# Top Quark Studies at the Tevatron


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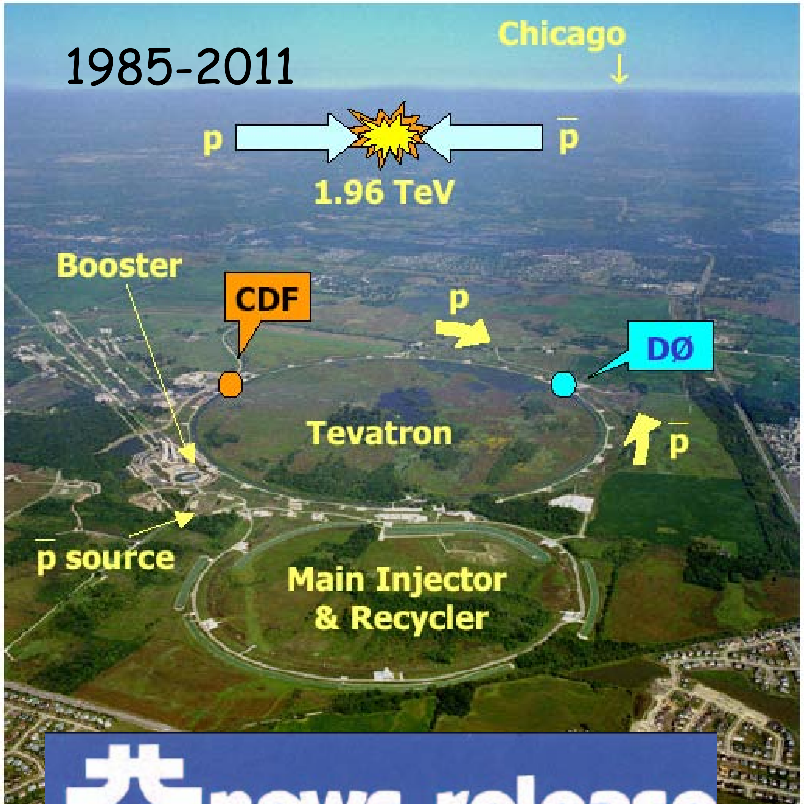
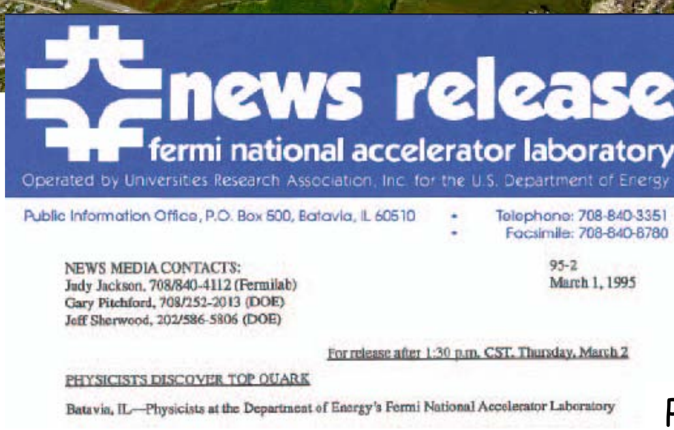
On behalf of the CDF and D0 Collaborations

Rencontres de Physique de la Vallée d'Aoste
La Thuile March 5, 2015

# The Fermilab Tevatron

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95-2
March 1, 1995

For release after 1:30 p.m. CST, Thursday, March 2

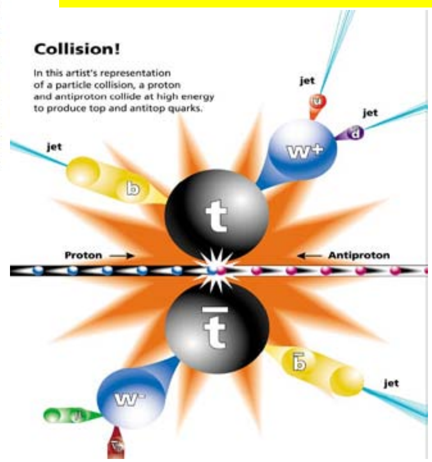
PHYSICISTS DISCOVER TOP QUARK

Batavia, IL—Physicists at the Department of Energy's Fermi National Accelerator Laboratory

Run II: $\sqrt{s}$ = 1.96 TeV, 10 $fb^{-1}$ on tape
Tevatron stopped operating on September 2011 after a 26 years career

The birthplace of the top quark, observed in 1995 by CDF and D0

**Announcement of top quark discovery: March 2nd, 1995**
**Top is twenty!!**




PRL 74 2626, PRL 74 2632 (1995)

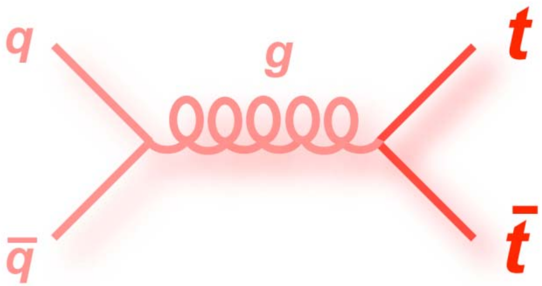
# Top Quark Production at Tevatron

- QCD pair production
- First observed at Tevatron in 1995 !! 20 years ago!!

$\sigma_{SM} = 7.35^{+0.28}_{0.33}$ pb

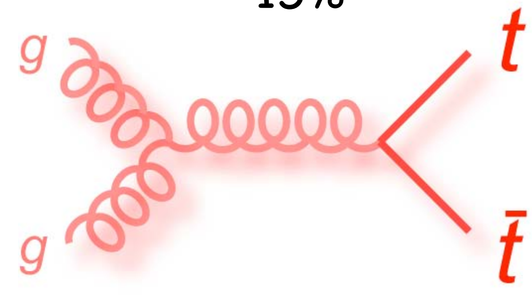
(for $m_{Top}$= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%




Dominant process at Tevatron

~15%




Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

# Top Quark Production at Tevatron

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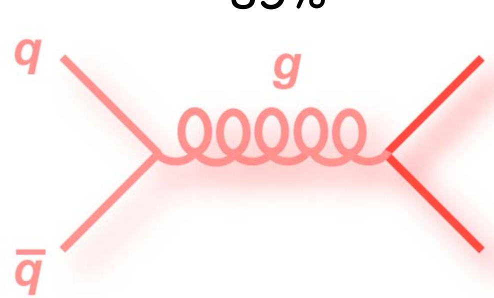
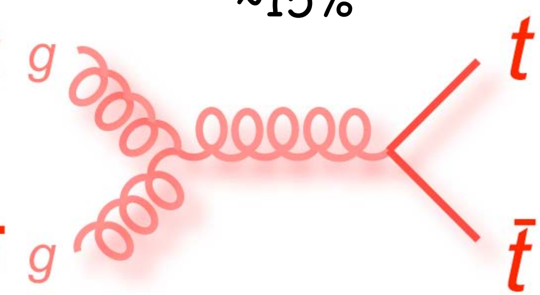



Dominant process at Tevatron

~15%




Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

- EWK single-top production
- first observed at Tevatron in 2009
- (PRL 103 092001, PRL 103 092002 (2009))

➢ s-channel: $\sigma_{SM}$ = 1.04 ± 0.06 pb

➢ t-channel: $\sigma_{SM}$ = 2.1 ± 0.1 pb

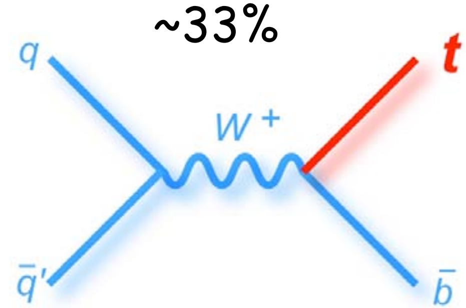
(for $m_{Top}$= 173 GeV)

PRD 83, 091503 (2011),PRD 81, 054028 (2010)
PRD 82, 054018 (2010) arxiv:1210.7813.

Dominant modes at Tevatron:

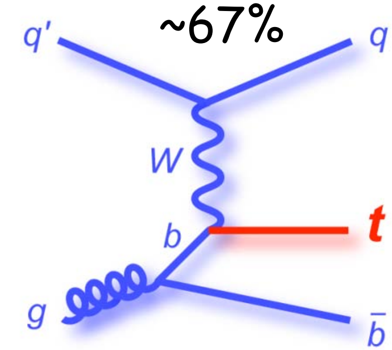
s-channel

~33%



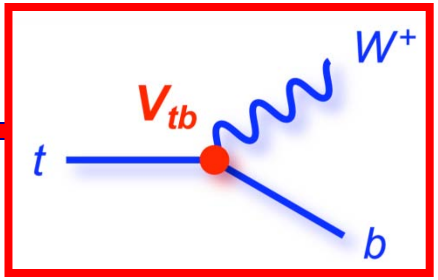

t-channel

~67%



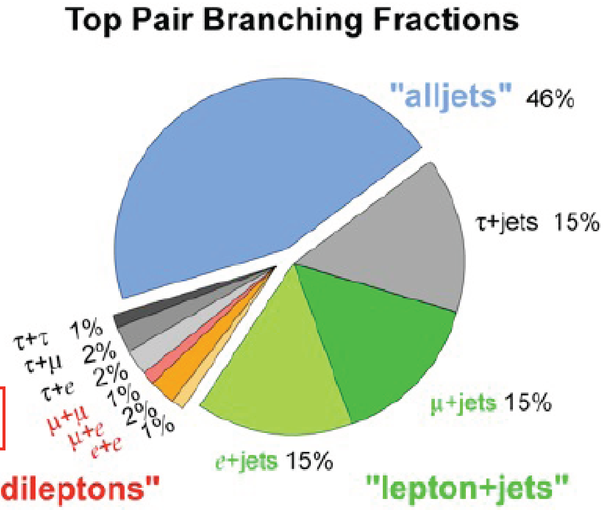

- Single top associated production Wt: σ ~ 0.22 pb, too small at the Tevatron

# Top Quark Decay




SM predicts BR( $t \to Wb$) ≈ 100%

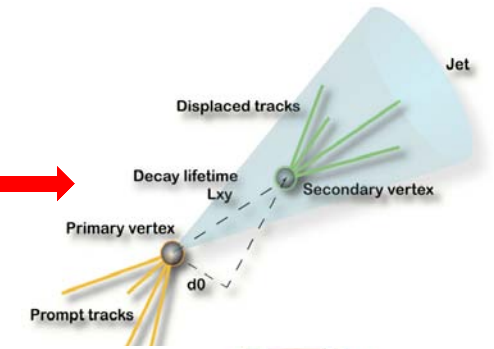
Event topology determined by the W decay modes

