Recent Top Physics Results from the Tevatron

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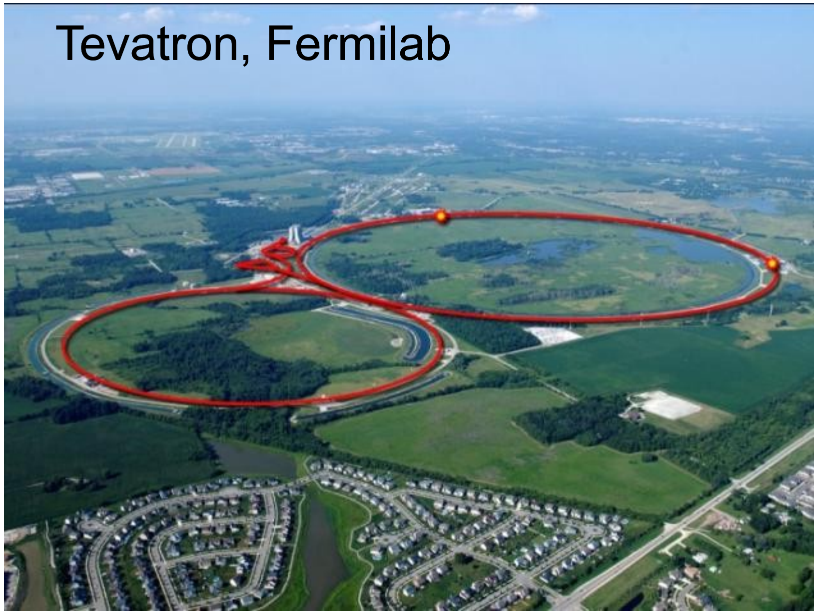
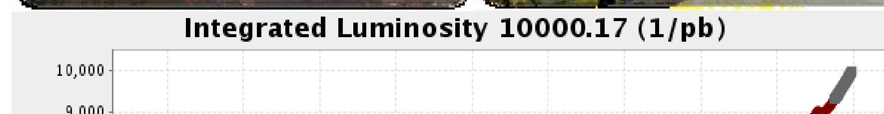
On behalf of the CDF and D0 Collaborations

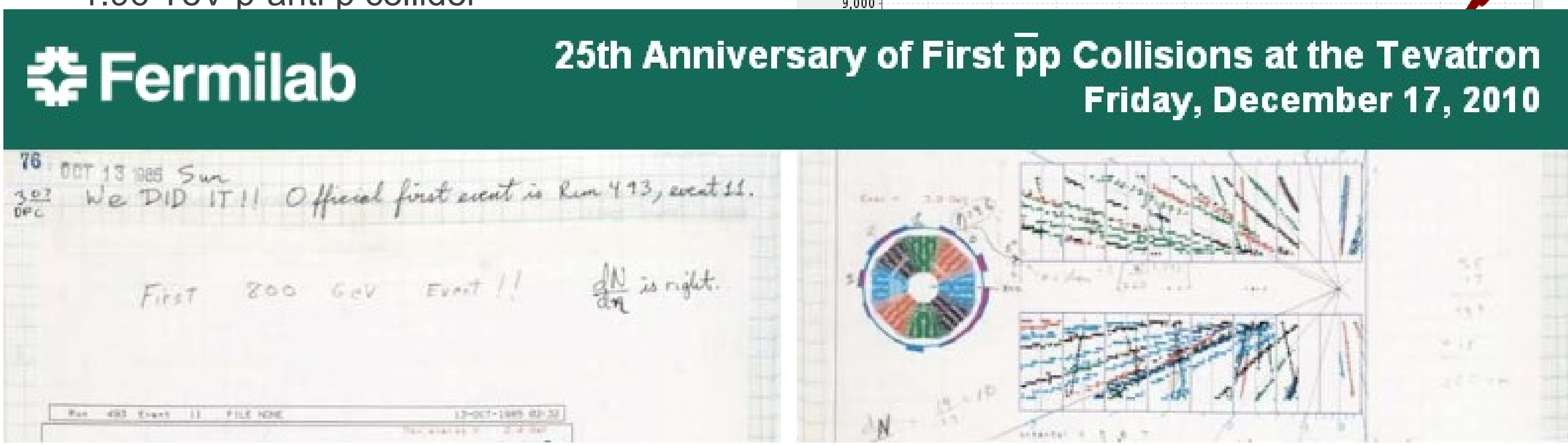
Photo by Reidar Hahn
Artwork by Jan Lueck

