Physics at the Tevatron

Lecture II

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Outline

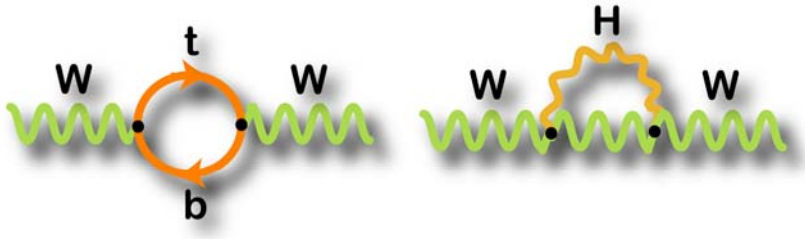
- Lecture I
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
    - Lepton identification
- Lecture II
  - The W boson mass, the Top Quark and the Higgs Boson
    - Lepton calibration, jet energy scale and b-tagging
- Lecture III
  - B_s mixing and $B_s \rightarrow \mu\mu$ rare decay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

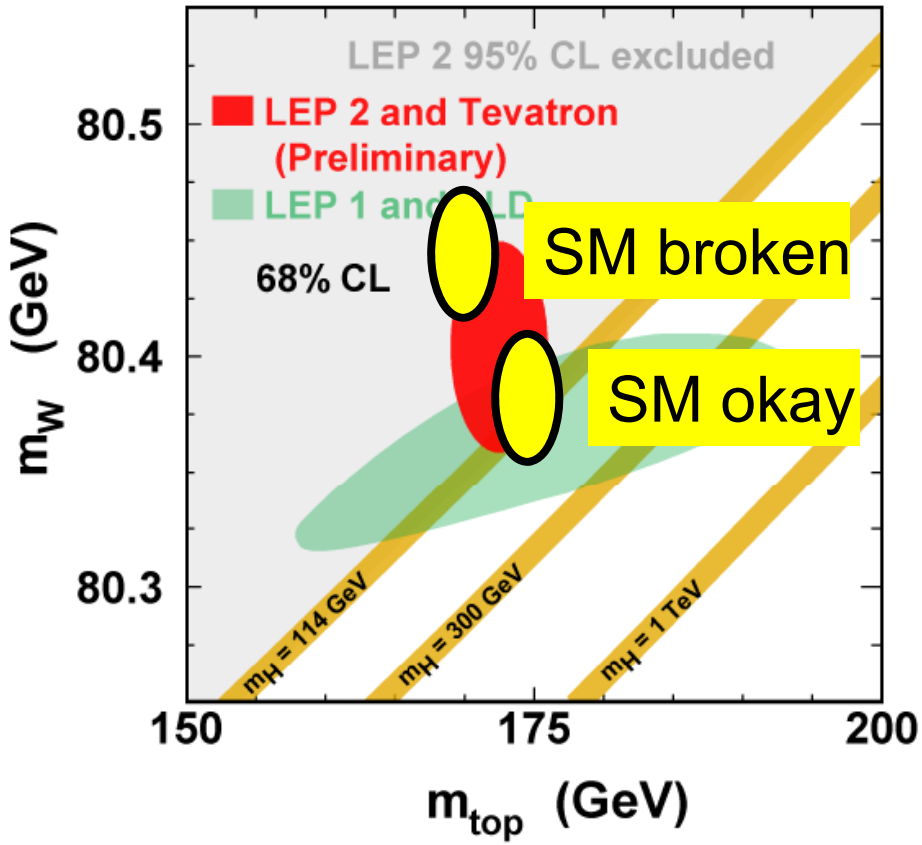
All lectures available at:

http://www-atlas.lbl.gov/~heinemann/homepage/publictalk.html

The W boson, the top quark and the Higgs boson

- Top quark is the heaviest known fundamental particle
  - Today: m_{top}=170.9+-1.8 GeV
  - Run 1: m_{top}=178+-4.3 GeV/c^2
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
    - <H>/(√2 mtop) = 0.997+-0.010
- Masses related through radiative corrections:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics

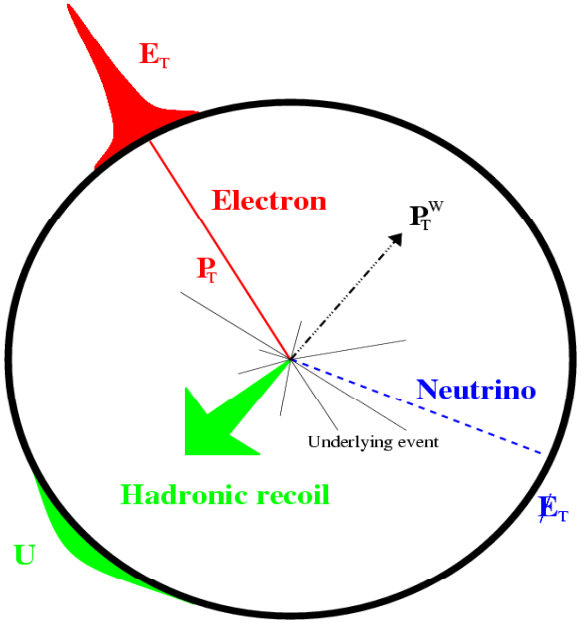




The $W^{\pm}$ boson

W Boson mass

- Real precision measurement:
  - LEP: M_W=80.367±0.033 GeV/c^2
  - Precision: 0.04%
    - => Very challenging!
- Main measurement ingredients:
  - Lepton p_T
  - Hadronic recoil parallel to lepton: $u_{||}$
- Z→ll superb calibration sample:
  - but statistically limited:
    - About a factor 10 less Z's than W's
    - Most systematic uncertainties are related to size of Z sample
      - Will scale with $1/\sqrt{N_Z}$ (=$1/\sqrt{L}$)



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Lepton Momentum Scale

- Momentum scale:
  - Cosmic ray data used for detailed cell-by-cell calibration of CDF drift chamber
  - E/p of e+ and e- used to make further small corrections to p measurement
  - Peak position of overall E/p used to set electron energy scale
    - Tail sensitive to passive material

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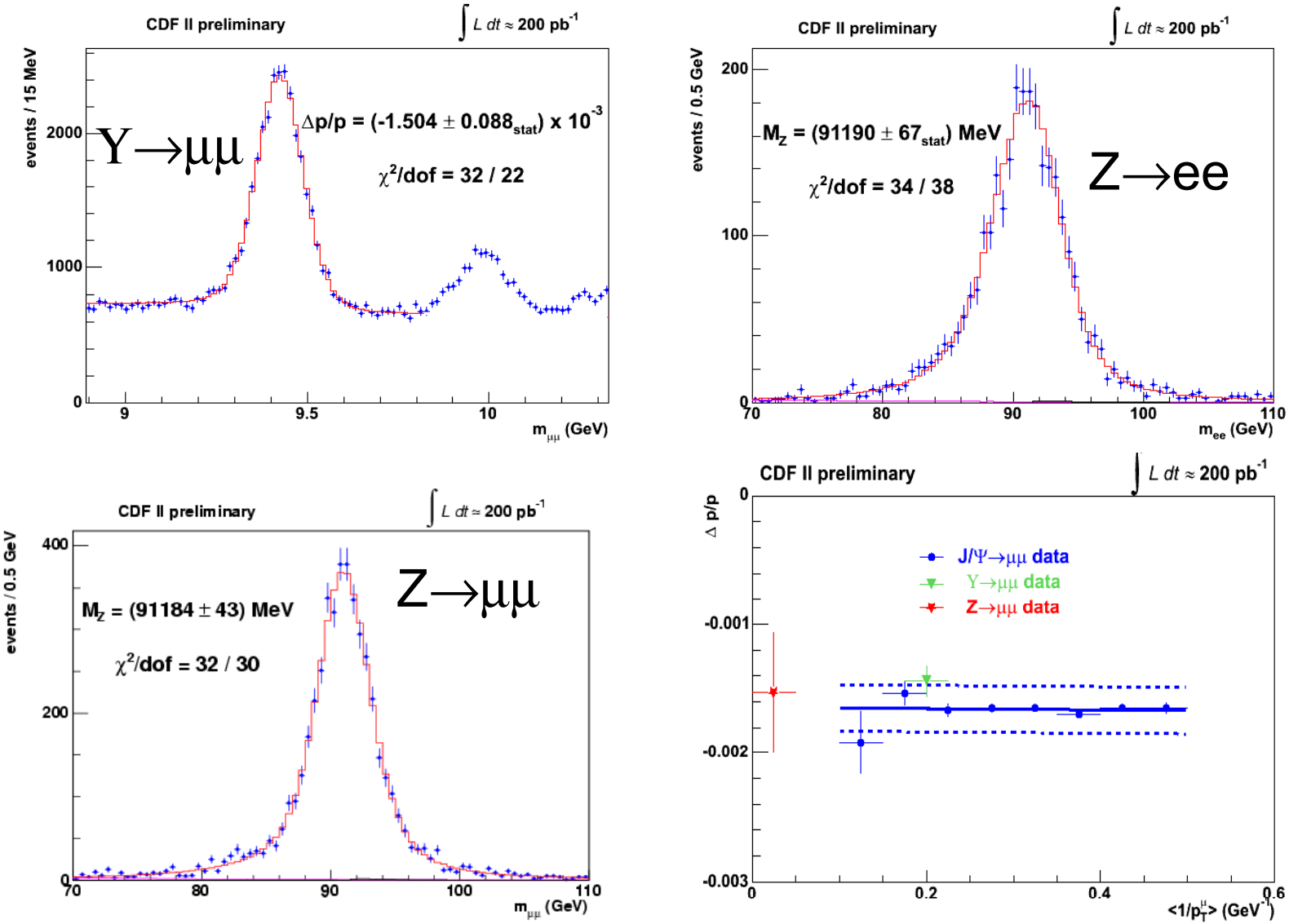
Lepton Momentum Scale and Resolution



- Systematic uncertainty on momentum scale: 0.04%

Systematic Uncertainties

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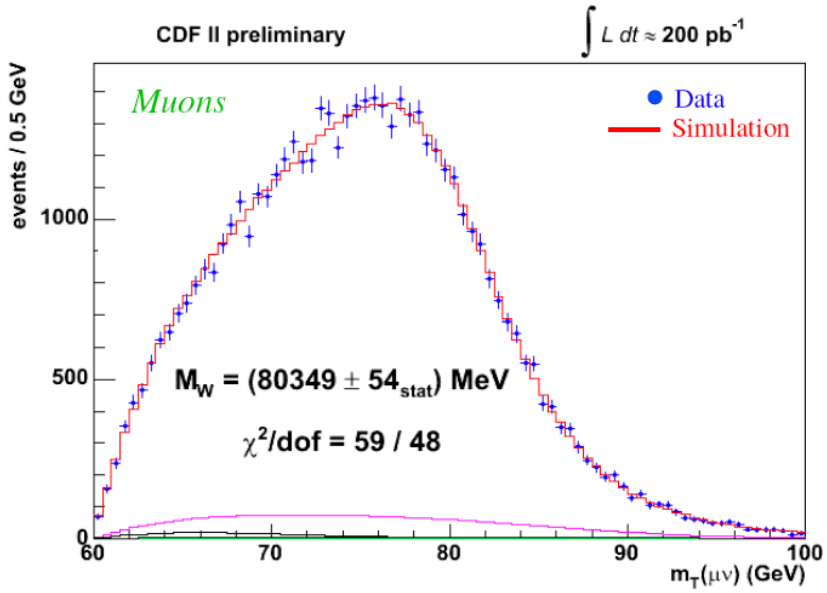
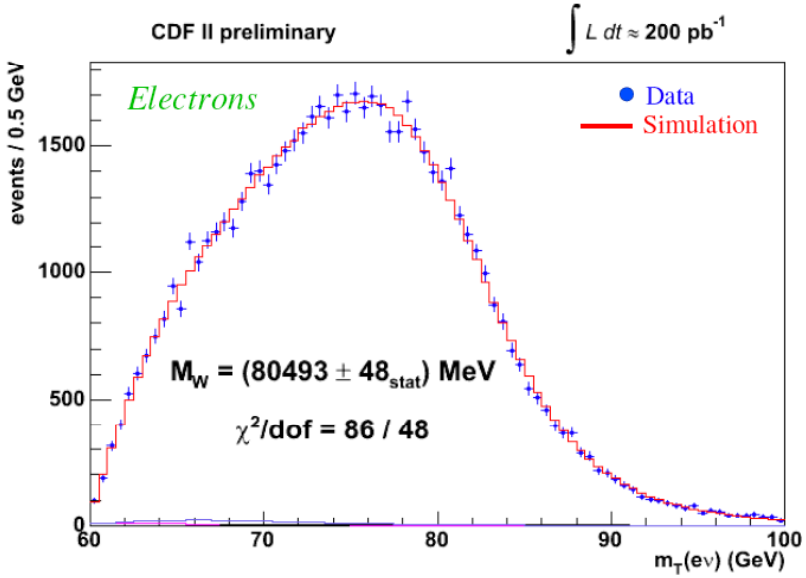
Limited by data statistics

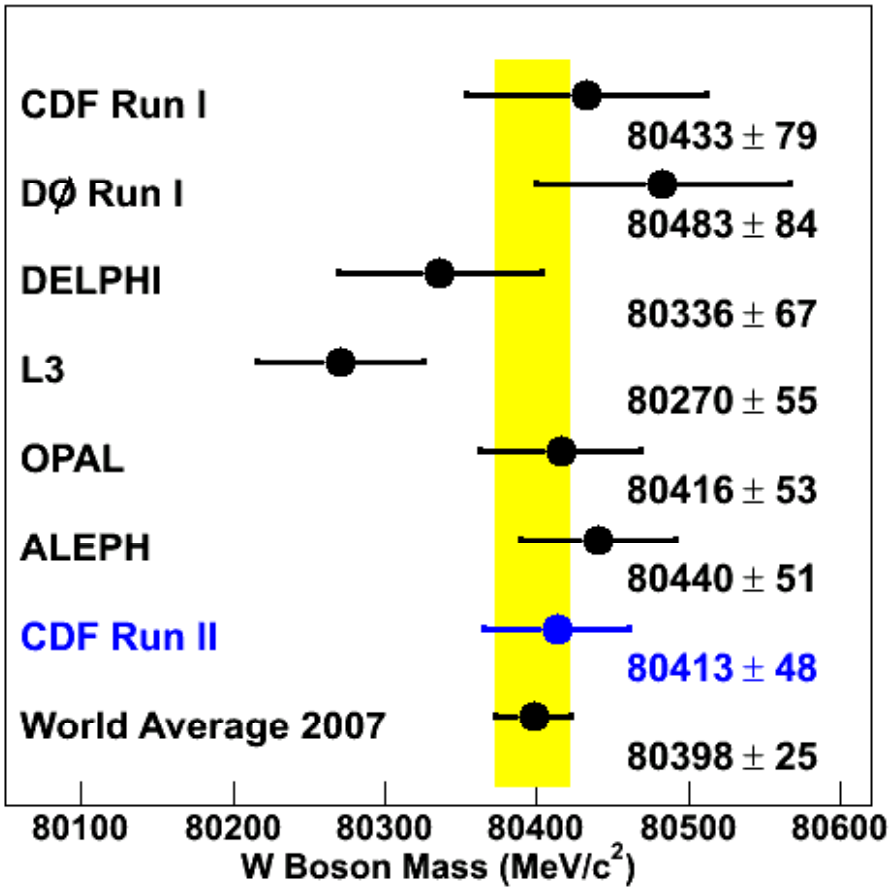
Limited by data and theoretical understanding

- Overall uncertainty 60 MeV for both analyses
  - Careful treatment of correlations between them
- Dominated by stat. error (50 MeV) vs syst. (33 MeV)

W Boson Mass







- New world average:

  M_W=80398 ± 25 MeV

- Ultimate Run 2 precision:

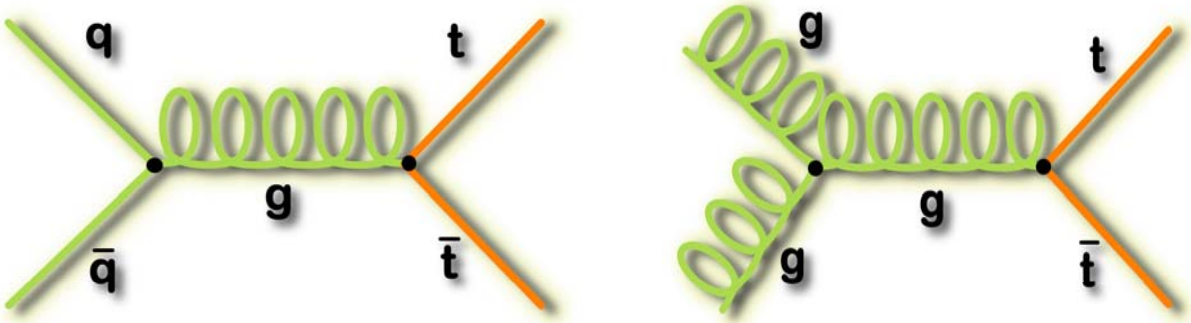
  ~15 MeV

The Top Quark

Top Quark Production and Decay

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

85%



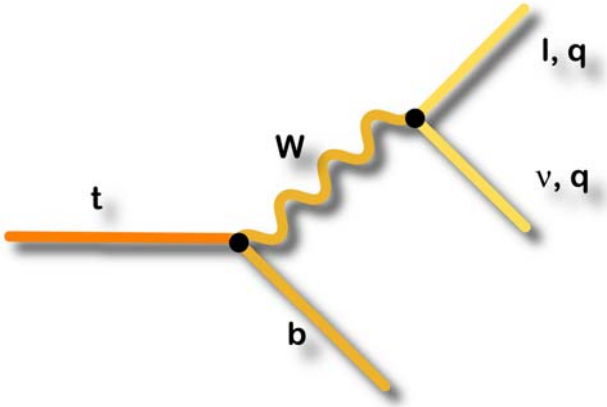
15%

- 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



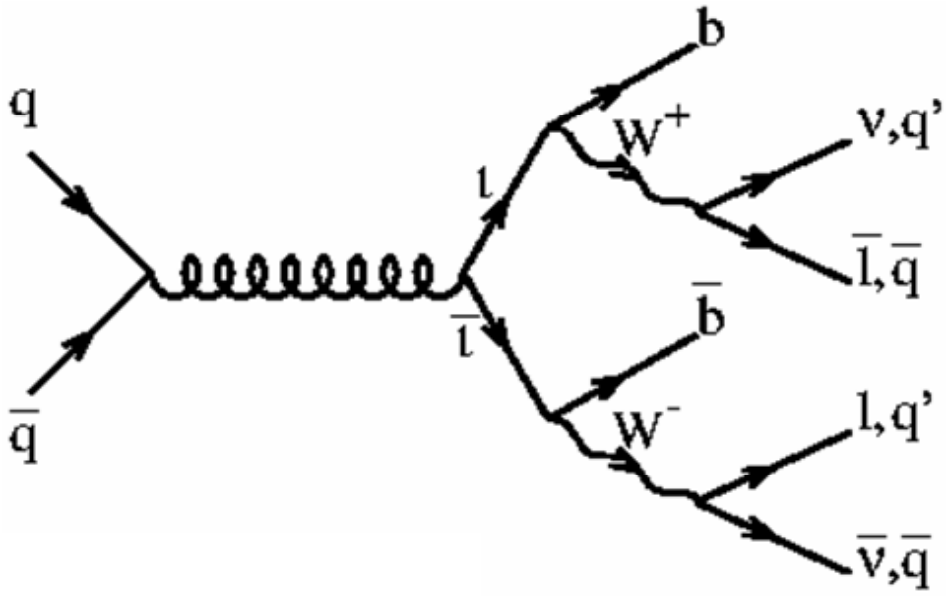
Different sensitivity and challenges in each channel

How to identify the top quark

SM: $t\bar{t}$ pair production, Br($t \to bW$)=100% , Br($W \to l\nu$)=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

(here: l=e,μ)



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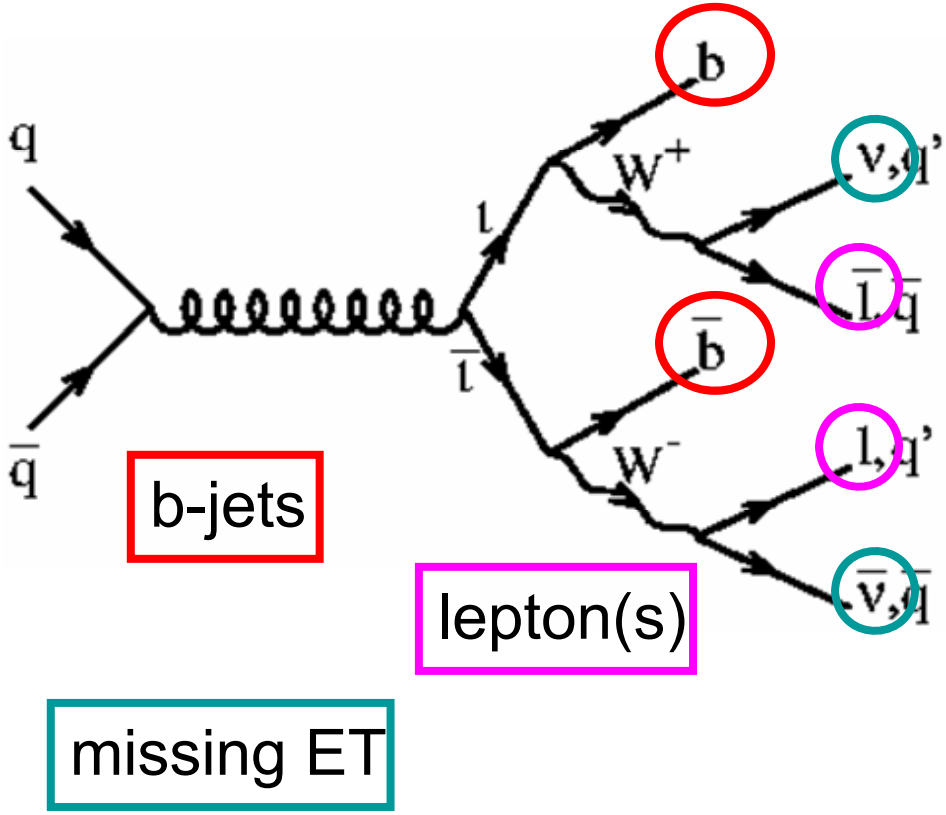

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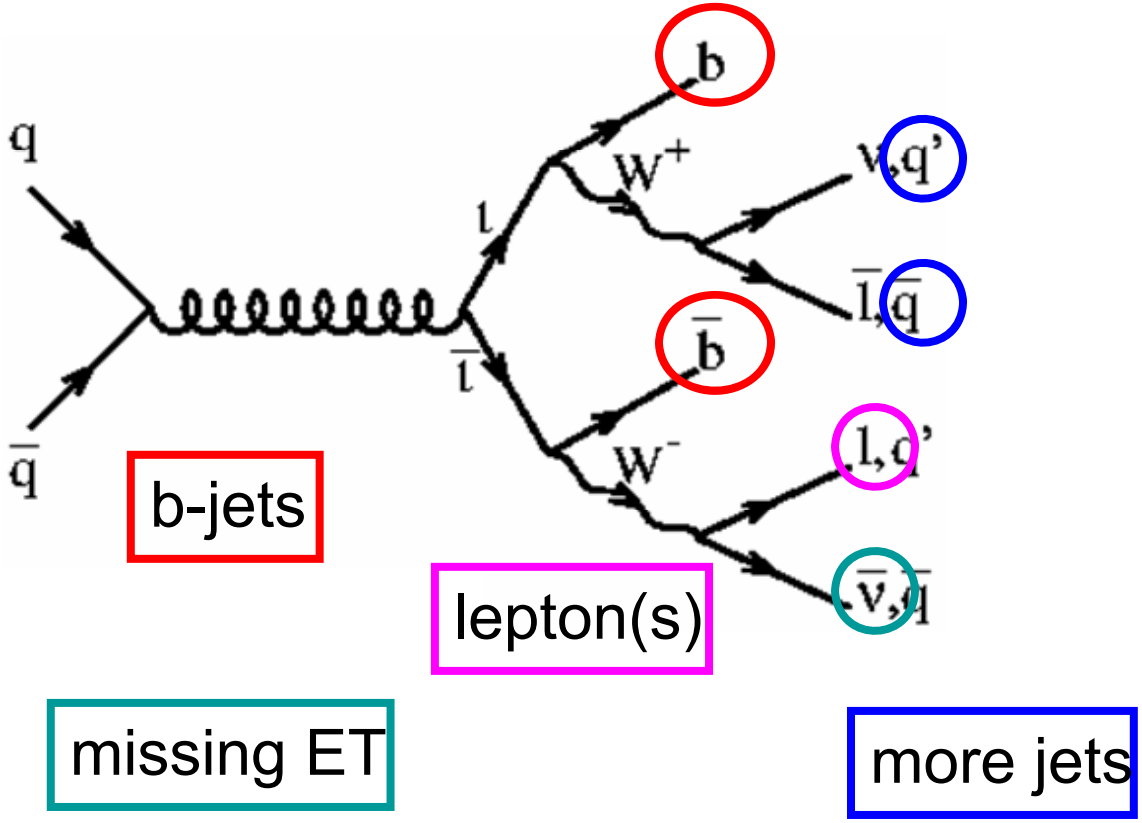

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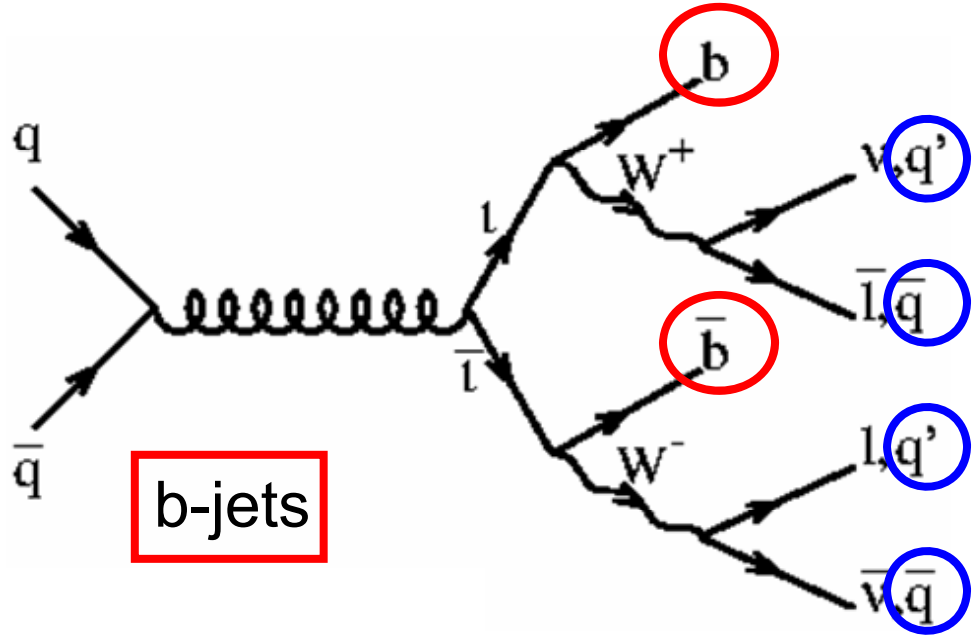
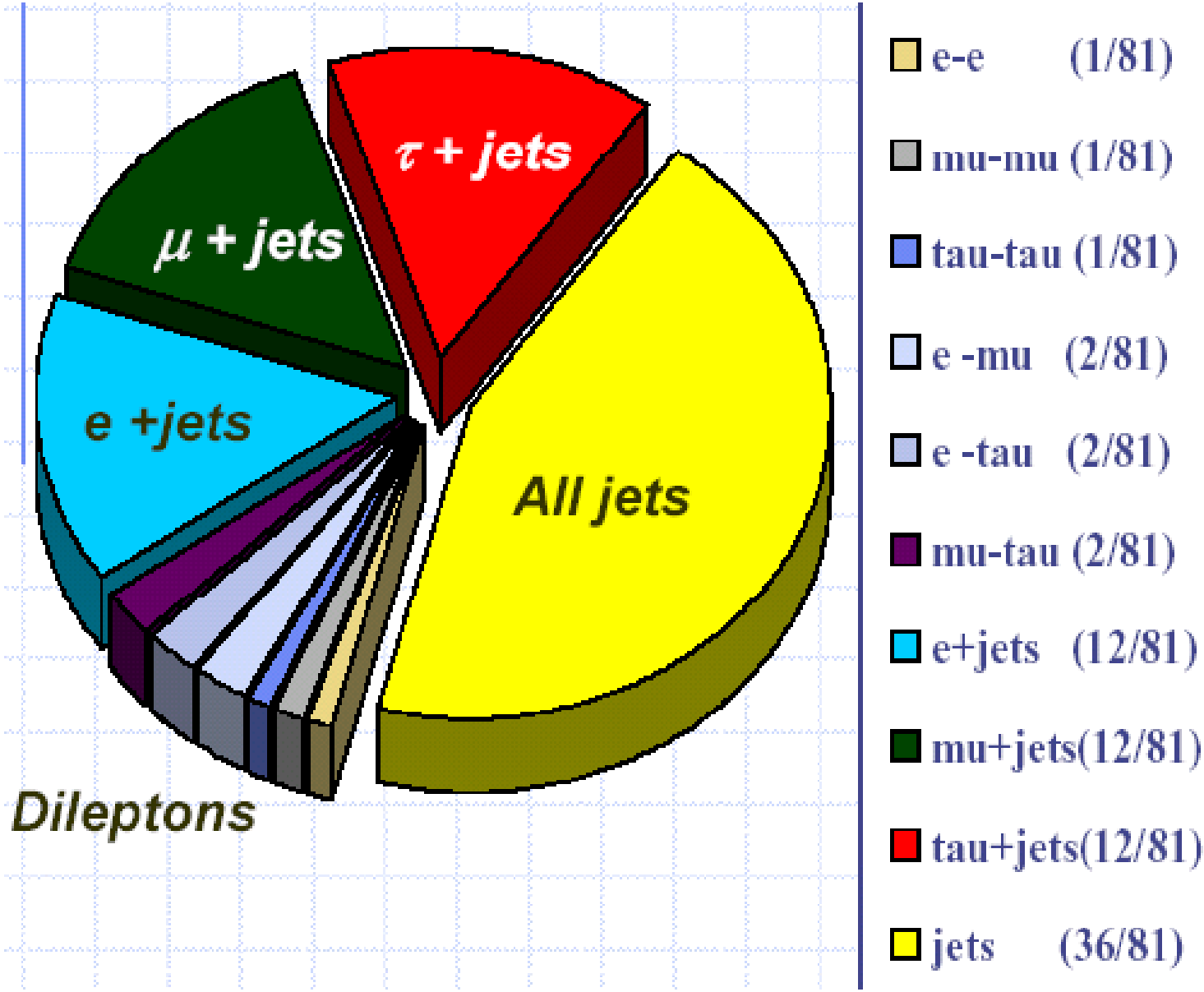


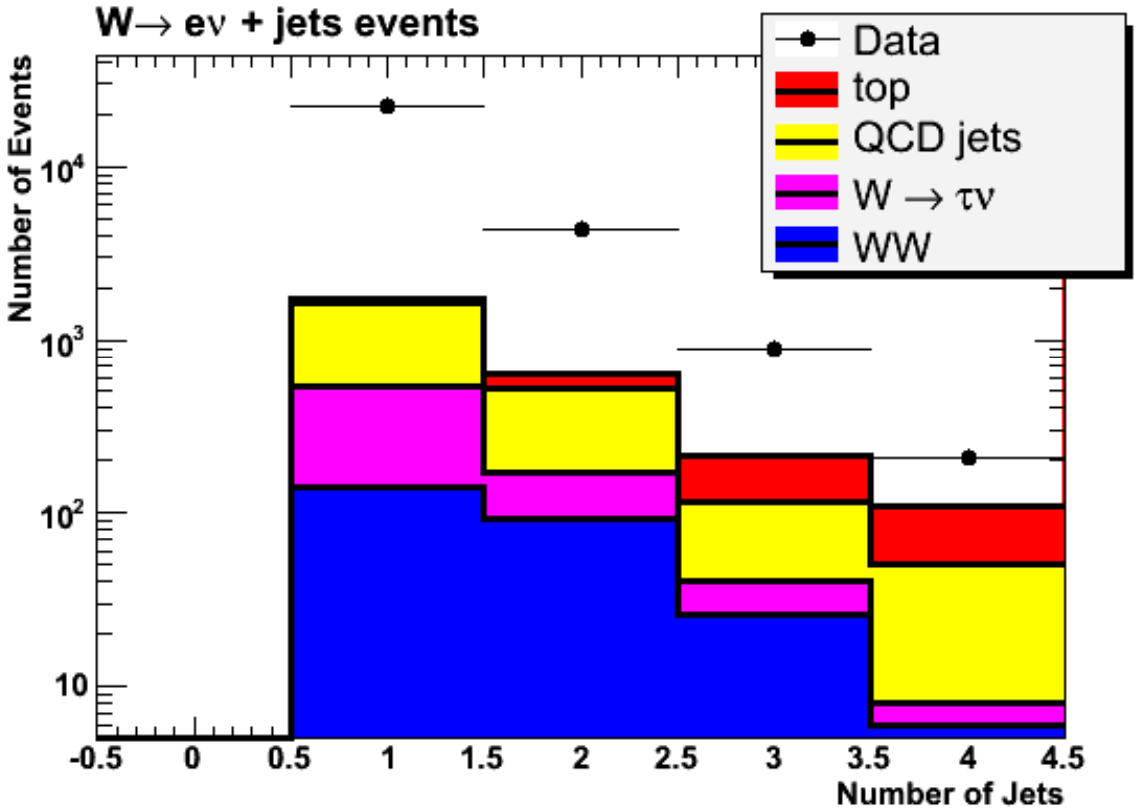
b-jets

more jets

Top Event Categories



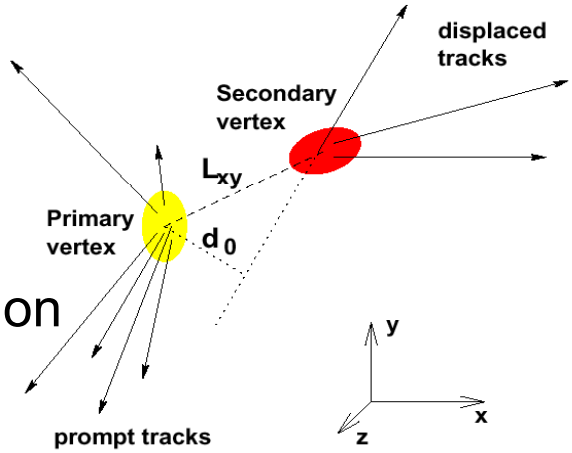
Finding the Top



- Top is overwhelmed by backgrounds:
  - Even for 4 jets the top fraction is only 30%
    - This is very different to the LHC (about 80%)!
- Use b-jets to purify sample
  - Also analyses using Neural Network to separate top kinematically