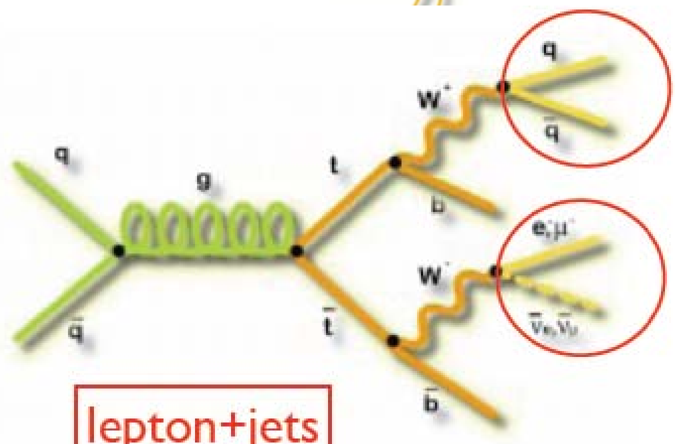



~4.5%

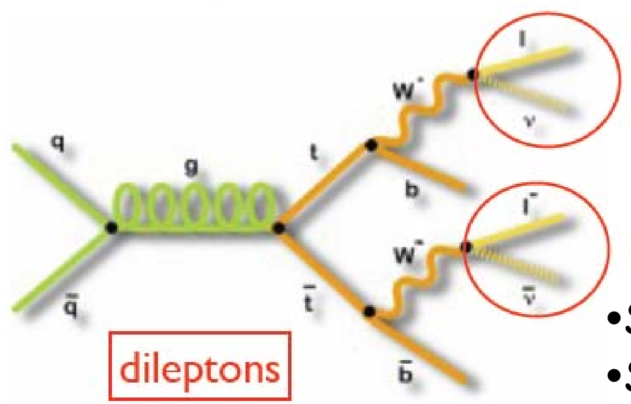
~30%

b quarks are always present




lepton+jets



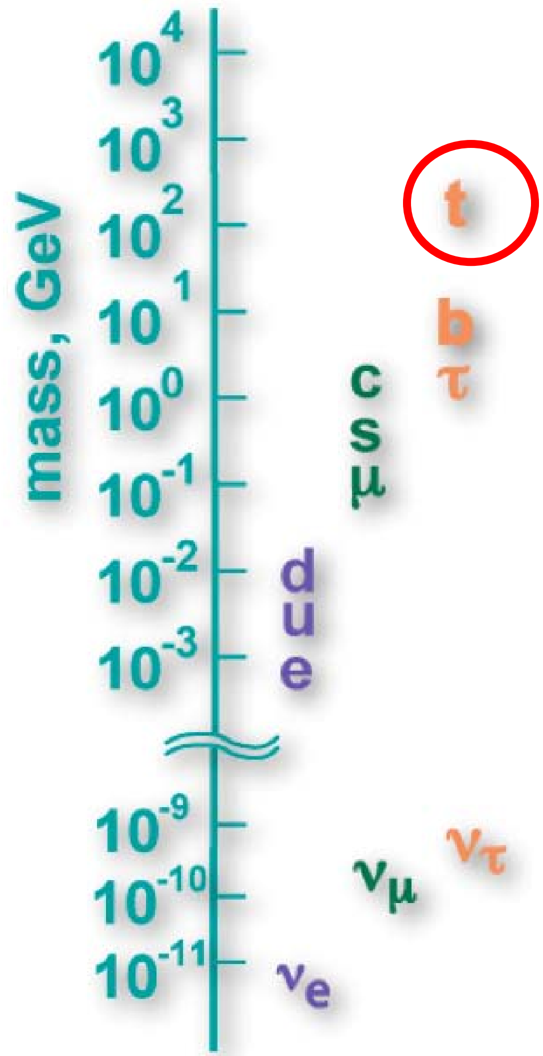

dileptons

- Small rate
- Small background

- Golden channel:
- Good rate
- Manageable background

# Why is top a special particle?

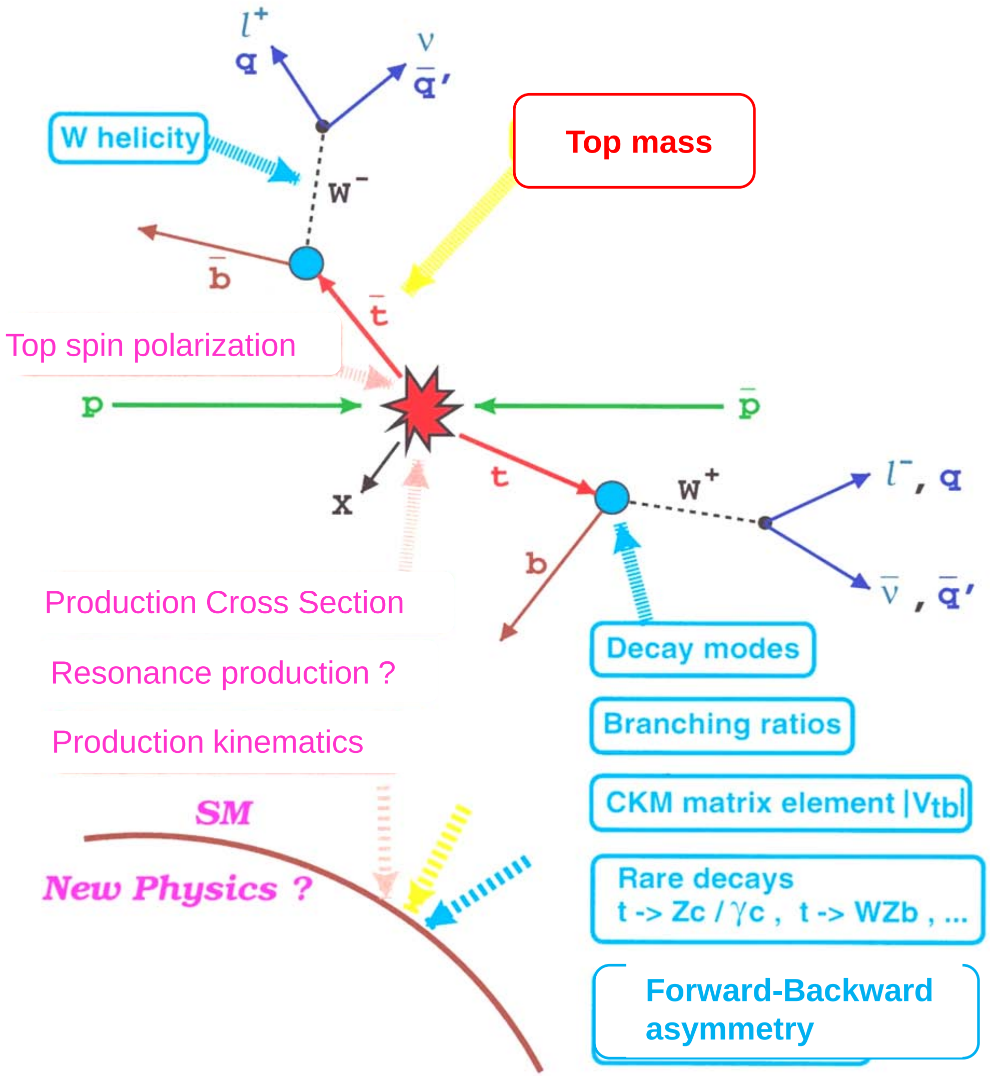
- Heavier than all known particles:
  - ⇒ Short lifetime → decays before hadronizing →
    - ✓ Properties can be studied from distributions of decay products
  - ⇒ Provides a probe for electroweak symmetry breaking
  - ⇒ Related to Higgs mass through loops
- Since top discovery:
  - ⇒ 20 years of top properties studies
  - ⇒ Is the observed top quark the Standard Model top quark?
  - ⇒ Any contribution from new physics?
- Deviation of the measured top quark properties from the SM prediction would be a signal of new physics



# What can we measure?

- This talk will focus on most recent measurements and those complementary / competitive with LHC
  - ⇒ ttbar cross section
  - ⇒ single top production
    - ⇒ observation of single top s-channel
  - ⇒ $A_{FB}$ asymmetry
  - ⇒ top mass
  - ⇒ branching fractions

All measurements based on full RunII dataset



# ttbar inclusive cross section

- Top pair XS measured in different decay channels
- Tevatron combination:

  ⇒ measurements from each experiment are combined for a CDF, a D0 and a Tevatron combination

  ⇒ combination taking into account statistical and systematic correlation

CDF combination:

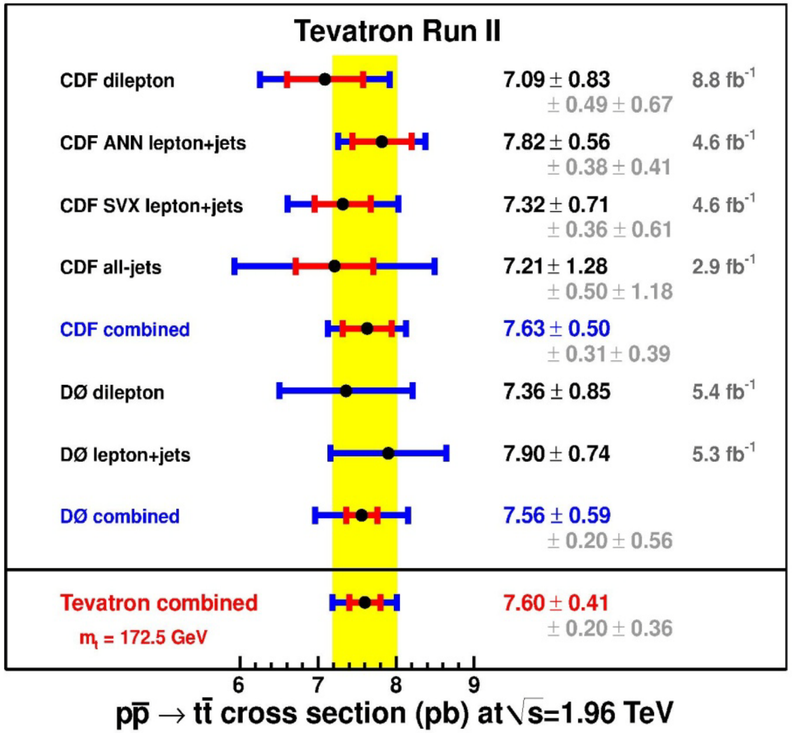
$\sigma$ = 7.63 ± 0.50 (stat+syst) pb

D0 combination:

$\sigma$ = 7.56 ± 0.59 (stat+syst) pb

Consistent results among different channels, methods, and experiments

For more details on recent D0 results see J. Franc talk at YSF-3




Tevatron combination:

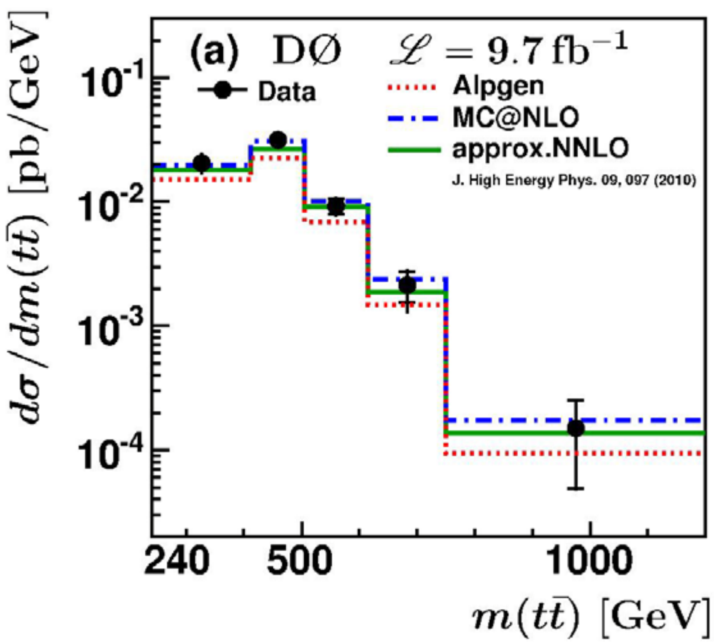
$\sigma$ = 7.60 ± 0.41 (stat+syst) pb

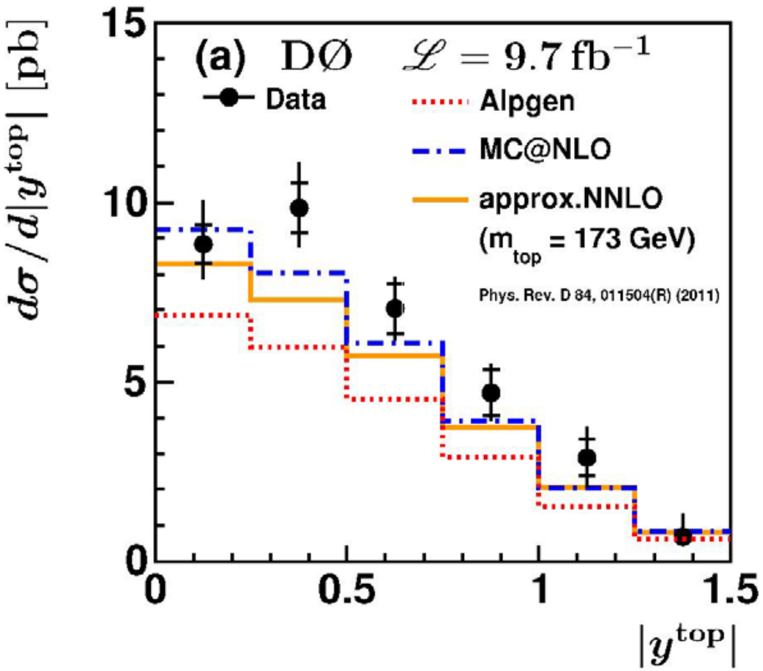
Experimental uncertainty 5.4%
PRD89, 072001 (2014)

Theory prediction uncert.≈ 4%
PRL110, 252004 (2013)

# ttbar differential cross section

- stringent tests of QCD in the top quark sector
- l + >= 4jets channel with 1 b-tag
  - ⇒ measurements vs m(tt), $p_T$(t), |y(t)|, data corrected for detector efficiency, acceptance and bin migration




⇒ Typical uncertainty: ~ 9 %

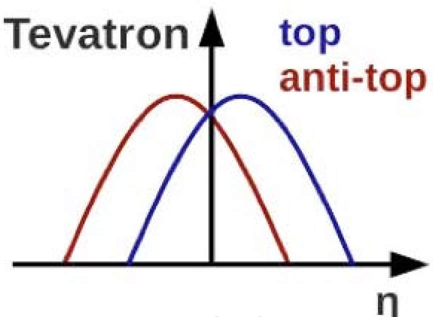
⇒ Overall good agreement with the predictions

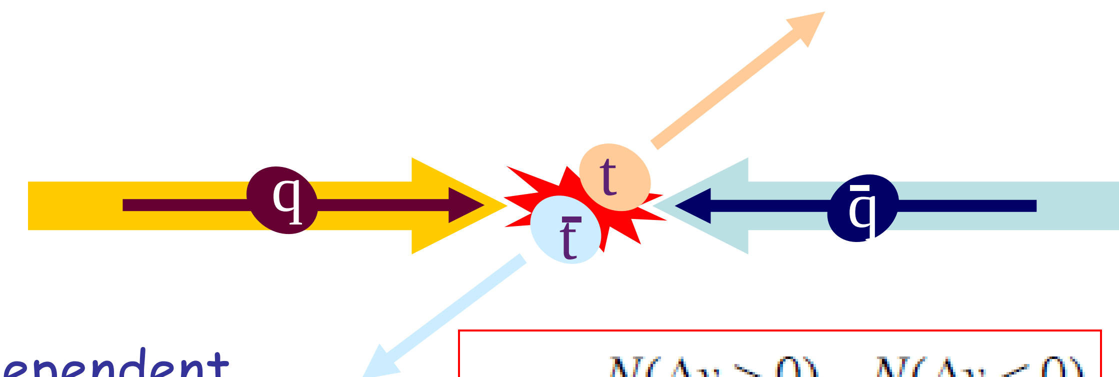
PRD 90, 092006 (2014)

# Forward backward asymmetry ($A_{FB}$)

- NLO QCD predicts small (~8%) asymmetry from qqbar➔ttbar, while gg remains symmetric. Recent NNLO predicts ~9.5%(arXiv:1411.3007)
- New physics can modify this asymmetry (Z´ ,axigluons,..)
- Experimentally, asymmetries based on fully reconstructed top quarks

using the rapidity difference (Δy) of t➔lvb and antitop t➔jjb or based on decay leptons




- In terms of frame-independent top-antitop rapidity difference:

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

- In terms of rapidity of charged lepton from top decay:

$$A_l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

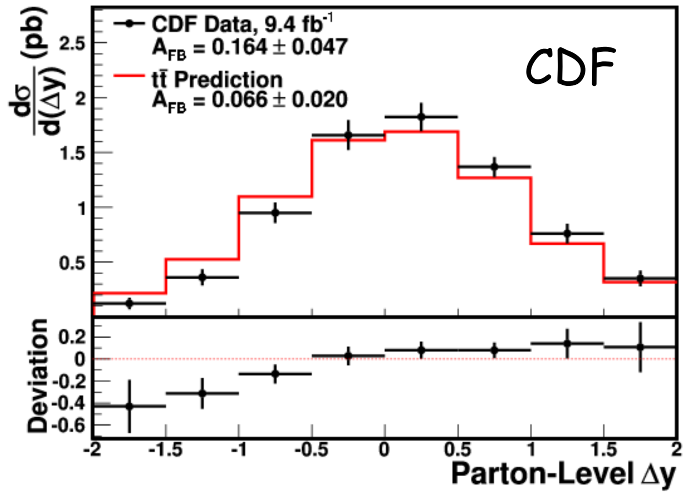
# Forward backward asymmetry ($A_{FB}$)

