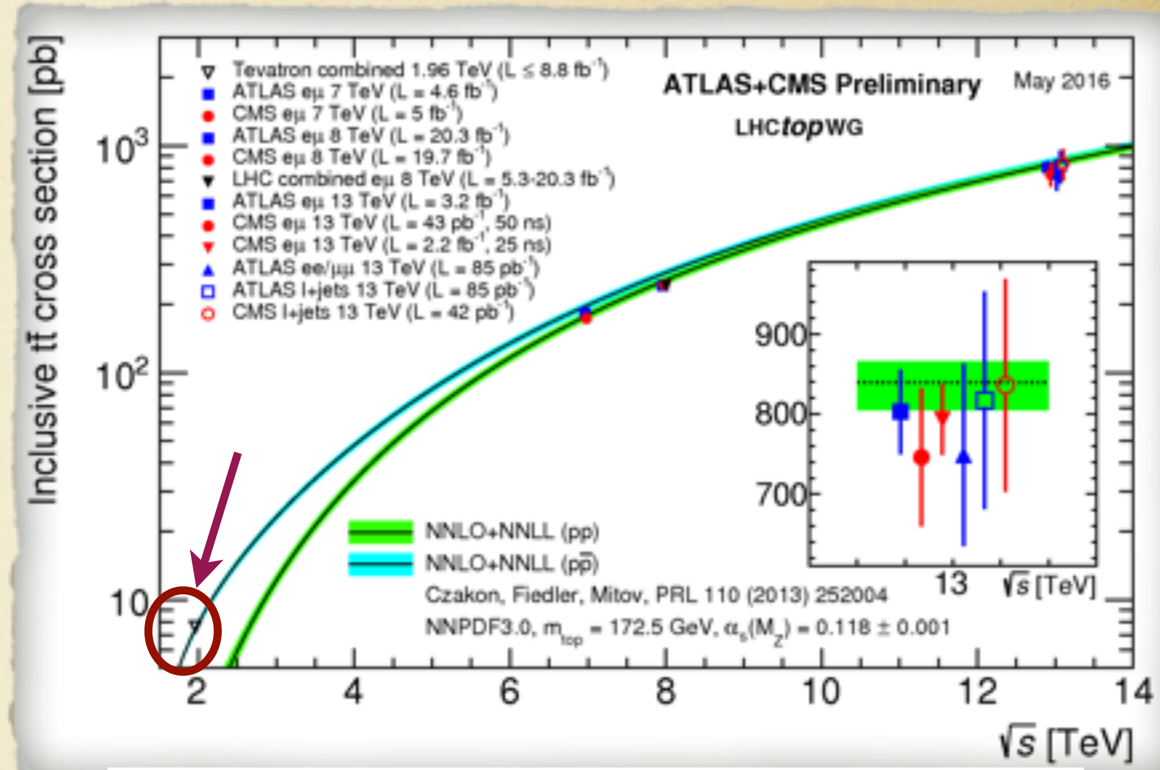
Phys. Rev. Lett. 115, 152003 (2015)

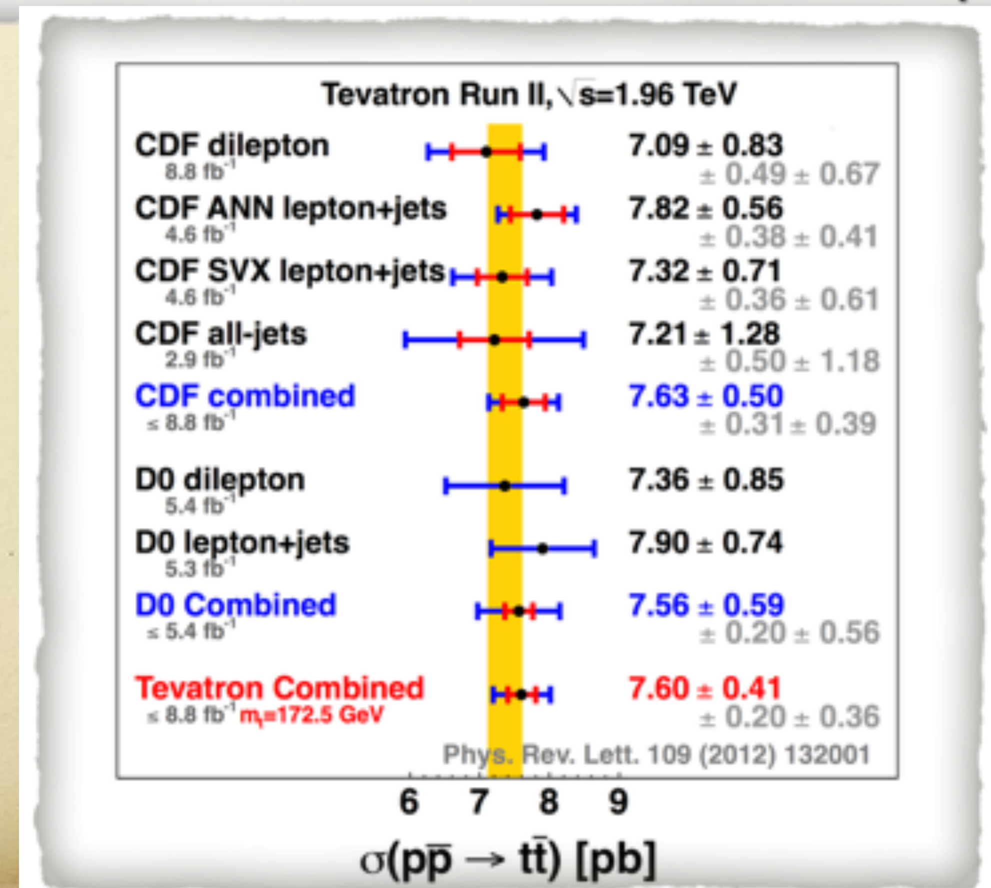




$t\bar{t}$ production cross section

- Different energies and dominant production between Tevatron and LHC
  - At Tevatron: 85% $q\bar{q}$ annihilation + 15% gg fusion, and opposite at the LHC (goes to 10% and 90% @13TeV)
- At Tevatron, we measured inclusive and differential cross section
  - D0 updated measurement with the full dataset
- Mainly done in dilepton & l+jets final states



