PASCOS 2009, DESY, Hamburg

July 6, 2009

Top physics at the Tevatron

- Motivation
- Top mass
- Top-antitop mass difference
- Cross section ratios and charged Higgs
- Single top
- All jets resonance search
- Summary

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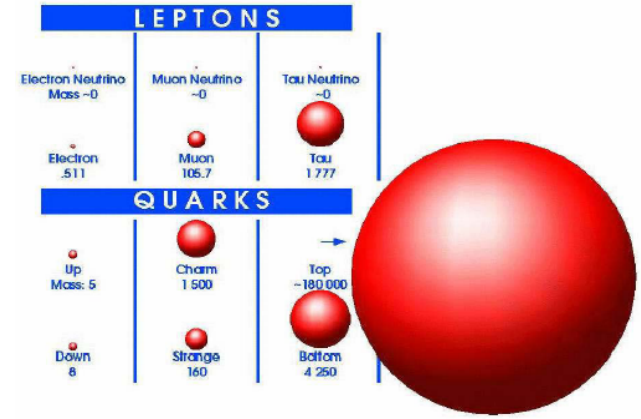
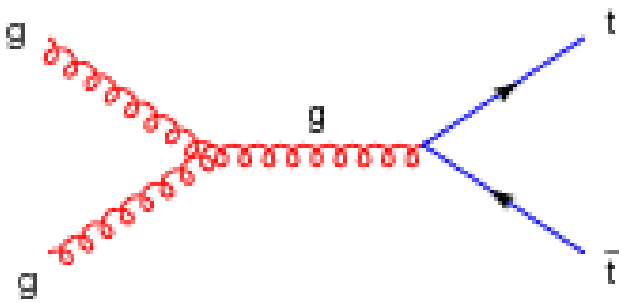
On behalf of CDF and DØ

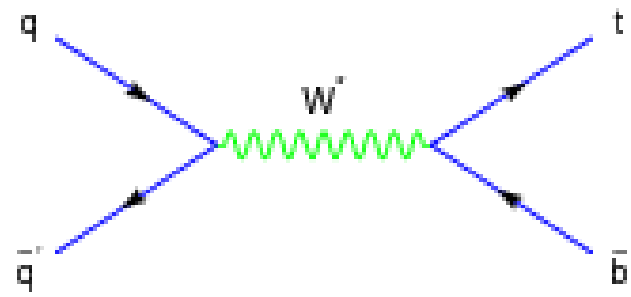
Top quark physics

- Heaviest known particle
  - $m_t \sim v/\sqrt{2} \rightarrow \lambda_t \sim 1$ Related to EWSB
  - Sensitive probe for new physics
- Decays as a free quark $\tau_t \sim 5 \cdot 10^{-25}$ s $\ll \Lambda_{QCD}^{-1}$
  - Spin information is passed to its decay products
  - Test V-A structure of the SM
- Production modes at the Tevatron:

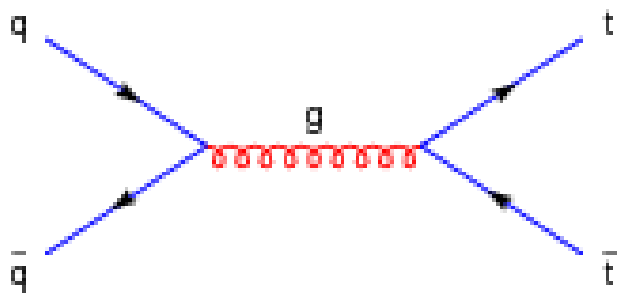




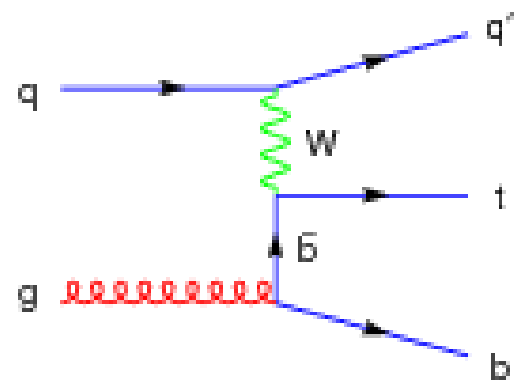
~15% σ_{tt}



~30% σ_t



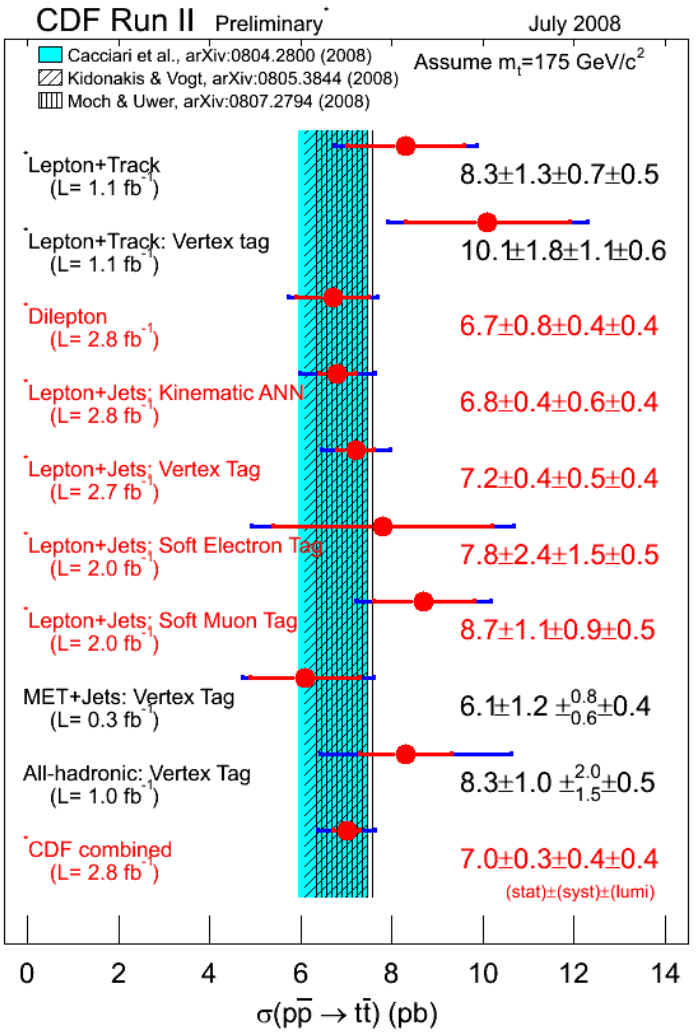
~85% σ_{tt}



~70% σ_t

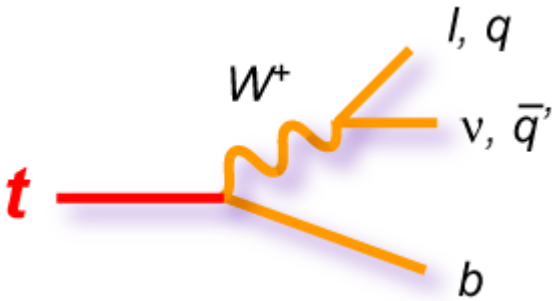
After 14 years of studies

- Still many properties to unravel!
- We know:
  - m_t = 173.1±1.3 GeV
  - $\sigma(tt)$ = 7.02±0.63 pb
  - $\sigma(t)$ = 3.94 ± 0.88 pb
  - $|V_{tb}|$ = 0.91±0.11(exp.)±0.07(theory)
  - Charge: exclude -4/3 @ 92% CL
  - Longitudinally polarized W: f_0=0.49±0.14 [f_0(SM)=0.7]
  - $\Delta m = m_t - m_{\bar{t}}$ = 3.8±3.7 GeV
  - Γ_t < 13.1 GeV @ 95% CL [Γ_t(SM) = 1.4 GeV]
  - $c\tau$ < 52.2 μm @ 95% CL
  - ... and many more limits on new physics



http://www-cdf.fnal.gov/physics/new/top/top.html
http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