Finding the b-jets

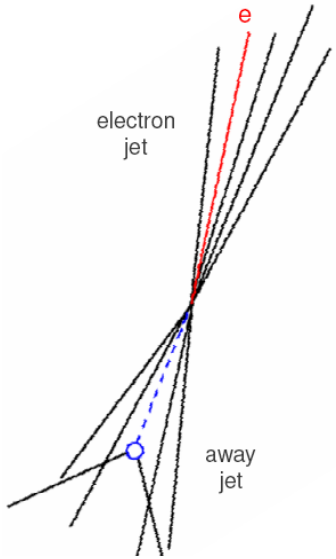
- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: $d=c\tau$
    - Lifetime τ =1.5 ps^{-1}
    - $d=c\tau$ = 460 μm
    - Can be resolved with silicon detector resolution

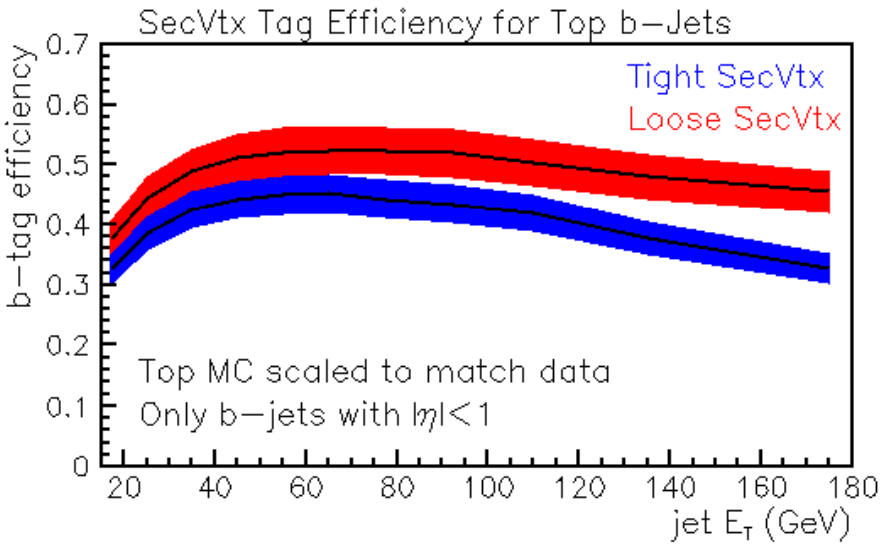


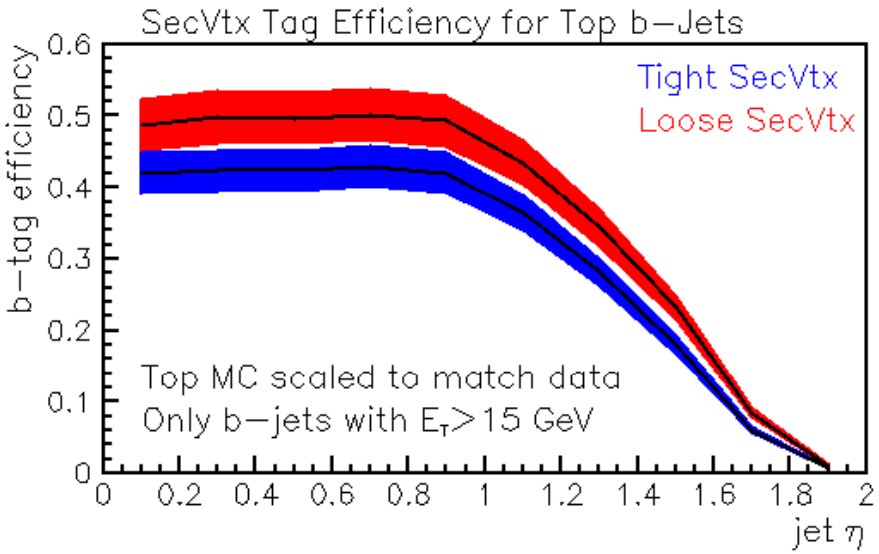
- Procedure "Secondary Vertex":
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with primary vertex (large d_0):
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - Require displacement of secondary from primary vertex
    - Form L_{xy}: transverse decay distance projected onto jet axis:
      - $L_{xy}>0$: b-tag along the jet direction => real b-tag or mistag
      - $L_{xy}<0$: b-tag opposite to jet direction => mistag!
    - Significance: $\delta L_{xy} / L_{xy} > 7$ i.e. 7σ significant displacement

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 semi-leptonic b-decay
  - Measure efficiency in data and MC



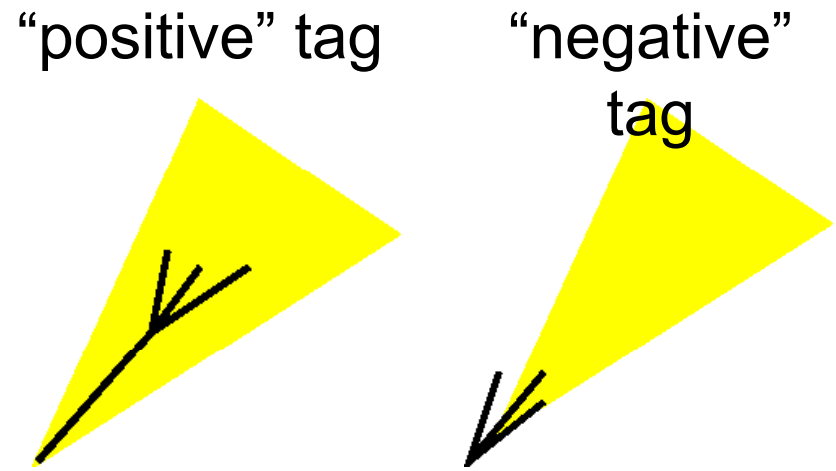


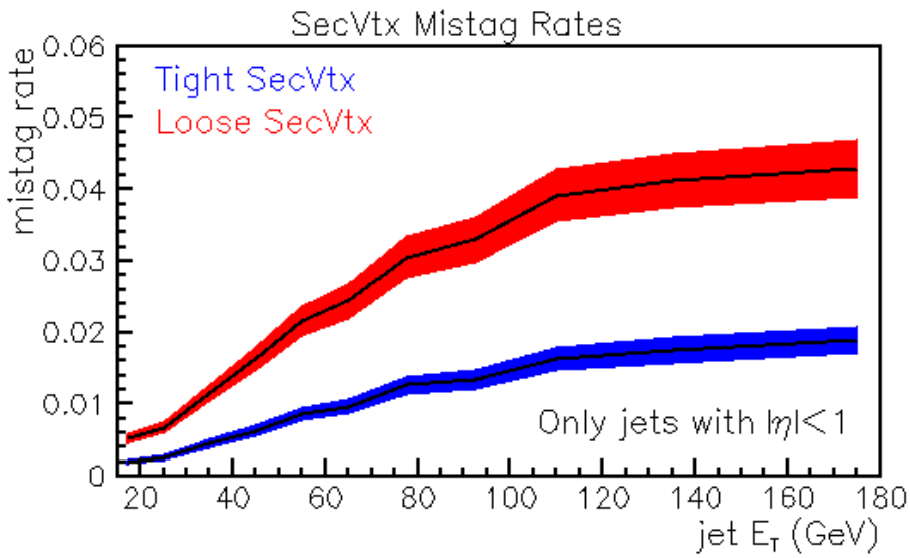


Achieve about 40-50%
(fall-off at high eta due to limited tracking coverage)

Characterise the B-tagger: Mistag rate

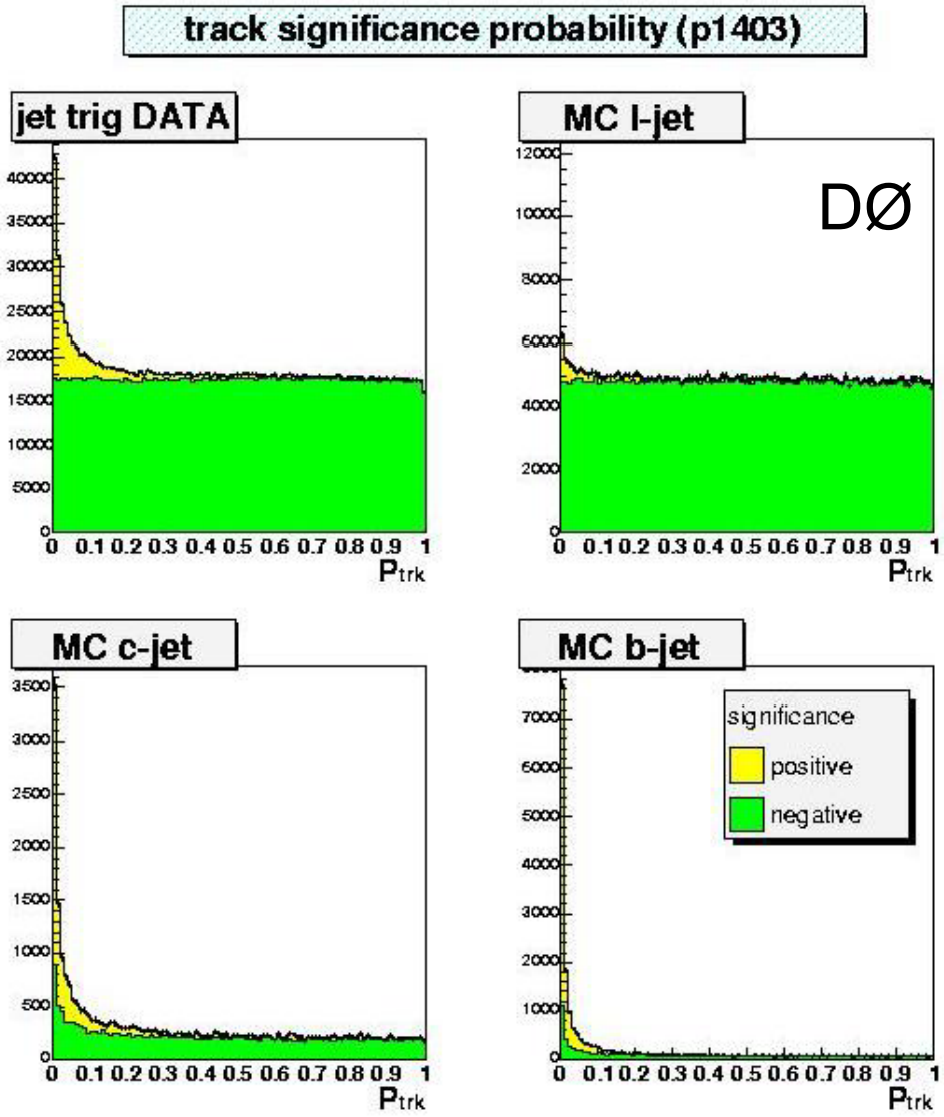
- Mistag Rate measurement:
  - Probability of light quarks to be misidentified
  - Use "negative" tags: $L_{xy}<0$
    - Can only arise due to misreconstruction
  - Mistag rate for E_T=50 GeV:
    - Tight: 0.5% (ε=43%)
    - Loose: 2% (ε=50%)
  - Depending on physics analyses:
    - Choose "tight" or "loose" tagging algorithm





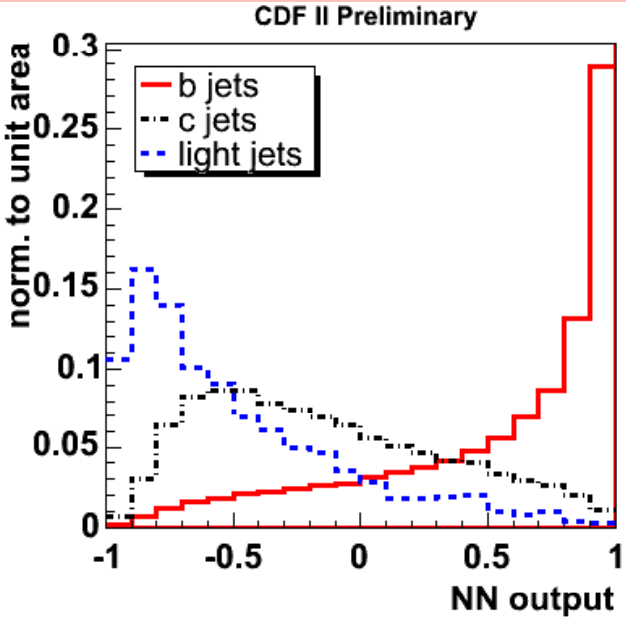
Jet Probability

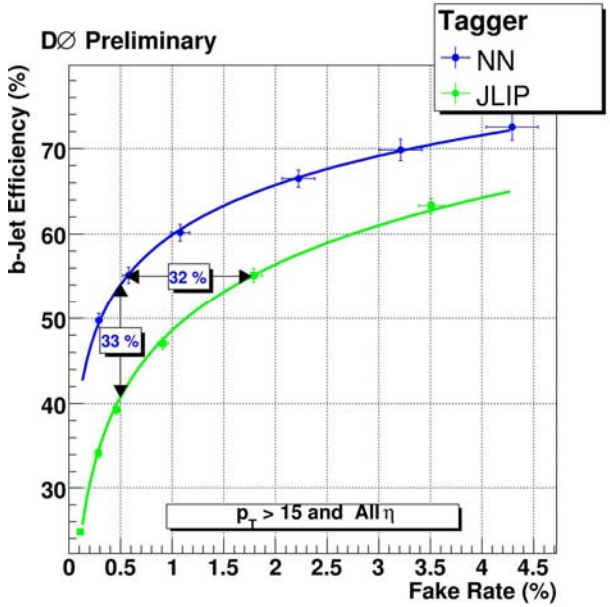
- Complementary to full secondary vertex reconstruction:
  - Evaluate probability of tracks to be prompt
    - Multiply probabilities of individual tracks together
  - "Jet Probability"
- Continuous distribution
  - Can optimize cut valued for each analysis
  - Can also use this well for charm



Neural Net B-tagging

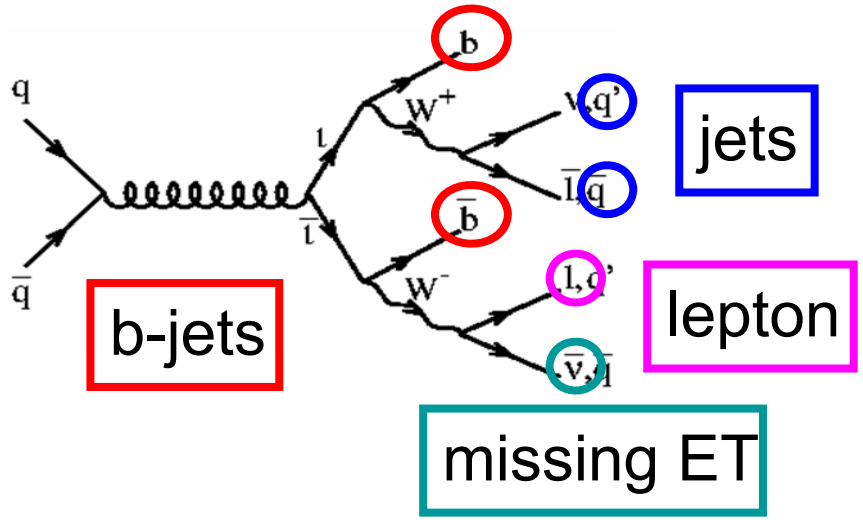
- Rather new for CDF and D0!
  - Nice to have continuous variable
  - Can be optimised depending on analysis requirements
- Several strategies
  - DØ uses 7 input variables from their three standard taggers
    - increase efficiency by 30% or purity by 30% over any single one
  - CDF uses 24 variables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



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are needed to see this picture.

