Review of Top Quark Physics

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23rd Rencontres de Blois
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discovery of the top quark

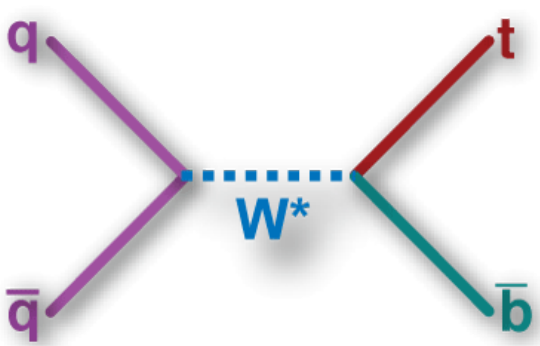
- in 1995 D0 and CDF observed and excess of events consistent with $p\bar{p} \rightarrow t\bar{t} \rightarrow W^+ b W^- \bar{b}$

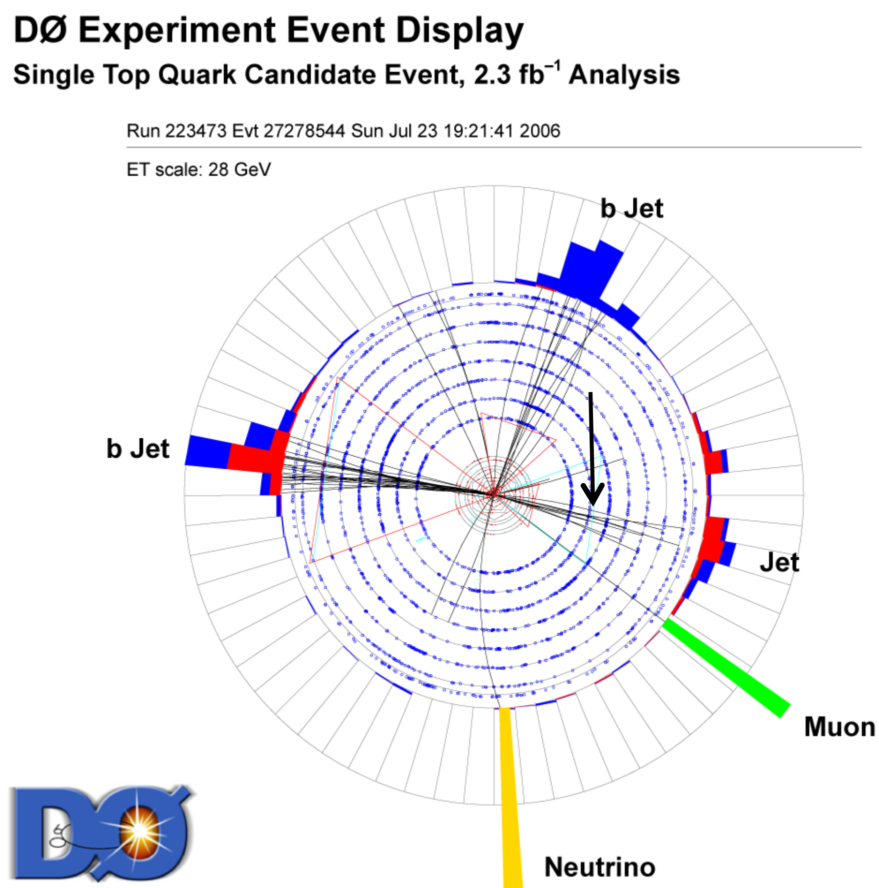
about 1760 citations each…

and…

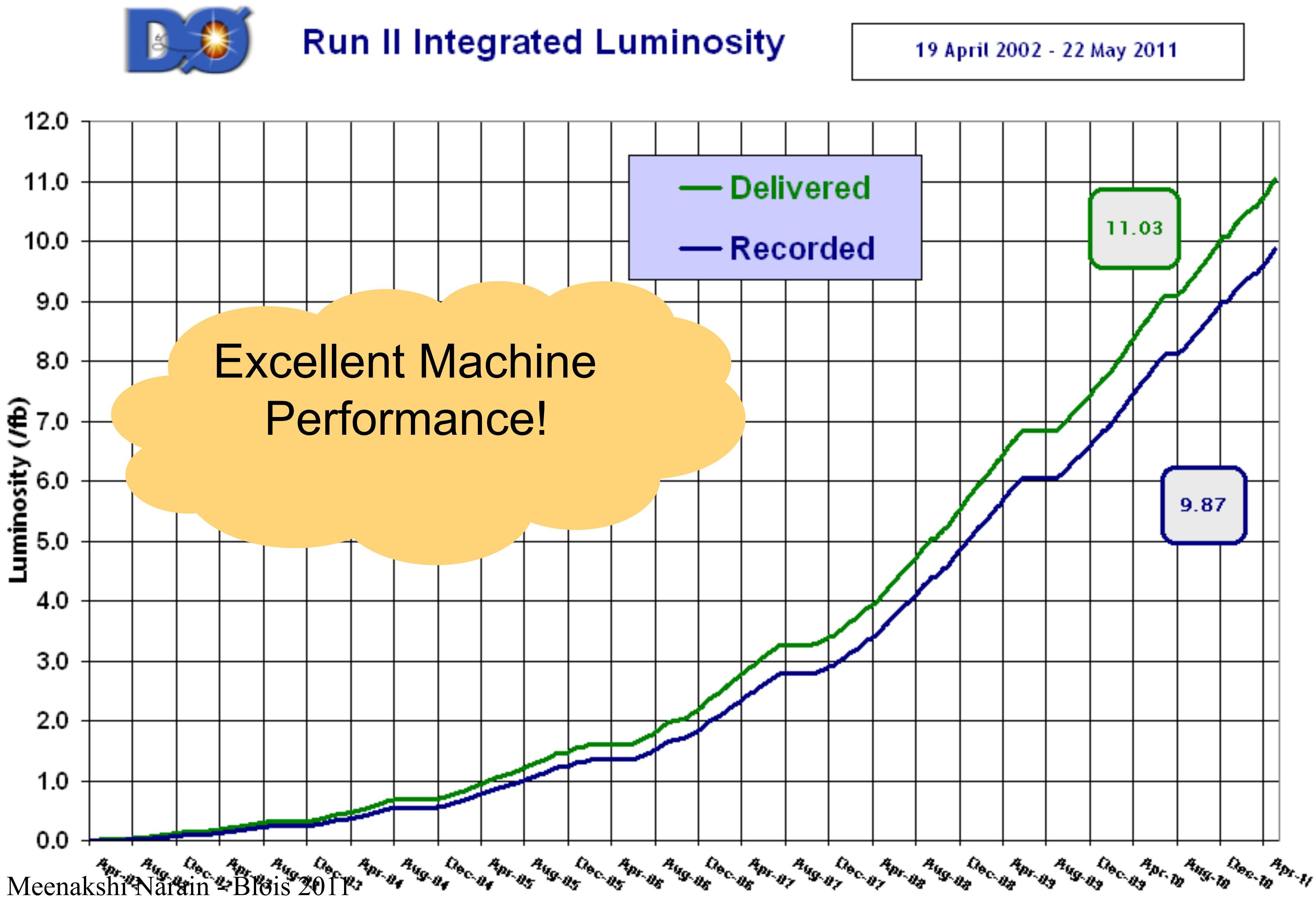
- 14 years later in 2009:

- Observed EWK production process: single top quark





Tevatron

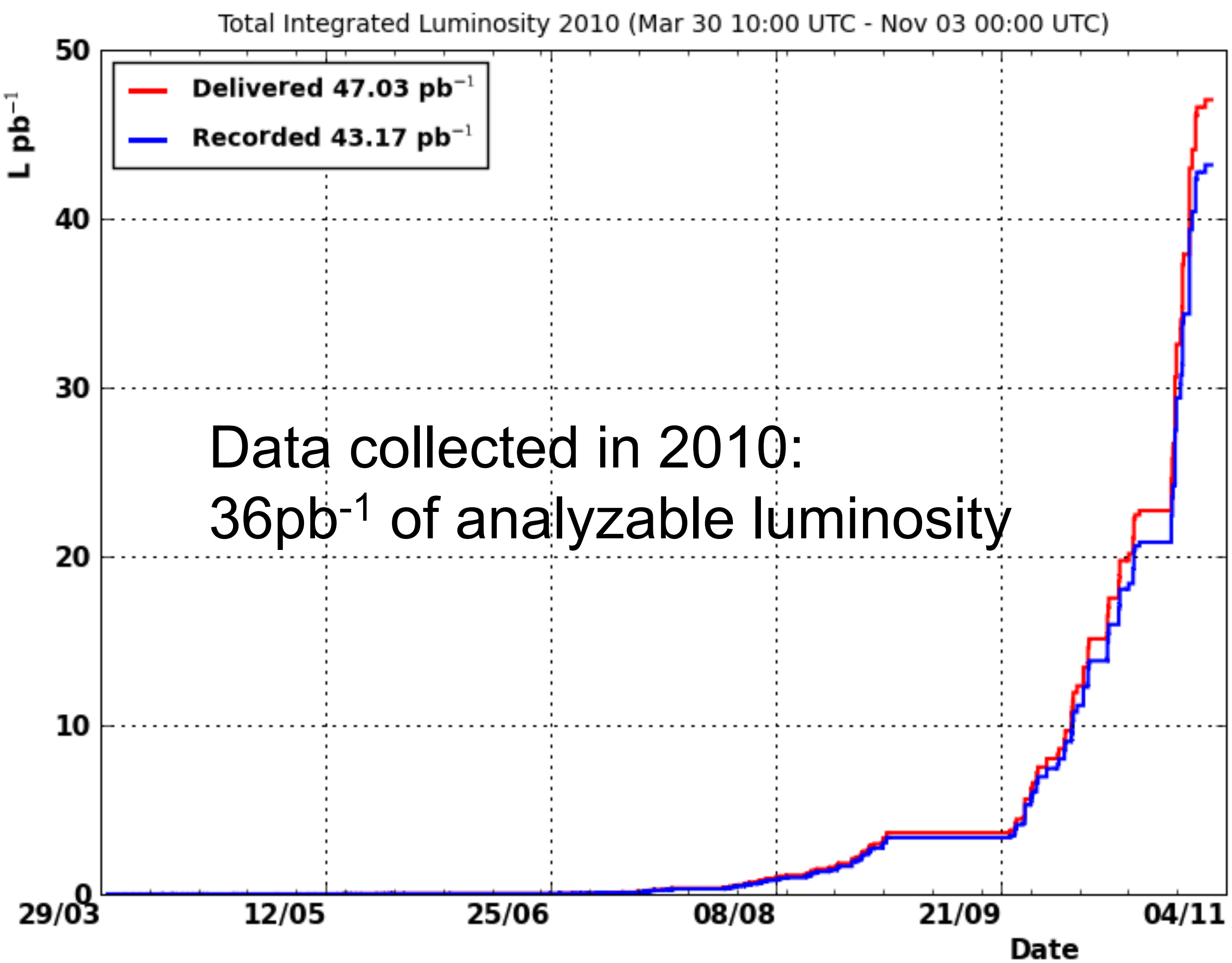


Run II Integrated Luminosity
19 April 2002 - 22 May 2011
Delivered
Recorded
11.03
9.87
Luminosity (/fb)
Excellent Machine Performance!

top at LHC!

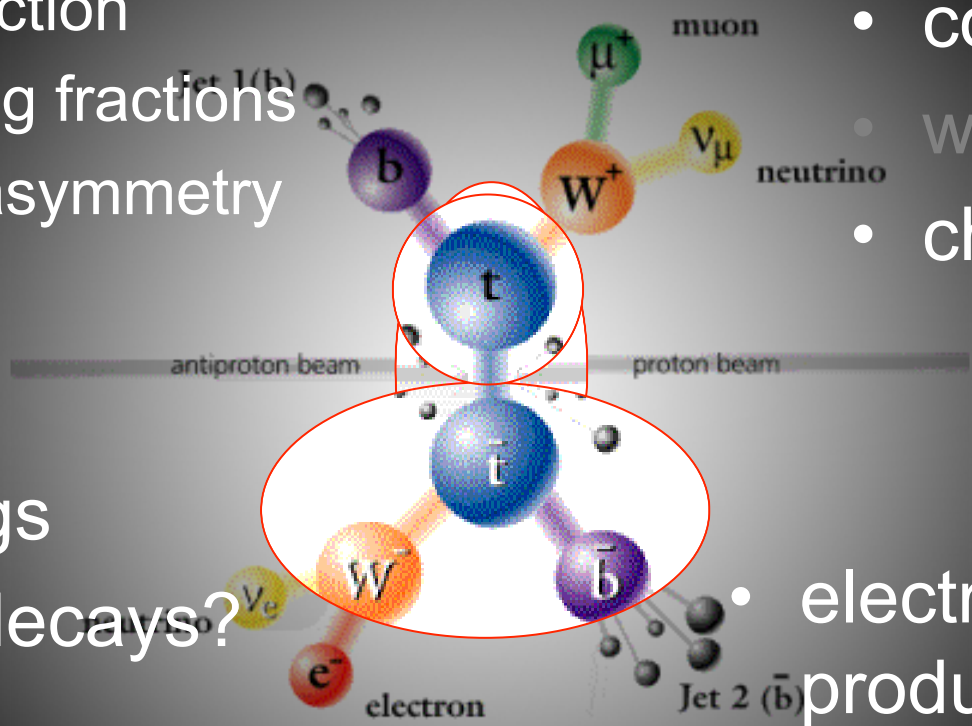
- First collisions at sqrt(s)=7 TeV in March 2010

LHC


Total Integrated Luminosity 2010 (Mar 30 10:00 UTC - Nov 03 00:00 UTC)
Delivered 47.03 pb⁻¹
Recorded 43.17 pb⁻¹
L pb⁻¹
50
40
30
20
10
0
29/03
12/05
25/06
08/08
21/09
04/11
Date
Data collected in 2010:
36pb⁻¹ of analyzable luminosity

outline

- strong production
  - cross section
  - branching fractions
  - charge asymmetry
- decay
  - couplings
  - FCNC decays?
- new physics?
  - tt resonances
  - process which mimic top (t’)
  - W’, H+



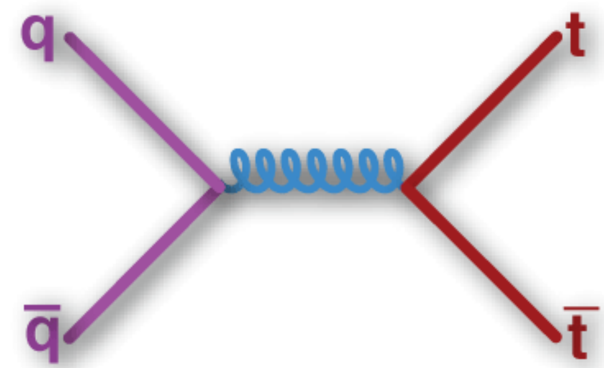
- mass
- couplings
- width
- charge
- electroweak production
  - single top quark
  - $|V_{tb}|$

top anti-top production

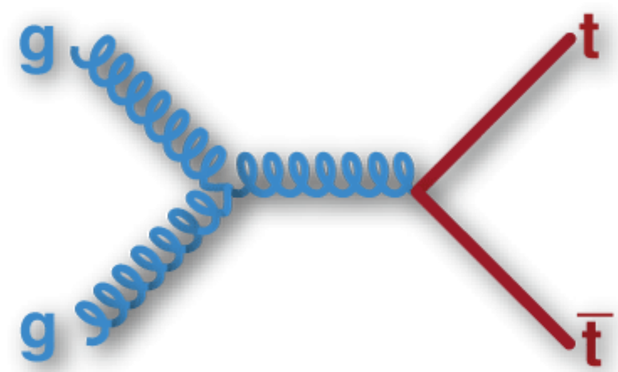
- strong interaction

→ top-antitop pairs

(σ = 7.6±0.6 pb) @Tevatron
predominantly from quark
anti-quark annihilation (85%)

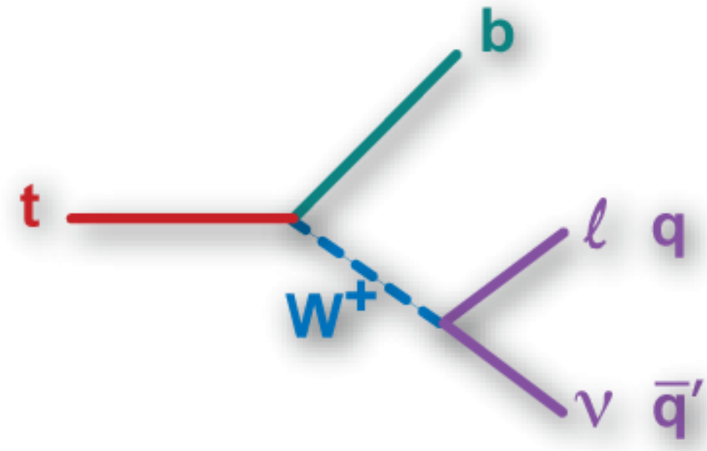


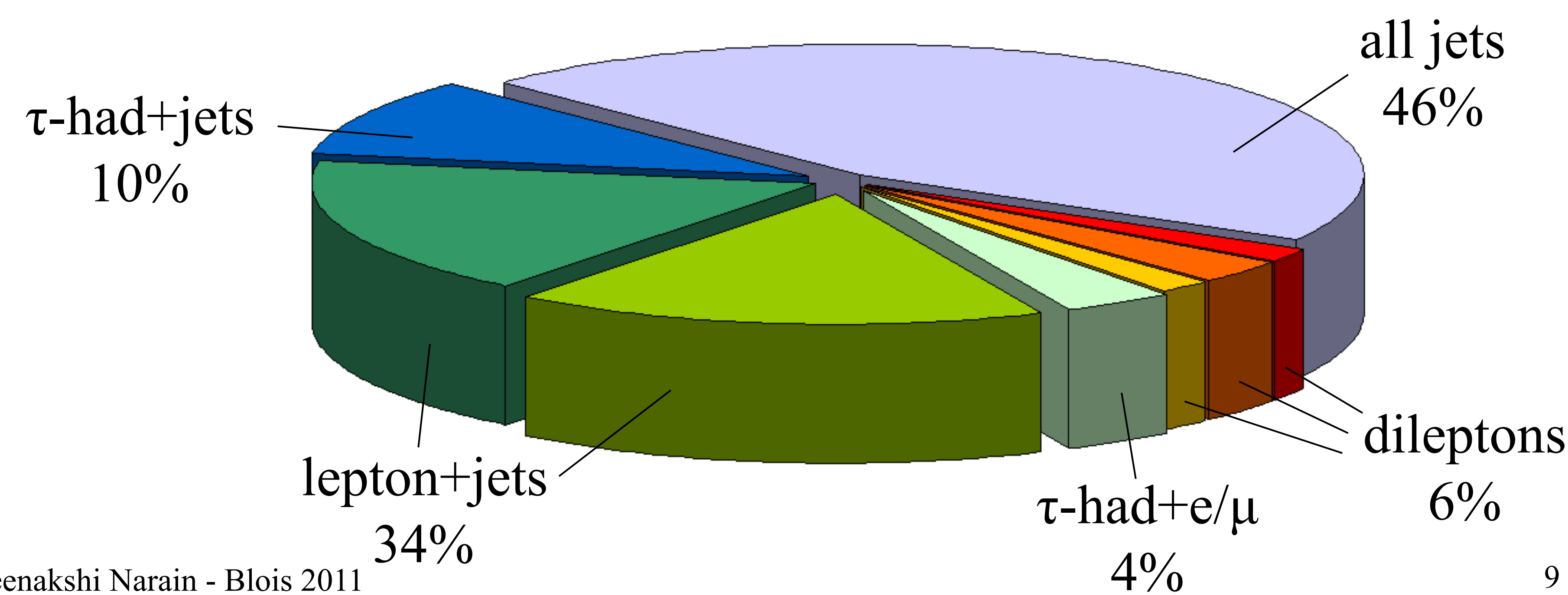
(σ = 164.6±15.7 pb) @ LHC
predominantly from gluon
fusion (87%)



standard model top decay

- t→Wb with $B \approx 100\%$
  - W→qq with $B \approx 67\ \%$
  - W→ℓν with $B \approx 11\%$
- final state signatures for top-antitop pairs





