Top quark production and properties

from the Tevatron, where else ?

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For the D0 and CDF Collaborations

Precision Determination of the Top Quark Mass

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On behalf of the
CDF and DØ Collaborations

Les Rencontres de Physique de la Vallee d'Aoste,
March 4-10, 2007, La Thuile, Aosta Valley, Italy

Single Top Quark Production at the Tevatron

Aurelio Juste
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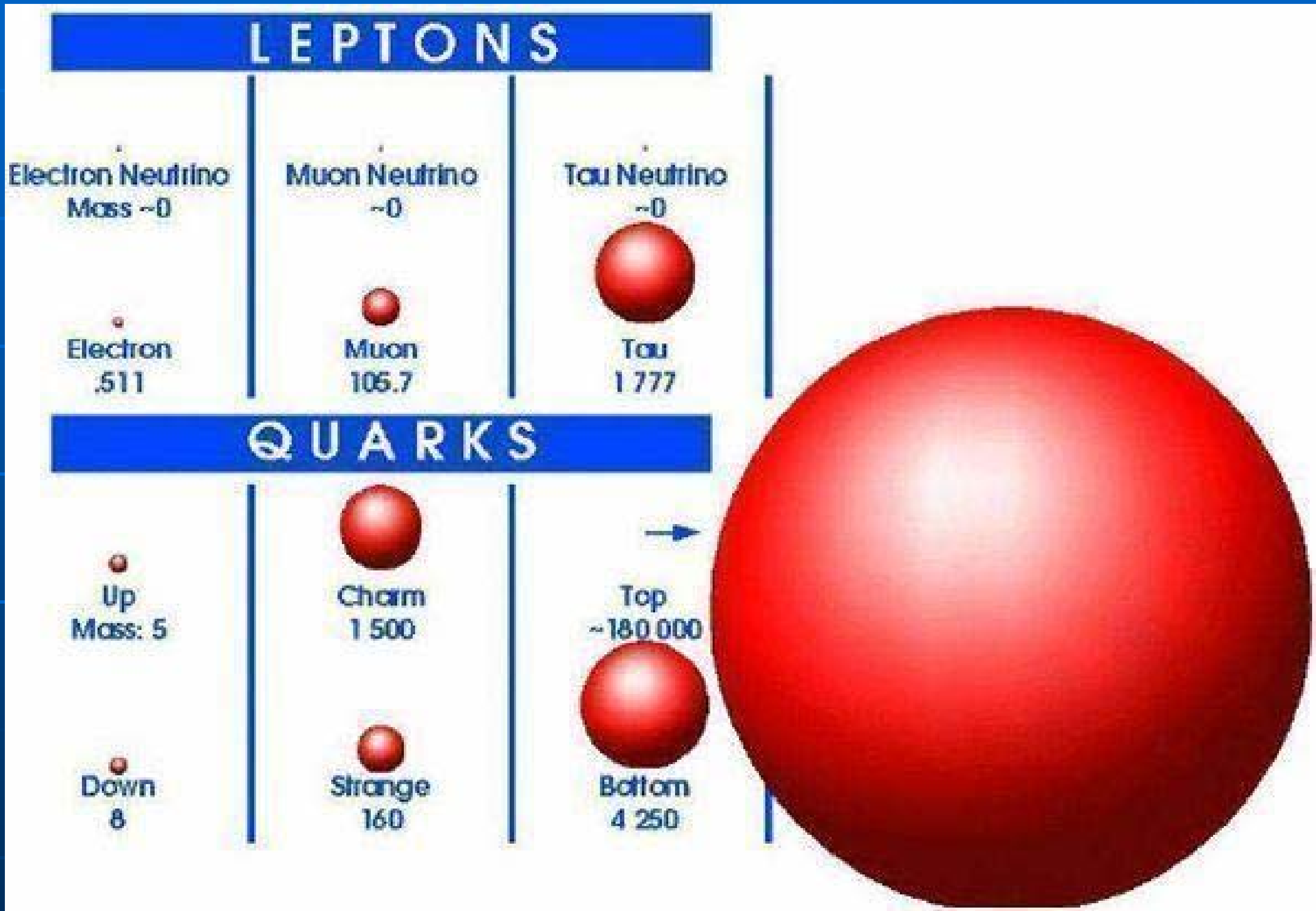
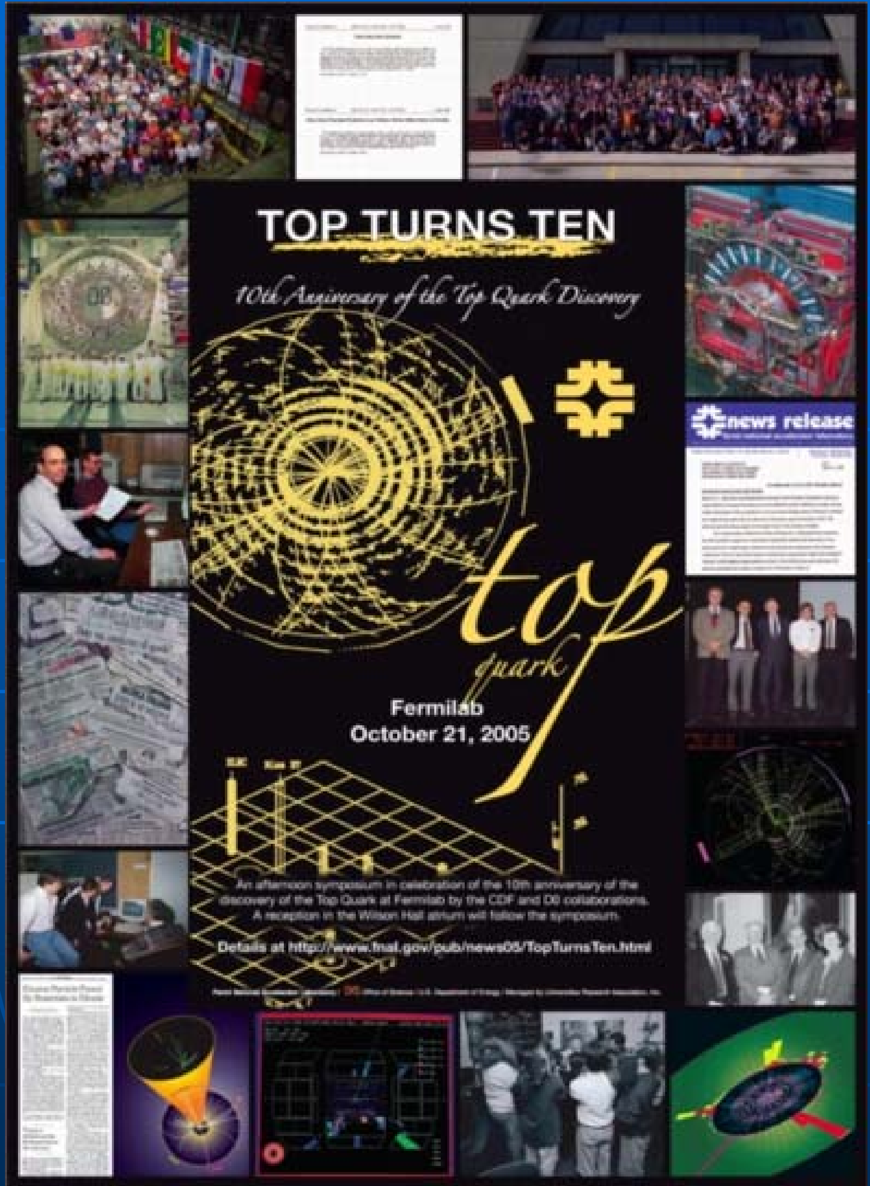
OUTLINE

- Motivation
- Experimental Challenge
- Search Strategy
- Results:
  - Evidence for Single Top Quark Production
  - First Direct Measurement of $|V_{tb}|$
- Summary

The top quark





TOP

TURNS

~~TEN~~

~~ELEVEN~~

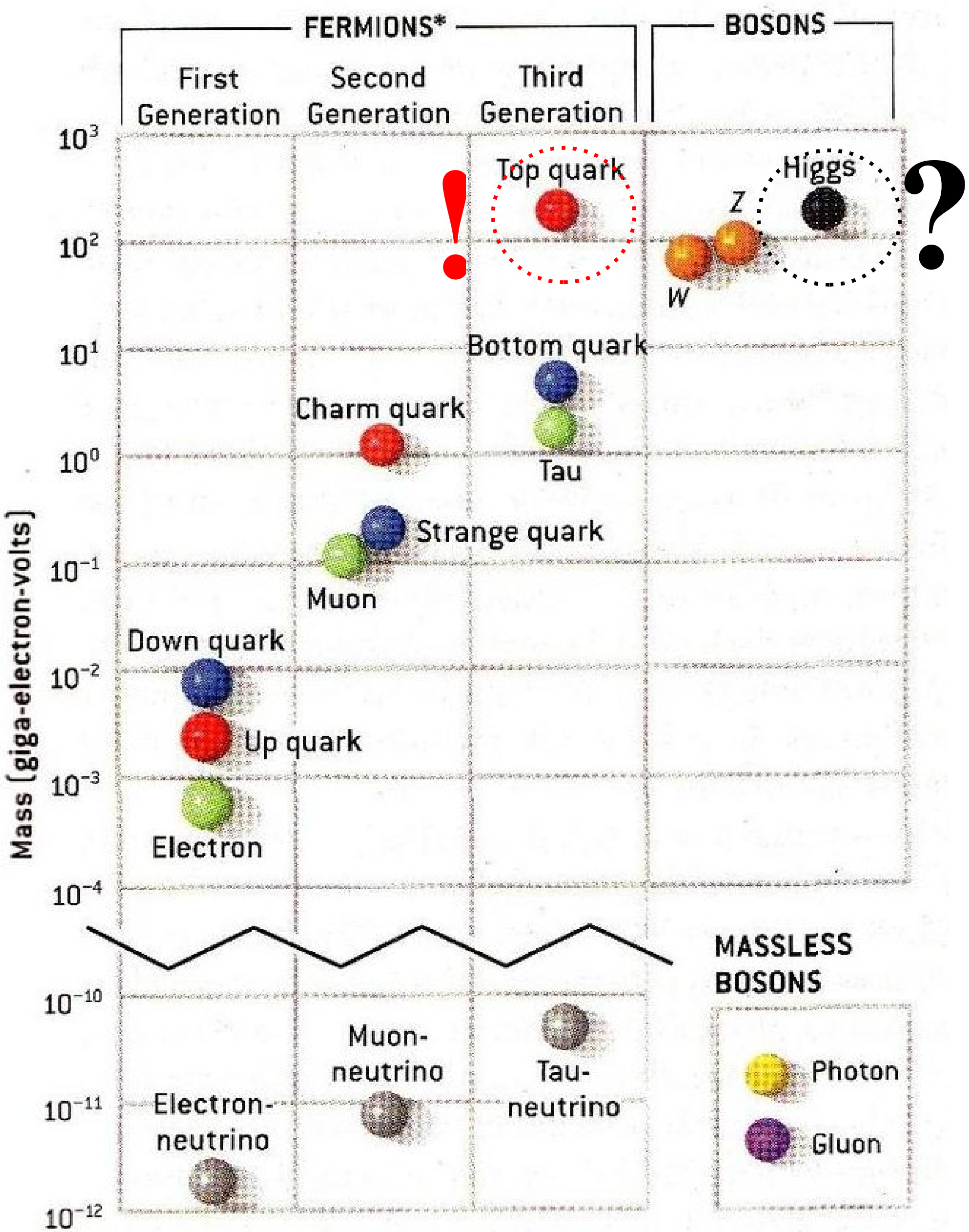
TWELVE

The Top Quark in the Standard Model

- Top quark was discovered 1995.
- It is required in the Standard Model (SM) as weak isospin partner of the bottom quark.

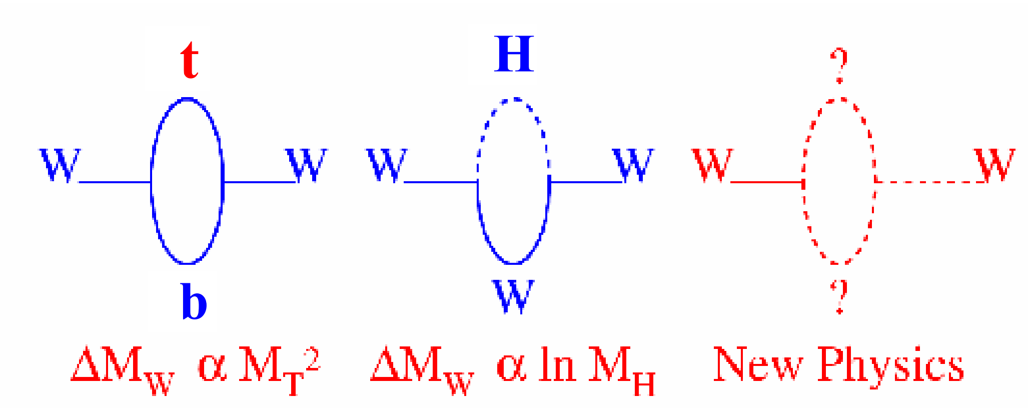
- Striking property: top quark mass is surprisingly large!
  - near electroweak symmetry breaking (EWSB) scale
  - Yukawa coupling ~ 1

- Higgs boson also required by the SM but not seen as yet.



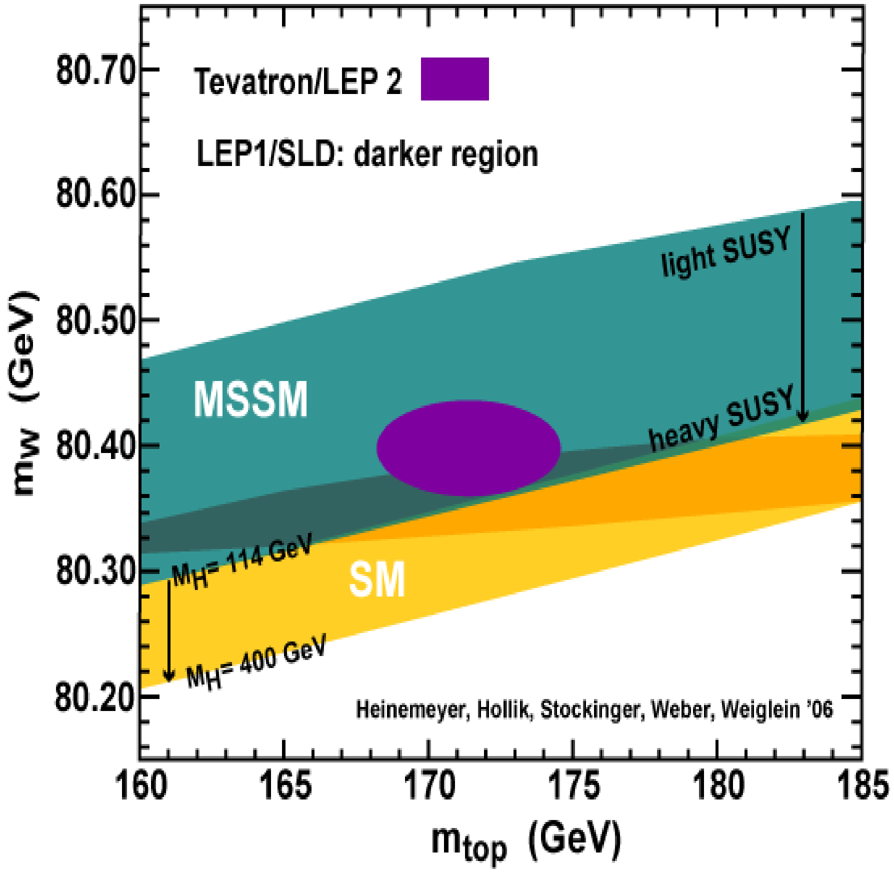
Why Measure the Top Quark Mass?

- Fundamental parameter
- Correlated to other SM parameters via electroweak corrections



- Prediction of the Higgs boson mass.
- Constraints for physics beyond the SM.
- A key to understand EWSB?

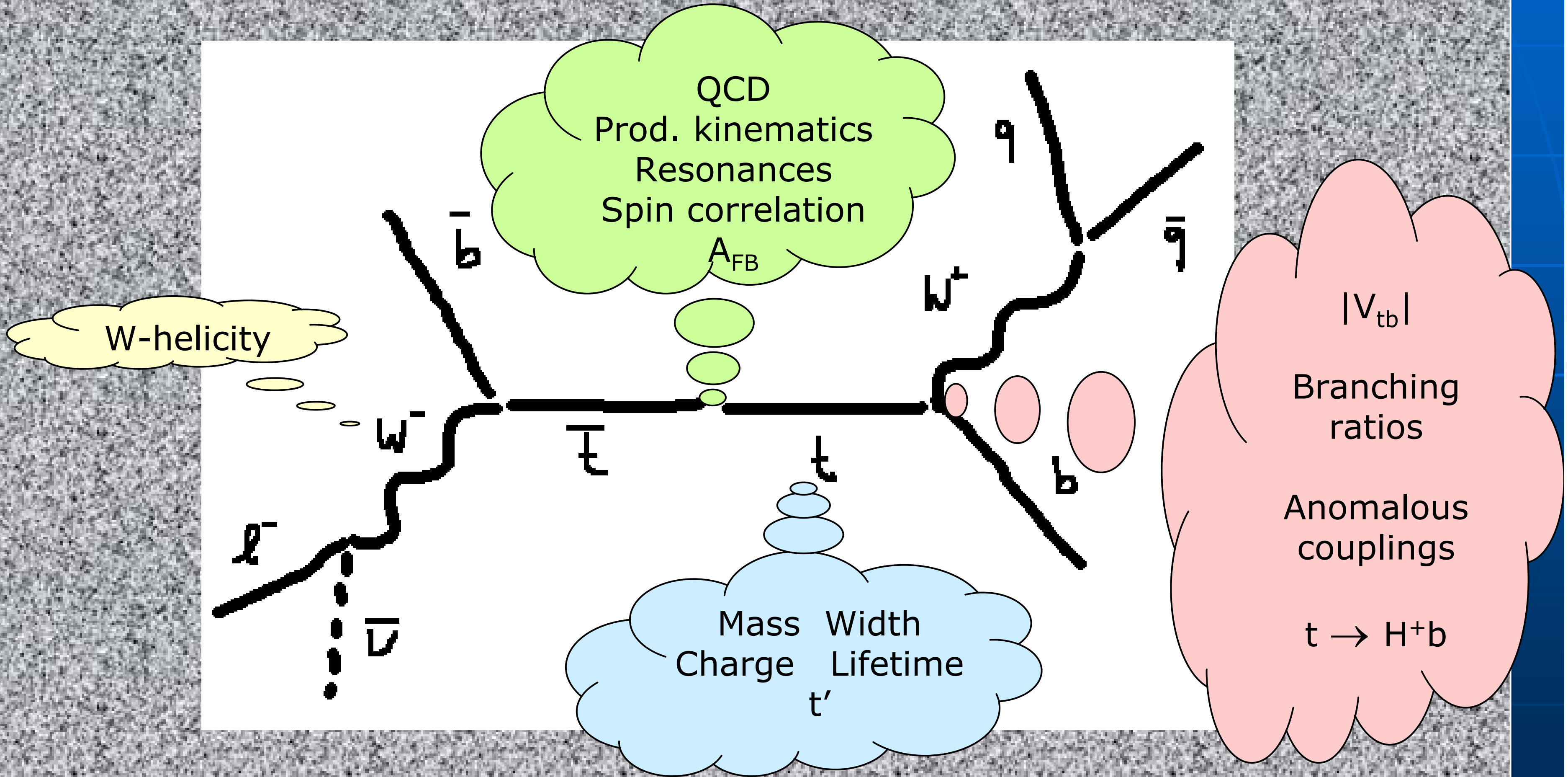
Heinemeyer et al. , JHEP 0608:052 (2006)



m_{top} and m_W (see C. Hays' talk) currently constrain m_{Higgs} to ~35%!

- Very active field in Tevatron CDF & DØ collaborations with more then 20(!) different measurements competing on the market.

Top quarks exist, what do we do with them ?

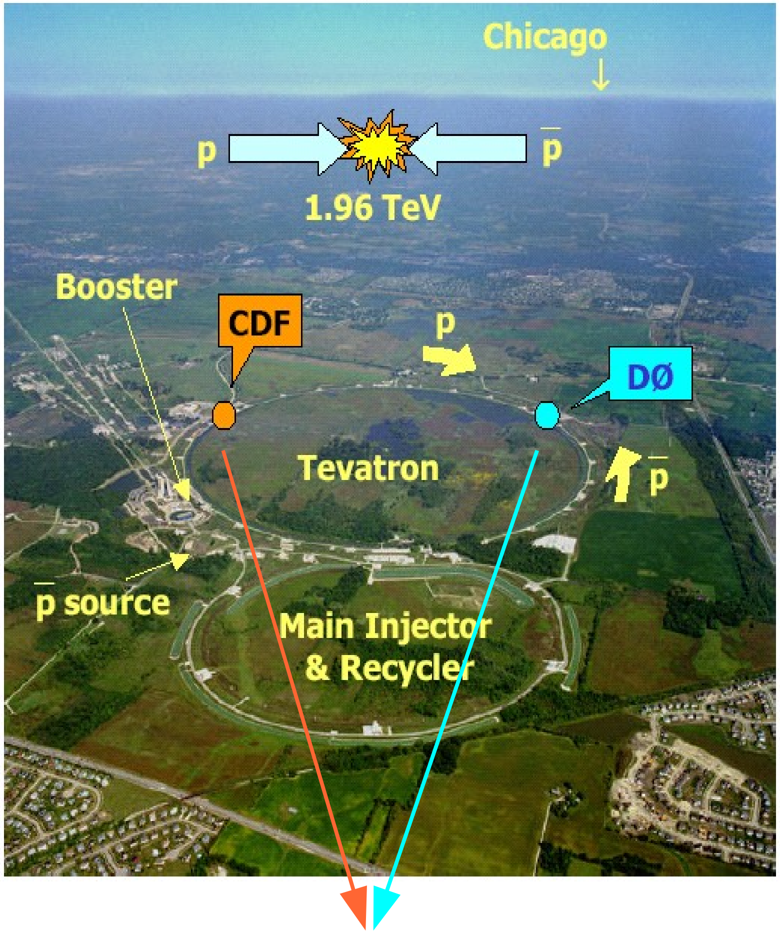


New Physics

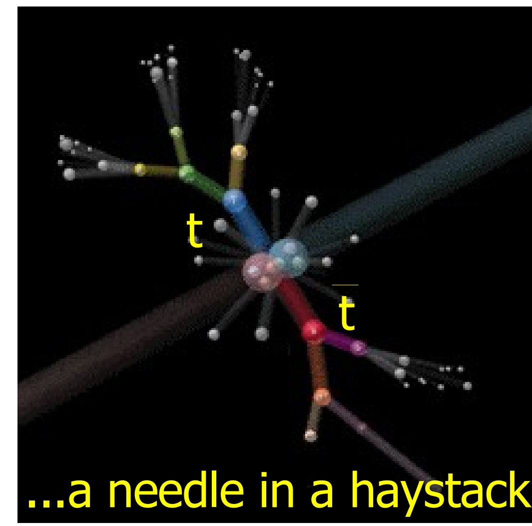
Outline

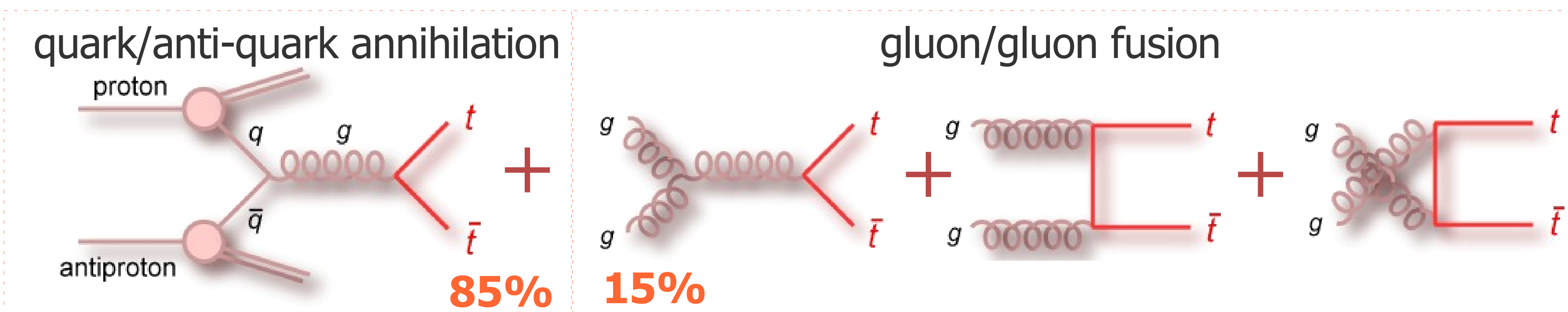
- Top quark production and identification
- Cross section measurements
- Properties of the top quark
- Wtb: branching ratio, W helicity
- Top and new physics

Top Quark Production



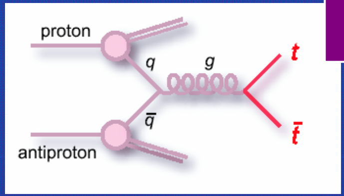
- Tevatron is only existing top production machine.
- Run II (since 2001): $\sqrt{s}$=1.96 TeV
- CDF & D0 experiments have ~2/fb on tape. Run-II goal: 4-8/fb.
- Top quarks are mainly produced in pairs via strong interaction: $\sigma_{t\bar{t}}(1.96\text{TeV})=6.1\text{pb}$
- 1 top quark pair each 10^{10} inelastic collisions...