The Tevatron Collider





- 1.96 TeV p-anti p collider

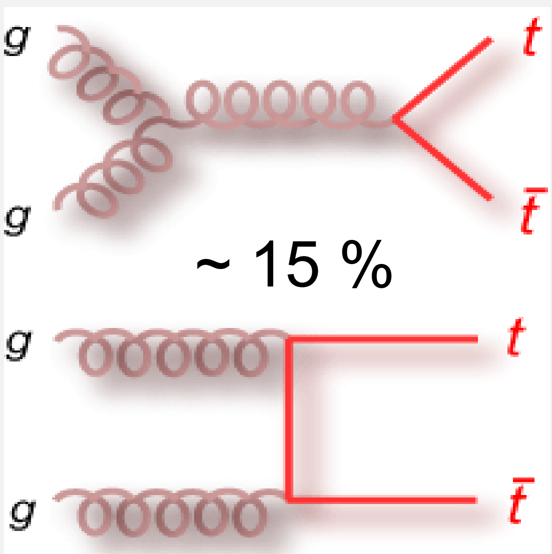


Top Quark Production at the Tevatron

Production

In Pairs

~ 85 %

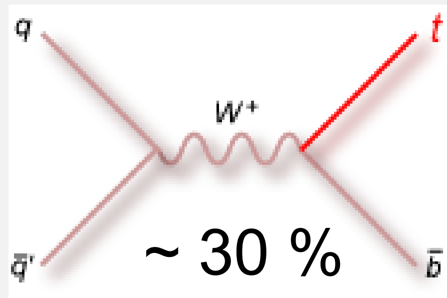


~ 15 %

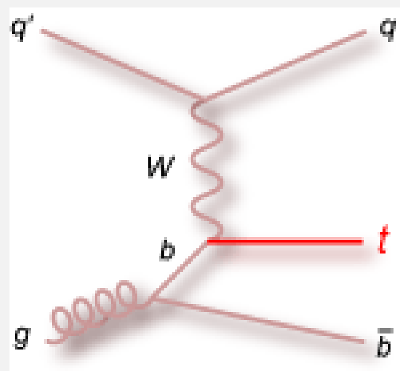
$\sigma_{NLO} = 7.4^{+0.5}_{-0.7}$ pb

m_t=172.5 GeV

Single



~ 30 %



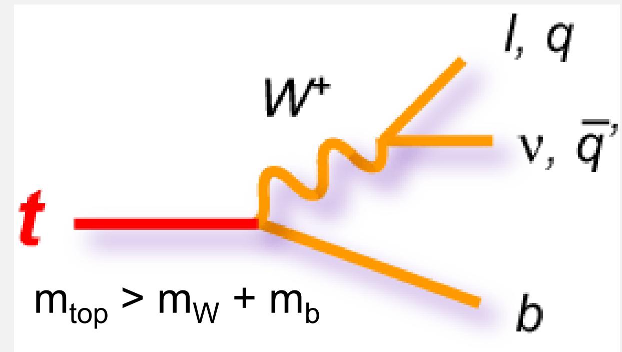
~ 70 %

σ_{NLO} = 3.0 ± 0.4 pb

NB:NNLO approx. available

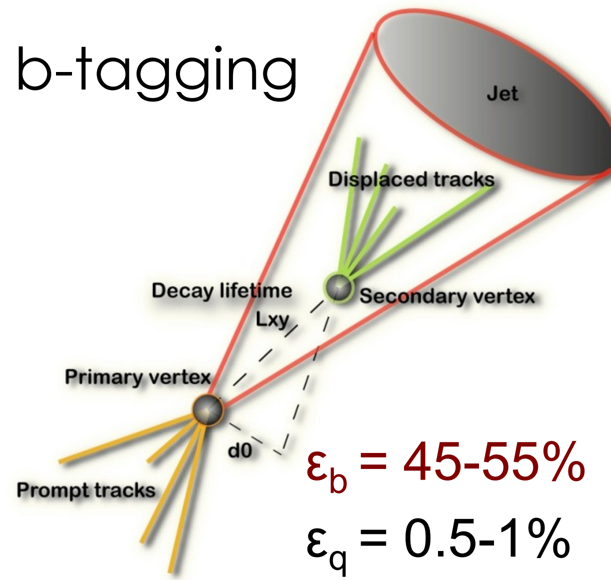
Decay

BR(t→Wb) ~100 %



$m_{top} > m_W + m_b$

b-tagging



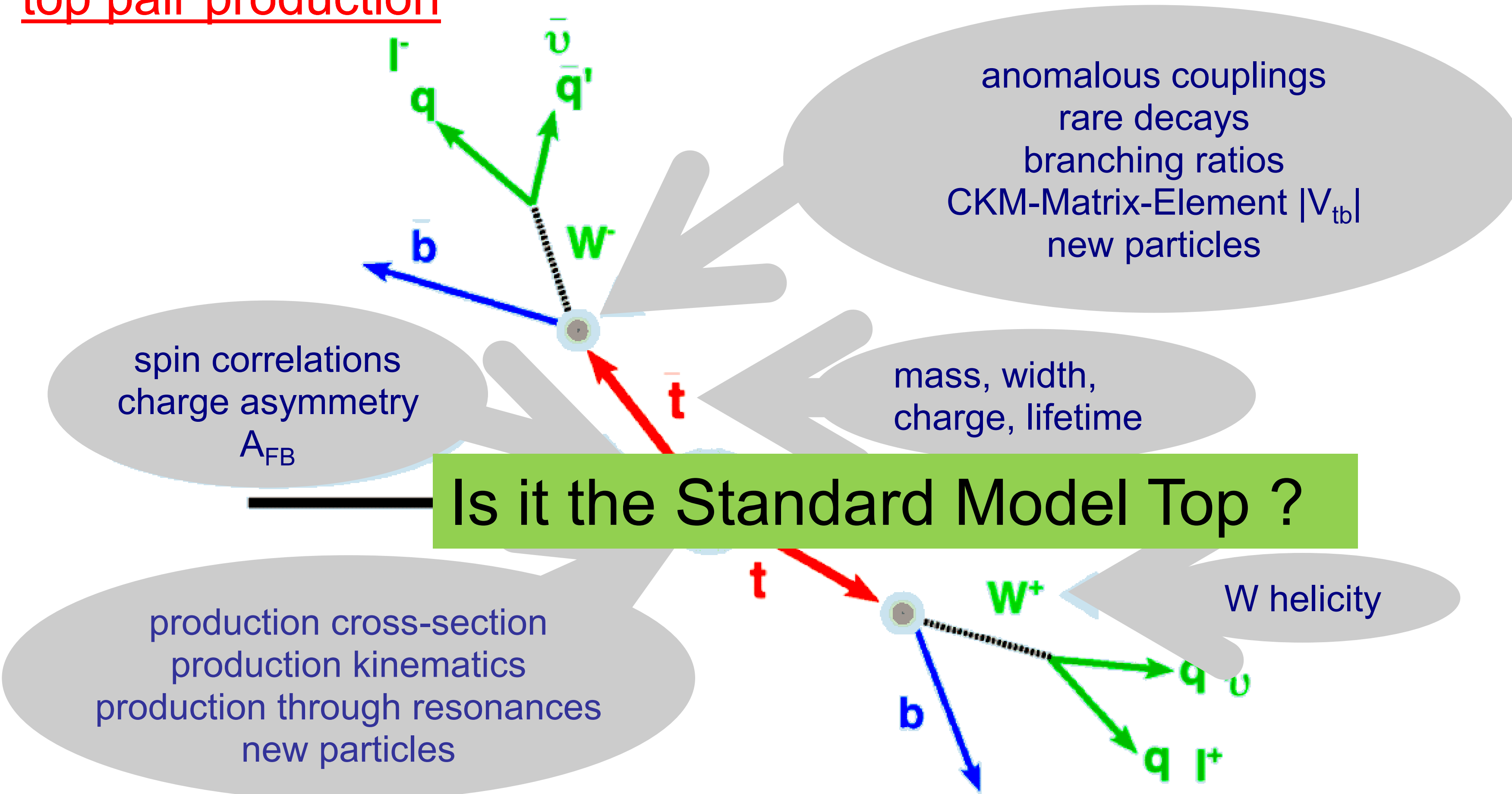
ε_b = 45-55%

ε_q = 0.5-1%

Top Quark Analyses at the Tevatron

up to 5.7 fb^{-1} of data: several 1000 top candidates per experiment

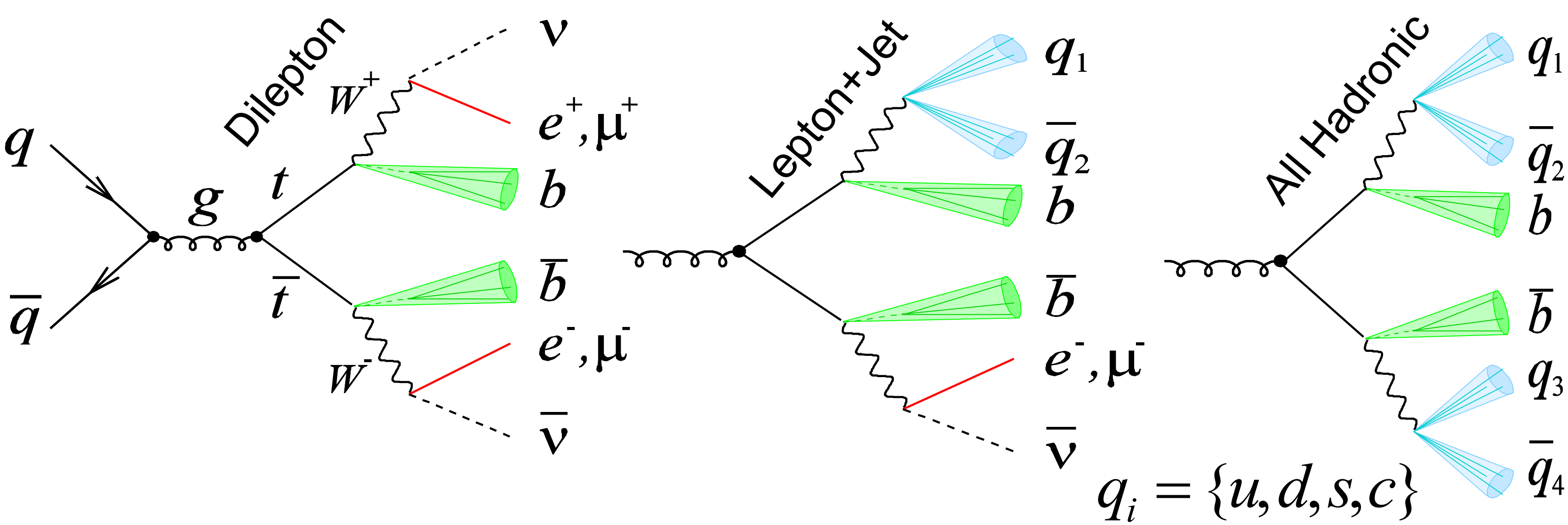
top pair production



single top production

production cross section, CKM-Matrix-Element $|V_{tb}|$, anomalous couplings, searches for new particles

Top Quark Pair Production and Decay



- **Dilepton** **(lepton = e or μ)** **(6%)**
  - Small rate, small backgrounds
  - Main background: Drell-Yan
  - *Highest purity*
- **Lepton+Jets** **(lepton = e or μ)** **(34%)**
  - Good rate and manageable backgrounds
  - Main background: W+jets,
  - *Good purity "Golden Channel"*
- **All-hadronic (46%)**
  - Large rate, large background
  - Main background: QCD multijet
  - *Least purity*
- **Hadronic Taus** **(tau+lepton, tau+jets)** **(14%)**
  - Small rate and large backgrounds
  - Main background: Multijets, W+jets
  - *Challenging purity*

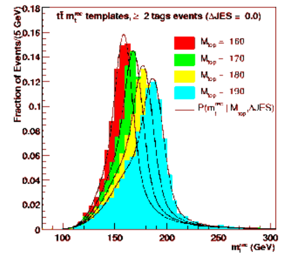
Analysis Strategies

background model validation

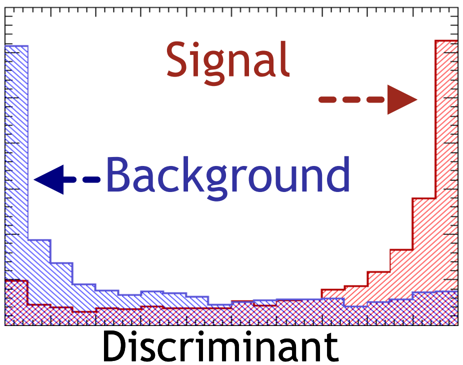
- Counting Experiment
  - Establish event selection and estimate background

$$\sigma = \frac{N_{observed} - N_{background}}{\int \text{Luminosity}\, dt \cdot \varepsilon}$$

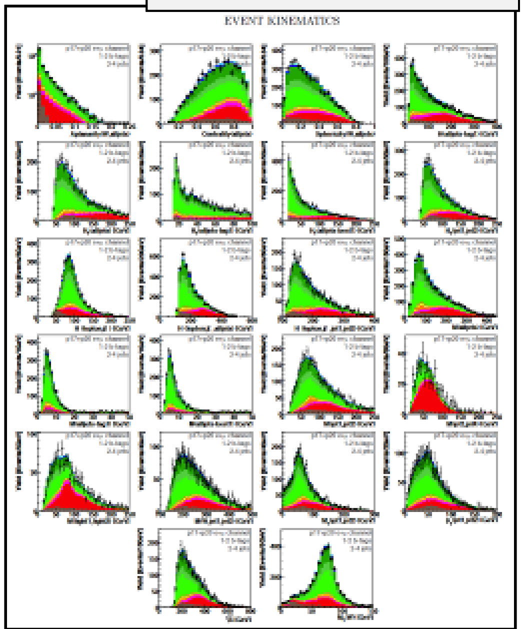
- Template Analysis
  - Fit 1D signal + background distribution to data



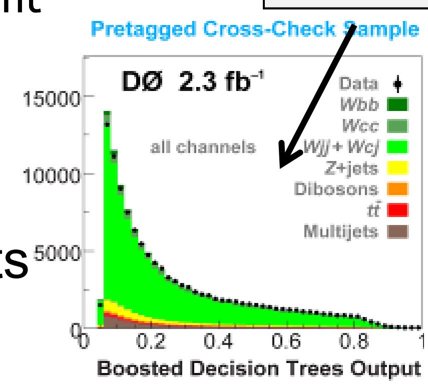
- Matrix Element
  - Use tree level matrix elements to classify signal and background like events

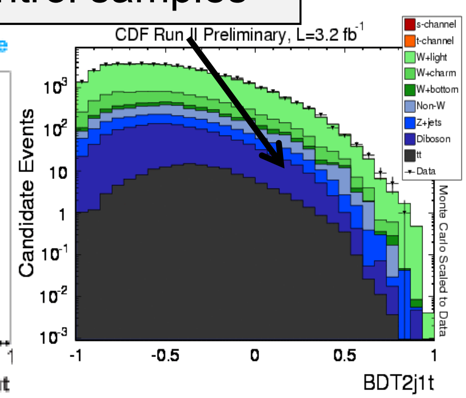


- Neural Networks, Decision Trees
  - Machine learning algorithm to classify signal and background events based on many input features



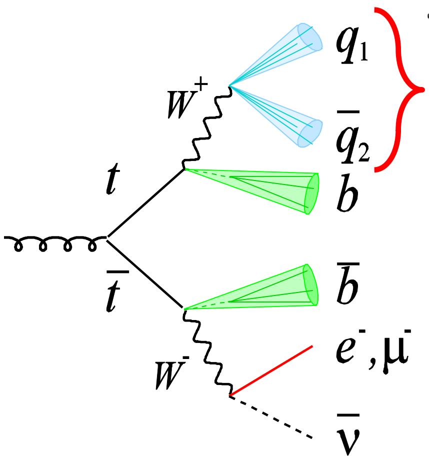
Evaluate discriminants in control samples

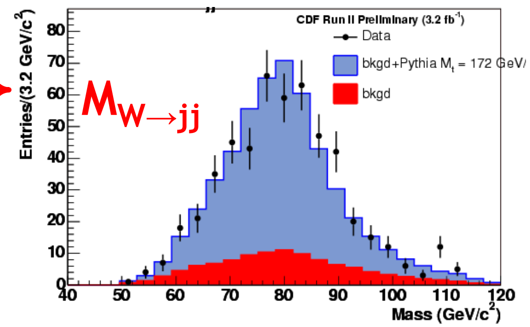


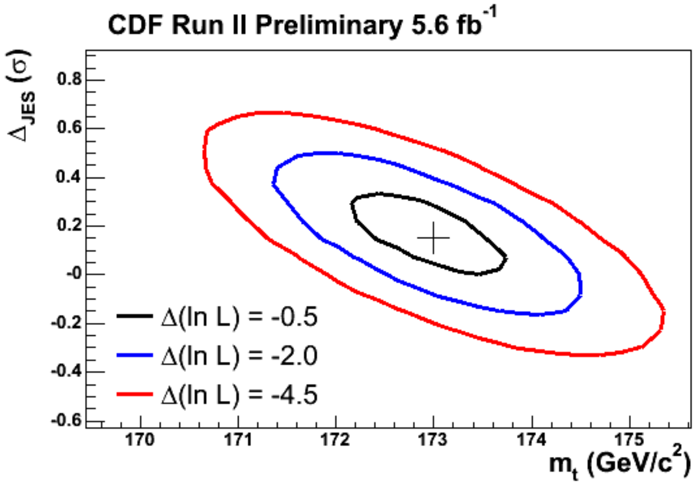


Top Quark Mass

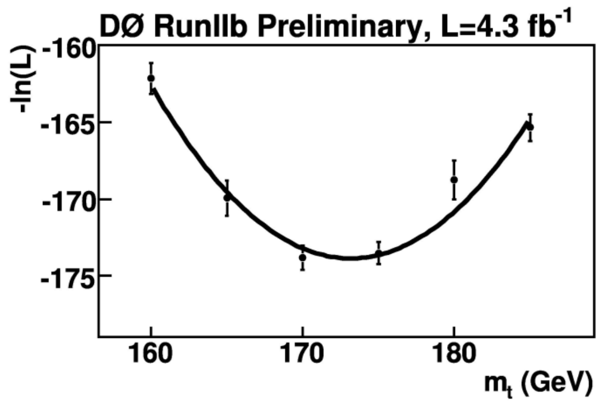
- Extraction techniques: Template and Matrix element method
- In-situ JES calibration (*W* constraint) in lepton+jets topology (golden channel)
- Main uncertainties:
  - -Jet energy scales and resolution
  - - MC modeling, ISR+FSR, …







- Complementary measurements in dilepton and all-hadronic channels



CDF (5.6 fb^{-1}):

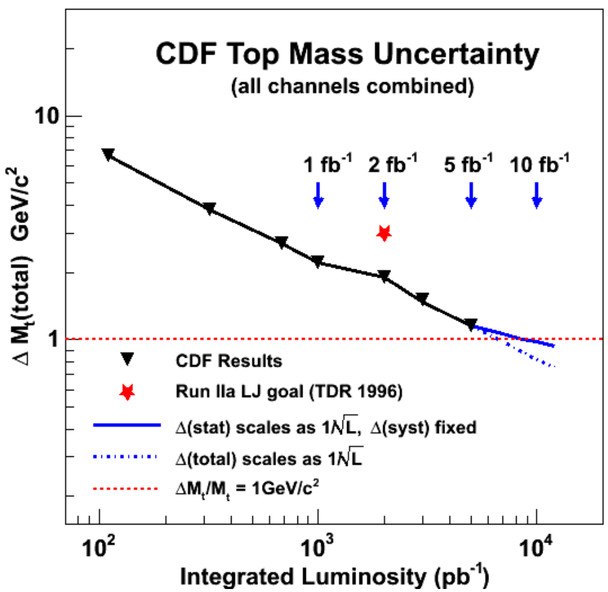
m_t(l+j)=173.0±0.9(stat +JES) ±0.9(syst) GeV

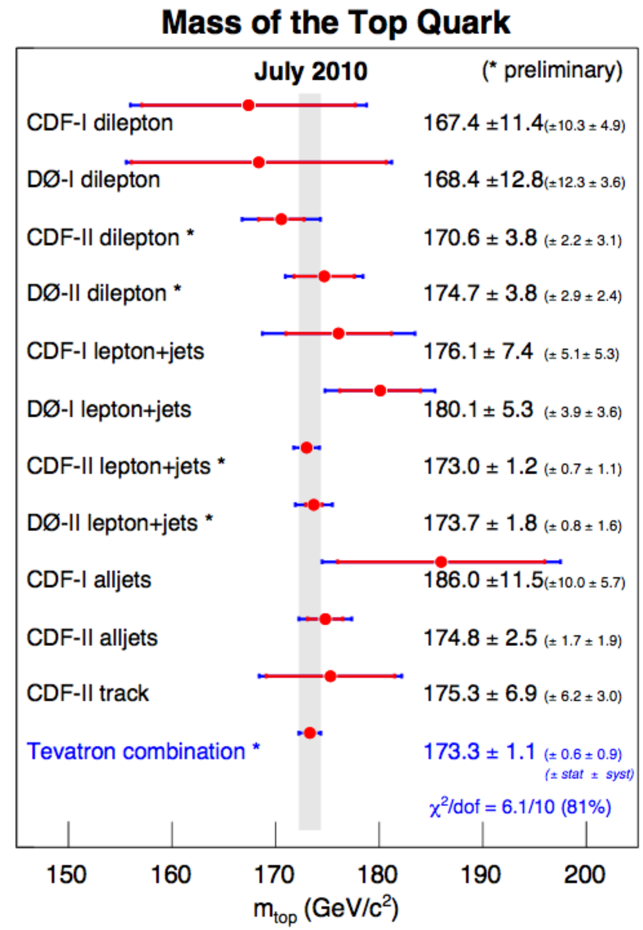
D0 (5.3 fb^{-1}):

m_t(eμ)=173.3±2.4(stat) ±2.1(syst) GeV

Top Quark Mass Combination

- Recent (July 2010) Tevatron Combination includes 11 results
- Largest systematic uncertainty is Jet Energy Scale (~ 0.46 GeV)
- Good agreement across both experiments and channels
- Single Experiment uncertainty of 1 GeV achievable in Run II:





$M_t = 173.3 \pm 1.1$ GeV

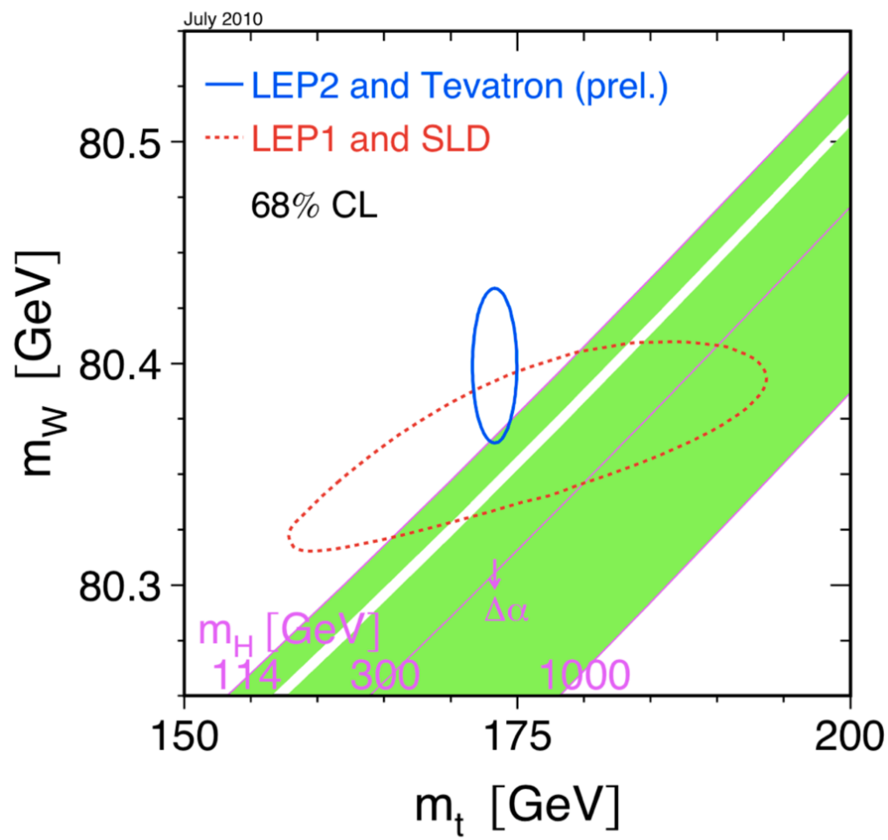
up to 5.6 fb^{-1}

$\Delta M / M \sim 0.6$ %

Impact on Higgs Mass

- Higgs Mass bounds from Electroweak Fit:

M_H < 158 GeV @ 95% CL
$M_H = 89^{+35}_{-26}$ GeV

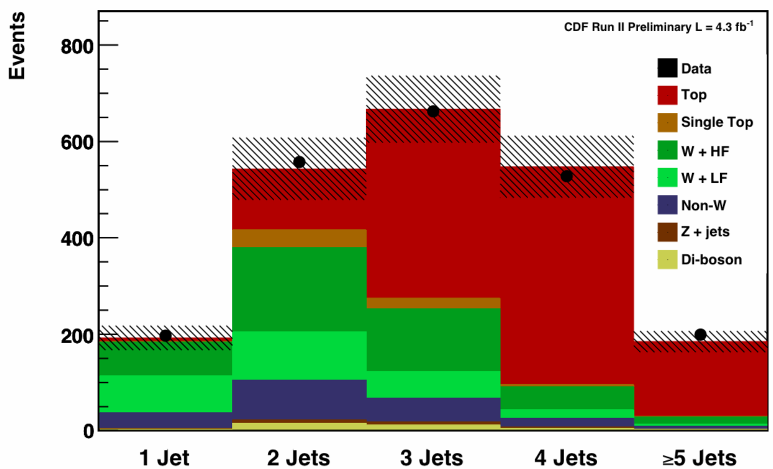


- SM Higgs Mass constraint now driven by Δm_W
  - $\Delta m_W \sim 0.006 \times \delta m_{top} \sim 7$ MeV for equal weights in Higgs limits

- m_{top} important SM parameter
  - EW observables, BSM Higgs sector ..

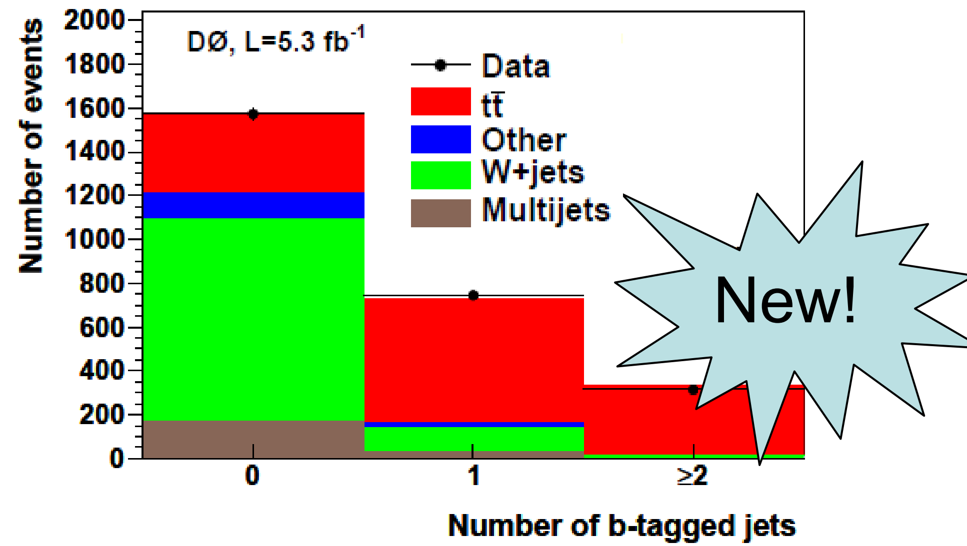
B-tagged lepton + jets cross section

- Inclusive cross section powerful test of perturbative QCD (known to ~ 6-8% NNLO"approx" V. Ahrens et. al. JHEP 09 097 (2010); U.Langenfeld et al. PRD80 (2009))
- B-tagging powerful tool to increase signal/background
- Conceptually "simple" counting experiment



σ_{tt} = 7.22 ± 0.35 ±0.56 ±0.44 pb

M_t=172.5 GeV (stat+syst+lum) (11%)



σ_{tt} = 8.13 ± 0.25 $^{+0.99}_{-0.86}$ (stat+syst) pb (12%)

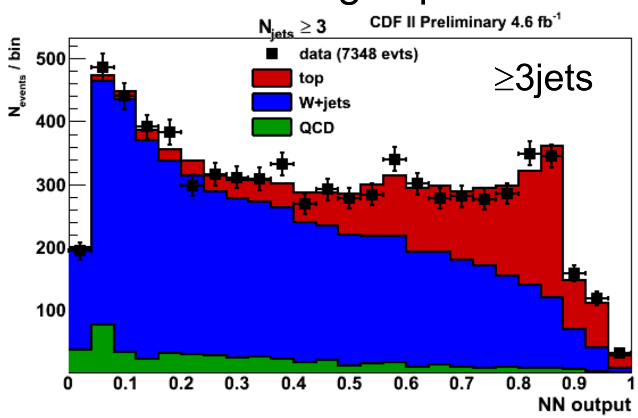
M_t=172.5 GeV

- Systematics limited:
  - luminosity (~6%)
  - b-tagging systematics

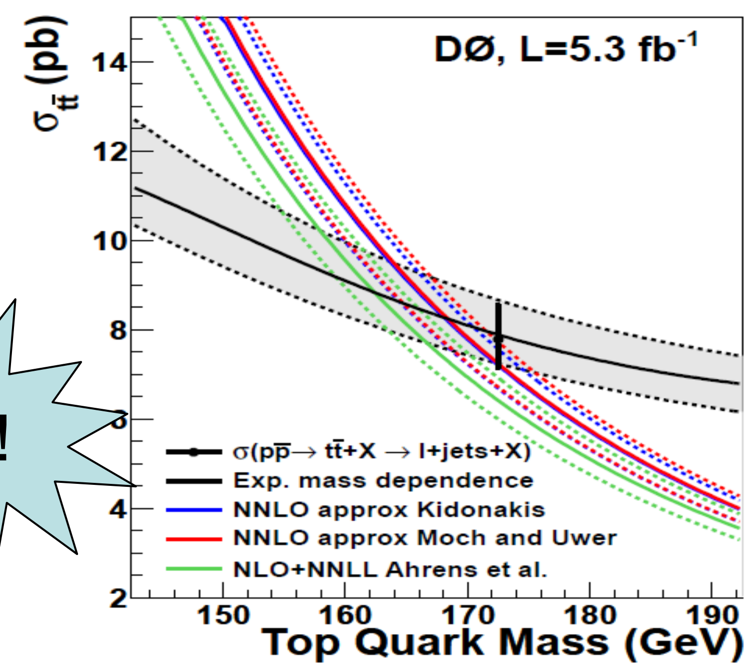
→ Complement with more sophisticated techniques

Lepton + jets improved cross section

- Use topological and kinematic quantities (aplanarity, sphericity, H_T…) to improve signal to background separation
  - ttbar more energetic, central and isotropic than W+jets
  - Discriminants using ANN (CDF) or BDT (D0)
- Combine with b-tag counting experiment
  - CDF:BLUE combination, D0: simultaneous MVA and counting experiment



New!



$$\sigma_{tt} = 7.78 \pm 0.25 \,^{+0.73}_{-0.59} \text{ pb}$$

M_t=172.5 GeV (stat+syst) (9%)

arXiv:1101.0124v1 hep-ex

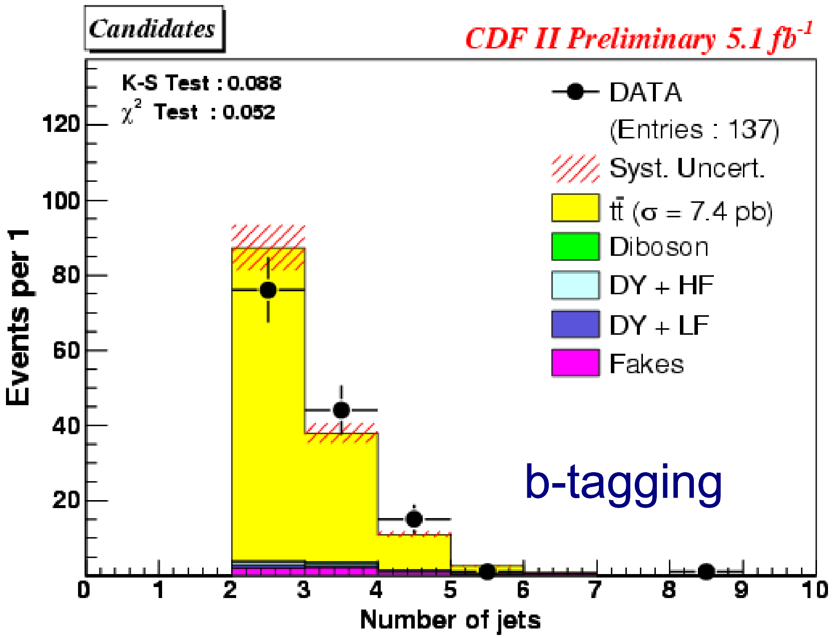
- Additional improvement (CDF): Normalize to inclusive Z-cross section
  - Luminosity uncertainty cancels