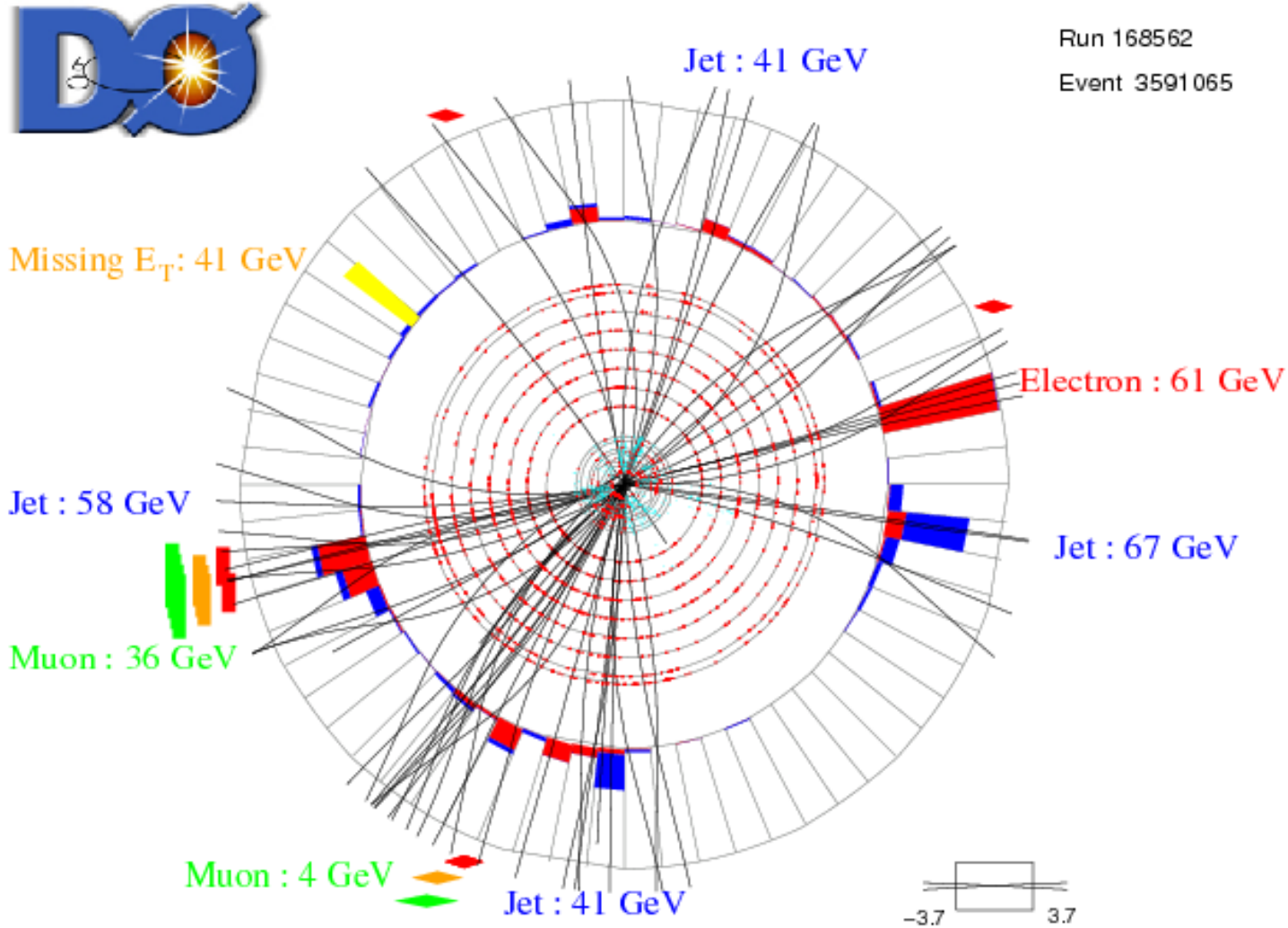
Decay modes



Top Pair Decay Channels

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	

dileptons

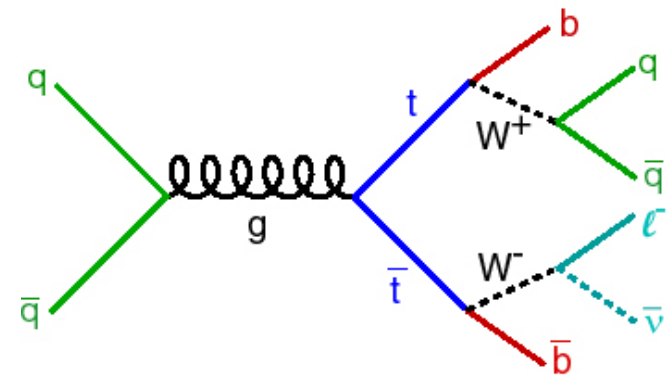


- Dilepton (~8%BR)
- l+jets (~30%BR)
- Alljets (~44%BR)

- Main backgrounds: W+jets and multijets; Z/γ for dilepton
- All subdetectors are involved: MET (ν), leptons, jets, and b-tags

Matrix Element mass measurement

- Measuring m_t is challenging
  - Combinatorics: how to assign jets to partons
  - Jet energy scale and resolution
    - W→qq: use m_W as built-in thermometer for jets
  - Gluon radiation: changes jet kinematics and can lead to jet misassignment
  - W+jets backgrounds: big uncertainties in modeling



- Need good b-tag, JES and res., and powerful algorithm to reconstruct m_t
- Matrix Element method is the most powerful (kinematics from theory)
- Build event by event probability

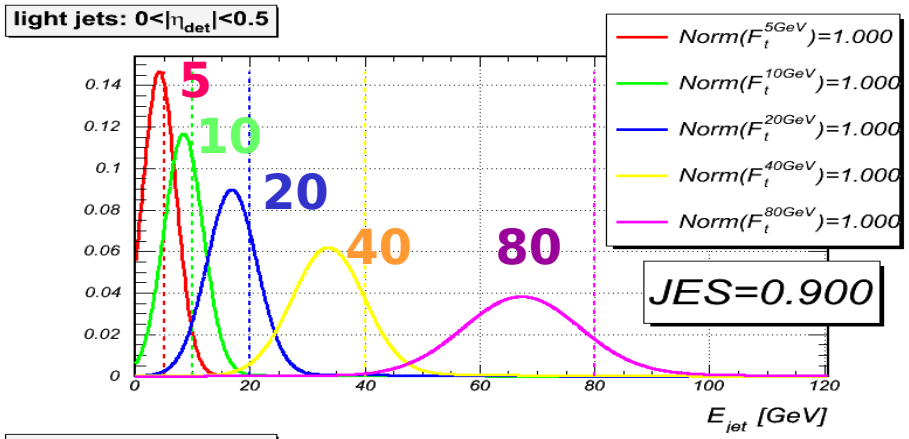
$$P_{sig}(\vec{x}) = \frac{1}{\sigma(m_t, JES)} \int f(q_1)dq_1 f(q_2)dq_2 \times |M(\vec{y})|^2 \phi(\vec{y})dy \times W(\vec{x}, \vec{y}; JES)$$

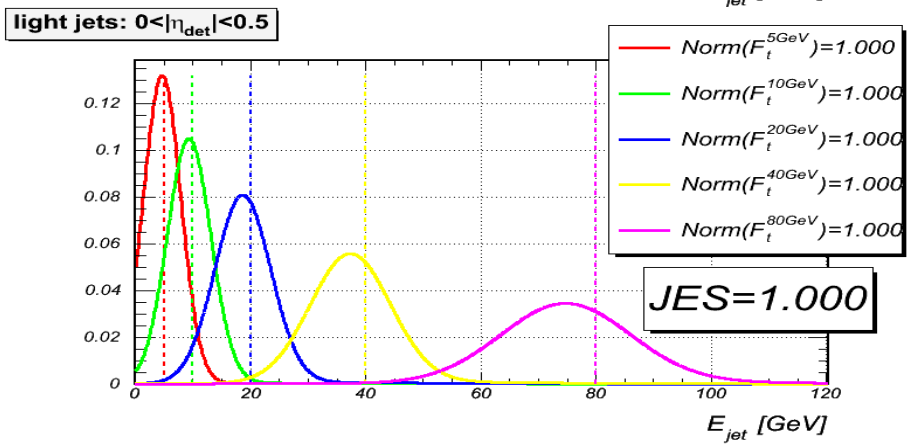
Parton distribution functions CTEQ6M | **Differential cross section (LO ME)** | **Transfer Function: maps parton level (y) to reconstructed variables (x)**

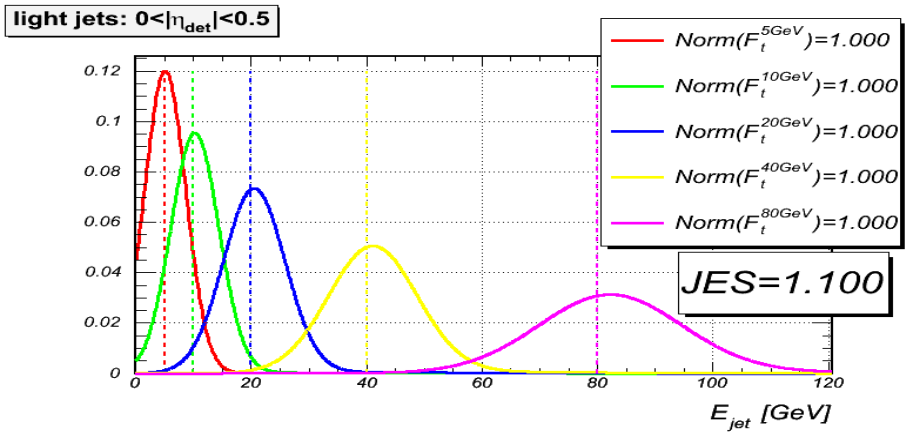
$$P_{evt}(\vec{x}) = f_{top} \cdot P_{sig}(\vec{x}, m_t, JES) + (1 - f_{top}) P_{bkg}(\vec{x}, JES)$$

From transfer to likelihood

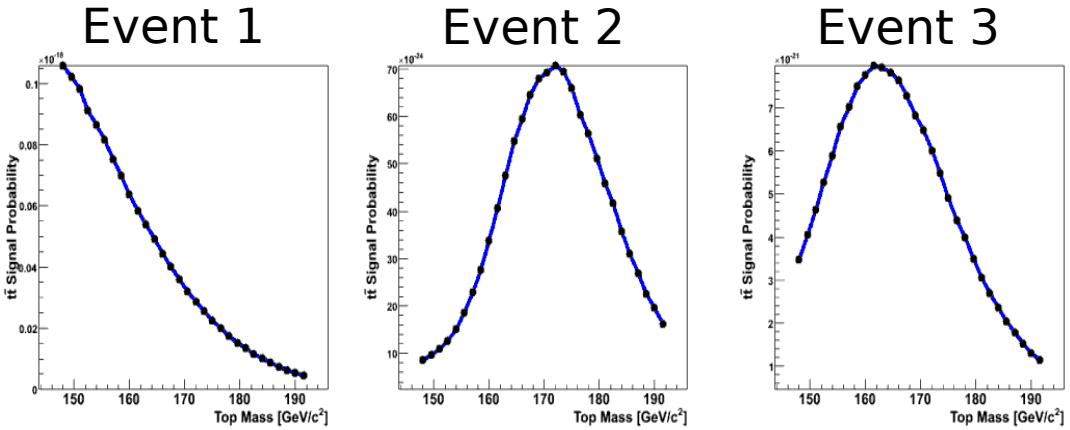
- JES is a free parameter, constrained in-situ by W mass