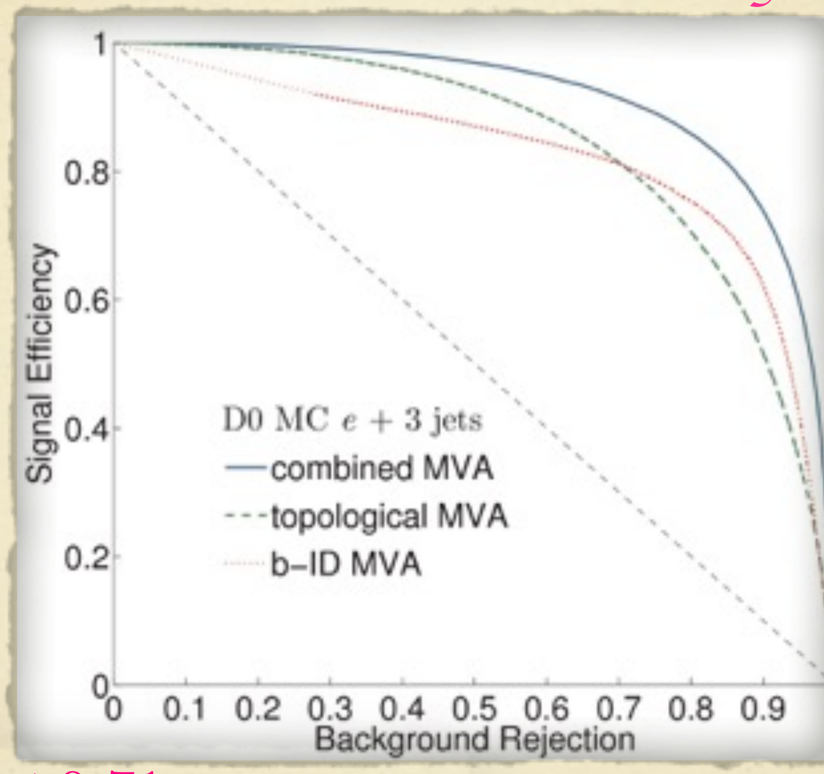


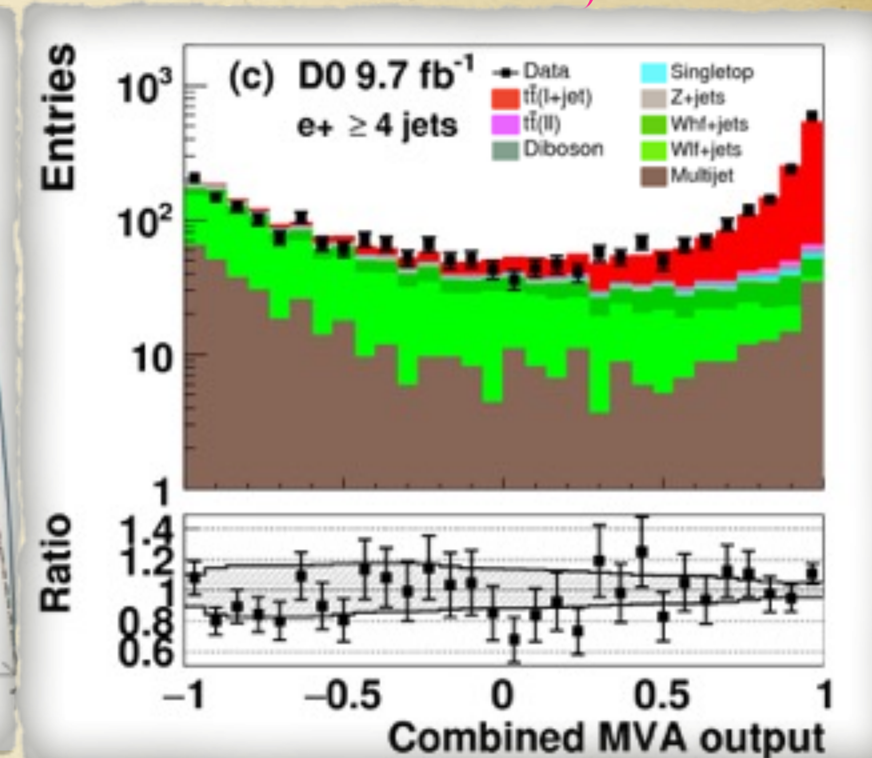
$t\bar{t}$ production cross section

New

arXiv:1605.06168; Submitted to Phys. Rev. D

- l+jets
  - separate by lepton flavor, and by 2,3 and 4+ jets
  - Use maximal b-tagging MVA output as additional input variable into combined MVA

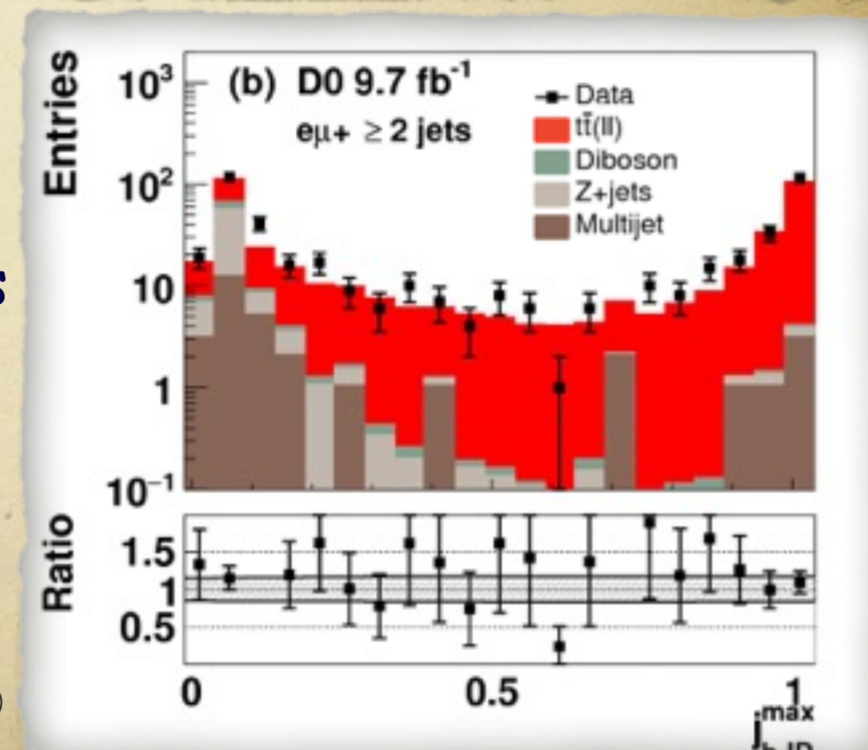




$$\sigma_{t\bar{t}} = 7.33 \pm 0.14(stat.)^{+0.71}_{-0.61}(syst.)pb$$

- ll+jets
  - separate by lepton flavor combinations, and 1 and 2+ jets
  - Use maximal b-tagging MVA output

$$\sigma_{t\bar{t}} = 7.58 \pm 0.35(stat.)^{+0.69}_{-0.58}(syst.)pb$$



- Combined

$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(stat.)^{+0.57}_{-0.50}(syst.)pb \quad \frac{\delta\sigma}{\sigma} = 7.6\%$$

Polarization

Conference Note 6471

- Top quarks are almost unpolarized in SM at the Tevatron
  - Small longitudinal polarization from parity-violating weak interactions
  - Transverse polarization is allowed in strong interactions
  - New physics can make it bigger
- Angular distributions of the decay products in the top rest frame give the polarization along a chosen axis

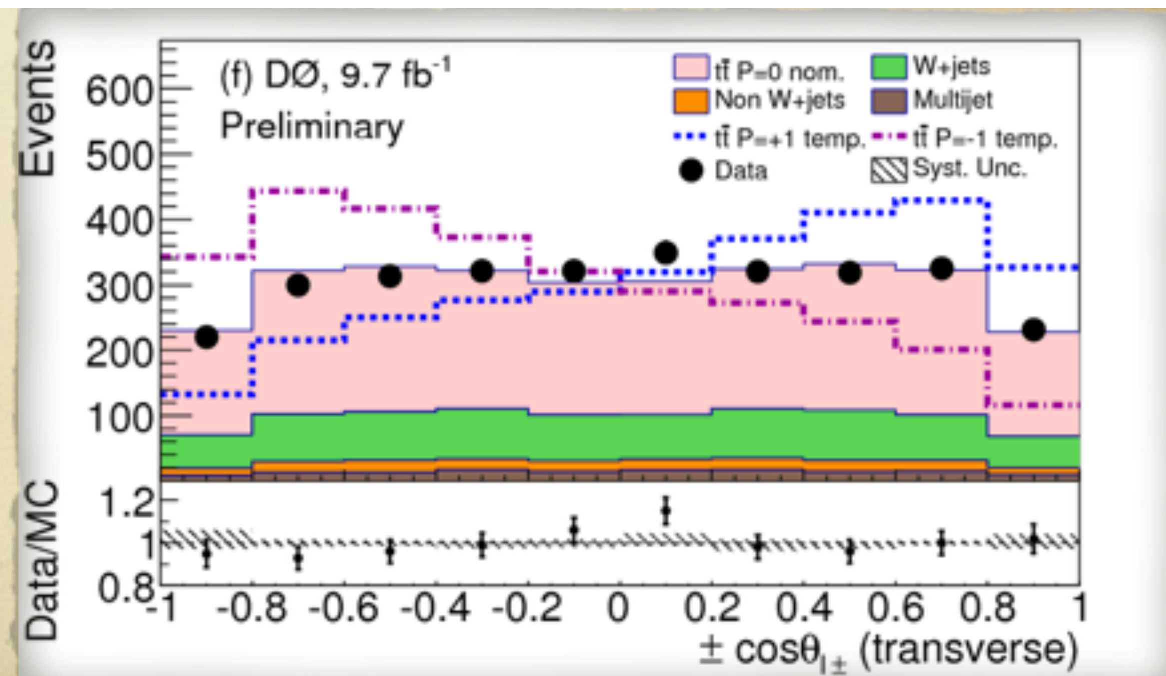
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2}(1 + P_{\hat{n}}\kappa_i \cos\theta_{i,\hat{n}})$$

  - κ_i = 1 for leptons (smaller for other decay products), θ angle between decay product and chosen axis

- Measured with respect to three axes
  - the beam axis (longitudinal)
  - the helicity axis (longitudinal)
  - the transverse axis

1st @hadron collider

Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$



Forward backward asymmetry

- Forward backward asymmetry in $t\bar{t}$ production at the Tevatron originates from NLO QCD effects
  - Top quarks more likely will go into direction of incoming quark
- Complementary to LHC
- Can be an indication of the new physics
- Measured with $t\bar{t}$

