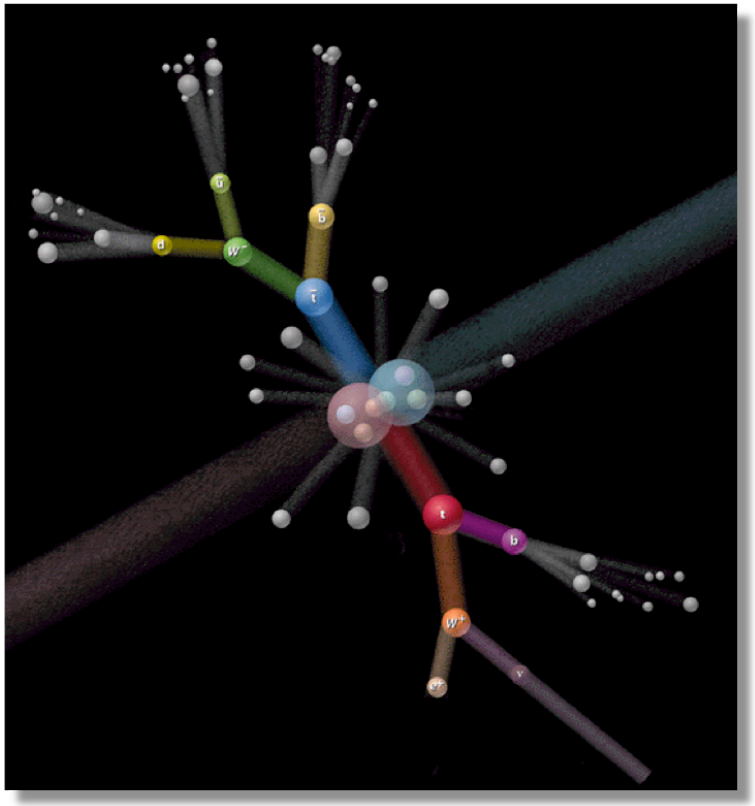
Top Quark Measurements
トップクォークの測定



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29th Physics in Collisions
Kobe, August 31st, 2009

Results from the Tevatron, on behalf of the CDF and D0 Collaborations

Thank you to the following people in helping preparing these slides:
Florencia Canelli, Veronica Sorin, Doug Glenzinski, Christian Schwanenberger

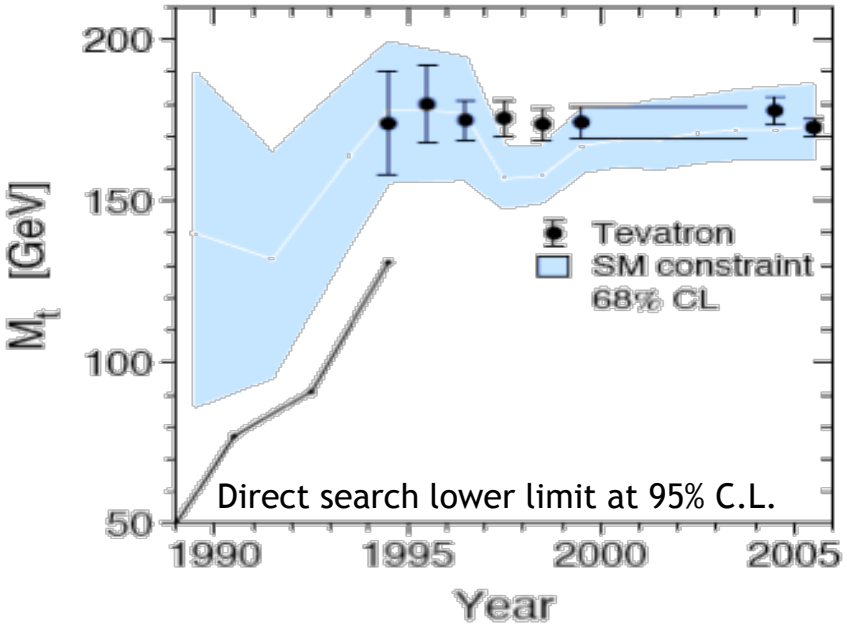
The Road to the Top

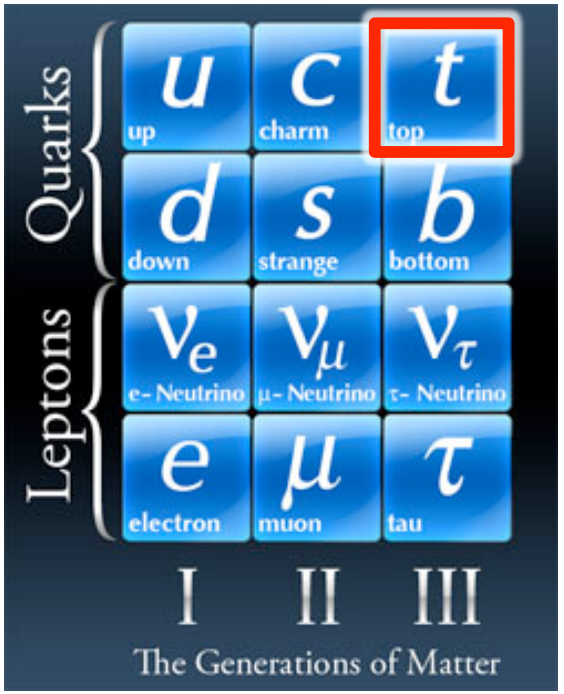
Discovery of top quarks in 1995 by CDF and D0 at the Tevatron

- *Indirect experimental/theoretical evidence emerged in 1970's*

– *CP violation in Kaon system*

– *Discovery of b-quark (1977) and it's properties require SU(2) partner*

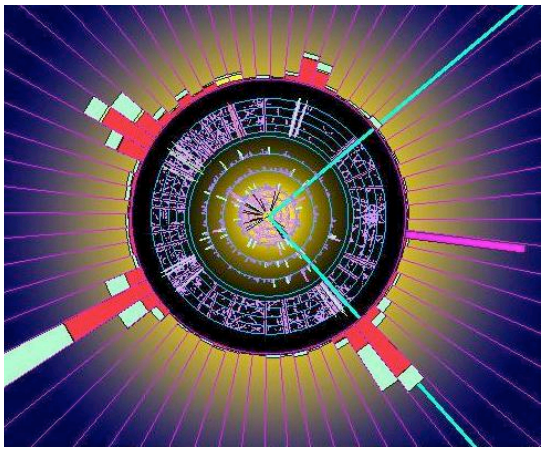




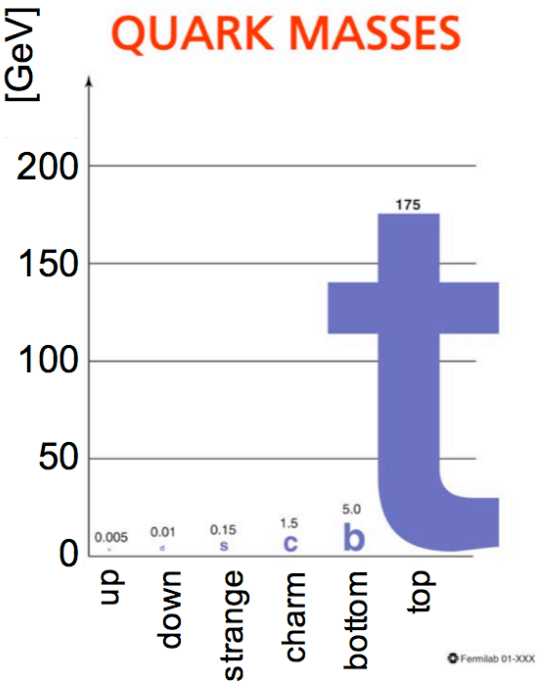
– *Precision EWK measurements in 1990's indicated a heavy top quark*

Why Study the Top Quark?

- Exciting physics!
  The Tevatron observation in 1995 ended a 20 year quest for the top



- Unanswered question
  Why is the top so heavy? m_{top} ~175 GeV ~ $m_{Au\text{-}atom}$!?



- Mechanism for EWSB couples to mass
  - *Top quarks are a good place to look for evidence of new physics – is top special?*

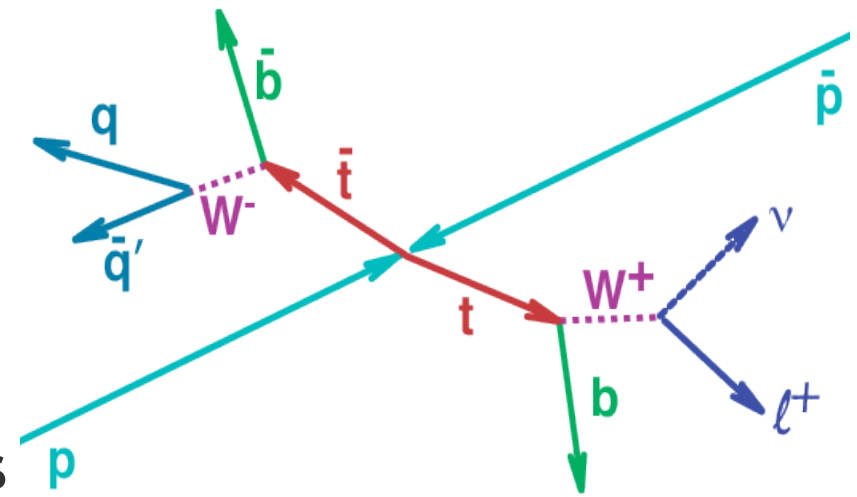
- Large mass comes with interesting features
  - *Decay through $t \rightarrow Wb$ kinematically allowed*
  - *Top quarks decay before they hadronize*
    Study properties of a "bare quark"

Physics with Top Quarks

- New Physics contributions
  - Might affect top-quark **production**
  - Might affect top-quark **decay**
  - Might affect top-quark **properties**
  - Might "contaminate" top-quark event samples
- *Tevatron program explores all these possibilities*

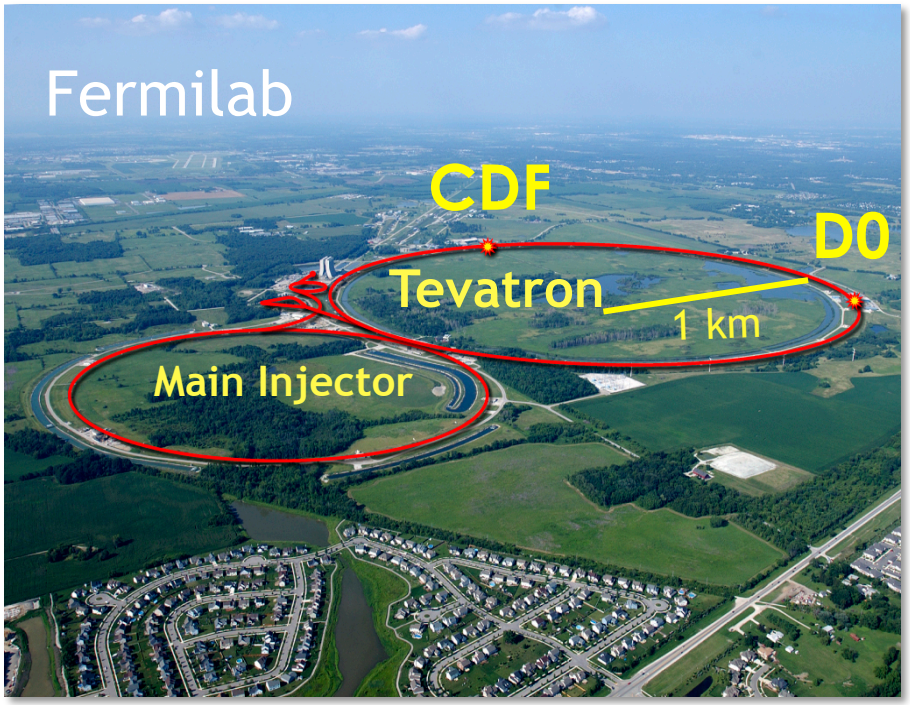
Top Quarks as a Window to new Physics

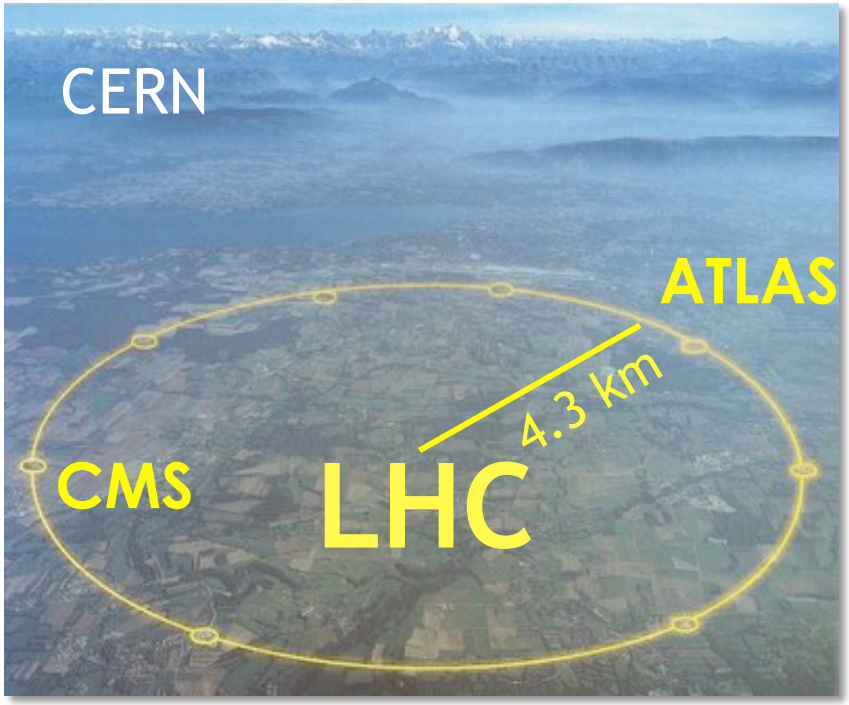
- Exploring top quark **production**
  - *Top pair production*
  - *Single top production*
- Exploring top quark **decay**
  - *W boson helicity in top decays*
  - *Probe the W-t-b vertex*
- Exploring top quark **properties**
  - *Mass, width, charge, spin*
- Explore exotic sources of top quarks
  - *Resonant top production, t', squarks*
  - *Forward-backward asymmetries*



Producing Top Quarks

~ The Energy Frontier ~





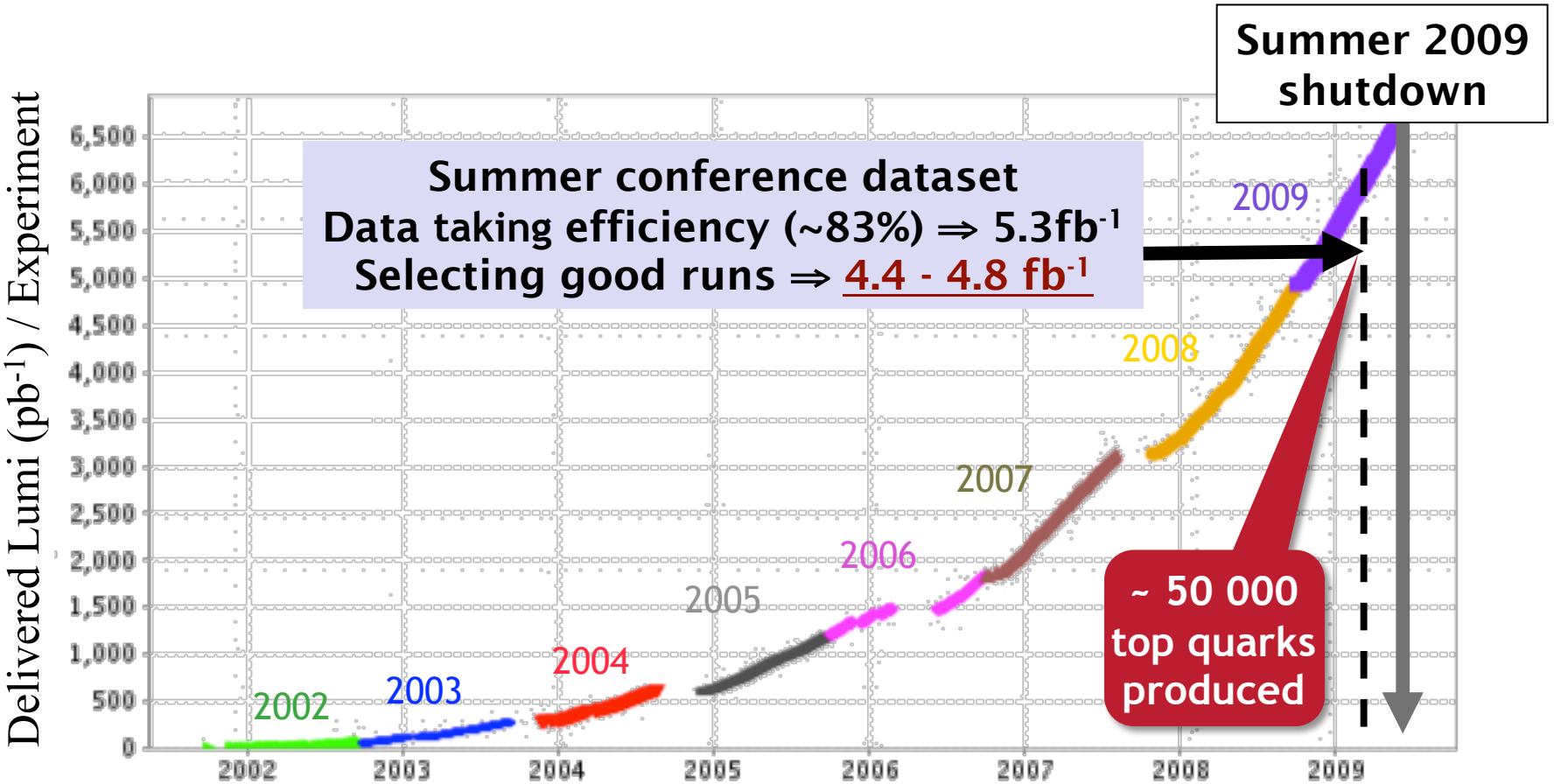
- 1.96 TeV $p\bar{p}$ collider
- Run II started in 2001
- *Record Inst. Lum. $3.6 \cdot 10^{32}$ [$cm^{-2}sec^{-1}$]*

Most of the results

- 14 TeV pp collider
- Restart in Nov 2009 at 7 TeV
- *Inst. Lum. 10^{32}-10^{34} [$cm^{-2}sec^{-1}$]*

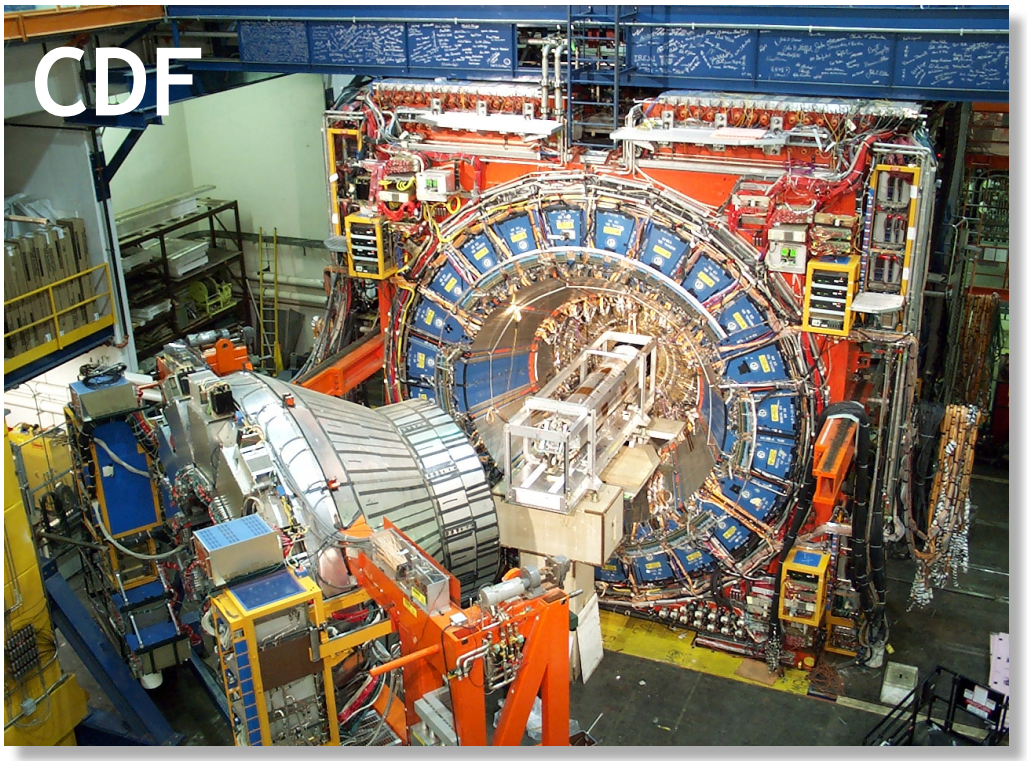
Brief outlook

Tevatron Performance



Run I: 1990-1995 110 pb^{-1} / experiment
Run II: 2001-2010/11 up to 12 fb^{-1} / experiment (delivered)