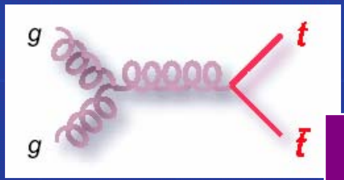


Top quark production

Top quark pair production via **strong** interaction



85%

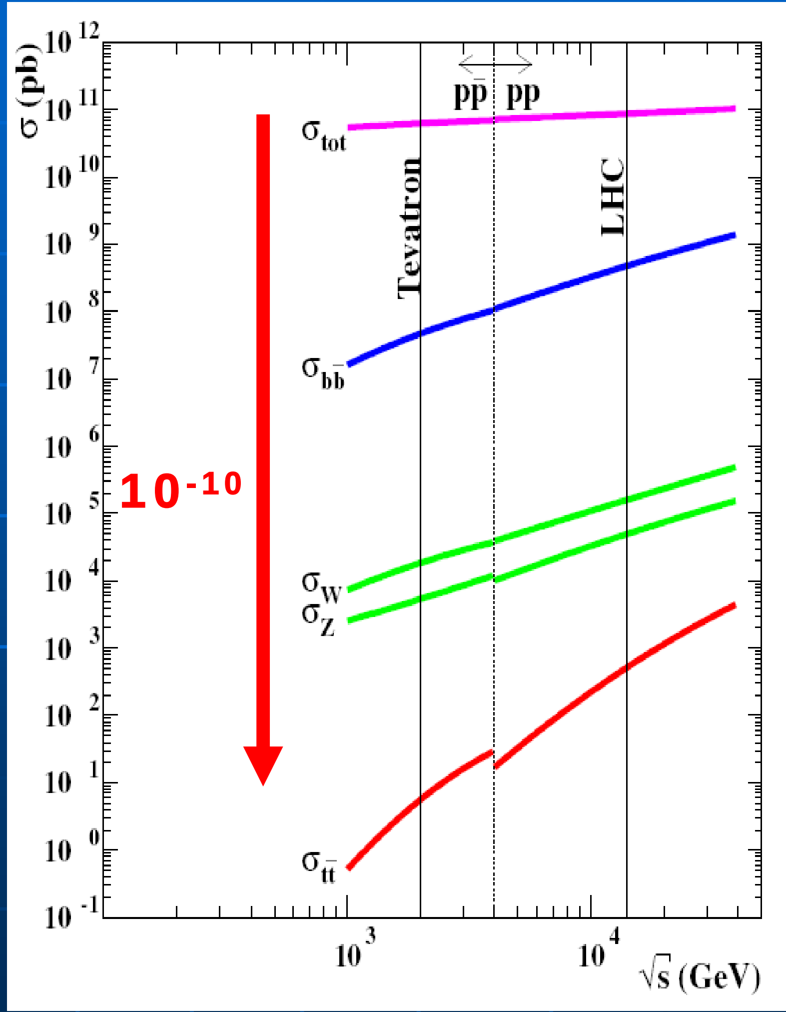


15%

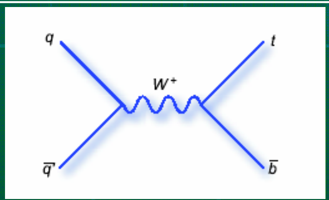
6.7 pb (1.96TeV, m_t=175GeV/c^2)

N. Kidonakis and R. Vogt, Phys. Rev. D68, 114014 (2003)

Cacciari etal, JHEP 0404, 068 (2004)



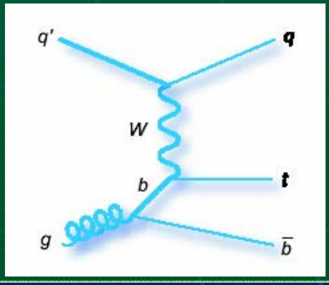
Single top quark production via **weak** interaction



See talk by A.Juste

s-channel: 1.0 pb

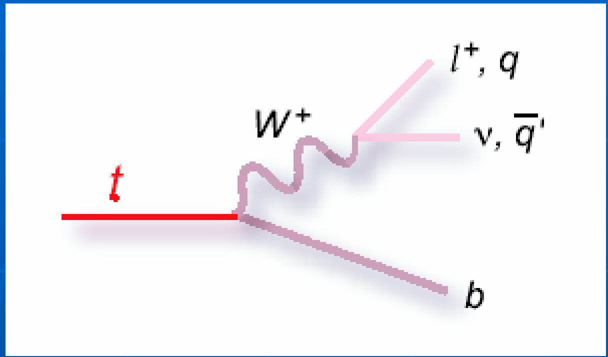
NNNLO, m_t=175 GeV



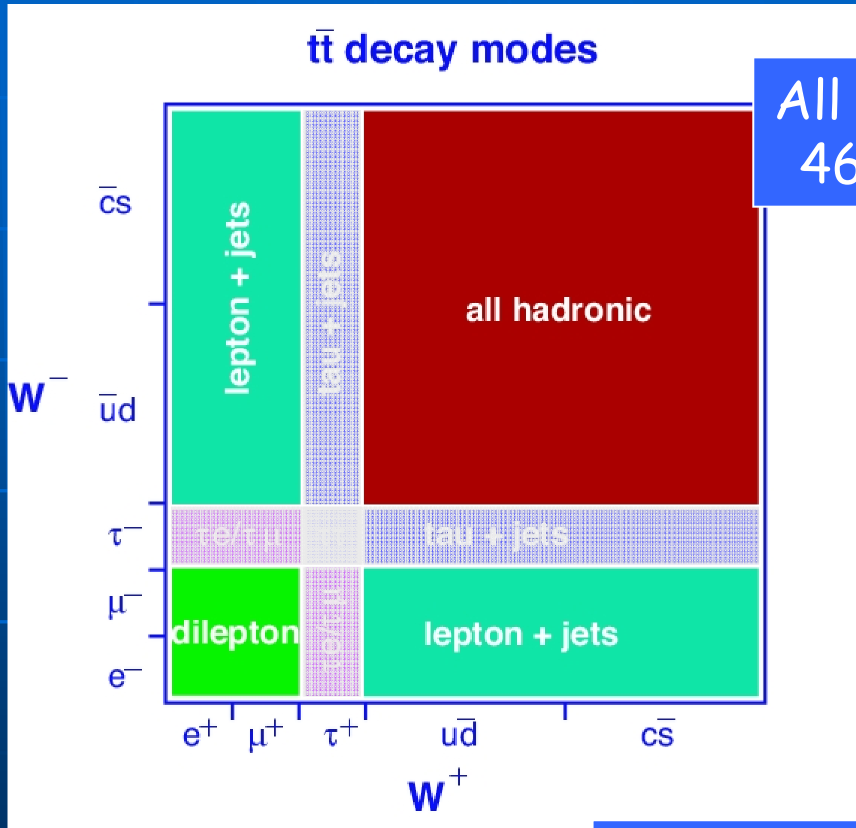
Kidonakis, Phys. Rev. D74, 114012 (2006)

t-channel: 2.2 pb

Top quark decay & identification



$t \rightarrow Wb \cong 100\%$



All jet
46%

Need to reconstruct and identify Electrons, muons, jets, b-jets and missing transverse energy

decay products have:

- good angular separation in the lab frame
- high transverse momentum

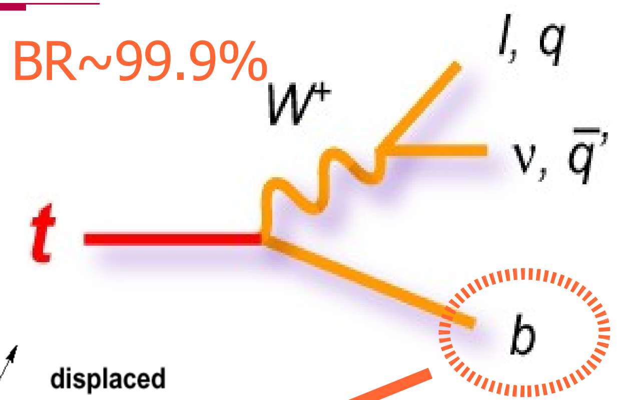
dilepton (e/μ)
4.5%

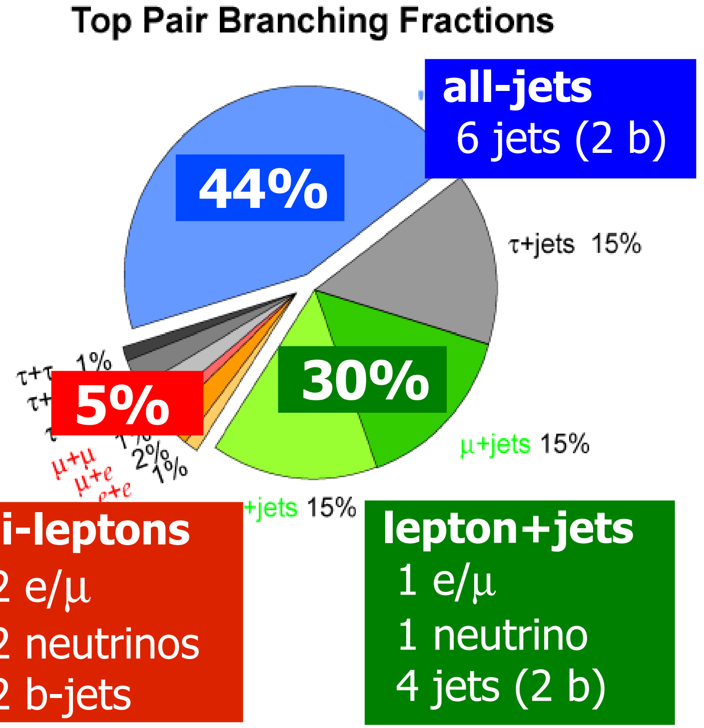
e/mu + jets
29%

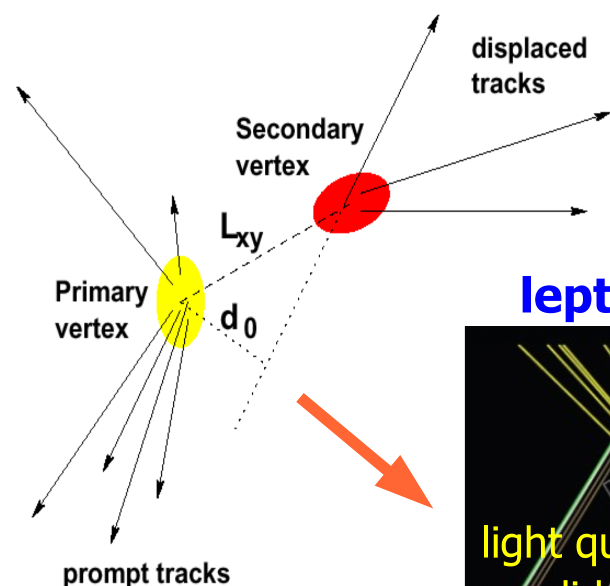
Top Quark Signature

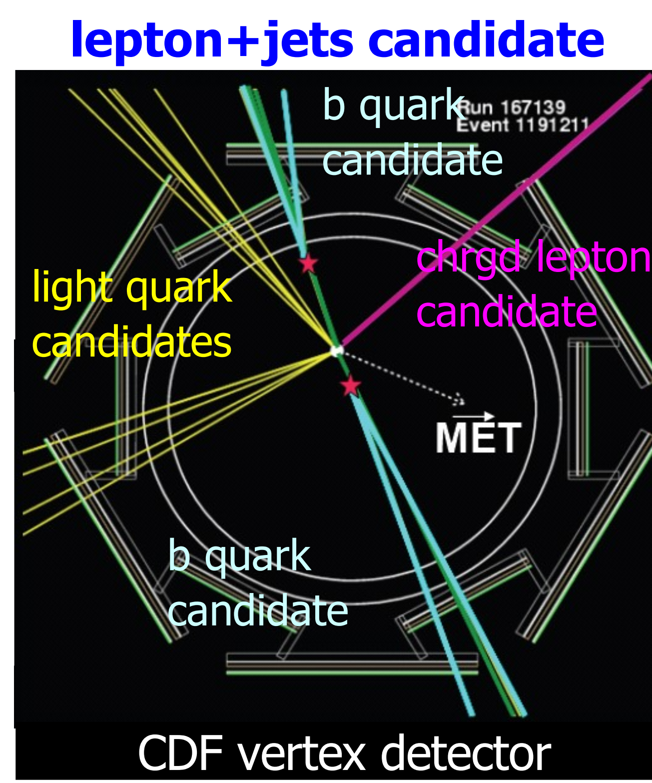
- SM top quark decays weakly before hadronization:
- W decay determines experimental signature:

(for more on top properties, see M. Weber's talk.)







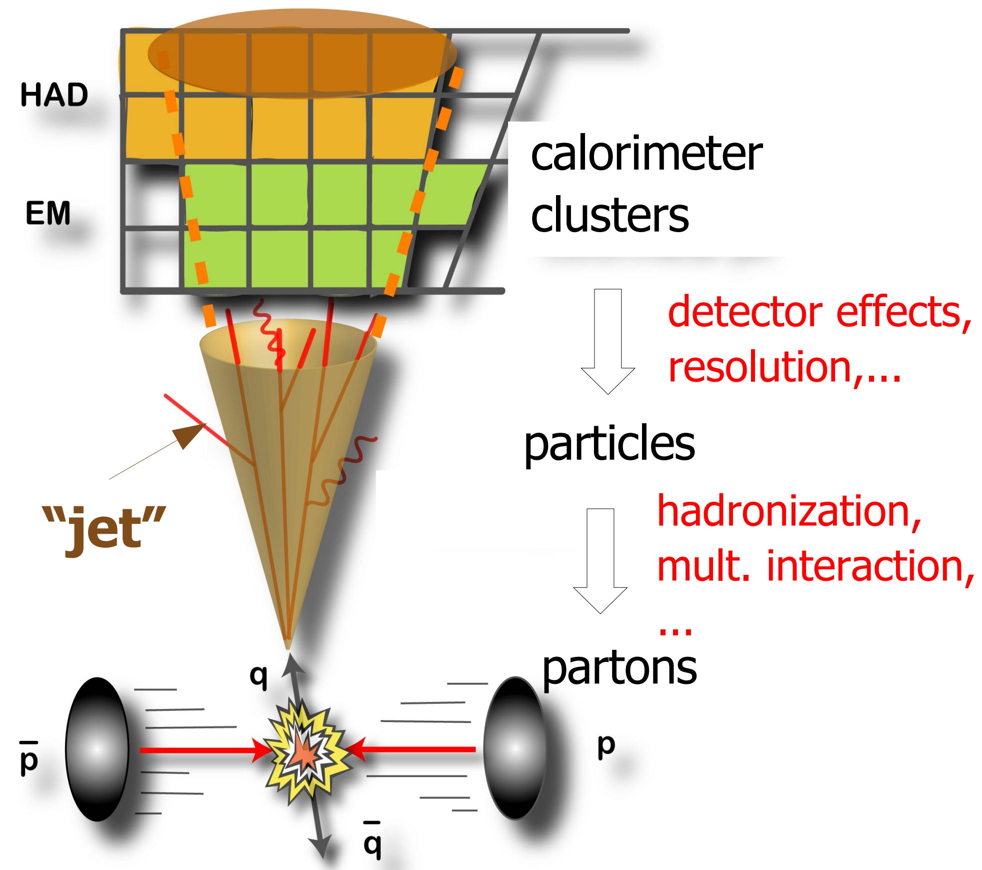


- CDF and DØ have vertex detectors to find displaced vertices from decay of long-lived b-hadrons ...crucial to reduce physics background!

Challenges of Top Quark Physics

- Requires full detector capabilities
  - tracking, calorimetry, hermeticity
  - secondary vertex finding
- Identification of electrons and muons
  $\rightarrow$ charged leptons from W decay
- Undetected ("missing") energy
  $\rightarrow$ neutrino reconstruction (p_z unknown)
- Calorimeter clusters ("jets")
  $\rightarrow$ quark reconstruction
- Secondary vertex tagging
  $\rightarrow$ quark flavor (b or light)

... reduces physics background and jet/quark combinatorics



Determination of the jet energy scale (JES):

- Correct jet energies for detector effects, hadronization, multiple interactions, ...
  $\rightarrow$ momenta of hadronic top decay products

JES known to **~3%** $\rightarrow$ dominant uncertainty in all current top quark mass measurements!

Production cross section

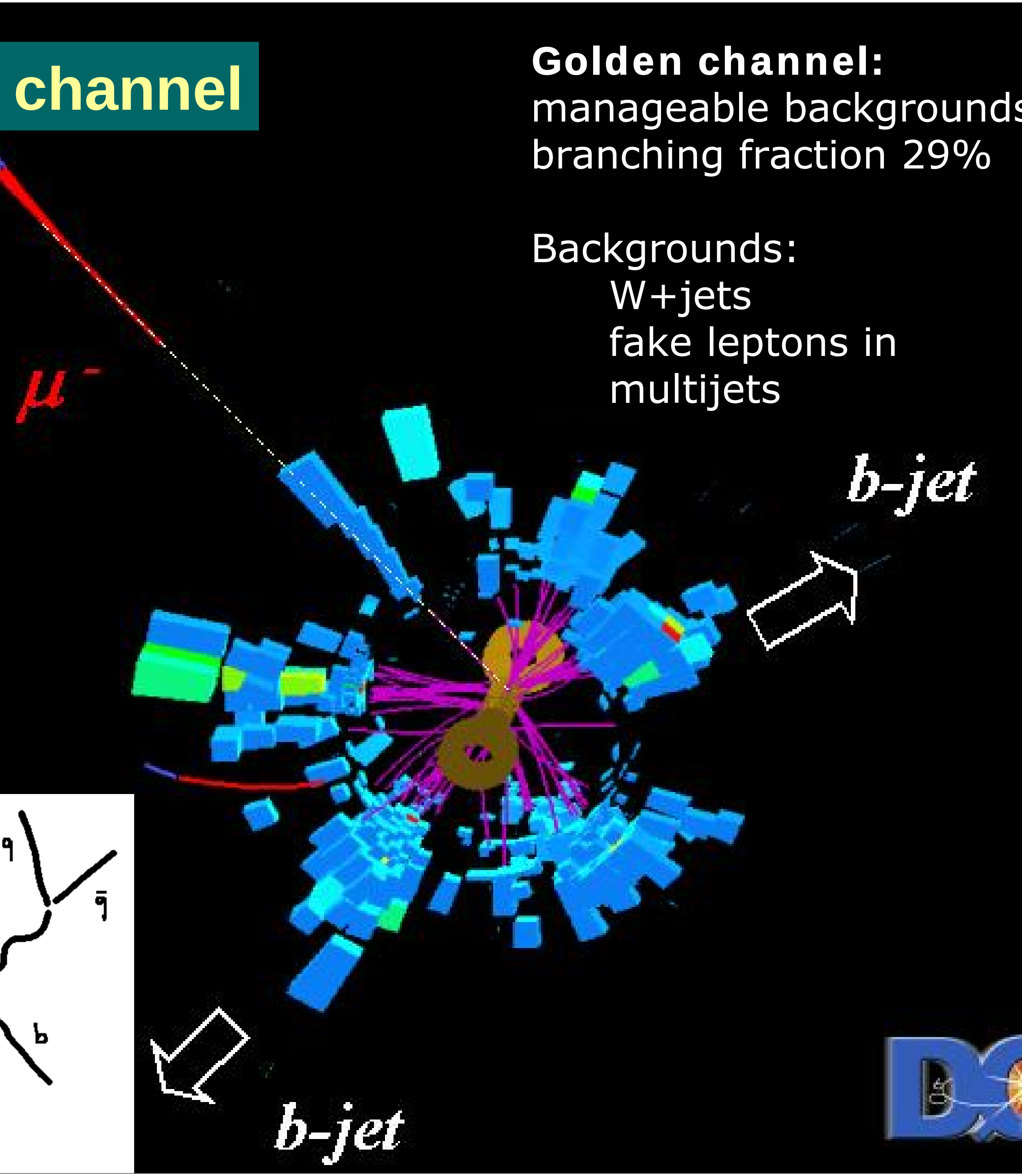
$$\sigma = \frac{N_{events} - N_{background}}{\text{Luminosity} * \varepsilon}$$

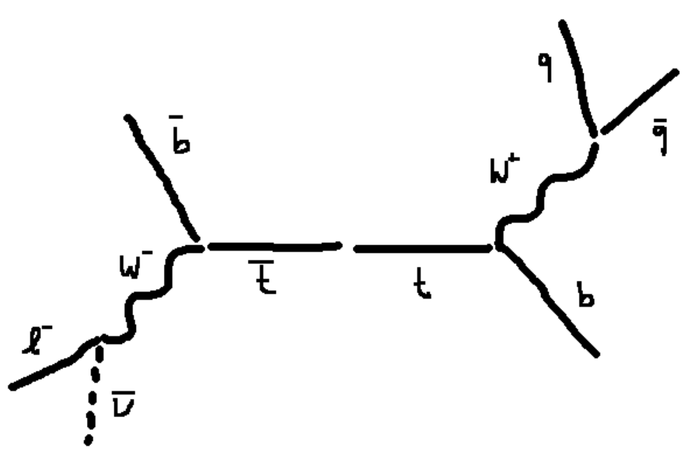
- Test of QCD at high Q^2
- Higher cross section than predicted could be a sign of new physics: resonant state $X \rightarrow t\bar{t}$ OR anomalous couplings in QCD?
- Lower cross section could also mean new physics: we make assumptions on the expected decay mode
- Important to measure all decay channels and topologies: different sensitivities to new physics possibilities
- Provides samples for properties measurements

Lepton + jets channel

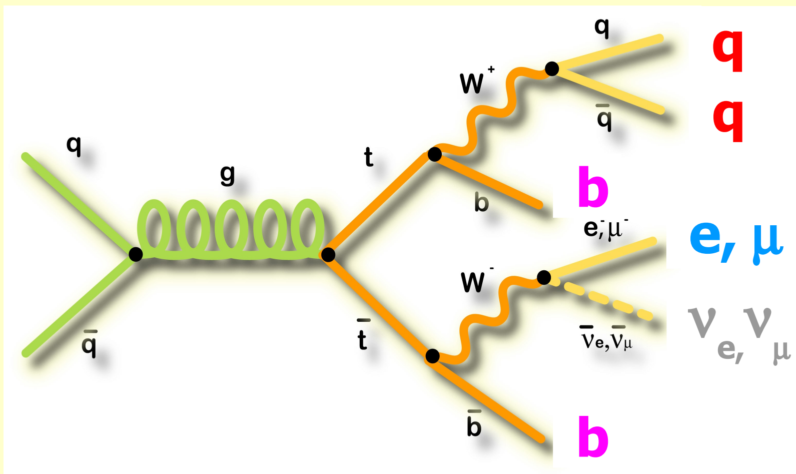
Golden channel:
manageable backgrounds
branching fraction 29%

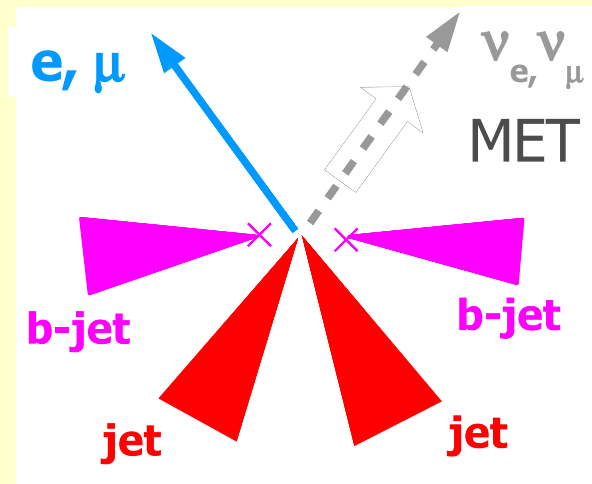
Backgrounds:
- W+jets
- fake leptons in multijets