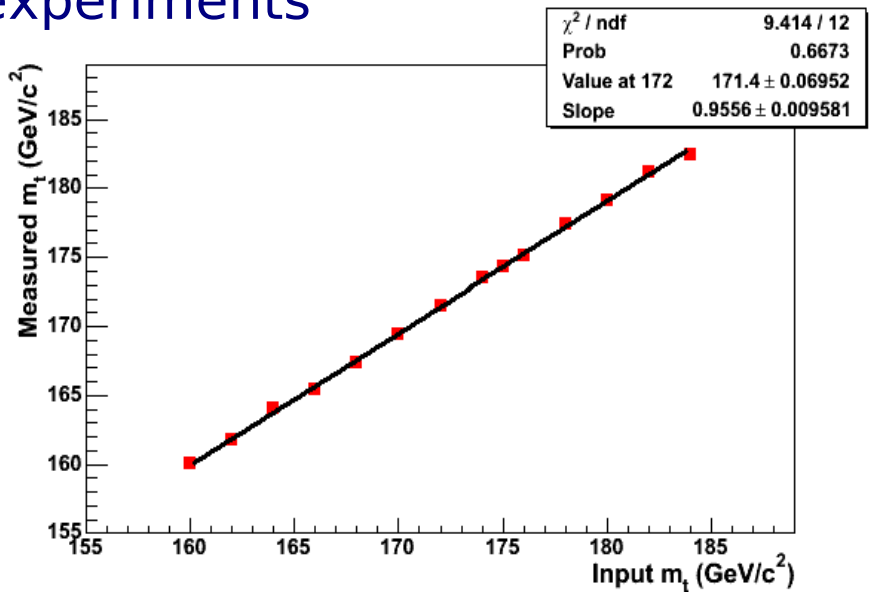




- Event by event probabilities

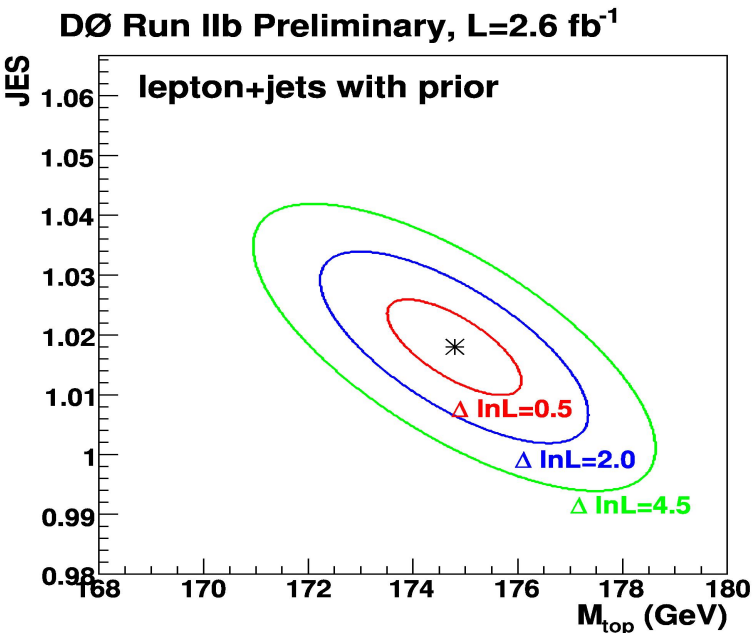


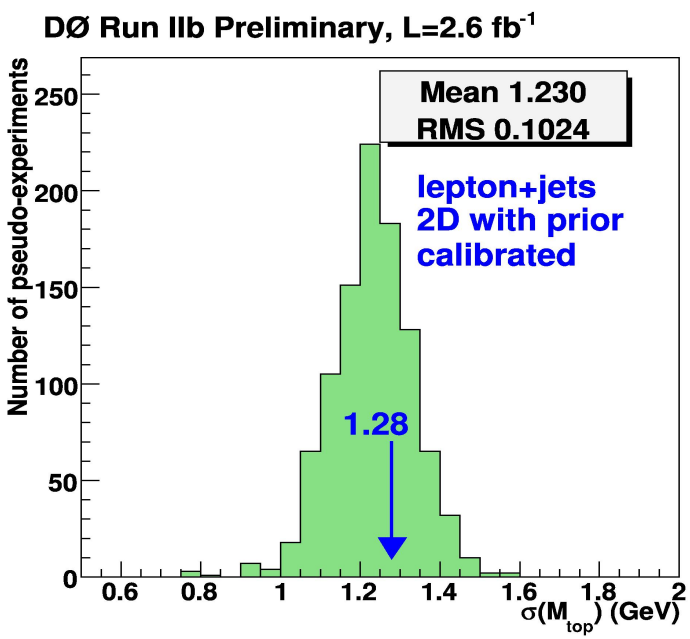
- Obtain max likelihood from P_{evt}
- Calibrate method with pseudo experiments



DØ ME ℓ+jets m_t results (3.6 fb^{-1})

- Use W+jets ME for background





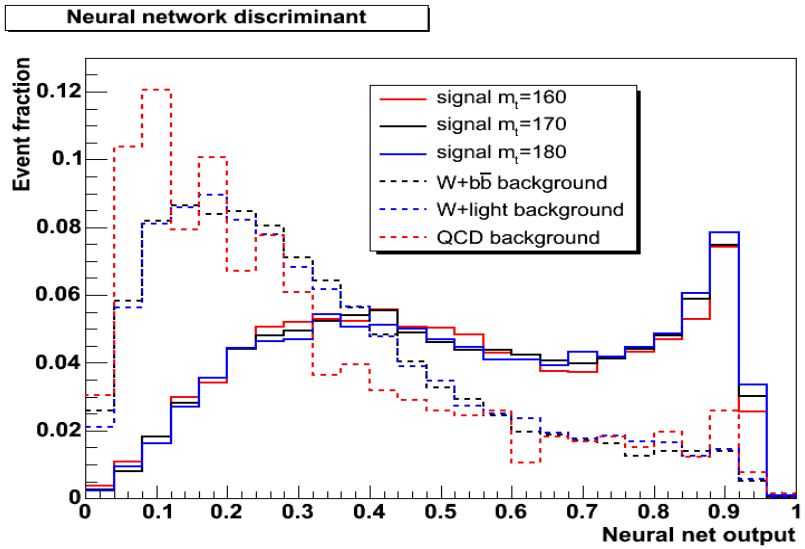
JES=1.018±0.008(stat+m_t)

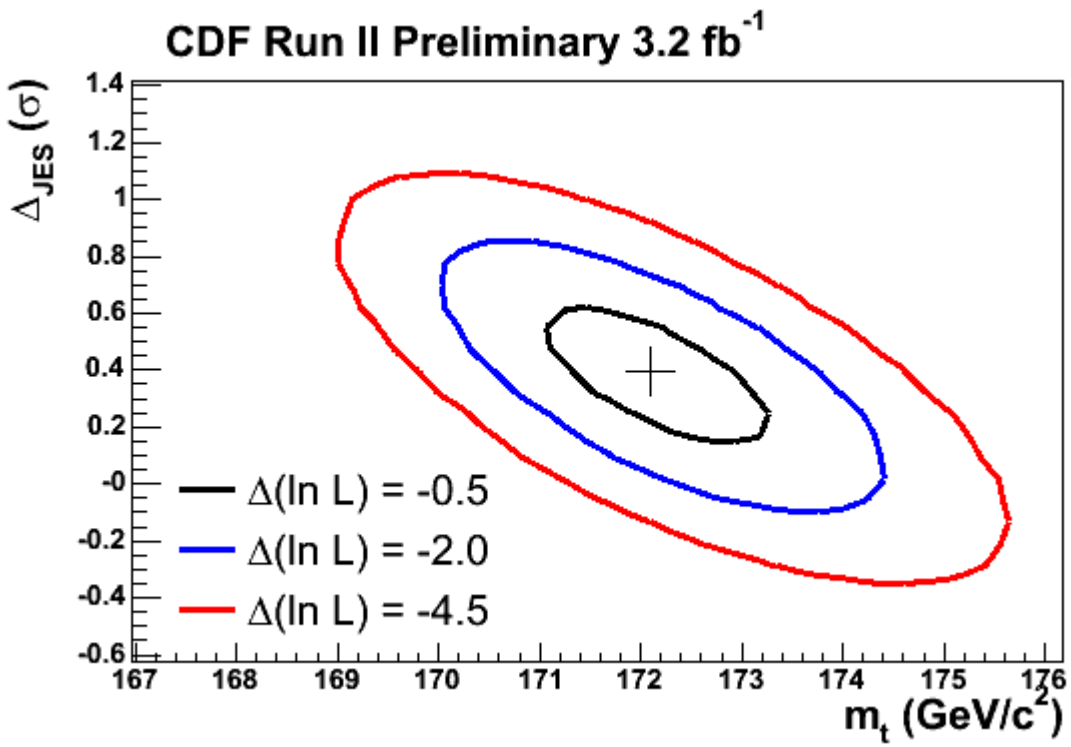
m_t=173.7±0.8(stat)±1.6(sys) GeV

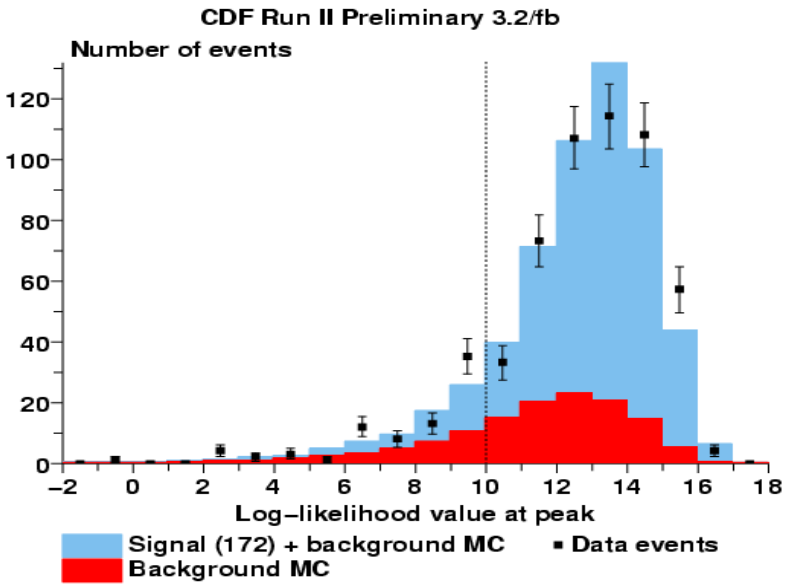
Main sources	Uncertainty (GeV)
ISR/FSR	0.25
Hadronization and UE	0.58
W heavy flavor factor	0.07
Color reconnection	0.40
PDF uncertainty	0.24
Residual JES	0.21
Sample dependent JES	0.56
Relative b/light JES	0.81
b-tagging efficiency	0.08
Jet energy resolution	0.32
Multijet background	0.14
MC calibration	0.20
Total (RunIIb 2.6 fb^{-1})	**1.41**

CDF ME ℓ+jets results (3.2 fb^{-1})

- CDF calculates background fraction based on a NN
- Trained on 10 variables against Wbb
- Signal ME is integrated over 19 variables
- Background ME is not integrated. Instead the average background likelihood, weighted by background fraction is subtracted from likelihoods for each individual event