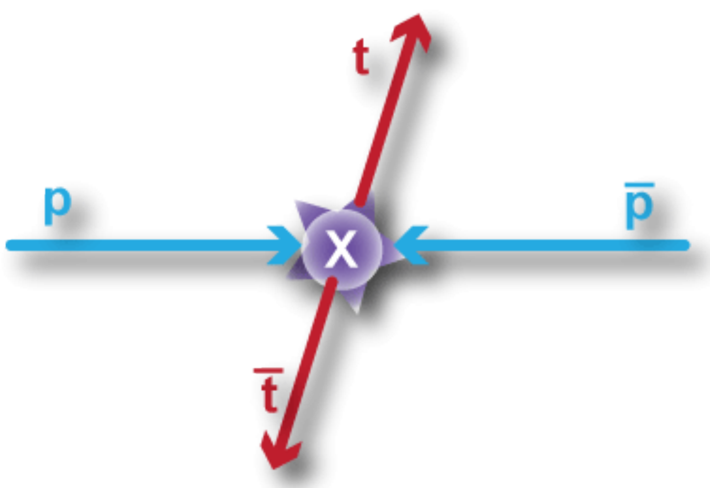
top production:

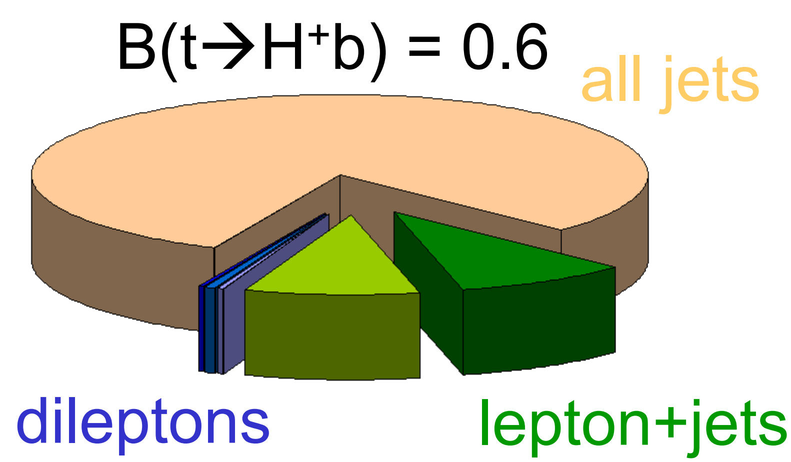
- Top pair production cross section
- Forward-backward charge asymmetry
- Electroweak production (single top)
- New particles produce or mimic top

- Boosted top production

why measure the ttbar cross section?

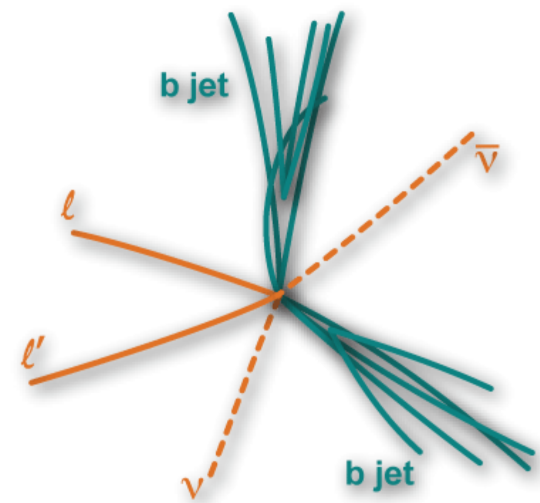
- cross section analysis
  - top production follows QCD prediction:
    - consistency between channels
    - decay branching fractions
  - is top produced by heavy particles
  - are there non-standard decays?

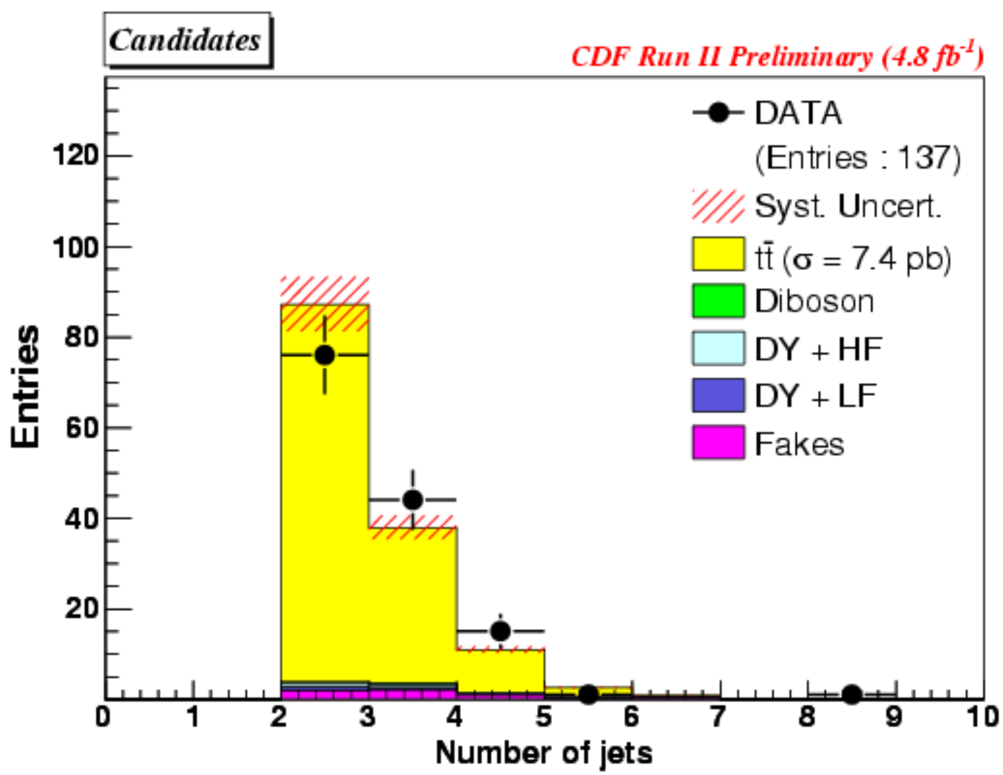


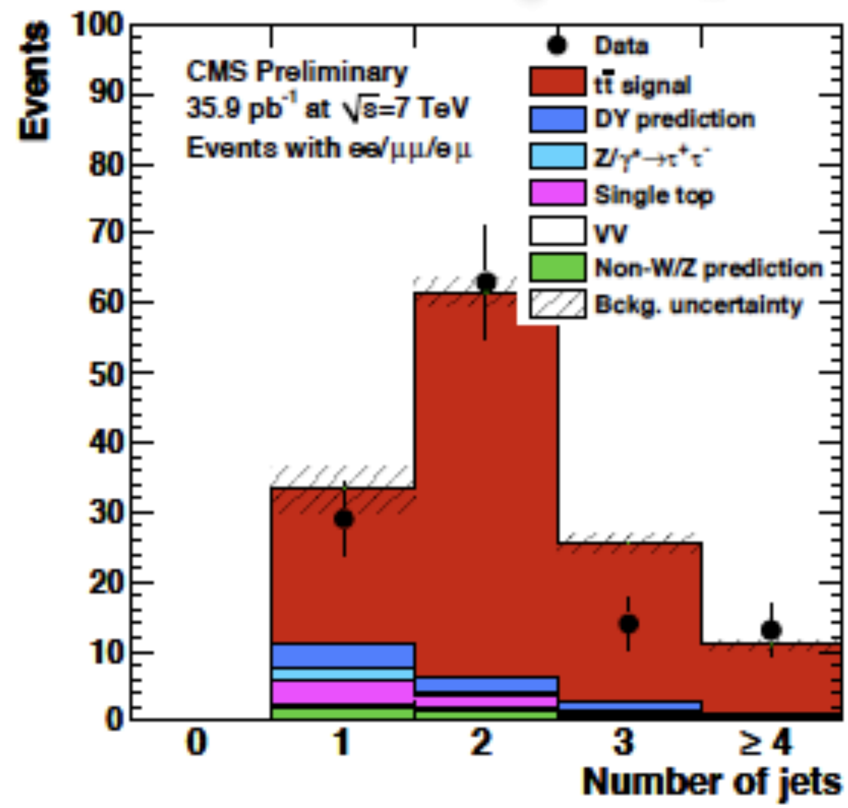


ttbar dilepton candidates:

- Select events with two High pT leptons, Missing Energy and jets, including b-tagged jets

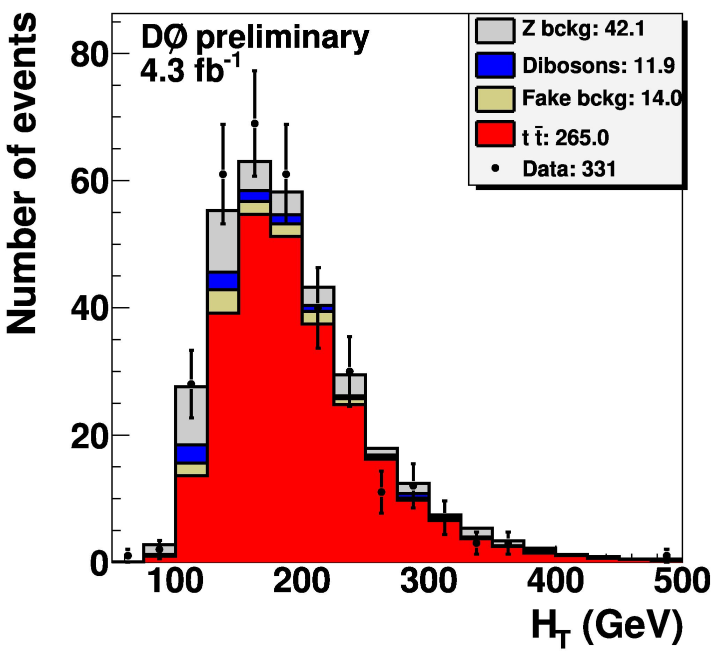


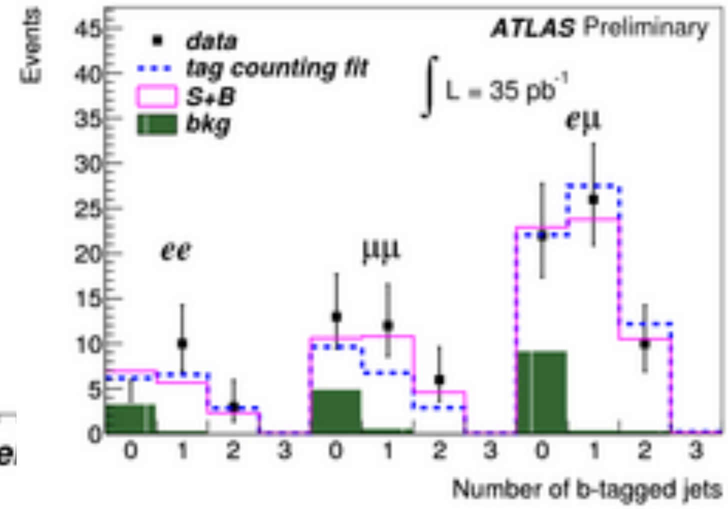


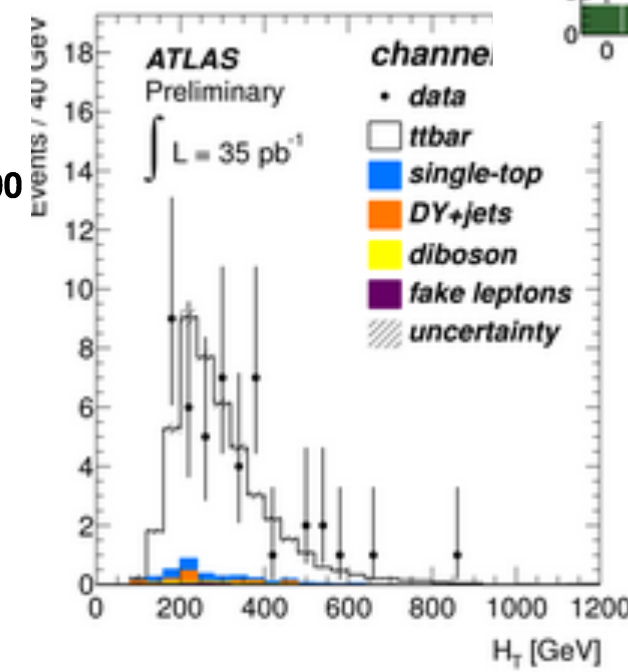


ttbar dilepton candidates:

- Properties of the selected dilepton events:

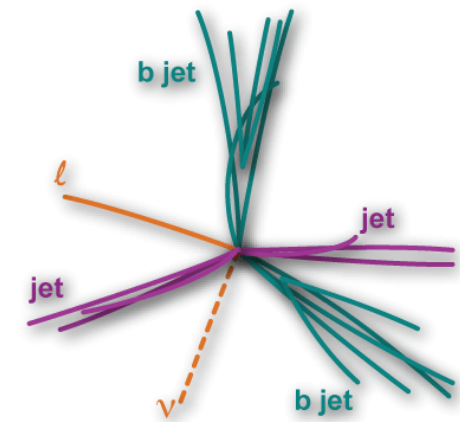


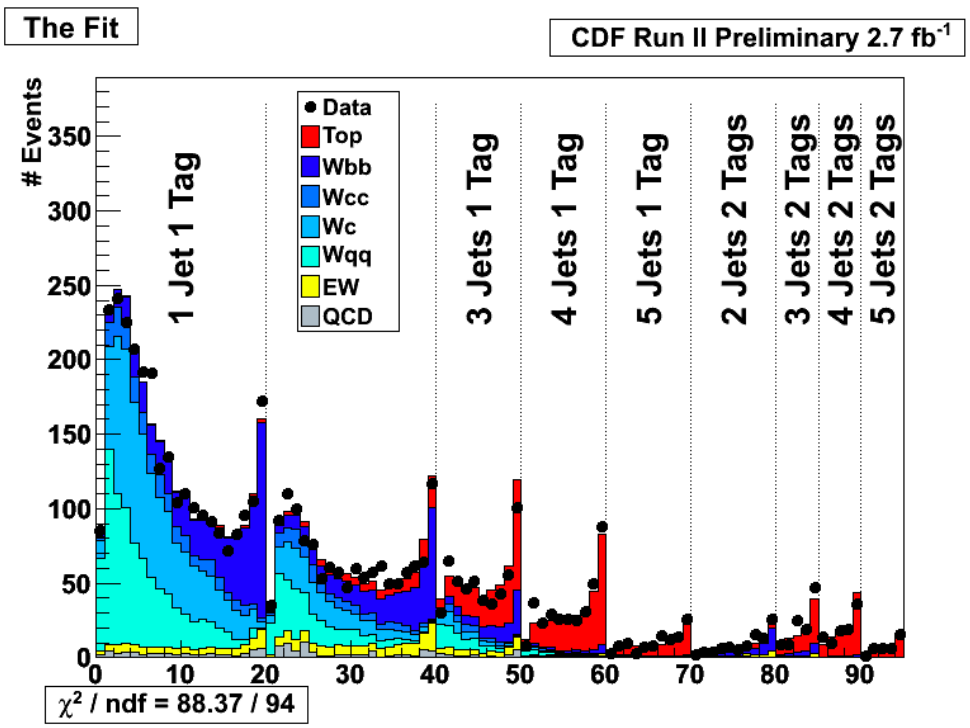


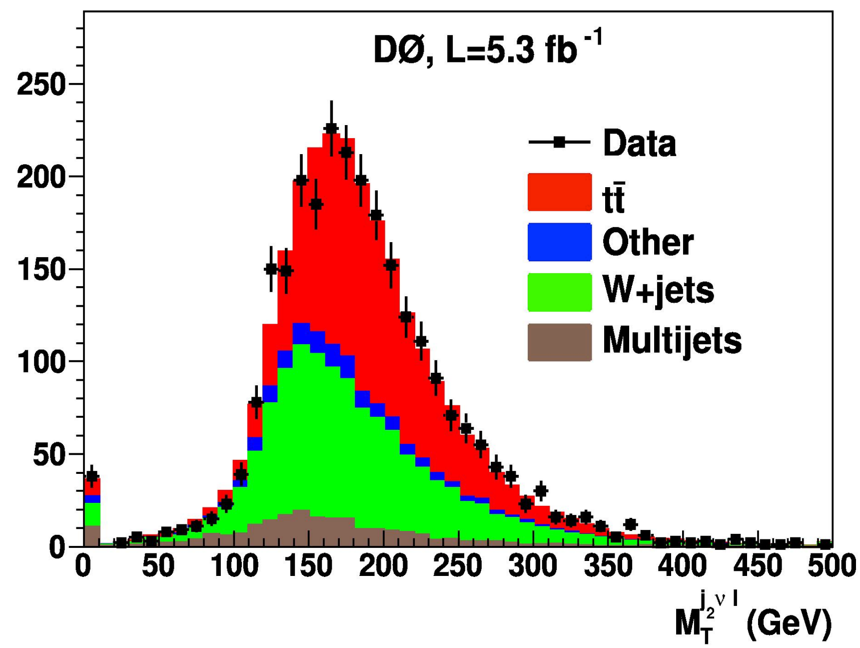


ttbar lepton+jets candidates:

- Select events with one high pT lepton, Missing Et and jets (including b-tagged).