Lepton-Jets Channel





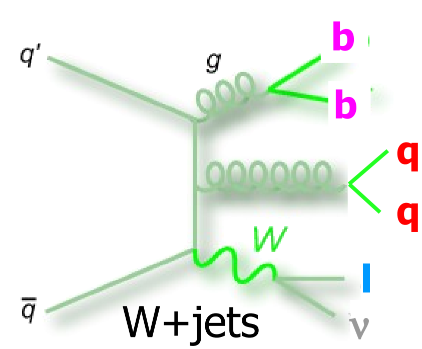
"Golden Channel": Compromise between statistics and purity:

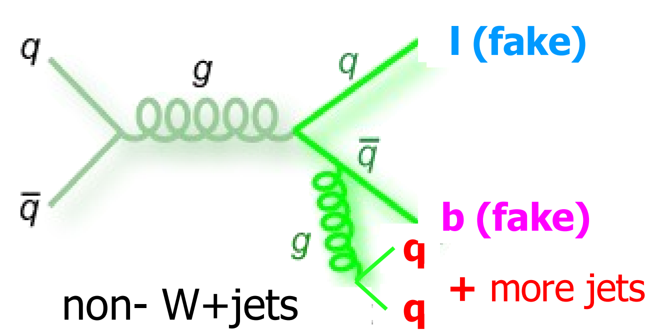
- BR ~ 30%
- S/B=1/4 – 11/1 (depending on b-tag requirement)

- 1 e/μ with large p_T
- 4 jets with large E_T
- Energy imbalance, high missing E_T
- 0, 1 or 2 b-tags

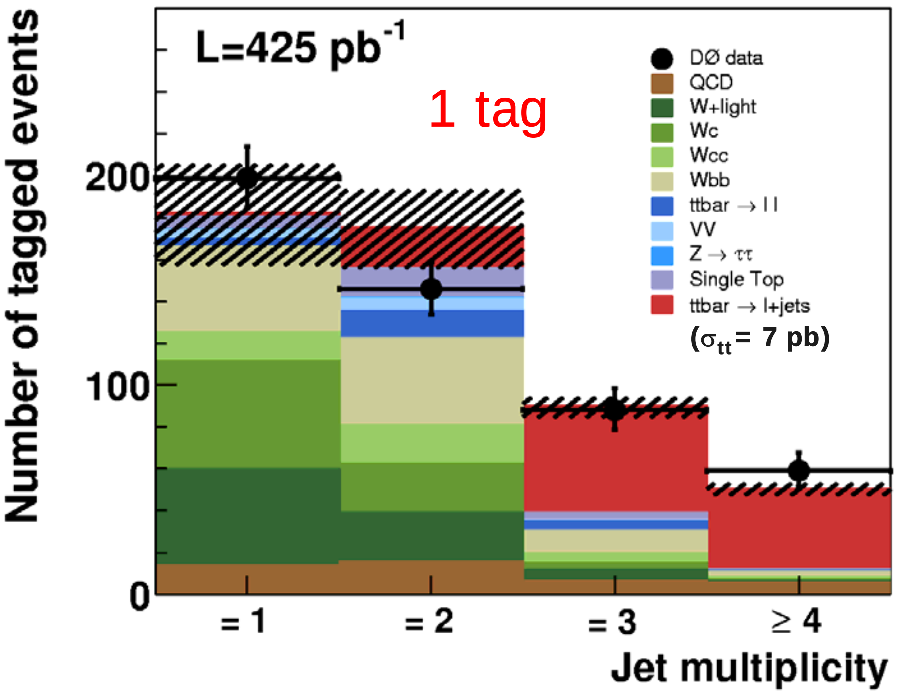
- Combinatorial quark/jet ambiguity: 12 (0 b-tag), 6 (1 b-tag), 2 (2 b-tags)
- Well defined kinematics: neutrino momentum partly derived from missing E_T

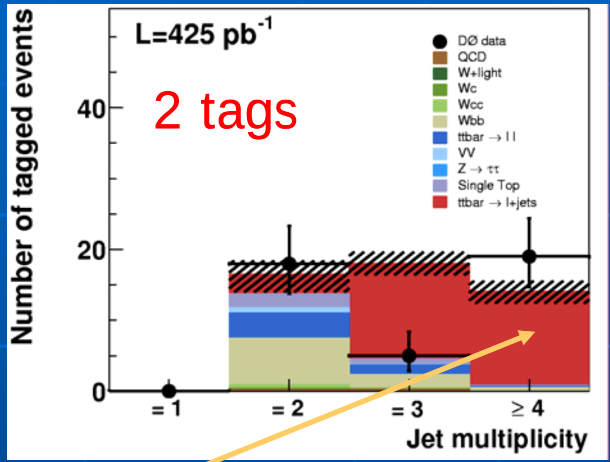
- Dominant background types:
  - Wbb, Wcc, Wc
  - W+light quarks
  - non-W+light quarks (fake b-tags)





Lepton+jets cross section





Ultra pure top sample:
≥4 jets, 2tags
0.6±0.4±0.1 BG expected
19 observed

Combining 1,2tags; 3,>4 jets; e,μ:

$$\sigma_{t\bar{t}} = 6.6 \pm 0.9(\text{stat} + \text{syst}) \pm 0.4(\text{lumi})\,\text{pb}$$

@ m_t=175 GeV

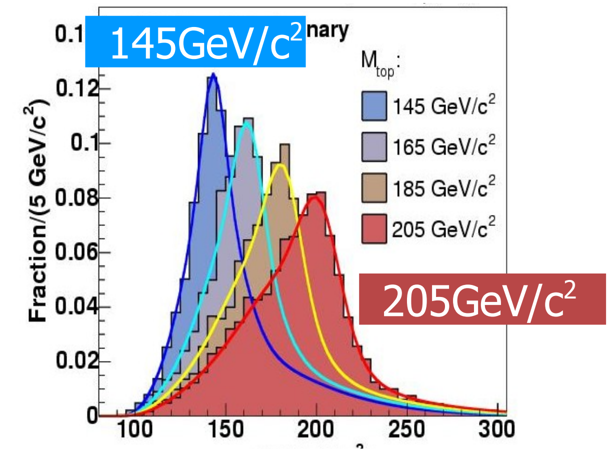
PRD 74, 112004 (2006)

Measurement Strategies

Template Method (TM)

- Calculate a per-event observable correlated with M_{top}.
- Compare simulated distributions (for signal+background) with varying M_{top} with data to obtain M_{top}.
- 2nd variable may be explored for JES determination.

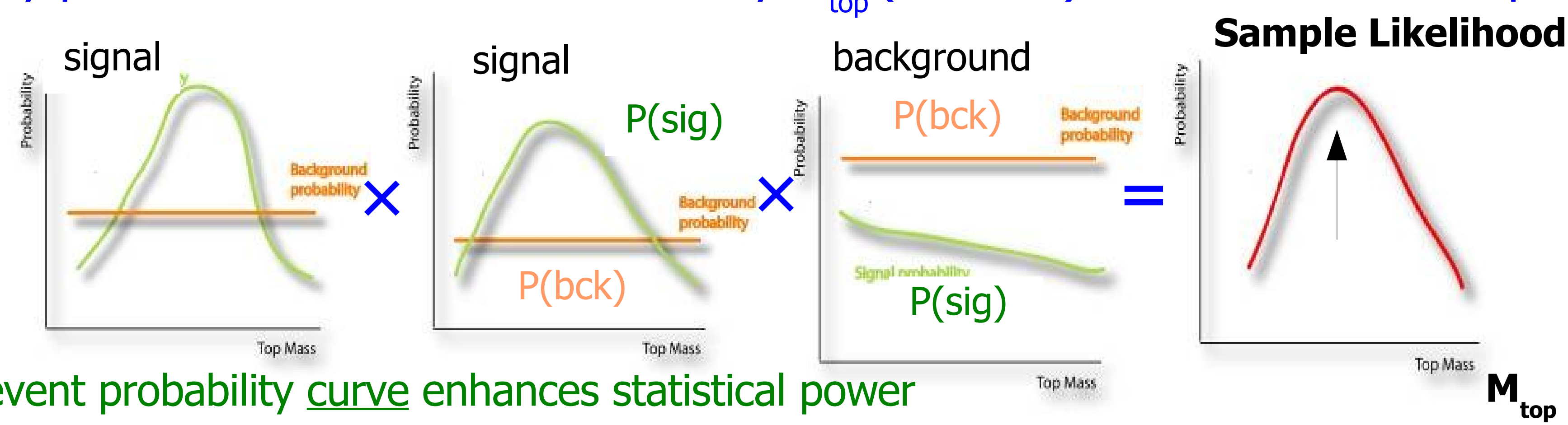
+ computationally simple
– just one number (for each template variable) per event



e.g.: "reconstructed" top mass

Matrix Element Method (ME)

- Calculate a per-event probability density (from ME) for sig.+bkg. as function of M_{top}.
- Multiply probabilities to extract most likely M_{top} (and JES) for whole data sample.



+ per-event probability curve enhances statistical power
– extremely CPU intensive numerical integration

Matrix Element Method

- Maximize mass information by exploring SM predictions for top quark dynamics.

$$P_{t\bar{t}}(M_{\text{top}},\text{JES}) = \frac{1}{N}\sum_{\text{comb}}\int \mathrm{d}\sigma_{t\bar{t}}(y, M_{\text{top}})\; \mathrm{d}q_1\,\mathrm{d}q_2\, f(q_1)\, f(q_2)\; w(\boldsymbol{x}, y, \text{JES})$$

sum over all neutrino solutions/ jet-quark combinations

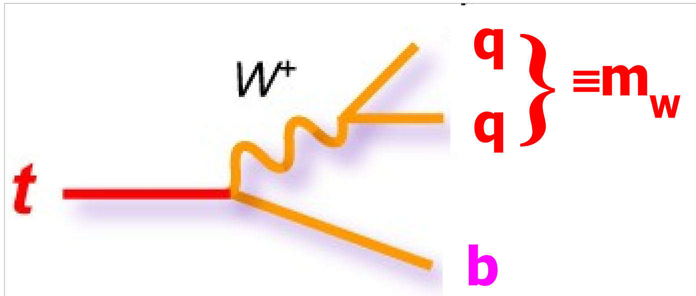
differential cross section
- phase space
- LO tt production ME

proton-parton density functions

"transfer functions" (link jets to quarks)

- Transfer functions are probabilities of a set of variables **x** to be measured given a set of parton level quantities **y**:
  - hadronization and detector resolution effects
  - simplifying assumptions: lepton momenta + jet/lepton angles exactly known

- Similar expression for background probability but no M_{top} dependence.



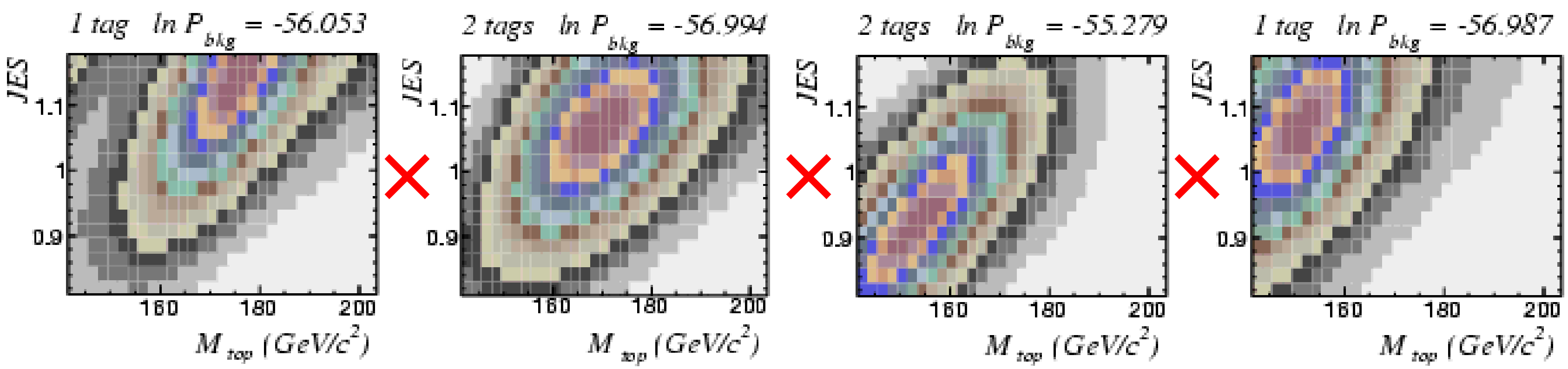
JES is determined "in-situ" using W invariant mass: "Penalty" in probability if JES hypothesis leads to a W mass inconsistent with world average value.

→ Part of JES uncertainty becomes statistical component of top mass uncertainty!

CDF: Matrix Element, Lepton+Jets 955pb^{-1}

sample likelihood: signal probability background probability

$$L(M_{top}, \mathrm{JES}, C_s) \propto \prod_{i=1}^{events} \left[C_s P_{t\bar{t}}^{(i)}(M_{top}, \mathrm{JES}) + (1 - C_s) P_{bck}^{(i)}(\mathrm{JES}) \right]$$



163 more events

× …

- M_{top}, JES extracted in a 2-D maximum likelihood fit

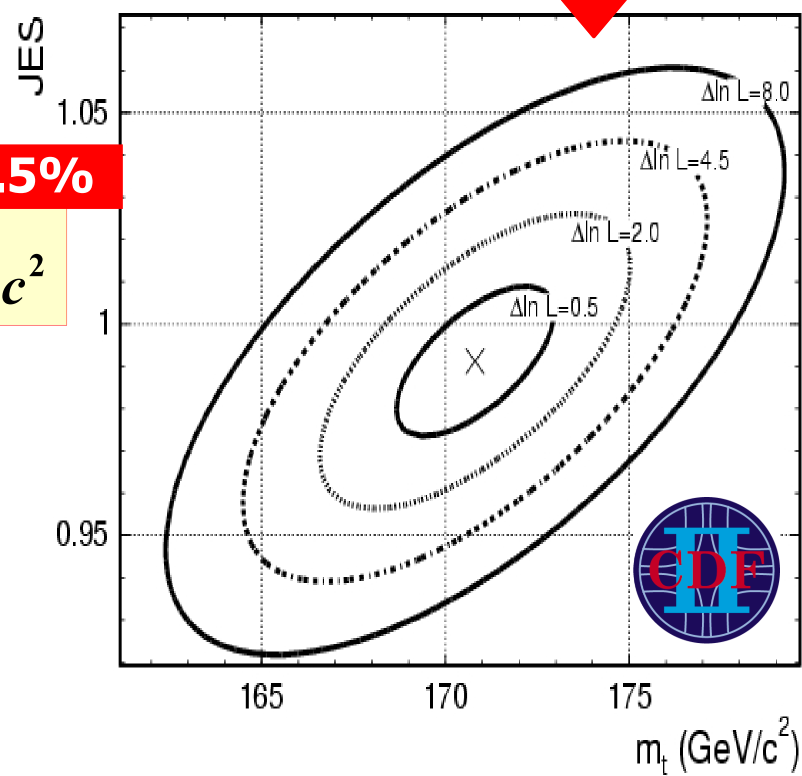
Result using 167 candidate events (≥1 b-tag):

$$M_{top} = 170.8 \pm 1.6(\mathrm{stat.}) \pm 1.5(\mathrm{JES}) \pm 1.4(\mathrm{syst.})\,\mathrm{GeV}/c^2$$

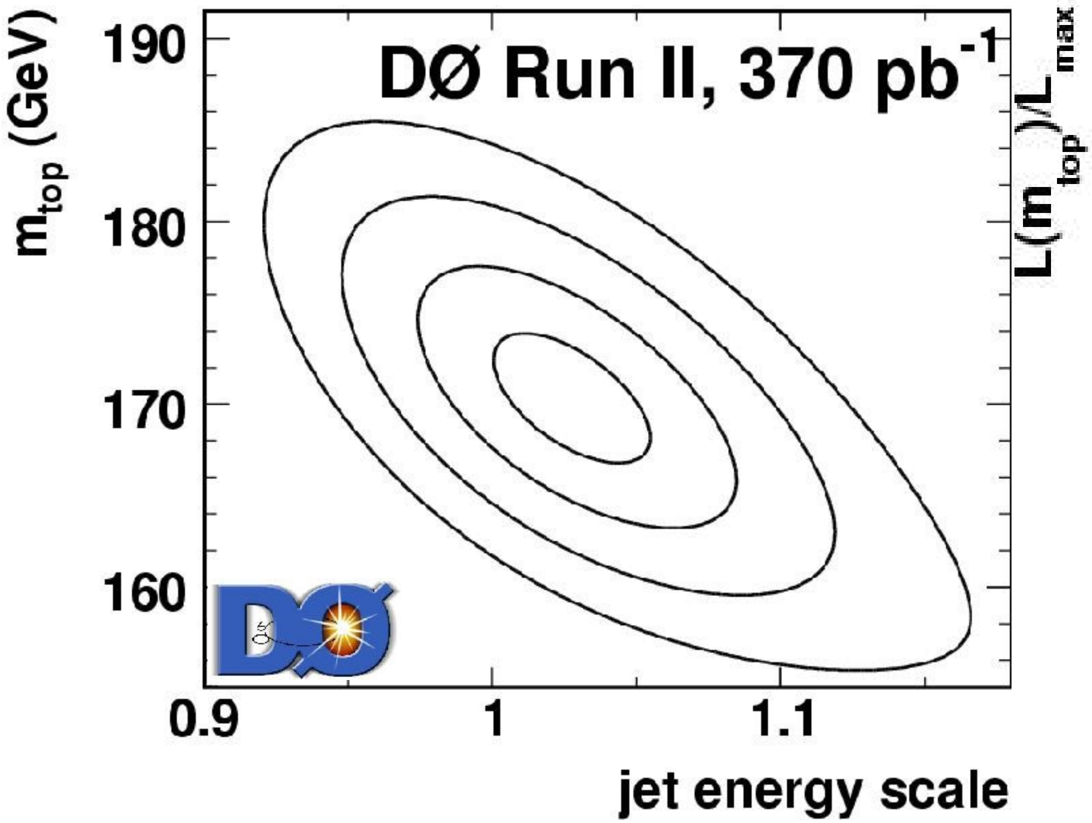
1.5%

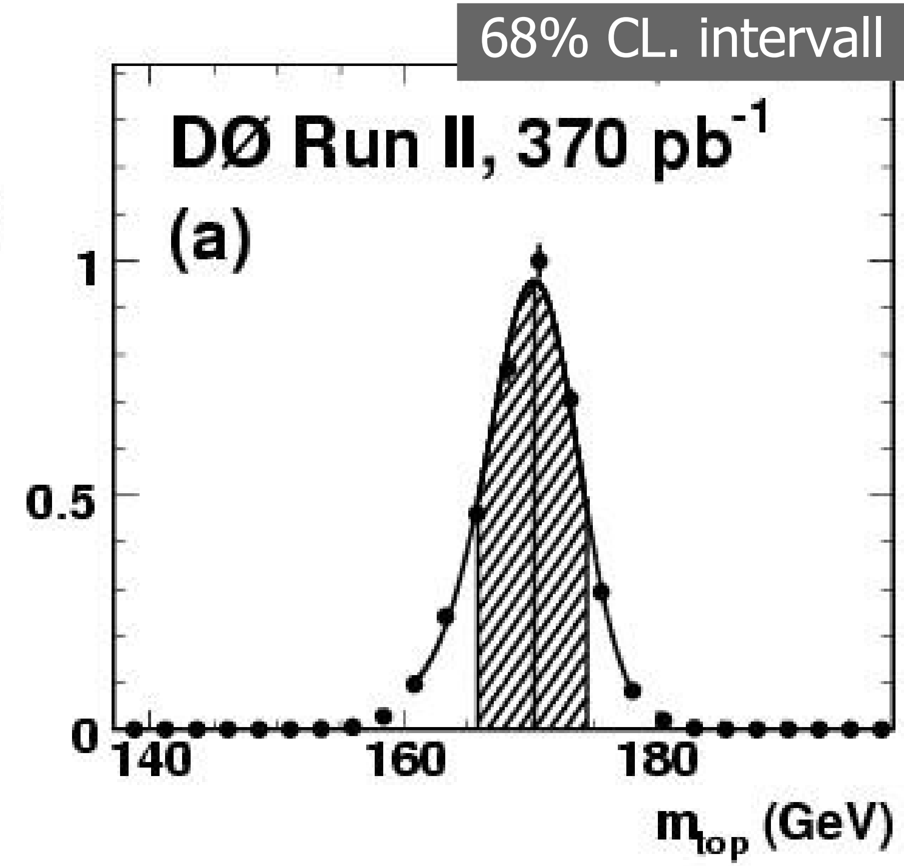
...most precise single top quark mass measurement so far!

- In-situ technique greatly reduces JES uncertainty. Will further scale down with integrated luminosity.



DØ: Matrix Element, Lepton+Jets 370pb^{-1}





- Similar 2-D Likelihood analysis with in-situ JES calibration.
- Includes also events w/o b-tags.

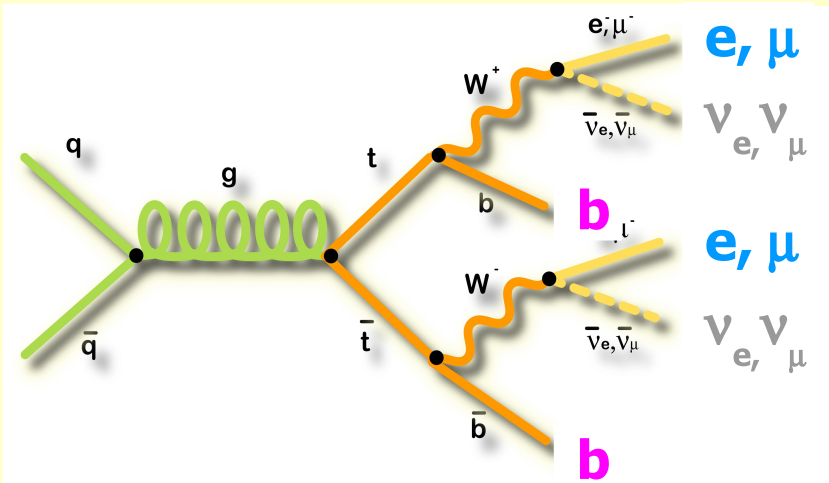
2.6%

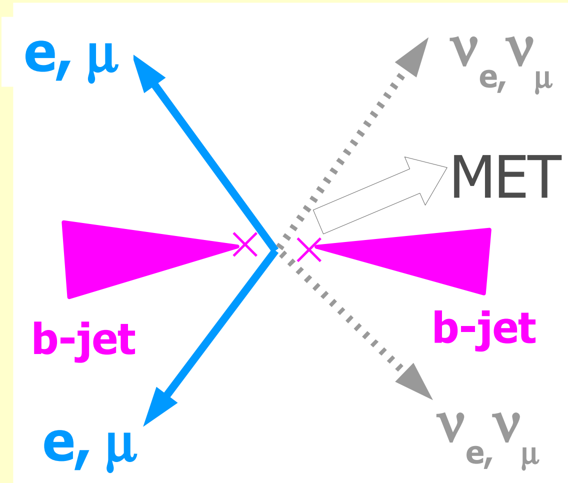
Result using 175 candidate events (≥0 b-tag):

$$M_{top} = 170.3 \pm 2.5\,(\text{stat.}) \pm 3.5\,(\text{JES}) \pm 1.5\,(\text{syst.})\ \text{GeV}/c^2$$

- DØ update coming soon!

