Tevatron Results: QCD and Top

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Outline

- QCD
  - ➔ Inclusive photon production
  - ➔ Inclusive jet production
  - ➔ Dijet correlations
  - ➔ Z/W + jets

✓ Testing QCD for hard and soft processes
✓ Verifying and tuning Monte Carlo tools

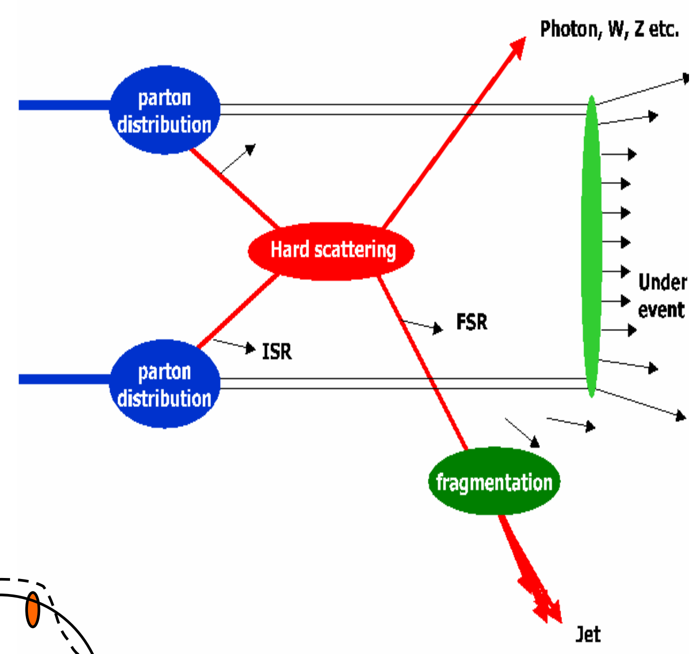
- Top
  - ➔ Top pair production
  - ➔ Top mass
  - ➔ $t\bar{t}$ resonance and $t\bar{t}H$ searches
  - ➔ Properties: a summary

✓ Testing SM with heaviest known fermion
✓ Developing advanced analysis methods

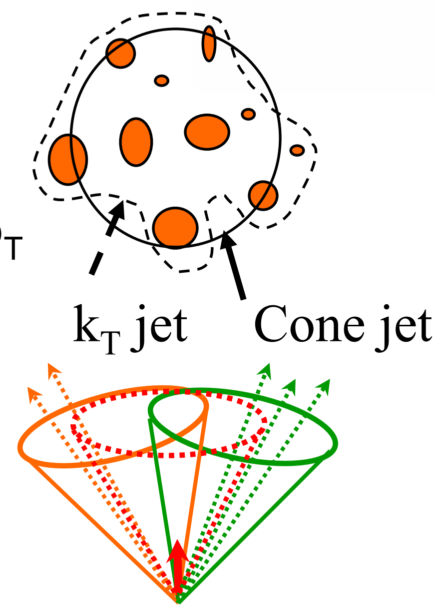
- Conclusions

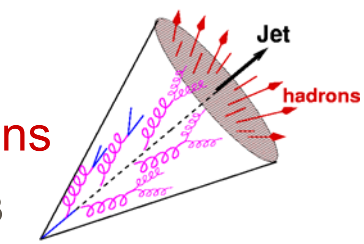
✂ Only a small set of selected results could be presented
☞ See CDF and D0 public web pages for more information
♪ Single top in the next talk

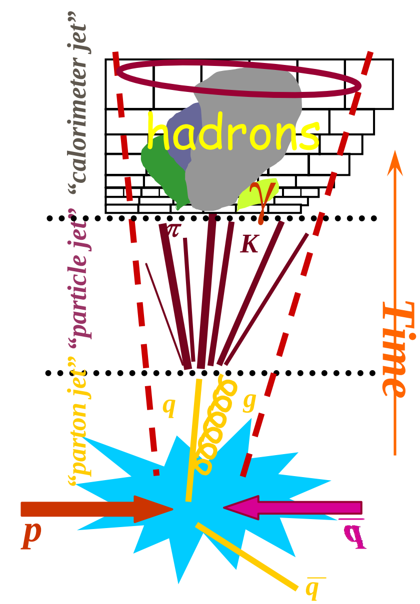
QCD at Tevatron



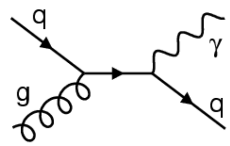
- Tevatron QCD measurements important for:
  - ➔ Better determination of proton structure at large x
  - ➔ Testing pQCD at a new level (resummation, NLO and multi-jet event generators,…)
  - ➔ Continued searches for new physics while probing distances ~10^{-19} m
- Jet algorithms:
  - ➔ KT clusters particles based on relative p_T
  - ➔ Midpoint Cone: add midpoints between jets as seeds
  - ➔ Jet constituents combined by 4-vector addition ("E-scheme" → massive jets)
- Correct to particle level:
  - ➔ Data: standard procedures
  - ➔ Theory: apply parton-to-hadron corrections

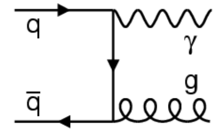






Inclusive Photon Production





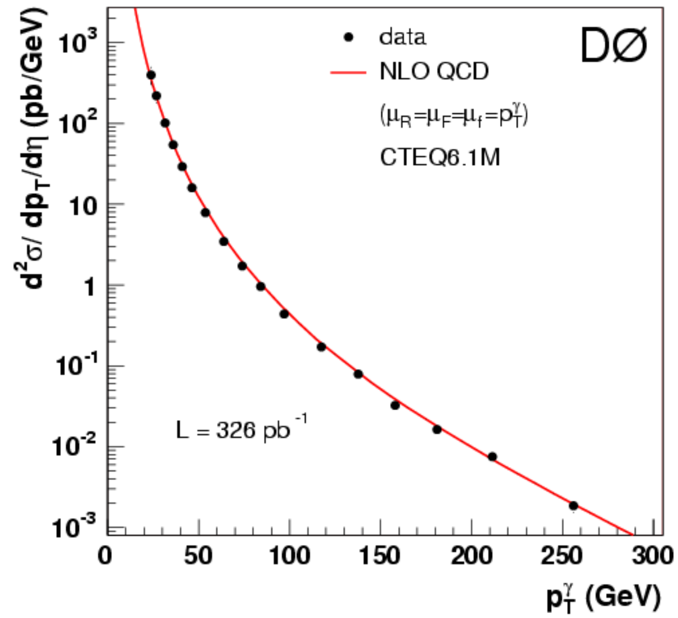
- A clean test of pQCD
  - ➔ Fewer fragmentation effects than for jets
- Sensitivity to parton distributions
  - ➔ Constrain large-x gluon without using jets → cleaner search for quark substructure

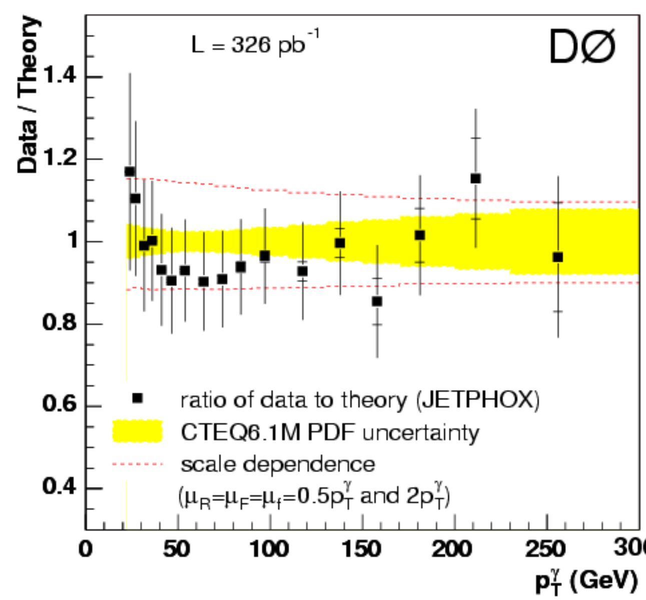
- D0 L = 326 pb^{-1}:
  - ➔ 1st Run 2 inclusive photon measurement
  - ➔ Neural Net is trained to discriminate between photons and photon-like jets

- Good agreement with NLO pQCD

  (JETPHOX, CTEQ6.1 PDFs and $\mu_r = \mu_f = \mu_F = p_T^\gamma$)
  - ➔ Low-p_T increase consistent with extra k_T ~3 GeV

- Enhancing PDF sensitivity requires:
  - ➔ Reduced experimental uncertainties
  - ➔ Improved theory (resummation / NNLO)