Tevatron Experiments

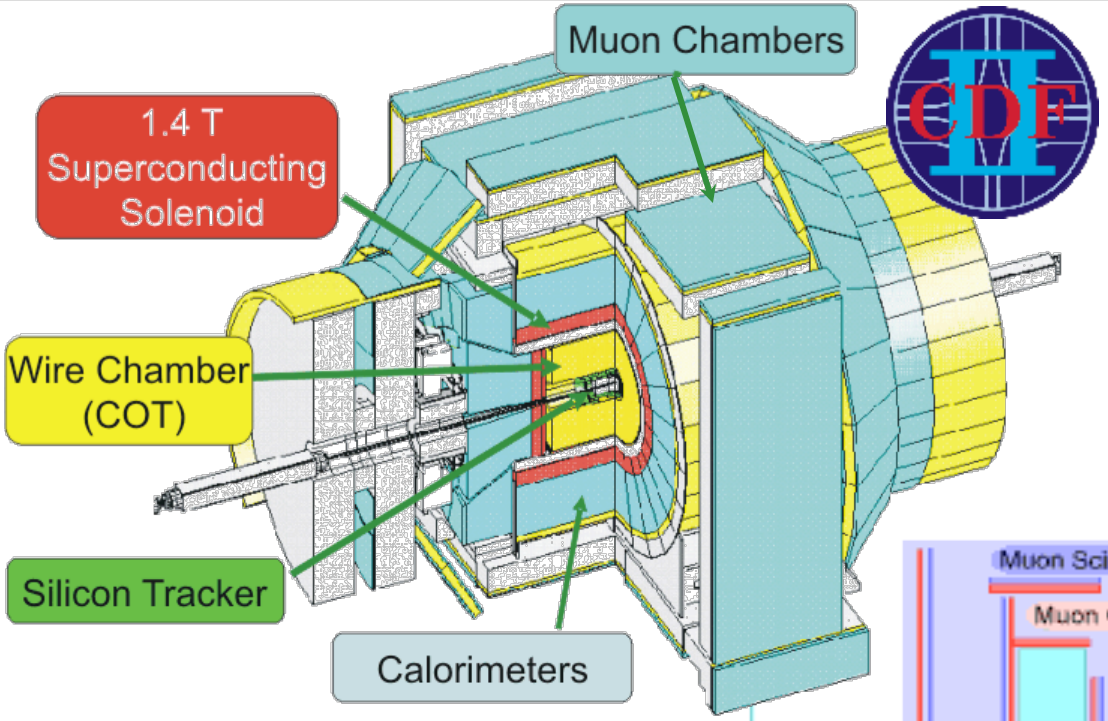


Two Experiments: CDF and D0

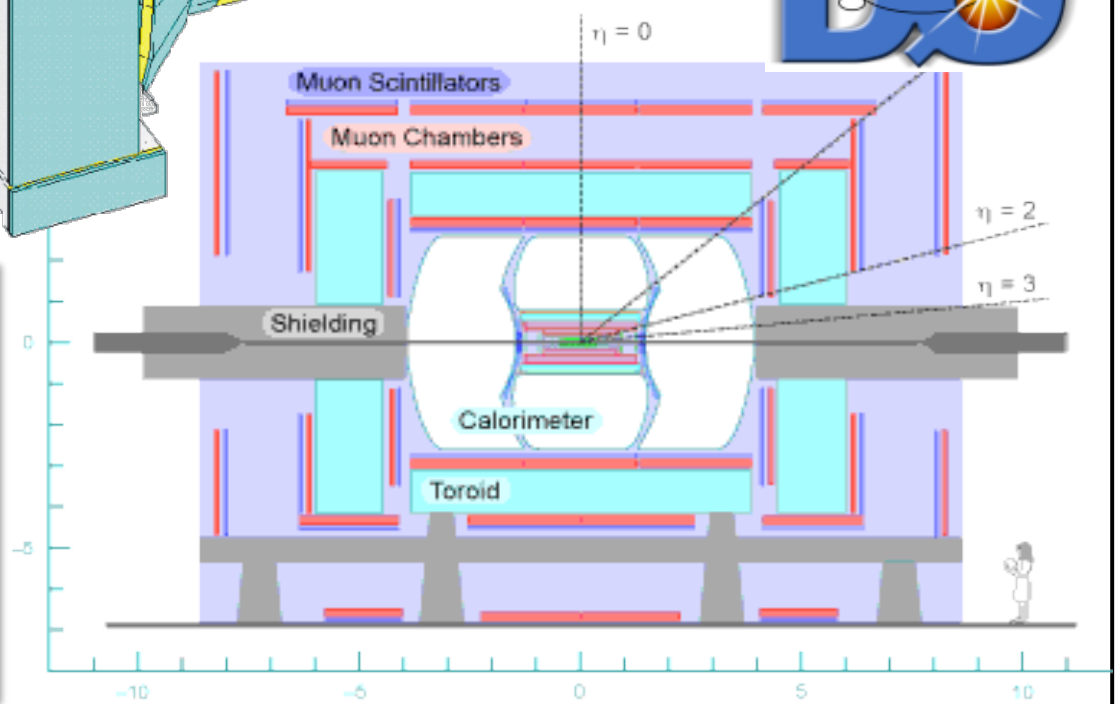
Multipurpose collider detectors

Large international collaborations, 600+ members each

Tevatron Run II Detectors

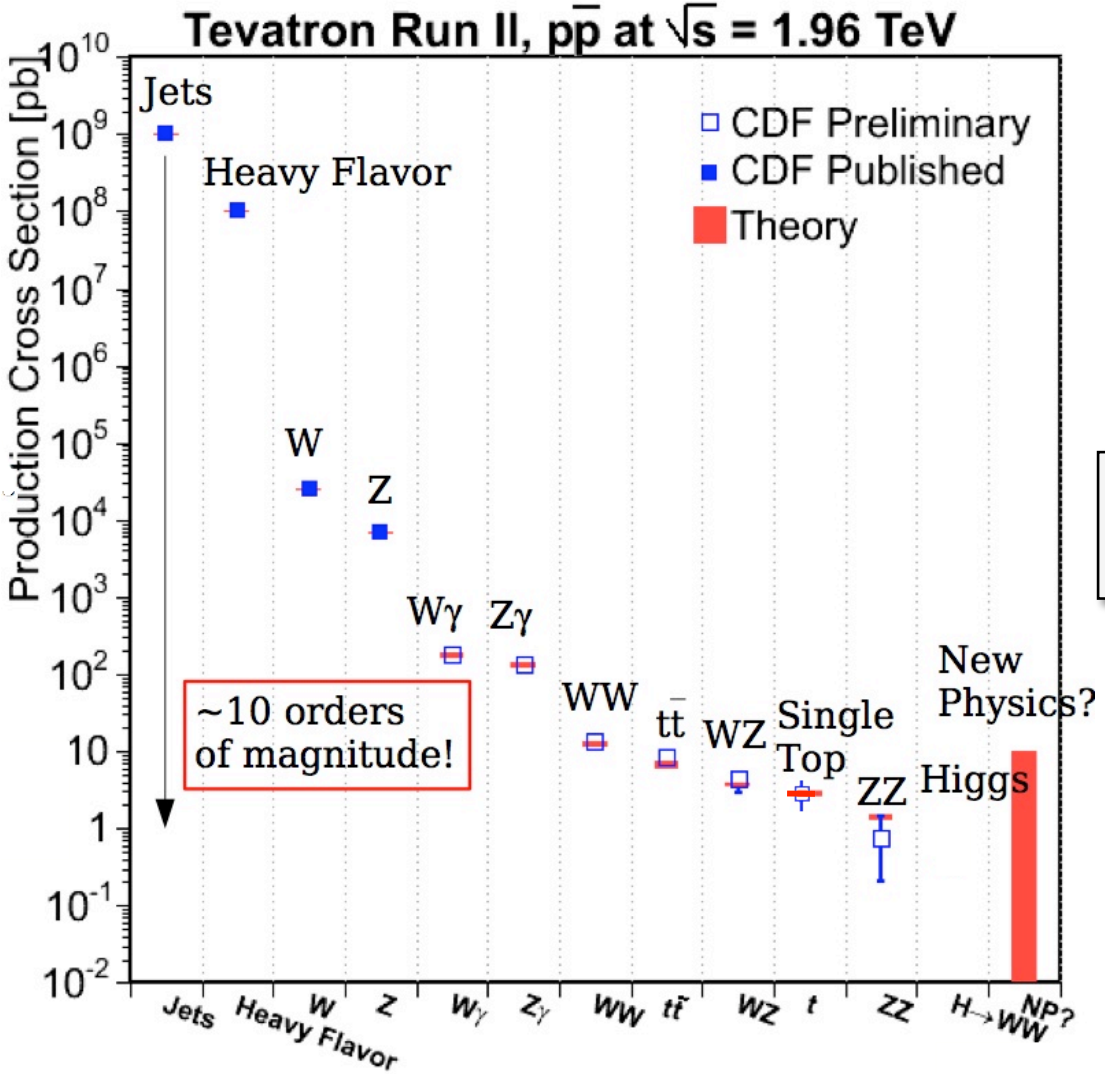


D0 and CDF in very efficient data taking mode since 2002



- Silicon strip detector for precision vertexing
- Precision tracking
- Calorimetry *(hermetic → missing E_T)*
- Muon systems

Tevatron Physics Program



Tevatron produces top, but that is *not* the only thing it makes..

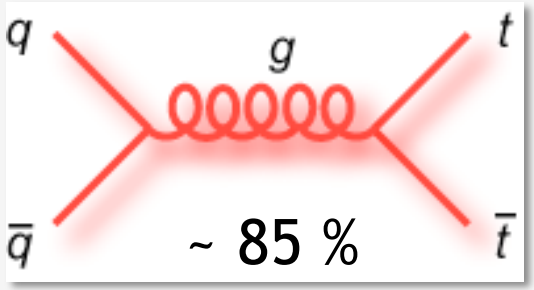
Top quarks are rare!
1 in 10 billion inelastic collisions..

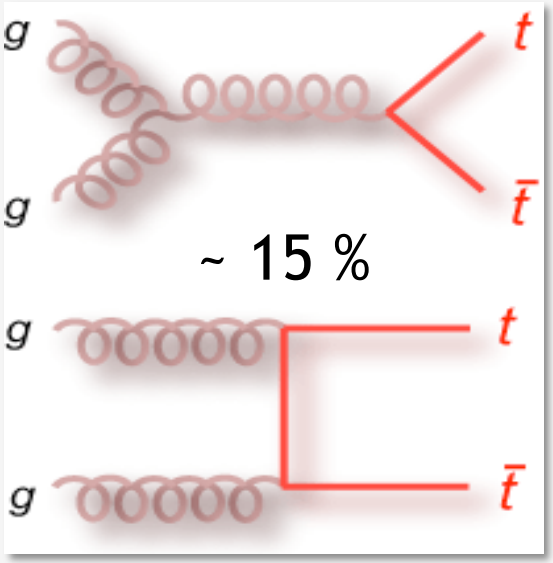
All other processes show up as "background" in one way or another..

Top Quark Production at the Tevatron

Production

In Pairs

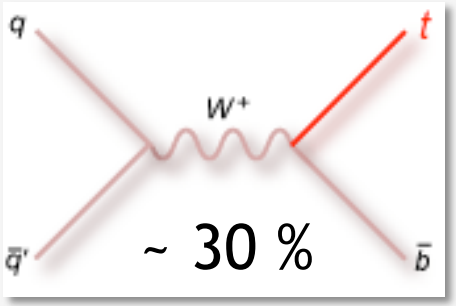


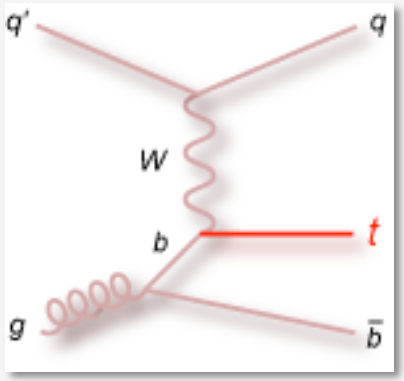


$\sigma_{NLO} = 7.4^{+0.5}_{-0.7}$ pb

JHEP 0809, 127 (2008)

Single





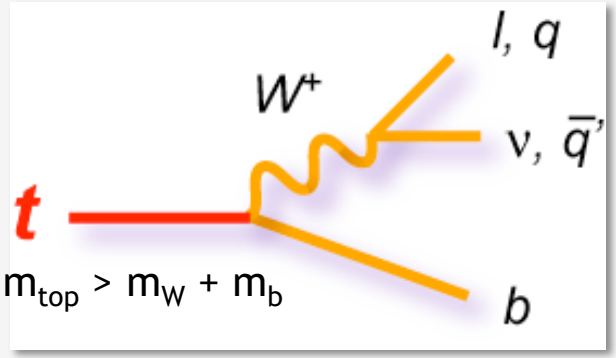
~ 70 %

$\sigma_{NLO} = 3.0 \pm 0.4$ pb

PRD 66, 054024 (2002)

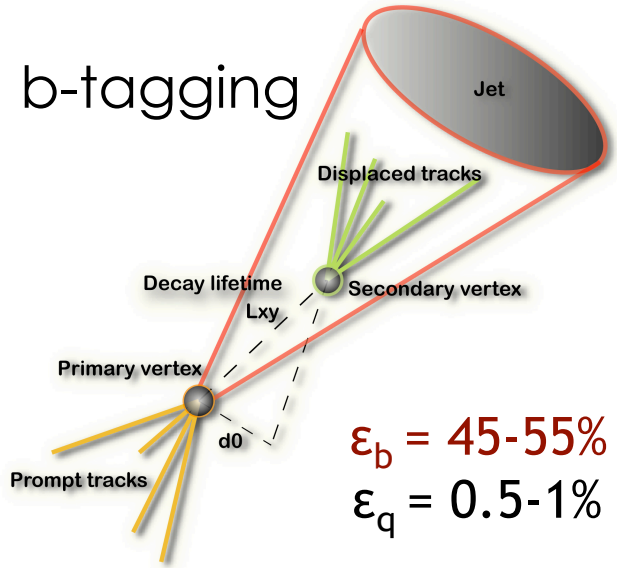
Decay

BR(t→Wb) ~100 %



$m_{top} > m_W + m_b$

b-tagging

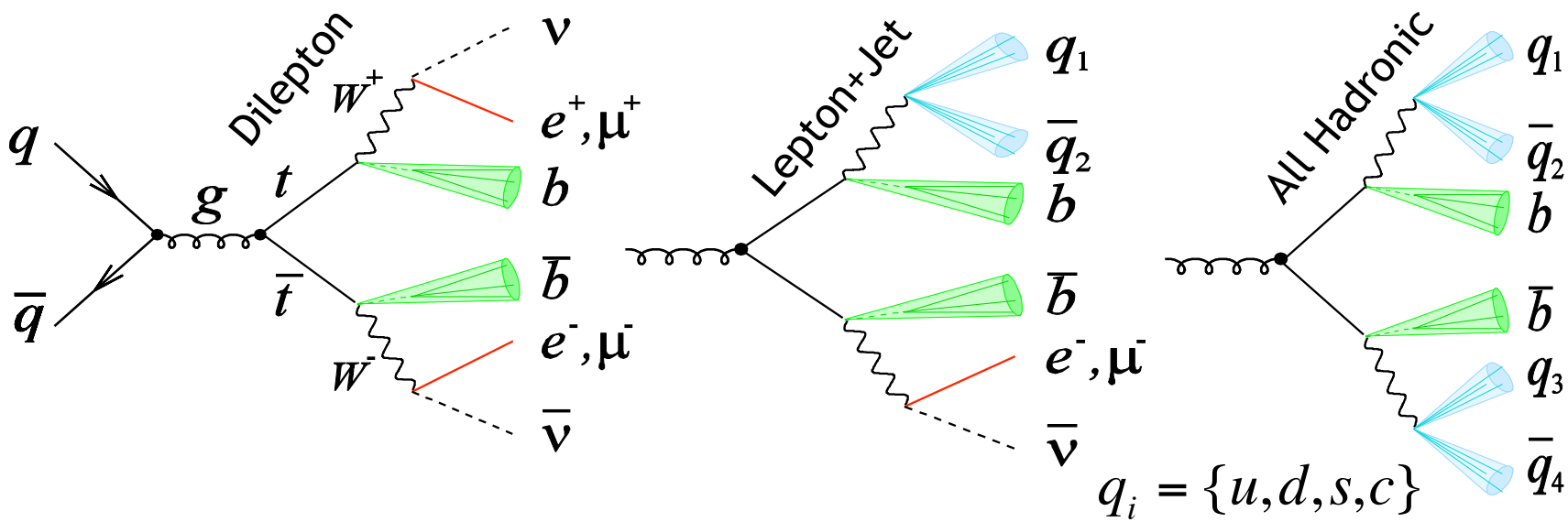


ε_b = 45-55%

ε_q = 0.5-1%

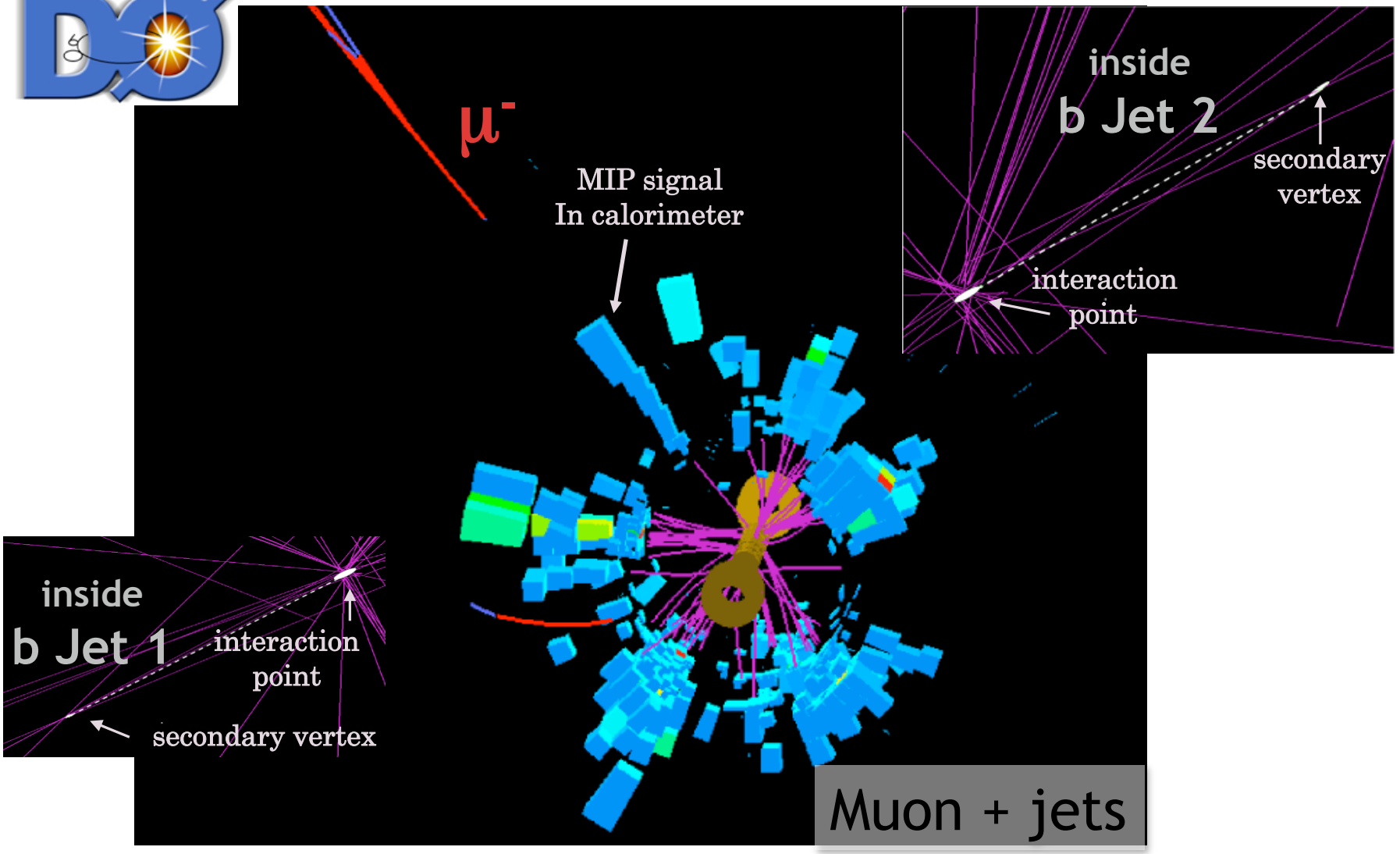
m_t=172.5 GeV

Top Quark Pair Production



- **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*

Collision Event Display



Top Quark Properties Measurements

Property	Run II Measurement	SM prediction	Lumi (fb^{-1})
m_t	CDF: 172.6 ± 0.9(stat) ± 1.2(syst) GeV D0: 174.2 ± 0.9(stat) ± 1.5(syst) GeV		4.3 3.6
σ_{ttbar} (m_t=172.5 GeV) σ_{ttbar} (m_t=170 GeV)	CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb D0: $7.84^{+0.46}_{-0.45}$ (stat)$^{+0.66}_{-0.54}$ (syst) $^{+0.54}_{-0.46}$ (lumi) pb	7.4 ± 0.6 pb 8.06 ± 0.6 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
$\|V_{tb}\|$	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	0	1
σ(tt→ll)/σ(tt→l+jets)	D0: $0.86^{+0.19}_{-0.17}$ (stat+syst)	1	1
σ(tt→τl)/σ(tt→ll + l+jets)	D0: $0.97^{+0.32}_{-0.29}$ (stat+syst)	1	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	CDF: <13.1 GeV @ 95%C.L.	1.5 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=0.62 ± 0.11 F_+=-0.04 ± 0.05 D0: F_0=0.490±0.13 F_+=-0.110±0.059(stat)±0.052 (syst)	F_0 = 0.7 F_+ = 0	2 2.7
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 = 0.32 + 0.55 - 0.78, -0.46 < K < 0.87 @ 68%C.L. D0: κ = $-0.17^{+0.65}_{-0.53}$ (stat + syst)	$0.78^{+0.027}_{-0.022}$	2.8 4.2
Charge asymmetry	CDF: 0.19 ± 0.07(stat) ± 0.02(syst) % D0: 12 ± 8 (stat) ± 1 (syst) %	0.05 +- 0.015	3.2 0.9