Di-Lepton Channel





Clean sample but poor statistics:

- BR ~ 5%
- S/B ~ 2 (≥0 b-tag)
  S/B ~ 20 (≥1 b-tag)

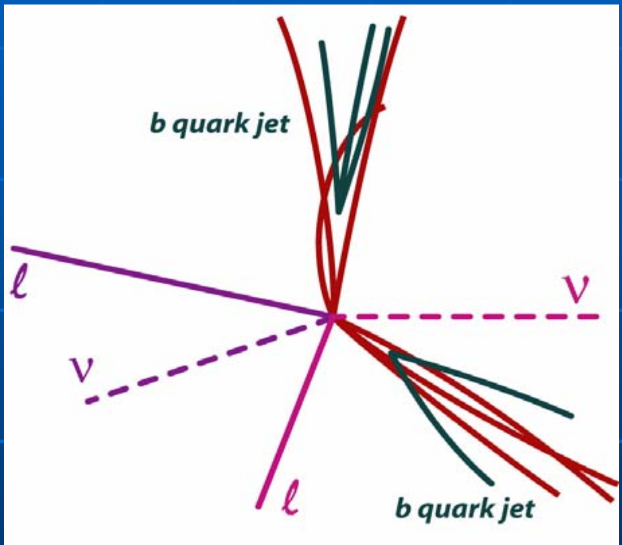
- 2 opp. charged lepton candidates
- 2 high E_T jets
- ≥0 or ≥1 b-tag
- large missing E_T
- high total transverse energy

- Small combinatorial ambiguity: 2 jet-quark assignments
- Under-constrained kinematics: 2 neutrinos but only one missing energy variable
  ...requires assumptions of/integration over unmeasurable quantities to solve M_{top}

- Major background types:
  Z/γ*+2jets WW+2 jets W+3jets (fake leptons)

Dilepton cross section

low BG, but also
low branching fraction (4.5%)



Increase efficiency by requiring one fully reconstructed lepton, and require an additional track

370pb^{-1}

$$\sigma_{tt} = 8.6^{+1.9}_{-1.7}(\text{stat})^{+1.1}_{-1.1}(\text{syst})\text{pb}$$

Combined with e-μ
(which has both leptons fully reconstructed)

Backgrounds:
- WW/WZ, Z/γ*→ττ→ll
- fake MET in DY or
- fake leptons in multijet

$$\sigma_{tt} = 9.0 \pm 1.3(\text{stat}) \pm 0.5(\text{syst})\text{pb}$$

March 5 2007, 1.1fb^{-1}

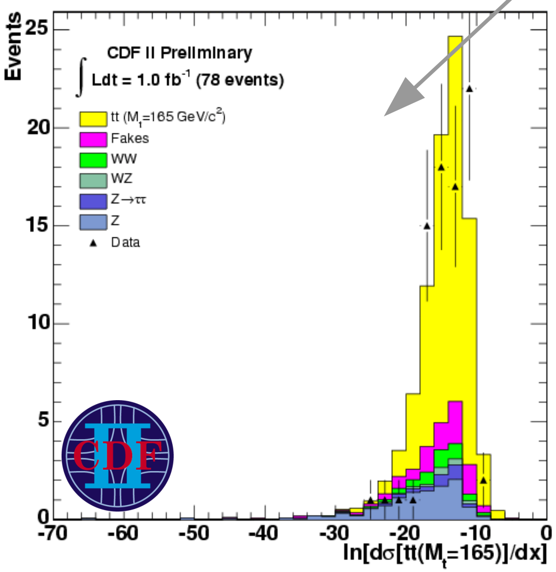
CDF: Matrix Element, Di-Lepton 1030pb^{-1}

- Event probability is weighted sum of signal and of three major backgrounds

$$P_{t\bar{t}}(\boldsymbol{x}; M_{top}) = P_s(\boldsymbol{x}; M_{top})\, w_s(M_{top}) + \sum_{i=1}^{3} P_b^{(i)}(\boldsymbol{x})\, w_b^{(i)}(M_{top})$$

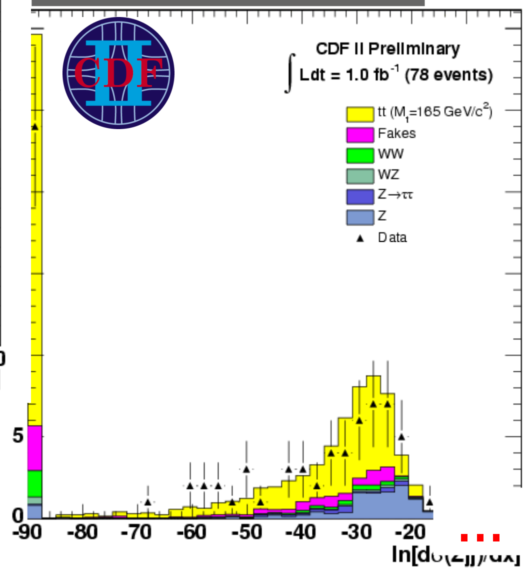
signal from LO matrix element

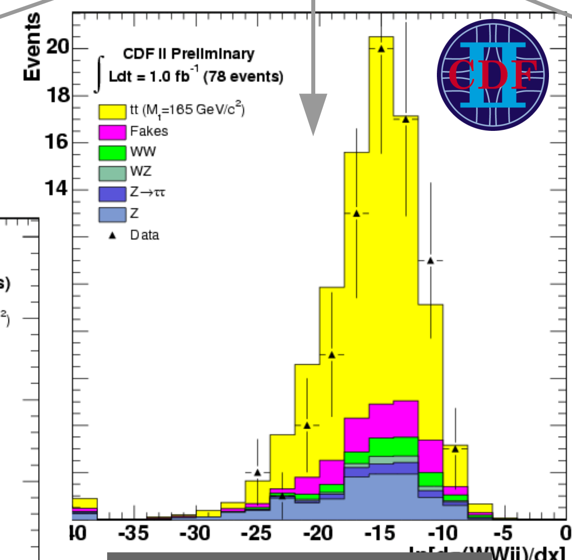
background, fixed weights $w_b^{(i)}$



tt probability distribution

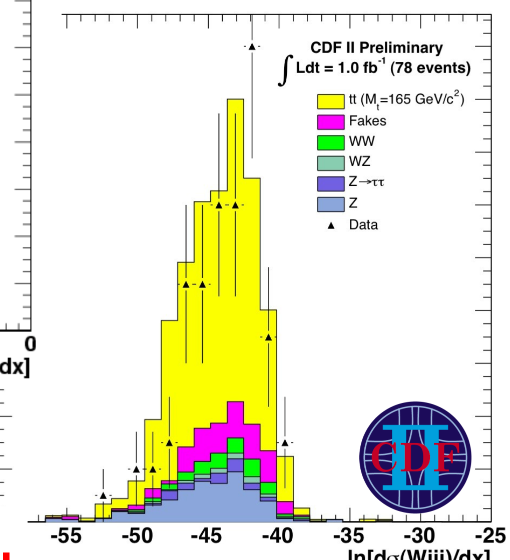
Z/γ qq̄ probability distribution





WWqq̄ probability distribution

fake lepton probability distribution

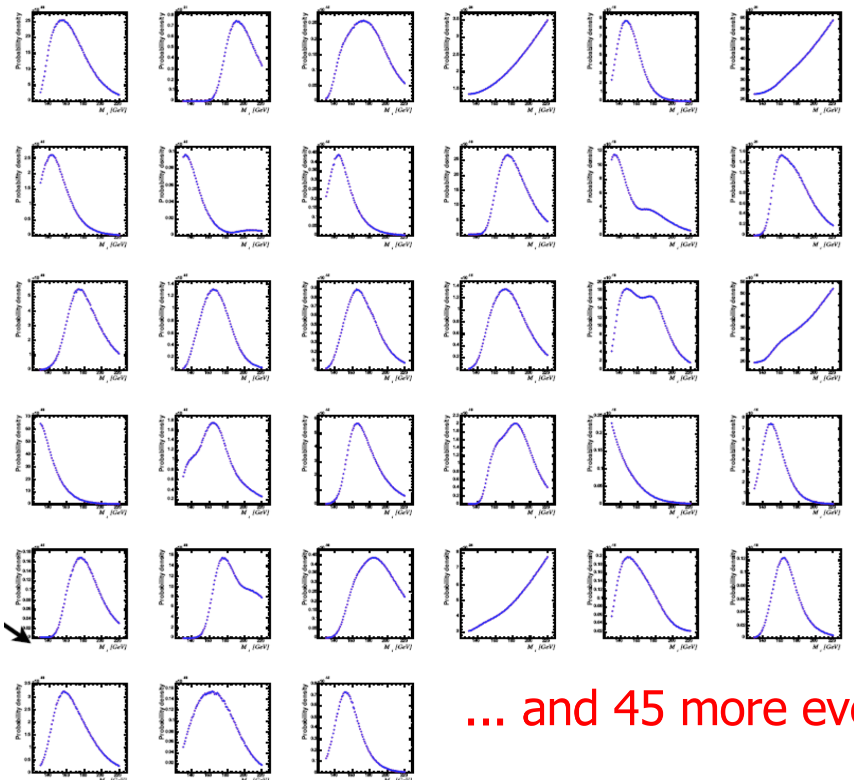


... agree well with data.

Log(dσ/dx)

- Background probabilities reduce M_{top} uncertainty by 15%
- In-situ JES calibration not possible for the signal.

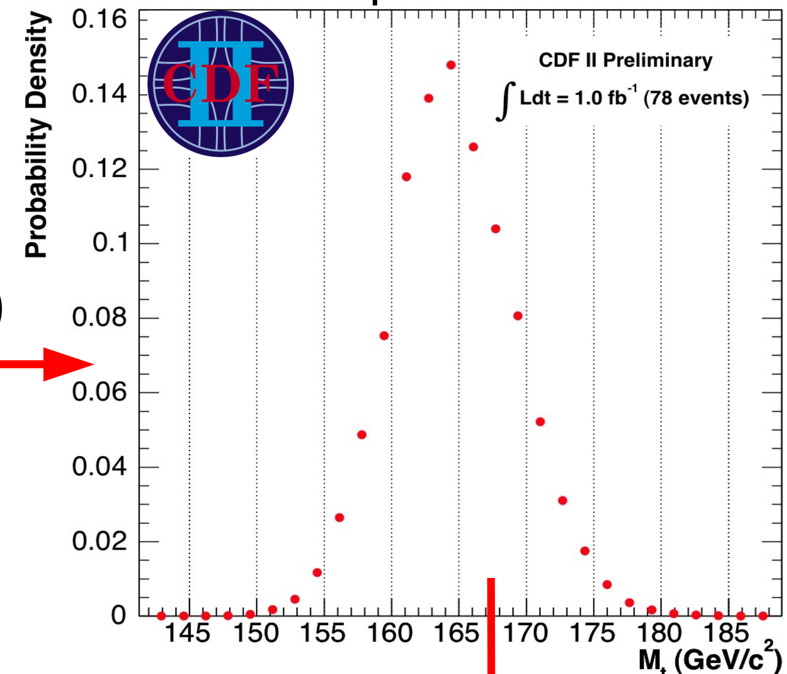
CDF: Matrix Element Method, Di-Lepton, 1030pb^{-1}



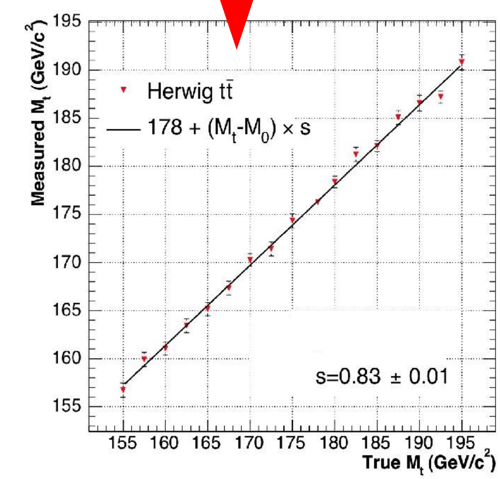
... and 45 more events

$$\prod P_{t\bar{t}}(\boldsymbol{x}\,;M_{top})$$

sample likelihood



calibrate



slope <1 due to background

3.4%

Result using 78 candidate events (≥0 b-tag):

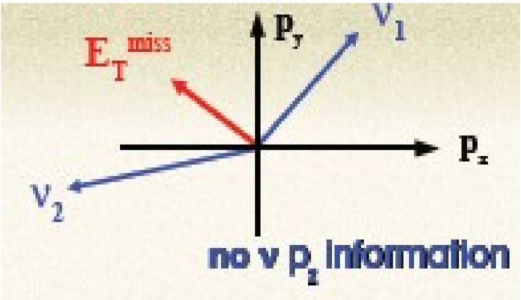
$$M_{top}=164.5\pm3.9(\text{stat.})\pm3.5(\text{JES})\pm1.7(\text{syst.})\,\text{GeV}/c^2$$

... most precise single di-lepton top quark mass!

Cross check using 30 candidate events (≥1 b-tag):

$$M_{top}=167.3\pm4.6(\text{stat.})\pm3.3(\text{JES})\pm1.9(\text{syst.})\,\text{GeV}/c^2$$

DØ: Template, Di-Lepton 370pb^{-1}



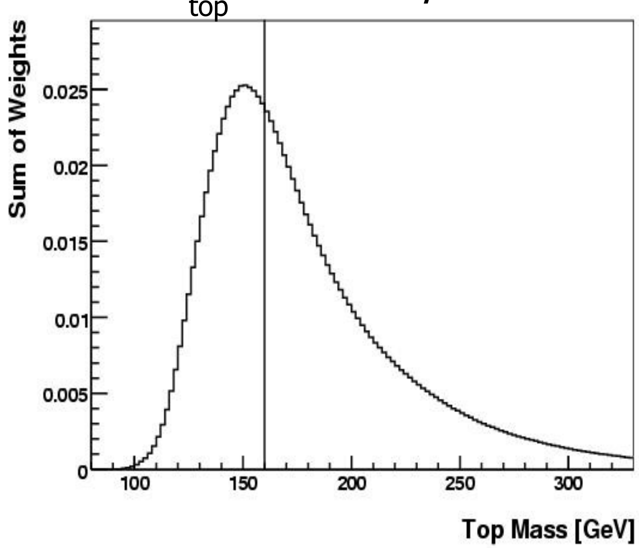
- Di-lepton template methods handle kinematic ambiguity by assuming values for kinematic variables to extract a M_{top} solution and assigning weights to different solutions.

Neutrino Weighting Method: Assume (scan) neutrino pseudo rapidities $\eta(\nu_1)$, $\eta(\nu_2)$ and m_t, assign a weight to the solution based on the compatibility with the observed missing E_T:

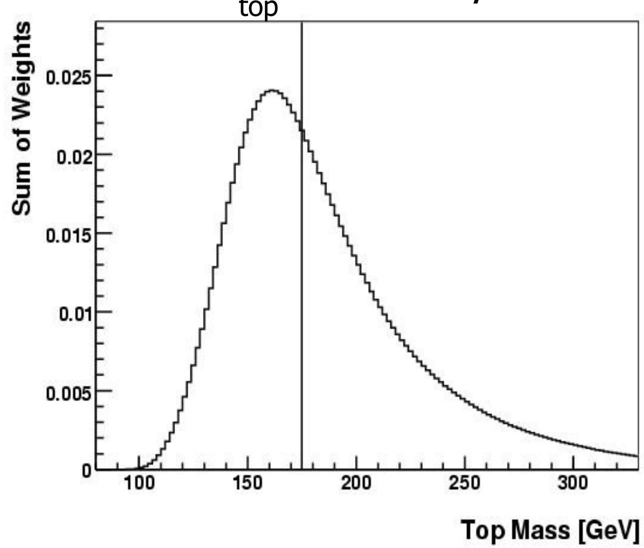
$$w(m_t) \propto \sum_{\nu\,\text{assumptions}} \exp\left(\frac{-\left(E_x^{\text{miss, calc}}(i) - E_x^{\text{miss, obs}}\right)^2}{2\sigma^2_{E_x^{\text{miss}}}}\right) \exp\left(\frac{-\left(E_y^{\text{miss, calc}}(i) - E_y^{\text{miss, obs}}\right)^2}{2\sigma^2_{E_y^{\text{miss}}}}\right)$$

M_{top} templates are formed using sum of weights vs. m_t.

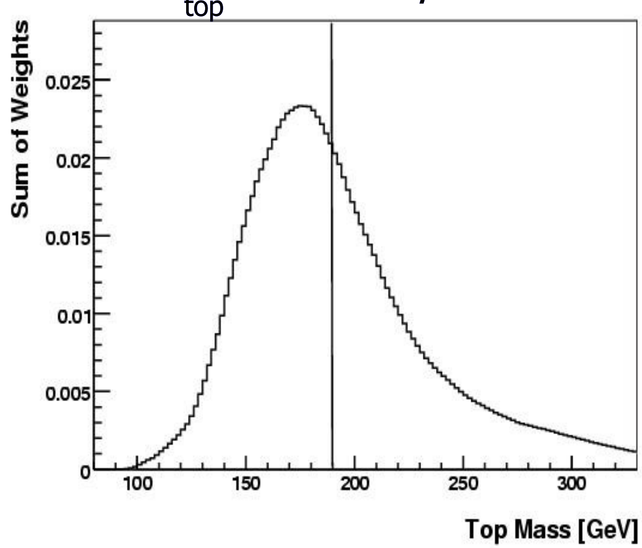
$M_{top}=160\text{GeV}/c^2$



$M_{top}=175\text{GeV}/c^2$



$M_{top}=190\text{GeV}/c^2$



DØ: Template, Di-Lepton 370pb^{-1}

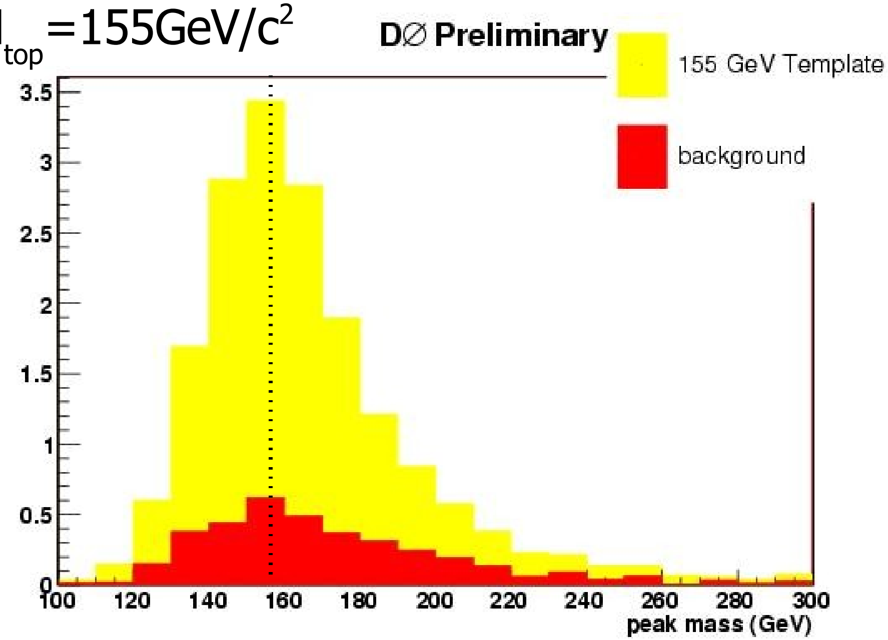
Matrix Element Weighting Method: Assume (scan) over m_t and at most 4 ν solutions (given a m_t, m_W, lepton/quark/missing E_T configuration), assign a weight based on the compatibility of ME prediction with the observed lepton transverse momenta:

$$w(m_t) \propto \sum_{\nu \text{solutions}} \sum_{\text{jets}} f_{\text{PDF}}(x_{q_1}) f_{\text{PDF}}(x_{q_2}) p(E_l^*; m_t) p(E_{\bar{l}}^*; m_t)$$

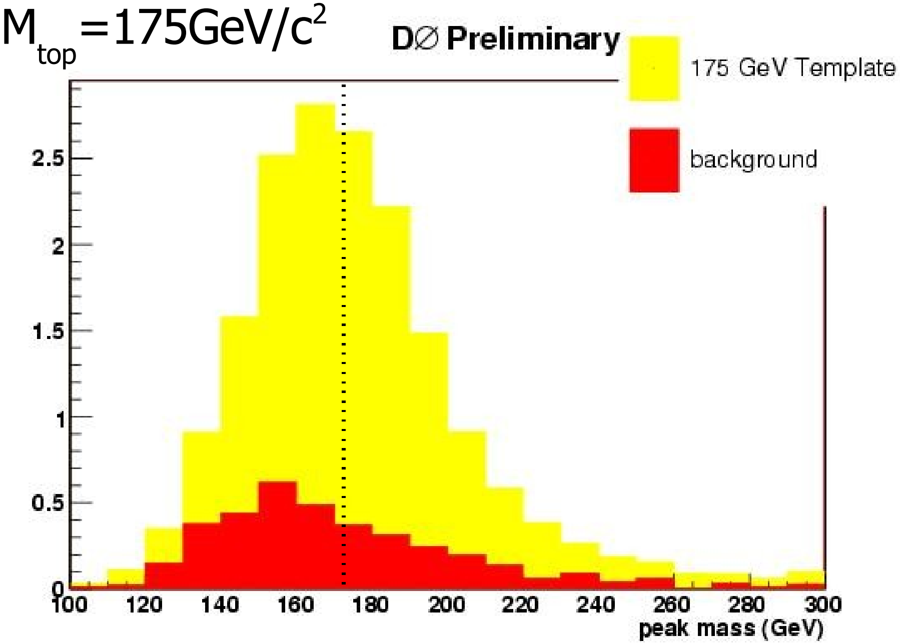
M_{top} templates are formed using m_t values which gives maximum weight ("peak mass").

- Repeat calculations with jet/lepton momenta/missing E_T randomly smeared within their detector resolutions, solve the equations and average the weights.

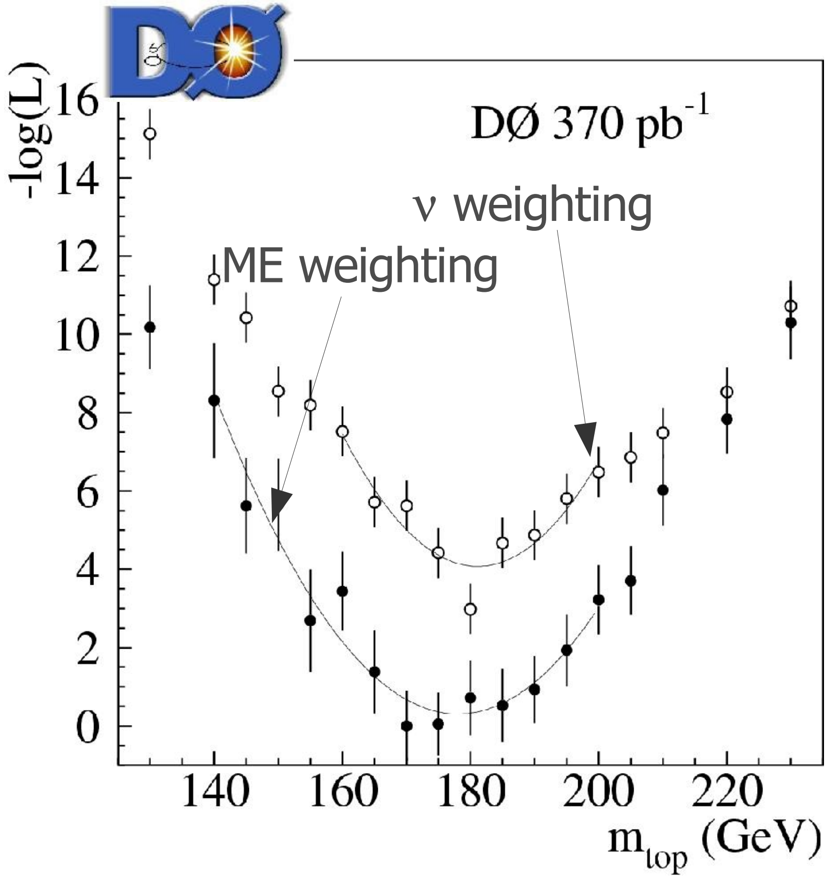
M_{top}=155GeV/c^2



M_{top}=175GeV/c^2



DØ: Template, Di-Lepton 370pb^{-1}



- M_{top} obtained from max. likelihood fit for ν-weighting and binned likelihood fit for ME weighting.
- Both results are combined considering correlations.