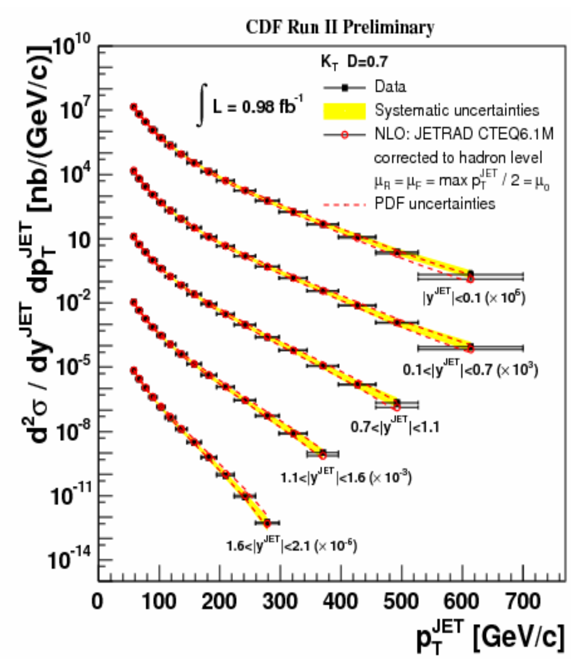


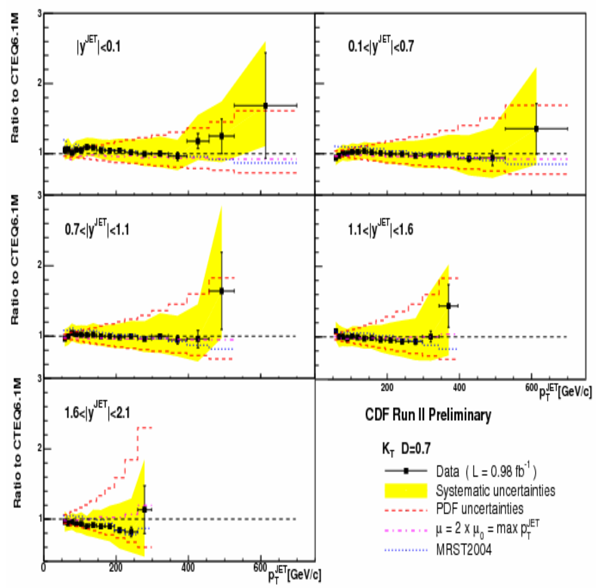


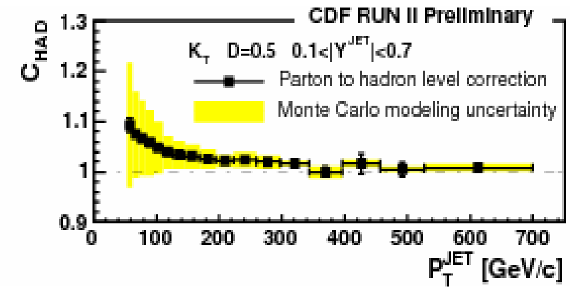
Inclusive Jet Cross Section: KT

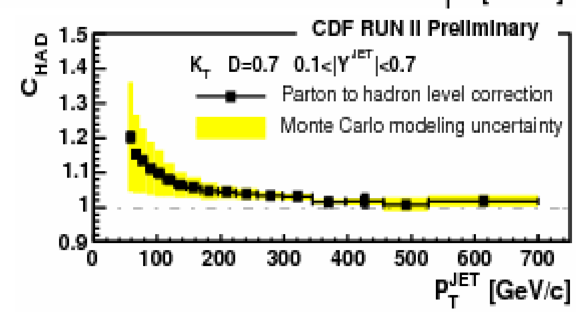
- CDF: 5 rapidity bins, $p_{T,jet}$ > 54 GeV, L=0.98 fb^{-1}
  - ➔ Ellis-Soper inclusive KT algorithm with D=0.7
  - ➔ Data corrected to hadron level
  - ➔ Corrections for underlying event and hadronization effects (C_{HAD}) essential for agreement with theory
- KT algorithm has been shown to work well for jet reconstruction in hadron collider environment
- Recent KT and MidPoint Cone jet cross sections from CDF and D0 start constraining large-x PDFs

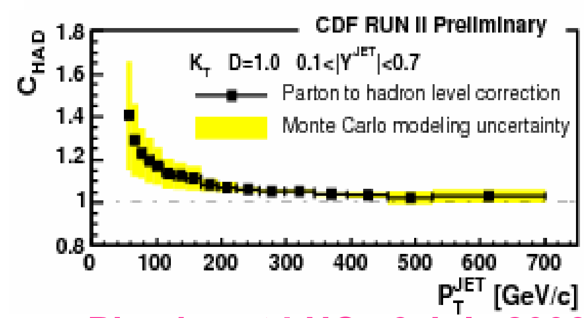
Strong sensitivity of hadronization corrections to the size parameter D





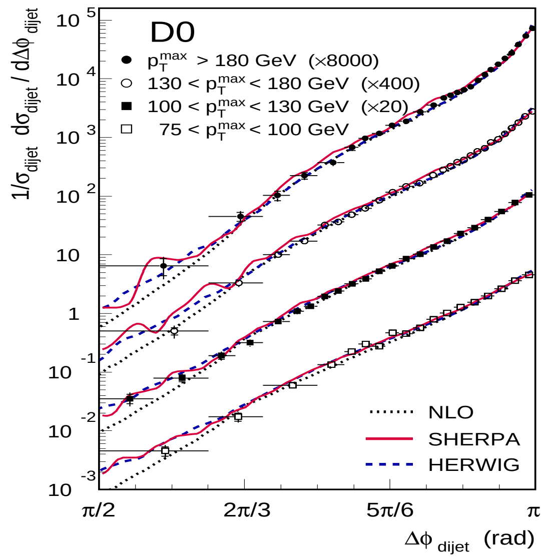


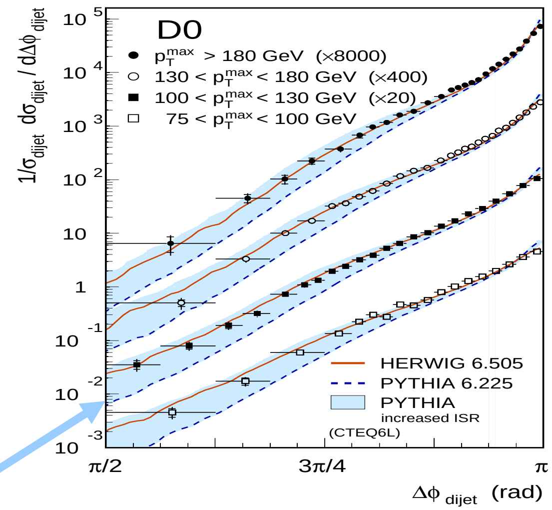


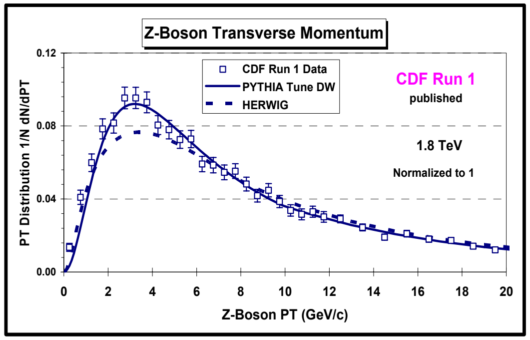


Jet Azimuthal Correlations

- Measurements of multi-jet processes require good understanding and modeling of QCD radiation
- Radiation effects can be studied in distributions of the azimuthal angle between the two leading jets, $\Delta\Phi$
  - ➔ No need for explicit reconstruction of extra jets
- D0 measurement L = 150 pb^{-1}
  - ➔ Leading jet p_T in 4 bins, 2^{nd} leading p_T > 40 GeV; $|y|<0.5$
- Good description by NLO QCD (for 3 jet production), Herwig, Sherpa and Alpgen (+PS MC)
  - ➔ A test of PS-ME matching prescriptions (MLM, CKKW) across a range of jet multiplicities
- Tuning Parton Showers in Pythia:
  - ➔ Default Pythia 6.2 (low edge) does not describe data
  - ➔ Data prefer larger Initial State Radiation
    -- although less than in CDF Tune-A → upper edge
  - ➔ New tunes DW & DWT using $\Delta\Phi$ data now available
    - ❖ Best tune at Tevatron with 2 different extrapolations to LHC



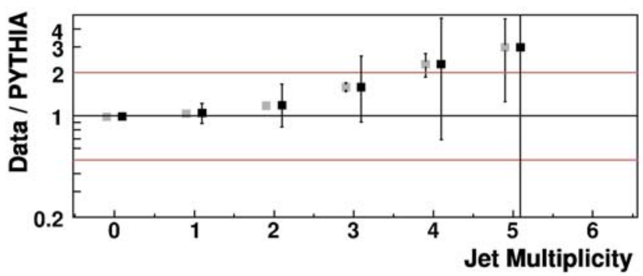


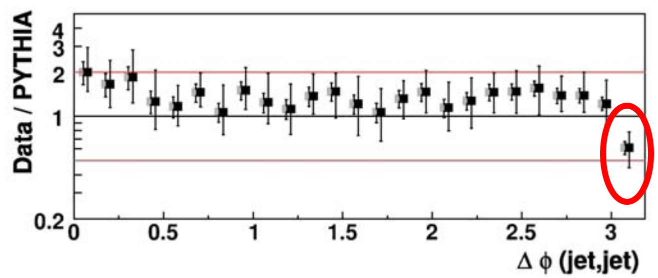


Z + n jets

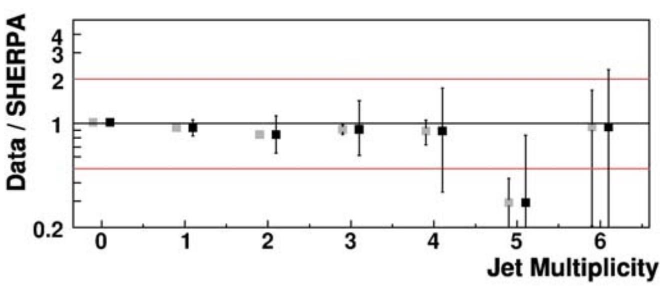
- D0 L = 0.95 fb^{-1}:
  - ➔ $Z/\gamma^* \rightarrow e^+e^-$ mode; jet p_T > 15 GeV
- MCs: Pythia TuneA + CTEQ6L1; Sherpa + CTEQ6L
  - ➔ Full detector simulation; zero-bias overlay from data
  - ➔ Both MCs normalized to total # of Z/γ^* events in data sample