66 double-tagged events, nearly no background

Check backgrounds

Top Signal

$\sigma(t\bar{t}) = 8.3^{+0.6}_{-0.5}(\text{stat}) \pm 1.1\ (\text{syst})\ \text{pb}$

Data and Monte Carlo Comparison

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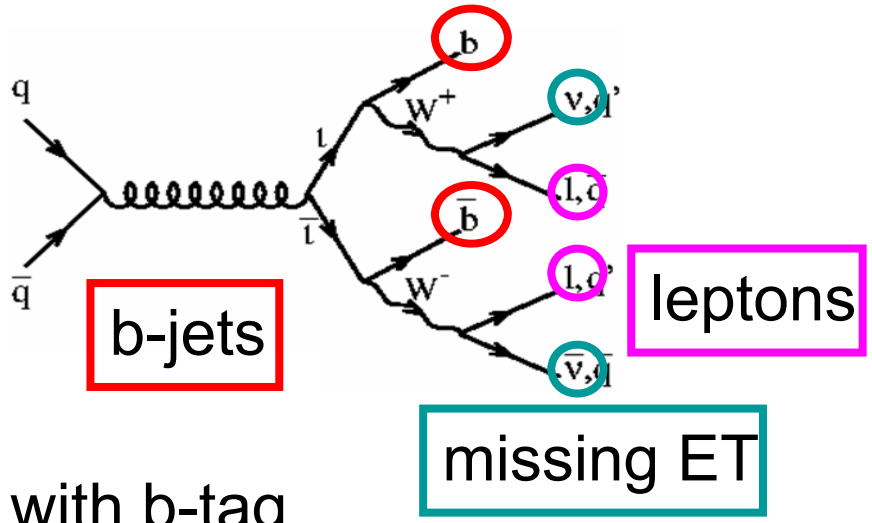
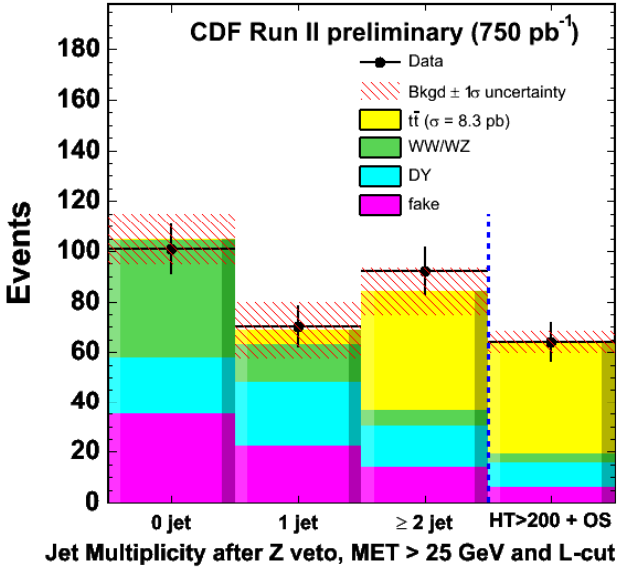
The Top Signal: Dilepton

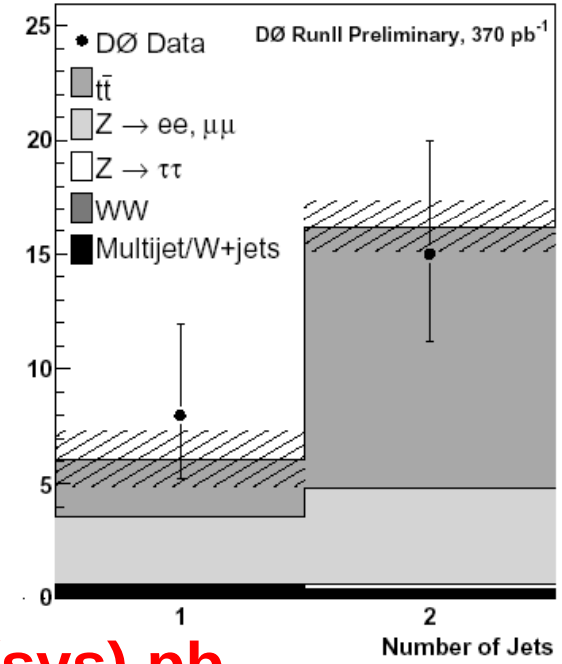
- Select:
  - 2 leptons: ee, eμ, μμ
  - Large missing E_T
  - 2 jets (with or w/o b-tag)



w/o b-tag

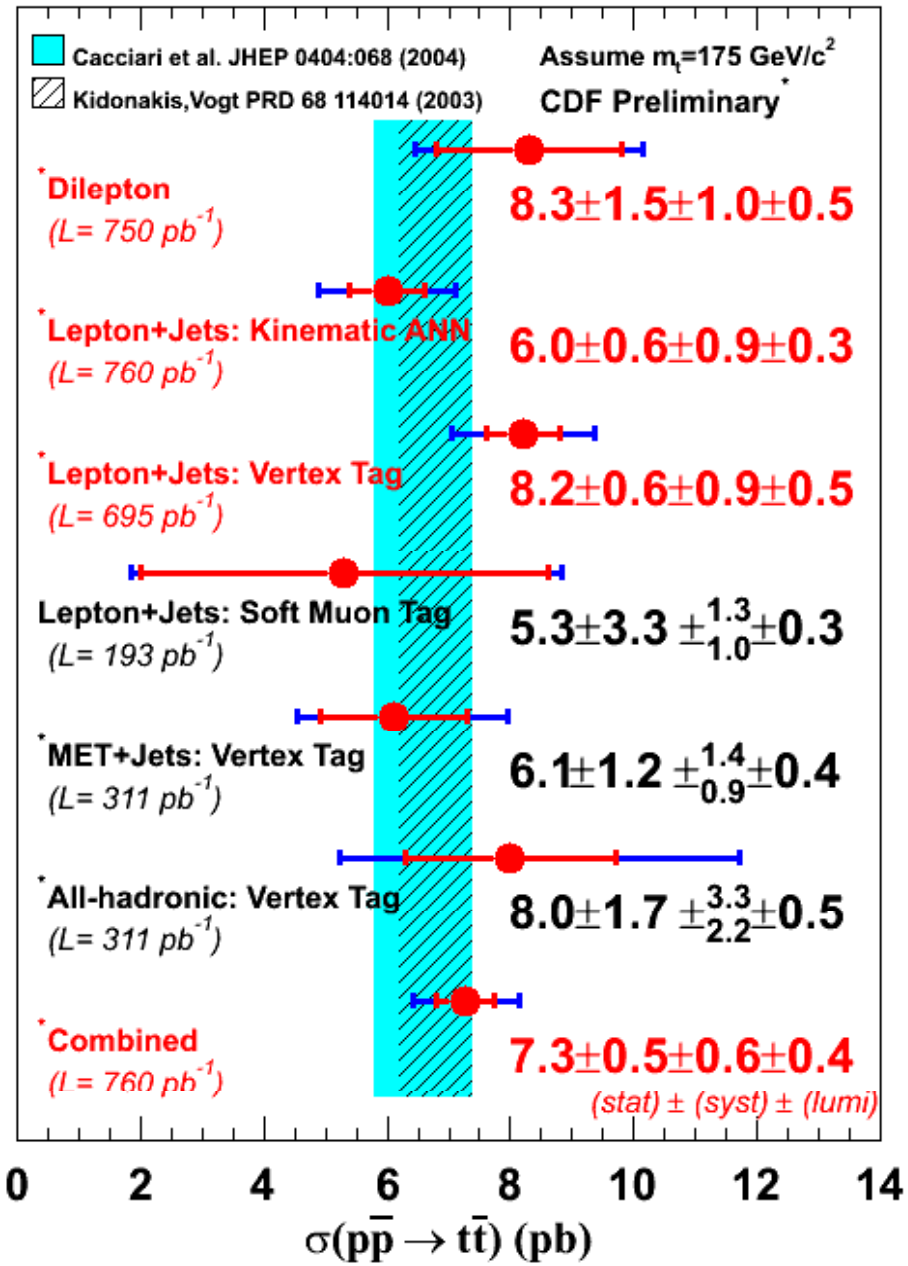


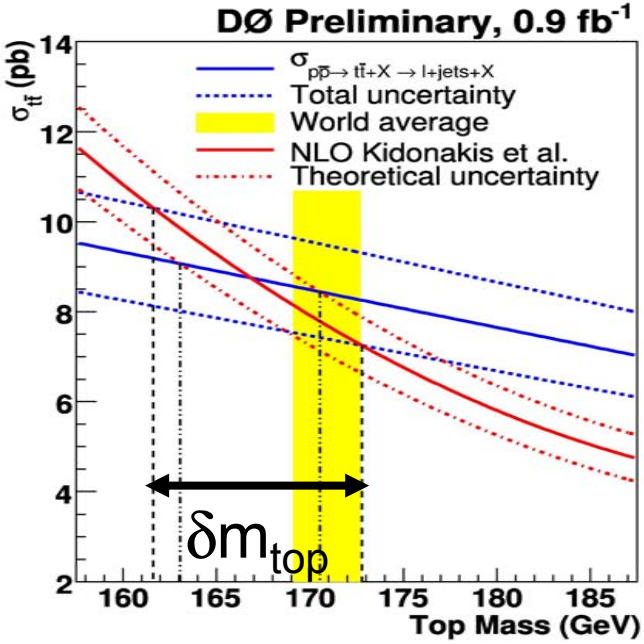
with b-tag



σ=6.2 ± 0.9 (stat) ± 0.9 (sys) pb

The Top Cross Section





- Measured using many different techniques
- Good agreement
  - between all measurements
  - between data and theory
- Can be used to extract top mass:
  - $m_{top}=166.9\ ^{+7.0}_{-6.4}$ GeV/c^2

Top Mass Measurement: $tt \rightarrow (bl\nu)(bqq)$

- 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

QuickTime™ and a
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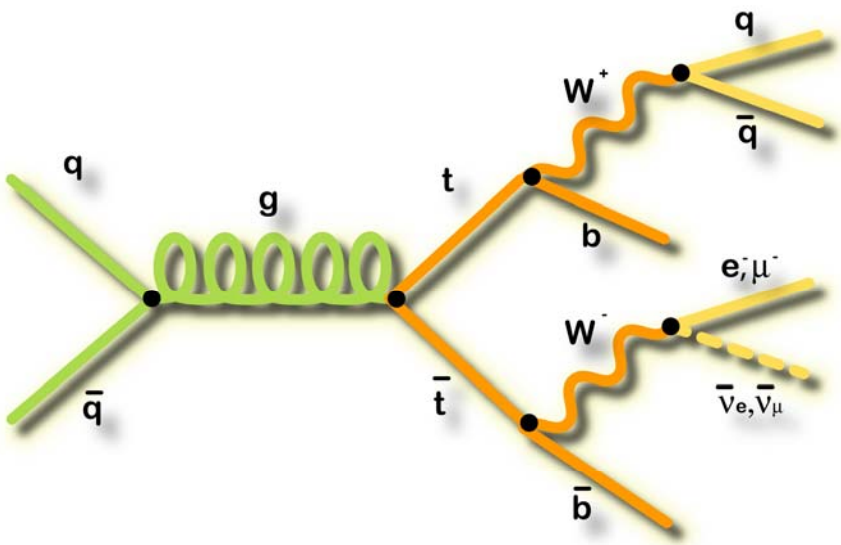
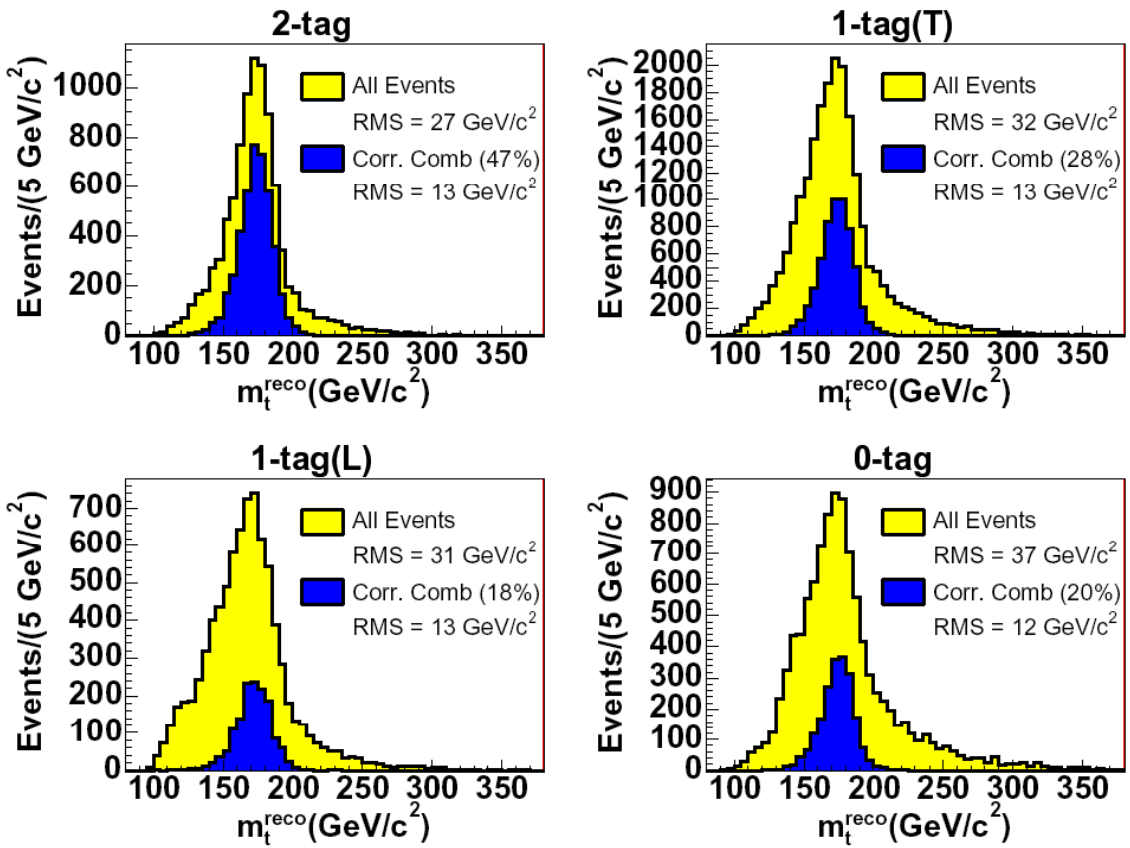


Top Mass Determination

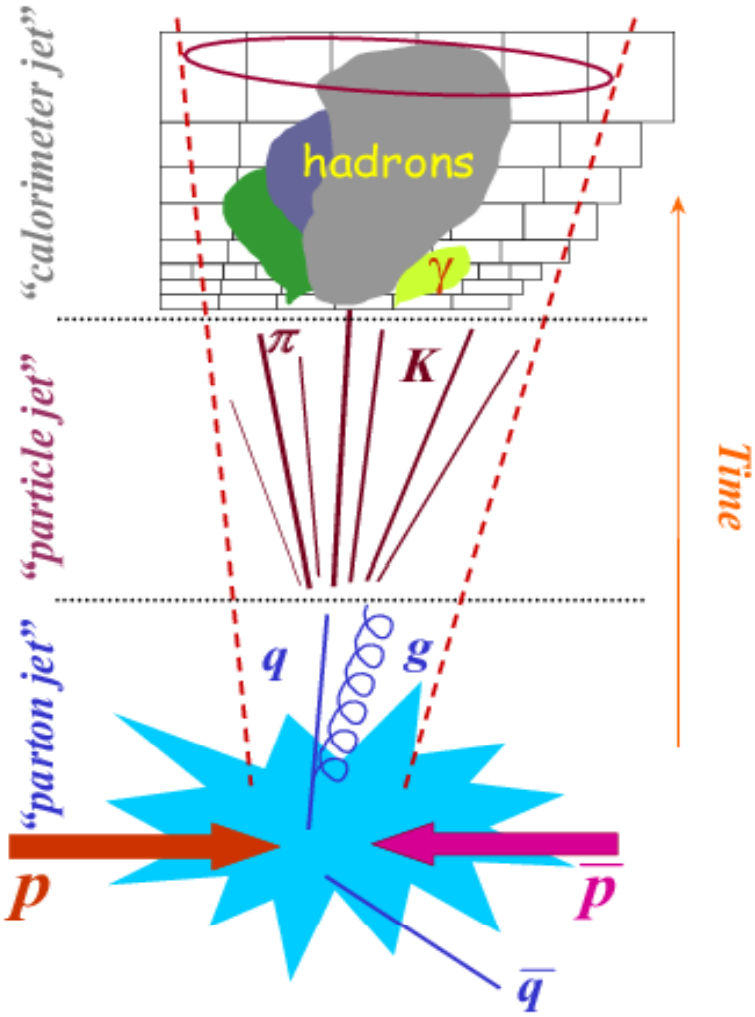
- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,\nu}=-(p_{T,l}+p_{T,UE}+\sum p_{T,jet})$
- Constraints:
  - $M(l\nu)=M_W$
  - $M(q\bar{q})=M_W$
  - $M(t)=M(\bar{t})$
- Unknown:
  - Neutrino p_z
- 1 unknown, 3 constraints:
  - Overconstrained
 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



