Physics at Hadron Colliders

Lecture II

Beate Heinemann

University of California, Berkeley and
Lawrence Berkeley National Laboratory

CERN, Summer Student Lectures, 2008

Outline

- Lecture I: Introduction
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current and near future colliders: Tevatron and LHC
  - Hadron-hadron collisions
- Lecture II: Standard Model Measurements
  - Standard Model Cross Section Measurements as Tests of QCD
  - Precision measurements in electroweak sector
- Lecture III: Searches for the Higgs Boson
  - Standard Model Higgs Boson
  - Higgs Bosons beyond the Standard Model
- Lecture IV: Searches for New Physics
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)

Standard Model Cross Section Measurements as test of QCD

- **Jets**
- **W and Z bosons**
- **Top Quark Production**

What is a Cross Section?

- Differential cross section: $d\sigma/d\Omega$:
  - Probability of a scattered particle in a given quantum state per solid angle $d\Omega$
    - E.g. Rutherford scattering experiment
- Other differential cross sections: $d\sigma/dE_T(\text{jet})$
  - Probability of a jet with given E_T
- Integrated cross section
  - Integral: $\sigma = \int d\sigma/d\Omega \, d\Omega$

Measurement: $\sigma = (N_{obs} - N_{bg})/(\varepsilon L)$

Luminosity

Luminosity Measurement

$$R_{pp} = \mu_{pp} \cdot f_{BC} = \sigma_{inel} \cdot \varepsilon_{pp} \cdot \delta(L) \cdot L$$

σ_{LM}

L – luminosity

f_{bc} – Bunch Crossing rate

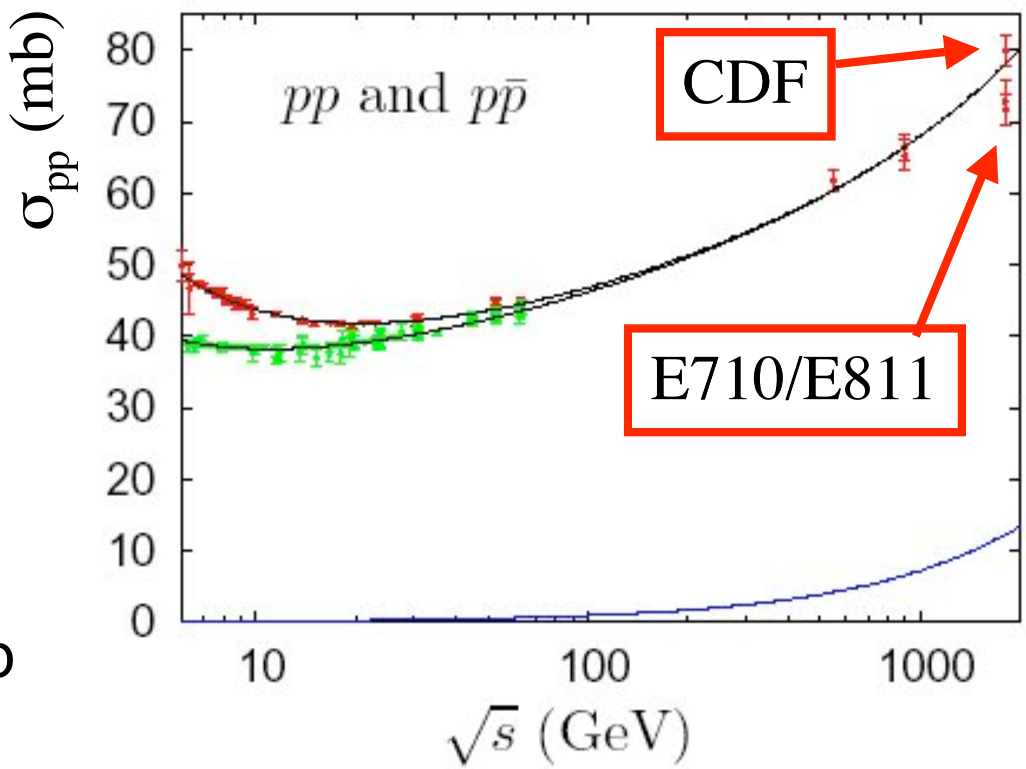
μ_a – # of pp / BC

σ_{inel} – inelastic x-section

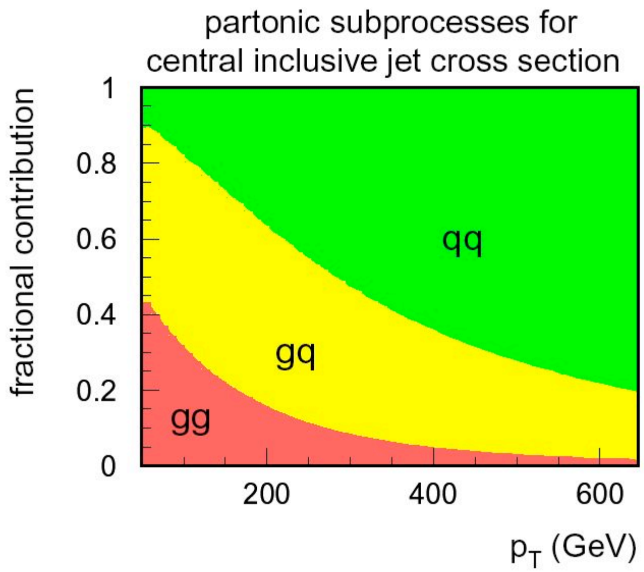
ε_{pp} – acceptance for a single pp

$\delta(L)$ – detector non-linearity

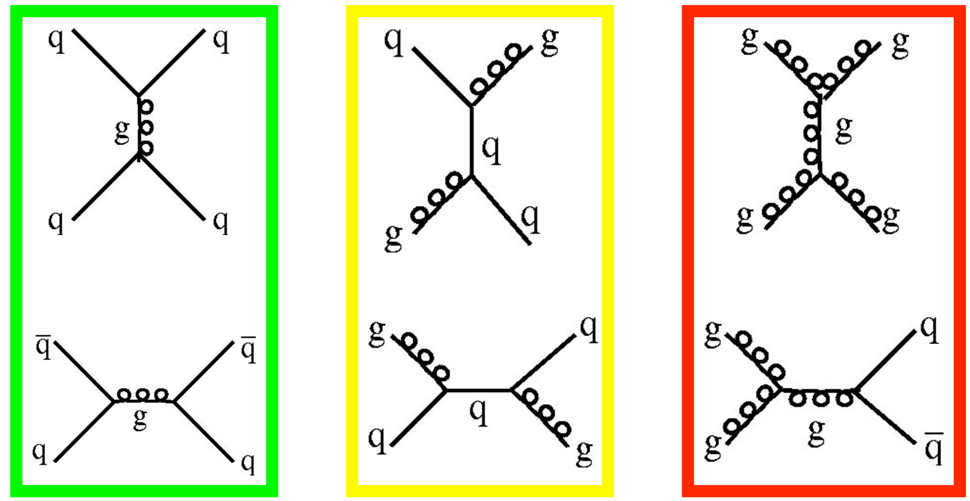
- Measure events with 0 interactions
  - Related to R_{pp}
- Normalize to measured inelastic pp cross section
  - Tevatron: 60.7+/-2.4 mb
- LHC: 70-120 mb

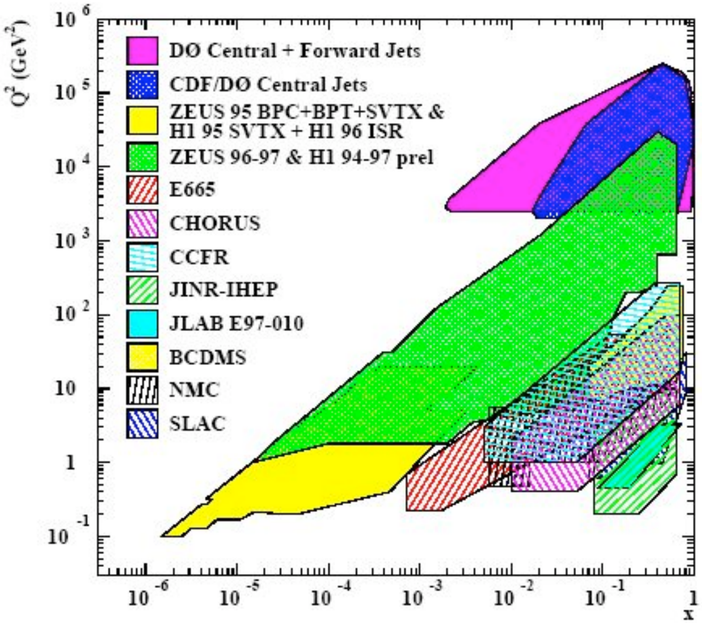


Jet Cross Sections



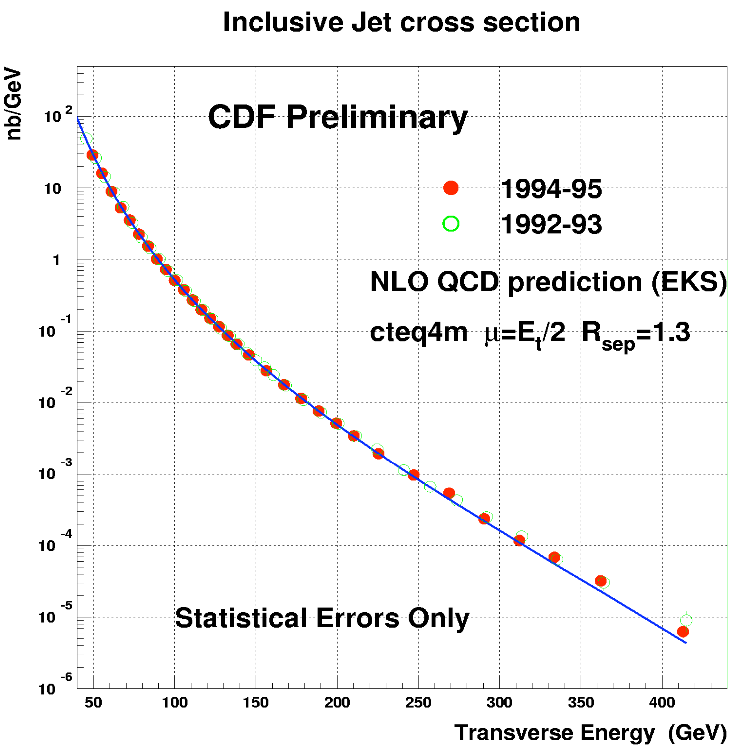
- Inclusive jets: processes qq, qg, gg

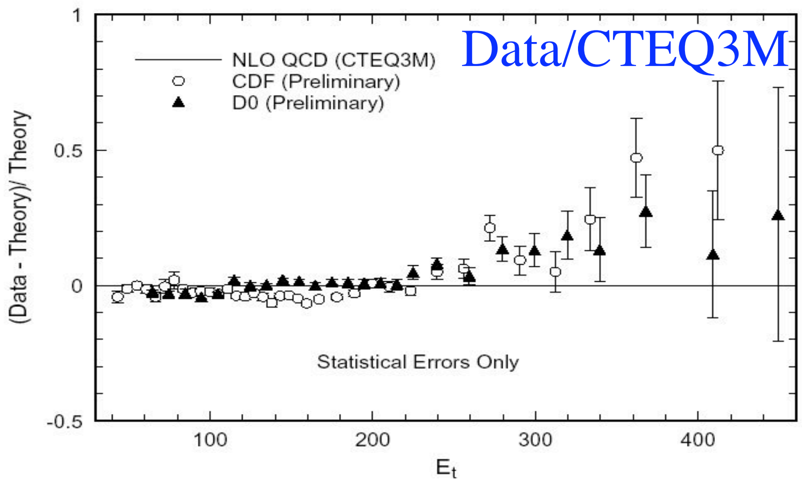




- Highest E_T probes shortest distances
  - Tevatron: $r_q < 10^{-18}$ m
  - LHC: $r_q < 10^{-19}$ m (?)
  - Could e.g. reveal substructure of quarks
- Tests perturbative QCD at highest energies

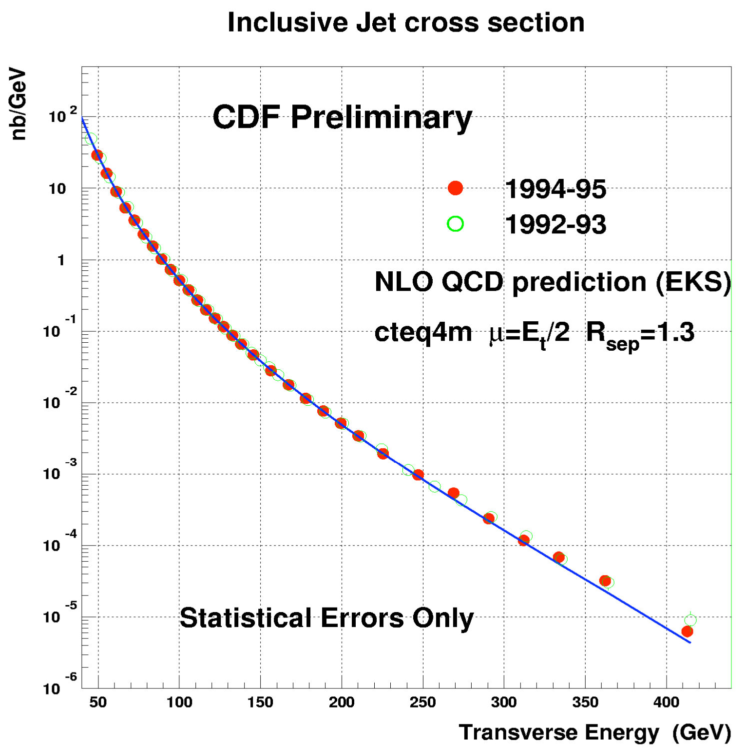
Jet Cross Section History



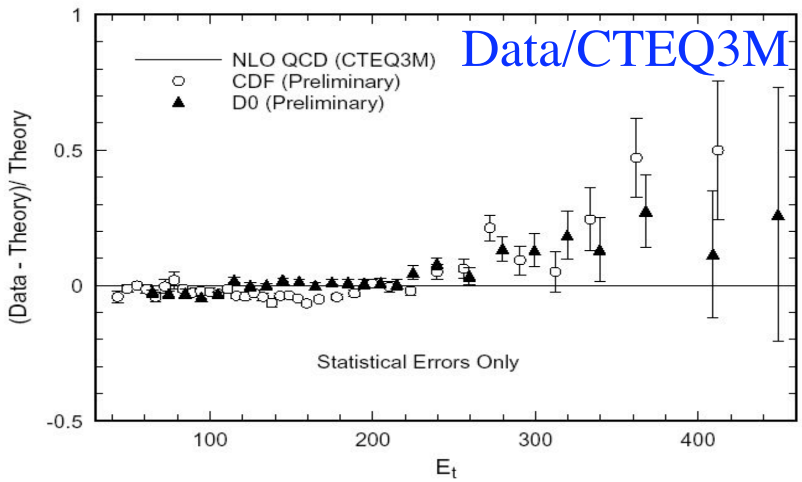


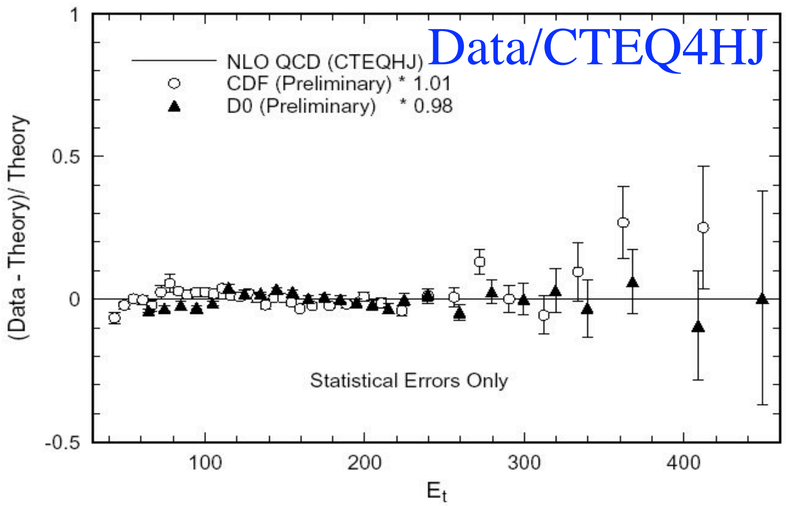
- Run I (1996):
  - Excess at high E_T
  - Could be signal for quark substructure?!?

