Physics at the Tevatron

Lecture II

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Outline

- Lecture I:
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
- Lecture II:
  - The Top Quark and the Higgs Boson
    - jet energy scale and b-tagging
- Lecture III
  - Supersymmetry and High Mass Dilepton/Diphoton
    - Missing ET
- Lecture IV
  - Bs mixing and Bs$\rightarrow\mu\mu$ rare decay
    - Vertex resolution and particle identification

The Top Quark

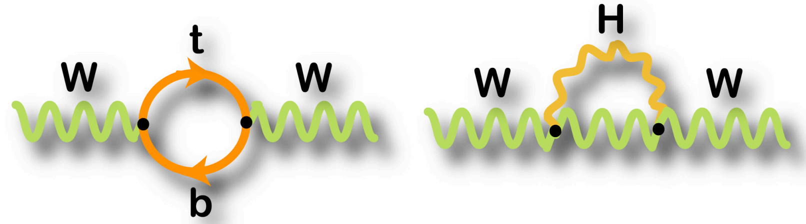
- Why is the top quark interesting?

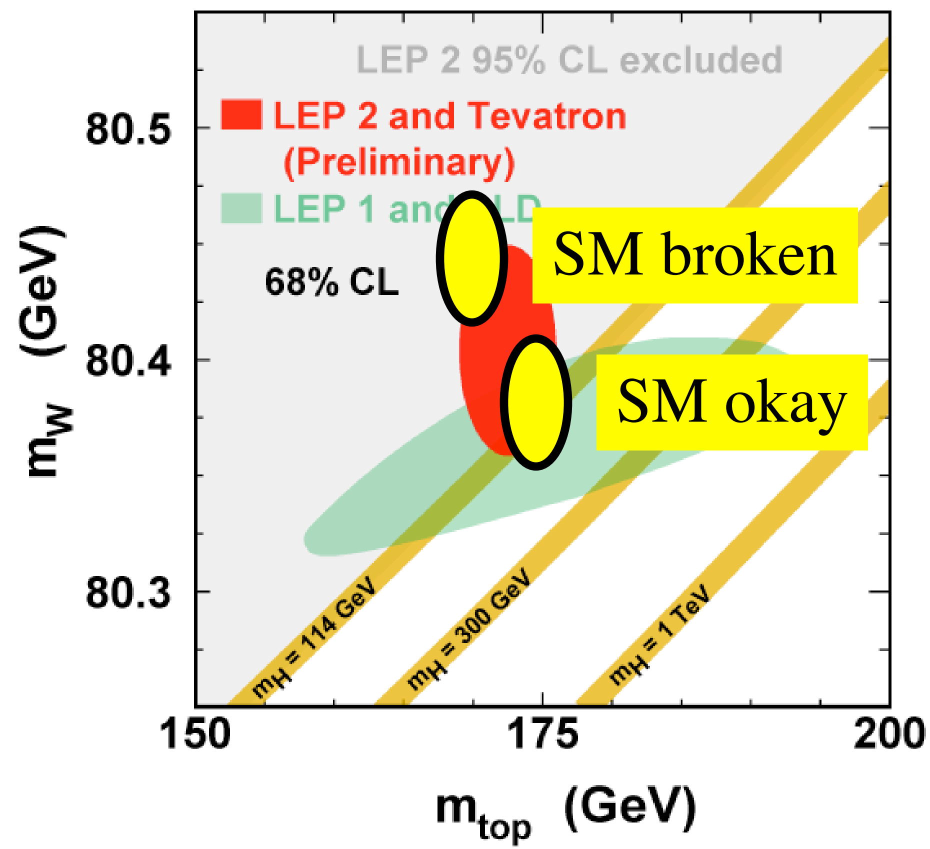
- How to identify the top quark
  - B-tagging plays key role

- How to measure the top quark mass
  - Jet energy scale critical

Why Is the Top Quark Interesting?

- Heaviest known fundamental particle
  - Today:
    - M_{top}=172.0+-2.7 GeV
  - Before run 2:
    - M_{top}=178+-4.3 GeV/c^2
- Is this large mass telling us something about electroweak symmetry breaking?
- Related to m_W and m_H:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics

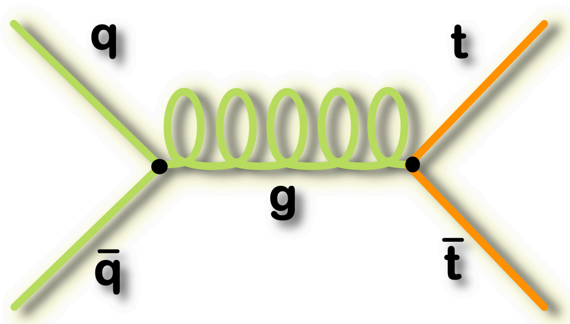


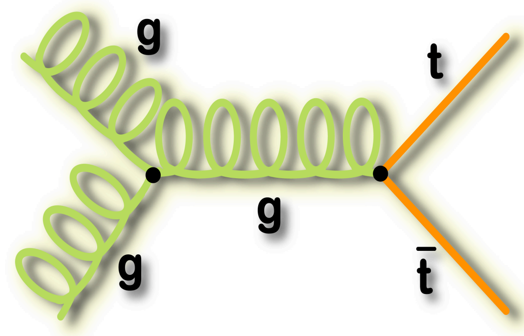


Production and Decay

- At Tevatron, mainly produced in pairs via the strong interaction

85%





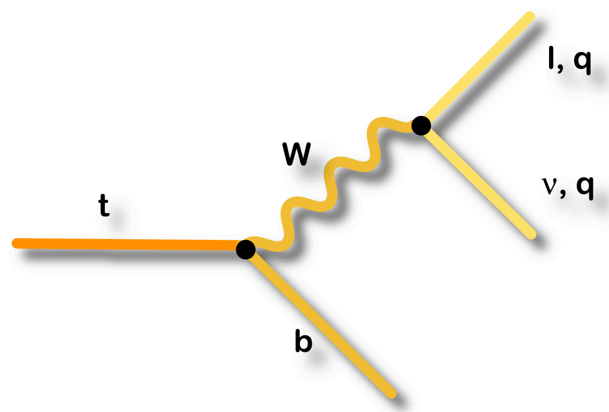
15%

- Decay via the electroweak interactions **Br(t →Wb) ~ 100%**
  Final state is characterized by the decay of the W boson

Dilepton

Lepton+Jets

All-Jets

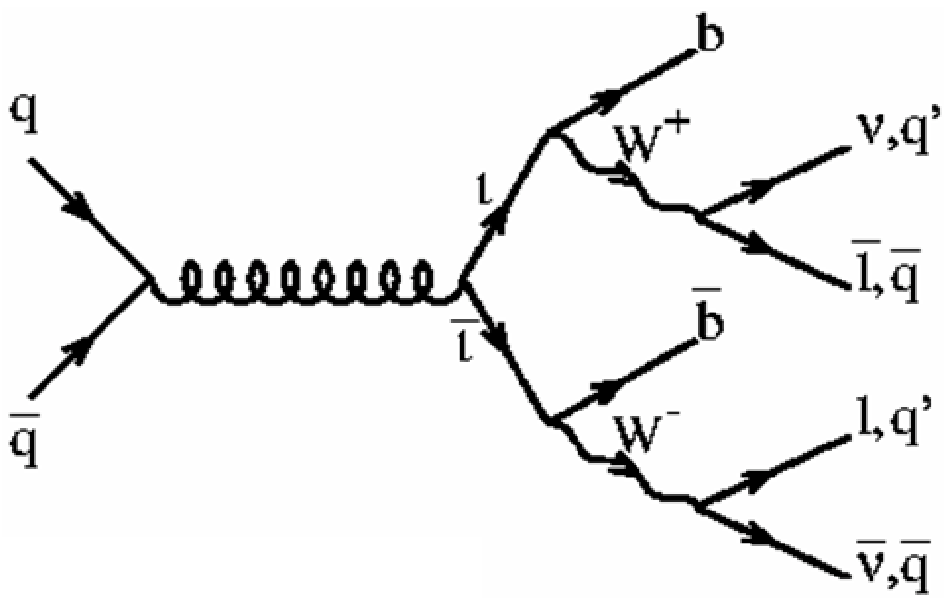


Different sensitivity and challenges in each channel

How to identify the top quark

SM: $t\bar{t}$ pair production, Br(t→bW)=100% , Br(W->lν)=1/9=11%

dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
l+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets



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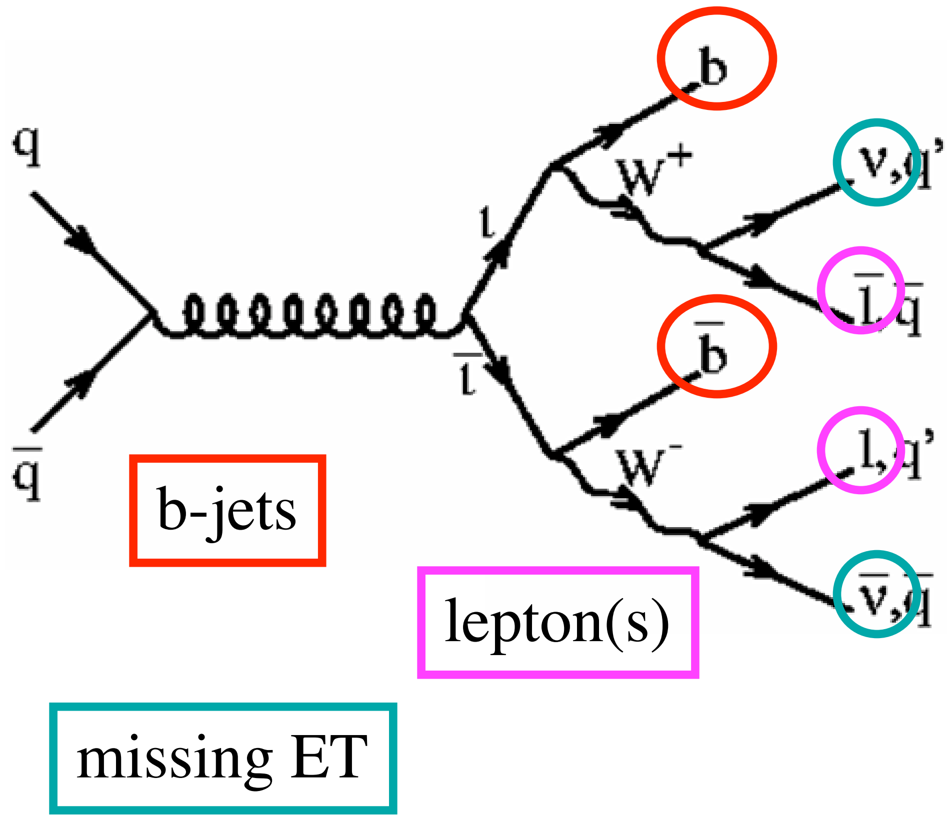

How to identify the top quark

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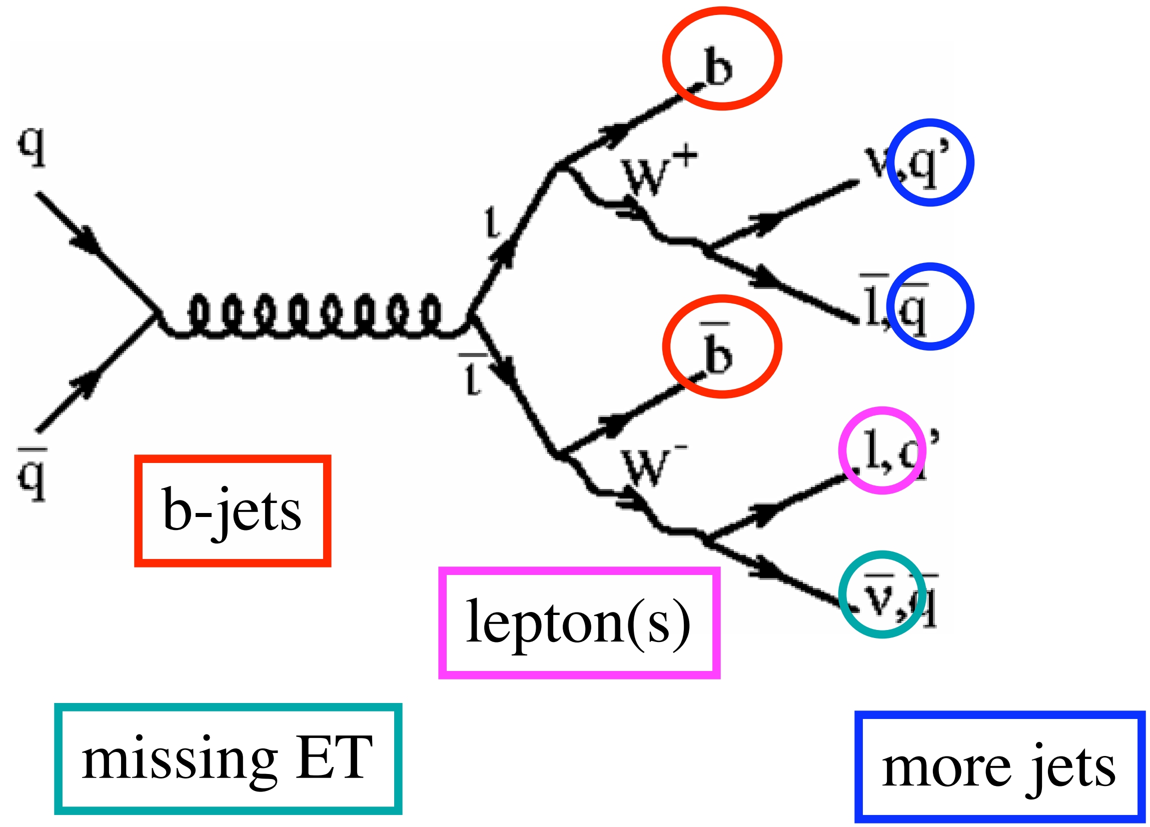

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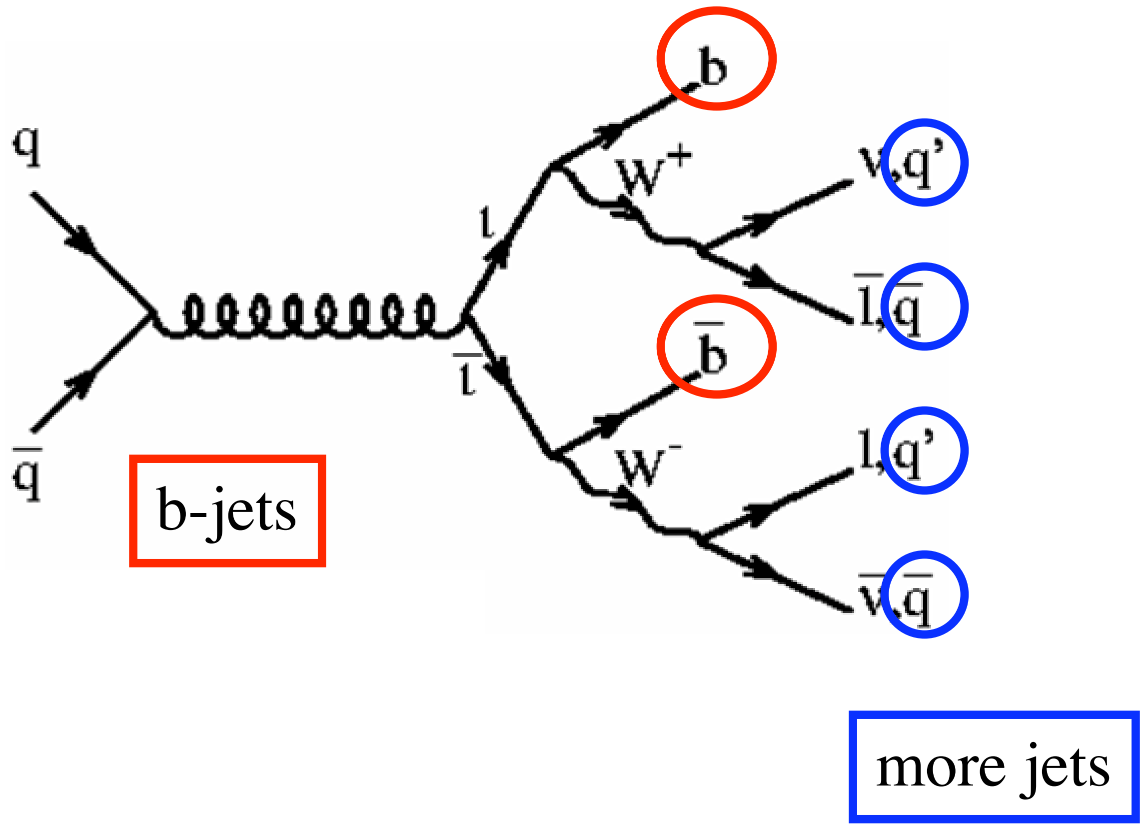
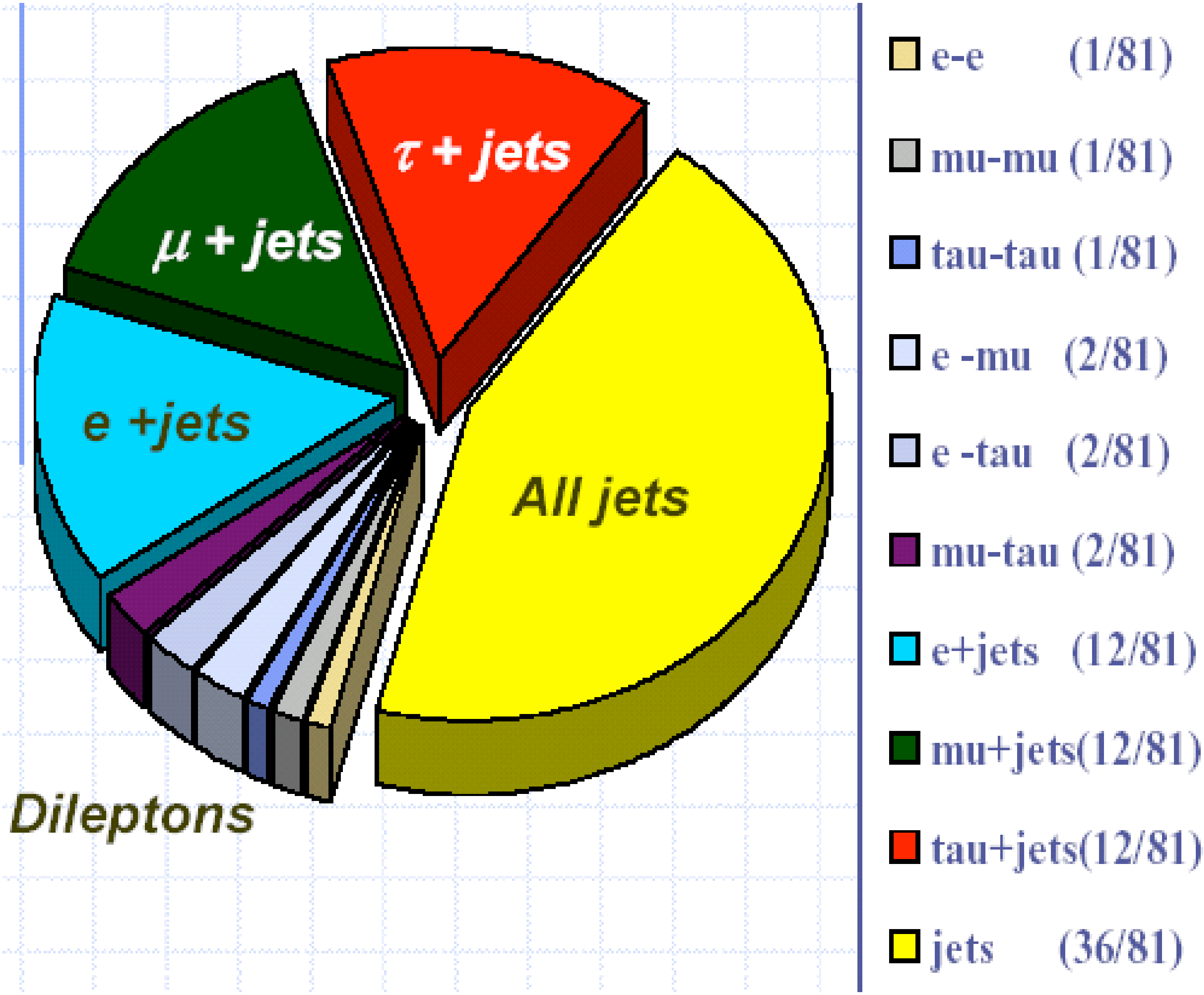
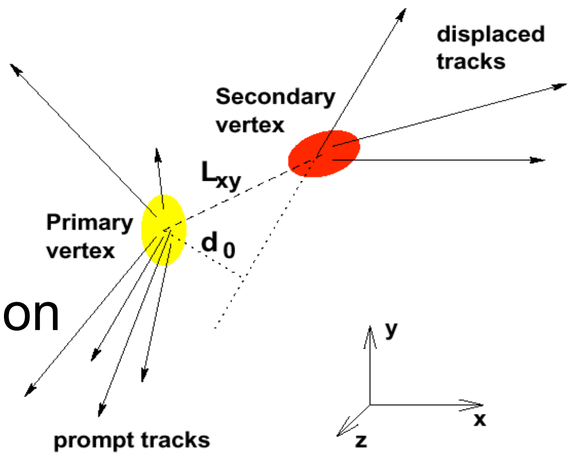