## Lepton + jets channel

- CDF 9.4 fb$^{-1}$
- Measure $\Delta y$ spectrum of $t\bar{t}$ in data
- Subtract background, correct for accept. and detector resolution effects
- Parton level result:

$\Rightarrow A = 16.4 \pm 4.7$ (stat+syst)%

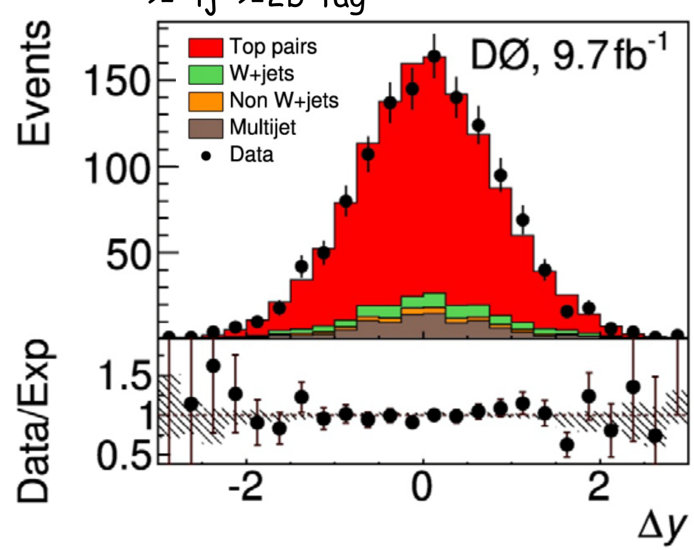
PRD87 92002 (2013)




- D0 9.7 fb$^{-1}$
- new kinematic fitting algorithm for events with four or more jets
- new partial reconstruction algorithm for events with only three jets
- Simultaneously unfold several channels:

$\Rightarrow A = 10.6 \pm 3.0$ (stat+syst )%

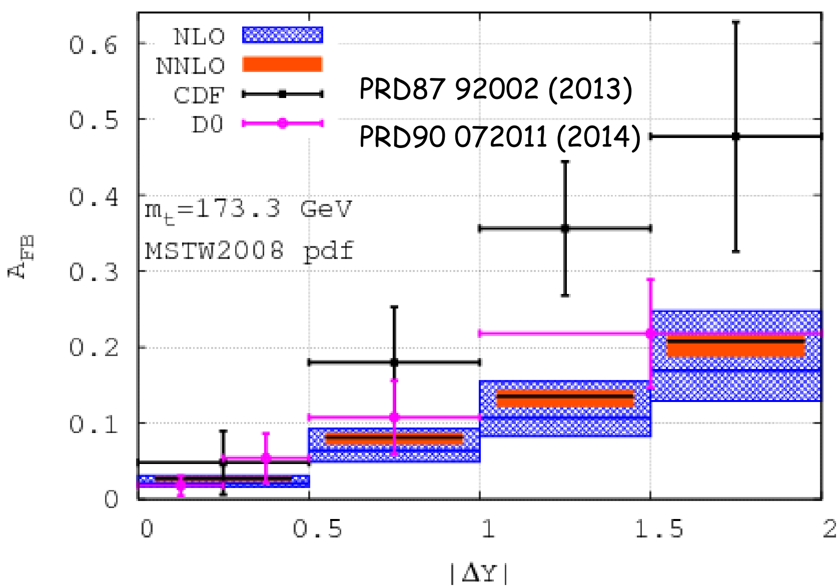
PRD90 072011 (2014)

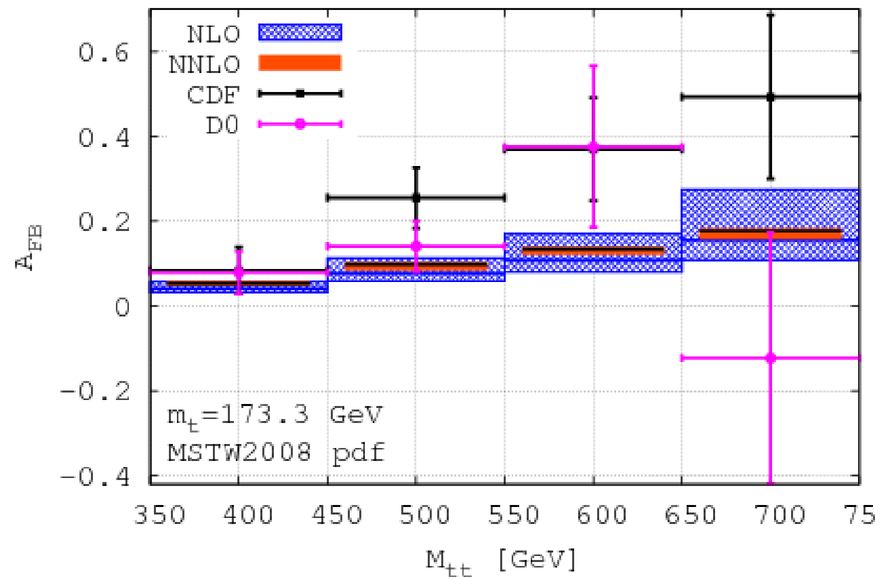


# Forward backward asymmetry ($A_{FB}$)

## Lepton + jets channel

- Check rapidity and mass kinematic dependence of asymmetry




- Kinematic dependencies in CDF data slightly larger than predicted by SM at both NLO and NNLO
- Overall NNLO predicted asymmetry; 9.5 ± 0.7 %

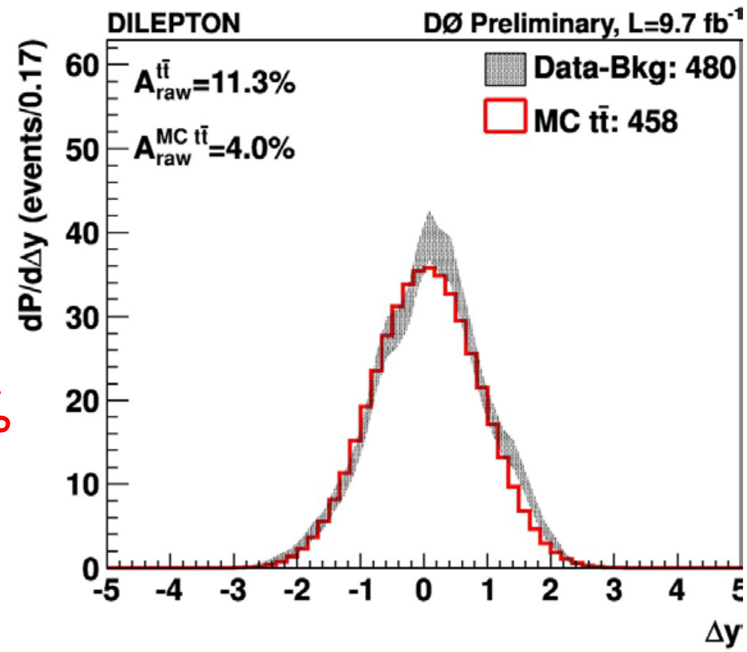
M. Czakon, P. Fiedler and A. Mitov arXiv:1411.3007

# $A_{FB}$ in dilepton channel

- New D0 measurement in dilepton channel using the matrix element method:

  $\Rightarrow$ assign a likelihood per event for most probable $\Delta y$ value

- Systematic uncertainties dominated by signal modeling




Data after background subtraction

- After background subtraction and calibration to true partonic asymmetry level:

$A_{FB}^{ll}$ = 18.0 ± 6.9(stat.+syst) ± 5.1 (model)%

DØ note 6445-CONF (2014)

- Old CDF result (5.1 $fb^{-1}$)
- $A_{FB}^{ll}$ = 42.0 ± 16.0 (stat.+syst)%

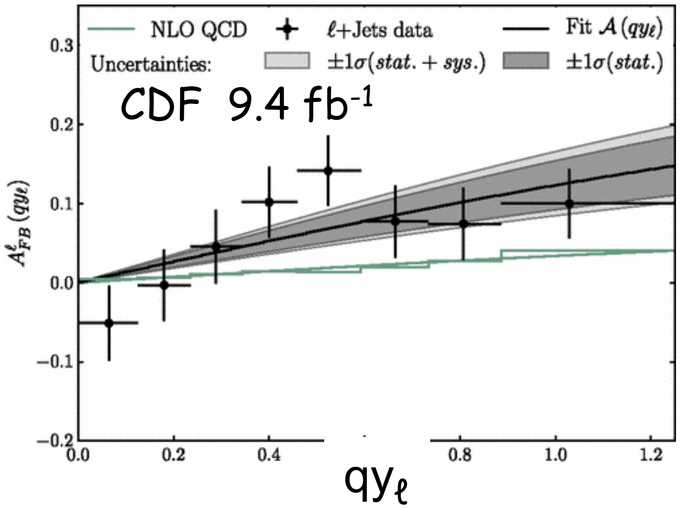
CDF Note 10436, (2011)

# Lepton Asymmetry in $\ell$ + jets

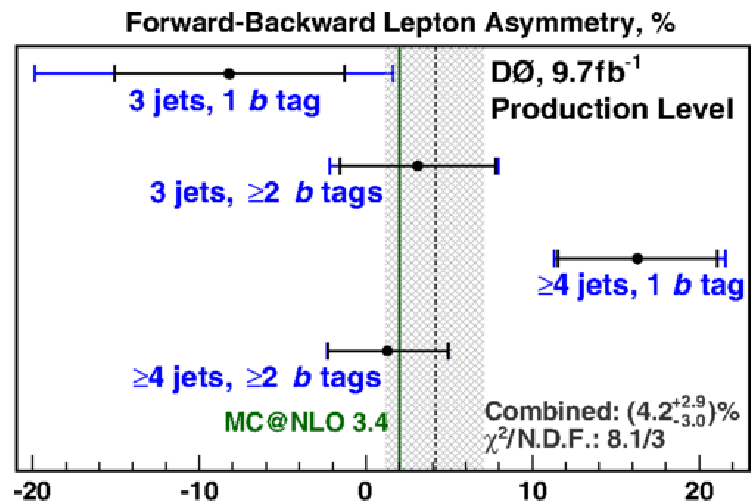
- $A^{\ell}$ parametrized as a function of $qy_{\ell}$ of the lepton from W decay, no need to reconstruct the ttbar system

  $\Rightarrow$ Insensitive to biases from top reconstruction procedure

- $A^{\ell}$ kinematically correlated with $A_{FB} \rightarrow A^{\ell} \sim (0.5) A_{FB}$ (model dependent: PRD 86 034026 (2012))




PRD 88,072003(2013)




PRD 90, 072001 (2014)

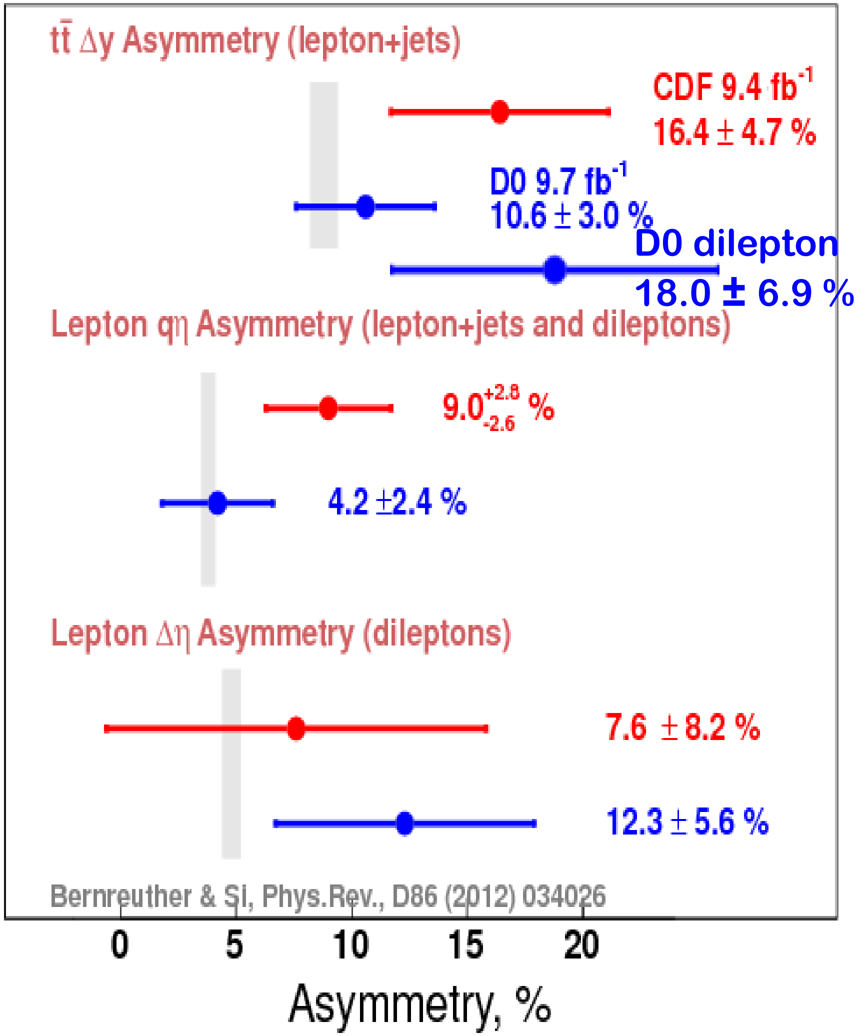
- CDF $A^{\ell} = 9.4 \pm 2.4(\text{stat})\ ^{+2.2}_{-1.7}(\text{syst})\ \%$
- D0 $A^{\ell} = 4.2 \pm 2.3\ (\text{stat.})\ ^{+1.7}_{-2.0}(\text{syst})\ \%$

Expected SM: 3.8 %
PRD 86 034026 (2012)

# Summary of top asymmetries

$t\bar{t}$-based and lepton-based results using full RunII dataset

- D0 data:
  - ⇒rather good agreement with QCD predictions
- CDF data:
  - ⇒ inclusive asymmetry slightly higher than predictions (~1.5 s.d. effect)
  - ⇒ asymmetry slopes vs $M_{t\bar{t}}$ and $|\Delta y|$ slightly higher (max ~2 s.d. effect)