Jet Cross Section History

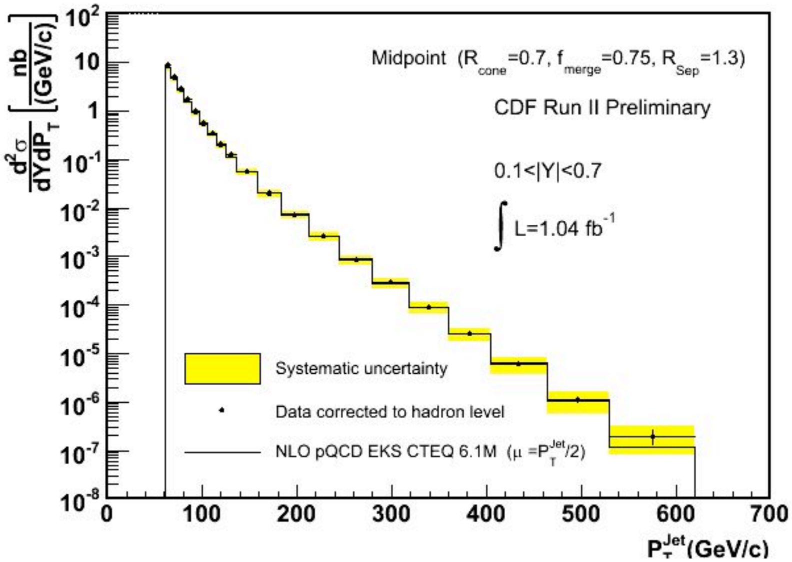


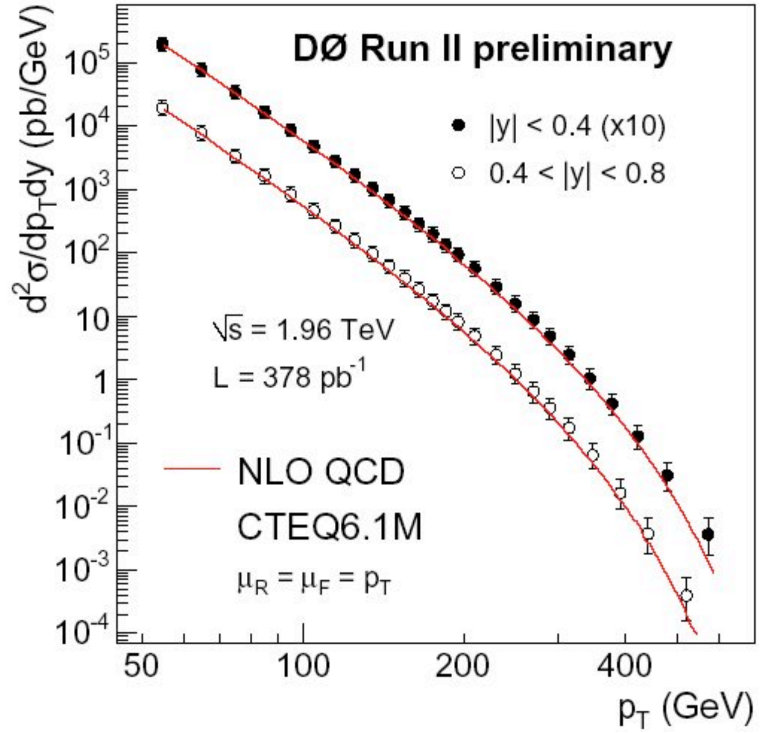
- Since Run I:
  - Revision of parton density functions
    - Gluon is uncertain at high x
    - It including these data describes data well

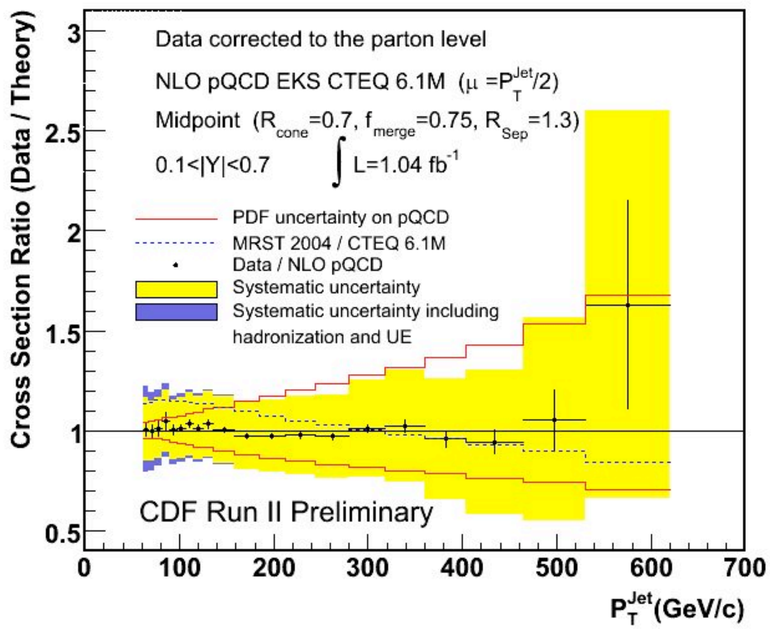




Jet Cross Sections in Run II

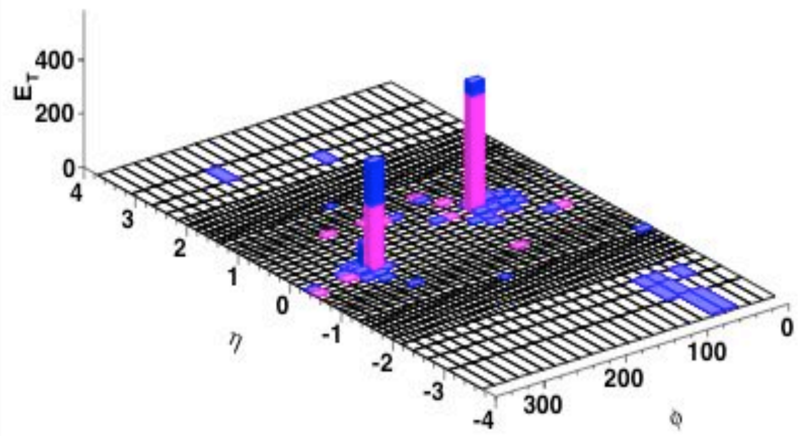






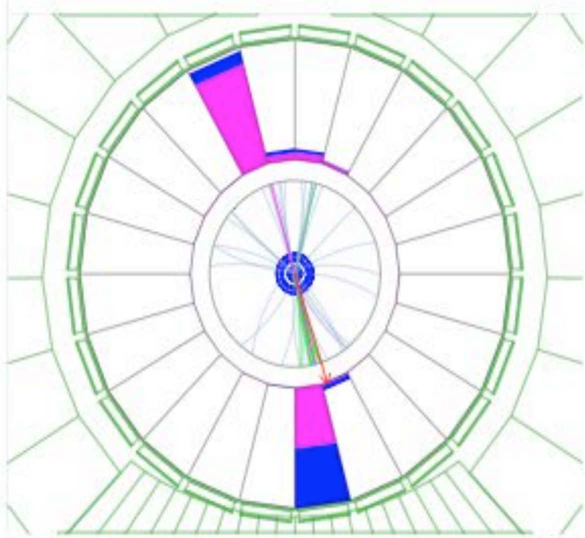
- Excellent agreement with QCD calculation over 8 orders of magnitude!
- No excess any more at high E_T
  - Large pdf uncertainties will be constrained by these data

High Mass Dijet Event: M=1.4 TeV



CDF Run II Preliminary

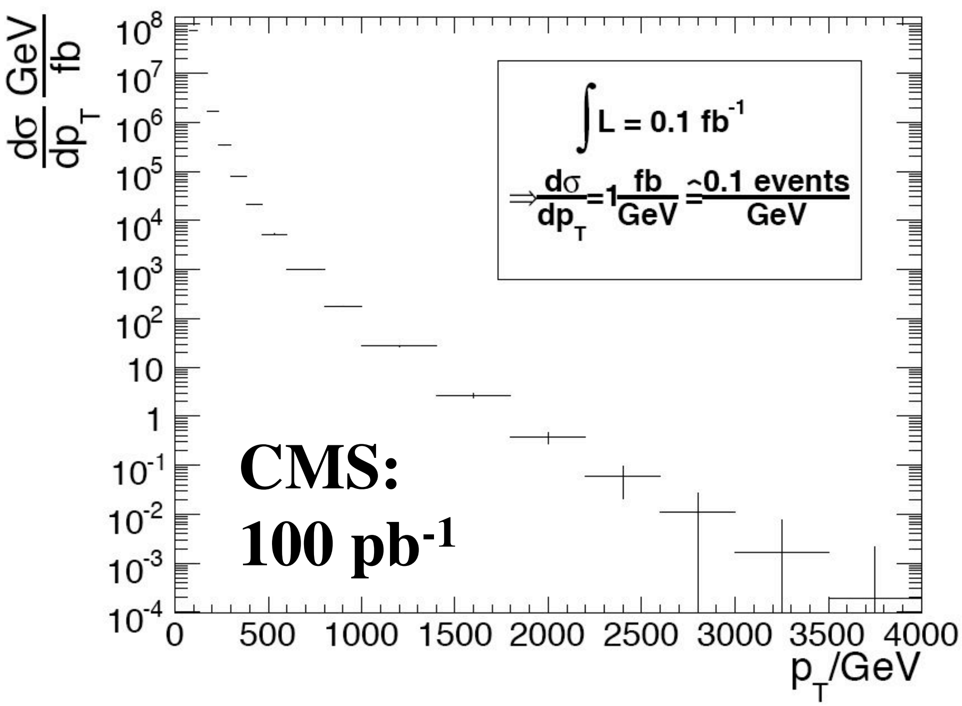
```
Jet Et1 = 666 GeV (corr)
          583 GeV (raw)
eta1    = 0.31 (detector)
          0.43 (corr z)

Jet Et2 = 633 GeV (corr)
          546 GeV (raw)
eta2    = -0.30 (detector)
          -0.19 (corr z)
```

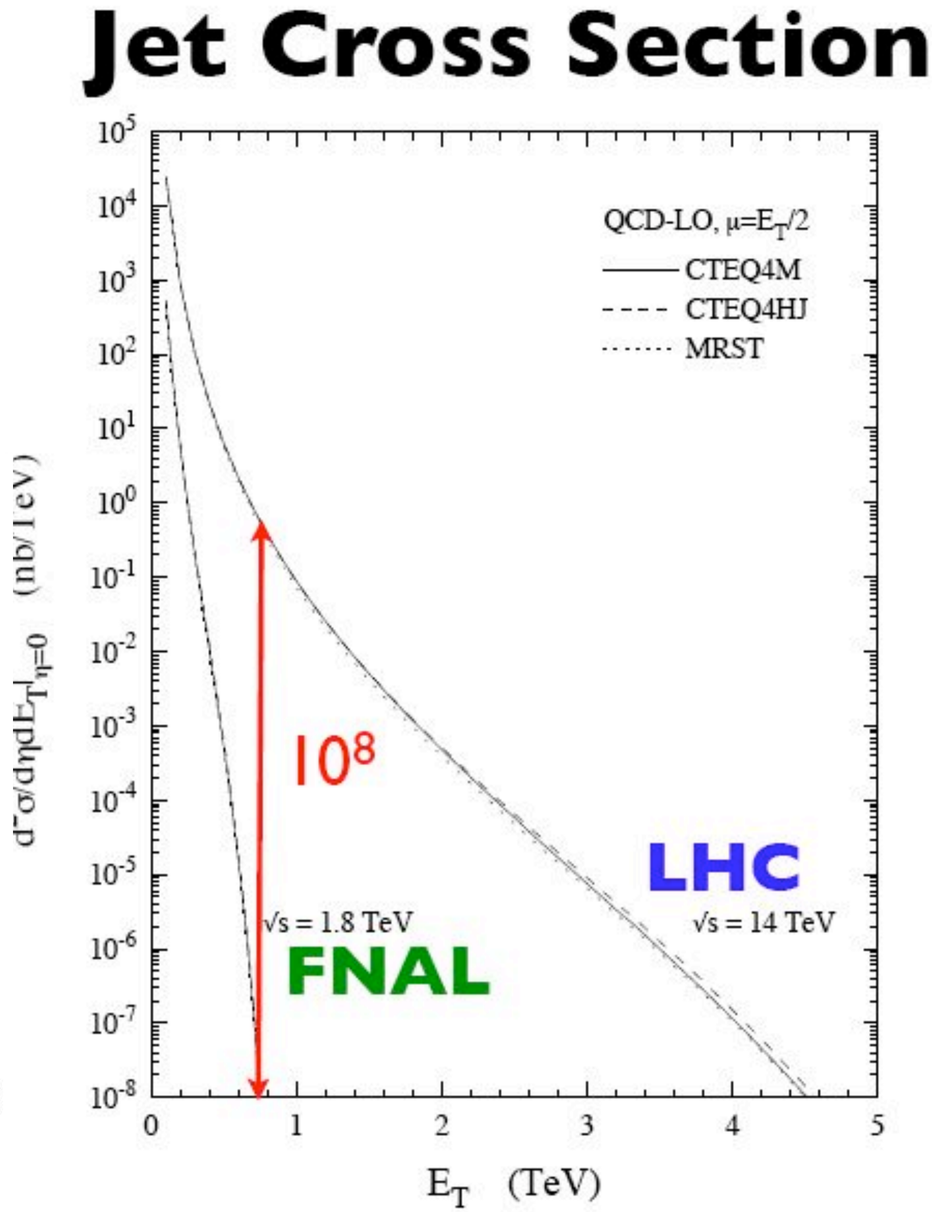


```
Run   152507
Event 1222318

DiJet Mass = 1364 GeV (corr)

z vertex   = -25 cm
```

Jets at the LHC

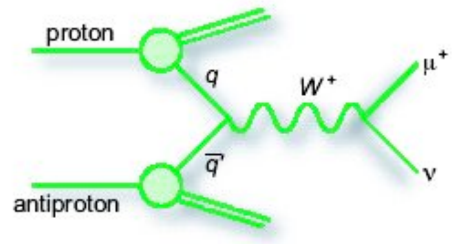
- Much higher rates than at the Tevatron
  - Reach ~3 TeV already with 100 pb^{-1} of LHC data

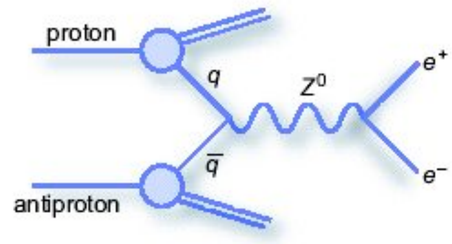


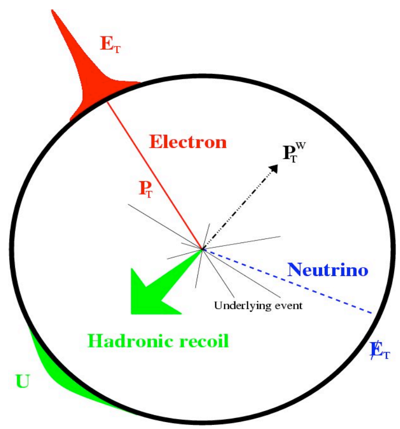


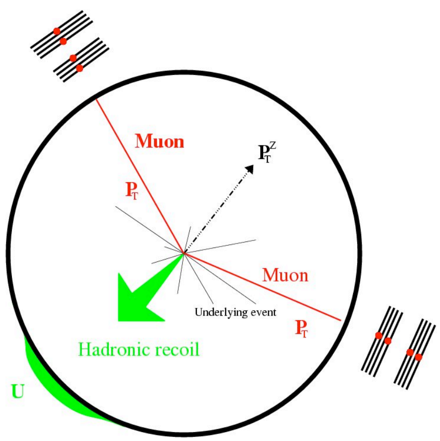
W and Z Bosons

- Focus on leptonic decays:
  - Hadronic decays ~impossible due to enormous QCD dijet background
- Selection:
  - Z:
    - Two leptons p_T>20 GeV
      - Electron, muon, tau
  - W:
    - One lepton p_T>20 GeV
    - Large imbalance in transverse momentum
      - Missing E_T>20 GeV
      - Signature of undetected particle (neutrino)
- Excellent calibration signal for many purposes:
  - Electron energy scale
  - Track momentum scale
  - Lepton ID and trigger efficiencies
  - Missing E_T resolution
  - Luminosity …



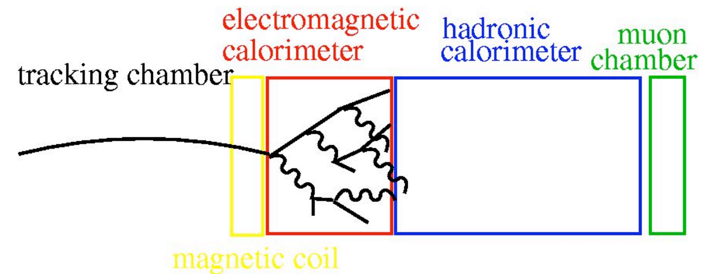




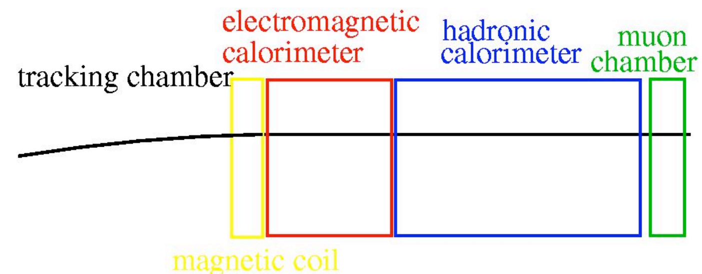


Lepton Identification

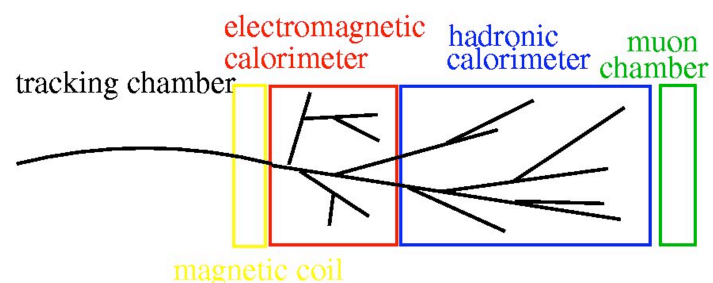
- Electrons:
  - compact electromagnetic cluster in calorimeter
  - Matched to track



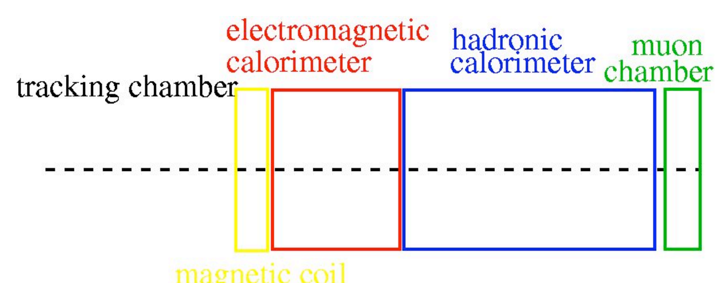
- Muons:
  - Track in the muon chambers
  - Matched to track