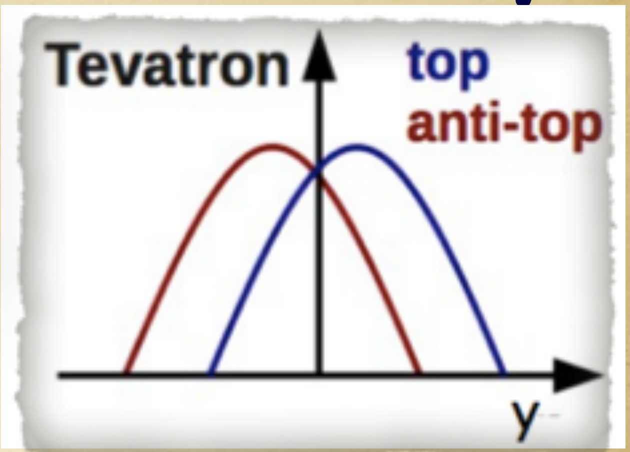
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- and with leptons

$$A_{FB}^{t\bar{t}} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$



- Measurement done in l+jets
  - full reconstruction possible and top charge determined from the lepton charge
- And in dileptons
  - top quark can be reconstructed using matrix elements (D0), and probabilistic methods are used for Δy distribution
  - Or lepton asymmetries are used instead

Forward backward asymmetry and polarization

Phys. Rev. D 92, 052007 (2015)

- Some BSM models would affect $t\bar{t}$ production, and thus they can enhance both asymmetry and polarization

- Polarization related to asymmetry in cosθ

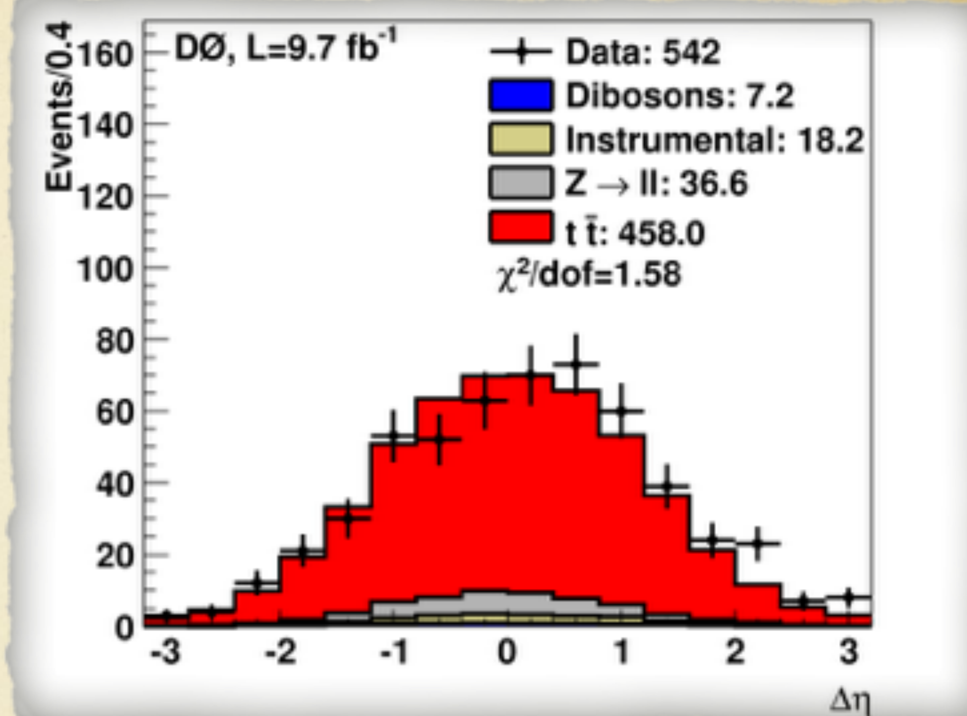
$$A^{l^\pm}_{\hat{n}} = \frac{N(\cos\theta^\pm > 0) - N(\cos\theta^\pm < 0)}{N(\cos\theta^\pm > 0) - N(\cos\theta^\pm < 0)}$$

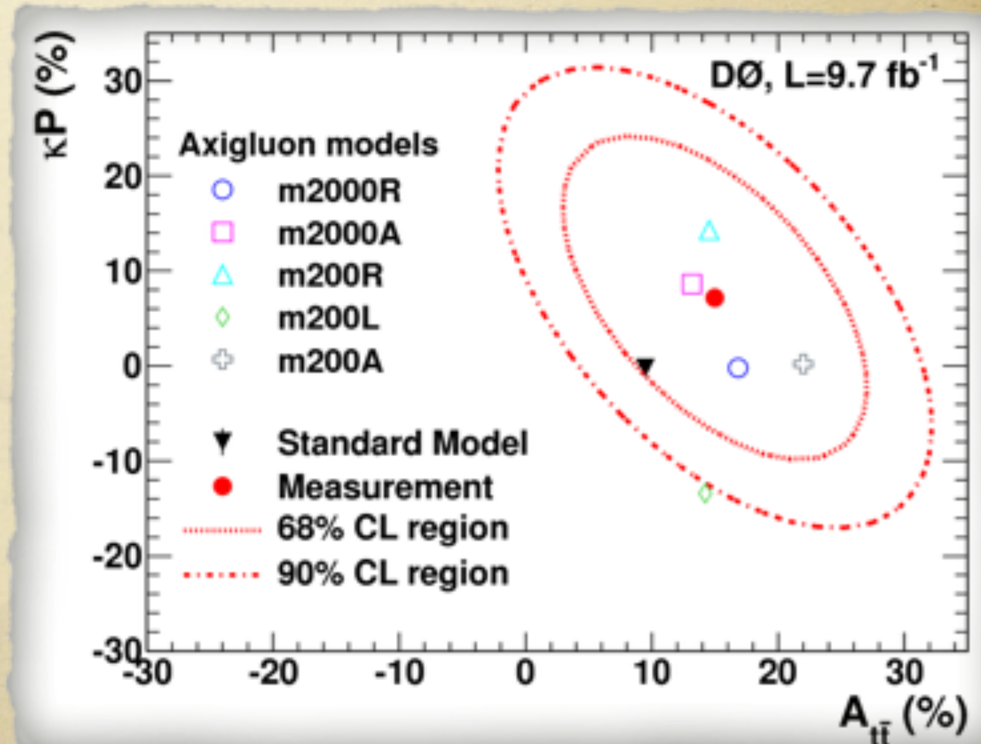
$$\kappa P = \frac{1}{2}(\kappa^+ P^+ - \kappa^- P^-) = A^{l^+} - A^{l^-}$$

- Analysis in dilepton channel

- Measured simultaneously: $A^{t\bar{t}} = (15.0 \pm 8.0)\%$, $\kappa P = (7.2 \pm 11.3)\%$

- Or assuming SM values: $\kappa P = (11.3 \pm 9.3)\%$, $A^{t\bar{t}} = (17.5 \pm 6.3)\%$