4.7%

Result using 26⊕36 candidate events (**370/pb**):

$$M_{top} = 178.1 \pm 6.7(\text{stat.}) \pm 4.3(\text{JES}) \pm 2.1(\text{syst.})\,\text{GeV}/c^2$$

5.3%

Prel. result using 28 candidate events (**835/pb**):

$$M_{top} = 171.6 \pm 7.9(\text{stat.})\,^{+5.1}_{-4.0}(\text{syst.})\,\text{GeV}/c^2$$

(eμ channel only)

- **New**: CDF template di-lepton analysis based on 1/fb data set:
- Makes assumptions about the longitudinal momentum of the $t\bar{t}$ system to solve equations (see appendix):

4.1%

Result using 64 candidate events (**1030/pb**)

$$M_{top} = 168.1\,^{+5.6}_{-5.5}(\text{stat.}) \pm 3.2(\text{JES}) \pm 2.4(\text{syst.})\,\text{GeV}/c^2$$

CDF: Template, Di-Lepton, 1030pb^{-1}

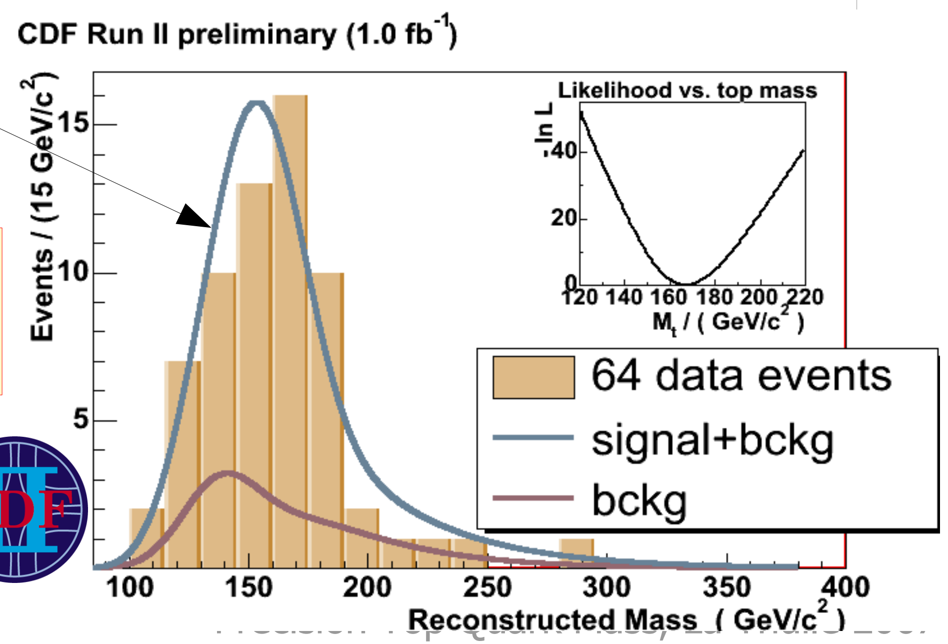
- Under-constrained problem requires assumption for one kinematic variable...
  here: longitudinal momentum P_z of $t\bar{t}$ system

$$
\begin{aligned}
P_{\nu_1 x} + P_{\nu_2 x} &= \not{E}_{T_x} \\
P_{\nu_1 y} + P_{\nu_2 y} &= \not{E}_{T_y} \\
P_{tz} + P_{\bar{t}z} &= P_{t\bar{t}z} \\
M_t &= M_{\bar{t}} \\
M_W &= 80.4 \\
\vec{P}_b + \vec{P}_{W+} &= \vec{P}_t \\
\vec{P}_{\bar{b}} + \vec{P}_{W-} &= \vec{P}_{\bar{t}} \\
\vec{P}_{l+} + \vec{P}_{\nu} &= \vec{P}_{W+} \\
\vec{P}_{l-} + \vec{P}_{\bar{\nu}} &= \vec{P}_{W-}
\end{aligned}
$$

- Assume $P_z(t\bar{t})=0$, $\sigma\{P_z(t\bar{t})\}=180\text{GeV}/c^2$:
  No top mass dependence, same for signal and background
  ...derived from MC and lepton plus jets data;
- Solve numerically equations within allowed phase space:
  For each event, dice 10K times the two b-quark energies, E_T(miss), and $P_z(t\bar{t})$ around their measured/assumed values within their given resolutions.
- Sum up and take the most probable resulting ("raw reconstructed") top quark mass to build the template.

- No in-situ JES calibration.

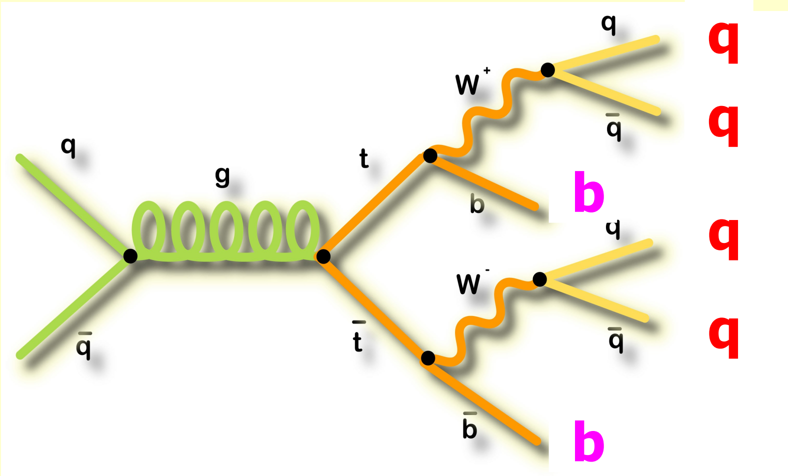
MC expected

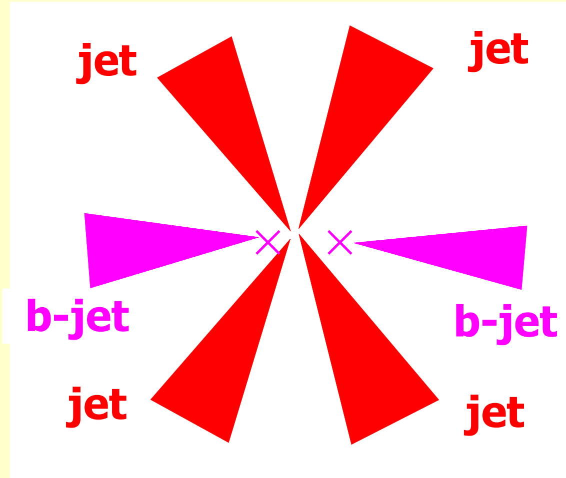


Result using 64 candidate events (≥0 b-tag):

$$M_{top}=168.1^{+5.6}_{-5.5}(\text{stat.})\pm 3.2(\text{JES})\pm 2.4(\text{syst.})\,\text{GeV}/c^2$$

All-Jets Channel





Good statistics but huge background:

- BR ~ 44%
- S/B ~ 1/23 (≥0 b-tag)
  S/B ~ 1/6 (≥1 b-tag)

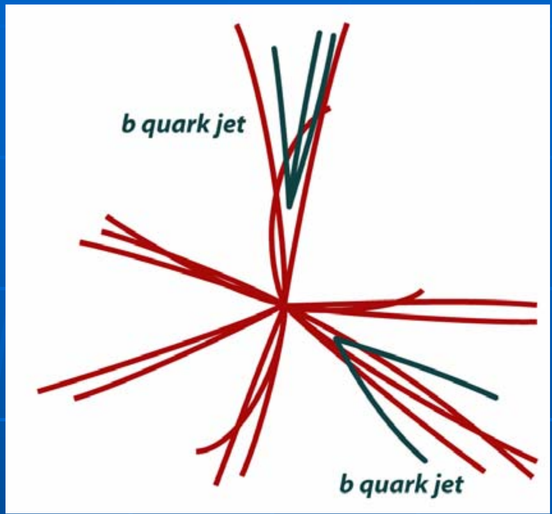
- Exactly 6 jets with high E_T
- Lepton veto
- Low missing E_T significance
- ≥1 or 2 b-tags
- Large total transverse energy
- Spherical isotropic event topology

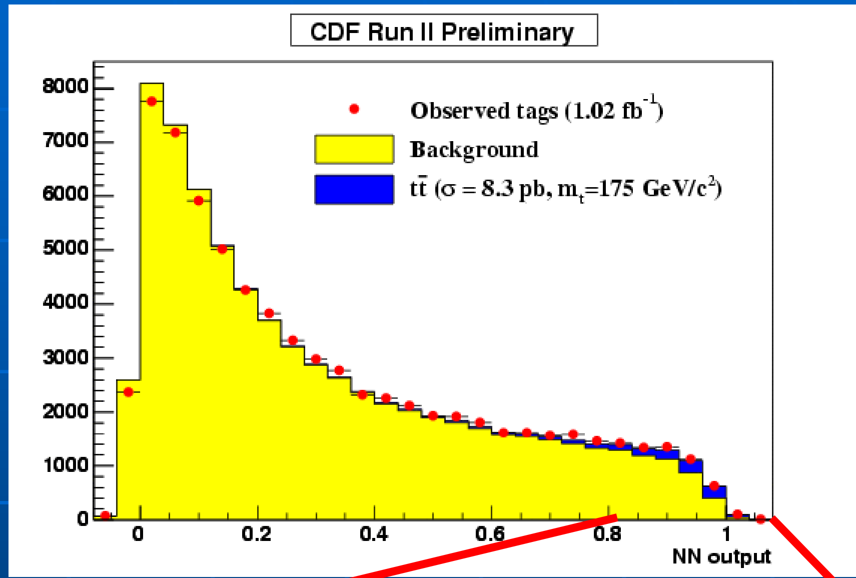
- Large combinatorial ambiguity: 90 (1 b-tag), 24 (2 b-tags)
- Well measurable kinematics, no neutrinos.

- Dominant background types:
  non-W bb4q   non-W 6q (fake b-tags)

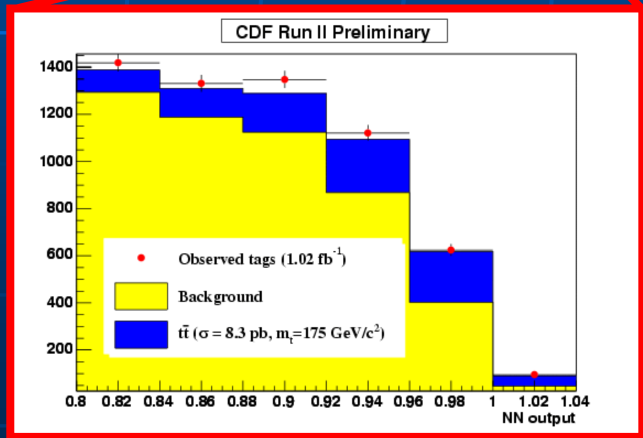
- Additional signal probability cut (from ME calculation) yields
  S/B ~ 1/1 … very restrictive but usable for >1/fb.

All-hadronic cross section





- Large branching fraction (46%)
- Huge multijet background (S/B~1/300)
- Need b-jet tagging



NN-based analysis

$$\sigma_{t\bar{t}} = 8.3 \pm 1.0(\text{stat})^{+2.0}_{-1.5}(\text{syst}) \pm 0.5(\text{lumi})\ \text{pb}$$

1.02 fb^{-1}

CDF: Template Method, All-Jets, 943pb^{-1}

- 2-D templates for M_{top} and JES: Signal from ME, background model from data. (0 b-tag sample, has negligible signal)

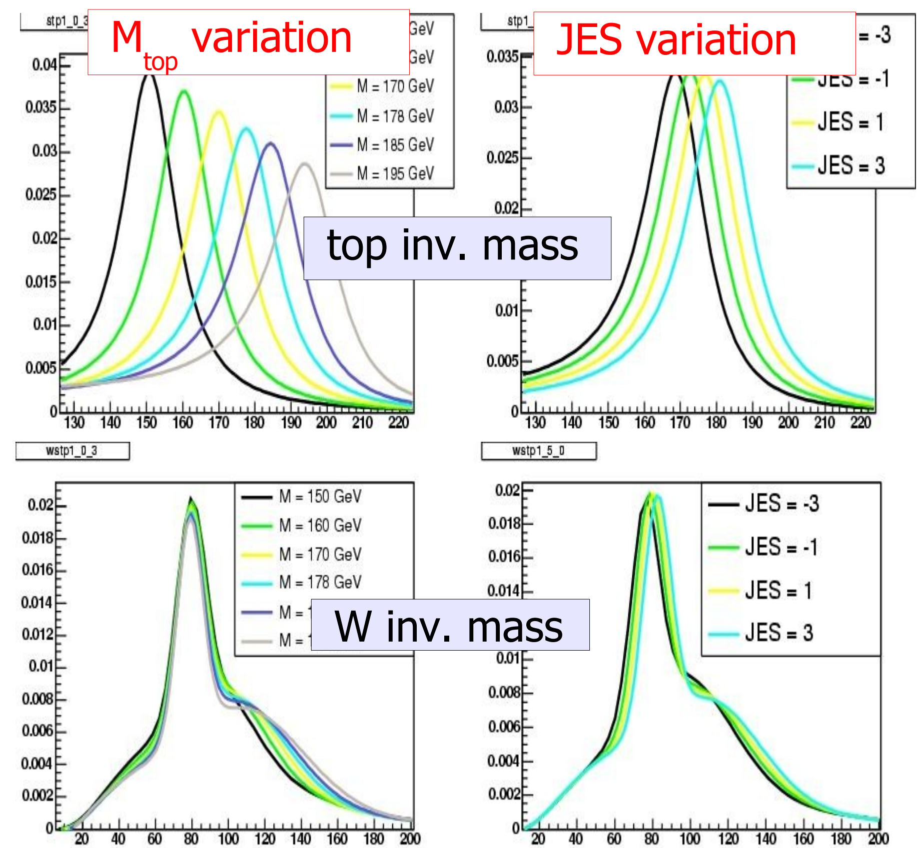
- Signal+background probability densities:

P (m_t | M_{top}, JES)   P (m_W | M_{top}, JES)

$$L_{1,2\text{ b-tag}} = L^{(\text{top})}_{\text{shape}} \times L^{(W)}_{\text{shape}} \times L_{\text{obs}} \times L_{\text{sig}}$$

constrain to number of observed events

constrain to number of signal events



- Sample likelihood:

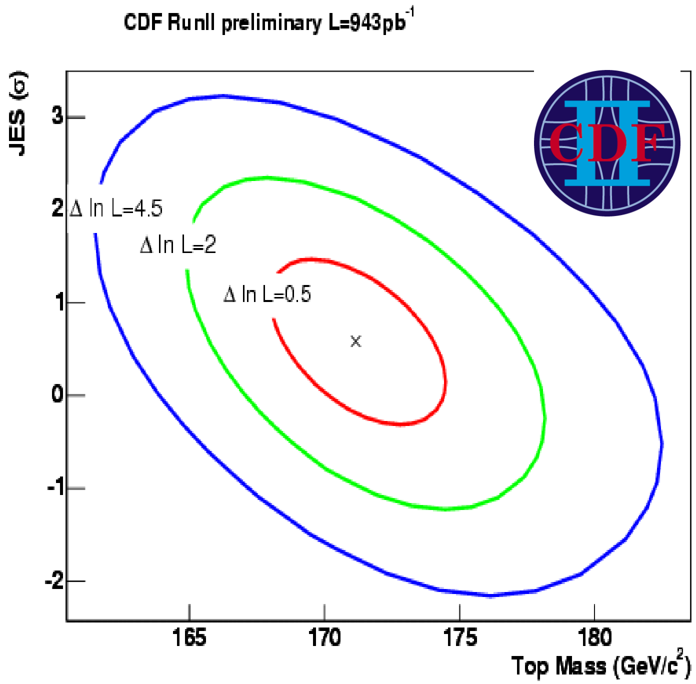
constrain to a priori JES

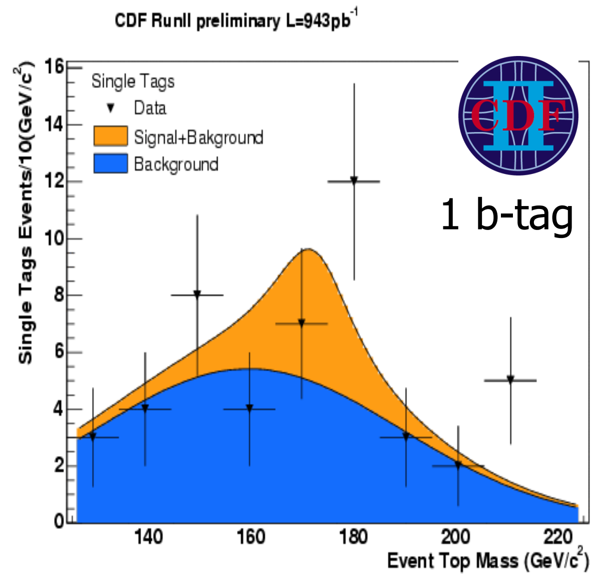
$$L = L_{1\text{ b-tag}} \times L_{2\text{ b-tags}} \times L_{\text{JES}}$$

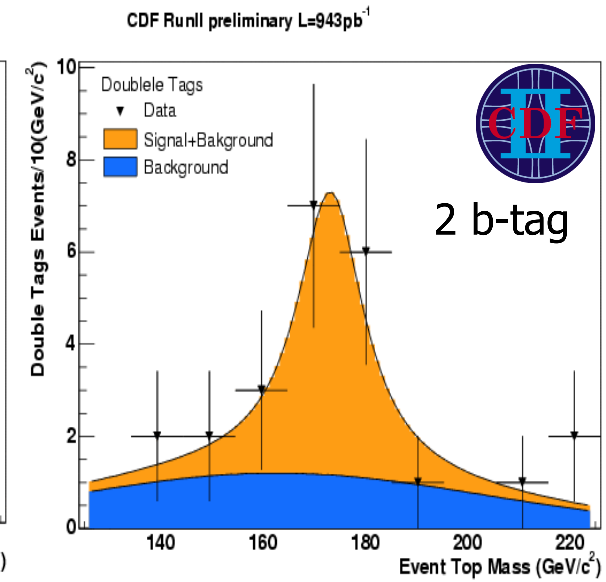
- Likelihood is maximized w.r.t:

M_{top}, JES & number of 1(2) b-tagged signal/back. events respecting constraints (background fraction poorly known in All-Jets channel!)

CDF Template Method, All-Jets, 943pb^{-1}







2.5%

Result using 64 candidate events (≥ 1 b-tag):

$$M_{top} = 171.1 \pm 2.8\,(\text{stat.}) \pm 2.4\,(\text{JES}) \pm 2.1\,(\text{syst.})\ \text{GeV}/c^2$$

- First All-Jets result with in-situ JES.
- All-Jets channel becomes competitive!

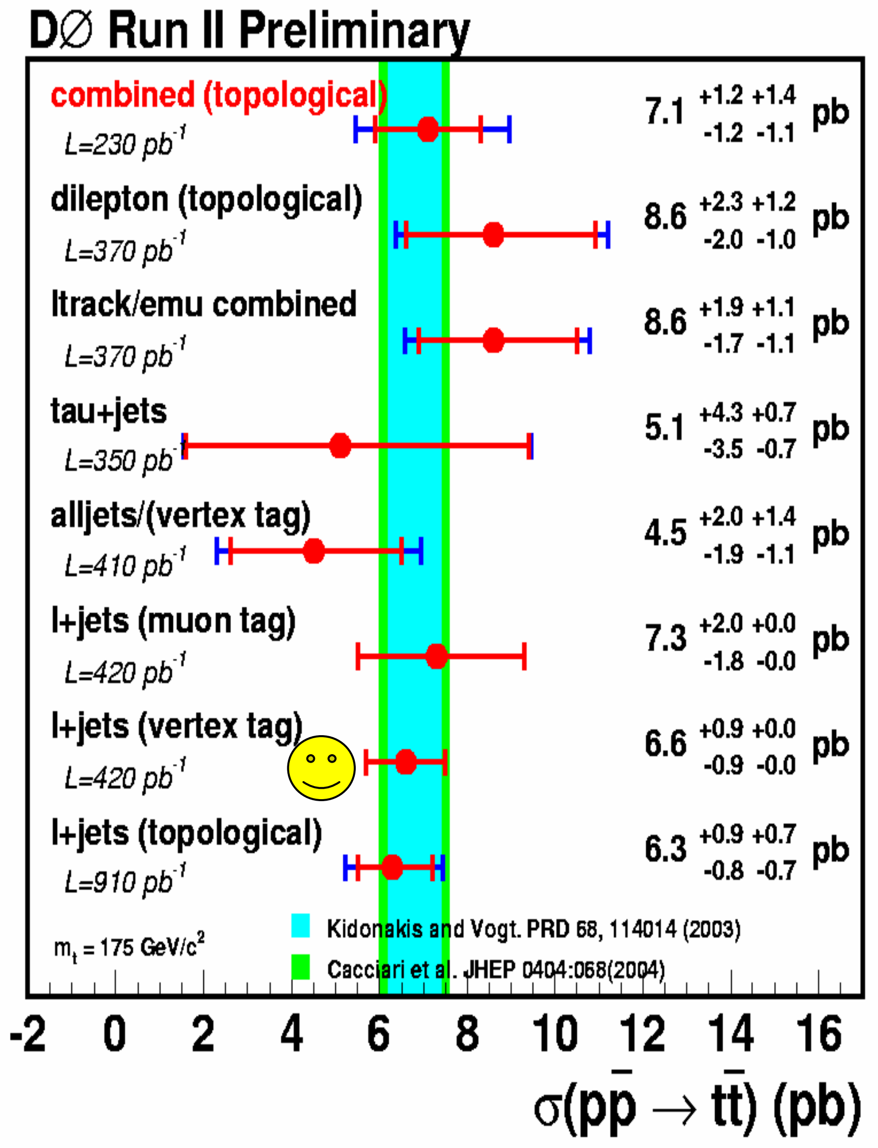
- Recent result from "traditional" 1-D template method using a kinematic mass fitter:
  - no in-situ JES calibration, no restrictive signal probability cut:

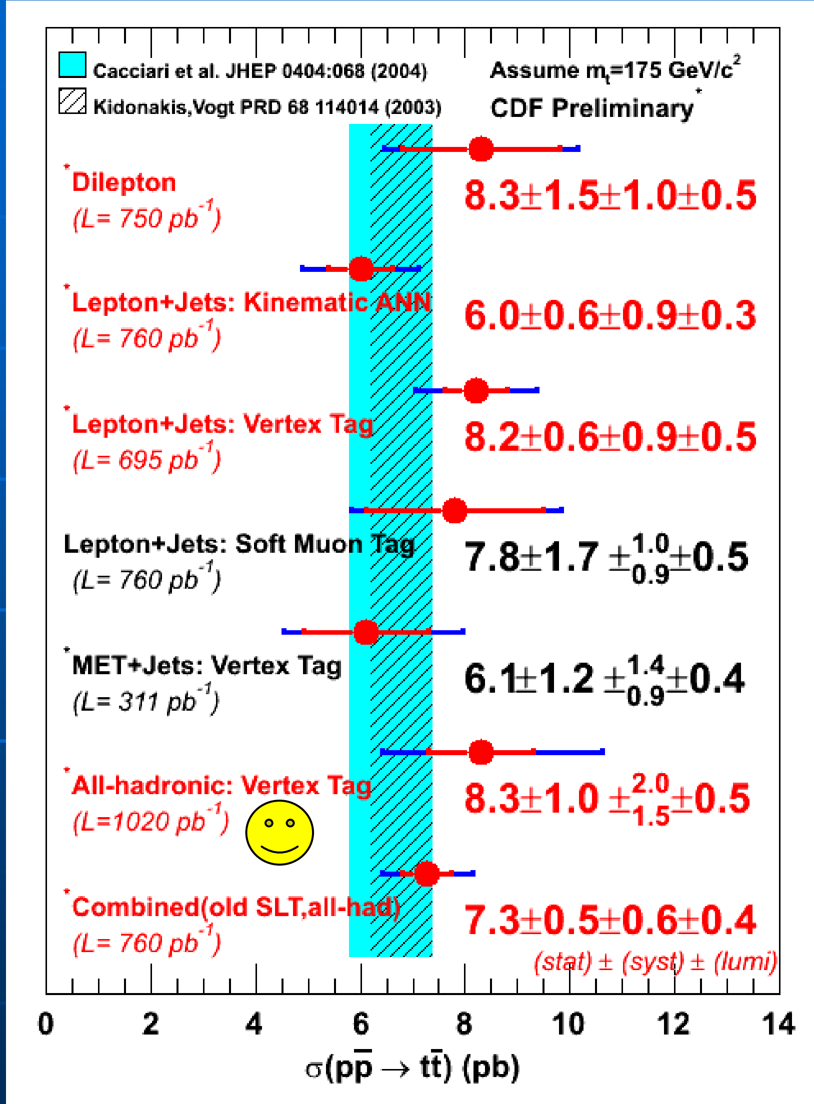
3.0%

1-D template, 1020pb^{-1}, 772 candidate events (≥ 1 b-tag):

$$M_{top} = 174.0 \pm 2.2\,(\text{stat.}) \pm 4.5\,(\text{JES}) \pm 1.7\,(\text{syst.})\ \text{GeV}/c^2$$