- Taus:
  - Narrow jet
  - Matched to one or three tracks

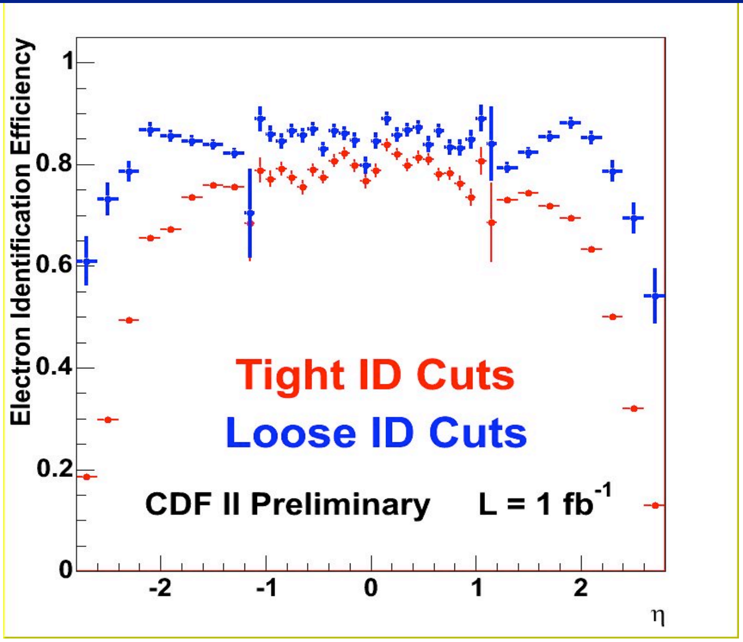


- Neutrinos:
  - Imbalance in transverse momentum
  - Inferred from total transverse energy measured in detector
  - More on this in Lecture 4

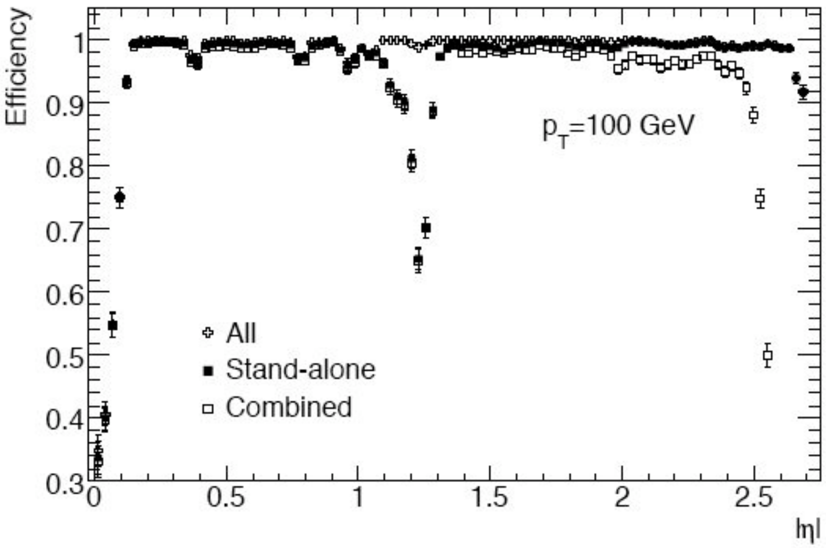


Electron and Muon Identification

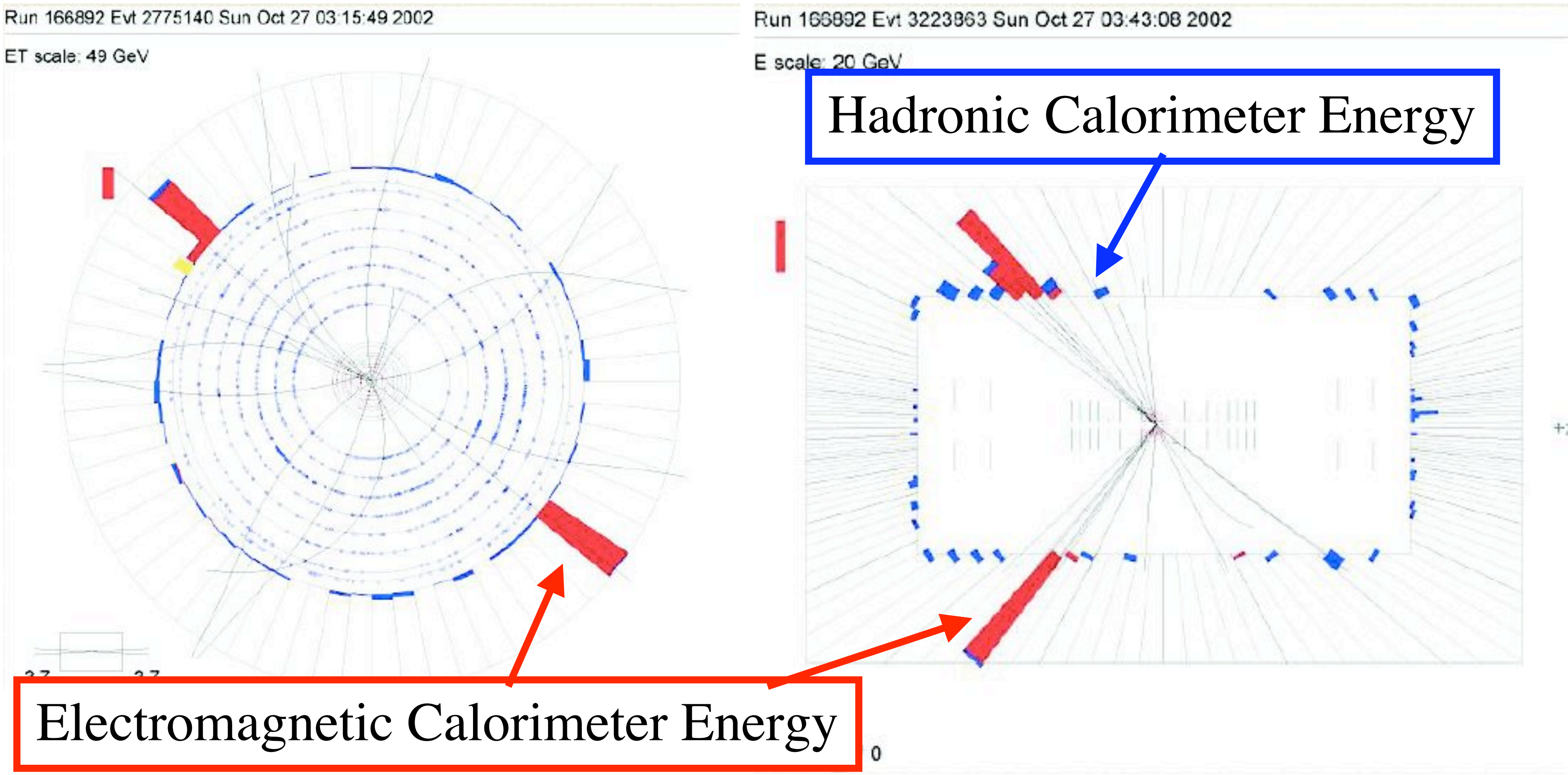
- Desire:
  - High efficiency for isolated electrons
  - Low misidentification of jets



- Performance:
  - Efficiency:
    - 60-100% depending on |η|
    - Measured using Z's



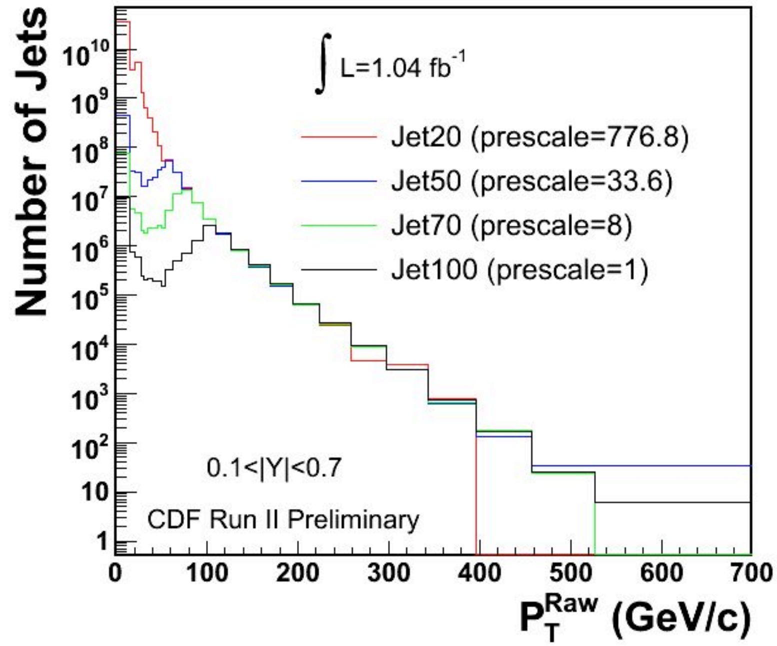
Electrons and Jets



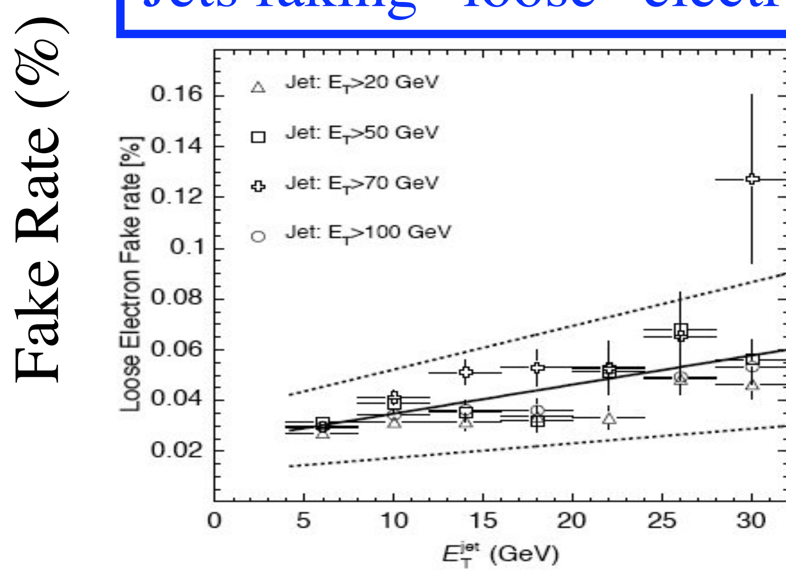
- Jets can look like electrons, e.g.:
  - photon conversions from π^0's: ~13% of photons convert (in CDF)
  - early showering charged pions
- And there are lots of jets!!!

Jets faking Electrons

- Jets can pass electron ID cuts,
  - Mostly due to
    - early showering charged pions
    - Conversions: $\pi^0 \to \gamma\gamma \to ee+X$
    - Semileptonic b-decays
  - Difficult to model in MC
    - Hard fragmentation
    - Detailed simulation of calorimeter and tracking volume
- Measured in inclusive jet data at various E_T thresholds
  - Prompt electron content negligible:
    - N_{jet}~10 billion at 50 GeV!
  - Fake rate per jet:
    - CDF, tight cuts: 1/10000
    - ATLAS, tight cuts: 1/80000
  - Typical uncertainties 50%



Jets faking "loose" electrons



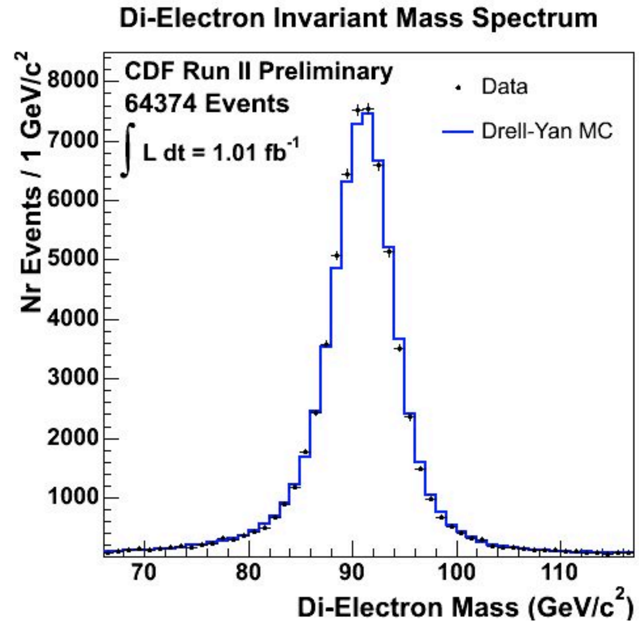
W's and Z's

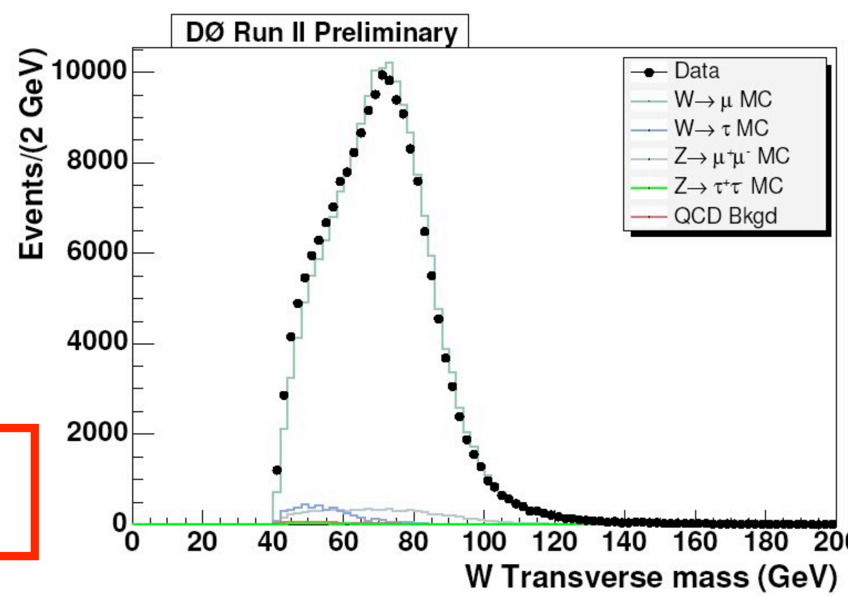
- Z mass reconstruction
  - Invariant mass of two leptons

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

  - Sets electron energy scale by comparison to LEP measured value
- W mass reconstruction
  - Do not know neutrino p_Z
  - No full mass resonstruction possible
  - Transverse mass:

$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}$$



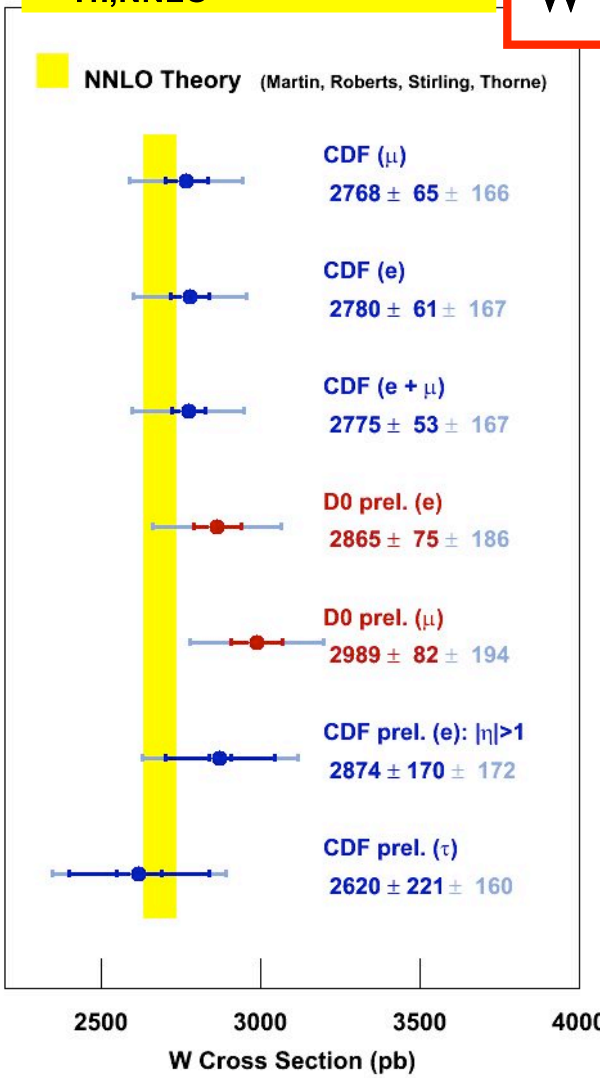


Tevatron W and Z Cross Section Results

- Uncertainties:
  - Experimental: 2%
  - Theortical: 2%
  - Luminosity: 6%
- Can we use these processes to normalize luminosity?
  - Is theory reliable enough?