Top Quark Production

トップクォークの生成

Analysis Strategies

- **Counting Experiment**

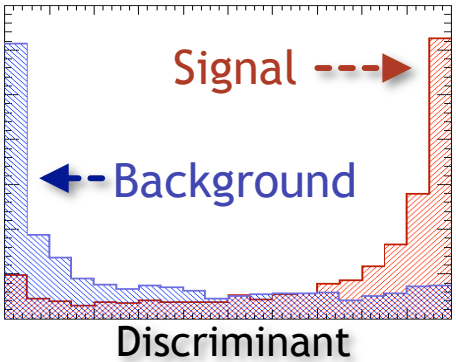
$$\sigma = \frac{N_{observed} - N_{background}}{\int \text{Luminosity}\, dt \cdot \varepsilon}$$

  - Establish event selection and estimate background

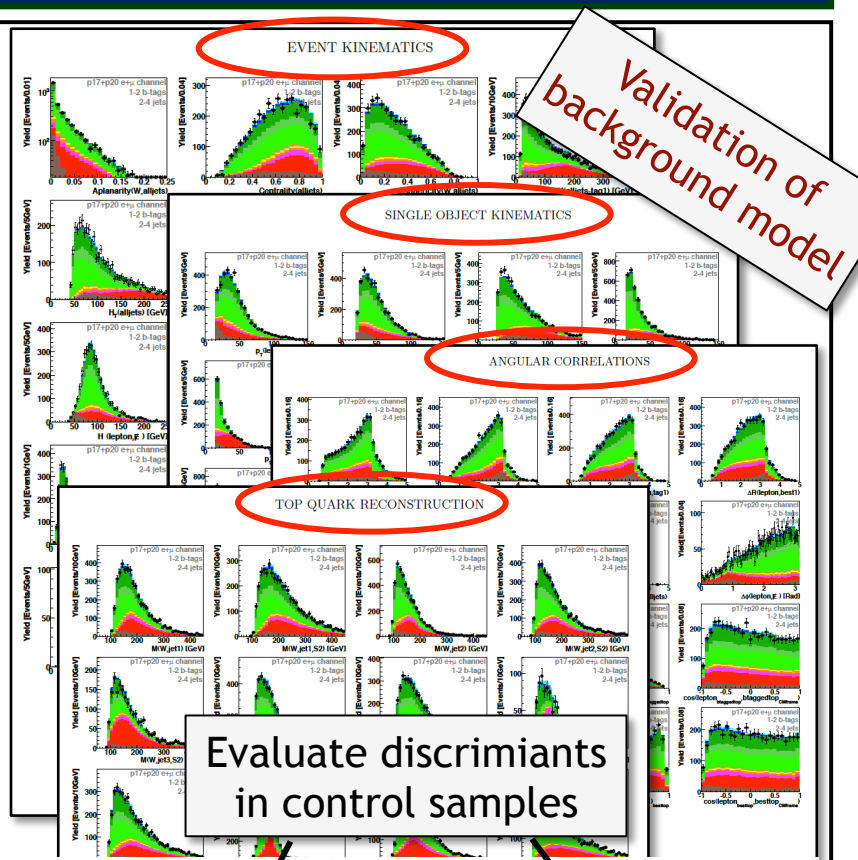
- **Template Analysis**
  - Fit 1D signal + background distribution to data

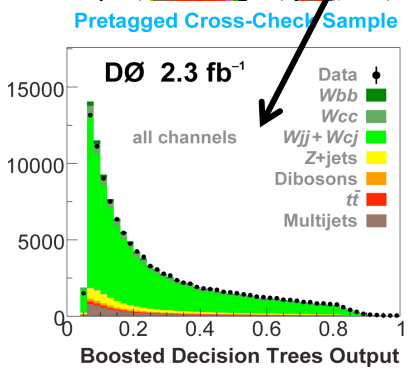
- **Matrix Element**
  - Use tree level matrix elements to *classify* signal and background like events

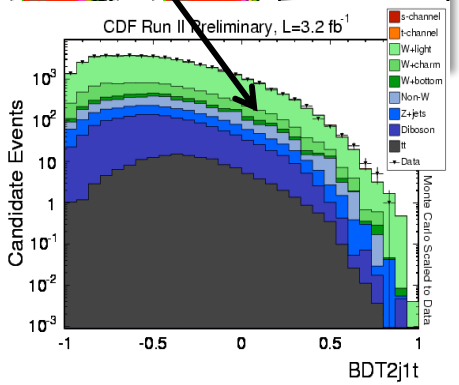
- **Neural Networks, Decision Trees**
  - Machine learning algorithm to *classify* signal and background events based on many input features mapped to a 1D distribution



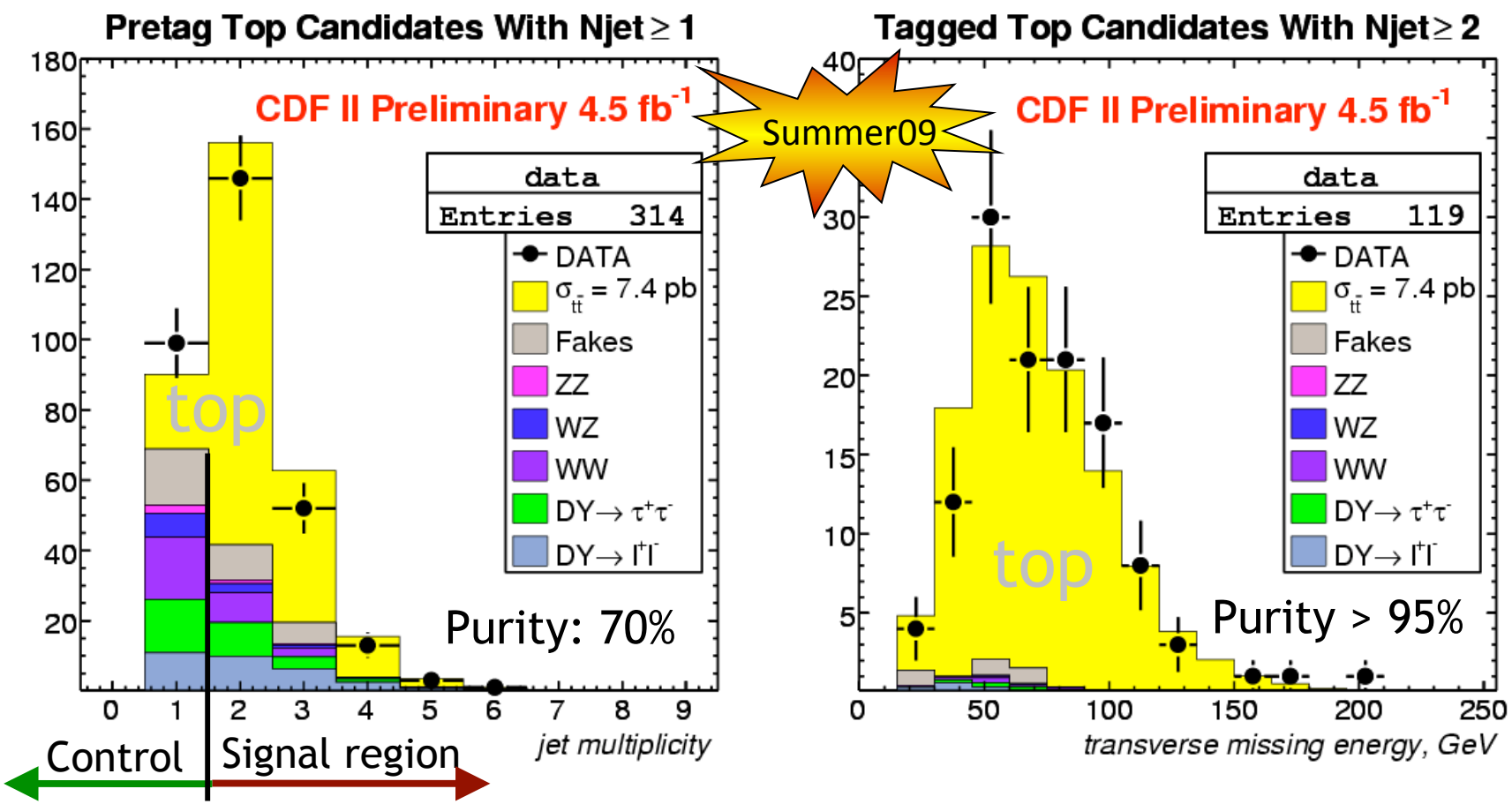
Multivariate techniques are more sensitive but require careful validation work to evaluate systematics.
Example: single top







Dilepton Channel

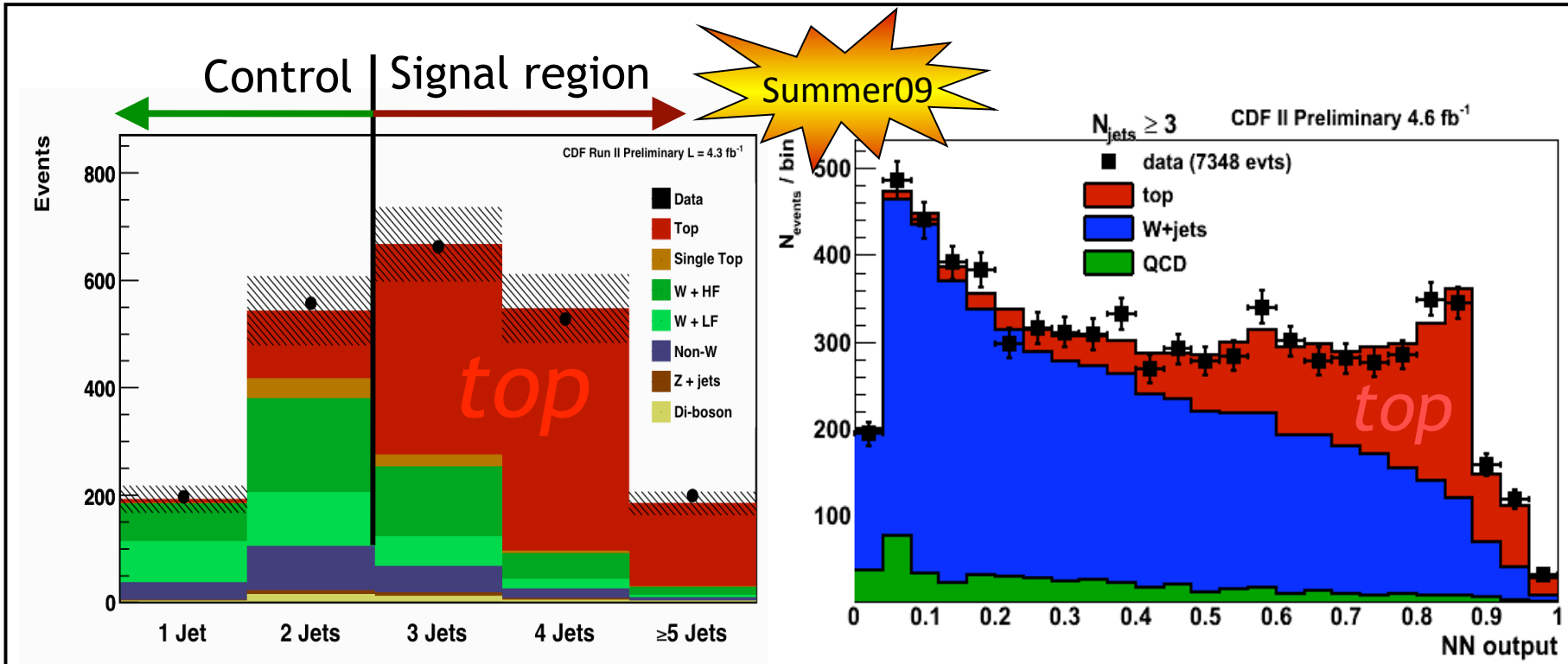


CDF (4.5 fb^{-1}, m_t= 172.5 GeV), pre-tagged, :
σ_{tt}=6.6±0.6(stat)±0.4(syst)±0.4(lumi) pb

CDF (4.5 fb^{-1}, m_t= 172.5 GeV), b-tagged:
σ_{tt}=7.3±0.7(stat)±0.4(syst)±0.4(lumi)pb

High purity sample, good test of signal model

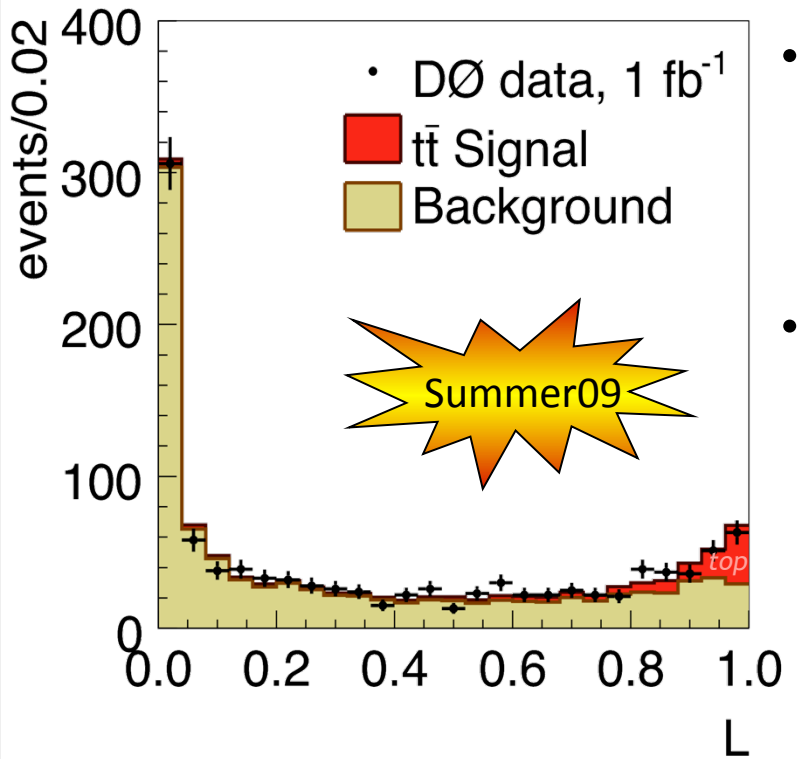
Lepton + Jets Channel



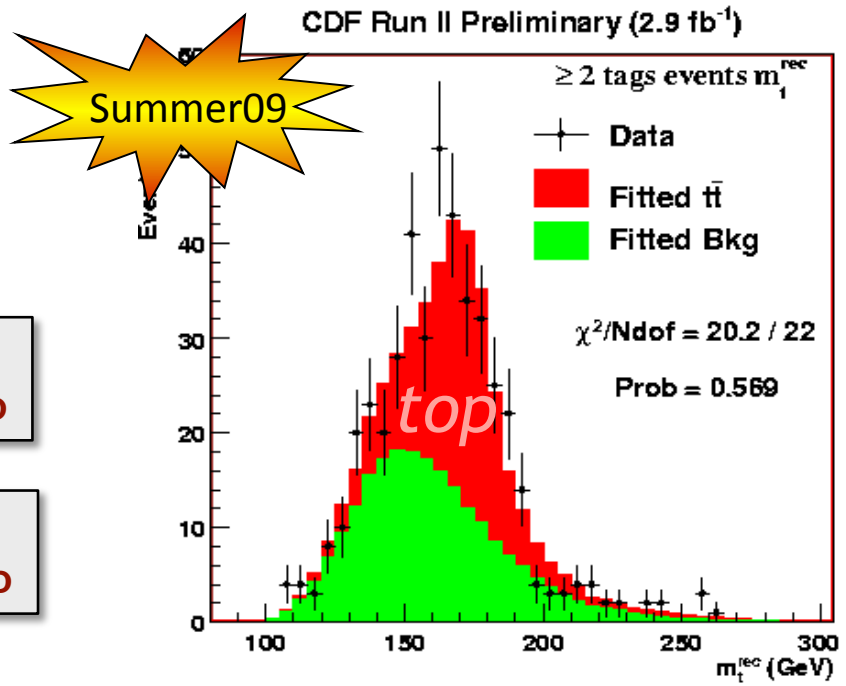
- Measure top using b-tagging *or* using topological Neural Network
- Luminosity is the largest uncertainty in both measurements
  - Reduced by normalizing to *Z cross section* $\sigma_{t\bar{t}} = R \bullet \sigma_Z^{theory}$

CDF (4.3 fb^{-1}, m_t= 172.5 GeV), b-tagged:	CDF (4.6 fb^{-1}, m_t= 172.5 GeV), topo NN:
σ_{tt}=7.1±0.3(stat)±0.6(syst)±0.1(norm)pb	σ_{tt}=7.6±0.4(stat)±0.3(syst)±0.1(norm) pb

All Hadronic Channel



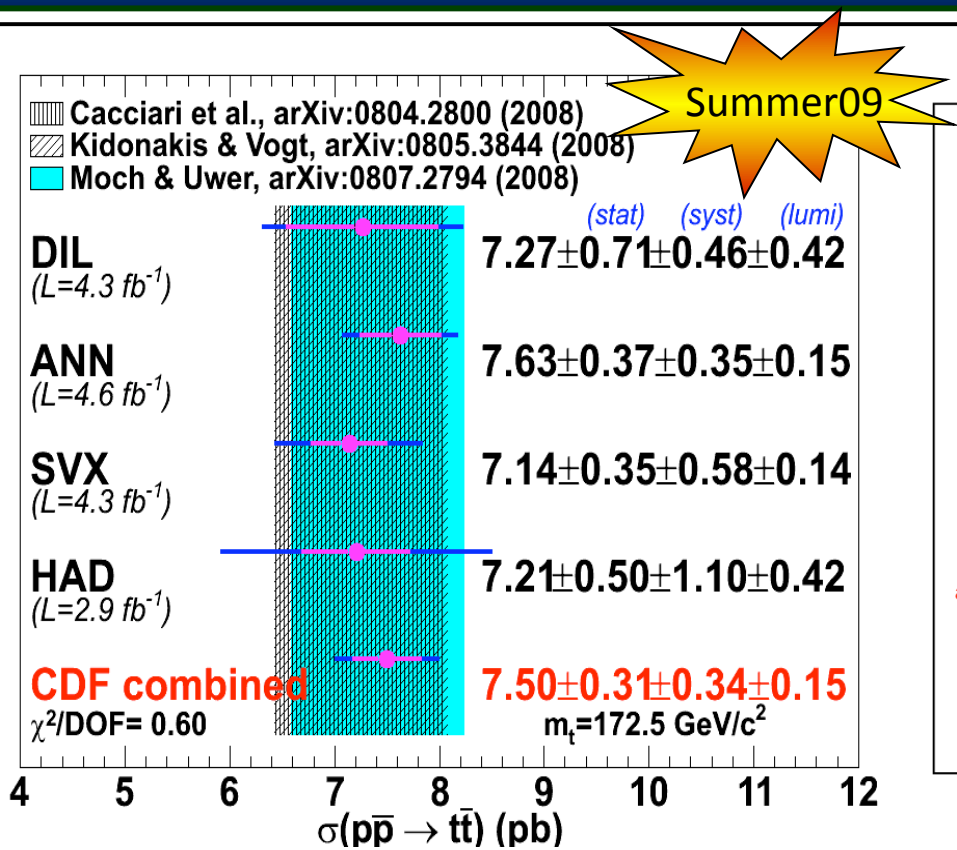
- Measurement in background dominated sample - enormous multijet background
  - Data driven background model
- Topological Neural Network to purify the sample (and measure properties)

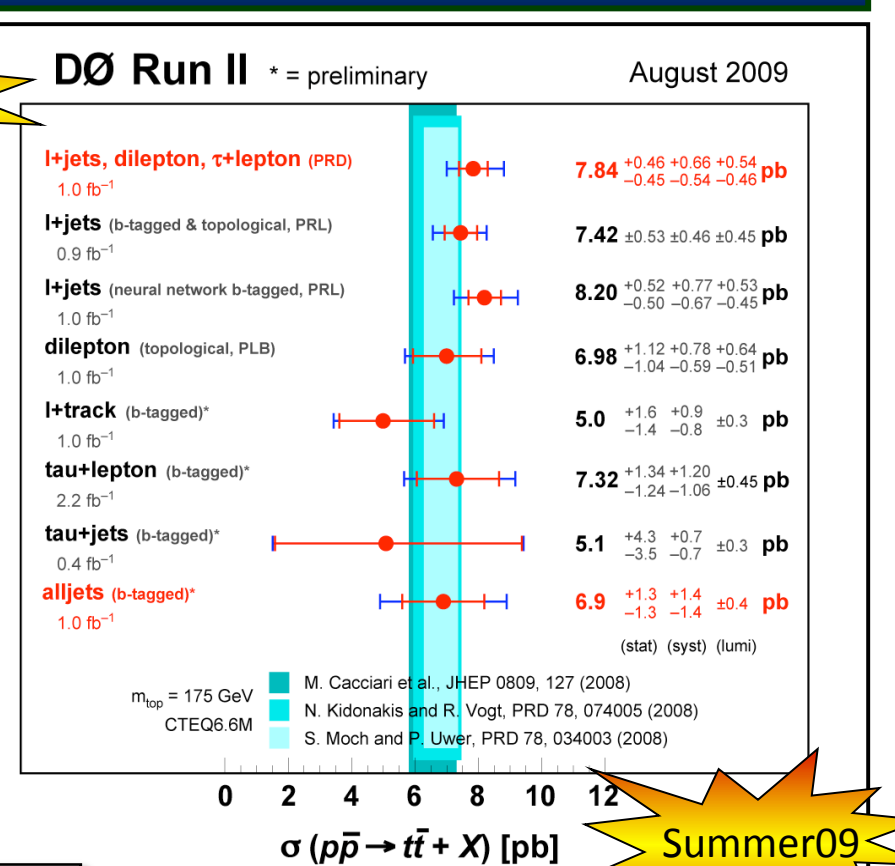


D0 (1 fb^{-1}, m_t= 175 GeV):
σ_{tt} = 6.9 ± 1.3(stat) ± 1.4(sys) ± 0.4(lumi) pb

CDF (2.9 fb^{-1}, m_t= 172.5 GeV):
σ_{tt}= 7.2 ± 0.5(stat) ± 1.4(syst) ± 0.4(lumi) pb

Combination





Combination has precision of 6.5%!