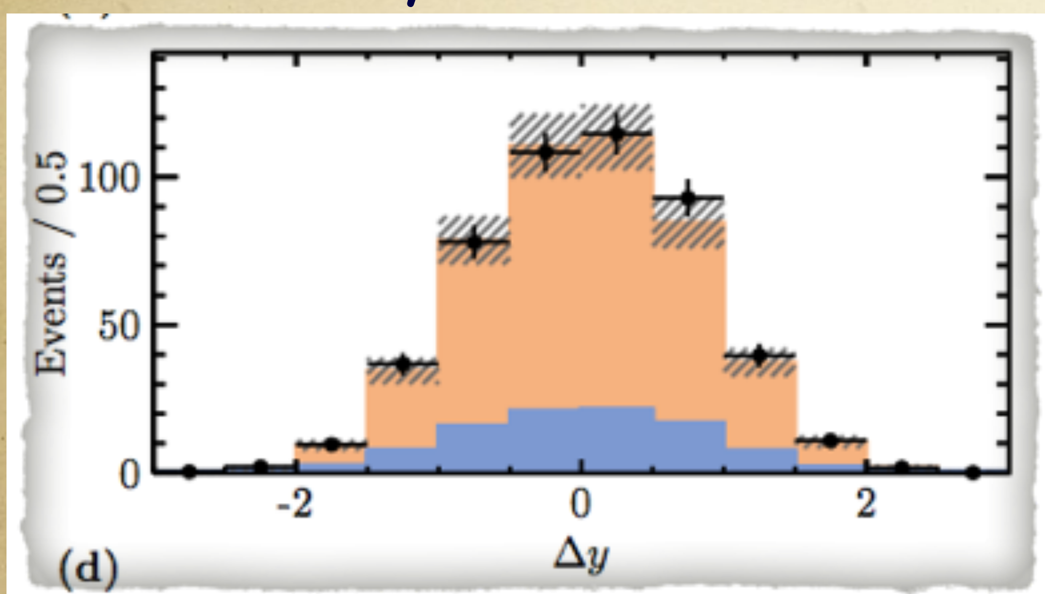


Forward backward asymmetry

New

arXiv: 1602.09015, submitted to PRD

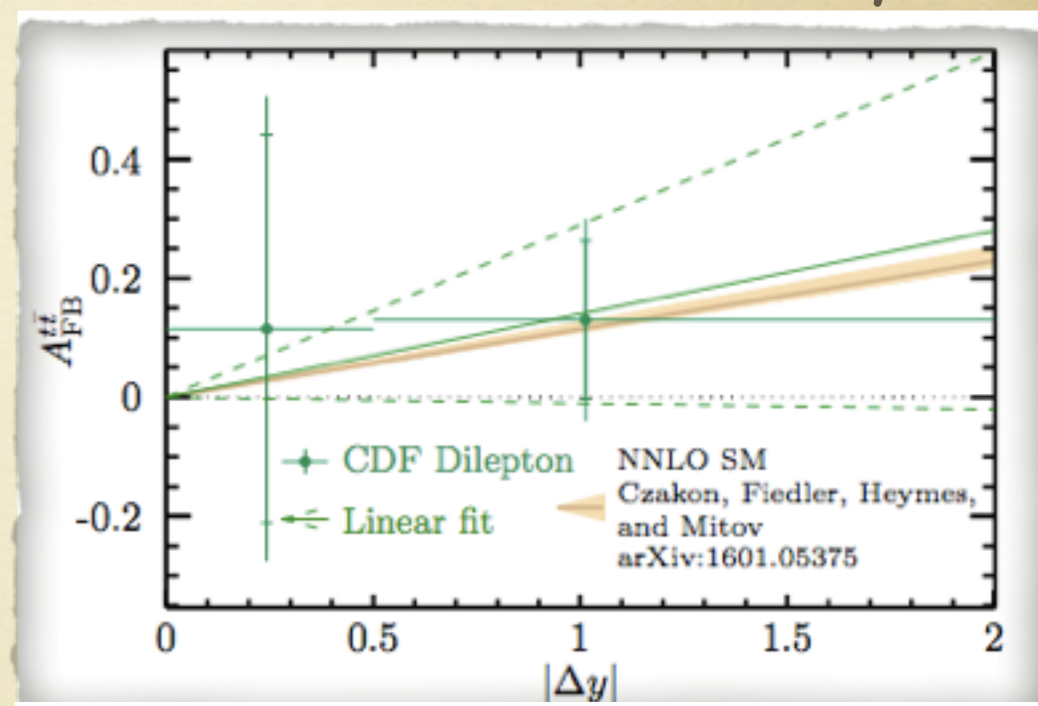
- Dilepton final state
- Procedure:
  - reconstruct top quarks and obtain Δy

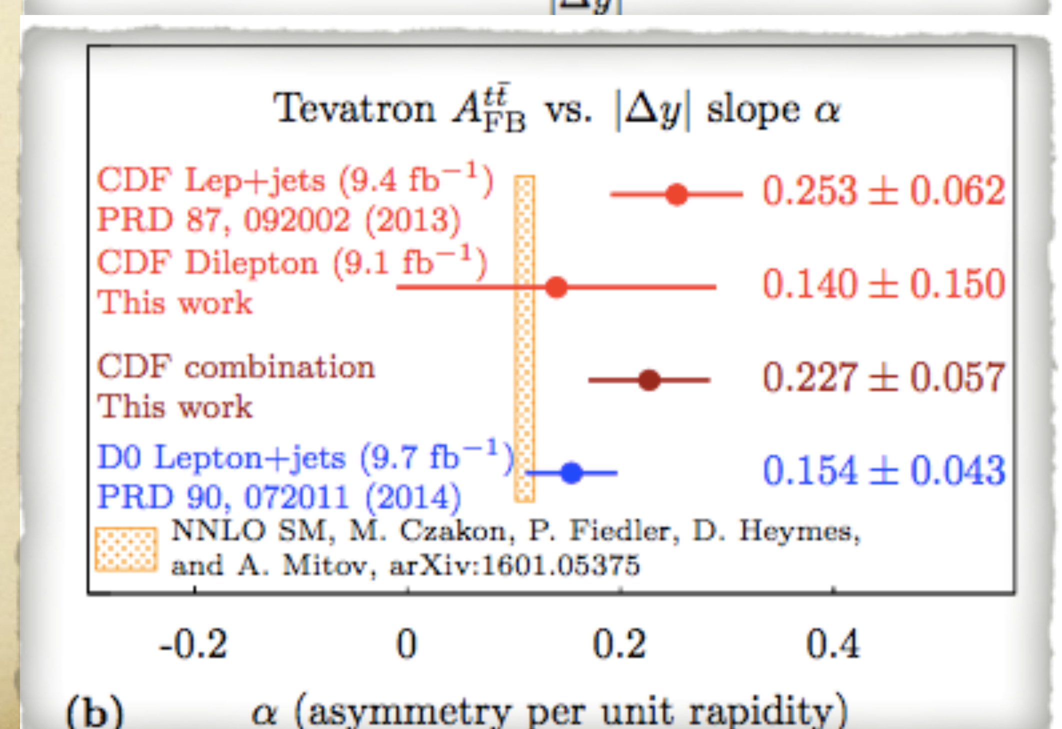


  - unfold objects back to partons
- Result consistent with Tevatron measurements and with SM

$A_{FB}^{t\bar{t}} = 0.12 \pm 0.11(stat) \pm 0.07(syst)$

- Differential distribution: slope of A_{fb} as a function of Δy





Forward backward asymmetry

- Final word
  - Improved SM calculations

$$A_{FB}^{t\bar{t}} = 10.6 \pm 3$$

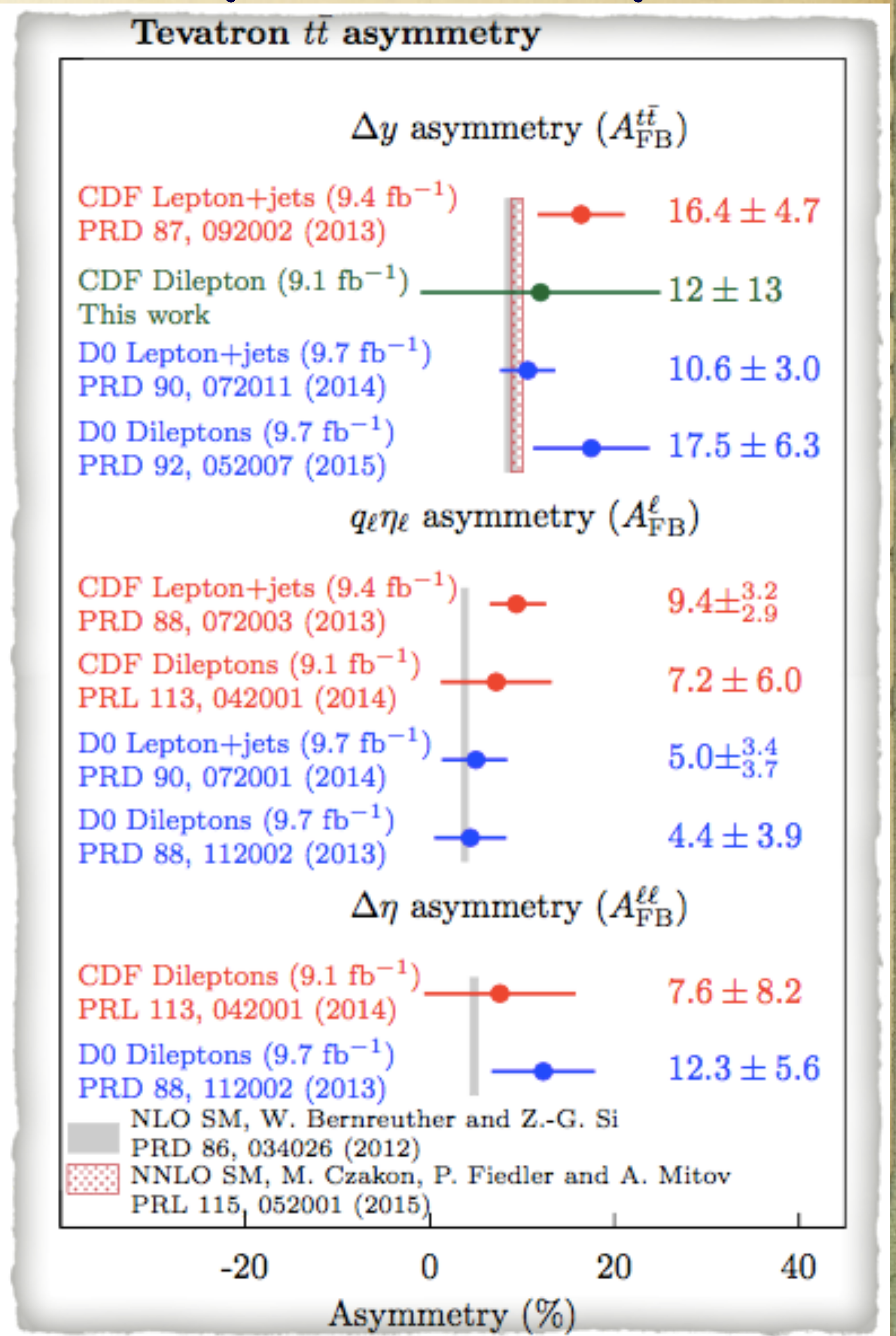
  - CDF

$$A_{FB}^{t\bar{t}} = 16.0 \pm 4.5$$

  - D0

$$A_{FB}^{t\bar{t}} = 11.8 \pm 2.8$$

- Consistent with SM and with each other
- Tevatron combination expected



Spin correlations

Phys. Lett. B 757, 199 (2016)