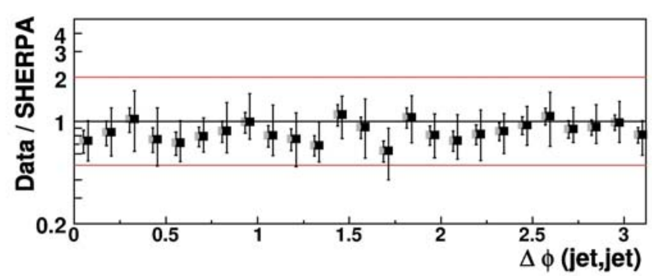
- Pythia underestimates jet multiplicity; overshoots at $\Delta\Phi \sim \pi$ (also for dijets)
- Sherpa describes data distributions well





Pythia

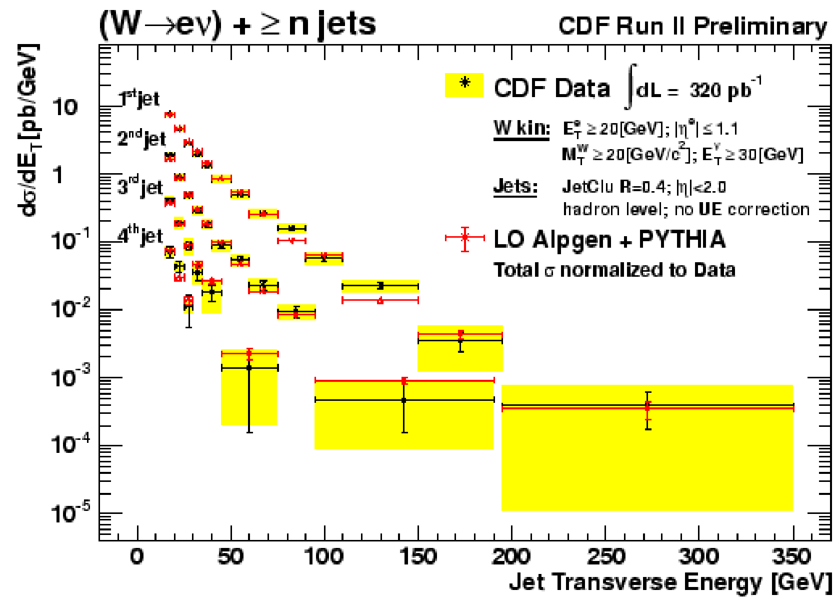


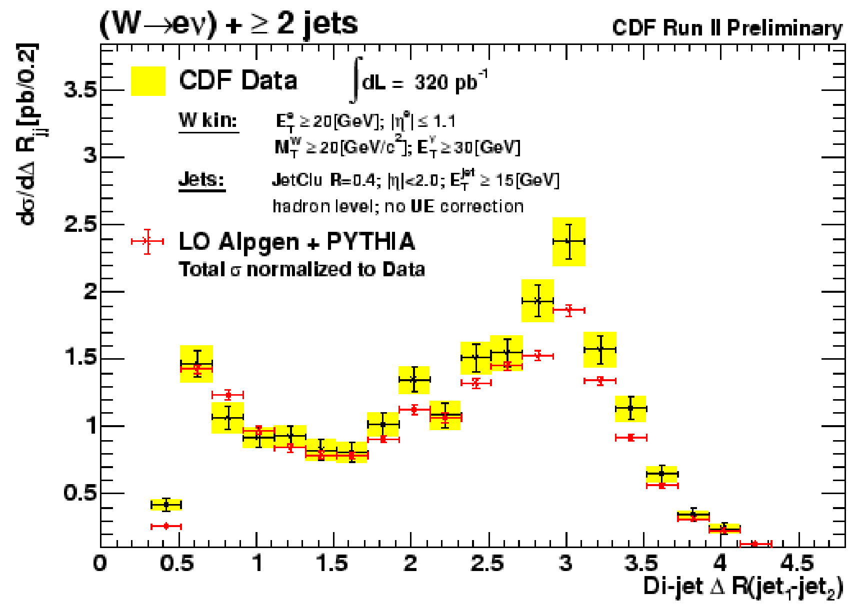


Sherpa

W + n jets

- Good understanding of W + jets production essential for top, Higgs, SUSY physics!
- CDF L = 320 pb^{-1}
  - ➔ Jets corrected to hadron level (JetClu algorithm used here)
  - ➔ Kinematic cuts imposed to reduce model dependence on acceptance and efficiency
- Reasonable description by Alpgen + Pythia
  - ➔ But: MC has been normalized to data in each jet multiplicity bin
  - ➔ Need further tuning of MC params





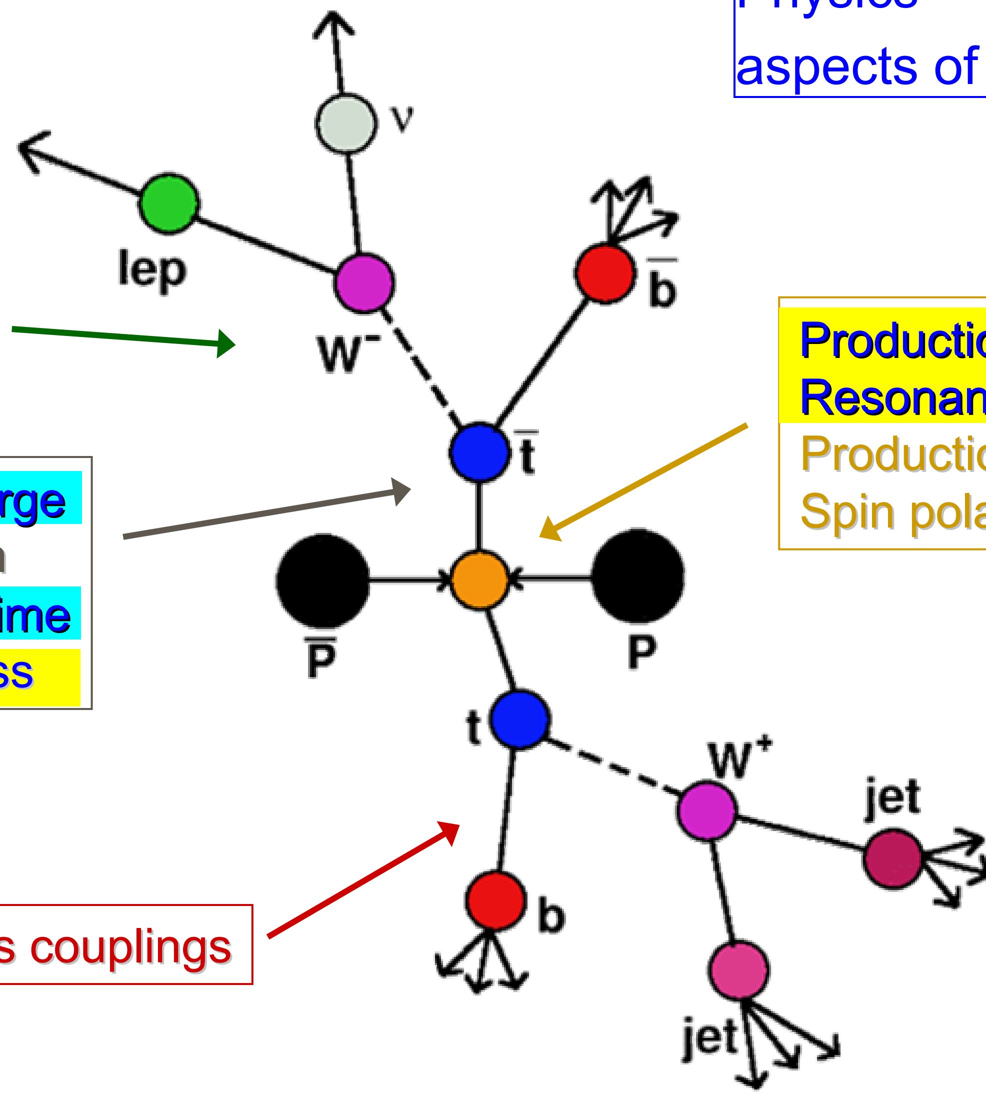
Top Quark Physics

Large top mass suggests special connection to New Physics → investigate all aspects of top!