- Consistency among channels, experiments and *with theory*
- All channels limited by systematic uncertainties

- Tevatron combination underway -

Finding Single Top Quarks

シングルトップクォークの探索

Single Top Quarks

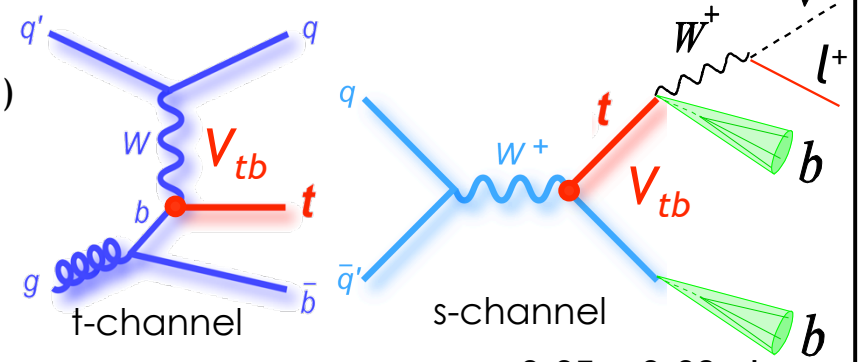
- Predicted in ~1985
  - t-channel: Willenbrock and Dicus, PRD 34, 155 (1986)
  - s-channel: Cortese and Petronzio, PLB 253, 494 (1991)

- Not an easy measurement
  - Small cross section
  - Less striking signature compared to top pairs
  - Large backgrounds with large uncertainties

- Direct access to CKM element $|V_{tb}|$

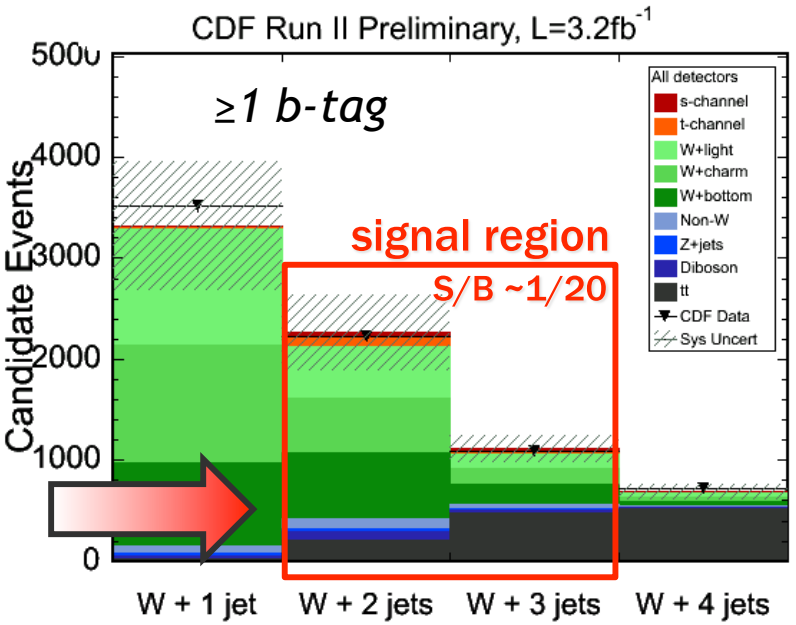
- Need advanced techniques + *b* tagging to separate dwarf signal from background
  - *Likelihood Function*
  - *Neural Networks*
  - *Decision Trees*
  - *Matrix Elements*
  - *Neuro Evolution*

EWK single top quark production



σ_{NLO} = 2.05 ± 0.22 pb σ_{NLO} = 0.95 ± 0.08 pb

PRD 66, 054024 (2002) m_{top}=172.5 GeV/c^2



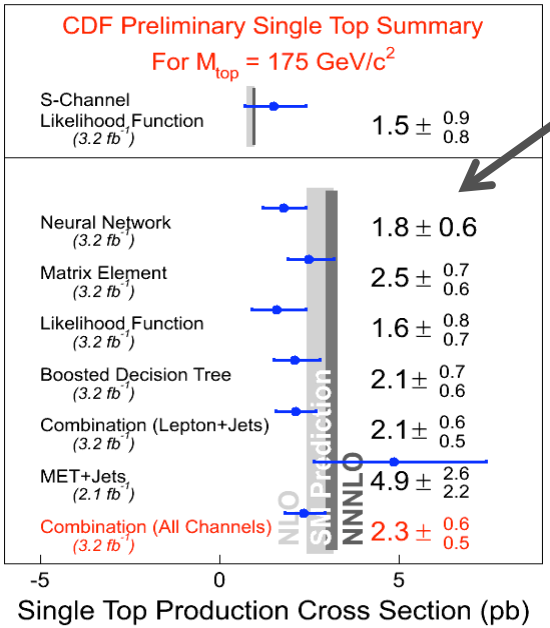
Single Top

CDF and D0 reported observation of single top quark production on March 4th 2009

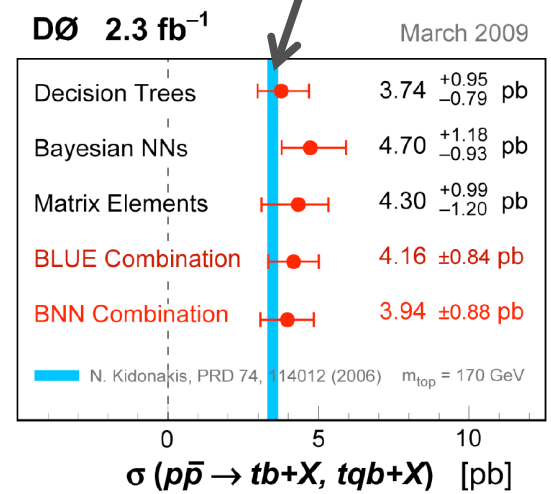
Phys. Rev. Lett. 103, 092001
Phys. Rev. Lett. 103, 092002

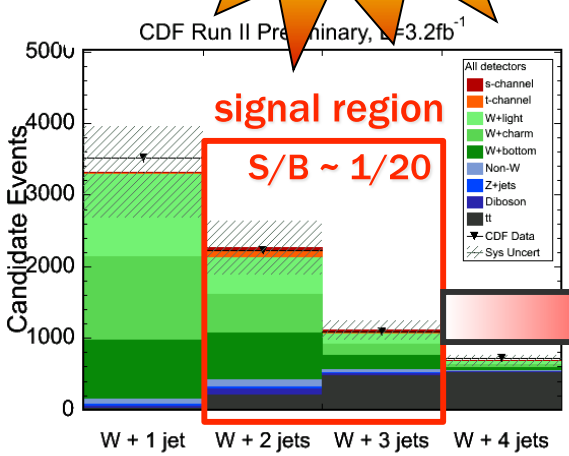
	Data	Sensitivity	Observed
CDF	3.2 fb^{-1}	>5.9 sd	5.0 sd
D0	2.3 fb^{-1}	4.5 sd	5.0 sd

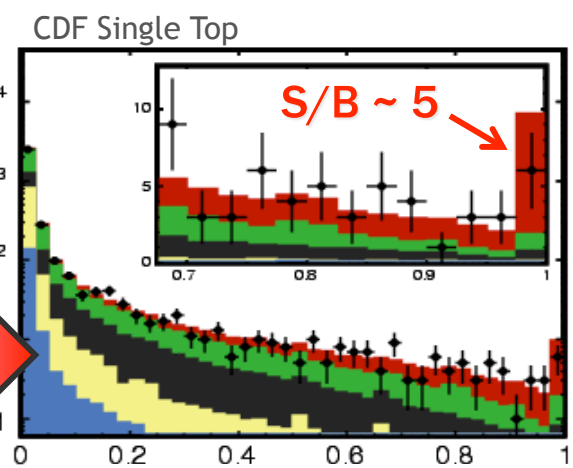
CDF & D0
5σ Observation!



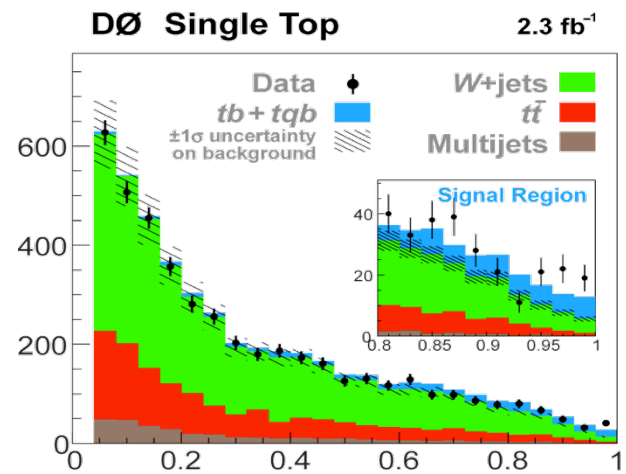
Consistency among results using different techniques







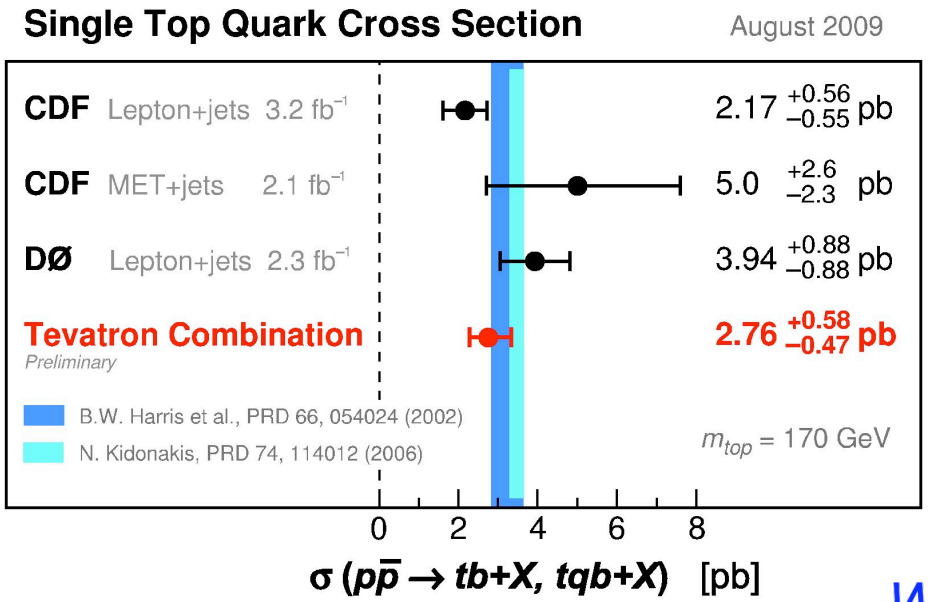
CDF Combination Output

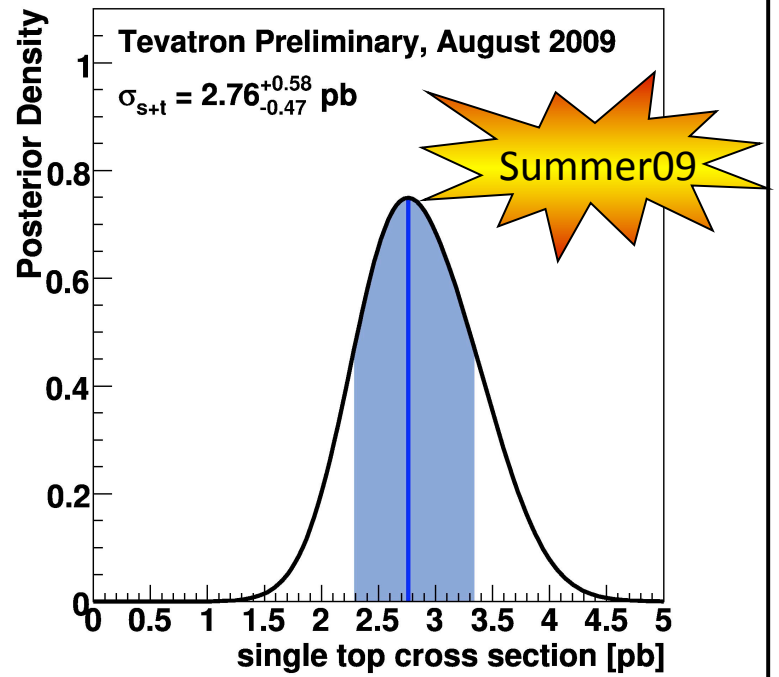


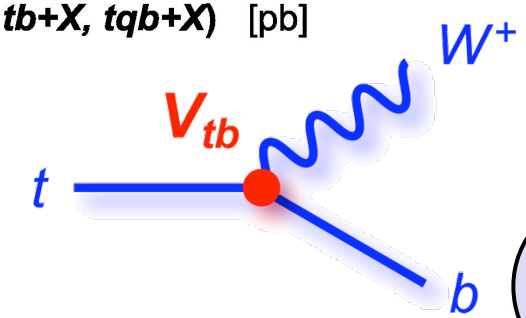
D0 Combination Output

Tevatron Combination and $|V_{tb}|$

- Combination of CDF and D0 results







- $\sigma_{Single\ Top} \sim V_{tb}^2$

<u>Assume</u>:

a) $|V_{ts}|, |V_{td}| << |V_{tb}|$ (from top BR measure)

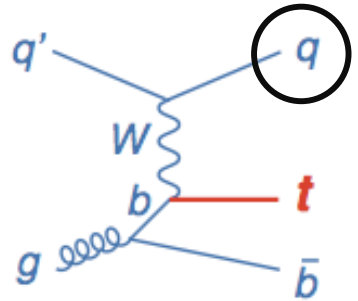
b) Pure (V-A) coupling

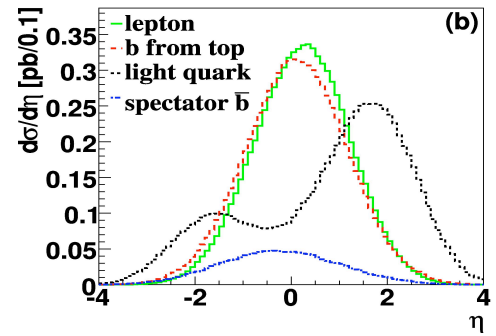
Tevatron (3.2 fb^{-1}):
σ_{s+t}=2.76 $^{+0.58}_{-0.47}$ (stat+syst) pb

Tevatron (3.2 fb^{-1})
$|V_{tb}|$=0.91 ± 0.08 (stat+syst)

Single Top – Channel by Channel

- Extract t-channel and s-channel contribution to single top signal
- New physics scenario can affect single top channels differently
  - *s-channel sensitive to new resonances*
  - *t-channel sensitive to FCNC*





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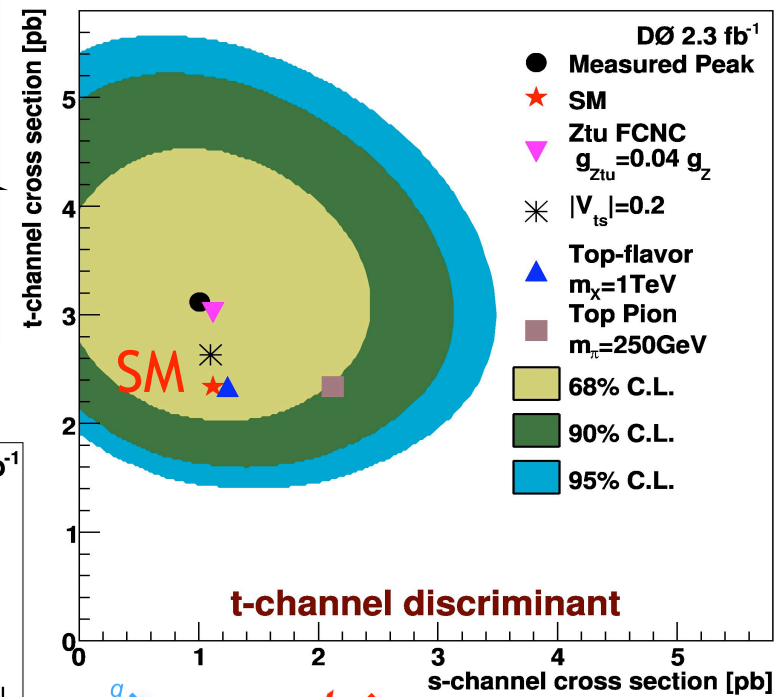
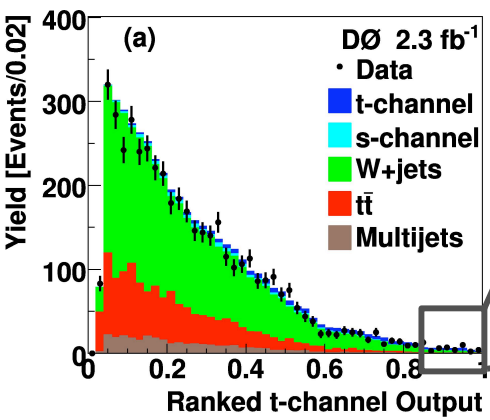
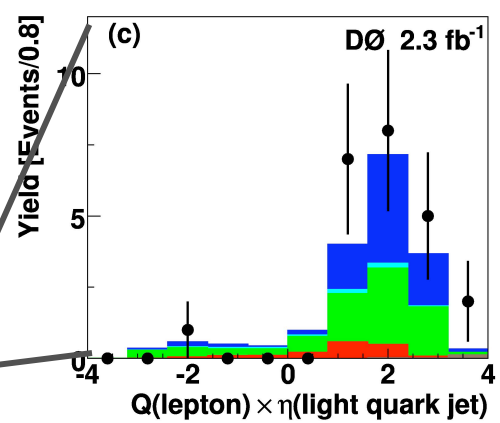
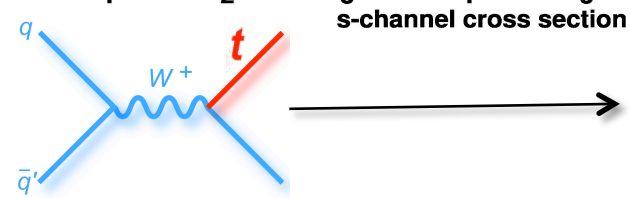
D0 (2.3 fb^{-1}):
σ_t=3.14 + 0.94 - 0.81(all) pb

Strong evidence with 4.8 sd!