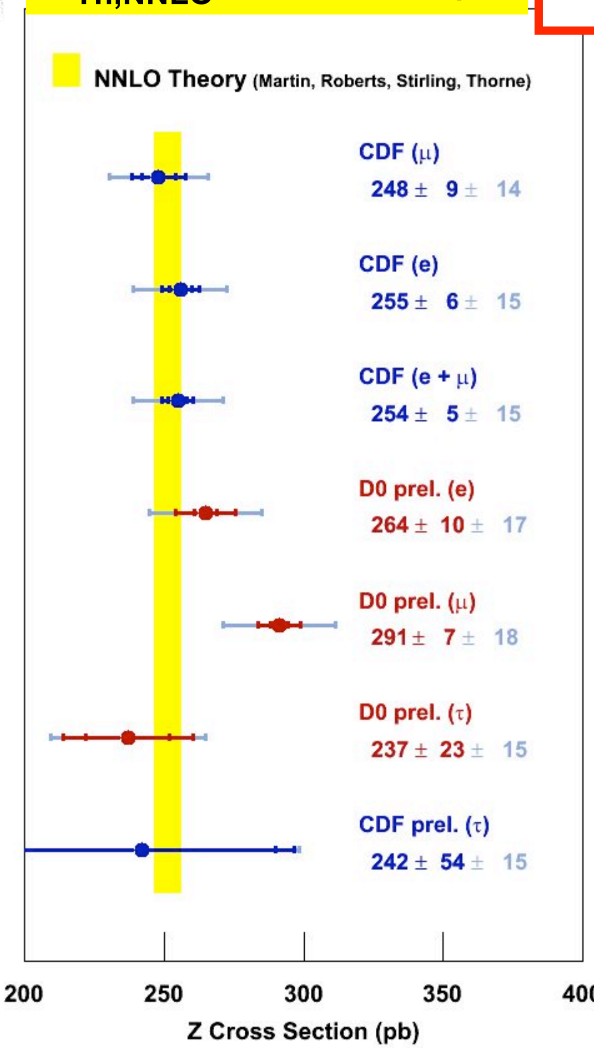
$\sigma_{Th,NNLO}$=2687±54pb

W

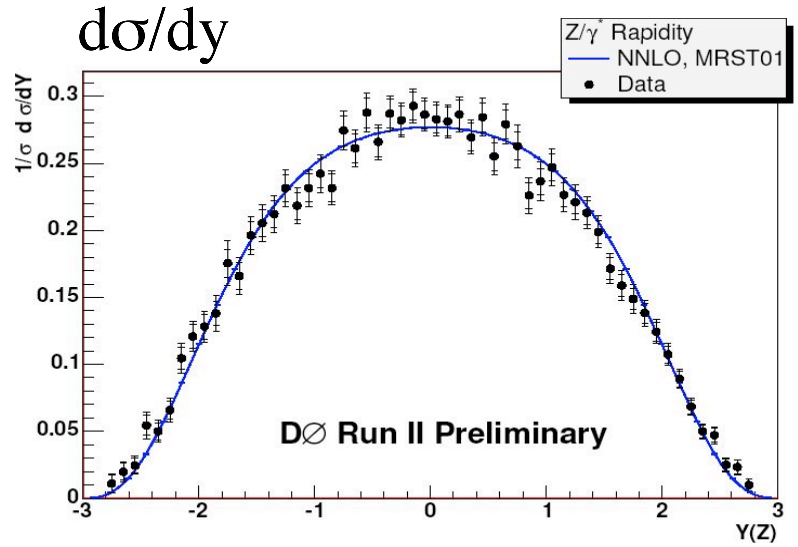


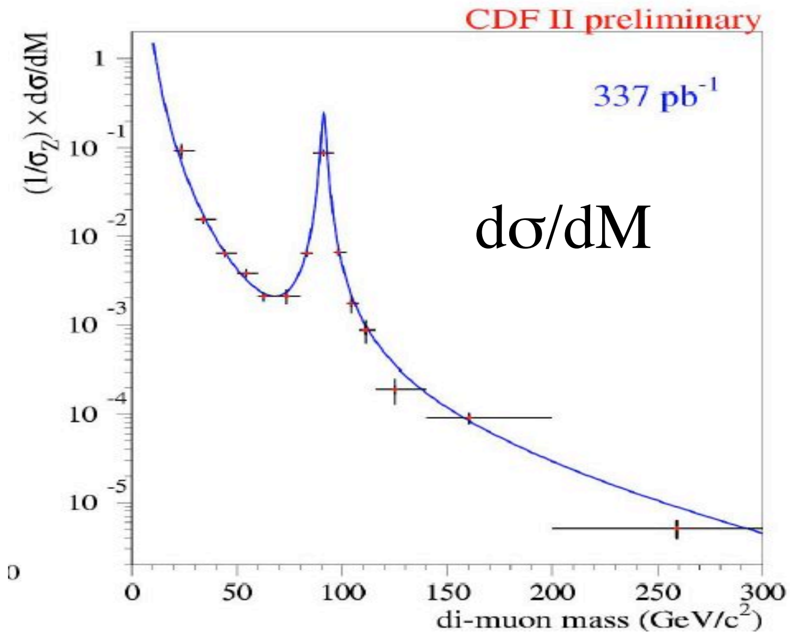
$\sigma_{Th,NNLO}$=251.3±5.0pb

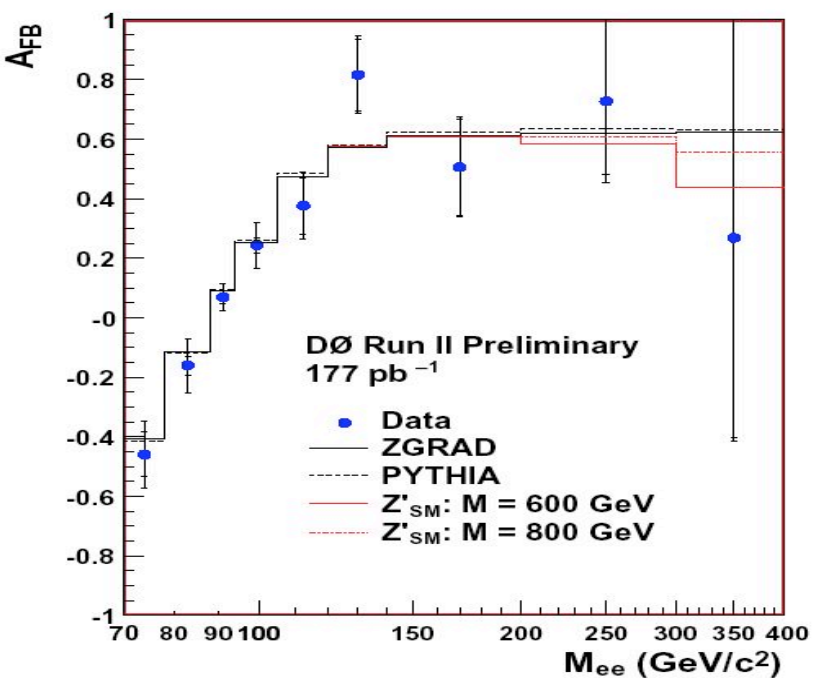
Z

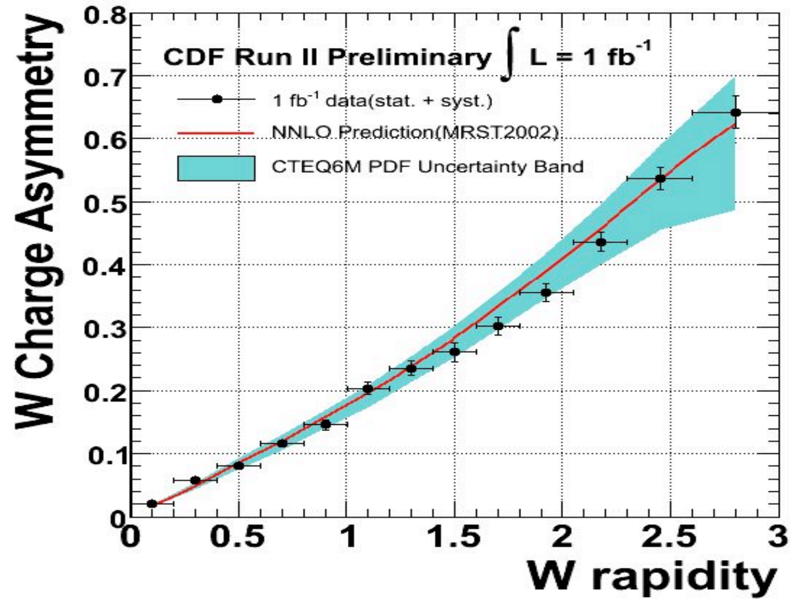


More Differential W/Z Measurements

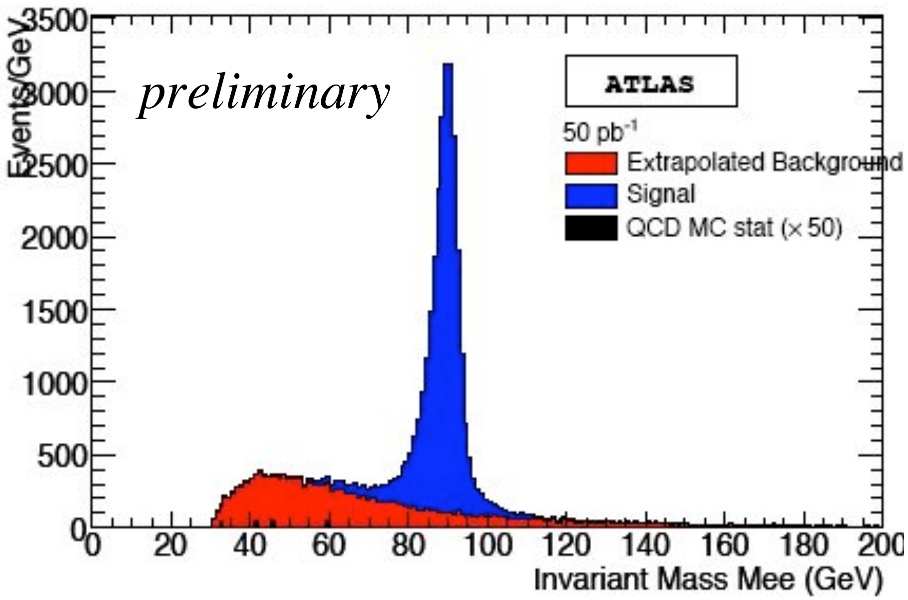


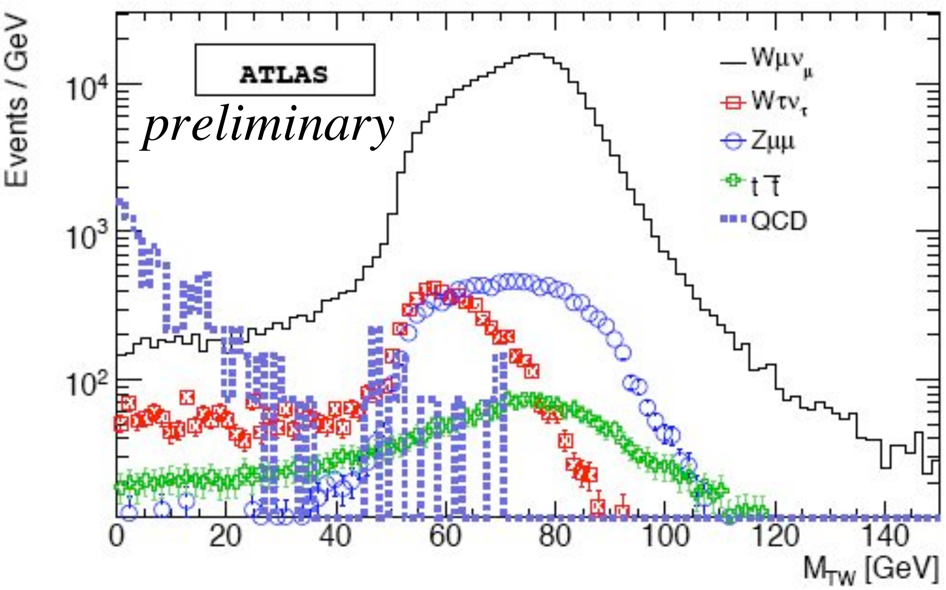






LHC signals of W's and Z's with 50 pb^{-1}



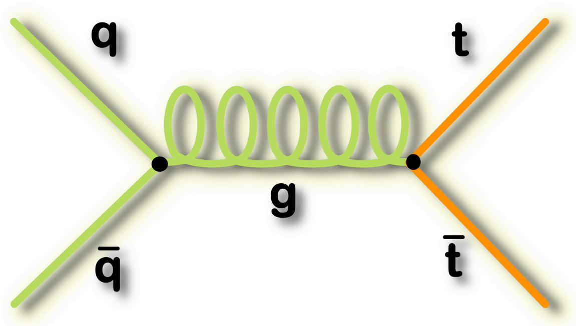


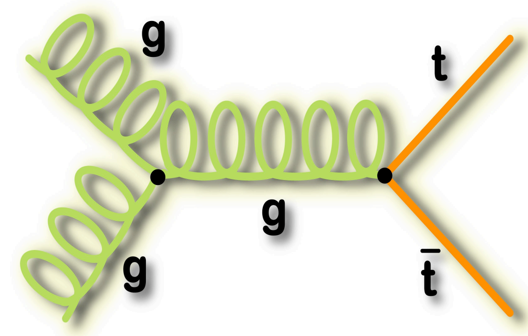
- 50 pb^{-1} yield clean signals of W's and Z's
- Experimental precision
  - ~5% for 50 pb^{-1} ⊕ ~10% (luminosity)
  - ~2.5% for 1 fb^{-1} ⊕ ~10% (luminosity)

Top Quark Production and Decay

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

85%





15%

- Decay via the electroweak interactions

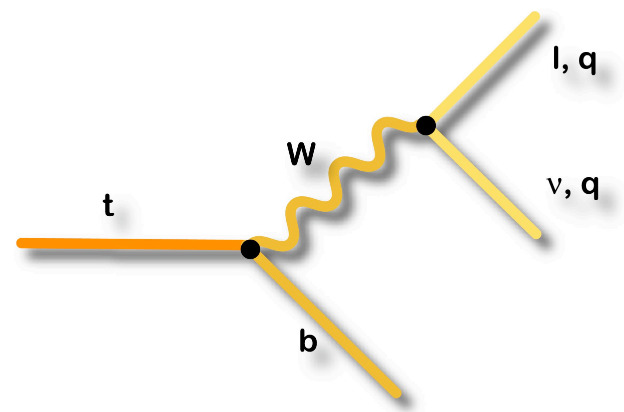
  Br($t \to Wb$) ~ 100%

  Final state is characterized by the decay of the W boson

Dilepton

Lepton+Jets

All-Jets



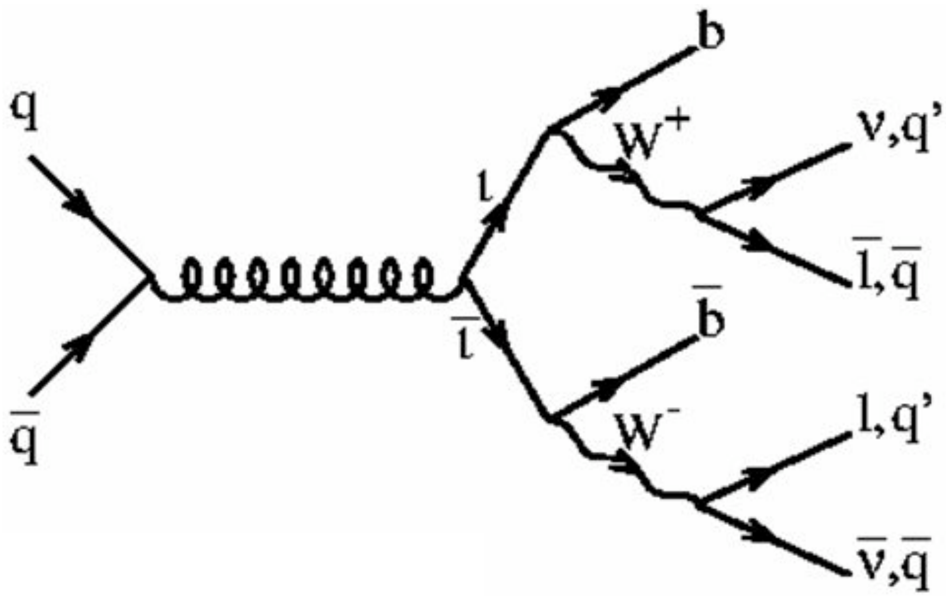
Different sensitivity and challenges in each channel

How to identify the top quark

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

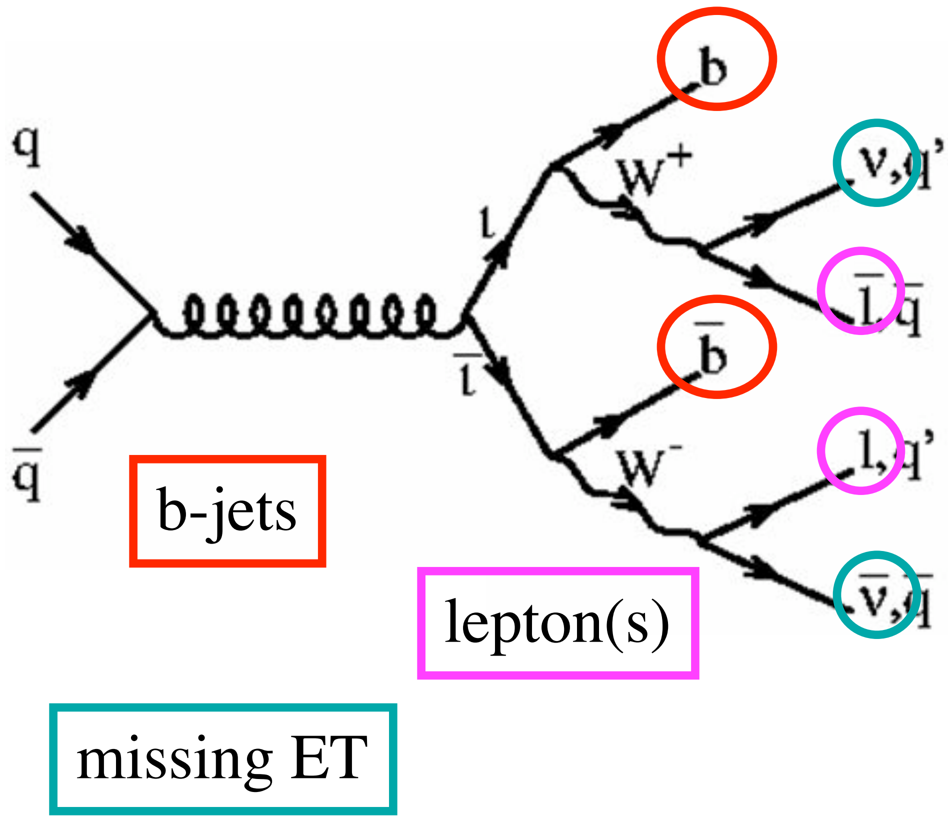
(here: l=e,μ)