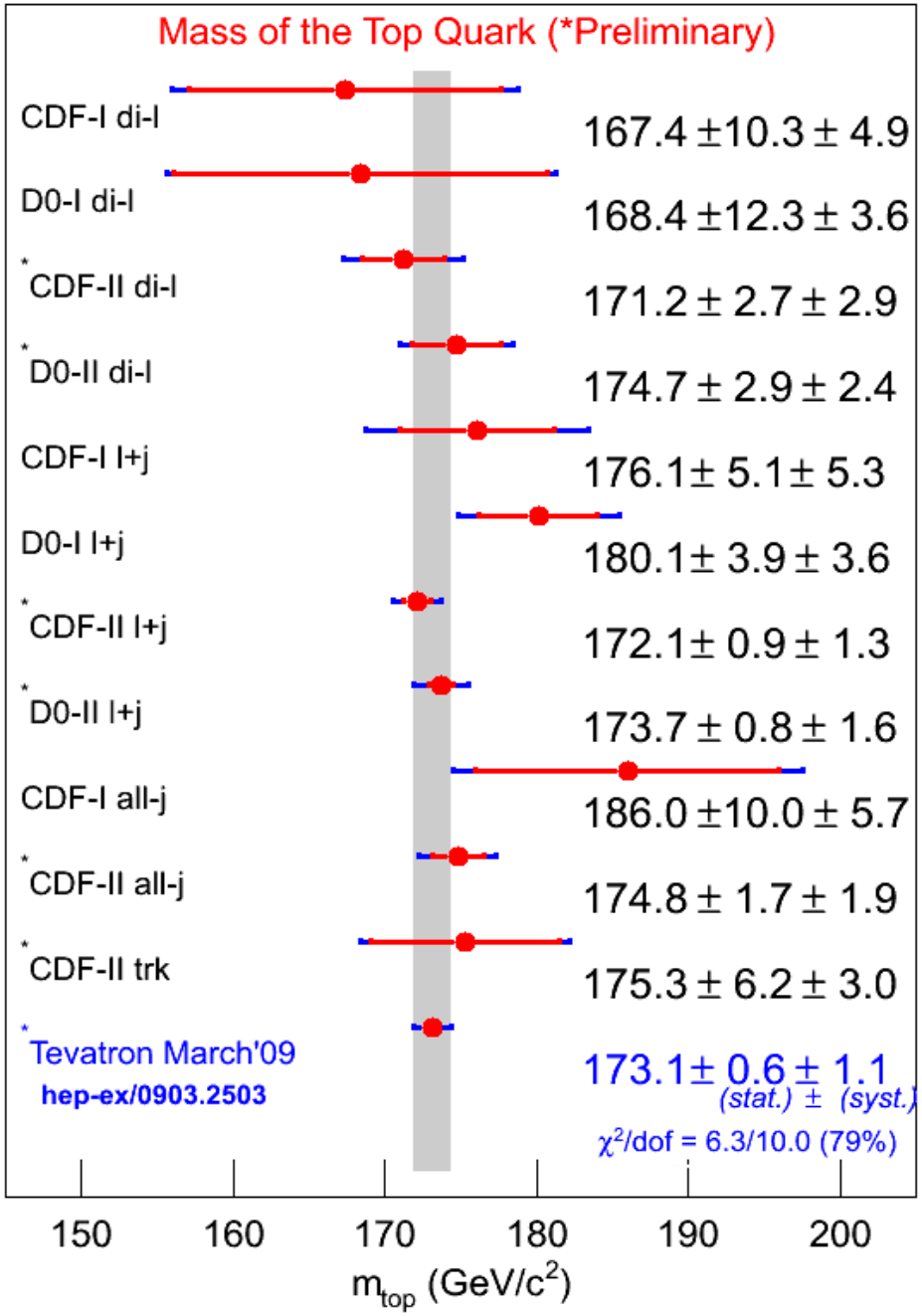




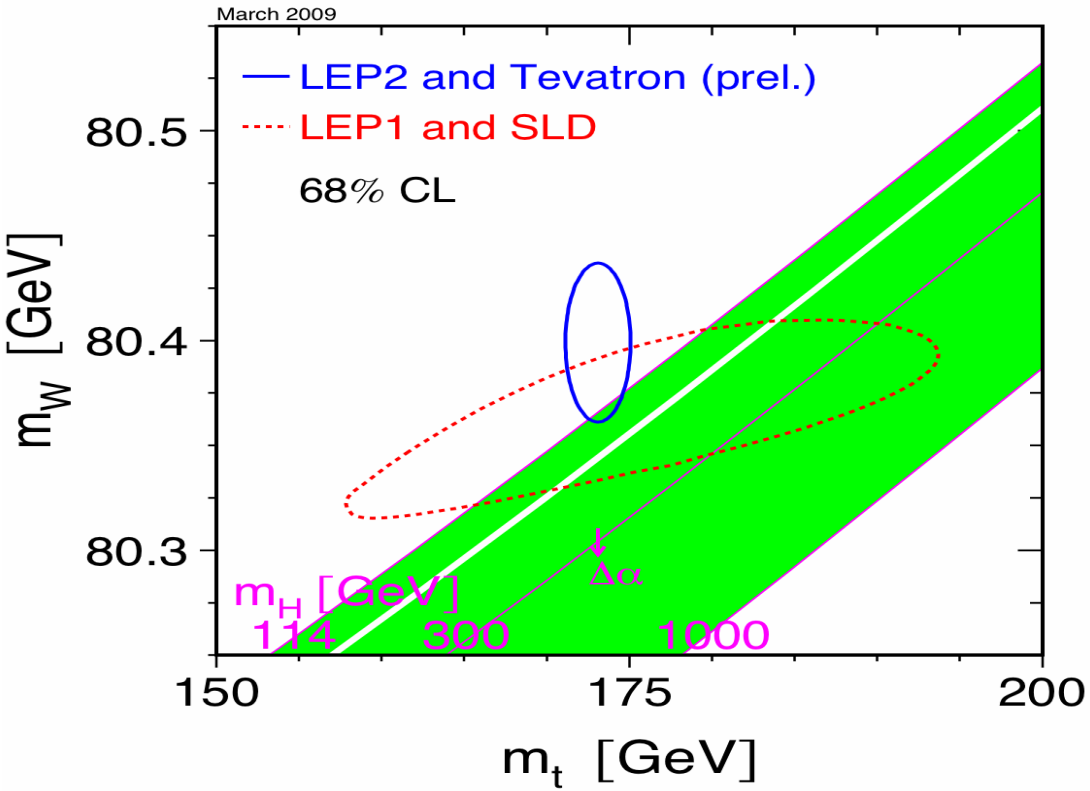


m_t=172.1±1.6(tot) GeV

CDF & DØ m_t combination

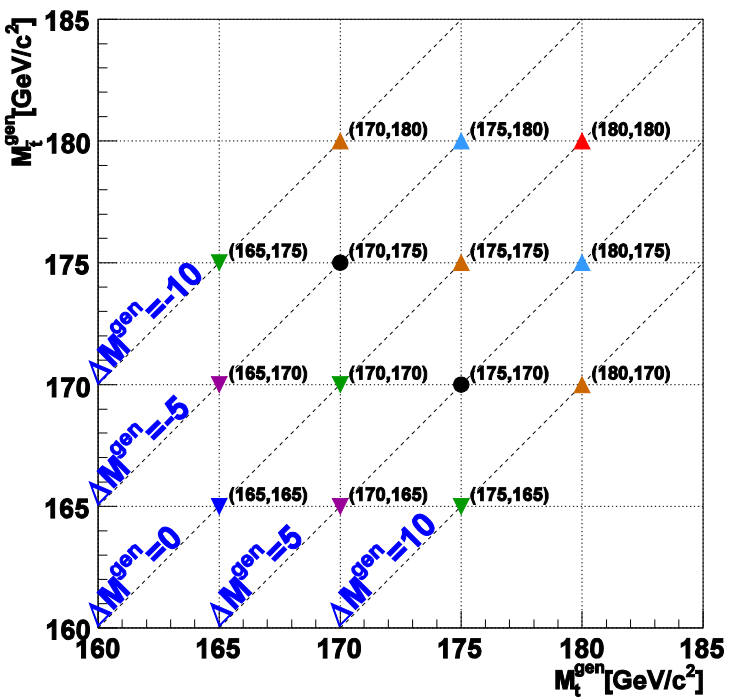


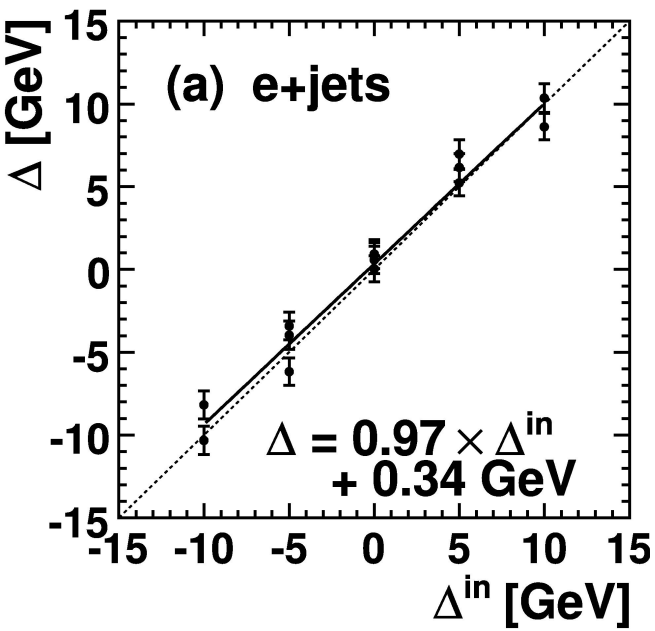
- Improved precision better than just adding luminosity
- Common approach to deal with systematics
- Careful evaluation of all sources is now the goal