Top Event Categories



Finding the b-jets

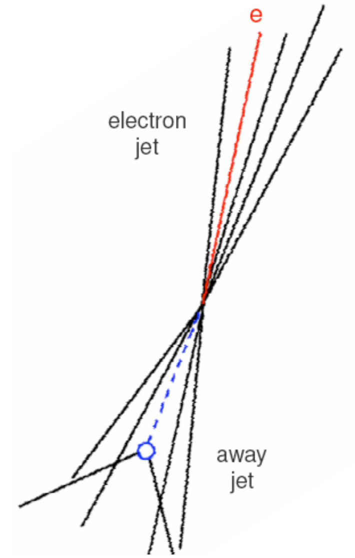
- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: $d=c\tau$
    - Lifetime τ =1.5 ps^{-1}
    - $d=c\tau$ = 460 μm
    - Can be resolved with silicon detector resolution

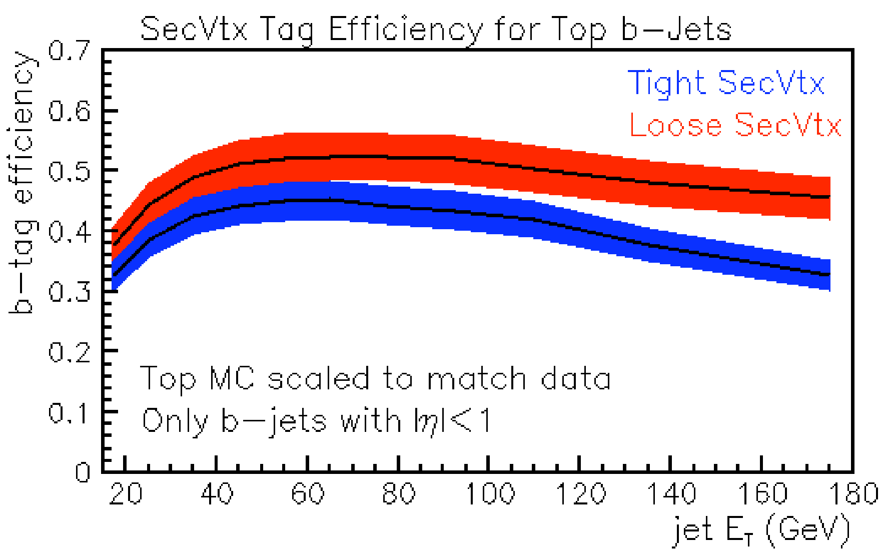


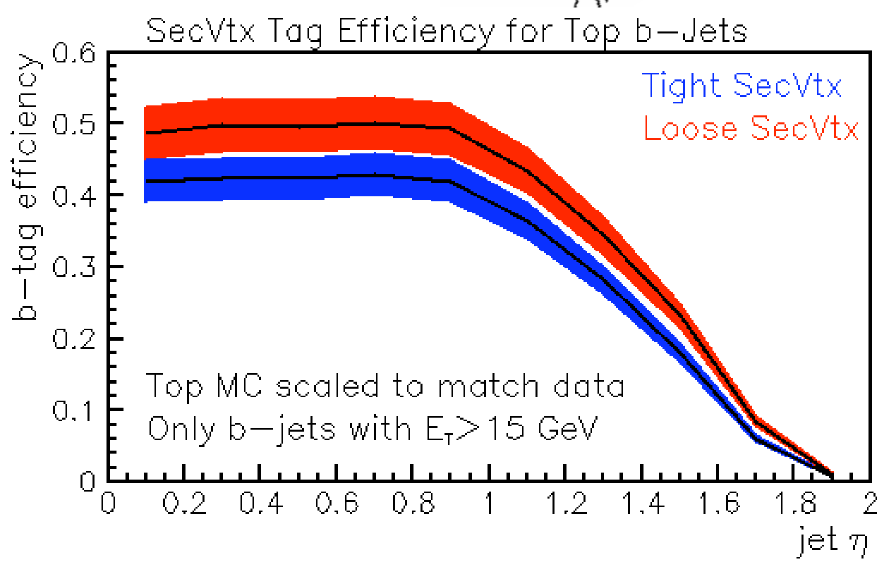
- Procedure "Secondary Vertex":
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with primary vertex:
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - Require displacement of secondary from primary vertex
    - Form Lxy: transverse decay distance projected onto jet axis:
      - Lxy>0: b-tag along the jet direction => real b-tag or mistag
      - Lxy<0: b-tag opposite to jet direction => mistag!
    - Significance: L_{xy} >7 $\delta(L_{xy})$ i.e. 7 sigma

Characterise the B-tagger: Efficiency

- Efficiency of tagging a true b-jet
  - Use Data sample enriched in b-jets
  - Select jets with electron or muons
    - From semileptonic b-decay
  - Measure efficiency in data and MC





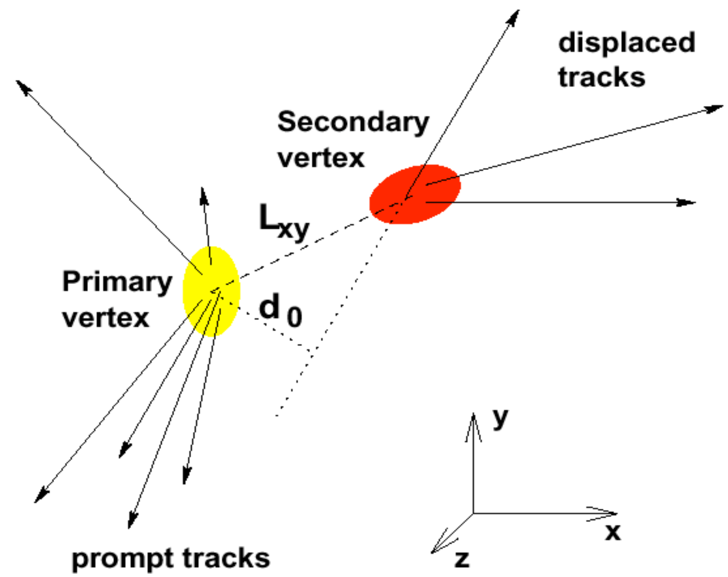


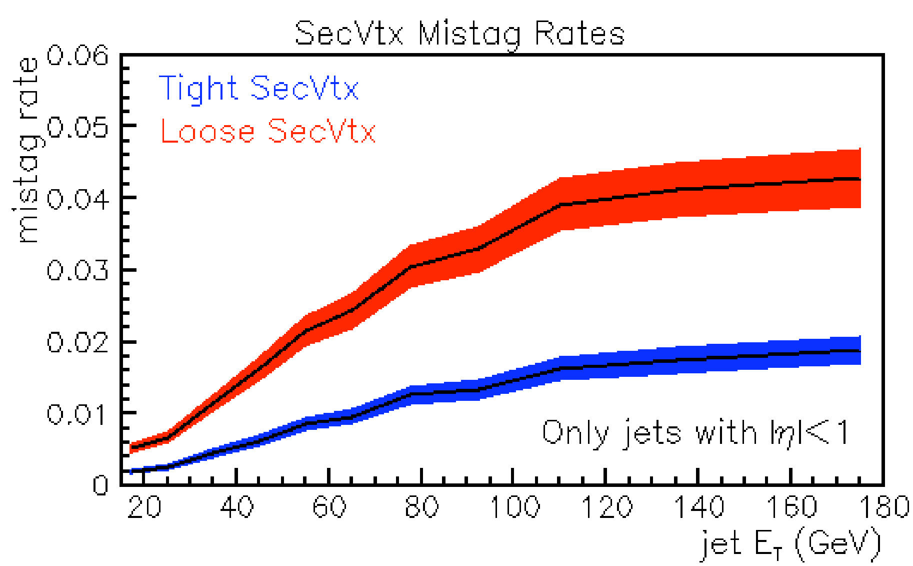
Achieve about 40-50%

(fall-off at high eta due to limited tracking coverage)

Characterise the B-tagger: Mistag rate

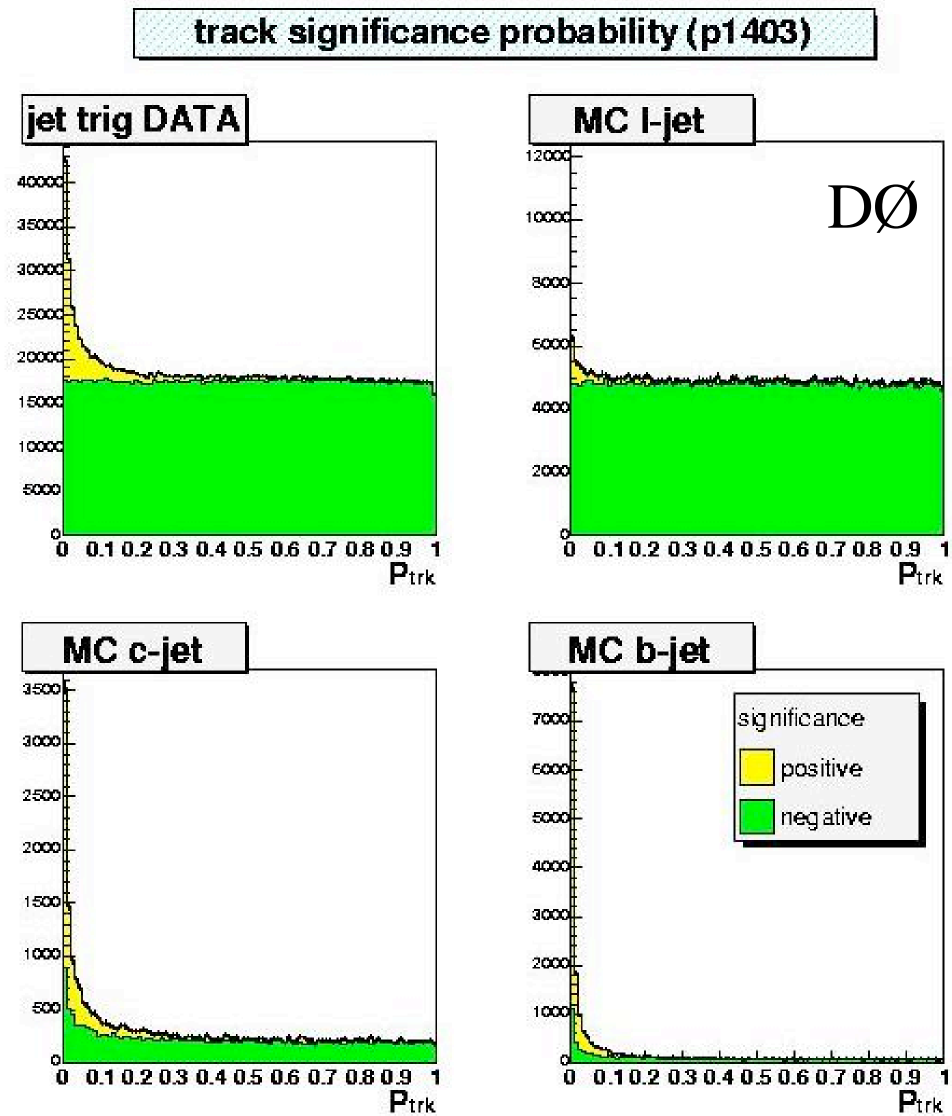
- Mistag Rate measurement:
  - Probability of light quarks to be misidentified
  - Use “negative” tags: $L_{xy}<0$
    - Can only arise due to misreconstruction
  - Result:
    - Tight: 1% (ε=40%)
    - Loose: 3% (ε=50%)
  - Depending on physics analyses:
    - Choose “tight” or “loose” tagging algorithm





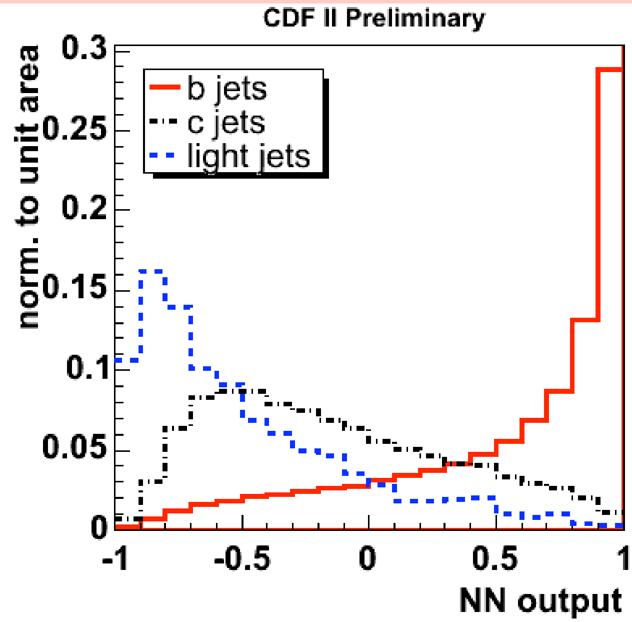
Jet Probability

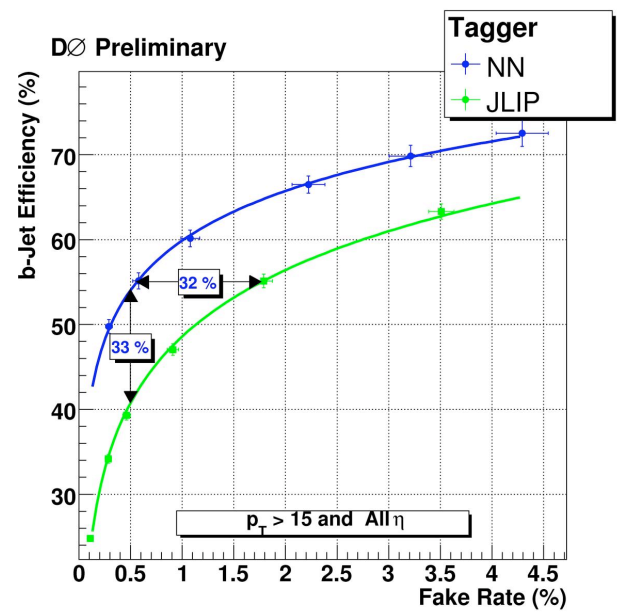
- Complementary to full secondary vertex reconstruction:
  - Evaluate probability of tracks to be prompt
    - Multiply probabilities of individual tracks together
  - "Jet Probability"
- Continuous distribution
  - Can optimize cut valued for each analysis
  - Can also use this well for charm



Neural Net B-tagging

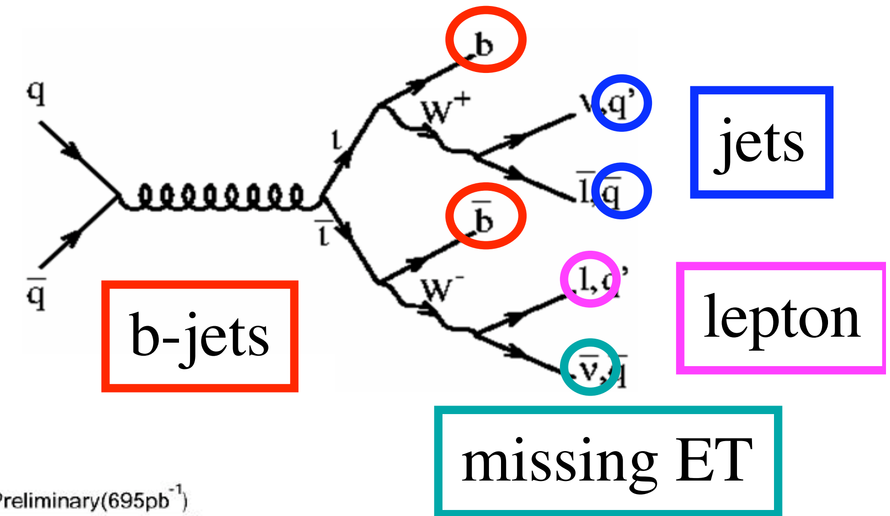
- Rather new for CDF and D0!
  - Nice to have continuous variable
  - Can be optimised depending on analysis requirements
- Several strategies
  - DØ uses 7 input variables from their three standard taggers
    - increase efficiency by 30% or purity by 30% over any single one
  - CDF uses 24 variables on top of SecVtx only
    - Improve purity of tags by 50-70%
    - Sacrifice 10% of efficiency