How to identify the top quark

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

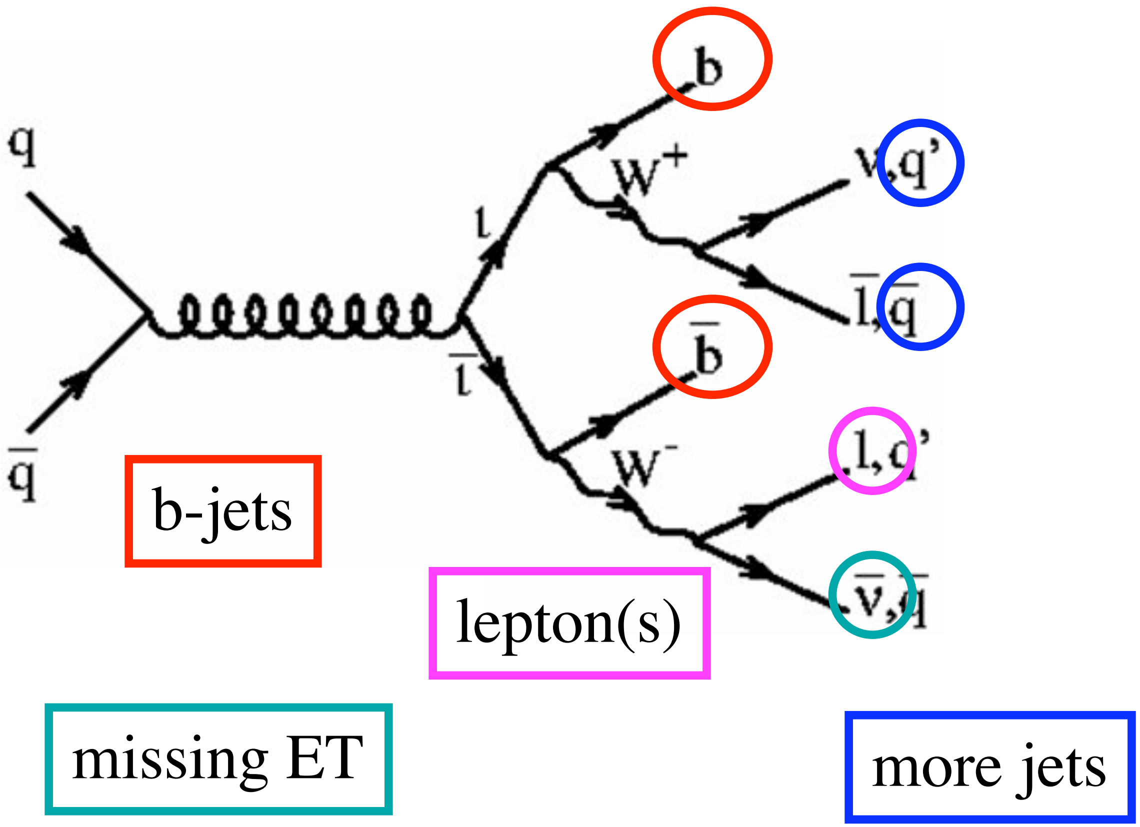
dilepton *(4/81)* 2 leptons + 2 jets + missing E_T
lepton+jets *(24/81)* 1 lepton + 4 jets + missing E_T
fully hadronic *(36/81)* 6 jets



How to identify the top quark

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

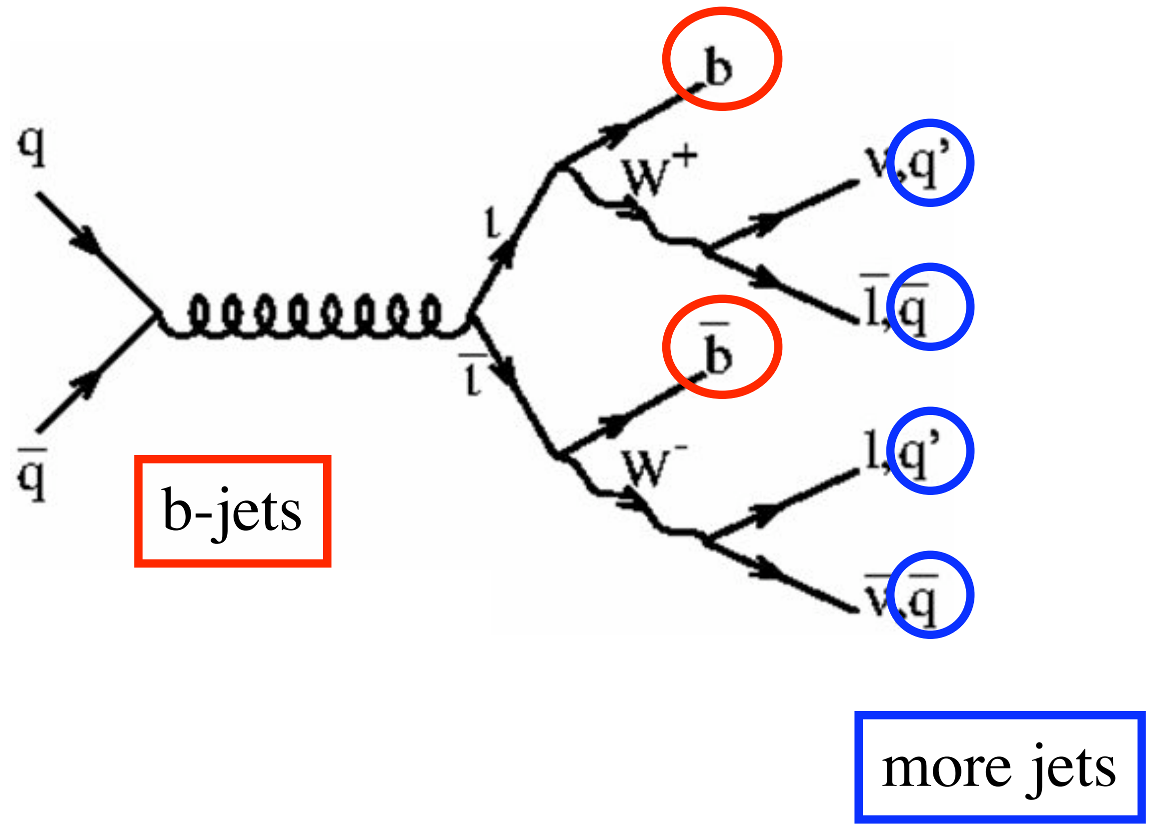
dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
lepton+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets



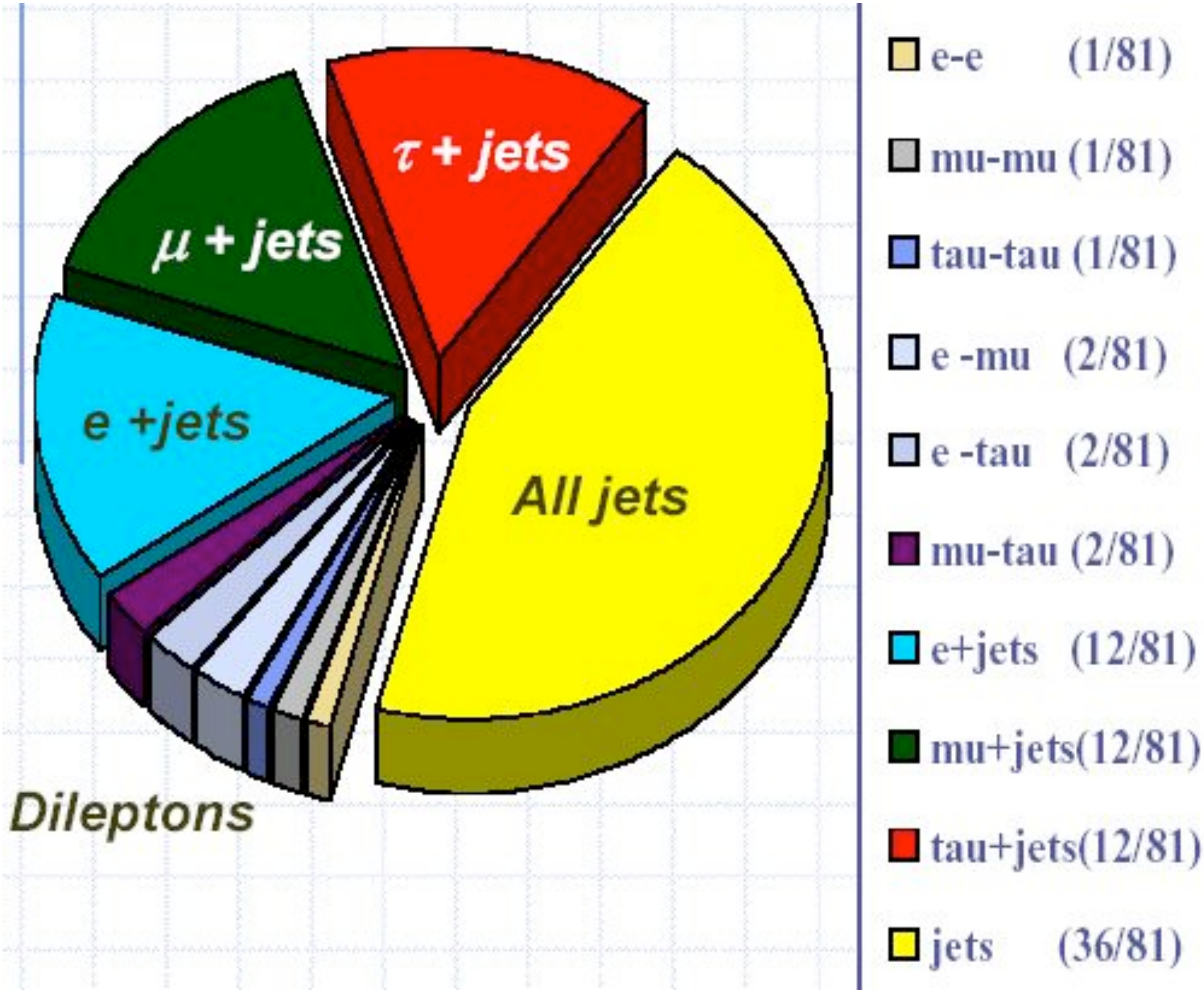
How to identify the top quark

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

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

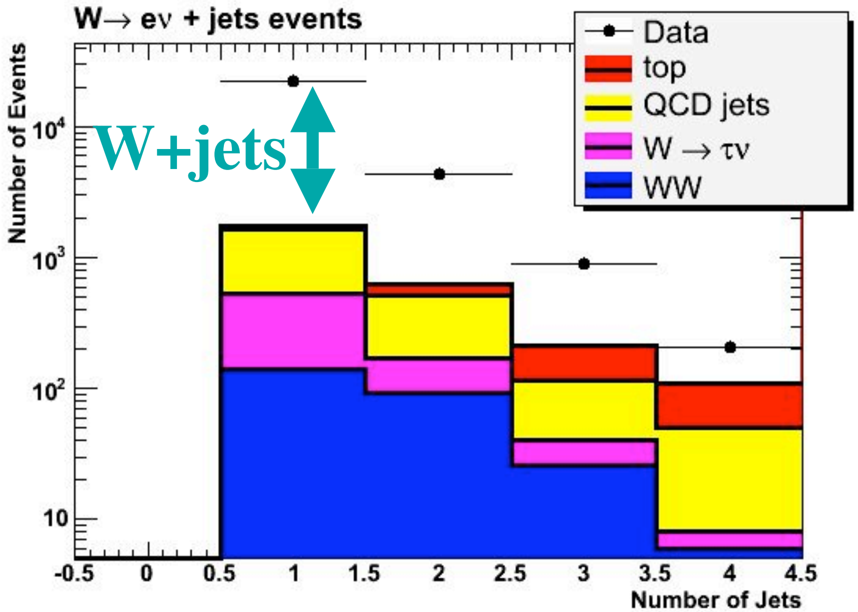


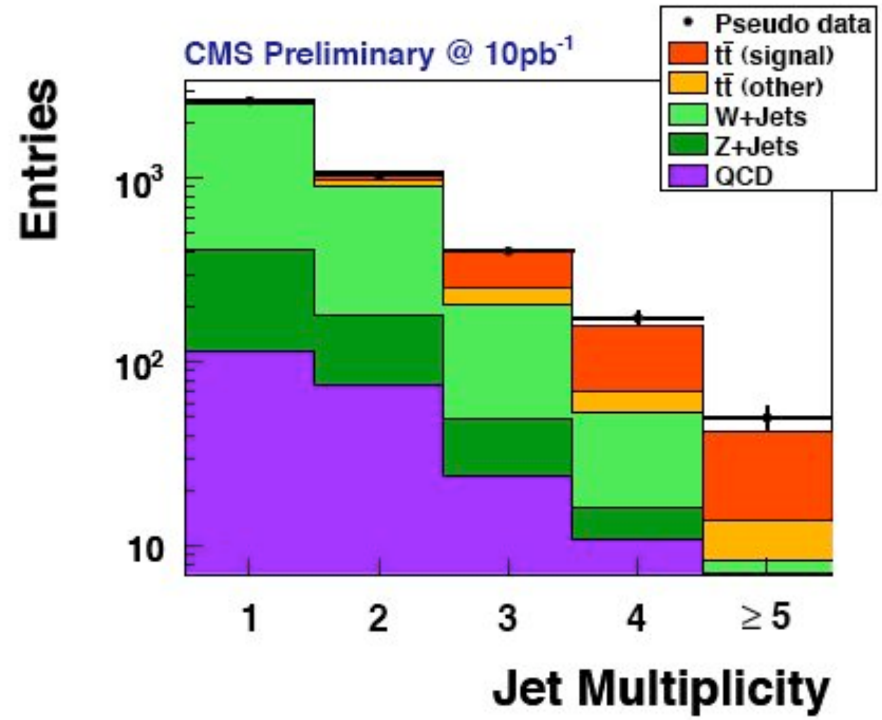
Top Event Categories



Finding the Top at Tevatron and LHC without b-quak identification

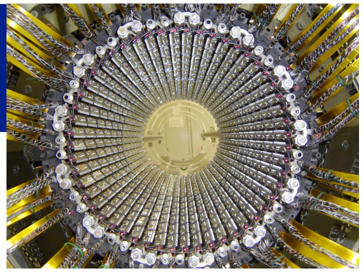
Tevatron



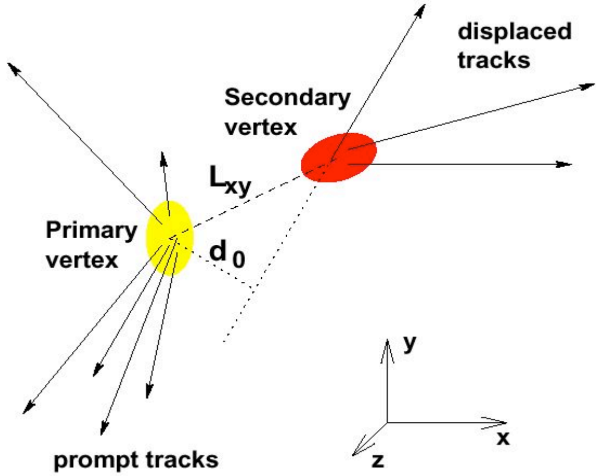


- Tevatron:
  - Top is overwhelmed by backgrounds:
  - Even for 4 jets the top fraction is only 30%
  - Use b-jets to purify sample
- LHC
  - Signal clear even without b-tagging: S/B>1.5

Finding the b-jets



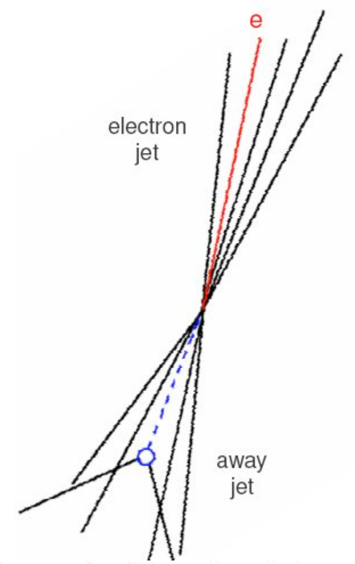
- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: $d=c\tau$
    - Lifetime τ =1.5 ps^{-1}
    - $d=c\tau$ = 460 μm
    - Can be resolved with silicon detector resolution

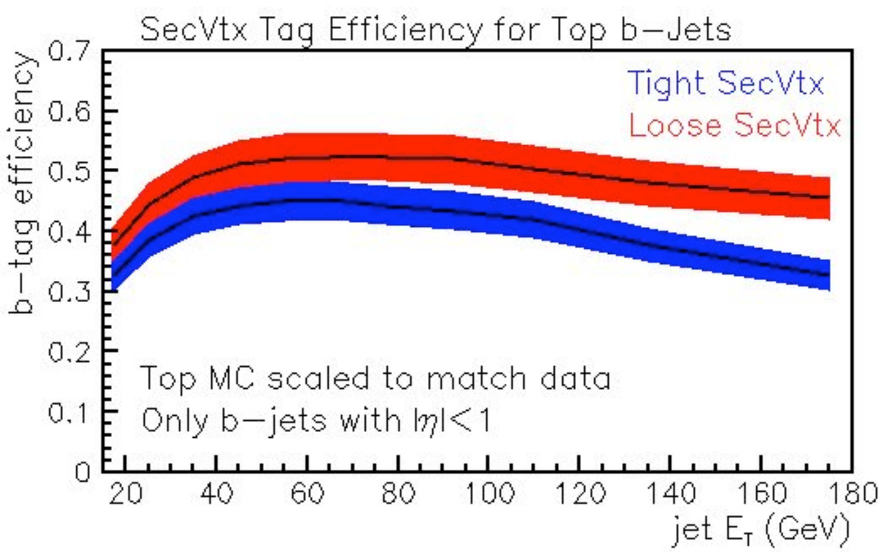


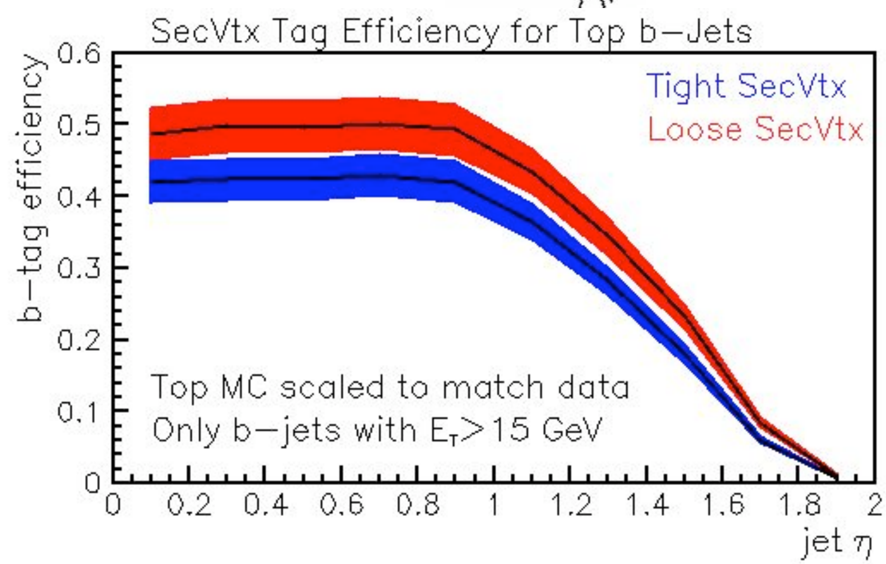
- Procedure “Secondary Vertex”:
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with primary vertex (large d_0):
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - Require displacement of secondary from primary 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: e.g. $\delta L_{xy} / L_{xy}$ >7 (i.e. 7σ significant displacement)
- More sophisticated techniques exist