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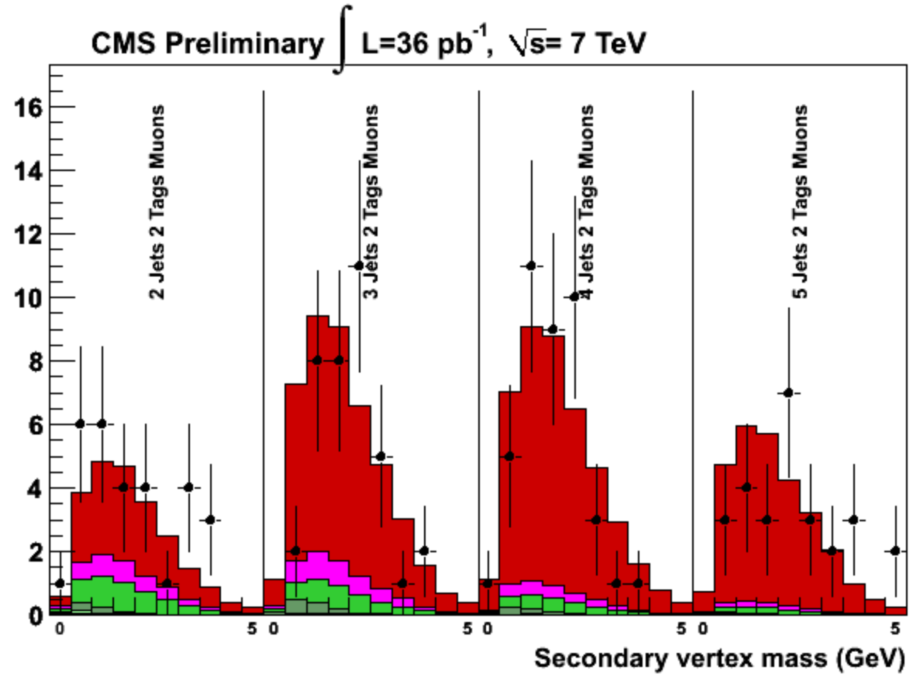
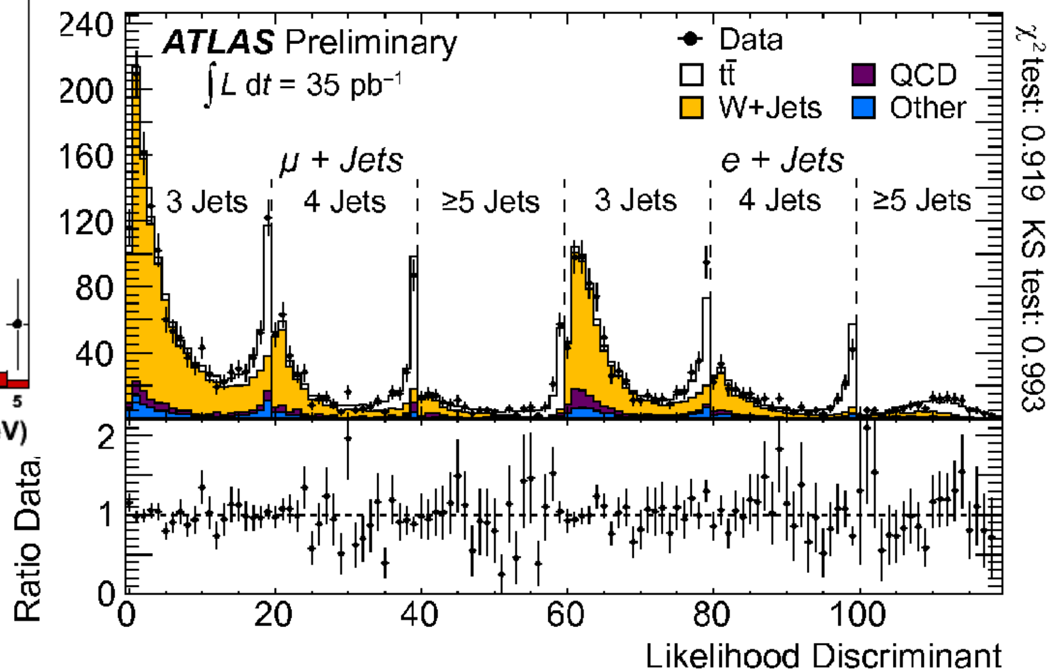
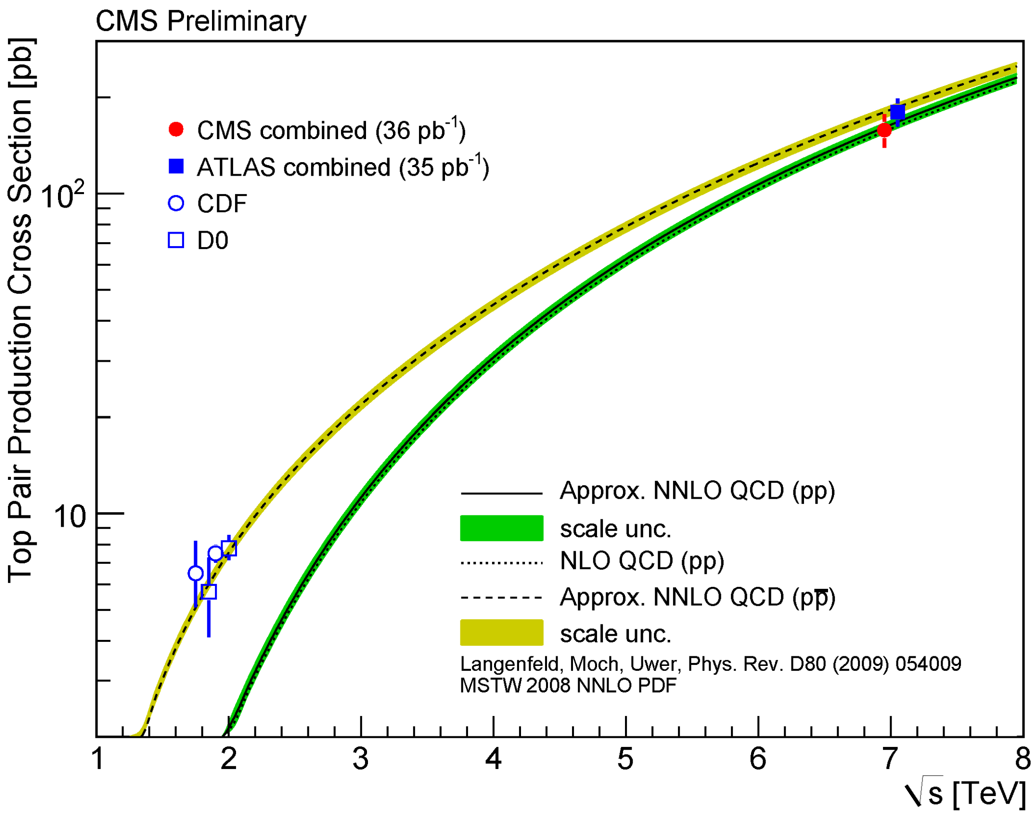




Binned Likelihood Fits to the secondary vertex mass or another discriminant are performed to extract signal yields, b-tagging efficiency, constrain heavy flavor fraction and jet energy scale.

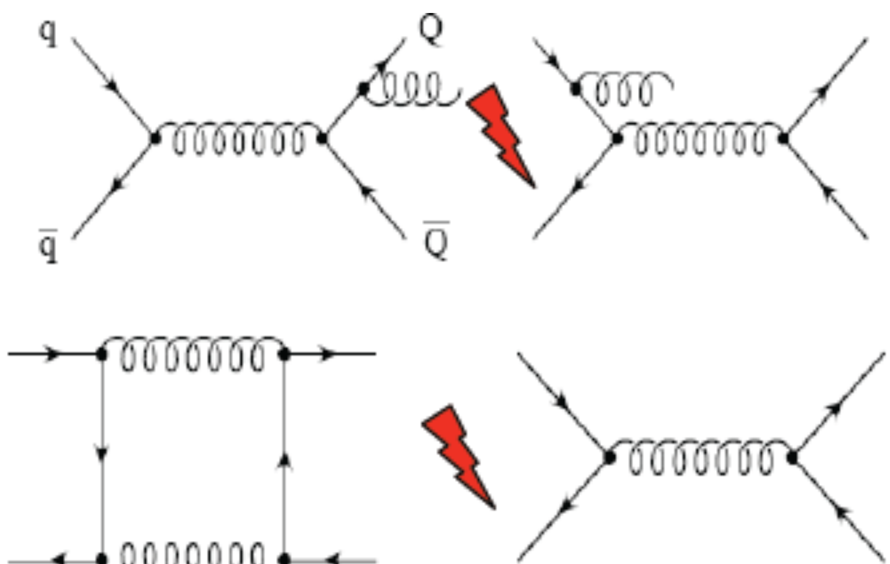
ttbar cross section

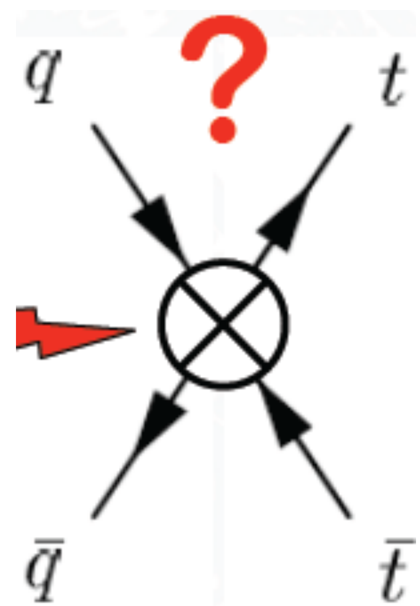
$$\sigma\left(t\bar{t}\right) = \frac{N_{events} - N_{bkg}}{\varepsilon \bullet A \bullet L}$$



color charge asymmetry A_{FB}

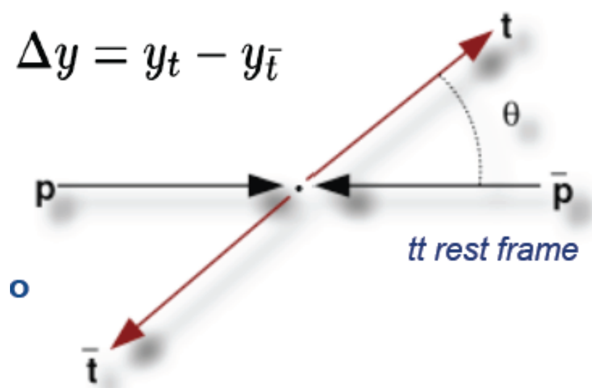
- Tevatron: at LO, completely symmetric
- At higher orders, interference terms influence t and t-bar production asymmetrically, e.g.: 4-6% expected at NLO in the parton frame
- New Physics could enhance the asymmetry.



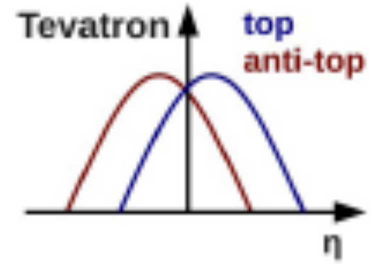


color charge asymmetry A_{FB}

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



$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$



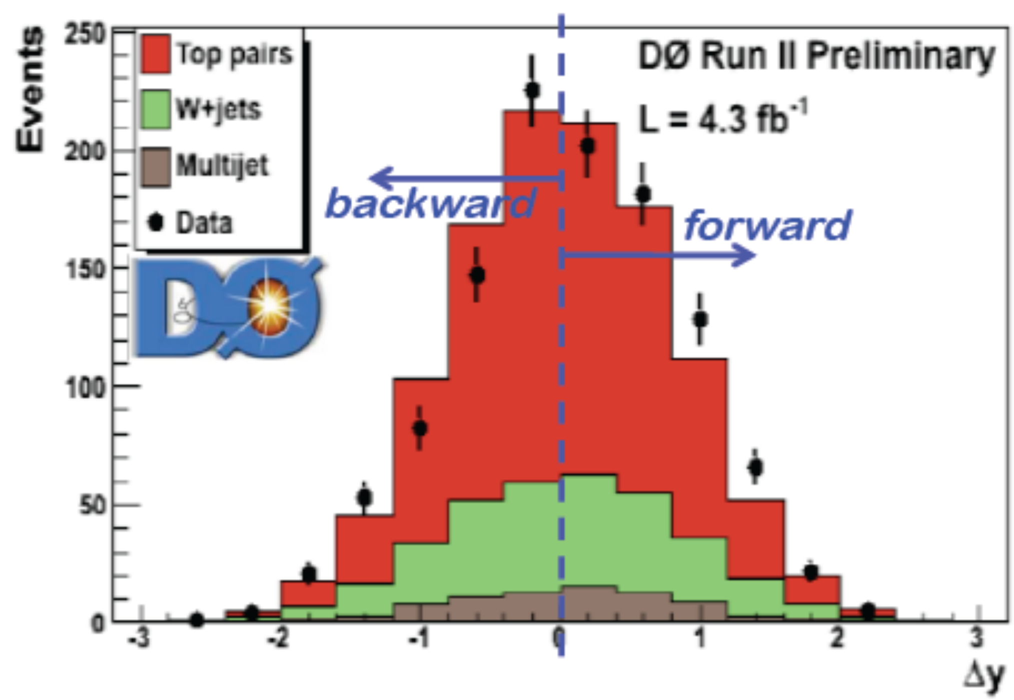
- Dzero:

  $A_{fb} = 8 \pm 4\%$ (2σ)

  Raw result (not unfolded)

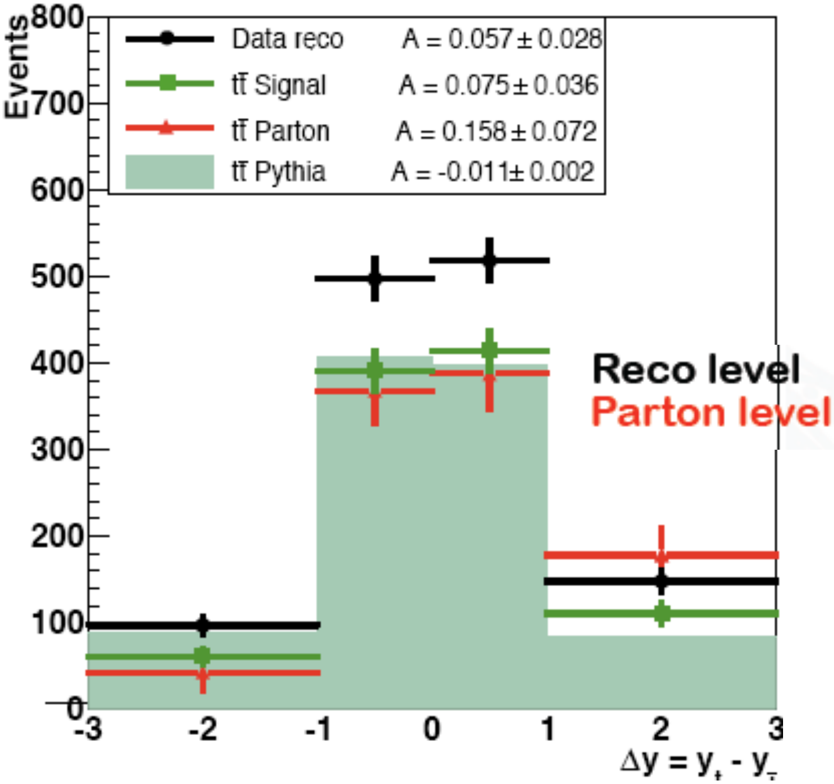
- mc@nlo

  prediction: $1 \pm 2\%$

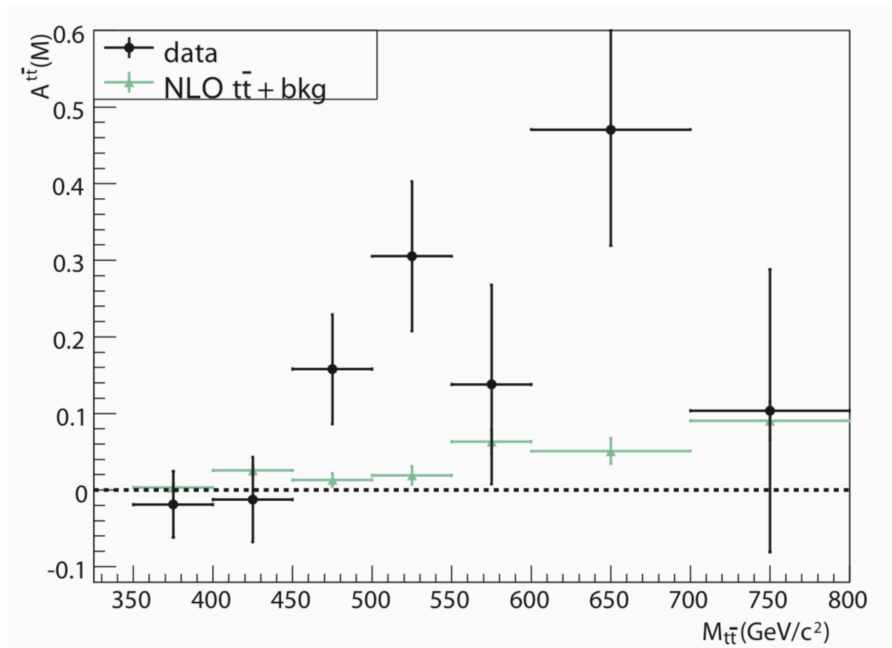


color charge asymmetry A_{FB}

- CDF



- A_{FB} as a function of M_{tt}



A_{fb}=15 ± 5 % (2σ)

mc@nlo prediction: 6 ± 1%

A_{fb}=48 ± 11 % (>3σ)

8.8 ± 1.3%

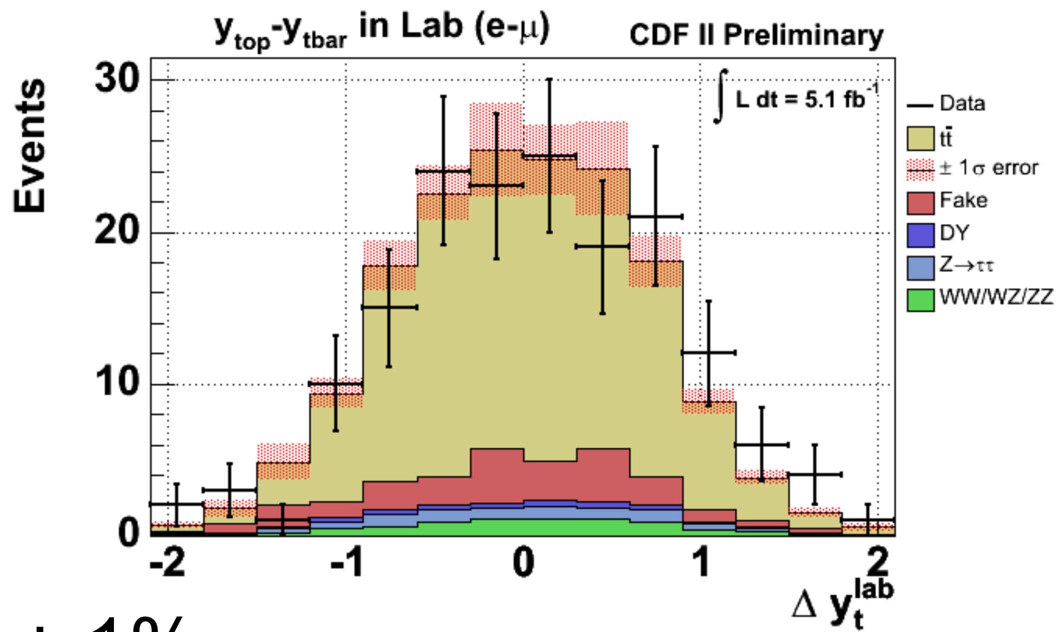
(Parton Level: corrected for reconstruction)