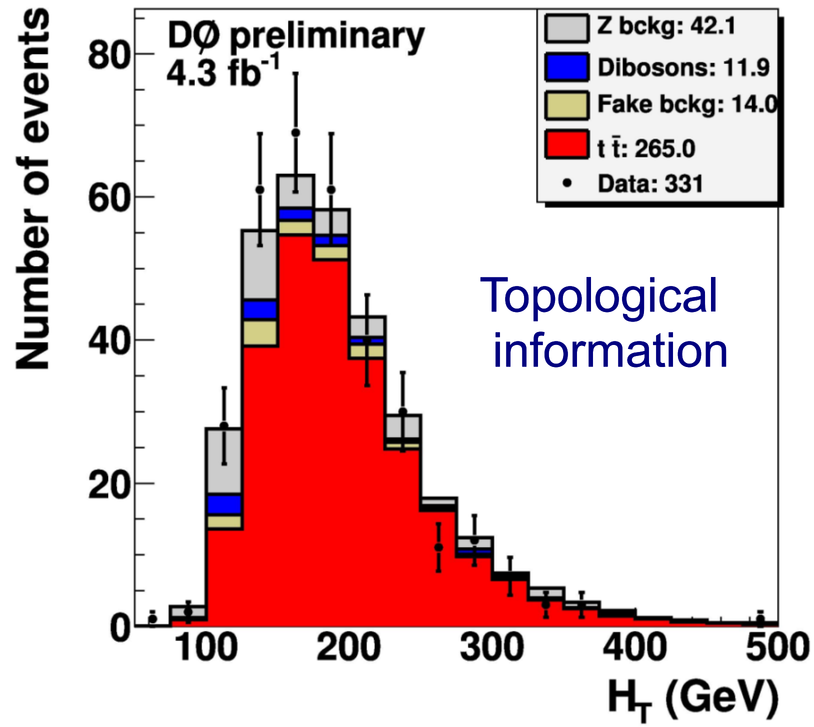
$$\sigma_{tt} = 7.82 \pm 0.38 \pm 0.37 \pm 0.15 \text{ pb}$$

M_t=172.5 GeV (stat+syst+Z th.) (7%)

Surpassing Tevatron goal (~10%) and ~ theory precision

Dilepton cross section





σ_{tt} = 7.40 $\pm$ 0.58 $\pm$0.63 $\pm$0.45 pb

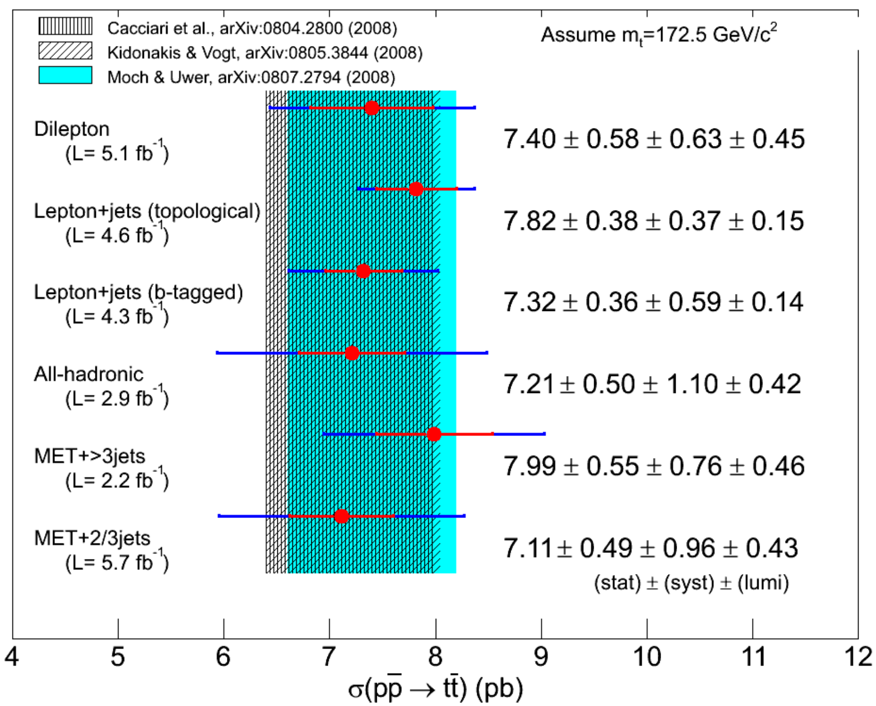
M_t=172.5 GeV (stat+syst+lum) (13%)

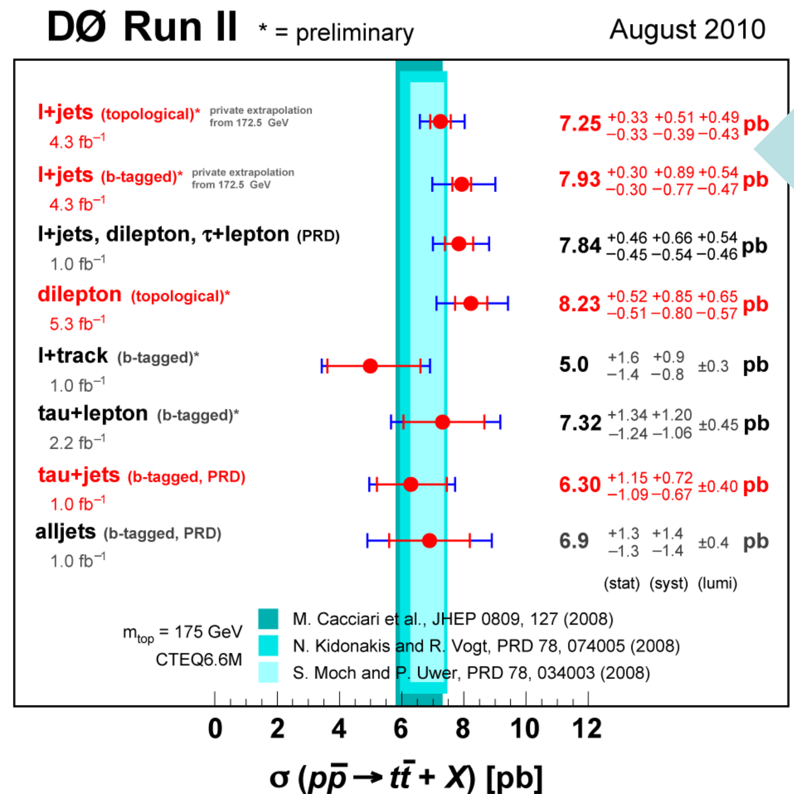
σ_{tt} = 8.23 $\pm$ 0.52 $\pm$0.83 $\pm$0.61 pb

M_t=172.5 GeV (stat+syst+lum) (13%)

Achieving good precision

Top Pair Production Cross sections





updated

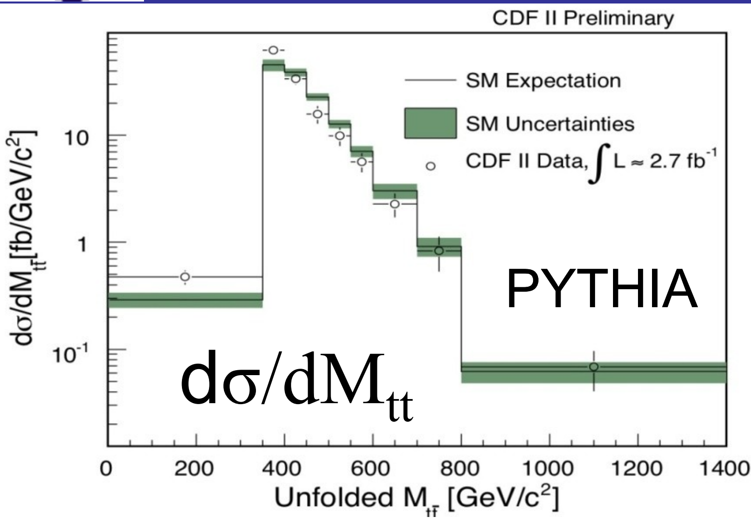
CDF: σ_{tt} = 7.50 ± 0.31 ± 0.34 ± 0.15 pb (stat+syst+lum/ Z thy) **(6%)**

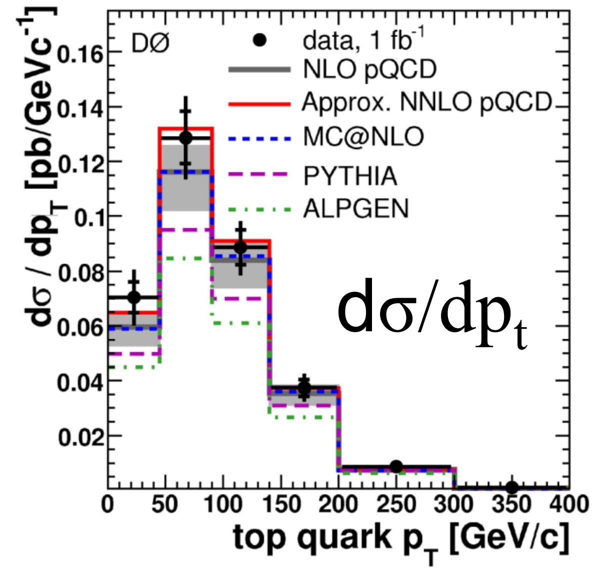
m_{top} = 172.5 GeV

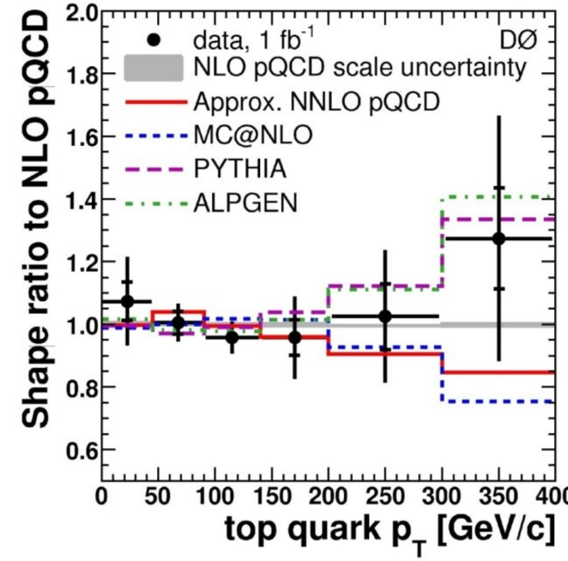
All channels measured except for $\tau_h\ \tau_h$

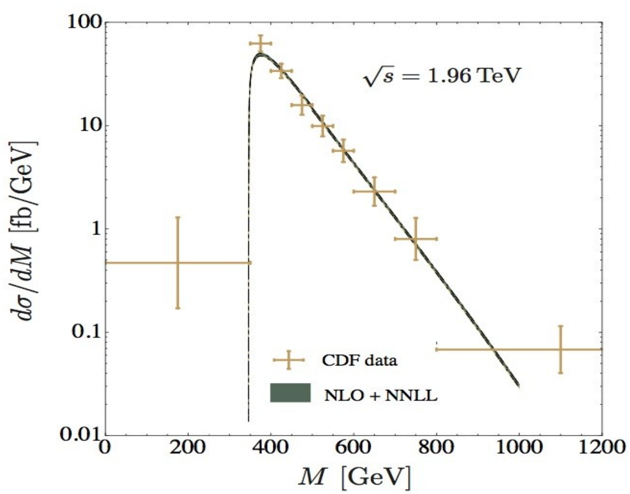
Good agreement in all channels

Differential Cross Section









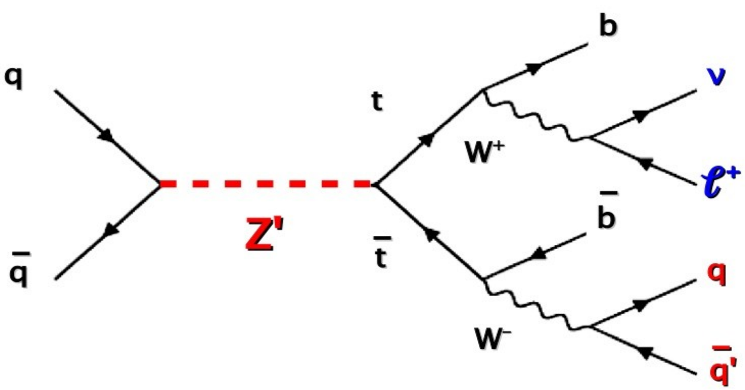
Need ≥NLO to describe normalization

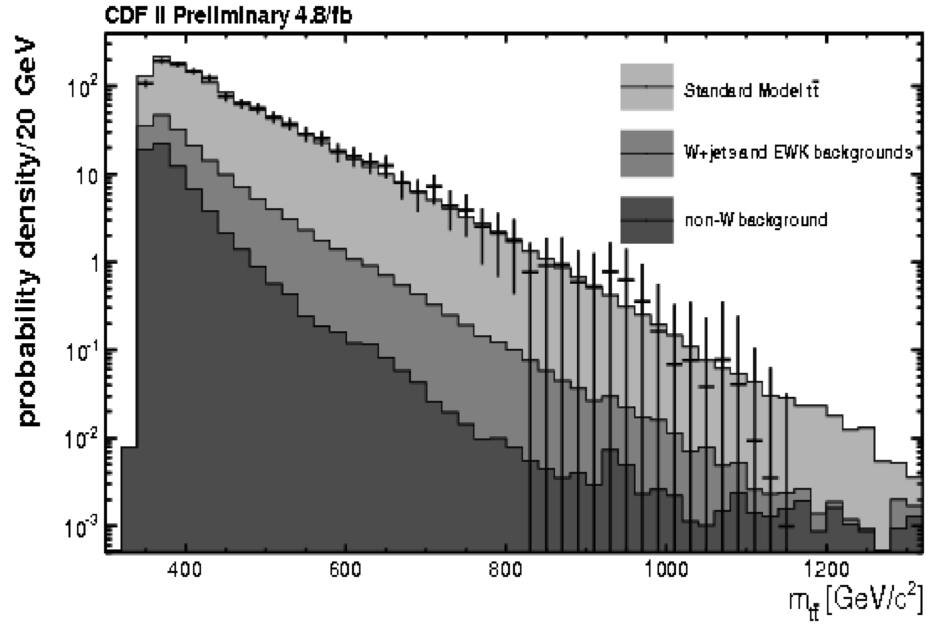
No deviation from SM

Improved description with NLO+NNLL Ahrens, Ferrogia, Neubert, Pecjak, Yang arXiv:1006.4682 [hep-ph]