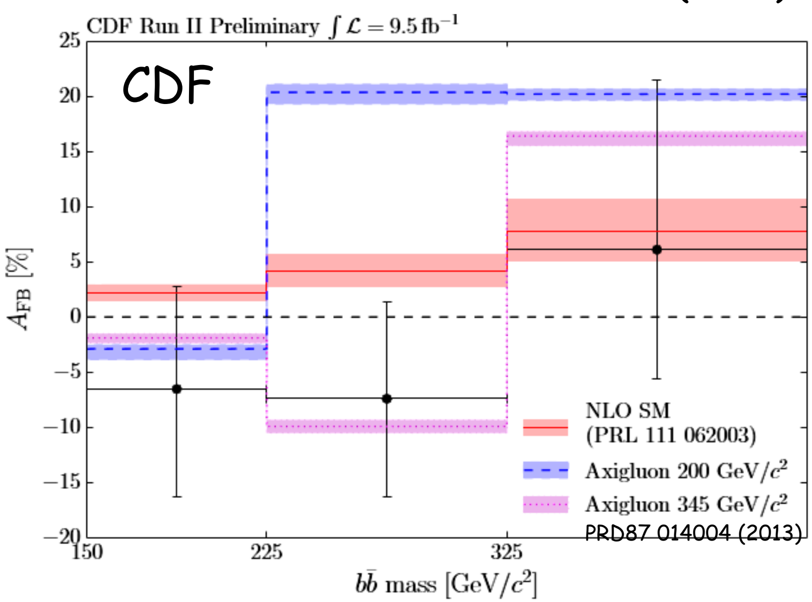


# $A_{FB}$ in $b\bar{b}$ pairs

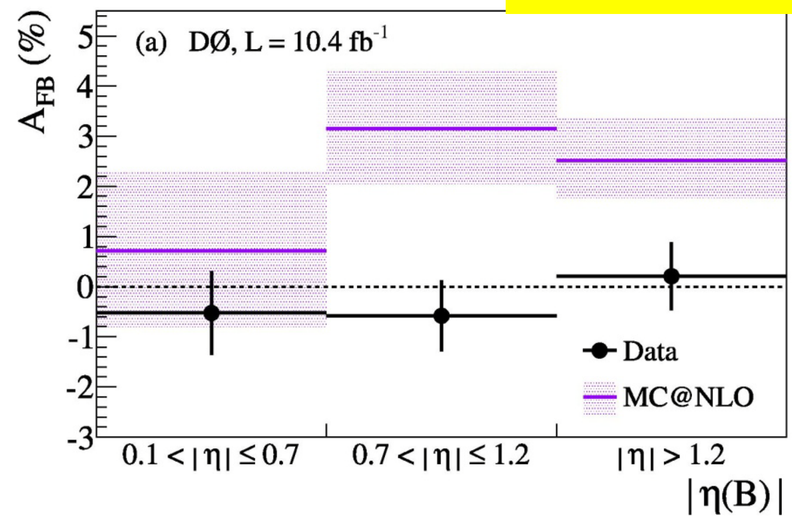
- Select kin. region where quark-antiquark initial state is enhanced
- CDF: $A_{FB}$ in bb pairs at large $b\bar{b}$ mass using jet-triggered data and jet charge to identify b from $\bar{b}$
- The asymmetry is consistent with both zero and with the SM predictions as a function of $m(b\bar{b})$.
- D0 uses $B^{\pm} \to J/\psi K^{\pm}$ to probe asymmetry of b-quarks
- Use unbinned maximum likelihood fit

For more details see J. Hogan talk at YSF-2

CDF Conf. Note 11092 (2014)



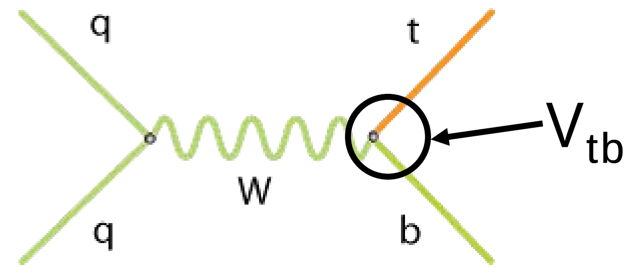

PRL 114, 051803 (2015)




$A_{FB}$ = [- 0.24 ± 0.41 (stat)± 0.19 (syst)] %

# Why measure Single Top Production

- $\sigma_{\text{single top}} \propto |V_{tb}|^2$
- Give access to the W-t-b vertex
  - ⇒ probe V-A structure
  - ⇒ access to top quark spin




- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:

Direct measurements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Ratio from Bs oscillations

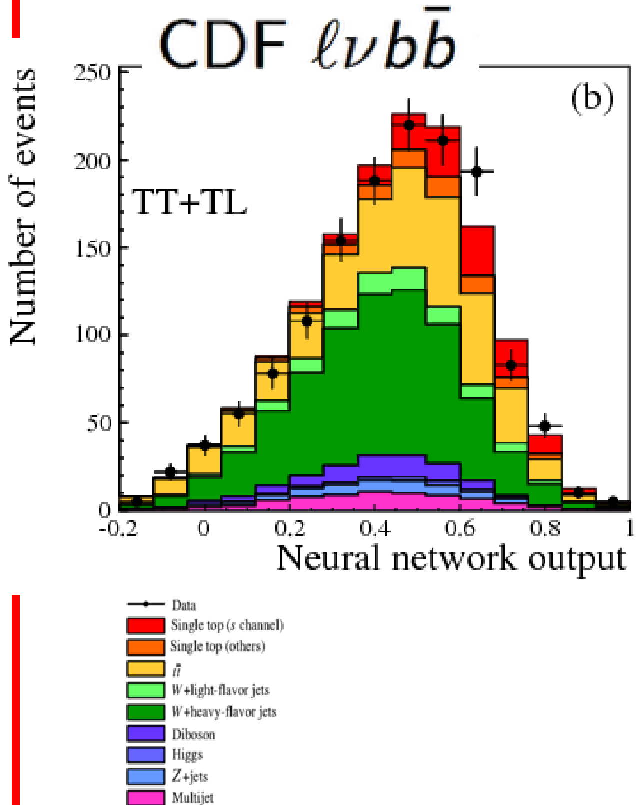
Not precisely measured Inferred using unitarity

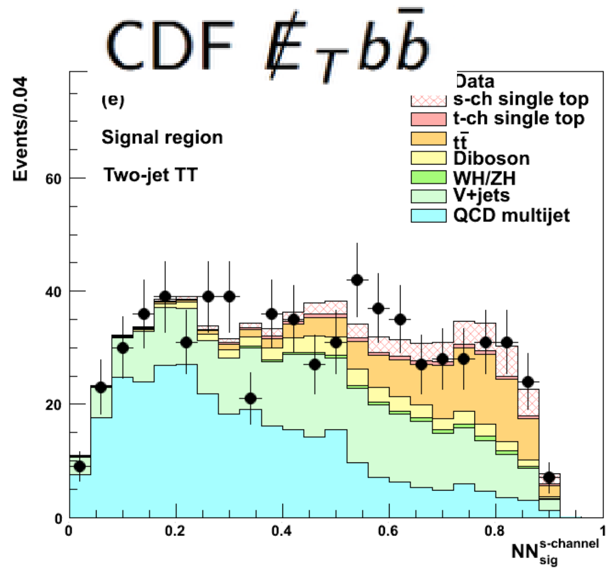
- Each channel of the single-top production is sensitive to different classes of SM extensions:
  - ⇒ Independently studying the production of these channels provides more restrictive constraints on SM extensions than just studying the combined production rate.
    - ✓ e.g. s-channel → heavy W′ boson, charged Higgs $H^+$

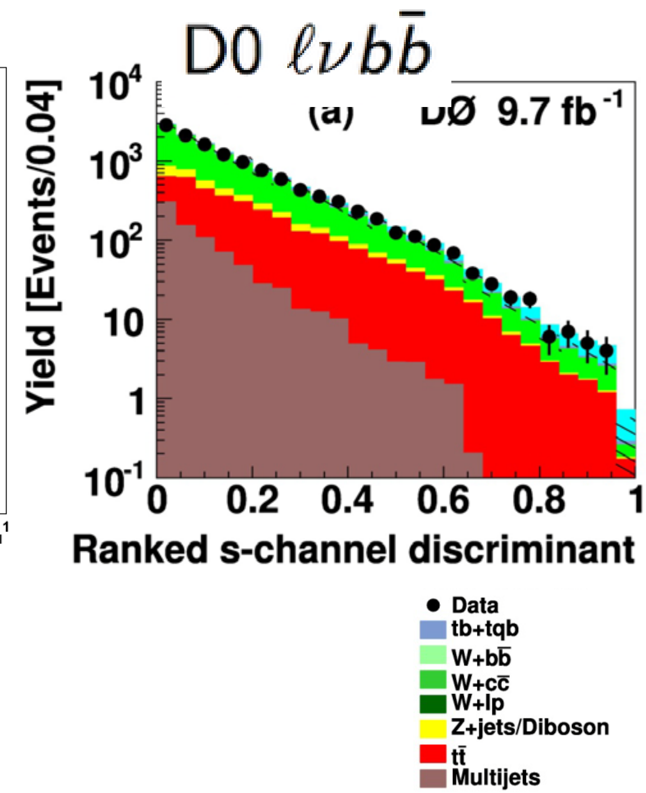
PRD63, 014018 (2001)

# Tevatron s-channel combination

- Single top s-channel observed by combining evidence in D0 and CDF data
- Build multivariate discriminants, optimized to separate s-channel signal from backgrounds



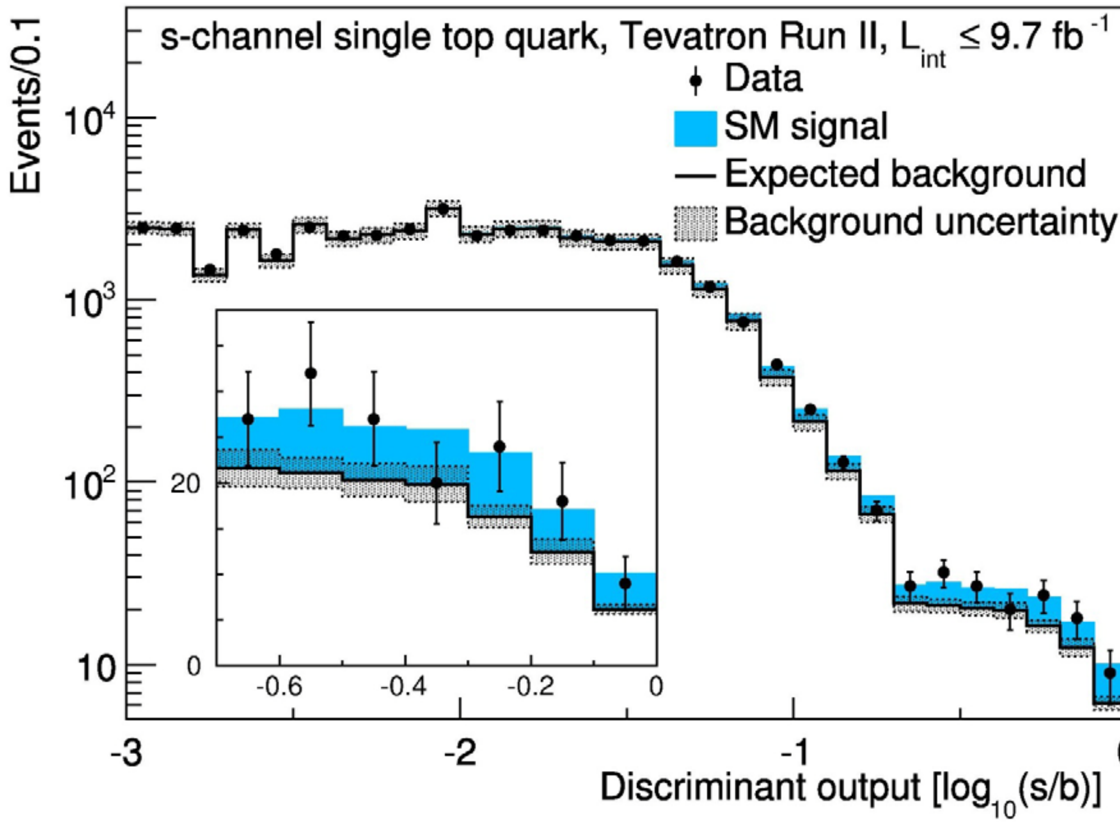




PRL 112 231805 (2014)

PLB726 (2013)656--64

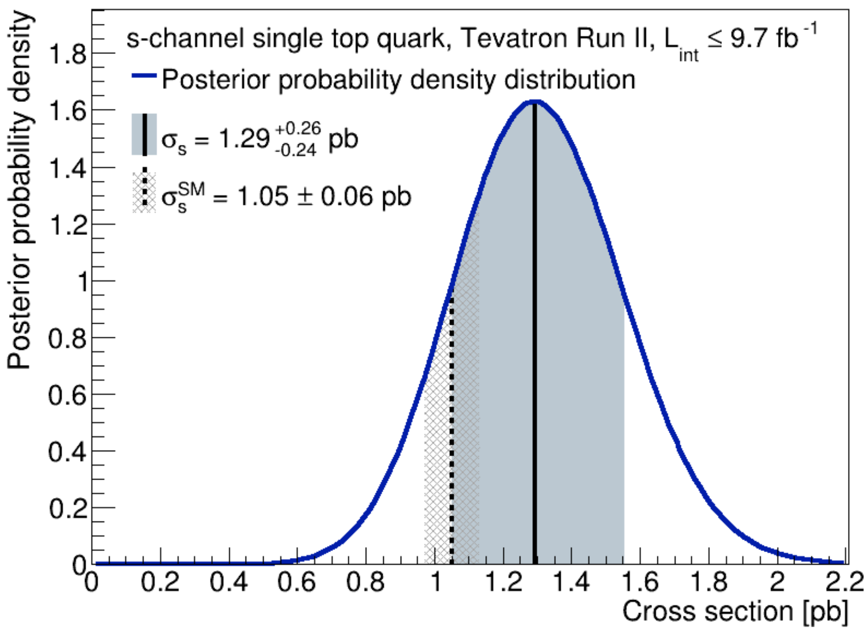
# Tevatron s-channel combination

- Single top s-channel observed by combining evidence in D0 and CDF data
- Build multivariate discriminants, optimized to separate s-channel signal from backgrounds
- Combine individual discriminants including all correlations:

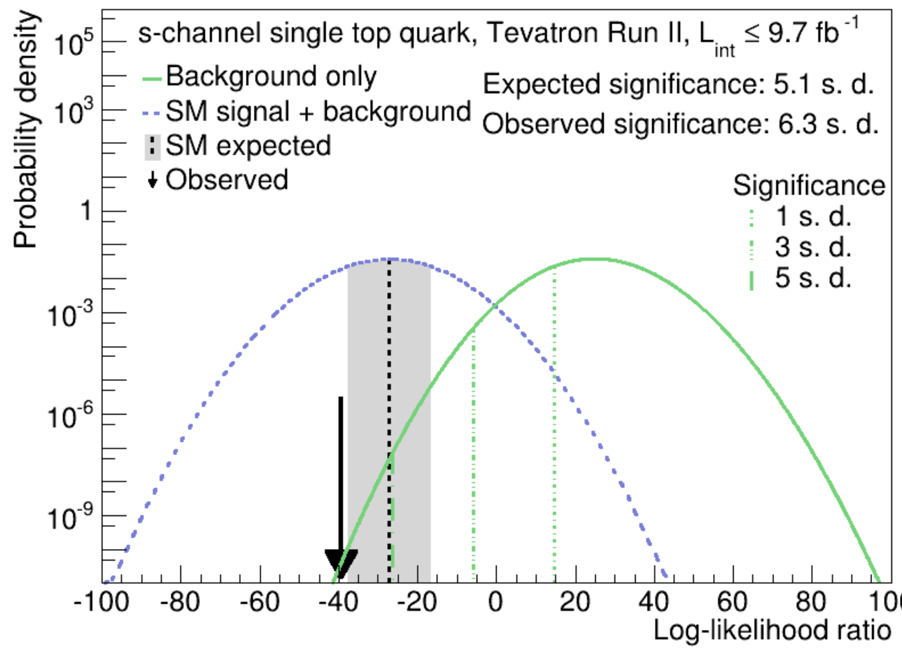



PRL 112 231803 (2014)

# Tevatron s-channel observation




Posterior probability density for the Combined result



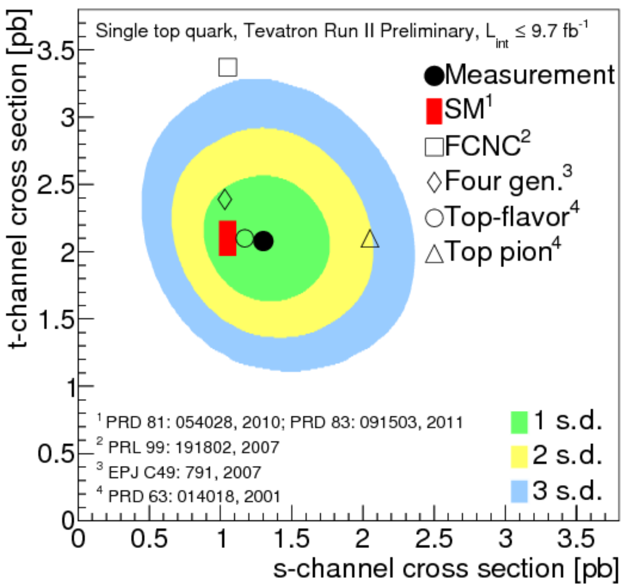

$\sigma_s = 1.29\ ^{+0.26}_{-0.24}$ (stat+syst) pb **(±19%)** **6.3σ (5.1σ expected)**

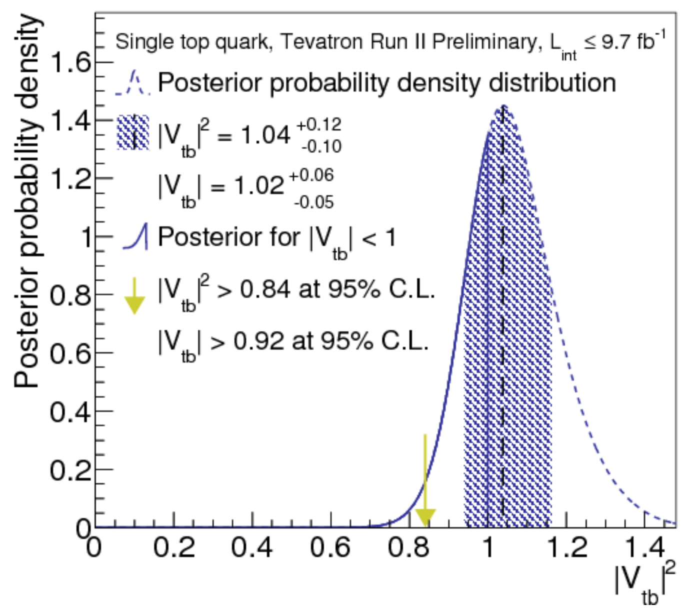
First observation of s-channel single top production

PRL 112 231803 (2014)

# Tevatron s+t combination

- Combine CDF and D0 analysis, discriminants trained on s-channel or t-channel
→ both discriminants used simultaneously
- Construction of 2D posterior probability density function of $\sigma_s$ and $\sigma_t$
- Combined $\sigma_{s+t}$: measured by forming 2D posterior for $\sigma_{s+t}$ versus $\sigma_t$
→ integrate out $\sigma_t$ with no assumption on SM $\sigma_s / \sigma_t$



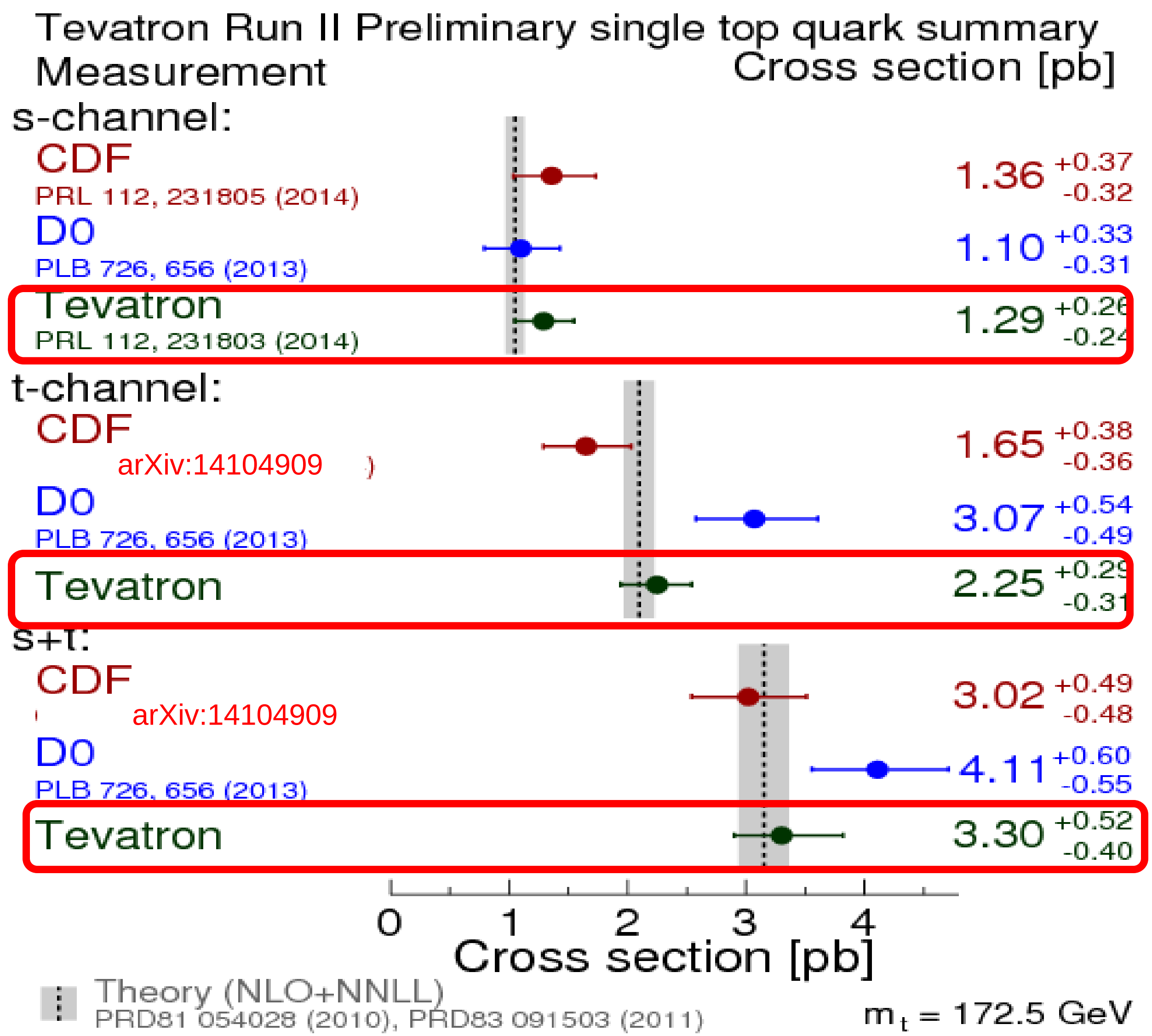

$\sigma_{s+t} = 3.30^{+0.52}_{-0.40}$ pb (±13%)

$\sigma_t = 2.25^{+0.29}_{-0.31}$ pb (±13%)

$|V_{tb}| > 0.92$ at 95% C.L.

Conf. Note 11133 (2014)

# Summary of single top measurements




± 19%

± 13%

± 13%

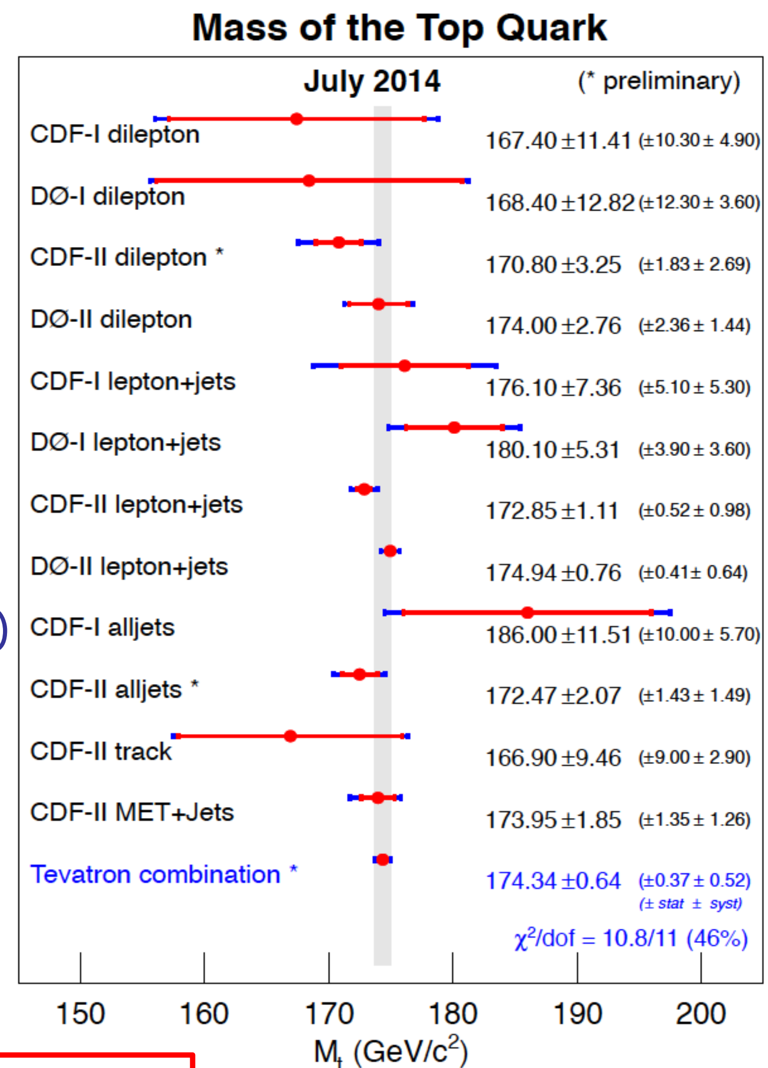
# Tevatron top mass combination

- 5 Run I and 7 Run II results
- Combination performed using BLUE

- Limited by systematic uncertainties
  - ⇒ Dominant: signal modeling and jet energy scale uncertainties

- Total uncertainty ± 0.64 GeV/$c^2$ (< 0.4%)

(better than world comb. March 2014: ± 0.76 GeV/$c^2$)