A_{FB}

- Dilepton Events:

A_{fb}=42 ± 16 %
(2.5σ)

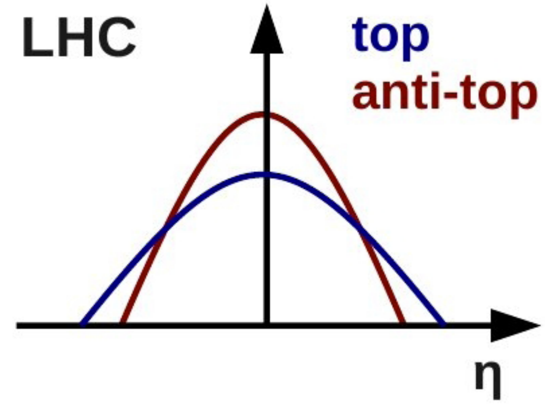
(Parton Level: corrected for reconstruction)



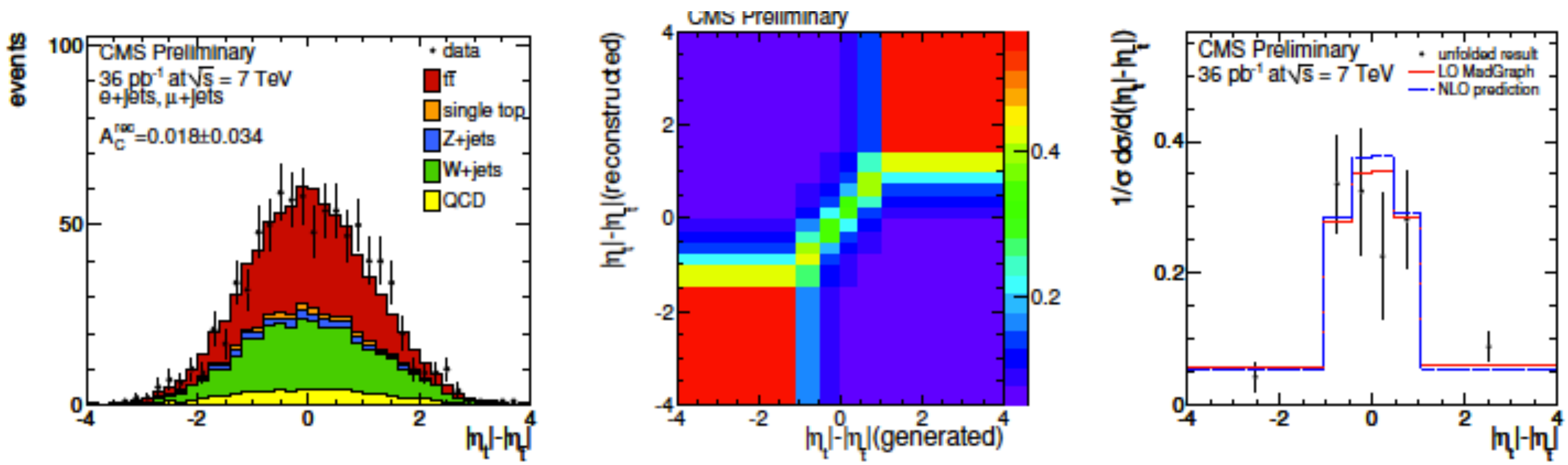
- mc@nlo prediction: 6 ± 1%

- Some tension between SM prediction and Tevatron data
- Higher order SM prediction at α_s^4?
- Soft QCD effects?
- About 2x the data is available for a closer look!

color charge asymmetry - LHC



- Initial state is symmetric
- charge asymmetry visible in $|\eta_t| - |\eta_{\bar{t}}|$
- Expected asymmetry A_C small ≈1.3%
- Z' or an axigluon could enhance the asymmetry

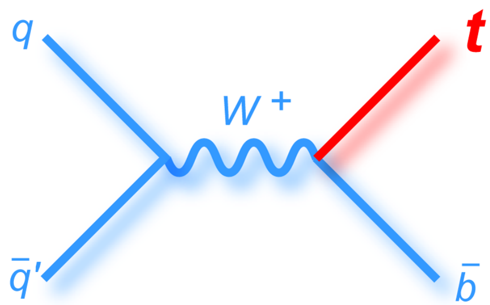


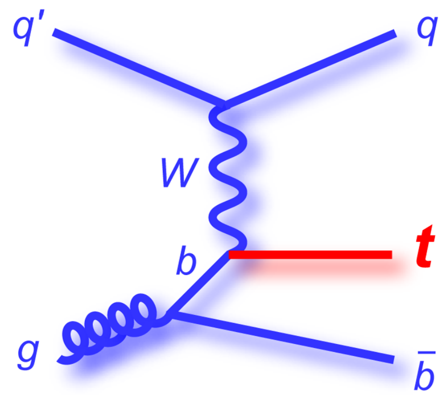
$A_C = 0.060 \pm 0.134\ (\text{stat}) \pm 0.026\ (\text{syst})$

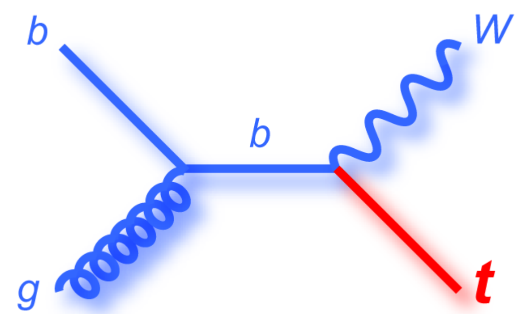
- First such measurement, & expect L = 1 fb^{-1} to start to compete with Tevatron

single top production

electroweak process







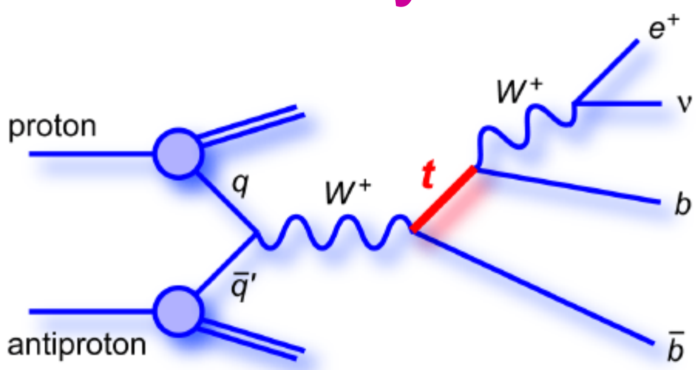
Tevatron: σ_s = 1.12 pb σ_t = 2.34 pb σ_{tW} = 0.30 pb

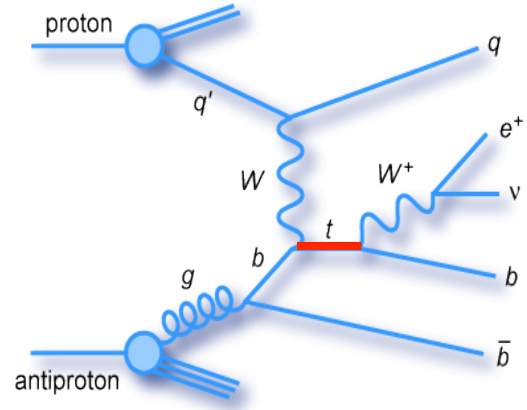
LHC(7TeV): σ_s = 4 pb σ_t = 66 pb σ_{tW} = 15 pb

- Direct Access to the W-t-b coupling (s_{st})
  - Measure V_{tb} of the CKM directly
  - CKM Unitarity
- s and t channels are sensitive to different types of new physics
  - s-channel sensitive to new resonances: W′, top pions, H^+, SUSY, etc.
  - t-channel sensitive to FCNC, 4^{th} generation, anomalous couplings
  - it is important to measure the rates independently
- Polarized top quarks
- Backgrounds to Higgs

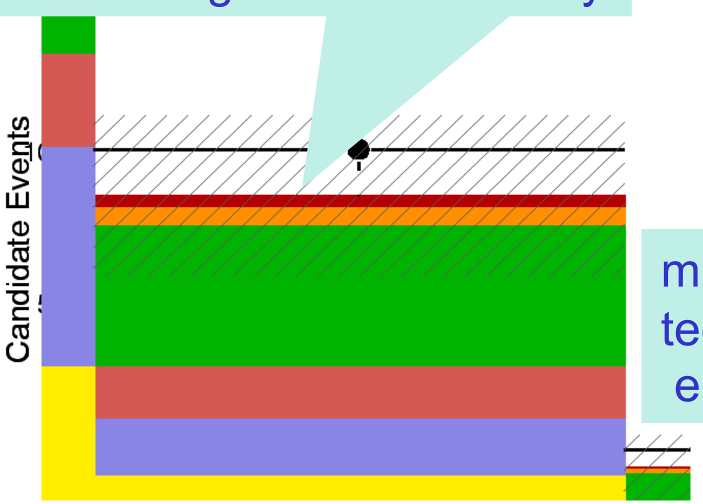
single top production

Tevatron analyses:

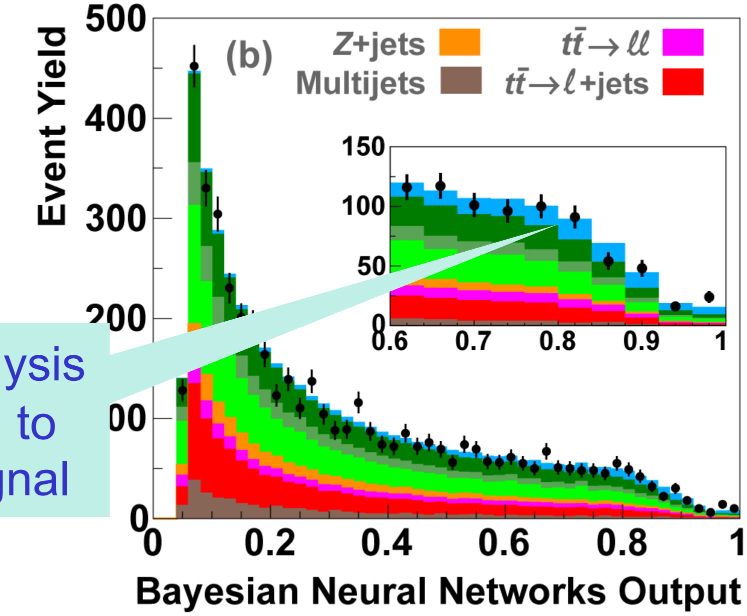




best channels S/B ≈ 1/20
Signal < background uncertainty



multivariate analysis techniques used to enhance the signal

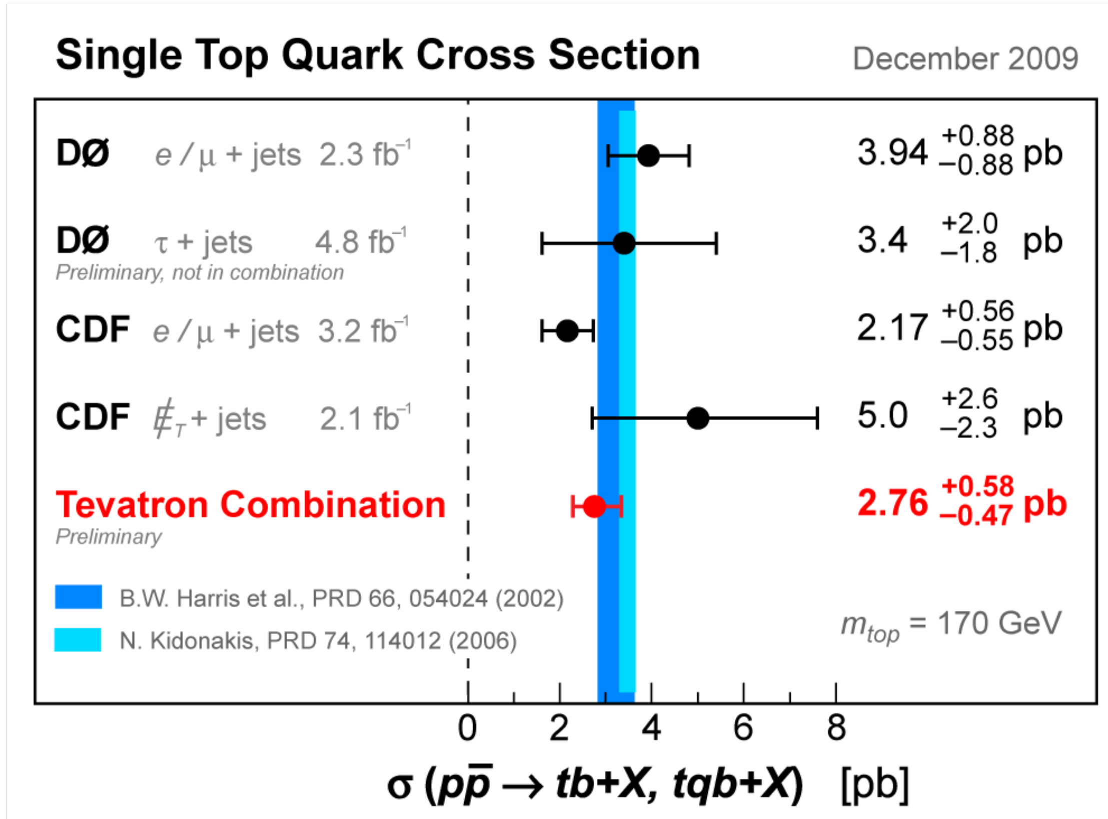


single top production

- Tevatron Results until 2009:

5σ Observation with

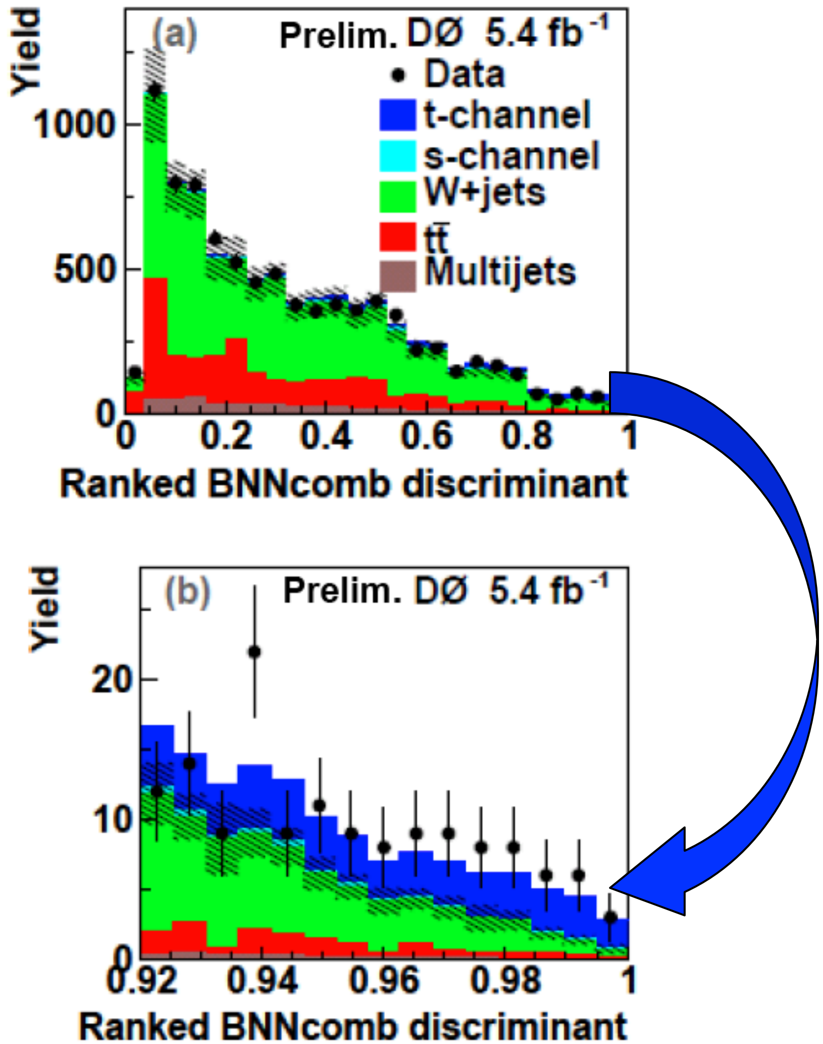
uncertainty of 22% (with 18% statistical and 13% systematics)

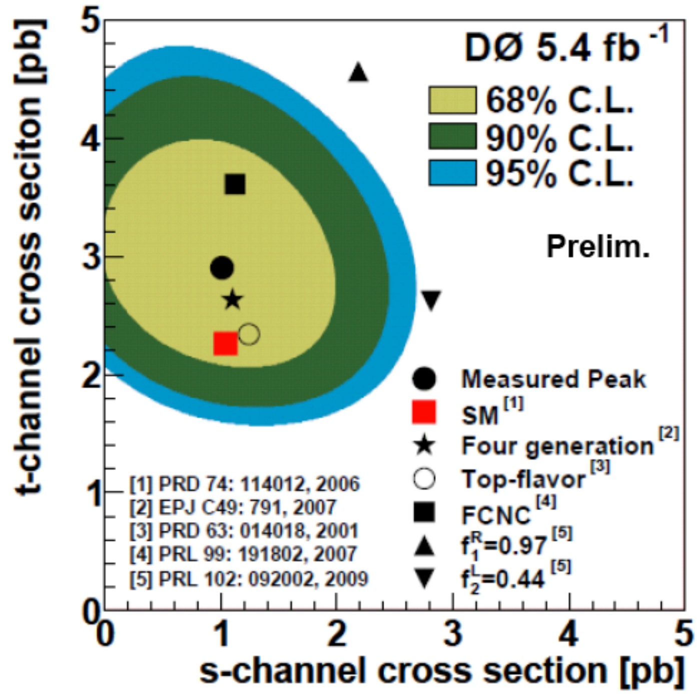


- combined s+t channel cross section measurements.