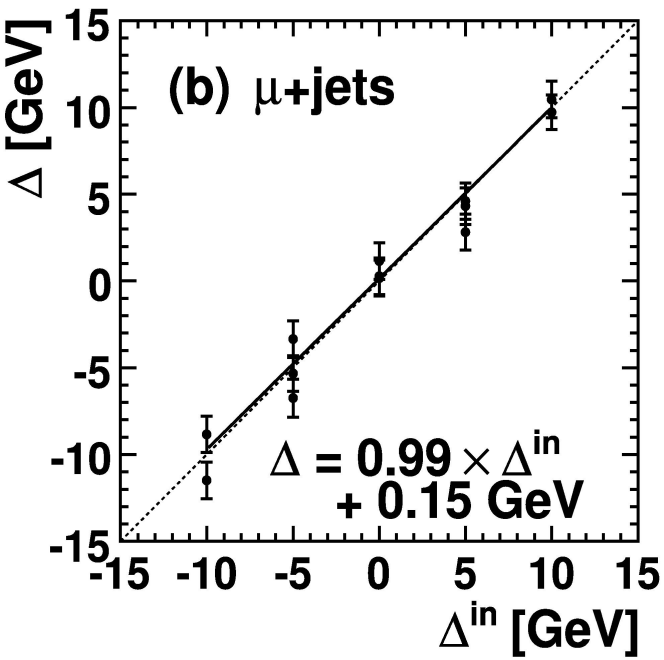


Top-antitop mass difference

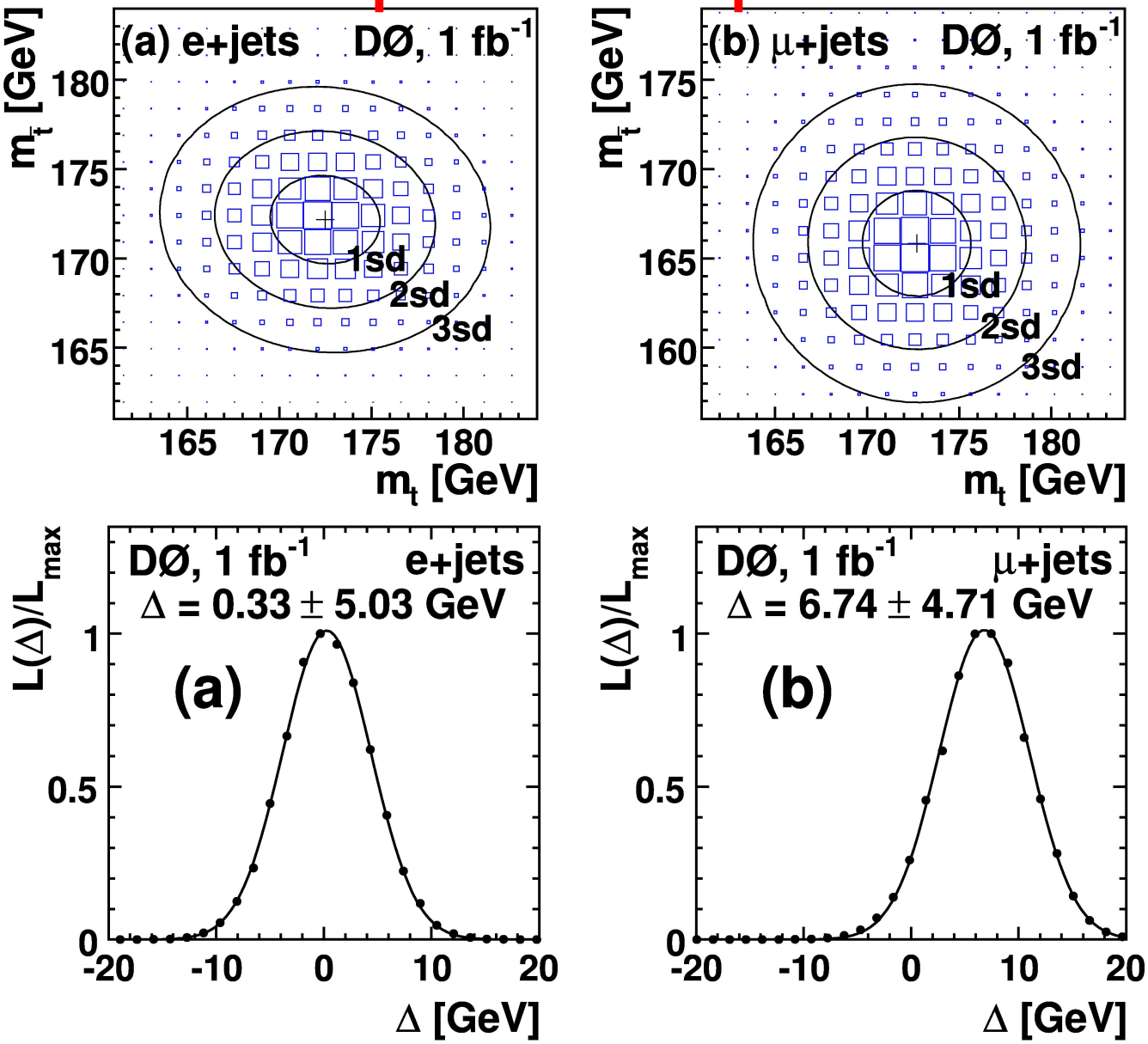
- No direct measurement of the mass difference between a quark and its antiquark has ever been attempted since quarks are never produced in isolation
- m_q and $m_{\bar{q}}$ should be equal: $\Delta m = m_q - m_{\bar{q}}$ tests CPT invariance
- Use ME ℓ+jets mass analysis ($1 fb^{-1}$)
  - $P_{evt}(m_t, JES) \rightarrow P_{evt}(m_t, m_t)$
- Modified PYTHIA to generate different m_t in same event (14 samples)







Top-antitop mass difference



$\Delta m = 3.8 \pm 3.7\,\mathrm{GeV}$

$m_{ave} = 170.9 \pm 1.5\,(\mathrm{stat})\,\mathrm{GeV}$

Submitted to PRL:

arXiv:/0906.1172 [hep-ex]

No deviation from CPT invariance

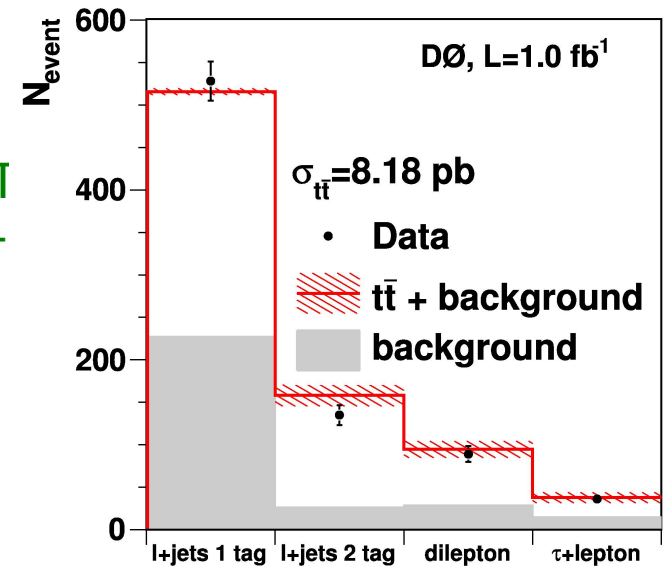
Cross section combination/ratios

- First combination of tt cross sections in DØ with fully exclusive subsamples
  - ℓ+jets: only one isolated ℓ; ≥4 jets; 1,2 btags; MET
  - Dilepton: 2 isolated ℓ; ≥2 jets; ≥1 btag; large MET
  - $\tau\ell$: like dilepton but with one hadronic decaying τ
- Derive σ from maximum Likelihood:

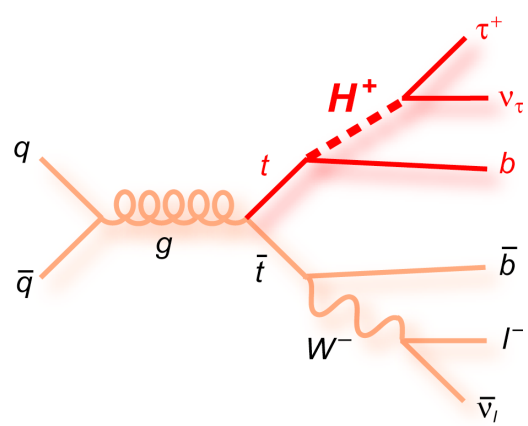
$$\mathcal{L} = \prod_{i=1}^{14} \mathcal{P}(n_i, m_i) \times \prod_{j=1}^{14} \mathcal{P}(n_j, m_j) \times \prod_{k=1}^{K} \mathcal{G}(\nu_k; 0, \mathrm{sd})$$

All subsamples — QCD samples — Systematics

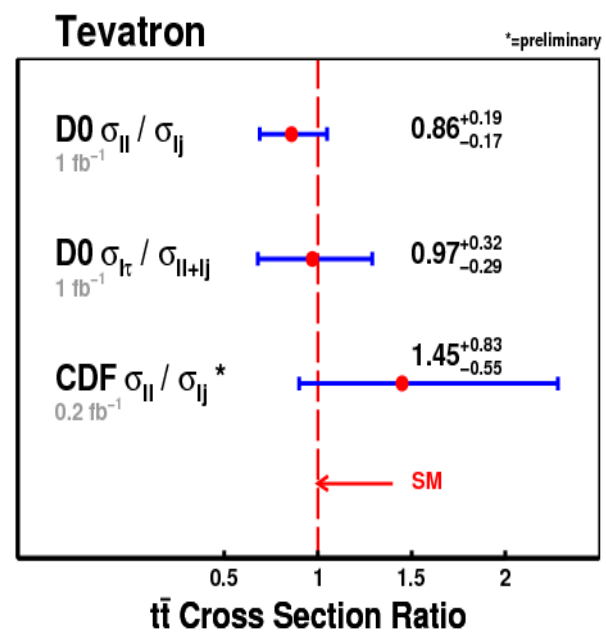
$$\sigma_{t\bar{t}} = 8.18^{+0.98}_{-0.87} \text{ pb}$$



Submitted to PRD:
arXiv:/0903.5525 [hep-ex]