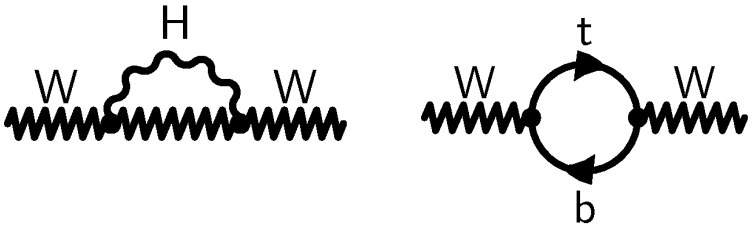


Top Quark Mass

トップクォークの質量

Top Quark Mass

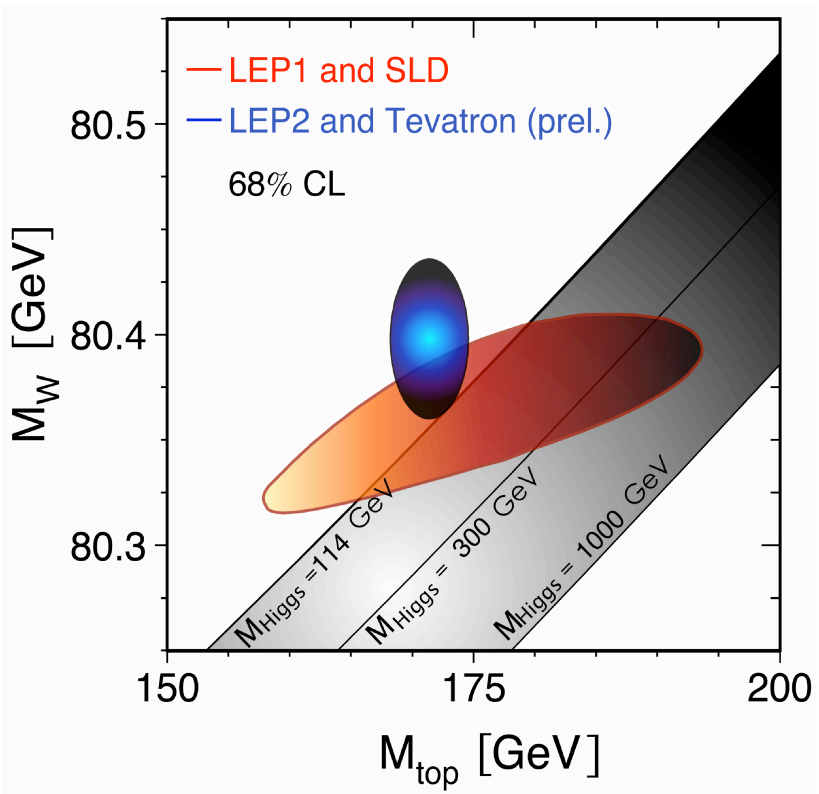
- Top quark mass is a fundamental parameter of the Standard Model



$\Delta M_W \propto \ln M_H$ $\Delta M_W \propto M_{top}^2$

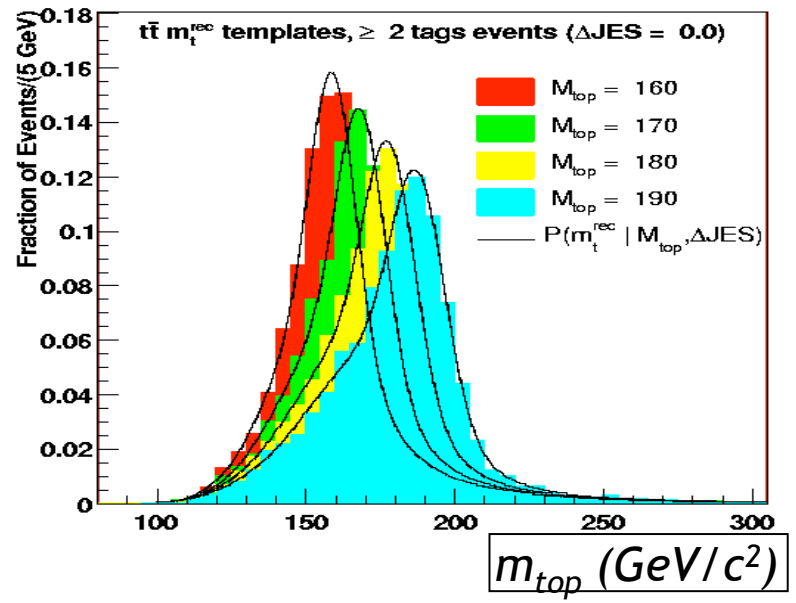
- Since m_{top} is very large, quantum loops involving top quarks are important when calculating precision observables ($sin\theta_W^2$, R_b, m_W, …)

- Measuring the *W* boson mass and *top* quark mass *precisely* allows for prediction of the mass of the Higgs boson and constrain new physics



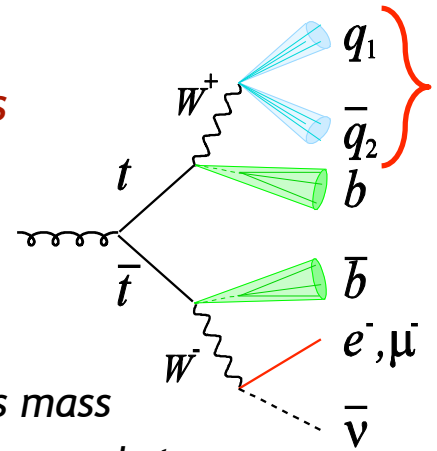
Top Quark Mass

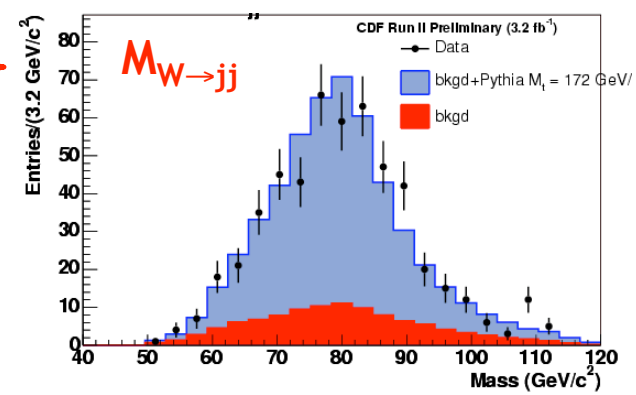
- Measured in 3 channels:
  - Dilepton (kinematics underconstraint)
  - Lepton+jets
  - All-hadronic



- Experimental Challenges
  - Measure jets not partons
  - Jet-parton assignment
  - QCD radiation

- Jet energy scale uncertainty dominates (~3%)
  - Can be reduced via *in situ* measurement from *W mass*





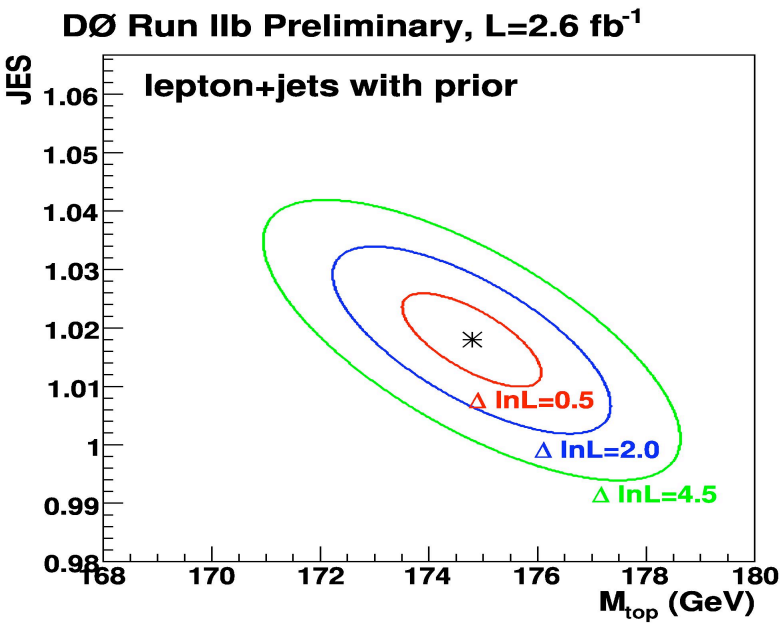
- Techniques
  - *Top reconstruction templates*
  - *Matrix Element Technique*
  - *"Indirect" top cross-section vs mass*
  - *"Subset of information" Lepton p_T, b-tag*

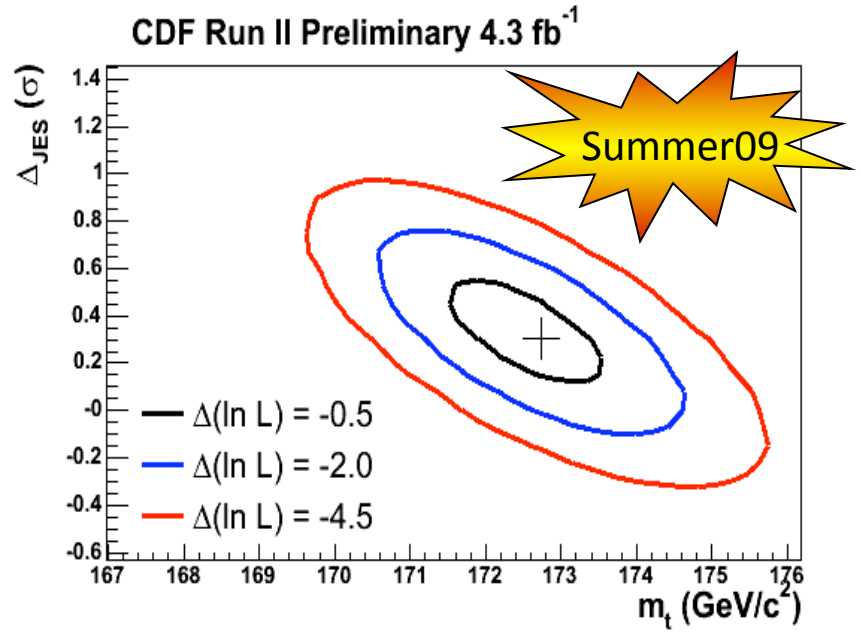
Most Precise from Single Channel

Matrix Element Technique in Lepton + Jets

- *Event likelihood based on differential cross section, parameterized in m_{top} and JES*
- *Use Transfer Functions to model detector effects*

$$P_{t\bar{t}}(x;m_t,JES) = \frac{1}{\sigma}\int \frac{f(q_1)f(q_2)}{|q_1||q_2|}\sum_{comb}|M(m_t,y)|^2\, TF(x,y,JES)\, d\phi(y)$$

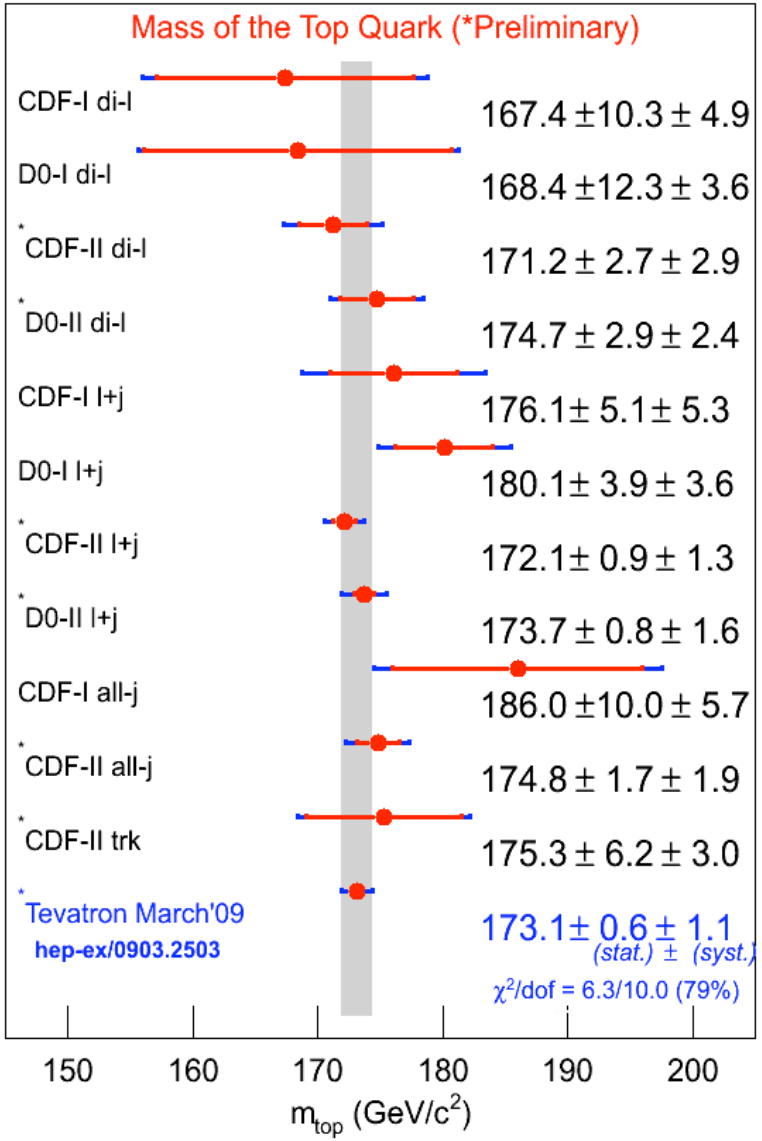




D0 (3.6 fb^{-1}):
173.7±0.8(stat)0.8(JES)±1.4(syst) GeV

CDF (4.3 fb^{-1}):
172.6±0.9(stat)±0.7(JES)±1.1(syst) GeV

Tevatron Results



arXiv:0903.2503

Tevatron (Winter 09):
m_t=173.1 ± 0.6(stat) ± 1.1(syst) GeV

Results from different channels are *consistent*

Different techniques to measure m_{top} produce *consistent* results

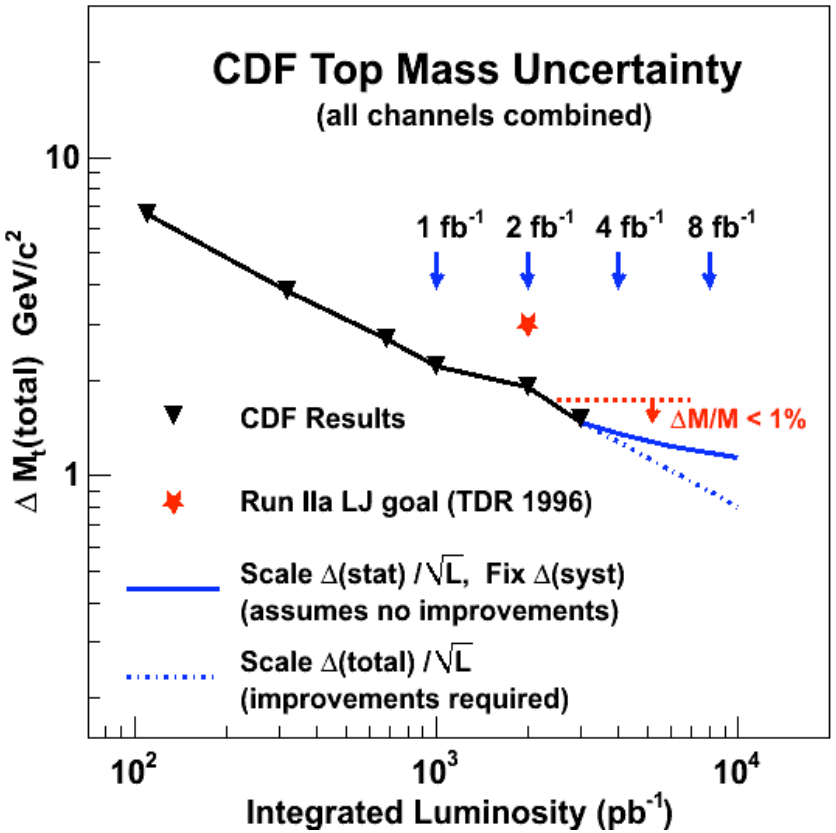
Ongoing work on improving systematic uncertainties (CDF+D0+theory community)

- *Are all sources of uncertainty covered?*
- *Is there overlap?*

χ^2/ndof 6.3/10 ⇒ 79 % probable

Top Quark Mass – Projecting the Future

CDF example



Lepton + Jets 4.3 fb^{-1}

Systematic Source	Δm_{top} [GeV]
Calibration	0.1
MC generator	0.5
QCD Radiation	0.4
Residual jet energy scale	0.5
b-jet energy scale	0.4
Lepton p_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.3
Total	**1.1**

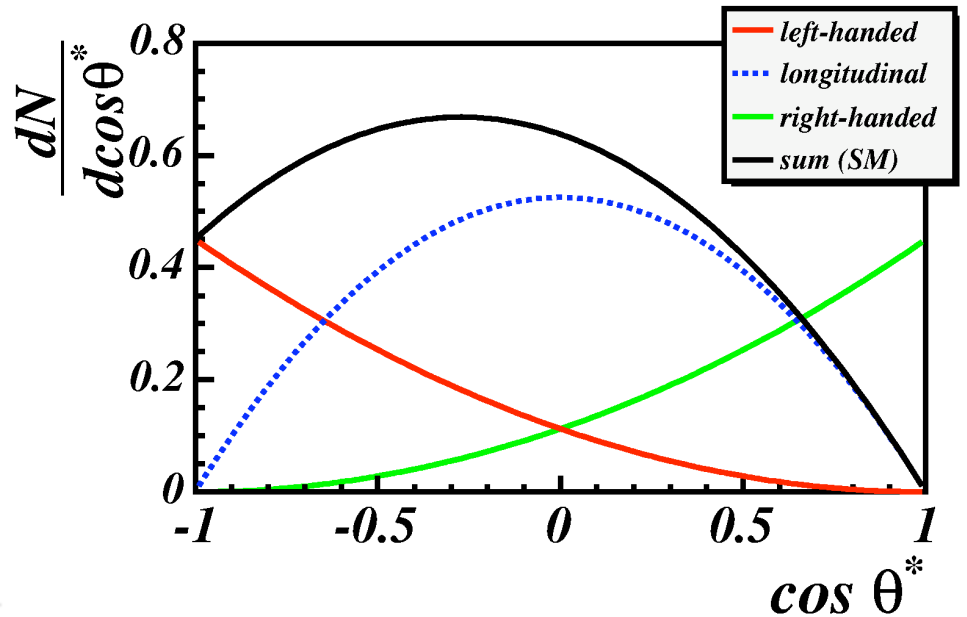
Magnitude of systematic uncertainties are comparable.
Top quark mass precision for single measurement approaches 1 GeV

Top Quark Decay

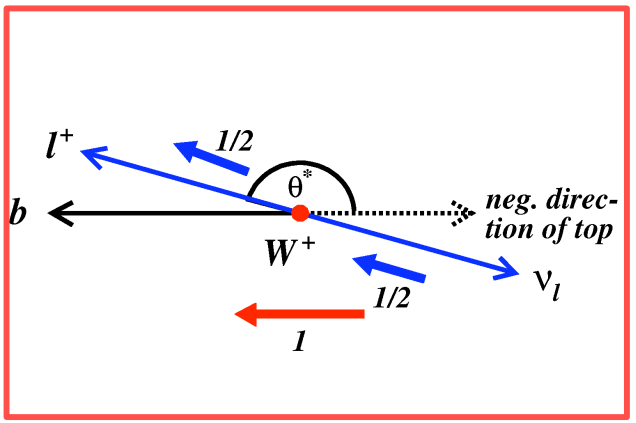
トップクォークの崩壊

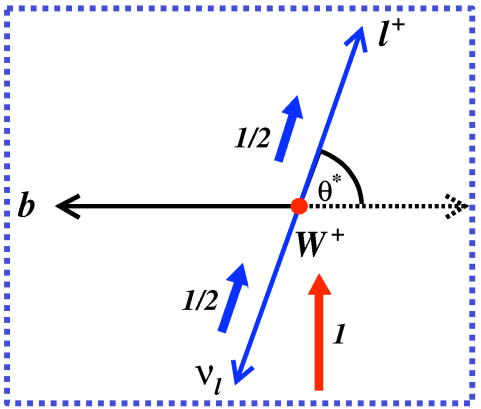
W Boson Helicity in Top Quark Decay

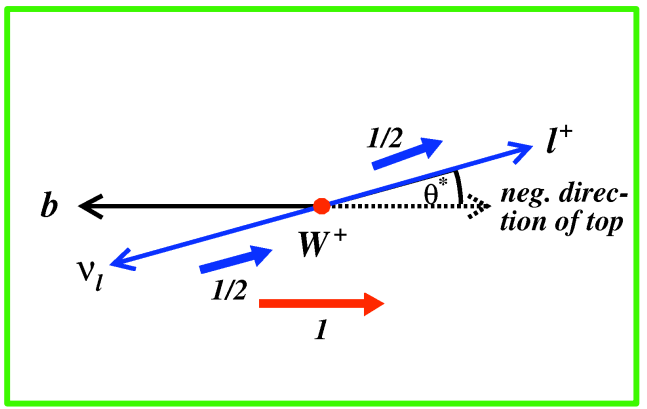
- Standard Model predicts purely left handed *t-W-b* coupling
- Directly probe *t-W-b* vertex at high Q^2
- In SM, the helicity of W boson:
  - longitudinal fraction f_0~70%
  - left-handed fraction f_- ~30%
  - right-handed fraction f_+~0%