$t\bar{t}$ Resonances

- Some BSM models predict $t\bar{t}$ resonances
  - e.g. Leptophobic Z' coupling strongly to 3rd generation





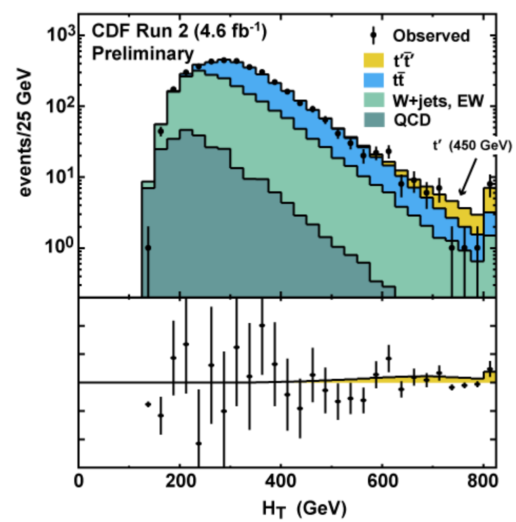
- No bumps in $t\bar{t}$ mass spectrum observed

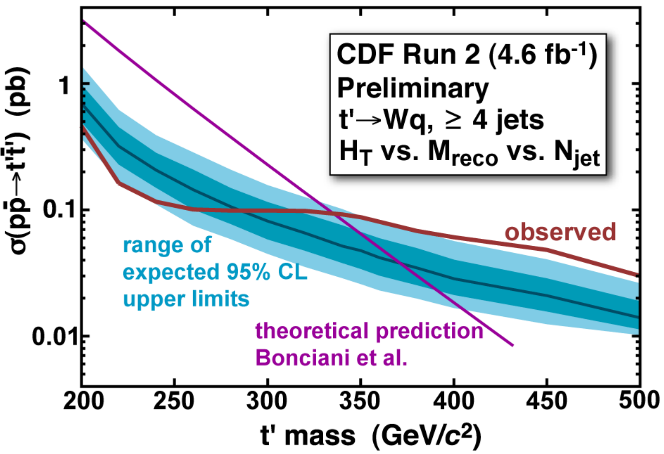
CDF: $M_{Z'}$ > 900 GeV (4.8 fb^{-1})

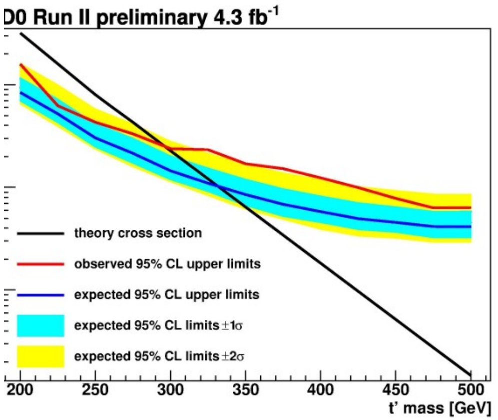
D0: $M_{Z'}$ > 820 GeV (3.6 fb^{-1})

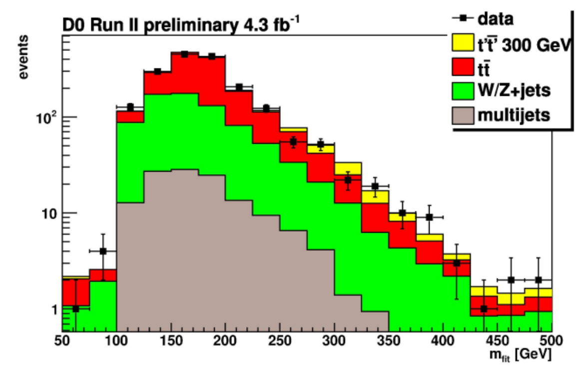
Search for 4th generation t'

- Treat t' as a more massive top quark
  - t' → Wq
- Look for excess in reconstructed mass of t' and H_T







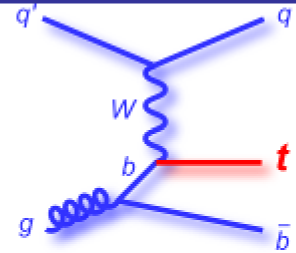


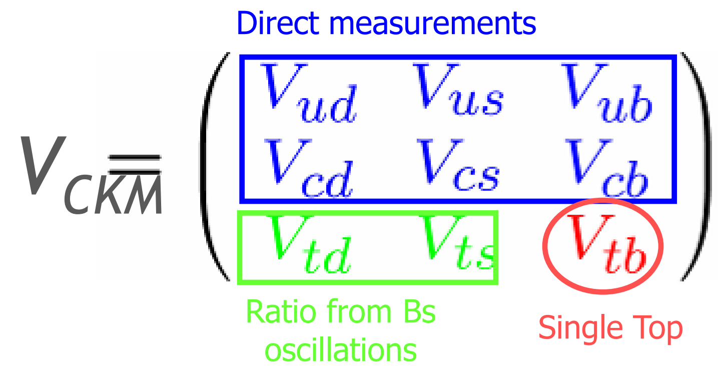
CDF: $M_{t'} > 335$ GeV ($4.6\ fb^{-1}$)	D0: $M_{t'} > 296$ GeV ($4.3\ fb^{-1}$)

- Observed limits weaker than expected (~2σ)

Electroweak Single Top Production

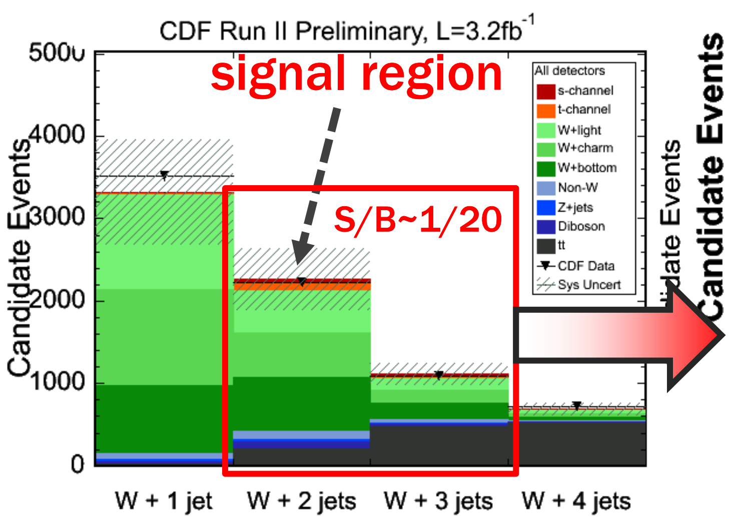
- Test V-A structure of W-t-b vertex
- Access $|V_{tb}|$

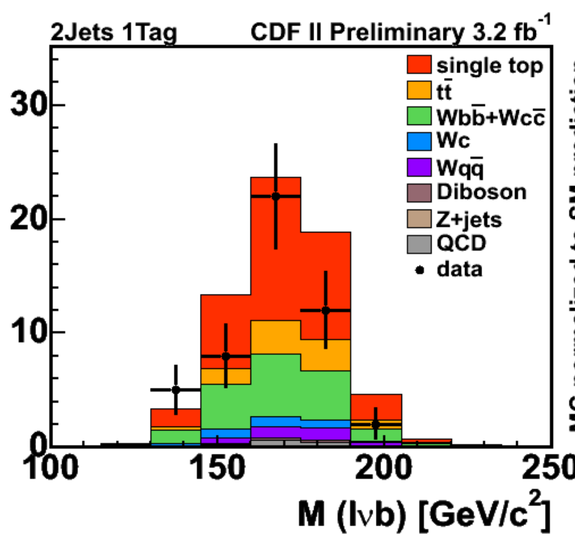


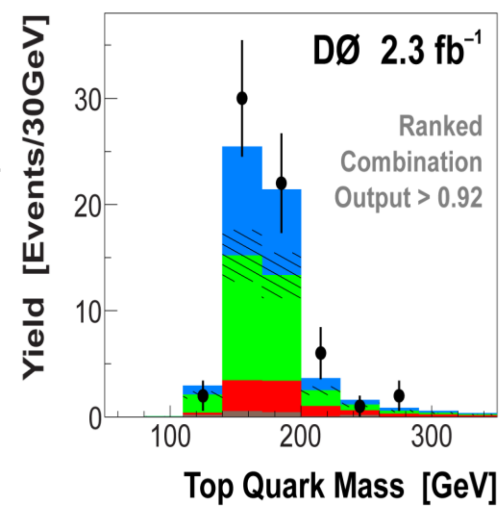


- Single top signature (W + 2 jets) less distinct than top pairs
- Large and many backgrounds

⇒Multivariate analyses essential to establish small signal (Matrix Element, Neural Net, Boosted Decision Trees…)





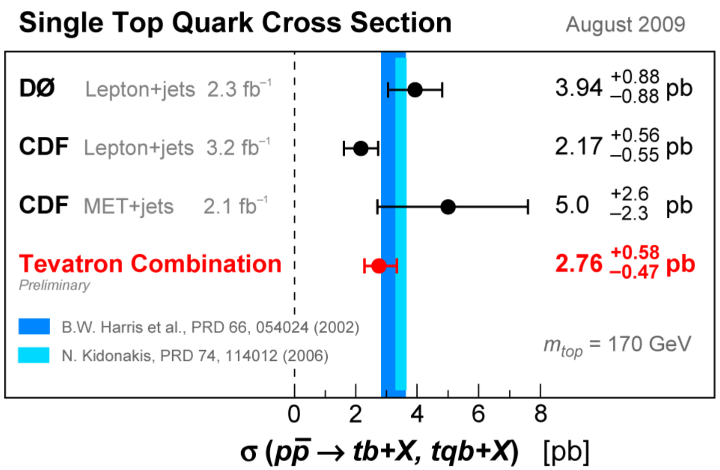


Single Top Cross section and $|V_{tb}|$

- Tevatron combination:

  $\sigma_{s+t}=2.76^{+0.58}_{-0.47}$ pb
  $|V_{tb}|= 0.88\pm0.07$ (>0.77 @95% CL)

  => compatible with Standard Model
  In all channels

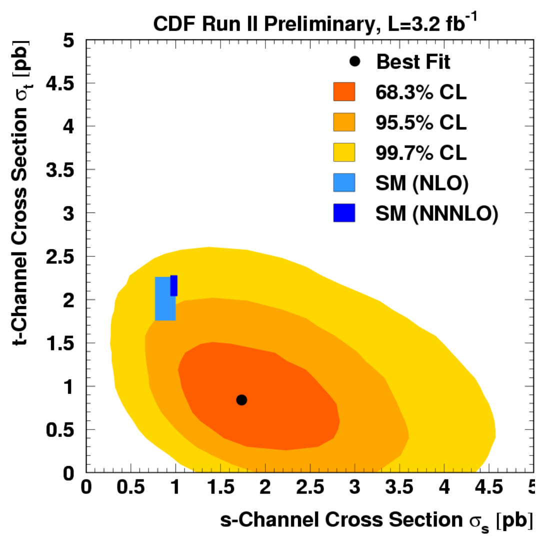


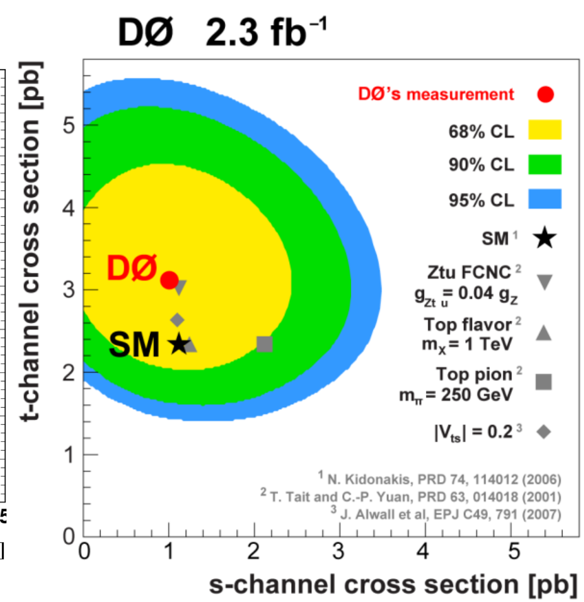
- Independent s- and t-channel measurements

  - Good overall agreement with Standard Model

  - ~2σ effect in CDF result NOT explained by recent theory progress in t-channel signal MC (Campbell et al)