t-channel cross section measurement

- new analysis by Dzero



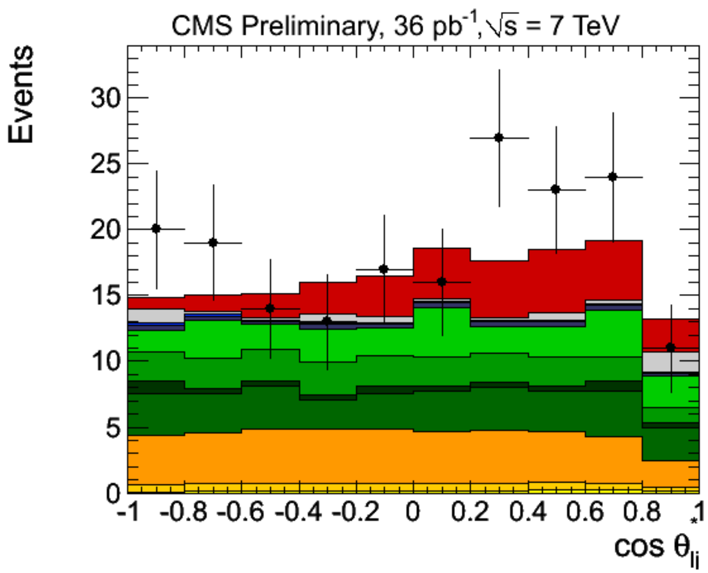


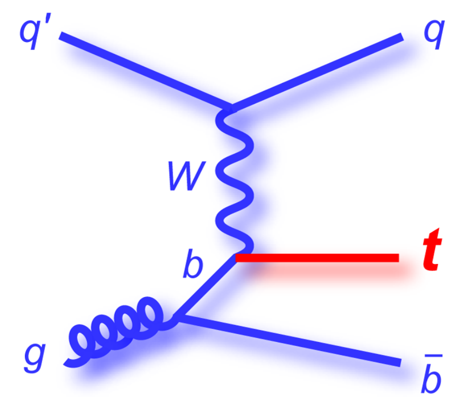
$\sigma_t = 2.9 \pm 0.6$ pb

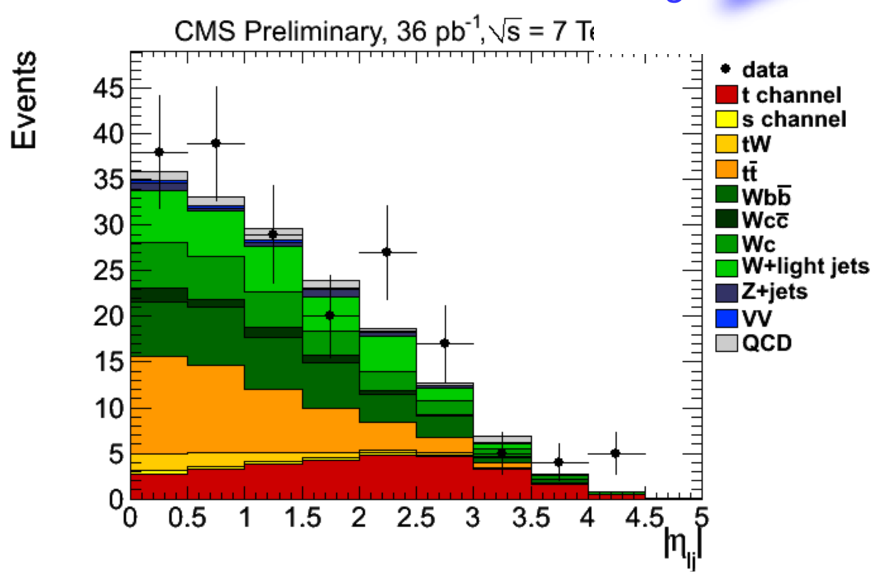
$\sigma_s = 0.98 \pm 0.6$ pb

t-channel single top production: LHC

- Identify variables representing the characteristics of single top
- Extract signal yields by fits to 2D spectra cosθ* vs η (jet) or
- multivariate techniques: Likelihood ratios, Boosted Decision Trees







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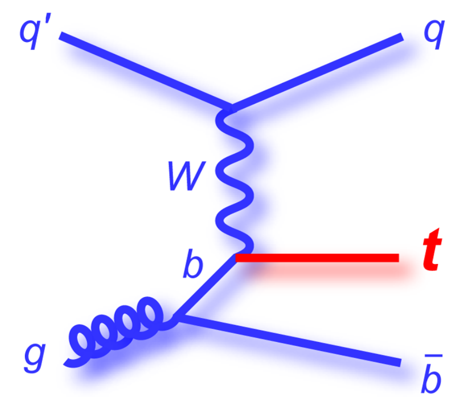
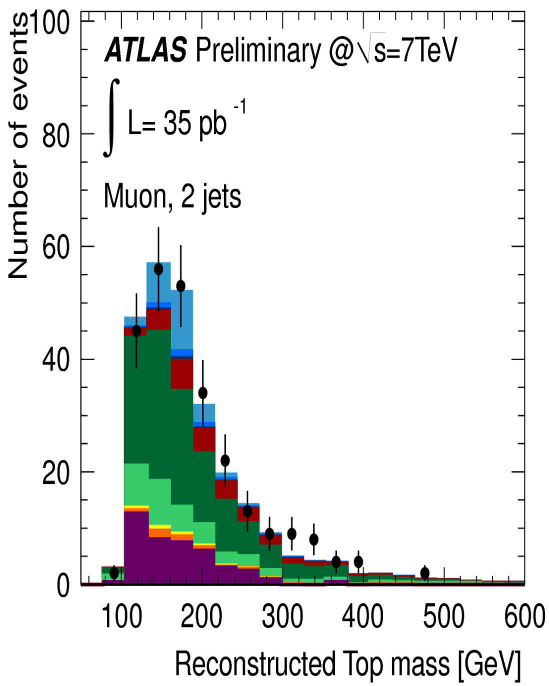
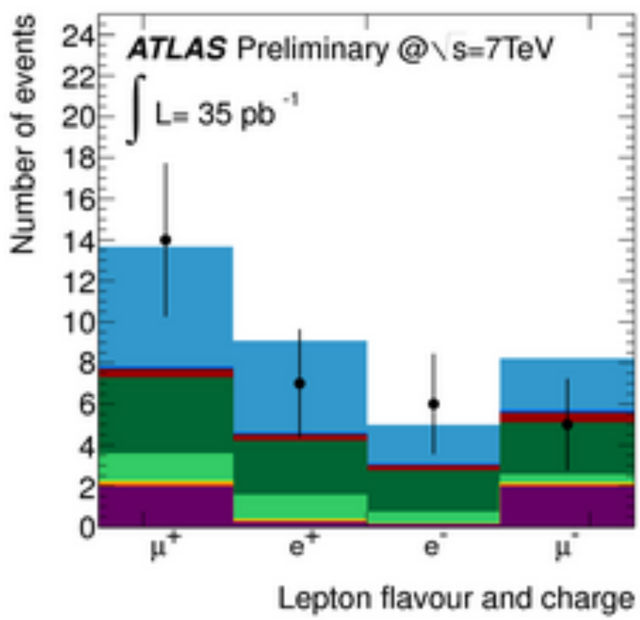
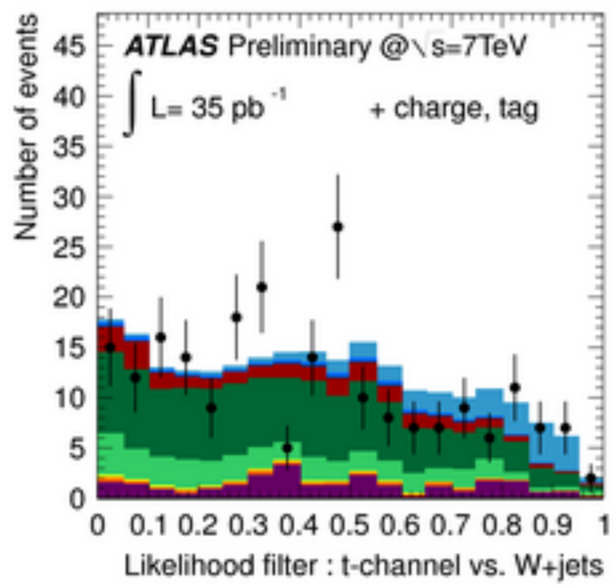




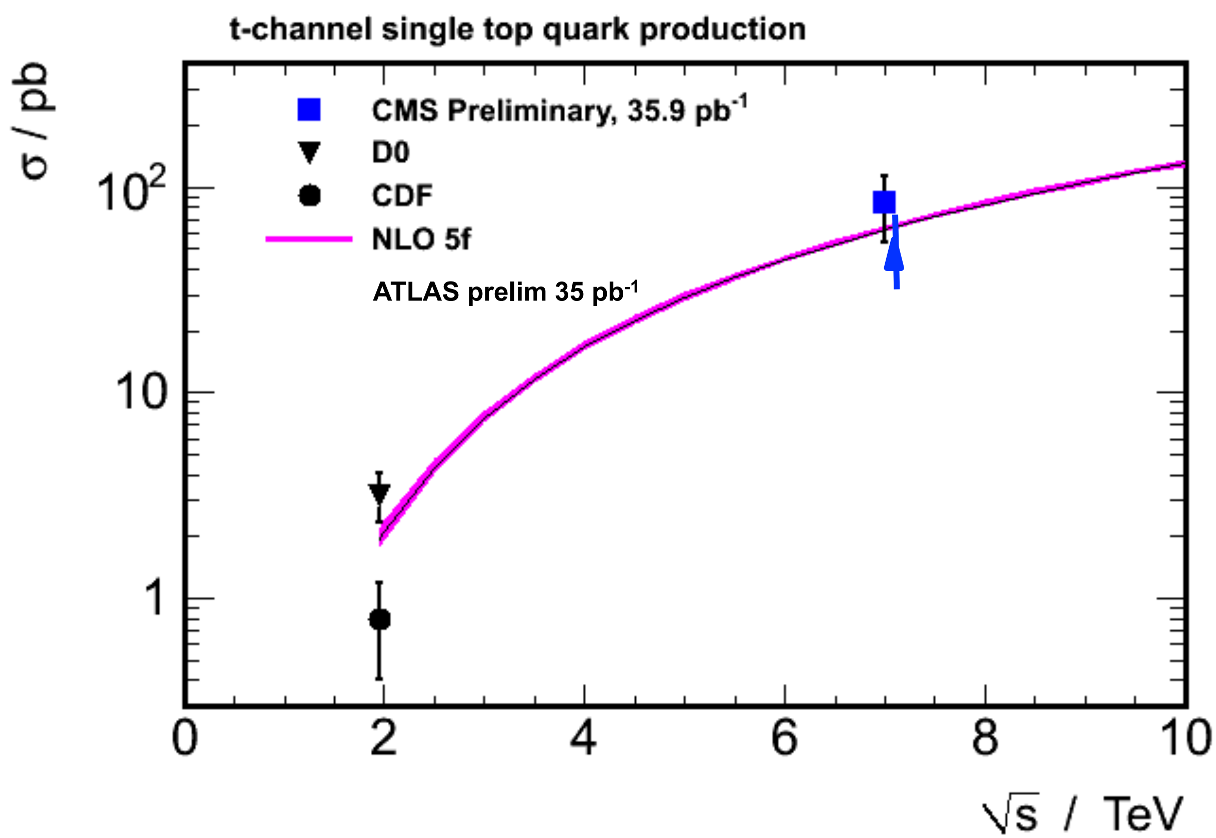




single top production:

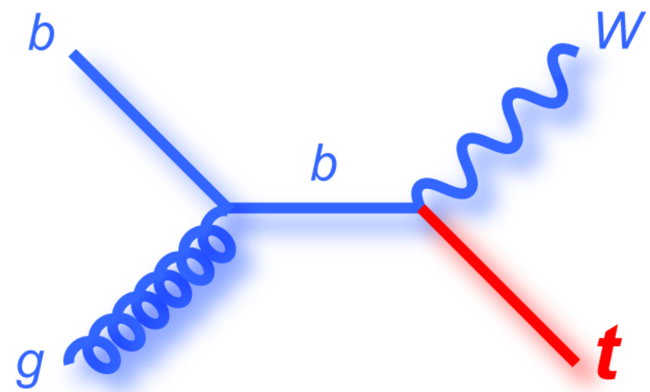
- t-channel cross section measurement

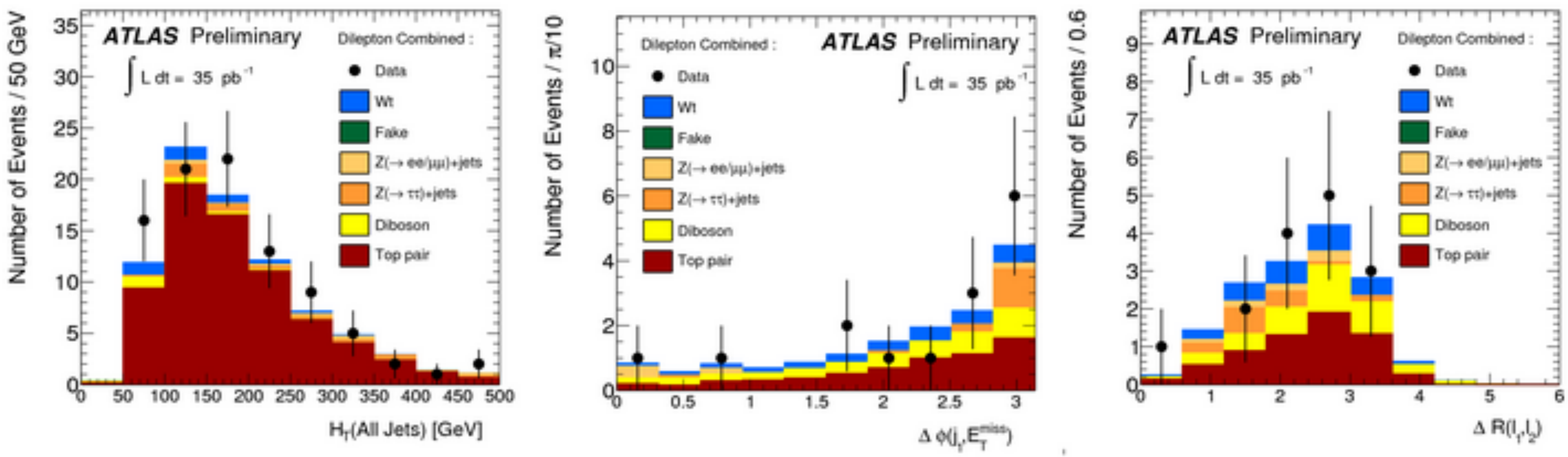
ATLAS: $\sigma_t = 53^{+27}_{-24}$ (stat) $^{+38}_{-27}$ (syst) pb
CMS: $\sigma_s = 83.6 \pm 29.8$ (stat+sys) ± 3.3(lumi) pb



single top production

- associated Wt production:
  - lepton+jets & dilepton events



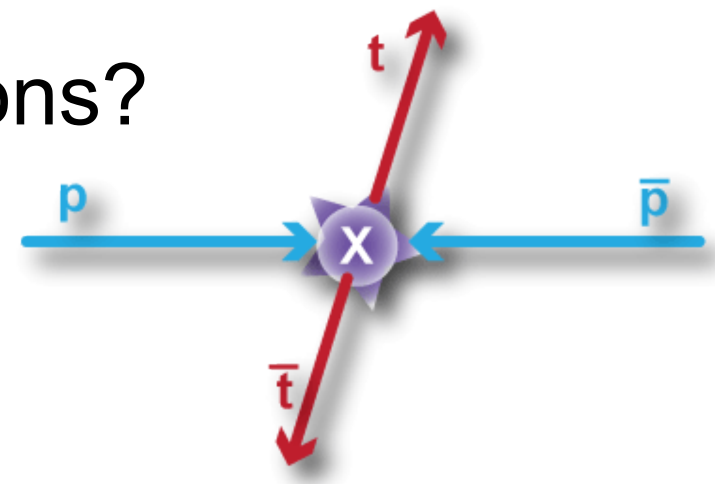


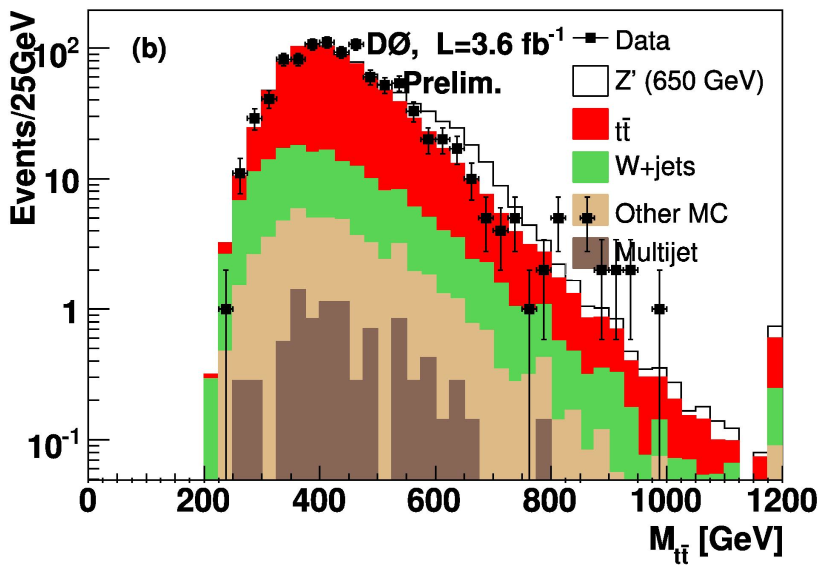
σ_{tW} <158 pb @95% C.L.

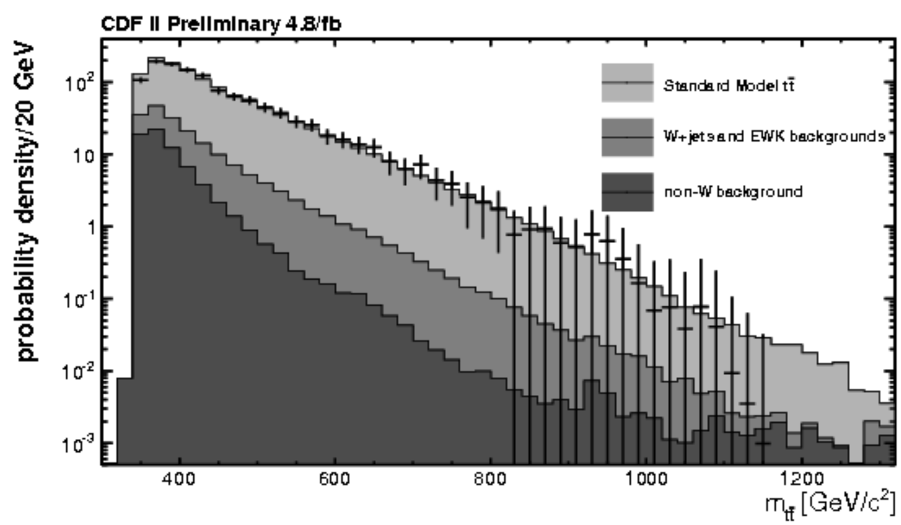
  - First study of this channel

top production via a resonance?