Selecting correct combination 20-50% of the time

Jet Energy Scale

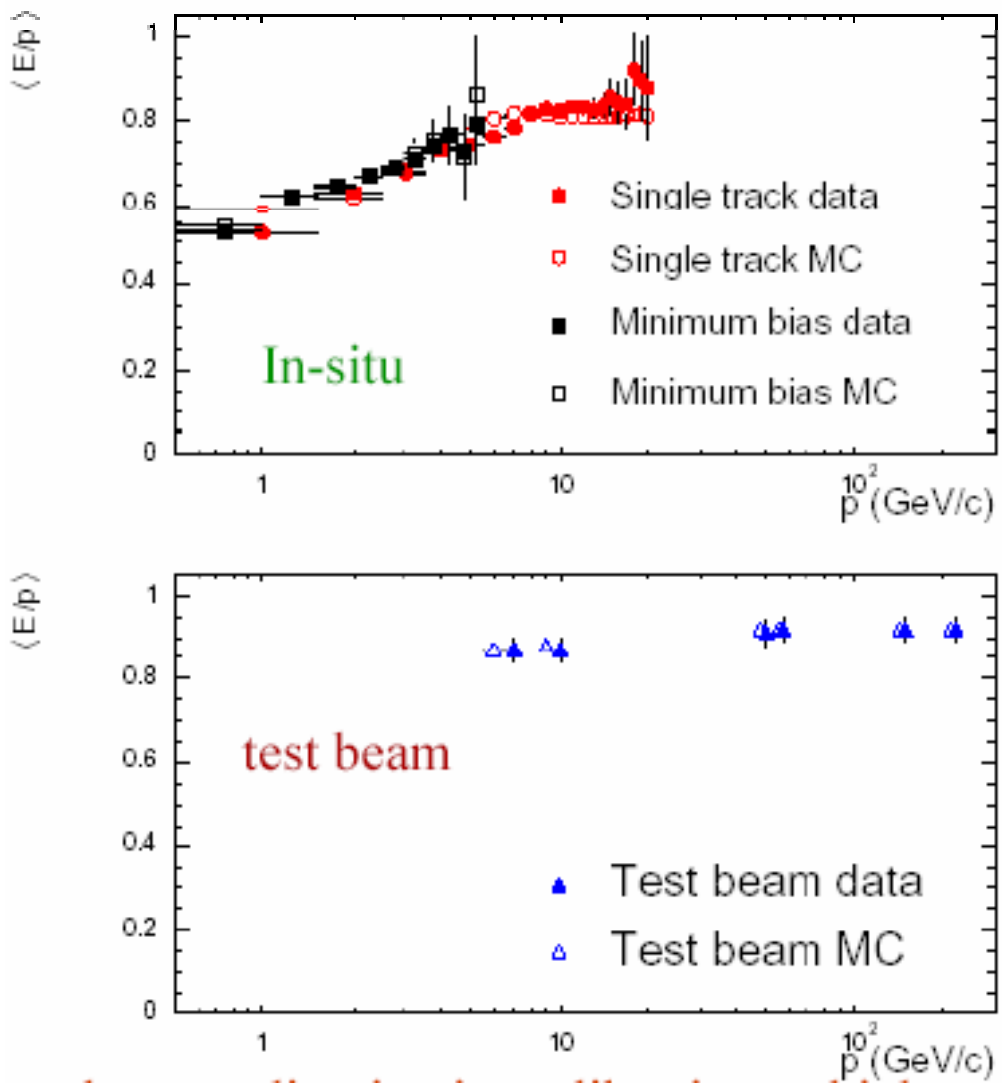
- Jet energy scale
  - Determine the energy of the partons produced in the hard scattering process
  - Instrumental effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - Physics effects:
    - Initial and final state radiation
    - Underlying event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



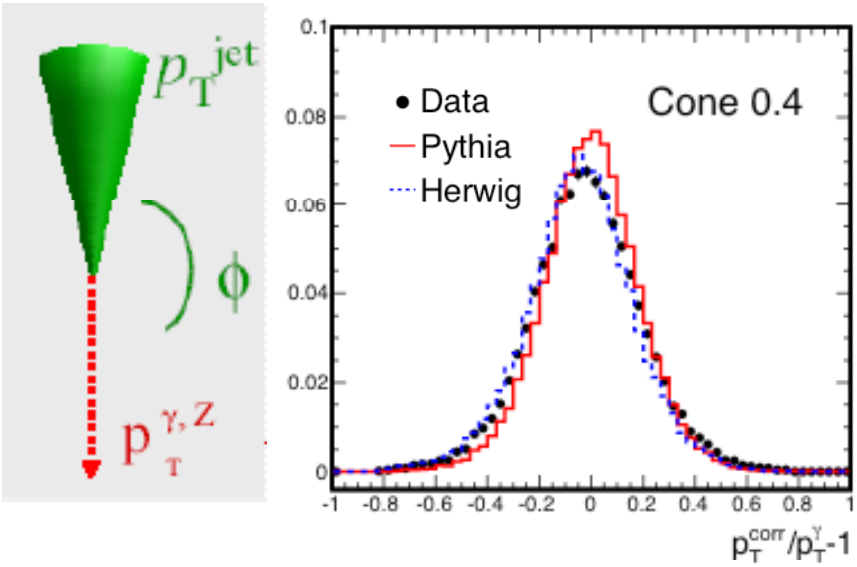
$$P_{T,jet}^{particle} = \left[P_{T,jet}^{measured} \times f_{rel} - MI\right] \times f_{abs}, \qquad P_T^{parton} = P_{T,jet}^{particle} - UE + OOC$$

Jet Energy Scale Studies

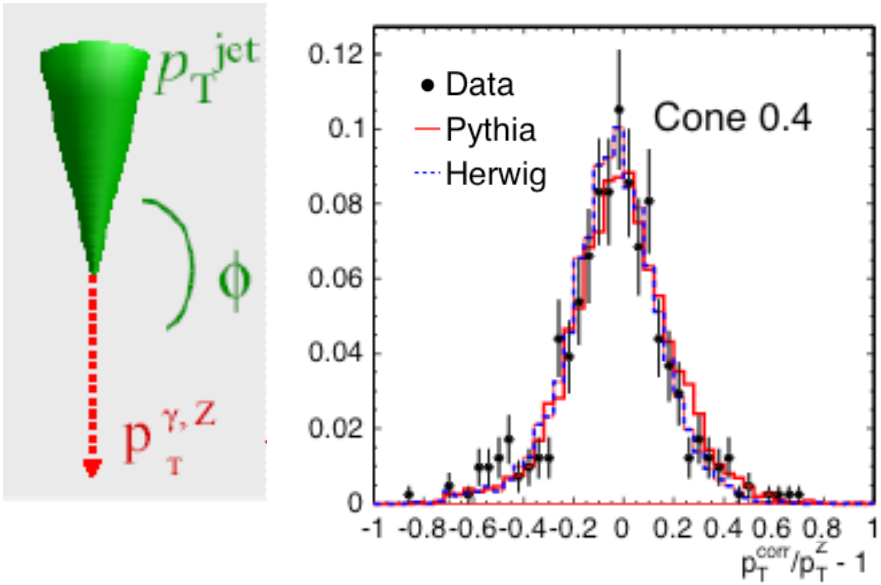
- Measure energy response to charged particles
  - Test beam and in situ
  - CDF: Response rather non-linear
  - DØ: compensating =>has better response
    - Some compensation “lost” due to shorter gate in run 2
- CDF uses fast parameterized showers:
  - GFLASH
  - Tuned to data
- DØ uses full GEANT



Testing Jets in Photon-Jet and Z-Jet Data



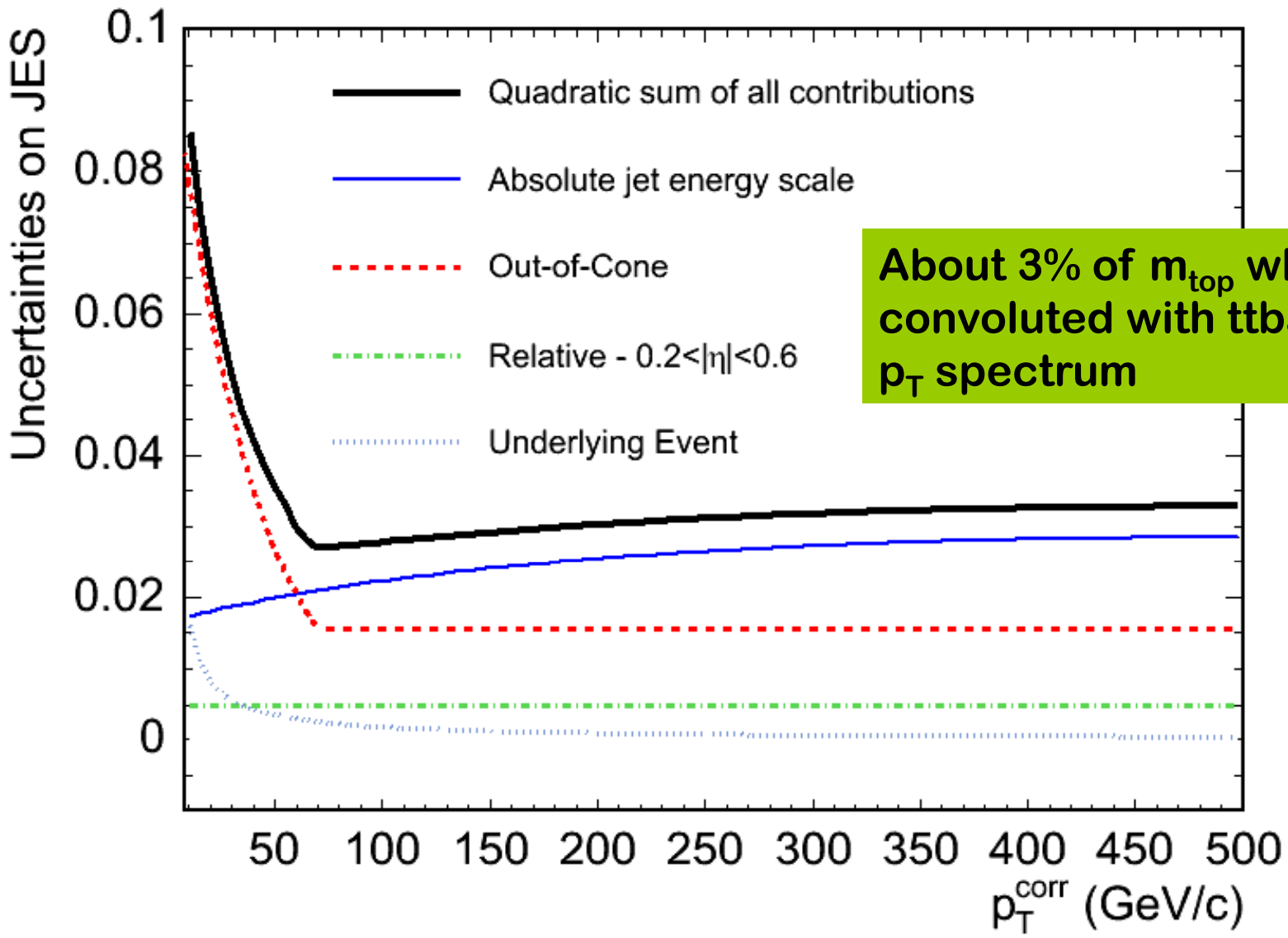
$p_T^{jet}/p_T^{\gamma}-1$



$p_T^{jet}/p_T^{Z}-1$

- Agreement within 3% but differences in distributions!
  - Data, Pythia and Herwig all a little different in photon-jet data
- These are physics effects!
  - Detailed understanding with higher statistics and newer MC in progress

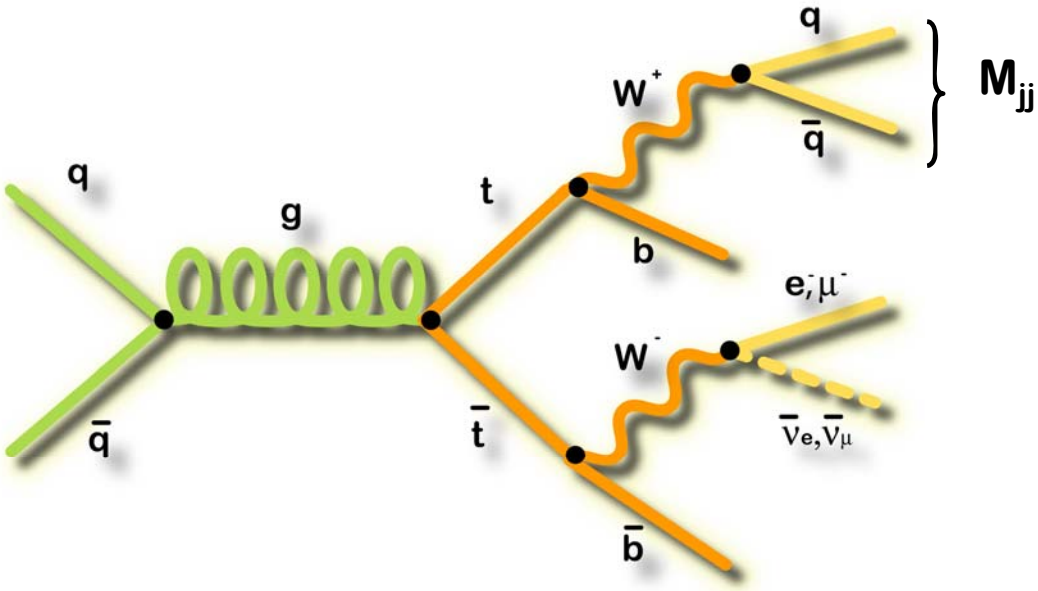
Jet Energy Scale Uncertainties



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

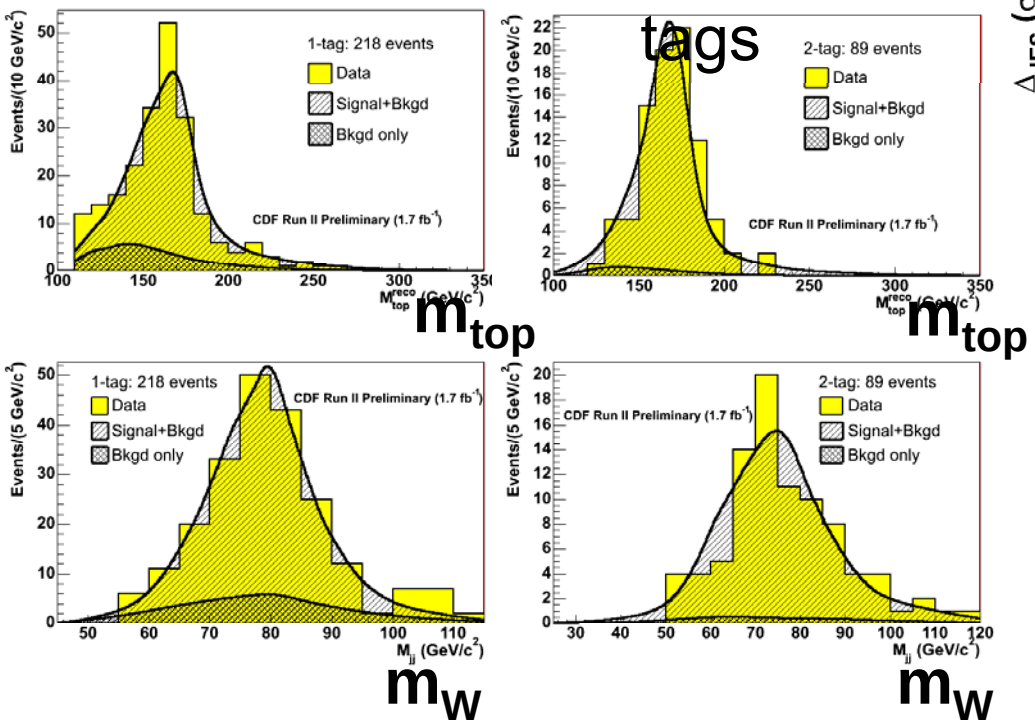
Measurement of JES scales directly with data statistics

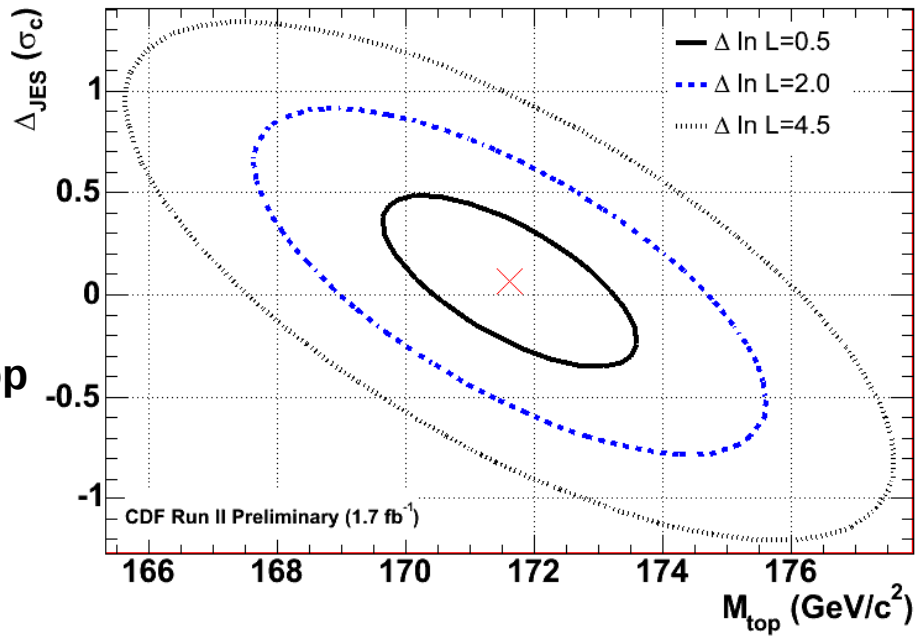
Template Analysis Results on m_{top}

- Using 307 candidate events in 1.7 fb^{-1}
- Using in-situ JES calibration results in factor two improvement on JES