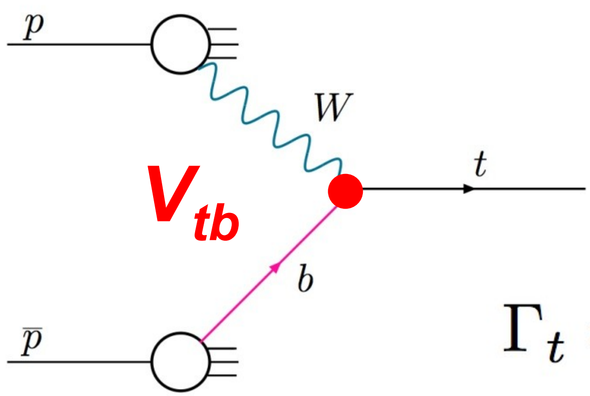
    => See talk by R. Frederix



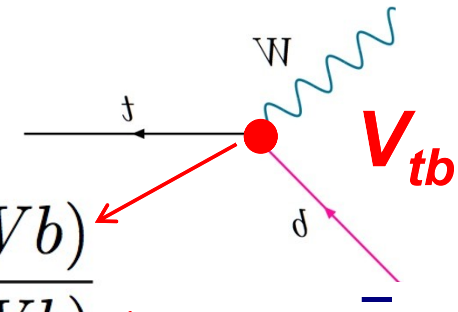


Top Quark Width

- In SM: $\Gamma(t \to Wb) = 1.26$ GeV (NLO), $m_t = 170$ GeV
- D0: indirect measurement via t-channel single top cross section
  - assume same coupling in decay and production



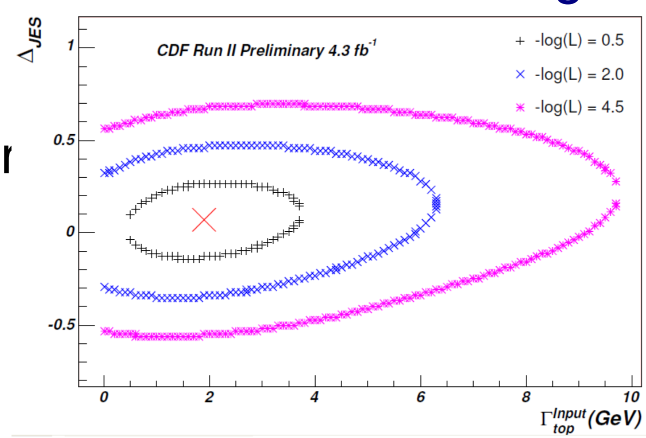
$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$$



From tt production: ratio of different # of b-tags

$\Gamma_t = 2.05^{+0.57}_{-0.52}$ GeV

- CDF: direct measurement from well reconstructed single + double tagged leptons + jets top pair



$\Gamma_t < 7.6$ GeV (95%CL),
$0.3 < \Gamma_t < 4.4$ GeV (68%CL interval)

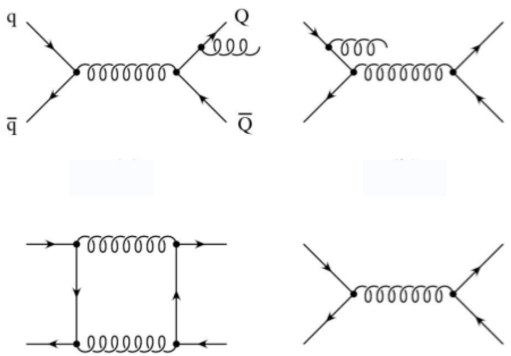
Top Quark A_{FB}

- Test of discrete symmetries in strong interactions

$$A_{FB} = \frac{N_{\Delta Y>0} - N_{\Delta Y<0}}{N_{\Delta Y>0} + N_{\Delta Y<0}}$$

- at Tevatron ($p\bar{p}$), A_{FB} can be reconstructed in lab frame

- NLO QCD predicts small asymmetry A_{FB} ~ 5% in $q\bar{q} \rightarrow t\bar{t}$ – top quark preferentially in proton direction



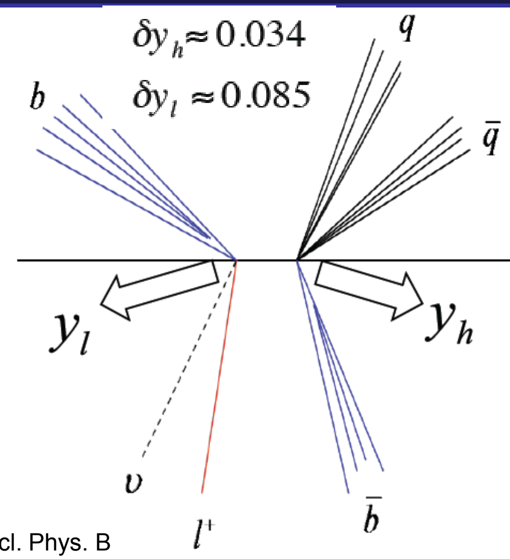
A_{FB} ~ - 7% (NLO)

A_{FB} ~ - 1% (NNLO)

S. Dittmaier, et al. Nucl. Phys. B Proc. Suppl. 183, 196 (2008).

A_{FB} ~ +10-12% (NLO)

NNLO still missing



$$\Delta y_{t\bar{t}} = q \cdot (y_l - y_h)$$
$$= y_t - y_{\bar{t}}$$
$$\Delta y_{t\bar{t}} = 2 y_t^{t\bar{t}}$$
$$\delta \Delta y \approx 0.100$$

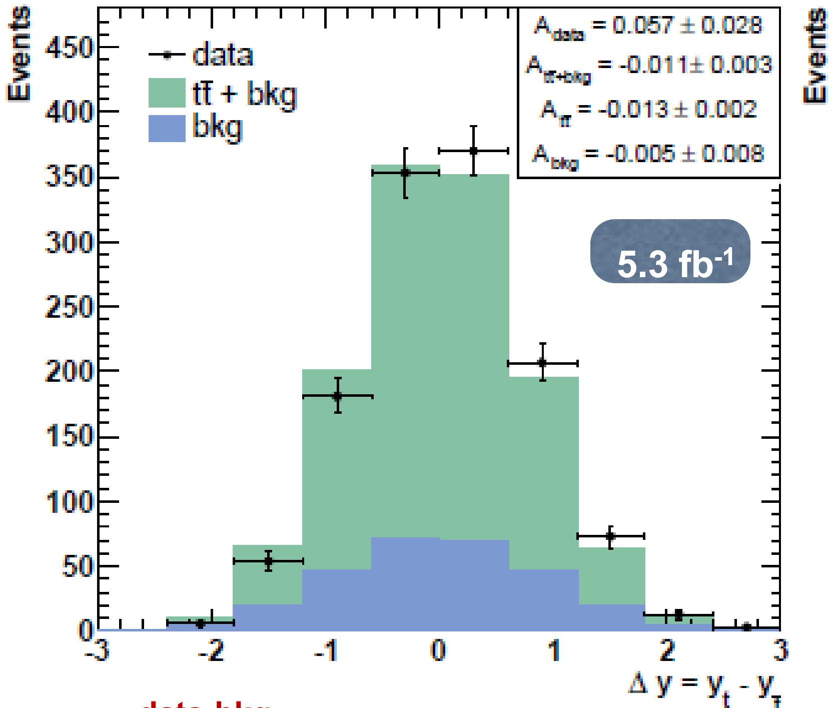
- New physics can modify/enhance A_{FB}
  - Extra heavy gluon octet, W', Z' with anom. couplings

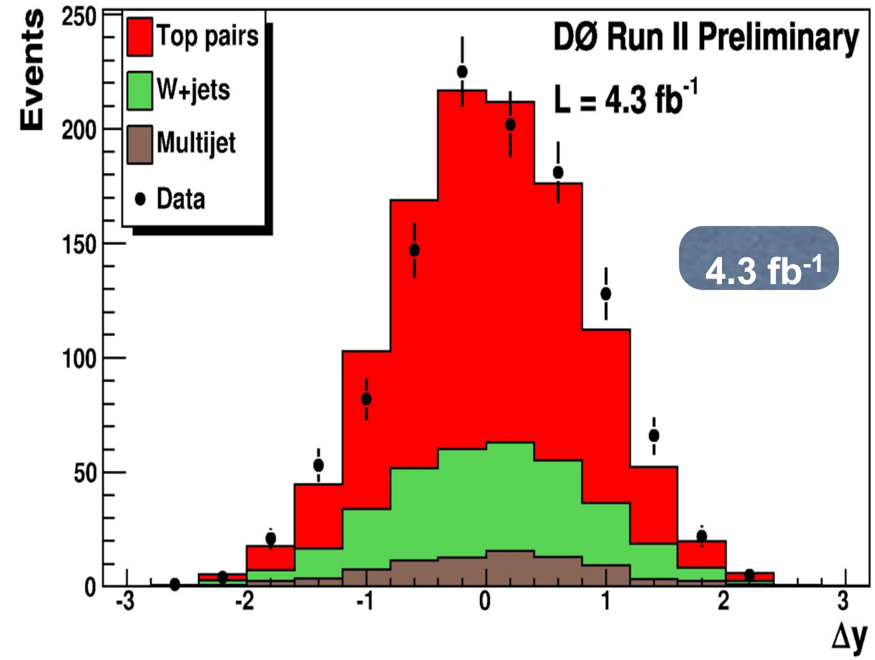
New!

- **(Brand-) new CDF result based on 5.3 fb^{-1}** http://arxiv.org/abs/1101.0034
  - Δy (~ cos θ^*_{tt}) and M_{ttbar} (~ Q^2) dependence

FNAL Wine and Cheese Seminar 7 January 2011!

Inclusive Asymmetries in $t\bar{t}$-Rest Frame





$A_{FB}^{data\text{-}bkg} = 7.5 \pm 3.7_{(stat+sys+thy)}$ %

$A_{FB}^{mc@nlo} = 2.4 \pm 0.5$ %

Parton Level: (correcting acceptance, reconstruction, resolution, backgrounds)

$A_{FB} = 15.8 \pm 7.4_{(stat+sys+thy)}$ %

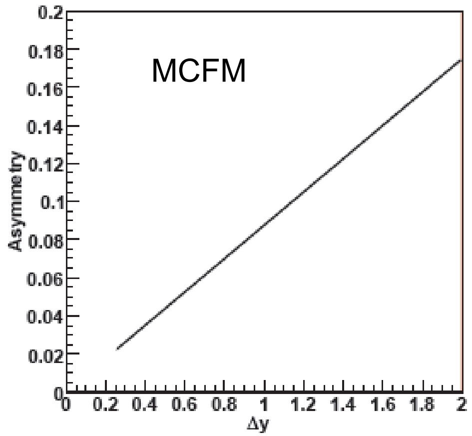
$A_{FB}^{mcfm} = 5.8 \pm 0.9$ %

} ~ 1.5σ

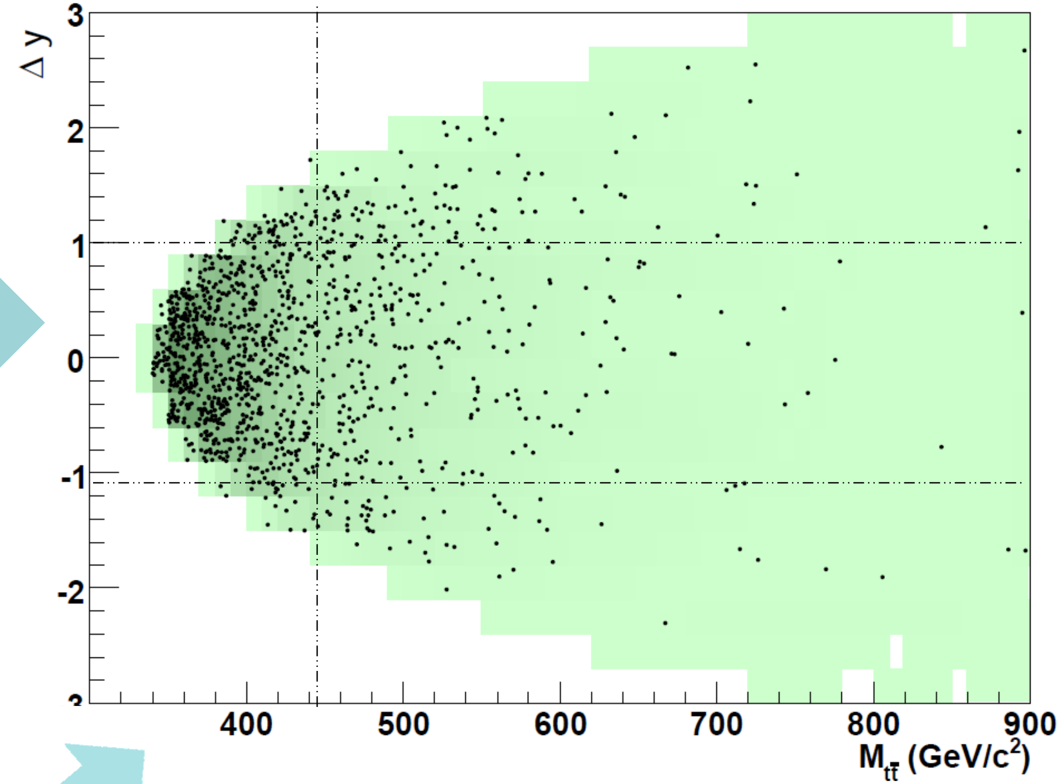
$A_{FB}^{data\text{-}bkg} = 8 \pm 4_{stat+sys}$ %