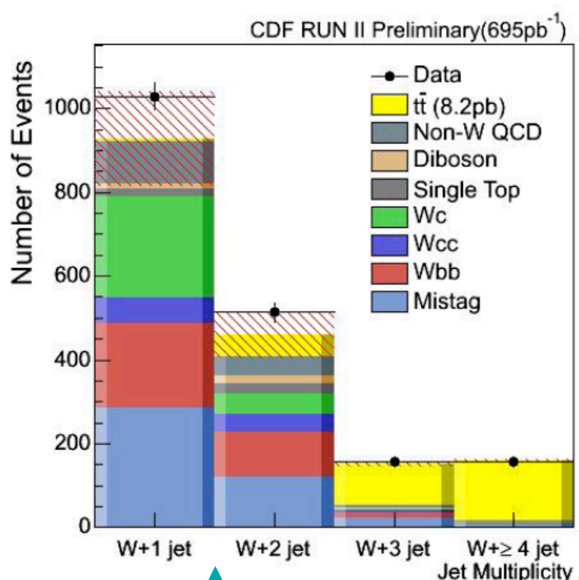


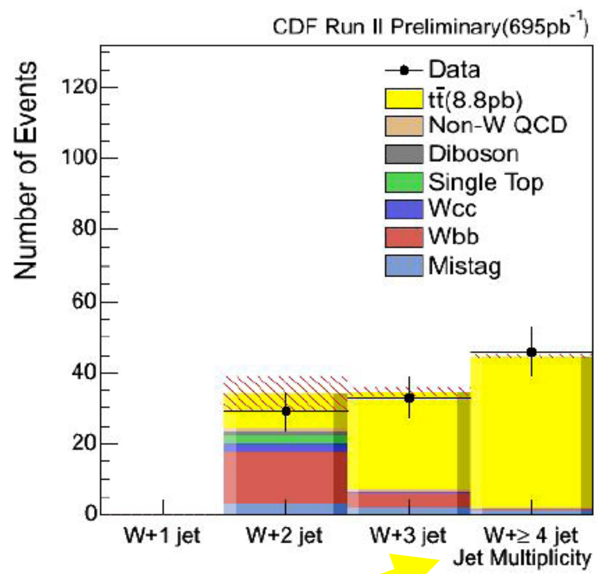


The Top Signal: Lepton + Jets

- Select:
  - 1 electron or muon
  - Large missing E_T
  - 1 or 2 b-tagged jets







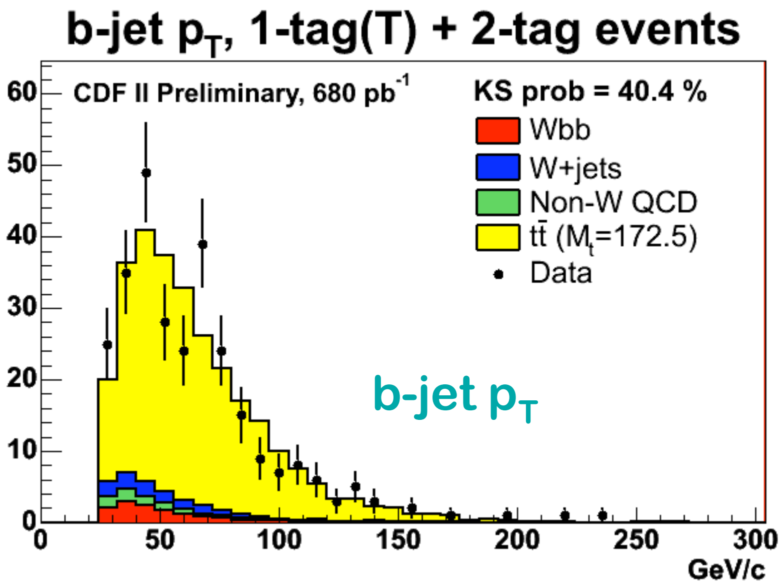
45 double-tagged Events, nearly no background

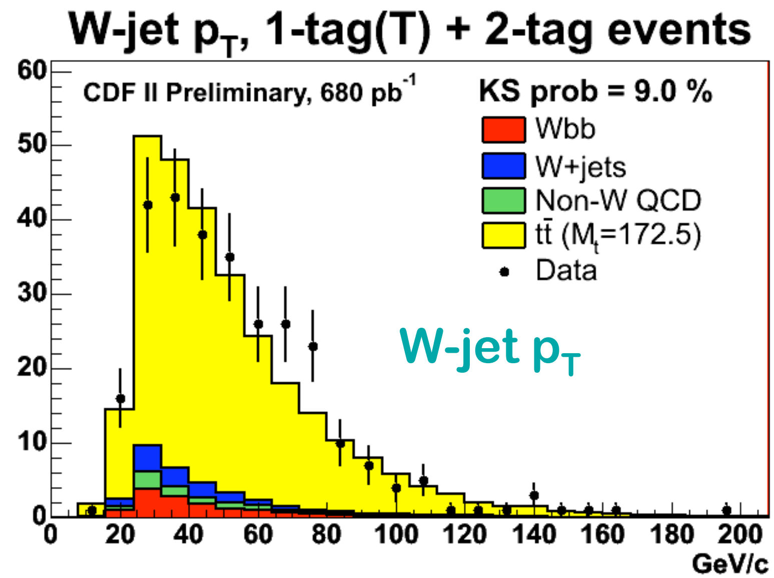
Check backgrounds

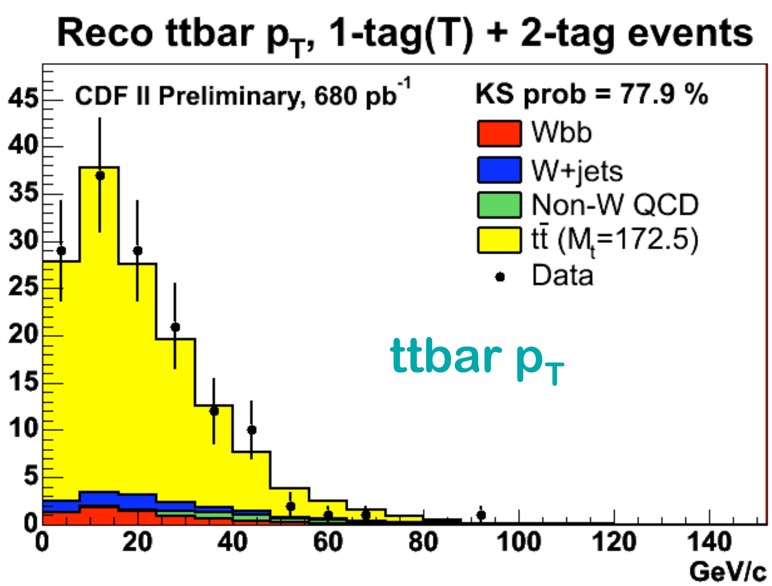
Top Signal

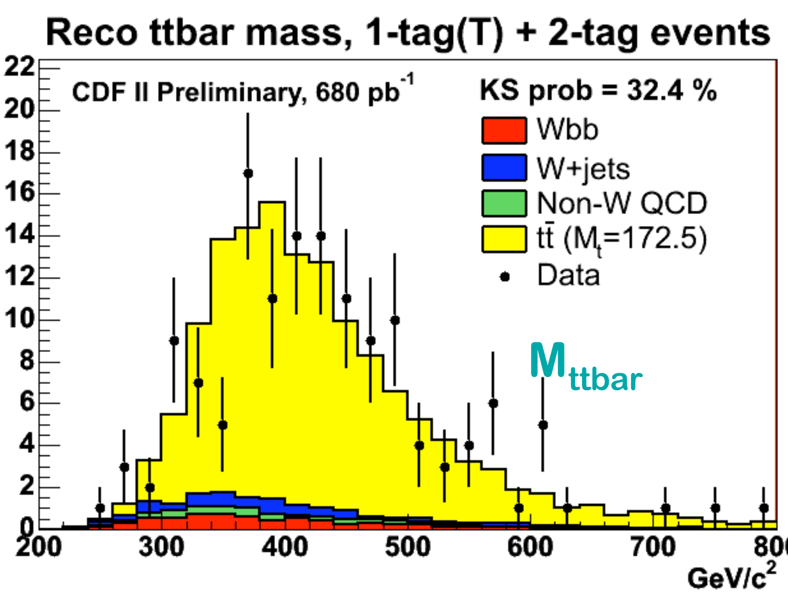
$\sigma(t\bar{t})$ = 8.2 ± 0.6 (stat) ± 1.1 (syst) pb

Data and Monte Carlo



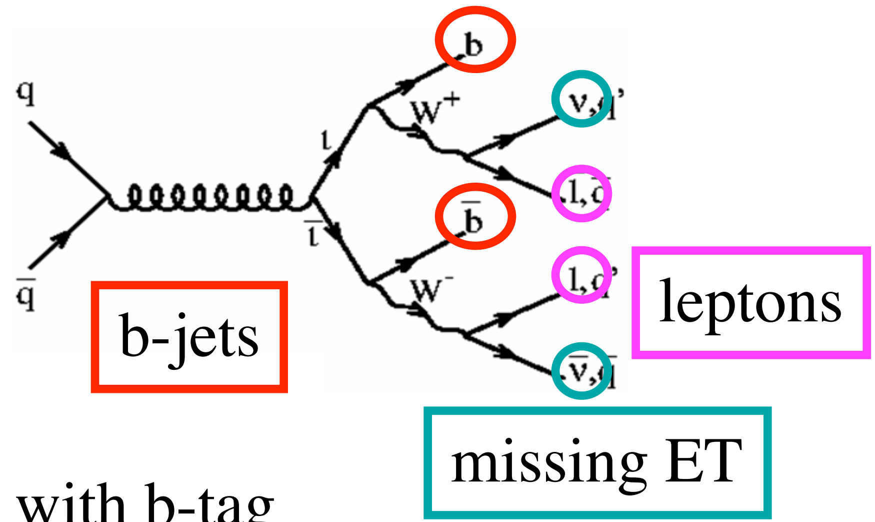




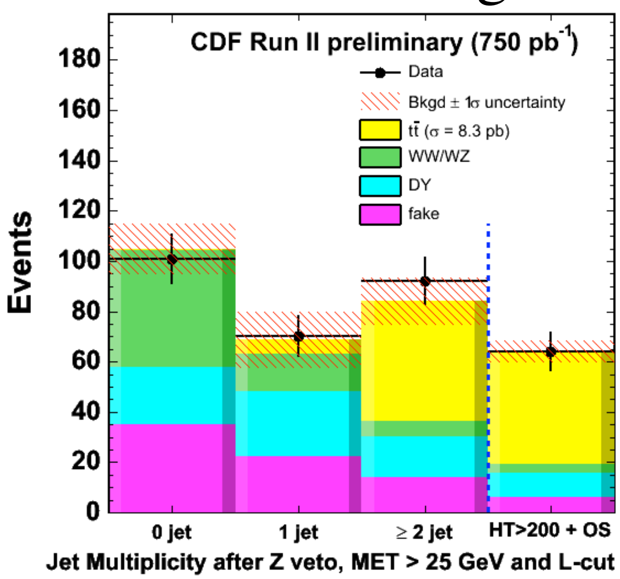


The Top Signal: Dilepton

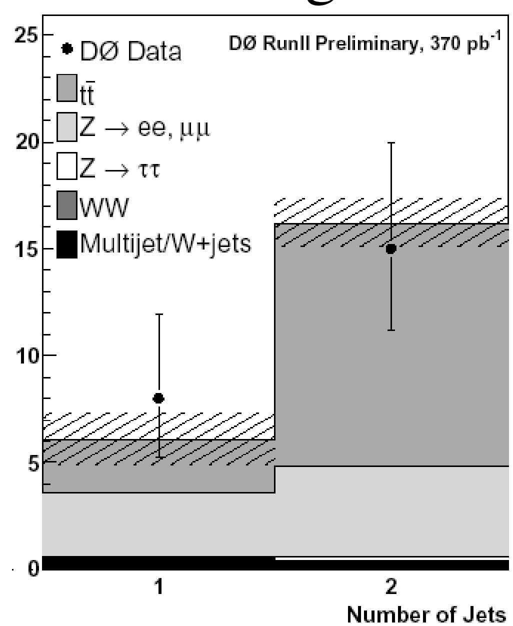
- Select:
  - 2 leptons: ee, eμ, μμ
  - Large missing E_T
  - 2 jets (with or w/o b-tag)



w/o b-tag

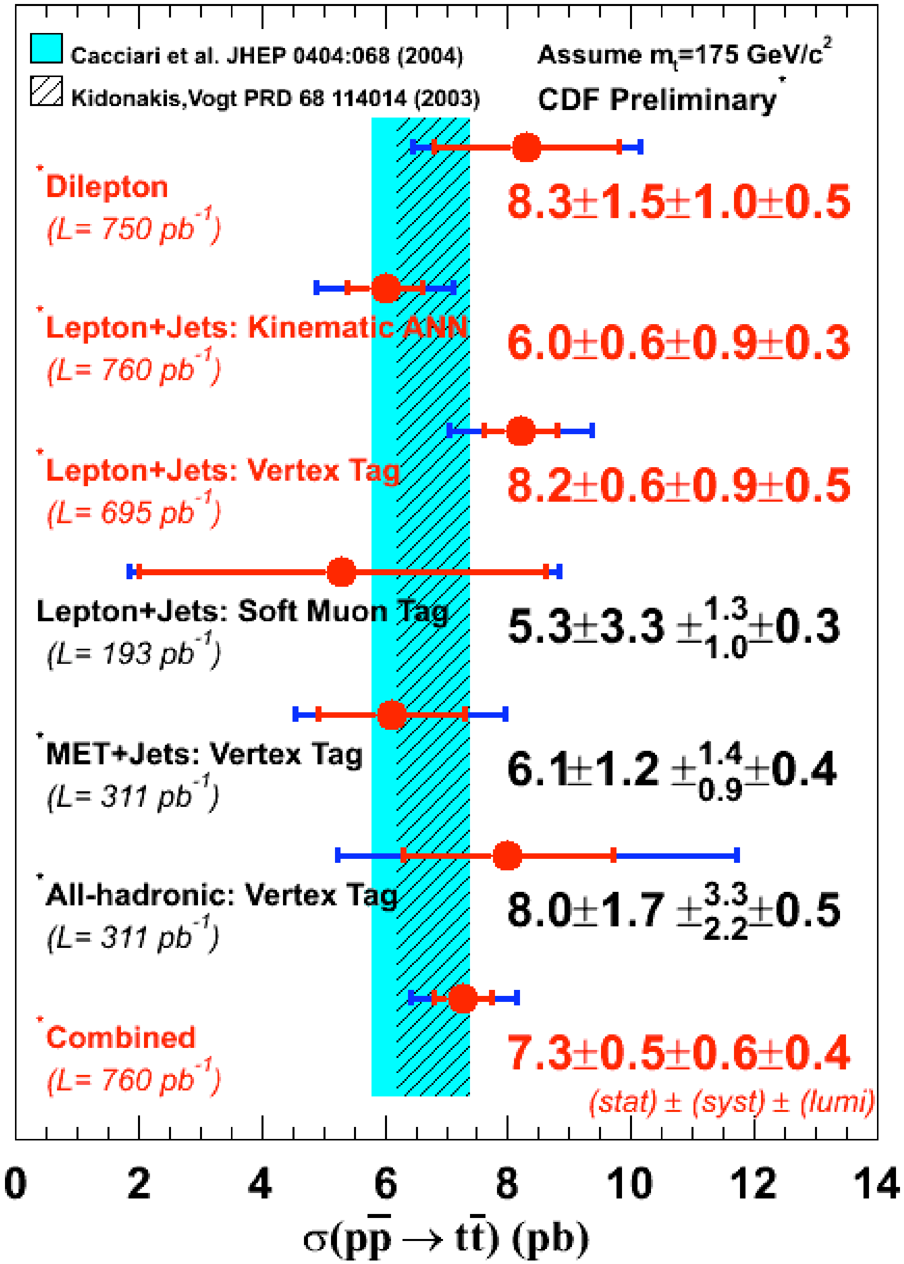


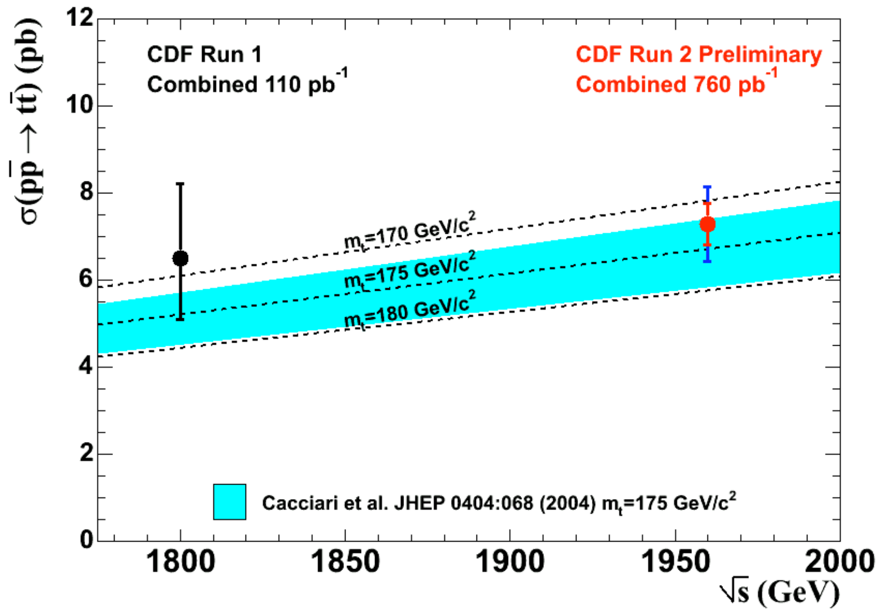
with b-tag



σ=8.3±1.5(stat) ±1.1(sys) pb

The Top Cross Section

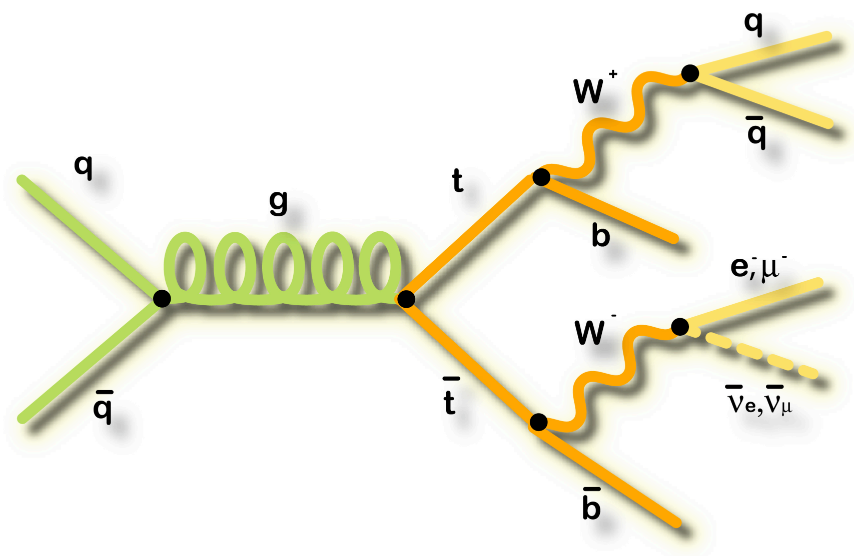




- Measured using many different techniques
- Good agreement
  - between all measurements
  - Between data and theory
- Data precision starting to challenge theory precision