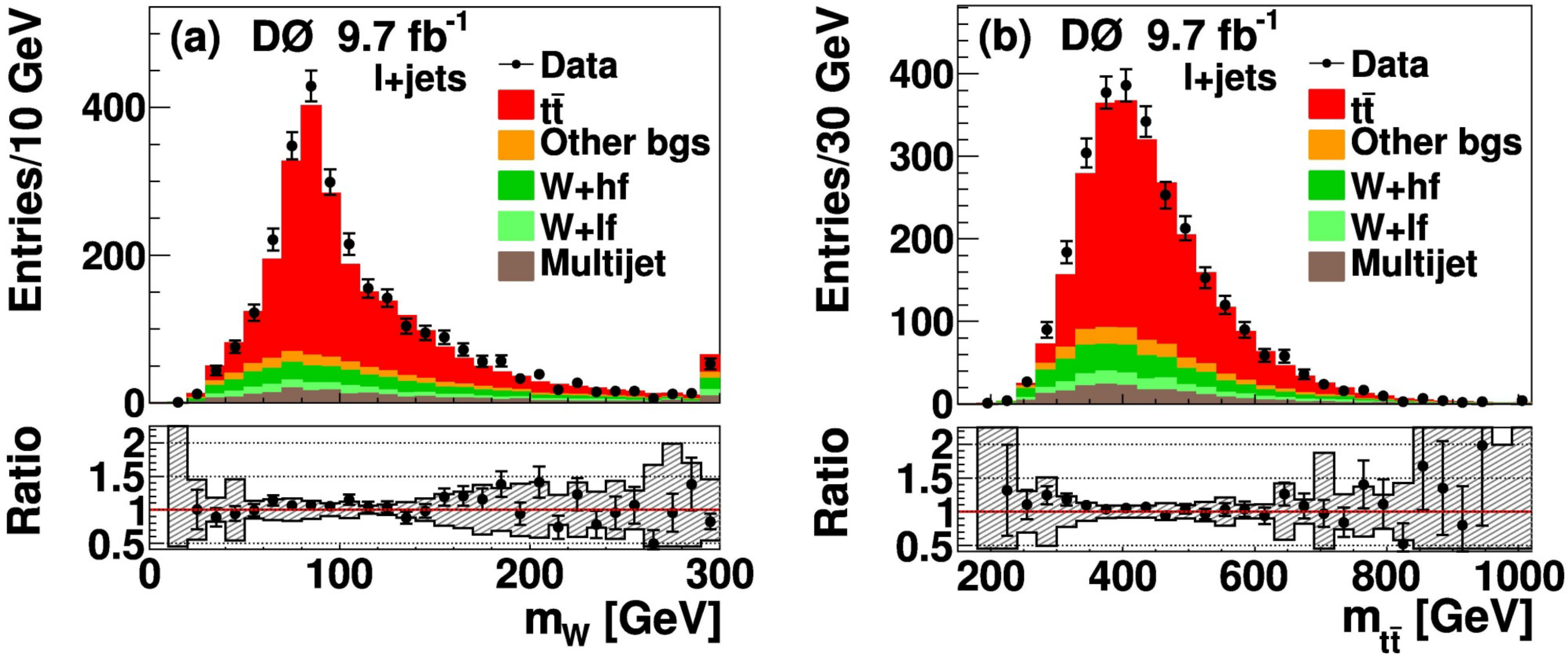



$$M_{top} = 174.34 \pm 0.37\ (stat) \pm 0.52\ (syst)\ GeV/c^2$$

arXiv:1407.2682

# Lepton plus jets top-quark mass

- Use Matrix element technique
- Overall jet energy scale constrained *in situ* by the mass of the W boson
- Most precise single measurement of the top-quark mass.




$M_{top}$ = 174.98 ± 0.76 (stat+syst) GeV/$c^2$

± 0.58(stat+JES) ± 0.49 (syst) GeV/$c^2$

PRL113 032002 (2014)
More details in: arXiv:1501.07912

# Dilepton top-quark mass

- Measurement with the full Tevatron dataset

→ statistics is no longer the limiting uncertainty, this analysis optimized the influence of jet energy scale

- Template analysis using an hybrid variable

→ $M_t^{reco}$: reconstructed top mass (neutrino Φ weighting)

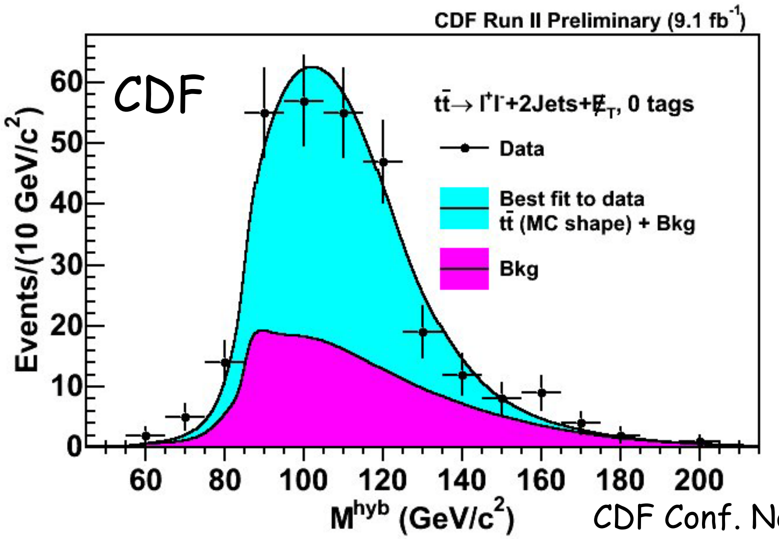
→ $M_{lb}^{alt}$: based only on lepton 4-momenta and jet directions

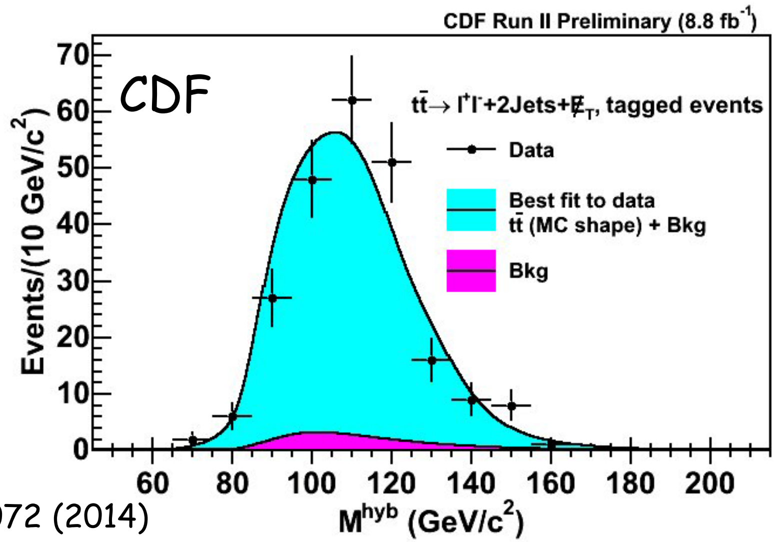
→ optimization of the uncertainty obtained with w = 0.6

$$M^{\rm hyb} = w \cdot M_t^{\rm reco} + (1-w) \cdot M_{lb}^{\rm alt}$$

$M_{top}$ = 171.5 ± 1.9 (stat) ± 2.5(syst) GeV/$c^2$

14% reduced uncertainty compared to the previous CDF result in this channel




CDF Conf. Note 11072 (2014)

# Conclusion

- 3.5 years after the end of RunII Tevatron continues providing valuable top physics results
- Many top quark areas of study (i.e. cross sections, single top s-channel, $A_{FB}$) are complementary to LHC.
- CDF & D0 are in the process of making Tevatron legacy measurements, the current combined Tevatron top quark mass has an uncertainty < 0.4%
- The final Tevatron single top cross section measurements are now available:
  - ⇒ Single top quark s-channel production observed in 2014
  - ⇒ Tevatron combined s+t almost ready to be published
- All measurements shown here in agreement with SM
  - ⇒ Historical disagreement of $A_{FB}$ from CDF data with new NNLO SM prediction < 2 s.d.

# Conclusion

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- CDF & D0 are in the process of making Tevatron legacy measurements, the current combined Tevatron top quark mass has an u
- The final Tev easurements are now available.

Thank you!

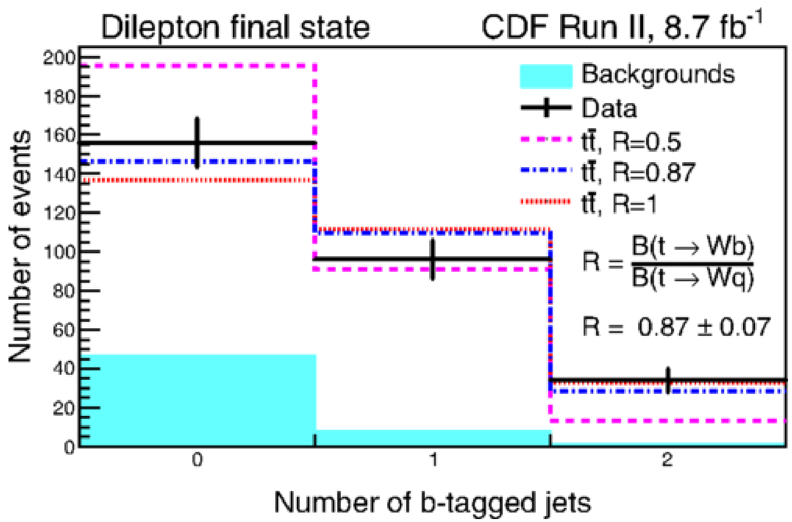
- For more details:
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov

# Backup

# Ratio of branching fractions R

$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- SM: R~1 constrained by CKM unitarity, R<1 would indicate new physics
- Expect 2 b's in each top-antitop event.
- Comparing $t\bar{t}$ cross section measurements vs number of b-tag jets
- Latest CDF measurement in the dilepton channel




R = 0.87 ± 0.07 (stat.+syst)
|Vtb| = 0.93 ± 0.04 (stat.+syst)
PRL 112, 221801 (2014)

- D0 combined measurement in the l+jets and dilepton channel
R = 0.90 ± 0.04 (stat+syst)
$|V_{tb}|$ = 0.95 ± 0.02
PRL 107, 121802 (2011)

- CDF l+jets measurement:
R = 0.94 ± 0.09 (stat+syst)
$|V_{tb}|$ = 0.97 ± 0.05
PRD 87, 111101 (2013)

# Tevatron ttbar cross section

TABLE IV. CDF and D0 measurements of $\sigma_{t\bar{t}}$ and their combination (in pb), with individual contributions to their uncertainties (in pb). Correlation indicates whether a given uncertainty is treated as fully correlated between the CDF and D0 measurements.

| | CDF | D0 | | Tevatron |
|---|---|---|---|---|
| Central value of $\sigma_{t\bar{t}}$ | 7.63 | 7.56 | | 7.60 |
| Sources of systematic uncertainty | | | Correlation | |
| Modeling of the detector | 0.17 | 0.22 | No | 0.13 |
| Modeling of signal | 0.21 | 0.13 | Yes | 0.18 |
| Modeling of jets | 0.21 | 0.11 | No | 0.13 |
| Method of extracting $\sigma_{t\bar{t}}$ | 0.01 | 0.07 | No | 0.03 |
| Background modeled from theory | 0.10 | 0.08 | Yes | 0.10 |
| Background based on data | 0.08 | 0.06 | No | 0.05 |
| Normalization of $Z/\gamma^{*}$ prediction | 0.13 | ··· | No | 0.08 |
| Luminosity: inelastic $p\bar{p}$ cross section | 0.05 | 0.30 | Yes | 0.15 |
| Luminosity: detector | 0.06 | 0.35 | No | 0.14 |
| Total systematic uncertainty | 0.39 | 0.56 | | 0.36 |
| Statistical uncertainty | 0.31 | 0.20 | | 0.20 |
| Total uncertainty | 0.50 | 0.59 | | 0.41 |

The CDF measurement has a weight of 60%, while the D0 measurement has a weight of 40%.
The correlation between the measurements of the two experiments is 17%.

# Angular differential cross section

- cosθ of top quark wrt the beam axis in ttbar rest frame
- Asymmetry summarizes the angular distribution in one number: what component of angular shape explains $A_{FB}$?
- Characterize using expansion in Legendre polynomials:

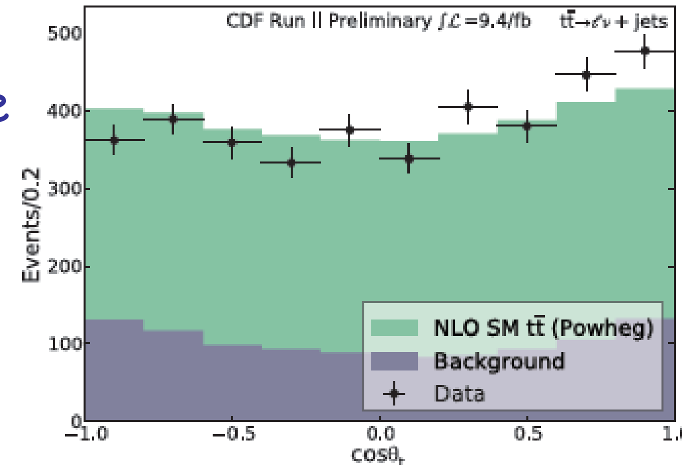
$$\frac{d\sigma(t\bar{t})}{d\cos\theta} = \sum a_l P_l(\cos\theta)$$

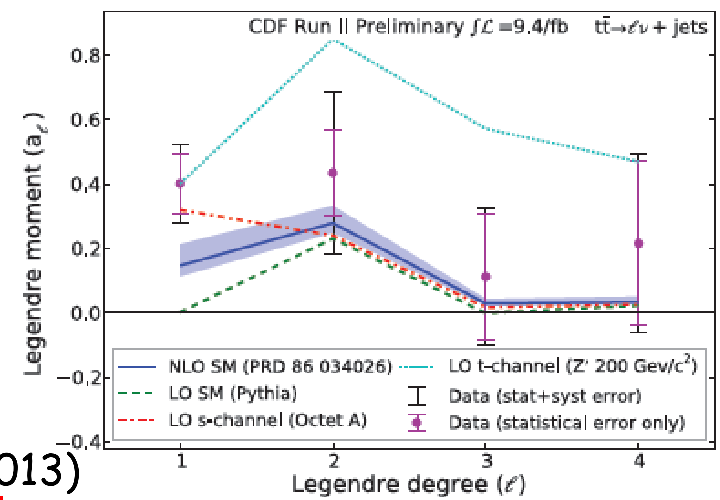
- Measure moments $a_1$ - $a_8$

| $\ell$ | $a_\ell$ (obs) | $a_\ell$ (pred) |
|---|---|---|
| 1 | $0.40\pm0.12$ | $0.15^{+0.066}_{-0.033}$ |
| 2 | $0.44\pm0.25$ | $0.28^{+0.053}_{-0.030}$ |
| 3 | $0.11\pm0.21$ | $0.030^{+0.014}_{-0.007}$ |
| 4 | $0.22\pm0.28$ | $0.035^{+0.016}_{-0.008}$ |
| 5 | $0.11\pm0.33$ | $0.0048^{+0.002}_{-0.001}$ |
| 6 | $0.24\pm0.40$ | $0.0060^{+0.002}_{-0.003}$ |
| 7 | $-0.15\pm0.48$ | $-0.0028^{+0.001}_{-0.001}$ |
| 8 | $0.16\pm0.65$ | $-0.0019^{+0.0003}_{-0.0003}$ |