Branching ratios
Rare decays
Non-SM decays
Decay kinematics
W helicity
$|V_{tb}|$

Top charge
Top spin
Top lifetime
Top mass

Production cross section
Resonance production
Production kinematics
Spin polarization



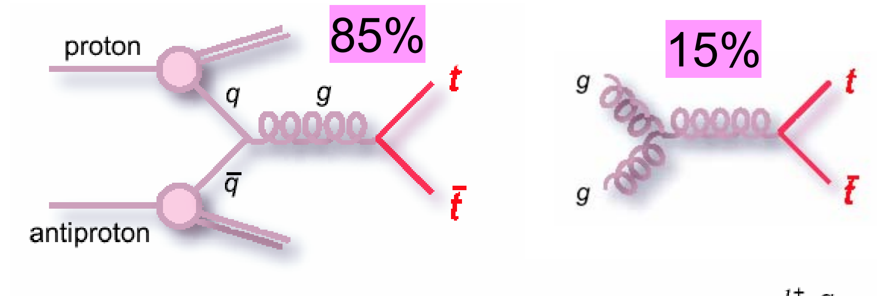
Anomalous couplings

Discussed

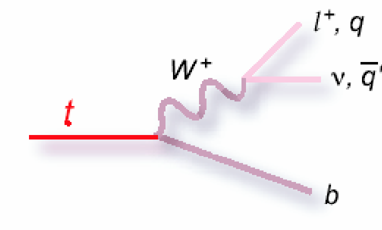
Mentioned

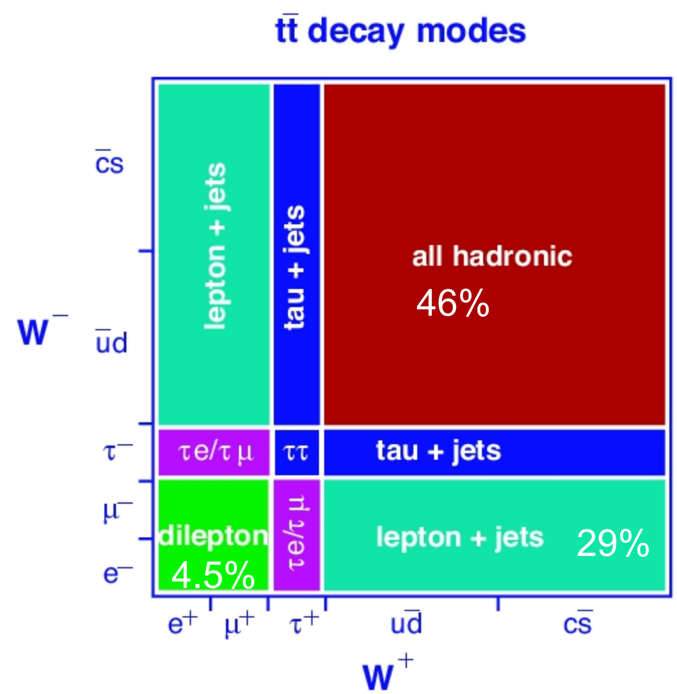
$t\bar{t}$ Production and Decay

- At Tevatron, top quark pairs are produced via strong interaction
  - ➔ NNLO QCD: 6.77 ± 0.42 pb ($\sqrt{s}$ = 1.96 TeV, M_t = 175 GeV)
- Final states are classified according to decay modes of the W's:
  - ➔ Dileptons (ee/μμ/eμ +2b +MET)
    - ❖ lepton+track (e/μ + 1track +2b +MET) (recover efficiency for lepton ID)
  - ➔ Lepton + jets (e/μ +2b +2q +MET)
  - ➔ Alljets (2b +4q)
- Need to reconstruct and identify electrons, muons, jets, b-jets and missing transverse energy
  - ➔ b-tagging effective in reducing background
- Major backgrounds:
  - ➔ Multi-jet QCD (+jets faking leptons) (use data)
  - ➔ W/Z +jets (use MC)
  - ➔ Dibosons +jets (use MC)



$t \rightarrow Wb$ ~100%



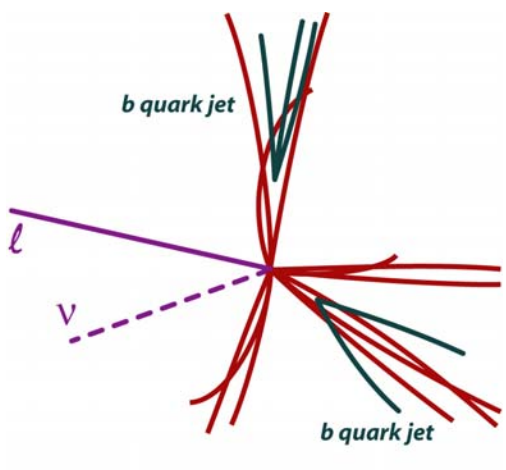


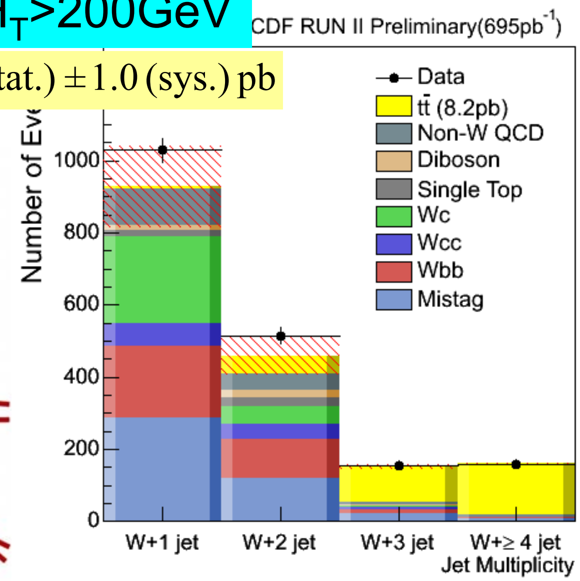
$t\bar{t}$ Cross Section: Lepton + Jets + b-tag

- CDF L = 695 pb^{-1}
- b-tagging allows selecting very pure top samples
  - ➔ Secondary Vertex Tagging algorithm
- Significance of cross section with 2 b-tags exceeds 5σ
- JES *not* the dominant systematics…

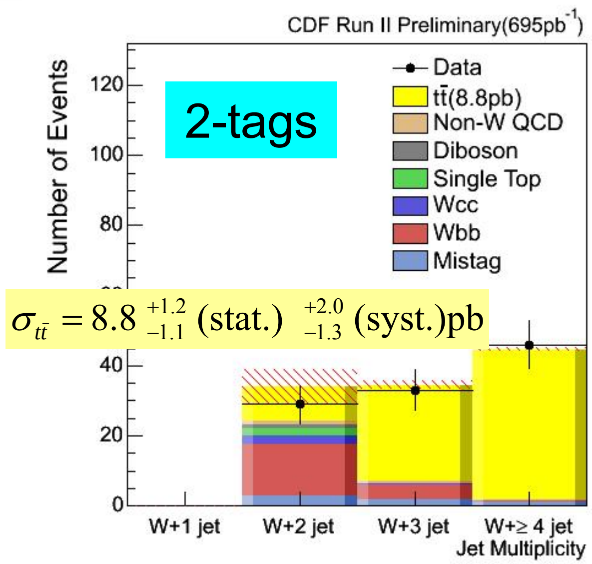
1-tag and H_T>200GeV

CDF best: $\sigma_{t\bar{t}} = 8.2 \pm 0.6\,(\text{stat.}) \pm 1.0\,(\text{sys.})\,\text{pb}$



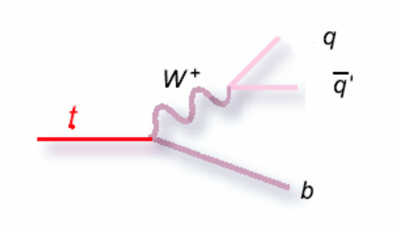


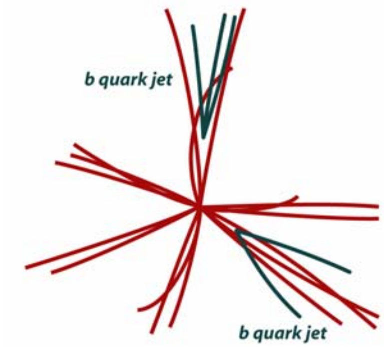
Source	Uncertainty (%)
b-tagging	6.5
luminosity	6.0
parton distribution functions	5.8
jet energy scale	3.0
initial/final state radiation	2.6
lepton identification	2.0
Total	11.5



$\sigma_{t\bar{t}} = 8.8\,^{+1.2}_{-1.1}\,(\text{stat.})\,^{+2.0}_{-1.3}\,(\text{syst.})\text{pb}$

$t\bar{t}$ Cross Section: Alljets





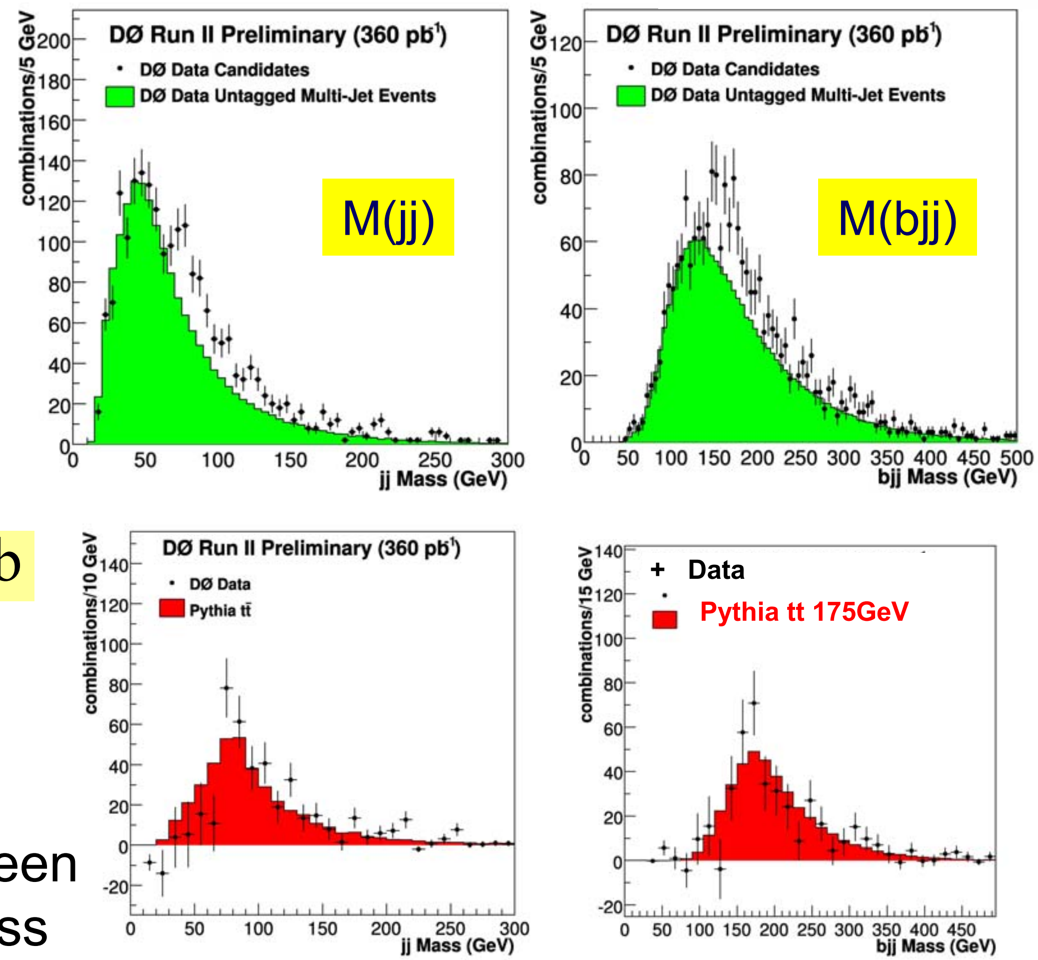
- High yield but also high background
- Can use b-tagging to improve signal/background: 2 SVT b-tags
- D0 L=360 pb^{-1}:

  Top and W peaks clearly seen in "natural" event distributions!

  ➔ Background distributions derived from untagged data

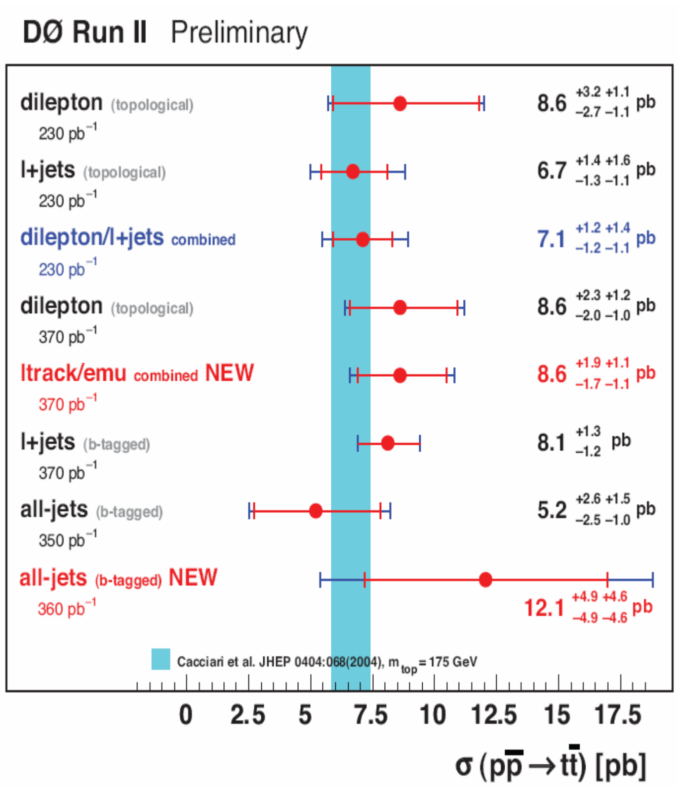
$$\sigma = 12.1 \pm 4.9(\text{stat}) \pm 4.6(\text{syst})\,\text{pb}$$

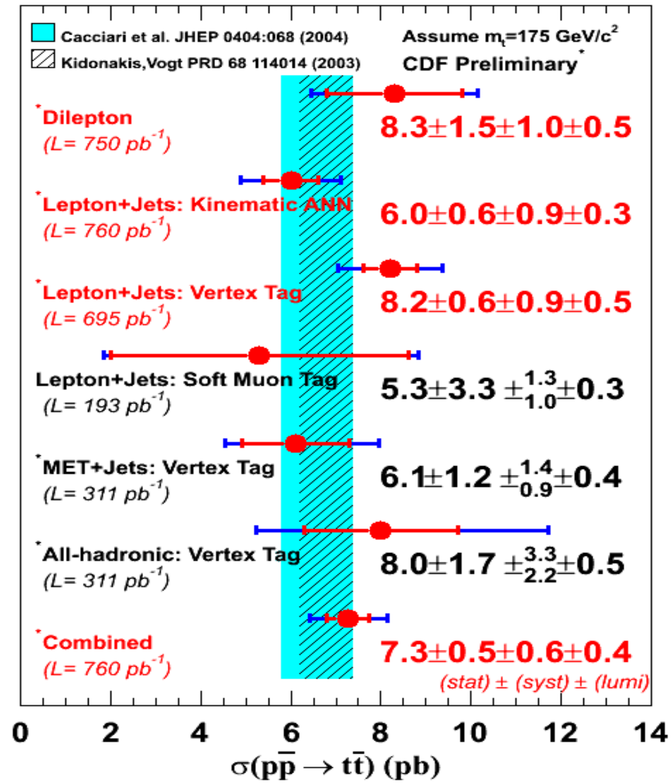
- Great potential for improvement with increased sample
- Other Alljet analyses also have been developed at D0 and CDF for cross section and mass measurements



Background subtracted

$t\bar{t}$ Cross Section Summary



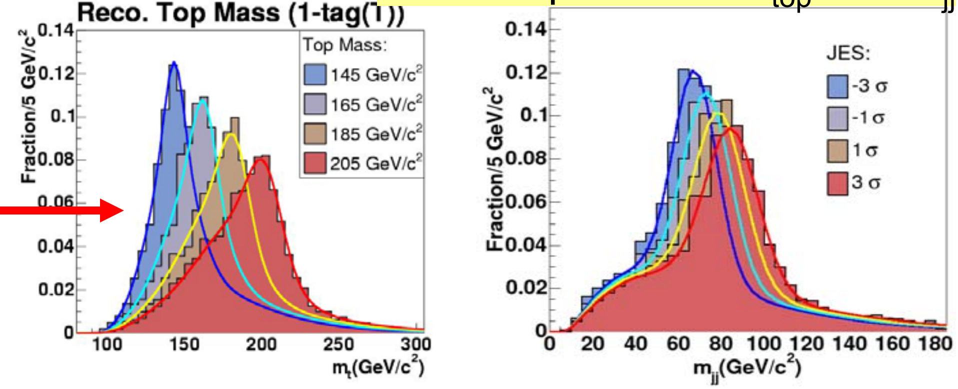


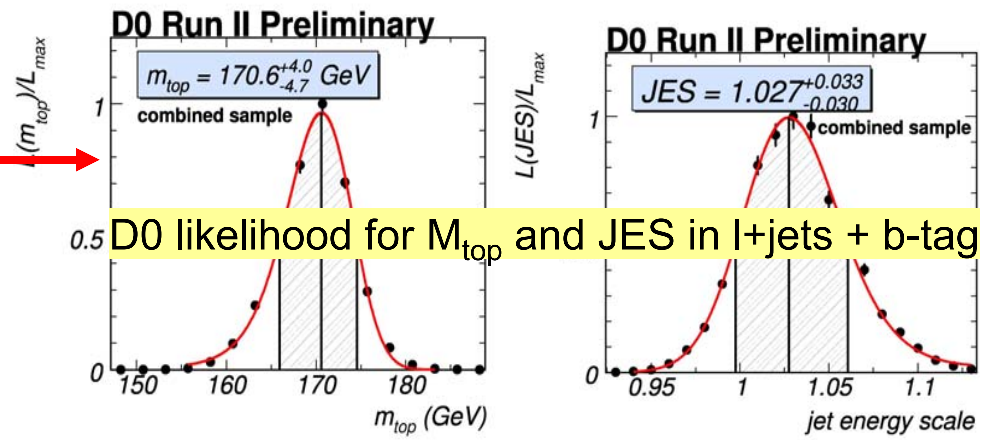
- Approaching 10% precision
  - ➔ b-tagging helps select high-purity top samples
  - ➔ Many advanced analysis techniques yield consistent results
- Good agreement with SM expectations
- The one top result that LHC will *not* improve on…

Top Mass: Methods

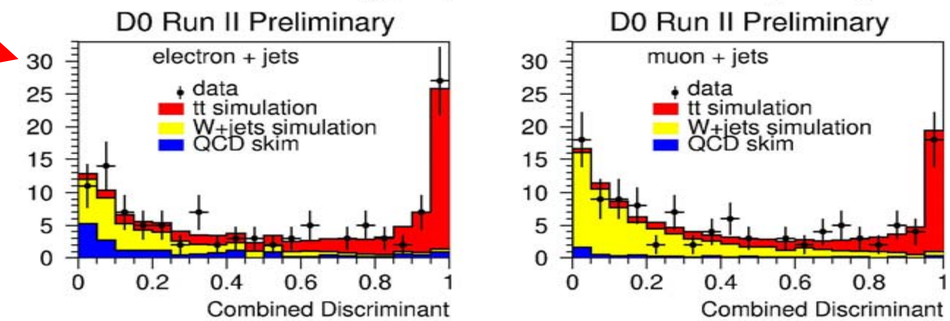
- Templates
  - ➔ Reconstruct M_{top} event-by-event, pick the best value per each event
  - ➔ Create "templates" using MC for several M_{top} and backgrounds
  - ➔ Maximum Likelihood fit using signal+backgrounds templates
- Matrix Element
  - ➔ Calculate probability as function of M_{top} for all combinations in each event using LO Matrix Element calculation
  - ➔ Build sample likelihood from the probabilities
  - ➔ Calibrate measured mass and error using simulated events
- Ideogram
  - ➔ Combines elements of both above
  - ➔ Use signal/background discriminant
- To improve purity/precision:
  - ➔ Use b-tagging information
  - ➔ Use *in-situ* jet calibration: W→jj
- >15 recent M_{top} analyses at CDF+D0