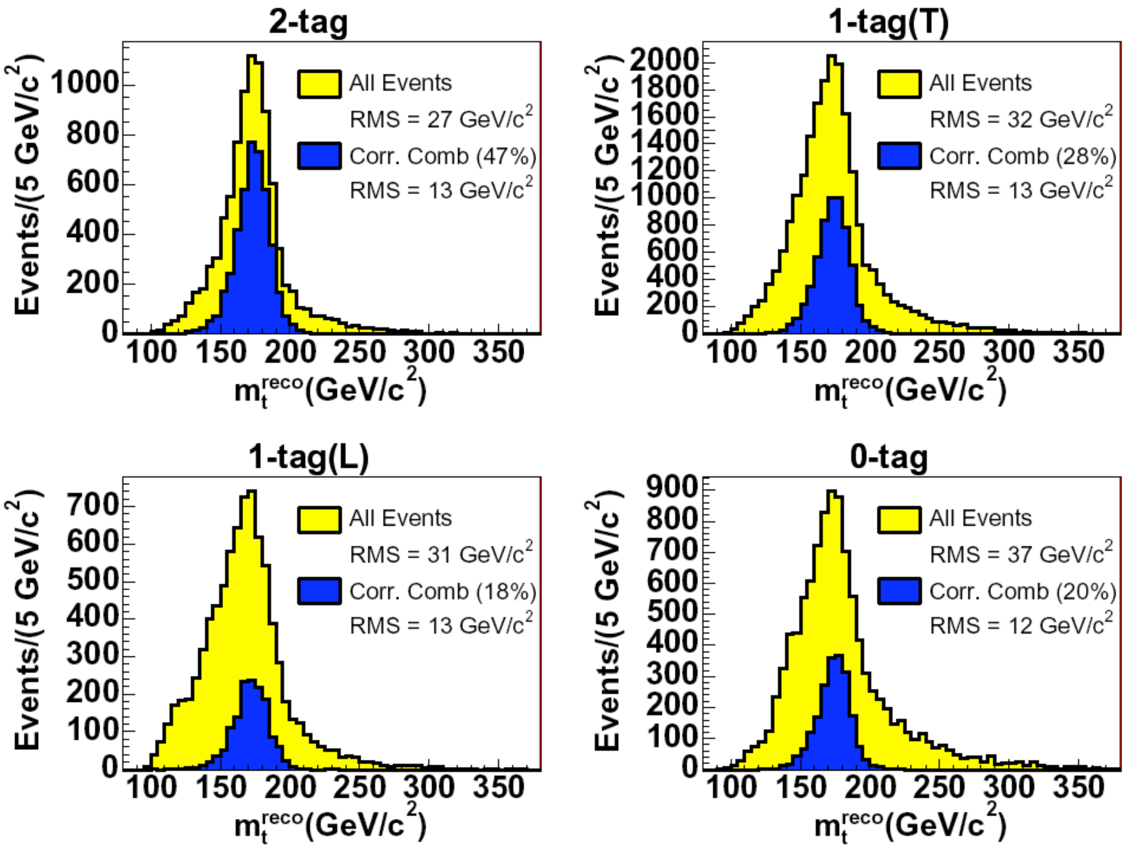
Top Mass Measurement: $t\bar{t} \rightarrow (bl\nu)(bqq)$

- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires $m(t)=m(\bar{t})$
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top



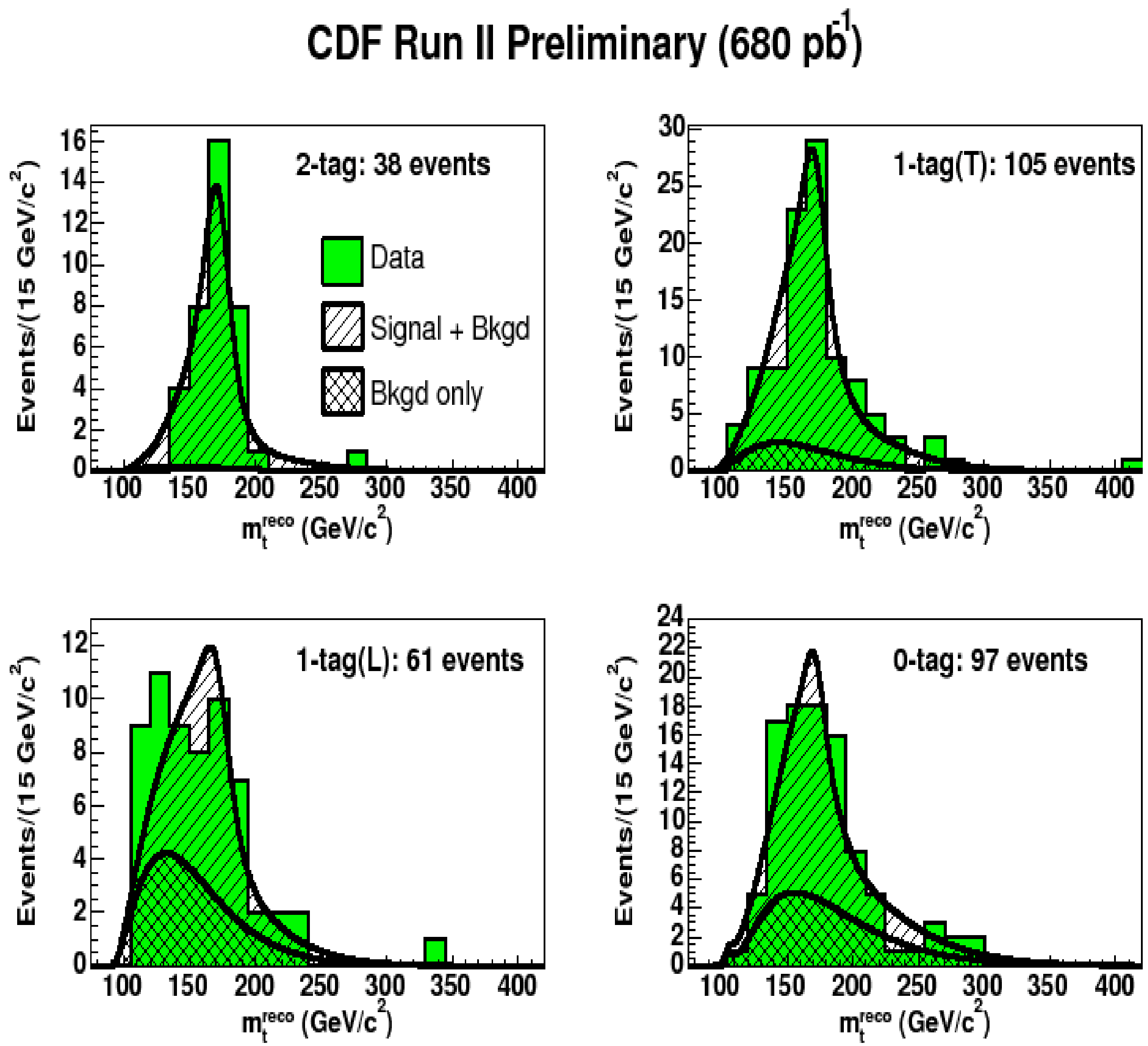
Top Mass Fit

- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,\nu}=-(p_{T,l}+p_{T,UE}+\sum p_{T,jet})$
- Constraints:
  - $M(l\nu)=M_W$
  - $M(q\overline{q})=M_W$
  - $M(t)=M(\overline{t})$
- Unknown:
  - Neutrino p_z
- 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure M(t) for each event: m_t^{reco}



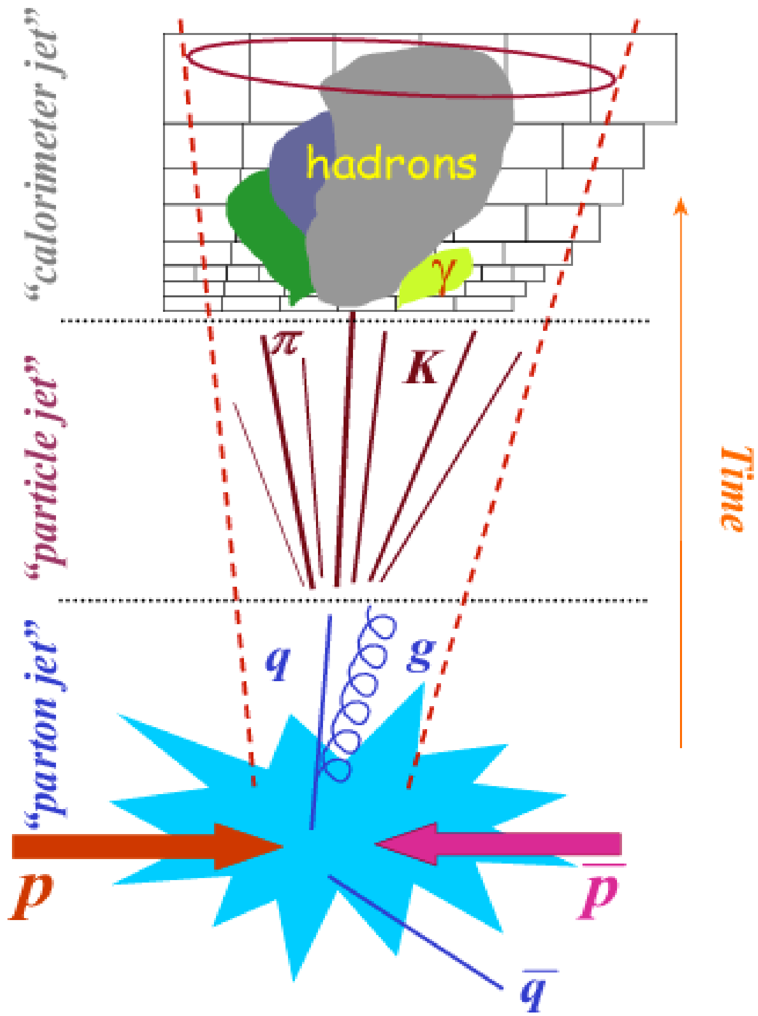
Selecting correct combination 20-50% of the time

Top Mass Distributions



Jet Energy Scale

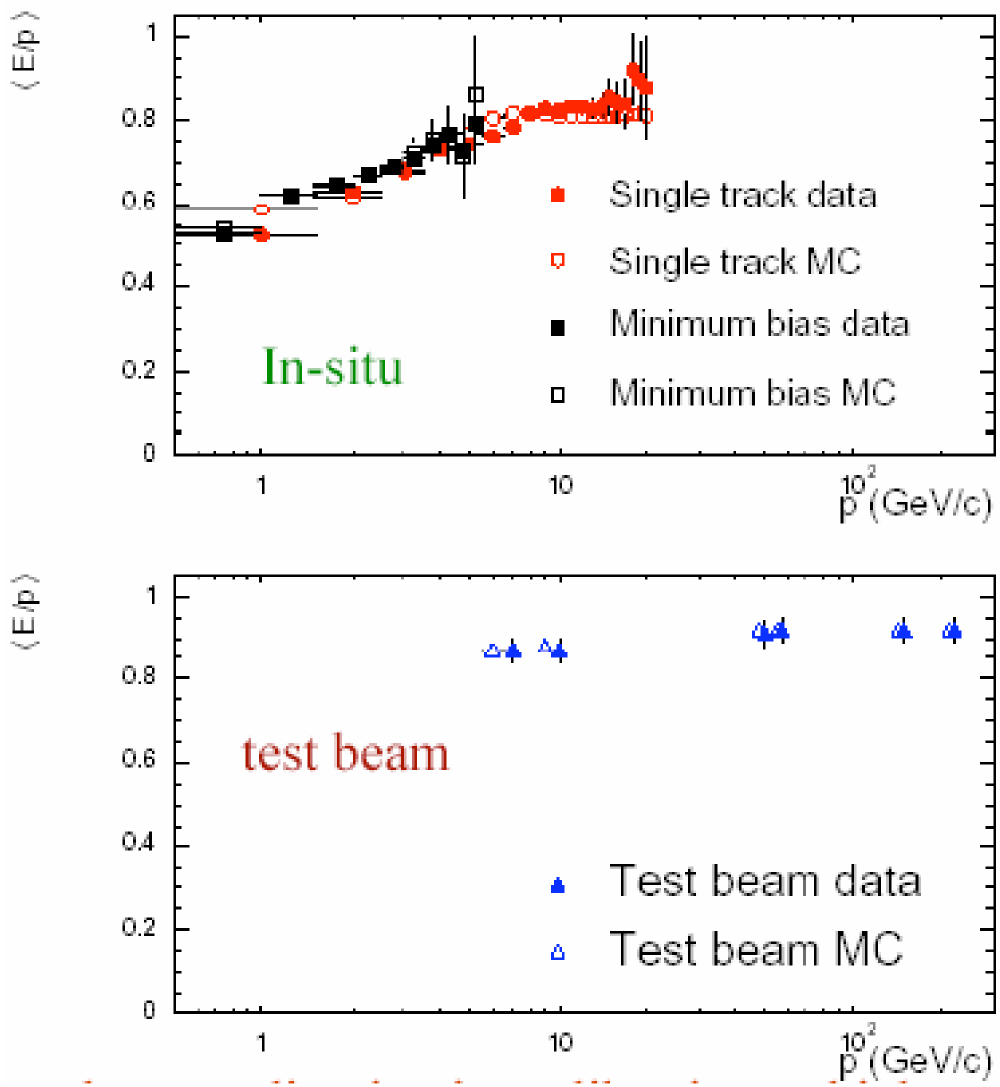
- Jet energy scale
  - Determine the energy of the partons produced in the hard scattering process
  - Instrumental effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - Physics effects:
    - Initial and final state radiation
    - Underlying event
    - Hadronization
    - Flavor of parton
- Test each in data and MC



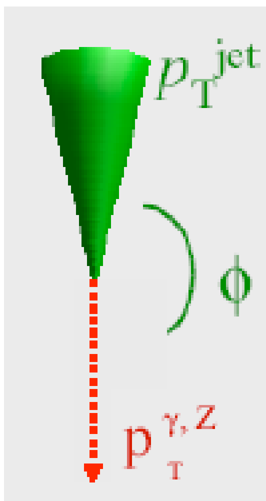
$$P_{T,jet}^{particle} = \left[P_{T,jet}^{measured} \times f_{rel} - MI\right] \times f_{abs}, \qquad P_T^{parton} = P_{T,jet}^{particle} - UE + OOC$$

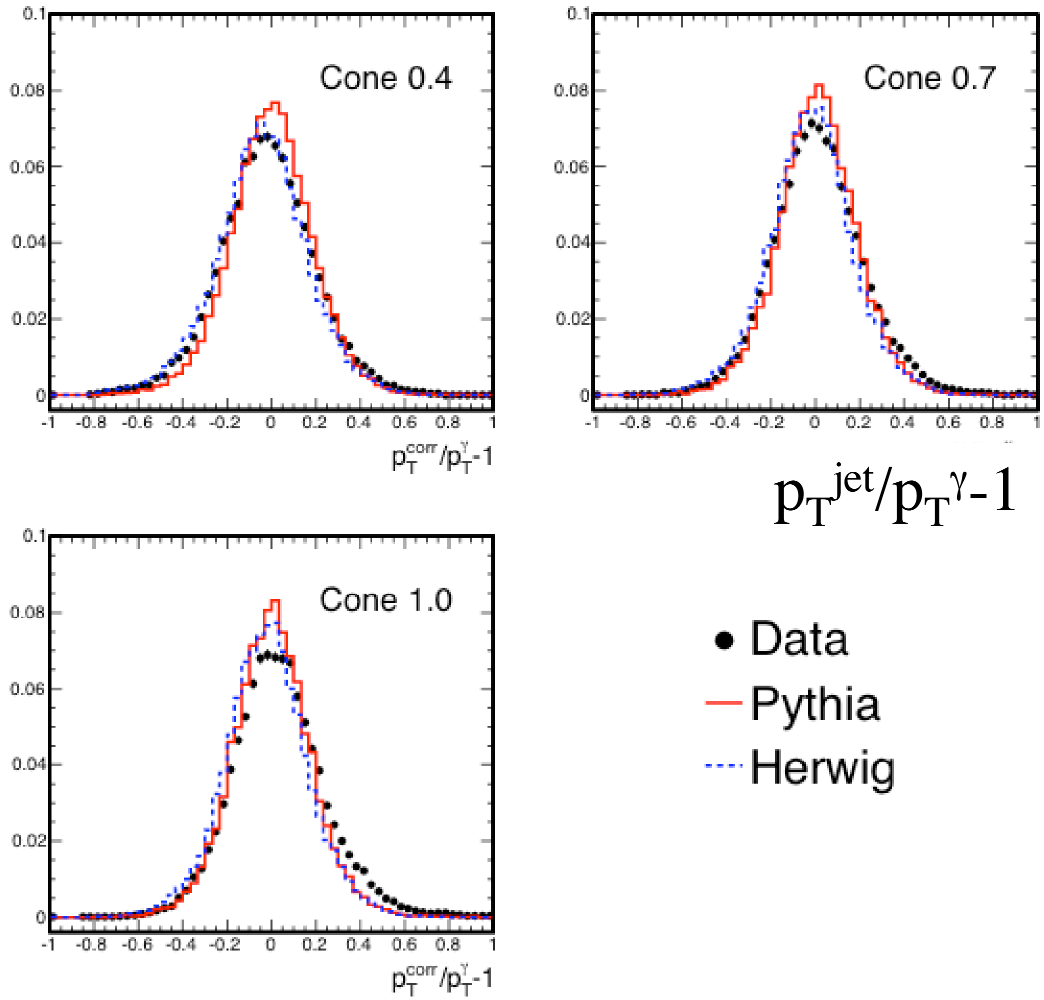
Jet Energy Scale Studies

- Measure energy response to charged particles
  - Test beam and in situ
  - CDF: Response rather non-linear
  - DØ: compensating =>has better response
    - Some compensation "lost" due to shorter gate in run 2
- CDF uses fast parameterized showers:
  - GFLASH
  - Tuned to data
- DØ uses full GEANT



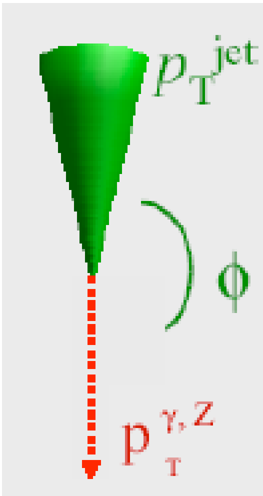
Testing Jets in Photon-Jet Data

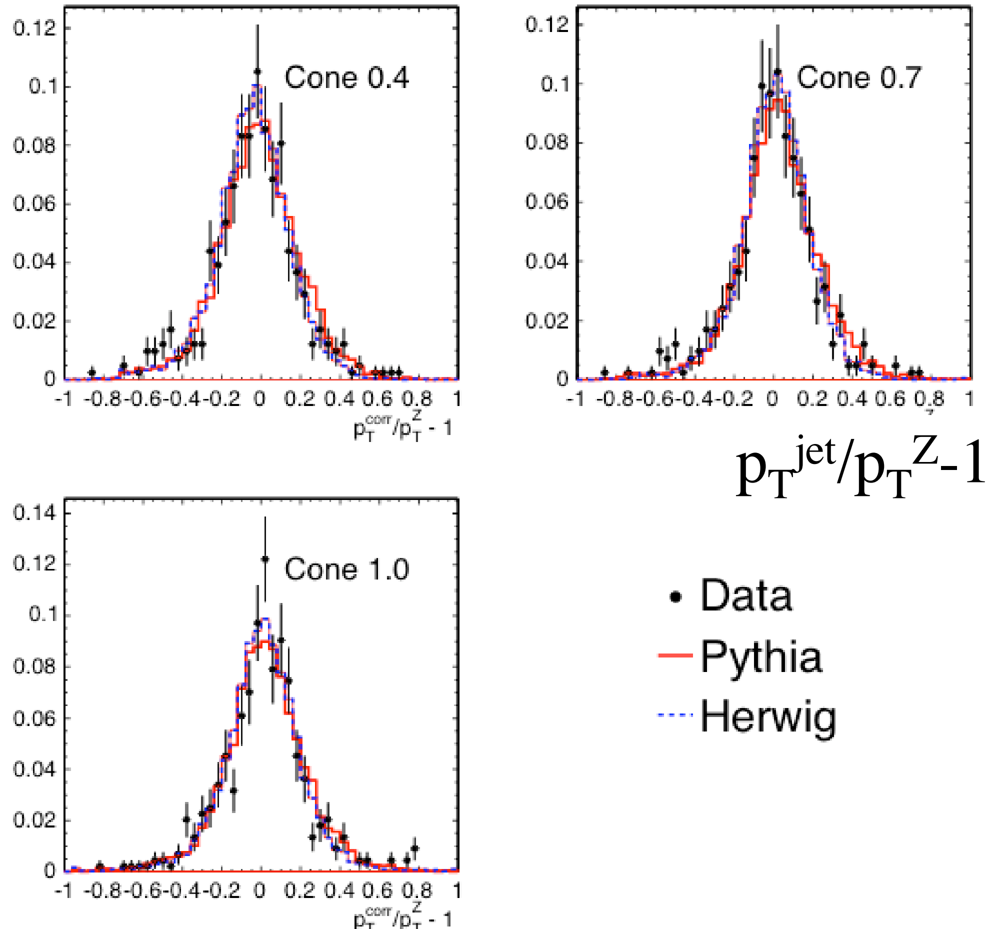




- Agreement within 3% but differences in distributions!
  - Data, Pythia and Herwig all a little different
- These are physics effects!