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



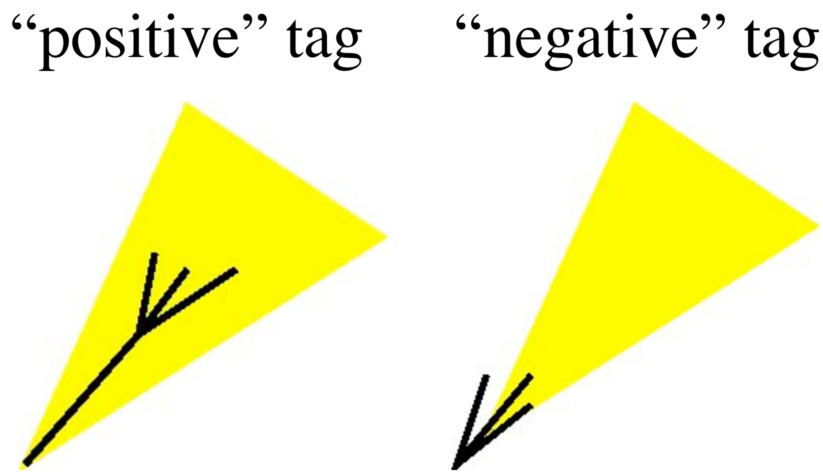


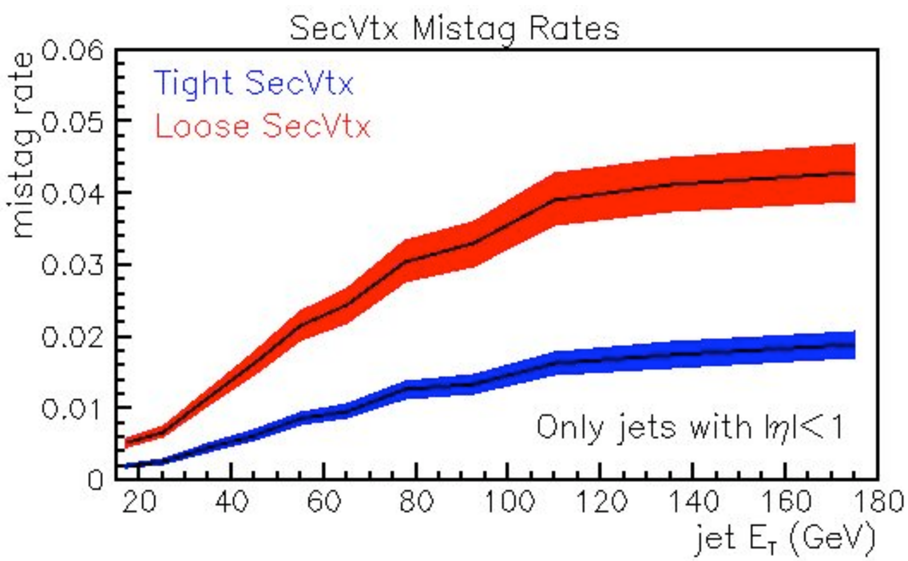


Achieve efficiency of about 40-50% at Tevatron
(can use top events directly to measure efficiency at LHC)

Characterise the B-tagger: Mistag rate

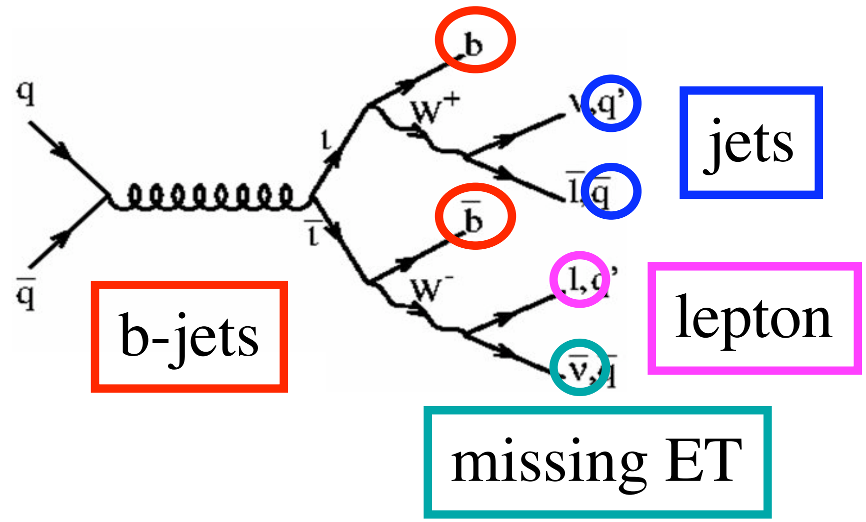
- Mistag Rate measurement:
  - Probability of light quarks to be misidentified
  - Use “negative” tags: $L_{xy}<0$
    - Can only arise due to misreconstruction
  - Mistag rate for E_T=50 GeV:
    - Tight: 0.5% (ε=43%)
    - Loose: 2% (ε=50%)
  - Depending on physics analyses:
    - Choose “tight” or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

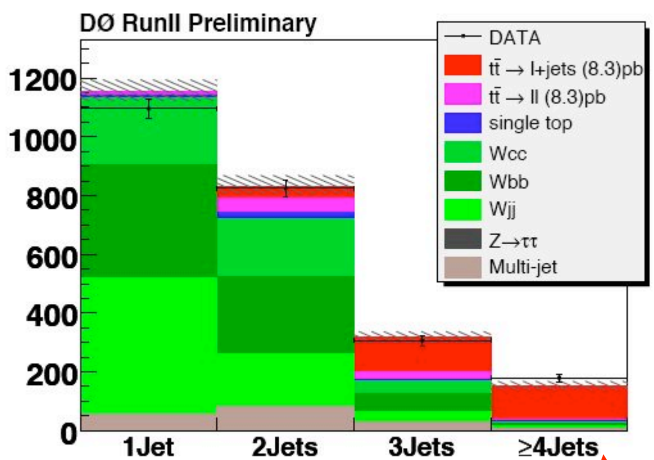


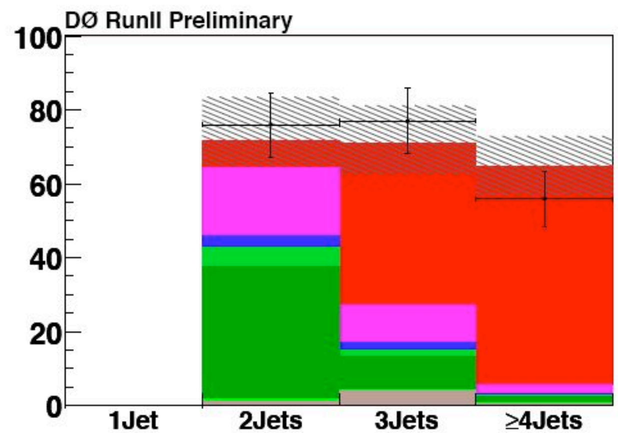


The Top Signal: Lepton + Jets

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







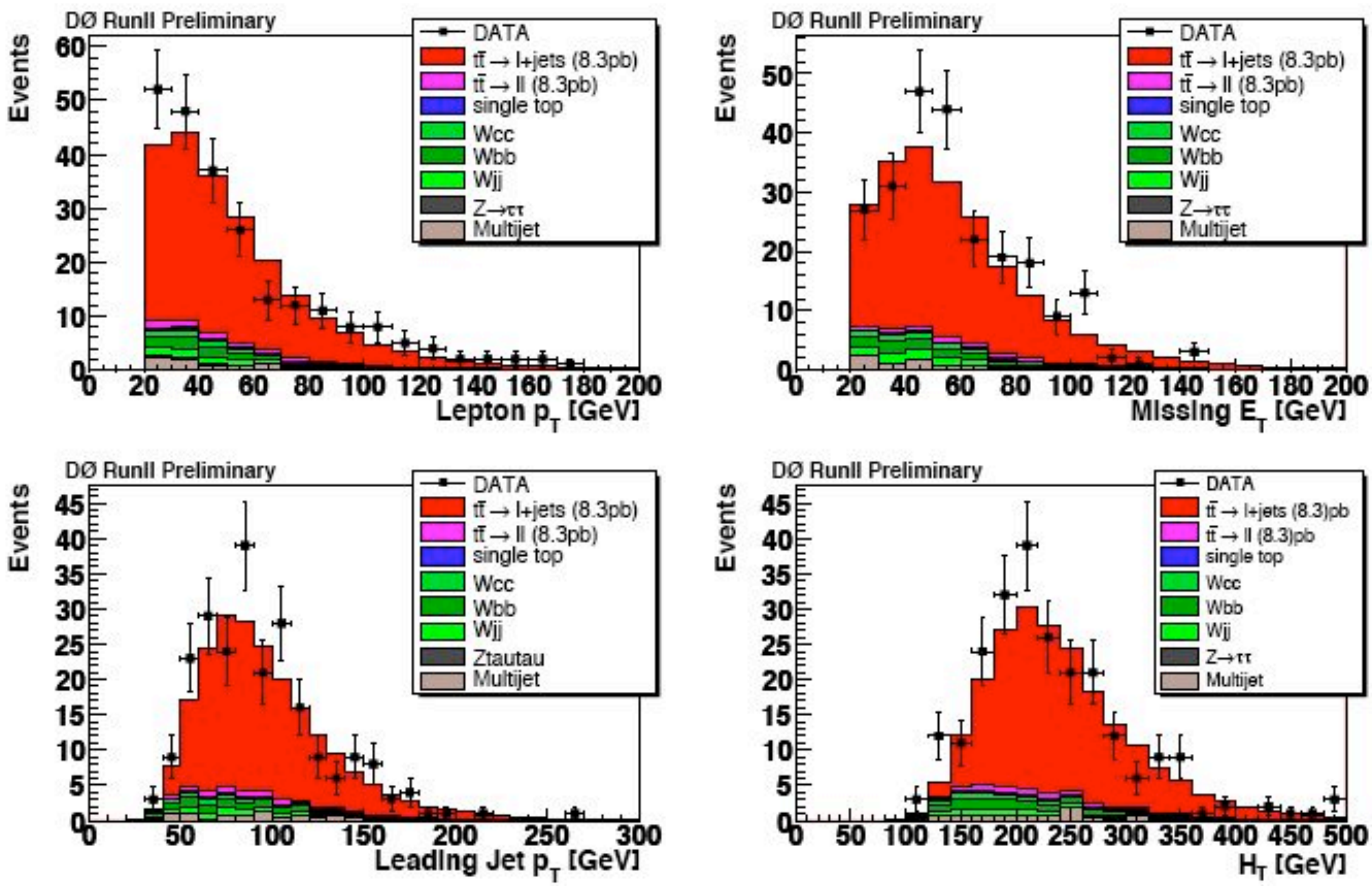
double-tagged events, nearly no background

Check backgrounds

Top Signal

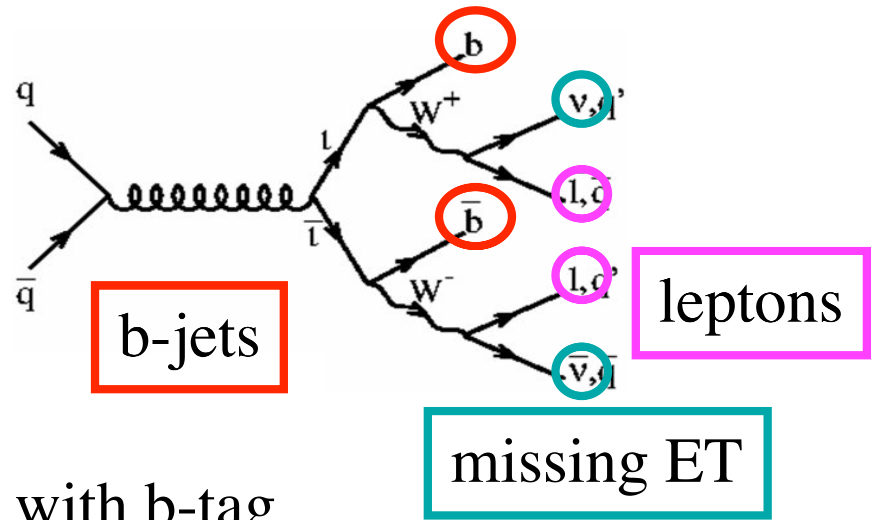
$\sigma(t\bar{t}) = 8.3^{+0.6}_{-0.5}(\text{stat}) \pm 1.1\ (\text{syst})$ pb

Data and Monte Carlo Comparison

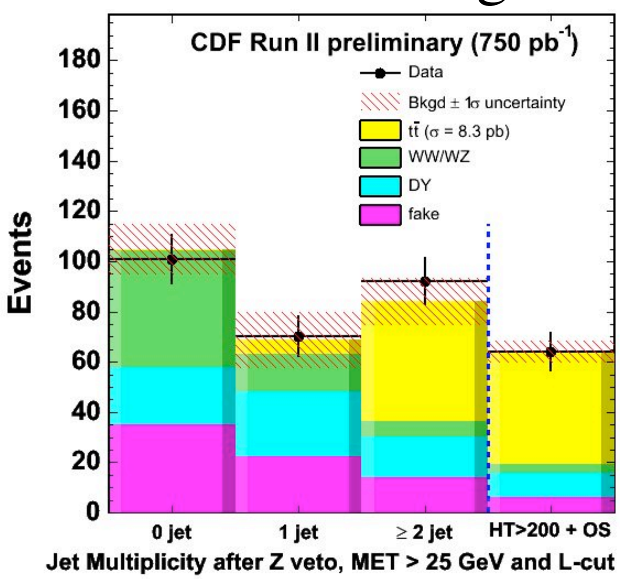


The Top Signal: Dilepton

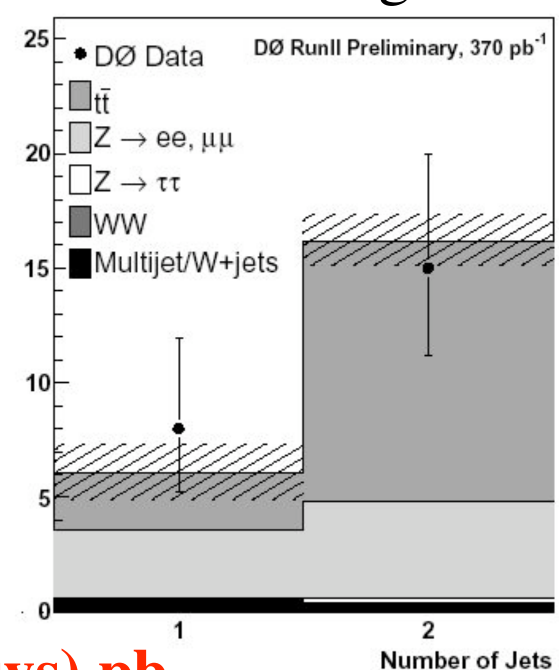
- Select:
  - 2 leptons: ee, eμ, μμ
  - Large missing E_T
  - 2 jets (with or w/o b-tag)



w/o b-tag

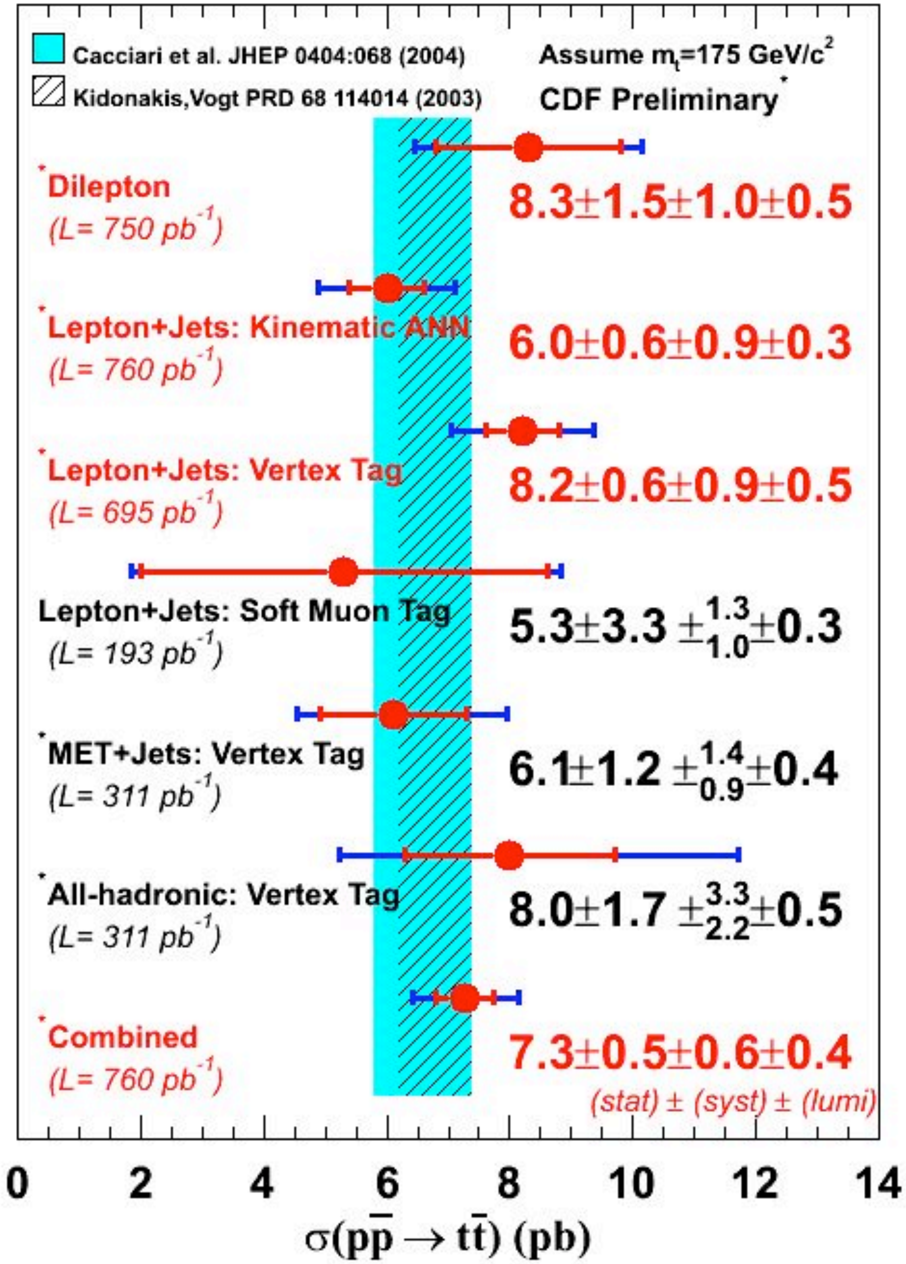


with b-tag



σ = 6.2 ± 0.9 (stat) ± 0.9 (sys) pb

The Top Cross Section



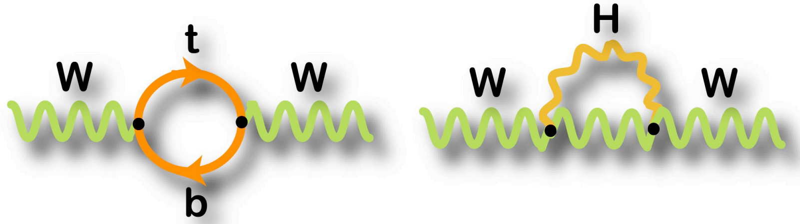
- **Tevatron**
  - Measured using many different techniques
  - Good agreement
    - between all measurements
    - between data and theory
  - Precision: ~13%
- **LHC:**
  - Cross section ~100 times larger
  - Measurement will be one of the first milestones (already with 10 pb^{-1})
    - Test prediction
    - demonstrate good understanding of detector
  - Expected precision
    - ~4% with 100 pb^{-1}