1 b-tag

2 b-tags



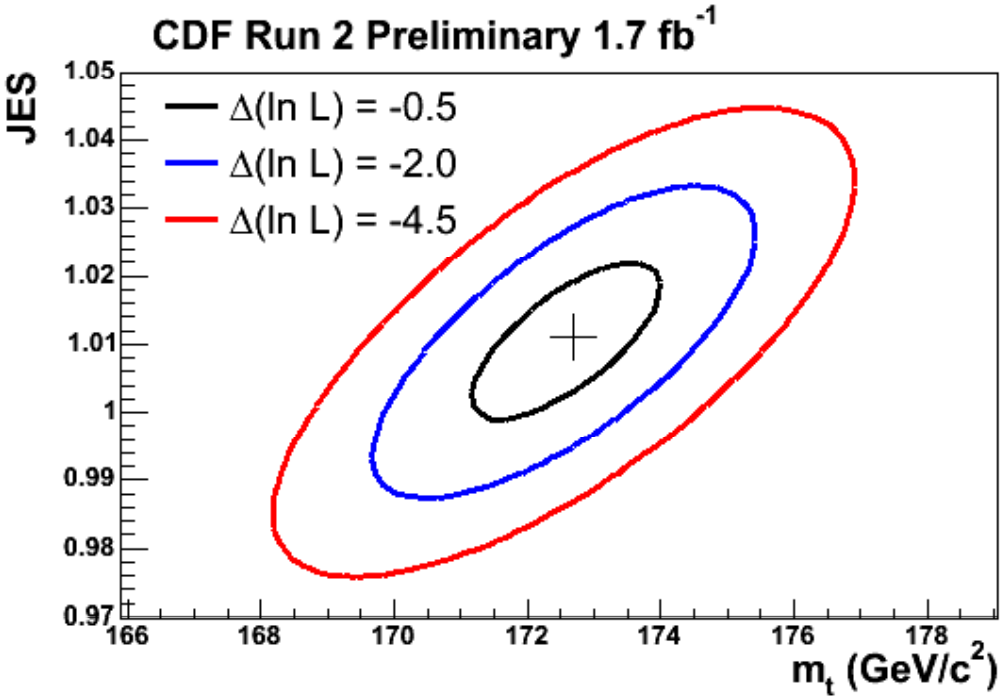


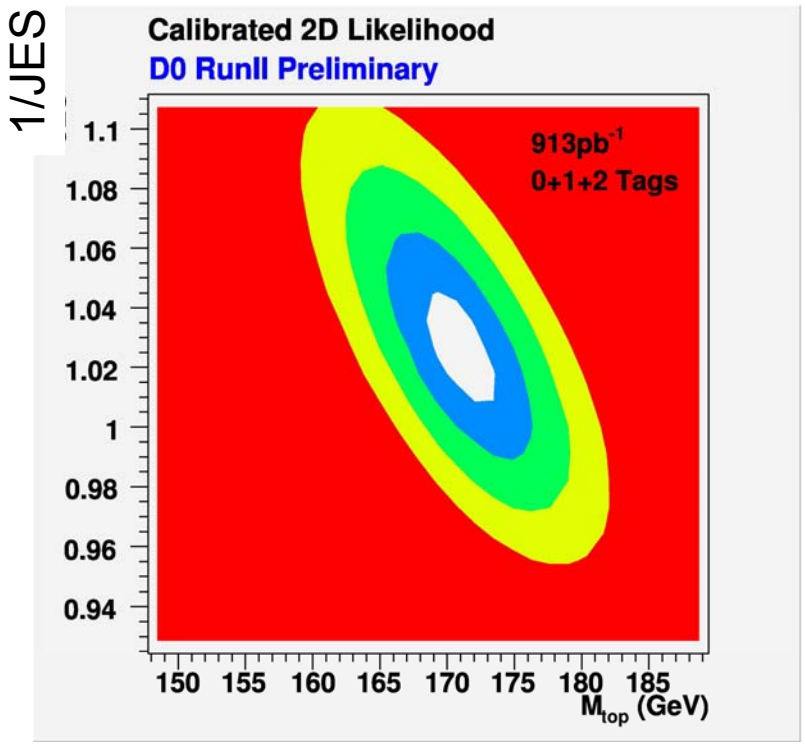
$$m_{top} = 171.6 \pm 2.1 \pm 1.1 = 171.6 \pm 2.4\ GeV/c^2$$

Matrix Element Results on m_{top}

- Using most recent analysis of 343 candidates in 1.7 fb^{-1} m_{top} is:

$$m_t = 172.7 \pm 1.3\ (\text{stat.}) \pm 1.2\ (\text{JES}) \pm 1.2\ (\text{syst})\ \text{GeV}/c^2 = 172.7 \pm 2.1\ (\text{total})\ \text{GeV}/c^2$$

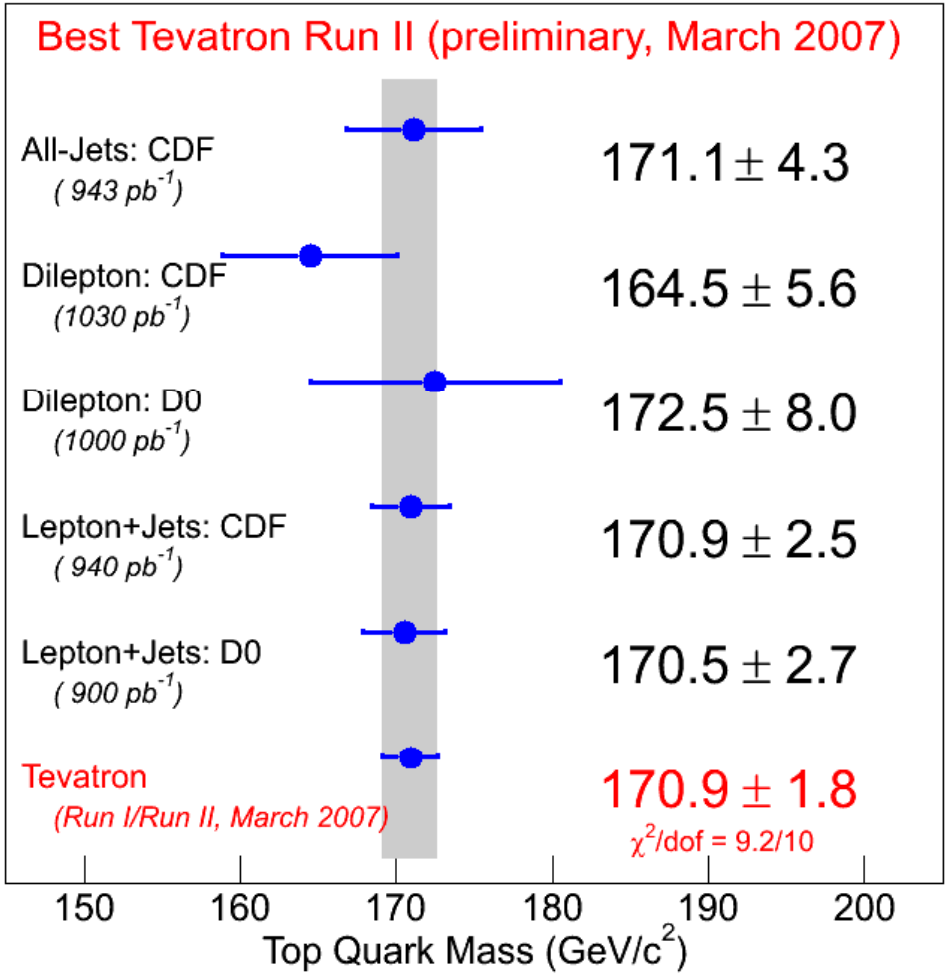




Consistent result. Slightly better precision than Template Method

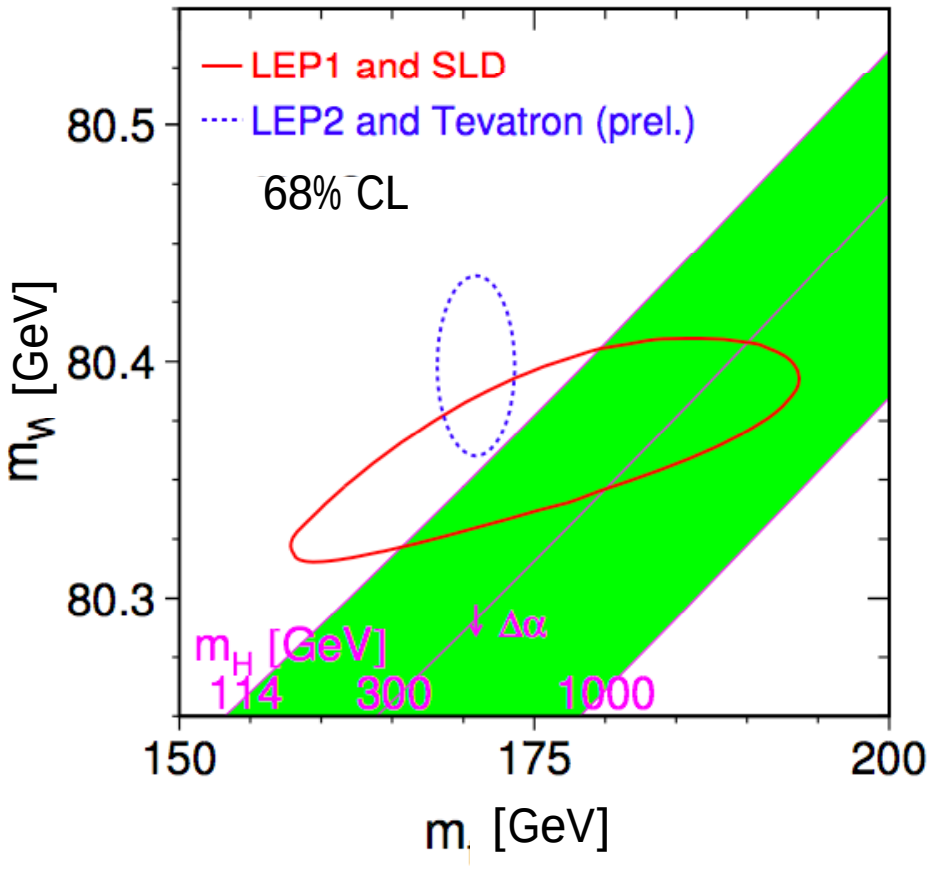
Combining M_{top} Results

- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- New uncertainty: 1.8 GeV
  - Dominated by systematic uncertainties

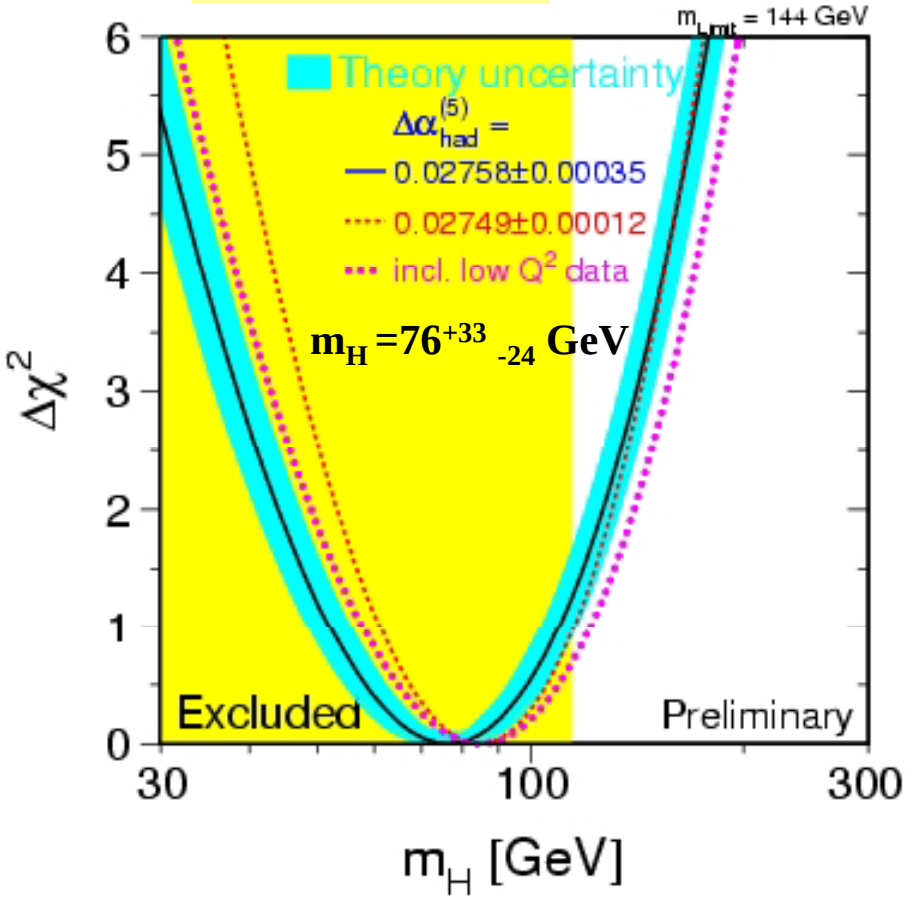


Implications for Higgs Boson

m_H constrained in the Standard Model



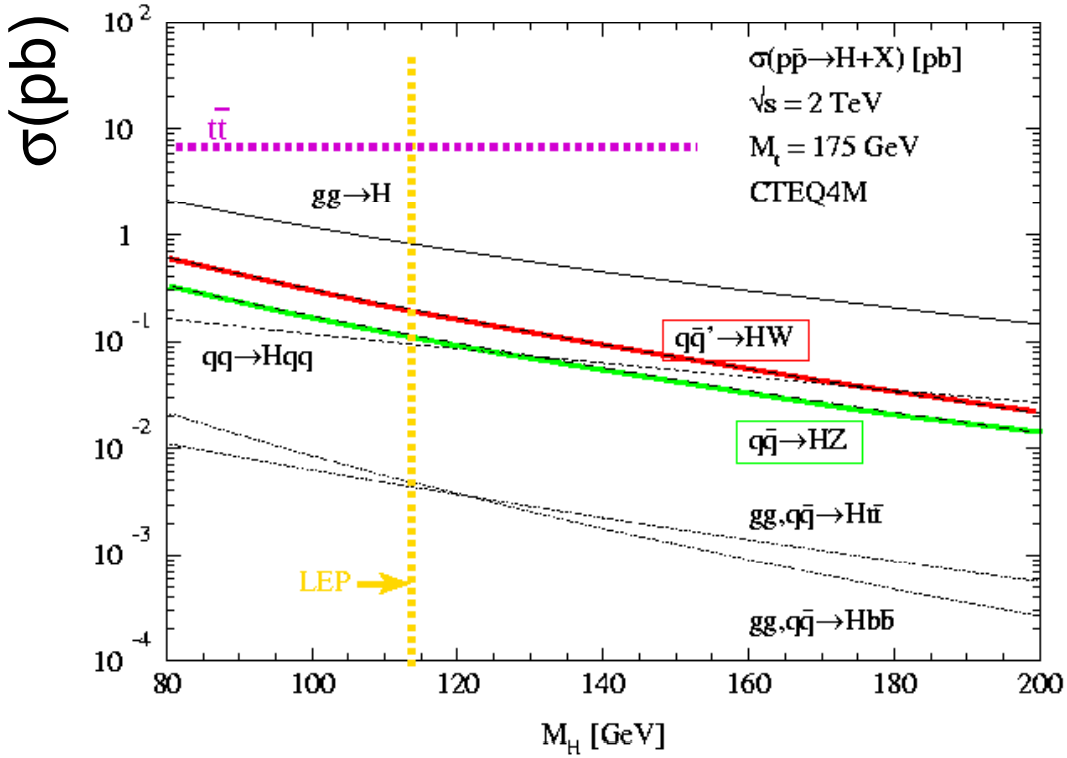
LEPEWWG 07/07

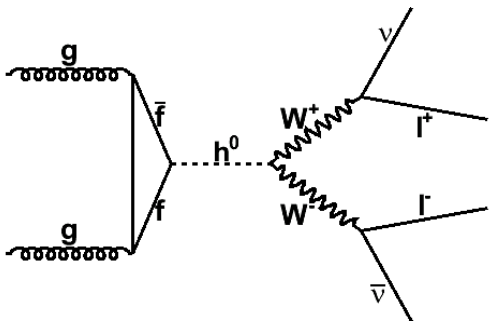


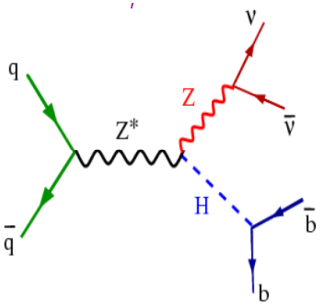
Direct searches at LEP2:
m_H>114.4 GeV @95%CL

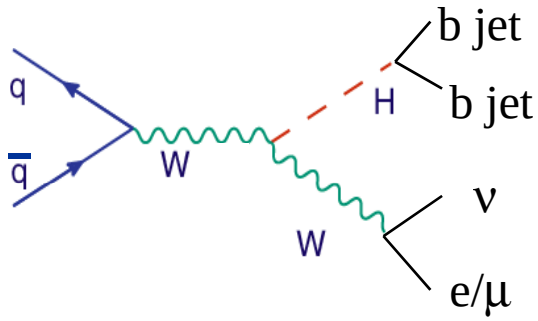
Indirect constraints:
m_H<144 GeV @95%CL