=shown in previous slides

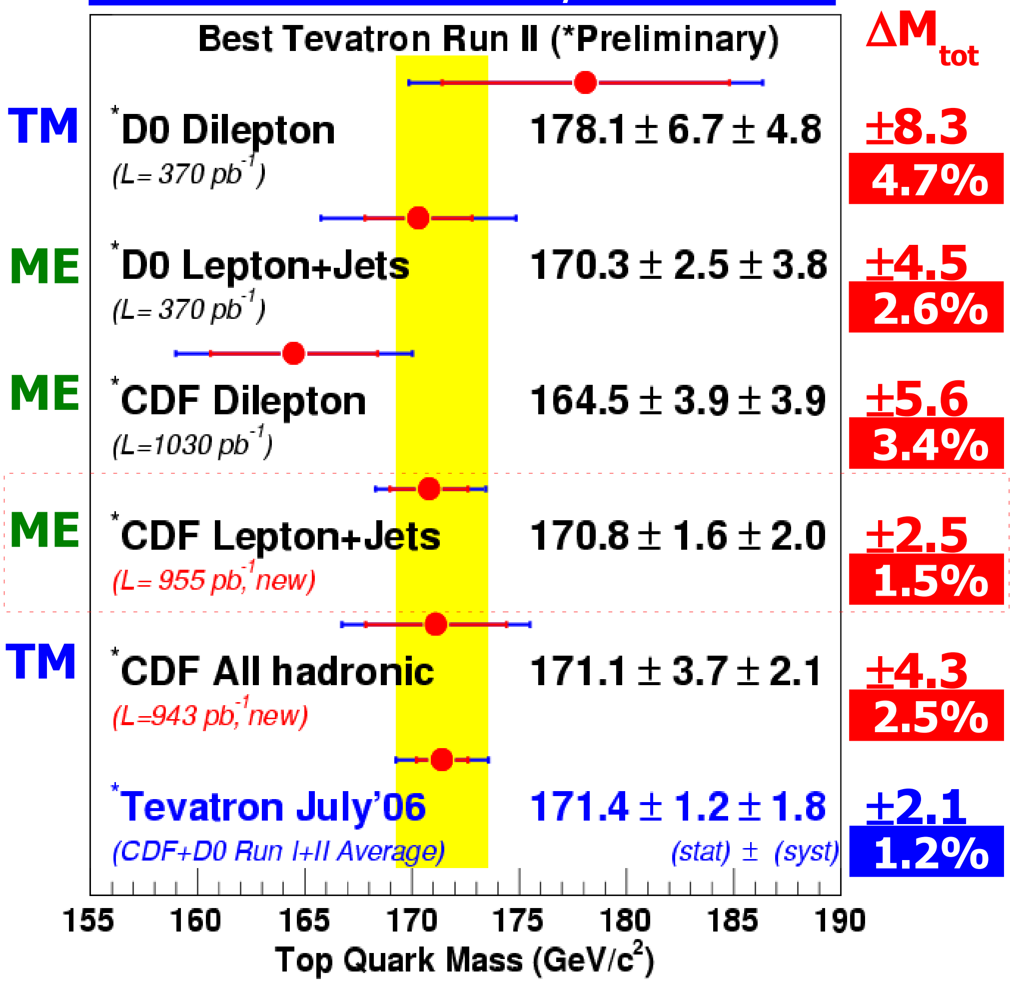




lepton+track in the plot by next week…

Comparisons

Best individual CDF/DØ results



(status 03/07/2007)

- Combination of best Run-I & II results for each experiment (new CDF All-Jets result not included here):

$$M_{top}(\text{all-jets}) = 173.4 \pm 4.3\,\text{GeV}/c^2$$
$$M_{top}(\text{lep-jets}) = 171.3 \pm 2.2\,\text{GeV}/c^2$$
$$M_{top}(\text{di-lepton}) = 167.0 \pm 4.3\,\text{GeV}/c^2$$

(status Aug. 2006)

- Detailed comparison taking correlations between systematic uncertainties into account

→ Results from different channels are consistent!

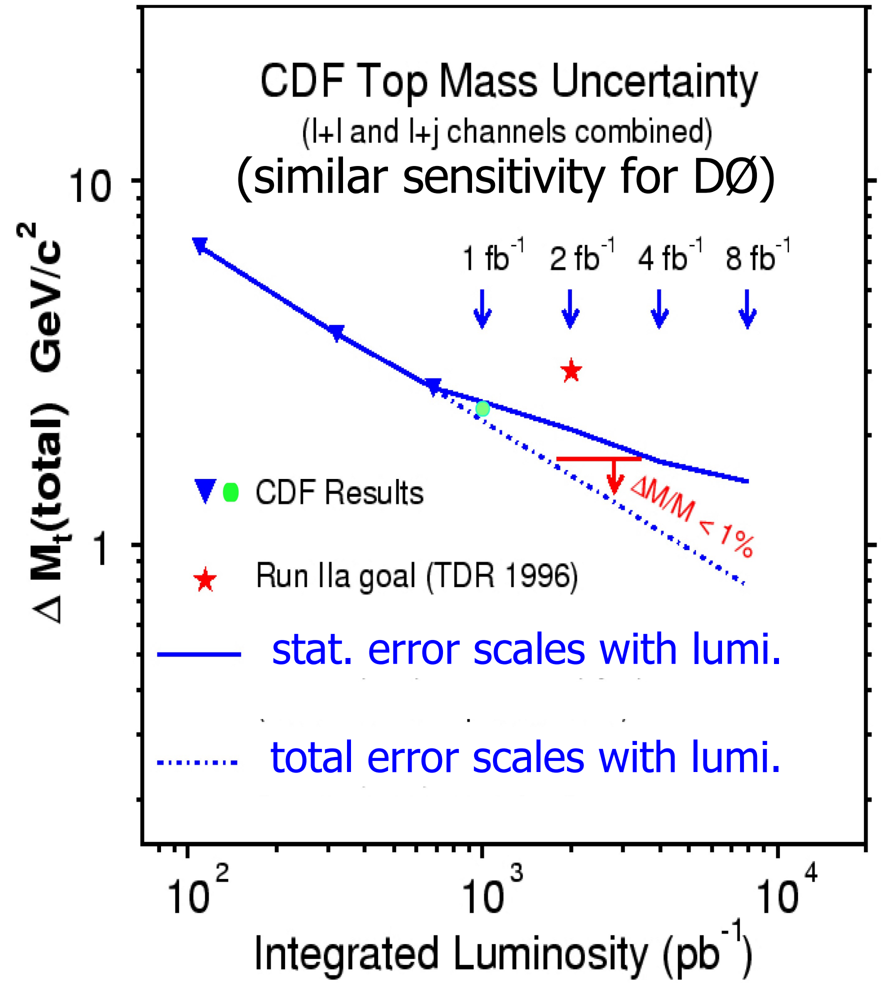
- DØ will present new 1/fb results soon.

Conclusions and Outlook

- Confidence through consistent picture of many excellent top mass determinations.
- Important lesson: JES uncertainty can be greatly reduced by in-situ W calibration.
- CDF&DØ have reached a combined precision of 1.2% (better than Run-IIa goal).

$$M_{top} = 171.4 \pm 2.1\, \mathrm{GeV}/c^2$$

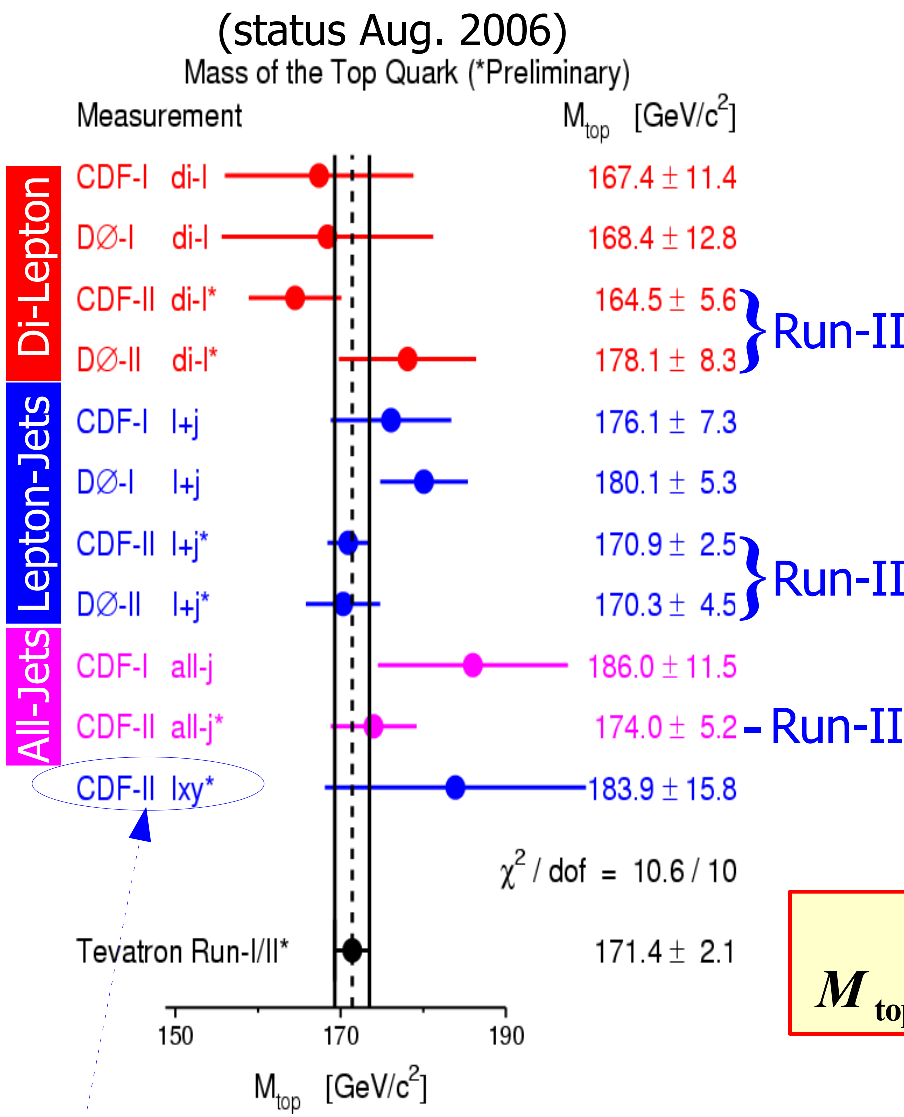
- Can reach 1% precision with full Run-II data, may even push to $\Delta m_{top} \sim 1 \mathrm{GeV}/c^2$ (expected after 5-10 years LHC!)



Tevatron might be the lasting legacy for the top quark mass!

(...at least for a while)

Tevatron Combination



- Significant improvements w.r.t. Run-I.

Combination of best individual results using BLUE technique: ("Best Linear Unbiased Estimate", NIM A270 110, A500 391)

- Account for correlations
- Include Run-I results

(New CDF All-Jets result not yet incorporated.)

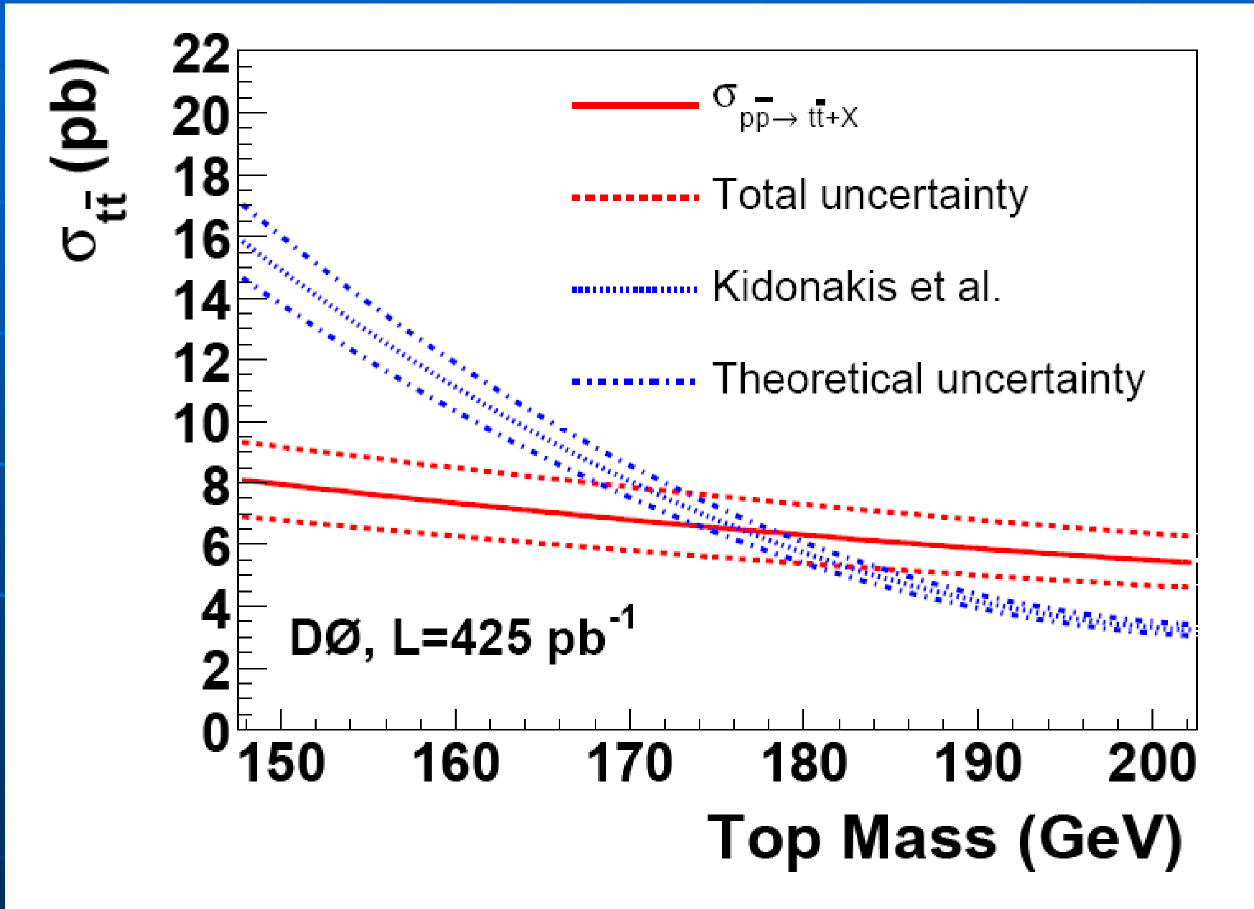
Tevatron combined (status Aug. 2006)

$$M_{top} = 171.4 \pm 1.2(\text{stat.}) \pm 1.4(\text{JES}) \pm 1.0(\text{syst.})\,\text{GeV}/c^2$$

Decay length technique: systematics uncorrelated with other measurements, promising for LHC (see appendix).

Non-JES will be limiting factor at the end of Run-II (see appendix).

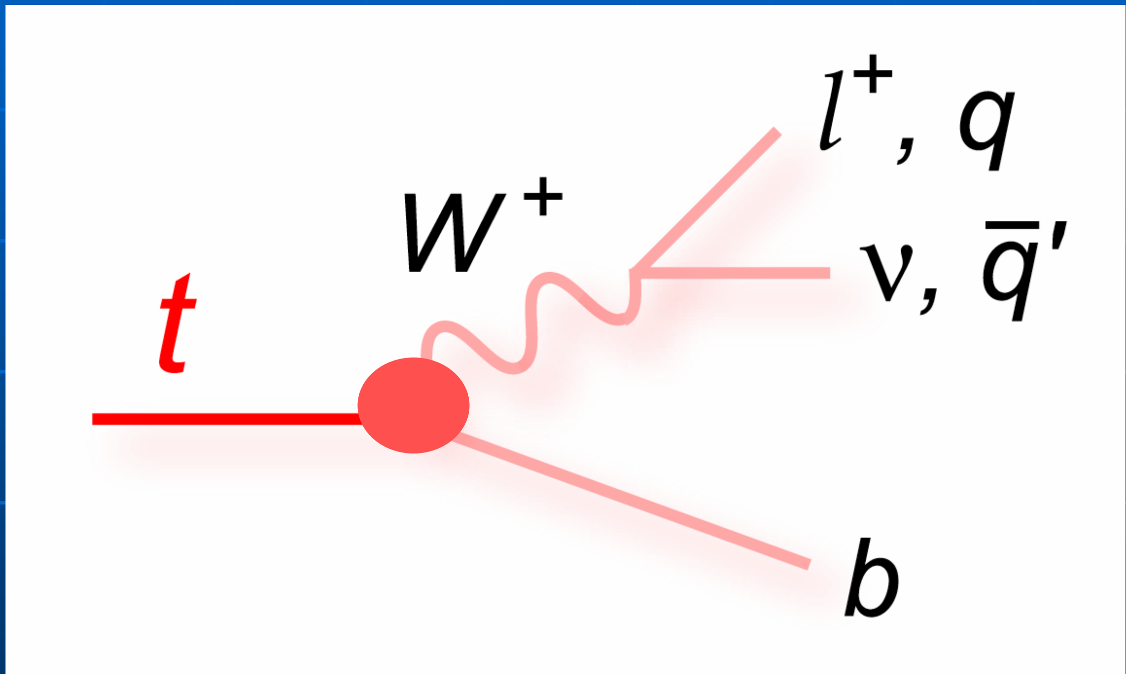
Mass dependence



All cross sections are measured at mt=175 GeV

Dependence on mass is studied both for measurement (detection) and theory (production)

Probing the Wtb vertex



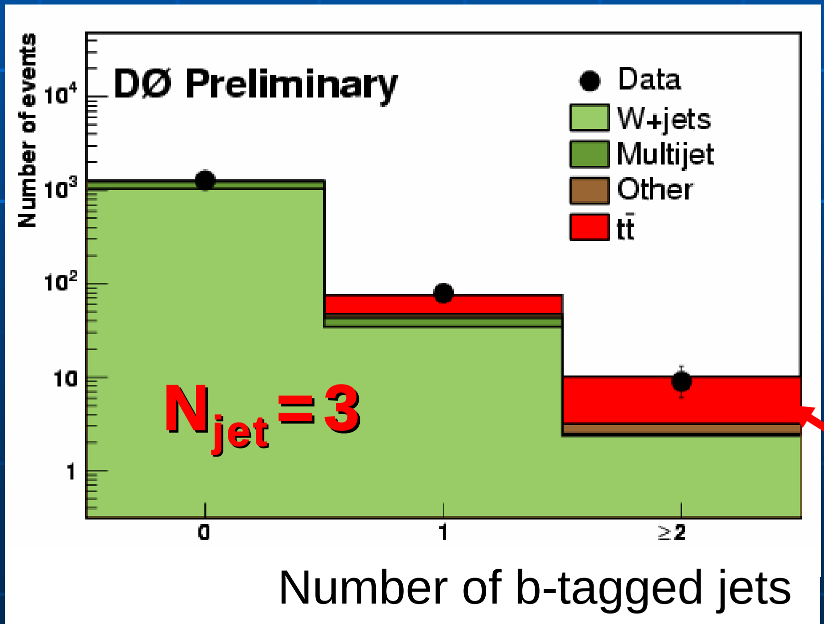
- $t \rightarrow Wb$ / $t \rightarrow Wq$
- W helicity in top events

Probing the assumption t→Wb

$$R = \frac{Br(t \to Wb)}{Br(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.9980 \text{ to } 0.9984$$

(True in SM with three quark generations)

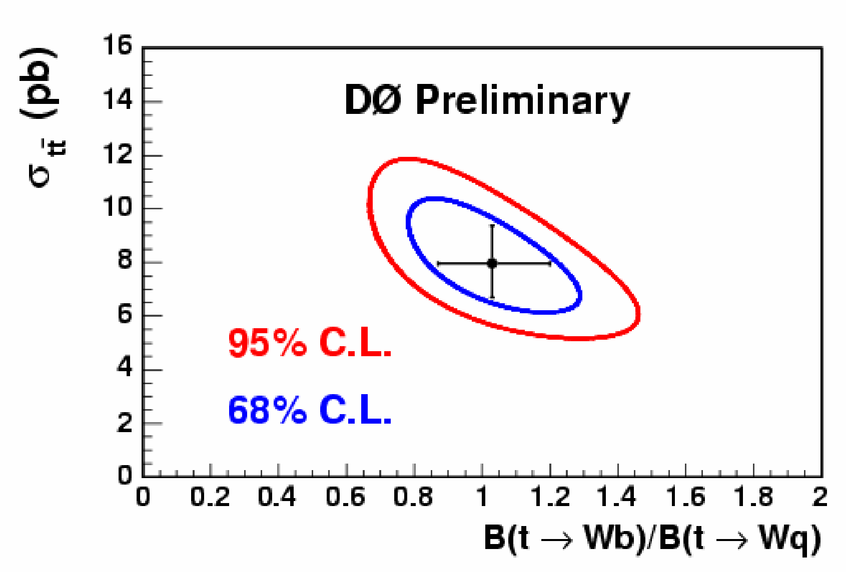
Measurement: count b-jets.
The number of b-jets depends strongly on R and the tagging efficiency.