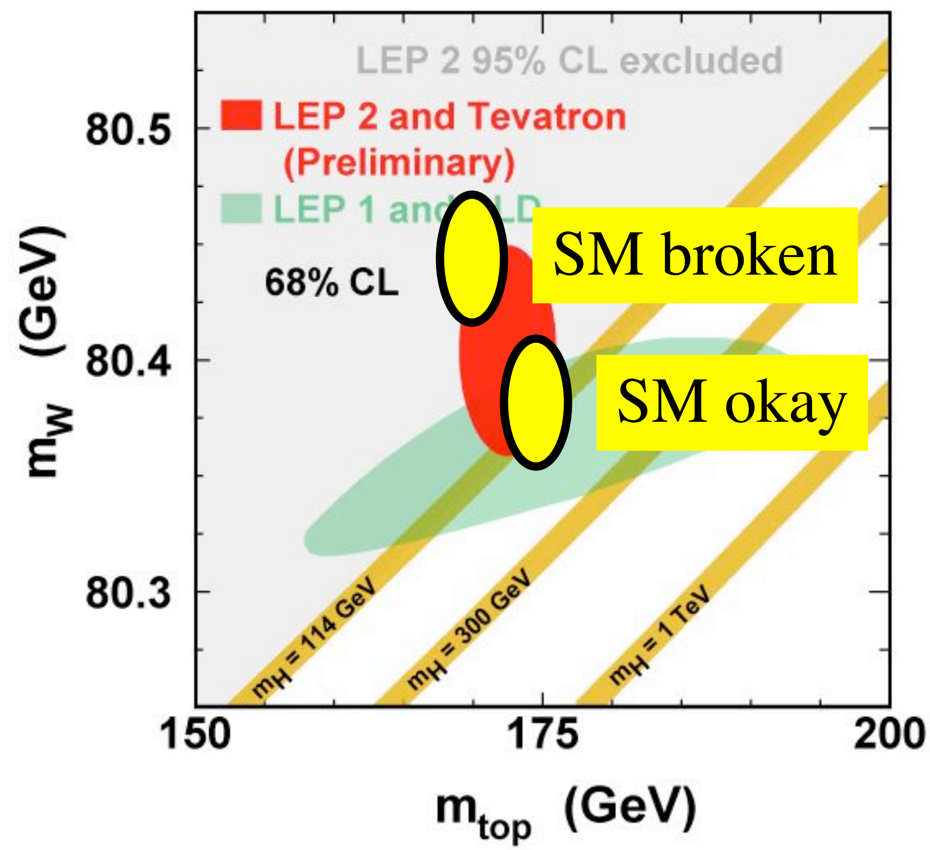
Precision Measurement of Electroweak Sector of the Standard Model

- W boson mass
- Top quark mass
- Implications for the Higgs boson

The W boson, the top quark and the Higgs boson

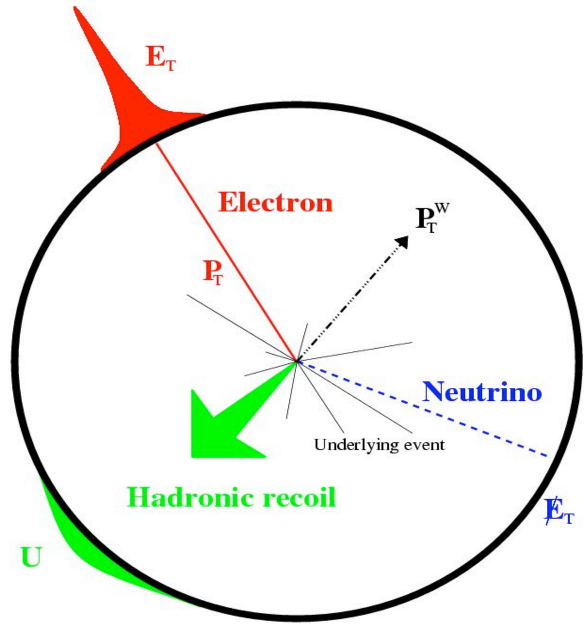
- Top quark is the heaviest known fundamental particle
  - Today: m_{top}=172.6+-1.4 GeV
  - Run 1: m_{top}=178+-4.3 GeV/c^2
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
    - <H>/(√2 mtop) = 1.008+-0.008
- Masses related through radiative 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





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 $1/\sqrt{N_Z}$ $(=1/\sqrt{L})$

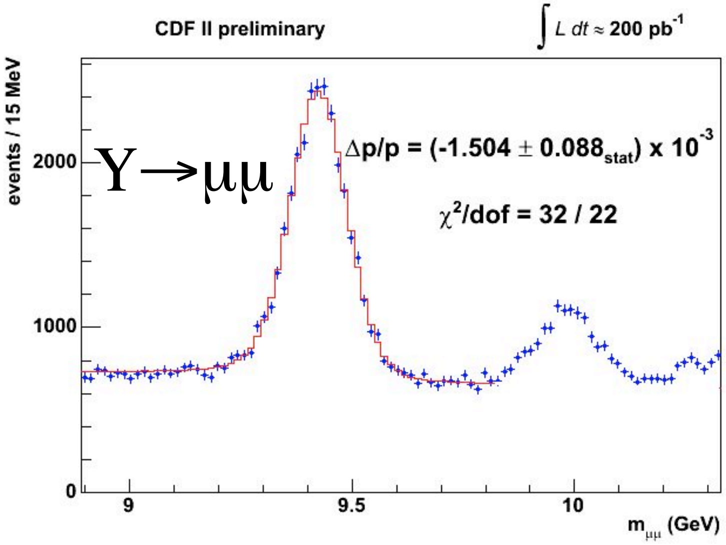


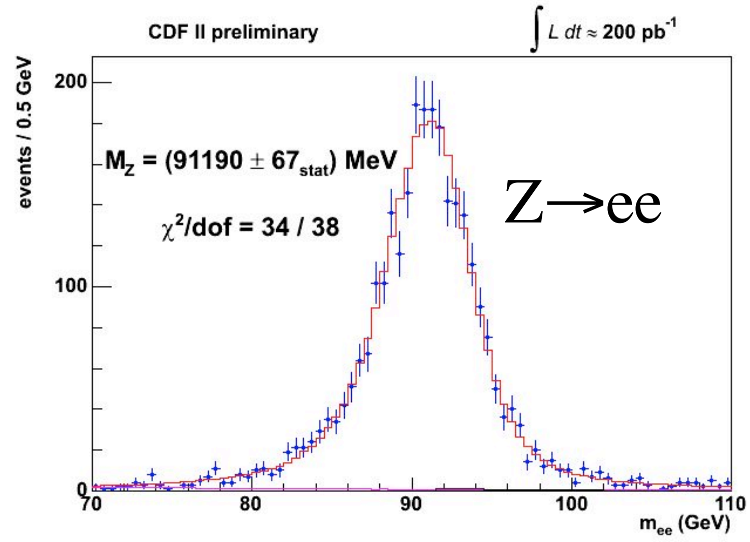
$$m_T = \sqrt{2 p_T^l \not{p}_T \left(1 - \cos\Delta\phi\right)},$$

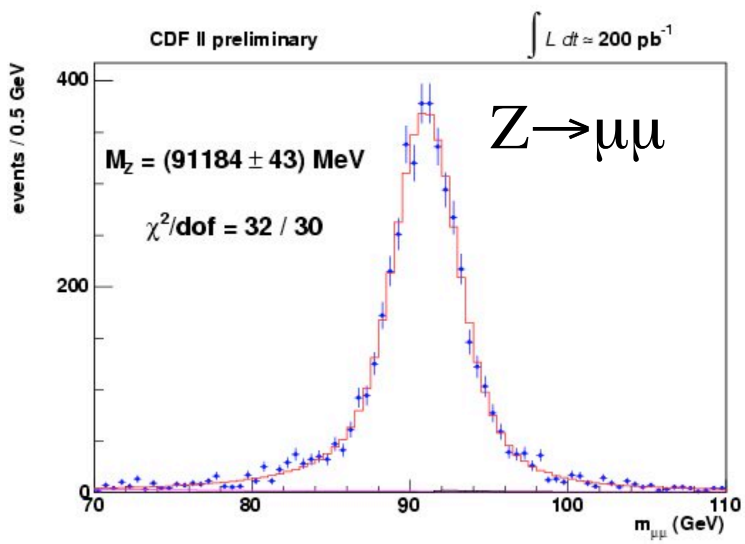
$$\not{p}_T \approx |p_T + u_{||}|$$

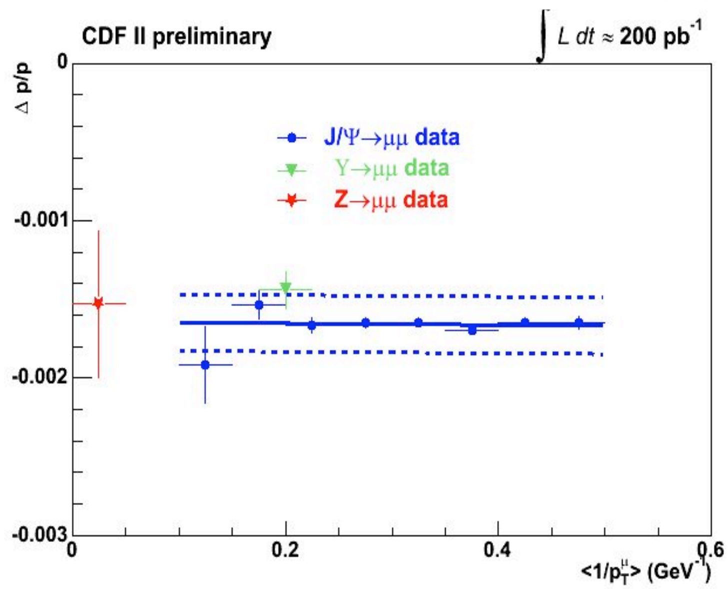
$$m_T \approx 2p_T\sqrt{1 + u_{||}/p_T} \approx 2p_T + u_{||}$$

Lepton Momentum Scale and Resolution









- **Systematic uncertainty on momentum scale: 0.04%**

Systematic Uncertainties

m_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

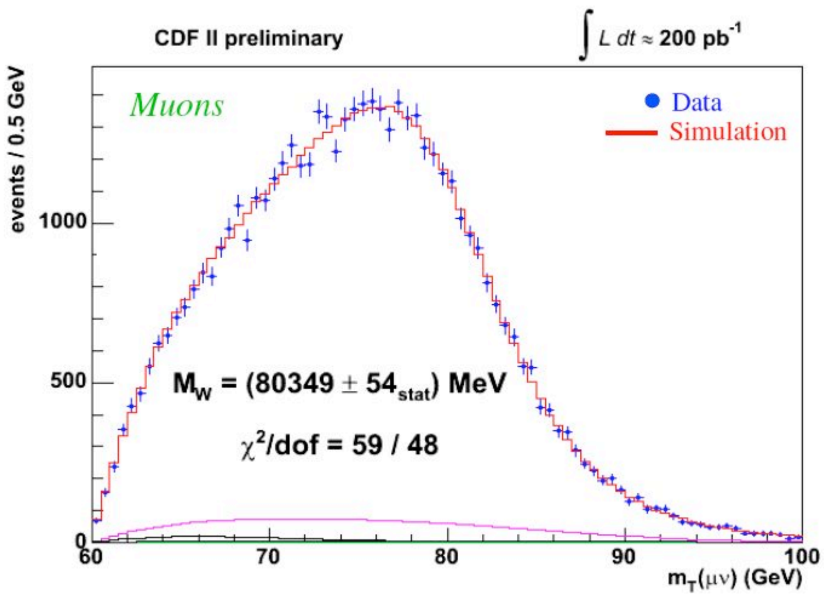
Limited by data statistics

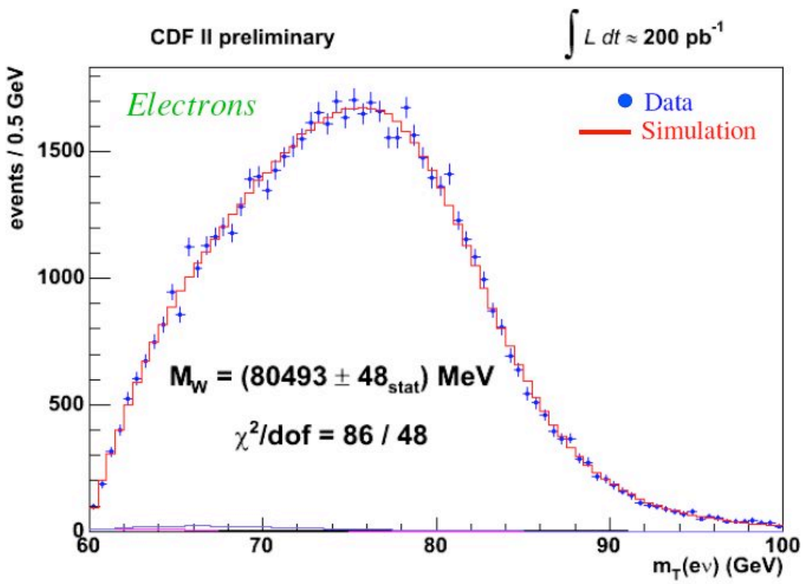
Limited by data and theoretical understanding

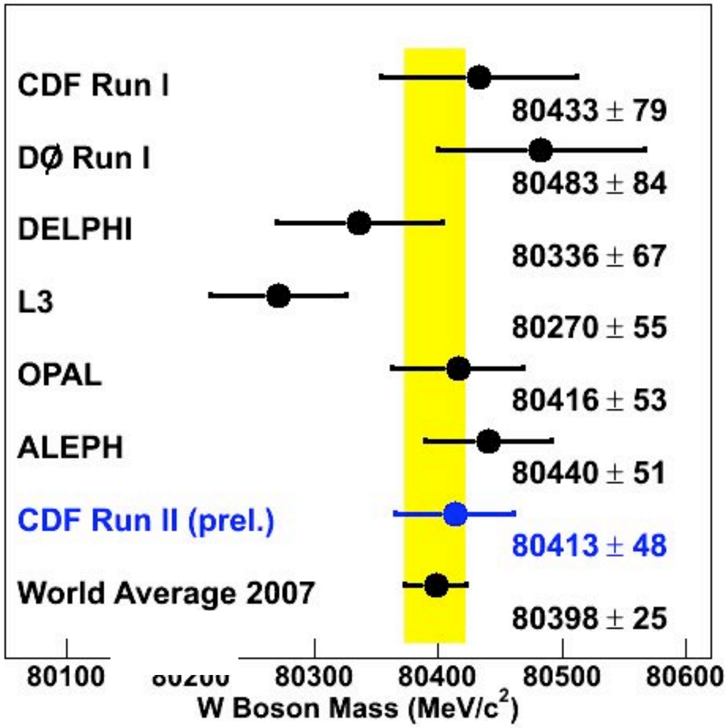
TABLE IX: Uncertainties in units of MeV on the transverse mass fit for m_W in the $W \to \mu\nu$ and $W \to e\nu$ samples.

- 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

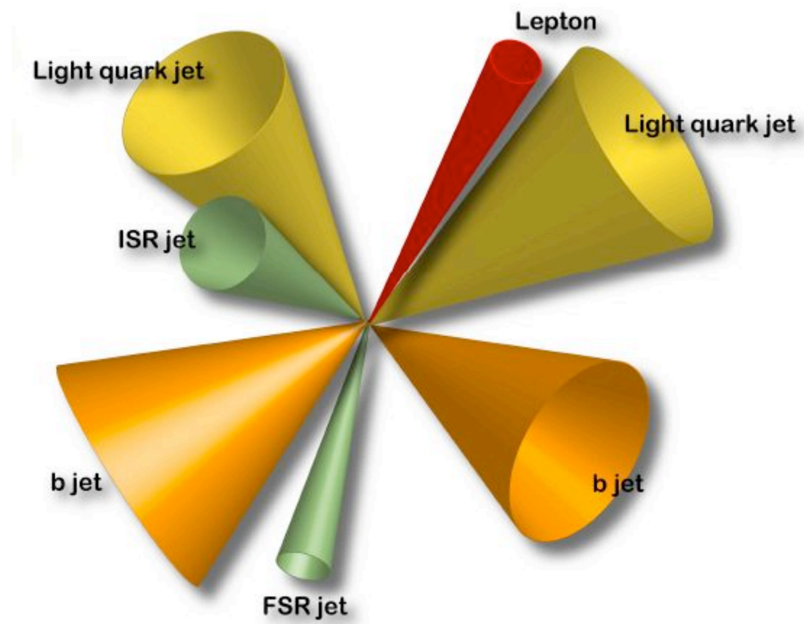
Ultimate precision:

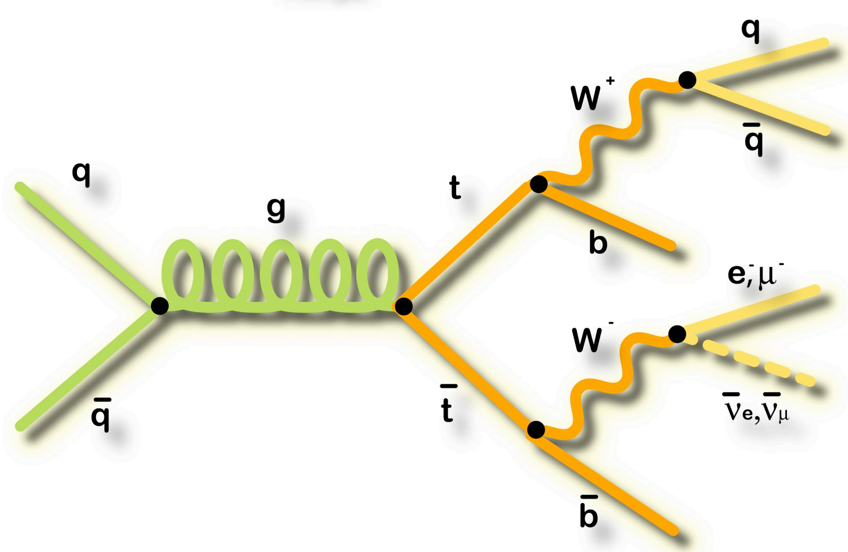
Tevatron: 15 MeV

LHC: unclear (5 MeV?)