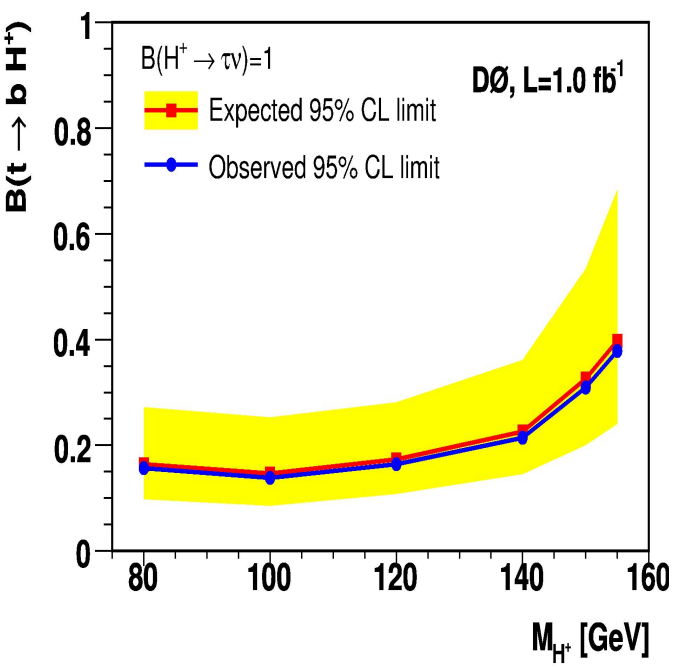


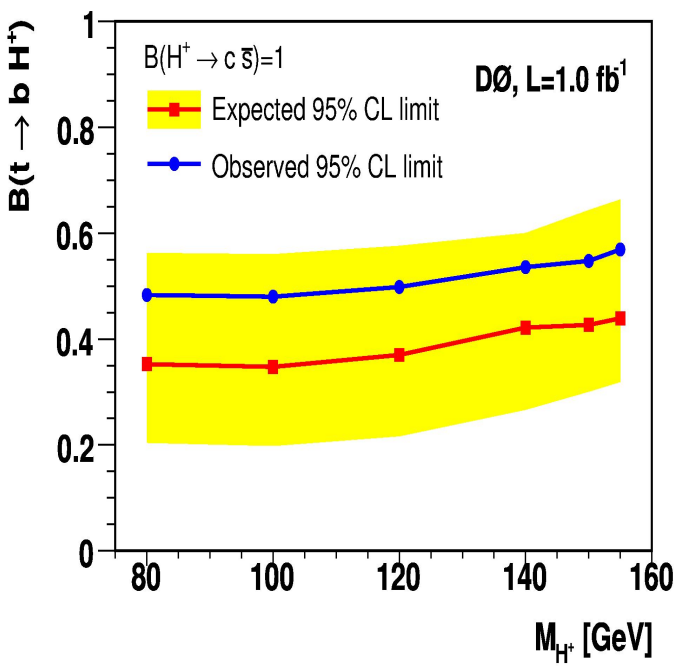
- Then calculate ratios:
  - $R_1 = \sigma(\ell\ell)/\sigma(\ell\text{jets})$
  - $R_2 = \sigma(\tau\ell)/\sigma(\ell\ell+\ell\text{jets})$
- If $t \to H^+ b \to csb$ (leptophobic) then $R_1 < 1$
- If $t \to H^+ b \to \tau\nu b$ then $R_2 > 1$

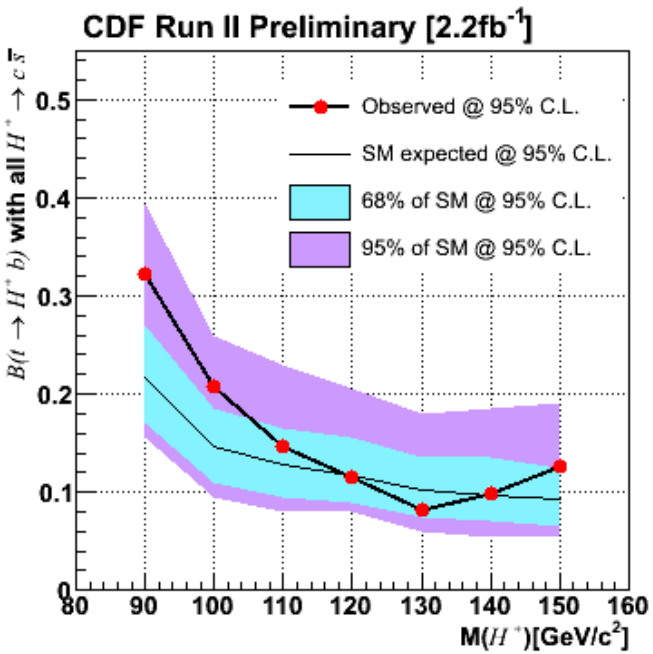


Limits on BR(t→H⁺b)

- Set σ_{tt} to SM value and create pseudodata for numerator and denominator channels at a fixed BR(t→H⁺b)
- Fit σ_{tt} in numerator and denominator separately assuming BR(t→H⁺b)=0
- Result is a distribution of R for each true BR(t→H⁺b)
- Limits from direct searches are also available from CDF and DØ
- Ratios allow to look for deviations from SM in a model independent way







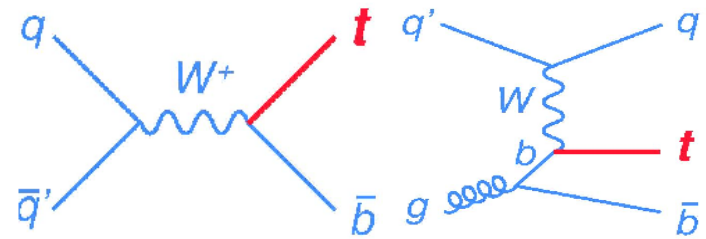
Single top physics

Electroweak production: tb and tqb

- Access directly W-t-b coupling (CKM)
- New physics:
  - s-channel sensitive to resonances
  - t-channel sensitive to anomalous couplings, FCNCs
- Extract small signal out of a large background: Higgs searches

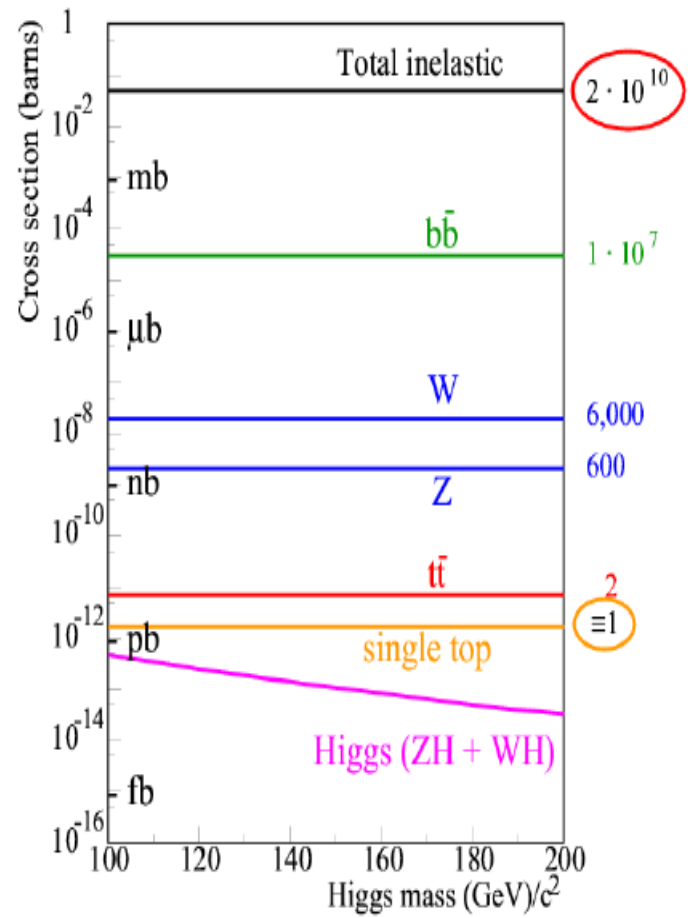
Experimental challenge:

- Lower cross section: $\sigma_t \sim 1/2\ \sigma_{tt}$
- ℓ+MET+2 jets (harder environment)
- Wbb irreducible background
- S/B~1/200 before b-tagging



s-channel σ(tb)=0.88pb

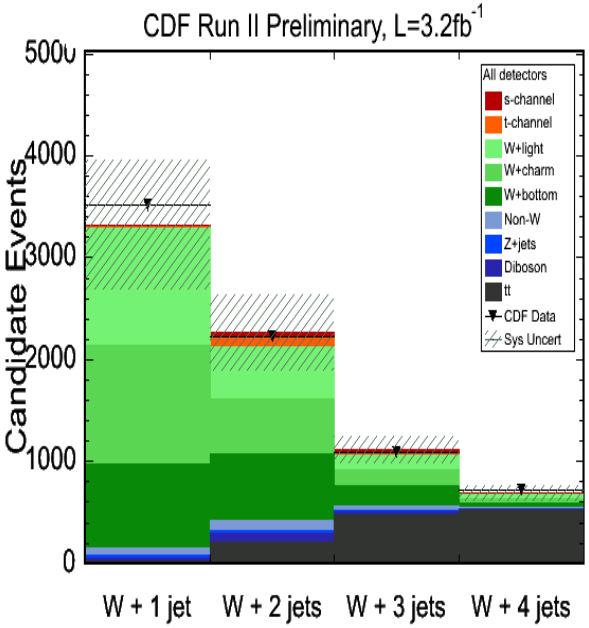
t-channel σ(tqb)=1.98pb

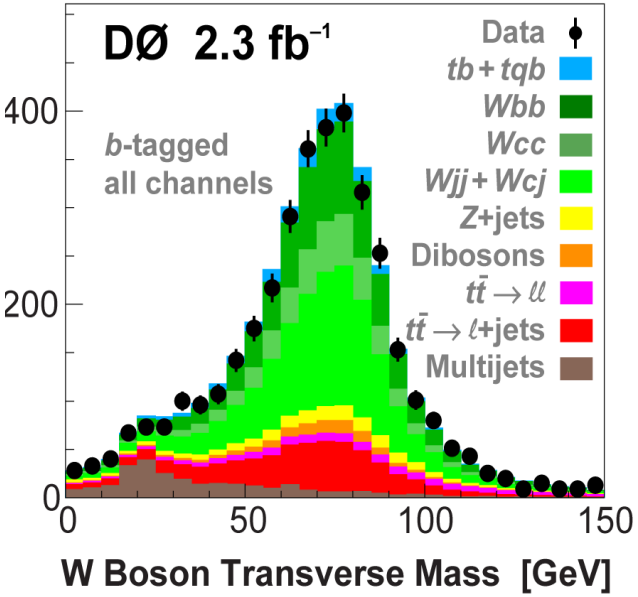


Single top selection

- Selection designed to be as open as possible: describe bkgs well
  - ℓ+jets: only one isolated ℓ; 2,3,4 jets; 1,2 btags; MET