Testing Jets in Z-Jet Data



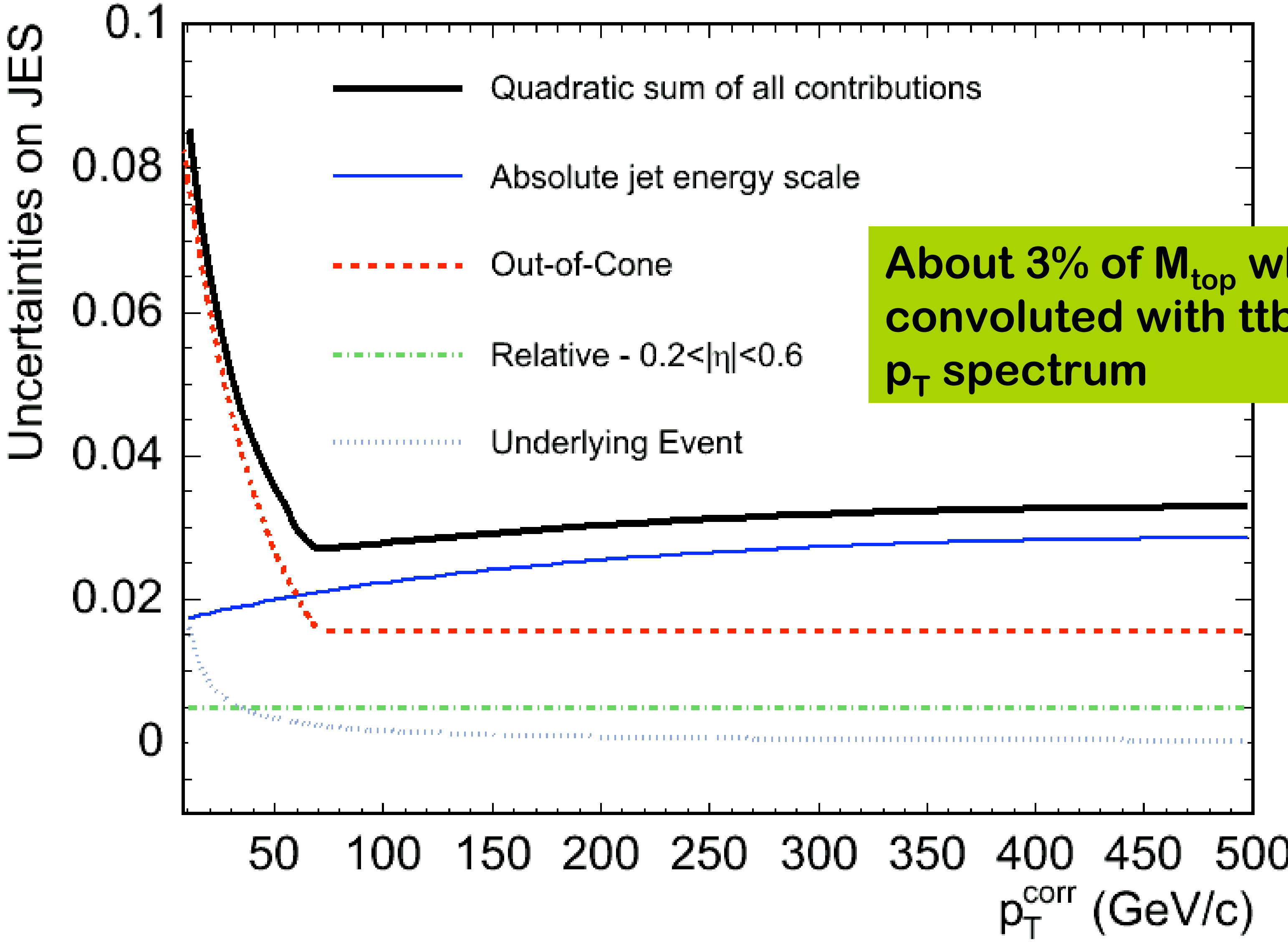


p_T^{jet}/p_T^Z-1

p_T^{jet}/p_T^Z-1

- Better agreement of data and MC than in photon-jet data
  - In progress of understanding this better together with Herwig and Pythia authors

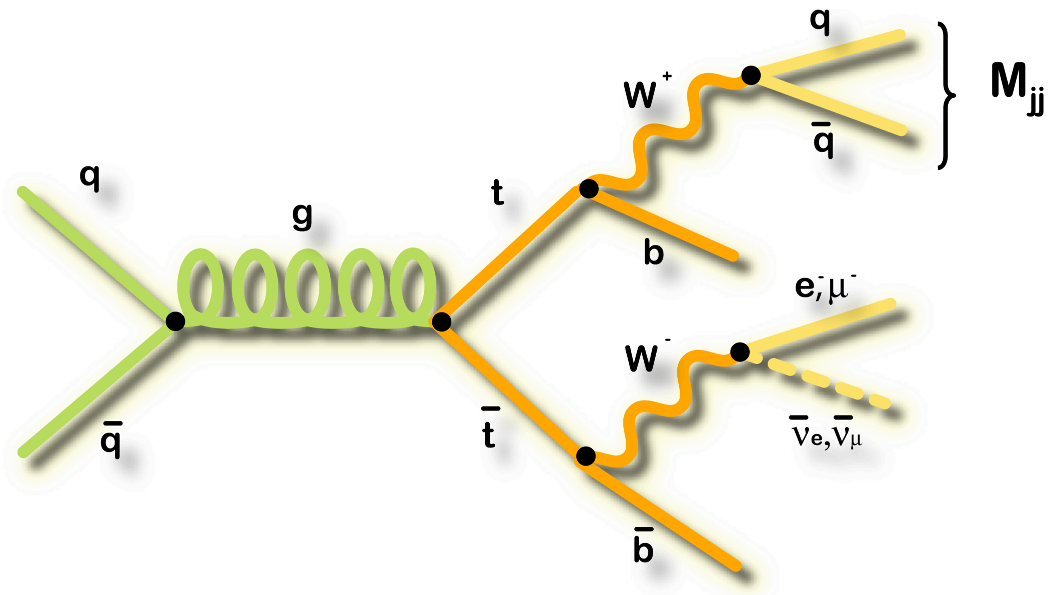
Jet Energy Scale Uncertainties



About 3% of M_{top} when convoluted with ttbar p_T spectrum

In-situ Measurement of JES

- Additionally, use $W \rightarrow jj$ mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty



2D fit of the invariant mass of the non-b-jets and the top mass:

JES $\propto$ M(jj)- 80.4 GeV/c^2

Measurement of JES scales directly with data statistics

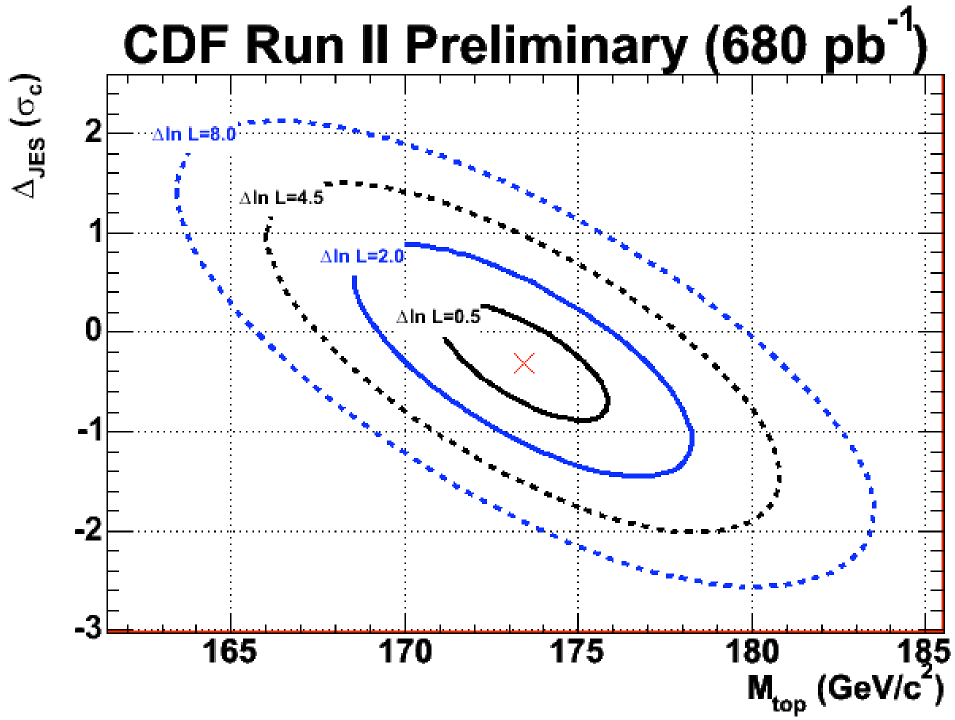
Template Analysis Results

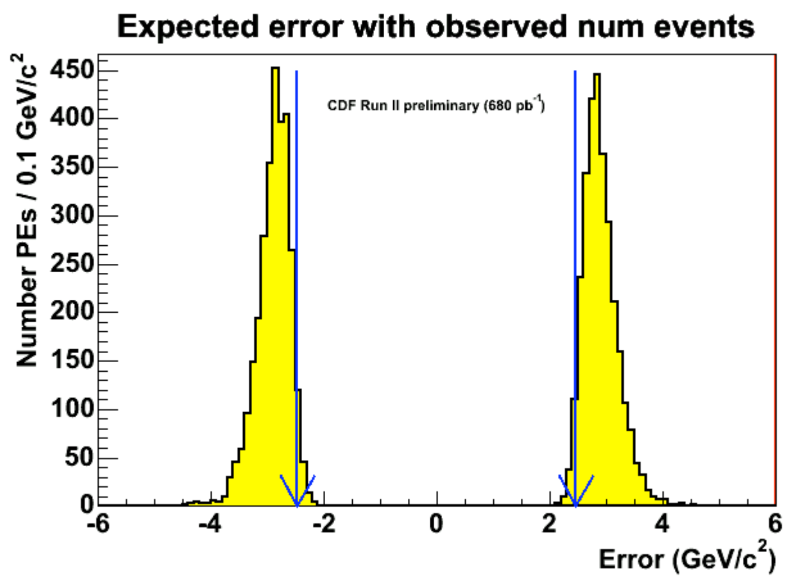
- Using 360 candidate events in 680 pb^{-1} we measure

$$M_{top} = 173.4 \pm 1.7\,(stat) + 1.8\,(JES) \pm 1.3\,(syst)\ GeV/c^2$$

- Using in-situ JES calibration results in 40% improvement on JES

$$\delta_{JES} = -\,0.31 \pm 0.59\ \sigma_{JES}$$





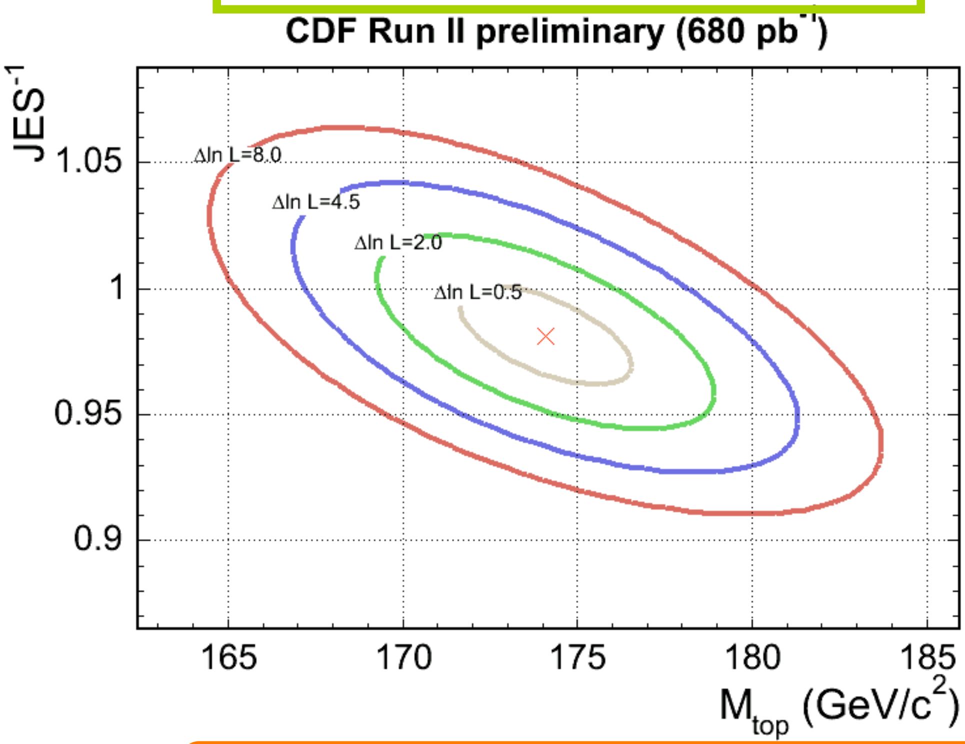
Better sensitivity than the previous world average!

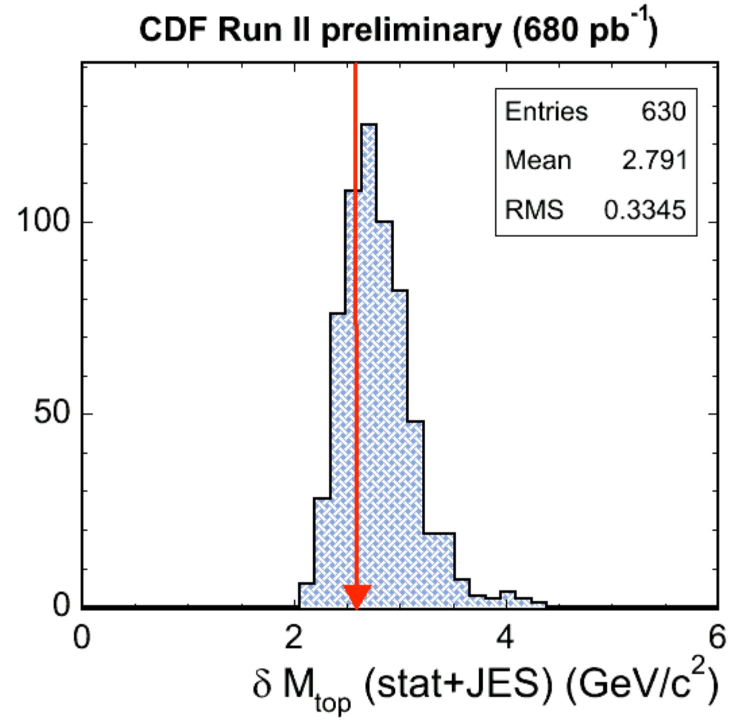
Matrix Element Results

- Using the 118 candidates in 680 pb^{-1} our M_{top} is:

M_{top} = 174.1 ± 2.0 (stat) ± 1.5 (JES) ± 1.3 (syst) GeV/c^2

with JES = 1.019 ± 0.022 (stat)

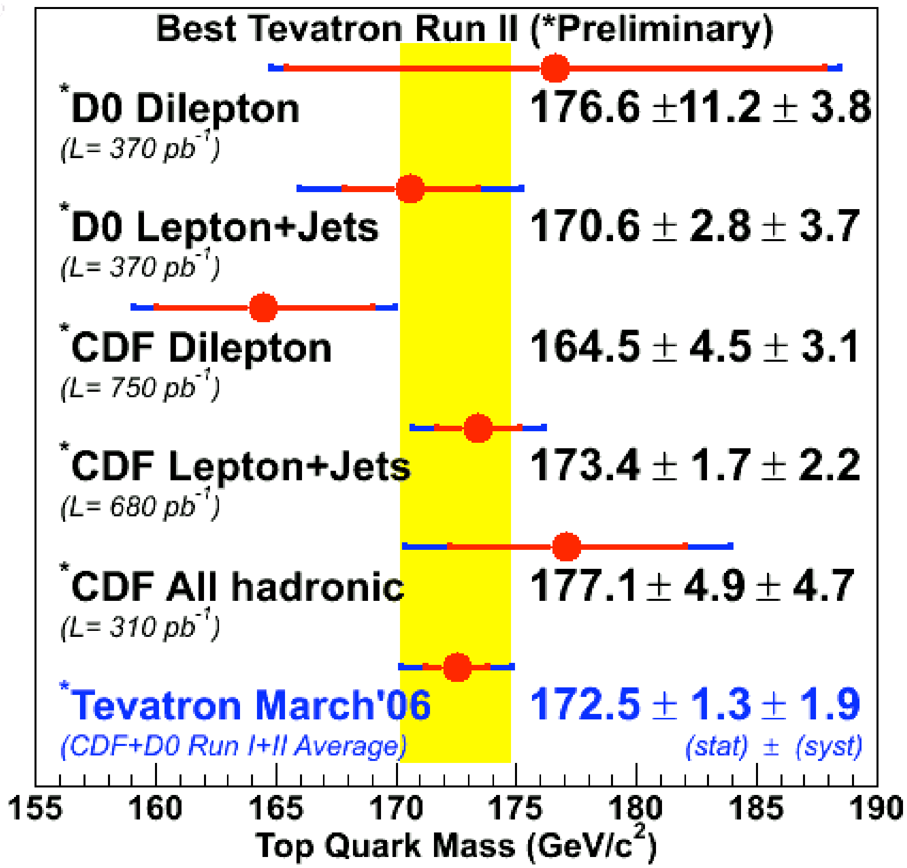




Consistent result. Similar precision as Template Method

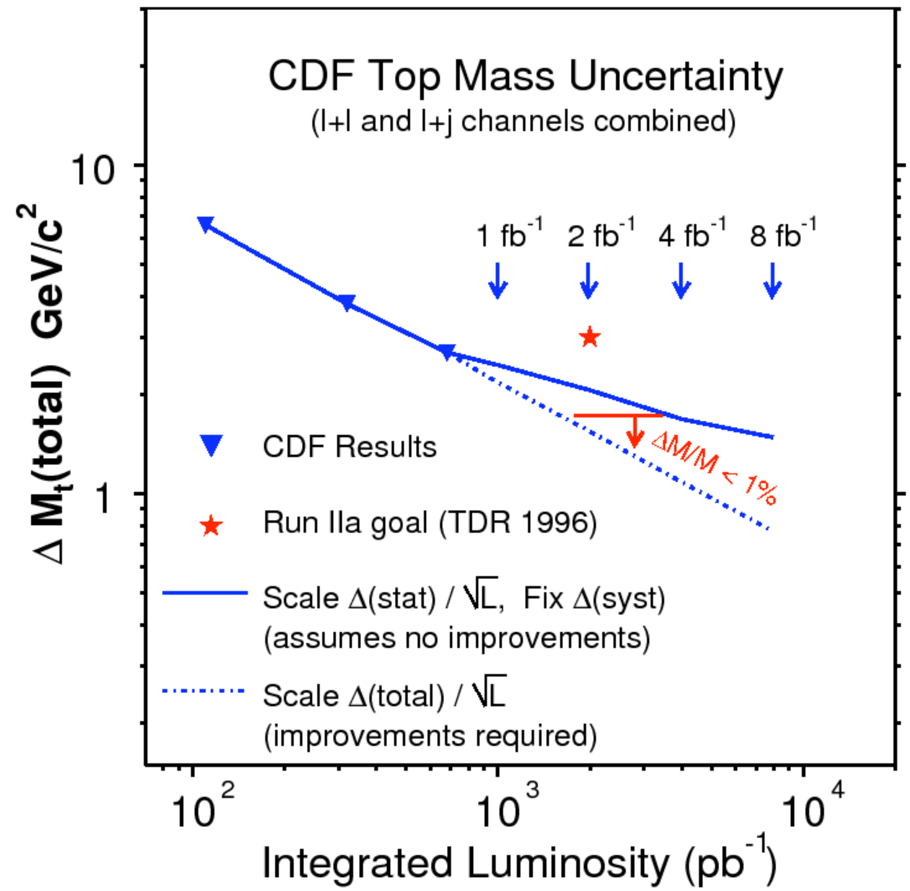
Combining M_{top} Results

- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- New uncertainty: 2.3 GeV
  - Dominated by systematic uncertainties