- First moment shows tension with prediction (2.2σ): sufficient to explain excess in $A_{FB}$

PRL 111, 182002 (2013)

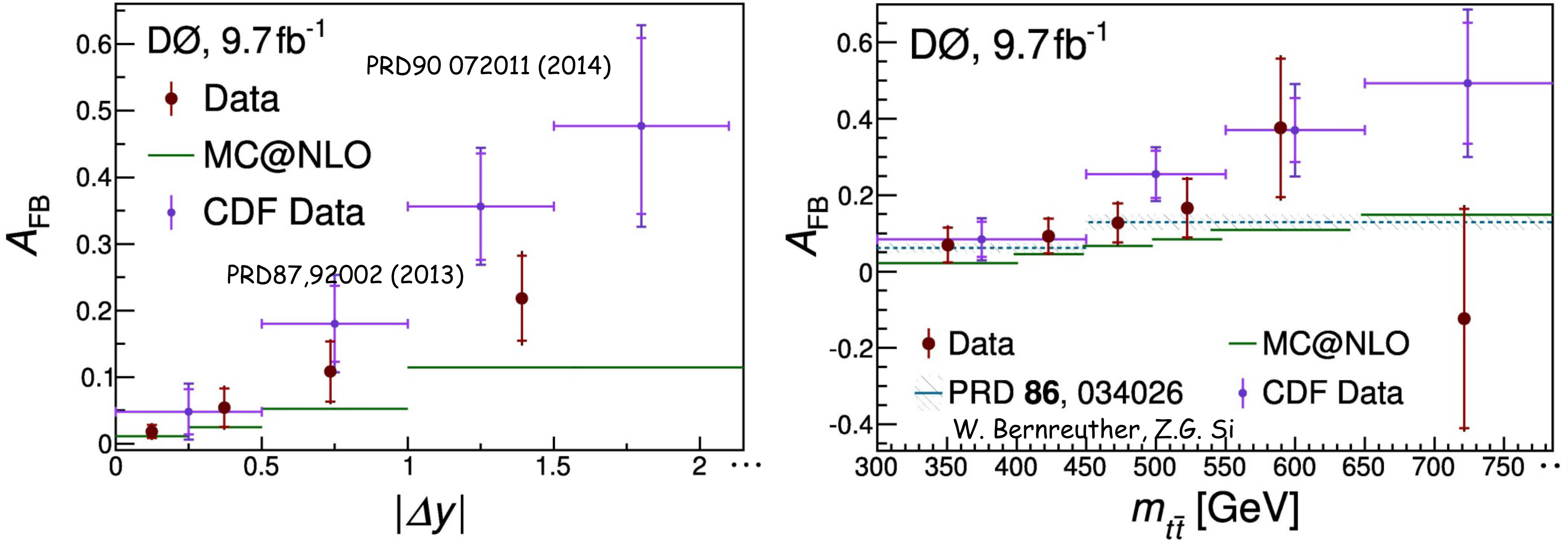


# Forward backward asymmetry ($A_{FB}$)

## Lepton + jets system

- Check mass, rapidity (and $p_T$) kinematic dependence of asymmetry




- Kinematic dependencies larger than MC@NLO predicted by SM

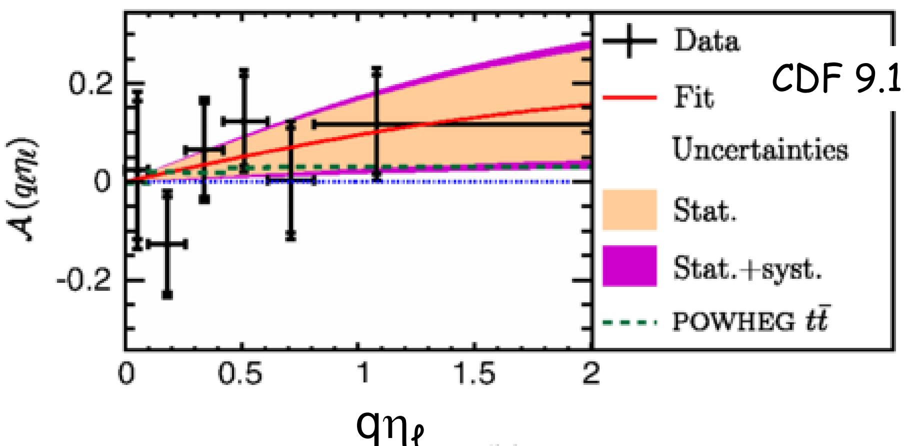
# Lepton Asymmetry in $\ell\ell$+jets

- Final states contain two charged leptons
- Comparison of the observed number of leptons as a function of $q\eta_\ell$ with the SM expectations.

PRD 88, 112002 (2013)

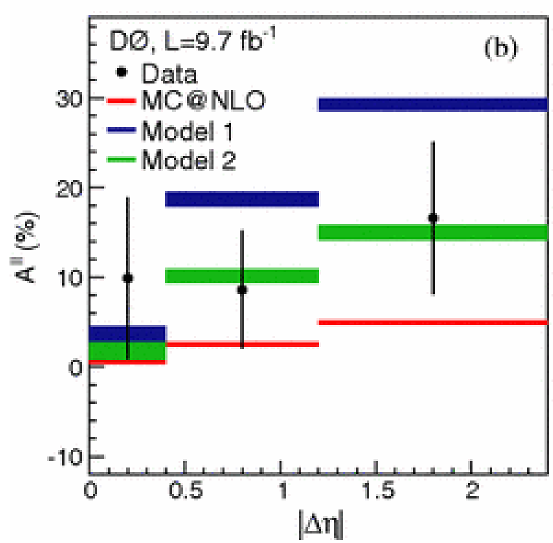
CDF

PRL113, 042001 (2014)



(b)

CDF 9.1 fb-1




$A^\ell$ = 7.2 ± 6.0 (stat.+syst) %

$A^\ell$ = 4.4 ± 3.9(stat.+syst) %

Secondary result: $A^{\ell\ell}$ of $\Delta\eta$ between the two leptons in each event.

$A^{\ell\ell}$ $(\Delta\eta)$ = 7.6 ± 8.2 (stat+syst)%

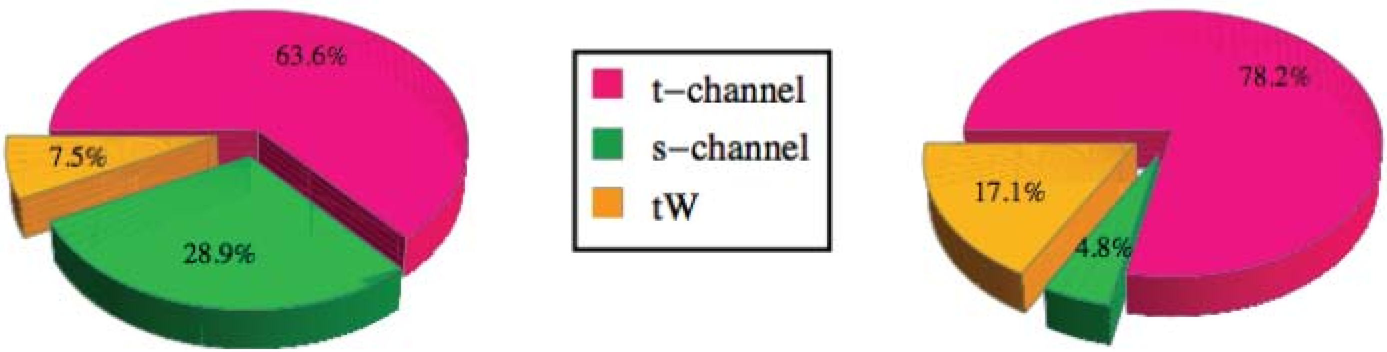
$A^{\ell\ell}$ $(\Delta\eta)$= 12.3 ± 5.6 (stat+syst)%

Expected SM: 4.8 %

# Single top production: Tevatron vs LHC

- Tevatron and LHC are both sensitive to t channel
- Wt-channel: negligible at the Tevatron
- s-channel: challenging at the LHC

**Tevatron: $\sigma_{tot}$ = 3 pb** **LHC: $\sigma_{tot}$ = 114 pb @ 8 TeV**




| Cross section(pb) | $t\bar{t}$ | $s$-channel | $t$-channel |
|---|---|---|---|
| Tevatron(1.96 TeV) | 7.08 | 1.05 | 2.08 |
| | ×33 | ×5.3 | ×42 |
| LHC(8 TeV) | 234 | 5.55 | 87.2 |

(N. Kidonakis, arXiv:1210.7813)

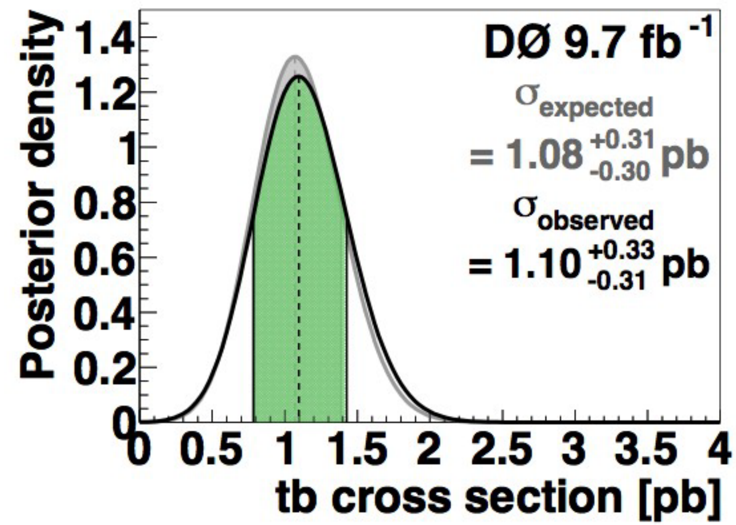
| | | | |
|---|---|---|---|
| | ×130 | ×11 | ×117 |
| LHC (14 TeV ) | 920 | 11.86 | 244 |

# First evidence for s-channel

- The s-channel measurement from D0 was the first evidence for single top s-channel production
- Excess of 3.7 standard deviations!

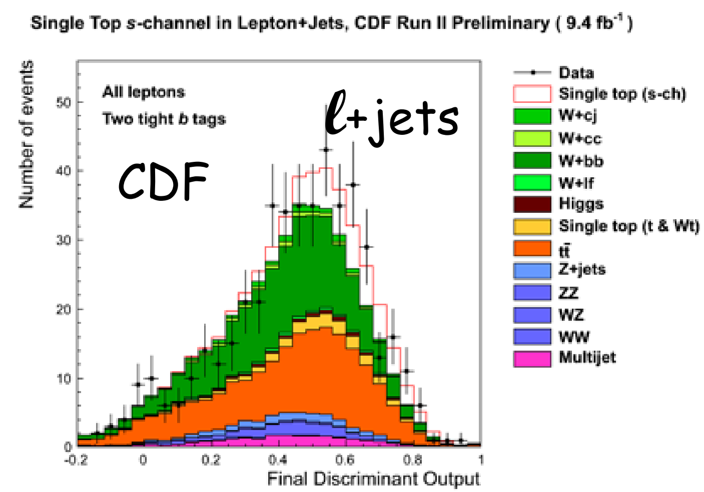
- $\sigma_s = 1.1^{+0.33}_{-0.31}$ (stat+syst) pb

PLB726 (2013)656---664




- CDF performed new lepton+jets and MET+jets s-channel optimized analyses based on Higgs search tools and selection
- CDF combined s-channel:
- $\sigma_s = 1.36^{+0.37}_{-0.32}$ (stat+syst) pb

PRL 112 231805 (2014)




PRL 112 231804 (2014)

# Tevatron s-channel combination

Build multivariate discriminants, optimized to separate s-channel signal from backgrounds

Combine individual discriminants including all correlations:

| Systematic uncertainty | CDF Norm | CDF Dist | D0 Norm | D0 Dist | Correlated |
|---|---|---|---|---|---|
| Lumi from detector | 4.5% | | 4.5% | | No |
| Lumi from cross section | 4.0% | | 4.0% | | Yes |
| Signal modeling | 2–10% | • | 3–8% | | Yes |
| Background (simulation) | 2–12% | • | 2–11% | • | Yes |
| Background (data) | 15–40% | • | 19–50% | • | No |
| Detector modeling | 2–10% | • | 1–5% | • | No |
| $b$-jet-tagging | 10–30% | | 5–40% | • | No |
| JES | 0–20% | • | 0–40% | • | No |

PRL 112 231803 (2014)