CDF templates for M_{top} and m_{jj}



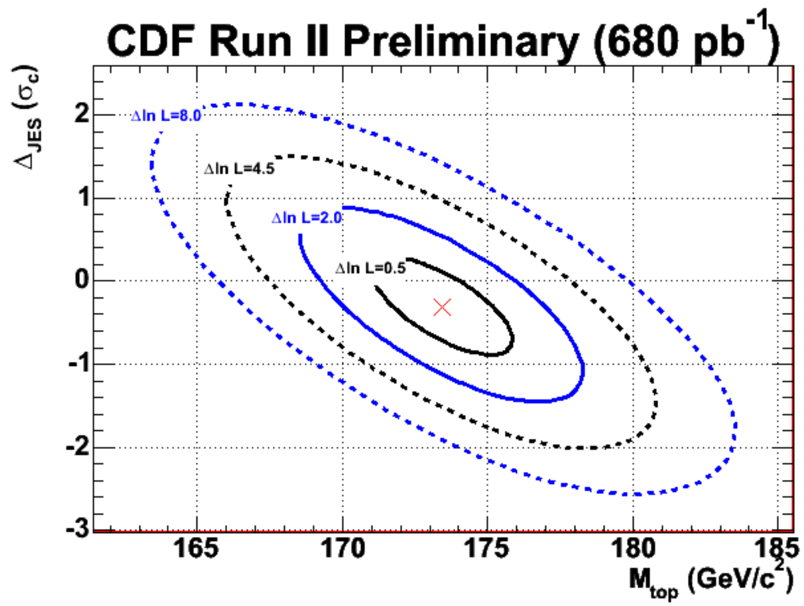


D0 likelihood for M_{top} and JES in l+jets + b-tag



Top Mass: Lepton + Jets (Template)

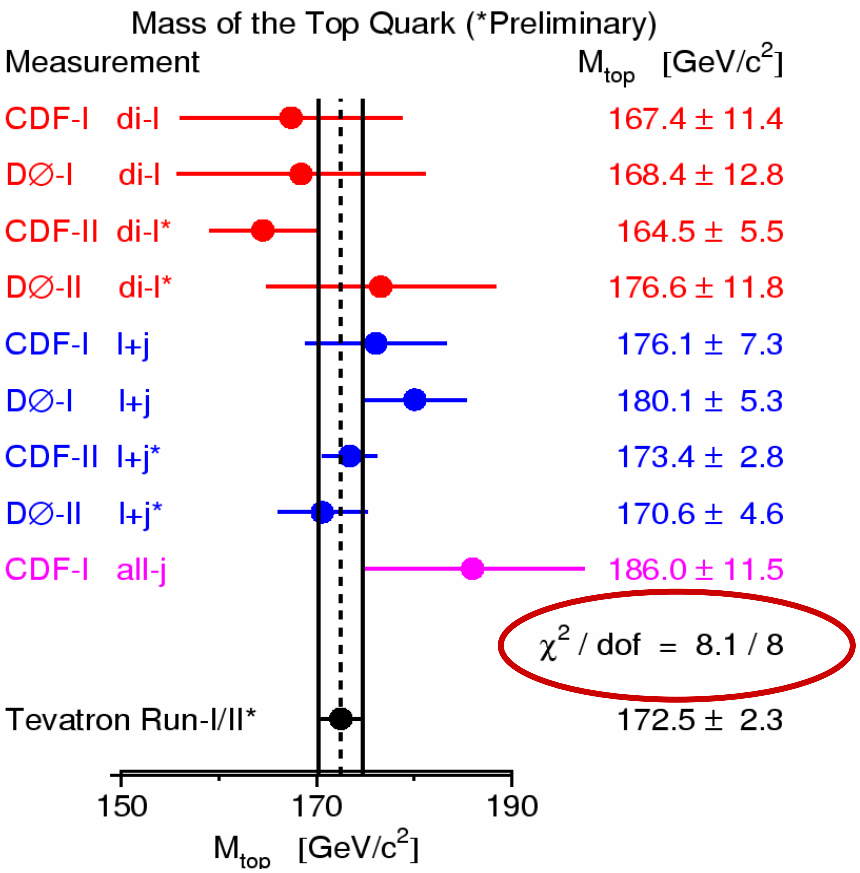
- CDF L = 680 pb^{-1}
- Best single measurement of M_{top}
- Analysis highlights:
  - ➔ Separation into 4 b-tag subsamples (2 tags, 1 tag with tight and loose cuts on 4^{th} jet p_T, 0 tags)
  - ➔ Simultaneous fit to M_{top} and JES (using W→jj mass)
  - ➔ 40% improvement on JES using *in-situ* JES calibration
  - ➔ Largest systematics: modeling of b-jets, ISR, FSR

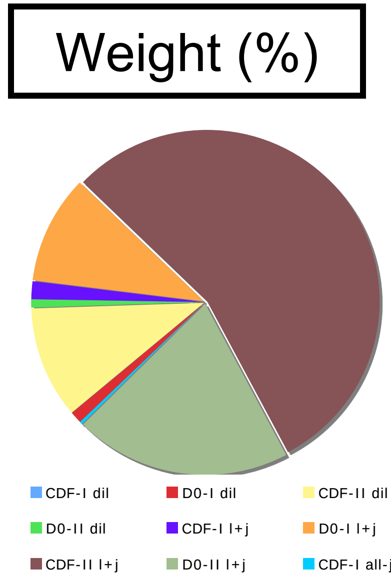


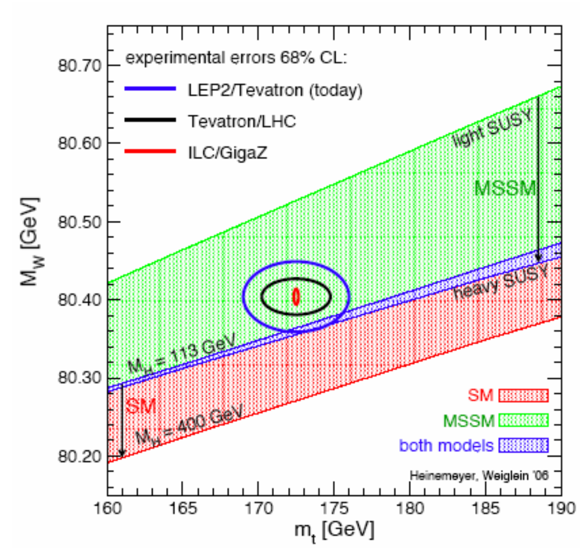
$$M_{top} = 173.4 \pm 2.5(\text{stat.} + \text{JES}) \pm 1.3\ (\text{syst.})\ \text{GeV}/c^2$$

Top Mass: Tevaron Average (March 2006)

Published Run 1 and best preliminary Run 2



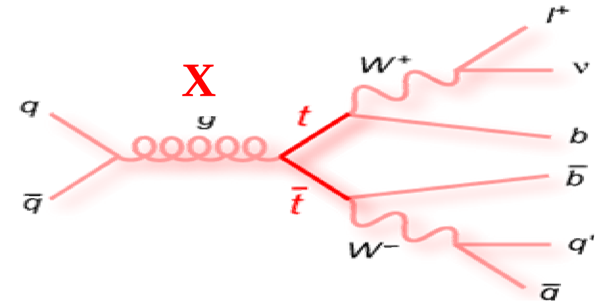




$$M_{top} = 172.5 \pm 2.3\, \text{GeV}/c^2 \ (1.3\%)$$

- Approaching 1% precision!
  - ➔ Already systematics-limited
  - ➔ Reaching the point of diminishing returns?
- Indicates a light Higgs
  - ➔ Opportunity for Tevatron, challenge for LHC?

Resonant $t\bar{t}$ Production

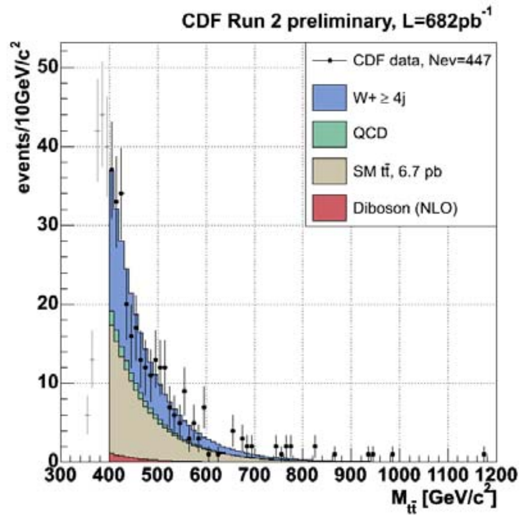


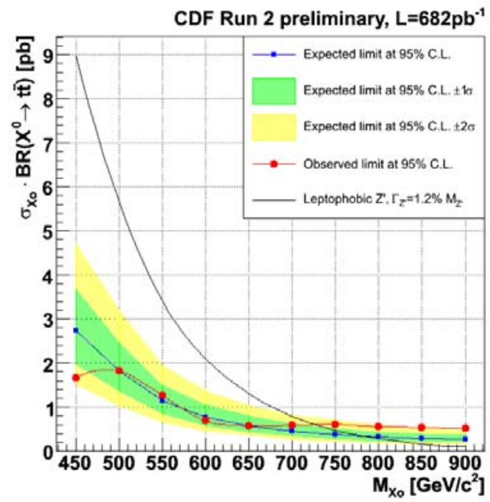
- Are top pairs sometimes produced through intermediate resonance?