- technicolor Z', massive gluons?
- Reconstruct mass of ttbar







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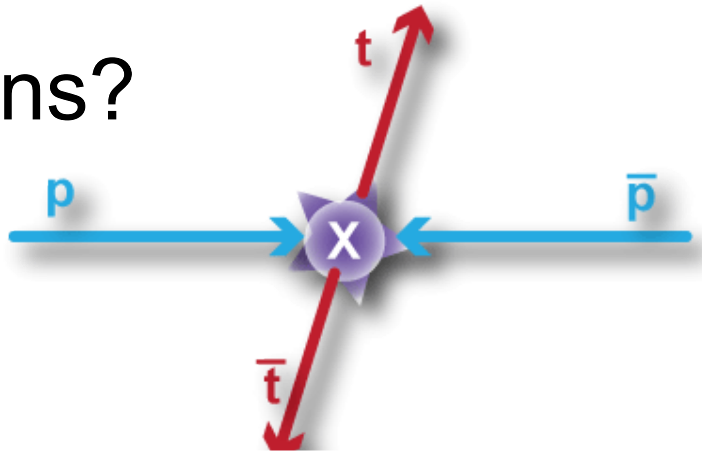
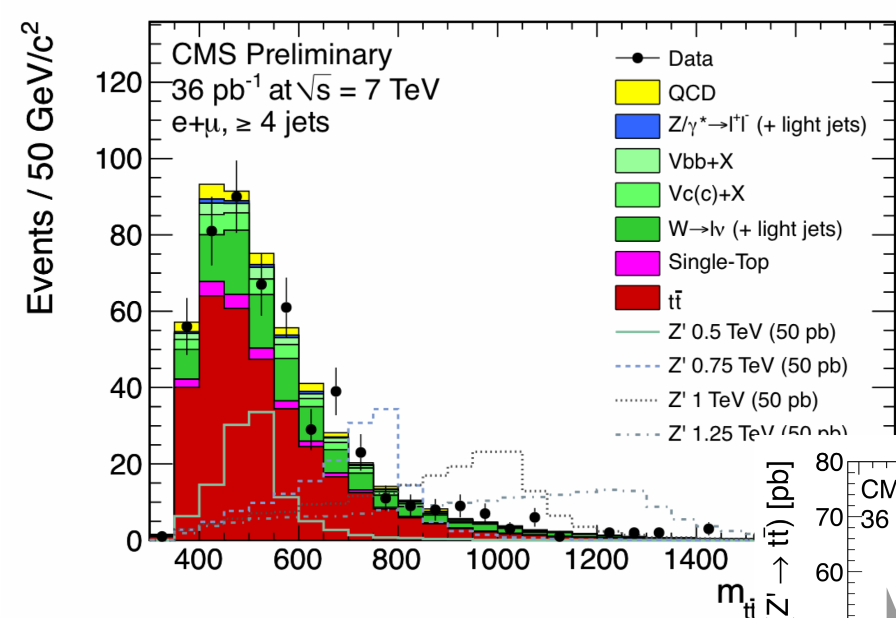
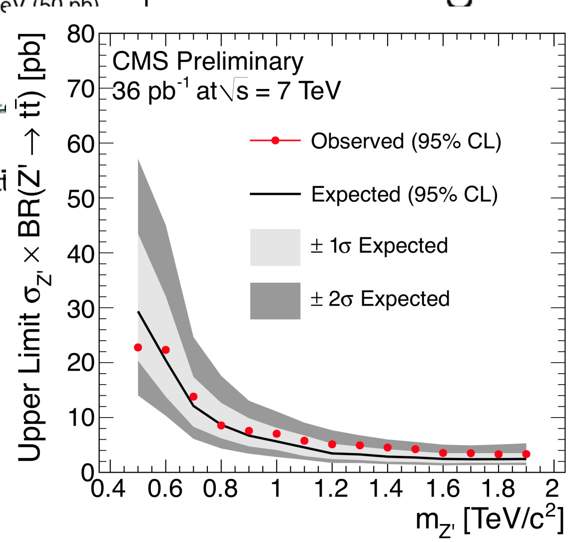
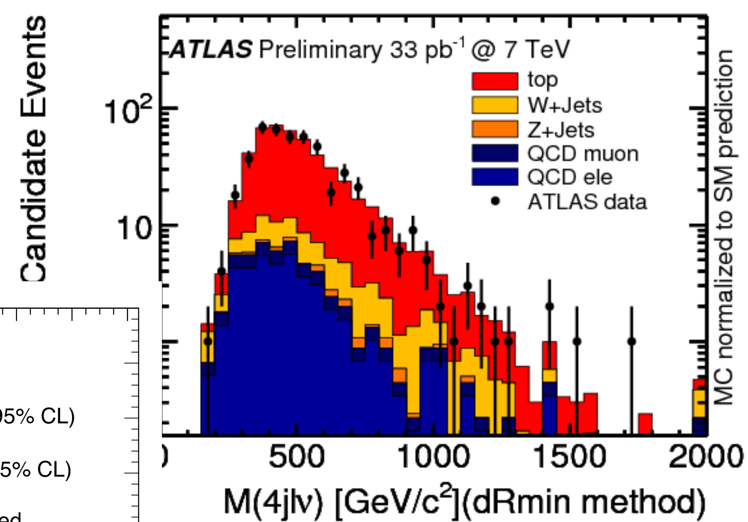


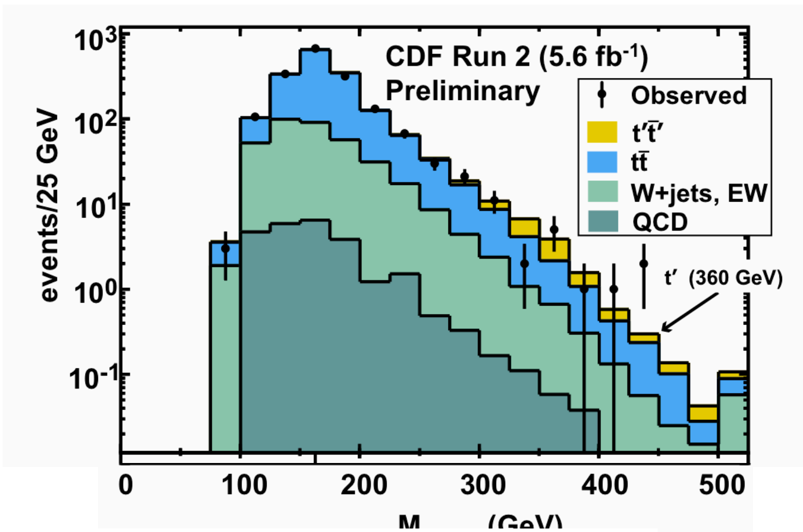


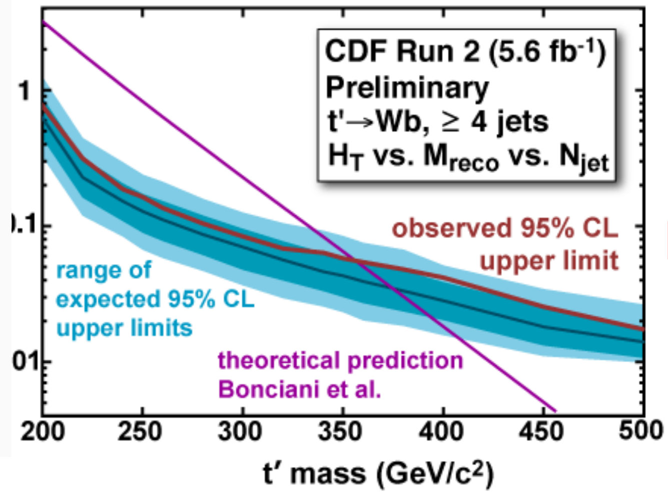




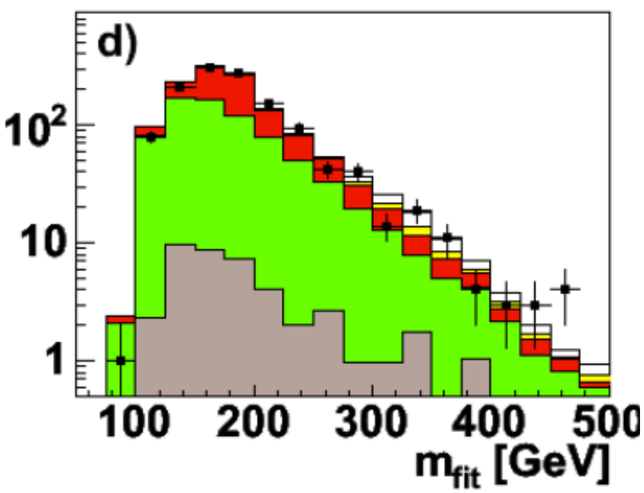
signatures which mimic top

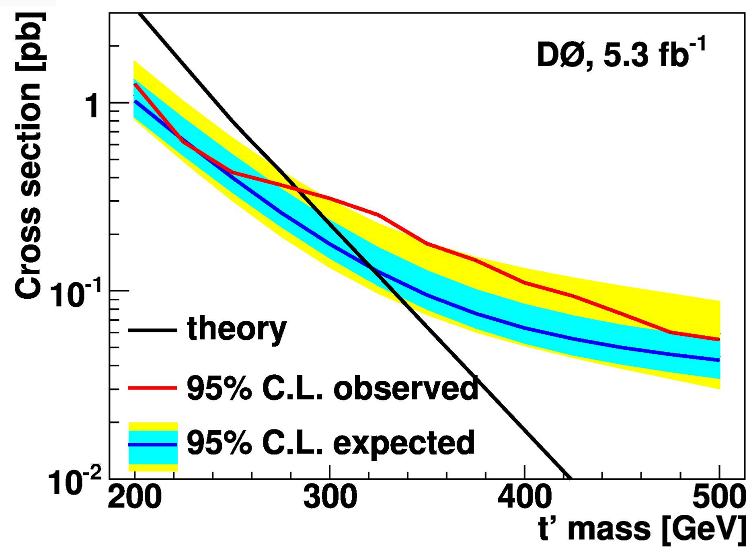
- t' search at the tevatron





Mass t′ > 358 GeV
(@95% C.L.)





Mass t′ > 285 GeV
(@95% C.L.)

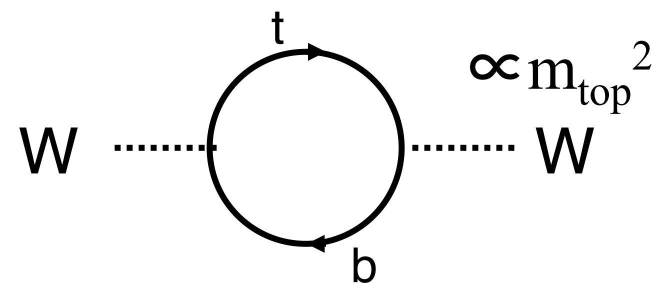
Top Properties:

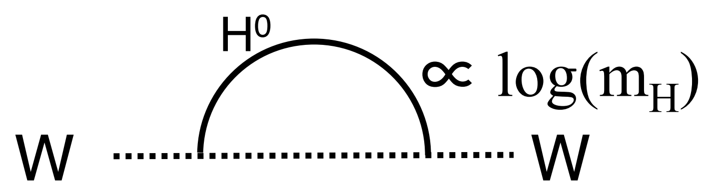
- Top Mass
- Mass (t v. tbar)
- Charge of Top Quark

- Top Quark Width

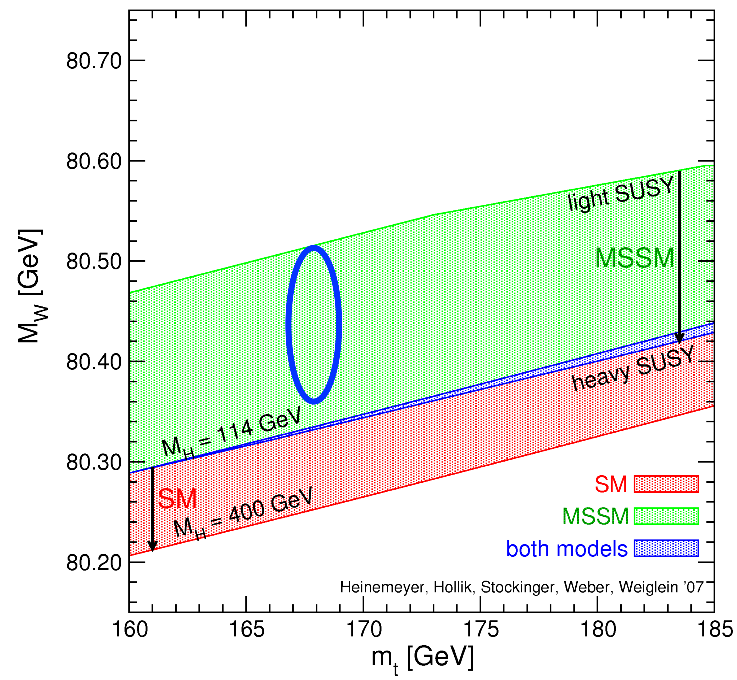
top quark mass measurement

- why is it important?
- most massive elementary particle
  - dominant contributor to radiative corrections





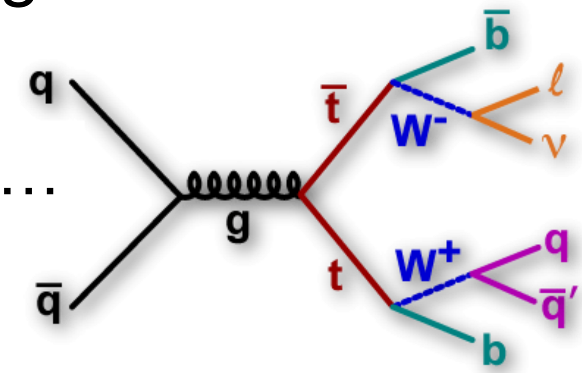
  - how is its mass generated?
    - topcolor?
  - does it couple to new physics?
    - massive G, heavy Z', H^+, …
- need to know the mass precisely.
  - Different influence in different final states?
  - Check consistency across channels.



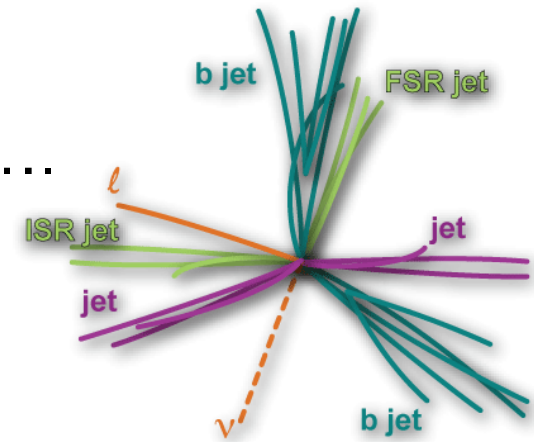
top quark mass measurement

- Challenges and Solutions:

From theory…



to reality….

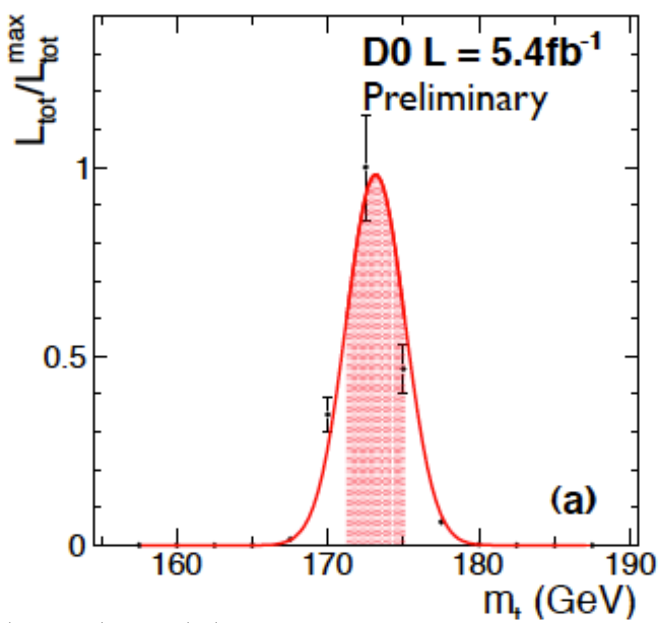


- Jet energy scale: ±2%ΔJES ~ ±2GeVΔm_t
  – in-situ JES by using the constraint from hadronic W mass, can be done in l+jets and all hadronic channels, not in di-lepton channel alone.
  – look at quantities insensitive to JES, e.g. lepton p_T.
- Jet-parton match: n_{jet}! Permutations
  – b-jet ID helps reducing the number of permutations.
  – kinematic fitter to pick up the permutation(s) with best X^2

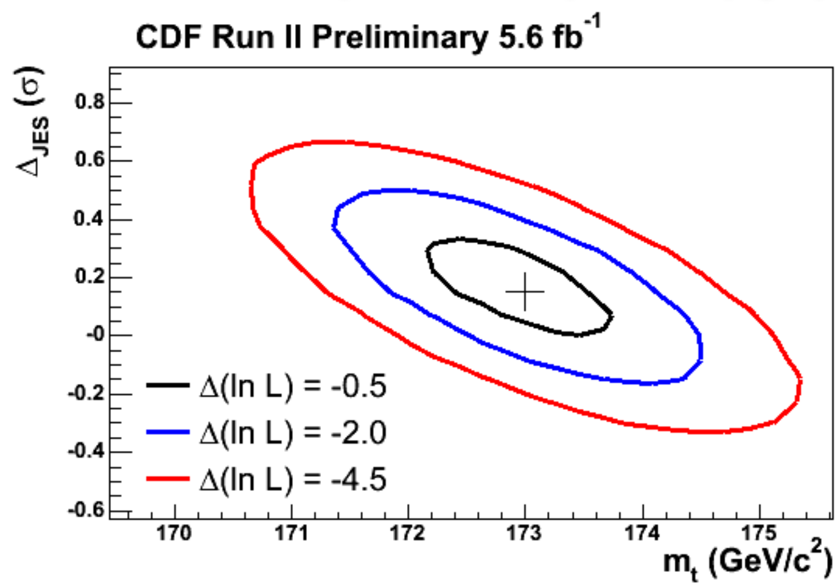
Tevatron

- Most precise measurements obtained using the Matrix Element technique
- For lepton+jets use the 2D fit in the Mtop and JES plane

D0 (dilepton events) m_{top} = 174.0 ± 1.8 (stat) ± 2.4 (sys) GeV



CDF (lepton+jets events) m_{top} =173.0 ± 0.9(stat+JES) ± 0.9(sys) GeV

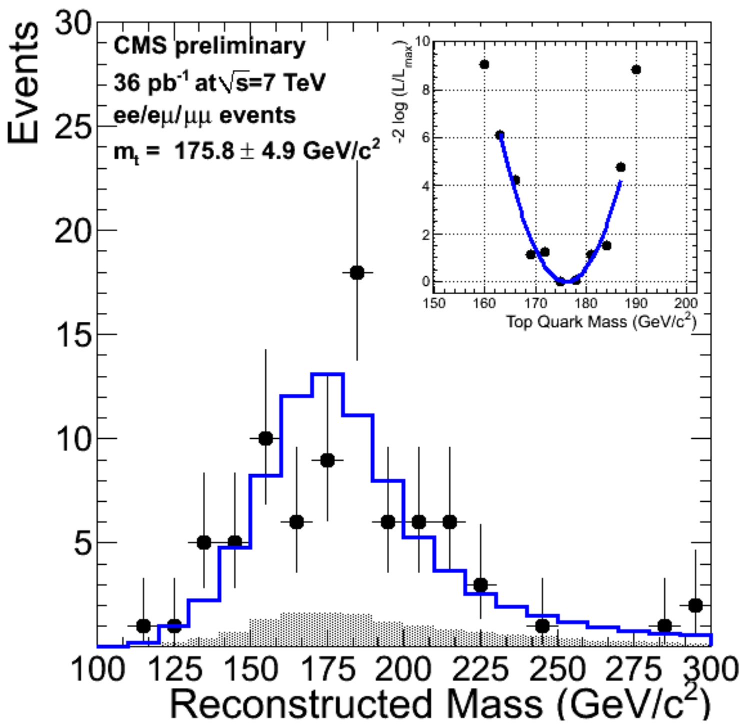


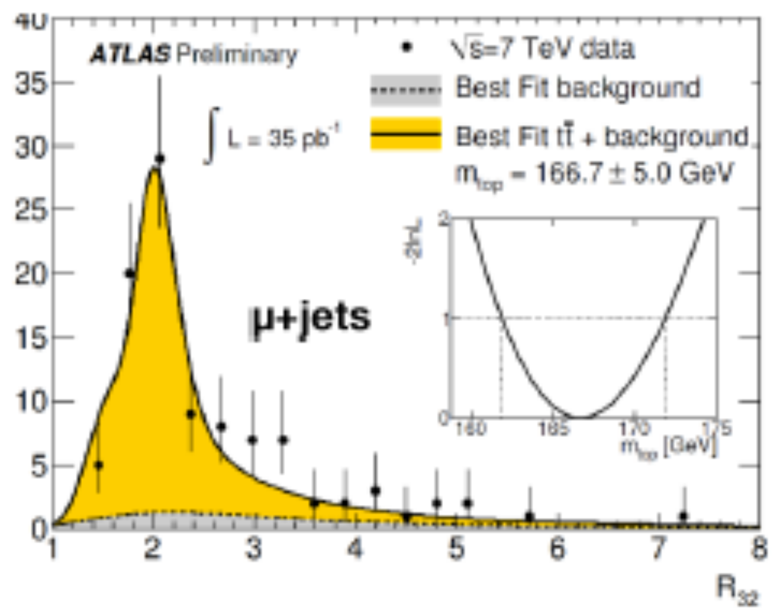
LHC

- First measurements of the top mass @LHC
- Template Fits
- Lepton+Jets $R_{32} = M_{jjb}(t)/M_{jj}(W)$
- Dilepton: reconstruct most likely mass for the event