Higgs Production at the Tevatron



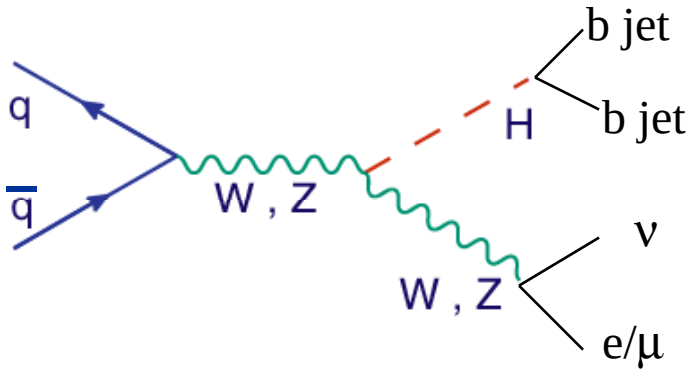






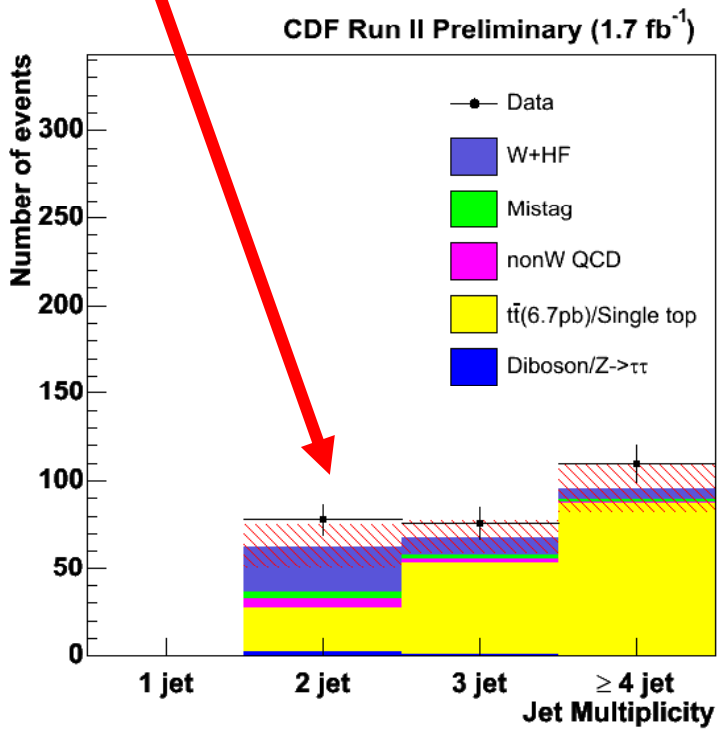
dominant: gg→ H, subdominant: HW, HZ

WH→lνbb



- **WH selection:**
  - **1 or 2 tagged b-jets**
  - **electron or muon with p_T > 20 GeV**
  - **E_T^{miss} > 20 GeV**

Now looking for 2 jets

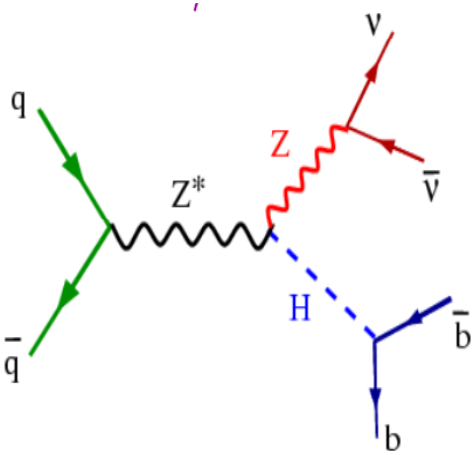


Expected Numbers of Events:

WH signal: 0.85 + 0.65

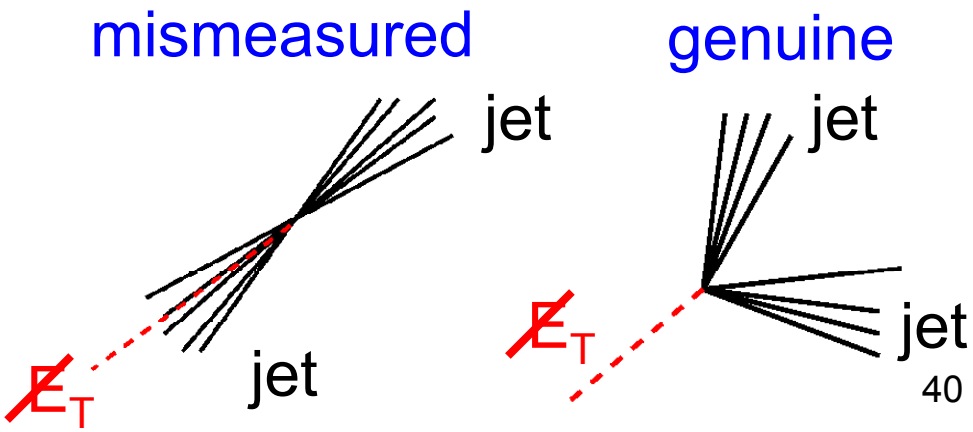
Background: 62±13 + 69±12

ZH→ννbb



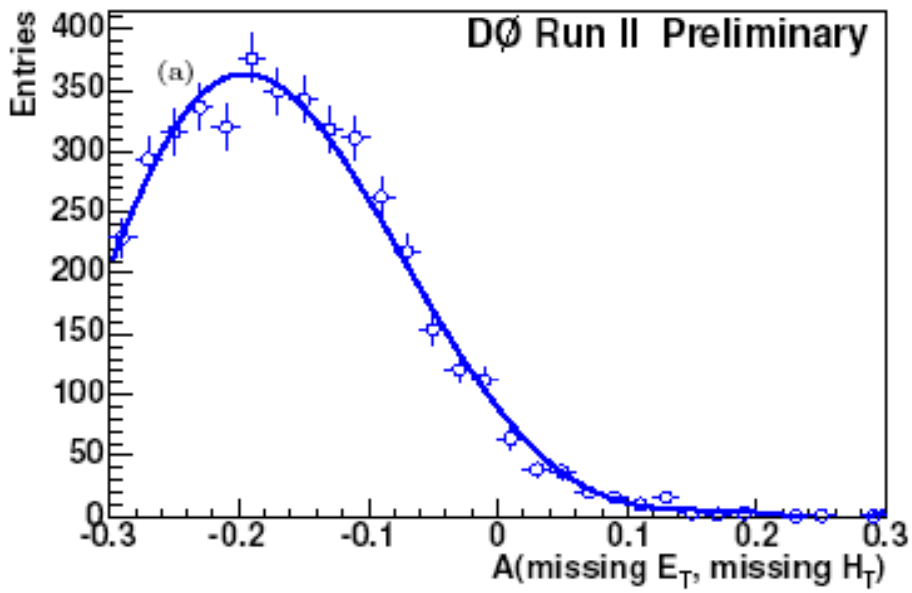
- Event selection:
  - ≥ 1 tagged b-jets
  - Two jets
  - E_T^{miss} > 70 GeV
  - Lepton veto
  - Veto missing E_T along jet directions

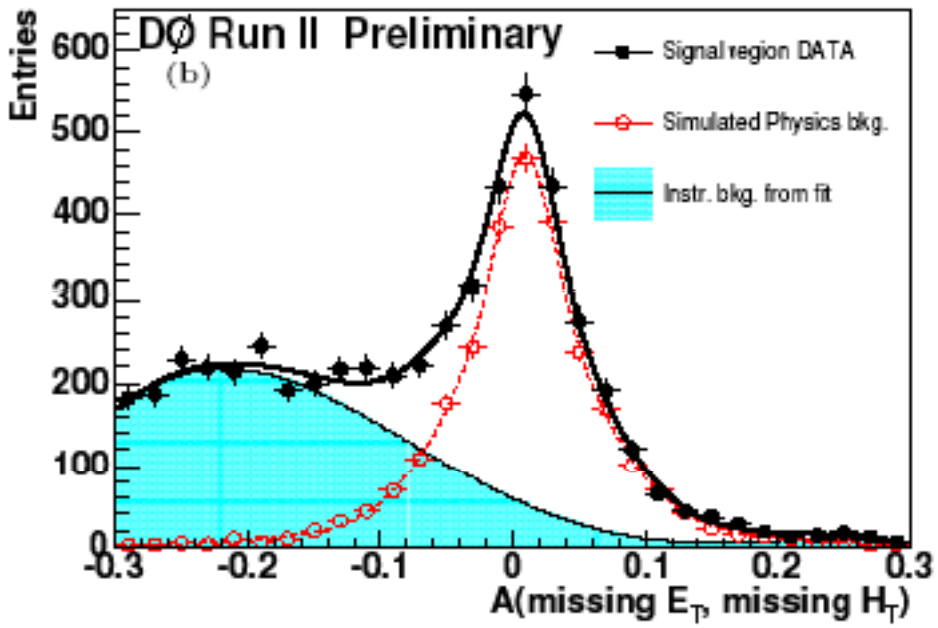
- Big challenge:
  - Background from mismeasurement of missing E_T
  - QCD dijet background is HUGE
    - Generate MC and compare to data in *control regions*
    - Estimate from data
- Control:
  - Missing E_T direction
  - Missing E_T in hard jets vs overall missing E_T



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

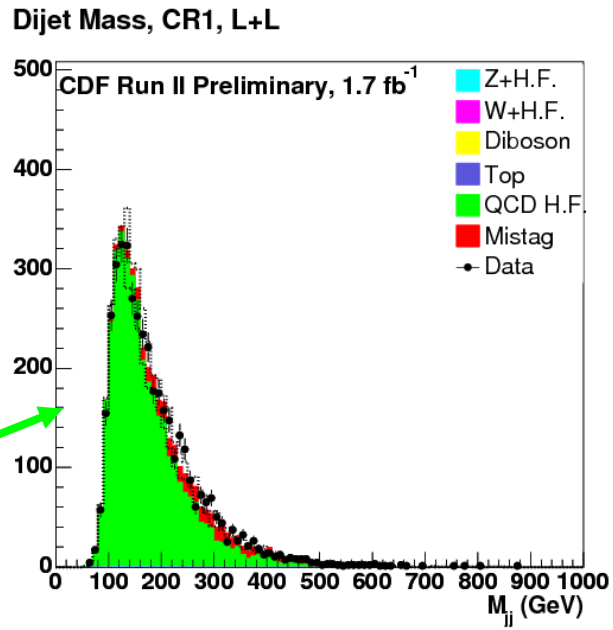




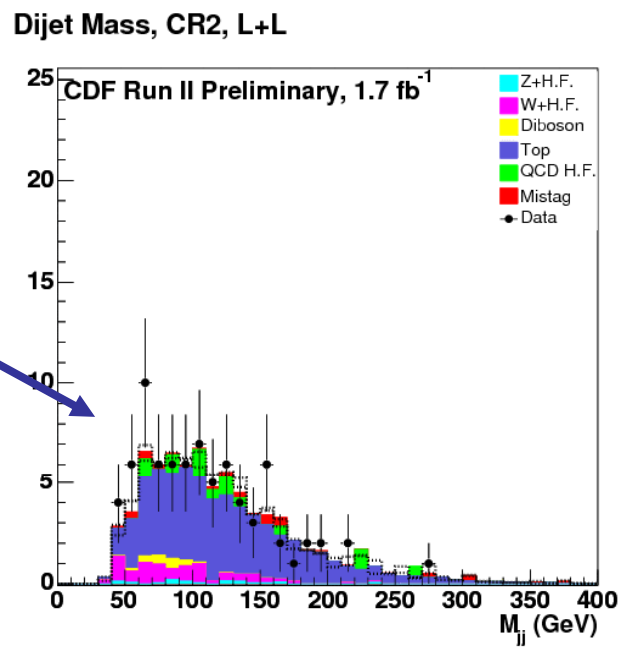
Background understanding using MC

- CDF use MC and check it in detail against data

"QCD" control region:
Jet aligned with missing E_T
$\Rightarrow$Completely dominated by QCD jets and mistags

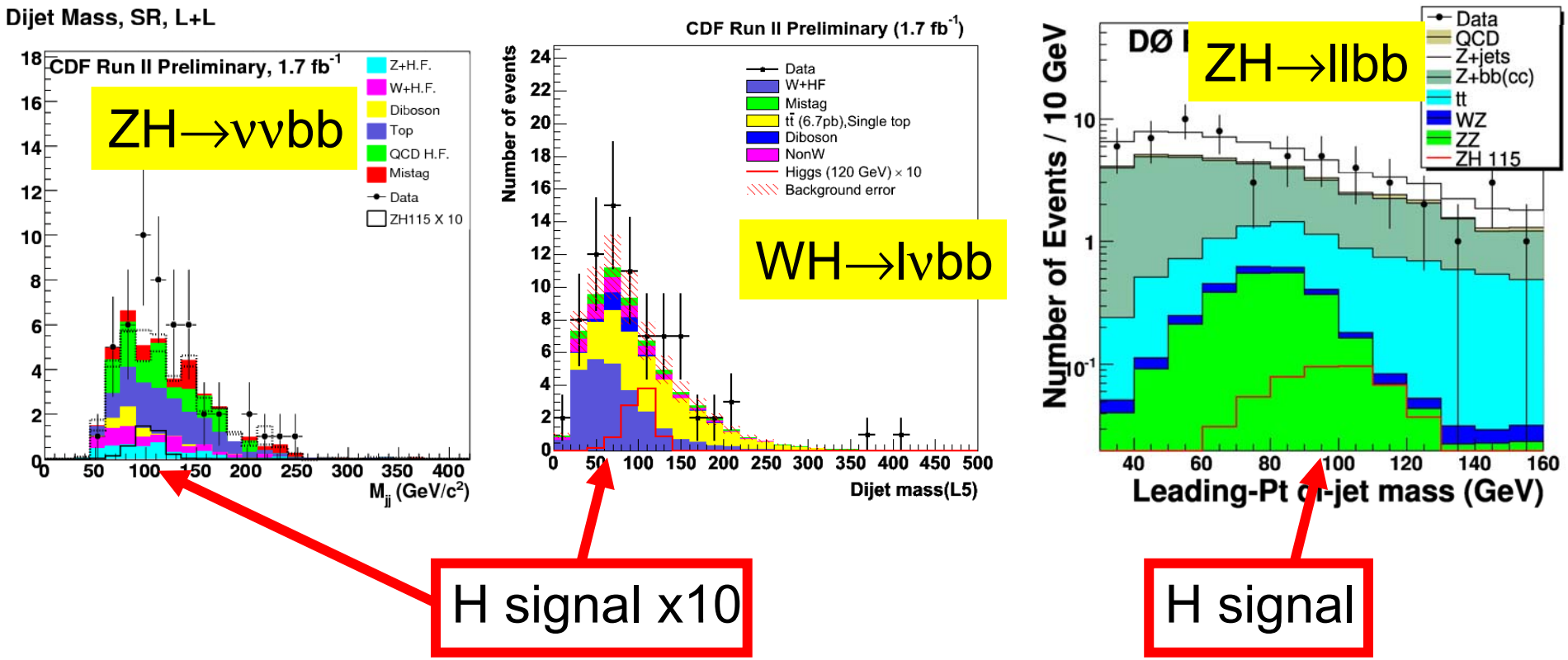


"EWK" control region:
Identified lepton in event
=> Dominated by top



Look at data only when control regions look satisfactory

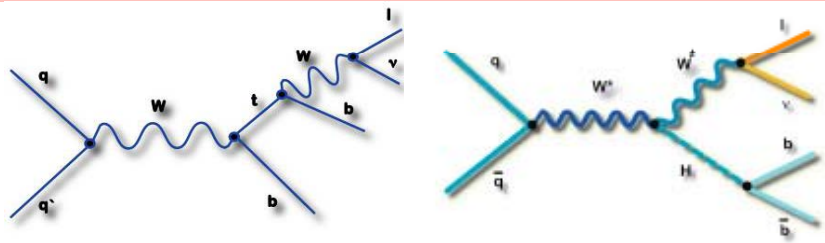
Dijet Mass distributions

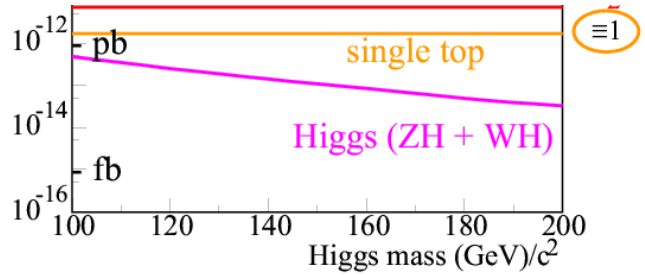


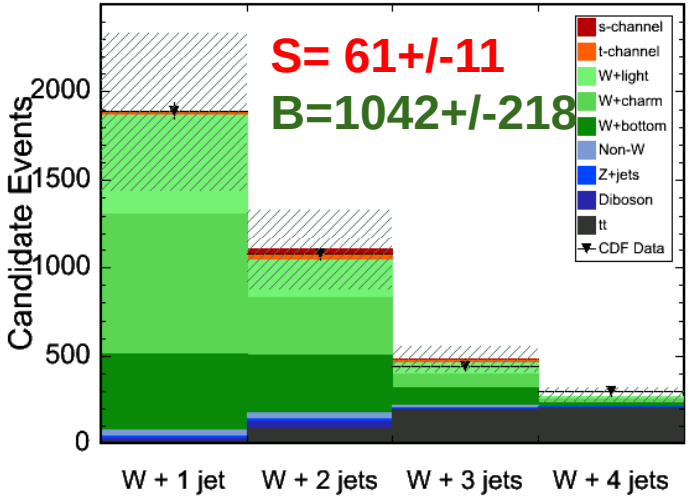
- Backgrounds still much larger than the signal:
  - Further experimental improvements and luminosity required
  - E.g. b-tagging efficiency (40->60%), *NN selection*, higher lepton acceptance