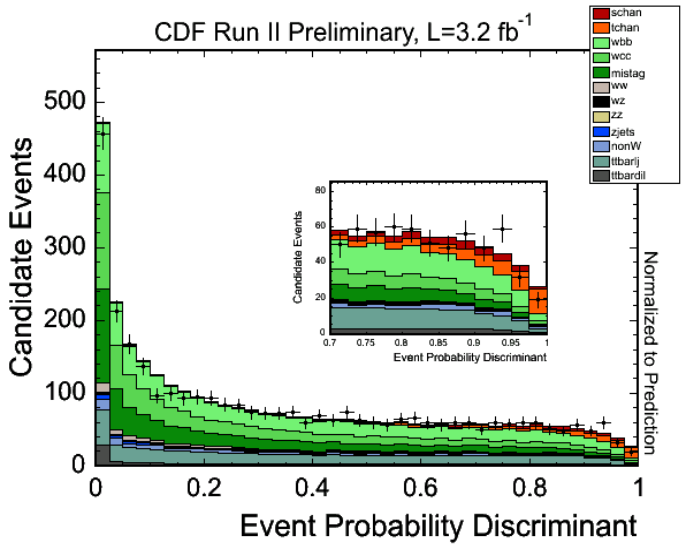
Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
s-channel tb	62 ± 9	24 ± 4	7 ± 2
t-channel tqb	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \to \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \to \ell$+jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724

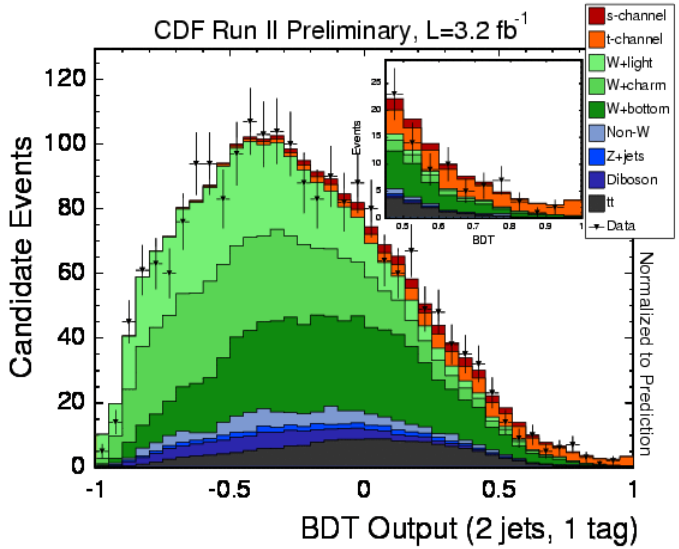


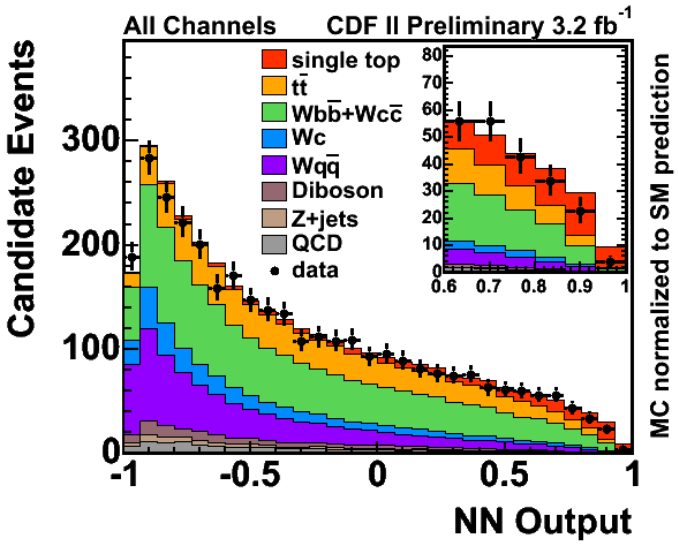


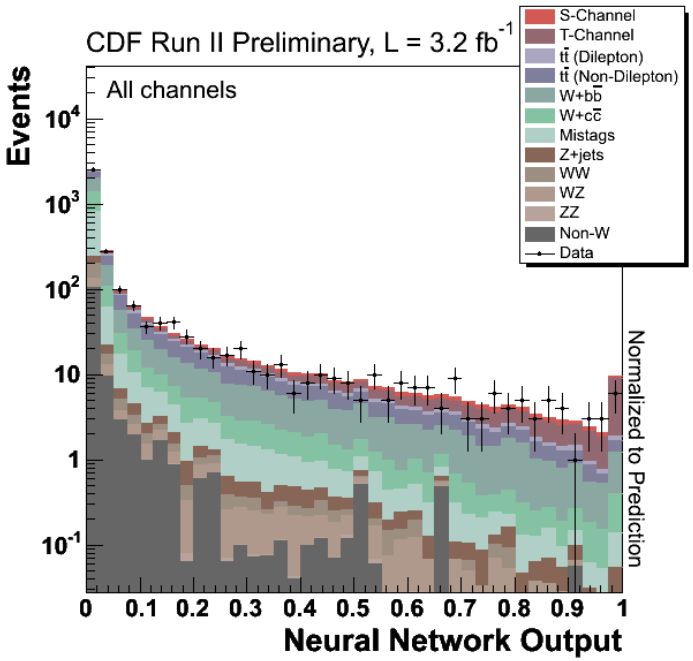
- Main uncertainty: Wbb & Wcc normalization
  - Use W+jets enriched cross-check samples to study
- No single good kinematic variable to discriminate
- Use multivariate techniques (on same data) and combine
  - Matrix Element, Neural Net, Boosted Decision Trees, Likelihood
- CDF also uses the MET+jets channel (t→Wb→qqb)

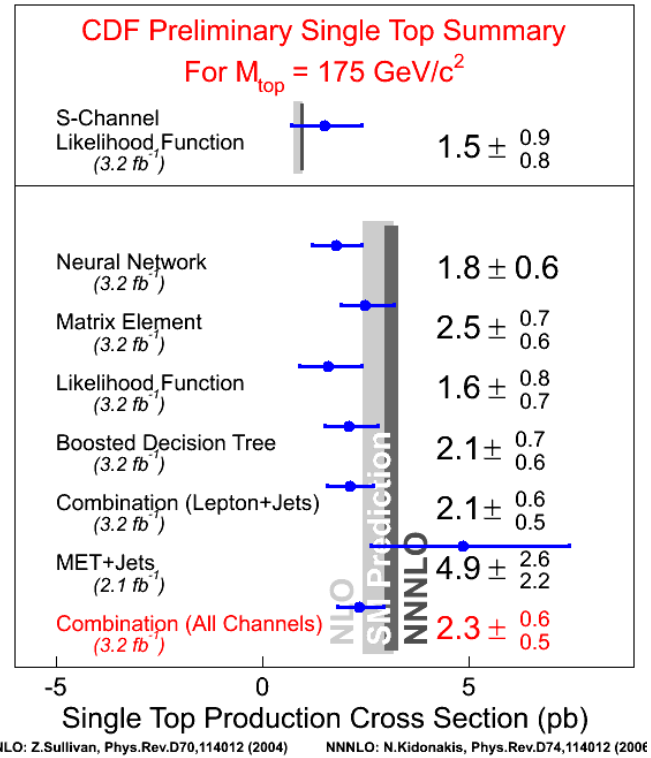
Single top results



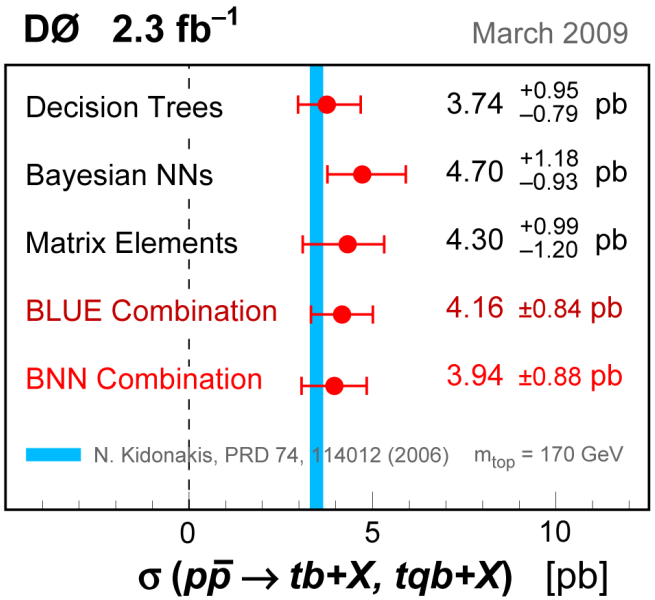




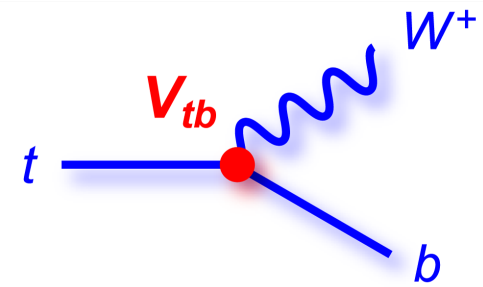




Both with 5σ excess



Constraining V_{tb}



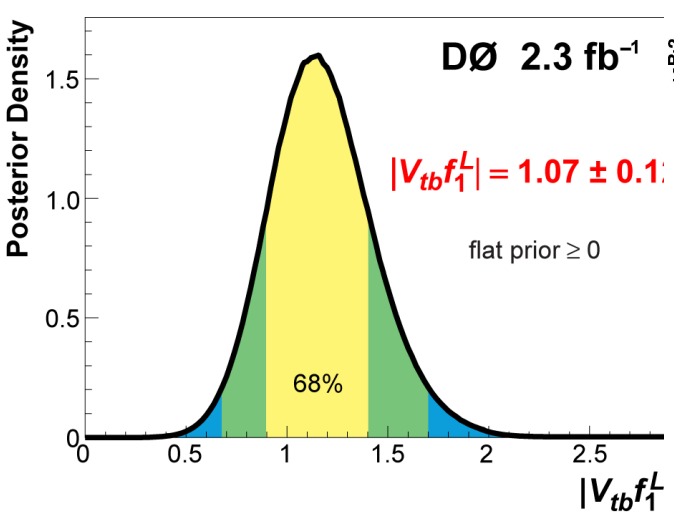
- Assume $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$, pure V-A and CP conserving Wtb vertex
- No assumption on number of families or unitarity
- Single top cross section $\propto |V_{tb}|^2$