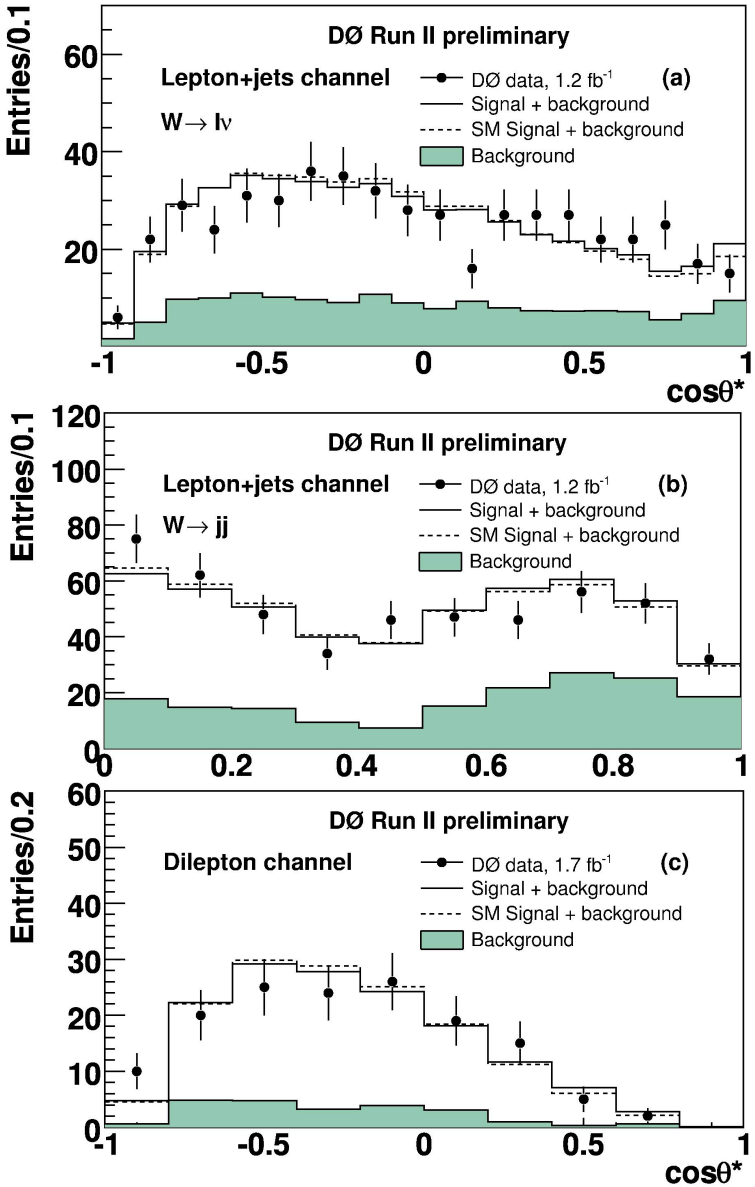
- Can use $\cos\theta^*$ to measure f_0, f_+, f_-







W-boson Helicity Fractions



Measure f_0 and f_+ simultaneously
⇒ Model independent

D0 LeptonJets + Dilepton (2.7 fb^{-1})

$$f_0 = 0.49 \pm 0.11\,(\text{stat}) \pm 0.09\,(\text{syst})$$

$$f_+ = 0.11 \pm 0.06\,(\text{stat}) \pm 0.05\,(\text{syst})$$

PRL 100 062004 (2008)

CDF Lepton+Jets (2.0 fb^{-1}, m_t= 172.5 GeV):

$$f_0 = 0.65 \pm 0.19\,(\text{stat}) \pm 0.03\,(\text{syst})$$

$$f_+ = -0.03 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})$$

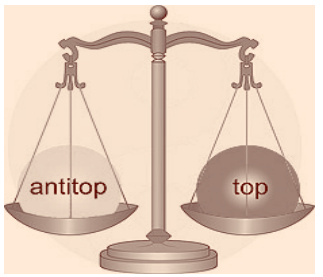
PLB 674 p160 (2009)

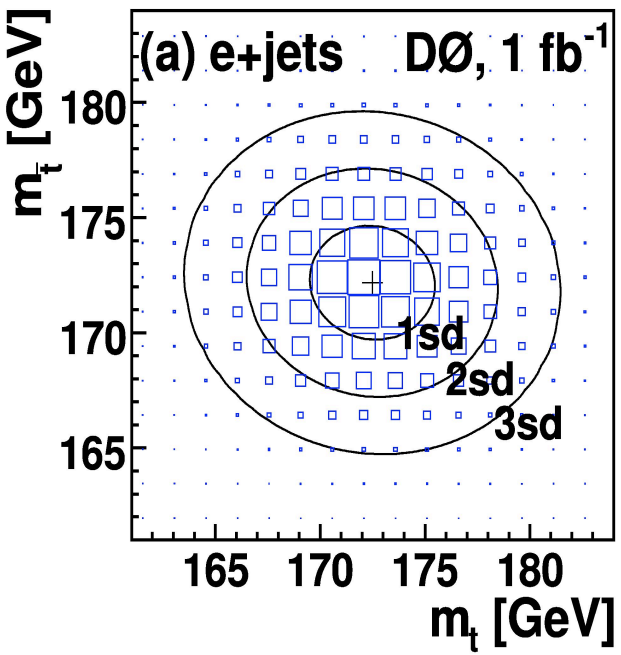
Consistent with the Standard Model

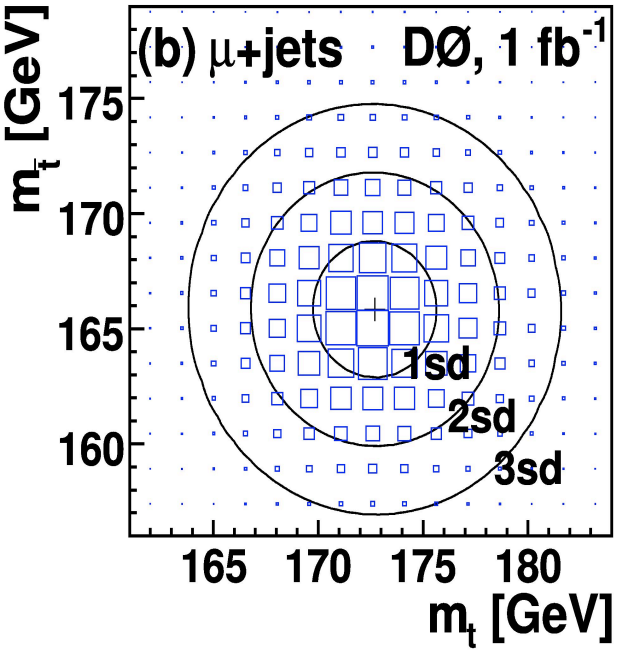
Top Quark Properties
トップクォークの特性

Top Anti-top Mass Difference

- Mass difference would imply *CPT-violation*
- Measured in lepton + jets events (ME technique)







Summer09

First time measured for a "bare quark"

Consistent with SM expectations

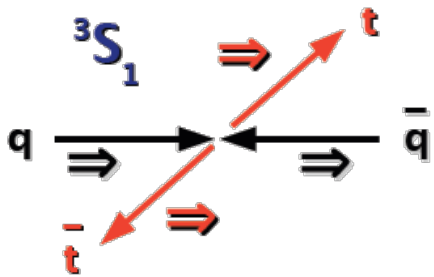
D0 (1 fb^{-1}):
Δm_t=3.8 ± 3.7 GeV

statistics limited

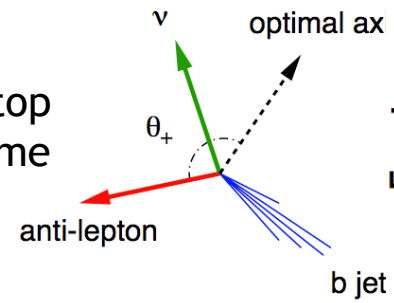
arXiv:0906.1172

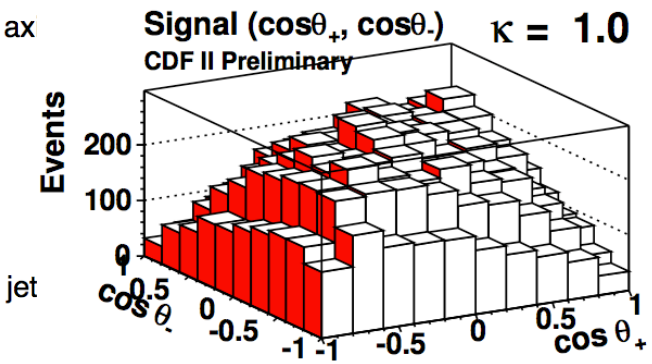
Top Quark Spin-Spin Correlations

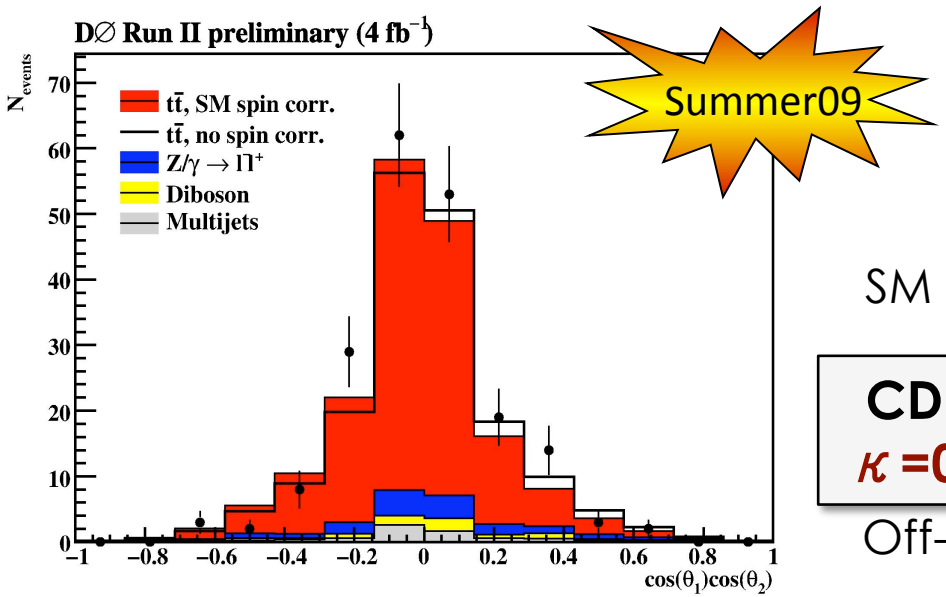
- Top spins are correlated only if *top lifetime is short enough*
  - Spin-spin correlation is observable in the top quark decay products



In top frame







$$\kappa = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\uparrow\downarrow)}$$

SM predicts κ = 0.78 Nucl.Phys.B690, 81 (2004)

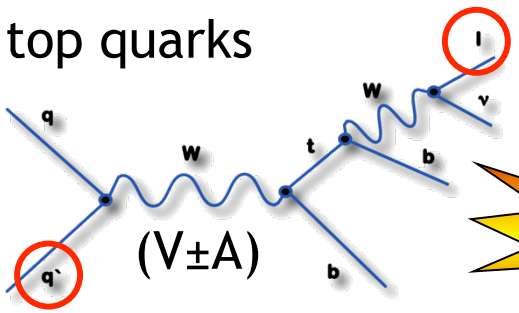
CDF (2.8 fb^{-1}):
$\kappa = 0.32^{+0.55}_{-0.78}$
Off-diagonal axis

D0 (4 fb^{-1}):
$\kappa = -0.17^{+0.64}_{-0.53}$
Beam axis

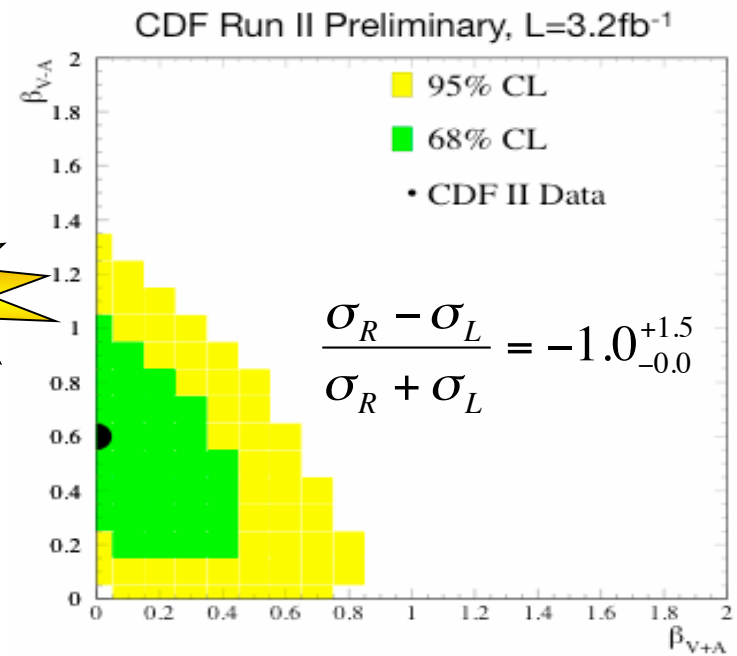
First CDF and D0 RunII result, agreement with SM within 1σ (CDF), 2σ (DØ)

Top Quark Spin Polarization

- Single top offers a source of ~100 % polarized top quarks



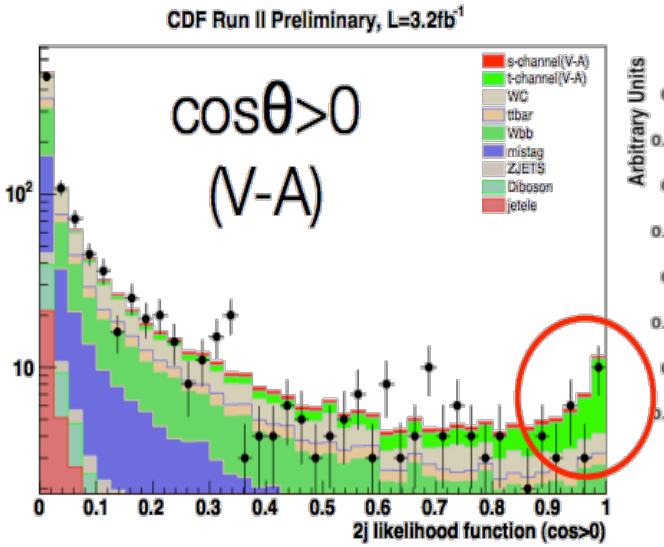
Summer09

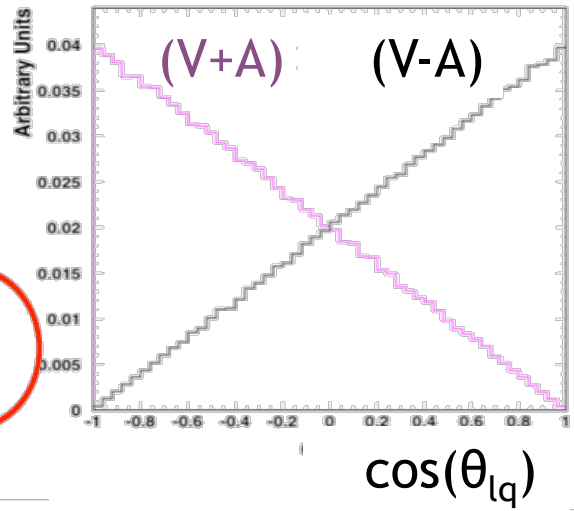


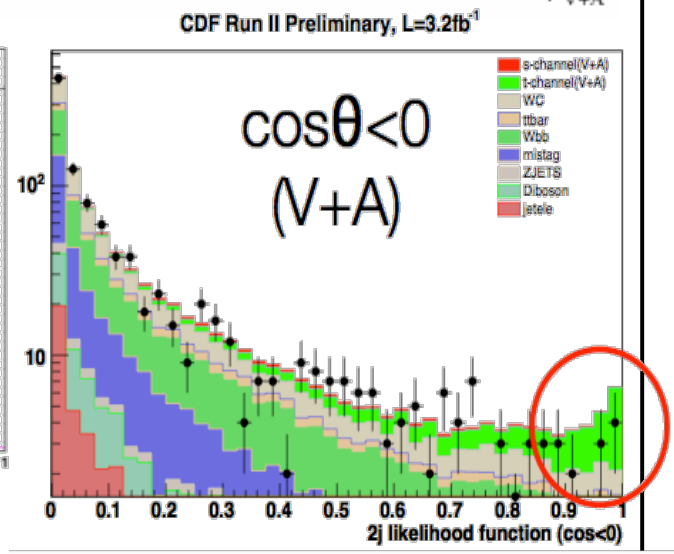
$$\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1.0^{+1.5}_{-0.0}$$

- Extract single top under left handed (V-A) and right handed (V+A) production hypothesis

- Data prefers (V-A) production





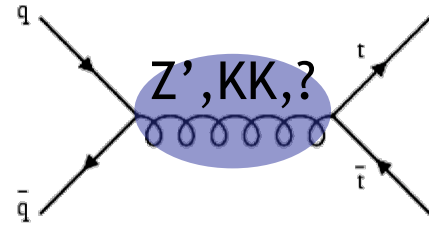


Top Quarks as a Window to New Physics

トップクォークによる新しい物理の探索

Search for Narrow Resonance in M_{tt}

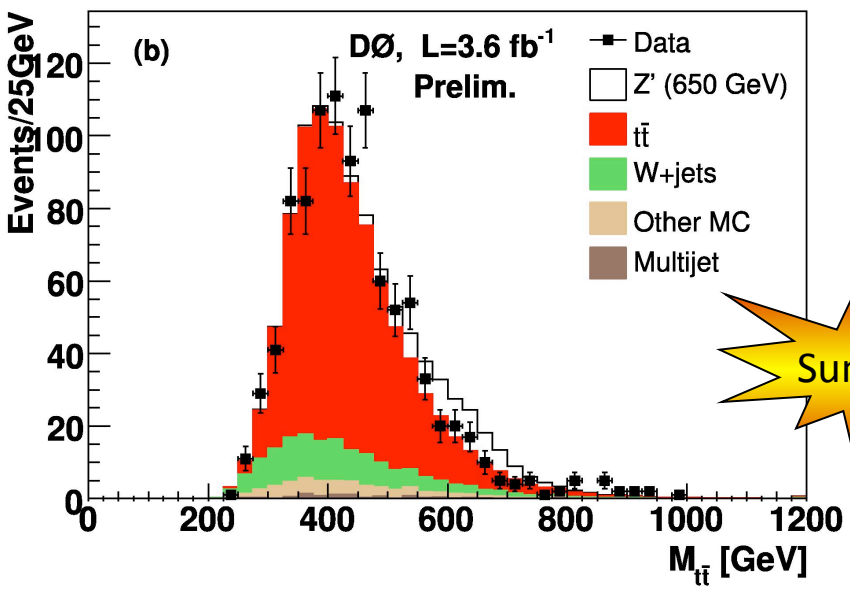
- Resonance production of $t\bar{t}$ is predicted by several new physics models
  - Top color assisted technicolor with leptophobic Z´
  - Randall Sundrum KK-gluons, colorons, etc..
- Search for bumps in M_{tt}
  - Assume narrow width (1.3%), dominated by resolution



D0 (3.6 fb^{-1}):
>820 GeV/c^2 at 95% CL

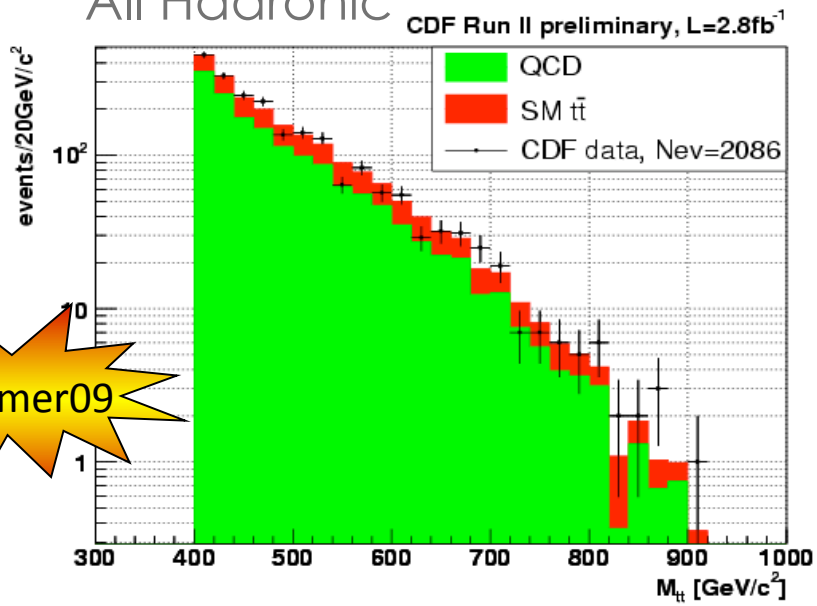
CDF (2.8 fb^{-1}):
>805 GeV/c^2 at 95% CL