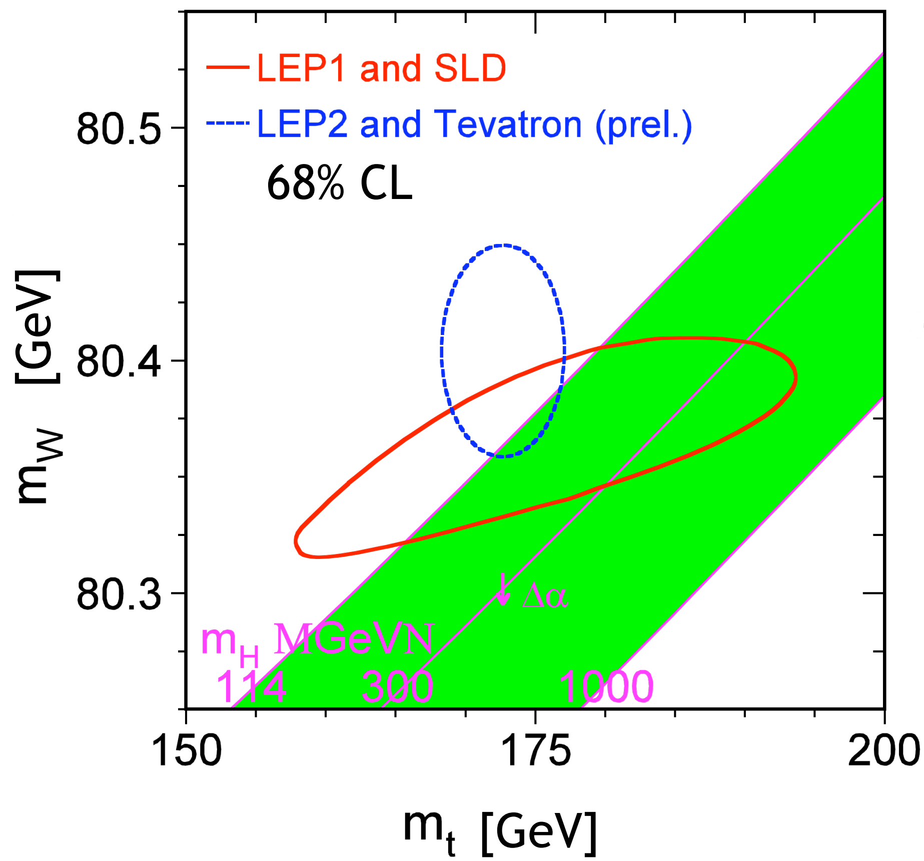
Systematic Uncertainty

Source	δm_{top} (GeV/c^2)
Remaining JES	1.0
Initial State QCD radiation	0.5
Final State QCD radiation	0.2
Parton distribution functions	0.3
MC modelling	0.2
background	0.5
B-tagging	0.1
MC statistics	0.3
total	1.3



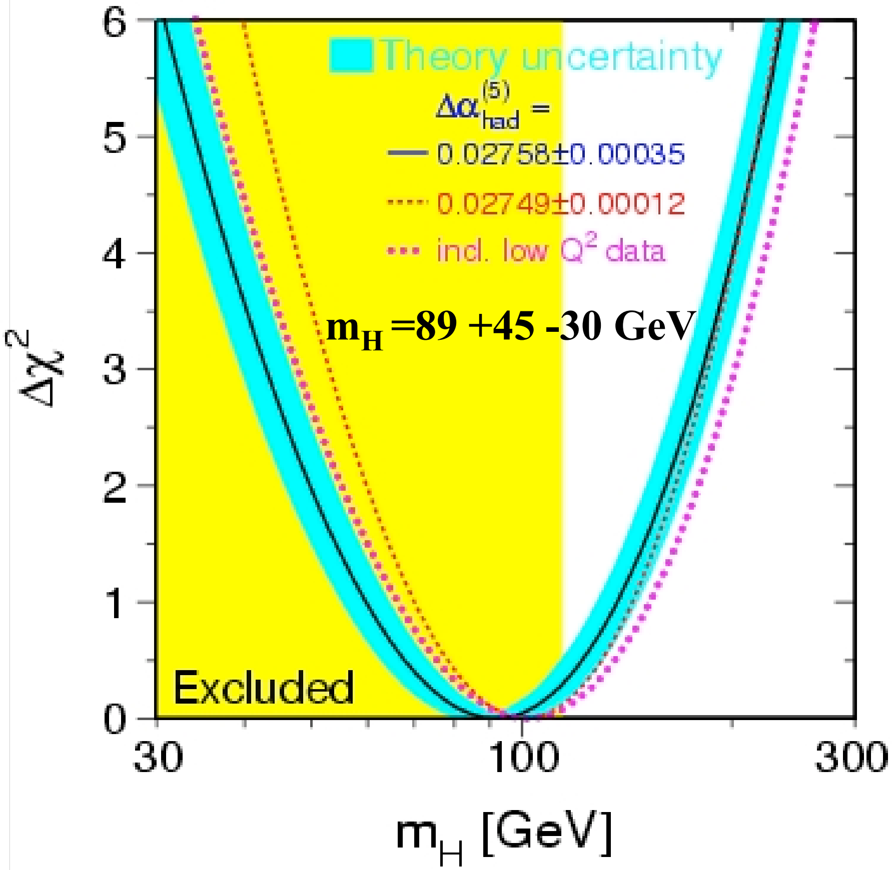
Implications for Higgs Boson

m_H constrained in the Standard Model



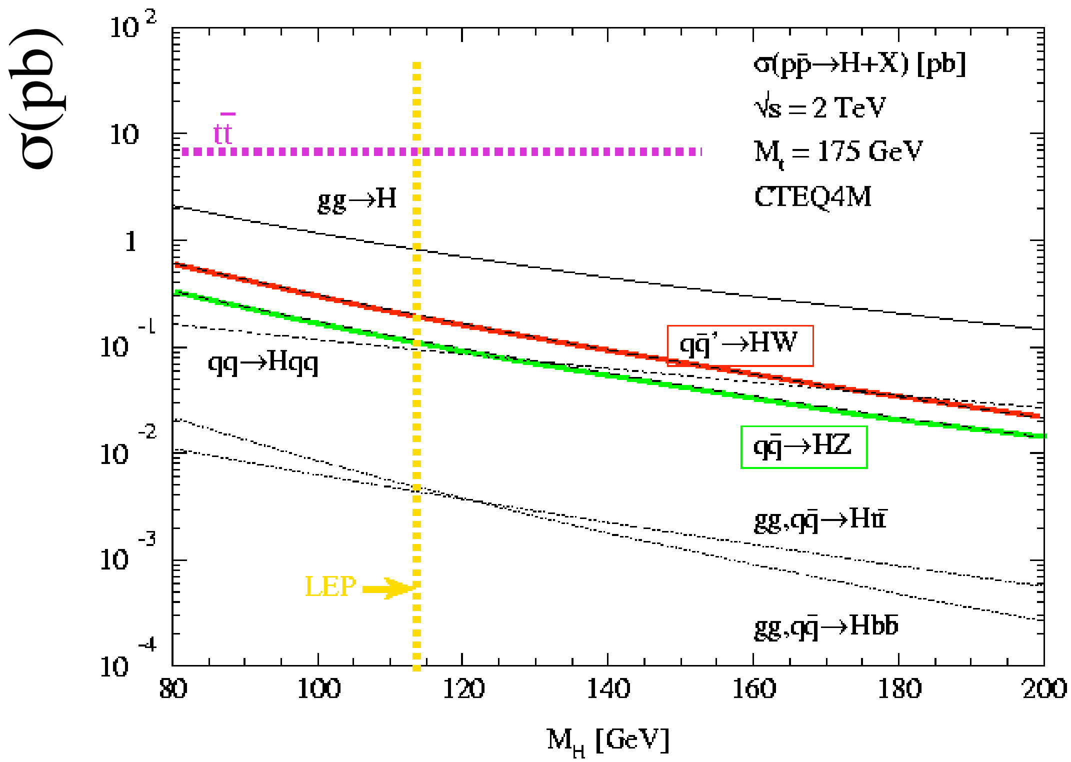
Direct searches at LEP2:
m_H>114.4 GeV @95%CL

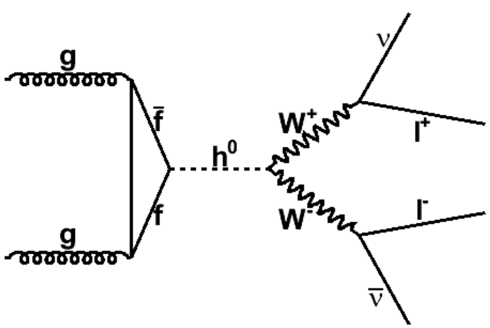
LEPEWWG 18/03/06

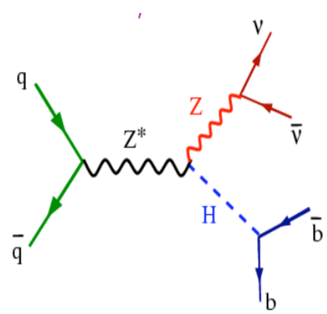


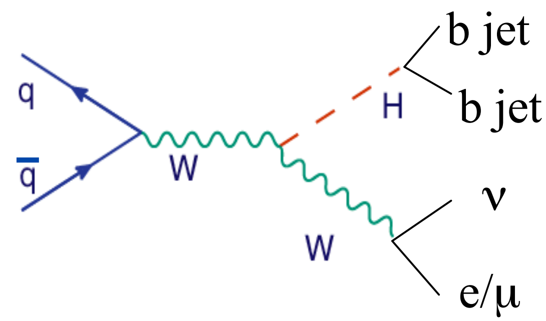
m_H<175 GeV @95%CL
(< 207 GeV if LEP2 limit incl.)

Higgs Production at the Tevatron



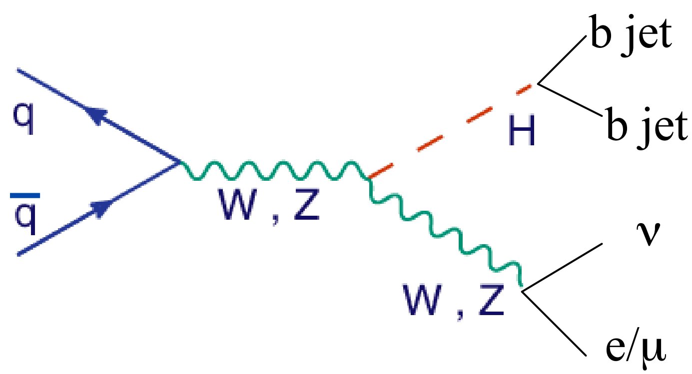






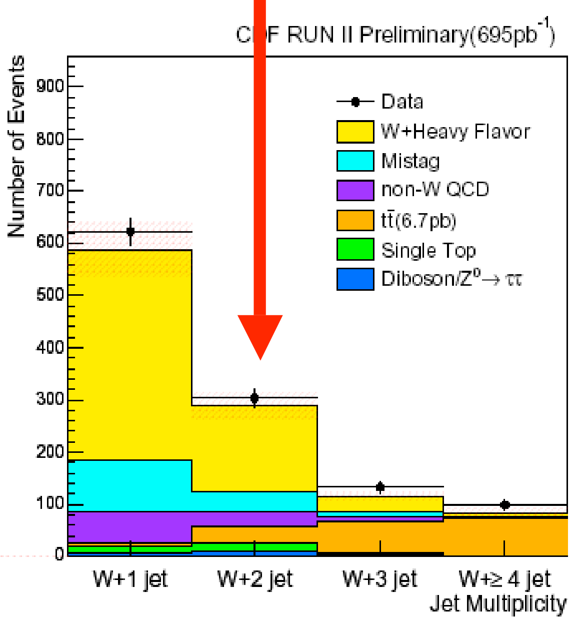
dominant: gg→ H, subdominant: HW, HZ

WH→lνbb (l=e,μ)

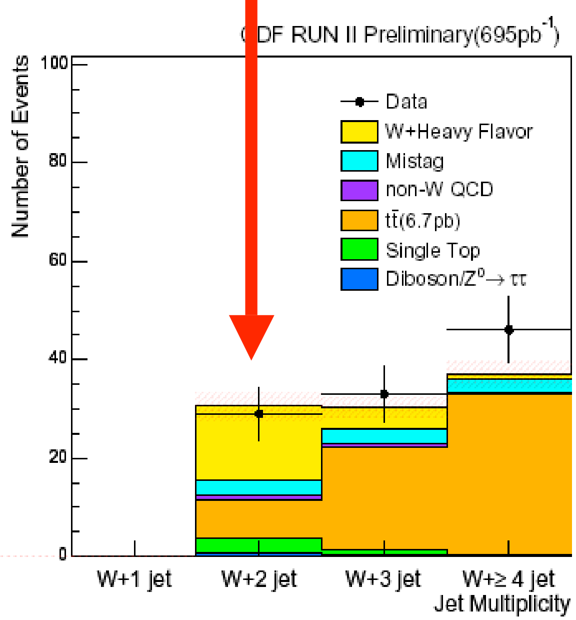


- **Muon and electron channel combined:**
  - **1 or 2 tagged b-jets**
  - **electron or muon with p_T > 20 GeV**
  - **E_T^{miss} > 20 GeV**

Now looking for 2 jets



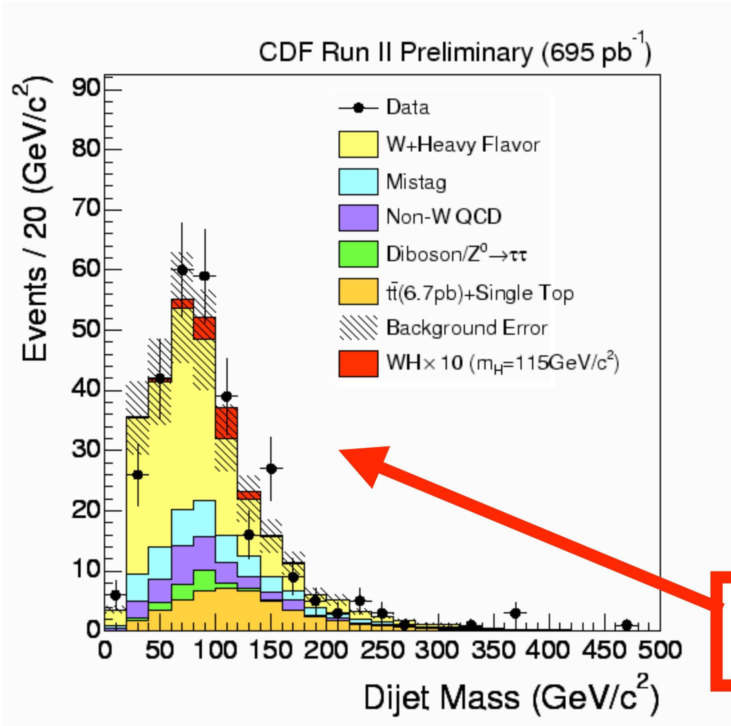
$=1$ tag w/ NN tag

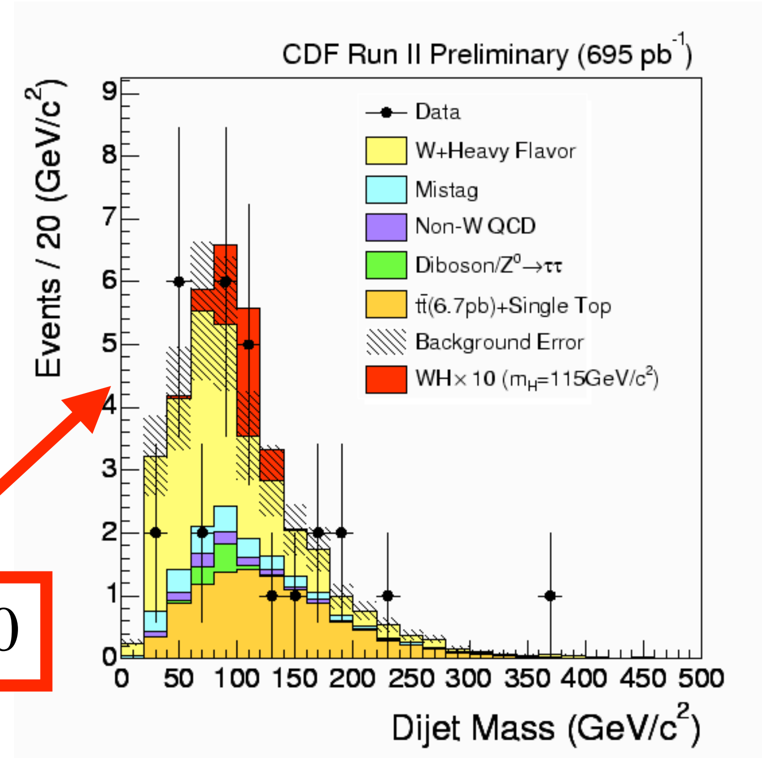


≥ 2 tag

Expected WH events:
-single tag: 1.3
-double tag: 0.4

Dijet Mass distributions

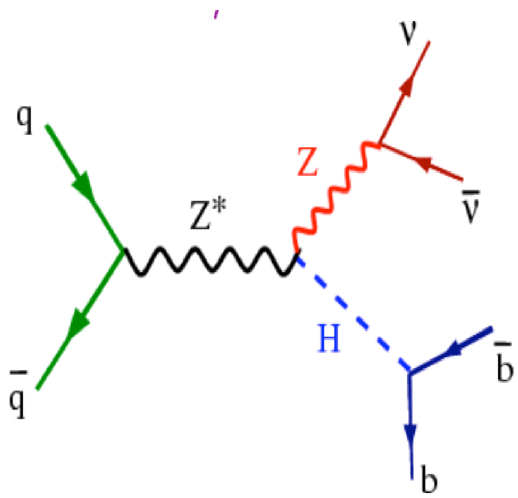




WH signal x10

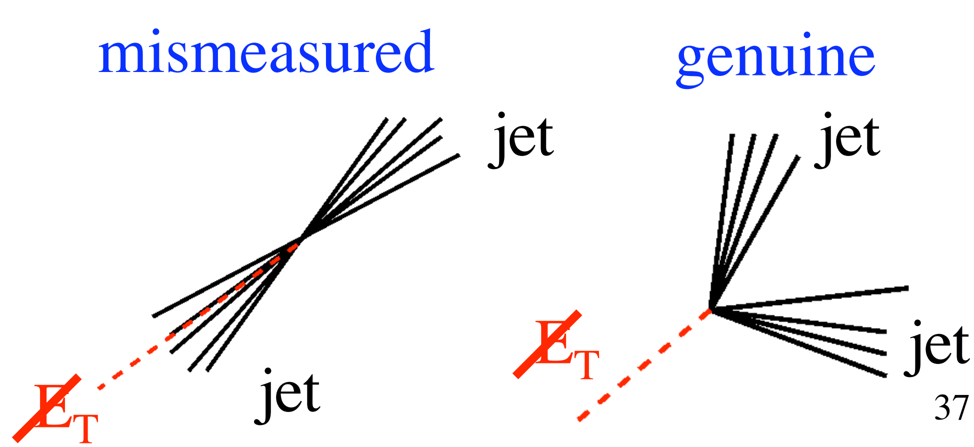
- Further experimental improvements and luminosity required:
  - E.g. b-tagging efficiency (40->60%), NN selection, higher lepton acceptance