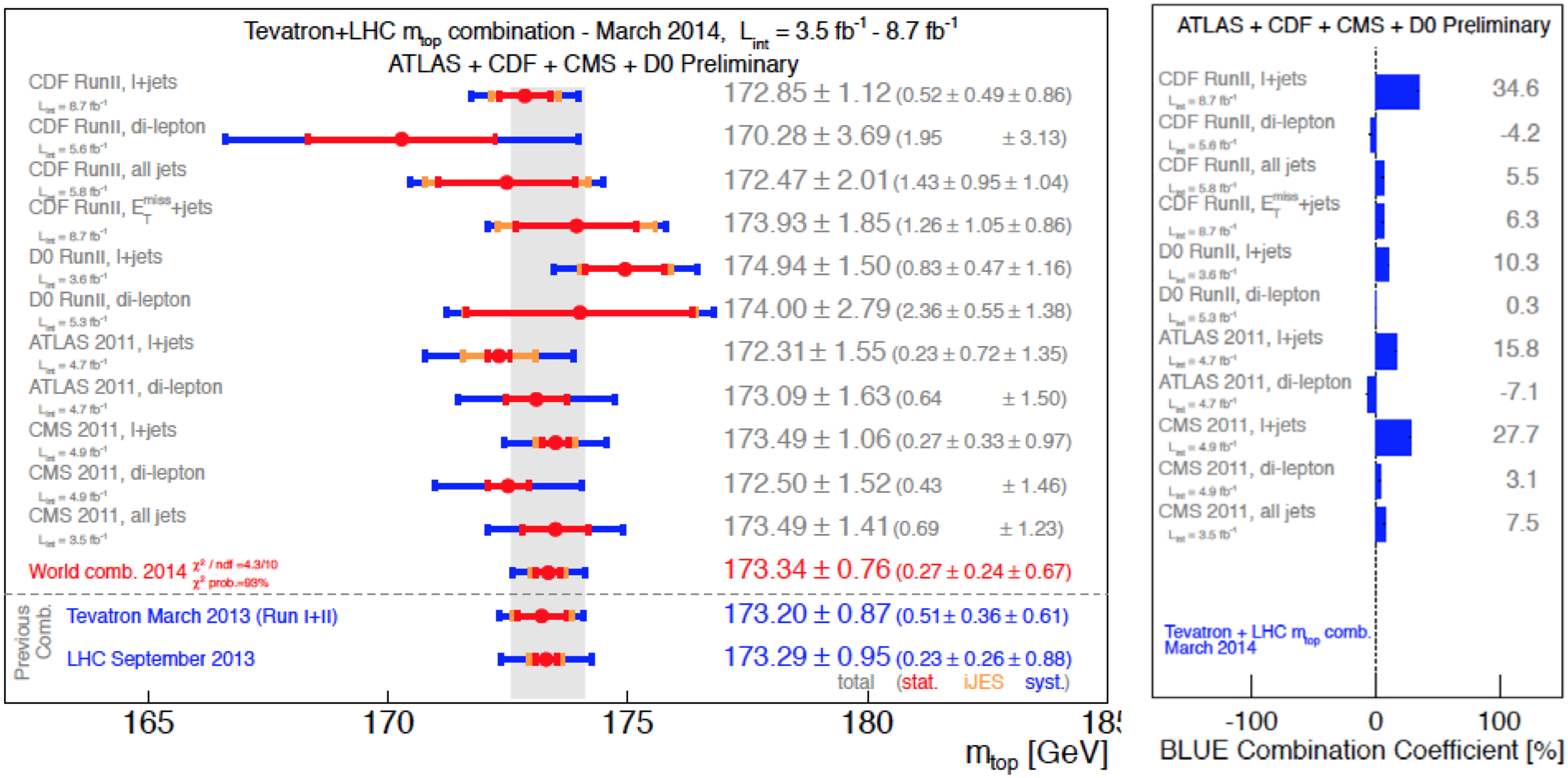
# Tevatron top mass combination

- Total uncertainty < 0.4% (better than world comb. March 2014: 0.76 GeV)

| | Tevatron combined values (GeV/$c^2$) |
|---|---|
| $M_t$ | 174.34 |
| *In situ* light-jet calibration (iJES) | 0.31 |
| Response to $b/q/g$ jets (aJES) | 0.10 |
| Model for $b$ jets (bJES) | 0.10 |
| Out-of-cone correction (cJES) | 0.02 |
| Light-jet response (1) (rJES) | 0.05 |
| Light-jet response (2) (dJES) | 0.13 |
| Lepton modeling (LepPt) | 0.07 |
| Signal modeling (Signal) | 0.34 |
| Jet modeling (DetMod) | 0.03 |
| $b$-tag modeling ($b$-tag) | 0.07 |
| Background from theory (BGMC) | 0.04 |
| Background based on data (BGData) | 0.08 |
| Calibration method (Method) | 0.07 |
| Offset (UN/MI) | 0.00 |
| Multiple interactions model (MHI) | 0.06 |
| Systematic uncertainty (syst) | 0.52 |
| Statistical uncertainty (stat) | 0.37 |
| Total uncertainty | 0.64 |

arXiv:1407.2682

# Top Quark Mass: World Combination




- Uncertainty of 0.76 GeV → including newest results from Tevatron and LHC should be reduced even further!
- Compatibility between input results will need careful consideration

arXiv:1403.4427

# Lepton plus jets top quark mass

- Use Matrix element technique
  - Calculate the event probability on an event-by-event basis
- 

$$P_{\rm evt}(m_{\rm top}) \propto f P_{\rm sig}(m_{\rm top}) + (1-f) P_{\rm bgr}$$

$$P_{\rm sig}(m_{\rm top}) \propto \int ... d\sigma_{t\bar{t}}(m_{\rm top})$$

$$d\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2 (m_{\rm top})$$

- Advantages: Use 4-vectors with maximal kinematic and topological information a $\rightarrow$ maximal statistical sensitivity
- Constrain energies of the two jets from W to be consistent with $M_W$
- Maximise the likelihood in $M_t$ and in the overall scale factor for jet energies $k_{JES}$
- Improvements:
  - reduction of ME calculation time
  - increase of ME calibration samples
  - increase of data sample and MC samples
  - new JES calibration including flavour-dependent response correction
  - ttbar modeling (ISR/FSR, hadronisation

PRL113 032002 (2014)

# Lepton plus jets top quark mass

## Systematic uncertainties:

| Source of uncertainty | Effect on $m_t$ (GeV) |
|---|---|
| *Signal and background modeling:* | |
| Higher order corrections* | 0.15 |
| Initial/final state radiation* | 0.09 |
| Hadronization & UE* | 0.26 |
| Color reconnection* | 0.10 |
| Multiple $p\bar{p}$ interactions | 0.06 |
| Heavy flavor scale factor | 0.06 |
| $b$-jet modeling | 0.09 |
| PDF uncertainty | 0.11 |
| *Detector modeling:* | |
| Residual jet energy scale | 0.21 |
| Data-MC jet response difference | 0.16 |
| $b$-tagging | 0.10 |
| Trigger | 0.01 |
| Lepton momentum scale | 0.01 |
| Jet energy resolution | 0.07 |
| Jet ID efficiency | 0.01 |
| *Method:* | |
| Modeling of multijet events | 0.04 |
| Signal fraction | 0.08 |
| MC calibration | 0.07 |
| *Total systematic uncertainty* | 0.49 |
| *Total statistical uncertainty* | 0.58 |
| *Total uncertainty* | 0.76 |

PRL113 032002 (2014) 9.7 fb$^{-1}$

**0.49 GeV**

**1.02 GeV**

| Source | Uncertainty (GeV) |
|---|---|
| *Modeling of production:* | |
| *Modeling of signal:* | |
| Higher-order effects | $\pm0.25$ |
| ISR/FSR | $\pm0.26$ |
| Hadronization and UE | $\pm0.58$ |
| Color reconnection | $\pm0.28$ |
| Multiple $p\bar{p}$ interactions | $\pm0.07$ |
| Modeling of background | $\pm0.16$ |
| $W$+jets heavy-flavor scale factor | $\pm0.07$ |
| Modeling of $b$ jets | $\pm0.09$ |
| Choice of PDF | $\pm0.24$ |
| *Modeling of detector:* | |
| Residual jet energy scale | $\pm0.21$ |
| Data-MC jet response difference | $\pm0.28$ |
| $b$-tagging efficiency | $\pm0.08$ |
| Trigger efficiency | $\pm0.01$ |
| Lepton momentum scale | $\pm0.17$ |
| Jet energy resolution | $\pm0.32$ |
| Jet ID efficiency | $\pm0.26$ |
| *Method:* | |
| Multijet contamination | $\pm0.14$ |
| Signal fraction | $\pm0.10$ |
| MC calibration | $\pm0.20$ |
| Total | $\pm1.02$ |

PRD84 032004 (2011) 3.6 fb$^{-1}$

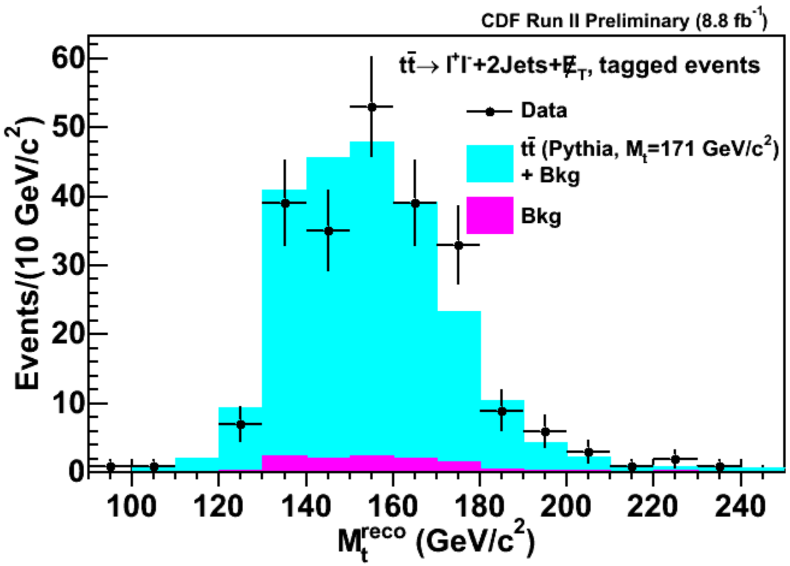
# Dilepton top-quark mass

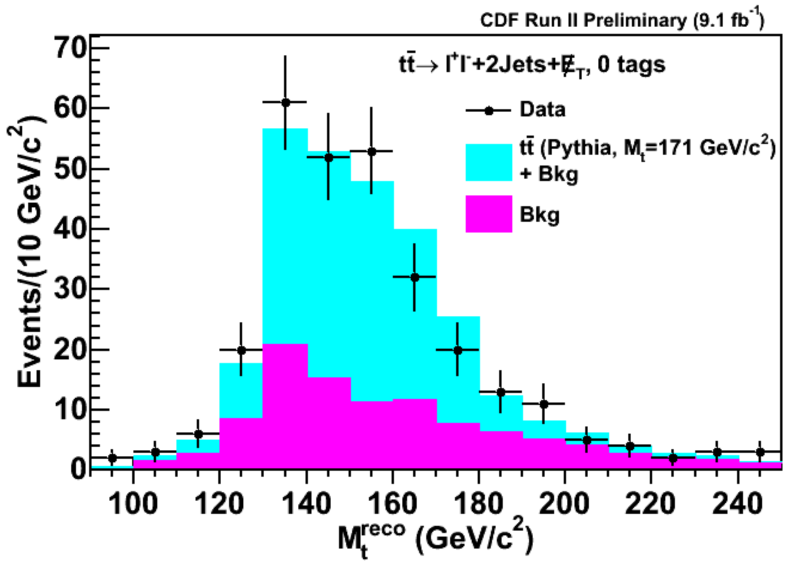
Summary of uncertainties

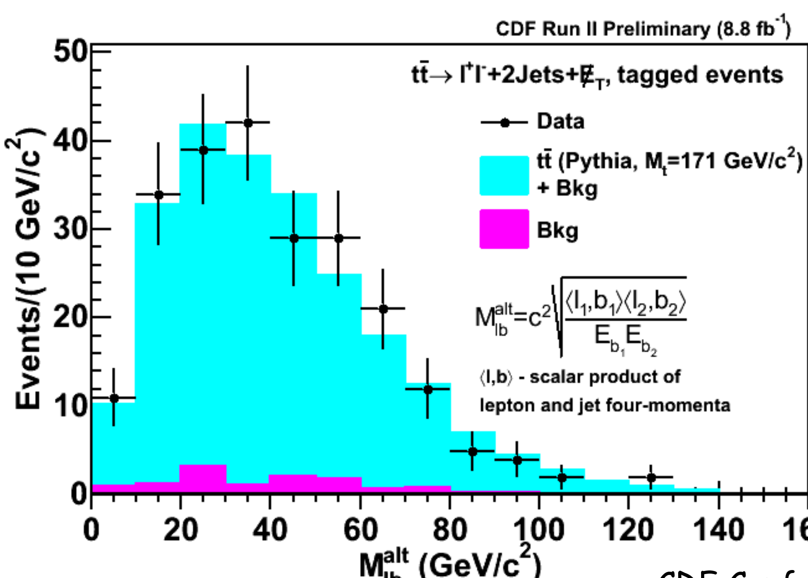
| Source | Uncertainty (GeV/$c^2$) |
|---|---|
| Jet-energy scale | 2.2 |
| NLO effects | 0.7 |
| Monte Carlo generators | 0.5 |
| Lepton-energy scale | 0.4 |
| Background modeling | 0.4 |
| Initial- and final-state radiation | 0.4 |
| $gg$ fraction | 0.3 |
| $b$-jet-energy scale | 0.3 |
| Luminosity profile | 0.3 |
| Color reconnection | 0.2 |
| MC sample size | 0.2 |
| Parton distribution functions | 0.2 |
| $b$-tagging | 0.1 |
| Total systematic uncertainty | 2.5 |
| Statistical uncertainty | 1.9 |
| Total | 3.2 |

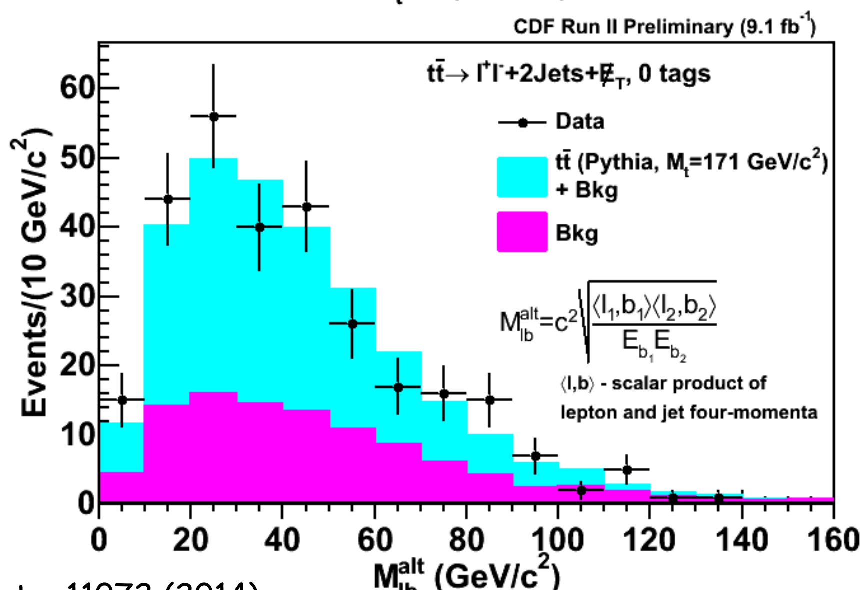
CDF Conf. Note 11072 (2014)

# Dilepton top-quark mass

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