Lepton+Jets

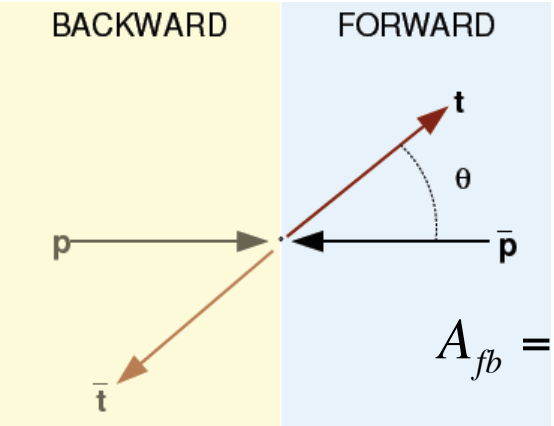


Summer09

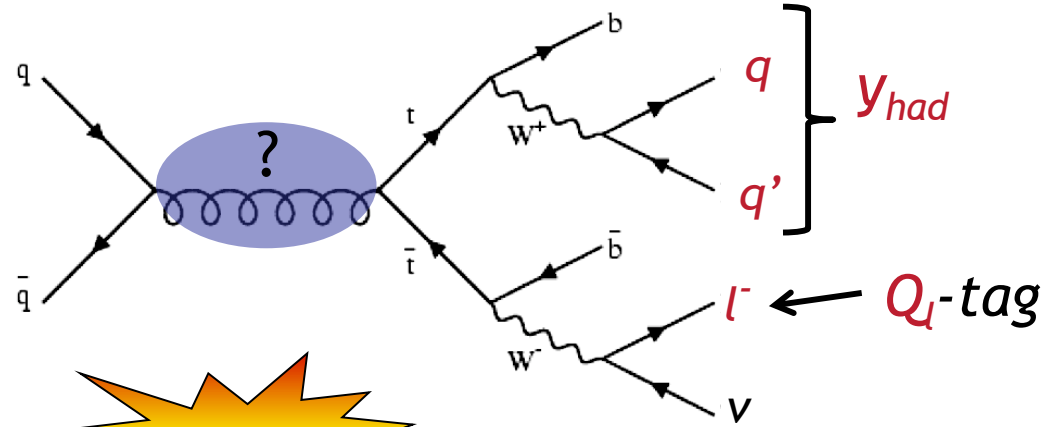
All Hadronic



Forward Backward Asymmetry



$$A_{fb} = \frac{F - B}{F + B}$$



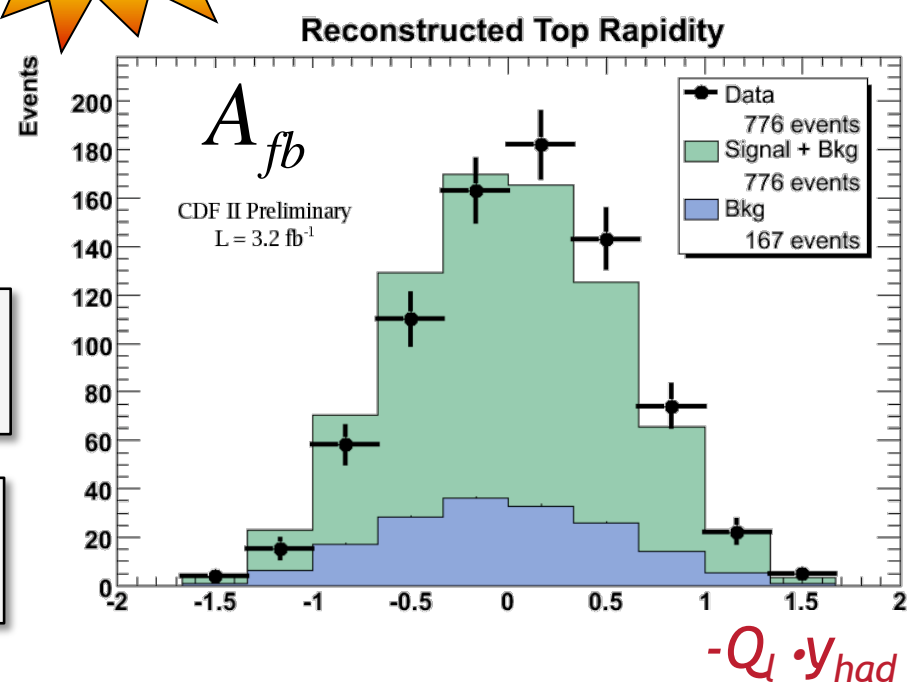
Summer09

- New physics could give rise to a *asymmetry* (Z´,axigluons,..)
- NLO QCD: A_{fb}=0.05 ± 0.015 %

CDF (3.2 fb^{-1}):
A_{fb}=0.193 ± 0.065 (stat) ± 0.024 (syst)

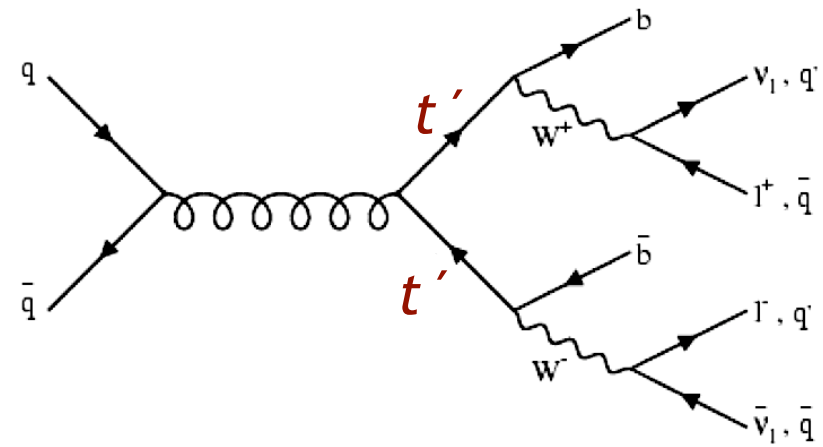
D0 (1.0 fb^{-1}):
A_{fb}^{det}=0.12 ± 0.08 (stat) ± 0.01 (syst)

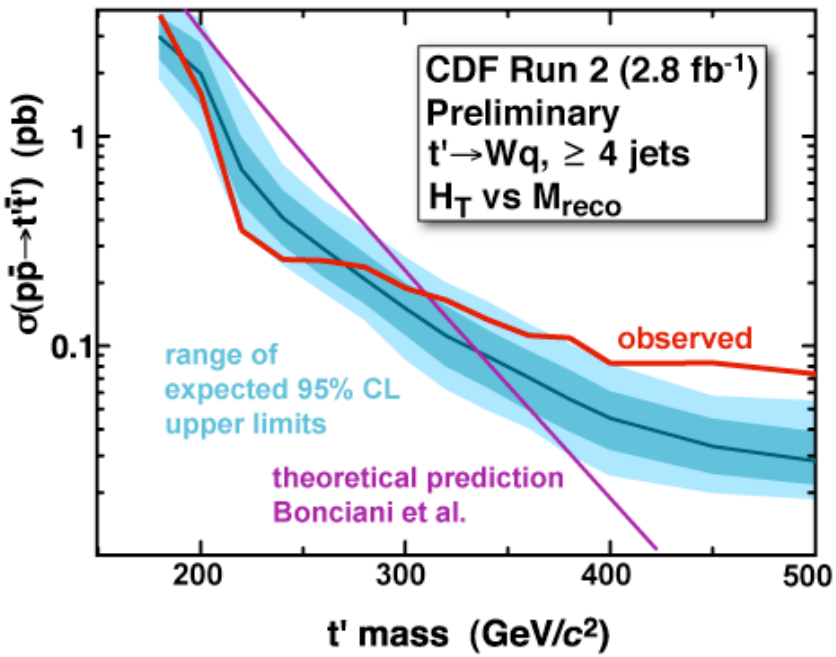
PRL 100, 062004 (2008)

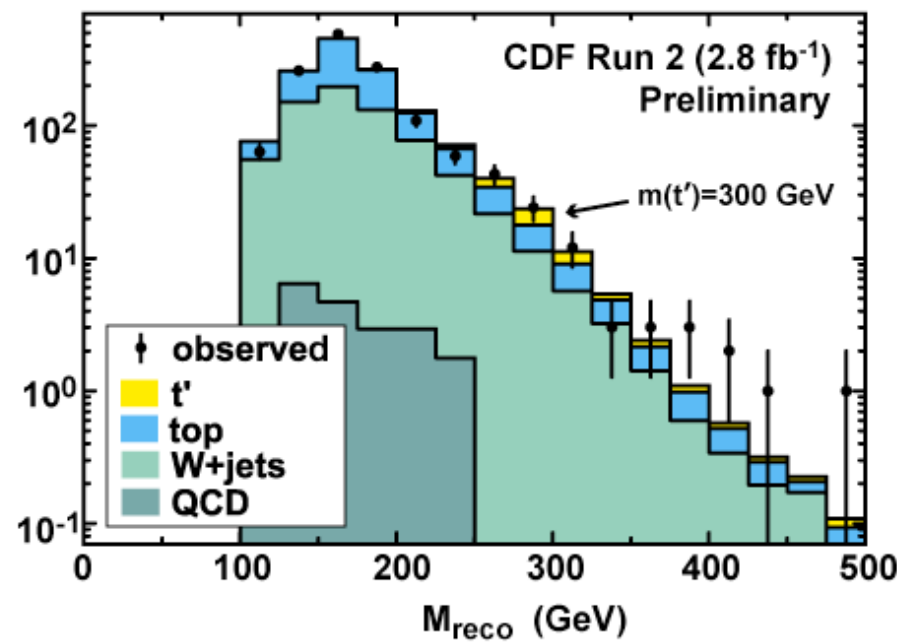


Search for Heavy t´

- Heavy t´production
  - *suggested in 4th generation models, little Higgs, 2HD models, Beautiful mirrows etc.*
- Search for t´t´ in Lepton + Jets







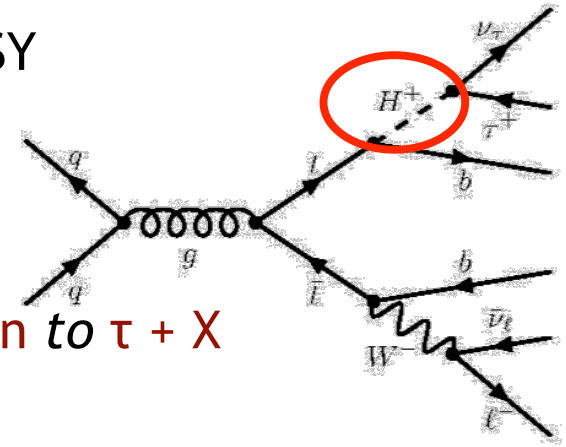
CDF (2.8 fb^{-1}):

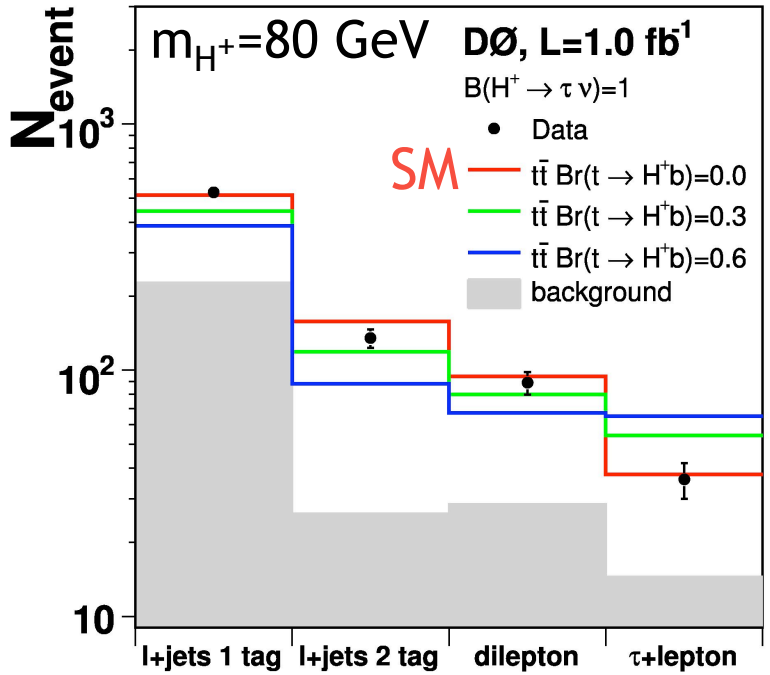
M(t´) > 311 GeV/c^2 at 95% C.L.

Search for Charged Higgs in Top Decay

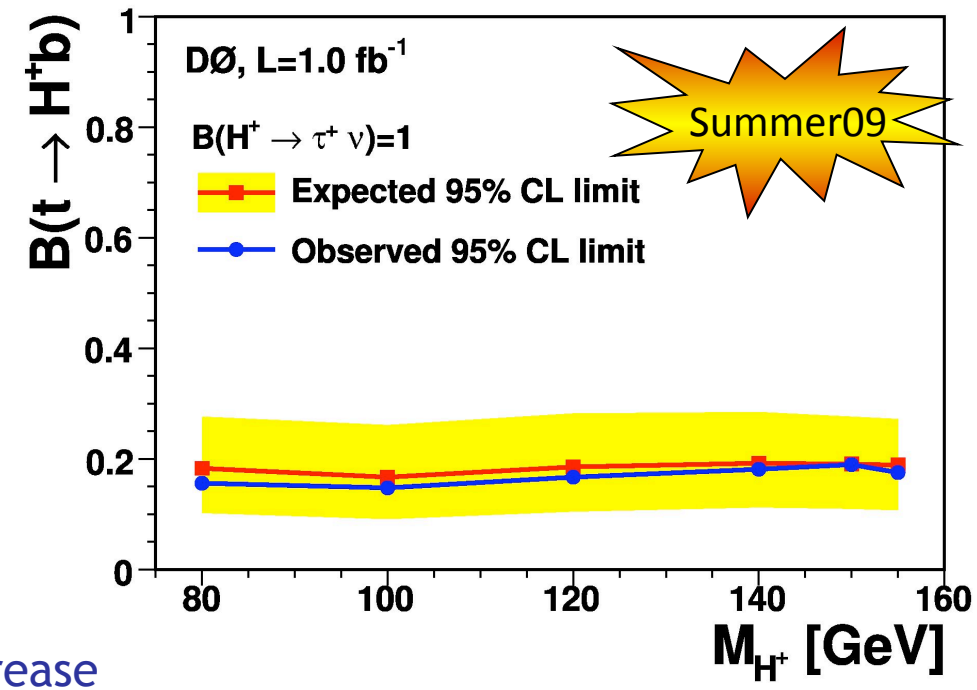
- If kinematically allowed, $t \to H^+b$ happens in SUSY
- Charged Higgs decay: $H^+ \to cs$ or $H^+ \to \tau\nu$
  - Branching ratios depend on *tanβ*
- Observable:

  Altered rates in final states: L+jets *to* Dilepton *to* τ + X





decrease increase

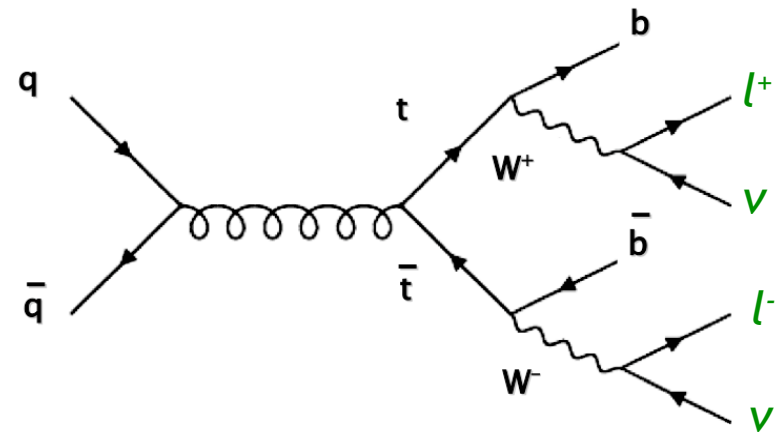


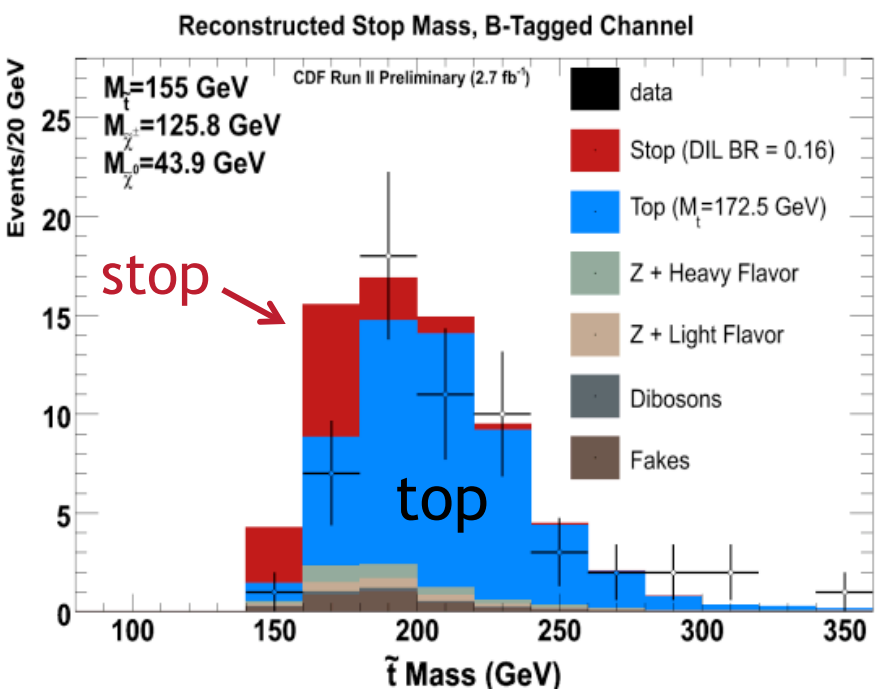
arXiv:0908.1811

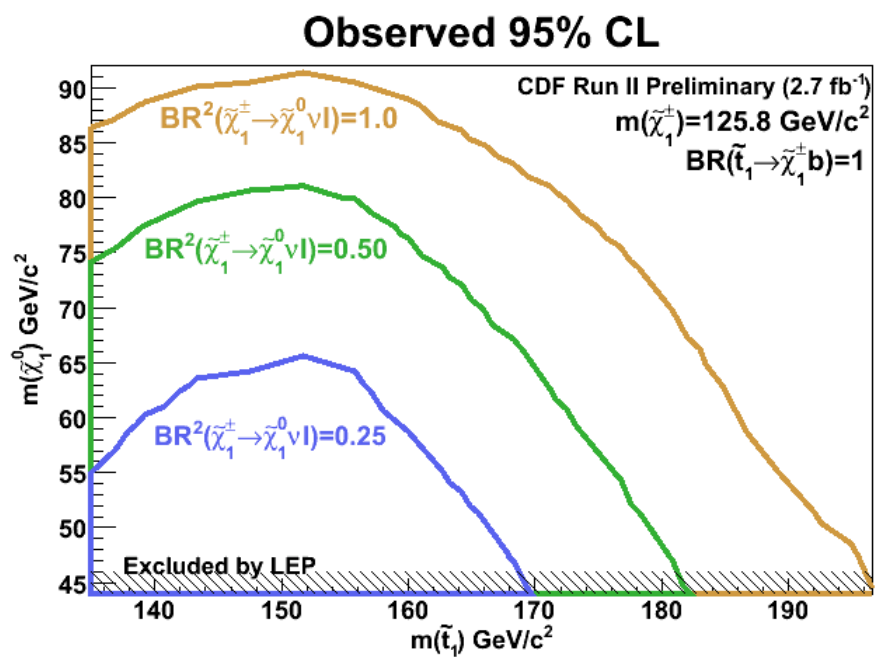
Stop Quarks in the Top Sample?

- Could top quark SUSY partner (stop) hide in the top quark samples?