$A_{FB}^{mc@nlo} = 1^{+2.0}_{-1.0}$ %

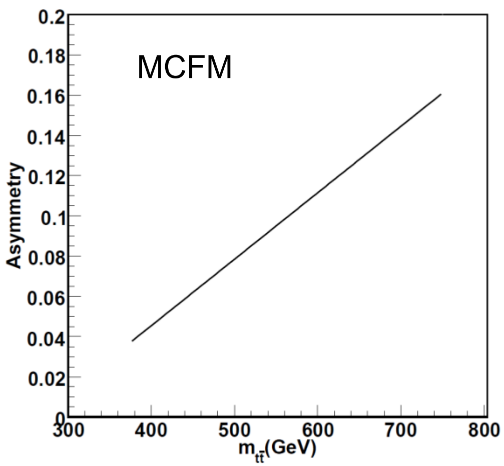
Δy and $M_{t\bar{t}}$ dependence



NLO predicts ~ linear dependence of AFB on Δy on parton level



$M_{tt} = 2\, m_T^{tt} \cosh(\Delta y)$

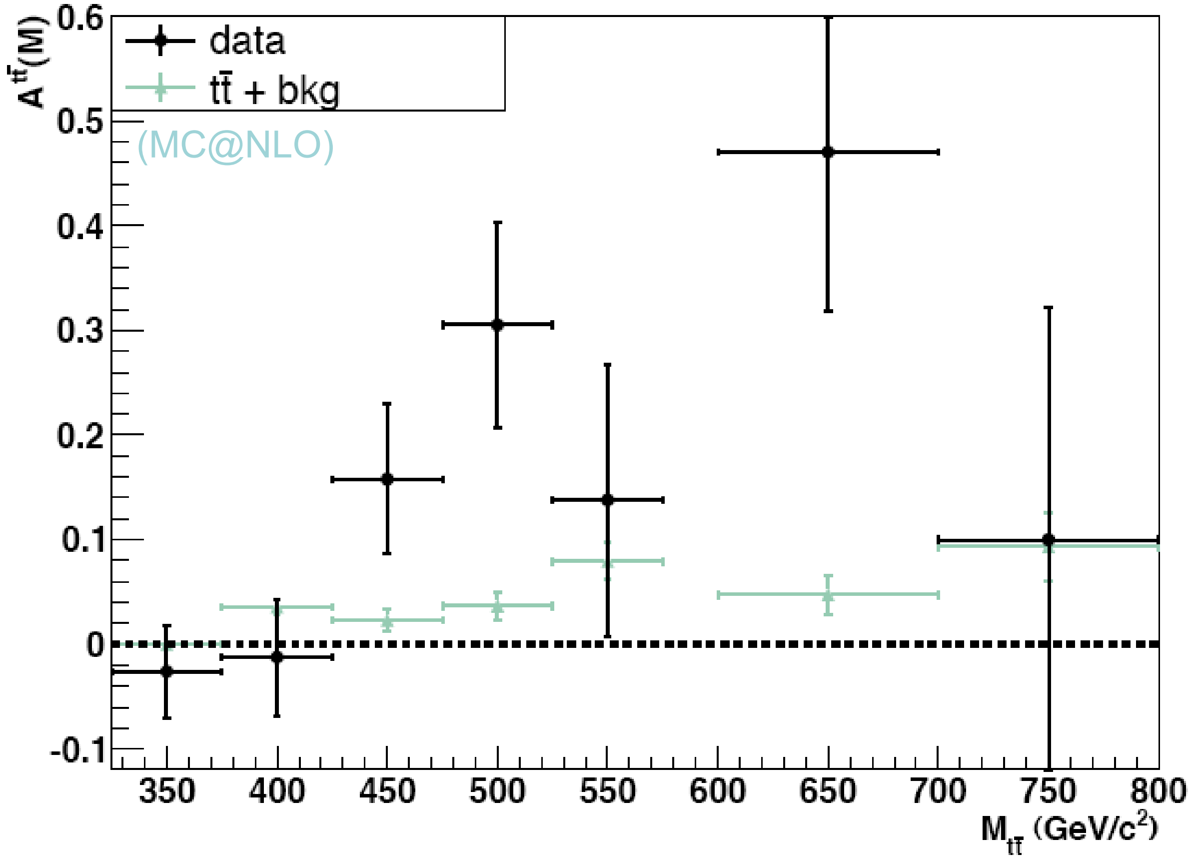


NLO predicts ~ linear dependence of AFB on M_{ttbar} on parton level

Scrutinize asymmetry in bins of Δy and M_{tt}

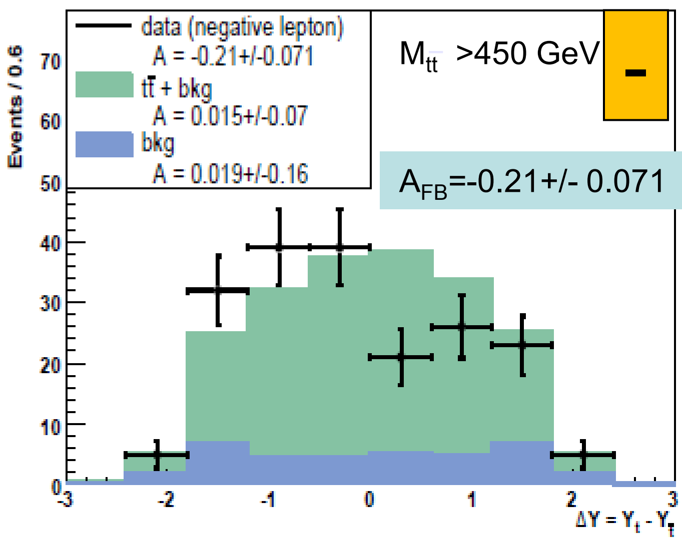
$M_{t\bar{t}}$ dependence

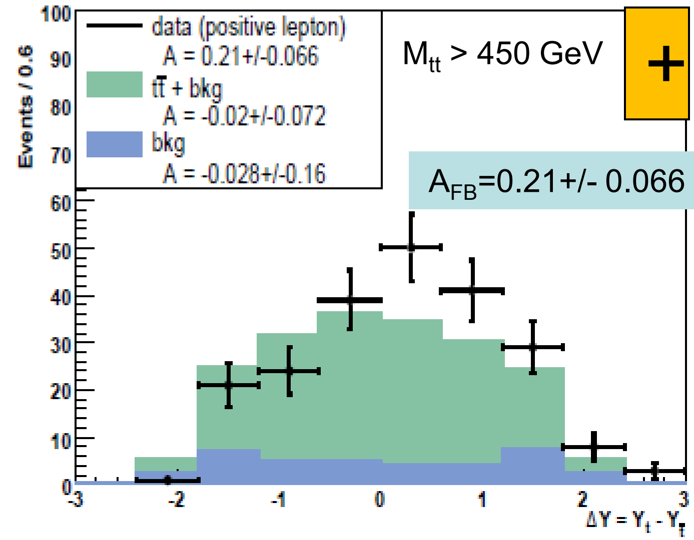
Reconstructed (data) level:



Reconstructed A_{FB} (data) overshoots MC@NLO prediction

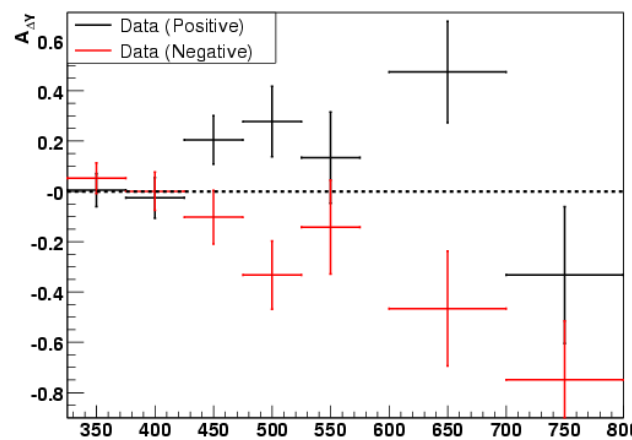
Cross checks : lepton charge



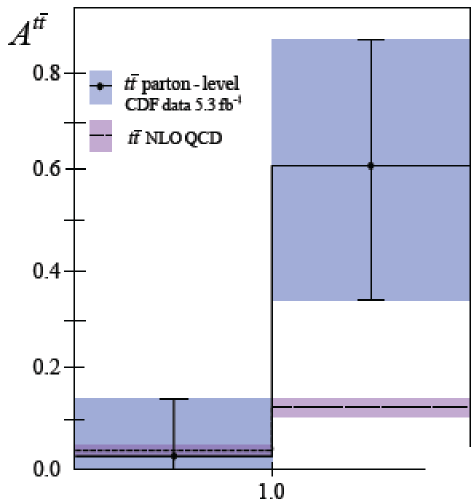


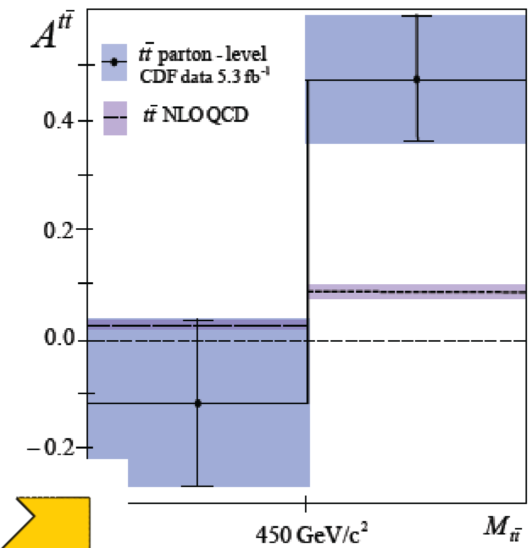
- Lepton charge tags the top quark flavor => sign selects preferential rapidity range of top quark
- $A_{FB}(+) = - A_{FB}(-)$ suggests CP invariance of underlying process

=> Underlines physics origin of the effect

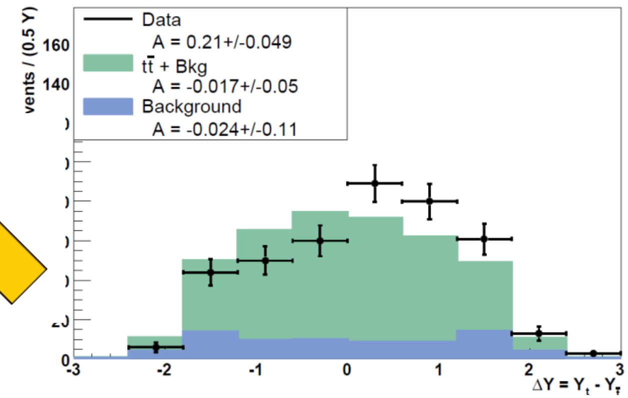


Unfolded Δy and M_{tt} Dependence





~3.4σ



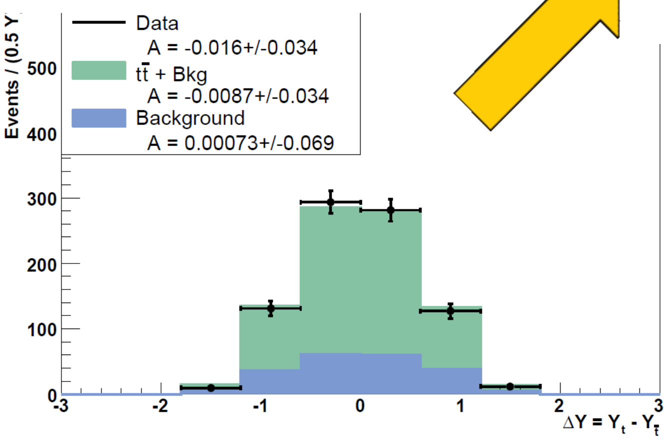


TABLE XIII: Asymmetry $A^{t\bar{t}}$ at high and low mass compared to prediction.

selection	$M_{t\bar{t}} < 450$ GeV$/c^2$	$M_{t\bar{t}} \geq 450$ GeV$/c^2$
data	-0.016 ± 0.034	0.210 ± 0.049
$t\bar{t}$+bkg (MC@NLO)	$+0.012 \pm 0.006$	0.030 ± 0.007
data signal	$-0.022 \pm 0.039 \pm 0.017$	$0.266 \pm 0.053 \pm 0.032$
$t\bar{t}$ (MC@NLO)	$+0.015 \pm 0.006$	0.043 ± 0.009
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

Significant A_{FB} at high M_{tt} (and Δy)