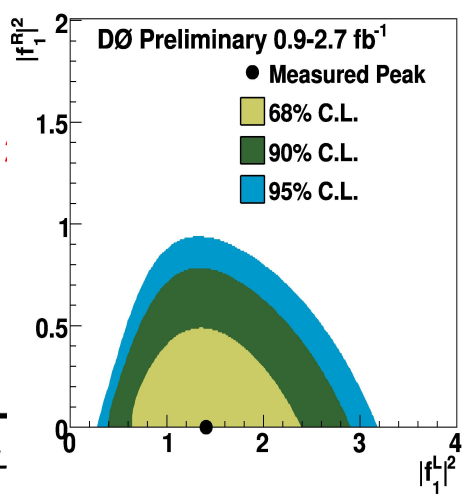
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

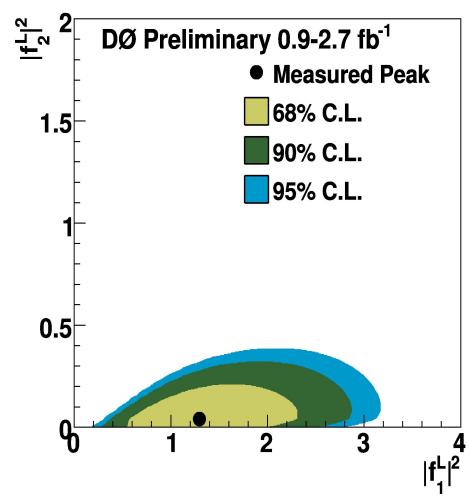
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

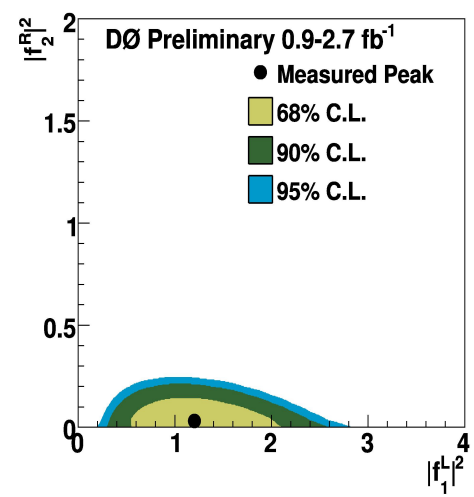
- Possible terms: f_1^L, f_1^R, f_2^L, f_2^R
- In SM: $f_1^L=1$, the rest is 0

Previous analysis of single top data + W helicity constraints:



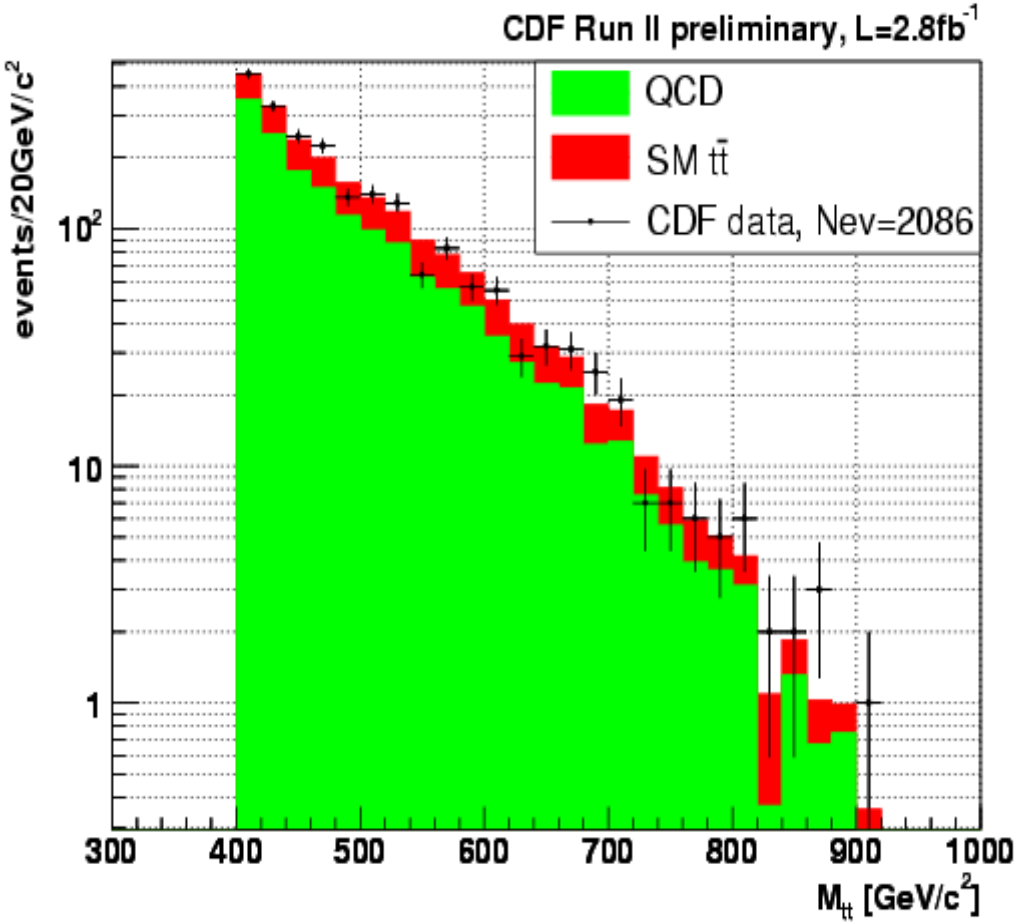


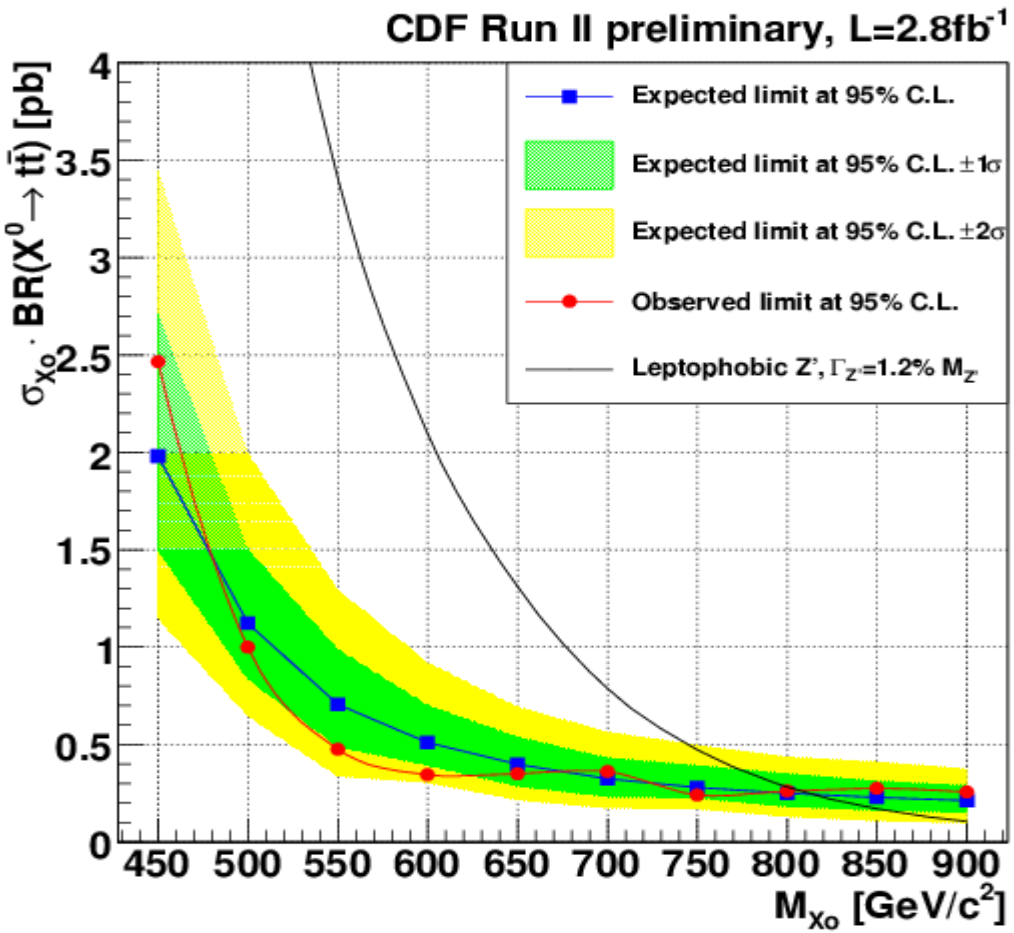


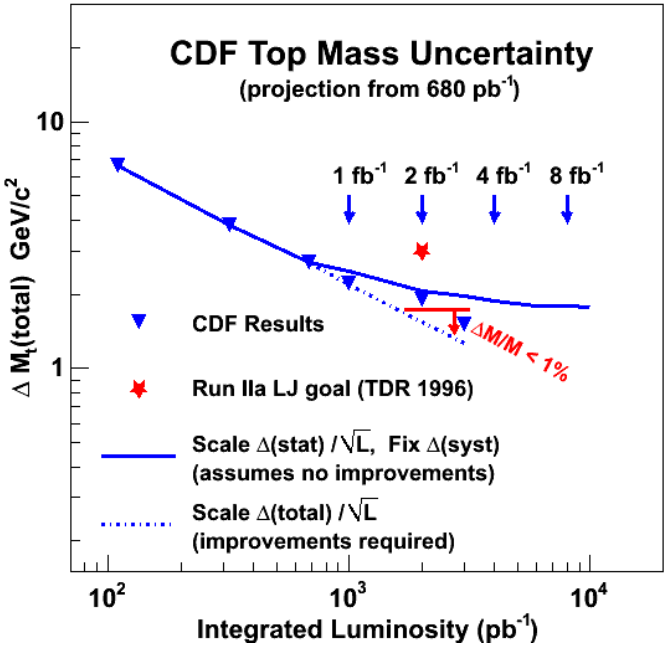


Looking for resonances

- All jets channel: 6,7,8 jets with 1 or 2 b-tags
- Used ME to discriminate against multijets and combine with other variables in NN
- Obtain probability that data contains vector resonance with given mass and cross section: $m_{Z'} > 805$ GeV





Summary

- An exciting and comprehensive top physics program at the Tevatron
- Top mass precision is now 0.7%
  - Jet energy scale calibration improved
  - World average now systematics dominated
- Single top production established
  - Flagship measurement of Run II
  - $|V_{tb}|$ model independent precision ~15%
- SM is in very good shape in top sector, but plenty of room for surprises
- Intensively looking for new physics
- Still many analyses possible at the Tevatron: lots of data, tuned detectors