- Result is obtained from a binned maximum likelihood fit to data for N_{jet} =3 and N_{jet} =4
- Simultaneous fit to R and cross section

Br(t→Wb)=1 and σ_{tt}=7 pb

Probing t→Wb



230 pb^{-1}

$$B = \frac{Br(t \to Wb)}{Br(t \to Wq)} = 1.03^{+0.19}_{-0.17}(\text{stat} + \text{syst})$$

PLB 639, 616 (2006)

Also allows for a model independent cross section measurement:

$$\sigma_{t\bar{t}} = 7.9^{+1.7}_{-1.5}(\text{stat}+\text{syst})\text{pb}$$

Assuming CKM unitarity
$|V_{tb}|>0.78$ @ 95% CL

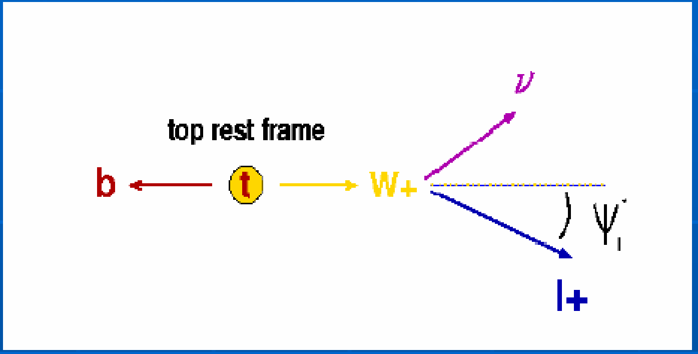
Direct $|V_{tb}|$ measurement with single top → see talk by Juste

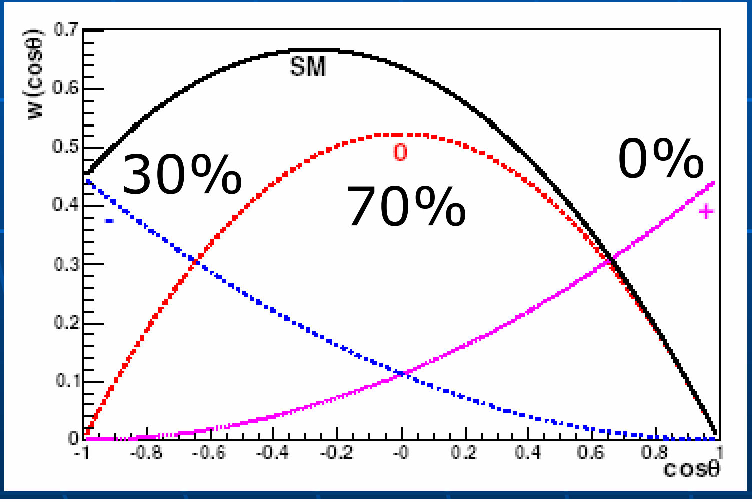
$$\frac{Br(t \to Wb)}{Br(t \to Wq)} = 1.12^{+0.21}_{-0.19}(\text{stat})\ ^{+0.17}_{-0.13}(\text{syst})$$

PRL 95, 102002 (2005)

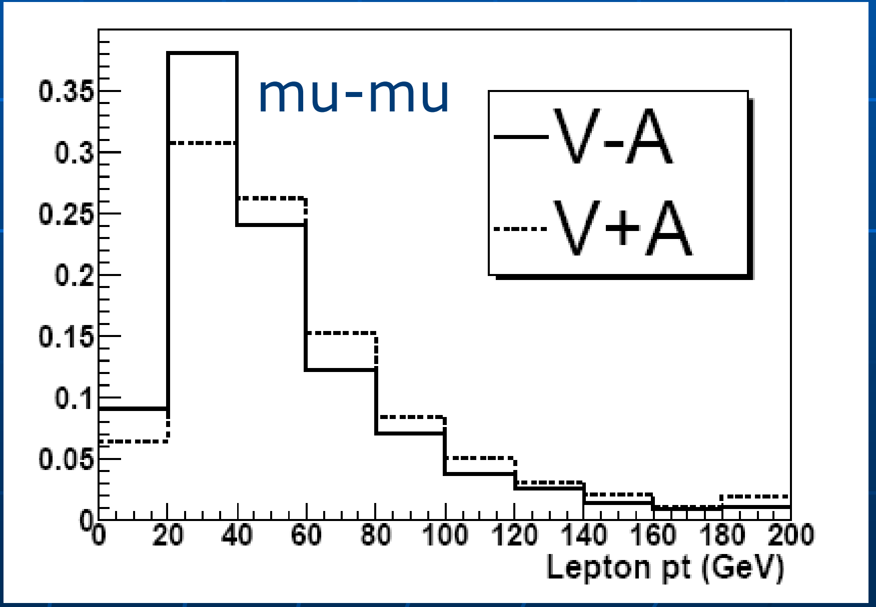
W Helicity from t→Wb Decays

- Examines the nature of the tWb vertex, probing the structure of weak interactions at energy scales near EWSB
- Stringent test of SM and its V-A type of interaction.
- Uses boosted W from top decays

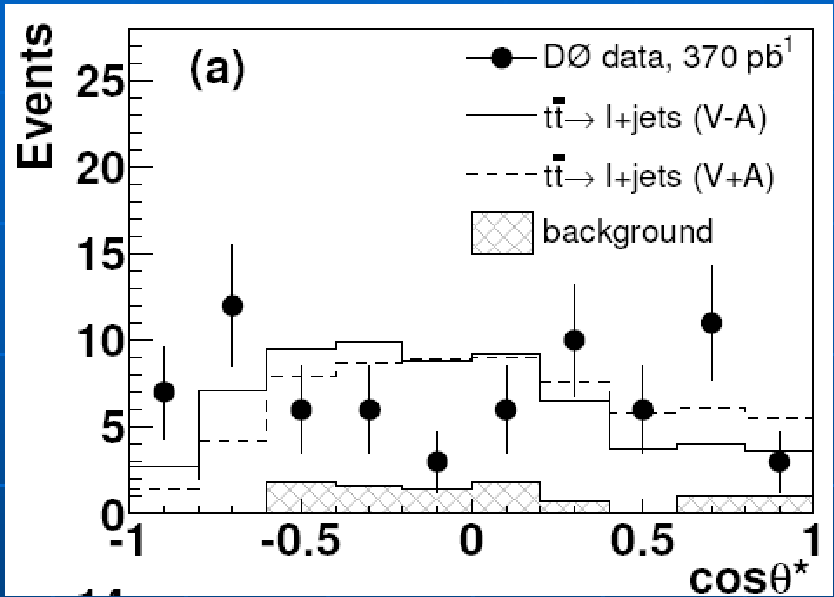


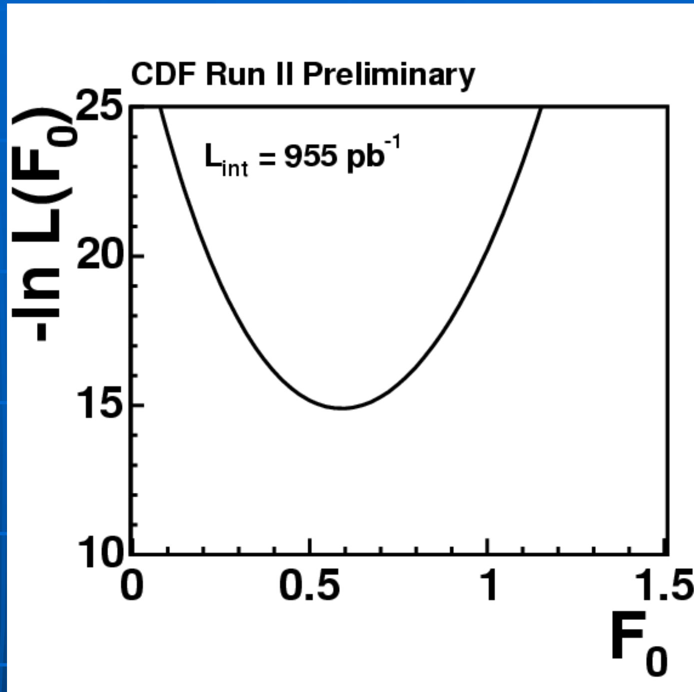


$$M_{l+b}^2 = 1/2 \cdot (M_T^2 - M_W^2)(1 + cos\psi_l^\star)$$



Results (2 selected)





lepton+jets and dilepton

F+ = 0.056 +- 0.080 (stat) +- 0.057 (syst)
F+ < 0.23 @ 95% C.L.

PRD 75, 031102(R) (2007)

lepton+jets

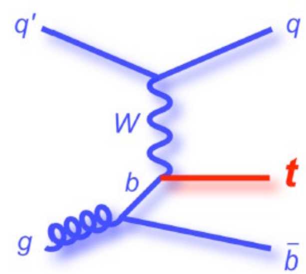
F0= 0.59 +-0.12(stat)+-0.07 (syst)
F+ < 0.10 @ 95% C.L.

(Earlier result with 0.7 fb^{-1}:
PRL 98, 072001 (2007))

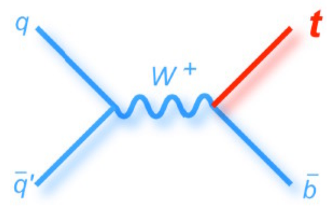
Single Top Quark Production

- Main SM production mechanisms at a hadron collider:

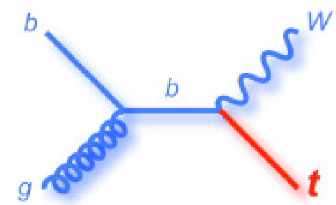
t-channel ("tqb")



s-channel ("tb")



associated production ("tW")



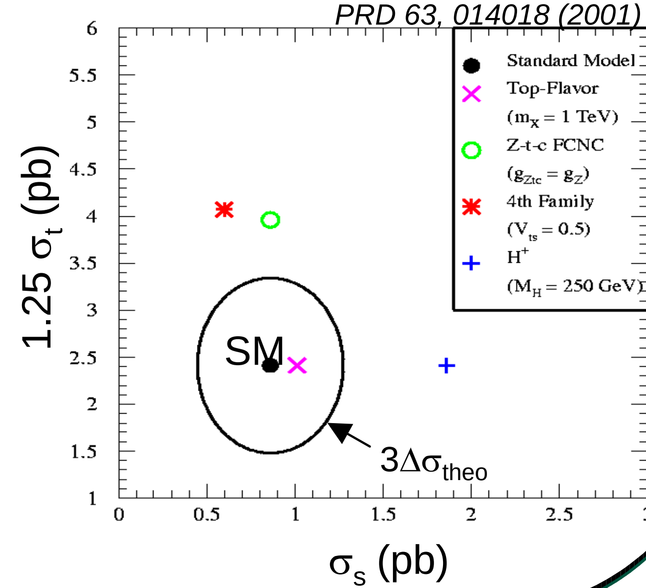
	t-channel	s-channel	tW
Tevatron ($\sqrt{s}$=1.96 TeV):	~2.2 pb	~1.0 pb	~0.25 pb
LHC ($\sqrt{s}$=14 TeV):	~235 pb	~11 pb	~95 pb

(for m_t=175 GeV)
hep-ph/0609287
hep-ph/0701080

- Not discovered yet. It has been the subject of intense search at the Tevatron since Run I. Here will discuss the experimental status based on ~1 fb^{-1} of Run II data.

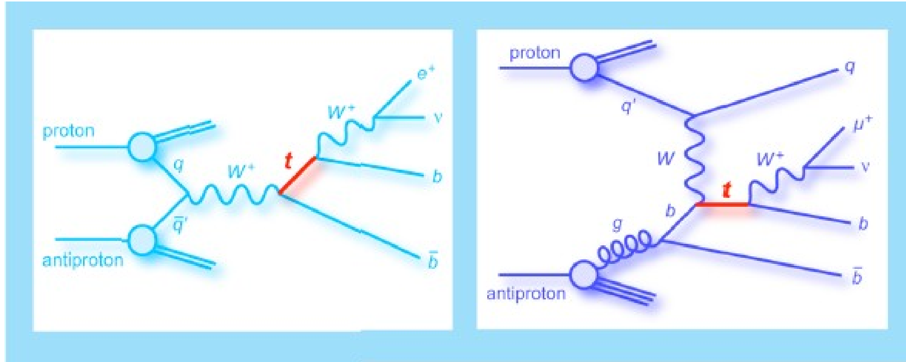
- Motivation:
  - Study of the *tbW* interaction:
    - Direct measurement of $|V_{tb}|$: $\sigma \propto |V_{tb}|^2$
    - Anomalous couplings
  - Sensitivity to different New Physics:
    - s-channel: W', $H^{\pm}$, W_{KK},…
    - t-channel: FCNC interactions, 4^{th} family,..
  - Top spin physics (~100% polarized top quark)
  - Develop/exercise techniques to extract small signal in a large background (e.g. Higgs search).

PRD 63, 014018 (2001)

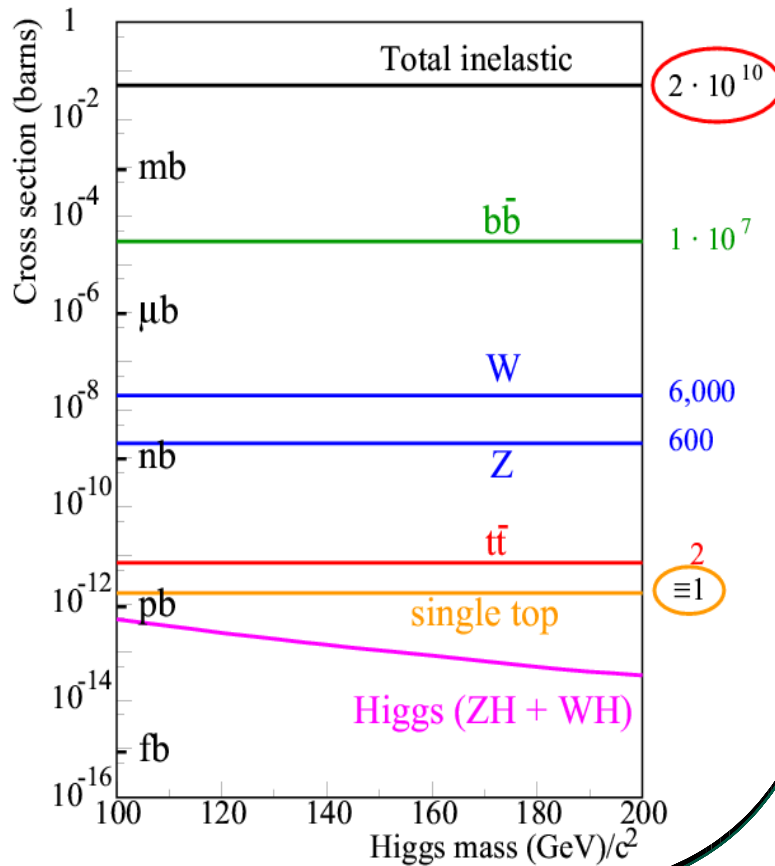


Experimental Signature and Event Selection

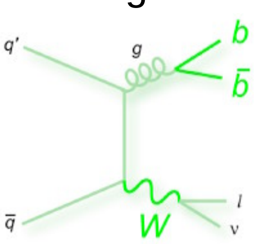
- Experimental signature:
  - One high p_T isolated lepton (e or μ)
  - High missing transverse energy
  - $\geq$2 jets ($\geq$1 b-tag)

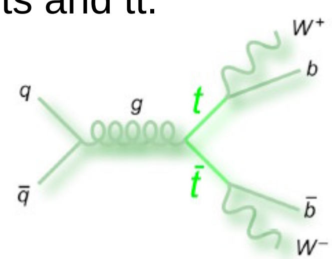


e:	p_T>20 GeV, $\lvert\eta\rvert$<2.0	p_T>15 GeV, $\lvert\eta\rvert$<1.1
μ:	p_T>20 GeV, $\lvert\eta\rvert$<1.1	p_T>18 GeV, $\lvert\eta\rvert$<2.0
Missing E_T	MET>25 GeV	15<MET<200 GeV
Jets	=2, p_T^{uncorr}>15 GeV, $\lvert\eta\rvert$<2.8	2-4, p_T>15 GeV, $\lvert\eta\rvert$<3.4 $p_{T,1}$>25 GeV, $\lvert\eta_1\rvert$<2.5 $p_{T,2}$>20 GeV
B-jet	1 or 2	



- Experimental signature similar to tt→lepton+jets but lower jet multiplicity.
- Main backgrounds: W+jets and tt.





Search Strategy Overview

- In order to achieve the highest possible sensitivity, analyses underwent careful optimization:
  - Maximize acceptance (loose lepton identification, low p_T thresholds, wide η range, improved b-tagging performance,…)
  - Include as many channels as possible:
    DØ: 2-4 jets
  - Perform analysis in separate channels since S/B different and combine at the end:
    DØ: (e,μ) x (2,3,4 jets) x (1,2 tags) = 12
  - Develop sophisticated multivariate analysis techniques for best possible signal-to-background discrimination.
  - Optimize analysis for combined (tb+tqb) search (also perform separate searches).

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

Signal acceptances (including BR)

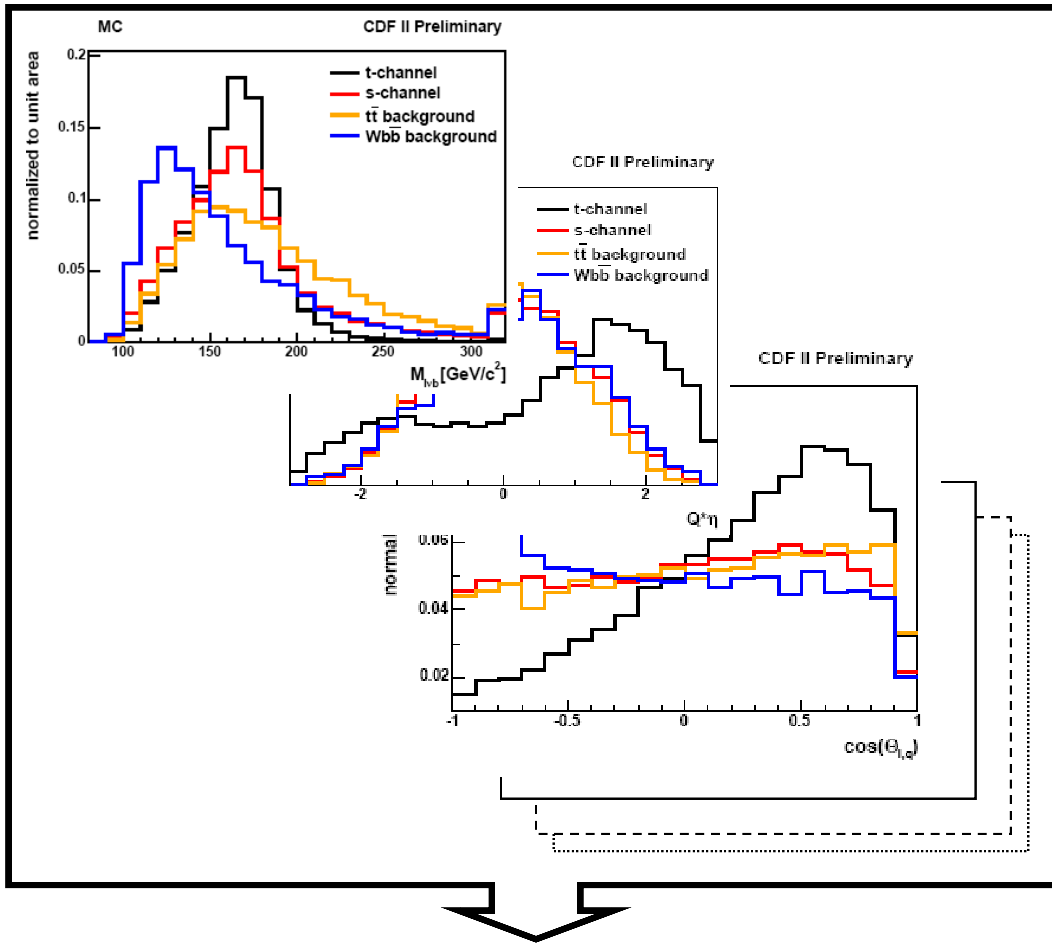
	tb	tqb
CDF (2 jets)	~1.9%	~1.3%
DØ (2-4 jets)	~3.2%	~2.1%

Multivariate Analysis Techniques

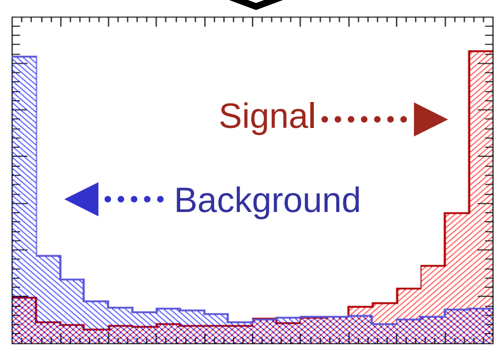
- A number of discriminant variables between signal and background can be identified:
  - B-tagging NN
  - Reconstructed top mass
  - Q(lepton)•η(untagged jet)
  - Top spin-related angular variables
  - ….

but no single variable is powerful enough to cut on it.

⇒ Combine a number of variables into a single more powerful discriminant variable by using a multivariate analysis technique.



Standard Neural Network
Bayesian Neural Network (*)
Likelihood Discriminants (*)
Matrix Element Discriminants
Boosted Decision Trees

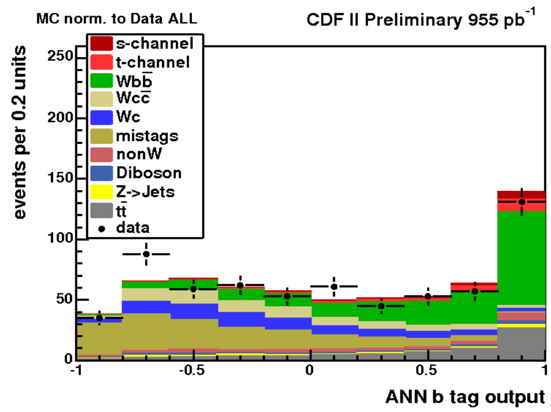


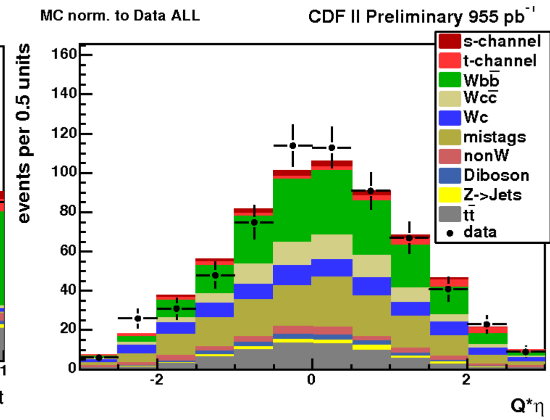
(*) Not discussed in detail

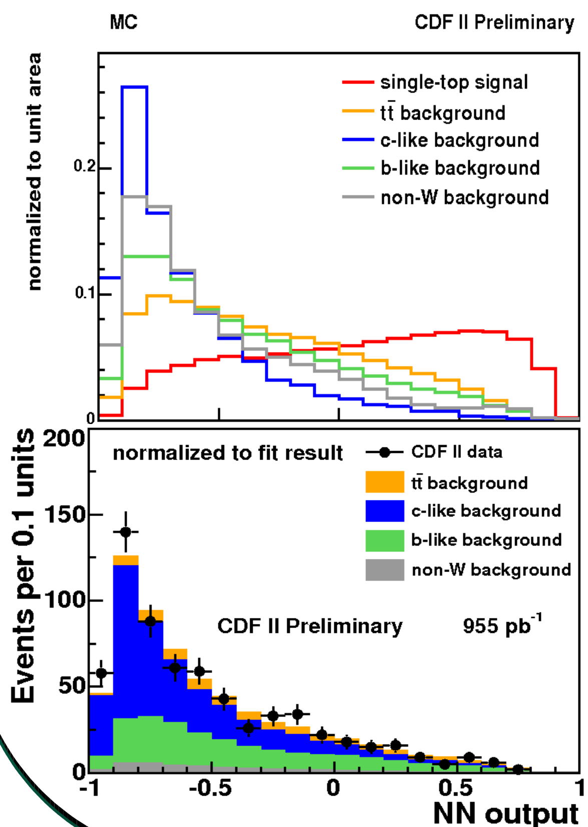
Event Discriminant

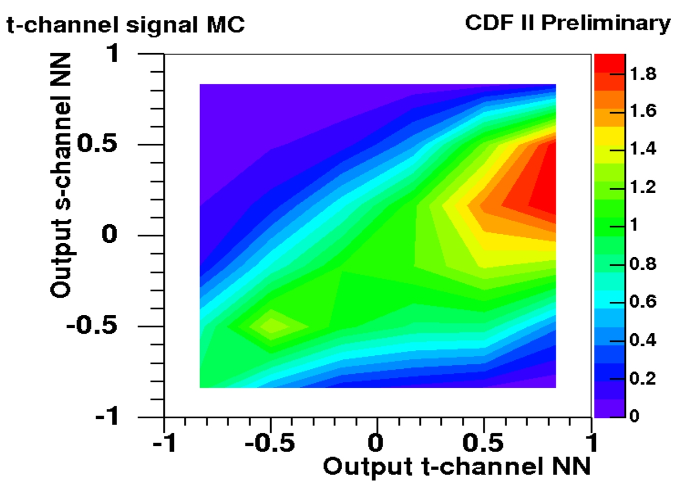
Neural Network Analysis

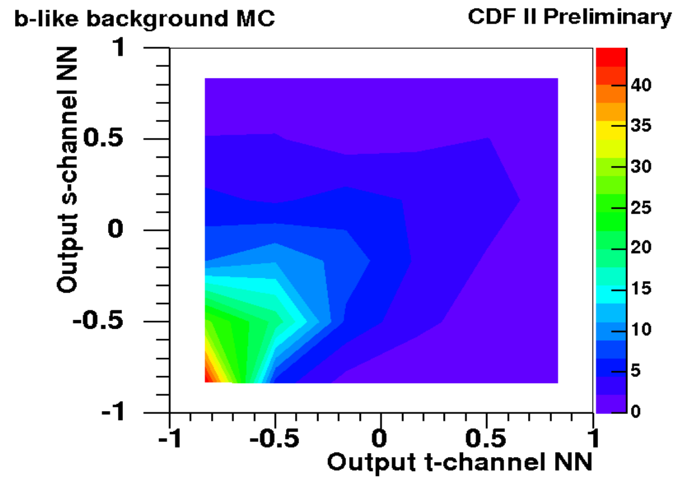
- Consider 26 kinematic or event-shape variables: b-tagging NN, reconstructed top mass, Qxη, etc.
- Three NNs trained for combined (tb+tqb) and separate (tb and tqb) searches.
- Build templates for five categories: signal, tt, c-like, b-like and non-W.











Expected Performance	Median p-value (CDF)	σ_{95} (*)
Combined search	0.5% (2.6σ)	2.6 pb
Separate search	0.4% (2.7σ)	1.3 pb (tqb) 1.5 pb (tb)

(*) Assuming no single top

Matrix Element Discriminants

- Pioneered by DØ in Run I top mass measurement. Now being used in a search.
- Attempt to make an optimal use of the kinematic information in the event.
- Principle: compute event probability density for a given hypothesis (e.g. single top) making use of all reconstructed objects in the event (integrate over unknowns).