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

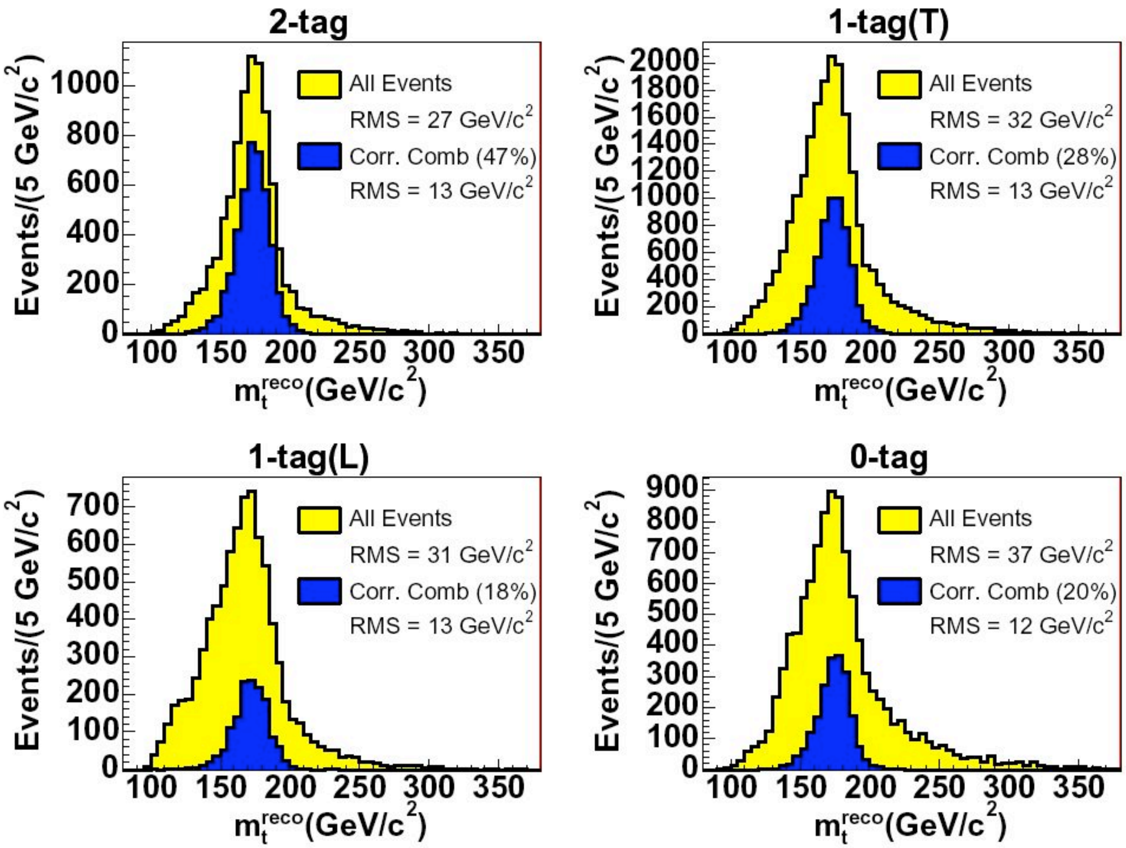
- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag   => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires $m(t)=m(\bar{t})$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





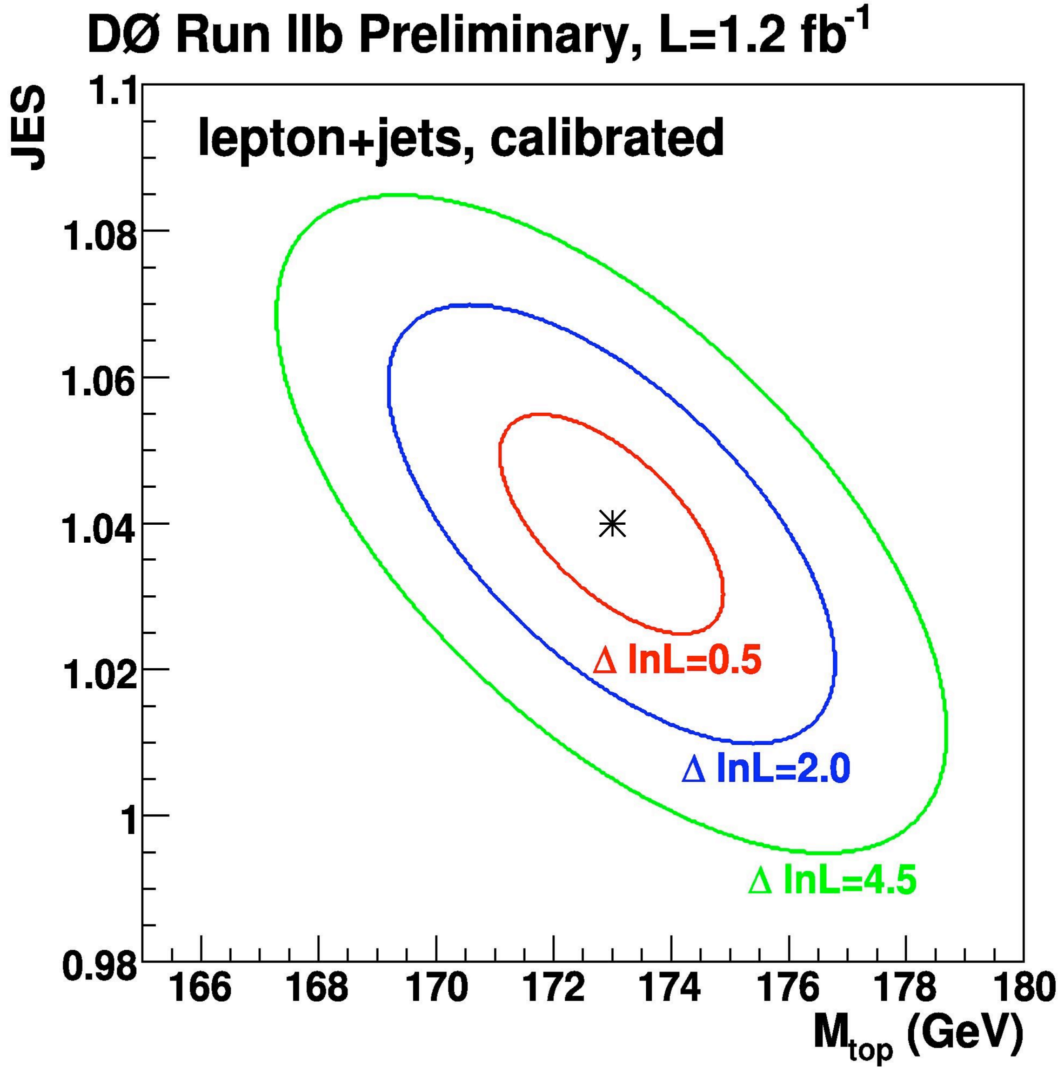
Top Mass Determination

- 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}
  - Leave jet energy scale ("JES") as free parameter



Selecting correct combination 20-50% of the time

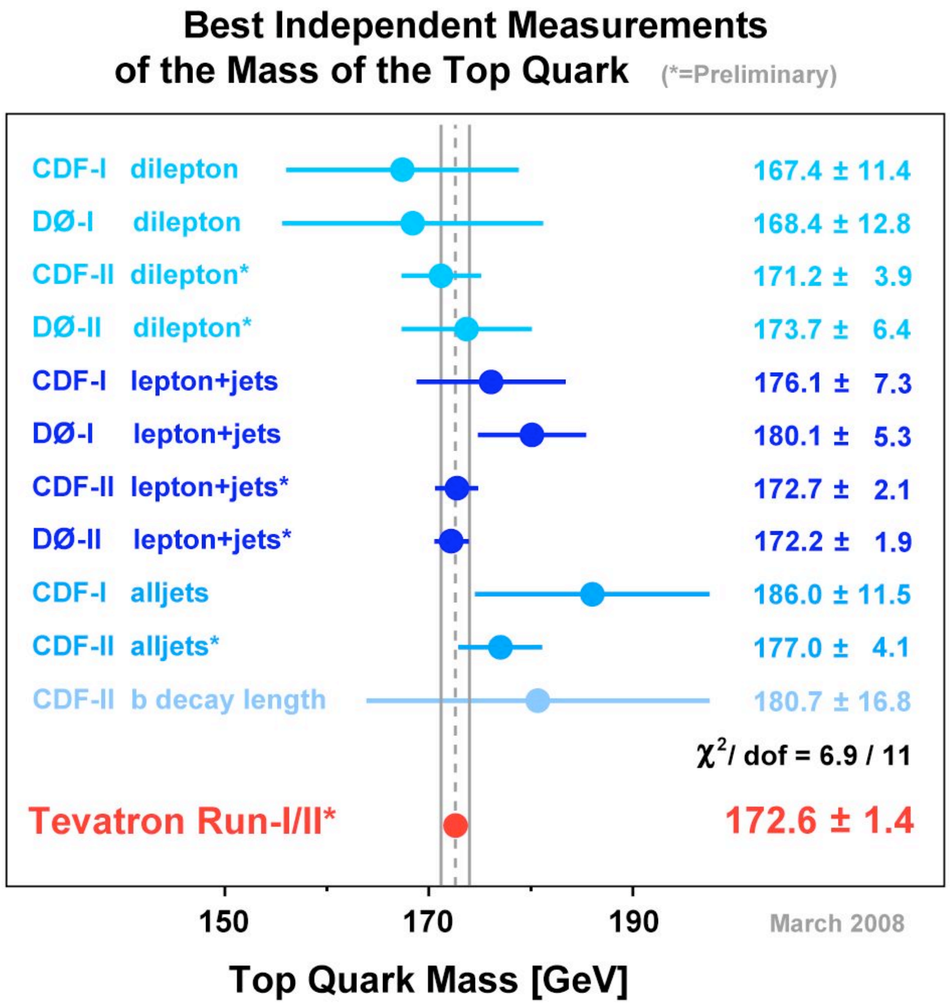
Example Results on m_{top}



172.2 +/- 1.9 GeV/c^2

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
- **Uncertainty: 1.4 GeV**
  - Dominated by syst. uncertainties
- Precision so high that theorists wonder about what it's exact definition is!

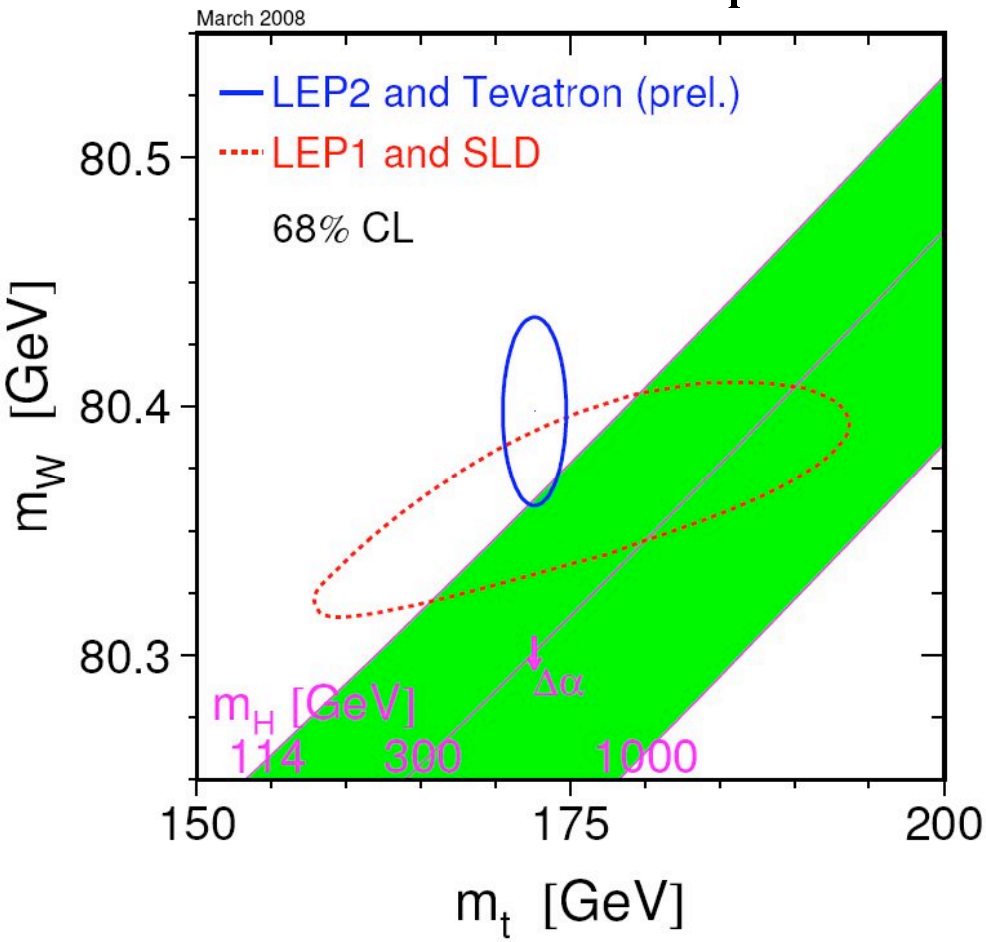


Tevatron/LHC expect to improve precision to ~1 GeV

Implications for the Higgs Boson

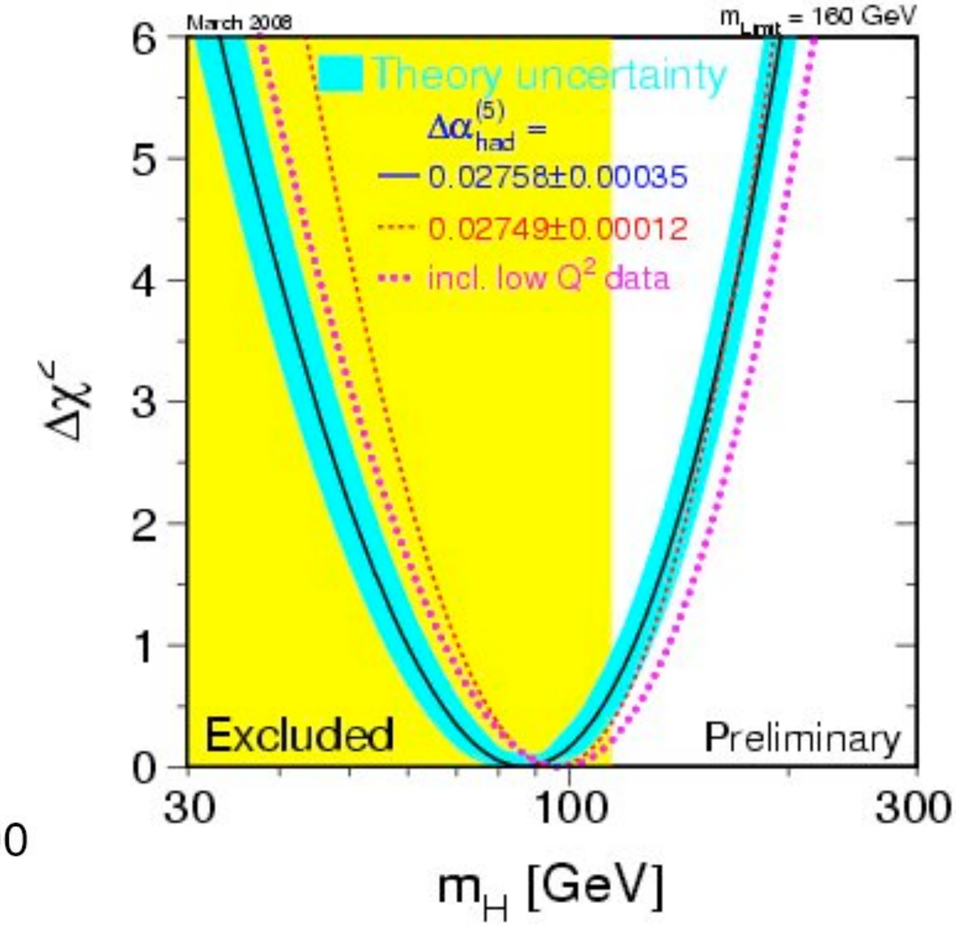
LEPEWWG 03/08

Relation: M_W vs m_{top} vs M_H



Standard Model still works!

$m_H = 86^{+36}_{-27}$ GeV



Indirect constraints:
m_H<160 GeV @95%CL

Conclusions

- Perturbative QCD describes hadron collider data successfully:
  - Jet cross sections: $\Delta\sigma/\sigma \approx$ 20-100%
  - W/Z cross section: $\Delta\sigma/\sigma \approx$ 6%
  - Top cross section: $\Delta\sigma/\sigma \approx$ 15%
- High Precision measurements
  - W boson mass: $\Delta M_W/M_W$ =0.031%
  - top quark mass: $\Delta m_{top}/m_{top}$=0.8%
- Standard Model still works!
  - Higgs boson constrained
    - $114<m_H<160$ GeV/c^2 at 95% C.L.
  - Let's look for it in the next lecture!