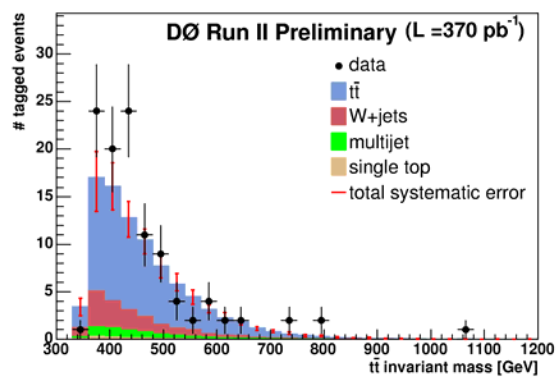
- Both CDF and D0 searched in lepton + jets channel
  - ➔ Reconstruct both tops
  - ➔ Measure pair mass M_{tt}
  - ➔ Set limit on $\sigma_X \times \Gamma(X \rightarrow t\bar{t})$
  - ➔ Convert to 95% CL limit on M_X for a specific model (narrow leptophobic X, Γ_X = 1.2% M_X):

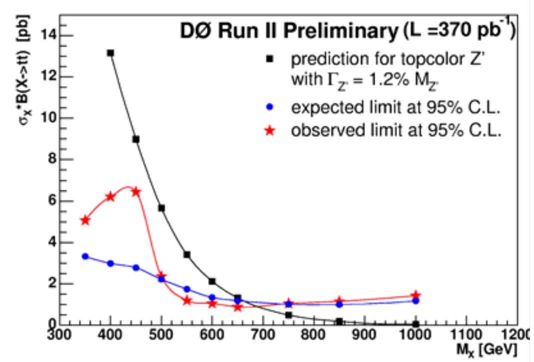
  CDF: M_X > 725 GeV

  D0: M_X > 680 GeV









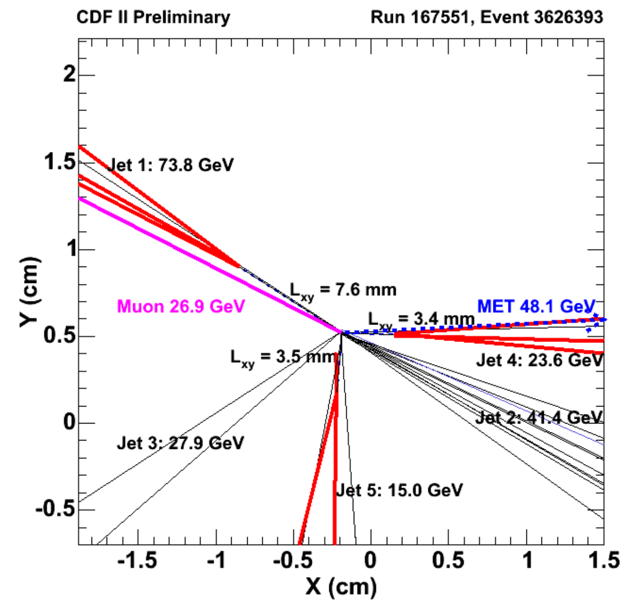
- We will keep looking…

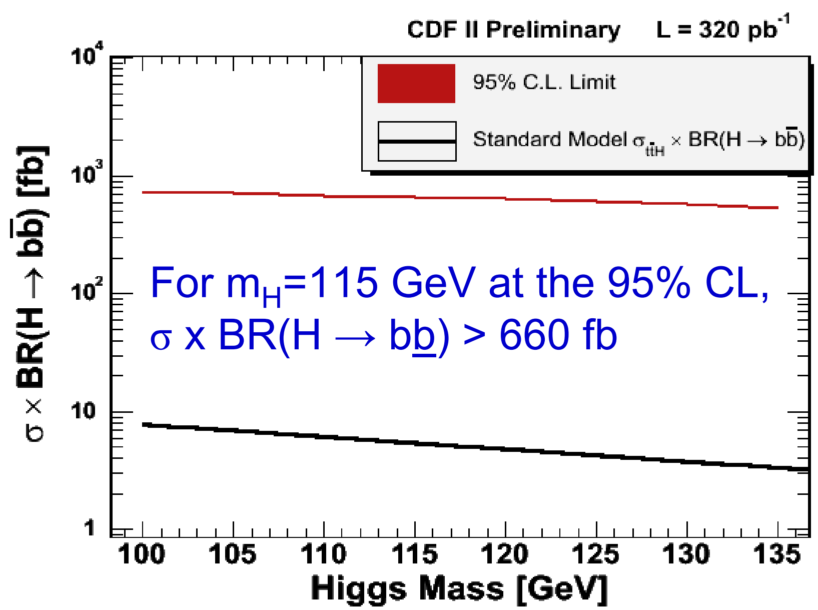
Search tor $t\bar{t}H$ ($H\rightarrow b\bar{b}$)

- First CDF search with 320 pb^{-1} of data in the $W(l\nu)W(jj)$+4b-jets final state:
  - ➔ Exactly one identified electron or muon, p_T > 20 GeV
  - ➔ Five or more jets, p_T > 15 GeV
  - ➔ ME_T > 10 GeV
  - ➔ 3 or more b-tags
- Backgrounds:

Source	Event Yield
Mistag	0.49 ± 0.10
Irreducible	0.36 ± 0.07
QCD	0.04 ± 0.04
Total Background	0.89 ± 0.12
Signal (m_H=115 GeV)	0.024±0.005
Observed	1

- The experimental hunt for $t\bar{t}H$ is on!





Top Properties: Summary

- With large samples of top events available, both CDF and D0 are pursuing many studies of top properties
  - ➔ Testing the V-A structure of tWb vertex
    - ❖ Helicity of W-boson in top decays: $F^{+} = 0.08 \pm 0.08(stat) \pm 0.06(sys)$ (D0)
    - ❖ $BR(t \rightarrow Wb)/BR(t \rightarrow Wq) = 1.03^{+0.19}_{-0.17}$ (D0)
  - ➔ First direct limit on top charge: +2/3 93.7% CL (vs -4/3 model) (D0)
  - ➔ First direct limit on top quark lifetime: $c\tau < 53\ \mu m$ @ 95% CL (CDF)
  - ➔ Searches for $t\bar{t}$ resonance: mass limit $M_X > 725$ GeV @ 95% CL (CDF)
  - ➔ First limit $\sigma(t\bar{t}H) \times BR(H \rightarrow b\bar{b}) < 660$ fb @ 95% CL for $m_H = 115$ GeV (CDF)
  - ➔ Searches for top decays to light charged Higgs
  - ➔ Searches for a heavy t'

- Top Properties is becoming a precision field
  - ➔ Still lots of room for finding effects of New Physics
  - ➔ But, so far, everything is frustratingly consistent with the SM…

Conclusions

- Tevatron measurements push forward understanding of QCD aspects for “soft” and “hard” processes
  - ➔ Higer-order QCD effects, multi-jet radiation, resummation, Monte Carlo tools, PDFs, jet algorithms and calibration
- Top-quark studies have entered precision era
  - ➔ ~10% for σ_{tt}, ~1% for M_{top}
  - ➔ Many advanced analysis techniques developed
  - ➔ b-tagging, *in-situ* W calibration of JES are essential
- Tevatron experience will benefit “re-discovery” of SM and searches for New Physics at the LHC

Backups

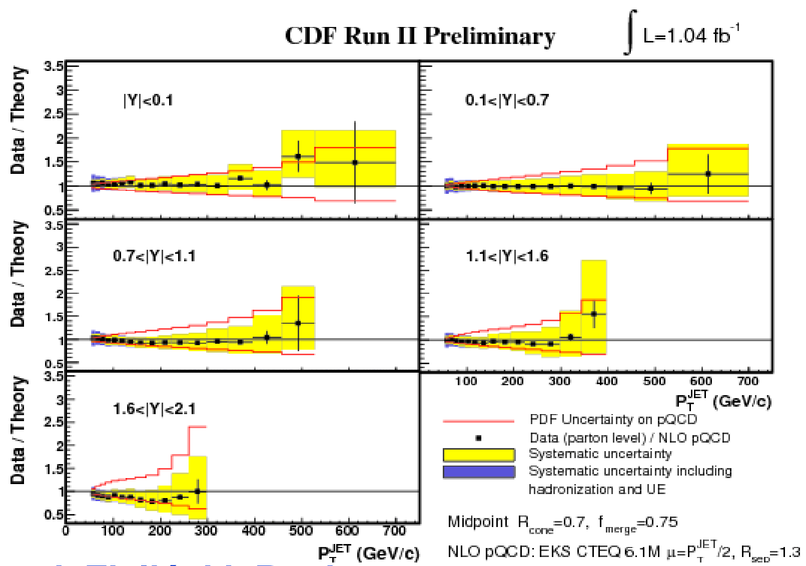
Inclusive Jet Cross Section: MidPoint

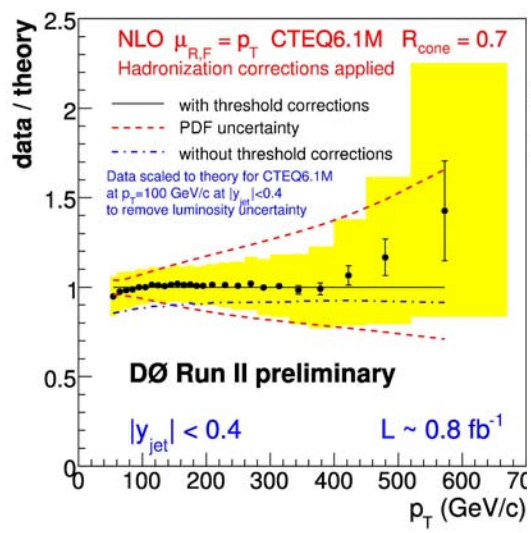
- CDF L = 1 fb^{-1}
  - ➔ 5 rapidity bins
  - ➔ Midpoint algorithm R=0.7 (with search cone)
- Data fully unfolded to parton level
  - ➔ Hadronization corrections applied to data
  - ➔ NLO calculations using EKS