E.g. 2 jet events: $\vec{x} = \{p_\ell^\mu, p_{j1}^\mu, p_{j2}^\mu\}$ — Only 6 "discriminant variables" used!!

differential cross section (LO matrix element)

parton distribution functions

$$P_i(\vec{x}) = \frac{1}{\sigma} \int \cdots \int \sum_{comb} d^n\sigma_i(\vec{y}) dq_1 dq_2 f(q_1) f(q_2) W(\vec{x} \mid \vec{y})$$

$$d^n\sigma_i(\vec{y}) = \frac{(2\pi)^4}{2s} |M_i(\vec{y})|^2 \, d\Phi^n(\vec{y})$$

transfer function: mapping from parton-level variables (y) to reconstructed-level variables (x)

Maximize sensitivity by:

- summing over all permutations of jets and neutrino solutions
- allowing better measured events to contribute more (via the transfer function)
- implementing b-tagging information

- Matrix element discriminant defined as:

$$EPD = \frac{b \cdot P_{tb+tqb}(\vec{x})}{b \cdot P_{tb+tqb}(\vec{x}) + b \cdot P_{Wbb}(\vec{x}) + (1-b) \cdot (P_{Wcc}(\vec{x}) + P_{Wcj}(\vec{x}))}$$

b = b-tagging NN probability (event-by-event)

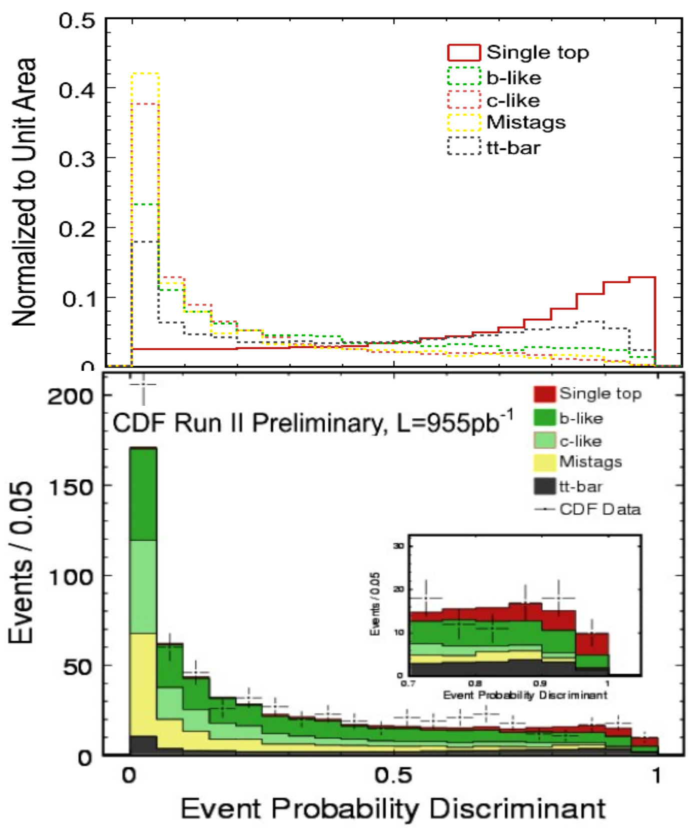
$$D_S(\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_{bckg}(\vec{x})}; \qquad S = tb \text{ or } tqb$$

$$P_{bckg}^{2j}(\vec{x}) = c_{Wbb} P_{Wbb}(\vec{x}) + c_{Wcg} P_{Wcg}(\vec{x}) + c_{Wgg} P_{Wgg}(\vec{x})$$

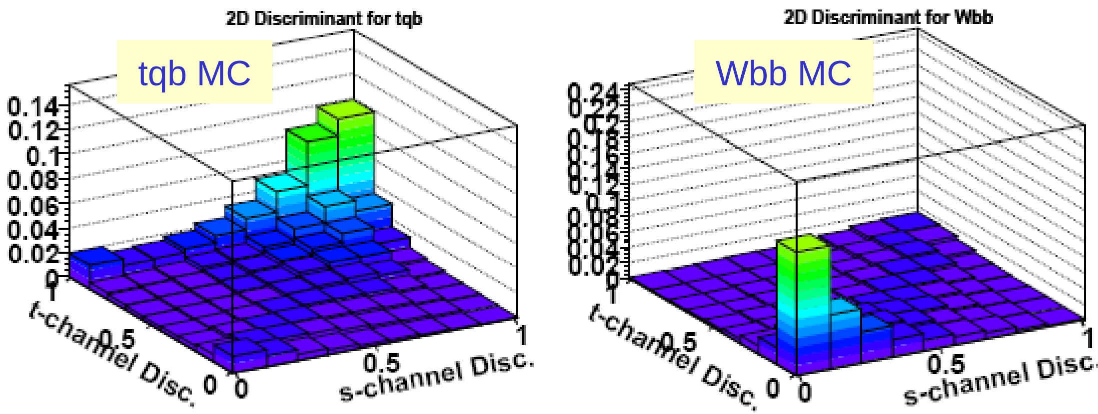
$$P_{bckg}^{3j}(\vec{x}) = P_{Wbbg}(\vec{x})$$

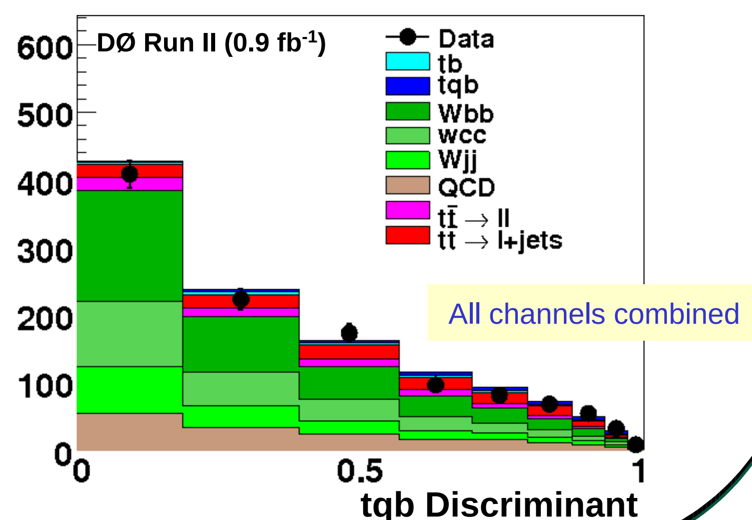
Matrix Element Analyses

- Consider only 2-jet events.
- Single channel search
  (e+μ,1tag and 2tags combined)
- Combined search based on 1D disc:



- Consider 2-jet and 3-jet events.
- Six separate search channels
  (e,μ) x (2,3 jets) x (1,2 tags)
- Combined search based on 2D disc:

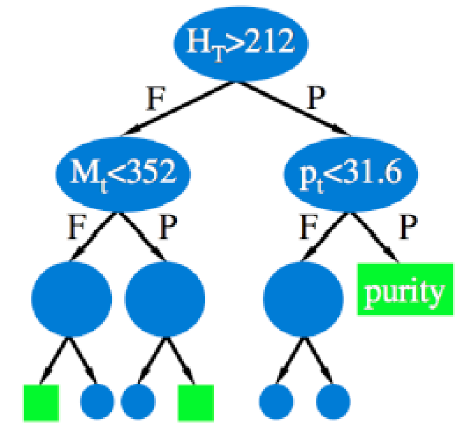




Not comparable!

Expected Performance	median p-value (CDF)	p-value (DØ)
CDF ME analysis	0.5% (2.6σ)	
DØ ME analysis		3.6% (1.8σ)

Boosted Decision Trees Analysis

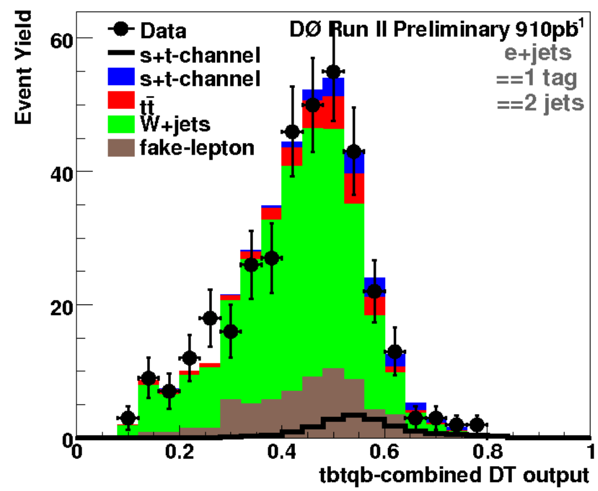


- Machine learning technique, widely used in social sciences, some use in HEP (e.g. MiniBooNe).
- Idea: recover events that fail criteria in cut-based analyses.

- Start at first "node " with "training sample" of all signal and background events.
- Select variable and splitting value with best separation to produce two "branches".
- Repeat recursively at each node. Stop when there is no improvement or too few events are left.
- DT output = "leaf " purity, close to 1(0) for signal(background)
- Improve performance of DT by using "adaptive boosting", which averages over many trees, diluting the piecewise nature of the DT output.

- Consider a total of 49 variables to discriminate between signal and backgrounds.
  - Most sensitive variables: M(all jets), $M(W,b_1)$ ("top mass"), $Q\times\eta$, $\cos\theta(\text{lepton},b_1)|_{\text{top rest-frame}}$
  - Adding more variables does not reduce discrimination.
  - Reducing number of variables always reduces sensitivity.
  - Same list of variables used for all analysis channels.
- Trained 36 sets of trees:

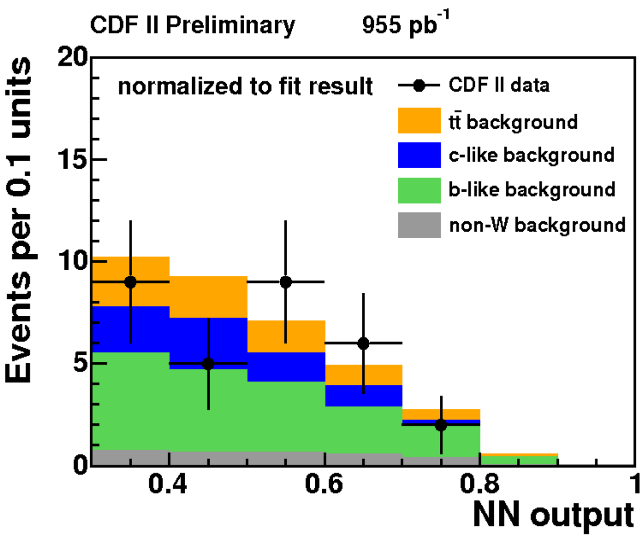
(tb+tqb, tb, tqb) x (e,μ) x (1,2,3,4 jets) x (1tag, 2tags)
  - Signal trained against sum of all backgrounds.
  - Combined search (tb+tqb) has best sensitivity.



Expected Performance	p-value (DØ)
Combined search	1.8% (2.1σ)

CDF Results

NN analysis

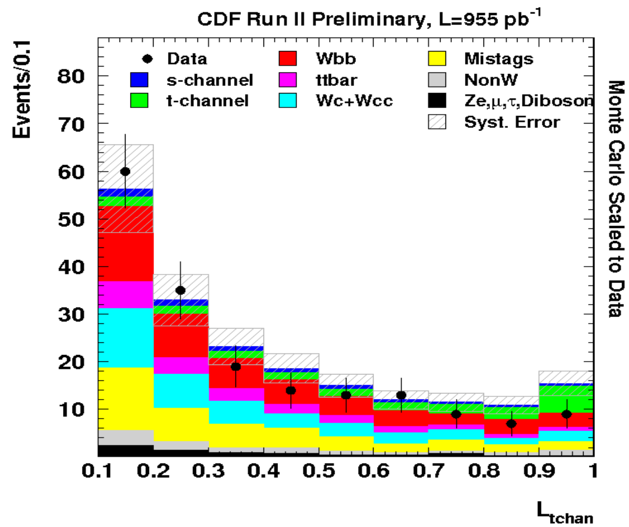


$\sigma_{tb} = 0.7^{+1.5}_{-0.7}\ pb;\ \sigma_{tqb} = 0.2^{+1.1}_{-0.2}\ pb$

$\sigma_{tb+tqb} < 2.6\ pb\ @\ 95\%\ CL$

No evidence of signal

Likelihood Function analysis

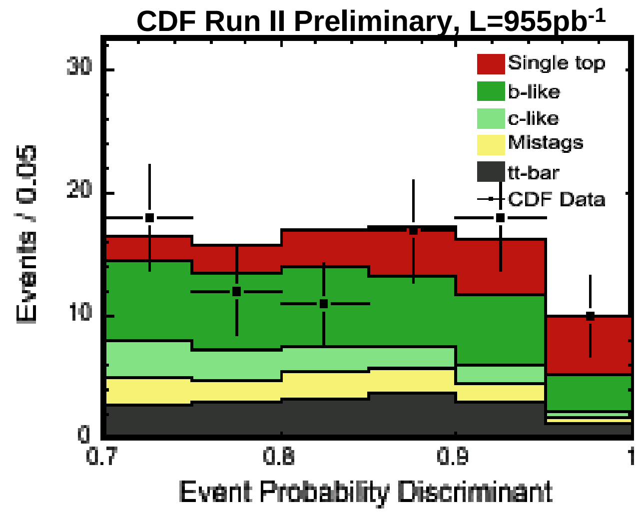


$\sigma_{tb} = 0.1^{+0.7}_{-0.1}\ pb;\ \sigma_{tqb} = 0.2^{+0.9}_{-0.2}\ pb$

$\sigma_{tb+tqb} < 2.7\ pb\ @\ 95\%\ CL$

No evidence of signal

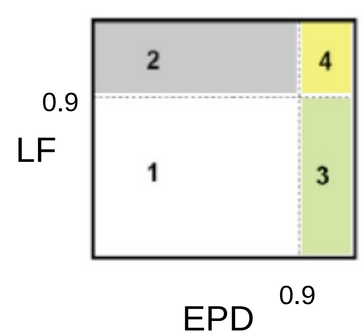
Matrix Element analysis



$\sigma_{tb+tqb} = 2.7^{+1.5}_{-1.3}\ pb$

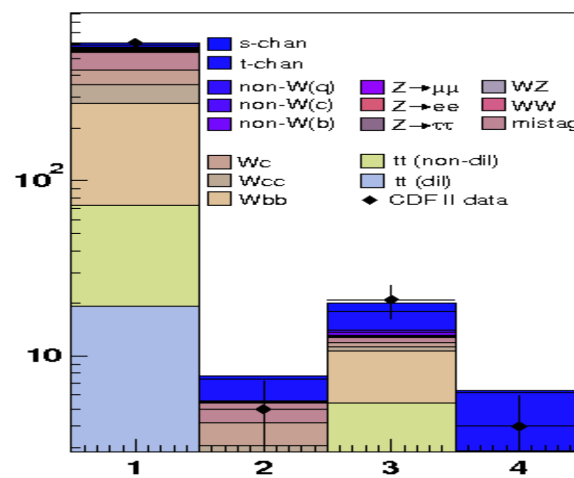
Observed p-value: 1.0% *(2.3σ)*

- Studies ongoing to quantify compatibility of results. ME-LF:
  - correlation of fit results: ~53%
  - compatibility of measurement in data: ~4-6%
- Analyzing more data should shed some light.



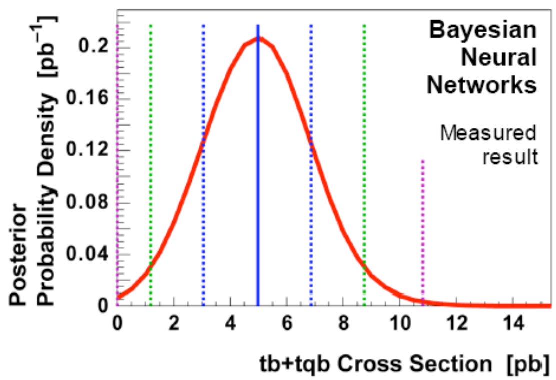
Prob(null hyp) = 33.7%

Prob(signal hyp) = 49.8%



DØ Results

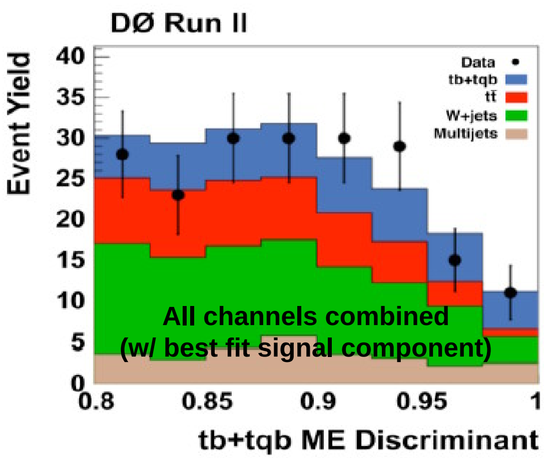
Bayesian NN analysis



$\sigma_{tb+tqb} = 5.0 \pm 1.9\ pb$

Observed p-value: 1.15% *(2.3σ)*

Matrix Element analysis

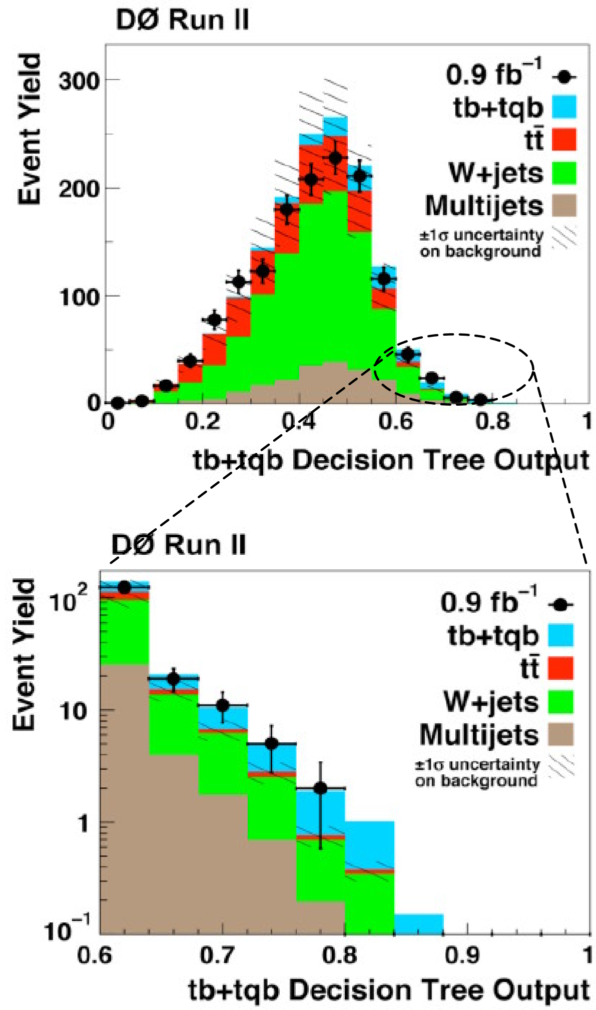


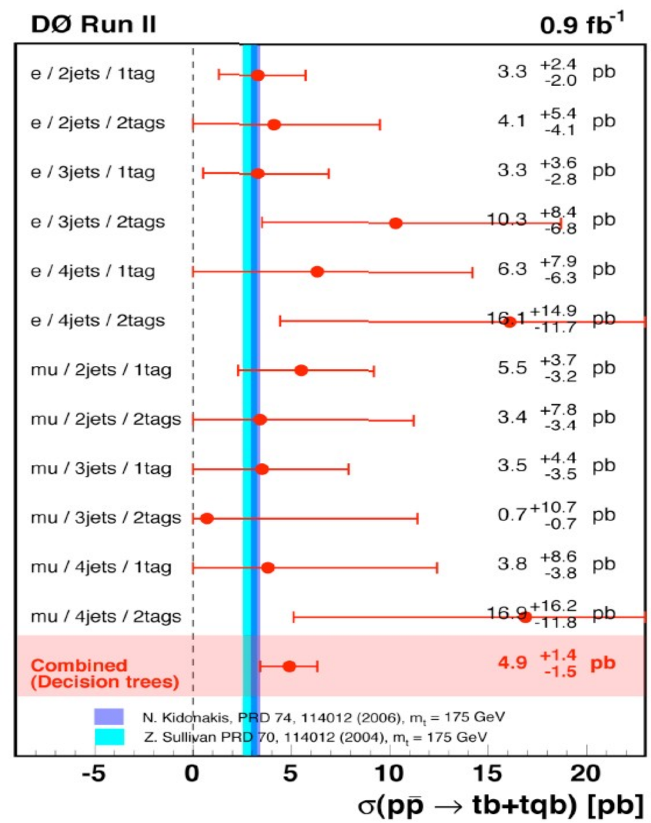
$\sigma_{tb+tqb} = 4.8^{+1.8}_{-1.5}\ pb$

Observed p-value: 0.20% *(2.9σ)!*

Boosted Decision Trees analysis

All channels combined
(w/ best fit signal component)





$\sigma_{tb+tqb} = 4.9 \pm 1.4\ pb$

Observed p-value: 0.034% ***(3.4σ) !!***

Compatibility with SM: 11%

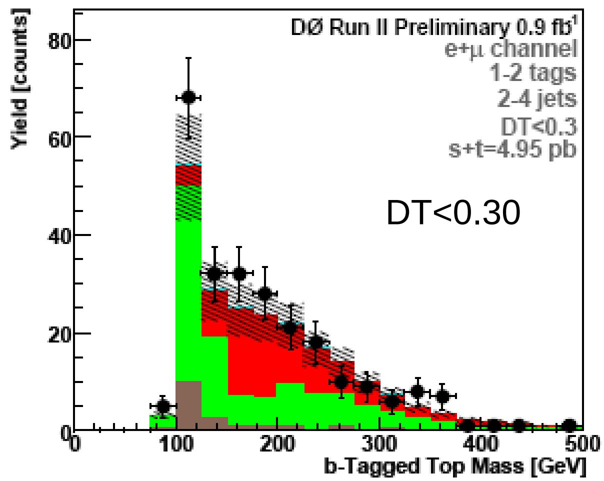
hep-ex/0612052
Submitted to Phys. Rev. Lett.

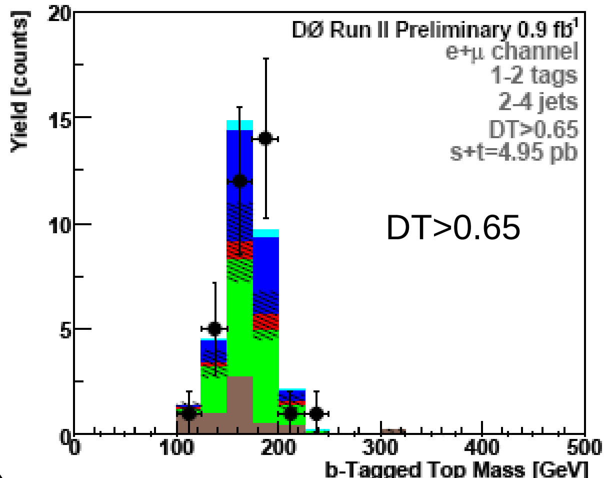
Evidence for single top production!

DØ Results

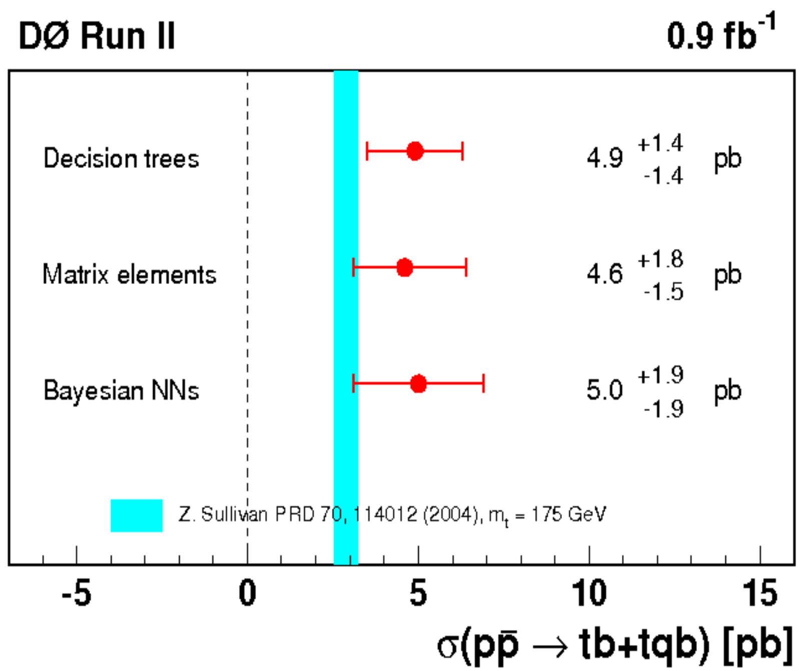
Event Characteristics

All channels combined
(w/ best fit signal component)





Summary of Measurements



- Results from the three analyses are consistent with each other.
- Overlap within the subset of 50 highest-discriminant events per analysis: ~50%.
- Preliminary estimate of correlation in measured cross section between analyses using pseudo-experiments (incl. syst. uncertainties): ~50%.

Combined cross section and significance will soon become available.

Discoveries…