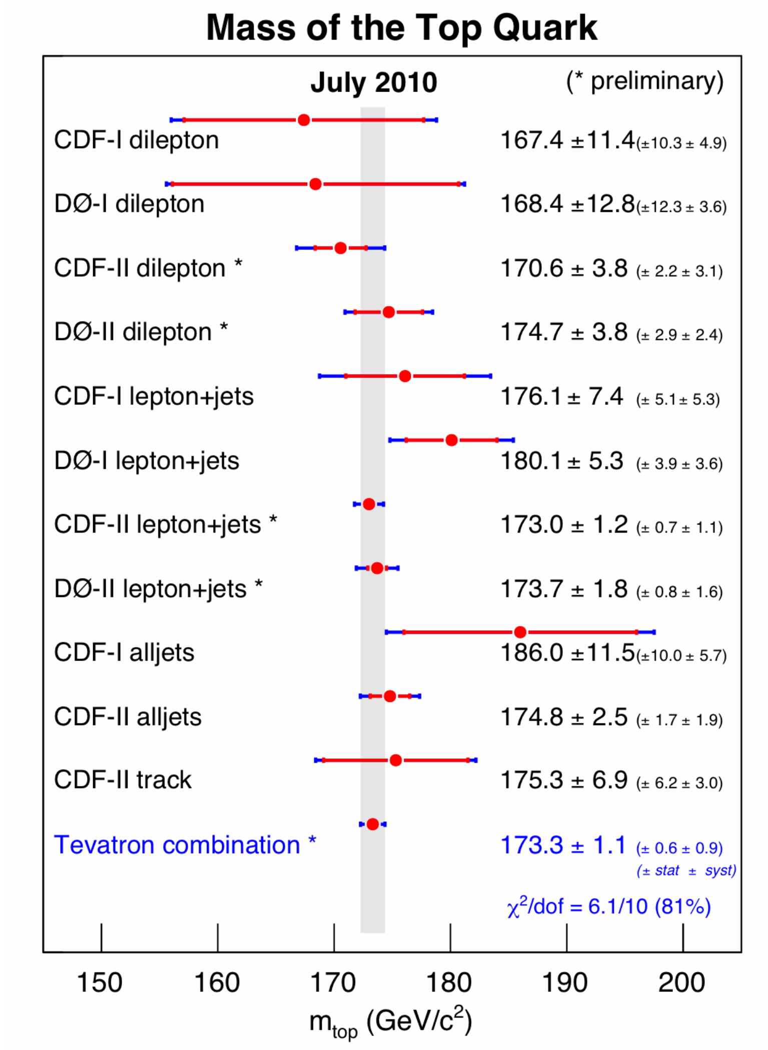
CMS:
m_{top} =175.5 ± 4.6(stat) ± 4.6(sys) GeV

ATLAS
m_{top} =169.3 ± 4.0(stat) ± 4.9(sys) GeV





Tevatron Summary

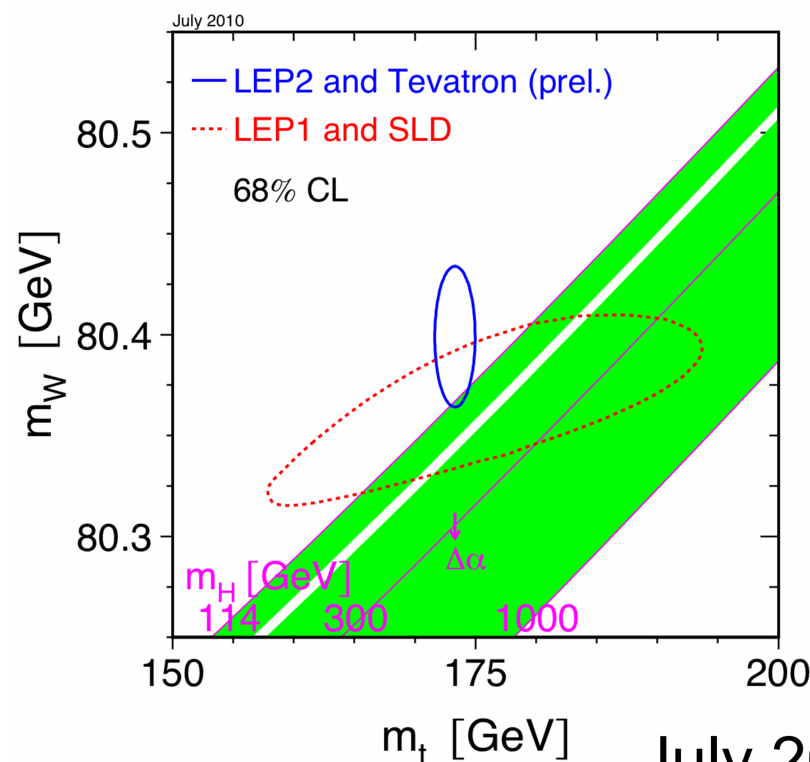


CDF winter'11

m_{top} =172.7 ± 0.6(stat) ± 0.9(sys) GeV

D0 winter '11

m_{top} = 175.2 ± 0.6(stat) ± 0.9(sys) GeV

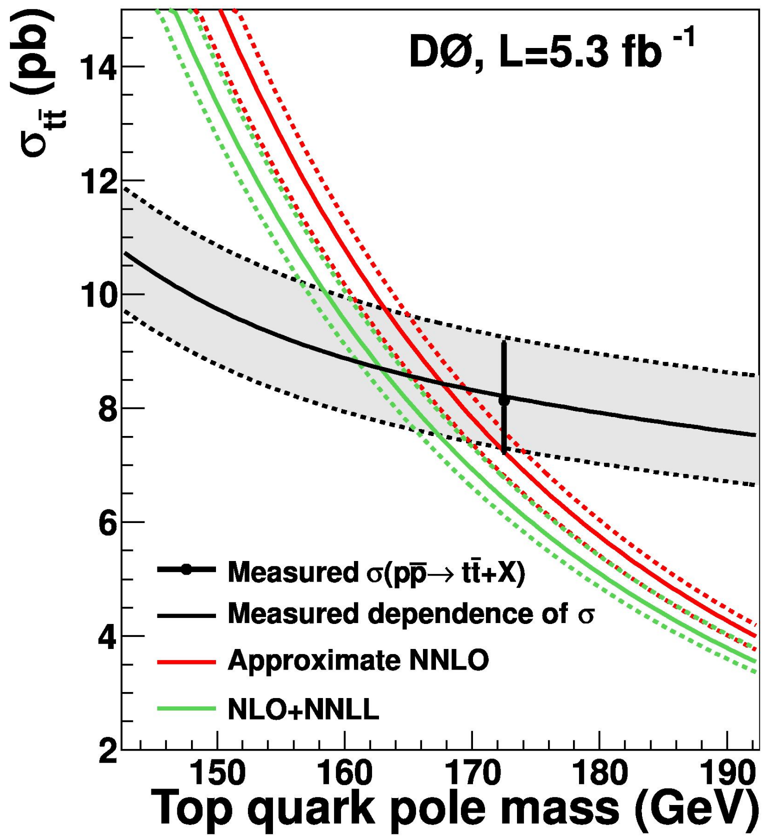


Δm/m<0.6%

July 2010

mass from cross section

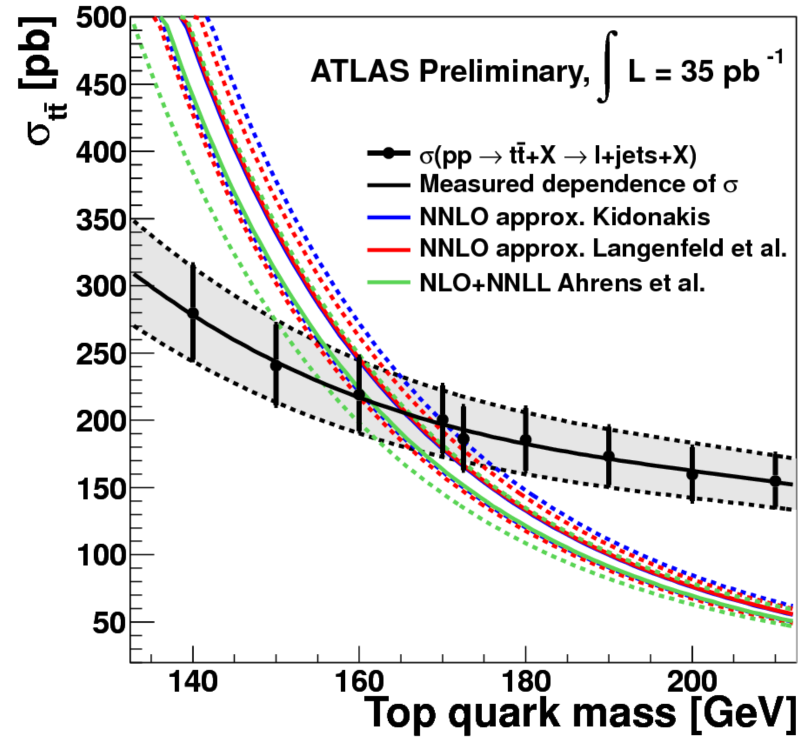
- Quark masses depend on the renormalization scheme.
- Direct measurements use LO MC with parton shower to extract the mass from data
  - The renormalization scheme is not well defined.
- Is the mass from direct measurements (ie MC) the pole mass?
- compare with theory and across channels.
  - Extracted mass agrees with MC/ pole mass measured average within ~1σ



$$M_{top} = 167.5\ ^{+5.4}_{-4.9}\ (stat + sys)\ \mathrm{GeV/c^2}$$

mass from cross section

- Quark masses depend on the renormalization scheme.
- Direct measurements use LO MC with parton shower to extract the mass from data
  - The renormalization scheme is not well defined.
- Is the mass from direct measurements (ie MC) the pole mass?



$$M_{top} = 166.4\ ^{+7.8}_{-7.3}(stat + sys)\ \mathrm{GeV/c^2}$$

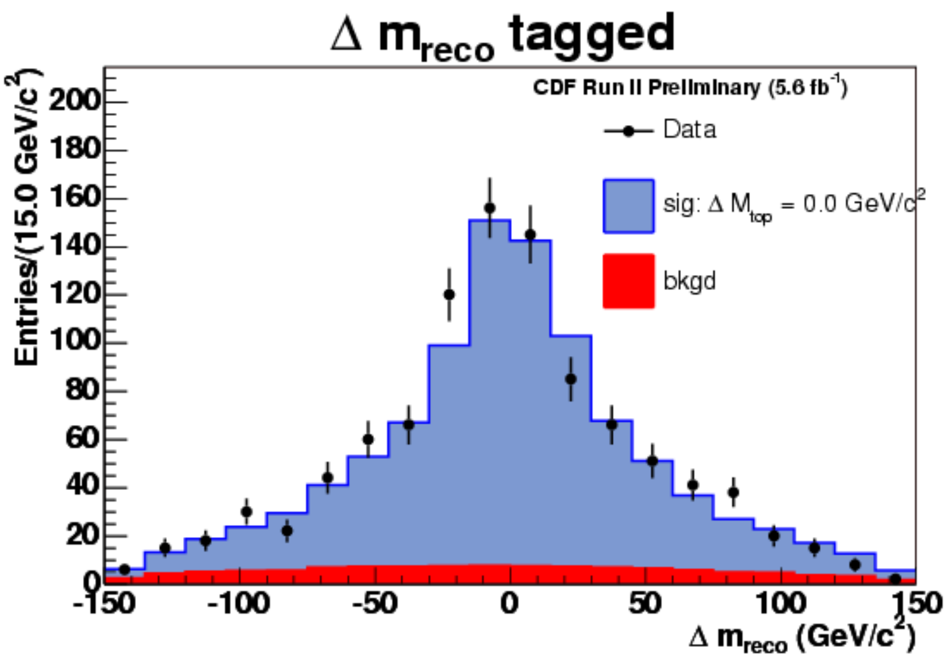
- compare with theory and across channels.
  - Extracted mass agrees with MC/ pole mass measured average within ~1σ

mass (top) vs mass (anti-top)

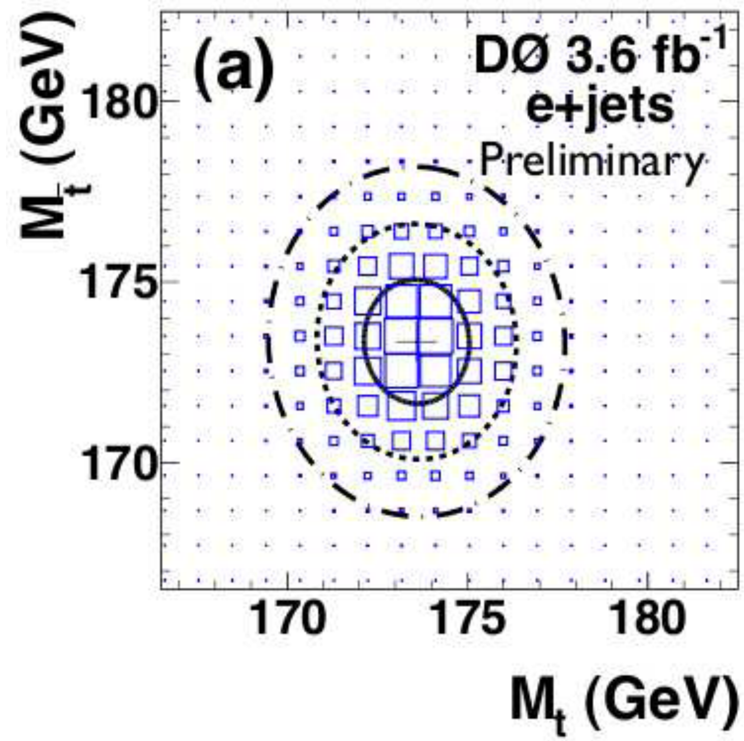
- Test of CPT invariance

CDF: Δm_{top} =
-3.3 ± 1.4(stat) 1.0(syst)GeV

D0: Δm_{top}
= 0.8 ± 1.8(stat) 0.8(syst)GeV

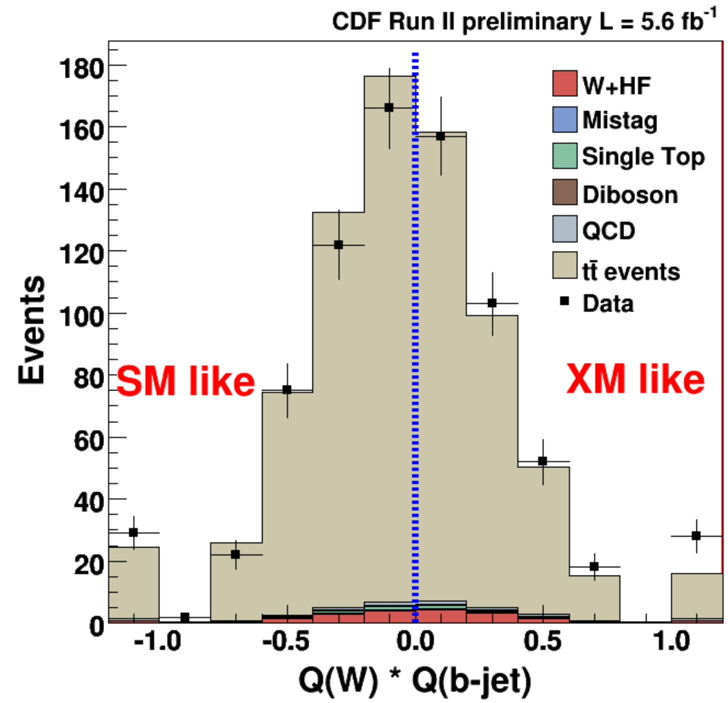


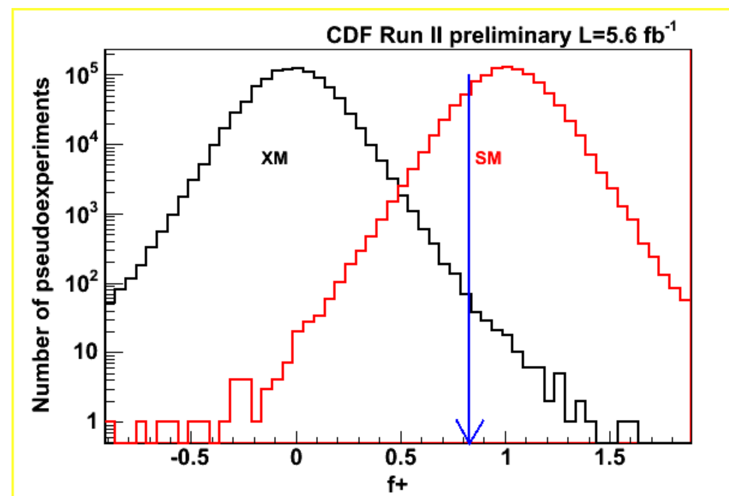
2σ effect ?



top quark charge

- is it
  - $t \rightarrow W^+ b$ (Q_{top} = 2/3 e)
  - $t \rightarrow W^- b$ (Q_{top} = -4/3 e)
- Exotic model
  - doublet (–1/3e,–4/3e) ?
  - D. Chang et al., PRD59 (1999) 091503
- pair W's & b's using kinematic fit
- determine charge of b-jet
- plot Q_W x Q_b
- D0 PRL 98, 041801 (2007)
  - 4/3e excluded at 92% CL
  - fraction of exotic quark pairs < 0.80 (90% CL)
- CDF result with 5.6/fb
  - p-value for SM: 0.33
  - p-value for XM: 1.4×10^{-4}
  - exotic model XM excluded with 95% CL





top decays:

- W helicity (V-A)
- FCNC

- Spin correlations
- Color Flow

top quark coupling

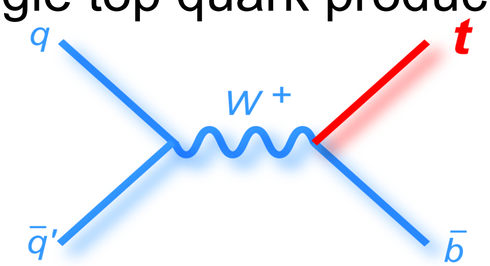
- if top plays a special role in ewk symmetry breaking its couplings to W bosons may differ from predictions
  - modifications to top quark interactions, in particular with weak gauge bosons, could yield the first signs of new physics
- most general CP-conserving W-t-b vertex involves four couplings

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

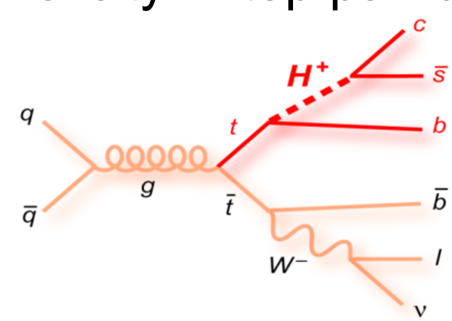
where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

- probing tWb vertex:

Anomalous couplings in single top quark production and decay



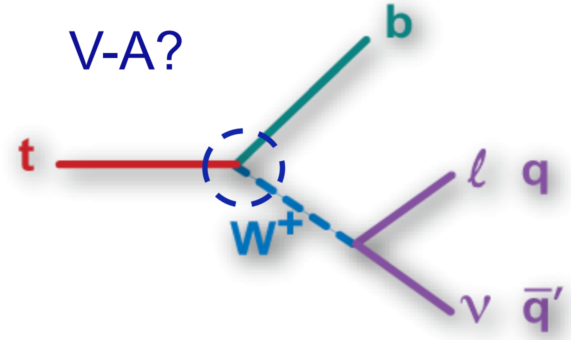
W helicity In top pair decays

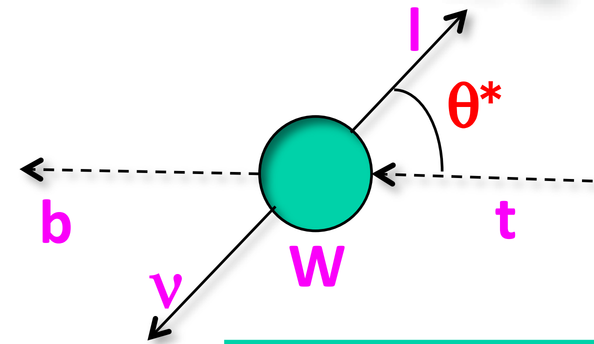


  - Both measurements can be combined to fully specify the tbW vertex

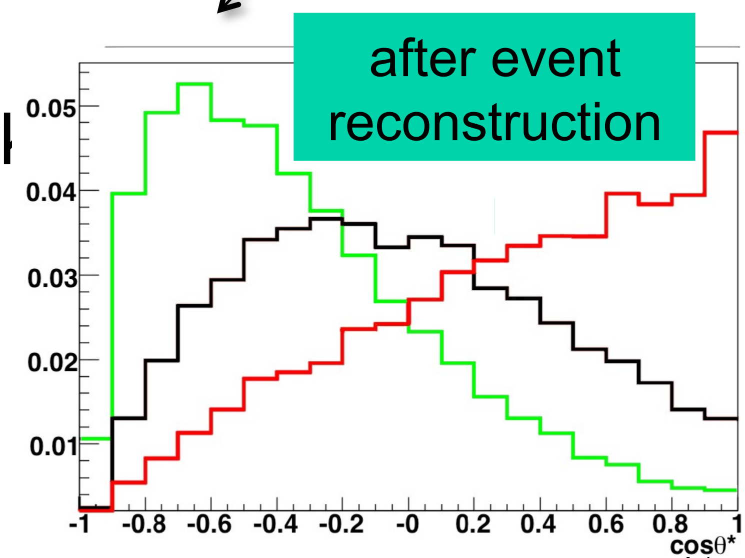
t-W-b coupling via W boson helicity

- sm predicts V-A coupling at W-t-b
  $\rightarrow$ helicity of W boson
  $F_0 = 0.7$, $F\_ = 0.3$, $F_+ = 0.0$
  (longitudinal, left-handed, right-handed)
  (V+A: F_0=0.7, F_+=0.3)



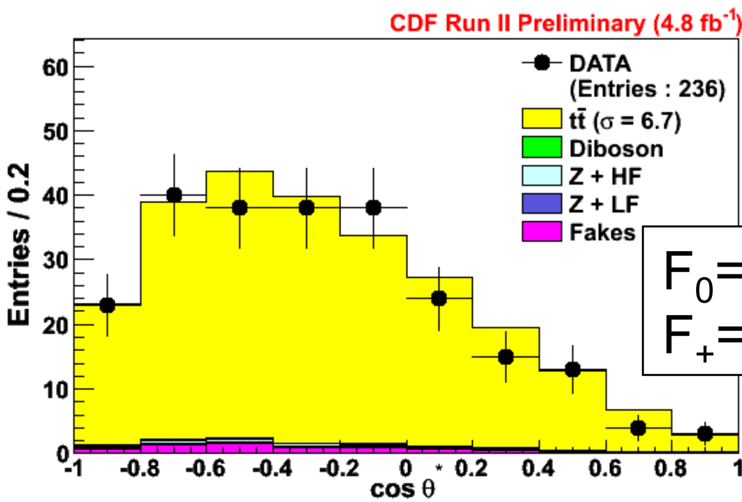


- model-independent measurement based on reconstruction of cosθ* distribution - angle between down-type fermion and top quark in the W boson rest frame
  - distribution of cos θ∗ depends on the W boson helicity fractions

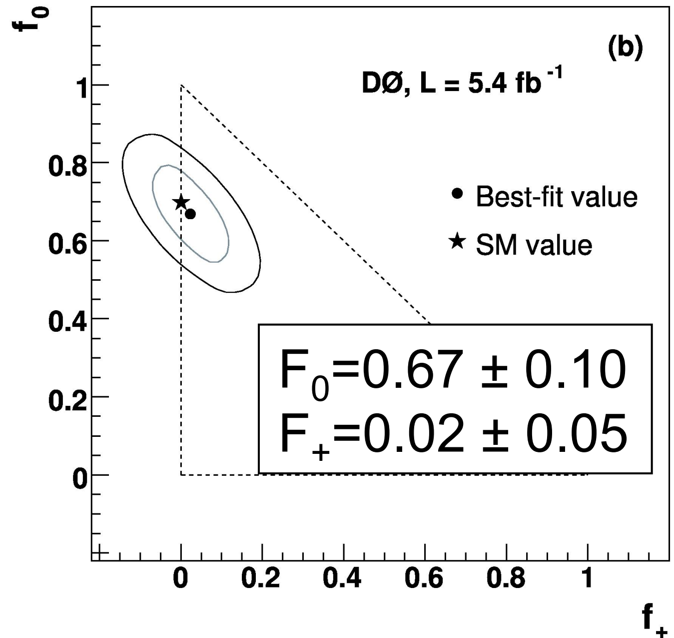


W boson helicity – what do the data tell us?

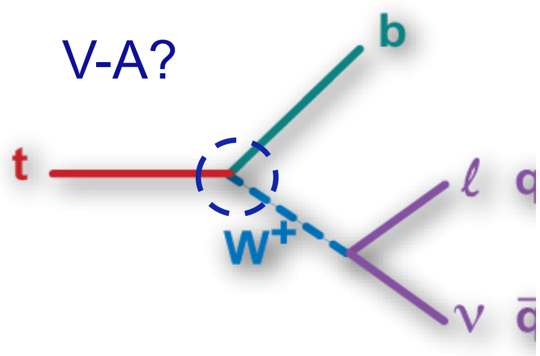
- SM: F_0= 0.7, $F_{\_}$ = 0.3, F_+ = 0.0
  (longitudinal, left-handed, right-handed)

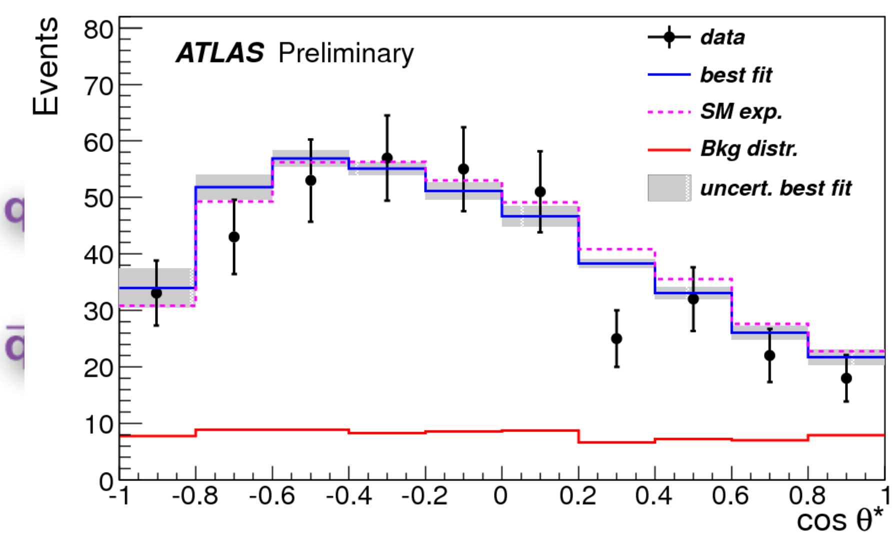


F_0=0.78 ± 0.20,
F_+=-0.12 ± 0.12



F_0=0.67 ± 0.10
F_+=0.02 ± 0.05





F_0=0.65 ± 0.15,
F_L=-0.36 ± 0.10
F_R = -0.01 ± 0.07

anomalous t-W-b couplings

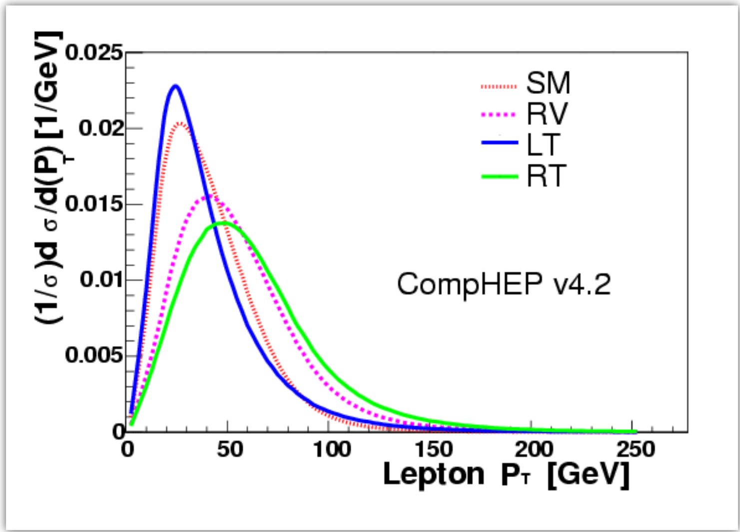
- Left & Right handed Vector and Tensor couplings

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

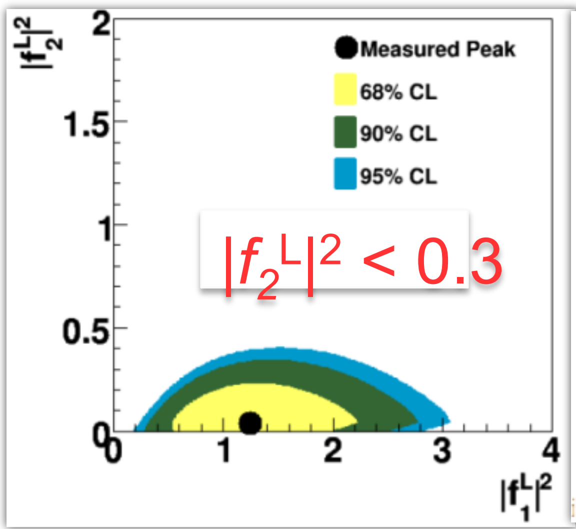
- presence of anomalous couplings changes the production cross-section, and kinematics and angular distributions

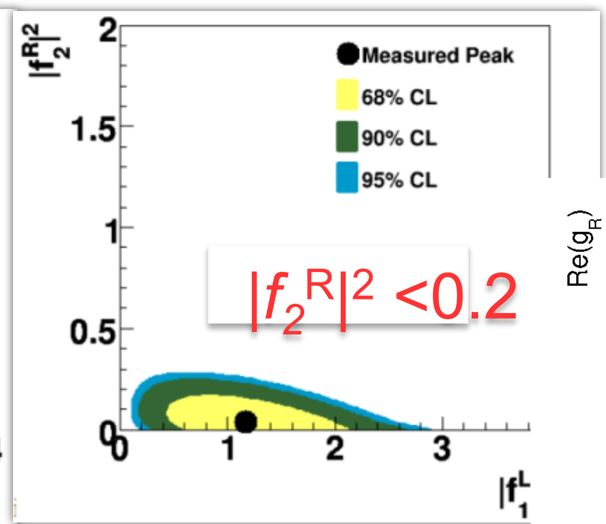
s-channel("*tb*")

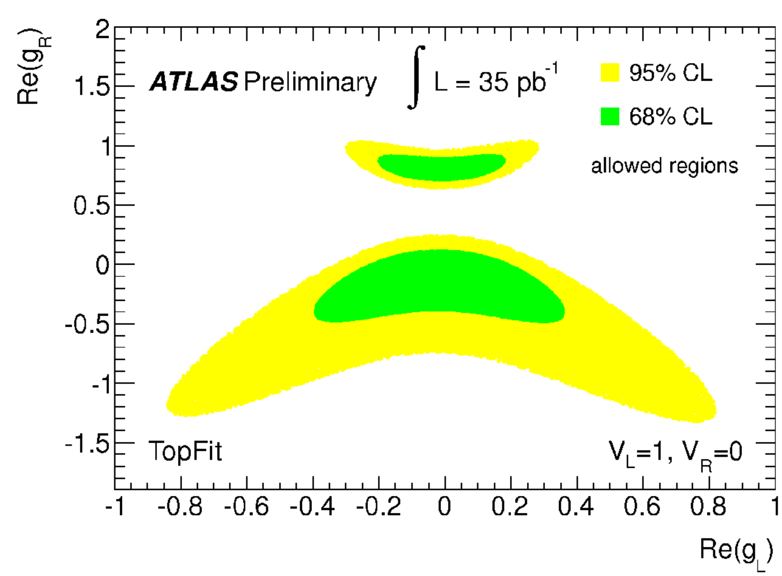


anomalous t-W-b couplings

- Limits on tensor couplings:
- Dzero analysis use single top and top pair events
- ATLAS analysis based on top pair events

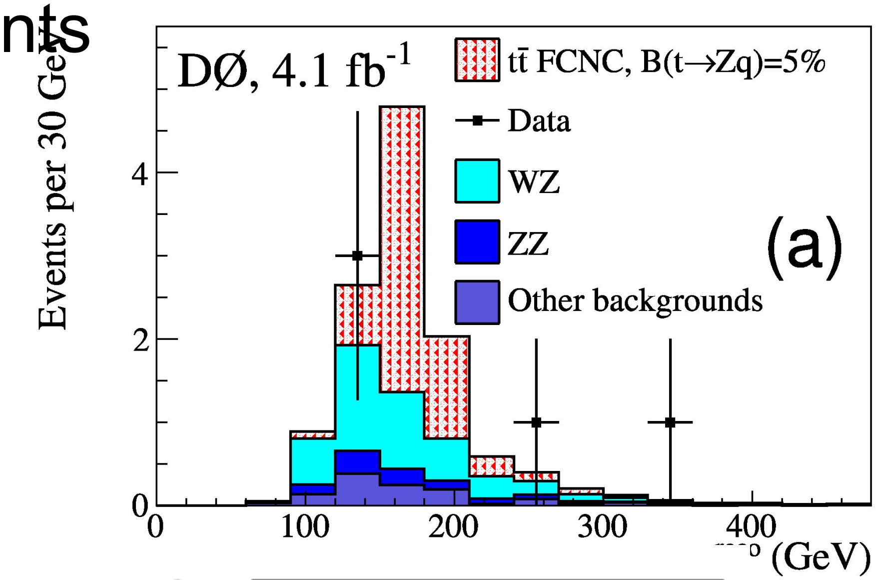


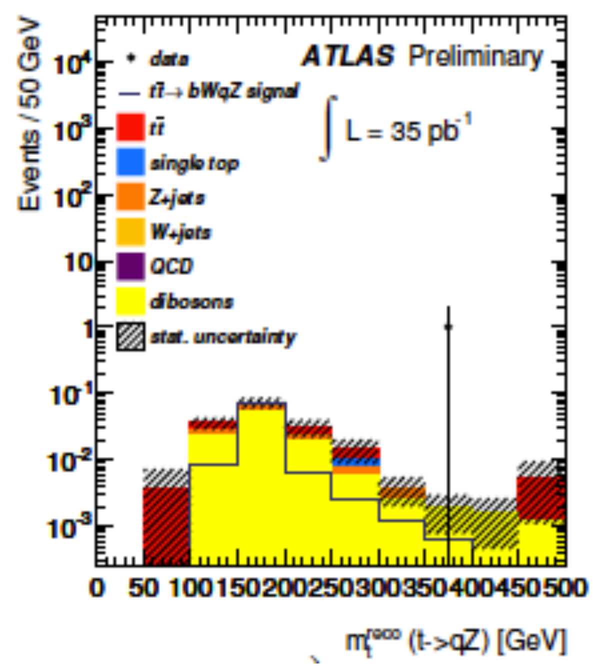




FCNC decays of top quarks

- flavor changing neutral currents
  - highly suppressed in sm
- Search for t→Zq
  - Dilepton+jets (CDF, 1.9 fb^{-1})
    - B(t→Zq) < 3.7% @ 95% CL
  - Trilepton+ missingET
    - Dzero, 4.1 fb^{-1}
    - B(t→Zq) < 3.3%
    - ATLAS
    - B(t→Zq) < 17%
- Search for qg→t→Wb
    - σxB(qg→t→Wb) <17.3
    - (all limits at 95% CL)





conclusion

- top quark physics has come a long way since 1995
- Tevatron has delivered 11 fb^{-1} @ 1.96 TeV
  - precision measurements of top quark properties
  - top quark mass measured to 0.6%
    - uncertainties below 1 GeV
- LHC is catching up quickly @ 7 TeV
  - beautiful results with 36 pb^{-1} of data from 2010
  - almost 0.5 fb^{-1} in hand → competitive results very soon
- top production/properties generally consistent with SM
  - some intriguing deviations
    - charge A_{FB}
    - t' search

thank you

and many thanks to Tevatron and LHC collaborations