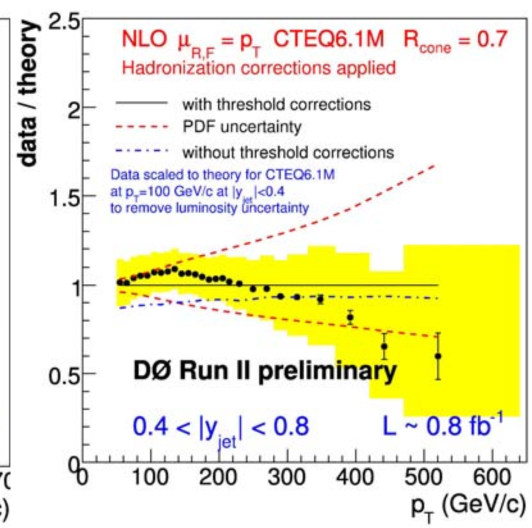
- D0 L= 0.8 fb^{-1}
  - ➔ 2 rapidity bins
  - ➔ Midpoint algorithm R=0.7
  - ➔ Data are scaled to theory at p_T = 100 GeV/c (to be removed soon)
- Hadronization corrections applied to theory
  - ➔ NLO + threshold corrections at 2-loop (Kidonakis & Owens)

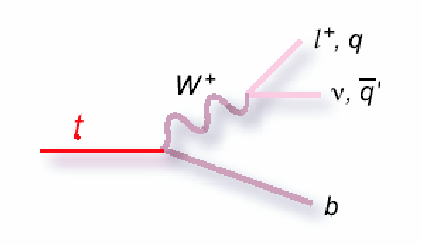
Good agreement with theory over a wide pT range and 9 orders of xs magnitude

Tevatron jet measurements start constraining large-x pdfs

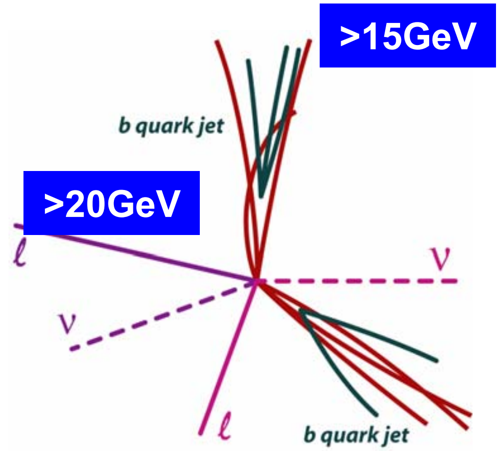






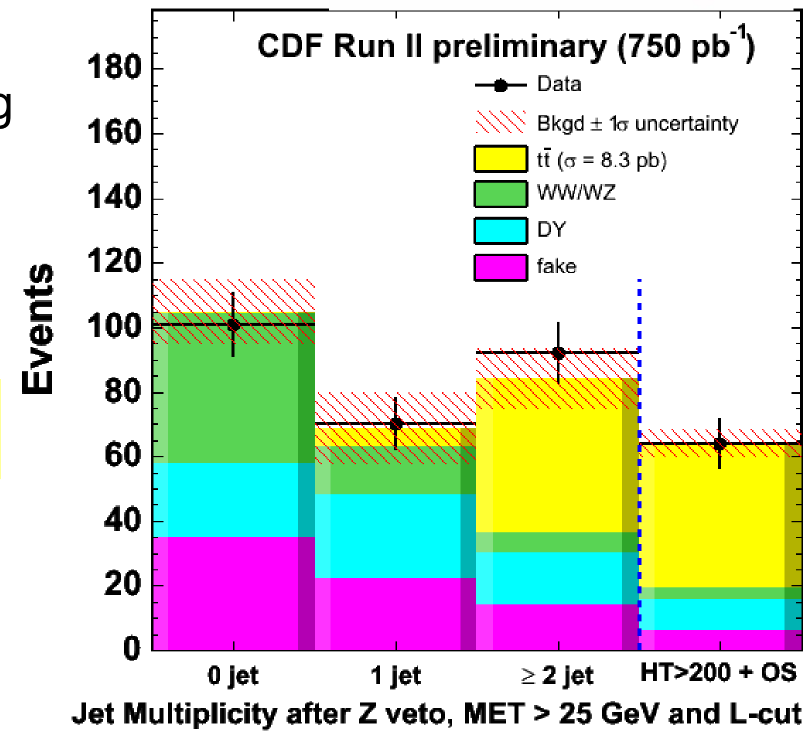


Cross Section: Dileptons + Jets



- Traditionally, low background ("clean") but low yield channel
- CDF L = 750 pb^{-1}
- Counting experiment:
  - ➔ Require 2 leptons (e, μ) with p_T > 20 GeV, MET > 25 GeV, suppress Z-peak
  - ➔ Use 0- and 1-jet bins to verify understanding of backgrounds
  - ➔ Use $\geq$2-jet bin (+ cuts: HT > 200 GeV and Opposite Sign of leptons) to determine top signal

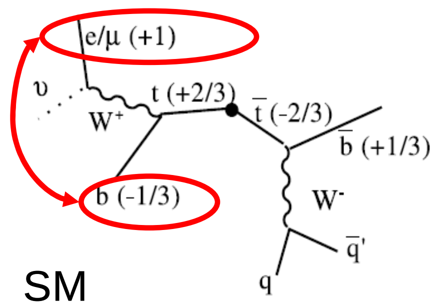
$$\sigma_{tt} = 8.3 \pm 1.5(\text{stat}) \pm 1.0(\text{syst}) \pm 0.5(\text{lumi})\,\text{pb}$$

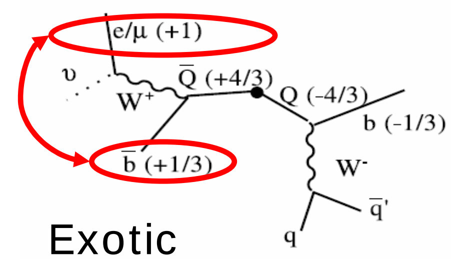


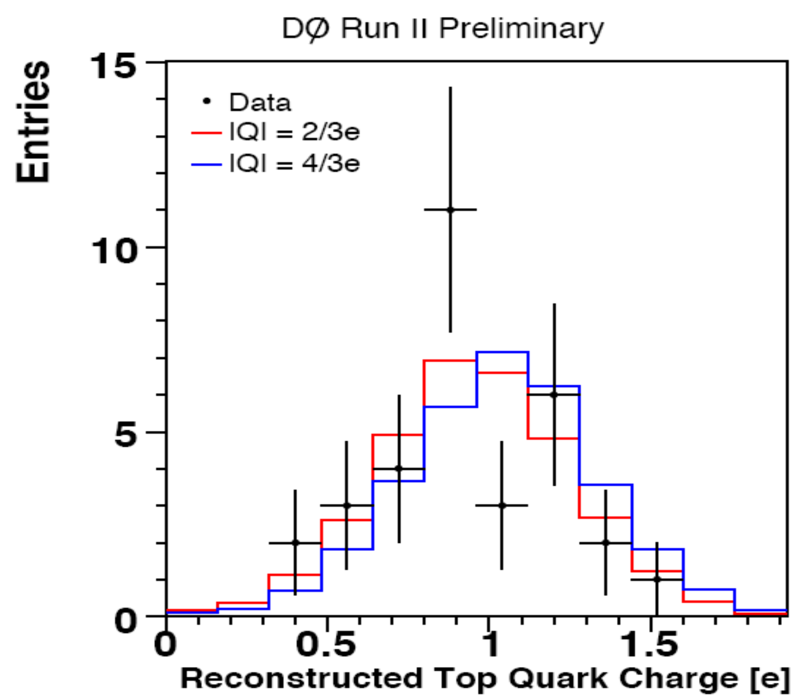
- Related analysis: lepton+track (D0 & CDF)
  - ➔ Recover efficiency for lepton ID
  - ➔ Add b-tagging to reduce increased bckg

Top Charge

- Is the observed "top" the "SM top"?
- D0 tested the non-standard bW^- pairing, which yields Q=-4/3
  - ➔ Possibility existing in some models with an exotic 4th family
- Method:
  - ➔ Determine probabilistic charge of b-jets based on charged tracks in jet
  - ➔ Use kinematic fit to pair b-jet and W
  - ➔ Compare to templates for Q=+2/3 and -4/3 (+background)
  - ➔ Using pseudo-experiments and a likelihood function set the first direct limit on top charge:







93.7% C.L. that top has +2/3 charge