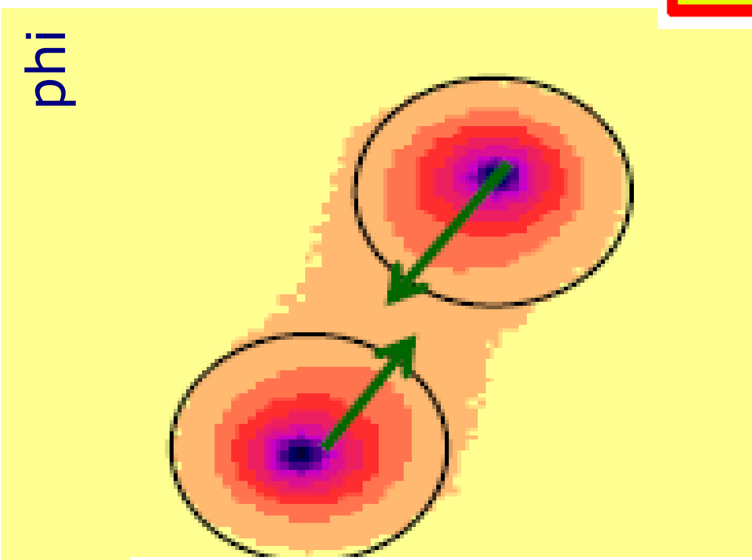
- cross checks: possible bias from unfolding physics model (Pythia versus Color Octet Model P. Ferrario,G. Rodrigo PRD80 051701 (2009)), reconstruction quality, lepton species, b-tagging/anti-tag cross check, jet multiplicity …
- Awaiting further theory input (NNLO)

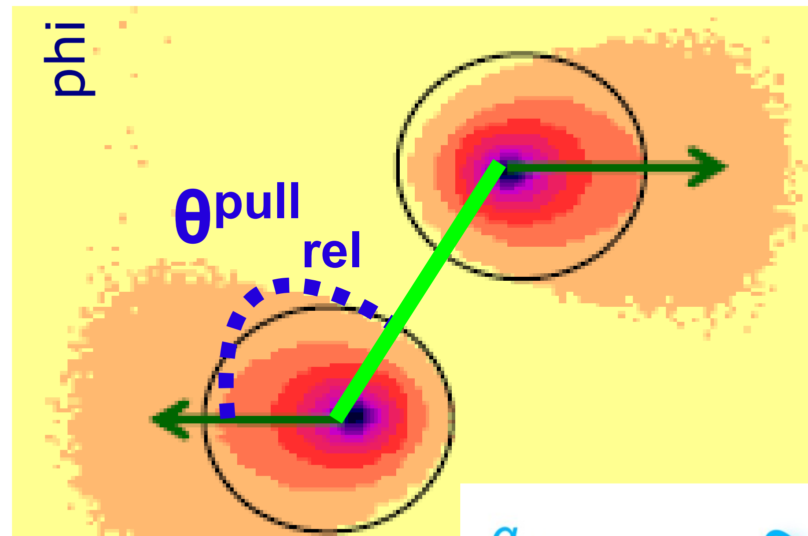
Jet Color Flow Measurement

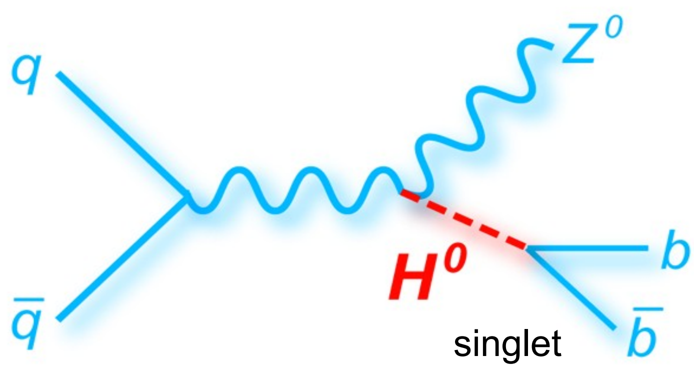
Use color flow between jets as additional handle to separate signal and background: “Jet Pull”

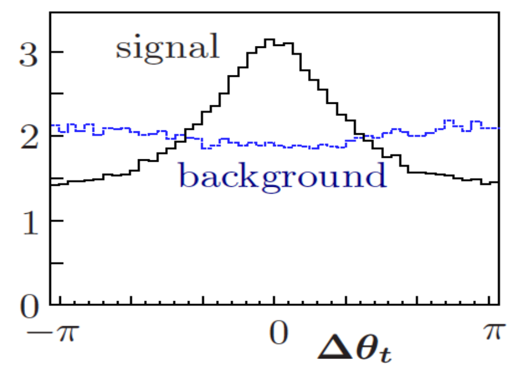
$$\vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i$$

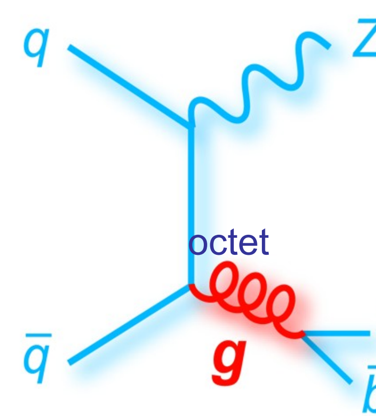
Gallicchio, Schwartz, PRL 105, 022001 (2010)







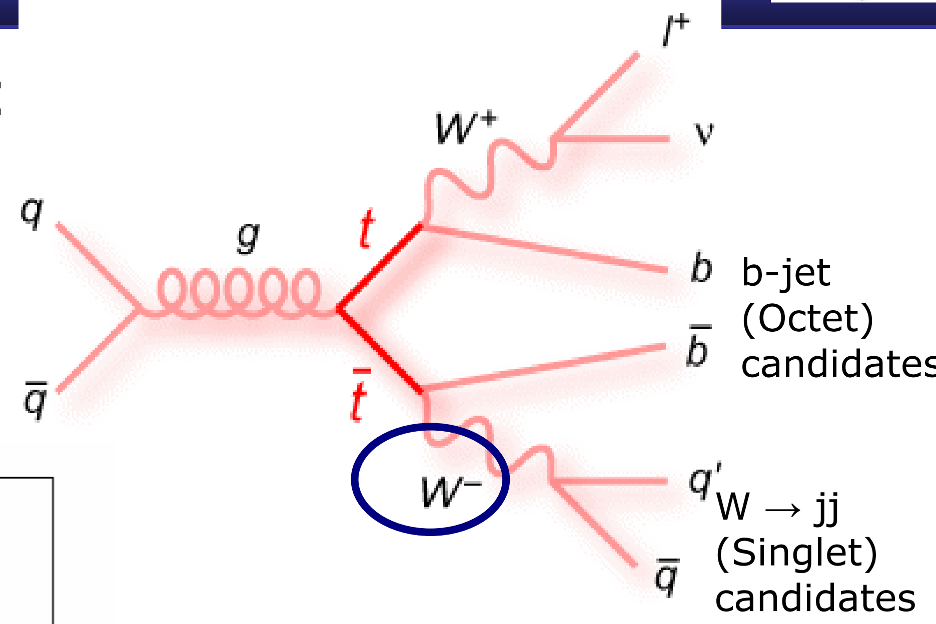


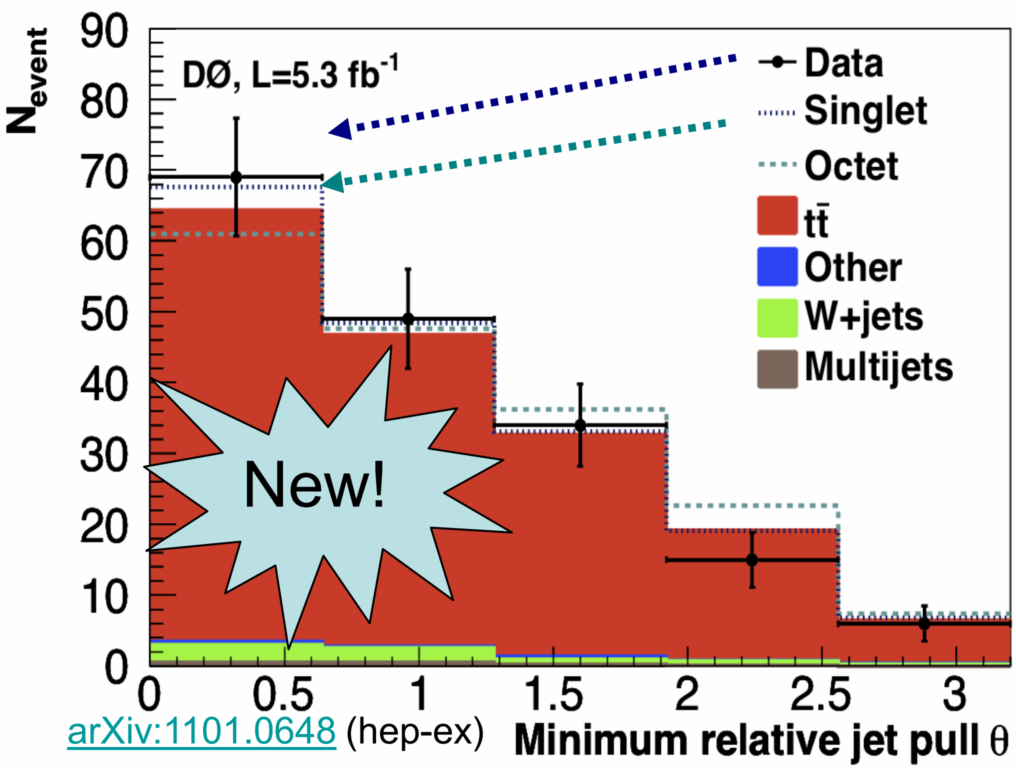


Jet Color Flow Measurement in tt

- Proof of principle in tt events:

Test if W_{had} is singlet or octet – $f_{singlet}$ =1?





arXiv:1101.0648 (hep-ex)

$f_{Singlet}$=0.56±0.38(stat+syst) ±0.19(MC stat)

First study of color flow in tt events!

Top Quark Properties Measurements

Property	Run II Measurement	SM prediction	Lumi (fb^{-1})
m_t	Tevatron: 173.3 ± 1.1 GeV		4.3-5.6
σ_{ttbar} (m_t=172.5 GeV) σ_{ttbar} (m_t=172.5 GeV)	CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb D0: $7.78^{+0.77}_{-0.64}$ pb	$7.46^{+0.48}_{-0.67}$ pb / $6.41^{+0.51}_{-0.42}$ pb	4.5 1
$\sigma_{singletop}$ (@m_t=170 GeV)	Tevatron: $2.76^{+0.58}_{-0.47}$ (stat+syst)	2.86±0.8 pb	3.2-2.3
$\lvert V_{tb}\rvert$	Tevatron: 0.91 ± 0.08 (stat+syst)	1	3.2-2.3
σ(gg->ttbar)/σ(qq->ttbar)	D0: 0.07+0.15-0.07(stat+sys)	0.18	1
m_t - m_{tbar}	D0: 3.8 ± 3.7 GeV CDF -3.3±1.7 GeV	0	1
$\sigma_{ttbar+jets}$ (@m_t=172.5 GeV)	CDF: 1.6 ± 0.2 (stat) ± 0.5 (syst)	1.79+0.16 -0.31 pb	4.1
$c\tau_{top}$	CDF: 52.5μm @ 95%C.L.	10^{-10} μm	0.3
Top width	D0: Γ_t=2.05 +0.57 -0.52 GeV CDF: Γ_t < 7.6 GeV @ 95%C.L.	1.26 GeV	1
BR(t->Wb)/BR(t->Wq)	CDF: >0.61 @ 95% C.L. D0: $0.97^{+0.09}_{-0.08}$ (stat+syst)	1	0.2 0.9
W-boson Helicity	CDF: F_0=0.88 ±0.11 ±0.06 F_+=-0.15 ± 0.07±0.06 D0: F_0=0.67±0.08(stat)±0.07 (syst) F_+=0.02±0.04(stat)±0.03 (syst)	F_0 = 0.7 F_+ = 0	2 5.4
Charge	CDF: 4e/3 excluded with 87% C.L. D0: 4e/3 excluded at 92% C.L.	2/3	1.5 0.37
Spin correlations	CDF: κ = 0.7 ±0.6 ±0.3 (lj) D0: κ = $-0.2^{+0.6}_{-0.5}$ (stat + syst) (ll)	$0.78^{+0.027}_{-0.022}$	5.0 4.2
Charge asymmetry	CDF: 0.16 ± 0.07 % D0: 0.08 ± 0.04 %	0.05 +- 0.015 0.01 + 0.02 -0.01	5.3 4.3

Watch this

Summary

- Top Physics vibrant at the Tevatron!
  - Already 3 new results this year ☺
- Precision era in top quark physics
  - Top quark mass <1% will be a Tevatron legacy measurement for years to come
  - Precision of total $t\bar{t}$ pair production cross section requires (N)NLO
  - Beginning to probe $t\bar{t}$ pair production differential distributions ~ (N)NLO
  - Electroweak single top production established
- Mapping Top Quark Properties
  - Width, spin, helicity, anomalous V_{tb} … so far no surprises
  - Still most measurements statistics limited
- Standard Model prevails but a few intriguing effects
  - Weak t' limits
  - A_{FB}
- Still a factor of ~2 more data to come – or possibly more
  - Stay tuned