New

- Due to the short top lifetime, it is possible to study spin related phenomena
- The strength of spin correlation depends on production mechanism
  - @Tevatron the most significant contribution is from the qq annihilation ~0.99 (~ -0.36 from gg fusion)

$$O_{ab} = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\downarrow\uparrow) - \sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\downarrow\uparrow) + \sigma(\uparrow\downarrow)}$$

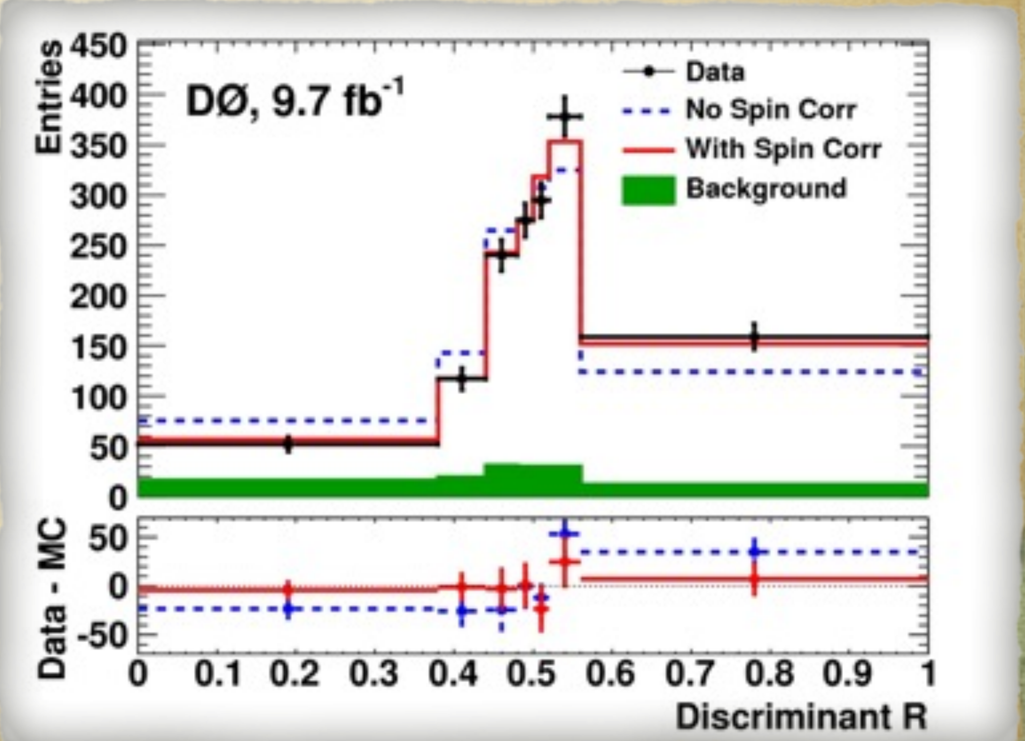
- Build discriminant based on event-by-event probability calculated from matrix elements about spin correlations predicted by SM and null (no correlation) hypothesis

$$R(x) = \frac{P_{t\bar{t}}(x, SM)}{P_{t\bar{t}}(x, SM) + P_{t\bar{t}}(x, null)}$$

- Result consistent with SM (0.8) with an evidence of spin correlations at @4.2σ

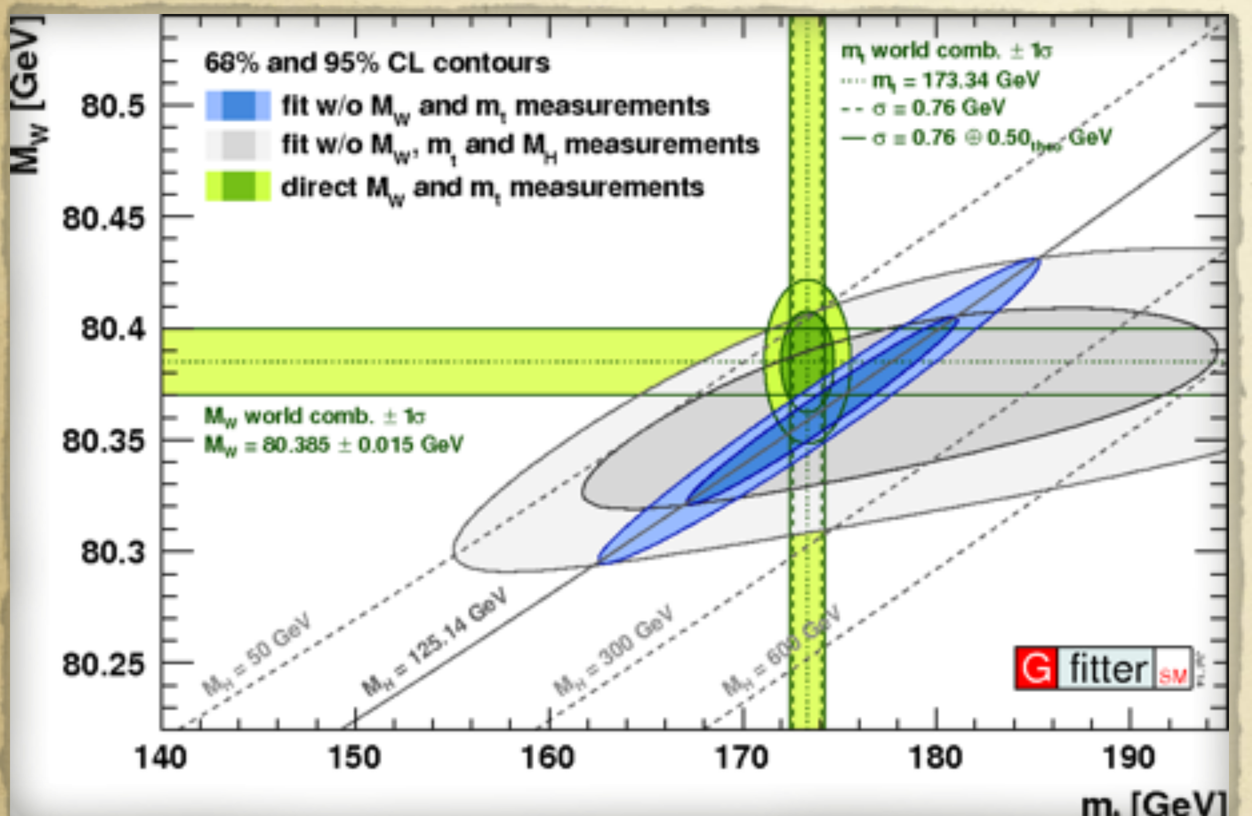
$$O_{off} = 0.89 \pm 0.22(stat + syst)$$

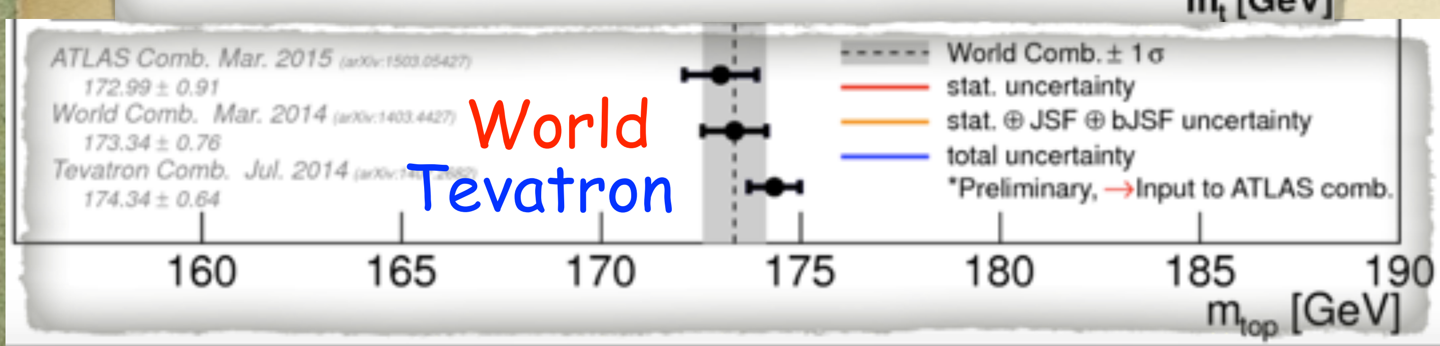
- Obtained a fraction of gg fusion in production, also consistent with the SM (0.135) $f_{gg} = 0.08 \pm 0.16$