ZH→ννbb



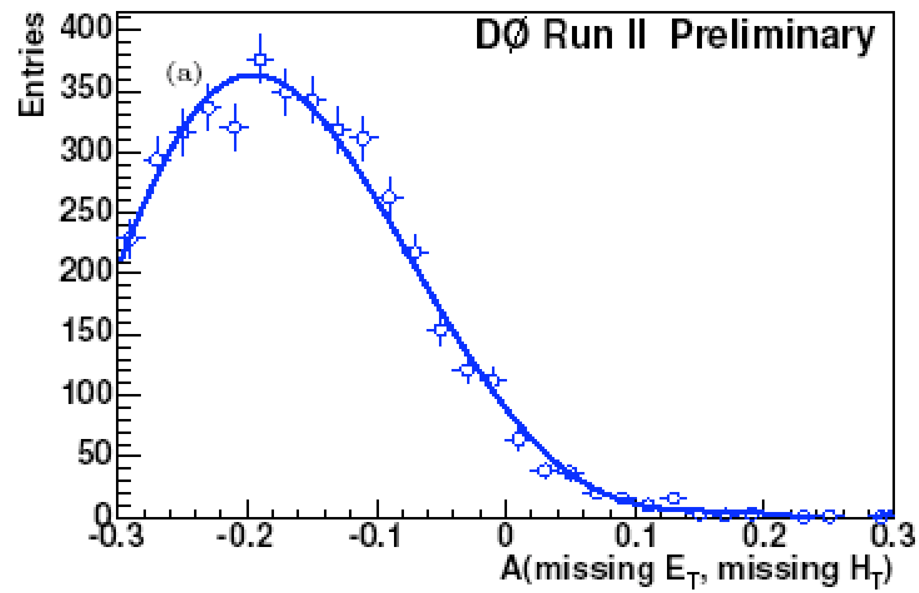
- Event selection:
  - ≥ 1 tagged b-jets
  - Two jets
  - E_T^{miss} > 50 GeV
  - Lepton veto

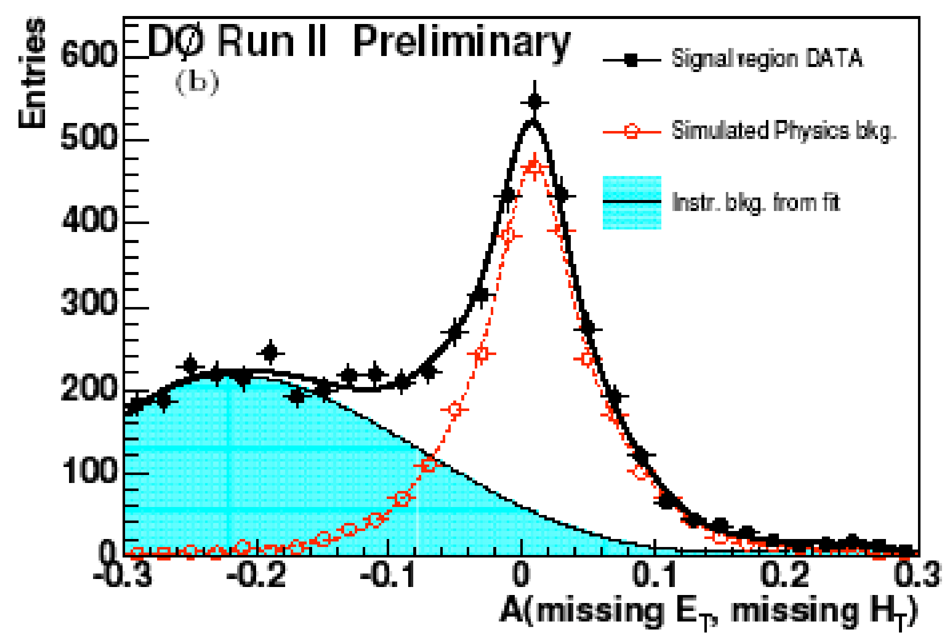
- Main challenge:
  - Background from mismeasurement of missing E_T
  - QCD dijet background is HUGE
    - Generate MC and compare to data in *control regions*
      - See 4th lecture
    - Estimate from data
- Control:
  - Missing E_T direction
  - Missing E_T in hard jets vs overall missing E_T



QCD Jet Background to ZH→ννbb

- DØ uses data
  - Define variable that can be used to normalize background
  - Asymmetry between
    - missing E_T inside jets and
    - overall missing E_T
  - Sensitive to missing E_T outside jets
    - Background has large asymmetry
    - Signal peaks at 0

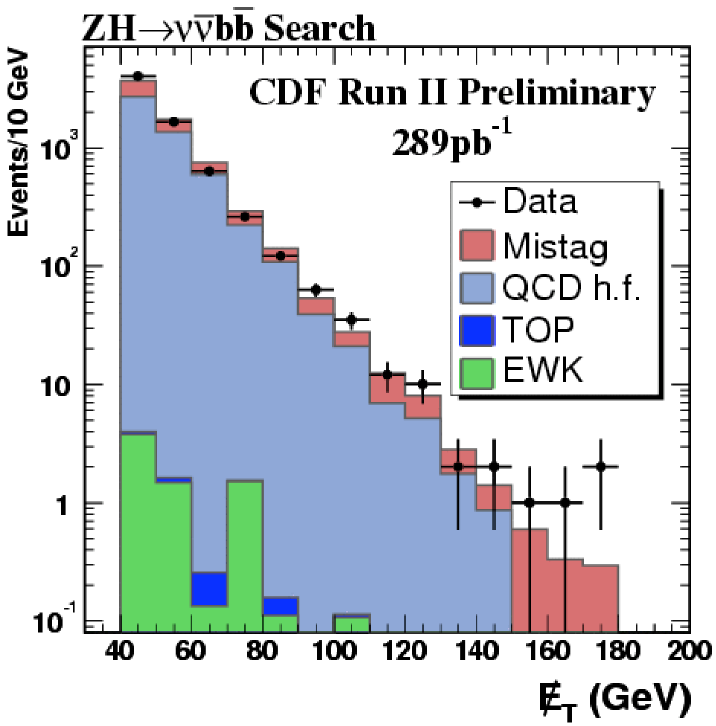


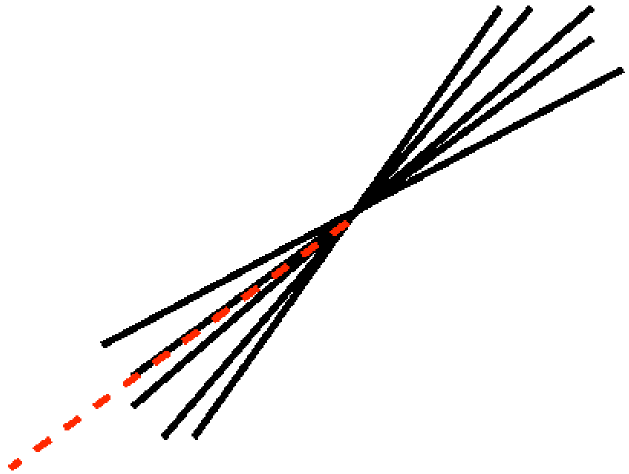


QCD Jet Background to ZH→ννbb

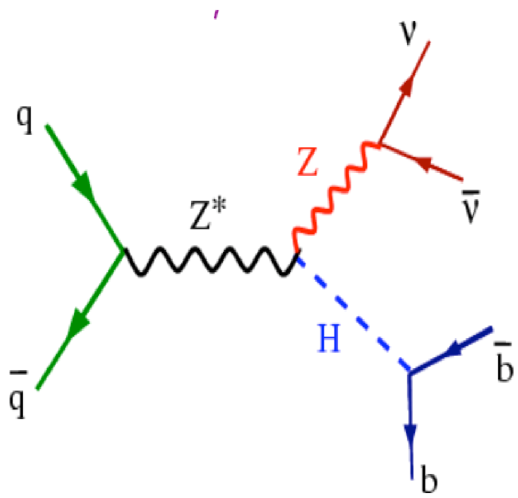
- CDF uses MC => requires
  - detailed understanding of detector response simulation
  - Vast number of QCD dijet events required

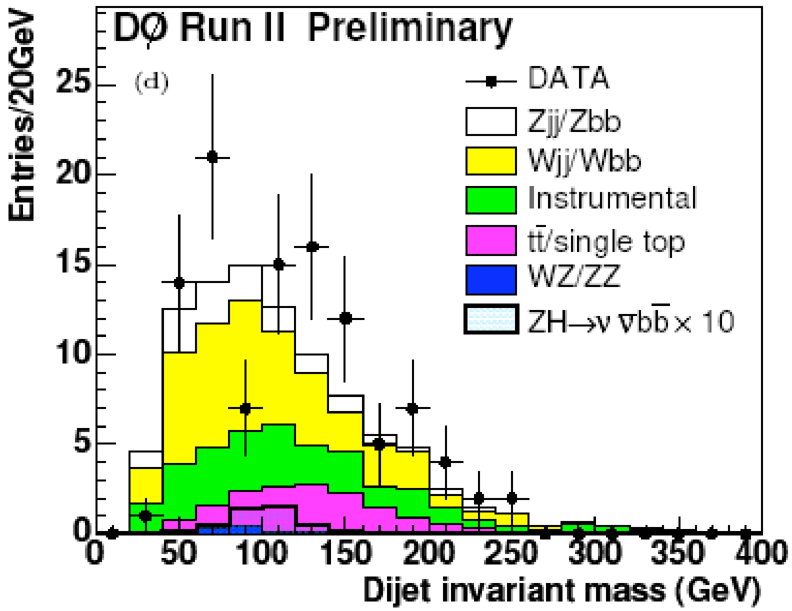
- Use control region to check agreement:
  - Jets back-to-back region
  - Data agree well with background



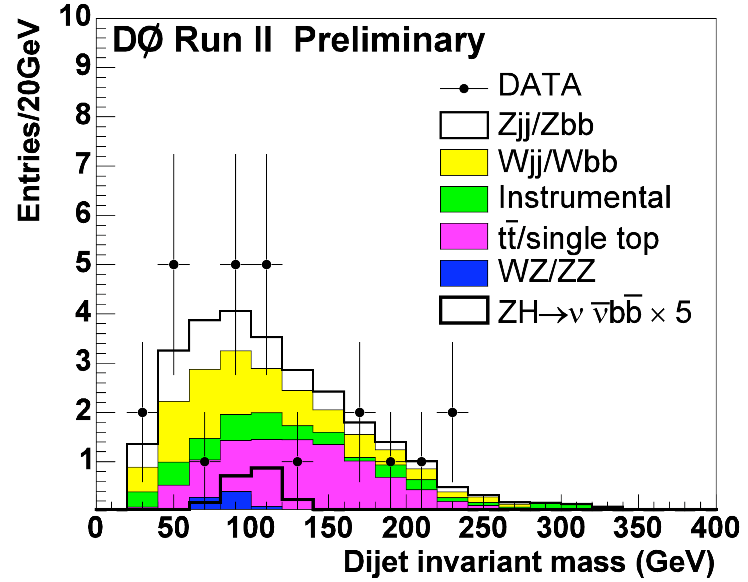


ZH→ννbb Analysis

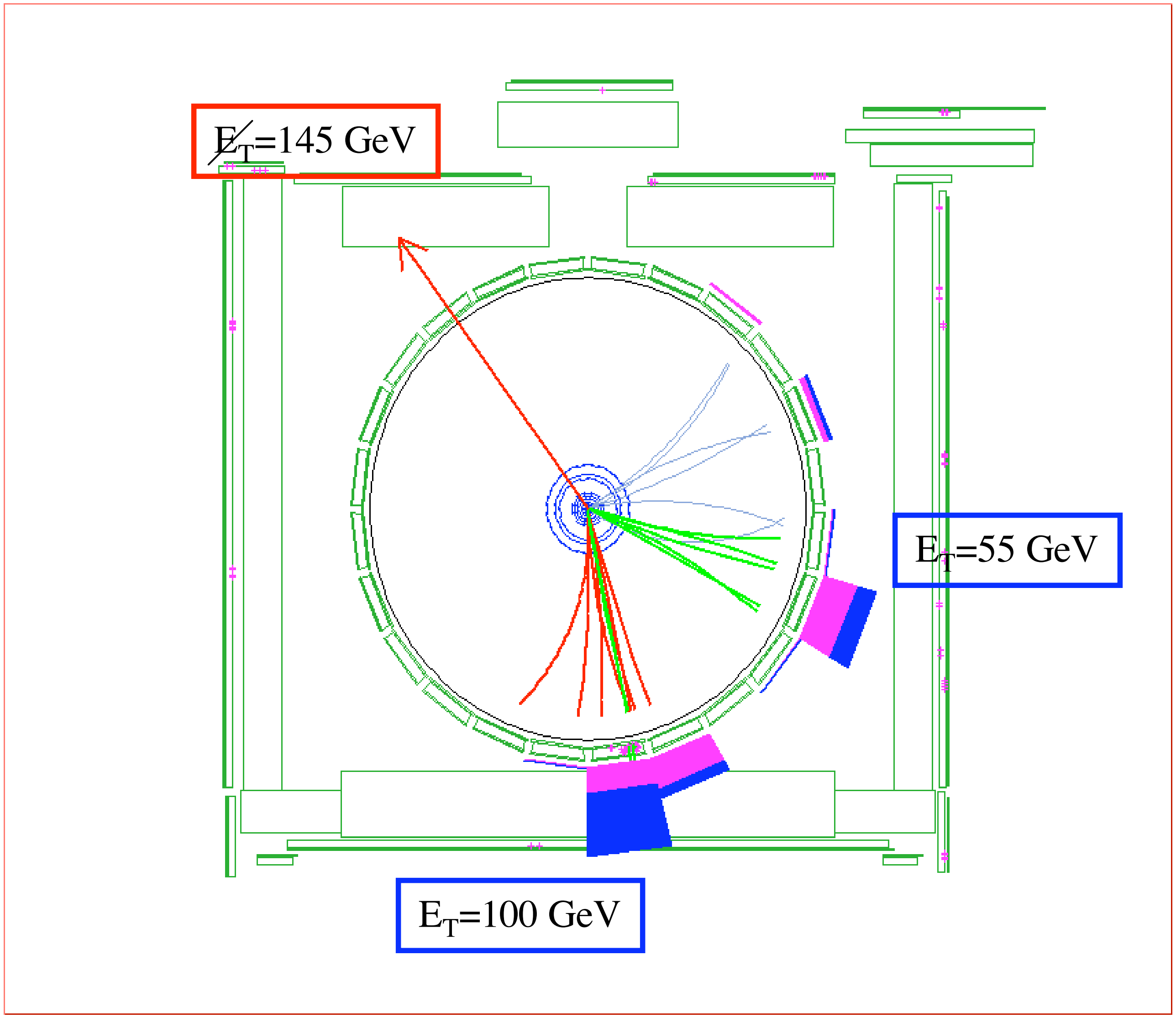




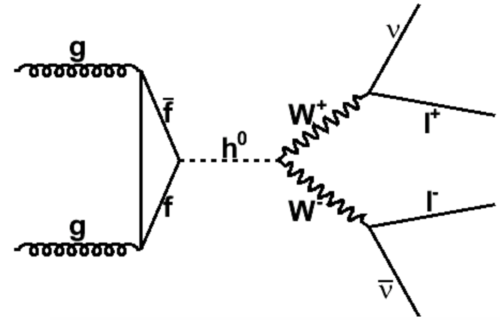
- Key discriminating variable:
  - Invariant mass of two jets
  - Expect peak from H->bb decay



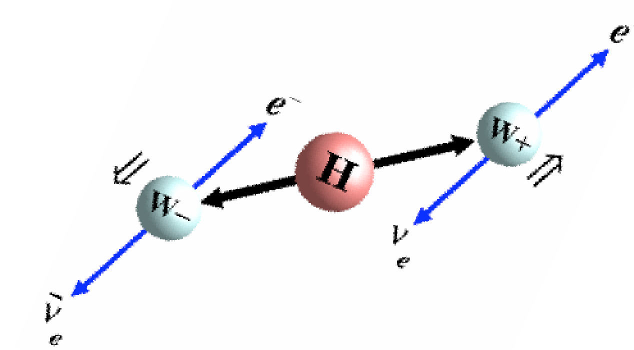
ZH→ννbb candidate

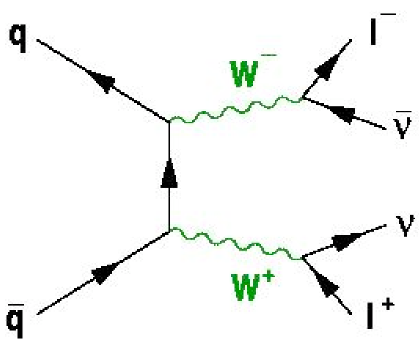


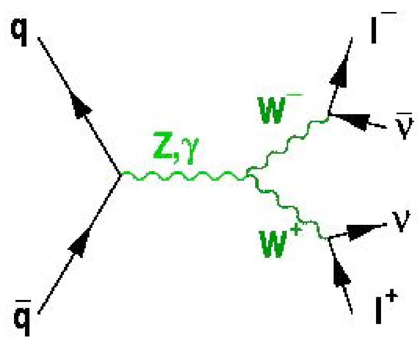
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\bar{\nu}$