- Assume:
  1. $\tilde{\chi}_1^0$ is the LSP
  2. $m_{\tilde{t}_1} \lesssim m_t$
  3. $m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$







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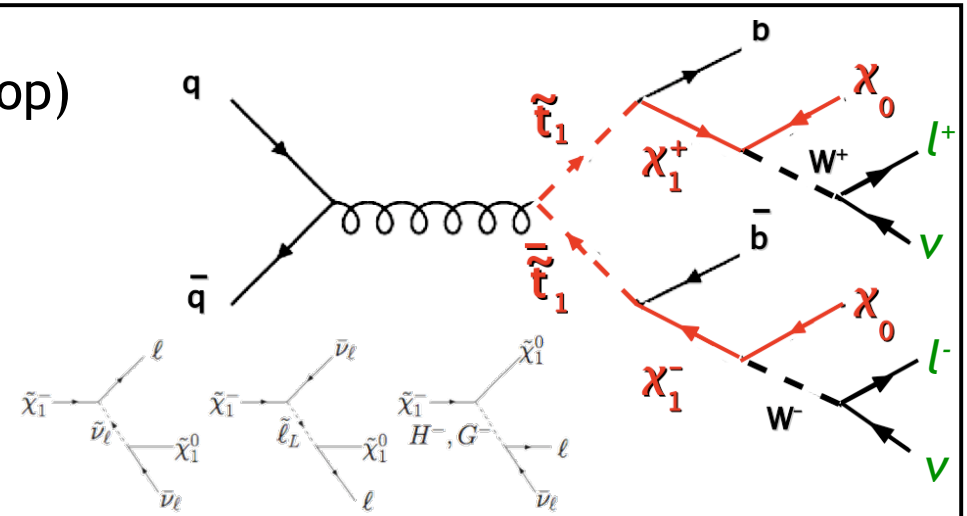
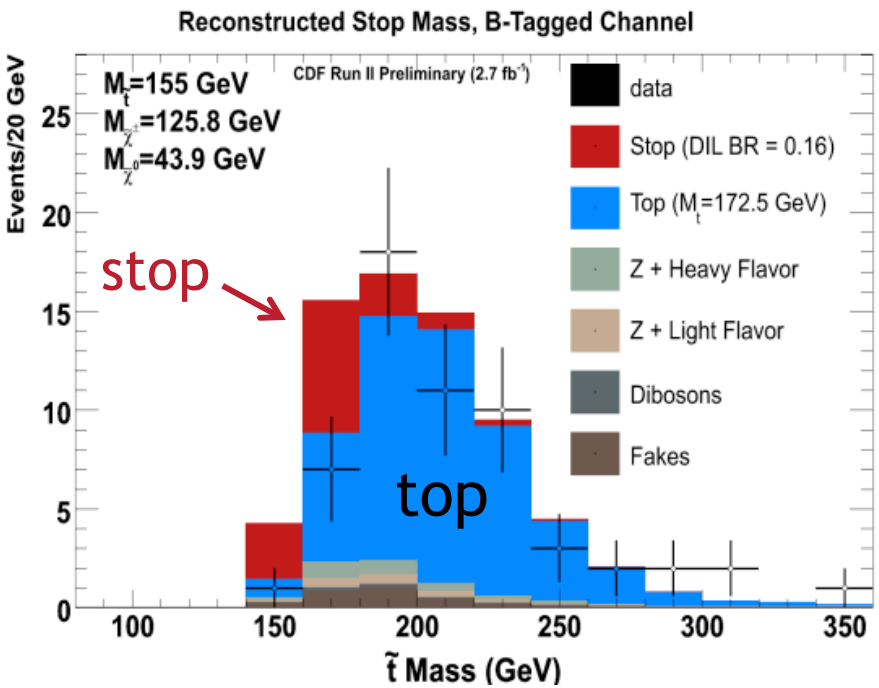
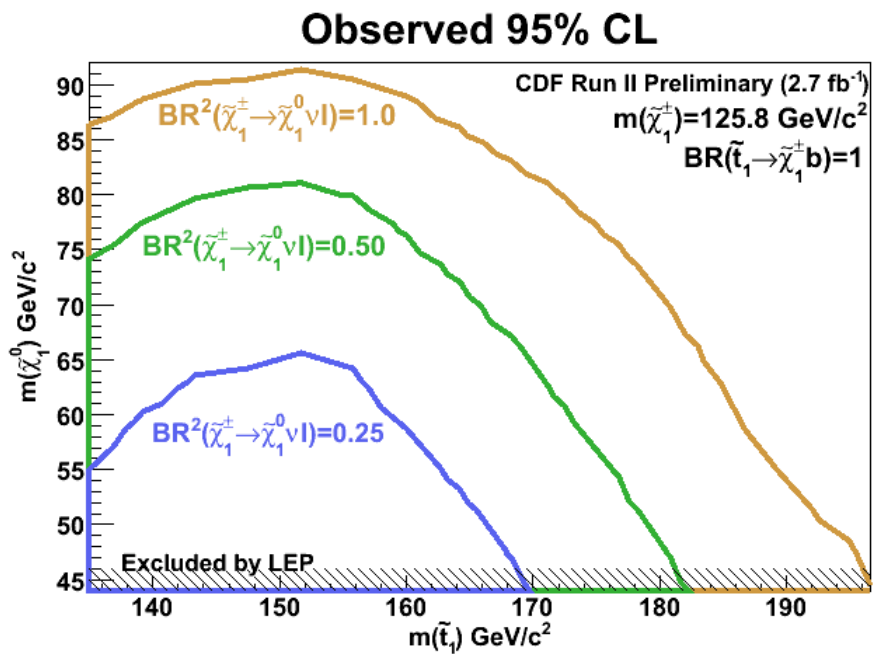


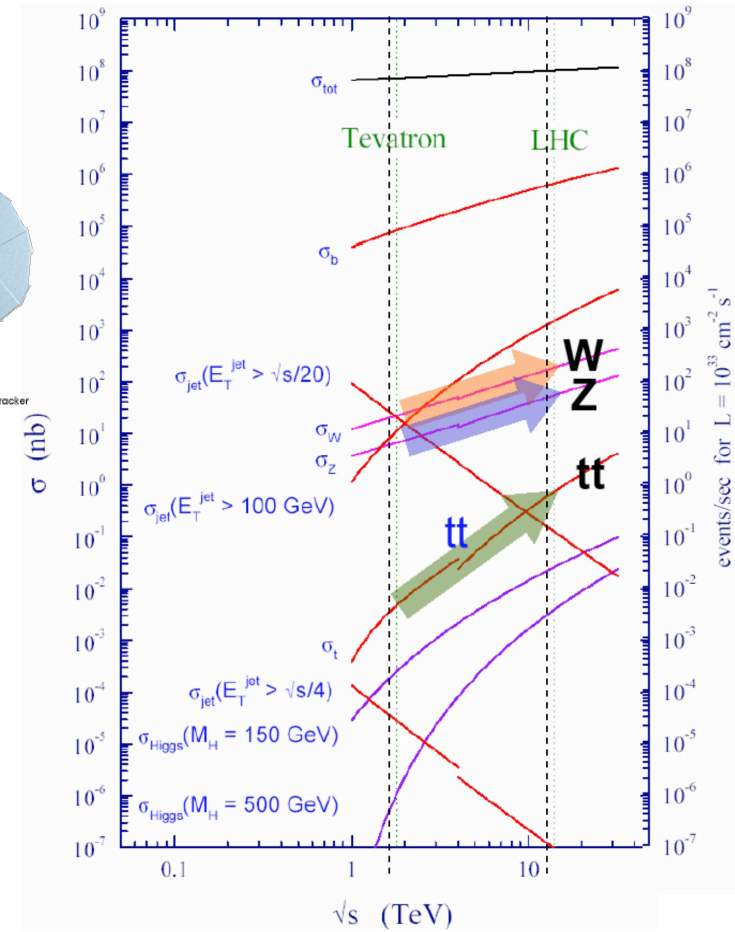




Top Quark Physics at the LHC

LHCにおけるトップクォークの物理

Large Hadron Collider

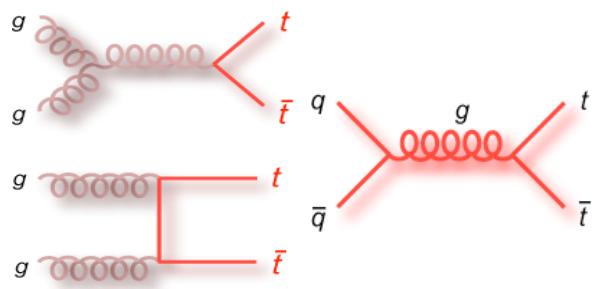


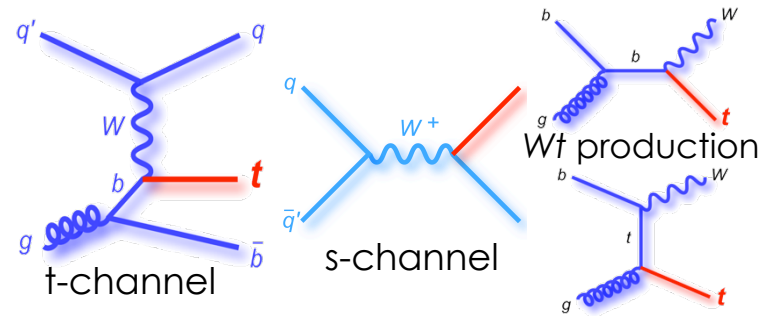
E_{CM} = 7 TeV *initially*
= 10 TeV *in summer 2010 ?*
= 14 TeV *in 2011 ?*

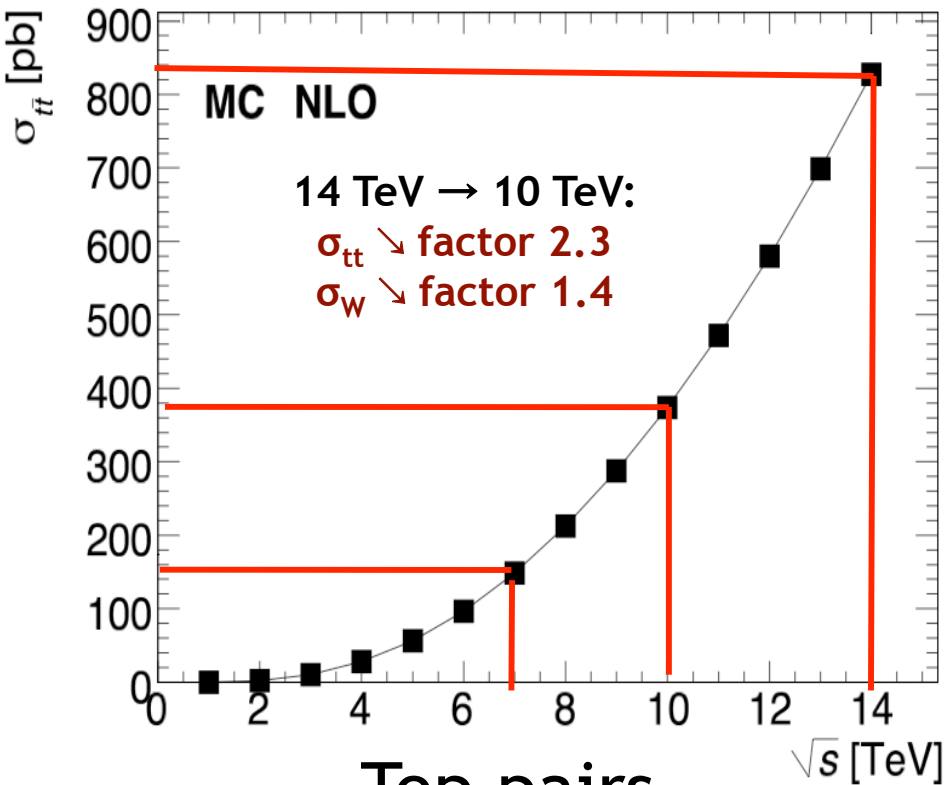
σ_{tt} ~ **830 pb**
$\sigma_{single\ top}$ ~ **315 pb**
(~100 x Tevatron)

Expect 200 pb^{-1} by end of 2010.

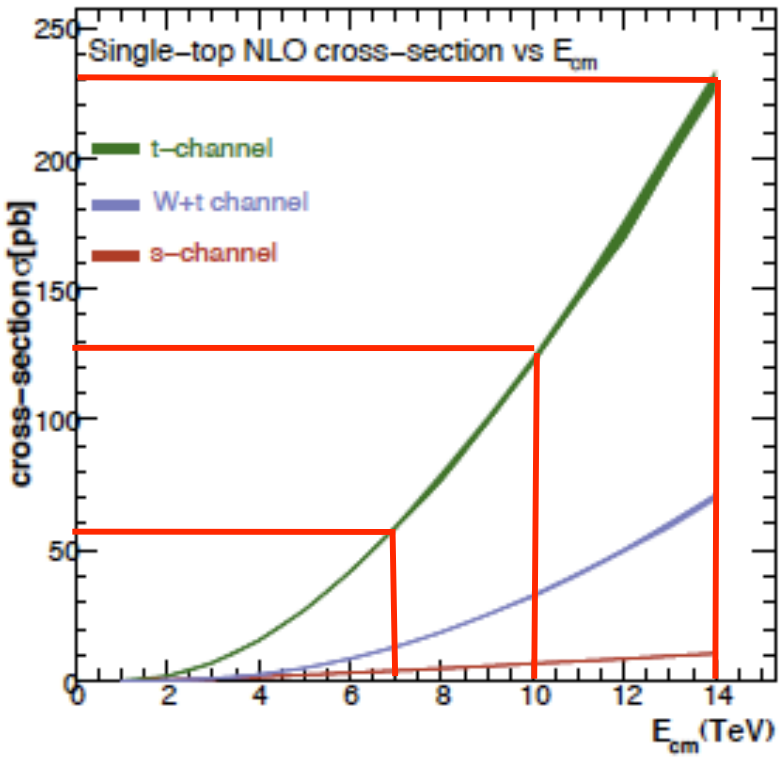
Top Cross Section at LHC







Top pairs



Single Top

Z. Sullivan, arXiv: hep-ph 0408049 (2004).

Top Quark Physics in Early LHC Data

Rediscover top quarks with ~ 10 pb^{-1}

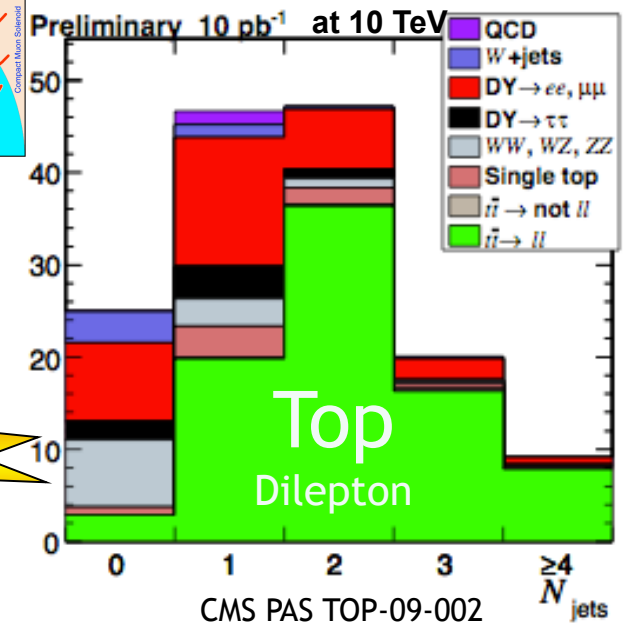
Possibly first in dilepton channel

$\Delta\sigma_{tt}$ = 15% (stat) ± 10% (syst) ± 10% (lumi)

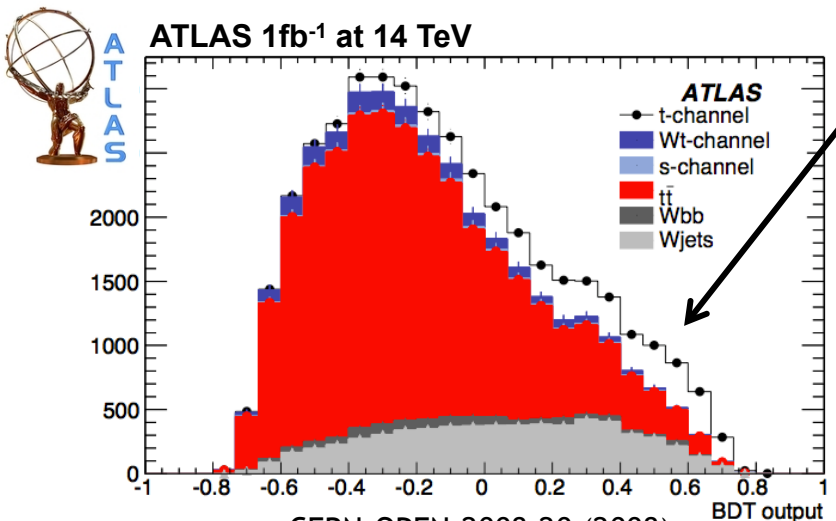
Top quarks are an excellent testbed

- Understand lepton ID (incl. taus)
- Efficiency of b-tagging
- Jet energy scale

Summer09



CMS PAS TOP-09-002



CERN-OPEN-2008-20 (2008)

Single Top at the LHC

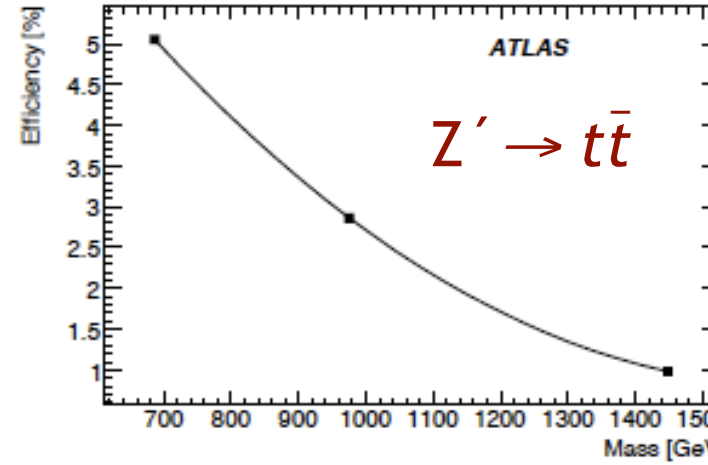
- t-channel most sensitive channel
- Requires b-tagging + MVA
- *See Patrick Ryan, MSU (poster)*

$\Delta|V_{tb}|$ = 12% (stat + syst + theo)

CDF + D0 $\Delta|V_{tb}|$ = 10 %

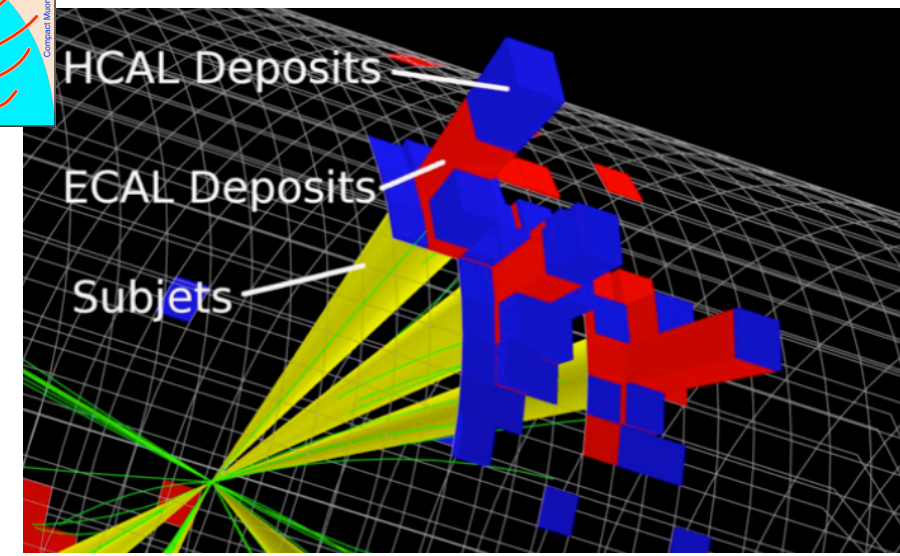
Boosted Tops

- Searches for resonant top pair production at very high mass will suffer from "***jet merging***" because of highly boosted top quarks



- Traditional top reconstruction works up to ~0.75 – 1 TeV
- Efficiency drops rapidly

- New development: Tagging of *boosted* top jets



⇒ CMS: ~ 46% efficiency, ~ 2% fake rate for p_T(top) = 600 GeV

Using constraints on top/W mass

Conclusions

- The discovery of the top quark opened up a rich field in HEP
- A broad top physics program is underway at the Tevatron
  - *So far, the data seems consistent with the SM*
  - *Tevatron expects to double data sets if running through 2011*
- Single top quarks have been observed!
  - *Most precise direct determination of V_{tb} to date*
- The precision on the top quark mass has reached 0.75 %
- With the LHC, an enormous top quark factory is beginning operations - continue to *explore the truth about the top...*

Further Information

Top Physics Results from the Tevatron

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

http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm

Top Physics Projections for the LHC

https://twiki.cern.ch/twiki/bin/view/Atlas/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults#TOP_physics

Thank You!
ご静聴ありがとうございました。