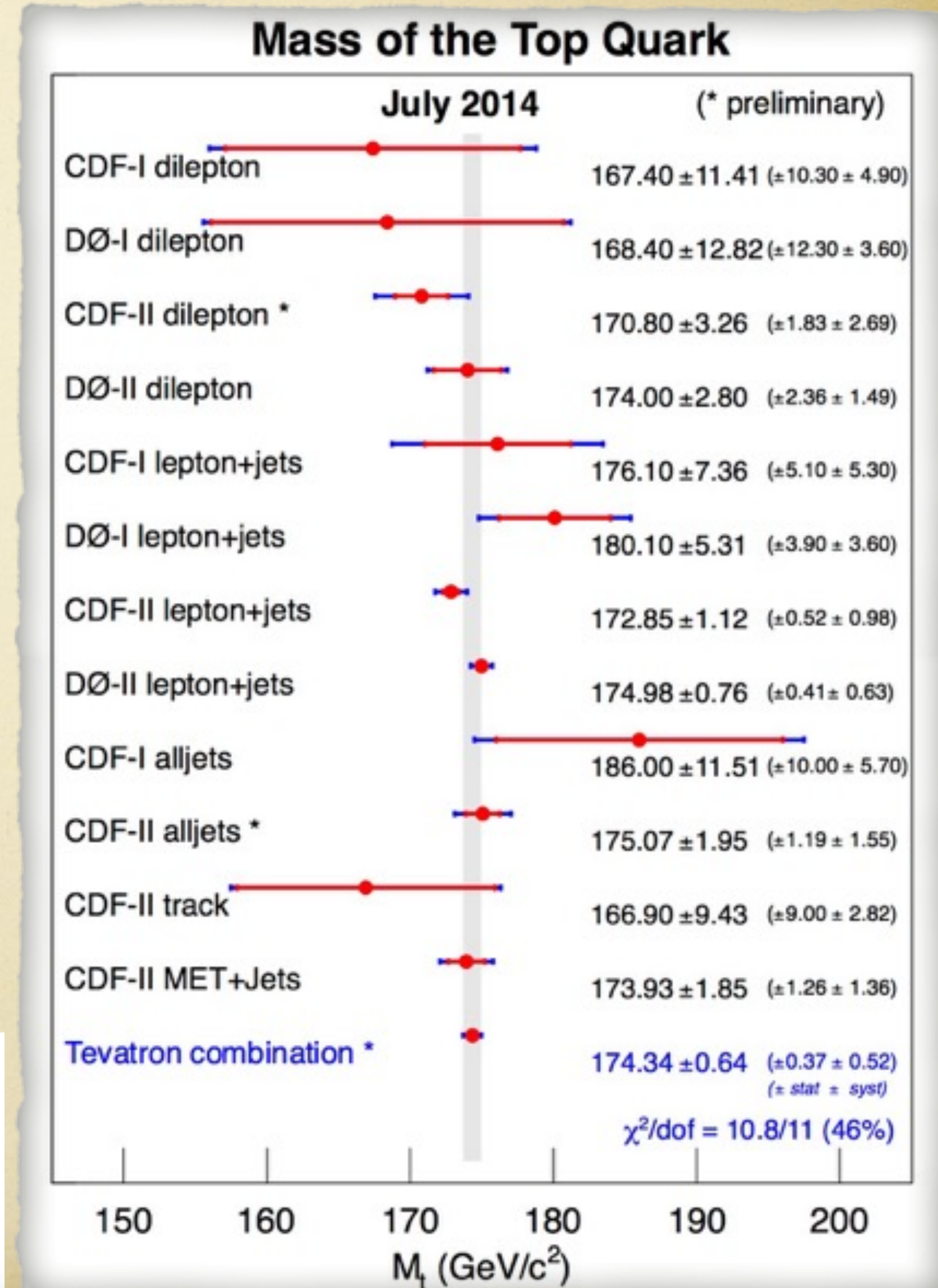


Top quark mass

- The top mass, the W mass, and the Higgs mass are related through radiative corrections that provide an internal consistency check of the SM

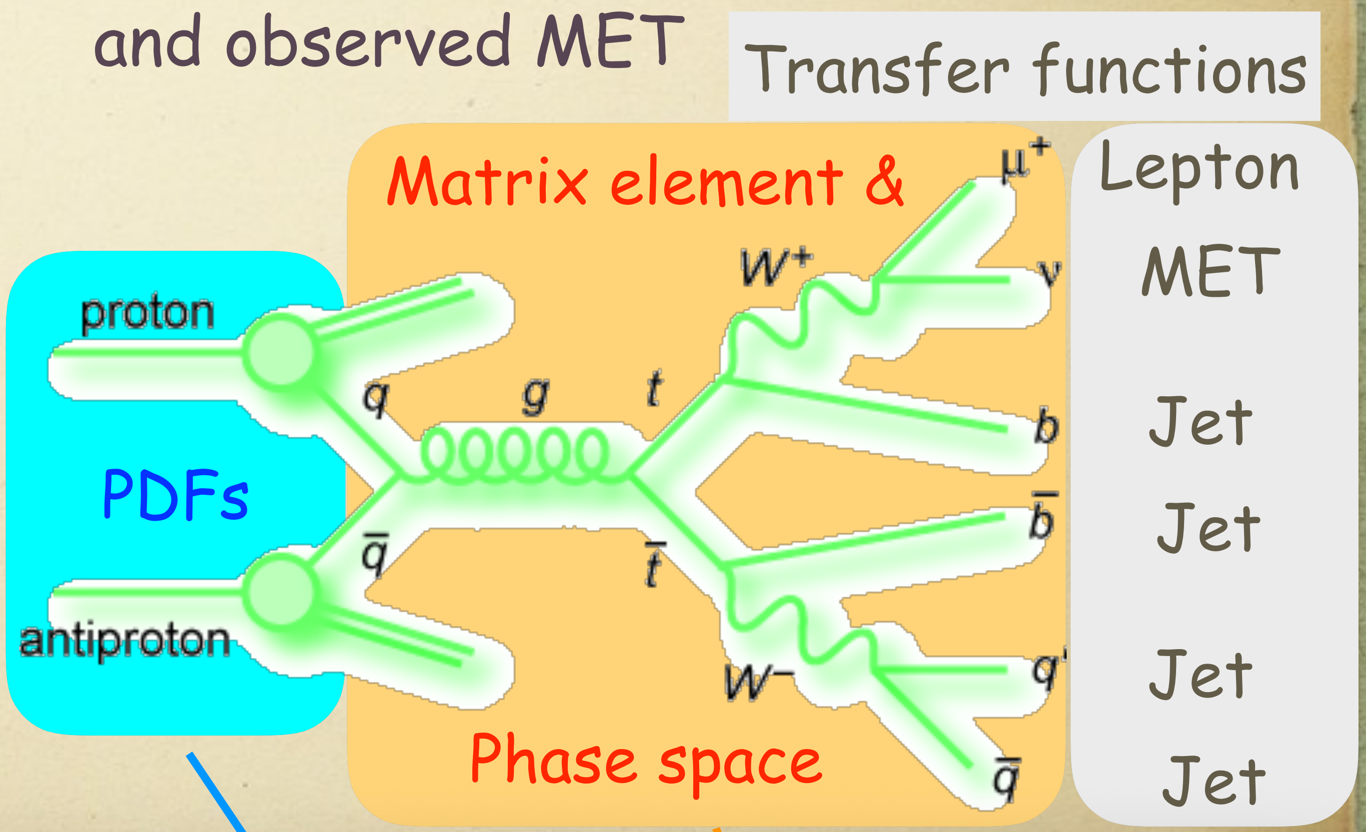






Top quark mass

- Methods:
  - Template
    - Use variable sensitive to top mass, e.g. m_{top}^{reco}
    - Maximum likelihood fit to mass templates
  - Matrix Element
    - Calculate a probability of each event using signal and background hypothesis
    - Use full event kinematics
- Neutrino weighting
  - Integrate over phase space for η of neutrinos for different m_{top} and jet-lepton assignments
  - obtain weights based on calculated and observed MET



$$P_{sig}(x;m_{top}) = \frac{1}{\sigma_{obs}} \int \sum dq_1 dq_2 dy\, f(q_1) f(q_2) \sigma(y;m_{top}) W(x,y)$$