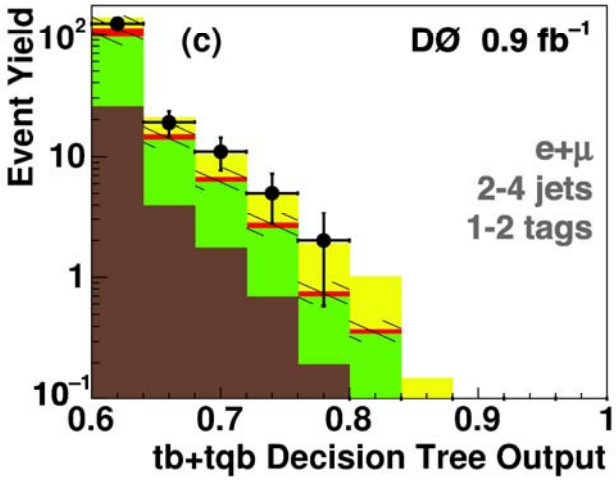
Single Top Quark Production

- Interesting benchmark for Higgs production
  - Same final state as WH
    - cross section 10 times higher though!
  - S/B too low for counting experiment
    - Advanced techniques are employed:
      - Boosted decision trees (DØ)
      - Neural Networks (CDF/DØ)
      - Matrix Element (CDF/DØ)
      - Likelihood (CDF)









- 12/06: DØ see 3.4σ with 0.9 fb^{-1}: **σ=4.9+/-1.4 pb**
- 07/07: CDF see 3.1σ with 1.5 fb^{-1}: **$\sigma=3.0^{+1.2}_{-1.1}$ pb**
- Both Agree with SM: **σ=2.9+/-0.4 pb**

Higgs Search with Neural Network

no b-tags

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

1 b-tag

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

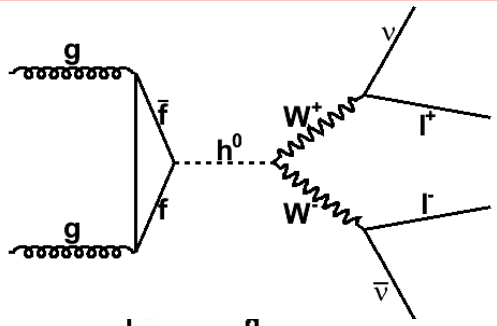
2 b-tags

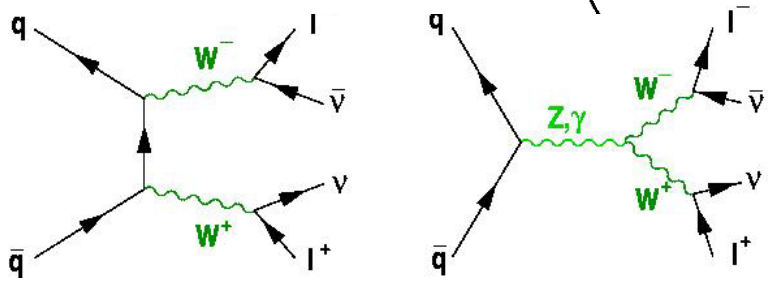
- Construct neural network can be powerful to improve discrimination:
  - Here 10 variables are used in 2D Neural Network
- Critical:
  - understanding of distribution in control samples

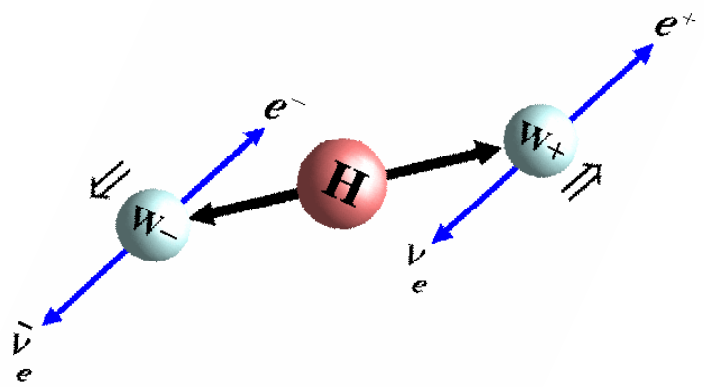
$\sigma_{SM}(ZH)$x19

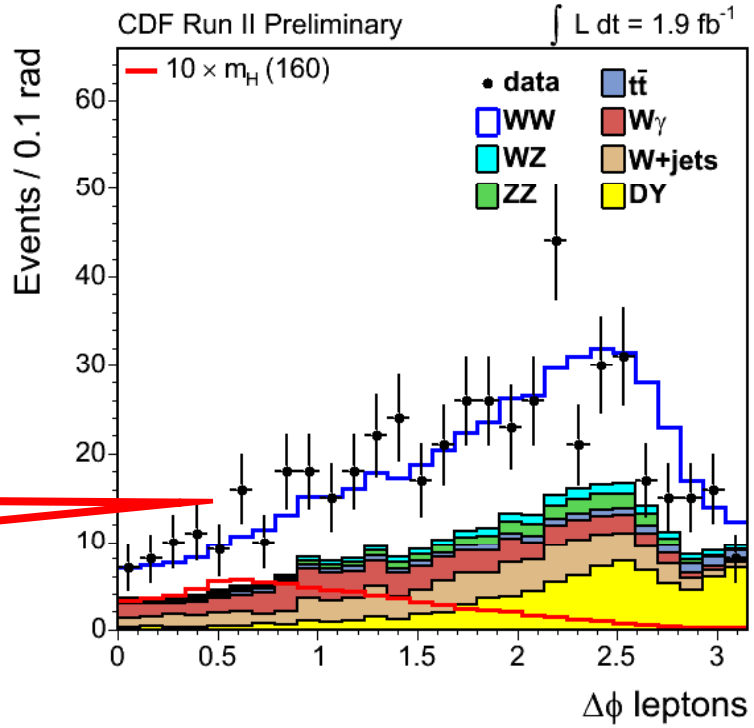
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\bar{\nu}$

- 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





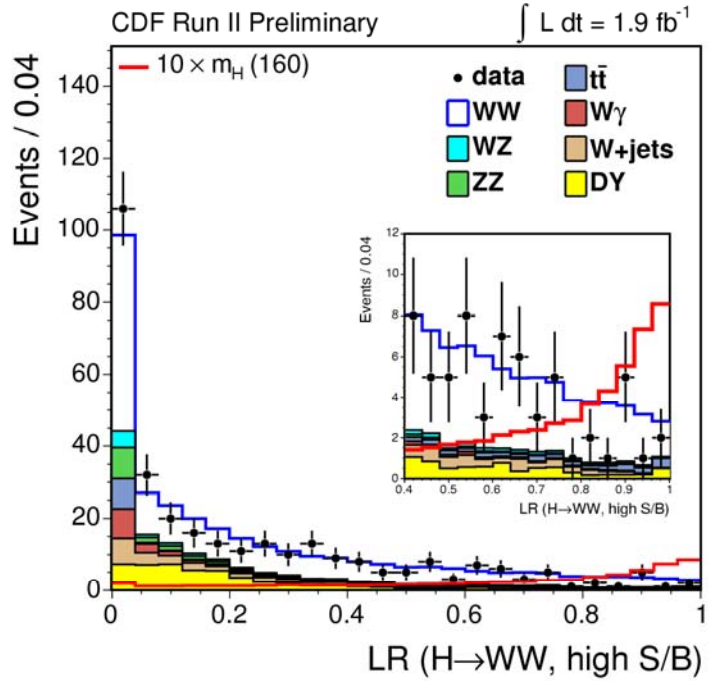


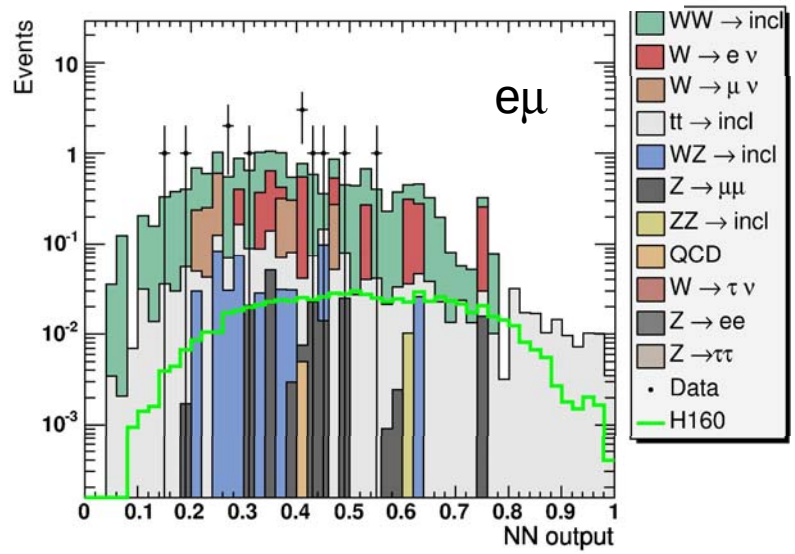


10x 160 GeV Higgs

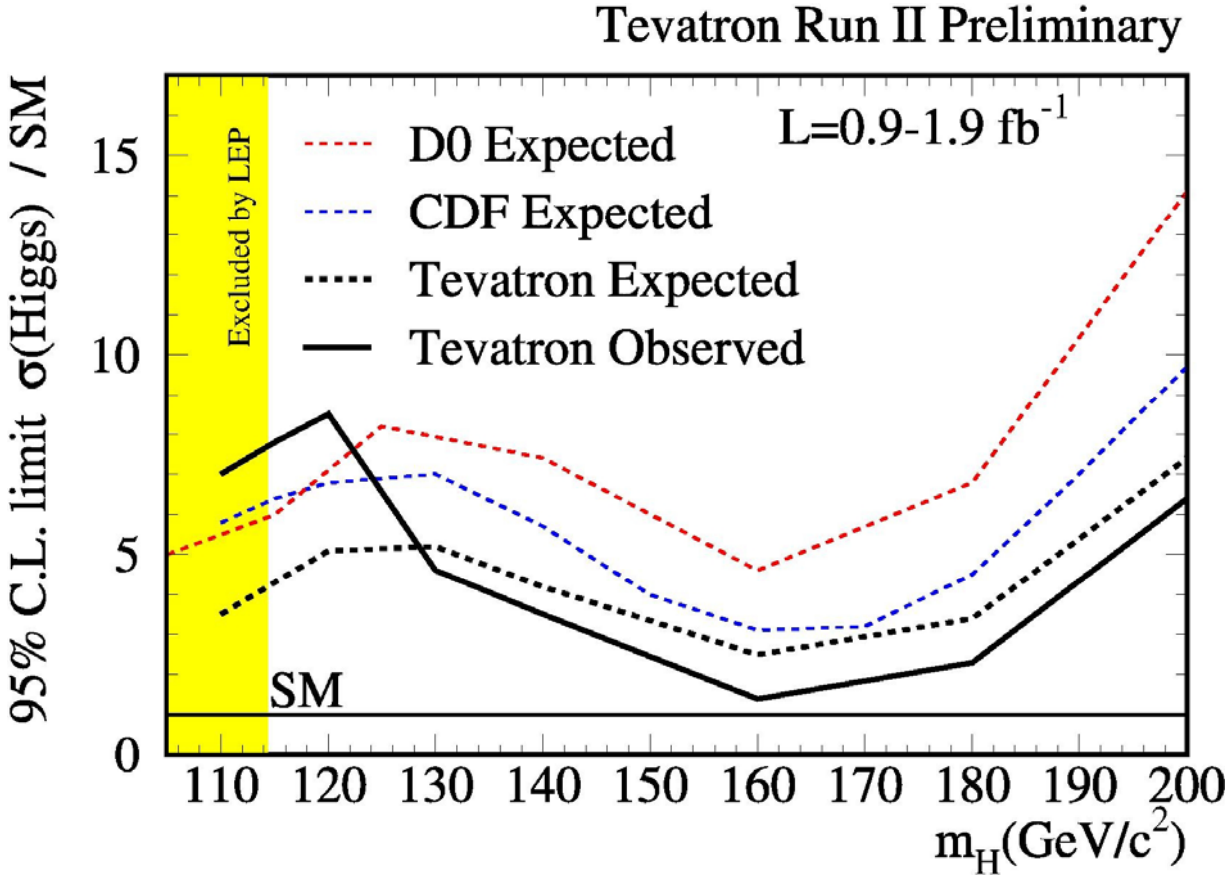
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ (l=e,μ)

- **Event selection:**
  - 2 isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets
- **Separate signal from background**
  - Use matrix-element or Neural Network discriminant to
- **Main backgrounds**
  - SM WW production
  - Top
  - Drell-Yan
  - Fake leptons





Ratio to Standard Model



- Further experimental improvements and luminosity expected
  - Will help to close the gap
  - Expect to exclude 160 GeV Higgs boson soon
  - At low mass still rather far away from probing SM cross section

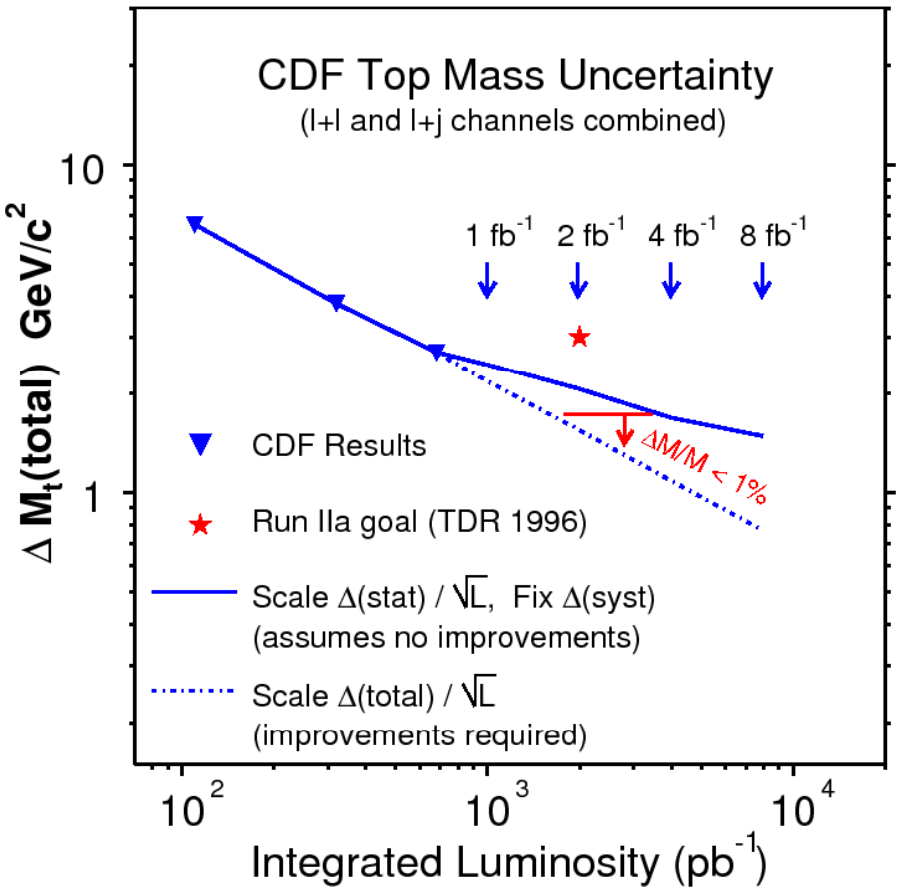
Conclusions

- The W boson, top quark and Higgs boson require
  - Lepton momentum scale
  - b-tagging
  - Jet energy calibration
- Probe electroweak sector of the Standard Model
  - **$\delta M_W/M_W$=0.07%, $\delta M_{top}/M_{top}$=1%**
  - **m_H<144 GeV at 95% CL**
- Higgs searches ongoing
  - Steady progress towards probing SM cross section
    - Expectations were set high and collaborations are working on meeting these specs
  - Expect sensitivity to 160 GeV Higgs with $\int L$=2-4 fb^{-1}

Backup

Systematic Uncertainties

Source	δm_{top} (GeV/c^2)
Remaining JES	1.0
Initial State QCD radiation	0.3
Final State QCD radiation	0.2
Parton distribution functions	0.3
MC modelling	0.2
background	0.6
B-tag	0.2
MC model	0.2
total	1.16



ZH→ννbb candidate