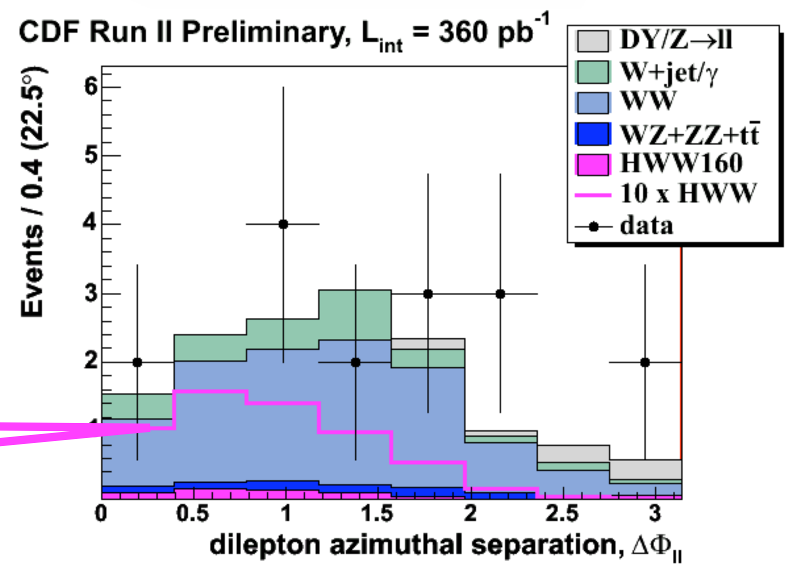


- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Main background: WW production









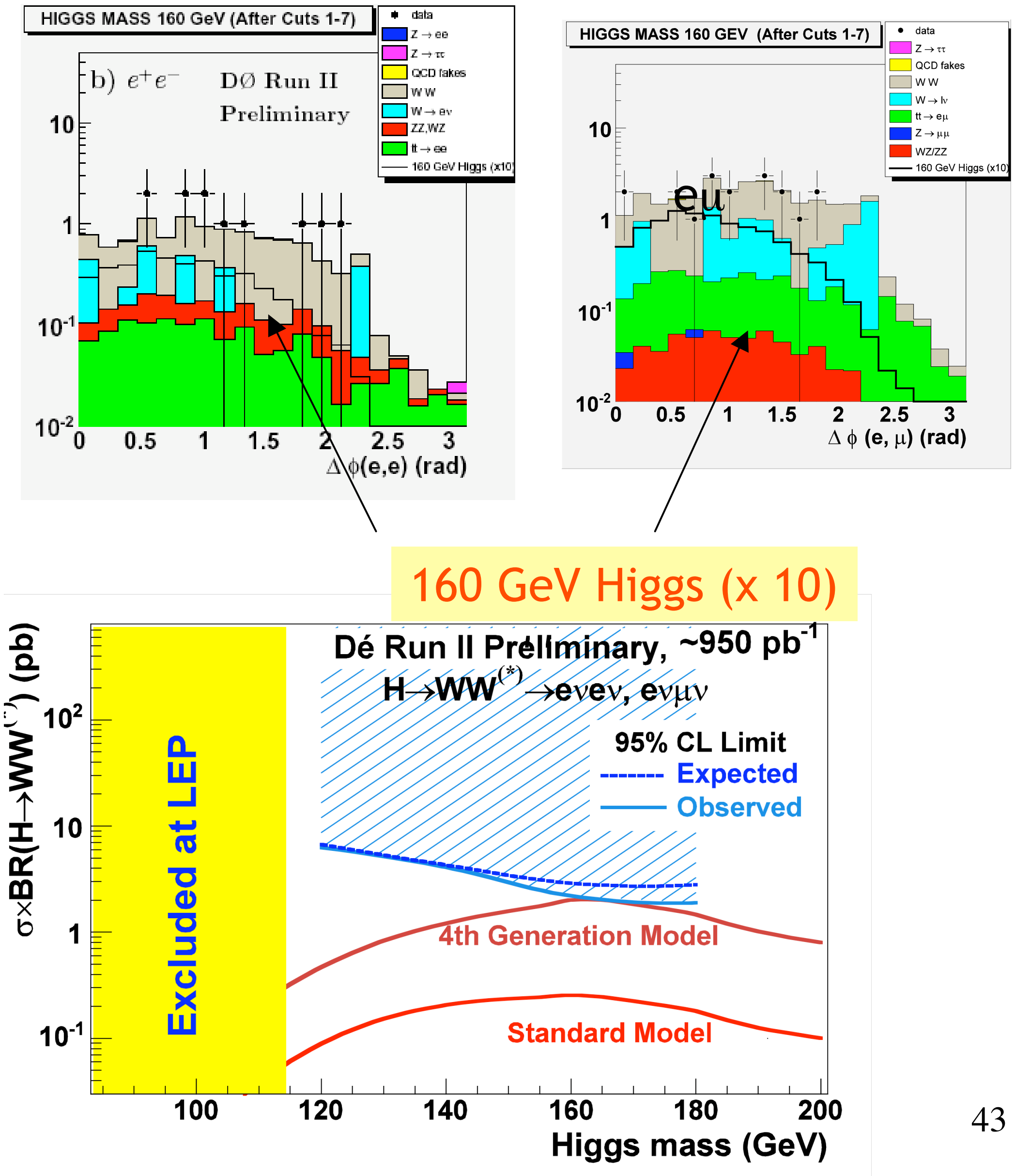
10x 160 GeV Higgs

$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ ($l=e,\mu$)

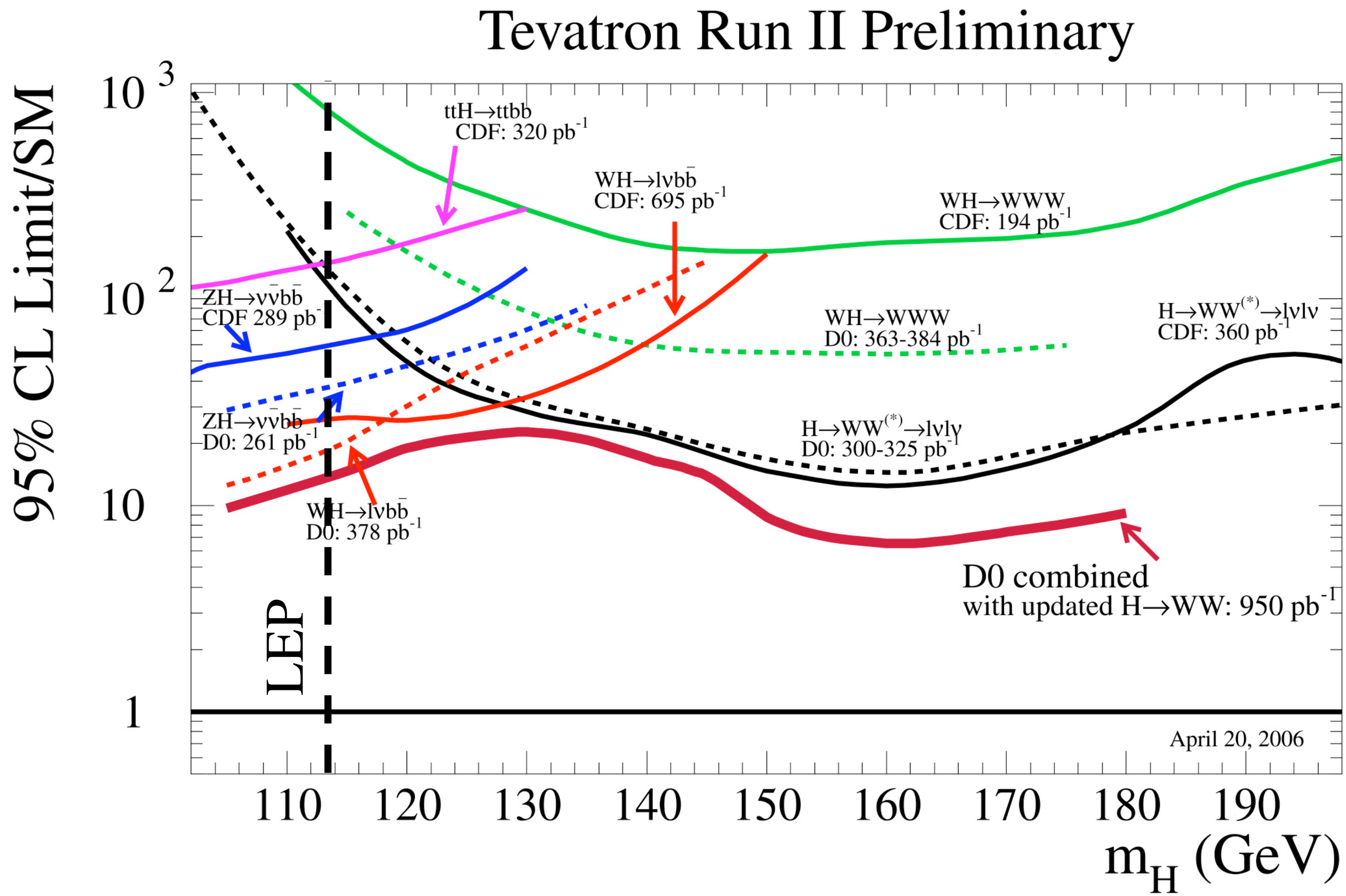
- DØ analysis: L= 950 pb^{-1}
- ee and eμ channels

- Event selection:
  - Isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets

- E.g. for M_H = 120 GeV:
  - 31 events observed
  - 32.7 +/- 2.3 (stat) predicted
  - Bkg systematic uncertainty: 15%
  - σ_{95} = 6.3 pb



Ratio to Standard Model



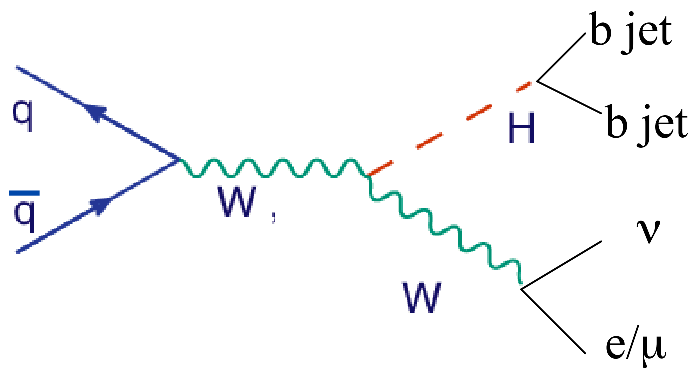
- Further experimental improvements and luminosity expected
  - Will help to close the gap
  - Expect to exceed LEP limit with about 2 fb^{-1}

Conclusions

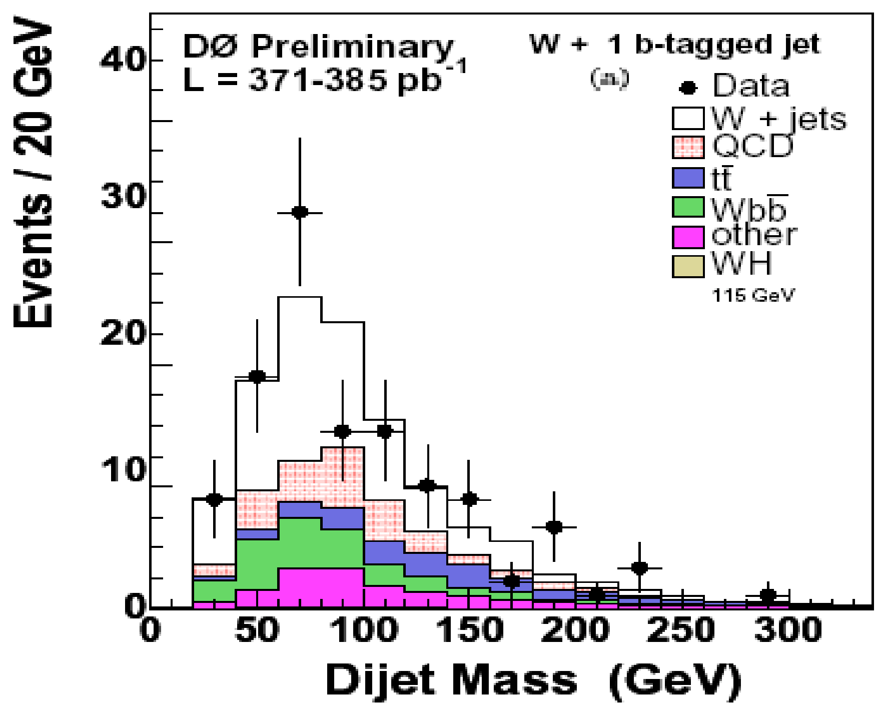
- Top Quark and Higgs boson require
  - b-tagging
  - Good understanding of jets
- Top signal well established in Run II
  - Very clean sample of 45 double-tagged events
  - Cross section measured in all three modes
  - Top mass improved impressively in Run II
- Higgs searches ongoing
  - Steady progress towards probing SM cross section
  - Expectations were set high
    - Collaborations are working on meeting these specs
  - Expect sensitivity to 115 GeV Higgs with 2-3 fb^{-1}

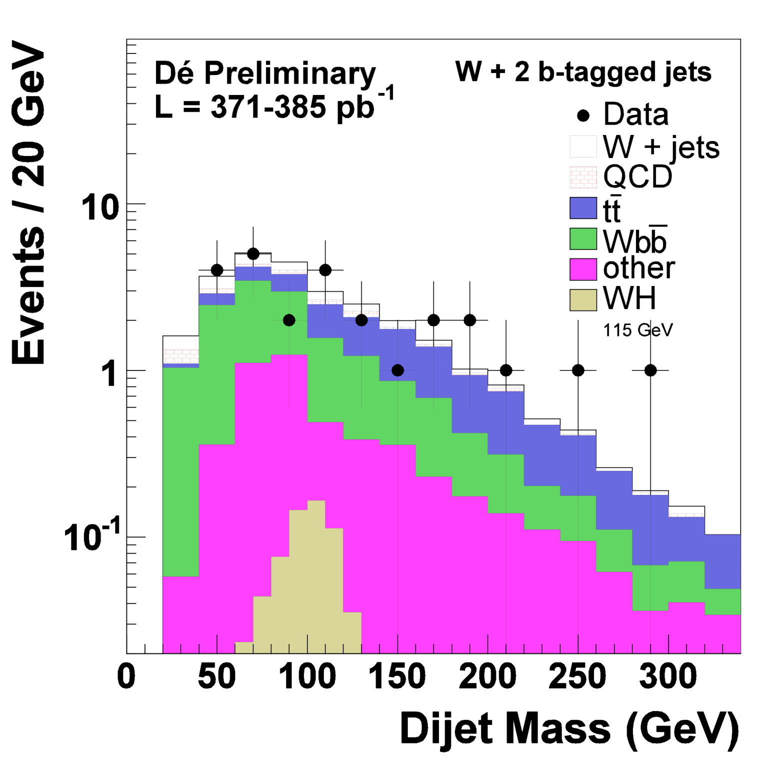
Backup

Tevatron: WH→lνbb (l=e,μ)



- Muon and electron channel combined:
  - 1 or 2 tagged b-jets
  - electron or muon with p_T > 20 GeV
  - E_T^{miss} > 20 GeV





A Few Comments on Monte Carlo

- Critical for understanding the acceptance and the backgrounds
  - Speed: CDF ~10s per event, DØ ~ 3m per event
- Two important pieces:
  - Physics process simulation:
    - PYTHIA, HERWIG
      - Working horses but limitations at high jet multiplicity
    - “ME generators”: ALPGEN, MADGRAPH, SHERPA, COMPHEP,…
      - Better modeling at high number of jets
      - Some processes only available properly in dedicated MC programs
        - » e.g. Wγ or single top
    - NLO generators (MC@NLO)
      - Not widely used yet but often used for cross-checks
  - Detector simulation:
    - GEANT, fast parameterizations (e.g. GFLASH)
- Neither physics nor detector simulation can generally be trusted!
    - Most experimental work goes into checking Monte Carlo is right

Can we close the Gap?

- Assume current analyses as starting point
  - Scale current systematic uncertainties by $1/\sqrt{L}$
- Reevaluated all improvements using latest knowledge

	Luminosity equivalent=$(S/\sqrt{B})^2$		
Improvement	WH->lvbb	ZH->vvbb	ZH->llbb
mass resolution	1.7	1.7	1.7
Continuous b-tag (NN)	1.5	1.5	1.5
Forward b-tag	1.1	1.1	1.1
Forward leptons	1.3	1.0	1.6
Track-only leptons	1.4	1.0	1.6
NN selection	1.75	1.75	1.0
WH signal in ZH	1.0	2.7	1.0
Product of above	8.9	13.3	7.2
CDF+DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

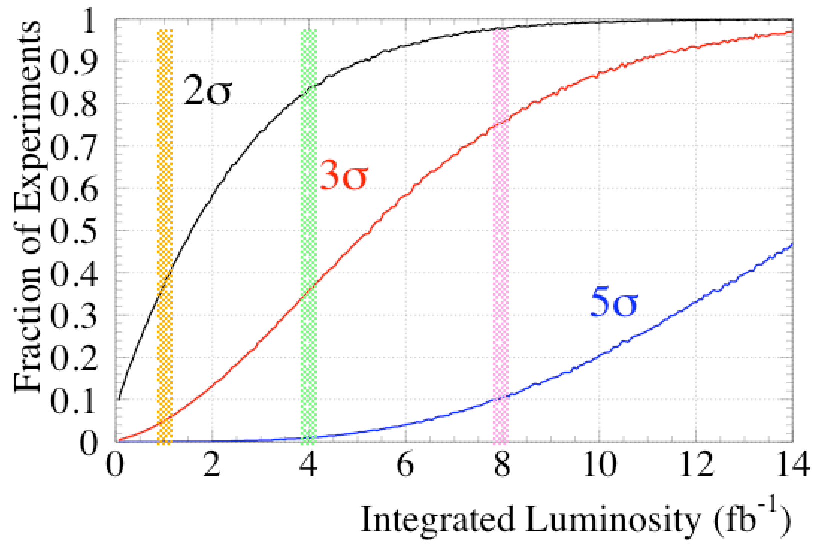
Expect factor ~10 improvements and CDF+DØ combination:

=> Need 2.5 fb^{-1} for 95%C.L. exclusion of 115 GeV Higgs

"God Does Not Play Dice" (with the Physicist)?

- All numbers given so far were
  - a 50% probability of an experiment achieving discovery or exclusion
  - We perform 1 experiment
- Could get statistically lucky or unlucky (m_H=115 GeV/c^2):
  - with L=1 fb^{-1}:
    - 5% chance for 3σ evidence
    - 0% chance for 5σ discovery
  - with L=4 fb^{-1}:
    - 35% chance for 3σ evidence
    - 2% chance for 5σ discovery
  - with L=8 fb^{-1}:
    - 75% chance for 3σ evidence
    - 10% chance for 5σ discovery

m_H=115 GeV/c^2



Combining M_{top} Results

- Are the channels consistent?

M_{top}(All Jets) = 178.7 ± 5.5 GeV/c^2
M_{top}(Dilepton) = 164.8 ± 4.8 GeV/c^2
M_{top}(Lepton+Jets) = 173.5 ± 2.8 GeV/c^2

- We compare them taking into account their correlated systematics
- Discrepancy might reveal missing systematic? *or New Physics?*