Top quark mass

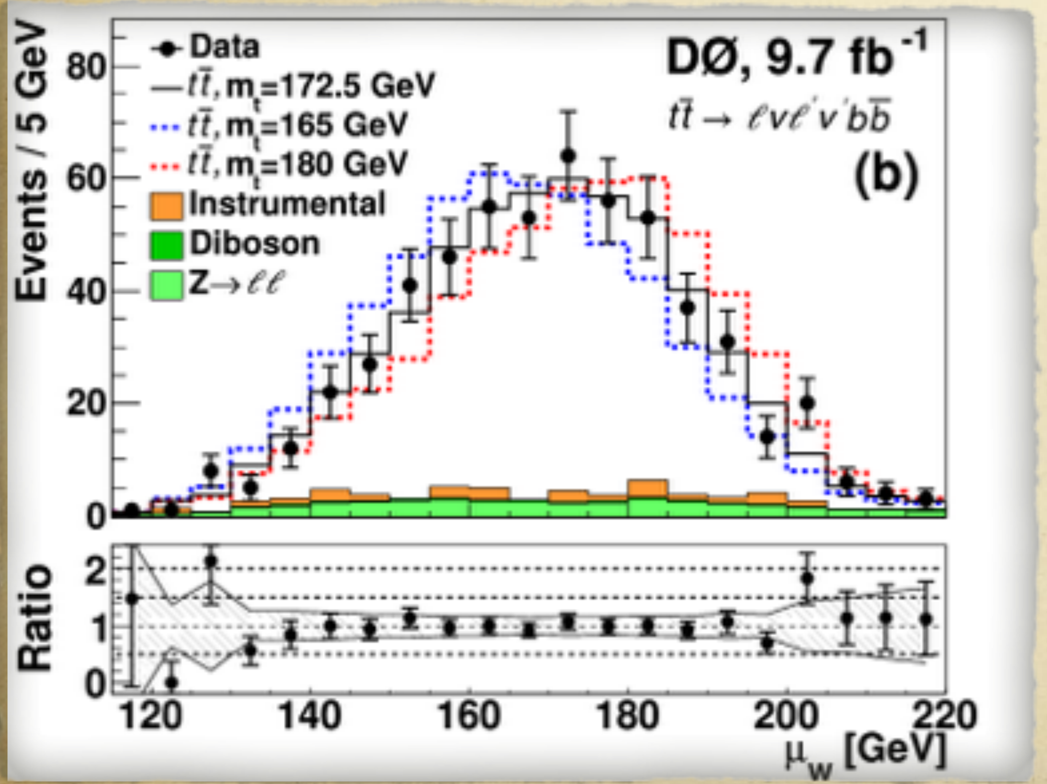
Dilepton channel

New

- Neutrino weighting *Phys. Lett. B 752, 18 (2016)*

$$\omega = \frac{1}{N}\sum_{i=1}^{N}\prod_{j=x,y} exp(-\frac{(\not{E}_T^{calc} - \not{E}_T^{obs})^2}{2\sigma^2_{\not{E}_T}})$$

  - weight parametrized with mass estimator μ and resolution σ
  - Jet energy correction factor derived from l+jets analysis



$m_t = 173.32 \pm 1.36(stat) \pm 0.85\ GeV$

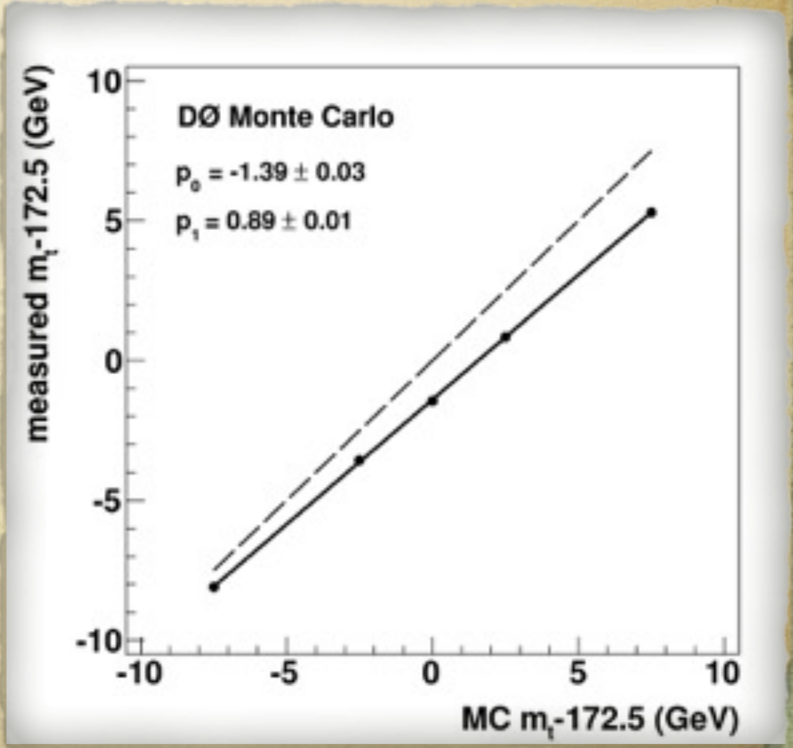
- Matrix elements *Conference Note 6483*

  - Top mass extracted using a log-likelihood function

$$-lnL(x_{1,n}; f_{t\bar{t}}, m_t) = -\sum_{i=1}^{n} \ln(P_{evt}(x_i; f_{t\bar{t}}, m_t))$$

  - Method corrected for biases in the measured mass and statistical uncertainty

$$m_{meas} = \frac{m_{lh} - p_0 - 172.5}{p_1} + 172.5$$

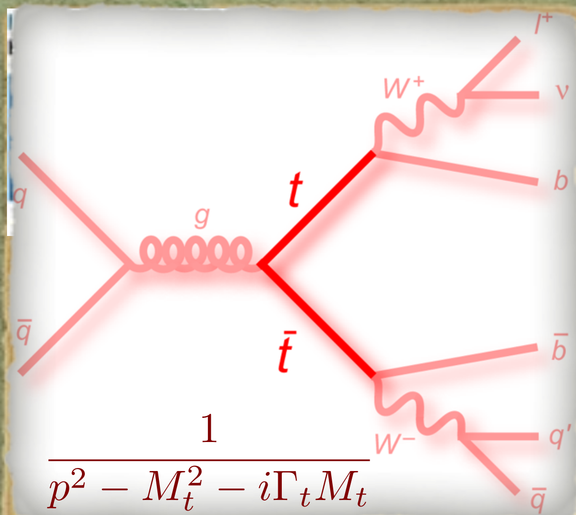


Preliminary

$m_t = 173.9 \pm 1.5(stat) \pm 0.9\ GeV$

Top quark pole mass

New



arXiv:1605.06168;

Submitted to Phys. Rev. D

- Direct mass measurements are based on top quark mass scheme implemented in the MC

  $m_t^{MC} \neq m_t^{pole} (\Delta \simeq 1\ GeV)$

- Can not be used directly for precise NLO/NNLO theoretical predictions

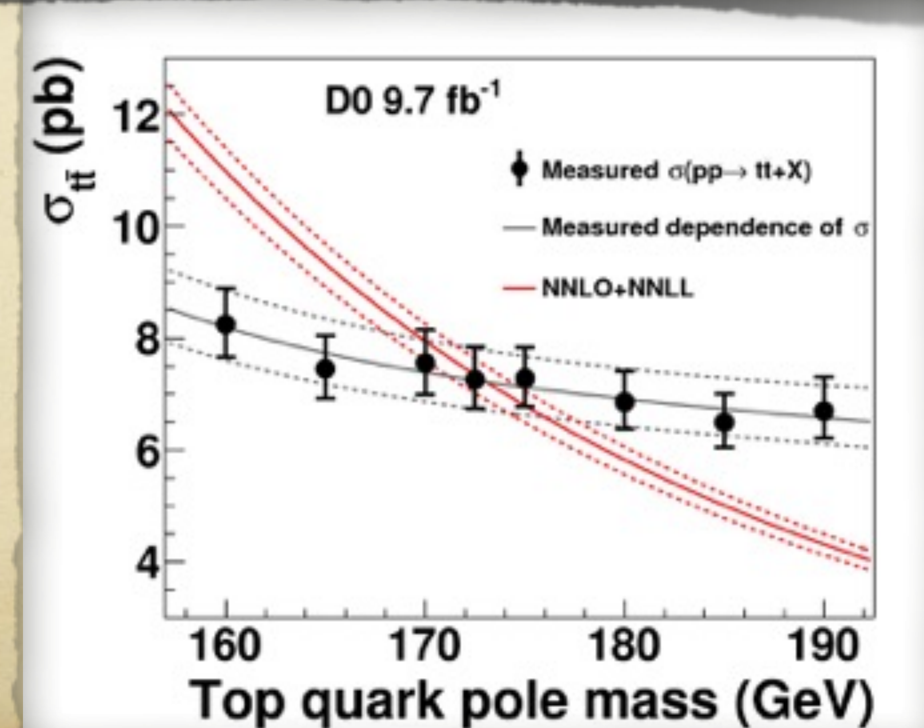
- Pole mass can be extracted from inclusive cross section measurement
  - Well defined mass parameter in QFT

- Use l+jets and dilepton channel cross section measurement
  - Employ the dependence of the inclusive cross section on the mass as calculated in pQCD

Top quark mass [GeV]	Cross section $\sigma(t\bar{t})$ [pb]
150	$9.70 \pm 0.16\,(\text{stat.})^{+0.73}_{-0.67}\,(\text{syst.})$
160	$8.25 \pm 0.14\,(\text{stat.})^{+0.63}_{-0.57}\,(\text{syst.})$
165	$7.46 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.51}\,(\text{syst.})$
170	$7.55 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.55}\,(\text{syst.})$
172.5	$7.26 \pm 0.12\,(\text{stat.})^{+0.57}_{-0.50}\,(\text{syst.})$
175	$7.28 \pm 0.12\,(\text{stat.})^{+0.54}_{-0.49}\,(\text{syst.})$
180	$6.86 \pm 0.12\,(\text{stat.})^{+0.53}_{-0.47}\,(\text{syst.})$
185	$6.50 \pm 0.11\,(\text{stat.})^{+0.50}_{-0.43}\,(\text{syst.})$
190	$6.70 \pm 0.11\,(\text{stat.})^{+0.60}_{-0.47}\,(\text{syst.})$

$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(stat.)^{+0.57}_{-0.50}(syst.)pb$$

$$m_t = 172.8 \pm 1.1(theo)^{+3.3}_{-3.1}(exp)\ GeV$$



Summary

- Tevatron was operating for 25 years
    - One of the highlights was the top quark discovery followed by more than 20 years of interesting results
- Top quark studies are coming to conclusion
    - Few remaining results are still expected to be published
- Due to the cross section dependency on initial states many measurements are complementary to the LHC
    - Results are in agreement with the standard model
- Top quark mass is measured with excellent and competitive precision
- Many analysis techniques were developed in these studies and passed to the next generation experiments

Publications

http://www-cdf.fnal.gov/physics/new/top/top.html

http://www-d0.fnal.gov/d0_publications/d0_pubs_list_bytopic.html#top

Backup

Spin correlations

New

Phys. Lett. B 757, 199 (2016)

- The top lifetime (~5×10^{-25} s) smaller than the spin-decorrelation time from spin-spin interactions (~3×10^{-21} s)
  - Possible to study spin related phenomena

$$O_{ab} = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\downarrow\uparrow) - \sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\downarrow\uparrow) + \sigma(\uparrow\downarrow)}$$

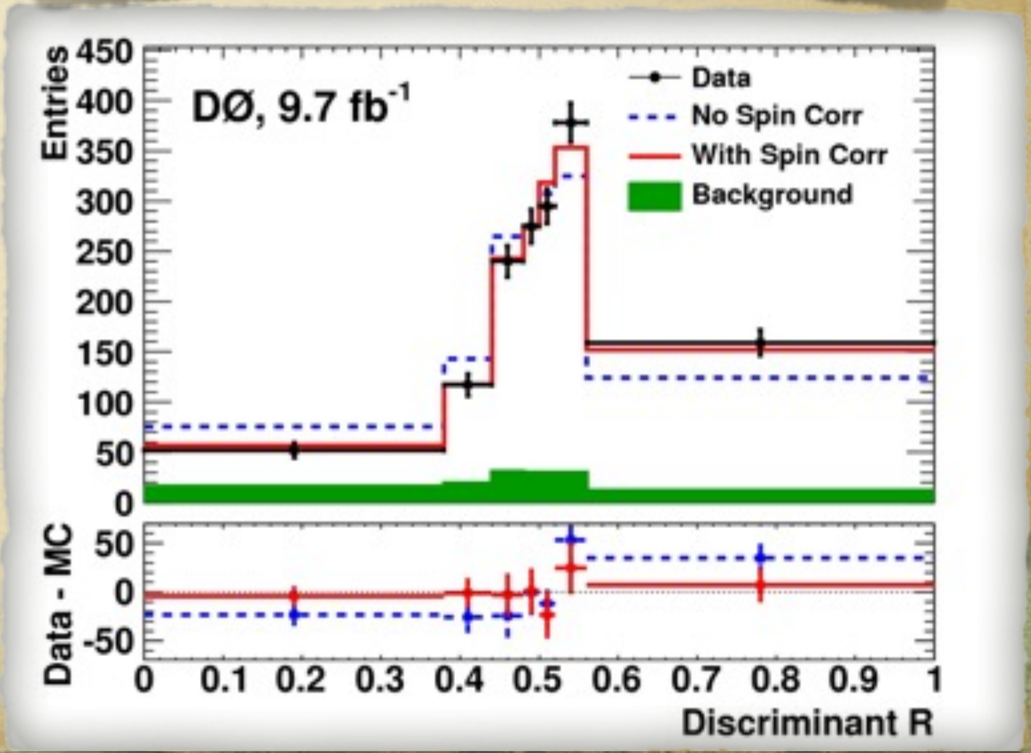
- The strength of spin correlation depends on production mechanism
  - @Tevatron the most significant contribution is from the qq annihilation ~0.99 (~ -0.36 from gg fusion)
- In SM expect spin correlation, while in some BSM models, like SUSY stop pair production don't
- Build discriminant based on event-by-event probability about spin correlations predicted by SM and null (no correlation) hypothesis

$$R(x) = \frac{P_{t\bar{t}}(x, SM)}{P_{t\bar{t}}(x, SM) + P_{t\bar{t}}(x, null)}$$

  - In P_{tt} assumption about hypothesis is in matrix element
- Result consistent with SM (0.8) with an evidence of spin correlations at @4.2σ

$$O_{off} = 0.89 \pm 0.22(stat + syst)$$

- Obtained a fraction of gg fusion in production, also consistent with the SM (0.135) $f_{gg} = 0.08 \pm 0.16$



tt production cross section

Systematic uncertainties

TABLE IV. Sources of grouped post-fit systematic uncertainties for the $t\bar{t}$ cross section measurement. Owing to the complexity of the correlations among the systematic uncertainties, we only show here the symmetrized uncertainties. For the top quark signal and background contributions we assume $m_t = 172.5$ GeV. For each group, the systematic uncertainty on the inclusive cross section is given for the ℓ+jets, $\ell\ell$, and combined measurement. The last column shows the shift in pb in the combined inclusive cross section due to a particular group. A shift of 0.00 pb indicates a shift of less than 0.004 pb. The total uncertainty is provided by the nominal fit, when including all individual sources of systematic uncertainties, and denoted as "central COLLIE". For comparison only we also provide the combined systematic uncertainty (quadratic sum) of the grouped post-fit systematic uncertainties. Due to correlations between the systematic uncertainties, that value differs from the total systematic uncertainty of the nominal fit.

Source of uncertainty	$\delta_{\ell+\text{jets}}$, pb	$\delta_{\ell\ell}$, pb	$\delta_{\text{comb},}$, pb	Shift, pb
Signal modeling				
Signal generator	±0.21	±0.05	±0.17	+0.08
Hadronization	±0.26	±0.33	±0.25	+0.12
Color reconnection	±0.08	±0.05	±0.09	+0.02
ISR/FSR variation	±0.08	±0.04	±0.06	−0.05
PDF	±0.04	±0.03	±0.02	−0.01
Detector modeling				
Jet modeling & ID	±0.11	±0.08	±0.04	+0.07
b-jet modeling & ID	±0.27	±0.26	±0.23	−0.15
Lepton modeling & ID	±0.20	±0.26	±0.17	−0.11
Trigger efficiency	±0.32	±0.08	±0.16	+0.01
Luminosity	±0.30	±0.30	±0.27	+0.10
Sample Composition				
MC cross sections	±0.07	±0.13	±0.09	+0.01
Multijet contribution	±0.11	±0.02	±0.10	+0.10
W+jets scale factor	±0.21	±0.01	±0.15	−0.50
Z/γ^*+jets scale factor	±0.07	±0.11	±0.12	+0.12
MC statistics	±0.01	±0.01	±0.02	+0.00
Total systematic uncertainty (quadratic sum)	±0.70	±0.64	±0.60	
Total systematic uncertainty (central COLLIE)	±0.67	±0.73	±0.55	

Polarization

- the beam axis given by the direction of the proton beam,
- the helicity axis given by the direction of the parent top quark,
- the transverse axis t, given as perpendicular to the production plane defined by the proton and parent top quark directions. The positive t axis is given by cross product p(p) × p(t) [8, 9]